

Astrophysics Group  
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# **Dusty Star-Forming Galaxies and their Environments**

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## Abstract

Since their discovery over three decades ago, there has been astounding progress in our understanding of DSFGs. Roughly half all optical and UV emission from star formation is absorbed and re-radiated as infrared light by dust. This dust enshrouded star formation is contained within DSFGs, with some harbouring SFRs of thousands of solar masses per year, yielding infrared luminosities greater than  $10^{13} L_{\odot}$ . DSFGs are thought to be the progenitors of elliptical galaxies that are predominantly found within massive, galaxy clusters in the local Universe. This thesis aims to build on this progress by investigating the nature of DSFGs and their environments. We first investigate the molecular gas properties of galaxies in the Antlia cluster, a potentially useful low redshift analogue to developing protoclusters at higher redshifts. We find that the disturbed cluster environment is not strong enough to strip the molecular gas reservoirs of its member galaxies, yielding the observed high SFRs in this population. We also study the properties of candidate members of the massive SpARCS-0330 galaxy cluster at  $z \sim 1.6$ , where we find significant ongoing star formation. Quenching in SpARCS-0330 is likely driven by secular processes that scale with stellar mass rather than environment, suggesting that either the cluster environment cannot truncate star formation or the galaxy members have not yet inhabited the cluster for long enough to be significantly affected. We also investigate the multiplicities and properties of four candidate  $z > 4$  DSFGs. We find that three resolve into multiple components, suggesting that this population is more diverse than predicted by simulations. We additionally investigate SDSS1607, a fascinating quasar-SMG system at  $z = 3.65$ , using observations from the VLA, SMA and *HST*. Finally, we discuss the implications of these results and the exciting avenues for future research produced by this work.



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## Dedication

*To Amy,  
For your love and support  
Through this adventure  
And those to come.*

*... The universe is, instant by instant, recreated anew.*

*... There is in truth no past, only a memory of the past.*

*Blink your eyes, and the world you see next did not exist when you closed them.*

*Therefore, the only appropriate state of the mind is surprise.*

*The only appropriate state of the heart is joy.*

*The sky you see now, you have never seen before.*

*The perfect moment is now.*

*Be glad of it.*

— Terry Pratchett, *Thief of Time*



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# Chapter 1

## Introduction

### 1.1 A Brief Introduction to Cosmology

#### 1.1.1 The $\Lambda$ -CDM Model

Our modern cosmological models are the result of thousands of years of dedicated thought and study. However, it wasn't until the early 20<sup>th</sup> century that the ground-breaking observations of Shapley and Hubble truly started to reveal the nature of the Universe and our place within it.

Based on their observations and countless others, we find that our Universe appears to be homogeneous and isotropic on large scales, flat, and expanding at an accelerating rate (e.g. Hubble, 1929; Riess et al., 1998; Planck Collaboration et al., 2016, 2020). Many modern cosmological models have been proposed to explain the observed features of our Universe, but the model that is currently most favoured is known as the  $\Lambda$ -CDM model. In this model, the Universe is comprised of three components; an unknown form of energy known as dark energy, closely associated with the cosmological constant  $\Lambda$ ; a hypothetical form of matter known as dark matter (with “CDM” referring to cold, or non-relativistic, dark matter); and baryonic matter. Recent observations suggest that dark energy makes up the majority ( $\approx 69\%$ ) of the energy density of the Universe, while matter (including both dark matter and baryonic matter) and radiation make up  $\approx 31.5\%$  and  $\ll 1\%$  of the energy density of the Universe respectively

(Planck Collaboration et al., 2020).

In the  $\Lambda$ -CDM model, the Universe began  $\sim 13.8$  billion years ago (Planck Collaboration et al., 2020) with the Big Bang, a concept (arguably) first posited by Lemaître (1927, 1931). This was followed by a period of inflation (e.g. Guth, 1981; Sato, 1981a,b; Guth and Pi, 1982; Linde, 1982; Albrecht and Steinhardt, 1982; Linde, 1983) which left the Universe as a high energy, opaque plasma with all particle species in local thermodynamic equilibrium. The existence and nature of this inflationary period is still a topic of vigorous debate, but in our current paradigm it remains necessary to address a number of conceptual problems with  $\Lambda$ -CDM cosmology, most notably the Horizon and Flatness problems (e.g. Guth, 1981; Tsujikawa, 2003; Baumann, 2009). As the Universe expanded and cooled, particles began to decouple from this plasma. Around 2 – 3 minutes after the Big Bang, the Universe was cool enough for Big Bang nucleosynthesis to begin, in which protons and neutrons combined to produce the first light elements, including He and Li (Baumann, 2009). After subsequent cooling, this was followed by recombination (e.g. Zeldovich et al., 1969), in which H nuclei captured electrons to produce the first H atoms. As matter transitioned from a hot plasma into neutral atoms, photons were no longer coupled to free electrons via Thomson scattering and hence were allowed to travel freely, producing the relic radiation observed today as the Cosmic Microwave Background (CMB: Penzias and Wilson, 1965), observations of which provide much of the basis of our modern cosmological framework (e.g. Baumann, 2009; Planck Collaboration et al., 2020). The subsequent epoch in the history of the Universe is typically known as the Dark Ages as, although the Universe had become transparent, the first stars and galaxies were yet to have formed.

### 1.1.2 The Formation of Stars, Galaxies and Clusters

The key to the formation of the observed ‘Cosmic Web’ of large scale structure (Bond et al., 1996) in the  $\Lambda$ -CDM model is the fact that the Universe exhibited small density fluctuations superimposed onto the homogeneous and isotropic background that were generated during the inflationary epoch (e.g. Hawking, 1982; Starobinsky, 1982; Guth and Pi, 1982; Bardeen et al., 1983). The presence of these primordial density fluctuations is inferred from small



anisotropies of order  $\sim 10^{-5}$  measured in the CMB (e.g. Freeman and Bland-Hawthorn, 2002). Overdense regions became more dense by attracting nearby material, but must also have grown spatially due to the expansion of the Universe. The result of these two competing effects is that overdensities grew in spatial scale proportionally to a power law, and hence slower than the surrounding regions of the Universe, but continued to become denser due to the attraction of the surrounding gas (e.g. Partridge and Peebles, 1967; Baumann, 2009). At some “turn-around” point, a growing overdensity would have become dense enough to break away from the Universe’s expansion to collapse under its own gravity, providing the seeds for large scale structure formation (e.g. Partridge and Peebles, 1967; Gott, 1977; Kravtsov and Borgani, 2012).

The different forms of matter contained within these overdensities are expected to have collapsed differently. Dark matter acts only through the gravitational force and, as such, cannot effectively cool as it collapses. Instead, the system is driven to a state of quasi-equilibrium via a process known as violent relaxation (Lynden-Bell, 1967), in which the mixing of dark matter particles in a time-dependent gravitational potential causes a rapid broadening in their distribution of energies. Through this process of mixing, individual dark matter particles can either gain or lose energy, but the overarching effect is that particles are either expelled or settle into more stable orbits, such that the total system tends towards a state of quasi-equilibrium, although never settling into a perfectly relaxed system (Tremaine et al., 1986). As such, dark matter halos likely formed first in the history of large scale structure, but may still be evolving in the present epoch (Freeman and Bland-Hawthorn, 2002).

The baryonic matter is collisional and can cool via numerous radiative processes during its collapse. This radiation provides some pressure support to oppose the effects of gravity, but efficient cooling would result in a catastrophic collapse of cold gas which, in turn, could fragment to produce the first stars within the first protogalaxies. Any residual angular momentum from tidal interactions during the initial collapse would provide rotational support to the system, such that the material would settle into a disc-like structure (e.g. Eggen et al., 1962; Partridge and Peebles, 1967). In the  $\Lambda$ -CDM paradigm, galaxy clusters are thought to be formed from the most massive gravitational instabilities in the Universe, followed by growth via the hierarchical build up of many individual halos containing either individual galaxies or galaxy groups (e.g.

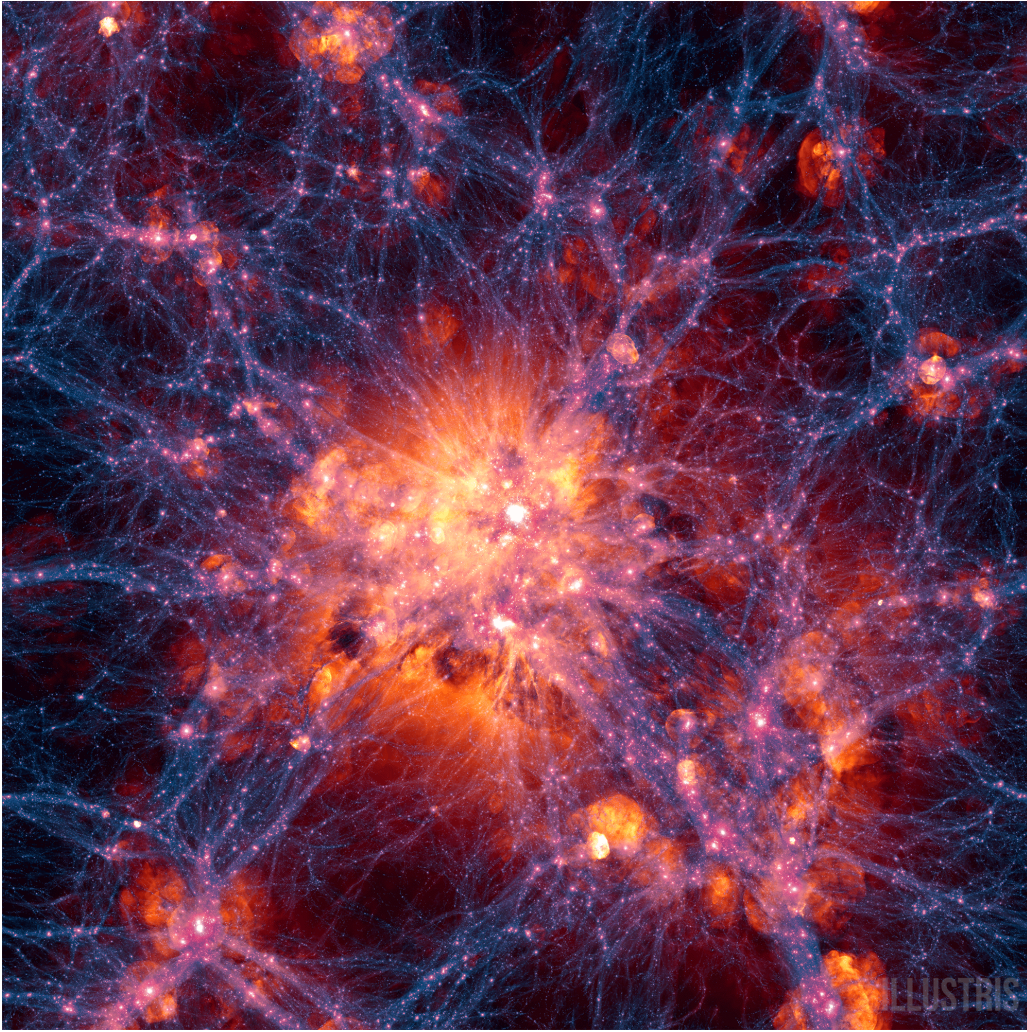


Figure 1.1: A visualisation of the ‘Cosmic Web’, centred on the most massive cluster in the Illustris simulations. Image credit: Illustris Collaboration (<https://www.illustris-project.org/media/>).

Van Albada, 1961; Peebles, 1970; Press and Schechter, 1974; White, 1976; White and Rees, 1978; Blumenthal et al., 1984; Davis et al., 1985; Freeman and Bland-Hawthorn, 2002; Kravtsov and Borgani, 2012). In Figure 1.1, we show the resulting Cosmic Web of large scale structure reproduced by the Illustris simulation.

## 1.2 Observational Astronomy in the Infrared

### 1.2.1 The Birth of FIR Astronomy

Prior to the 1990s, the vast majority of our understanding of the formation and evolution of galaxies was based on the Cosmic Optical Background, comprised of light with wavelengths between  $0.1 - 5 \mu\text{m}$  produced via direct emission from stars and Active Galactic Nuclei (AGN), and contamination from Zodiacal light (Driver et al., 2016; Andrews et al., 2017). However, as early as the 1960s (e.g. Low and Tucker, 1968) it had been postulated that, if dust were to exist in galaxies throughout cosmic history, then a large proportion of the light from both stellar nucleosynthesis and AGN would be reprocessed by dust into infrared wavelengths, producing an analogous Cosmic Infrared Background (CIB) spanning  $\approx 5 - 1000 \mu\text{m}$  (Savage and Mathis, 1979; Puget et al., 1996; Fixsen et al., 1998; Hauser and Dwek, 2001; Driver et al., 2008).

The first satellite designed to provide deep observations in the infrared was the Infrared Astronomical Satellite (*IRAS*: Neugebauer et al., 1984), launched in 1983 with the aim of surveying the entire sky at infrared wavelengths. *IRAS* was fitted with four filters with central wavelengths of 12, 25, 60 and  $100 \mu\text{m}$ , as well as a Low Resolution Spectrometer with a wavelength range of  $7.5 - 23 \mu\text{m}$  and a resolving power<sup>1</sup> of  $14 - 35$  (Neugebauer et al., 1984). *IRAS* successfully surveyed more than 96% of the sky, mapping  $\approx 250,000$  point sources as well as  $\approx 20,000$  extended sources down to a limiting flux density of  $0.5 \text{ Jy}$  in the 12, 25 and  $60 \mu\text{m}$  filters, and  $1.5 \text{ Jy}$  in the  $100 \mu\text{m}$  filter (Beichman et al., 1988). These observations resulted in the discovery of a population of galaxies that emit  $> 95\%$  of their bolometric luminosity in the IR, clearly distinct from the population of optical and UV bright sources (Soifer et al., 1987), and more recently classified as Luminous Infrared Galaxies (LIRGs:  $10^{12} L_{\odot} > L_{\text{IR}} \geq 10^{11} L_{\odot}$ , Sanders, 1997). Subsequent observations discovered more IR-luminous examples of this population, leading to the classification of Ultra-Luminous Infrared Galaxies (ULIRGs:  $10^{13} L_{\odot} > L_{\text{IR}} \geq 10^{12} L_{\odot}$ ), and Hyper-Luminous Infrared Galaxies (HLIRGs:  $L_{\text{IR}} > 10^{13} L_{\odot}$ ), the brightest individual FIR/sub-mm objects in the Universe (e.g.

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<sup>1</sup>Resolving power is defined as  $R = \lambda/\Delta\lambda$ , where  $\Delta\lambda$  is the difference in wavelengths that can be distinguished at a wavelength of  $\lambda$ .

Rowan-Robinson, 2000; Lonsdale et al., 2006). It was predicted that such a population would produce a significant CIB, and so observing this CIB became one of the scientific objectives of the *Cosmic Background Explorer* (*COBE*) satellite, launched in 1989.

*COBE* was fitted with three instruments, two of which could detect and characterise the CIB. The Diffuse Infrared Background Experiment (DIRBE) probed the  $1 - 300\ \mu\text{m}$  wavelength range in 10 bands, while the two channels of the Far-Infrared Absolute Spectrometer (FIRAS) extended this range from  $0.12\ \text{mm}$  out to  $1\ \text{cm}$  (Boggess et al., 1992). Puget et al. (1996) made the first tentative detection of the CIB with the FIRAS instrument, and the CIB spectrum was later characterised by the full FIRAS and DIRBE datasets (Fixsen et al., 1996, 1998). The results from *COBE* demonstrated that the total energy density of the CIB is comparable to that of the COB.

Subsequent observations strengthened this conclusion. By integrating the SED shape yielded by stacked infrared observations from *ISO*, *Spitzer* MIPS, FIRAS and SCUBA, between  $\approx 8 - 1000\ \mu\text{m}$  and comparing to a similar analysis based on optical observations from *HST*, HESS and *Spitzer* IRAC from  $\approx 0.1 - 8\ \mu\text{m}$ , Dole et al. (2006) estimate total energy densities of  $23\ \text{nW m}^{-2}\ \text{sr}^{-1}$  and  $24\ \text{nW m}^{-2}\ \text{sr}^{-1}$  for the COB and CIB respectively. Similar values were recovered by Driver et al. (2016) based on deep galaxy number counts from the Galaxy and Mass Assembly Survey (GAMA: Driver et al., 2009) and the Cosmic Evolution Survey (COSMOS: Scoville et al., 2007), and from the LORRI camera on *New Horizons* (Lauer et al., 2021). These results suggest that we can directly observe just half of the total amount of light produced from stars and AGN across cosmic time, with the other half reprocessed by dust.

Moreover, direct measurements of the total energy density from the CIB broadly agree with estimates of the total energy density produced by Dusty Star-Forming Galaxies (DSFGs) based on analyses of integrated galaxy number counts across a range of wavelengths (Dole et al., 2006; Béthermin et al., 2012; Magnelli et al., 2013; Geach et al., 2013a; Driver et al., 2016), indicating that DSFGs are likely responsible for the vast majority of the total emission from the CIB. DSFGs must therefore provide a significant contribution to the total energy density emitted by galaxies, likely representing a vital stage in their formation and evolution. These early findings

provided the groundwork for what would become a key field in the study of galaxy formation and evolution.

### 1.2.2 Details of IR Astronomy

DSFGs are challenging to observe, primarily because the direct emission from starlight and AGN is efficiently absorbed by dust in the ISM and re-radiated in the infrared region of the spectrum, making them faint or even invisible in the optical. As such, the identification and characterisation of DSFGs typically requires observations in the FIR/sub-mm regime where the emission spectrum from dust is at its most luminous. In this section, we discuss the benefits and challenges of infrared observations.

#### Dust Emission and Attenuation

One of the more complex challenges facing infrared astronomy is understanding the manner in which dust in the Interstellar Medium (ISM) processes light, both in terms of the attenuation of UV and optical emission from stars and AGN, and the infrared emission from dust grains. Both effects are complex, and depend on the density, geometry and composition of the interstellar dust, as well as numerous other factors.

The absorption, scattering and emission properties of interstellar dust depend crucially on its composition, typically inferred from a number of spectral features in both its emission spectrum and extinction curve. The latter characterises the attenuation of starlight by dust as a function of wavelength, including the effects of both absorption and scattering. In the Milky Way, the strongest spectroscopic dust extinction feature lies at  $2175\text{\AA}$ , coinciding closely with the expected position and width of absorption from small spheres of graphite (Stecher and Donn, 1965; Draine, 2004b). This feature is most likely produced by Polycyclic Aromatic Hydrocarbon (PAH) molecules; aromatic rings of Carbon surrounded by Hydrogen atoms (Draine, 2004b). The numerous vibrational modes of PAH molecules stochastically excited by UV photons are additionally responsible for a series of strong lines in the emission spectra of dust between

$\approx 3 - 14 \mu\text{m}$  (e.g. Leger and Puget, 1984; Allamandola et al., 1985; Li and Draine, 2001; Draine, 2004b). At  $9.7 \mu\text{m}$ , another strong feature typically appears in the dust extinction curve, likely due to the Silicon-Oxygen stretching mode of silicate dust grains (Draine, 2004a,b). An additional absorption feature at  $3.4 \mu\text{m}$  is commonly observed in the ISM of the Milky Way, produced by the Carbon-Hydrogen stretching mode in aliphatic<sup>2</sup> hydrocarbons (Sandford et al., 1991; Draine, 2004b). Although the exact composition of interstellar dust remains a subject of intense research, most modern dust models can successfully reproduce the observed dust extinction curves and emission spectra with some combination of silicates and carbonaceous grains, including both graphite-like grains and PAH molecules, with smaller contributions from, for example, ices and/or metal oxides (Stein and Soifer, 1983; Siebenmorgen and Kruegel, 1992; Weingartner and Draine, 2001; Li and Draine, 2001; Draine, 2004b,a; Dwek, 2005; Draine and Li, 2007; Compi  gne, 2010; Siebenmorgen et al., 2014).

The grain size distribution also affects the absorption and emission properties of the interstellar dust. For example, modelling by Weingartner and Draine (2001) and Li and Draine (2001) suggests that a grain size distribution in which the silicate and graphite-like carbonaceous grain sizes peak at  $\approx 3000 \text{ \AA}$ , and the PAH grain size peaks at  $\approx 6 \text{ \AA}$  best recovers both the observed dust emission and the UV and optical extinction towards regions of the Milky Way and both the Small and Large Magellanic Clouds (SMC and LMC respectively).

The observed emission spectra from dust in the ISM is also the result of numerous different heating and excitation mechanisms. For large grains ( $> 100 \text{ \AA}$ ), their heat capacity is large enough that absorption of individual UV and optical photons will not significantly alter the grain temperature (Draine, 2004b). As such, the population of large dust grains is typically considered to be in thermal equilibrium with an approximately constant temperature of  $15 - 20 \text{ K}$ , dominating the infrared luminosity at wavelengths greater than  $\approx 50 \mu\text{m}$ , accounting for  $\approx 2/3$  of the total infrared luminosity and peaking at wavelengths of  $\approx 130 \mu\text{m}$  (Draine, 2004b; Conroy, 2013). By contrast, smaller grains are able to cool in between individual events of photon absorption and, as such, the infrared spectrum between  $\approx 12 - 50 \mu\text{m}$  is dominated by small grains stochastically heated by individual UV photons (Draine, 2004b). At shorter

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<sup>2</sup>i.e. hydrocarbons based on chains of Carbon atoms.

wavelengths (between  $3 - 12 \mu\text{m}$ ), the infrared emission spectrum is dominated by strong PAH emission line features which, in combination with the thermal emission from small dust grains, comprise the remaining  $\approx 1/3$  of the total infrared emission from dust in the ISM (Draine, 2004b; Conroy, 2013). The functional form of the dust emission due to these three components will be discussed further in Section 1.3.3.

Finally, we will briefly consider the attenuation properties of dust in the ISM. As outlined in Salim and Narayanan (2020), extinction describes the amount of light lost along a single line of sight due to both absorption and scattering out of the line of sight by dust, while attenuation describes the effective amount of light lost by averaging both the absorption and scattering out of the line by dust, as well as the effects of scattering into the line of sight and emission from unobscured stars, over numerous sightlines. As such, the concept of dust attenuation naturally includes the geometry of stars and dust within the galaxy, while dust extinction provides a simpler estimate of the loss of light along a single line of sight. Dust extinction curves, describing the extinction of dust as a function of wavelength, have primarily been measured based on observations of the Milky Way, SMC and LMC. Early attempts made use of the ‘pair’ method, in which extinction is quantified by comparing the amount of “reddening” observed in a given star seen through a dusty medium with a star of a similar spectral type seen through a dust-free medium (e.g. Stebbins et al., 1939; Fitzpatrick and Massa, 1986; Fitzpatrick and Massa, 1988; Cardelli et al., 1989; Gordon and Clayton, 1998; Fitzpatrick and Massa, 2007). This reddening is typically characterised by the “colour excess” between two optical bands which, in the case of the commonly used  $B$  and  $V$  bands, is defined as:

$$E(B - V) = A_B - A_V = (B - V)_{\text{obs}} - (B - V)_{\text{int}}, \quad (1.1)$$

where  $A_V$  and  $A_B$  represent the total extinction in the  $B$  and  $V$  bands, and  $(B - V)_{\text{int}}$  and  $(B - V)_{\text{obs}}$  represent the intrinsic colour gradient between the two bands, and the colour gradient observed through a dusty medium respectively. More recently, extinction curves have been estimated based on large samples of stars, using a specific population with known colour gradients as calibrators (Salim and Narayanan, 2020). However, converting from an extinction

curve to an attenuation curve is non-trivial. The same dust extinction constraints can produce extremely different attenuation curves due to differences in models of the dust-star geometry, which can range from analytic models describing somewhat oversimplified geometries (e.g. Charlot and Fall, 2000), to more complex models in which the dust-star geometry can vary over time, but which require sophisticated hydrodynamic modelling to realise (e.g. Narayanan et al., 2018; Trayford et al., 2020). A popular solution to modelling the complex star-dust geometry is to derive empirical template attenuation curves based on nearby galaxy spectra. For example, Calzetti et al. (1994), and later Calzetti (1997), derived template relative attenuation curves for nearby starburst galaxies by taking their optical/UV spectra and separating them into bins of relative attenuation based on their measured Balmer decrements<sup>3</sup>, producing average spectra for each bin and comparing these spectra with the reference spectrum from galaxies in the lowest attenuation bin (Salim and Narayanan, 2020). This was converted into an absolute attenuation curve via a measurement of the absolute attenuation in a single band, which is typically provided by assuming that the attenuation tends to zero at FIR/mm wavelengths (Calzetti, 1997; Battisti et al., 2017; Salim and Narayanan, 2020).

Dust therefore has a tremendous impact on the observed properties of a galaxy. The topic of dust will be revisited in Section 1.3.3.

## Atmospheric Opacity

The opacity of our atmosphere to light of different wavelengths has been a subject of interest since the early 1900s. Early works attempted to characterise the attenuation of infrared radiation due to water vapour and a number of atmospheric molecules such as CO<sub>2</sub>, H<sub>2</sub>O and Ozone (e.g. Gebbie et al., 1951; Howard et al., 1956a,b; Taylor and Yates, 1957). These studies found that the atmosphere is almost uniformly opaque to radiation in the infrared, mostly due to absorption via the rotational transitions of water vapour in the atmosphere. As such, ground-based infrared observatories are typically found in locations in which the Precipitable

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<sup>3</sup>The Balmer decrement describes the ratio of bright Hydrogen emission lines in the Balmer series, tracing the attenuation within HII regions surrounding massive stars.



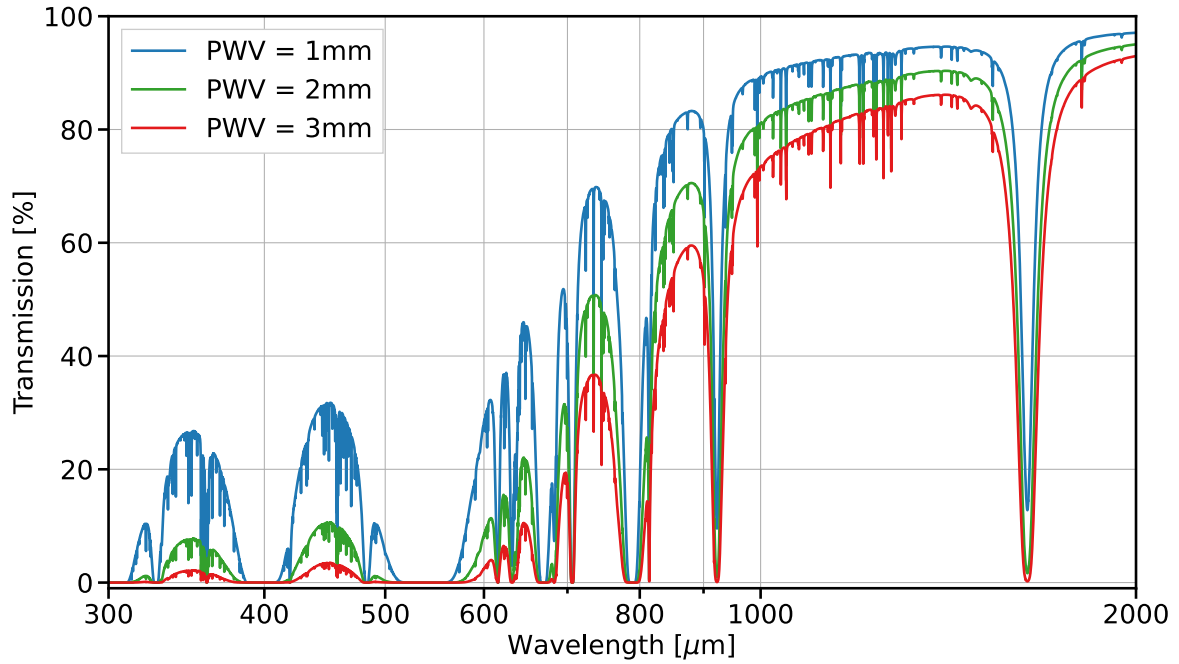


Figure 1.2: The fraction of light transmitted through the atmosphere at the summit of Mauna Kea, Hawaii as a function of wavelength. The red, blue and green lines represent PWV values of 1, 2 and 3 mm respectively. The model transmission fractions are taken from <http://www.submm.caltech.edu/cso/weather/atplot.shtml> and calculated from Pardo et al. (2001).

Water Vapour (PWV<sup>4</sup>) is extremely low. These locations are typically found at high altitude where the atmosphere is at its thinnest, such as the summit of Mauna Kea in Hawaii, or the Chajnantor plateau in Chile. As an example, Figure 1.2 shows the fraction of infrared radiation transmitted through the atmosphere as a function of wavelength at the summit of Mauna Kea. At this location, the average PWV is  $\approx 2$  mm, yet the atmosphere is opaque to much of the infrared spectrum excluding a few distinct bands.

The issue of atmospheric opacity is particularly challenging for infrared astronomy, as dust emission typically peaks at a rest frame wavelength of  $\sim 100 \mu\text{m}$  (see Figure 1.3 for an example of a typical galaxy SED). In order to characterise DSFGs in the absence of spectroscopy, it is standard practice to estimate a photometric redshift, typically by constraining the peak of the FIR SED. Figure 1.2 demonstrates that all atmospheric windows short-ward of the  $850 \mu\text{m}$  window require exceptionally good weather, and so the shortest wavelength at which infrared radiation can be routinely observed from the ground is  $850 \mu\text{m}$ . However, ground-based observations of galaxies at  $z < 8$  at this wavelength will miss the peak of the dust SED. The

<sup>4</sup>Precipitable Water Vapour is defined as the amount of water within a column of unit area in a given location, assuming that all of that water were precipitated as rain.

majority of infrared observatories must therefore be space-based, which introduces significant costs and additional technological challenges to infrared astronomy.

### Confusion Noise and Multiplicity

A second major problem with observing in the infrared involves the degradation of imaging resolution. Considering a typical single-dish facility, in which the minimum angular distance between two marginally resolved sources is determined by diffraction through a circular aperture

$$\theta = 1.22 \frac{\lambda}{D}, \quad (1.2)$$

where  $\theta$  is the angular distance between the two sources (i.e. the angular resolution),  $\lambda$  is the wavelength of light and  $D$  is the diameter of the circular aperture. Therefore, longer wavelength observations result in the degradation of angular resolution for the same aperture size, and sources that may be easily resolved at shorter wavelengths can become blurred together. As such, the highest angular resolution available to a single-dish infrared telescope is naturally limited by the engineering required to build larger dishes. This produces two distinct issues.

In longer wavelength observations, the poorer angular resolution means that the noise is dominated by the number of unresolved sources within the beamsize of the instrument, which varies from region to region, typically known as confusion noise. In order to determine an accurate luminosity for a galaxy, it is vital that this noise is accounted for, but as the number of sources within the beam is essentially random, there is currently no method of modelling the confusion noise and no observational techniques that can fully account for it. This means that the confusion noise sets an absolute limit, below which individual sources may not be detected.

The degraded resolution of infrared observations can also blend together multiple sources to produce an apparently single, extremely IR-luminous galaxy. This problem is known as multiplicity, and is exacerbated by the fact that there are many objects luminous in the FIR/sub-mm regime that are undetected in the optical (and vice versa). Therefore, although the resolution

of shorter wavelength observations is superior to FIR observations for the same aperture size, optical observations could miss galaxies that contribute to the FIR flux of a region but have no optical signature. Even if one or more optical counterparts can be identified for the FIR source, they may not necessarily be responsible for the FIR emission. The multiplicities of objects luminous in the FIR will be discussed further in Section 1.4.4.

### **The Negative $K$ Correction**

The observed brightness of an astrophysical source is a function of its intrinsic luminosity, the distance between the object and the observer, and the shape of the object's SED. Consider the following relationship between the apparent magnitude  $m$  and the absolute magnitude  $M$  of an extragalactic object, local to the observer such that we can consider  $z \approx 0$ , and observed in a single bandpass:

$$m = M + 5 \log_{10} \left( \frac{D_L}{10 \text{pc}} \right), \quad (1.3)$$

where  $D_L$  represents the luminosity distance to the source. In this simple case, the observed magnitude depends only on the intrinsic brightness of the source and the distance between the source and the observer. However, for objects at  $z > 0$ , the frequency at which the source is observed,  $\nu_{\text{obs}}$ , differs from the frequency of the light emitted,  $\nu_{\text{em}}$ , by  $\nu_{\text{obs}} = \nu_{\text{em}}/(1+z)$  due to the effects of redshift. As such, the bandpass in which the object is observed,  $R$ , is no longer the same as the bandpass in which the light was emitted  $Q$ . This effect is accounted for with a small correction factor, yielding

$$m_R = M_Q + 5 \log_{10} \left( \frac{D_L}{10 \text{pc}} \right) + K_{QR}, \quad (1.4)$$

where  $K_{QR}$  is defined as the “ $K$  correction” (Hogg et al., 2002). This  $K$  correction crucially depends on the redshift of the object and the shape of its SED between the observed and emitted bandpasses.

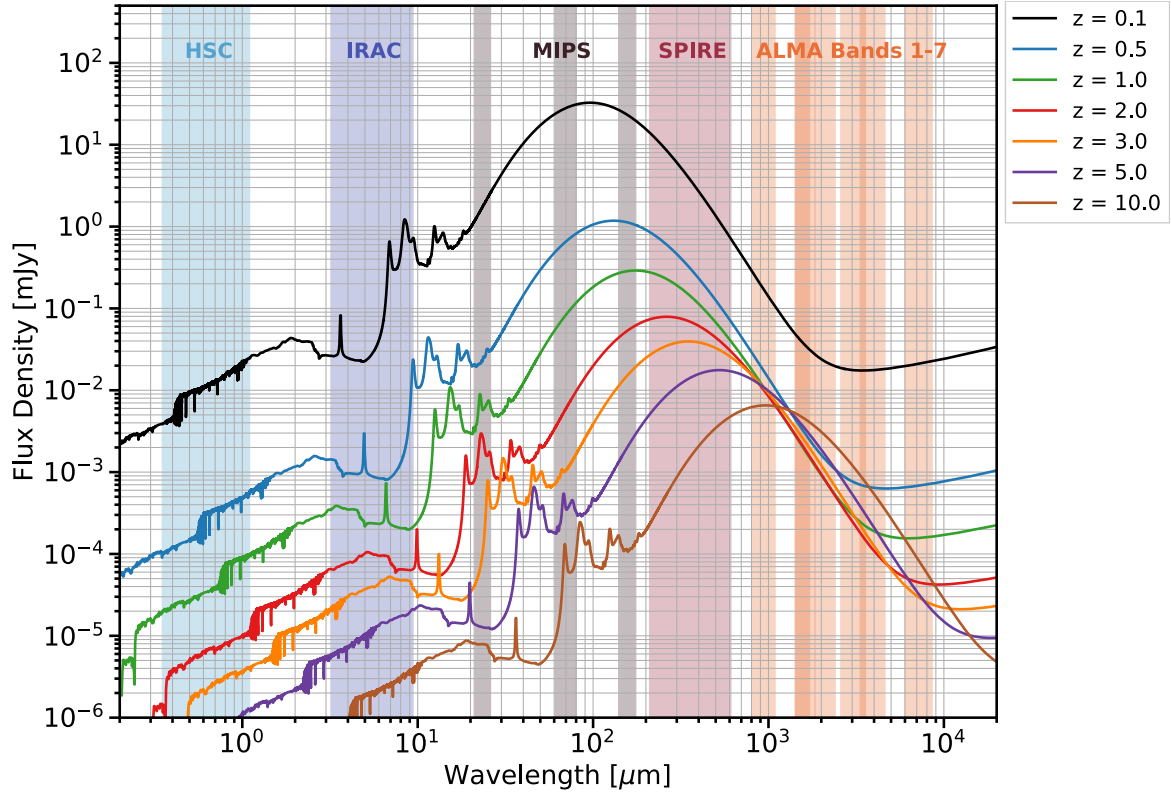


Figure 1.3: The ALESS average SED normalised to an arbitrary flux density, placed at different redshifts between  $z = 0.1 - 10$ . Plotted as shaded regions are the wavelength ranges probed by numerous instruments.

In Figure 1.3 we present a more intuitive representation of the  $K$  correction, in which we take the average SED from the ALESS (Karim et al., 2013; Hodge et al., 2013) survey normalised to an arbitrary flux density, and place it at different redshifts in the range  $z = 0.1 - 10$ . It is apparent that with increasing distance between source and observer, the observed SED becomes both redshifted ( $\lambda_{\text{obs}} = \lambda_{\text{em}}(1 + z)$ ) and attenuated such that

$$S_{\nu}(\nu_{\text{obs}}) = \frac{L_{\nu}(\nu_{\text{em}})(1 + z)}{4\pi D_L^2}, \quad (1.5)$$

where  $S_{\nu}(\nu_{\text{obs}})$  is the flux density of the object at an observed frequency  $\nu_{\text{obs}}$ ,  $L_{\nu}(\nu_{\text{em}})$  is the intrinsic luminosity of the object in the emitted frame, and  $D_L^2$  is the luminosity distance to the object (Hogg et al., 2002). Plotted as shaded regions are the wavelengths probed by various instruments. Observations in the UV, optical and NIR suffer from a “positive  $K$  correction”, such that the same object would appear significantly fainter at higher redshift than at lower redshift. By contrast, FIR observations benefit from a “negative  $K$  correction” since, although

the bolometric luminosity of the source is still attenuated, the effect of redshifting pushes the peak of the dust SED closer to the observed waveband, effectively cancelling the dimming of the overall luminosity. As such, an object lying at  $z \gtrsim 4$  would appear to have a similar flux density in a given FIR/mm waveband to the same object placed more locally. In fact, at some wavelengths, the negative  $K$  correction is extreme enough that the source actually becomes more luminous with redshift. For example at 2 mm, the flux density increases with redshift as  $S_{2\text{mm}} \propto (1+z)^\eta$  where  $\eta \approx 0.5 - 1.0$  (Casey et al., 2021a). Observations in the FIR/mm therefore allow us to much more readily observe galaxies at the highest redshifts.

### 1.2.3 Interferometry

The first generation of IR observatories and satellites were designed as single-dish facilities. More recently, observers probing the FIR, sub-mm and radio have made use of interferometers, arrays of multiple antennae which combined yield much higher angular resolutions than can be achieved with single-dish observations. In the simplest case, consider observations made with two separate antennae, such that Equation 1.2 becomes

$$\theta = 1.22 \frac{\lambda}{B}, \quad (1.6)$$

where  $B$  is the distance between the two antennae, known as the baseline. For an array of antennae, the angular resolution is therefore inversely proportional to the longest baseline. This thesis makes numerous uses of interferometric observations and so, in this section, we will explore the concept of interferometry in more detail<sup>5</sup>.

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<sup>5</sup>This discussion is based on the following series of lectures: Basic Radio Interferometry I by Karol Sanchez (<https://www.youtube.com/watch?v=xavu2z2o33U>), Introduction to Radio Interferometry II by Aaron Parsons (<https://www.youtube.com/watch?v=xavu2z2o33U>, <https://www.youtube.com/watch?v=39g0hTTn5n8>, <https://www.youtube.com/watch?v=quZfMV0Ai3A>), Imaging and Deconvolution in Radio Interferometry by David Wilner (<https://www.youtube.com/watch?v=mRUZ9eckHZg>).

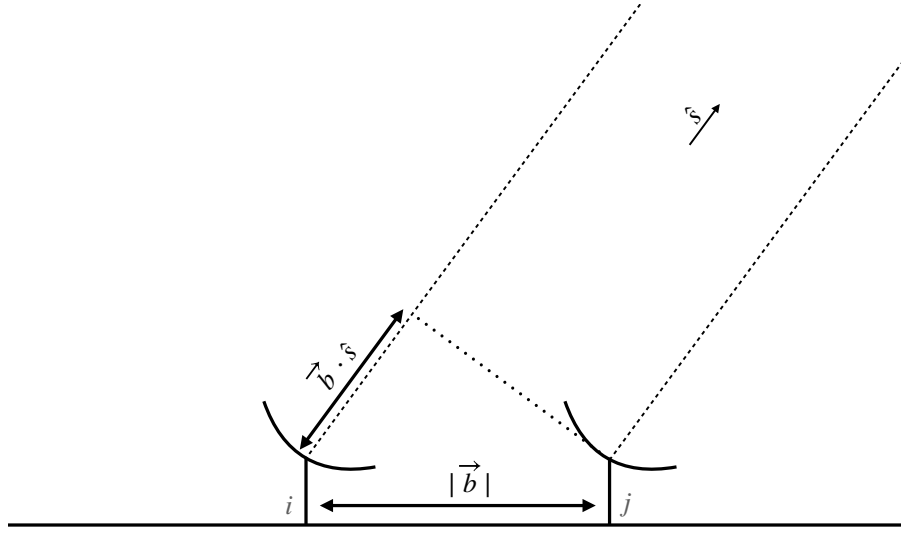


Figure 1.4: A simple diagram of a two element interferometer, consisting of antennae  $i$  and  $j$  separated by the baseline  $b = |\vec{b}|$ .

### The Simple Case

Consider two antennae,  $i$  and  $j$ , separated by  $b = |\vec{b}|$ , as in Figure 1.4. Both antennae point in the direction of source 1 along the unit vector  $\hat{s}$ . Light from an extragalactic object will arrive in plane waves, such that antenna  $j$  will receive the signal before antenna  $i$ . The time difference between the two antennae receiving the signal is “the geometric delay”,  $\tau = \vec{b} \cdot \hat{s}/c$ , where  $\vec{b} \cdot \hat{s}$  is the extra distance the signal has to travel to reach antenna  $i$  compared to antenna  $j$ , and  $c$  is the speed of light. A second source (source 2) in a slightly different on sky position yields a different geometric delay, such that  $\tau_1 = \vec{b} \cdot \hat{s}_1/c$  and  $\tau_2 = \vec{b} \cdot \hat{s}_2/c$ . We define the time difference such that receiver  $i$  receives the signals at time  $t$ , while receiver  $j$  receives the same signals at  $t + \tau_1$  and  $t + \tau_2$  respectively. The receivers cannot distinguish between the two signals, and so the resulting observation is simply a combined voltage from both sources

$$E_i(t) = e_1(t) + e_2(t) \quad (1.7)$$

$$E_j(t) = e_1(t - \tau_1) + e_2(t - \tau_2) \quad (1.8)$$

where  $E_i(t)$  and  $E_j(t)$  are the composite signals received by antennae  $i$  and  $j$  at time  $t$ , and  $e_1$

and  $e_2$  are the signals received from sources 1 and 2 respectively. In order to discern information about the individual sources, the signals are run through a correlator, yielding

$$(E_i(t) * E_j(t))(\tau) = \int [e_1(t) + e_2(t)] [e_1(t - \tau_1 - \tau) + e_2(t - \tau_2 - \tau)] dt. \quad (1.9)$$

By expanding this equation and considering that the signals from the two sources are independent (such that terms including both  $e_1$  and  $e_2$  integrate away as random noise), we are left with

$$(E_i(t) * E_j(t))(\tau) = \int e_1(t)e_1(t - \tau_1 - \tau) + e_2(t)e_2(t - \tau_2 - \tau) dt. \quad (1.10)$$

To provide meaningful signal information, we wish to find the maxima of the correlated signals, which occur at  $\tau = -\tau_1$  or  $\tau = -\tau_2$ , yielding solutions of  $\langle e_1^2 \rangle$  and  $\langle e_2^2 \rangle$ . A set of geometric delays therefore results in a set of power values which rise above the signals with no significant correlations. In this simple case, the correlation gives us a one-dimensional image of the sky in the direction parallel to the baseline of the telescope.

### **From a Single Astronomical Source to the Entire Sky**

We now wish to generalise this result to an array of multiple antennae tuned to a single wavelength  $\lambda$ . We first express the geometric delay as a phase difference,  $\phi$ , between the astronomical signals reaching the two antennae, such that

$$\phi = \exp \left( -2\pi i \frac{\vec{b} \cdot \hat{s}}{\lambda} \right) = \exp (-2\pi i \tau \nu) \quad (1.11)$$

where  $\nu$  is the frequency of the observations. This small change in terminology from geometric delay to phase difference allows us to more simply express the “visibility”, quantifying the amplitude of the oscillations in our image produced by the interference of the signals received by

the two antennae. In the case of a two-element interferometer, the visibility of an extragalactic object with a flux density  $S_\nu$  at frequency  $\nu$  is defined as

$$V_{ij}(\nu) = S_\nu \exp \left( -2\pi i \frac{\vec{b} \cdot \hat{s}}{\lambda} \right). \quad (1.12)$$

We will extrapolate this equation to determine the visibilities over the entire sky but, for simplicity, we first re-define some of the terms. By convention, we define the baseline in terms of the number of wavelengths, such that  $\vec{b}/\lambda = (u, v, w)$ , where  $u$  defines the East-West direction,  $v$  the North-South direction and  $w$  the up-down direction. We similarly expand the unit vector defining the direction of the source into three components, yielding  $\hat{s} = (l, m, \sqrt{1 - l^2 - m^2})$ , where  $l$  and  $m$  define the East-West and North-South directions respectively. The difference in the number of wavelengths between the two antennae receiving the signal from the source is then

$$\frac{\vec{b} \cdot \hat{s}}{\lambda} = ul + vm + w\sqrt{1 - l^2 - m^2}. \quad (1.13)$$

For each point on the sky, Equation 1.13 provides a phase term defined by its coordinates and the coordinates of the baseline. In practice, the  $w\sqrt{1 - l^2 - m^2}$  term is usually neglected as interferometric arrays are constructed to minimise the up-down component of the baselines. As such, the visibility across the entire sky can then be expressed as

$$V_\nu(u, v, w) = \iint A(l, m) I(l, m) \exp(-2\pi i (ul + vm)) dl dm. \quad (1.14)$$

Notice that Equation 1.14 describes a Fourier transform, such that the visibility across the entire sky in the observation plane (often known as the  $uv$ -plane) is simply the Fourier transform of the sky in the source plane.

What does this visibility look like across the entire sky? Consider two antennae on a flat plane separated by a baseline with only a  $u$  component, with the phase centre (defined as the



origin point on the sky with respect to which the  $(u, v, w)$  coordinates are expressed) directly above and equidistant to the two antennae. As our baseline is only in the  $u$  direction, the  $\exp(-2\pi i(ul + vm))$  term will collapse to a sin wave representing the real component of the complex response of the interferometer on the sky in the  $l$  direction. If the interferometer has a  $v$  component to its baseline, then there would be additional sin waves along the  $m$  direction on the sky. This response is inherent to the choice of baseline and is known as the “fringe pattern”. Note that, as  $u$  and/or  $v$  increase (i.e. the baseline becomes longer), the frequency of the sin wave as a function of  $l$  and  $m$  also increases, such that longer baselines produce tighter fringe patterns, picking out smaller scale features and yielding higher resolutions.

### Sampling with Multiple antennae

Equation 1.14 demonstrates that visibilities in the  $uv$ -plane are simply the Fourier transform of the perceived sky in the source plane. However, this is only strictly true in the case where we can sample every point on the  $uv$ -plane. In practice, only a finite number of baselines can be constructed in a given array, so only a finite number of points on the  $uv$ -plane can be sampled.

Real interferometric observations essentially multiply the Fourier transform of the perceived sky in the  $uv$ -plane,  $\hat{I}$ , with the sampling pattern of the array,  $V$ . The Fourier transform of the product of two functions yields the convolution of the Fourier transforms of the individual functions, such that  $F[\hat{I} \cdot V] = F[\hat{I}] * F[V] = I * \hat{V}$ . In other words, rather than obtaining the true sky distribution, real interferometric observations return the image of the true sky convolved with the Fourier transform of the sampling pattern, sometimes known as the “dirty beam”. This image is typically known as the “dirty map”, examples of which can be found in Chapters 3 and 5.

In order to recover the true intensity map of the sky from the dirty map, we must deconvolve the true sky image from the Fourier transform of the sampling pattern. In the most intuitive sense, deconvolution essentially aims to extrapolate sampled regions of the  $uv$ -plane into unsampled regions. While there are numerous deconvolution methods, this summary will focus on a method known as CLEANing which will be used throughout this thesis.

The CLEAN algorithm relies on two assumptions. Firstly, it is assumed that the observed sources in the true sky image are point sources. A true point source has the same amplitude in any  $uv$  pixel, and so the deconvolution process essentially aims to get the phases represented by the different  $uv$  pixels to agree on the exact location of the point source on the sky. The second assumption is that the point sources are located at the positions of the brightest pixels in the image. The algorithm then works iteratively as follows:

1. Initialise a “residual map” and a “clean component list”
2. Find the pixel in the residual map with the highest value and subtract off a fraction of the flux using a scaled dirty beam
3. Add the location and amplitude of the source to the clean component list
4. Return to (2) unless some defined maximum number of iterations is reached (if the map is dynamic range limited) or the value of the peak pixel in the residual map is below some defined threshold (if the map is noise limited)

The final step in the algorithm is to construct the “restored” image, a model image based on the point sources in the clean component convolved with the “clean beam” (an elliptical Gaussian fit to the main lobe of the dirty beam), combined with the residual map of noise and structure below the threshold.

## Visibility Weighting

In the most simple case, the sampling pattern is constructed by assigning  $W(u, v) = 1$  to points on the  $uv$ -plane that are sampled by the array and  $W(u, v) = 0$  everywhere else. The visibility weighting function allows the user to modify the sampling function and hence change the shape of the dirty beam, which can be advantageous depending on the science goals of the observations. Outlined below are three different weighting schemes that are used and/or discussed in this thesis.

- **Natural Weighting:** Expressed as  $W(u, v) = 1/\sigma^2$  in occupied  $uv$  cells and  $W(u, v) = 0$  everywhere else (where  $\sigma$  is the noise variance in the image), this function effectively weights the dirty image by the noise, achieving maximum point source sensitivity, but degrading angular resolution.
- **Uniform Weighting:**  $W(u, v)$  is inversely proportional to the local density of  $uv$ -points, such that the sum of the weights of  $uv$ -points in a cell must be equal to some constant. This gives larger weights to longer baselines (which tend to be more sparsely sampled in the  $uv$ -plane), improving the angular resolution of the observations, but at the expense of shorter baselines, resulting in a loss of point source sensitivity.
- **Briggs Weighting:** Providing a compromise between Natural and Uniform weighting, Briggs weighting is a variant of Uniform weighting that avoids assigning too much weight to  $uv$ -cells with a low Natural weight. It is implemented via the equation

$$W(u, v) = \frac{1}{\sqrt{1 + S_N^2/S_{\text{thresh}}^2}} \quad (1.15)$$

where  $S_N$  is the Natural weight of a cell and  $S_{\text{thresh}}$  is a defined threshold weight, often referred to as the “robust parameter”. By tuning the robust parameter, the optimum combination of point source sensitivity and spatial resolution can be reached to match the scientific goals of the observations.

#### 1.2.4 Instrumentation

With an understanding of the fundamental concepts underpinning astronomical observations, we can begin to discuss some of the most important modern instruments and observatories. In particular, we focus on the facilities that have been most useful to this thesis.

## The Atacama Pathfinder Experiment (APEX) Telescope

The Atacama Pathfinder Experiment (APEX: Güsten et al., 2006) telescope<sup>6</sup>, is a sub-mm/mm observatory situated in the Chajnantor plateau, consisting of a 12 m modified prototype dish from the Atacama Large Millimeter/Sub-Millimeter Array (ALMA: Wootten and Thompson, 2009), with numerous instruments allowing observations from  $\sim 200 - 850$  GHz. Most notably for this work is the PI230 dual polarisation heterodyne receiver mounted at the Naysmith-B focus of the telescope, covering the  $200 - 270$  GHz frequency range in 524,288 channels, reaching spatial resolutions of  $\sim 30''$  and spectral resolutions of  $0.0796 \text{ km s}^{-1}$ . Other notable instruments include the Large Apex Bolometer Camera (LABOCA: Siringo et al., 2009), installed in 2006 and allowing continuum observations in the  $870 \mu\text{m}$  band. LABOCA probed the Extended Chandra Deep Field South (ECDFS) as part of the LABOCA ECDFS Submillimetre Survey (LESS: Weiß et al., 2009; Wardlow et al., 2011; Hickox et al., 2012), the precursor to the ALESS survey, which provided deep ALMA follow-up observations to the sub-mm galaxies discovered in LESS.

## The *Herschel* Space Observatory

*Herschel* (Pilbratt et al., 2010) was launched in 2009 fitted with three science instruments: the Photodetector Array Camera and Spectrometer (PACS: Poglitsch et al., 2010), the Spectral and Photometric Imaging Receiver (SPIRE: Griffin et al., 2010) and the Heterodyne Instrument for the Far Infrared (HIFI: de Graauw et al., 2010). Here we focus primarily on the photometric imaging capabilities of the PACS and SPIRE instruments. In photometry mode, the PACS instrument allowed simultaneous observations at  $160 \mu\text{m}$  and either  $70$  or  $100 \mu\text{m}$ , with a field of view of  $\sim 1.75' \times 3.5'$  (Poglitsch et al., 2010). SPIRE was a sub-mm instrument, allowing simultaneous imaging at  $250$ ,  $350$  and  $500 \mu\text{m}$  with a field of view of  $4' \times 8'$  in photometer mode (Griffin et al., 2010). The beamsizes of these instruments were approximately  $5''$ ,  $7''$  and  $12''$  for the  $70$ ,  $100$  and  $160 \mu\text{m}$  PACS bands and  $18''$ ,  $26''$  and  $36''$  in the  $250$ ,  $350$  and  $500 \mu\text{m}$  SPIRE bands (Casey et al., 2014). *Herschel* operated until its supply of coolant ran out in 2013.

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<sup>6</sup><http://www.apex-telescope.org/>

*Herschel* was involved in a number of key observing programmes<sup>7</sup> mapping vast areas of the sky. The largest of these surveys were the *Herschel* Multitiered Extragalactic Survey (HerMES: Oliver et al., 2012), the *Herschel* Astrophysical Terahertz Large Area Survey (H-ATLAS: Eales et al., 2010) and the PACS Evolutionary Probe (PEP: Lutz et al., 2011). *Herschel* further contributed both PACS and SPIRE Observations to the GOODS Survey (GOODS-Herschel: Elbaz et al., 2011). This thesis primarily makes use of the HerMES programme, which mapped  $\sim 380 \text{ deg}^2$  in a set of nested fields with both the SPIRE and PACS instruments, along with a further  $270 \text{ deg}^2$  mapped with the SPIRE instrument alone, resulting in observations of  $\sim 100,000$  galaxies at  $> 5\sigma$  in some of the best studied fields in the sky (Oliver et al., 2012). The large extension to the SPIRE observations was possible due to its superior efficiency in large area mapping compared to the PACS instrument (Casey et al., 2014).

### The *Hubble Space Telescope*

The *Hubble Space Telescope* (*HST*) was launched into low Earth orbit in 1990, fitted with a 2.4 m primary mirror and a 0.3 m secondary mirror. Over its 30 year operation, *HST* has been serviced and upgraded with improved instruments in five visits spread over four service missions, such that many of the instruments that it was launched with are no longer in operation. *HST* is currently fitted with five science instruments, alongside its Fine Guidance Sensors. This work primarily makes use of the Wide Field Camera 3 (WFC3<sup>8</sup>) instrument which features two separate cameras: the UV/Visible (UVIS) channel comprised of two  $4096 \times 2051$  CCD detectors providing imaging at 200–1000 nm, and the IR channel which uses a single  $1024 \times 1024$  detector array covering NIR wavelengths between 800 and 1700 nm. These two channels have pixel scales of  $0.0395'' \times 0.0395''$  and  $0.135'' \times 0.121''$ , and fields of view of  $162'' \times 162''$  and  $136'' \times 123''$  respectively.

<sup>7</sup>See <https://www.cosmos.esa.int/web/herschel/key-programmes> for details of each key programme.

<sup>8</sup><https://www.stsci.edu/hst/instrumentation/wfc3>

## The Sub-Millimetre Array (SMA)

The Sub-Millimetre Array (SMA: Ho et al. 2004) is a radio interferometer comprised of eight 6-meter dishes situated at the peak of Mauna Kea, operating in the frequency range 180–420 GHz with possible baselines ranging from 16–509 m, yielding spatial resolutions of between  $0.1''$  and several arcseconds (Ho et al., 2004). While subsequent interferometers were able to improve upon these resolutions (e.g. the Northern Extended Millimeter Array (NOEMA: Chenu et al., 2016) and ALMA), the SMA remains unsurpassed in available bandwidth for an interferometer due to the SWARM correlator, which was recently updated to yield up to 48 GHz of total bandwidth and a uniform resolution of 140 kHz<sup>9</sup>.

## The Sub-Millimetre Common User Bolometer Array 2 (SCUBA-2)

SCUBA-2 (Holland et al., 2013) is the successor to the first iteration of the SCUBA instrument (Holland et al., 1999), and was installed on the JCMT in 2011. SCUBA-2 is designed to observe simultaneously in the 450 and 850  $\mu\text{m}$  windows with beamsizes of  $7''$  and  $15''$  respectively, yielding the population of Sub-Millimetre Galaxies (SMGs: Blain et al., 2002), or those DSFGs selected in the 850  $\mu\text{m}$  band. SCUBA-2 consists of a 10,000 pixel bolometer camera that is able to scan the sky  $\sim 100 - 150$  times faster than the original SCUBA instrument (Holland et al., 2013) and is the first instrument that can effectively take observations in the 450  $\mu\text{m}$  window (see e.g. Geach et al., 2013b; Chen et al., 2013a; Roseboom et al., 2013). Given its improved mapping speed, SCUBA-2 was used for a number of large legacy surveys. Most notably, the SCUBA-2 Cosmology Legacy Survey (S2CLS: Geach et al., 2017) detected  $\sim 3000$  SMGs down to a sensitivity of  $\sim 1.2$  mJy in the 850  $\mu\text{m}$  band in a total of  $5 \text{ deg}^2$  spread across 7 different fields. The SCUBA-2 Ultra Deep Imaging EAO Survey (STUDIES: Wang et al., 2017) is a confusion noise-limited survey of SMGs, reaching a sensitivity of  $\sim 0.91$  mJy in the 450  $\mu\text{m}$  band, covering  $151 \text{ arcmin}^2$  in the COSMOS-CANDELS region. Finally, the S2COSMOS survey (Simpson et al., 2019) observed a contiguous area of  $2 \text{ deg}^2$  in the COSMOS field down to a sensitivity of  $\sim 1.2$  mJy in the 850  $\mu\text{m}$  band.

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<sup>9</sup><https://lweb.cfa.harvard.edu/sma/index.html>

## The Very Large Array (VLA)

The Very Large Array (VLA: Thompson et al., 1980) is a radio interferometer comprised of 27 active antennae, each with a 25 m diameter. The antennae of the VLA are distributed in a “Y” shape, with three arms each comprising 9 antennae. Four different configurations are used approximately every 16 months, with the length of each arm ranging from around two-thirds of a mile in the most compact D configuration, up to around 23 miles in the most extended A configuration, yielding angular resolutions of between  $0.2'' - 0.04''$ . Each VLA antenna houses eight receivers, allowing tuning to ten discrete bands, from the lowest frequency P-band spanning  $0.23 - 0.47$  GHz up to the highest frequency Q-band spanning  $40.0 - 50.0$  GHz.

## 1.3 Galaxies

While this thesis focuses on Dusty Star-Forming Galaxies and their environments, there are numerous components of a galaxy that are common to all populations. In terms of mass, the dominant component of a galaxy is the dark matter halo, a roughly spherical (e.g. Creze et al., 1998; Ibata et al., 2001) distribution of matter interacting only through the gravitational force, thought to extend well beyond the boundaries of the baryonic or visible matter (e.g. Kochanek, 1996). However, as dark matter can neither produce nor absorb electromagnetic radiation, the directly observable content of galaxies is comprised primarily of stars and the surrounding interstellar medium (ISM) of gas and dust. Some galaxies also harbour an Active Galactic Nucleus (AGN); a central Supermassive Black Hole (SMBH) that rapidly accretes material, producing extreme luminosities across the electromagnetic spectrum. In this section, we will briefly explore some of these key characteristics, with a particular focus on the directly observable content of galaxies, and how we can model these components to yield galaxy properties from their observed spectral energy distributions.

### 1.3.1 Morphology

Morphology is one of the most widely used properties for galaxy classification, and has been shown to correlate well with numerous other properties, such as star formation history (van der Wel, 2008), colour (Ball et al., 2008), stellar and/or halo mass (Bamford et al., 2009; Wilman and Erwin, 2012) and, most strongly, with environment (Hubble and Humason, 1931; Morgan, 1961; Abell, 1965; Oemler, 1974; Melnick and Sargent, 1977; Dressler, 1980; Postman and Geller, 1984; Whitmore and Gilmore, 1991; Goto et al., 2003; Wilman et al., 2009). Galaxies are broadly classified into three groups, spirals/discs, ellipticals/spheroidals or irregulars, usually based on the presence and/or relative contributions of the central bulge and the stellar disk to the total galaxy luminosity.

#### Spirals

Spiral galaxies harbour a significant flattened disc comprised of younger stars, gas and dust. This disc extends beyond the central bulge, which primarily contains the older stellar population and can range in size and brightness, in some cases dominating the luminosity of the disk. The bulge and disk are further enclosed within an extended and near-spherical halo of stars and globular clusters. Spiral galaxies are often further sub-divided based on numerous features within the galactic disk, such as bars, ovals, rings and dust lanes (e.g. Buta, 2011). Observations of spiral galaxies suggest that they are more star-forming and less massive than ellipticals, typically lying in rarefied field regions in the local Universe but become more prevalent in cluster environments at higher redshifts (e.g. Butcher and Oemler Jr, 1978; Dressler, 1980; Butcher and Oemler Jr, 1984; Dressler et al., 1994).

#### Ellipticals

Elliptical galaxies are defined as ellipsoidal distributions of baryonic matter supported by the effectively random motions of stars, with smooth continuously declining brightness distributions dominated by a typically old stellar population (e.g. Buta, 2011). Unlike disk-like galaxies,



ellipticals are typically red in colour, massive, with negligible amounts of gas and little ongoing star formation, and preferentially lie within massive galaxy clusters in the local Universe (e.g. Dressler, 1980; De Lucia et al., 2006). Ellipticals are often further sub-categorised into “boxy” ellipticals, those with slower rotational velocities and higher luminosities, and “disky” ellipticals, those flattened by more rapid rotation (e.g. Bender et al., 1988).

## Irregulars

Irregulars tend to be low mass and gas rich with significant ongoing star formation (e.g. Hunter, 1997), and were originally subdivided into clumpy irregulars with resolved stellar clusters, and those with a smoother brightness distribution which nevertheless show none of the characteristic features of spirals or ellipticals (Hubble, 1926). Irregulars are typically confined to more rarefied regions, such as the field and the outer regions of groups and clusters (Dressler, 1980; van der Wel et al., 2010; Grebel, 2011) and, while originally thought to be rare, are now believed to be the dominant component to all star-forming galaxies (Gallagher and Hunter, 1984). It is typically thought that irregular galaxies are either the relics of previous mergers or the result of galaxies (or gas clouds) in the process of interacting (Gallagher and Hunter, 1984).

### 1.3.2 Stellar Populations

Arguably the most influential component for the observable characteristics of a galaxy is its populations of stars. In the absence of a significant AGN component, the direct emission from stars dominates the galaxy luminosity in the UV, optical and near-infrared, as well as dominating the mass budget of the luminous matter. The stellar component is also responsible for numerous emission and absorption features in galaxy spectra. For example, recombination in HII regions, areas of ionised gas surrounding newly formed and typically massive O and B stars, are responsible for bright emission lines such as  $\text{Ly}\alpha$ ,  $\text{H}\alpha$  and the [OII] doublet, which have subsequently been used as tracers of star formation and ISM properties (e.g. Seaton and Osterbrock, 1957; Gallagher et al., 1989; Kennicutt Jr, 1992; Bronfman et al., 1996; Jansen

et al., 2001; Kewley and Dopita, 2002; Garn et al., 2010; Gilbank et al., 2010; Sobral et al., 2013, 2015; Sanders et al., 2016), while absorption in the stellar envelopes of cooler A and F type stars are responsible for absorption features such as the  $H\delta$  and  $H\gamma$  lines (e.g. Cananzi et al., 1993). Numerous other spectral features useful in the characterisation of galaxies are produced by their stellar populations, such as the 4000Å-break, often used to characterise the older stellar population (e.g. Dressler and Shectman, 1987), and the Lyman break, a useful distance indicator for the highest redshift galaxies (e.g. Giavalisco, 2002).

Towards the end of their life cycles, stars are responsible for the enrichment of the ISM with heavy metals (e.g. Madau et al., 2001; Tremonti et al., 2004) and dust (see Section 1.3.3) which, in turn, absorbs light from the younger stellar population and emits in the infrared. Massive stars are also responsible for the majority of emission in the radio (in the absence of a significant AGN component), as they produce both HII regions from which thermal free-free radio emission originates, and, at the end of their life cycles, supernovae remnants in which electrons are accelerated to produce radio synchrotron emission (Lisenfeld et al., 2015). Their crucial link to both the infrared and radio emission from galaxies yields the well-studied FIR-radio correlation (Helou et al., 1985; de Jong et al., 1985), which has subsequently been utilised as an indicator of both star formation (Condon, 1992; Heesen et al., 2014) and redshift (Carilli and Yun, 1999).

Aside from the directly observable consequences, the stellar population can also directly regulate the formation of stars within a galaxy. This process is known as “stellar feedback”, and is the culmination of numerous mechanisms working to either disperse or heat the surrounding gas, such as stellar radiation pressure (Krumholz and Matzner, 2009; Hopkins et al., 2014), energy release from supernovae (Hayes et al., 2016; Li, 2017), photoionisation (Dijkstra et al., 2004; Dale et al., 2005), shock-heating (Harper-Clark and Murray, 2009) and proto-stellar outflows (Offner and Chaban, 2017).

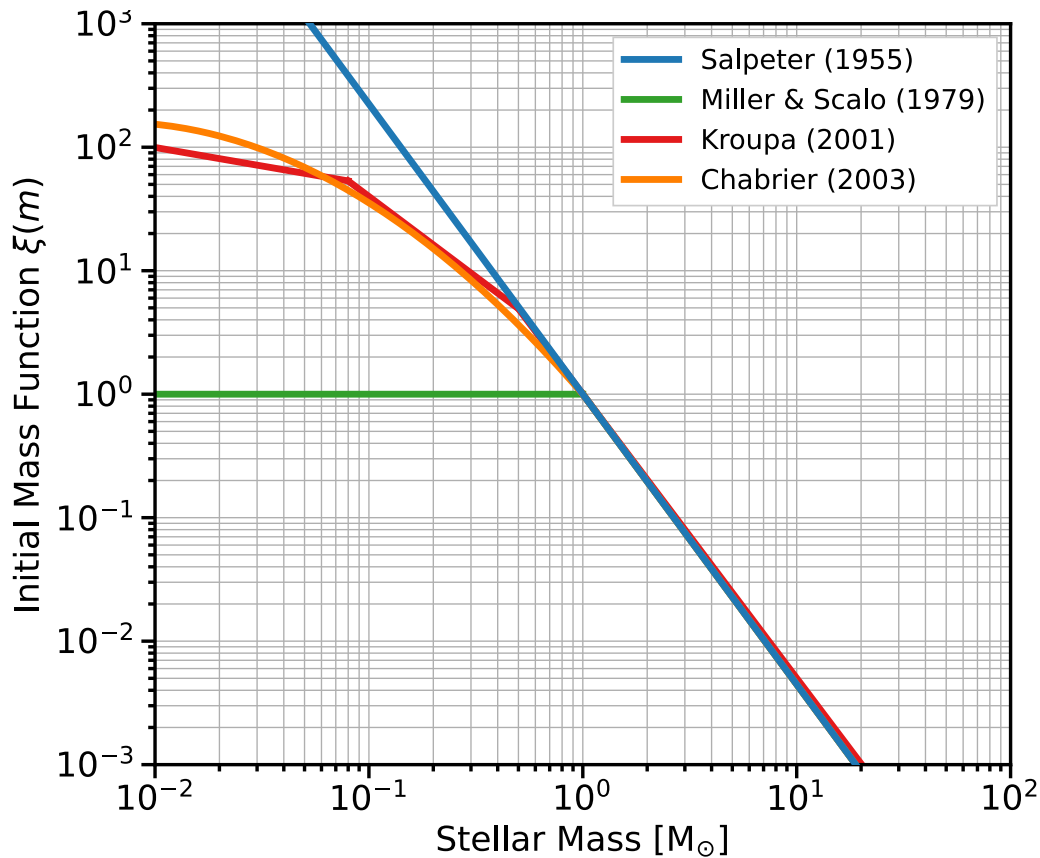


Figure 1.5: Initial Mass Functions popularly used to model stellar populations. For  $m > 1 M_{\odot}$ , each IMF agrees well with the canonical Salpeter IMF (Salpeter, 1955). At  $m < 1 M_{\odot}$ , Miller and Scalo (1979) predicted a sharp flattening of the IMF, while Kroupa (2001) and Chabrier (2003b) predicted a more gentle flattening following a log-normal distribution.

### Stellar Population Synthesis

While the various effects that the stellar component of a galaxy can have on its characteristics and evolution are reasonably well understood, it remains challenging to model the stellar populations of observed galaxies. The stellar population is a composite of stars with different masses, spectral types, ages and metallicities, each contributing to the total observed spectral energy distribution. This complex distribution of stars within a galaxy is typically modelled using a process known as Stellar Population Synthesis (SPS).

The foundation of SPS modelling is the creation of a Simple Stellar Population (SSP), describing the time-evolution of a coeval population of stars with a common metallicity and abundance pattern. Constructing an SSP requires an initial mass function (IMF), isochrones describing the stellar evolution, and a stellar spectral library (Conroy, 2013).

The IMF describes the initial distribution of masses within the stellar population. By convention, the IMF is typically described in relation to a distribution in the logarithm of the stellar mass, with the number of stars  $dN$  in the mass interval  $m$  to  $m + d(\log(m))$  usually defined by a power law,

$$dN \propto m^{-(\alpha-1)} d(\log(m)) \quad (1.16)$$

with slope  $\alpha$  (e.g. Bonnell et al., 2007). By observing the luminosity functions of main sequence stars in the solar neighbourhood, Salpeter (1955) estimated a power law IMF with a slope of  $\alpha = 2.35$ , a functional form that remains popular to this day. More recently, Chabrier (2003b) estimated the IMF within the galactic disk, finding a functional form that agrees well with the canonical Salpeter power-law IMF above  $1 M_{\odot}$  and follows a log-normal form below  $1 M_{\odot}$ . Most modern SED modelling algorithms make use of either the Salpeter or Chabrier IMFs, although other variations have been proposed (see Figure 1.5). It is additionally worth noting that the precise form of the IMF and whether it varies with redshift remains an active area of research (e.g. Bastian et al., 2010; Kroupa and Jerabkova, 2021, and references therein).

Given an IMF, the position of stars within the stellar population with common ages and metallicities on the Hertzsprung-Russell diagram is specified via stellar evolution theory, typically in the form of isochrones (Conroy, 2013). Commonly used libraries of stellar evolution models are provided by the Padova models (Alongi et al., 1993; Bressan et al., 1993; Fagotto et al., 1994a,b,c; Girardi et al., 1996) and the BaSTI models (Bag of Stellar Tracks and Isochrones: Pietrinferni et al., 2004, 2006; Cordier et al., 2007; Percival et al., 2009; Pietrinferni et al., 2009; Salaris et al., 2010; Pietrinferni et al., 2013; Hidalgo et al., 2018; Pietrinferni et al., 2021; Salaris et al., 2022) spanning a wide range of ages and metallicities, although alternative libraries of stellar evolution models are constantly being developed and updated (e.g. Marigo et al., 2017; Spada et al., 2017; Viani and Basu, 2017; Fu et al., 2018; Somers et al., 2020; Murphy et al., 2021; Spada et al., 2021).

Stellar evolution calculations based on libraries of isochrones and a given IMF yield properties

such as surface gravities and effective temperatures, but a stellar spectral library is required to convert these results into an SED model (Conroy, 2013). There are numerous theoretical (e.g. Lancon and Rocca-Volmerange, 1992; Lejeune et al., 1997; Leitherer et al., 2010) and empirical (e.g. Pickles, 1998; Le Borgne et al., 2003; Sánchez-Blázquez et al., 2006) spectral libraries available in the literature, and no one stellar spectral library can cover the necessary parameter space required for sophisticated SED fitting algorithms, such that typically multiple different spectral libraries must be used in tandem (Conroy, 2013).

Popular libraries of SSP models include the Bruzual and Charlot (2003) and Maraston (2005) libraries. Composite Stellar Populations can then be constructed from numerous SSPs, following defined star formation histories and chemical evolution models, as well as including the attenuation and emission by interstellar dust, yielding a more complex and realistic spectrum from the stellar population (Conroy, 2013).

### 1.3.3 Gas and Dust

#### Interstellar Gas

The observed characteristics of galaxies and their evolution over time are driven by the gas content. First and foremost, interstellar gas provides the fuel for star formation and hence dictates the assembly of stellar mass within a galaxy. This is most directly observed in the Kennicutt-Schmidt (KS) relation. Schmidt (1959) determined that the rate of star formation within a region is directly related to the surface density of the interstellar gas, such that

$$\Sigma_{\text{SFR}} \propto (\Sigma_{\text{ISM}})^n, \quad (1.17)$$

where  $\Sigma_{\text{SFR}}$  and  $\Sigma_{\text{ISM}}$  are the SFR surface density and interstellar gas surface density respectively, and estimated a value of  $n \approx 2$  based on numerous observations of stars and gas within the solar neighbourhood. Later work by Kennicutt (1989, 1998b) extended the analysis to extragalactic sources finding that, based on observations of the distribution of  $\text{H}\alpha$ ,  $\text{H I}$  and  $\text{CO}$

within nearby galactic disks, a value of  $n = 1.4 \pm 0.15$  is more appropriate. These results demonstrate the fundamental link between interstellar gas and star formation in the galactic disk.

As well as regulating star formation, observations of interstellar gas reservoirs can provide valuable insights into the chemical evolution of the ISM, which is linked to star formation, nucleosynthesis and gas flows (Tinsley, 1980). The cool, molecular gas that is the most direct fuel for star formation is dominated by molecular Hydrogen, although direct observations of  $\text{H}_2$  remain challenging due primarily to the high excitation requirements of its molecular emission lines (e.g. Carilli and Walter, 2013). As such, other tracers of the bulk of the molecular gas with more accessible emission spectra are typically used, most notably neutral  $\text{H I}$  (e.g. Magri et al., 1988; Cayatte et al., 1990; Solanes et al., 2001; Chung et al., 2009; Serra et al., 2012; Jaffé et al., 2012; Stroe et al., 2015b; Hess et al., 2015; Gazagnes et al., 2018; Džudžar et al., 2019; Krogager and Noterdaeme, 2020; Sardone et al., 2021; Yu et al., 2022) or the rotational  $\text{CO}$  transitions (e.g. Kenney and Young, 1986; Casoli et al., 1991; Edge, 2001; Boselli et al., 2002; Edge and Frayer, 2003; Salomé and Combes, 2004; Salomé et al., 2006; Combes et al., 2007; Dannerbauer et al., 2009; Geach et al., 2009; Bigiel et al., 2011; Corbelli et al., 2012; Tacconi et al., 2013; Cybulski et al., 2016; Hayashi et al., 2018; Cairns et al., 2019; Jarvis et al., 2020; Williams et al., 2021; Sanders et al., 2022).

The metallicity of the ISM is typically more difficult to estimate. Direct measurements of metallicity require multiple independent and often faint metal line diagnostics (such as  $[\text{O III}]$ ,  $[\text{N II}]$  and  $[\text{S II}]$ ) to break the degeneracies between metallicity, gas temperature, density and ionisation parameter (Nagao et al., 2006; Swinbank et al., 2012). Alternatively, numerous proxies tracing the chemical evolution of the ISM have been developed (see e.g. Peimbert, 1967; Urbaneja et al., 2005; Nagao et al., 2006; Kudritzki et al., 2008; Bresolin et al., 2009; Yates et al., 2020).

## Interstellar Dust

Interstellar dust is a natural consequence of the enrichment of the ISM with heavy metals from stellar evolution. While there remain disagreements as to the primary producer of cosmic dust, the most likely sites for dust grain condensation are the atmospheres of Asymptotic Giant Branch (AGB) stars (e.g. Valiante et al., 2011; Boyer et al., 2012), the ejecta from supernovae (e.g. Gall et al., 2011b,c; Ferrara et al., 2016) and cold, dense regions of the ISM (e.g. Draine, 2009; Michałowski et al., 2010; Hirashita, 2012; Dayal and Ferrara, 2018). It is perhaps not surprising that derived dust masses are found to correlate well with gas masses, although the inferred dust-to-gas mass ratio is sensitive to other galactic properties, such as metallicity (e.g. Oort and Van de Hulst, 1946; Devereux and Young, 1990; Issa et al., 1990; Young and Scoville, 1991; Lisenfeld and Ferrara, 1998; Hirashita et al., 2002; Draine et al., 2007; Galametz et al., 2011; Sandstrom et al., 2013; Rémy-Ruyer et al., 2014; Giannetti et al., 2017; Chiang et al., 2018; Kahre et al., 2018; De Vis et al., 2019; Li et al., 2019; Shapley et al., 2020; Triani et al., 2020; Galliano et al., 2021). It is worth noting, however, that while star formation plays a crucial role in the formation of ISM dust, it is also responsible for dust destruction through supernova shocks, consumption in star formation and disruption from stellar radiation, alongside other dust destruction mechanisms such as “sputtering” and collisions between dust grains (Draine and Salpeter, 1979a,b; Seab and Shull, 1986; McKee et al., 1987; Bianchi and Ferrara, 2005; Borkowski et al., 2006; Nozawa et al., 2007; Gall et al., 2011a; Jones and Nuth, 2011; Mattsson et al., 2012; Slavin et al., 2015; Temim et al., 2015; Zhukovska et al., 2016; Hoang et al., 2019; Osman et al., 2020; Priestley et al., 2021).

There are numerous options available for modelling the spectral energy distribution produced by dust in the ISM. The most flexible but computationally expensive methods rely on theoretical models, such as Draine and Li (2007) and Draine et al. (2014), with parameters describing, for example, the dust composition and stellar radiation field, along with an appropriate radiative transfer code. Alternatively, libraries of empirical dust emission templates, such as those of Dale et al. (2014), can be fitted to the observed dust emission. Another popular method is based on the fact that the bulk of the FIR emission from galactic dust is produced by larger grains

in thermal equilibrium, and can be approximated by a modified blackbody function, combined with a power law at shorter wavelengths describing emission from smaller grains stochastically heated by UV photons, as discussed in Section 1.2.2 (e.g. Casey, 2012; Riechers et al., 2013; Greenslade et al., 2020). In this model, the flux density  $S_\lambda$  at a given wavelength  $\lambda$  in units of Jy is defined as

$$S_\lambda = N_{\text{bb}} \frac{(1 - e^{-(\frac{\lambda_0}{\lambda})^\beta}) (\frac{c}{\lambda})^3}{e^{\frac{hc}{\lambda k_B T}} - 1} + N_{\text{pl}} \lambda^\alpha e^{-(\frac{\lambda}{\lambda_c})^2}, \quad (1.18)$$

where  $N_{\text{bb}}$  and  $N_{\text{pl}}$  are normalisation constants for the modified blackbody and power law components respectively,  $\lambda_0$  is the wavelength at which the optical depth of the dust is equal to unity,  $\alpha$  is the power law slope,  $\beta$  is the spectral emissivity index controlling the wavelength-dependent dust opacity (typically defined as  $\tau(\nu) = (\nu/\nu_0)^\beta$ ),  $T$  is the temperature of the dust in thermal equilibrium and  $\lambda_c$  is the turnover wavelength at which the modified blackbody begins to dominate the emission spectrum (Casey, 2012). In Figure 1.6, we present examples of these three dust emission models, assuming a Chabrier IMF and a delayed star formation history.

### 1.3.4 AGN

A fraction of the galaxy population have their SEDs dominated by emission from an Active Galactic Nucleus (AGN). All galaxies are thought to harbour a SMBH at their centres, with AGN representing a subset of these SMBHs that are actively accreting material, releasing vast amounts of energy to produce extremely luminous emission (Salpeter, 1964; Zel'dovich, 1964; Lynden-Bell, 1969).

AGN are typically classified broadly into Radio Loud (RL) and Radio Quiet (RQ), based on a comparison between their radio and optical luminosities (e.g. Kellermann et al. (1989) define RL AGN as those that are  $\approx 10$  times brighter at 5 GHz than in the  $B$  band). Both RL and RQ AGN can then be further sub-divided into two classes. Type 1 AGN typically show bright continuum emission and broad emission lines, while Type 2 AGN show only weak continuum



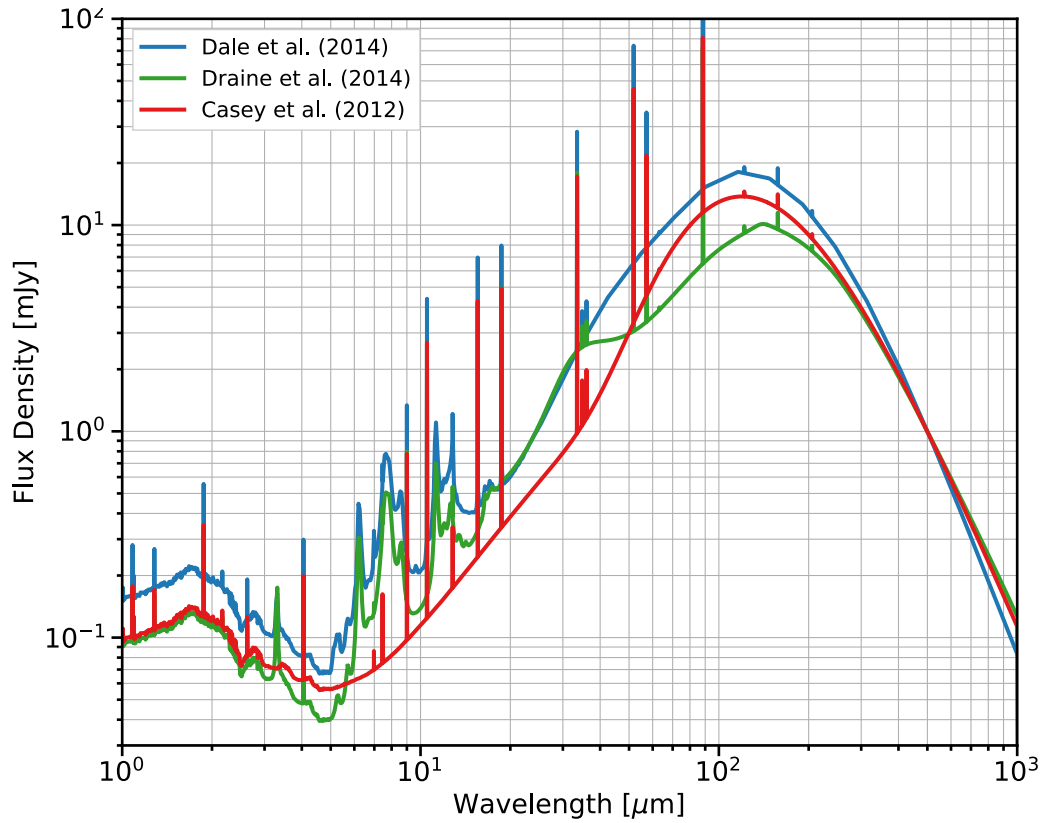


Figure 1.6: Model SEDs for dust emission from CIGALE based on a delayed exponential star formation history, a Chabrier IMF, and the default values for the parameters of each model. The resulting SEDs are normalised to a  $500\ \mu\text{m}$  flux density of 1 mJy for ease of comparison. Broadly, all three models share the same functional form, well described by a modified blackbody function combined with a MIR power law. The theoretical models and empirical templates benefit from a more accurate description of the emission features of PAH grains in the MIR.

emission and narrow emission lines (e.g. Urry and Padovani, 1995, and references therein). Type 1 AGN include Seyfert I galaxies (e.g. Weedman, 1977), lower luminosity Broad Line Radio Galaxies (BLRGs) and both Steep and Flat Spectrum Radio Quasars (SSRQs and FSRGs: Urry and Padovani, 1995). RQ Type 2 AGN include Seyfert II galaxies and Narrow Emission Line X-Ray Galaxies (NERGs: Mushotzky, 1982), while RL Type 2 AGN (often known as Narrow Line Radio Galaxies) are further sub-divided by morphology based on the classification scheme of Fanaroff and Riley (1974), with FR-I AGN describing those with lower radio luminosities and jets that decay in brightness at larger distances from the nucleus, and FR-II AGN describing those with higher radio luminosities and more defined radio lobes and hotspots, resulting in their jets becoming brighter at larger radii (Urry and Padovani, 1995). A small fraction of AGN fall into neither the Type 1 nor the Type 2 classification, such as BL Lacertae objects, RL AGN with only very weak spectral features, or Broad Absorption Line (BAL) quasars (e.g.

Turnshek, 1984).

While these categories demonstrate the variety and complexity in the observed properties of the AGN population, a popular school of thought suggests that the majority of different AGN classes may be the result of observing the same basic structure at different orientations. The emerging consensus is that AGN are comprised of a central SMBH surrounded by an accretion disk of material. Cold gas close to the central engine orbits with a large velocity, with the significant doppler shifting producing the broad line region, while the gas further from the central engine yields the narrow line region. This configuration is further surrounded by a dusty torus, typically described by a flared disc (e.g. Efstathiou and Rowan-Robinson, 1995; Manske et al., 1998; van Bemmelen and Dullemond, 2003; Fritz et al., 2006). RL AGN additionally produce powerful collimated jets, typically observed in the radio (Hardcastle and Croston, 2020). Based on this paradigm, we would expect to observe very different AGN properties at different viewing angles. For the case of the RQ AGN, RQ quasars, Seyfert 1 and Seyfert 2 galaxies are observed with increasing viewing angle perpendicular to the plane of the AGN, such that RQ quasars arise when directly viewing the central engine, as well as the broad and narrow line regions, while Seyfert 2 galaxies are produced when viewing the same structure through the dusty torus (e.g. Antonucci, 1993). Similarly, RL quasars are produced when the viewing angle allows observations of the central engine and both the broad and narrow line regions, BLRGs are observed at slightly larger viewing angles, while NLRGs are produced when the broad line region is fully obscured by the dusty torus (e.g. Urry and Padovani, 1995). Blazars, including the BL Lac and Optically Violent Variable (OVV) AGN, arise when viewing directly down the radio jet. It is worth noting, however, that the unification of different AGN types under a single population remains contentious, and there are numerous conflicting observations in the literature that argue for systematically different nuclear properties in different AGN types, suggesting that this theoretical model is not yet complete, or at least more complex than the simple model outlined above (e.g. Laurikainen and Salo, 1995; Dultzin-Hacyan et al., 1999; Nicastro, 2000; Tran, 2001; Chiaberge et al., 2002; Laor, 2003; Hardcastle et al., 2006; Ogle et al., 2006; Elitzur and Shlosman, 2006; Koulouridis et al., 2006; Wu et al., 2011; Ricci et al., 2011; Wang et al., 2012; Elitzur et al., 2014; Villarroel et al., 2017).

## 1.4 Dusty Star-Forming Galaxies and their Environments

While the previous section explored properties common to all galaxies, this section focuses on DSFGs and their various sub-varieties. The advances in infrared astronomy over the last two decades have allowed us to build large samples of DSFGs, from which we can begin to understand their global properties. In this section, we discuss our current understanding of the population of DSFGs based on these samples. In particular, much of this review focuses on the samples of SMGs detected at sub-millimetre wavelengths, typically by the  $850\,\mu\text{m}$  band of SCUBA-2.

### 1.4.1 Number Density

A key constraint in characterising the population of DSFGs is how numerous they are. However, due to the limited number of atmospheric bands available for observations in the infrared, only a handful of wavelengths benefit from accurate constraints of DSFG number counts. At  $850 - 870\,\mu\text{m}$ , large surveys undertaken with SCUBA and SCUBA-2, as well as observations from LABOCA and ALMA (Knudsen et al., 2008; Beelen et al., 2008; Chen et al., 2013b; Karim et al., 2013; Simpson et al., 2015; Geach et al., 2017; Michałowski et al., 2017) have yielded accurate number counts. Similarly, the  $450 - 500\,\mu\text{m}$  regime is well constrained from surveys with SCUBA-2 and *Herschel* (Clements et al., 2010b; Glenn et al., 2010; Geach et al., 2013b; Valiante et al., 2016; Zavala et al., 2017; Wang et al., 2017). The number counts are reasonably well constrained at  $70$ ,  $100$  and  $160\,\mu\text{m}$  from *Herschel* PACS observations and data from the Infrared Space Observatory (Kawara et al., 2004; Berta et al., 2011; Magnelli et al., 2013), at  $250$  and  $350\,\mu\text{m}$  from the other *Herschel* SPIRE bands and BLAST data (Patanchon et al., 2009; Clements et al., 2010b; Béthermin et al., 2010, 2012) and at  $1.1\,\text{mm}$  from observations with AzTEC and ALMA (Scott et al., 2010; Austermann et al., 2010; Hatsukade et al., 2011; Aretxaga et al., 2011; Scott et al., 2012; Hatsukade et al., 2016; Umehata et al., 2017). More recently, observations with, for example, ALMA and the SPT, have pushed our understanding of DSFG number counts to longer wavelengths (Hatsukade et al., 2013; Ono et al., 2014; Aravena

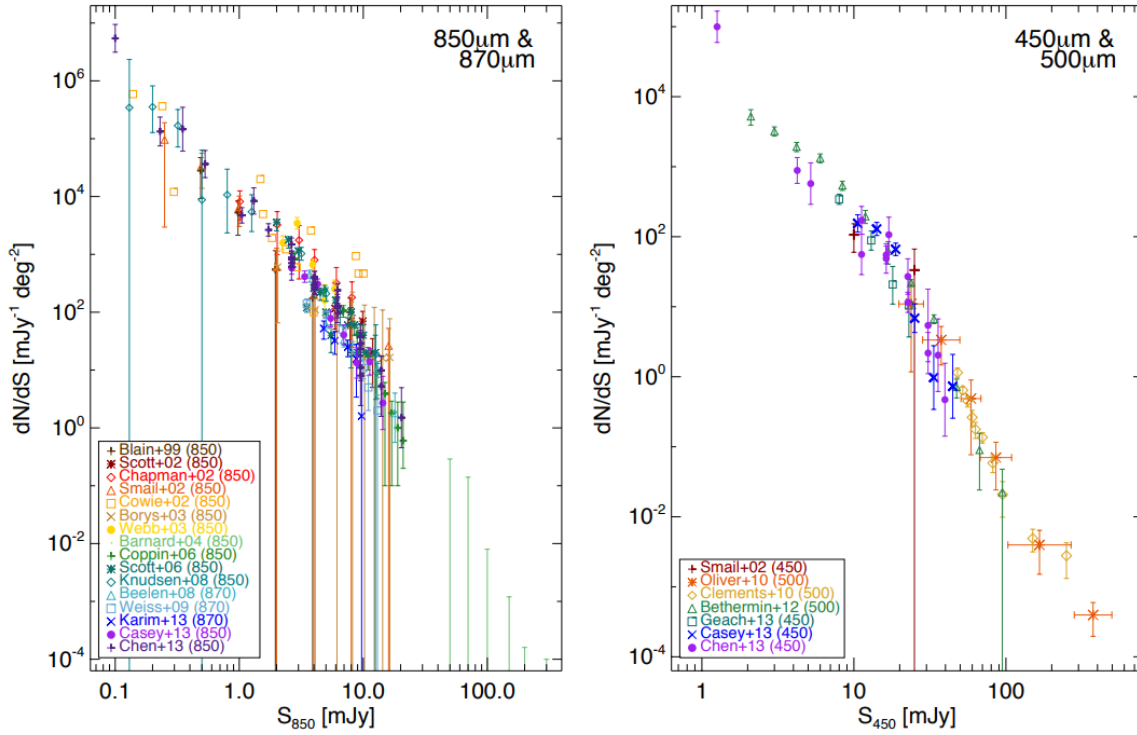


Figure 1.7: Differential number counts at 850 – 870  $\mu\text{m}$  (*left*) and at 450 – 500  $\mu\text{m}$  (*right*) from a number of studies. Figure reproduced with permission from Casey et al. (2014).

et al., 2016; Zavala et al., 2018; Muñoz Arancibia et al., 2018; Gómez-Guijarro et al., 2022; González-López et al., 2019; Everett et al., 2020; Casey et al., 2021a; Muñoz Arancibia et al., 2022), as well as providing stronger constraints at shorter wavelengths (e.g. Klitsch et al., 2020). Figures 1.7 and 1.8 show the form of the number counts in these regimes.

### 1.4.2 Redshift Distribution

Redshift distributions are typically determined separately for DSFGs selected in different bands, as they represent significantly different populations. At the shorter wavelength end, Desai et al. (2008) used spectra from the LRIS and DEIMOS (Faber et al., 2003) instruments on Keck to obtain spectroscopic redshifts for 421 DSFGs, finding that the redshift distribution of their sample peaks at  $z \sim 0.3$ , with smaller peaks at  $z \sim 0.9$  and  $z \sim 2.2$ , likely artefacts of the increased sensitivity of 24  $\mu\text{m}$  observations to bright PAH features emitted by galactic dust at these redshifts. Chapman et al. (2005) made the first attempt at describing the redshift distribution of SMGs using 73 SCUBA 850  $\mu\text{m}$ -selected sources via the identification of 1.4 GHz counterparts,

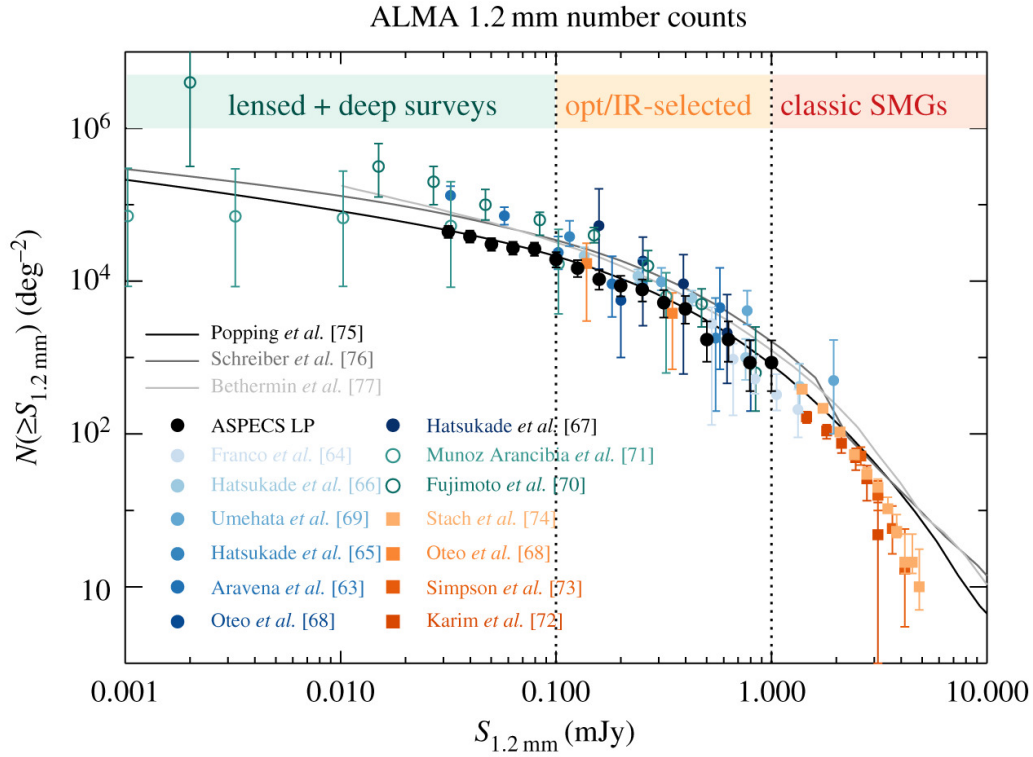


Figure 1.8: Cumulative number counts of SMGs (as well as optical/IR-selected sources and galaxies in deep lensing surveys) at 1.2 mm from a selection of studies using ALMA. Figure reproduced from Hodge and da Cunha (2020).

reporting a median redshift of  $z = 2.2$ , although this sample suffered from considerable selection effects. For example, galaxies lying in the redshift range  $1.2 < z < 1.9$  are poorly represented in the sample, as the spectral features typically used for redshift identification are shifted out of the bandpass of the LRIS instrument for these sources (Casey et al., 2014). Later work by Wardlow et al. (2011), and more recently Smith et al. (2017), independently determined the median redshift of SMGs to be  $z = 2.2 \pm 0.1$  and  $z = 2.05 \pm 0.03$ , with Smith et al. (2017) in particular finding that  $\sim 68\%$  of their sources lie between  $z = 1.06$  and  $z = 3.06$ . Similar results were found by other studies such as Koprowski et al. (2016), who measured the redshift distribution of SMGs from the SCUBA-2 Cosmology Legacy Survey. This suggests that SMGs tend to reside at  $z \sim 2 - 3$ , with all authors finding that their distributions show a long tail towards high redshifts, consistent with the extreme cases of DSFGs observed at  $z > 5$ . More recent observations have allowed the determination of the redshift distributions of DSFGs selected at longer wavelengths. For example, Reuter et al. (2020) obtained spectroscopic redshifts with ALMA for their sample of 81 DSFGs selected at 1.4 mm from the SPT-SZ survey, spanning

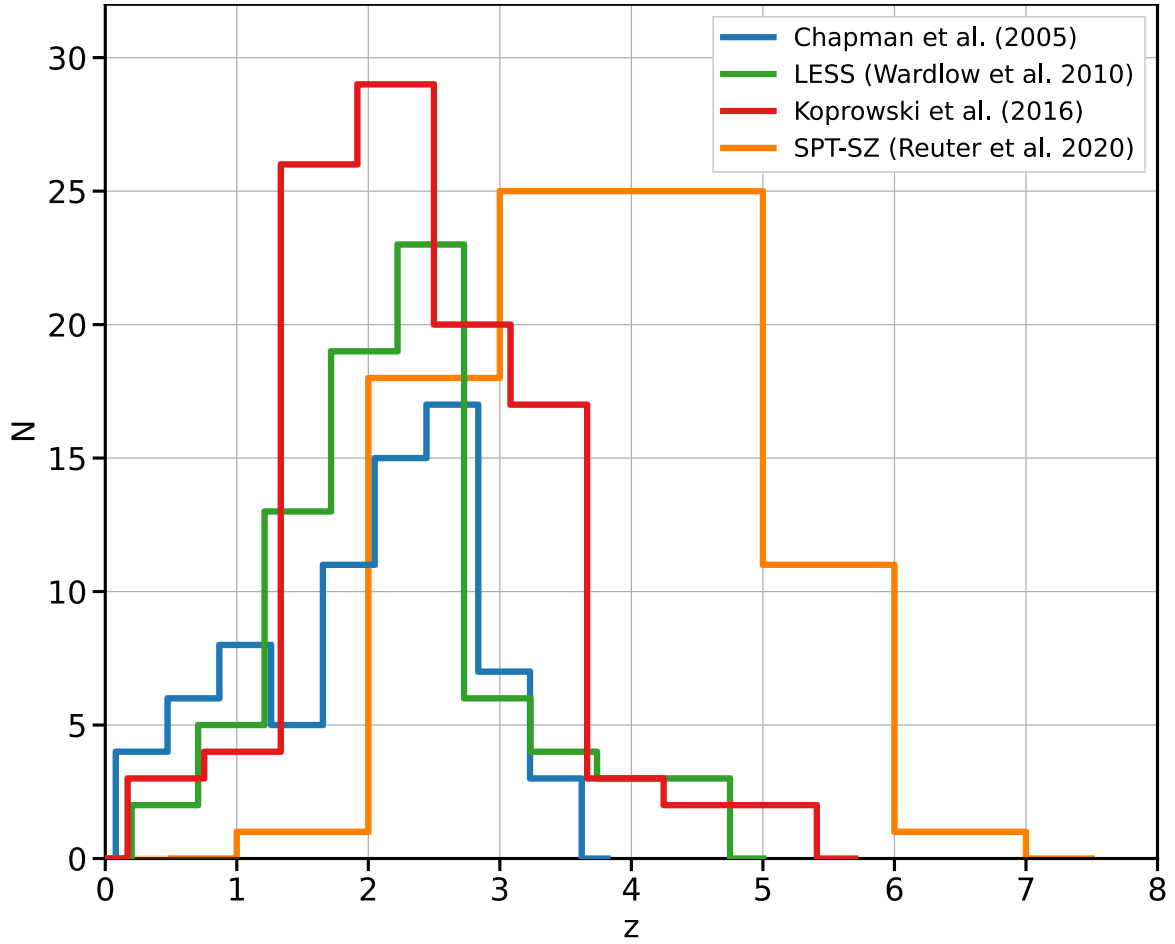


Figure 1.9: The redshift distribution for numerous surveys of SMGs. Here,  $N$  refers to the absolute number of galaxies in the survey at redshift  $z$ . For the population of sub-mm galaxies selected at  $850\,\mu\text{m}$ , the redshift distribution is remarkably consistent, peaking at  $z \sim 2$  with a significant high-redshift tail extending to  $z \sim 5 - 6$ . By comparison, the more recent SPT-SZ survey selects galaxies at slightly longer wavelengths of  $1.4\,\text{mm}$ , and as such is found to more effectively select DSFGs at  $z \sim 4$ .

$1.9 < z < 6.9$  and peaking at  $z = 3.9 \pm 0.2$ . The full redshift distributions for these samples can be found in Figure 1.9.

### 1.4.3 Luminosity and Star Formation

The integrated IR luminosity function is a simple yet powerful measure of the dust obscured star formation activity amongst a galaxy population. In its simplest form, the integrated IR luminosity function allows us to measure the number density of galaxies within defined IR luminosity ranges. As this IR luminosity is produced primarily by star formation (with some non-negligible contribution from AGN), this metric reveals how star formation activity

is distributed amongst the population of DSFGs. Moreover, we can trace the evolution of the functional form of the luminosity function with redshift, allowing us to better understand the evolution of dust obscured star formation activity with time and the contribution of dust-obscured star formation to the Cosmic Star Formation Rate Density (CSFRD).

Le Floc'h et al. (2005) used  $\approx 2600$  *Spitzer*  $24\mu\text{m}$ -selected sources with  $S_{24} \gtrsim 80\mu\text{Jy}$  to make the first measurement of the integrated IR luminosity function at  $0 < z < 1$ , extrapolating the  $24\mu\text{m}$  flux to longer wavelengths using a range of template SEDs and estimating  $L_{\text{IR}}$  for each source. Similar to predictions from IRAS data, Le Floc'h et al. (2005) found strong evolution in the contribution of DSFGs to the total IR energy density with redshift, likely due to evolution in both IR luminosity ( $L_{\text{IR}} \propto (1+z)^{3.2^{+0.7}_{-0.2}}$ ) and number density ( $\phi_{\text{IR}} \propto (1+z)^{0.7^{+0.2}_{-0.6}}$ ), such that galaxies with  $L_{\text{IR}} > 10^{11} L_{\odot}$  must contribute  $70 \pm 15\%$  to the comoving IR energy density. Later works similarly used *Spitzer*  $24\mu\text{m}$  and  $70\mu\text{m}$  data to constrain the integrated IR luminosity function first out to  $z \sim 2$  (Caputi et al., 2007) and later out to  $z \sim 2.3$  (Magnelli et al., 2011), with conclusions in broad agreement with those of Le Floc'h et al. (2005). These results suggested that ULIRGs make a significant contribution to the CSFRD at high redshifts, amounting to  $\sim 10\%$  of the cosmic SFR at  $z \sim 1$  and  $\sim 50\%$  at  $z \gtrsim 2$  (Casey et al., 2014). Subsequent studies similarly found that dust-obscured star formation contributes a significant fraction to the CSFRD, and can even dominate it at  $z \sim 2$  (e.g. Chapman et al., 2005; Wardlow et al., 2011; Barger et al., 2012; Lim et al., 2020; Rodríguez-Puebla et al., 2020).

While IR luminosity functions derived from *Spitzer* data used template SEDs to extrapolate MIR data to the FIR regime, *Herschel* data strongly constrained the peak of the FIR SED, in turn allowing stronger constraints on the luminosity function (Casey et al., 2014). Casey et al. (2012) derive the luminosity function for *Herschel* SPIRE-selected galaxies at  $0 < z < 1.6$ , while Magnelli et al. (2013) used photometry from *Herschel* PACS to derive the luminosity function at  $0 < z < 2.3$ , with both studies finding the luminosity function is best fit by a Schechter function. Gruppioni et al. (2013) used both *Herschel* PACS and SPIRE data to constrain the IR luminosity function out to  $z \sim 4$ , finding that both the luminosity function and number density evolve strongly with redshift, with the evolution of the integrated IR luminosity function depending on the source of the IR emission. In particular, Gruppioni et al. (2013) find that

AGN can only dominate the IR luminosity function at  $z > 2.5$ .

While the IR luminosity function is well constrained out to  $z \sim 4$ , there are significant tensions between studies at higher redshifts, although it is now widely believed that the contribution of dust-obscured star formation to the CSFRD is non-negligible at these redshifts (see e.g. Zavala et al., 2018). Some argue that the IR luminosity function can stay roughly constant above  $z \sim 4$  (e.g. Rowan-Robinson et al., 2016; Novak et al., 2017), while others suggest that individual DSFG luminosities can increase above  $z \sim 4$ , but that their number density decreases dramatically enough to cause the total integrated IR luminosity function to decrease at higher redshifts (e.g. Koprowski et al., 2017; Michałowski et al., 2017). More recent observations with ALMA are just beginning to provide constraints for this epoch. Gruppioni et al. (2020) estimated the total IR luminosity function based on multi-wavelength observations of 56 galaxies detected at  $\approx 1$  mm as part of the ALMA Large Program to Investigate [CII] at Early Times (ALPINE: Le Fèvre et al., 2020; Béthermin et al., 2020; Faisst et al., 2020b) survey, finding a flattening at the lower luminosity end and little evolution out to  $z \sim 6$ , suggesting little evolution in the contribution of dust-obscured star formation activity to the total CSFRD at early times. Zavala et al. (2021) combine deep ALMA number counts at 1.2 mm, 2 mm and 3 mm with a backwards evolution model, similarly finding a flattening of the luminosity function at the faint end, but additionally suggesting that, while dust-obscured star formation dominates from  $z \sim 2 - 4$ , it likely drops off significantly at higher redshifts, contributing  $\approx 20 - 25\%$  to the CSFRD at  $z = 6 - 7$ . While somewhat discordant, these results suggest that dust-obscured star formation provides a significant contribution to the total star formation activity in the Universe at early times.

Of particular interest is the bright end of the integrated IR luminosity function where we find some of the most intense sites of star formation in the Universe. Numerous examples of HIRGs have been discovered and characterised. Ma et al. (2015) infer the characteristics of six DSFGs at  $2.8 < z < 5.7$  finding SFRs as high as  $\approx 4800 M_{\odot} \text{ yr}^{-1}$  and stellar masses of up to  $\sim 10^{12} M_{\odot}$ . The host galaxy of the  $z = 6.42$  quasar J1148+5251 has been found to have a SFR in excess of  $3000 M_{\odot} \text{ yr}^{-1}$  and a total SFR surface density of  $\sim 1000 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  (Fan et al., 2003; Beelen et al., 2006; Wang et al., 2007; Riechers et al., 2009; Walter et al., 2009). The massive



starburst galaxy HFLS3 lies at  $z = 6.34$  and is known to host a  $\text{SFR} \sim 3000 \text{ M}_{\odot} \text{ yr}^{-1}$  with  $\sim 10^{11} \text{ M}_{\odot}$  of highly excited, chemically evolved interstellar medium (Riechers et al., 2013). Recent observations with LOFAR additionally suggest that these extreme objects are perhaps not as rare as once believed, with potentially as many as  $5 - 18$  existing per square degree (Wang et al., 2021b).

#### 1.4.4 Morphology, Multiplicity and Mergers

Arguably one of the most challenging aspects of observing SMGs is characterising their morphologies, which in turn provide clues to their evolutionary history. This is in part due to the distribution in redshifts of this population, as it is intrinsically more difficult to study the morphology of more distant objects. There is also the additional complication arising from observing in the infrared, with observations at longer wavelengths suffering from poorer angular resolutions compared to those at shorter wavelengths. As such, studying the population of SMGs on small spatial scales requires the use of FIR/radio interferometry, which typically cannot rapidly survey large samples or fields of view.

Studies aiming to determine the drivers of star formation in DSFGs based on their morphologies have produced mixed results. Some have found, via high resolution imaging/spectroscopic observations (Carilli et al., 2010; Targett et al., 2013; Michałowski et al., 2017) or cosmological simulations (Davé et al., 2010), that there are examples of DSFGs best described by an isolated, exponential disc of star formation, powered by smooth, sustainable accretion of gas from the galactic halo. Others find, typically via interferometry tracing popular gas emission lines (Engel et al., 2010; Ivison et al., 2012) or high resolution continuum imaging (Kartaltepe et al., 2007, 2012; Chen et al., 2015; Cochrane et al., 2021), that much of the DSFG population are likely merger driven, usually signposted by disturbed gas kinematics, irregular morphologies or multiple bright components associated with the source. There are additionally studies that find examples of both merger-driven and isolated systems. For example, Tacconi et al. (2008) present PdBI millimeter CO interferometry of four  $z \sim 2$  SMGs, finding that two show strong evidence of complex and disturbed gas kinematics, indicative of merger activity, with the other

two showing evidence that the star formation in SMGs is confined to very compact, rotating disks with a mean radius of  $\sim 1.6$  kpc. A consensus is thus emerging that, rather than being a homogeneous sample, the population of DSFGs is likely a composite of isolated systems undergoing sustained star formation, and merger-induced starbursts.

If DSFGs were primarily merger-induced systems, then we might expect a significant fraction of them to be observed as multiple systems prior to coalescence. However, while observing these multiple systems has become much more practical given the recent advancements in sub-mm and radio interferometry, determining whether they are physically associated sources or chance line-of-sight projections of DSFGs is much more challenging. Indeed, numerous examples of FIR-bright sources resolving into multiple counterparts have been observed (e.g. Tacconi et al., 2006, 2008; Engel et al., 2010; Smolčić et al., 2012; Karim et al., 2013; Hodge et al., 2013; Simpson et al., 2015; Chen et al., 2015; Riechers et al., 2017; Stach et al., 2018; Oteo et al., 2018; Miller et al., 2018; Wardlow et al., 2018; Lewis et al., 2018; Stach et al., 2019; Wicker et al., 2019; Cheng et al., 2019; Greenslade et al., 2020; Cairns et al., 2022). In fact, interferometric follow-up observations of large FIR/sub-mm single-dish surveys suggest that the majority of bright DSFGs are likely multiple systems. For example, Stach et al. (2018) present ALMA observations of 716 SMGs detected in the UKIDSS/UDS field as part of the SCUBA-2 Cosmology Legacy Survey, finding that  $44^{+16}_{-14}\%$  of those brighter than 9 mJy at  $850\ \mu\text{m}$  resolve into multiple sources. This is somewhat lower than the earlier work by Simpson et al. (2015), who found that  $61^{+19}_{-15}\%$  of their sample of 30 SMGs resolved into multiple systems based on high resolution follow-up observations with ALMA. By comparison, Hill et al. (2018) find a much lower fraction of  $\lesssim 15\%$  based on SMA observations of S2CLS DSFGs brighter than 8 mJy at  $850\ \mu\text{m}$ , although they note that their study was unable to probe potential multiples with very unequal flux distributions. Scudder et al. (2016) find that the problem of multiplicity is more severe, estimating that  $\approx 95\%$  of their sample of 360 Herschel  $250\ \mu\text{m}$ -selected sources break up into multiple strong components in  $3.6$  and/or  $24\ \mu\text{m}$  maps. They also find that, for the brightest  $250\ \mu\text{m}$  sources, the two brightest sources in the shorter wavelength maps contribute on average only  $\sim 70\%$  to the  $250\ \mu\text{m}$  flux, indicating that more than two sources are required. Simulations by Béthermin et al. (2017) further suggest that the brightest galaxy in the Herschel

beam contributes on average  $\sim 60\%$  to the total measured flux at  $500\,\mu\text{m}$ , requiring one or more fainter galaxies to provide the remaining flux.

However, the fraction of these multiple systems that are physically associated remains a topic of debate. Numerous examples of multiple DSFG systems have been spectroscopically confirmed as part of the same structure. Most notably, the protocluster cores discovered by Oteo et al. (2018) and Miller et al. (2018) based on ALMA and LABOCA follow-up observations of bright *Herschel* and SPT sources are each comprised of  $> 10$  DSFGs, spectroscopically confirmed to lie at the same redshift. Flores-Cacho et al. (2016) find that the thirteen galaxies associated with the bright *Planck* source PHz G95.5-61.6 are arranged into two high redshift structures at  $z \approx 1.7$  and  $z \approx 2$ , each of which is distinct and physically unassociated from the other. Numerous examples in older studies are further outlined by Casey (2016). However, these high multiplicity sources remain rare, and relatively little work has been dedicated to investigating whether multiples comprised of smaller numbers of DSFGs are likely to be physically associated. Gómez-Guijarro et al. (2019) present ALMA and VLA spectroscopy of three *Herschel*-bright sources previously shown to be multiples in ALMA  $870\,\mu\text{m}$  continuum imaging, finding that in all three systems the multiple DSFGs are physically associated. Other studies suggest that the majority ( $\approx 50 - 70\%$ ) of blended SMG systems are likely to be unassociated, typically based on either mock SMG catalogues from cosmological simulations (Hayward et al., 2013a; Cowley et al., 2015) or modelling the redshift probability density functions of galaxy samples based on multi-wavelength photometry and/or spectroscopy (Scudder et al., 2018). Therefore, the nature of these multiple DSFGs remains elusive, and large, high-resolution, spectroscopic follow-up surveys of these systems will be required to further understand and characterise this population.

### 1.4.5 Environments

There is a mounting body of evidence to suggest that DSFGs are likely to be the progenitors of the local massive ellipticals found preferentially within overdense environments such as galaxy groups and clusters. This evidence includes analysis of the SFHs of small samples of SMGs

at  $z \sim 2$  (Swinbank et al., 2006), spatial clustering of ULIRGs at  $1.5 < z < 3$  (Farrah et al., 2006), colour analysis of large samples of local cluster members (Eisenhardt et al., 2008), dark matter halo evolution modelling (Cook et al., 2010), and more recent analysis of the properties of large samples of SMGs selected from legacy surveys such as S2CLS (Wilkinson et al., 2017; Dudzevičiūtė et al., 2020). Moreover, Toft et al. (2014) analyse a sample of 18 SMGs spectroscopically confirmed to lie at  $3 < z < 6$ , finding that they are the most likely progenitors of the population of quiescent galaxies at  $z \sim 2$  based on comparisons of their star formation rates, stellar masses and co-moving number densities inferred from modelling of their SFHs.

Based on this emerging evidence, it seems not unreasonable to suggest that DSFGs at high redshift, if they do indeed evolve into the populations of massive, quiescent ellipticals observed at  $z = 0$ , might preferentially be found in the progenitors of these overdense environments. This, however, is in stark contrast to observations in the local Universe, where the star-forming population tends to reside in low-density, field regions while quiescent galaxies are generally found in denser cluster and group environments (see e.g. Dressler 1980; Balogh et al. 1998; Goto et al. 2003). Whether DSFGs indeed trace denser protocluster regions at high redshift is still a matter of debate. Capak et al. (2011) find an overdensity of DSFGs corresponding to a massive proto-cluster at  $z \sim 5.3$ . Clements et al. (2014) examine *Herschel* SPIRE images of 16 sources listed in the *Planck* Early Release Compact Source Catalogue, finding that four of these sources are high redshift ( $z \sim 0.8 - 2.3$ ) galaxy clusters comprised of overdensities of DSFGs. Clements et al. (2016) find an overdensity of both *Herschel* SPIRE and sub-mm sources around the  $z = 3.6$  lensed galaxy HATLAS12-00, concluding that this system is either a galaxy cluster/protocluster, or a larger scale structure that contains a number of galaxies undergoing coeval starbursts. Oteo et al. (2018) report the identification of an extreme protocluster of galaxies at  $z = 4$ , comprised of at least 10 DSFGs spectroscopically confirmed to lie at  $z = 4.002$ , with subsequent follow-up observations by Long et al. (2020) and Ivison et al. (2020) suggesting that the structure could be even larger, spread over several arcminutes and comprising numerous other SMGs. A qualitatively similar structure at  $z \approx 4.3$  was reported by Miller et al. (2018), originally thought to contain at least 14 coeval DSFGs, but with follow-up

observations suggesting that the structure comprises more than twice this number (Hill et al., 2020; Rotermund et al., 2021). Greenslade et al. (2018) find 27 candidate protoclusters of DSFGs in  $808.4 \text{ deg}^2$  of Herschel surveys, although they could not rule out the possibility that these candidate protoclusters are independent structures seen along the line of sight or chance alignments of unassociated sources. Based on a related sample, Cheng et al. (2019) provide SCUBA-2  $850 \mu\text{m}$  follow-up observations of likely multiple systems identified in *Planck* and *Herschel* observations, finding that 9/13 show significant overdensities compared to the field, with photometric redshift estimates suggesting that they could lie at  $z > 2$ .

Although these studies find examples of confirmed or candidate protoclusters at high redshifts, studies suggest that DSFGs are unlikely to be good tracers of overdense environments at high redshift. Chapman et al. (2009) present detailed observations of a cluster of SMGs at  $z \sim 2$ , postulating that, rather than tracing the most overdense regions in the high- $z$  Universe, DSFGs tend to trace regions in which the low matter density is very quickly evolving. Miller et al. (2015) use mock SMG catalogues created from cosmological simulations to show that SMGs exhibit complex biases, making them poor tracers of the most massive dark matter structures. They report that at  $z \lesssim 2.5$ , the most massive galaxies lying within denser cluster regions have already become quiescent due to the “downsizing” trend, and hence SMGs theoretically should not trace the densest regions. More recently García-Vergara et al. (2020) used the ALESS sample to demonstrate that the clustering of DSFGs and the subsequently inferred halo masses have typically been overestimated in single-dish surveys, suggesting that dark matter halos hosting SMGs at  $1 < z < 3$  are less massive than previously thought, and that only the brightest SMGs ( $S_{870} \gtrsim 5 \text{ mJy}$ ) should be the evolutionary predecessors of massive quiescent galaxies in the local Universe.

Evidence therefore seems to suggest that, while examples of massive structures in the early Universe populated with DSFGs may exist, overdensities of DSFGs may not necessarily be good tracers of these environments. In Chapters 2 and 4, we investigate the environments populated by DSFGs in more detail, including discussions of cluster selection methods and the evolution of these structures from protoclusters to galaxy clusters.

## 1.5 This Thesis

This work aims to further investigate the nature of DSFGs and the environments in which they form and evolve, providing observations of individual DSFG case studies, protocluster candidates and galaxy clusters at both low and high redshifts. As such, this work sheds light on the properties of DSFGs and the structures in which they are found, as well as providing promising targets for future follow-up observations.

In Chapter 2, we present molecular gas observations of star-forming galaxies in the Antlia galaxy cluster. This work investigates the effects of the disturbed cluster environment on its member galaxies, which provides a promising, low redshift analogue to the less accessible clusters in the process of formation at high redshifts, allowing us to infer how DSFGs may evolve in these environments.

In Chapter 3, we investigate the properties of four  $500\,\mu\text{m}$  risers, sources with a rising SED in the three *Herschel* SPIRE bands suggesting that they lie at  $z > 4$ . We use high resolution interferometric observations with the SMA to determine their multiplicities and wider field sub-mm observations with SCUBA-2 to determine the environments in which they are found, comparing them to known protoclusters such as the DRC and SPT2349-56. The available multi-wavelength photometry are further combined to investigate their properties, including photometric redshifts, integrated IR luminosities and associated SFRs.

In Chapter 4, we provide an analysis of the SpARCS-0330 galaxy cluster, one of the most massive and highest redshift galaxy clusters discovered to date. We combine *Spitzer* and *Herschel* observations with the multi-wavelength photometric catalogues compiled by Nantais et al. (2016) and archival observations to map out star formation and quenching within 15 Mpc of the cluster centre, allowing us to investigate how the evolution from  $z > 2$ , compact protocluster to more massive, local galaxy cluster proceeds.

In Chapter 5, we focus on a case study of the extremely luminous quasar-starburst system SDSS1607 at  $z = 3.65$ . By combining interferometric observations with the SMA and the VLA in the FIR/sub-mm and the radio with the high resolution optical imaging from *HST*

WFC3/IR discussed in Pitchford et al. (in prep), we characterise the morphology of this unusual source, disentangling the emission from the quasar, host galaxy and offset star formation, and investigate the build up of stellar mass in this high redshift DSFG.

We provide a summary of our results and avenues for further work and follow-up observations in Chapter 6. In each chapter we outline the cosmology used, typically selected to allow comparison with similar studies in the literature. Unless otherwise stated, a Chabrier IMF is used.

# Chapter 2

## Large Molecular Gas Reservoirs in Star-Forming Cluster Galaxies

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### 2.1 Introduction and Motivation

There remains a great deal of debate surrounding both the past and future evolution of DSFGs, and there is a growing consensus that they likely represent a diverse galaxy population in this respect. Numerous studies find examples of DSFGs that are isolated and gas-rich, with massive (but sustainable) SFRs primarily driven through secular processes (Carilli et al., 2010; Davé et al., 2010; Targett et al., 2013; Michałowski et al., 2017). Conversely, many studies find examples of DSFGs exhibiting massive, short-lived bursts of unsustainable star formation that are clearly driven by merger activity (Baugh et al., 2005; Tacconi et al., 2008; Engel et al., 2010; Ivison et al., 2012; Kartaltepe et al., 2012; Chen et al., 2015; Cochrane et al., 2021). A number of authors suggest that these merger-driven DSFGs are in fact a single stage in a much longer evolutionary sequence, followed by a bright quasar phase and eventual quenching to form a massive elliptical galaxy (Alexander et al., 2005; Farrah et al., 2006; Hopkins et al., 2008; Cook



et al., 2010; Toft et al., 2014; Wilkinson et al., 2017; Dudzevičiūtė et al., 2020).

In the local Universe, there is a well known bimodality concerning a galaxy’s morphology, SFR and the environment in which it resides. Massive, dynamically evolved galaxy clusters (such as Virgo or Coma) are primarily comprised of quiescent, elliptical galaxies, whereas field environments contain many more star-forming, spiral galaxies (Dressler, 1980; Balogh et al., 1998; Goto et al., 2003). Therefore, given that massive, elliptical galaxies in the local Universe preferentially reside within massive galaxy clusters, and that these massive, elliptical galaxies are likely descendants of DSFGs in the early Universe, it has been suggested that these early DSFGs should trace the intensely star forming regions that are the progenitors of the cores of massive and dynamically evolved galaxy clusters at  $z = 0$  (Umehata et al., 2015; Hung et al., 2016; Kato et al., 2016; Oteo et al., 2018; Lewis et al., 2018). Indeed, numerous studies have found examples of overdensities of DSFGs in the early Universe (Daddi et al., 2009; Capak et al., 2011; Walter et al., 2012; Clements et al., 2014; Dannerbauer et al., 2014; Umehata et al., 2015; Casey et al., 2015; Clements et al., 2016; Wang et al., 2016; Greenslade et al., 2018; Oteo et al., 2018; Miller et al., 2018; Kneissl et al., 2019; Gómez-Guijarro et al., 2019; Wang et al., 2021a; Álvarez Crespo et al., 2021; Jones et al., 2021). Moreover, observations of galaxy groups and clusters at  $z \sim 1$  favour a star formation history comprised of a massive but ultimately short-lived ( $\sim 100$  Myr) burst of star formation at high redshifts, followed by largely passive evolution (e.g. Eisenhardt et al., 2008). These observations open up the exciting possibility of using DSFGs as signposts for overdensities in the early Universe, from which we can learn about the formation and evolution of large scale structure.

It is, however, worth noting that DSFGs, and more specifically sub-millimeter galaxies (SMGs: Blain et al., 2002), are not considered to uniformly be ideal tracers of overdense regions in the Universe. For example, Miller et al. (2015) suggest that SMGs lying at redshifts of  $z \sim 2$  or lower are in fact extremely poor tracers of overdense regions, as these regions will typically have already evolved past their phase of active star formation. Moreover, numerous studies find examples of SMGs residing not within the very densest regions of a structure, but towards the outskirts of their cores (Dannerbauer et al., 2014; Casey et al., 2015; Kato et al., 2016), indicating that DSFGs may also be accreted into large scale structures at high redshift, rather

than uniformly tracing their very densest regions.

While a handful of high redshift protoclusters have been confirmed, determining how this evolving environment may affect its member galaxies remains a key observational challenge. In the local Universe, numerous environmental quenching mechanisms have been found to influence cluster members. The motion of infalling galaxies relative to the intracluster medium (ICM) is known to strip their reservoirs of interstellar gas, known as ram pressure stripping. (Gunn and Gott, 1972; Abadi et al., 1999; Fumagalli et al., 2014). High-energy, galaxy-galaxy close encounters and gravitational interactions between galaxies and the cluster potential can result in the distortion of cluster galaxies and the truncation of their haloes and disks, generally referred to as galaxy harassment (Moore et al., 1996, 1998; Fujita, 1998). Starvation occurs when the gas rich envelope of infalling galaxies is stripped, with the continued consumption of interstellar gas eventually exhausting the fuel for star formation (Larson et al., 1980; Bekki et al., 2002). Viscous stripping tends to occur in galaxies with higher binding energies, with the viscous flow of the ICM around the galaxy resulting in the stripping of the interstellar medium (ISM) via Kelvin-Helmholtz instabilities (Livio et al., 1980; Nulsen, 1982). Thermal evaporation can also strip galaxies of their ISM through the transfer of heat from the ionised plasma of the ICM to the colder interstellar gas via thermal conduction by electrons (Cowie and McKee, 1977; Sarazin, 1986). Evidence of these stripping mechanisms is typically obtained from either high-resolution optical/UV imaging or from the kinematics of the molecular/atomic gas reservoirs inferred from high-resolution spectral line surveys. However, at high redshifts, these techniques become increasingly difficult, primarily due to the challenges in obtaining the requisite spatial resolutions to determine any detailed kinematics in the high redshift DSFG samples. The magnification of strongly lensed galaxies can ease these problems, but interpreting these sources often relies on uncertain lens reconstruction modelling, and obtaining sufficiently detailed kinematic observations of a significant sample of gravitationally lensed sources remains challenging.

An alternative method would be to search for analogous environments to the evolving, high redshift clusters, but at significantly lower redshift. One of the main ways in which galaxy clusters grow is through mergers with other clusters, and the resulting disturbed galaxy clusters

could feasibly have similar characteristics to developing clusters at higher redshift. Moreover, a significant fraction of galaxy clusters have been observed in a disturbed state, with new generation instruments allowing large samples of galaxy clusters to be uniformly selected through the Sunyaev-Zel'dovich (SZ) effect. Recent independent studies found that, even at lower redshifts ( $z < 0.8$ ), about 70% of *Planck* SZ-selected clusters are non-cool core (NCC), disturbed clusters (Andrade-Santos et al., 2017; Rossetti et al., 2017). This fraction does not seem to evolve with redshift between  $z = 0$  and  $z \sim 0.8$  (Rossetti et al., 2017). Aside from providing a potentially analogous environment with which to study the development of young galaxy clusters, galaxy cluster mergers are the most energetic events in the Universe, and as such provide unique laboratories to connect large scale structure formation with processes occurring on kpc scales, such as particle acceleration in the ICM and star formation in member galaxies. As the most recently formed objects in the Universe, cluster mergers provide insight into the latest stage of cosmological structure formation (e.g. Springel et al., 2005). Disturbed clusters can act as contaminants and outliers for cosmological probes and scaling relations. Thus, understanding mergers is crucial for deriving precise cosmological parameters. Merging clusters have provided some of the most compelling evidence for the existence and nature of dark matter (e.g. Clowe et al., 2006; Dawson et al., 2012). Galaxy cluster mergers can have a profound impact on the ICM: the merger drives significant turbulence in the ICM (Fujita et al., 2003; Cassano and Brunetti, 2005; Vazza et al., 2009; Brunetti and Lazarian, 2011) and can release a large amount of energy into the ICM in the form of cluster-wide travelling shock waves (Markevitch et al., 2005; Pfrommer et al., 2006; van Weeren et al., 2010; Macario et al., 2011).

While disturbed cluster environments provide a unique cluster environment compared to their more dynamically evolved counterparts, little research has been dedicated to understanding the evolution of their member galaxies. A handful of recent studies suggest that the environmental trends observed in relaxed clusters may be reversed in disturbed clusters. Simulations suggest that travelling shocks induced by cluster mergers can enhance star formation for a few 100 Myr once the shock has interacted with the gas rich cluster members (e.g. Roediger et al., 2014). Stroe et al. (2017) find that, on average, merging clusters have higher densities of  $H\alpha$  emitters than the surrounding fields, particularly for merging clusters displaying evidence of ICM shocks.

High fractions of star-forming or very recently quenched disk galaxies, particularly located close to shock fronts, were also found in studies of individual merging clusters, such as: CIZA J2242.8+5301 (Stroe et al., 2014, 2015a), Abell 3921 (Pranger et al., 2013), Abell 520 (Deshev et al., 2017), Abell 521 (Ferrari et al., 2003; Umeda et al., 2004) and Abell 2744 (Owers et al., 2012). These unexpectedly large populations of star-forming galaxies are typically attributed to interactions between the cluster members and the disturbed intracluster medium (ICM) provided by either cluster-wide shocks from galaxy cluster mergers or accretion of young groups. Mulroy et al. (2017) demonstrated that the variation in average cluster colour decreases for more disturbed galaxy clusters, implying that SFRs in disturbed clusters may be ‘standardised’ by system-wide shocks. Cava et al. (2017) studied the morphologies of galaxies residing in both relaxed and disturbed clusters, finding that disturbed clusters are less efficient at converting star-forming spiral galaxies into gas-deficient lenticulars (S0 galaxies).

However, it remains unclear how this enhanced star formation activity in disturbed cluster environments is fuelled. It is therefore necessary to link observations tracing recent star formation to the reservoirs of cold, molecular gas within the member galaxies. Although the molecular gas mass in galaxies is dominated by  $\text{H}_2$ , the lowest ro-vibrational states of molecular hydrogen are forbidden and have high excitation requirements (Carilli and Walter, 2013). As a result, many studies use neutral hydrogen,  $\text{HI}$ , as a proxy for the molecular gas (e.g. Magri et al. 1988; Cayatte et al. 1990; Solanes et al. 2001; Chung et al. 2009; Serra et al. 2012). These studies find that spiral galaxies lying near the centre of relaxed clusters are much more deficient in  $\text{HI}$  than those found further from the cluster centre. Cayatte et al. (1994) demonstrate that this deficiency is most likely due to stripping of the gas through interactions with the ICM. This trend, however, is not recovered for disturbed cluster environments. Stroe et al. (2015b) find that  $\text{H}\alpha$  emission-line galaxies in the ‘Sausage’ cluster contain comparable amounts of  $\text{HI}$  gas to their field counterparts around the cluster. Similarly, Jaffé et al. (2012) find that many of the galaxies surrounding the central region of Abell 2192, a  $z = 0.19$  cluster in the process of forming, preserve their  $\text{HI}$  reservoirs. These findings suggest that gas-rich cluster members can retain their gas during cluster mergers, and that interaction between these gas-rich member galaxies and the travelling shock waves from the cluster merger can trigger star formation.

While observations of HI gas can provide useful insights into gas reservoirs, carbon monoxide (CO) rotational transitions are superior tracers of the cold, molecular gas which more directly fuels star formation (e.g. Leroy et al. 2008; Cybulski et al. 2016) as CO is abundant, has low excitation requirements and its lower rotational transitions are easily observable from the ground (Carilli and Walter, 2013). A great deal of research probes molecular gas reservoirs via the CO rotational transitions. Much of the current literature, however, focuses on detecting CO rotational transitions in either low- $z$ , relaxed clusters (Kenney and Young, 1986; Casoli et al., 1991; Boselli et al., 2002; Wilson et al., 2009a; Corbelli et al., 2012; Koyama et al., 2017; Zabel et al., 2019), Ultra-Luminous Infrared Galaxies (ULIRGS) and submillimetre galaxies (see review by Carilli and Walter, 2013), or in the central regions of cooling flow clusters (e.g. Edge, 2001; Edge and Frayer, 2003; Salomé and Combes, 2004; Salomé et al., 2006). A handful of other studies detect CO rotational transitions in intermediate- $z$  (Geach et al., 2009; Jablonka et al., 2013) and high- $z$  (Hayashi et al., 2018) clusters, or in field environments (Wong and Blitz, 2002; Combes et al., 2007; Dannerbauer et al., 2009; Bigiel et al., 2011; Tacconi et al., 2013; Cicone et al., 2017). As a result, the molecular gas properties of star-forming galaxies lying in disturbed cluster environments remain unknown.

The Antlia cluster (Abell S636, RA=10<sup>h</sup>30<sup>m</sup>03<sup>s</sup>, DEC=−35°19′24″) is perfectly suited to provide a statistical sample of molecular gas measurements in disturbed cluster spirals. It is the most nearby disturbed galaxy cluster, residing around 40 Mpc away ( $z \sim 0.009$ ), making CO rotational lines easily accessible. The cluster is relatively massive, with an estimated virial mass of around  $5 \times 10^{14} M_{\odot}$  (e.g. Hopp and Materne, 1985; Hess et al., 2015). Antlia contains  $\sim 375$  galaxy members, with a galaxy density around 1.7 times higher than Virgo and 1.4 times higher than Fornax (Ferguson and Sandage, 1990). At its centre, the Antlia cluster hosts two main concentrations of galaxies surrounding the massive ellipticals NGC 3268 and NGC 3258, but contains at least five subclusters in total (Hopp and Materne, 1985). The elongated galaxy and X-ray distribution of the Antlia cluster is indicative of a cluster in an intermediate merger state (e.g. Nakazawa et al., 2000). A number of previous studies have targeted the Antlia cluster members, primarily focussing on either the population of Early-Type Galaxies (ETGs) (Smith Castelli et al., 2008; Calderón et al., 2015), dwarf galaxies (Caso et al., 2013, 2014; Vaduvescu

et al., 2014) or the two central massive ellipticals and their surrounding systems (Dirsch et al., 2003; Bassino et al., 2008). In their study of the HI content of the cluster members, Hess et al. (2015) detect 37 cluster members, out to a projected radius of 0.9 Mpc. The velocity distribution of the HI detections can be described as multi-modal, and is systematically redshifted from the optical velocity distribution by  $700 \text{ km s}^{-1}$ . At large radii, the HI rich galaxies are distributed asymmetrically, which the authors attribute to accretion along filaments.

In this study, observations of the CO  $J = 2 - 1$  rotational transition (hereafter known as the CO(2 - 1) transition) from the Atacama Pathfinder Experiment (APEX) telescope are used to trace the cold, molecular gas in the star-forming members of the Antlia cluster, in order to determine the effect of disturbed environments on the molecular gas content of star forming galaxies.

In Section 2.2 we discuss the ancillary and archival data that is used for both analysis and selection of the Antlia cluster members in this work. In Section 2.3 we outline the selection criteria for our sample and in Section 2.4 we present the observing strategy and the methods used for data reduction. In Section 2.5 we discuss our data analysis and we present our molecular gas measurements in Section 2.6. In Section 2.7 we provide a discussion of our results, by placing the detections in the context of the host galaxy properties and the larger scale cluster environment, and in Section 2.8 we summarise our main conclusions. We assume a standard  $\Lambda$ CDM cosmology with  $H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_\Lambda = 0.685$  and  $\Omega_M = 0.315$  (Planck Collaboration et al., 2014). At the average redshift of the Antlia cluster,  $\langle z \rangle \approx 0.009$ ,  $1''$  corresponds to  $0.192 \text{ kpc}$ .

## 2.2 Ancillary Data

As the most nearby, disturbed galaxy cluster Antlia has been the target of numerous previous observations and, as such, benefits from a wealth of multi-wavelength ancillary data. In this Section, we outline the ancillary data used in this study.

### 2.2.1 Optical Imaging

In order to study the morphologies of the cluster galaxies, we use the deepest archival multi-band optical imaging available. This data comes from the Second Generation of the Digitized Sky Survey (DSS2<sup>1</sup>), comprising a set of all-sky surveys taken on photographic plates in the 1980s and 1990s. Observations in the southern sky were taken with the 1.2 m Oschin Schmidt Camera at the Palomar Observatory as part of the Second Palomar Observatory Sky Survey (POSS-II: Reid et al., 1991). This instrument is comprised of a 1.8 m primary mirror and a 49.5 inch corrector plate, resulting in a focal ratio of  $f/2.44$  and a plate scale of 67.19" per millimeter. Each 14 square inch plate produced an unvignetted field of view of diameter 5.4°. Observations were taken in three bands, blue (IIIa-J emulsion and GG395 filter,  $\lambda_{eff} = 4800 \text{ \AA}$ ), red (IIIa-F and RG610,  $\lambda_{eff} = 6500 \text{ \AA}$ ) and near-infrared (IVN and RG9,  $\lambda_{eff} = 8500 \text{ \AA}$ ) down to limiting magnitudes of 22.5, 20.8 and 19.5 respectively. The 894 individual fields included in POSS-II cover the entirety of the northern sky and a fraction of the southern sky down to a declination of  $\delta \sim 3^\circ$  (de Carvalho et al., 2005). For the southern sky, observations were provided in numerous surveys taken with the UK Schmidt Telescope (UKST), another 1.2 m Schmidt telescope similar in design to the Oschin Schmidt Camera, positioned at Siding Spring Observatory in Australia. These surveys<sup>2</sup> included:

- The ESO/SERC Southern Sky Survey and Atlas, surveying the entire sky south of  $\delta = -20^\circ$  on IIIa-J emulsion with the blue GG395 filter, reaching sky-limited magnitudes of  $B_J = 22.5$  in 606 individual fields.
- The Second Epoch Survey covering the same 606 fields as the ESO/SERC Southern Sky Survey and Atlas on IIIa-F emulsion with a red OG590 filter, reaching sky-limited magnitudes of  $R = 21.5$ .
- The SERC I/SR Survey and Atlas of the Milky Way and Magellanic Clouds, which provided exposures in 151 fields with  $\delta < 0^\circ$  using infrared (IV-N emulsion and RG715

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<sup>1</sup><https://archive.stsci.edu/dss/>

<sup>2</sup><https://www.roe.ac.uk/ifa/wfau/ukstu/platelib.html>

filter) and short exposure red (IIIa-F emulsion and RG630 filter) plates down to a limiting magnitude of  $I = 19$ .

- the SERC Equatorial Sky Survey and Atlas which consisted of 288 fields in blue and red filters covering the area between POSS-II to the north and the Second Epoch Survey to the south.

In total, DSS2 observations cover 45%, 98% and 99% of the sky in the blue, red and infrared bands respectively. The data were then digitized from the photographic plates using a modified PDS microdensitometer with a pixel size of either 25 or 15 microns<sup>3</sup>. We use this data to make RGB images for the cluster members, all of which are well detected in DSS2, with the ALADIN software<sup>4</sup> (Bonnarel et al., 2000; Boch and Fernique, 2014).

We also use sporadic optical data from other telescopes. Imaging in the  $r$  band is available from the Visible MultiObject Spectrograph (VIMOS) instrument mounted on the third unit telescope (UT3/Melipal) of the ESO Very Large Telescope (VLT) in Paranal. VIMOS is a visible wide-field multi-object spectrograph comprised of four arms, each with a  $7' \times 8'$  FoV and a pixel size of  $0.205''$ . VIMOS can operate as an integral field spectrograph (comprised of 6400 fibers with a scale of  $0.33'' - 0.67''$ , covering up to  $54'' \times 54''$  on sky) and a multi-object spectrograph (with spectral resolution of  $R = 200 - 2500$  depending on the grism used), but we just use archival imaging data with a  $7' \times 8'$  FoV. The archival data was obtained as part of the ESO programmes 079.B-0480(A) (PI: Richtler) and 093.B-0148(A) (PI: D. Rijcke). We obtained  $r$  band data for 33 of the sources studied in this work. Moreover, we obtain archival *HST* data covering four sources from programmes 14920 (PI: Boizelle), 7919 (PI: Sparks) and 9427 (PI: Harris), downloaded through the Mikulski Archive for Space Telescopes<sup>5</sup>. These observations include imaging with the IR channel on WFC3 with the F110W and F160W filters (with effective central wavelengths of 11,534 and 15,369 Å respectively), the NIC3 camera on NICMOS (similarly with the F160W filter, but also the F190N filter with an effective central wavelength of 19,003 Å) and the WFPC2 instrument with the F814W filter (with an effective

<sup>3</sup><http://gsss.stsci.edu/SkySurveys/SkySurveys.htm>

<sup>4</sup><http://aladin.u-strasbg.fr/>

<sup>5</sup><https://archive.stsci.edu/>



central wavelength of 7924 Å).

### 2.2.2 Stellar Masses and Star Formation Rates from *WISE*

While we don't make any direct use of longer wavelength archival data, the star formation rates and stellar masses of galaxies in the Antlia cluster were estimated by Hess et al. (2015) based on mid-infrared data from the *Wide-Field Infrared Survey Explorer* (*WISE*: Wright et al., 2010), and we make use of these estimates in this work. (Jarrett et al., 2012) aimed to improve upon the resolution-degraded public-release *WISE* images, creating images more sensitive to resolved galaxy detection. They therefore used the Variable-Pixel Linear Reconstruction or “drizzle” technique (Jarrett et al., 2012) to produce *WISE* mosaics. We will discuss the basis for the drizzling technique in more detail in Chapter 5, where we employ a drizzling algorithm to combine dithered *HST* observations.

Hess et al. (2015) construct  $\sim 3 \text{ deg}^2$  mosaics from the individual *WISE* images in all four infrared bands, following the drizzling method used to create the *WISE* High Resolution Galaxy Atlas (Jarrett et al., 2011, 2012, 2013). Based on its position, the Antlia field is covered by  $\sim 27$  orbits in the W1 and W2 bands, and around half this amount in the longer wavelength *WISE* bands (Hess et al., 2015). Accordingly, Hess et al. (2015) build up their catalogue of *WISE* sources by using the *WISE* galaxy characterisation pipeline (Jarrett et al., 2013) on the more sensitive W1 band, resulting in 480 extended sources detected in total for the Antlia field, limited to  $\text{SNR} = 10$  or a limiting Vega magnitude of 16.05. Hess et al. (2015) expect all Antlia cluster members to be resolved given its relatively close proximity and the  $\sim 6''$  angular resolution of *WISE*. Flux densities in the W2, W3 and W4 bands were then extracted based on the source position in the W1 band, reaching limiting Vega magnitudes of 15.8, 12.9 and 8.9 in the W2, W3 and W4 bands respectively (Hess et al., 2015). The *WISE* photometry is then used to estimate stellar masses and SFRs for their sample.

The *WISE*  $3.4 \mu\text{m}$  band is dominated by emission from the photospheres of evolved stellar populations, which contain the majority of baryonic matter in a galaxy and emit most of their radiation at near-infrared wavelengths (Zhu et al., 2010; Jarrett et al., 2013; Cluver et al.,

2014). A simple baryonic stellar mass can therefore be estimated using the luminosity at these wavelengths with a mass-to-light (M/L) ratio and an assumed IMF (Zhu et al., 2010). Jarrett et al. (2013), based on their sample of 17 spatially resolved galaxies from the *WISE* Enhanced Resolution Galaxy Atlas spanning a wide range of morphologies, colours, SFRs and stellar masses, demonstrated that the M/L ratio is strongly dependent on mid-infrared colour. They constructed their stellar M/L ratio by estimating stellar masses based on the  $K_s$  “in-band” luminosities of their sample from the Two Micron All Sky Survey (2MASS: Skrutskie et al., 2006), with the ‘light’ component estimated from the W1 luminosity. Note that “in-band” luminosities refer to the luminosity of an object relative to the Sun in a given band, and can be defined as

$$L = 10^{-0.4(M-M_{\odot})} \quad (2.1)$$

where  $L$  represents the luminosity of the source in a given band in units of  $L_{\odot}$ ,  $M$  is the absolute magnitude of the source, and  $M_{\odot}$  in this case is the absolute magnitude of the sun in that same band. Their stellar masses were based on the following relation from Zhu et al. (2010) constructed from their sample of 1,454 objects crossmatched between the *Spitzer* SWIRE and Sloan Digital Sky Survey (SDSS: York et al., 2000; Stoughton et al., 2002) DR7 surveys:

$$\log_{10} \left( \frac{M_{\star,ref}}{\nu L_{\nu}(K_s)} \right) = (-1.29 \pm 0.05) + (1.42 \pm 0.06) \times (g - r), \quad (2.2)$$

where  $M_{\star,ref}$  represents reference stellar masses for their sample taken from the Max-Planck-Institute for Astrophysics and Johns Hopkins University archives and estimated by fitting the (Bruzual and Charlot, 2003, BC03) stellar population synthesis models to SDSS photometry,  $\nu L_{\nu}(K_s)$  is the total power in Watts based on the 2MASS  $K_s$  band photometry, and  $(g - r)$  represents a small correction based on SDSS photometry accounting for the dependence of the M/L ratio on the star formation history (SFH) of the galaxy. Zhu et al. (2010) demonstrate that, while the  $K_s$  band photometry proved to be the most robust stellar mass estimator based on the relative insensitivity of the M/L ratio estimated in the  $K_s$  band to, for example, galaxy

morphology and  $E(B - V)$  colour excess, the  $M/L$  ratio does have a small dependence on  $H\alpha$  equivalent width (EW), which is used as a proxy for the SFH (Kennicutt, 1998a) given its close correlation with the stellar birthrate parameter  $b$  (defined as the ratio of the current SFR to the SFR averaged over the age of the disk: Scalo, 1986). Additionally, they showed that there is a strong anti-correlation between  $H\alpha$  EW and  $g - r$  colour, which allows the  $g - r$  colours from SDSS to act as the small correction factor in Equation 2.2.

Jarrett et al. (2013) used the  $M/L$  ratios estimated using this method to demonstrate that  $M/L$  ratio correlates strongly with both  $W1 - W2$  and  $W2 - W3$  colour, with higher  $M/L$  ratios for early type, bulge-dominated galaxies, and lower  $M/L$  ratios for late type, star forming galaxies. Cluver et al. (2014) later calibrated this relation based on a larger sample of nearby ( $z < 0.15$ ) galaxies, a subsample of the Galaxy and Mass Assembly (GAMA: Driver et al., 2009, 2011) survey. Their stellar masses were similarly estimated by fitting the BC03 stellar population synthesis models to optical photometry from SDSS in the  $u$ ,  $g$ ,  $r$ ,  $i$  and  $z$  bands, but Cluver et al. (2014) use only the  $W1 - W2$  *WISE* colours given the improved detection rate in the  $W2$  band compared to the  $W3$  band. As previously discussed, the galaxies in the Antlia cluster are expected to be well resolved and extended in the *WISE* images, and so Hess et al. (2015) estimate stellar masses from the  $M/L$  relations based only on the resolved galaxies in the Cluver et al. (2014) sample, defined as

$$\log_{10} \left( \frac{M_{\star}}{L_{W1}} \right) = -2.54 (W1 - W2) - 0.17 \quad (2.3)$$

where  $L_{W1}$  is the in-band luminosity for the  $W1$  band. These calculations result in stellar mass estimates for the resolved Antlia cluster members between  $\sim 10^{7.8} M_{\odot}$  and  $\sim 10^{11.1} M_{\odot}$  (Hess et al., 2015).

Hess et al. (2015) use both the  $W3$  and  $W4$  *WISE* bands to estimate the SFRs of galaxies in the Antlia cluster. The  $W3$  band is the more sensitive of the two bands (Cluver et al., 2014) and at rest frame covers both the  $11.3 \mu\text{m}$  PAH feature and the  $[\text{Ne II}]$  emission line at  $12.8 \mu\text{m}$ . The  $11.3 \mu\text{m}$  PAH feature is a result of the C-H out-of-plane bending mode with no adjacent

H atoms (i.e. “mono” H mode: Allamandola et al., 1989), stimulated by stochastic heating due to absorption of an energetic (usually UV) photon from starlight (Li and Draine, 2002). This makes PAH features useful tracers of star formation, as they should be predominantly excited around young stars producing large amounts of UV radiation. For example, Donoso et al. (2012) find that  $\sim 70\%$  of  $12\,\mu\text{m}$ -selected *WISE* sources are star-forming galaxies, and that  $\sim 80\%$  of the  $12\,\mu\text{m}$  emission from star-forming galaxies is produced by young ( $< 0.6\,\text{Gyr}$ ) stellar populations. Indeed numerous studies have subsequently calibrated PAH luminosity as a SFR indicator (Houck et al., 2007; Farrah et al., 2007; Zhu et al., 2008; Kennicutt et al., 2009; Shipley et al., 2016). However, there are significant issues with using the luminosities of PAH features alone as SF indicators. Firstly, PAH emission features can be produced by emission from cooler stars as well as more energetic photons and therefore, unlike the fine structure lines produced in HII regions, will additionally trace some fraction of older, cooler stars (Uchida et al., 2000; Li and Draine, 2002; Boselli et al., 2004; Calzetti, 2011; Bendo et al., 2020). PAH emission has been shown to have a strong metallicity dependence, with PAH luminosity suppressed in low metallicity regions (Engelbracht et al., 2005, 2008; Madden et al., 2006; Calzetti et al., 2007; Whitcomb et al., 2020). PAH features are also observed to be suppressed in regions with a harsh UV radiation field, such as star forming and PDR regions (Calzetti et al., 2005; Prescott et al., 2007; Bendo et al., 2008), in which they can be readily destroyed (Boulanger et al., 1988, 1990; Helou et al., 1991; Houck et al., 2004; Pety et al., 2005; Calzetti et al., 2007). Despite these problems, Shipley et al. (2016) find a scatter of just 0.14 dex in their PAH luminosity – SFR relation based on *Spitzer* IRS spectra with a metallicity correction, similar to the scatter estimated by other star formation indicators such as the hydrogen recombination lines, and Whitcomb et al. (2020) suggest that, while PAH emission alone may be a poor SFR indicator, the sum of the integrated luminosities of the [Ne II] and [Ne III] emission lines in combination with a major PAH feature provides an excellent SFR indicator, with minimal variation due to metallicity. The [Ne II] emission line is typically associated with HII regions and hence traces the young stellar population ( $< 10\,\text{Myr}$ ), as the low excitation potential of  $\text{Ne}^+$  (21.6 eV) means it is easily ionised in the regions surrounding young stars (see e.g. Roche et al., 1991; Thornley et al., 2000; Pereira-Santaella et al., 2010; Inami et al., 2013). As such, [Ne II] has been readily

detected directly from both galactic and extragalactic HII regions (Giveon et al., 2002; Dale et al., 2006; Rubin et al., 2007, 2008; Lebouteiller et al., 2008; Gordon et al., 2008; Rubin et al., 2016; Seok et al., 2018), star-forming galaxies (Verma et al., 2003; Brandl et al., 2006; Farrah et al., 2007; Beirão et al., 2008; Engelbracht et al., 2008; Pereira-Santaella et al., 2010; Magdis et al., 2013; Zhuang and Ho, 2019) and AGN (Sturm et al., 2002; Deo et al., 2007; Pereira-Santaella et al., 2010; Magdis et al., 2013; Xie et al., 2021). Zhuang et al. (2019) find that [Ne II] proves to be an excellent SFR indicator if any contribution from the AGN Narrow Line Region can be removed (typically based on other MIR fine structure lines such as [Ne V]).

By comparison, while the W4 band is less sensitive than the W3 band (Cluver et al., 2014), it is dominated by continuum emission from warm dust in thermal equilibrium heated by young, massive stars and has consistently proved to be a reliable SFR indicator (Alonso-Herrero et al., 2006; Calzetti et al., 2007; Rieke et al., 2009; Jarrett et al., 2013; Cluver et al., 2014, 2017), showing excellent agreement with other SFR indicators (e.g. hydrogen recombination lines or hybrid indicators). Hess et al. (2015) calculate SFRs from the *WISE* W3 and W4 bands based on the following empirical relations from Cluver et al. (2014):

$$\log_{10}(\text{SFR}) = 1.13 \log_{10}(\nu L_{12\mu\text{m}}) - 10.24 \quad (2.4)$$

$$\log_{10}(\text{SFR}) = 0.82 \log_{10}(\nu L_{22\mu\text{m}}) - 7.3 \quad (2.5)$$

where SFR refers to the star formation rate in  $\text{M}_{\odot}\text{yr}^{-1}$ , while  $L_{12\mu\text{m}}$  and  $L_{22\mu\text{m}}$  represent the luminosity in the  $12\mu\text{m}$  and  $22\mu\text{m}$  *WISE* bands. Based on these relations, Hess et al. (2015) estimate that the majority of galaxies in the Antlia cluster field have low SFRs, with only a handful estimated to have  $\text{SFR} > 1 \text{ M}_{\odot}\text{yr}^{-1}$ .

### 2.2.3 HI Observations and Neutral Gas Masses

Complementary to our observations of the molecular gas reservoirs of sources in the Antlia cluster are the observations of Hess et al. (2015), who studied the neutral gas masses of Antlia cluster members based on observations of HI atomic hydrogen with the seven-dish Karoo Array

Telescope (KAT-7: Carignan et al., 2013; Foley et al., 2016). KAT-7 is a precursor to the Karoo Array Telescope (MeerKAT Jonas, 2009), which in turn is the South African pathfinder for the Square Kilometer Array (SKA: Dewdney et al., 2009) currently under construction in Australia and South Africa. KAT-7 is an extremely compact (baselines between 12 m and 26 m) seven-dish interferometer situated in the Karoo desert in South Africa, with each dish of diameter 12 m and probing the frequency range 1200 – 1950 MHz. Hess et al. (2015) observed the Antlia galaxy cluster with a seven-point mosaic, totalling  $4.4 \text{ deg}^2$  degrees on the sky, centred on a frequency of 1406.7 MHz with 4096 channels covering 25 MHz in total. This configuration resulted in a synthesised beam FWHM of  $3.7' \times 3.0'$  and an RMS noise of 0.97 mJy/beam (Hess et al., 2015). These observations yielded 37 HI detections associated with the cluster, although Hess et al. (2015) note that only 18 of their HI detections have an optical counterpart within  $0.5'$ .

## 2.2.4 Velocities and Redshifts

Finally, we gather redshifts for all galaxies within  $1.5 \text{ deg}$  of the nominal centre of the Antlia cluster from the compilation of Caso and Richtler (2015). Caso and Richtler (2015) obtained optical velocities for galaxies across six fields in the Antlia cluster, based on VLT-VIMOS multi-object spectroscopy from programmes 60.A-9050(A) and 079.B-0480(B) (PI: T. Richtler), with a wavelength coverage of  $3700 - 6600 \text{ Å}$  and a spectral resolution of  $\sim 2.5 \text{ Å}$ , as well as GEMINI-GMOS multi-object spectra from programme GS-2013A-Q-37 (PI: J. P. Calderón), covering the wavelength range  $3300 - 7200 \text{ Å}$ . On top of the 67 heliocentric radial velocities calculated from their data, Caso and Richtler (2015) compile radial velocities from Smith Castelli et al. (2008, 2012), as well as from numerous additional sources in the NASA/IPAC Extragalactic database<sup>6</sup> (e.g. Lauberts and Valentijn, 1989; De Vaucouleurs et al., 1991; Mathewson et al., 1992; Matthews et al., 1995; Longhetti et al., 1998; Theureau et al., 1998; Ogando et al., 2008; Jones et al., 2009; Huchra et al., 2012).

After assembling the optical redshifts for sources in this region, we construct our cluster mem-

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<sup>6</sup><https://ned.ipac.caltech.edu/>

bership criteria. Smith Castelli et al. (2008) note that, given its disturbed nature, the Antlia galaxy cluster has significant substructure and complex dynamics, making a more relaxed membership criteria appropriate. Therefore, following both Smith Castelli et al. (2008) and Hess et al. (2015), we consider those sources within a  $3\sigma$  dispersion of the mean radial velocities of galaxies in the Antlia cluster from Hopp and Materne (1985) to be genuine cluster members. This corresponds to a relative velocity of  $1200 - 4200 \text{ km s}^{-1}$  or a redshift of  $0.004 - 0.014$ .

## 2.3 Sample Selection

We aim to study the cold molecular gas reservoirs of star forming galaxies within the Antlia galaxy cluster using two complementary samples: a selection based on obtaining a broad sampling of the stellar mass – SFR plane, and a selection based on galaxies with significant reservoirs of atomic gas from the observations of Hess et al. (2015). These samples are discussed in more detail in Sections 2.3.1 and 2.3.2 respectively.

### 2.3.1 Optically-Selected Sample

The primary scientific goal of this study is to investigate the relationship between the cold molecular gas reservoirs and SFRs of galaxies residing in a disturbed cluster environment. We therefore design our first sample to cover as much of the stellar mass – SFR plane as possible, whilst also including a variety of morphological types. The selection criteria for this sample is designed to select sources that:

- Are detected in the most sensitive  $3.4 \mu\text{m}$  band of *WISE* as an extended source
- Are within a two-dimensional projected cluster-centric radius of  $1.5^\circ$ , equivalent to  $\sim 1 \text{ Mpc}$  at the redshift of the Antlia galaxy cluster
- Have a redshift in the NASA/IPAC Extragalactic Database within the membership criteria outlined in Section 2.2.4 (i.e.  $0.004 < z < 0.014$  or  $1200 \text{ km s}^{-1} < v < 4200 \text{ km s}^{-1}$ )

- Have a *WISE*-estimated stellar mass of  $M_{\star} > 10^8 M_{\odot}$
- Have a *WISE*  $12\mu\text{m}$ -estimated star formation rate of  $\text{SFR} > 0.0005 M_{\odot}\text{yr}^{-1}$ .

This results in a sample of 72 galaxies, hereafter referred to as the optically-selected sample, spanning a wide range of stellar mass ( $10^{8.1} M_{\odot} < M_{\star} < 10^{11.2} M_{\odot}$ ) and star formation rate ( $10^{-3.3} M_{\odot}\text{yr}^{-1} < \text{SFR} < 10 M_{\odot}\text{yr}^{-1}$ ), and probing a similar range to contemporary state-of-the-art field surveys at comparable redshifts (e.g. Ciccone et al., 2017). We note that, based on the archival optical imaging discussed in Section 2.2.1, the optically-selected sample includes a variety of morphologies, including spirals, ellipticals and irregulars. It is additionally worth noting that the final sample excludes twelve sources with *WISE* detections that do not meet the stellar mass and/or SFR criteria, and 150 sources with no *WISE* counterparts at all. In Table 2.1, we show the properties of the galaxies in the optically-selected sample.

Table 2.1: Properties of the optically-selected sample.

| Source  | RA<br>J2000 | DEC<br>J2000 | v<br>$\text{km s}^{-1}$ | z      | $M_{\star}$<br>$10^9 M_{\odot}$ | SFR<br>$M_{\odot} \text{yr}^{-1}$ | Type <sup>†</sup> |
|---------|-------------|--------------|-------------------------|--------|---------------------------------|-----------------------------------|-------------------|
| J102330 | 10 23 30.19 | −35 27 20.6  | 4169                    | 0.0139 | $2.5 \pm 0.4$                   | $0.061 \pm 0.002$                 | I                 |
| J102507 | 10 25 07.62 | −35 36 17.9  | 3472                    | 0.0116 | $6.9 \pm 7.8$                   | $0.011 \pm 0.001$                 | S                 |
| J102622 | 10 26 22.22 | −34 57 48.7  | 3402                    | 0.0113 | $15.5 \pm 2.1$                  | $0.983 \pm 0.021$                 | S                 |
| J102632 | 10 26 32.43 | −34 18 43.3  | 3706                    | 0.0124 | $16.2 \pm 2.2$                  | $0.025 \pm 0.001$                 | E                 |
| J102702 | 10 27 02.49 | −36 13 41.1  | 3122                    | 0.0104 | $11.7 \pm 1.4$                  | $1.849 \pm 0.036$                 | S                 |
| J102720 | 10 27 20.43 | −35 16 27.4  | 2931                    | 0.0098 | $8.5 \pm 1.2$                   | $0.006 \pm 0.001$                 | S                 |
| J102722 | 10 27 22.73 | −33 52 38.1  | 2946                    | 0.0098 | $5.5 \pm 0.8$                   | $1.052 \pm 0.022$                 | S                 |
| J102733 | 10 27 33.05 | −35 59 11.4  | 2722                    | 0.0091 | $7.6 \pm 1.0$                   | $0.011 \pm 0.002$                 | S                 |
| J102757 | 10 27 57.38 | −35 49 18.1  | 2261                    | 0.0075 | $5.1 \pm 0.8$                   | $0.004 \pm 0.001$                 | S                 |
| J102803 | 10 28 03.06 | −35 26 32.4  | 3188                    | 0.0106 | $4.1 \pm 0.7$                   | $0.154 \pm 0.005$                 | S                 |
| J102808 | 10 28 08.09 | −35 38 24.9  | 2986                    | 0.0100 | $5.1 \pm 0.7$                   | $0.003 \pm 0.001$                 | S                 |
| J102816 | 10 28 16.03 | −35 32 01.4  | 2382                    | 0.0079 | $2.3 \pm 0.4$                   | $0.014 \pm 0.002$                 | S                 |
| J102819 | 10 28 19.17 | −35 27 16.4  | 2734                    | 0.0091 | $16.2 \pm 2.2$                  | $0.015 \pm 0.002$                 | E                 |
| J10281B | 10 28 19.24 | −35 45 30.6  | 2519                    | 0.0084 | $13.2 \pm 1.8$                  | $0.011 \pm 0.001$                 | S                 |
| J102823 | 10 28 23.97 | −35 31 46.7  | 2428                    | 0.0081 | $11.0 \pm 1.5$                  | $0.009 \pm 0.001$                 | E                 |
| J102831 | 10 28 31.96 | −35 42 18.2  | 2786                    | 0.0093 | $14.8 \pm 2.0$                  | $0.021 \pm 0.001$                 | S                 |
| J102834 | 10 28 34.26 | −35 27 39.1  | 2890                    | 0.0096 | $1.3 \pm 0.4$                   | $0.007 \pm 0.002$                 | I                 |
| J102847 | 10 28 47.12 | −35 39 29.6  | 3200                    | 0.0107 | $21.9 \pm 3.0$                  | $0.026 \pm 0.001$                 | S                 |
| J102853 | 10 28 53.56 | −35 36 19.9  | 2792                    | 0.0093 | $154.9 \pm 17.8$                | $0.250 \pm 0.006$                 | E                 |



Table 2.1: Continued.

| Source  | RA<br>J2000 | DEC<br>J2000 | v<br>km s <sup>-1</sup> | z      | $M_{\star}$<br>10 <sup>9</sup> M <sub>⊙</sub> | SFR<br>M <sub>⊙</sub> yr <sup>-1</sup> | Type <sup>†</sup> |
|---------|-------------|--------------|-------------------------|--------|-----------------------------------------------|----------------------------------------|-------------------|
| J102906 | 10 29 06.43 | −35 35 42.4  | 2416                    | 0.0081 | 36.3 ± 5.0                                    | 0.138 ± 0.004                          | E                 |
| J102911 | 10 29 11.05 | −35 41 16.4  | 2104                    | 0.0070 | 1.6 ± 0.3                                     | 0.171 ± 0.005                          | S                 |
| J102913 | 10 29 13.14 | −35 29 14.6  | 1355                    | 0.0045 | 5.4 ± 0.7                                     | 0.005 ± 0.001                          | S                 |
| J102928 | 10 29 28.41 | −34 40 21.8  | 4093                    | 0.0136 | 1.8 ± 0.3                                     | 0.017 ± 0.001                          | U                 |
| J102930 | 10 29 31.00 | −35 15 35.9  | 1852                    | 0.0062 | 14.5 ± 2.0                                    | 0.023 ± 0.002                          | S                 |
| J102948 | 10 29 48.63 | −35 19 20.2  | 3709                    | 0.0124 | 45.7 ± 6.3                                    | 0.040 ± 0.002                          | S                 |
| J102951 | 10 29 51.48 | −34 54 42.1  | 2549                    | 0.0085 | 34.7 ± 4.0                                    | 0.105 ± 0.003                          | S                 |
| J102953 | 10 29 53.04 | −35 22 30.4  | 1781                    | 0.0059 | 7.6 ± 1.0                                     | 0.008 ± 0.001                          | S                 |
| J102957 | 10 29 57.05 | −35 13 28.1  | 3754                    | 0.0125 | 66.1 ± 7.6                                    | 0.089 ± 0.003                          | S                 |
| J10295B | 10 29 51.23 | −35 09 51.1  | 2609                    | 0.0087 | 6.6 ± 0.9                                     | 0.015 ± 0.002                          | E                 |
| J103000 | 10 30 00.65 | −35 19 31.3  | 2800                    | 0.0093 | 173.8 ± 20.0                                  | 0.257 ± 0.006                          | E                 |
| J103001 | 10 30 01.12 | −35 48 50.3  | 1960                    | 0.0065 | 2.6 ± 0.5                                     | 0.003 ± 0.001                          | S                 |
| J103018 | 10 30 18.26 | −35 11 49.1  | 1768                    | 0.0059 | 3.2 ± 0.5                                     | 0.004 ± 0.001                          | E                 |
| J103019 | 10 30 19.51 | −34 24 18.0  | 3040                    | 0.0101 | 5.1 ± 0.7                                     | 0.482 ± 0.010                          | S                 |
| J103020 | 10 30 20.74 | −35 35 31.2  | 2364                    | 0.0079 | 0.5 ± 0.2                                     | 0.007 ± 0.001                          | I                 |
| J103025 | 10 30 25.82 | −35 06 29.1  | 1781                    | 0.0059 | 6.6 ± 0.9                                     | 0.177 ± 0.005                          | S                 |
| J103026 | 10 30 26.48 | −35 21 34.1  | 3804                    | 0.0127 | 128.8 ± 14.8                                  | 0.368 ± 0.008                          | S                 |
| J103029 | 10 30 29.18 | −35 36 38.1  | 2503                    | 0.0083 | 61.7 ± 7.1                                    | 0.117 ± 0.003                          | S                 |
| J10302B | 10 30 25.31 | −35 33 48.2  | 2140                    | 0.0071 | 5.1 ± 0.7                                     | 0.076 ± 0.002                          | S                 |
| J103044 | 10 30 44.95 | −35 21 32.8  | 3078                    | 0.0103 | 1.1 ± 0.3                                     | 0.008 ± 0.001                          | I                 |
| J103047 | 10 30 47.91 | −34 19 37.6  | 2691                    | 0.0090 | 1.7 ± 0.3                                     | 0.013 ± 0.001                          | S                 |
| J103051 | 10 30 51.77 | −36 44 13.2  | 3161                    | 0.0105 | 97.7 ± 11.3                                   | 1.333 ± 0.027                          | S                 |
| J103059 | 10 30 59.61 | −34 33 46.4  | 2111                    | 0.0070 | 74.1 ± 8.5                                    | 0.286 ± 0.006                          | S                 |
| J103124 | 10 31 24.21 | −35 13 13.6  | 2597                    | 0.0087 | 10.2 ± 1.4                                    | 0.385 ± 0.009                          | S                 |
| J103148 | 10 31 48.20 | −36 01 53.6  | 3168                    | 0.0106 | 8.1 ± 1.1                                     | 0.097 ± 0.003                          | S                 |
| J103152 | 10 31 52.11 | −34 51 13.3  | 3200                    | 0.0107 | 4.0 ± 0.5                                     | 10.691 ± 0.207                         | S                 |
| J103155 | 10 31 55.73 | −35 24 35.1  | 2476                    | 0.0083 | 39.8 ± 5.5                                    | 0.059 ± 0.002                          | S                 |
| J103156 | 10 31 56.21 | −34 59 28.9  | 1981                    | 0.0066 | 8.7 ± 1.2                                     | 0.011 ± 0.001                          | E                 |
| J103158 | 10 31 58.46 | −35 11 53.9  | 2289                    | 0.0076 | 15.8 ± 2.2                                    | 0.193 ± 0.005                          | S                 |
| J10315B | 10 31 52.19 | −35 12 18.1  | 2423                    | 0.0081 | 9.3 ± 1.3                                     | 0.012 ± 0.001                          | E                 |
| J103200 | 10 32 00.08 | −34 30 36.7  | 3571                    | 0.0119 | 1.8 ± 0.4                                     | 0.002 ± 0.001                          | S                 |
| J103208 | 10 32 08.44 | −34 40 29.2  | 2588                    | 0.0086 | 3.5 ± 0.6                                     | 0.003 ± 0.001                          | E                 |
| J103209 | 10 32 09.64 | −34 27 47.0  | 2937                    | 0.0098 | 1.6 ± 0.4                                     | 0.017 ± 0.002                          | I                 |
| J103212 | 10 32 12.72 | −34 40 24.0  | 2129                    | 0.0071 | 4.3 ± 0.6                                     | 0.043 ± 0.002                          | E                 |
| J103214 | 10 32 14.47 | −35 15 33.8  | 3825                    | 0.0127 | 2.1 ± 0.3                                     | 0.038 ± 0.002                          | S                 |
| J103224 | 10 32 24.87 | −34 59 55.9  | 3058                    | 0.0102 | 5.8 ± 0.8                                     | 0.271 ± 0.007                          | S                 |

Table 2.1: Continued.

| Source  | RA<br>J2000 | DEC<br>J2000 | v<br>km s <sup>-1</sup> | z      | $M_{\star}$<br>$10^9 M_{\odot}$ | SFR<br>$M_{\odot} \text{ yr}^{-1}$ | Type <sup>†</sup> |
|---------|-------------|--------------|-------------------------|--------|---------------------------------|------------------------------------|-------------------|
| J103248 | 10 32 48.73 | -34 23 58.1  | 3023                    | 0.0101 | $18.2 \pm 2.5$                  | $0.020 \pm 0.001$                  | S                 |
| J103259 | 10 32 59.55 | -34 53 10.2  | 2779                    | 0.0093 | $20.4 \pm 2.8$                  | $0.030 \pm 0.002$                  | S                 |
| J103400 | 10 34 00.76 | -35 16 56.8  | 2573                    | 0.0086 | $9.1 \pm 1.3$                   | $0.432 \pm 0.009$                  | S                 |
| J103407 | 10 34 07.42 | -35 19 24.0  | 2754                    | 0.0092 | $32.4 \pm 4.5$                  | $0.061 \pm 0.003$                  | S                 |
| J103408 | 10 34 08.69 | -34 38 01.6  | 2804                    | 0.0093 | $12.9 \pm 1.8$                  | $0.016 \pm 0.001$                  | E                 |
| J103413 | 10 34 13.64 | -36 14 00.5  | 3372                    | 0.0112 | $1.2 \pm 0.2$                   | $0.030 \pm 0.002$                  | S                 |
| J103419 | 10 34 19.08 | -34 24 12.1  | 2644                    | 0.0088 | $11.2 \pm 1.6$                  | $0.394 \pm 0.009$                  | S                 |
| J103445 | 10 34 45.04 | -35 28 14.0  | 2662                    | 0.0089 | $3.0 \pm 0.6$                   | $0.035 \pm 0.002$                  | S                 |
| J103551 | 10 35 51.16 | -34 16 11.5  | 3845                    | 0.0128 | $3.2 \pm 0.5$                   | $0.135 \pm 0.004$                  | S                 |
| J103639 | 10 36 39.06 | -34 45 21.8  | 4061                    | 0.0135 | $0.2 \pm 0.0$                   | $0.010 \pm 0.001$                  | S                 |
| TJ10250 | 10 25 05.48 | -35 59 00.6  | 3220                    | 0.0107 | $2.6 \pm 0.9$                   | $0.008 \pm 0.001$                  | I                 |
| TJ10274 | 10 27 47.07 | -34 31 56.3  | 3242                    | 0.0108 | $0.3 \pm 0.1$                   | $0.000 \pm 0.001$                  | I                 |
| TJ10283 | 10 28 31.27 | -35 40 36.2  | 3608                    | 0.0120 | $0.4 \pm 0.2$                   | $0.001 \pm 0.001$                  | I                 |
| TJ10290 | 10 29 01.94 | -35 33 58.4  | 2721                    | 0.0091 | $0.7 \pm 0.4$                   | $0.001 \pm 0.001$                  | I                 |
| TJ10300 | 10 30 06.12 | -35 23 22.5  | 3593                    | 0.0120 | $1.1 \pm 0.5$                   | $0.000 \pm 0.001$                  | I                 |
| TJ10314 | 10 31 49.57 | -35 12 20.4  | 2423                    | 0.0081 | $0.6 \pm 0.2$                   | $0.002 \pm 0.001$                  | I                 |
| TJ10331 | 10 33 16.22 | -34 31 09.7  | 1896                    | 0.0063 | $3.4 \pm 0.5$                   | $0.001 \pm 0.001$                  | E                 |

<sup>†</sup> S = Spiral, E = Elliptical, I = Irregular

### 2.3.2 HI Selected Sample

We supplement our optically-selected sample with a companion sample focused only on those galaxies with significant reservoirs of neutral, atomic hydrogen based on the blind KAT-7 observations of Hess et al. (2015). For this HI-selected sample, we simply impose a total integrated HI mass cut of  $M_{\text{HI}} > 10^{8.2} M_{\odot}$ , resulting in a sample of 20 galaxies. The properties of the galaxies in the HI-selected sample are shown in Table 2.2. We note that within this complementary sample, there are five sources that were additionally selected as part of our optically-selected sample.

Table 2.2: Properties of the HI-selected sample.

| Source   | RA<br>J2000 | DEC<br>J2000 | v<br>km s <sup>-1</sup> | z      | $M_{\star}$<br>10 <sup>9</sup> M <sub>⊙</sub> | SFR<br>M <sub>⊙</sub> yr <sup>-1</sup> | $M_{\text{HI}}$<br>10 <sup>8</sup> M <sub>⊙</sub> |
|----------|-------------|--------------|-------------------------|--------|-----------------------------------------------|----------------------------------------|---------------------------------------------------|
| Antlia1  | 10 30 53.00 | −34 53 44.0  | 4108                    | 0.0137 | 0.3 ± 0.1                                     | —                                      | 8.74 ± 0.48                                       |
| Antlia12 | 10 31 23.00 | −35 13 10.0  | 2549                    | 0.0085 | 10.2 ± 1.4                                    | 0.390 ± 0.010                          | 4.09 ± 0.43                                       |
| Antlia19 | 10 29 26.00 | −35 00 57.0  | 1829                    | 0.0061 | 0.1 ± 0.0                                     | 0.010 ± 0.005                          | 3.56 ± 0.27                                       |
| Antlia20 | 10 29 10.00 | −35 41 20.0  | 2147                    | 0.0072 | 1.6 ± 0.3                                     | 0.170 ± 0.010                          | 4.28 ± 0.27                                       |
| Antlia22 | 10 29 24.00 | −34 40 50.0  | 4117                    | 0.0137 | 1.8 ± 0.3                                     | 0.020 ± 0.005                          | 3.10 ± 0.45                                       |
| Antlia23 | 10 28 43.00 | −34 41 54.0  | 4267                    | 0.0142 | 0.0 ± 0.0                                     | —                                      | 2.41 ± 0.40                                       |
| Antlia25 | 10 27 00.00 | −36 13 48.0  | 3079                    | 0.0103 | 11.7 ± 1.4                                    | 1.850 ± 0.040                          | 14.85 ± 0.61                                      |
| Antlia26 | 10 30 13.00 | −34 29 28.0  | 4381                    | 0.0146 | 0.0 ± 0.0                                     | 0.000 ± 0.001                          | 2.20 ± 0.27                                       |
| Antlia27 | 10 32 22.00 | −34 50 33.0  | 4287                    | 0.0143 | —                                             | —                                      | 5.15 ± 0.49                                       |
| Antlia28 | 10 30 19.00 | −34 24 31.0  | 2990                    | 0.0100 | 5.1 ± 0.7                                     | 0.480 ± 0.010                          | 3.40 ± 0.38                                       |
| Antlia30 | 10 28 37.00 | −36 26 00.0  | 3438                    | 0.0115 | —                                             | —                                      | 4.80 ± 0.11                                       |
| Antlia31 | 10 32 55.00 | −36 04 12.0  | 4145                    | 0.0138 | 0.7 ± 0.3                                     | —                                      | 1.96 ± 0.30                                       |
| Antlia32 | 10 32 13.00 | −34 32 10.0  | 3315                    | 0.0111 | 0.0 ± 0.0                                     | —                                      | 12.07 ± 0.68                                      |
| Antlia33 | 10 31 00.00 | −34 23 51.0  | 3794                    | 0.0126 | 0.6 ± 0.2                                     | 0.010 ± 0.005                          | 12.35 ± 0.60                                      |
| Antlia34 | 10 30 09.00 | −36 06 01.0  | 2241                    | 0.0075 | 0.8 ± 0.2                                     | 0.010 ± 0.005                          | 2.76 ± 0.51                                       |
| Antlia36 | 10 26 55.00 | −34 39 07.0  | 3904                    | 0.0130 | 0.1 ± 0.0                                     | 0.010 ± 0.005                          | 18.27 ± 1.08                                      |
| Antlia37 | 10 26 57.00 | −34 23 09.0  | 3797                    | 0.0127 | —                                             | —                                      | 16.28 ± 0.69                                      |
| Antlia4  | 10 26 25.00 | −34 57 58.0  | 3358                    | 0.0112 | 15.5 ± 2.1                                    | 0.980 ± 0.020                          | 6.33 ± 0.46                                       |
| Antlia6  | 10 31 32.00 | −35 32 06.0  | 3228                    | 0.0108 | —                                             | —                                      | 2.10 ± 0.30                                       |
| Antlia8  | 10 31 00.00 | −35 00 27.0  | 3142                    | 0.0105 | —                                             | —                                      | 6.19 ± 0.38                                       |

In Figure 2.1 we present the distribution of both samples on the stellar mass – SFR plane, while in Figure 2.2 we show their redshift distributions. In Figure 2.1, squares denote the five sources that were detected in both the HI-selected and optically-selected samples. We find that the HI sample probes a somewhat different parameter space in the stellar mass – SFR plane than much of the optically-selected sample. Sources detected only in the HI sample have lower stellar masses ( $M_{\star} < 9.3 \text{ M}_{\odot}$ ) and SFRs ( $\text{SFR} < 0.02 \text{ M}_{\odot} \text{ yr}^{-1}$ ) than the majority of the optically-selected sample. Moreover, we find that those detected in both samples also have systematically larger stellar masses and SFRs than those that are unique to the HI-selected sample.

Galaxies in the optically-selected sample are broadly split into two groups, a smaller subgroup

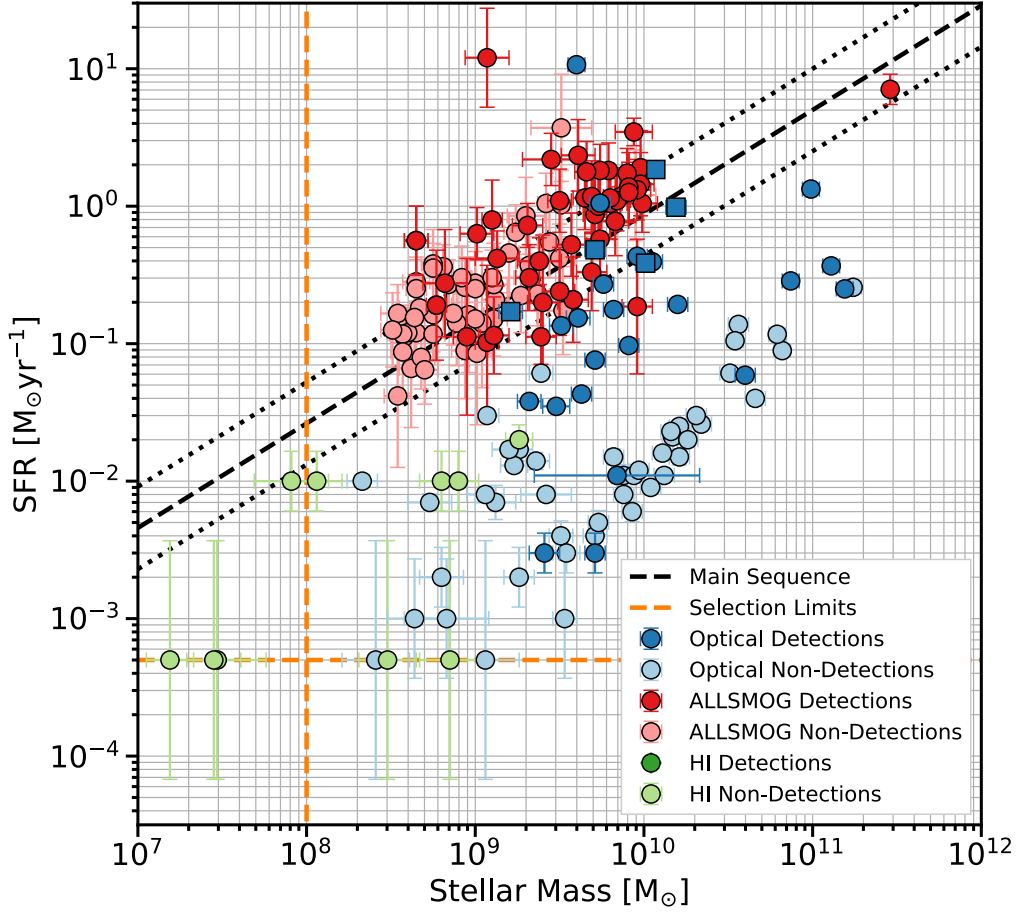


Figure 2.1: The distribution of both optically-selected and HI-selected Antlia cluster members in the  $M_{\star}$  – SFR plane., with squares denoting those sources detected in both samples. Darker colours indicate APEX CO(2 – 1) detections, whilst the lighter colours indicate non-detections. Cluster members are selected down to  $\text{SFR} > 0.0005 \text{ M}_{\odot} \text{ yr}^{-1}$  and  $M_{\star} > 10^8 \text{ M}_{\odot}$ . We overplot the local galaxy main sequence from (Renzini and Peng, 2015) and, for comparison, we show the ALLSMOG sample of field star-forming galaxies at a similar redshift (Cicone et al., 2017). We note that, while the ALLSMOG survey specifically targeted galaxies on the main sequence, our selection was broader and includes galaxies both on and significantly below the main sequence.

residing on or just below the main sequence, and a second larger subgroup residing significantly below the main sequence, indicative of galaxies that are in the process of having their star formation quenched.

### 2.3.3 Comparison Sample

Given that we are aiming to study the role that the disturbed environment within the Antlia cluster has on its member galaxies, we require a comparison sample of field galaxies that minimises the number of potential variables that could influence the interpretation of our results.

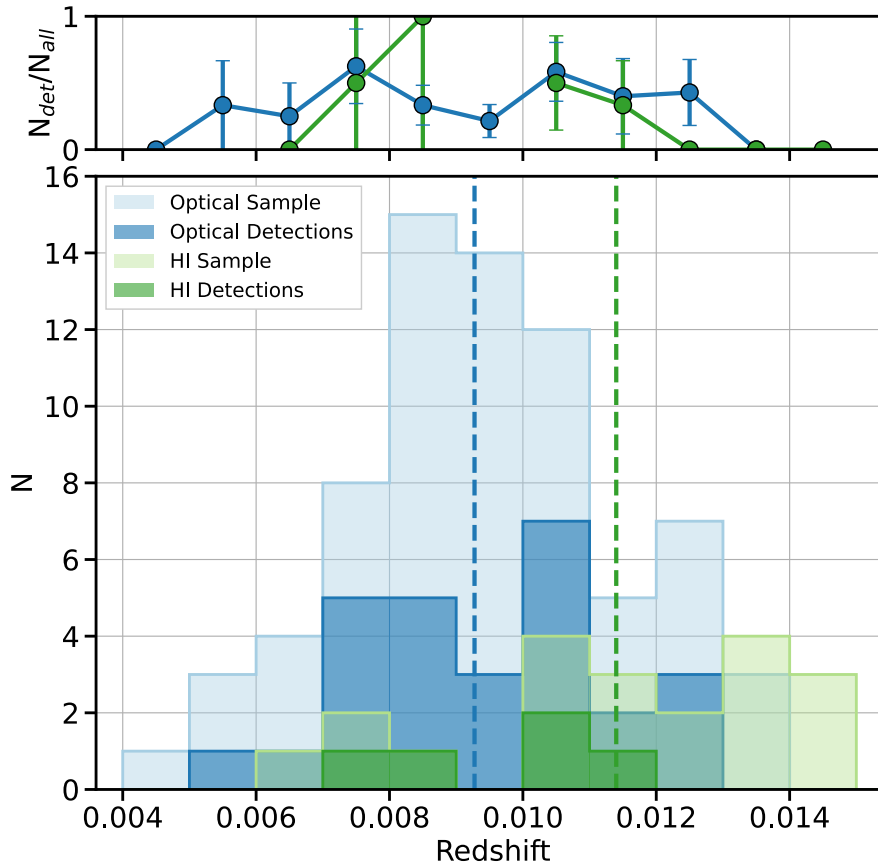


Figure 2.2: Redshift distribution of the optically-selected and HI-selected samples. Darker bars show detections, while lighter bars show the full sample. We note that, in this case, those sources that are selected in both samples are included in both sets of distributions. The dashed line shows the median redshift of each sample. We find that the HI-selected sample is offset from the bulk of the optically-selected sample, typically probing somewhat higher redshift galaxies. We find no significant relation between the detection rate and redshift for the optically-selected sample, and we note that the only detections associated with the HI sample are those included in both samples.

The most suitable comparison sample is the APEX Low-redshift Legacy Survey for Molecular Gas (ALLSMOG: Cicone et al., 2017), with an observing strategy that shares similarities with a number of our science goals. The ALLSMOG survey similarly aimed to use the APEX telescope to measure CO(2 – 1) emission tracing molecular gas reservoirs, although they primarily selected typical, main-sequence galaxies at low redshifts ( $0.01 < z < 0.03$ ) over a range of stellar masses ( $10^{8.5} M_{\odot} < M_{\star} < 10^{10} M_{\odot}$ ) (Cicone et al., 2017). These similarities remove numerous potential variables from the comparison, such as redshift evolution or evolution in the CO SLED and, as a result, we will primarily use the ALLSMOG survey as our comparison survey for this study.

We note that there are other potential comparison samples, such as the CO Legacy Database for the Galaxy All Sky Survey (COLD GASS: Saintonge et al., 2011a) as well as its successor xCOLD GASS (Saintonge et al., 2017). While these samples are extremely useful reference surveys, they display a number of key differences from our own science goals. First and foremost, they primarily cover massive star-forming and passive galaxies ( $M_{\star} > 10^{10} M_{\odot}$  over a slightly larger redshift range ( $0.025 < z < 0.05$ ), and so do not provide as much crossover with our samples as the ALLSMOG survey. Moreover, these surveys targeted the CO(1–0) line, and so we would rely on a conversion factor to directly compare to their CO luminosities, introducing an additional variable that could affect the comparison. There are also a number of differences between the two samples in terms of resolution effects and inclusion of AGN. We do however note that Ciccone et al. (2017) compare the ALLSMOG and COLD GASS surveys, finding that, given the large intrinsic scatter in the population of star-forming galaxies, many of the trends observed by COLD GASS at higher masses are fully recovered by the ALLSMOG survey. To minimise the number of unknowns and free parameters, and for ease of visualisation, here we use only the ALLSMOG survey as our comparison sample.

## 2.4 Observations and Data Reduction

For our HI-selected and optically-selected samples, we then aimed to obtain observations of the CO(2–1) emission line tracing their cold molecular gas reservoirs. We therefore observed our samples with the Atacama Pathfinder Experiment (APEX: Güsten et al., 2006) telescope<sup>7</sup>, a millimeter and sub-millimeter observatory situated in the Chajnantor plateau in the Atacama desert. The APEX telescope consists of a 12 m single dish and numerous instruments allowing observations from  $\sim 200$ –850 GHz. We use APEX with the PI230 dual polarisation heterodyne receiver mounted at the Naysmith-B focus of the telescope and covering the 200–270 GHz frequency range in 524,288 channels, reaching spatial resolutions of  $\sim 30''$  and spectral resolutions of  $0.0796 \text{ km s}^{-1}$ . The PI230 receiver can reach depths  $\sim 2\times$  better than the old SHFI-1 receiver in the same observing time. At 230 GHz, the beamsize of this configuration is  $\sim 26''$ , and so

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<sup>7</sup><http://www.apex-telescope.org/>

we expect these observations to recover  $> 85\%$  of the total flux from the extended sources in our sample and  $\sim 100\%$  of the flux for the more compact sources.

Our observing strategy was based on the ALLSMOG survey, as their observations were similarly taken with APEX targeting the CO(2 – 1) emission line in a sample of low redshift ( $z \sim 0.01 - 0.02$ ) field galaxies spanning a range of stellar masses ( $10^{8.5} M_{\odot} < M_{\star} < 10^{10} M_{\odot}$ ). Based on their results, we expect that the sources in our sample will have CO(2 – 1) luminosities of  $\sim 10^{7.5} K km s^{-1} pc^{-2}$ . Assuming an average velocity width for the gas distribution of  $\sim 150 km s^{-1}$  and a top-hat flux density distribution, we target a SNR  $> 5$  for  $10 km s^{-1}$  channel widths, yielding an RMS noise of  $\sim 1.3 mK$  per channel. Observations were taken in service mode as part of programme 0101.A-0681(A) (PI: A. Stroe).

For the HI-selected sample, the target position was defined based on the HI positions from Hess et al. (2015). Observations of the HI-selected sample were taken between the 26<sup>th</sup> and 30<sup>th</sup> June 2018. In total, 21 hours of observing time were used, with  $\sim 15$  hours spent on science targets.

For the galaxies in the optically-selected sample, we defined the target coordinates based on the available optical data. Observations were taken between the 23<sup>rd</sup> of April and the 26<sup>th</sup> of June 2018. The programme was completed in 48 hours, of which  $\sim 33.5$  hours were spent on science targets. We note that the five sources included in both samples are effectively observed twice with two slightly different pointings.

For both sets of observations we obtained calibration and pointing/focus scans prior to the science exposures. A variety of different astronomical objects were used for these calibration scans, including Venus, Jupiter, V Hydrae, RAFGL1235, RAFGL5254, OMC1, NGC6334I, SgrB2(N), 07454-7112 and L2-Pup. For the science observations, we used the “wobbler switching” observing technique, where the position at which the telescope is pointed is swapped between the science target and a sky position with an amplitude of  $60''$ , enabling more accurate sky subtraction and thus obtaining more stable baselines. In Figure 2.3, we show the variation in PWV across our science exposures. We find that the PWV varies between  $\sim 0.5 - 4 mm$ , with the majority of exposures taken under excellent weather conditions with  $PWV < 2.5 mm$ .

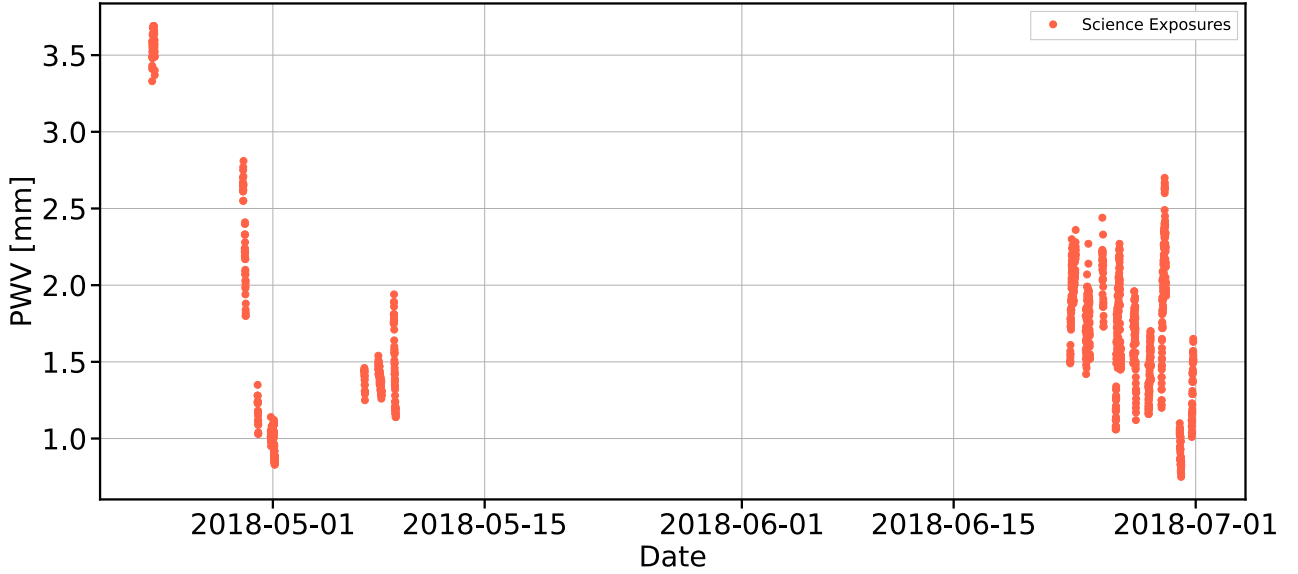


Figure 2.3: The variation of PWV values across our science observations. The vast majority of exposures were taken under excellent weather conditions, with  $\text{PWV} < 2.5$  mm.

We reduced the resulting APEX data using the standard **GILDAS** reduction software package **CLASS**<sup>8</sup> (Pety, 2018). Observations of each source from the PI230 instrument are taken as a set of four spectral windows, each with a width of 4 GHz and central frequencies of 223.825, 227.625, 239.625 and 243.425 GHz respectively. Additionally, each source was observed with numerous subscans. Given that the rest frame frequency of the  $\text{CO}(2-1)$  emission line is  $\nu_{\text{CO}(2-1)} = 230.54$  GHz, at the redshifts of the Antlia cluster members we would expect the  $\text{CO}(2-1)$  line to be placed within the 227.625 GHz spectral window. We therefore isolate this spectral window, flag the noisy channels towards the edge and mask a region  $500 \text{ km s}^{-1}$  either side of the expected position of the  $\text{CO}(2-1)$  emission line. For the baseline subtraction, we test fitting 0<sup>th</sup>, 1<sup>st</sup> and 2<sup>nd</sup> order polynomial functions, finding that a linear baseline subtraction provided the best results for our sample. Each spectral window has a total velocity width of  $\sim 5000 \text{ km s}^{-1}$  and so, even after masking  $\sim 1000 \text{ km s}^{-1}$  around the expected position of the  $\text{CO}(2-1)$  emission line, there are an ample number of channels left for calculating a robust baseline subtraction. We additionally search for serendipitous spectral line detections in the remaining three spectral windows, but no other lines are detected<sup>9</sup>. For each source, we average all subscans covering the same spectral window to create four high signal-to-noise, maximum

<sup>8</sup><http://www.iram.fr/IRAMFR/GILDAS>

<sup>9</sup>This is expected as, according to the Splatalogue online database (<https://www.cv.nrao.edu/php/splat/>), the frequency ranges of these windows do not probe any strong lines.



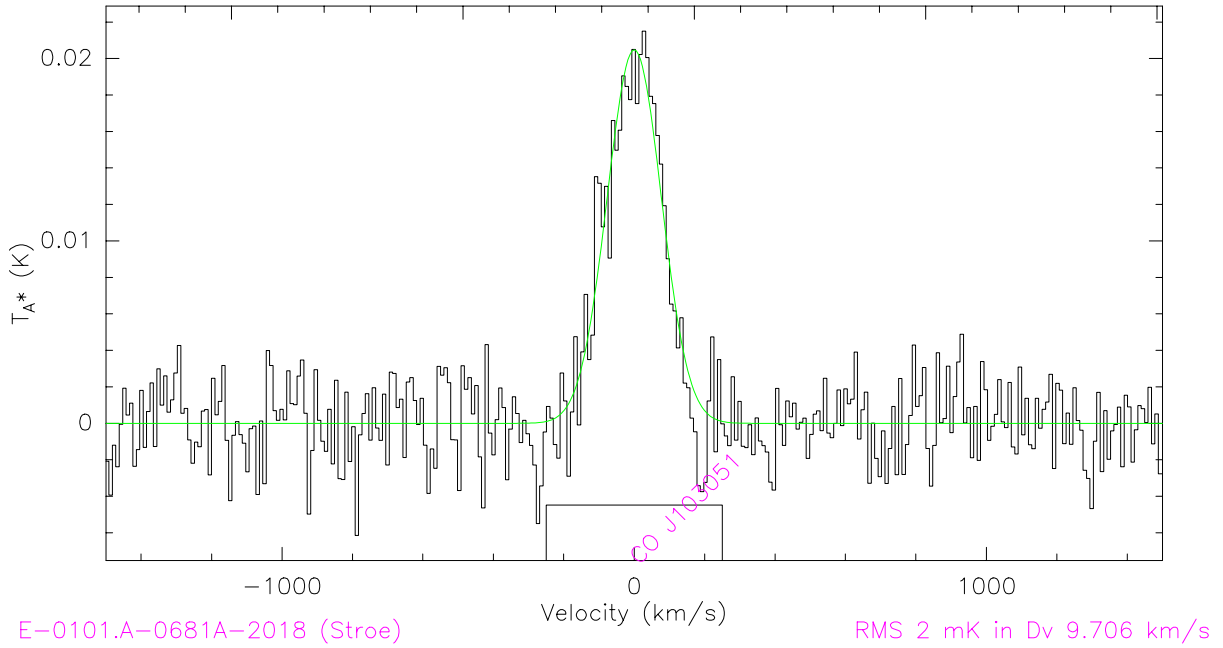


Figure 2.4: An example of the reduced spectra produced by the **CLASS** reduction software for the galaxy J103051. Resulting spectra are in units of antenna temperature corrected for atmospheric loss ( $T_A^*(K)$ ). The green line shows the best fit gaussian function to the CO(2 – 1) emission line estimated by **CLASS**.

resolution spectra covering each of the four spectral windows probed by the PI230 instrument. We checked each of these individual spectra by eye before stitching them together to create the ‘signal’ (221.825 – 229.625 GHz) and ‘image’ (237.624 – 245.425 GHz) spectra. In Figure 2.4, we show an example spectrum produced by **CLASS** for the galaxy J103051. Finally, the spectra are converted from their native units of antenna temperature corrected for atmospheric loss,  $T_A^*(K)$ , into units of flux density using the standard calibration factor<sup>10</sup>  $S_\nu/T_A^* = 42 \text{ Jy K}^{-1}$ .

We then smooth our spectra to the same spectral resolution as the ALLSMOG survey ( $50 \text{ km s}^{-1}$ ) in order to aid comparison between the RMS noise in our observations and those of ALLSMOG. In Figure 2.5, we show the RMS noise in the APEX spectra for both the HI and optical samples as a function of stellar mass, and in Figures 2.6 and 2.7 we show the resulting spectra for all of our sources alongside the optical image of their host galaxy. We find that the RMS values from our spectra are typically somewhat larger than the target RMS, with a median value of  $\sim 31 \text{ mJy}$ , although still reasonably consistent with the RMS noise in the ALLSMOG spectra (Cicone et al., 2017). We additionally produced spectra smoothed to a variety of velocity reso-

<sup>10</sup><http://www.apex-telescope.org/telescope/efficiency/index.php?yearBy=2018>

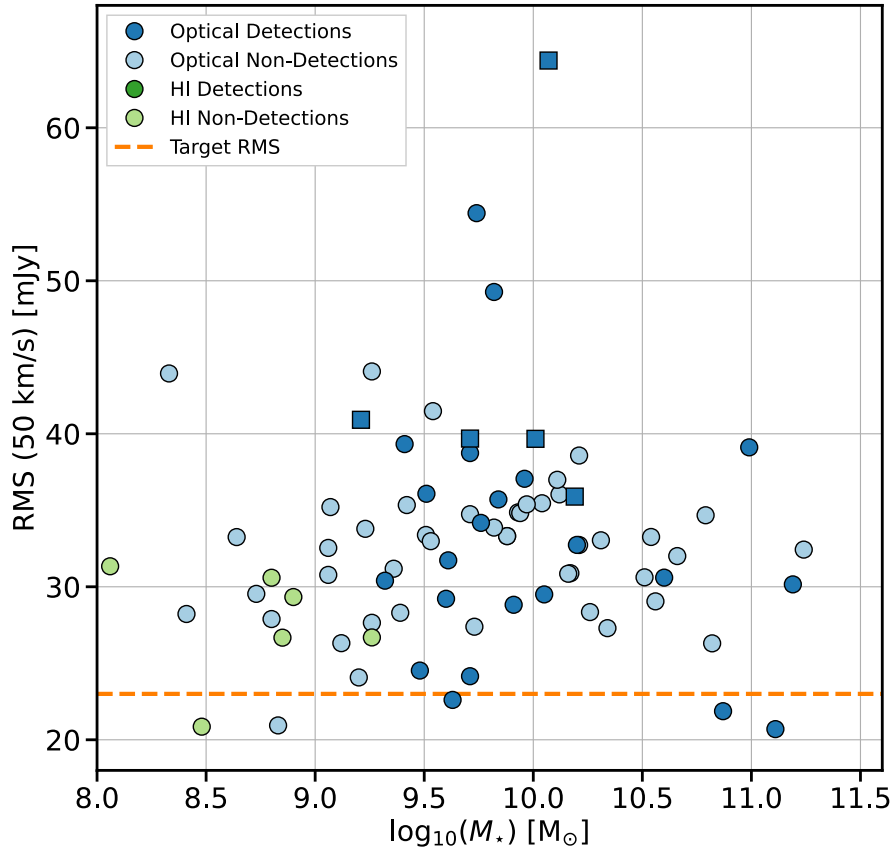


Figure 2.5: The  $1\sigma$  RMS noise in both our HI and optically-selected samples. The dark circles represent our  $S/N > 3$  detections and the light circles represent our non-detections, with squares denoting those sources in both samples. The dashed line represents the survey RMS goal of  $\sim 23$  mJy ( $\sim 0.6$  mK) for spectra smoothed to a velocity resolution of  $50 \text{ km s}^{-1}$ .

lutions (10, 15 and  $20 \text{ km s}^{-1}$ ) in order to evaluate whether the velocity resolution has a major influence on the result of the model fitting described in Section 2.5.1.

## 2.5 Analysis

### 2.5.1 Fitting Line Profiles

In order to probe the cold molecular gas reservoirs in our Antlia cluster members, we must calculate their  $\text{CO}(2-1)$  luminosities. For each galaxy, we test a number of different methods for fitting the  $\text{CO}(2-1)$  emission line profile, using both in-built **CLASS** functions and **LMFIT**<sup>11</sup> (Newville et al., 2014), a **Python** package specialising in non-linear least-squares minimisation

<sup>11</sup><https://lmfit.github.io/lmfit-py/>

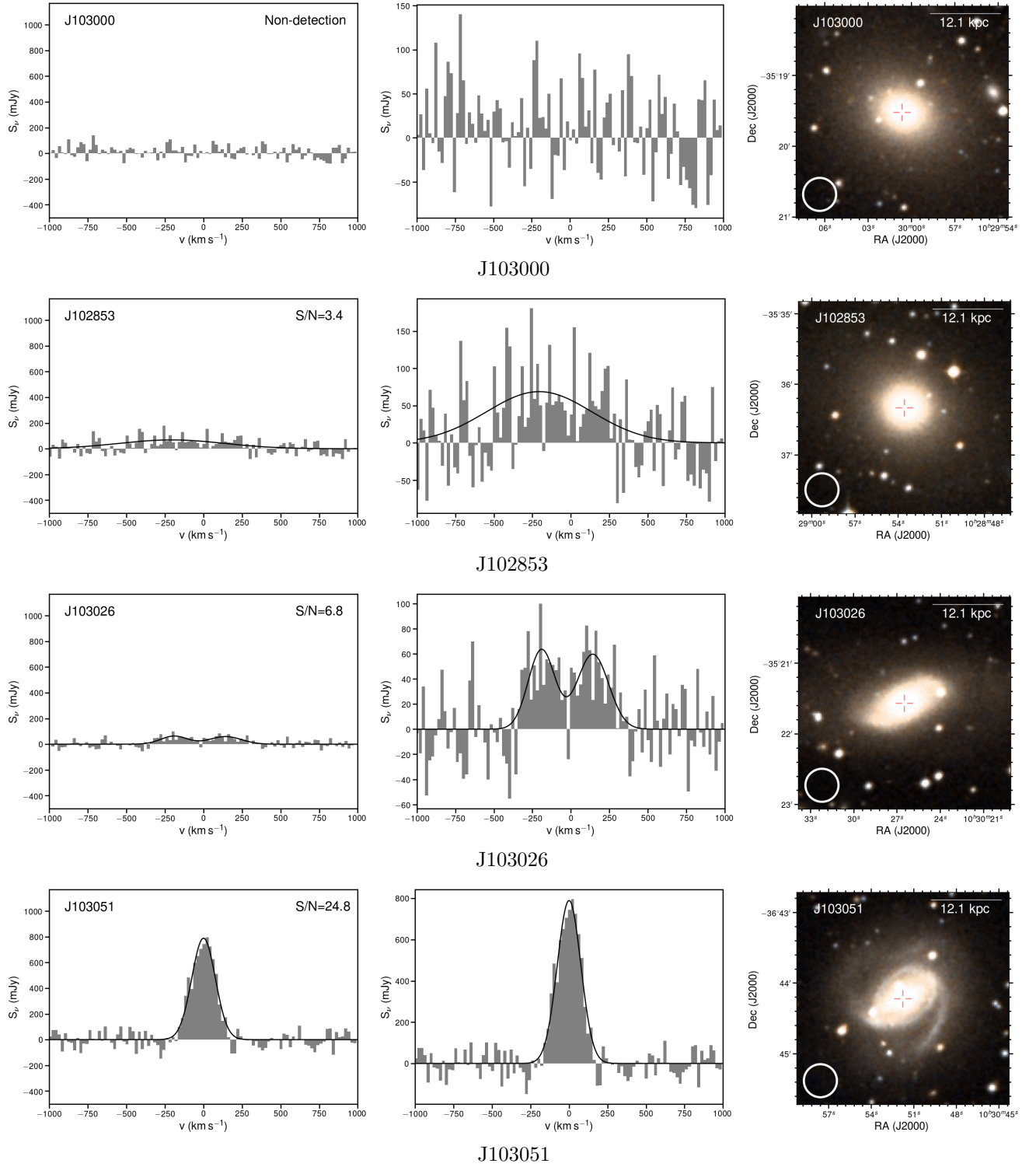


Figure 2.6: The spectra and optical images for sources in our optically-selected sample in descending order of stellar mass. Left: Observed spectrum in solid gray bars and fitted CO(2–1) Gaussian, double Gaussian or double horned profile in solid black line. All sources on the same scale. Middle: Spectrum scaled to the peak of the CO(2 – 1) emission. Right: RGB colour-composite from DSS.

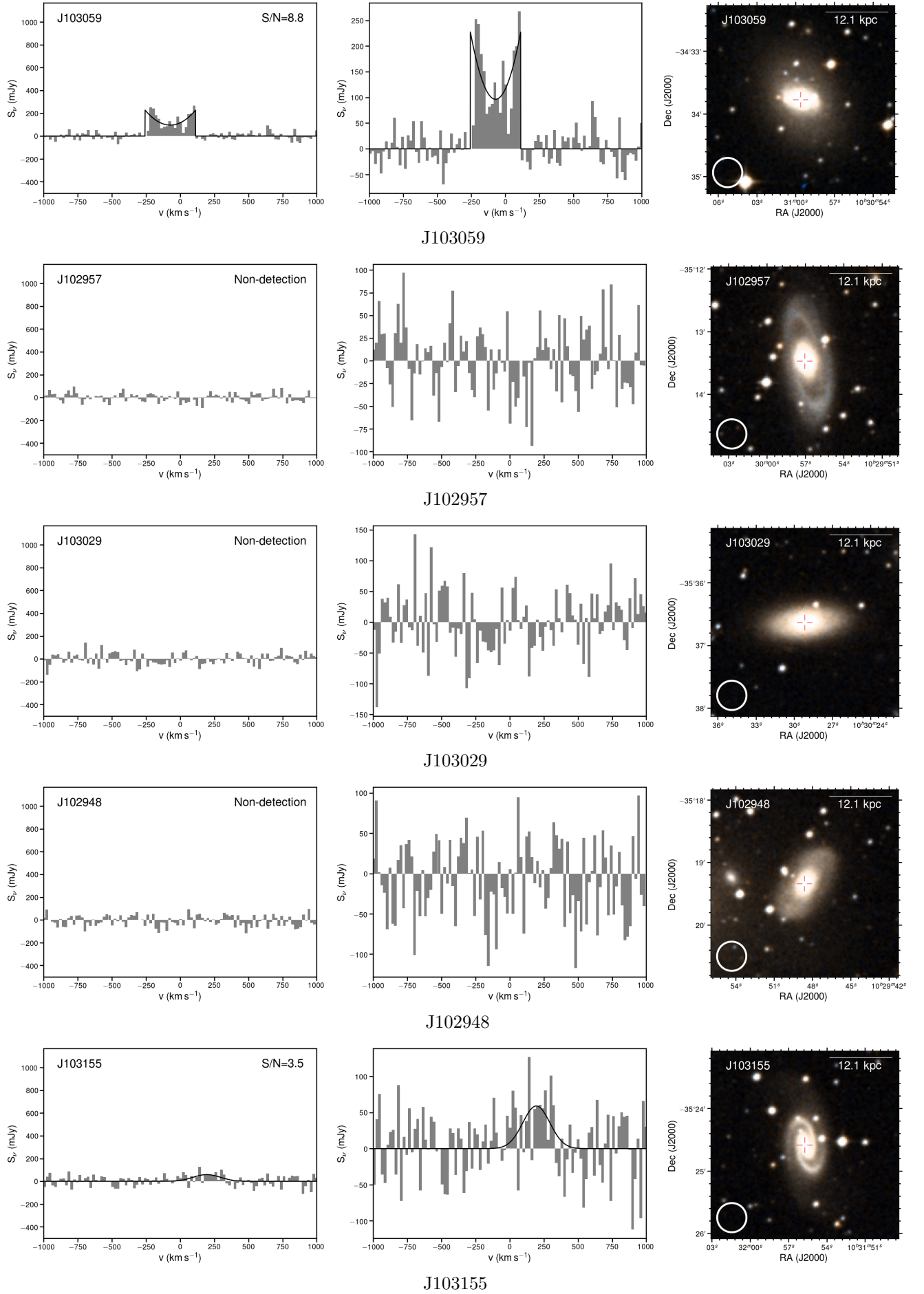


Figure 2.6: Continued.

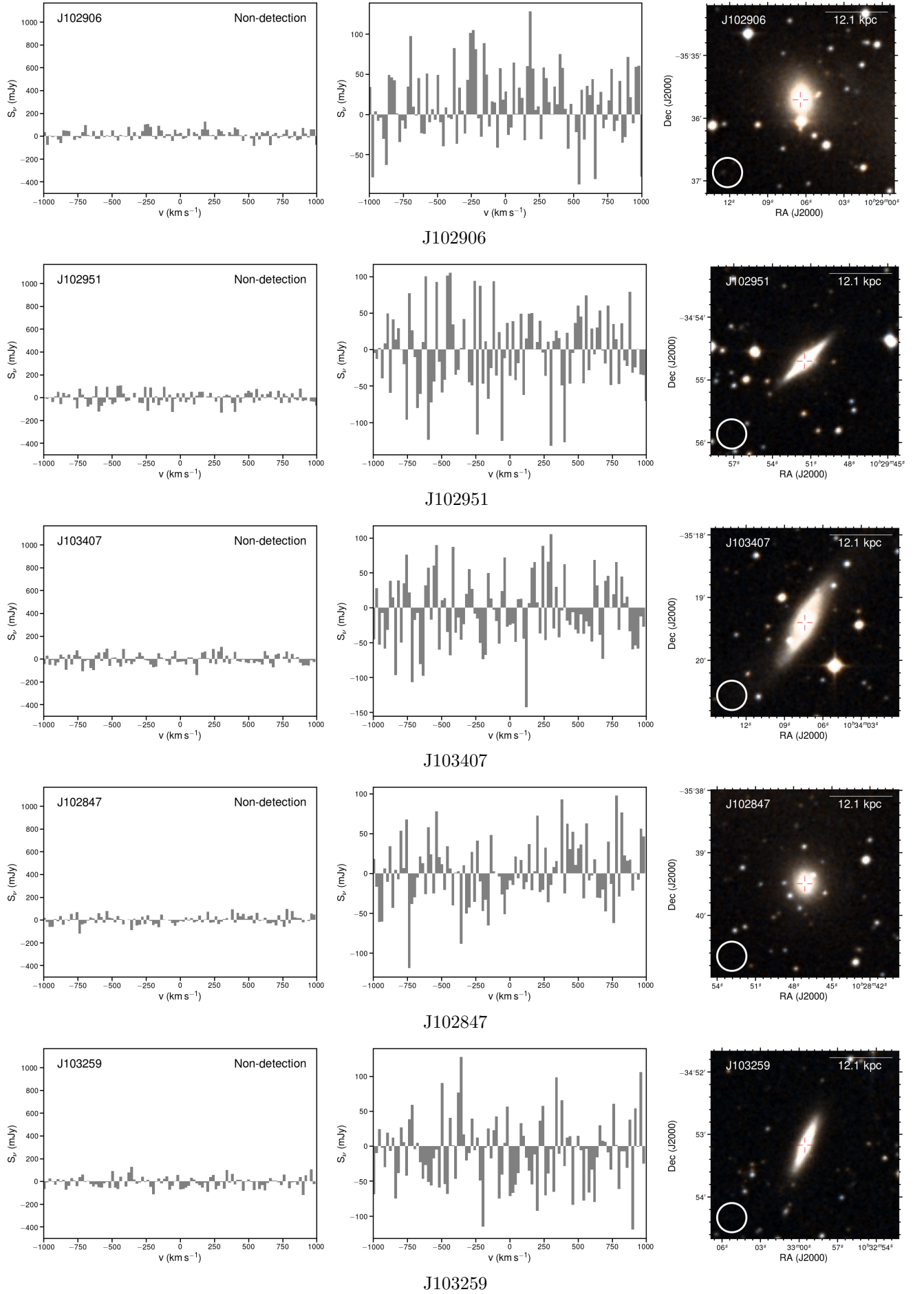


Figure 2.6: Continued.

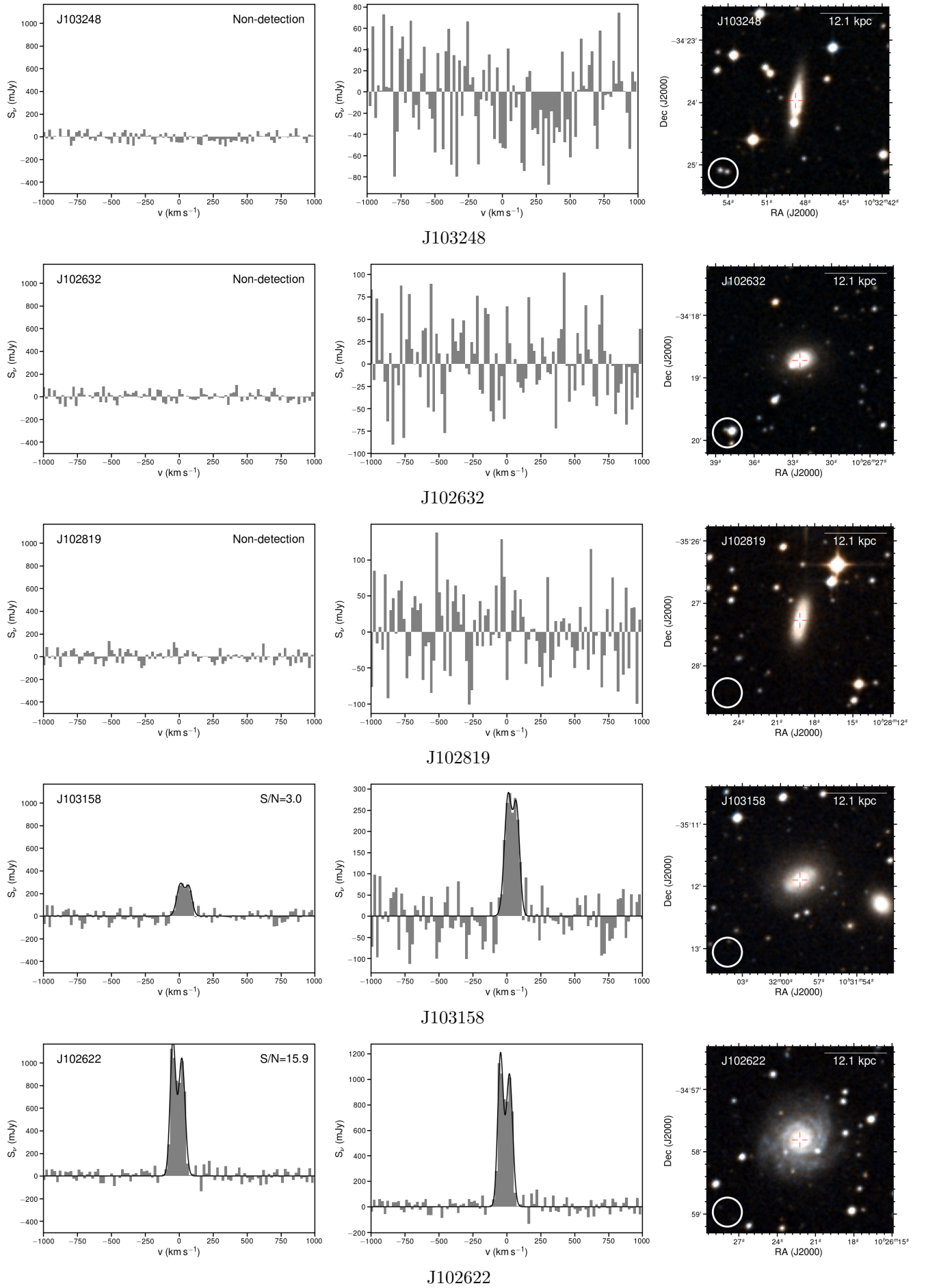


Figure 2.6: Continued.



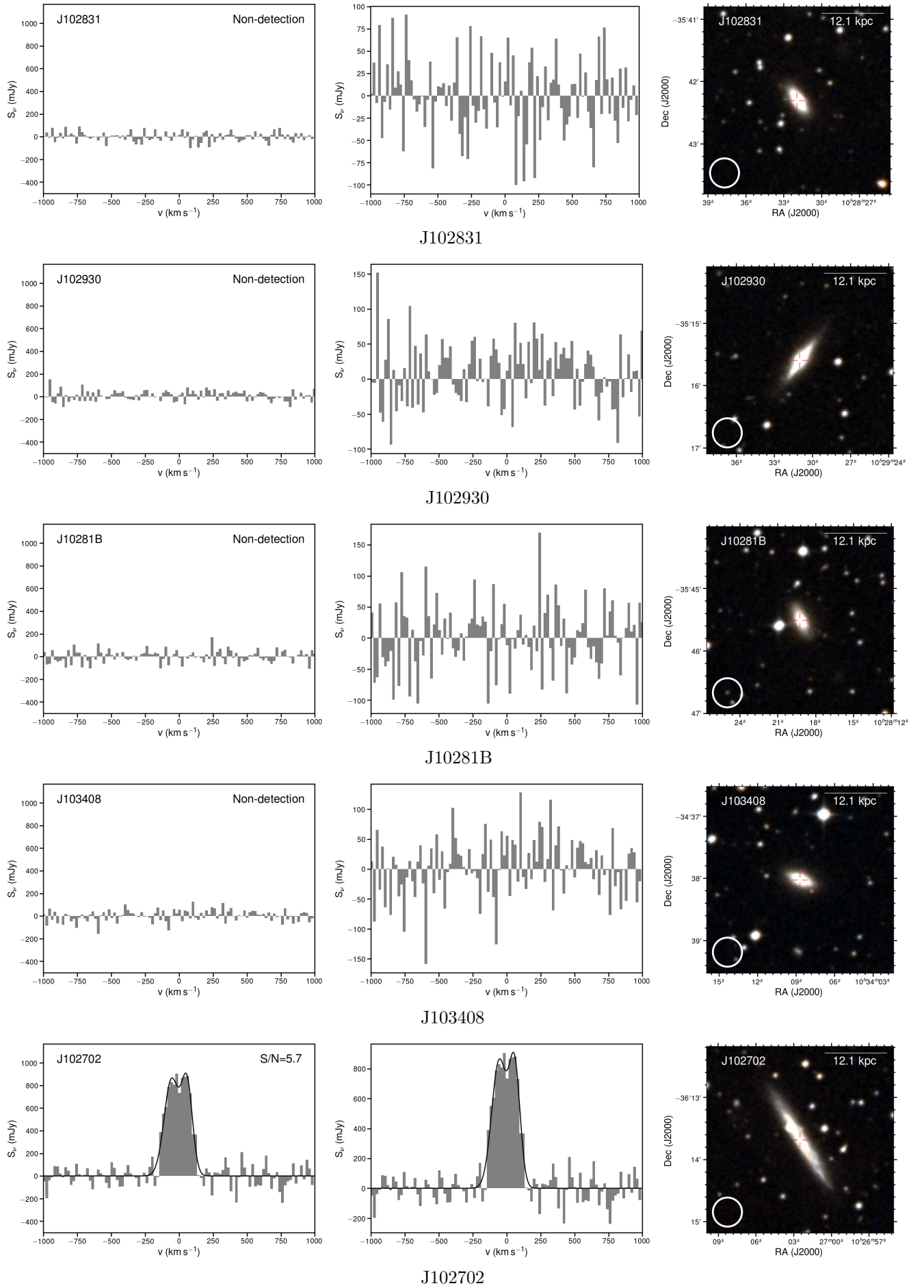


Figure 2.6: Continued.

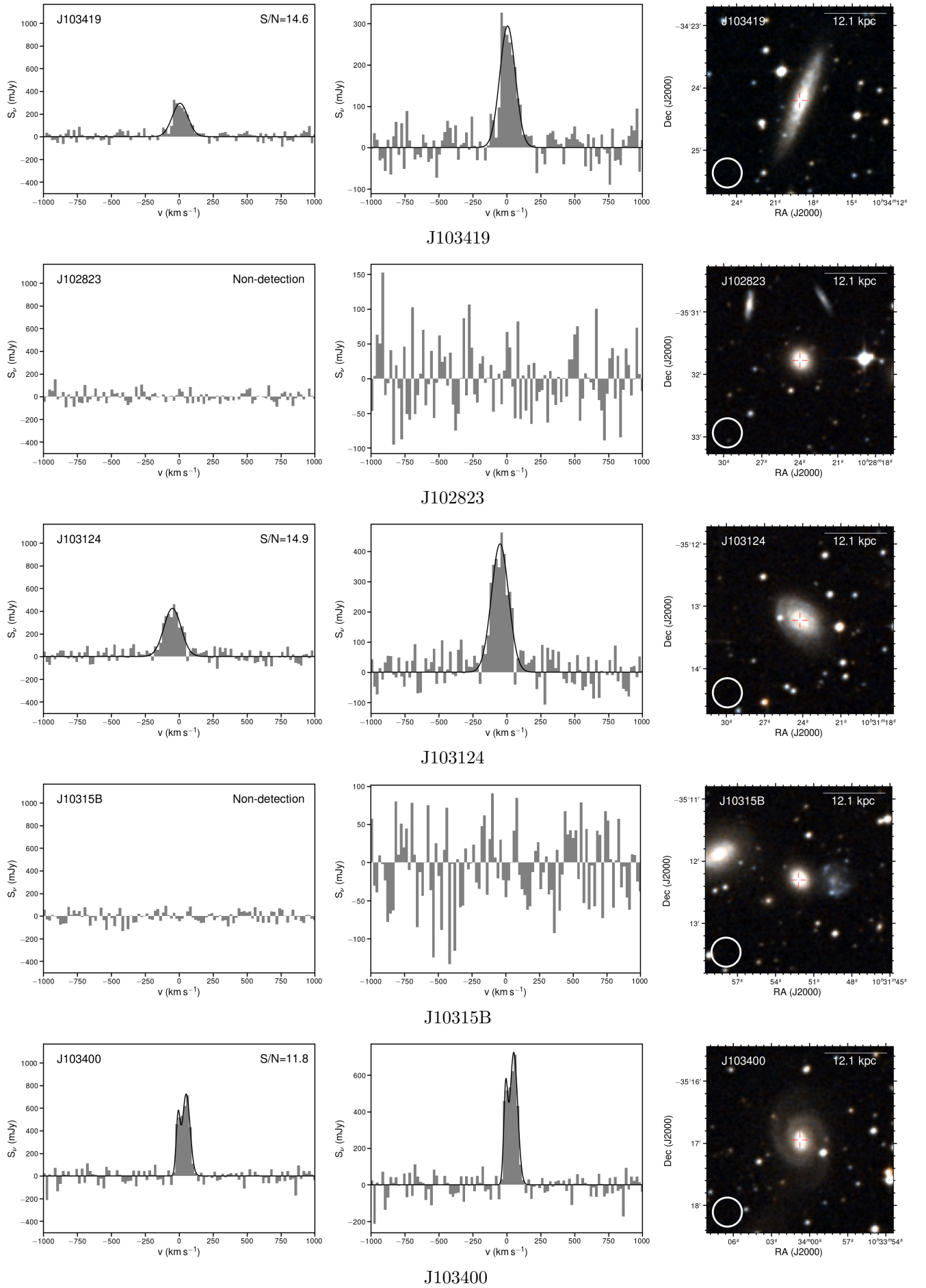


Figure 2.6: Continued.



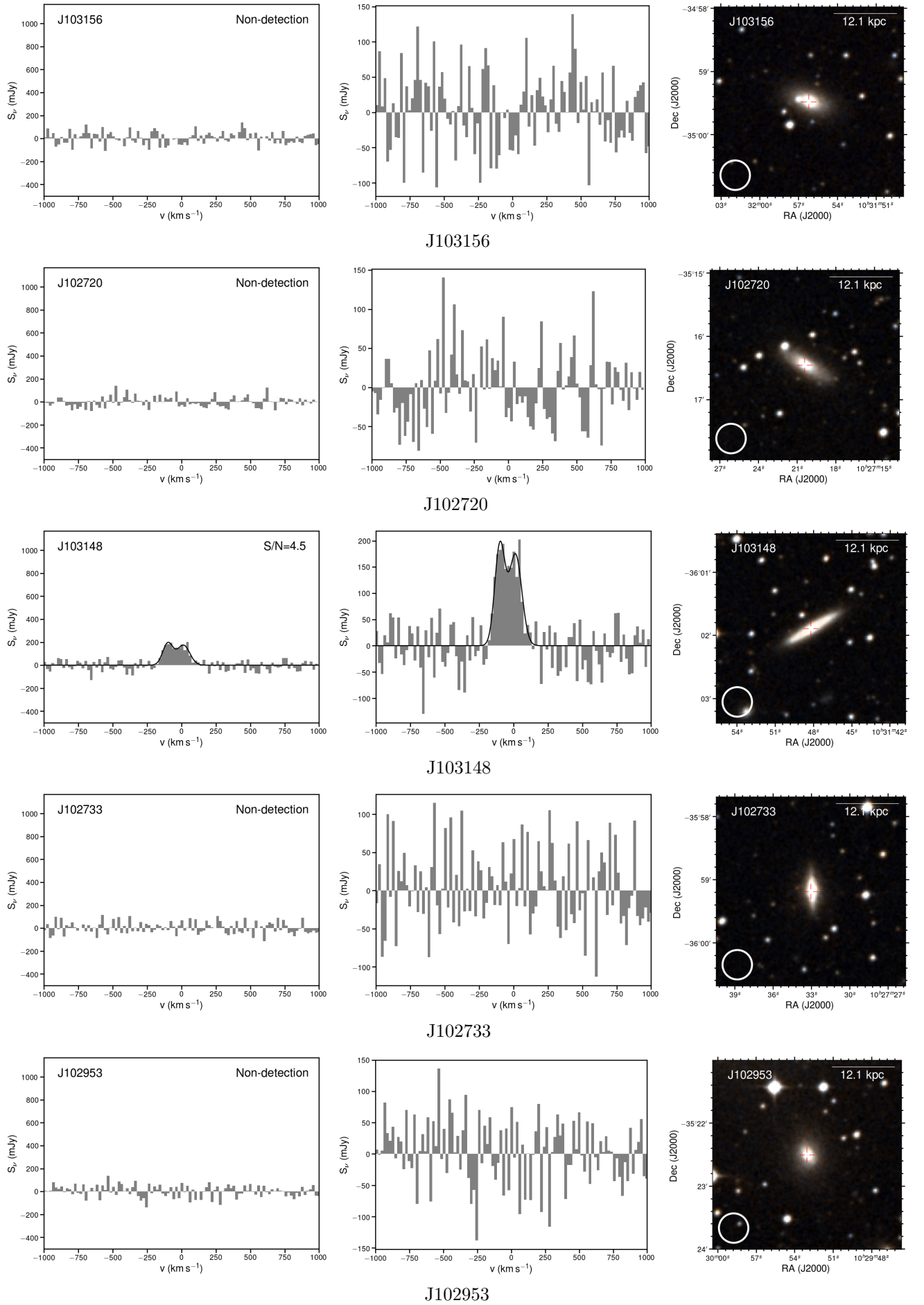


Figure 2.6: Continued.

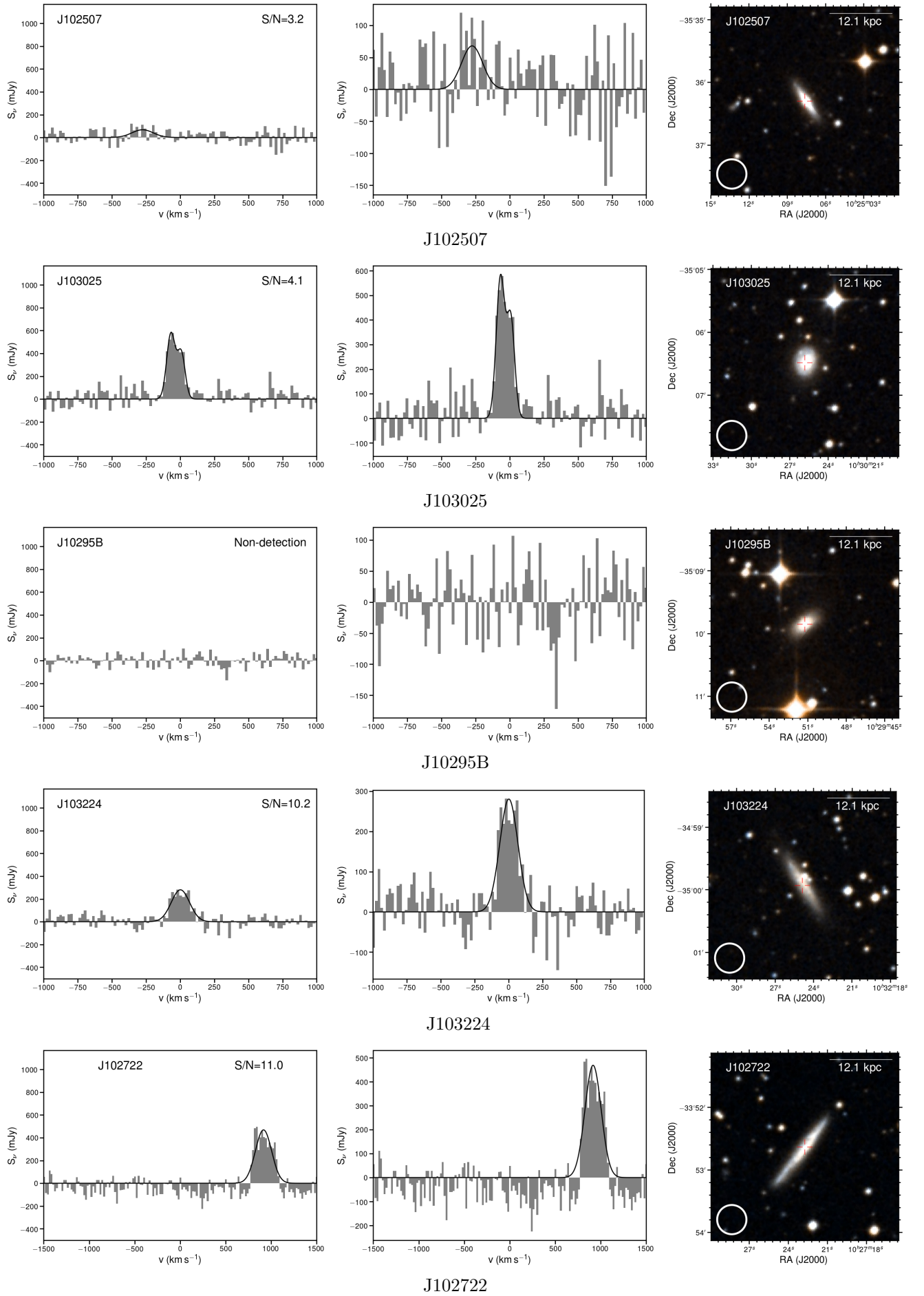


Figure 2.6: Continued.

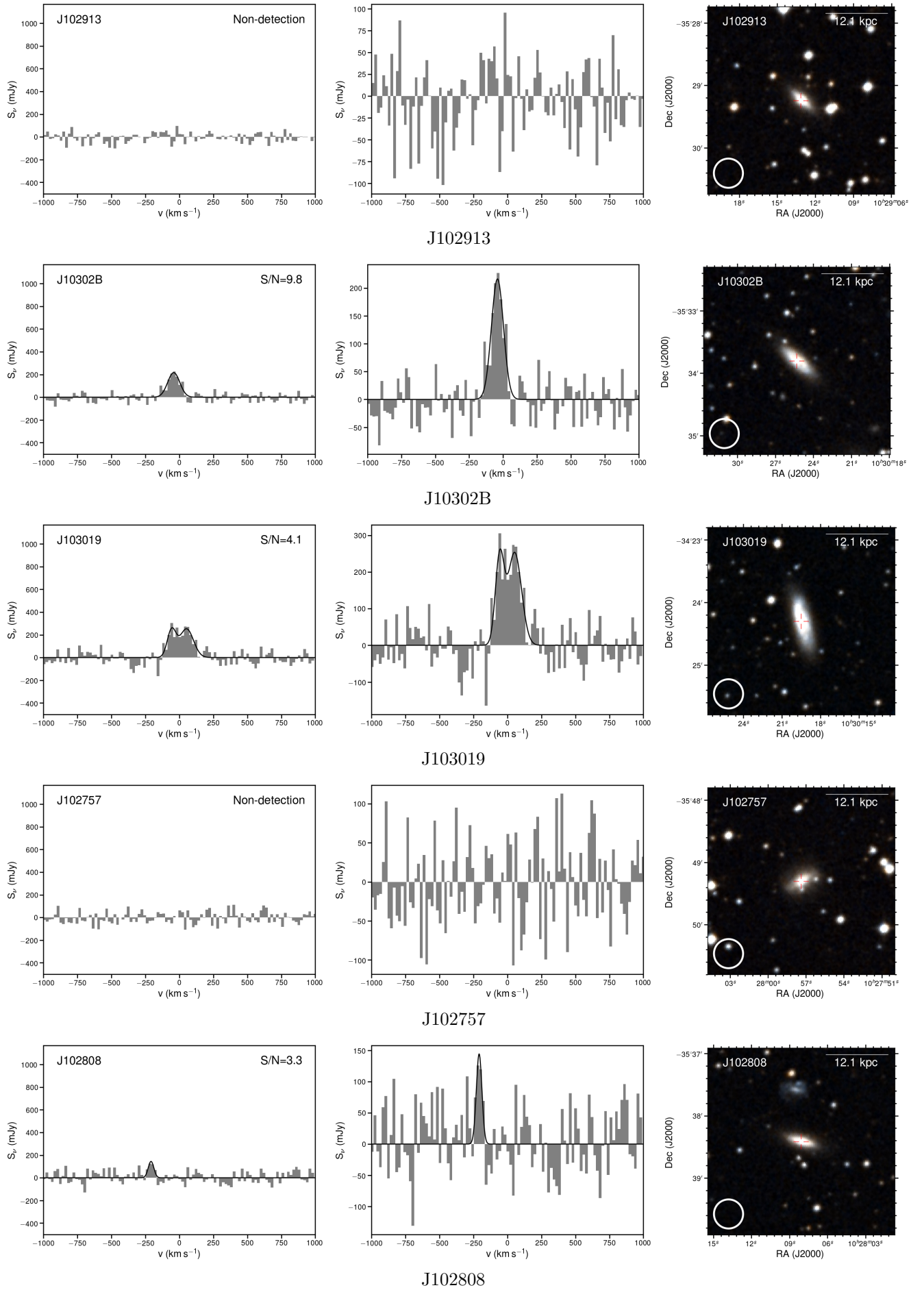


Figure 2.6: Continued.

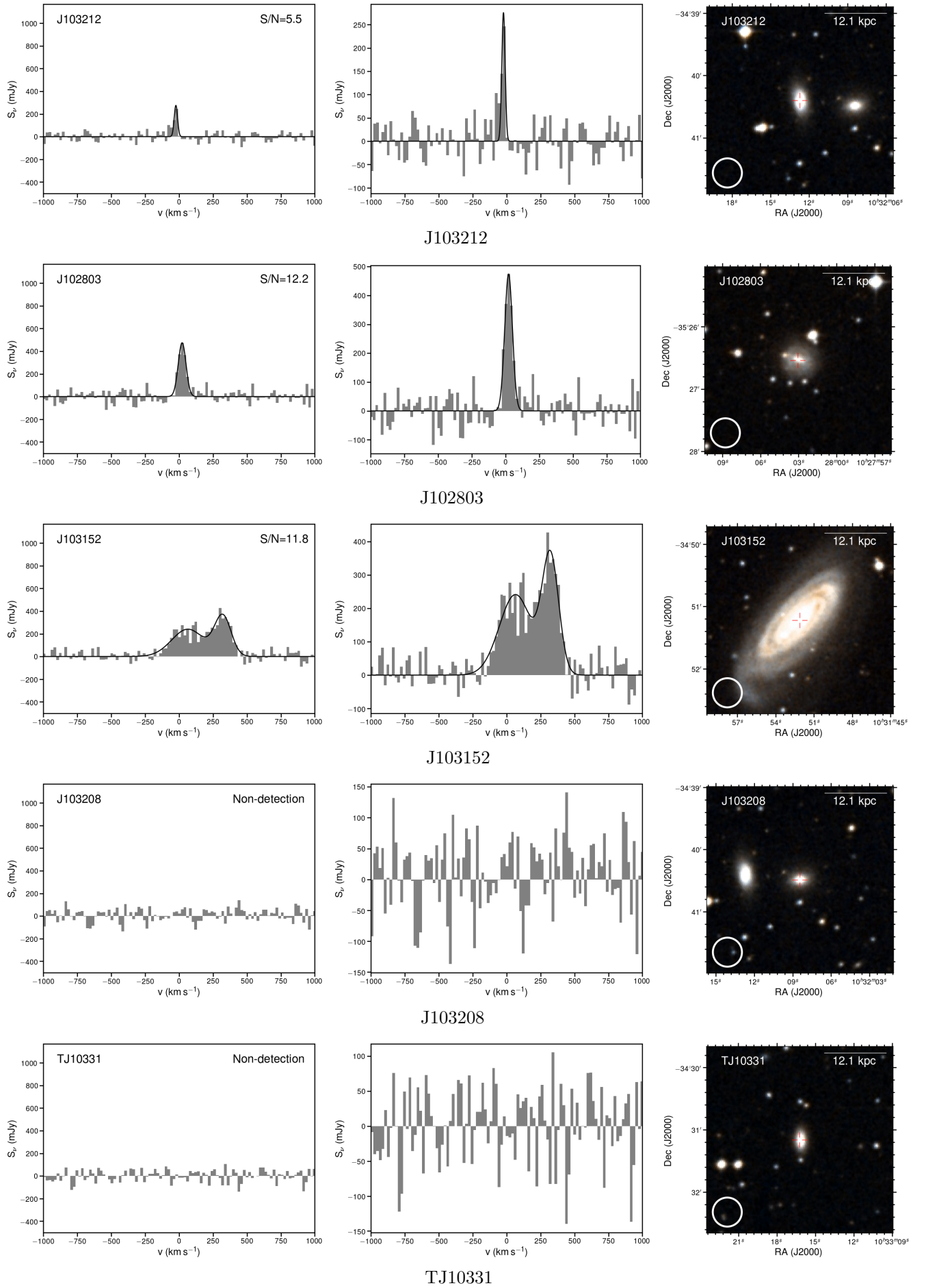


Figure 2.6: Continued.

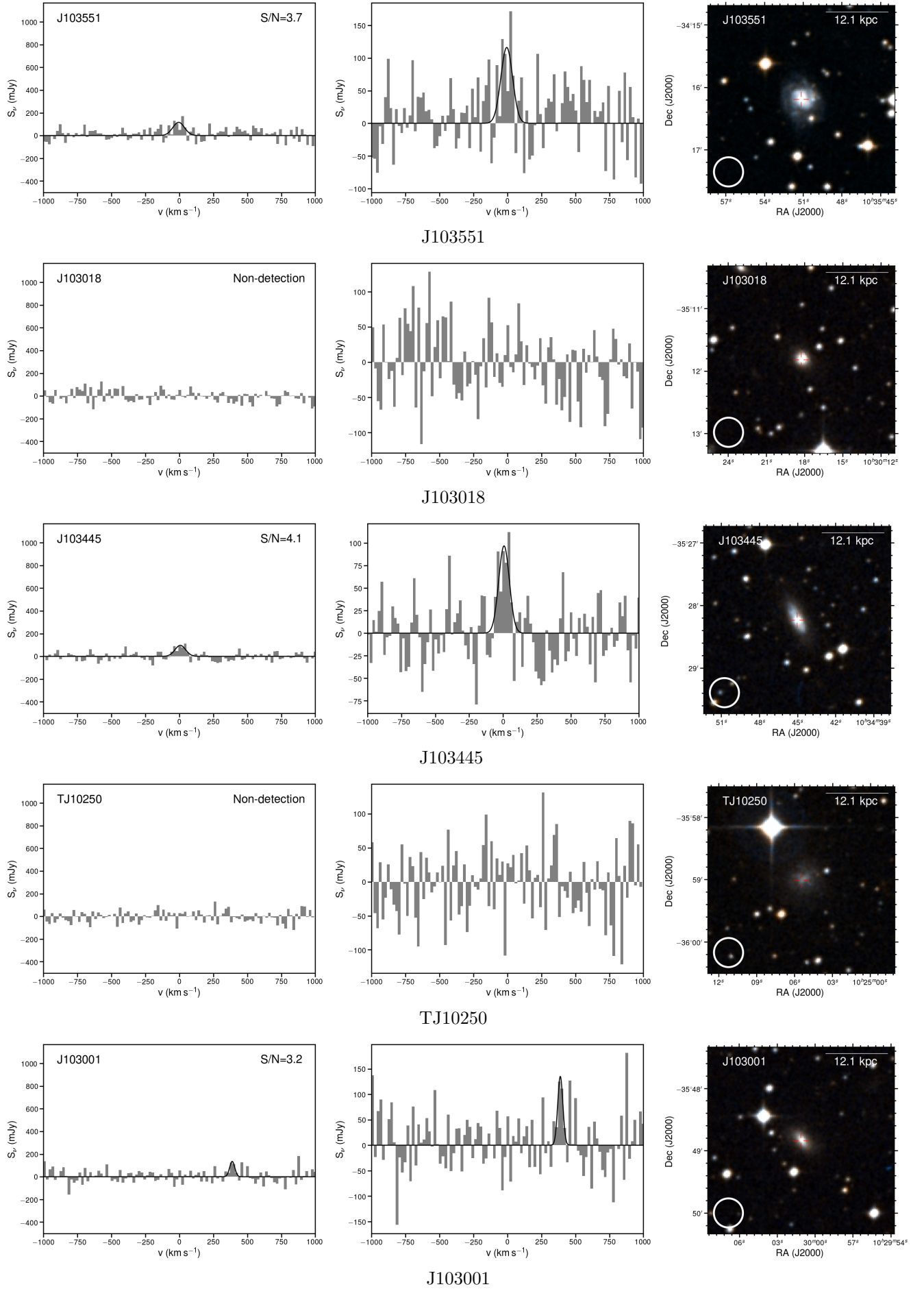


Figure 2.6: Continued.



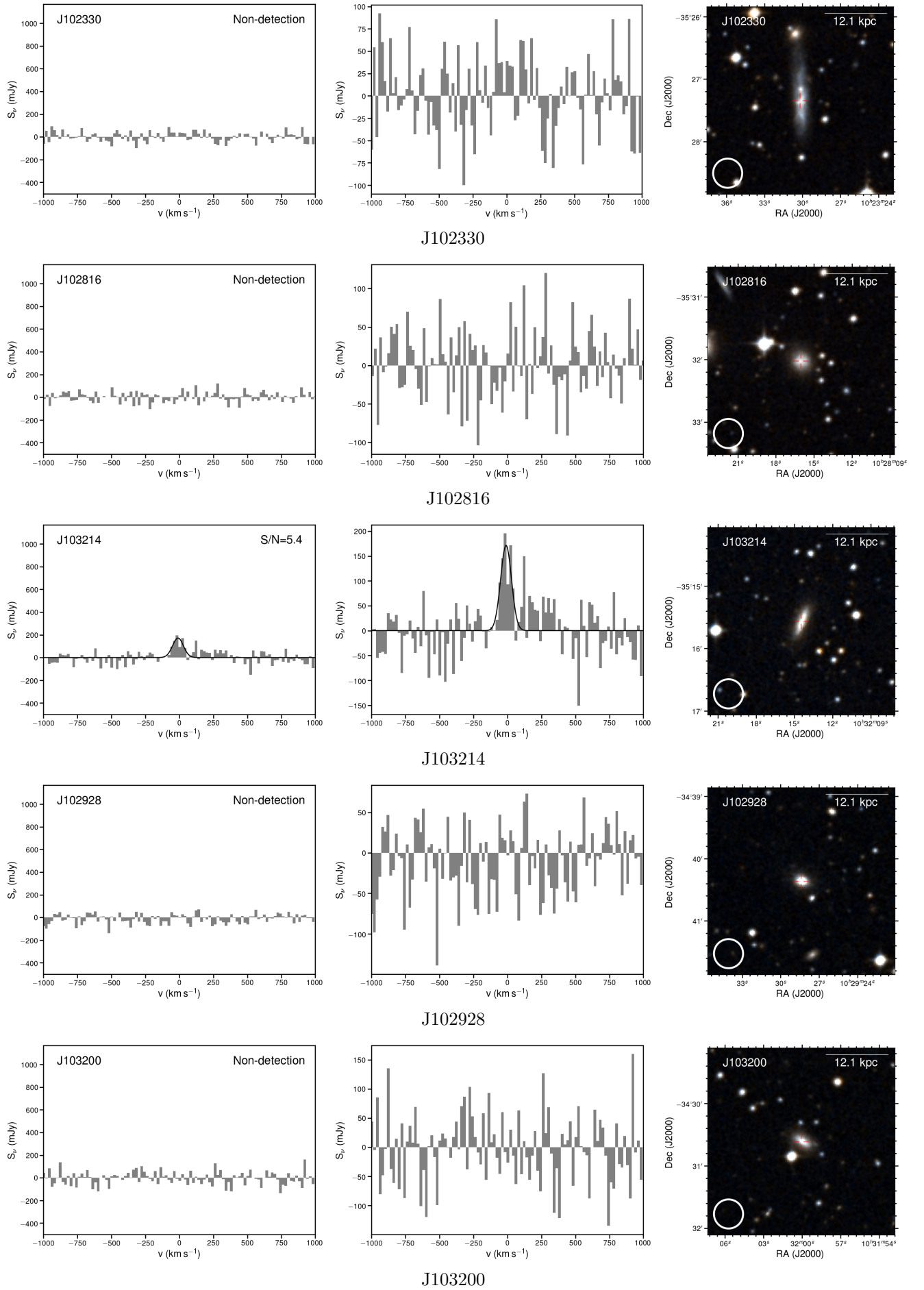


Figure 2.6: Continued.

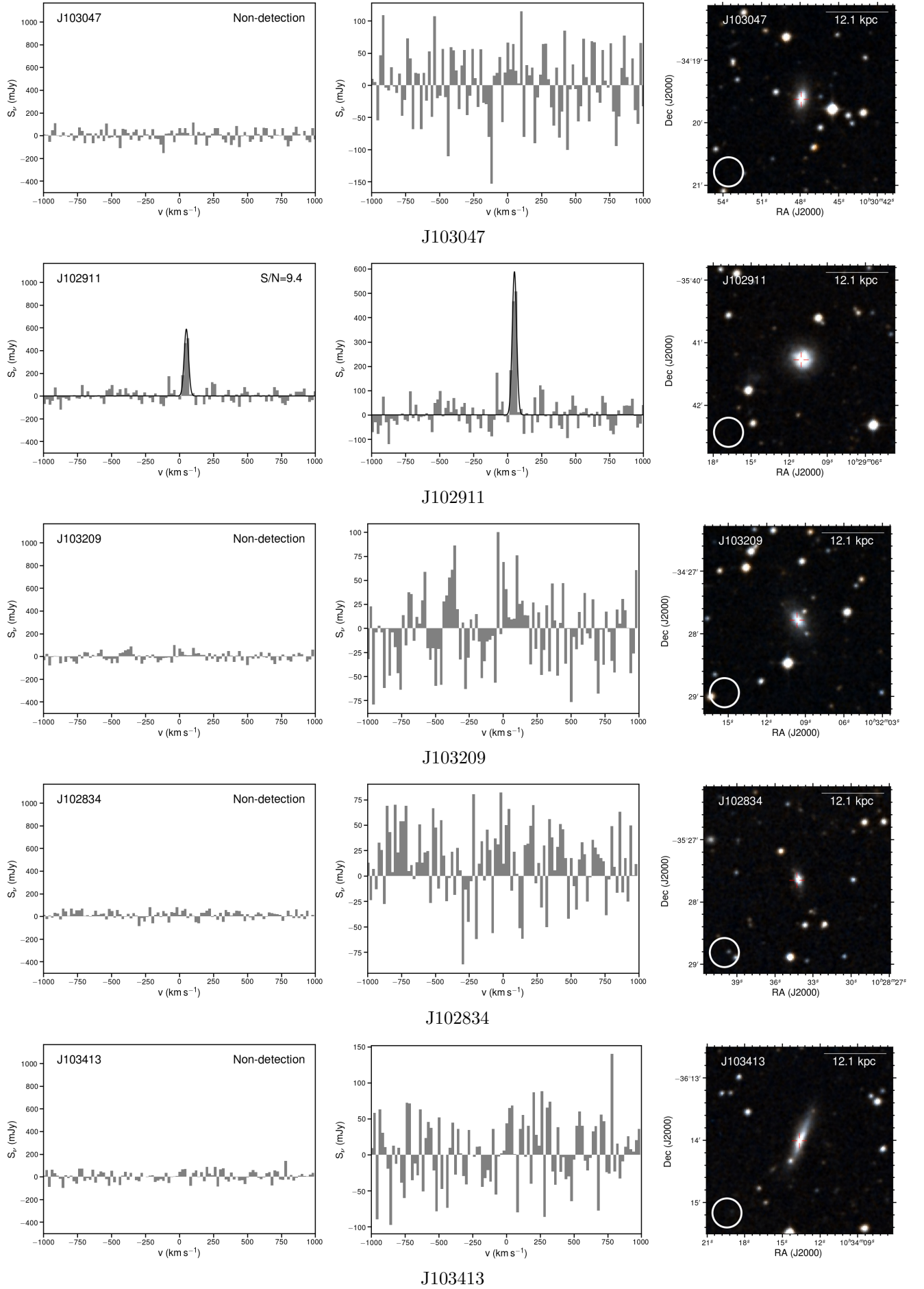


Figure 2.6: Continued.

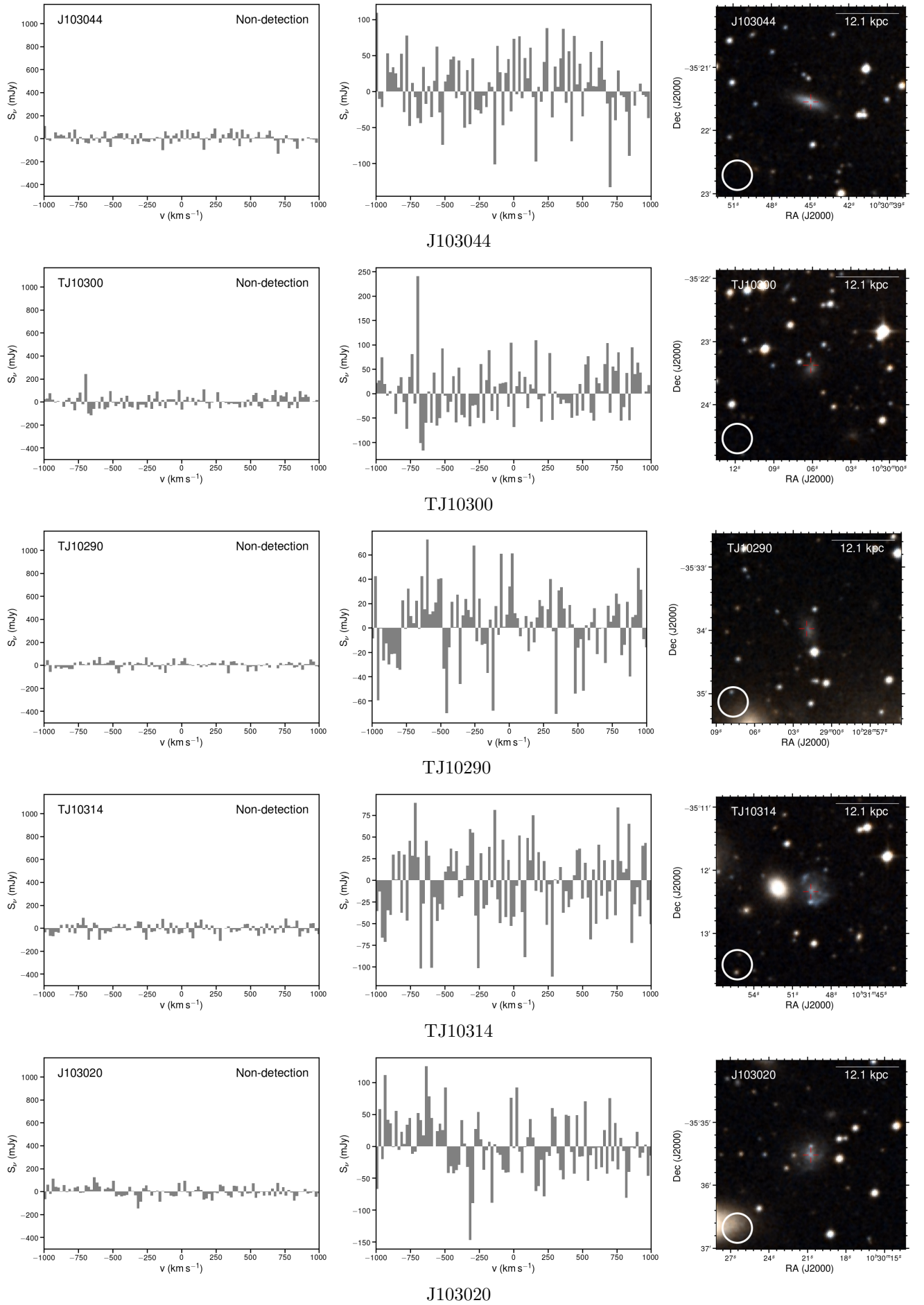


Figure 2.6: Continued.



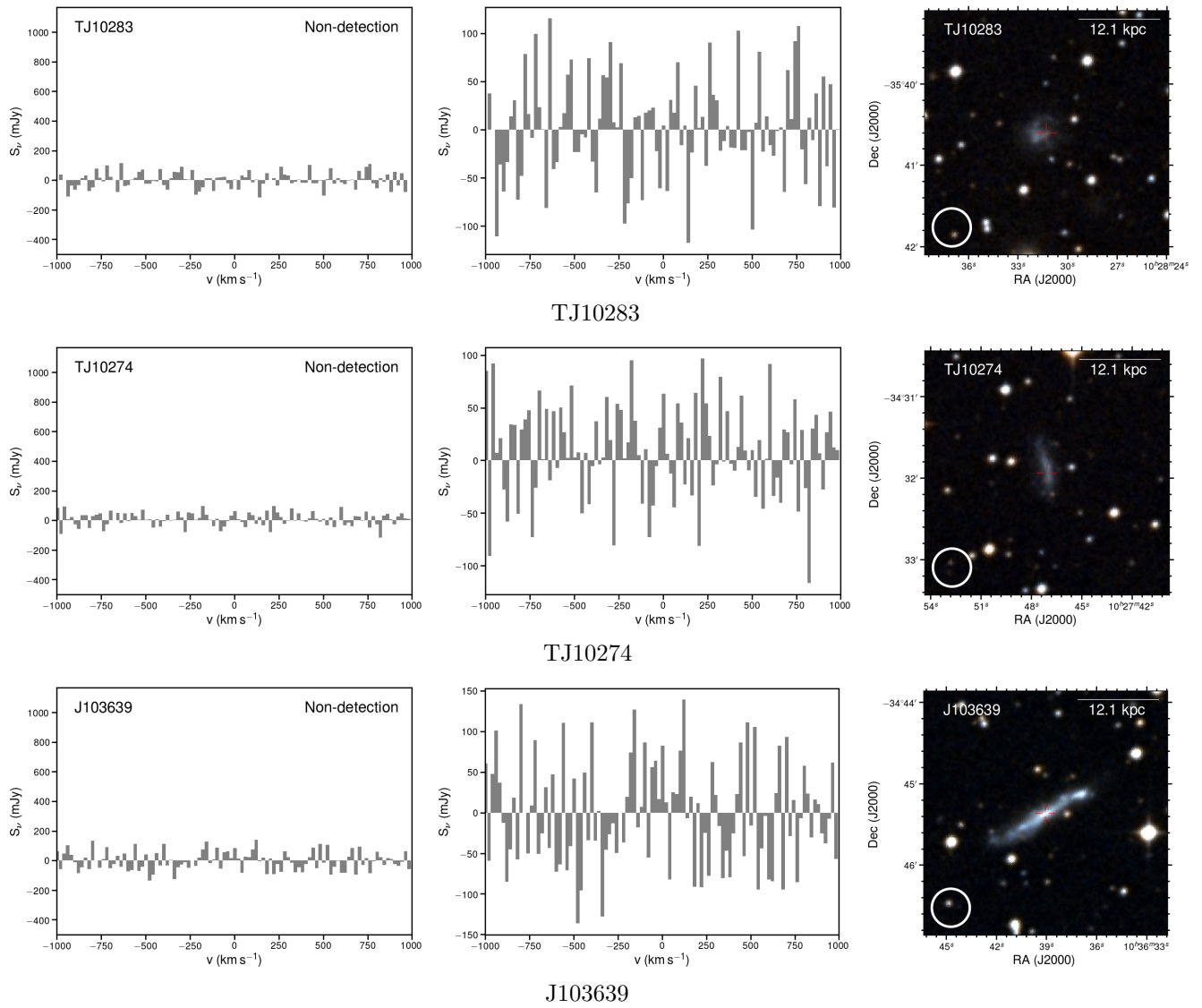


Figure 2.6: Continued.

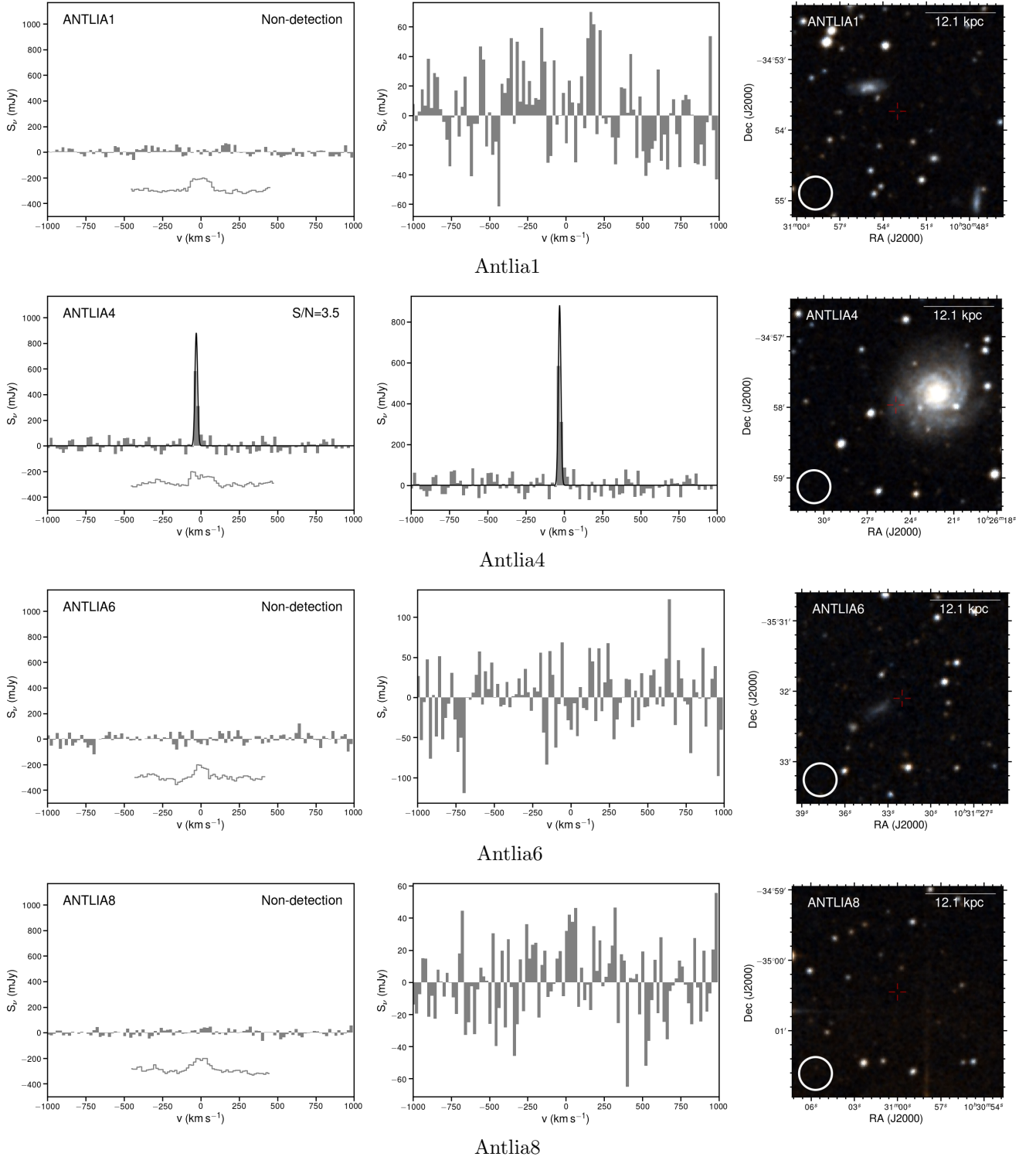


Figure 2.7: HI selected sources, in descending HI flux order. Left: Observed sub-mm spectrum in solid gray bars and fitted CO(2 – 1) Gaussian profile in solid black line. All sources are on the same scale. Solid light gray lines shows the arbitrarily scaled HI spectrum. Middle: Spectrum scaled to the CO(2 – 1) peak. Right: RGB colour-composite from DSS.

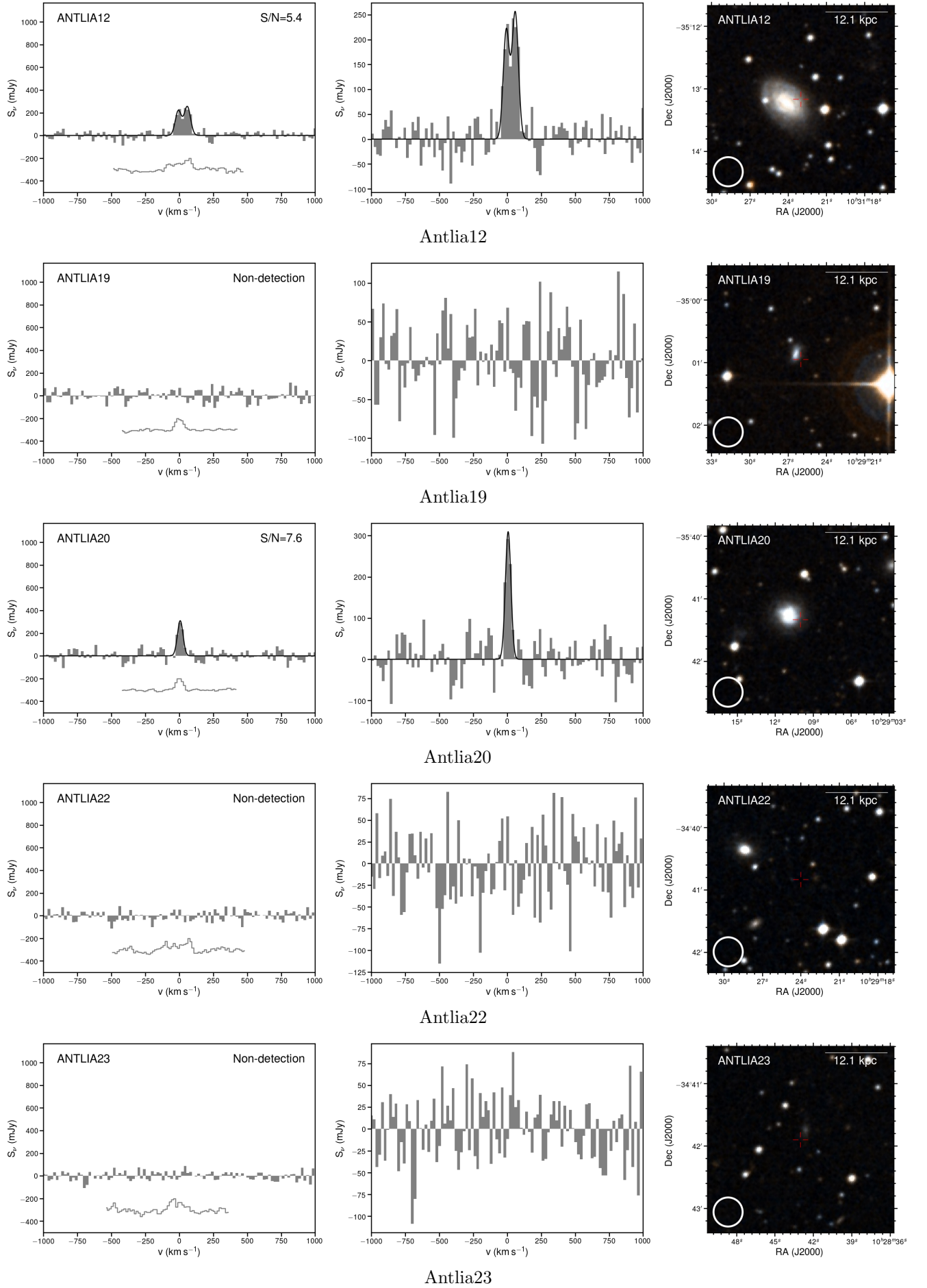


Figure 2.7: Continued.

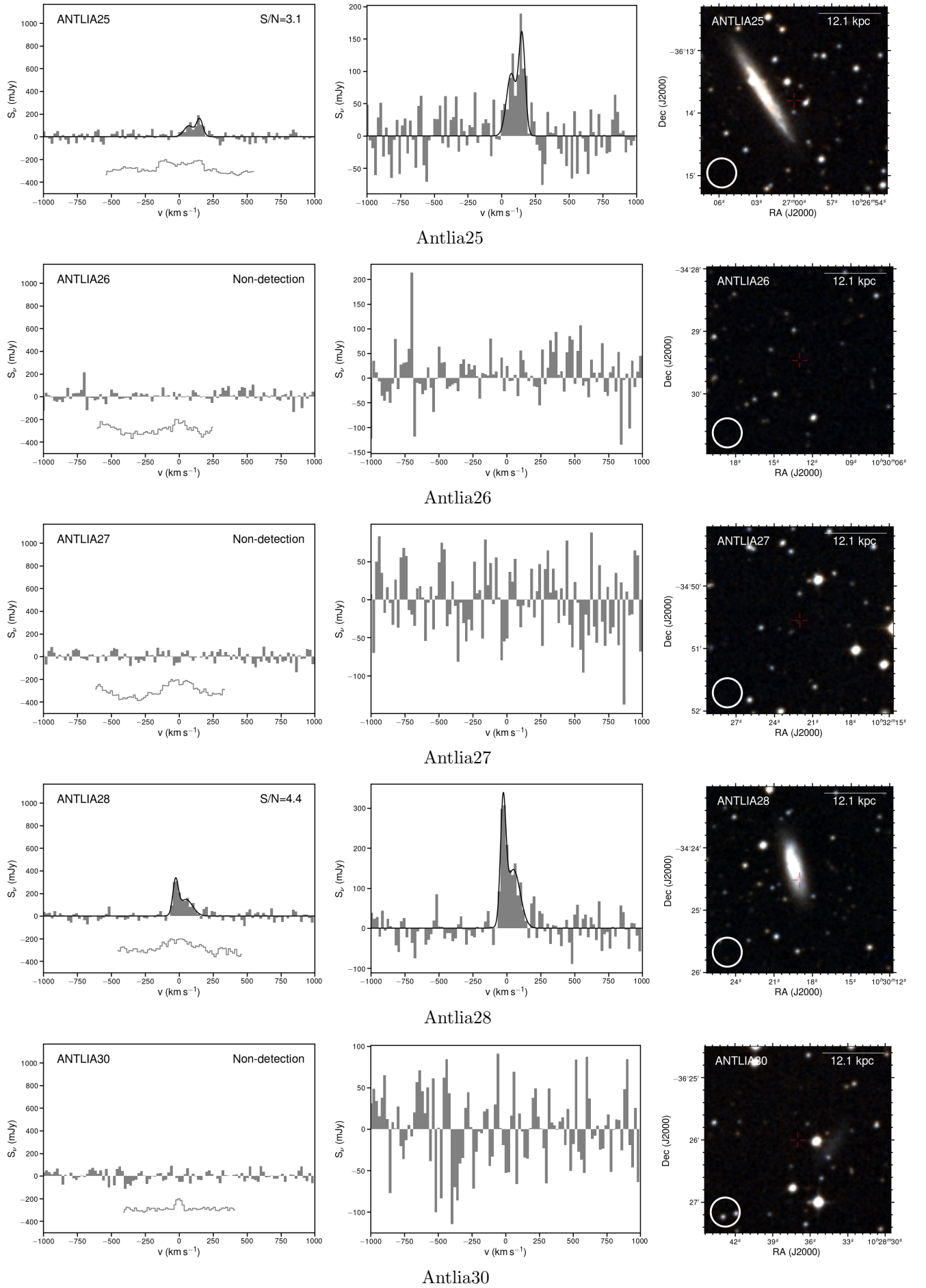


Figure 2.7: Continued.

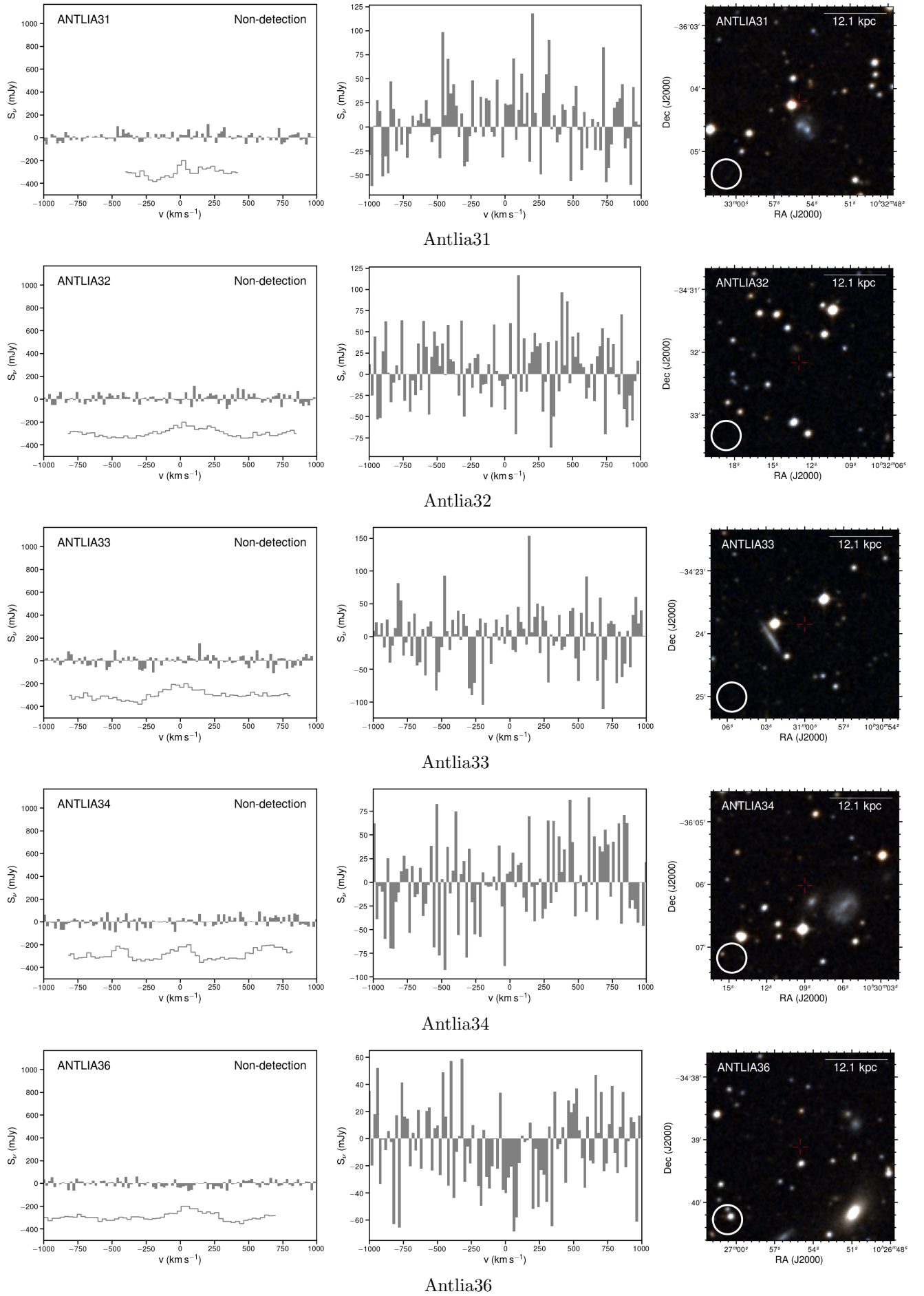


Figure 2.7: Continued.

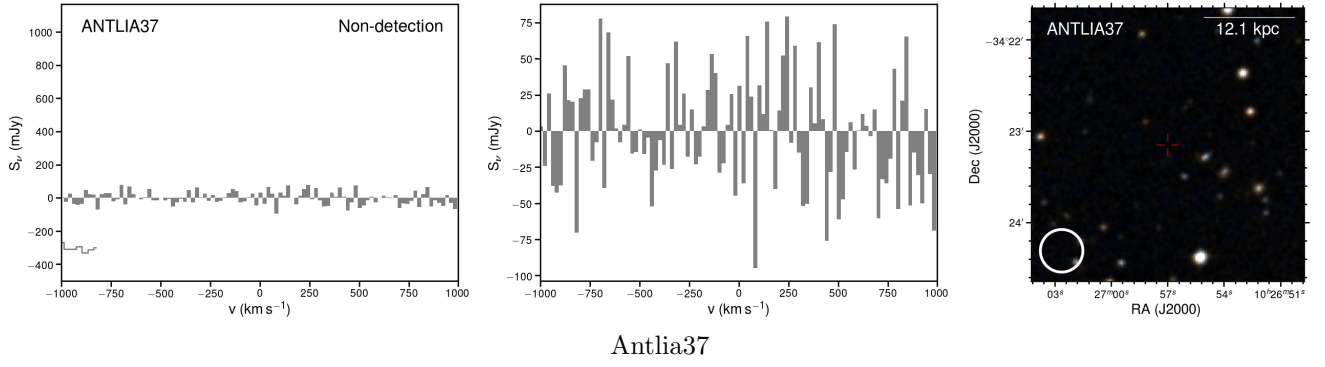


Figure 2.7: Continued.

and curve fitting. For sources showing a distinctly single-peaked CO(2 – 1) profile, we fit both Gaussian and Lorentzian profiles, defined respectively as

$$f(x; A, \mu, \sigma) = \frac{A}{\sigma\sqrt{2\pi}} \exp \left[ - (x - \mu)^2 / 2\sigma^2 \right] \quad (2.6)$$

$$f(x; A, \mu, \sigma) = \frac{A}{\pi} \left[ \frac{\sigma}{(x - \mu)^2 + \sigma^2} \right], \quad (2.7)$$

where in both cases  $A$ ,  $\mu$  and  $\sigma$  represent the amplitude, central frequency and standard deviation of the function. For the Gaussian function, the standard deviation is related to the FWHM via the equation  $\text{FWHM} = 2\sigma\sqrt{2\ln 2}$ , while for the Lorentzian function, the FWHM is simply equal to  $2\sigma$ . For those galaxies showing evidence of non-Gaussian emission profiles, we additionally fit both double-horned and double-Gaussian profiles. The double-Gaussian profile is simply defined as the sum of two individual Gaussian functions as described in Equation 2.6, and we tested fitting a single standard deviation to both peaks, and fitting individual  $\sigma$  values to each peak. For the double-horned profile we follow the parameterisation in the **SHELL** method<sup>12</sup> of **CLASS**, designed to describe spectra from the envelopes of stars:

$$f(x; A, \mu, \sigma, H) = \frac{A}{\sigma} \left[ \frac{1 + 4H[(x - \mu)/\sigma]^2}{1 + H/3} \right] \quad (2.8)$$

<sup>12</sup><https://www.iram.fr/IRAMFR/GILDAS/doc/html/class-html/node38.html>

where in this case,  $A$  represents the total area under the profile,  $\mu$  is the central frequency,  $\sigma$  is the full width of the profile and  $H$  is the dimensionless Horn-to-Centre parameter, allowing the double-peaked profile to vary from a parabola ( $H = -1$ ), to a flat-topped line ( $H = 0$ ) and up to a double-peaked profile ( $H > 0$ ). For all four profiles, we additionally tested fixing the continuum value to 0 Jy and allowing it to vary as a free parameter, and we fit the profiles to spectra smoothed to velocity resolutions of 10, 15 and 20 km s<sup>-1</sup> in order to evaluate whether the resolution of the spectra has a significant effect on the fitting results. In order to determine which profile and which combination of parameters provides the best fit to the data, we use the `fit_report` functionality of `LMFIT` which, as well as producing the best fit parameters and their associated uncertainties, produces a number of useful fit statistics including  $\chi^2$  and  $\chi^2_\nu$  values, as well as the Aikake and Bayesian Information Criterion, which balance the fit quality with the number of variable parameters used, defined respectively as

$$\text{aic} = N \ln (\chi^2/N) + 2N_{\text{varys}} \quad (2.9)$$

$$\text{bic} = N \ln (\chi^2/N) + \ln (N) N_{\text{varys}}, \quad (2.10)$$

where  $\chi^2$  is the chi-squared statistic for the model fit,  $N$  is the number of data points and  $N_{\text{varys}}$  is the number of variable parameters.

We found that, when fitting single-emission line profiles, both `CLASS` and `LMFIT` produced exceedingly similar results, irrespective of the velocity resolution of the spectra. We decided to perform the final fits using the `LMFIT` algorithm, as the limited functionality of `CLASS` means that it is currently not possible to fit a Lorentzian profile to the data, and the double-horned profile proved to be extremely sensitive to the initial guesses on the parameters. The fits to the three sets of spectra smoothed to different velocity resolutions were in good agreement within the uncertainties, and we selected the spectra smoothed to 20 km s<sup>-1</sup> for the final fits. Allowing the continuum to vary also made little difference to the result of the fitting and so, to reduce the number of free parameters, we fixed the continuum value to 0 Jy. We note that this is a



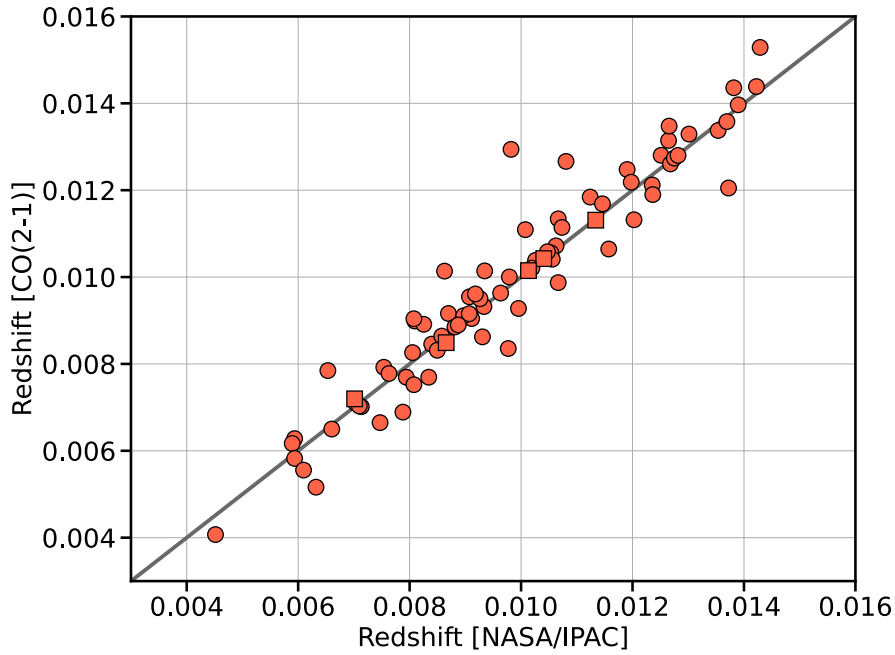


Figure 2.8: Distribution of redshifts derived from the CO(2 – 1) emission line compared to the optical redshift from the NASA/IPAC Extragalactic Database. The two sets of redshifts are broadly in good agreement, with the majority of values within  $\Delta z \sim 0.001$  of each other. The few exceptions could be caused by molecular gas stripping or small uncertainties in the optically- or CO-derived redshift.

physically motivated choice as the linear baseline subtraction performed in Section 2.4 should have removed any non-zero continuum.

For the 72 galaxies in the optically-selected sample, 11 showed evidence of CO(2 – 1) profiles inconsistent with a single peak, with 10 of these sources best fit by a double-Gaussian function, and the remaining source best fit by a double-horned profile. For the remaining sources in this sample, we fit a single-peaked Gaussian profile to their CO(2 – 1) spectra. For the HI-selected sample, we find evidence of non-single-peaked CO(2 – 1) emission in three of the 20 galaxies, all of which are best fit by double-Gaussian functions, but it is worth noting that these three are all included in both the optical and HI samples. For the remaining sources, we fit a single-peaked Gaussian to their CO(2 – 1) spectra. We note that, for one source in the optically-selected sample, the redshift inferred from the emission line was significantly offset from the optical redshift (J102722). This is demonstrated in Figure 2.8, where we present the distribution of offsets between the redshift inferred from the CO and optical data.

We define our detections based on a simple  $\text{SNR} > 3$  detection threshold, where the signal-to-



noise ratio is calculated by dividing the velocity-integrated flux density by its error estimated by `LMFIT`. We note that this detection threshold is somewhat more conservative than the one used by Cicone et al. (2017), who define their signal-to-noise ratio as the peak flux density of the CO(2–1) emission line divided by the RMS noise in the spectra. This difference is necessary, as Cicone et al. (2017) fit only single-peaked Gaussian profiles to their CO(2–1) spectra, whereas we allow four different models to be fit to the spectra depending on the profile of the CO(2–1) emission line including double-peaked models, making the definition of a ‘peak flux density’ more challenging. Our signal-to-noise ratios will therefore be underestimated compared to the ALLSMOG survey, which should be considered in any comparison of the two samples.

We find CO(2–1)  $\text{SNR} > 3$  detections in 27/72 (37.5%) spectra from galaxies in the optically-selected sample. We find detections in 5/20 (25%) HI-selected sources, although we note that these five sources are those included in both samples. Two additional sources (Antlia8 and Antlia23) would be detected with a more relaxed signal-to-noise threshold (e.g.  $\text{SNR} > 2.5$ ), but overall do not appear to be particularly convincing detections, and so we do not consider them in the later analysis. We therefore find that our detection rate is somewhat lower than that of the ALLSMOG survey, which we argue is primarily due to both the more stringent selection criteria imposed by Cicone et al. (2017) to maintain a sample of main sequence galaxies, as well as our stricter signal-to-noise detection threshold. In addition, Cicone et al. (2017) allow a number of marginal detections in their sample for which the central velocity of the CO(2–1) detection is in agreement with the expected velocity based on the HI 21 cm spectrum of the source. We note that when considering sources within 1 dex of the main sequence, our detection rate rises to 86%, much higher than the  $\sim 47\%$  recovered by the ALLSMOG survey.

### 2.5.2 Measuring CO Line Luminosities

For each of our  $\text{SNR} > 3$  detections, we use the best fit parameters estimated by `LMFIT` to calculate the CO(2–1) line luminosity based on the parameterisation of Solomon et al. (1997), defined as

$$L'_{\text{CO}(2-1)} = 3.25 \times 10^7 \frac{D_L^2}{\nu_{\text{obs}}^2 (1+z)^3} \int S_{\text{CO}(2-1)} dv \quad (2.11)$$

where  $L'_{\text{CO}(2-1)}$  is defined as the CO(2 – 1) brightness temperature luminosity in units of  $\text{K km s}^{-1} \text{ pc}^2$ ,  $D_L^2$  is the square of the luminosity distance measured in Mpc,  $\nu_{\text{obs}}$  is the observed central frequency of the CO(2–1) emission line in GHz,  $z$  is the cluster redshift and  $\int S_{\text{CO}(2-1)} dv$  is the velocity-integrated flux density measured in  $\text{Jy km s}^{-1}$ . We additionally apply a small correction factor to the velocity-integrated flux density due the possible loss of flux from CO(2–1) emission falling outside of the APEX beam. Cicone et al. (2017) estimated this value to be small, with a median correction factor 0.98, so we simply divide our estimated velocity-integrated flux densities by this value. For sources without a  $\text{SNR} > 3$  detection, we estimate informative upper limits on the velocity-integrated flux density based on the following equation from Cicone et al. (2017)

$$\int S_{\text{CO}(2-1)} dv = 3\sigma_{\text{RMS}} \sqrt{\delta v \Delta v_{\text{CO}(2-1)}} \quad (2.12)$$

where  $\sigma_{\text{RMS}}$  is the RMS noise of the spectrum smoothed to a velocity resolution of  $\delta v$  and  $\Delta v_{\text{CO}(2-1)}$  represents the expected CO(2–1) line width, which we take to be the average FWHM of our CO(2–1) detections ( $\Delta v_{\text{CO}(2-1)} \sim 170 \text{ km s}^{-1}$ ). For those sources that remain undetected in their CO(2–1) spectra, we then apply this upper limit on the velocity-integrated flux density to Equation 2.11 to estimate an upper limit on the CO(2 – 1) luminosity.

The standard method for estimating molecular gas masses based on CO spectra is to first convert the higher order CO luminosity into a CO(1 – 0) luminosity, before using a CO-to- $\text{H}_2$  calibration factor to convert this luminosity into a molecular gas mass. For the case of our CO(2 – 1) observations, we convert the CO(2 – 1) luminosities into CO(1 – 0) luminosities via the equation

$$r_{21} = \frac{L'_{\text{CO}(2-1)}}{L'_{\text{CO}(1-0)}} \quad (2.13)$$

where we assume a value of  $r_{21} = 0.8 \pm 0.2$  based on observations of local star-forming spirals (Braine et al., 1993; Leroy et al., 2009) and  $z \sim 1.5 - 2.0$  star-forming disks (Aravena et al., 2010, 2014). The molecular gas mass can then be estimated using the equation

$$M_{\text{mol}} = \alpha_{\text{CO}} L_{\text{CO}(1-0)} \quad (2.14)$$

where  $\alpha_{\text{CO}}$  is the standard CO-to-H<sub>2</sub> conversion factor. However, there are significant caveats to estimating the molecular gas mass based on these calibrations. While a Milky Way-like  $\alpha_{\text{CO}}$  conversion factor is typically assumed for studies of this kind, constraining the  $\alpha_{\text{CO}}$  conversion factor is still a very active area of research, with studies suggesting that it is likely strongly dependent on the local ISM conditions of the galaxy, including the pressure, gas dynamics and metallicity (Carilli and Walter, 2013). Moreover, theoretical studies (e.g. Wolfire et al., 2010; Glover and Mac Low, 2011) suggest that the  $\alpha_{\text{CO}}$  conversion factor is likely also a strong function of the dust extinction  $A_V$ . It is therefore worth noting that, while we follow Cicone et al. (2017) and use the typical Milky Way-like  $\alpha_{\text{CO}} = 4.3 \text{ M}_{\odot}/(\text{K km s}^{-1} \text{ pc}^2)$  (Bolatto et al., 2013) so that we can continue to compare the two samples, the molecular gas masses estimated using these methods are somewhat uncertain, and further observations constraining the properties of the local ISM will be required to estimate a more robust CO-to-H<sub>2</sub> conversion factor. In order to simplify the interpretation of our results, we typically use the CO(1–0) luminosity directly as a proxy for the molecular gas mass for the forthcoming analysis. The results of the aforementioned analysis for the optically-selected and HI-selected samples can be found in Tables 2.3 and 2.4 respectively.

Table 2.3: List of molecular gas properties for the optically-selected sources.

| Source  | $\int S_{\text{CO}(2-1)} dv$<br>Jy km s <sup>−1</sup> | $v_{\text{CO}(2-1)}$<br>km s <sup>−1</sup> | $L_{\text{CO}(1-0)}$<br>10 <sup>6</sup> K km s <sup>−1</sup> pc <sup>2</sup> | $M_{\text{mol}}$<br>10 <sup>8</sup> M <sub>⊙</sub> | Fit Type        |
|---------|-------------------------------------------------------|--------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------|-----------------|
| J102330 | < 7.6                                                 | —                                          | < 10.1                                                                       | < 0.43                                             | —               |
| J102507 | 14.3 ± 4.5                                            | −276 ± 28                                  | 19.4 ± 7.8                                                                   | 0.83 ± 0.33                                        | Gaussian        |
| J102622 | 132.5 ± 8.4                                           | −13 ± 2                                    | 180.1 ± 46.4                                                                 | 7.74 ± 2.00                                        | Double Gaussian |
| J102632 | < 8.8                                                 | —                                          | < 11.8                                                                       | < 0.51                                             | —               |
| J102702 | 212.9 ± 37.1                                          | 1 ± 8                                      | 288.8 ± 88.0                                                                 | 12.42 ± 3.79                                       | Double Gaussian |

Table 2.3: Continued.

| Source  | $\int S_{\text{CO}(2-1)} dv$<br>Jy km s <sup>-1</sup> | $v_{\text{CO}(2-1)}$<br>km s <sup>-1</sup> | $L_{\text{CO}(1-0)}$<br>10 <sup>6</sup> K km s <sup>-1</sup> pc <sup>2</sup> | $M_{\text{mol}}$<br>10 <sup>8</sup> M <sub>⊙</sub> | Fit Type        |
|---------|-------------------------------------------------------|--------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------|-----------------|
| J102720 | < 9.5                                                 | —                                          | < 12.6                                                                       | < 0.54                                             | —               |
| J102722 | 112.9 ± 10.2                                          | 915 ± 9                                    | 153.9 ± 40.9                                                                 | 6.62 ± 1.77                                        | Gaussian Offset |
| J102733 | < 9.7                                                 | —                                          | < 12.9                                                                       | < 0.55                                             | —               |
| J102757 | < 9.8                                                 | —                                          | < 13.0                                                                       | < 0.56                                             | —               |
| J102803 | 36.7 ± 3.0                                            | 22 ± 3                                     | 49.9 ± 13.1                                                                  | 2.15 ± 0.57                                        | Gaussian        |
| J102808 | 8.0 ± 2.4                                             | −209 ± 7                                   | 10.9 ± 4.3                                                                   | 0.47 ± 0.18                                        | Gaussian        |
| J102816 | < 8.5                                                 | —                                          | < 11.3                                                                       | < 0.49                                             | —               |
| J102819 | < 10.0                                                | —                                          | < 13.4                                                                       | < 0.57                                             | —               |
| J10281B | < 9.9                                                 | —                                          | < 13.2                                                                       | < 0.57                                             | —               |
| J102823 | < 9.7                                                 | —                                          | < 13.0                                                                       | < 0.56                                             | —               |
| J102831 | < 8.7                                                 | —                                          | < 11.7                                                                       | < 0.50                                             | —               |
| J102834 | < 6.6                                                 | —                                          | < 8.9                                                                        | < 0.38                                             | —               |
| J102847 | < 7.1                                                 | —                                          | < 9.5                                                                        | < 0.41                                             | —               |
| J102853 | 63.7 ± 18.8                                           | −206 ± 108                                 | 86.1 ± 33.3                                                                  | 3.70 ± 1.43                                        | Gaussian        |
| J102906 | < 8.3                                                 | —                                          | < 11.1                                                                       | < 0.48                                             | —               |
| J102911 | 25.6 ± 2.7                                            | 51 ± 2                                     | 34.5 ± 9.4                                                                   | 1.48 ± 0.40                                        | Gaussian        |
| J102913 | < 7.9                                                 | —                                          | < 10.5                                                                       | < 0.45                                             | —               |
| J102928 | < 8.0                                                 | —                                          | < 10.6                                                                       | < 0.46                                             | —               |
| J102930 | < 8.8                                                 | —                                          | < 11.7                                                                       | < 0.51                                             | —               |
| J102948 | < 8.6                                                 | —                                          | < 11.4                                                                       | < 0.49                                             | —               |
| J102951 | < 10.3                                                | —                                          | < 13.7                                                                       | < 0.59                                             | —               |
| J102953 | < 9.7                                                 | —                                          | < 12.9                                                                       | < 0.55                                             | —               |
| J102957 | < 7.3                                                 | —                                          | < 9.7                                                                        | < 0.42                                             | —               |
| J10295B | < 9.9                                                 | —                                          | < 13.2                                                                       | < 0.57                                             | —               |
| J103000 | < 8.7                                                 | —                                          | < 11.6                                                                       | < 0.50                                             | —               |
| J103001 | 6.8 ± 2.2                                             | 389 ± 7                                    | 9.2 ± 3.7                                                                    | 0.40 ± 0.16                                        | Gaussian        |
| J103018 | < 9.7                                                 | —                                          | < 13.0                                                                       | < 0.56                                             | —               |
| J103019 | 55.0 ± 13.3                                           | −3 ± 10                                    | 74.6 ± 25.9                                                                  | 3.21 ± 1.12                                        | Double Gaussian |
| J103020 | < 7.9                                                 | —                                          | < 10.5                                                                       | < 0.45                                             | —               |
| J103025 | 79.2 ± 19.2                                           | −30 ± 8                                    | 106.5 ± 37.1                                                                 | 4.58 ± 1.60                                        | Double Gaussian |
| J103026 | 31.4 ± 4.6                                            | −24 ± 15                                   | 42.8 ± 12.4                                                                  | 1.84 ± 0.53                                        | Double Gaussian |
| J103029 | < 9.2                                                 | —                                          | < 12.2                                                                       | < 0.53                                             | —               |
| J10302B | 26.0 ± 2.7                                            | −42 ± 5                                    | 35.1 ± 9.5                                                                   | 1.51 ± 0.41                                        | Gaussian        |
| J103044 | < 8.4                                                 | —                                          | < 11.2                                                                       | < 0.48                                             | —               |
| J103047 | < 9.5                                                 | —                                          | < 12.7                                                                       | < 0.54                                             | —               |
| J103051 | 163.0 ± 6.6                                           | −0 ± 4                                     | 221.2 ± 56.0                                                                 | 9.51 ± 2.42                                        | Gaussian        |

Table 2.3: Continued.

| Source  | $\int S_{\text{CO}(2-1)} dv$<br>Jy km s <sup>-1</sup> | $v_{\text{CO}(2-1)}$<br>km s <sup>-1</sup> | $L_{\text{CO}(1-0)}$<br>10 <sup>6</sup> K km s <sup>-1</sup> pc <sup>2</sup> | $M_{\text{mol}}$<br>10 <sup>8</sup> M <sub>⊙</sub> | Fit Type        |
|---------|-------------------------------------------------------|--------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------|-----------------|
| J103059 | 55.9 ± 6.3                                            | 20 ± 0                                     | 75.3 ± 20.7                                                                  | 3.24 ± 0.89                                        | Double Horned   |
| J103124 | 72.6 ± 4.9                                            | -49 ± 5                                    | 98.1 ± 25.4                                                                  | 4.22 ± 1.10                                        | Gaussian        |
| J103148 | 40.8 ± 9.1                                            | -43 ± 10                                   | 55.3 ± 18.5                                                                  | 2.38 ± 0.80                                        | Double Gaussian |
| J103152 | 135.5 ± 11.4                                          | 193 ± 8                                    | 184.2 ± 48.6                                                                 | 7.92 ± 2.10                                        | Double Gaussian |
| J103155 | 15.8 ± 4.5                                            | 195 ± 33                                   | 21.4 ± 8.1                                                                   | 0.92 ± 0.35                                        | Gaussian        |
| J103156 | < 10.0                                                | —                                          | < 13.4                                                                       | < 0.58                                             | —               |
| J103158 | 36.6 ± 12.2                                           | 41 ± 9                                     | 49.5 ± 20.6                                                                  | 2.13 ± 0.89                                        | Double Gaussian |
| J10315B | < 9.7                                                 | —                                          | < 12.9                                                                       | < 0.56                                             | —               |
| J103200 | < 11.4                                                | —                                          | < 15.3                                                                       | < 0.66                                             | —               |
| J103208 | < 11.3                                                | —                                          | < 15.1                                                                       | < 0.65                                             | —               |
| J103209 | < 6.8                                                 | —                                          | < 9.1                                                                        | < 0.39                                             | —               |
| J103212 | 9.2 ± 1.7                                             | -24 ± 3                                    | 12.5 ± 3.9                                                                   | 0.54 ± 0.17                                        | Gaussian        |
| J103214 | 18.5 ± 3.4                                            | -11 ± 9                                    | 25.2 ± 7.9                                                                   | 1.08 ± 0.34                                        | Gaussian        |
| J103224 | 50.8 ± 5.0                                            | 2 ± 8                                      | 68.9 ± 18.5                                                                  | 2.96 ± 0.80                                        | Gaussian        |
| J103248 | < 7.4                                                 | —                                          | < 9.9                                                                        | < 0.42                                             | —               |
| J103259 | < 9.1                                                 | —                                          | < 12.1                                                                       | < 0.52                                             | —               |
| J103400 | 75.1 ± 6.4                                            | 22 ± 2                                     | 101.5 ± 26.8                                                                 | 4.36 ± 1.16                                        | Double Gaussian |
| J103407 | < 8.7                                                 | —                                          | < 11.6                                                                       | < 0.50                                             | —               |
| J103408 | < 10.0                                                | —                                          | < 13.4                                                                       | < 0.58                                             | —               |
| J103413 | < 9.9                                                 | —                                          | < 13.2                                                                       | < 0.57                                             | —               |
| J103419 | 45.5 ± 3.1                                            | 6 ± 5                                      | 61.5 ± 15.9                                                                  | 2.65 ± 0.69                                        | Gaussian        |
| J103445 | 10.3 ± 2.5                                            | 7 ± 11                                     | 13.9 ± 4.8                                                                   | 0.60 ± 0.21                                        | Gaussian        |
| J103551 | 13.6 ± 3.6                                            | -6 ± 13                                    | 18.5 ± 6.8                                                                   | 0.79 ± 0.29                                        | Gaussian        |
| J103639 | < 12.1                                                | —                                          | < 16.1                                                                       | < 0.69                                             | —               |
| TJ10250 | < 10.2                                                | —                                          | < 13.7                                                                       | < 0.59                                             | —               |
| TJ10274 | < 8.4                                                 | —                                          | < 11.2                                                                       | < 0.48                                             | —               |
| TJ10283 | < 9.4                                                 | —                                          | < 12.5                                                                       | < 0.54                                             | —               |
| TJ10290 | < 5.9                                                 | —                                          | < 7.8                                                                        | < 0.34                                             | —               |
| TJ10300 | < 10.0                                                | —                                          | < 13.4                                                                       | < 0.58                                             | —               |
| TJ10314 | < 8.1                                                 | —                                          | < 10.9                                                                       | < 0.47                                             | —               |
| TJ10331 | < 9.9                                                 | —                                          | < 13.2                                                                       | < 0.57                                             | —               |

Table 2.4: List of molecular gas properties for the HI-selected sources.

| Source   | $\int S_{\text{CO}(2-1)} dv$<br>Jy km s <sup>-1</sup> | $v_{\text{CO}(2-1)}$<br>km s <sup>-1</sup> | $L_{\text{CO}(1-0)}$<br>10 <sup>6</sup> K km s <sup>-1</sup> pc <sup>2</sup> | $M_{\text{mol}}$<br>10 <sup>8</sup> M <sub>⊙</sub> | Fit Type        |
|----------|-------------------------------------------------------|--------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------|-----------------|
| Antlia1  | < 5.3                                                 | —                                          | < 7.1                                                                        | < 0.31                                             | —               |
| Antlia12 | 29.4 ± 5.5                                            | 26 ± 5                                     | 39.7 ± 12.4                                                                  | 1.71 ± 0.53                                        | Double Gaussian |
| Antlia19 | < 8.7                                                 | —                                          | < 11.6                                                                       | < 0.50                                             | —               |
| Antlia20 | 17.2 ± 2.3                                            | 7 ± 3                                      | 23.2 ± 6.6                                                                   | 1.00 ± 0.28                                        | Gaussian        |
| Antlia22 | < 7.4                                                 | —                                          | < 9.9                                                                        | < 0.42                                             | —               |
| Antlia23 | < 7.1                                                 | —                                          | < 9.6                                                                        | < 0.41                                             | —               |
| Antlia25 | 19.0 ± 6.1                                            | 111 ± 11                                   | 25.9 ± 10.5                                                                  | 1.11 ± 0.45                                        | Double Gaussian |
| Antlia26 | < 8.2                                                 | —                                          | < 11.0                                                                       | < 0.47                                             | —               |
| Antlia27 | < 7.7                                                 | —                                          | < 10.2                                                                       | < 0.44                                             | —               |
| Antlia28 | 35.3 ± 8.1                                            | 12 ± 9                                     | 47.9 ± 16.2                                                                  | 2.06 ± 0.70                                        | Double Gaussian |
| Antlia30 | < 8.2                                                 | —                                          | < 11.0                                                                       | < 0.47                                             | —               |
| Antlia31 | < 6.7                                                 | —                                          | < 9.0                                                                        | < 0.39                                             | —               |
| Antlia32 | < 7.3                                                 | —                                          | < 9.8                                                                        | < 0.42                                             | —               |
| Antlia33 | < 8.4                                                 | —                                          | < 11.2                                                                       | < 0.48                                             | —               |
| Antlia34 | < 8.0                                                 | —                                          | < 10.7                                                                       | < 0.46                                             | —               |
| Antlia36 | < 5.4                                                 | —                                          | < 7.2                                                                        | < 0.31                                             | —               |
| Antlia37 | < 8.0                                                 | —                                          | < 10.7                                                                       | < 0.46                                             | —               |
| Antlia4  | 20.2 ± 5.8                                            | -30 ± 4                                    | 27.4 ± 10.5                                                                  | 1.18 ± 0.45                                        | Gaussian        |
| Antlia6  | < 7.8                                                 | —                                          | < 10.4                                                                       | < 0.45                                             | —               |
| Antlia8  | < 4.2                                                 | —                                          | < 5.6                                                                        | < 0.24                                             | —               |

## 2.6 Results

In this Section, we outline the results of our study into the molecular gas properties of galaxies residing within the nearby Antlia cluster. We note that, while we initially aimed to study the molecular gas reservoirs of two separate samples, we find that no robust conclusions can be drawn from the HI sample. Firstly, we find that, excluding the five sources that are detected in both the optically-selected and HI-selected samples, no robust CO(2 – 1) detections are

found for the remaining galaxies in the HI sample. Moreover, by comparing the CO(2 – 1) luminosities of the five sources observed in both samples estimated using the optical and the HI pointings, we find that not only are the CO(2 – 1) luminosities estimated based on the HI positions systematically lower, but the percentage of the CO(2 – 1) luminosity derived from the optical pointing recovered by the HI-derived CO(2 – 1) luminosity is a strong function of the offset between the two pointings, dropping from  $\sim 65\%$  when the two pointings are offset by  $\sim 15''$  to just  $\sim 10\%$  when they're offset by  $\sim 30''$ . We demonstrate this by showing in Table 2.5 the derived CO(1 – 0) luminosities and offsets between the two pointings for all five sources that are observed in both samples. We interpret this relation as evidence that the optical emission is highly co-spatial with the emission from the molecular gas, and that the HI detections are significantly offset from this. Based on the lack of CO(2 – 1) detections in the HI sample and the offset HI pointings, we focus our analysis only on the 72 galaxies making up the optically-selected sample. We provide a discussion on the likely drivers of the HI pointing offsets in Section 2.7.1.

| Source  | HI ID    | RA<br>J2000 | Dec<br>J2000 | $L_{\text{CO}(1-0)}$<br>$10^6 \text{ K km s}^{-1} \text{ pc}^2$ | $L_{\text{CO}(1-0)}$<br>(HI pointing)<br>$10^6 \text{ K km s}^{-1} \text{ pc}^2$ | Offset<br>" |
|---------|----------|-------------|--------------|-----------------------------------------------------------------|----------------------------------------------------------------------------------|-------------|
| J102622 | Antlia4  | 10:26:22.22 | –34:57:48.7  | $180.1 \pm 46.4$                                                | $27.4 \pm 10.5$                                                                  | 35          |
| J102702 | Antlia25 | 10:27:02.49 | –36:13:41.1  | $288.8 \pm 88.0$                                                | $25.9 \pm 10.5$                                                                  | 31          |
| J102911 | Antlia20 | 10:29:11.05 | –35:41:16.4  | $34.5 \pm 9.4$                                                  | $23.2 \pm 6.6$                                                                   | 13          |
| J103019 | Antlia28 | 10:30:19.51 | –34:24:18.0  | $74.6 \pm 25.9$                                                 | $47.9 \pm 16.2$                                                                  | 14          |
| J103124 | Antlia12 | 10:31:24.21 | –35:13:13.6  | $98.1 \pm 25.4$                                                 | $39.7 \pm 12.4$                                                                  | 15          |

Table 2.5: List of HI selected sources with optical counterparts

In Figure 2.9 we present the spatial distribution of the 72 cluster members followed up in the optically-selected sample with molecular gas observations from APEX, including both detections and non-detections, overplotted onto a smoothed 0.5 – 2.4 keV X-ray image of the cluster from the ROSAT satellite (Truemper, 1990). In the following Sections, we discuss the detection rates and CO luminosities of our optically-selected sample as a function of numerous different galactic and environmental properties.

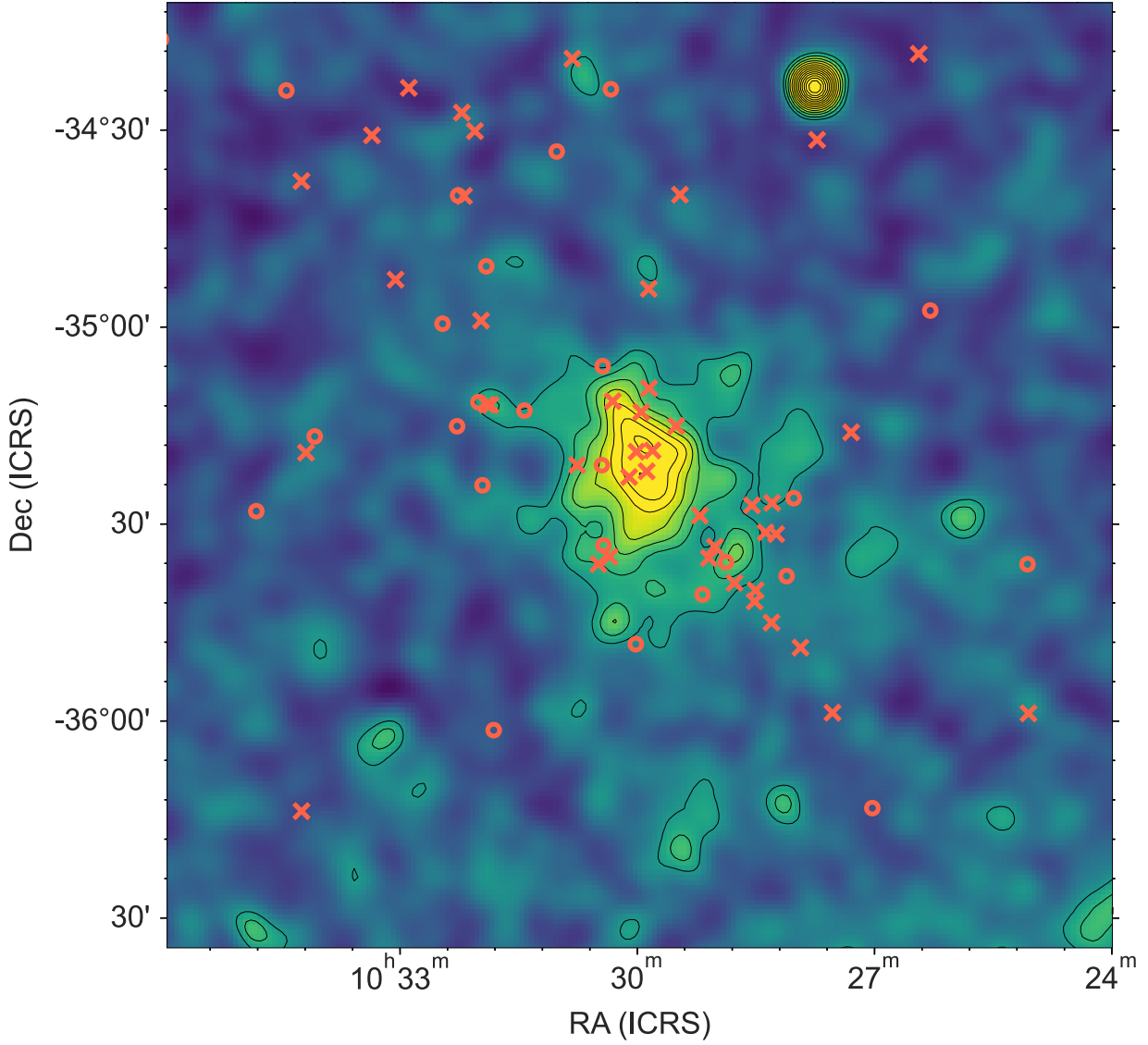


Figure 2.9: Distribution of Antlia cluster members (i.e.  $0.004 < z < 0.014$ ) in the optically-selected sample followed up with APEX CO(2-1) observations. The background shows a smoothed ROSAT 0.5 – 2.4 keV X-ray image of the cluster. Open circles denote CO detections ( $\text{SNR} > 3$ ) while crosses represent non-detections.



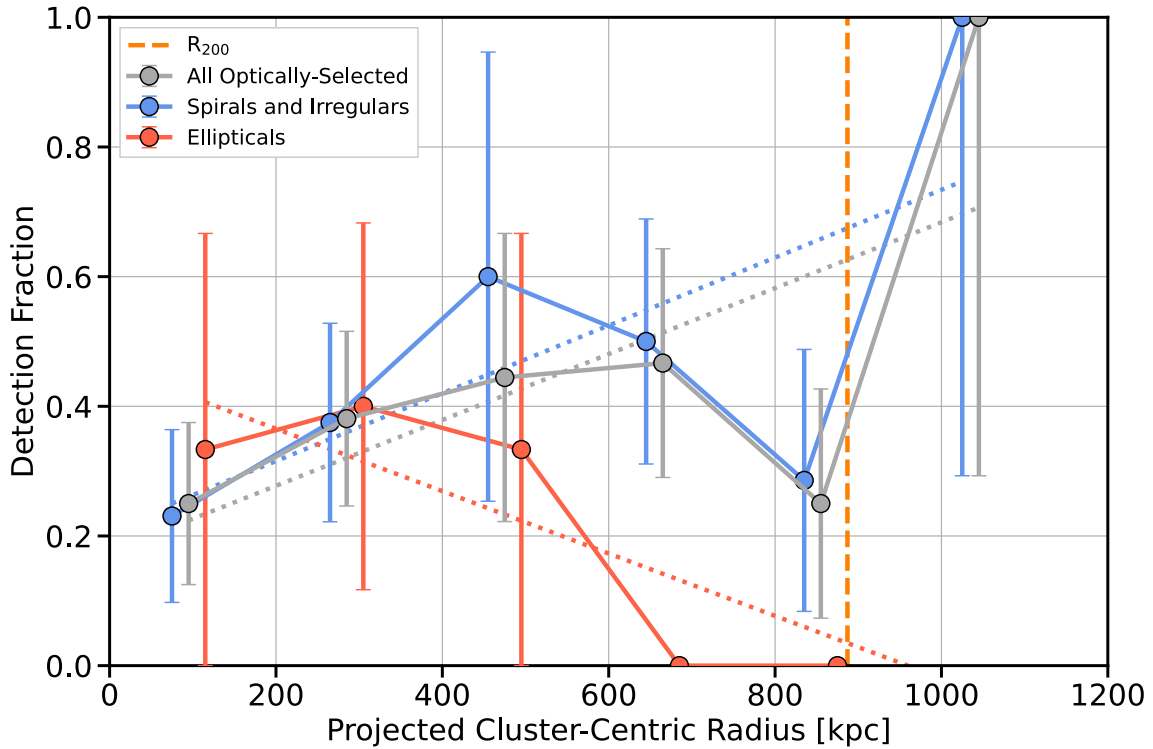


Figure 2.10: Detection fraction as a function of two-dimensional projected cluster-centric distance, with best fitting models overplotted as dotted lines. The orange dashed line shows the  $R_{200}$  radius. We further split the plot by morphology, with spirals and irregulars shown in blue, and ellipticals shown in red. For the whole sample, as well as the two subsamples, a linear model provides the best fit to the data, showing an increase in the detection fraction with cluster-centric radius on average, primarily driven by the preferential location of low-SFR ellipticals near the cluster centre, and an increase in star-forming spirals and irregulars beyond  $R_{200}$ .

### 2.6.1 Detection Rates as a Function of Radial Distance and Morphology

In Figure 2.10 we present the detection rate for the optically-selected sample as a function of two-dimensional projected cluster-centric radius. We additionally show this relation individually for the different morphologies in our sample. The  $R_{200}$  radius for the Antlia cluster (i.e. the radius within which the number density of galaxies is  $\geq 200 \Omega_m^{-1}$ , or at least two-hundred times greater than the number density of field galaxies) is measured by Wong et al. (2016) based on observations with the *Suzaku* X-ray observatory. We find that, on average, the detection rate increases with projected cluster-centric radius from  $\sim 20\%$  at radii  $\lesssim 200$  kpc up to  $\sim 70\%$  at radii  $\gtrsim 1000$  kpc. This relation is driven by both the elliptical galaxies in our sample, which

generally show lower SFRs and are preferentially located within  $\sim 500$  kpc from the cluster centre, and a small number of spirals and irregulars with detections out to 1000 kpc. We note that, while the detection fraction of the star-forming spirals and irregulars in our sample drops slightly at low radii ( $\lesssim 200$  kpc) and at higher radii ( $\sim 800$  kpc), the large error bars could imply an essentially flat detection rate with cluster-centric radius from 200 – 900 kpc. We note that, of the 27  $\text{SNR} > 3$  detections in our sample, only four are classified as elliptical, while the remaining 23 are classified as spirals or irregulars.

In order to provide a more quantitative analysis of this result, we use **LMFIT** to fit both linear and constant models to the six binned data points in Figure 2.10 to determine which model is favoured based on the chi-squared statistic ( $\chi^2$ ). For the constant model, the best fit value is  $0.386 \pm 0.077$ , while the linear model favours a functional form of  $\text{Detection Fraction} = (5.082 \pm 2.971) \times 10^{-4} \text{ kpc}^{-1} R + (0.176 \pm 0.195)$ , with chi-squared values of  $\chi^2_{\text{Constant}} = 0.386$  and  $\chi^2_{\text{Linear}} = 0.223$  respectively. Similar results are obtained for the elliptical and spiral/irregular samples individually, in that the linear model provides a slightly better fit than the constant model. In Figure 2.10, we show the best fit linear models for each sample as dotted lines.

However, based on the distribution of points, it is likely that the gradient of these linear models is driven to some extent by the rise in the detection fraction of spirals and irregulars outside  $R_{200}$ . In Figure 2.11, we therefore show the same relation, but replotted within the  $R_{200}$  radius. We find that, while the elliptical subsample is still best described by a negative linear correlation, the whole sample and the spiral/irregular subsample are effectively equally well-described by linear and constant models, with chi-squared values of  $\chi^2_{\text{Linear,All}} = 0.042$ ,  $\chi^2_{\text{Linear,Spirals/Irregulars}} = 0.087$  and  $\chi^2_{\text{Linear,Ellipticals}} = 0.041$  compared to  $\chi^2_{\text{Constant,All}} = 0.043$ ,  $\chi^2_{\text{Constant,Spirals/Irregulars}} = 0.092$  and  $\chi^2_{\text{Constant,Ellipticals}} = 0.155$  respectively. We note that **LMFIT** estimates a best fit linear model for the whole sample of  $\text{Detection Fraction} = (0.451 \pm 1.979) \times 10^{-4} \text{ kpc}^{-1} R + (0.337 \pm 0.108)$ . We similarly denote the best fitting models with dotted lines in Figure 2.11.

We therefore find that, on average, while we see a small decrease in the detection fraction at  $R < 200$  kpc and  $R \sim 800$  kpc, the detection fraction is consistent with remaining essentially

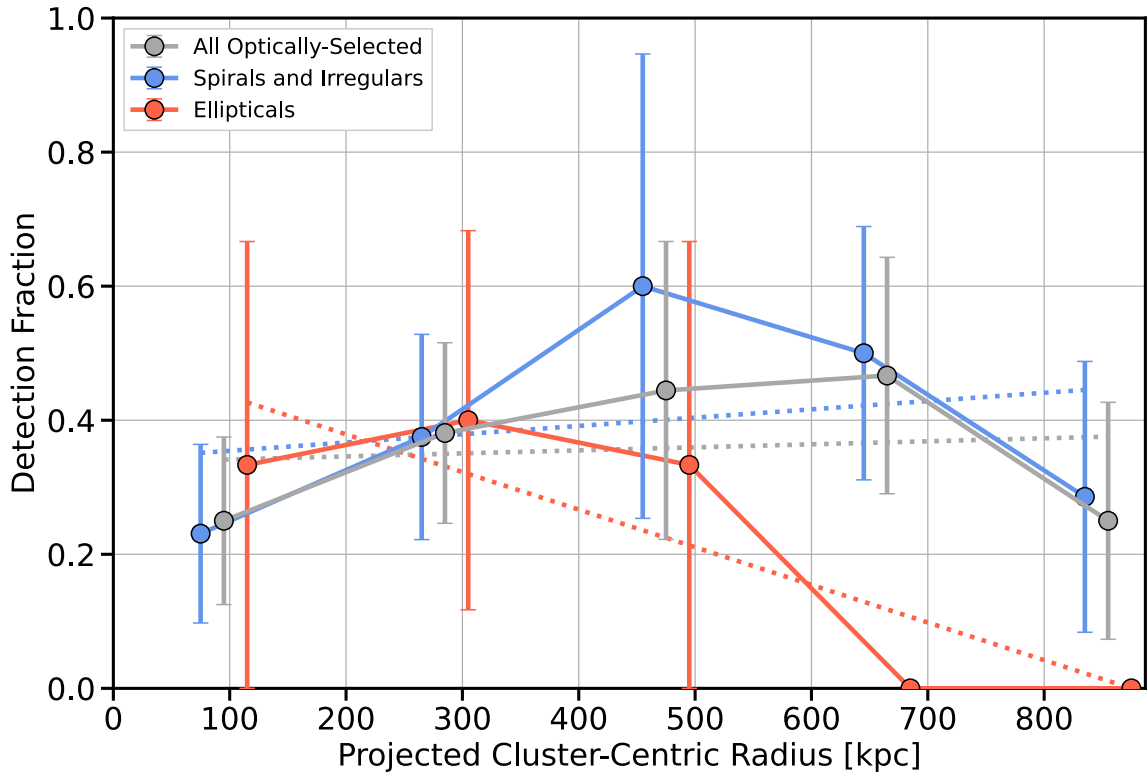


Figure 2.11: Detection fraction as a function of two-dimensional projected cluster-centric distance within the  $R_{200}$  radius, with best fitting models overplotted as dotted lines. We further split the plot by morphology, with spirals and irregulars shown in blue, and ellipticals shown in red. For the whole sample, as well as the two subsamples, a linear model provides the best fit to the data, showing an increase in the detection fraction with cluster-centric radius on average, primarily driven by the preferential location of low-SFR ellipticals near the cluster centre, and an increase in star-forming spirals and irregulars beyond  $R_{200}$ .

flat with cluster-centric radius within  $R_{200}$ . We then see an increase in the detection fraction outside  $R_{200}$ , driven by an increase in star-forming spiral and irregular galaxies outside of this radius. We detect only four elliptical galaxies in CO(2 – 1) emission in our optically-selected sample, all of which reside within  $\sim 500$  kpc of the cluster centre resulting in a sharp decrease in detection fraction with cluster-centric radius for this subsample. These results are consistent with similar studies demonstrating that galaxies residing in the outskirts of clusters tend to be more blue and star-forming. For example, Strazzullo et al. (2019) find that, as early as  $z \sim 1.5$ , the most massive clusters effectively suppress star formation in their central regions. Similarly, Annunziatella et al. (2014) find that, in the  $z = 0.44$  cluster M1206, tidal disruption near the cluster core can convert star-forming galaxies into passive ones, and can even destroy galaxies entirely.

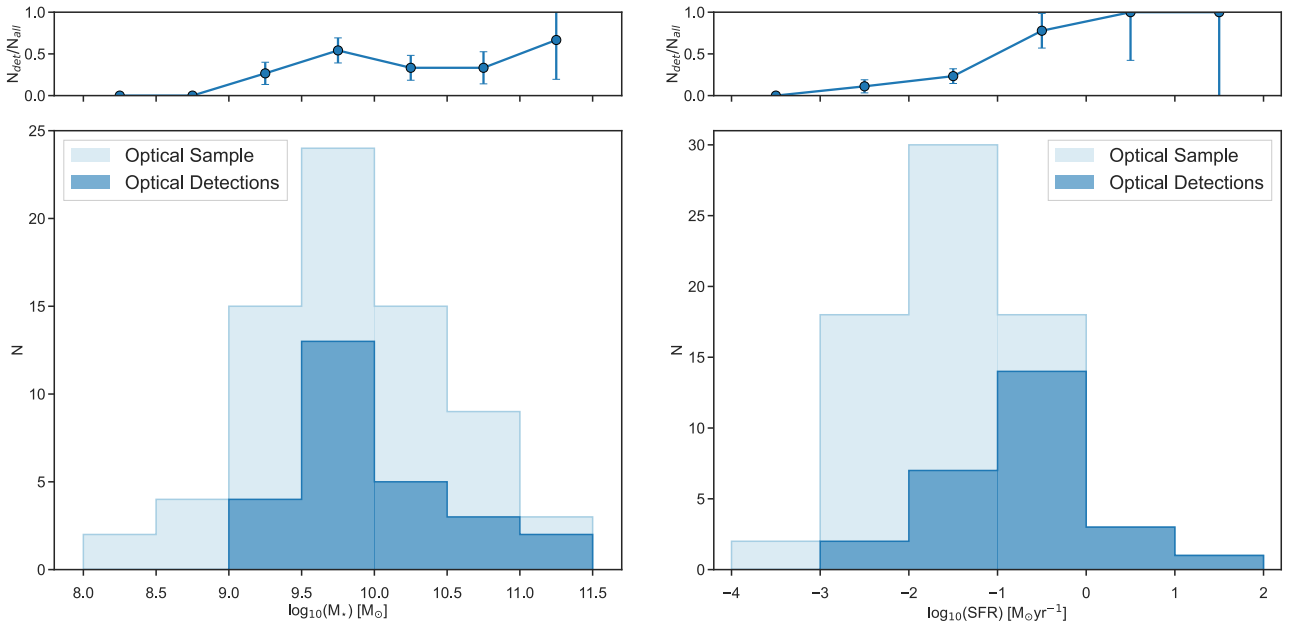


Figure 2.12: Detection fraction as a function of stellar mass (*left*) and SFR (*right*). The lower panels contain histograms showing the distributions of the entire optically-selected sample and the  $\text{SNR} > 3$  detections as light and dark bars respectively. The upper panels show the detection fraction in each bin as a function of either stellar mass or SFR with associated Poissonian errors. We find that the detection fraction increases with both stellar mass and SFR, although the correlation with SFR is somewhat stronger.

### 2.6.2 Detection Rates as a Function of Galaxy Properties

We then present the detection rate in our optically-selected sample as a function of galaxy properties. In Figure 2.2 we show the distribution of detections as a function of redshift. Within the rather large error bars and the very small redshift range, we find that the detection rate remains essentially flat.

In Figure 2.12 we present the detection rate for the optically-selected sample as a function of both stellar mass and SFR, with the upper panels showing the detection fraction as a function of these galaxy properties, and the lower panels showing the distribution of galaxy properties for the entire optically-selected sample, as well as for the  $\text{SNR} > 3$  detections. We infer that there is a clear evolution in the detection fraction with both stellar mass and SFR. We find no  $\text{CO}(2-1)$  detections in galaxies with  $M_\star < 10^9 M_\odot$ . The dip in the detection fraction at stellar masses above  $\sim 10^{10} M_\odot$  is driven primarily by the presence of passive elliptical galaxies in this stellar mass range. If we consider only the star-forming galaxies in the optically-selected

sample within 1 dex of the main sequence, the detection rate is  $\sim 86\%$ . Our comparison sample of star-forming field galaxies from the ALLSMOG survey (Cicone et al., 2017) shows a somewhat different trend, with the majority of detections clustered towards the high stellar mass end ( $> 10^{9.5} M_{\odot}$ ) of the sample. Figure 2.12 similarly shows a smooth increase in the detection fraction with SFR, but we find that the evolution of detection fraction with SFR is somewhat stronger than we find for stellar mass. Note that Figure 2.1 demonstrates that stellar mass and SFR are correlated in our sample, and so we would naturally expect the detection fraction to display a similar evolution with the two properties. We infer from these results that the majority of CO(2 – 1) detections are clustered towards the more massive and more star-forming galaxies in our optically-selected sample, while a significant fraction of this sample has reasonably low SFRs as demonstrated in Figure 2.1.

### 2.6.3 CO Luminosity as a Function of Galaxy Properties

The primary scientific goal of this study is to investigate the effect that disturbed cluster environments have on the molecular gas reservoirs of their member galaxies. To this end, we then investigate the CO(1 – 0) line luminosity, which we use as a proxy for the molecular gas mass, as a function of stellar mass and SFR, compared to the field sample of Cicone et al. (2017). However, before making such a comparison, it is important to note the differences between the selection criteria of the two samples, as it is possible that this will introduce biases into the analysis that should be fully considered. Firstly, Cicone et al. (2017) strictly select only those galaxies in the stellar mass range  $10^{8.5} M_{\odot} < M_{\star} < 10^{10} M_{\odot}$ , while we only impose a lower limit of  $M_{\star} > 10^8 M_{\odot}$ . Additional cuts are imposed on the ALLSMOG sample that are absent from our selected criteria. Cicone et al. (2017) select only those galaxies defined as star-forming based on their position on the  $\log_{10}([\text{OIII}]/\text{H}\beta)$  vs.  $\log_{10}([\text{NII}]/\text{H}\alpha)$  diagram, whereas we make a simple cut in SFR based on the *WISE* 12  $\mu\text{m}$  luminosity. Cicone et al. (2017) additionally make a cut based on galaxy metallicity, as well as imposing a slightly different definition of signal-to-noise, resulting in more marginal detections being allowed into the sample, as discussed in Section 2.5.1. We note that these additional cuts are necessarily absent from our selection

criteria, as we do not have the requisite data to make cuts on metallicity or position on the  $\log_{10}([\text{OIII}]/\text{H}\beta)$  vs.  $\log_{10}([\text{NII}]/\text{H}\alpha)$  diagram. As a result, Cicone et al. (2017) effectively select a sample of star-forming galaxies within  $\sim 1$  dex of the main sequence, while our selection is much broader, and includes galaxies both on and significantly below the main sequence.

In Figure 2.13 we present the relationships between CO(1 – 0) luminosity, stellar mass and SFR. When the entire optically-selected sample is considered, we find that there is no strong relation between CO(1 – 0) luminosity and stellar mass. This is contrary to the findings of Cicone et al. (2017) who find strong  $L_{\text{CO}(1-0)} - M_{\star}$  and  $L_{\text{CO}(1-0)} - \text{SFR}$  relations based on main sequence field galaxies in the ALLSMOG survey. However, the upper right panel in Figure 2.13 indicates a three-dimensional relationship between stellar mass, SFR and molecular gas, with those Antlia cluster members located within 0.7 dex of the main sequence lying well within the scatter of the  $L_{\text{CO}(1-0)} - M_{\star}$  relation for field galaxies. This becomes even more true for Antlia cluster members located within 0.3 dex of the main sequence. We therefore infer that the closer that the Antlia cluster members are to the star-forming main sequence, the closer they are to the field relation derived by Cicone et al. (2017). By extension, we find that galaxies in our optically-selected sample that lie significantly below the main sequence tend to lie below the scatter of the field relations, particularly for those with high stellar masses ( $M_{\star} \gtrsim 10^{10.5} \text{ M}_{\odot}$ ) which are generally classified as quiescent elliptical galaxies with SFRs  $\sim 100$  times lower than in their main sequence, star-forming counterparts. Cicone et al. (2017) additionally discuss that their sample selection likely misses the population of more quiescent galaxies residing below the main sequence which, in turn, are expected to lie below the  $L_{\text{CO}(1-0)} - M_{\star}$  relation. With these results, we can therefore confirm that the relations from Cicone et al. (2017) seem to hold only for star-forming galaxies and break down when extrapolated to galaxies residing below the main sequence. We conclude that the CO(1 – 0) luminosities for the majority of galaxies in our optically-selected sample are consistent with those of field galaxies residing just below the main sequence.

Interestingly, the lower panels of Figure 2.13 demonstrate that we find a strong  $L_{\text{CO}(1-0)} - \text{SFR}$  relation for the vast majority of  $\text{SNR} > 3$  detected Antlia cluster members, not just those residing close to the main sequence as we found for the  $L_{\text{CO}(1-0)} - M_{\star}$  relation. Such a tight

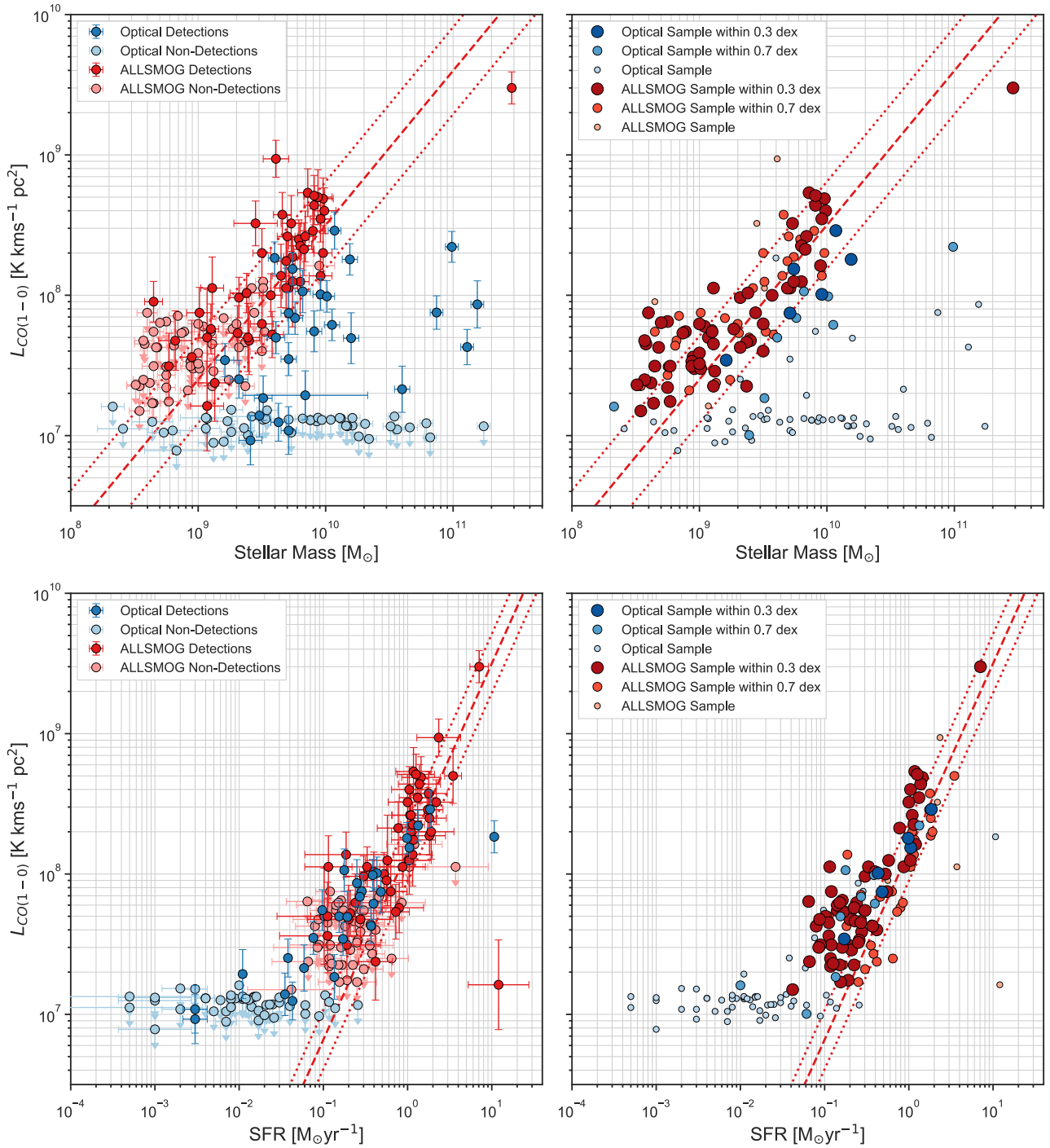


Figure 2.13: The CO(1 – 0) line luminosity of our optically-selected galaxies (*blue*) as a function of stellar mass (*upper panels*) and SFR (*lower panels*), alongside the ALLSMOG sample of field galaxies (*red*). In the left panels, detections and non-detections are represented by darker and lighter points respectively, with the upper limits in CO(1 – 0) luminosity estimated from Equation 2.12 following Ciccone et al. (2017). In the right panels, the size and colour of the points encodes the placement of the galaxy relative to the main sequence (Renzini and Peng, 2015), with the largest and darkest points indicating those sources within 0.3 dex. The dashed and dotted lines show the best fit relations from the ALLSMOG survey and the associated intrinsic scatter. We find that Antlia cluster members within 0.7 dex of the main sequence fall on the relation derived from their field counterparts. In the upper right panel, galaxies located off the main sequence scatter to the right of the field relation, and hence have smaller molecular gas reservoirs compared to galaxies of similar stellar mass located on the main sequence. This demonstrates the three-dimensional relationship between stellar mass, SFR and molecular gas.

correlation is also recovered by Ciccone et al. (2017) who suggest that this close linear relation between CO(1 – 0) luminosity and SFR is expected and likely the result of the well known empirical trend between the surface density of cold molecular gas and SFR (the Schmidt-Kennicutt law; Schmidt, 1959; Kennicutt, 1998b). We additionally find that the vast majority of  $\text{SNR} > 3$  detected Antlia cluster members with SFRs comparable to the range probed in the ALLSMOG survey are located within or very close to the intrinsic scatter of the  $L_{\text{CO}(1-0)}$ –SFR relation for field galaxies. We therefore conclude that, based on a given SFR, the Antlia cluster members within our optically-selected sample have comparable CO(1 – 0) luminosities to their counterparts, irrespective of their stellar masses. We note that there is one source in our sample (J103152) that is distinct from the rest of the population in the lower right panel of Figure 2.13, with a SFR roughly an order of magnitude larger than the galaxy with the next highest SFR in the sample. This galaxy has a stellar mass somewhat towards the lower end of the stellar mass distribution for the optically-selected sample ( $M_{\star} = 10^{9.6 \pm 0.1} M_{\odot}$ ) placing it significantly above the main sequence, and has some of the strongest evidence for disturbance of any of the Antlia cluster galaxies. This source will be discussed further in Section 2.7.5.

In order to investigate this three-dimensional relationship between stellar mass, SFR and molecular gas in more detail, we show in Figure 2.14 the distribution of Antlia cluster members in our optically-selected sample on the stellar mass–SFR plane, colour-coded by their CO(1 – 0) luminosity. We find that, when considering only those galaxies in our optically-selected sample with similar stellar masses and SFRs to those in the ALLSMOG survey of field galaxies, the Antlia cluster members tend to have similar CO(1 – 0) luminosities to their counterparts in the field, indicating that they have comparable reservoirs of molecular gas. Considering both Figures 2.13 and 2.14, we therefore find that the molecular gas reservoirs in these two samples are proportional to both stellar mass and SFR, but do not significantly depend on environment, and hence galaxies in both field and disturbed cluster environments lie on a single  $M_{\star}$  – SFR–molecular gas plane. The implications of these results will be discussed further in Section 2.7.3.



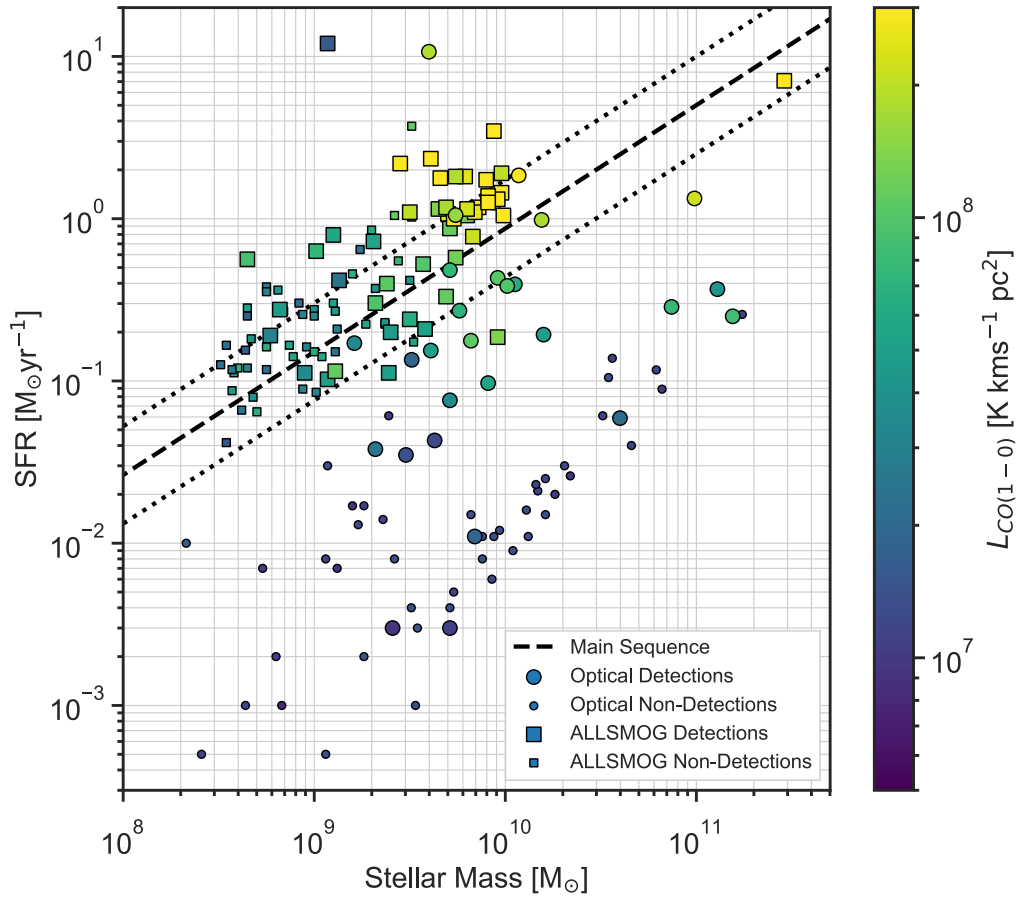


Figure 2.14: The distribution of our optically-selected Antlia cluster members on the  $M_{\star}$  – SFR plane, colour-coded by their CO(1 – 0) luminosity which we use as a proxy for the molecular gas mass. We show the ALLSMOG comparison sample of field galaxies as squares, with detections in both samples represented by larger symbols and non-detections represented by smaller symbols. We find that the Antlia cluster members in our sample contain a similar amount of CO(1 – 0) luminosity as field galaxies with comparable stellar masses and SFRs.

#### 2.6.4 Non-Gaussian Molecular Gas Profiles as a Function of Radial Distance

Finally, we focus on the Antlia cluster members in our optically-selected sample that display CO(2 – 1) emission line profiles that deviate from a simple, single-peaked Gaussian. In total, there are eleven galaxies with non-Gaussian CO(2 – 1) emission line profiles, comprised of nine double-Gaussian profiles, one double-horned profile and one offset-Gaussian profile. Of the ten galaxies displaying some form of double-peaked profile, the majority are roughly symmetric, and only one galaxy (J103152) shows a significantly asymmetric double-Gaussian CO(2 – 1) profile.

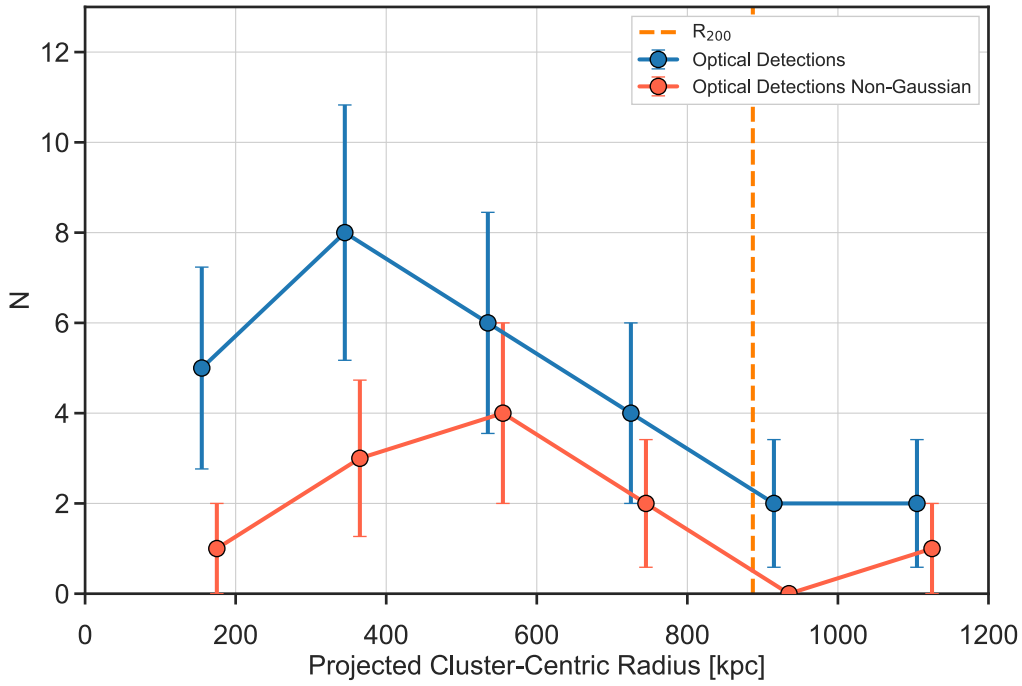


Figure 2.15: The distribution of Antlia cluster members in the optically-selected sample displaying non-Gaussian CO(2 – 1) emission line profiles (*red*) with two-dimensional projected cluster-centric radius, alongside the projected cluster-centric radius distribution for all SNR > 3 detections in the optically-selected sample (*blue*). We find that the number of sources with non-Gaussian CO(2 – 1) profiles peaks somewhat further out from the cluster centre ( $\sim 600$  kpc) than the total sample of detected galaxies, which peaks at  $\sim 400$  kpc. We note that the large error bars make this conclusion uncertain.

In Figure 2.15 we plot the distribution of galaxies with non-Gaussian CO(2 – 1) profiles as a function of projected cluster-centric distance. We find that, while the distribution of detections in the full optically-selected sample peaks at  $\sim 400$  kpc and decreases smoothly towards the cluster edge, the distribution of galaxies with non-Gaussian CO(2 – 1) profiles seems to peak further out at  $\sim 600$  kpc. We note that these are small number statistics, and the large error bars make the result somewhat uncertain. Nonetheless, we discuss the potential physical implications of these results in Section 2.7.5.

## 2.7 Discussion

### 2.7.1 HI Pointings

Before moving on to the main points of discussion in this work, we must first address the potential reasons for the offset HI pointings that severely impacted the conclusions we could draw for our HI-selected sample. In Section 2.6 we discussed that, based on the comparison between the CO(2–1) luminosities derived from the optical and HI pointings for the five sources observed in both samples, the optical emission is likely highly co-spatial with the molecular gas emission, and that the HI detections are offset from this location, resulting in systematically lower CO(2 – 1) luminosities.

In order to investigate the drivers behind these offset HI detections, we first consider whether ram pressure could be more efficient at stripping the diffuse, atomic gas than the molecular gas. If this were the case, we would expect to see a larger offset between the optical host and the HI detection compared to the optical host and the CO detection, and a higher molecular gas detection rate amongst sources with a higher HI mass. In Figure 2.16 we therefore plot the CO(2 – 1) detection rate as a function of both stellar mass and HI mass. We find no obvious increase in the CO detection fraction as a function of HI mass, although this could in part be due to the small number of galaxies in our sample with HI mass estimates as well as the large positional uncertainties in the HI detections. Therefore, for our Antlia cluster members, we find that galaxies with larger HI masses are not necessarily more likely to be detected in CO(2 – 1), which makes it unlikely that these large positional offsets are primarily driven by ram pressure stripping.

We therefore conclude that the lack of CO detections in most HI sources is driven by the large pointing errors, rather than any physical processes such as hydrodynamical stripping within the cluster. KAT-7, with which the HI observations were taken, has a beamsize of  $\sim 3'$ , resulting in a positional accuracy of worse than  $1'$ . By comparison, APEX has a spatial resolution of  $\sim 30''$ , and as such the flux loss and non-detections of molecular gas in the HI-detected sample can be fully explained by this positional uncertainty. Unfortunately, we therefore suggest that no

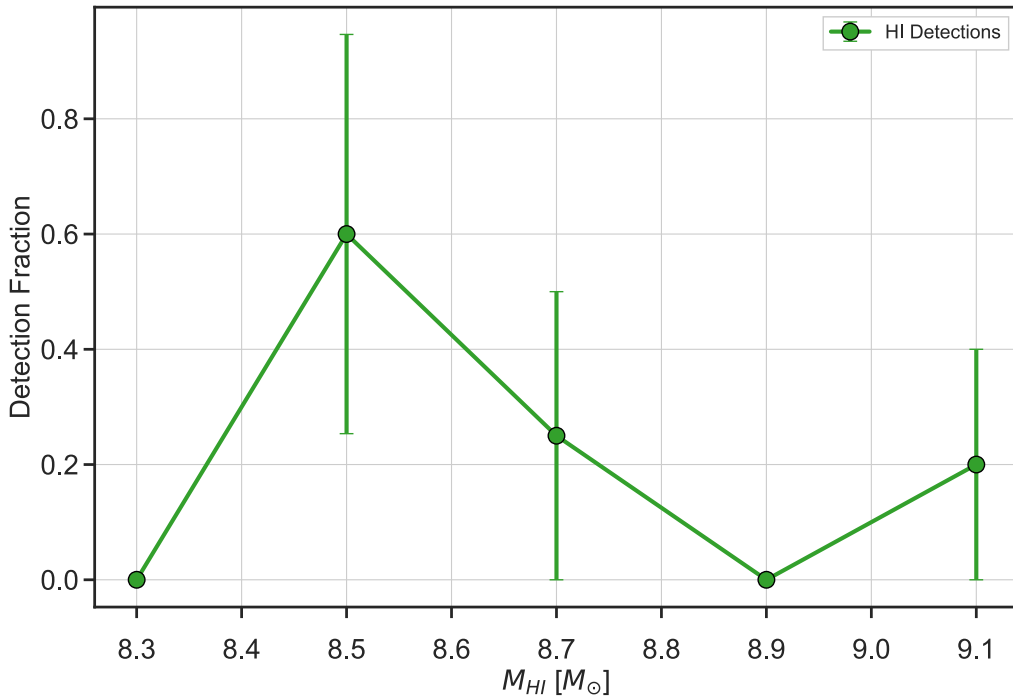


Figure 2.16: The CO detection fraction within the HI-selected sample as a function of estimated HI mass. We find no obvious dependence of the CO detection rate on HI mass, indicating that environmental quenching mechanisms such as ram pressure stripping are not the main drivers behind the offset HI pointings.

reliable interpretations can be drawn from the molecular gas measurements of our HI-detected sample.

### 2.7.2 Molecular and Atomic Gas in Relaxed Clusters

It is well established that the conditions within dynamically evolved clusters can have an immense impact on their member galaxies, primarily through the environmental quenching mechanisms outlined in Section 2.1. The vast majority of these environmental quenching processes directly affect the reservoirs of atomic HI gas, which is typically diffuse and broadly distributed across a galaxy. Indeed, cluster spirals at fixed mass are significantly deficient in atomic HI gas, with atomic gas reservoirs up to ten times smaller than similarly-selected counterparts in the field. It seems that the ability for a galaxy cluster to strip its member galaxies of their interstellar gas is not uniform however, as the magnitude of this effect depends on the X-ray properties of the cluster, such as 0.5 – 3.0 keV luminosity, indicating more effective removal

of HI for galaxies residing in more massive, luminous and relaxed clusters (e.g. Giovanelli and Haynes, 1983, 1985; Solanes et al., 2001; Chung et al., 2009). The deficiency of HI in cluster spirals is also strongly correlated with the cluster-centric radius of the galaxy (e.g. Giovanelli and Haynes, 1985). However, SFR does not seem to be directly suppressed in galaxies that have been stripped of their reservoirs of atomic gas, indicating that the molecular gas reservoirs of cluster galaxies, which provide the direct fuel for star formation, are less easily disturbed by the harsh conditions within the galaxy cluster (e.g. Kennicutt et al., 1984).

By comparison, the effect that the harsh conditions within a dynamically evolved cluster have on the molecular gas properties of their member galaxies is still the subject of intense research. Prior to the turn of the century, numerous studies focused on the member galaxies of the most nearby, relaxed galaxy clusters, such as Coma and Virgo, finding that galaxies residing in cluster environments display minimal evidence for molecular gas deficiencies, even in cases where the galaxies display significant deficiencies in their HI reservoirs (e.g. Kenney and Young, 1989; Boselli et al., 1995a, 1997). The stronger depletion of HI relative to molecular gas in star-forming cluster members was attributed to the resistance of molecular clouds to stripping due to their large surface area and their location deep within the potential wells of the inner discs of their host galaxies, effectively shielding them from the effects of stripping (e.g. Kenney and Young, 1989). However, a number of more recent studies using larger samples and spatially resolved observations of the atomic and molecular gas reservoirs find conflicting results, with HI deficient spiral galaxies also showing reduced molecular gas reservoirs relative to their field counterparts with comparable stellar masses (e.g. Bertram et al., 2006; Fumagalli et al., 2009; Jablonka et al., 2013; Boselli et al., 2014; Mok et al., 2016; Zabel et al., 2019; Lee et al., 2017). For example, Boselli et al. (2014) find in their sample of *K*-band selected galaxies in Virgo from the *Herschel* Reference Survey (HRS) that their molecular gas reservoirs are indeed depleted compared to comparable field galaxies, although not as efficiently as their atomic gas, and that while the molecular gas supply is cut off and the gas is consumed through star formation, the main cause for the deficiency is actually removal of gas through ram pressure.

### 2.7.3 The Molecular Gas Content of Galaxies within Disturbed Cluster

The literature results suggest that the molecular gas reservoirs within massive, dynamically evolved galaxy clusters are depleted compared to their counterparts in the field. However, one of the primary pathways for galaxy cluster growth is through mergers with other clusters, with the violent nature of these cluster mergers producing disturbed galaxy clusters. Recent independent studies found that, even at lower redshifts ( $z < 0.8$ ), about 70% of *Planck* SZ-selected clusters are non-cool core (NCC), disturbed clusters (Andrade-Santos et al., 2017; Rossetti et al., 2017), with this fraction remaining roughly constant with redshift between  $z = 0$  and  $z \sim 0.8$  (Rossetti et al., 2017). Therefore, if massive, relaxed galaxy clusters evolve from low-density environments rich in galaxies with significant molecular gas reservoirs, should we expect a lower deficiency in the molecular gas reservoirs of galaxies located in disturbed clusters that are in the process of formation?

Based on Figure 2.13 comparing the CO(1–0) luminosities of Antlia cluster members with our comparison sample of field galaxies from the ALLSMOG survey (Cicone et al., 2017), we find a strong  $L_{\text{CO}(1-0)} - \text{SFR}$  relation in good agreement with the relation for field galaxies, although we note from our  $L_{\text{CO}(1-0)} - M_\star$  relation (as well as the  $M_\star - \text{SFR}$  plane presented in Figure 2.1) that our optically-selected sample primarily probes galaxies lying just below the main sequence. Given that the ALLSMOG sample very effectively selects star-forming field galaxies on the main sequence, this makes a direct comparison between the two samples difficult. In Figure 2.14 we present a clearer comparison between the two samples, demonstrating where each galaxy sits on the three-dimensional  $M_\star - \text{SFR} - L_{\text{CO}(1-0)}$  relation. We infer that Antlia cluster members with a fixed stellar mass and SFR have similar molecular gas reservoirs to their counterparts in the field with comparable stellar masses and SFRs.

We can additionally compare these results to samples of galaxy cluster members selected from more massive and dynamically evolved clusters such as Coma or Virgo (e.g. Boselli et al., 1995b, 1997). Boselli et al. (1997) find, based on their sample of galaxies in the Coma cluster, that the molecular gas content correlates with star-formation only for Milky Way-like cluster galaxies

with stellar masses  $M_{\star} \sim 10^{10.8} M_{\odot}$ . The radiation from young stars can photo-dissociate the more diffuse molecular gas in less massive and lower metallicity cluster members, resulting in the lack of an observed correlation between CO luminosity and star formation in these sources, as well as the higher  $\alpha_{\text{CO}}$  conversion factors (e.g. Boselli, 1994). By comparison, we find a strong correlation between molecular gas content and SFR across the entire range of stellar mass ( $\sim 10^{8.5} - 10^{11.5} M_{\odot}$ ) probed by our sample of optically-selected Antlia cluster members, including those that reside on and below the main sequence. Moreover, Boselli et al. (1995b) suggest that the molecular gas reservoirs in low-mass cluster members could be underestimated when using the  $\alpha_{\text{CO}}$  conversion factor derived from more massive cluster members. Such an effect would boost the observed molecular gas contents in our Antlia cluster members, pointing to even higher star formation efficiencies than their counterparts in the field.

We interpret these results as evidence that the Antlia cluster represents an intermediate cluster environment, harsher than fields but less harsh than more relaxed galaxy clusters, in which the evolving ICM may just be starting to affect the cluster members, but is not yet strong enough to strip galaxies as effectively as in more evolved systems such as Coma or Virgo. We infer that the process of cluster merging significantly disturbs the ICM of the evolving cluster, enough to interact with the member galaxies and induce the observed high SFRs, as well as potentially beginning to quench the cluster members. This scenario simultaneously explains the high SFRs observed in numerous disturbed cluster environments as well as the significant molecular gas reservoirs that we have observed in the Antlia cluster.

We suggest that, as the Antlia cluster may represent this more intermediate cluster environment, it could be considered as a convenient laboratory in which to study the processes that likely occur in developing galaxy clusters at high redshift that are, by definition, much more challenging to investigate observationally. Tadaki et al. (2019) present ALMA CO(3 – 2) observations of 66 H $\alpha$ -selected galaxies in three protoclusters at  $z \sim 2.5$ , finding that lower mass galaxies in their sample ( $M_{\star} < 10^{11} M_{\odot}$ ) have enhanced molecular gas reservoirs compared to the scaling relations established for field galaxies, while their more massive galaxies ( $M_{\star} > 10^{11} M_{\odot}$ ) have comparable molecular gas reservoirs to their field counterparts. This result suggests that, similar to our sample of galaxies in the local Antlia cluster, the member galaxies of young clusters

in the process of forming at high redshift can also retain their reservoirs of molecular gas.

Resolved studies of galaxies infalling into massive relaxed clusters (e.g. Lee et al., 2017; Jáchym et al., 2014; Moretti et al., 2018) found that their molecular gas reservoirs can be both slightly stripped along the infall direction, and enhanced within sites of intense star formation (as traced by  $H\alpha$  and FUV emission). It is therefore expected that the molecular gas content of the galaxy can be modestly enhanced along tails behind and upstream of these galaxies, which could subsequently affect the star formation efficiency in the disc (Lee et al., 2017). These results are in good agreement with the predictions of simulations (e.g. Tonnesen and Bryan, 2009, 2012; Roediger et al., 2014), which find that ram pressure is typically insufficient to strip the molecular gas embedded within the member galaxies of even massive clusters, but that interactions between the cluster members and the ICM can disturb and compress their molecular gas reservoirs and trigger significant episodes of star formation. In lower mass, disturbed galaxy clusters such as Antlia, ram pressure is unlikely to be efficient enough to completely remove the molecular gas from infalling galaxies, but infalling galaxies could experience disturbances in their molecular gas reservoirs caused by interactions with the ICM, leading to temporary enhancements in the star formation efficiency. Our observations capture Antlia in an active phase of formation, with multiple smaller sub-clusters undergoing a series of mergers. Such developing clusters could feasibly retain a significant number of gas-rich galaxies, and those that fell into the cluster prior to the sub-cluster mergers could be experiencing interaction with the large scale phenomena caused by the cluster formation. Processes such as shocks and turbulence can also temporarily enhance the conversion of atomic into molecular gas which, in turn, will temporarily enhance the star formation activity (Roediger et al., 2014).

We therefore expect that the galaxies in disturbed cluster environments are either recently quenched, or in the process of becoming quenched. This expectation is supported by Figure 2.1, where we see that the majority of our sources lie just below, or well below the main sequence, possibly representing populations of galaxies that are in the process of quenching, and those that are fully quenched.



### 2.7.4 Molecular Gas Fuelling Future Star Formation

Based on our observations, we have found that galaxies residing within the disturbed Antlia galaxy cluster can retain a significant reservoir of molecular gas and are likely in the early stages of quenching by the more intermediate cluster environment. To what extent can these reservoirs of molecular gas fuel and sustain significant future star formation within the Antlia cluster?

Evidence from numerous studies suggests that different quenching processes dominate at different stellar masses. In samples of star-forming galaxies residing in both field environments and in massive, dynamically evolved clusters such as Virgo, the depletion time scale of molecular gas (defined simply as the molecular gas mass divided by the SFR) correlates with both stellar mass and SFR, but is mostly strongly correlated with the specific SFR, with ‘normal’ star-forming galaxies, LIRGS and ULIRGS all falling on the same steep relation in the depletion timescale–sSFR plane (Saintonge et al., 2011b; Mok et al., 2016). In the COLD-GASS survey, the large variation in depletion timescale with respect to sSFR is attributed to two separate effects. Firstly, at the high mass end, Saintonge et al. (2011b) suggest a preferential quenching of star formation due to internal, secular processes that effectively prevent molecular gas from forming stars without destroying it. This mechanism, typically known as morphological quenching, is produced when a galaxy becomes spheroid-dominated rather than disc-dominated due to, for example, merger events or disc instabilities (Martig et al., 2009). The now dominant pressure-supported stellar spheroid effectively stabilises the disk and prevents the molecular gas from fragmenting and collapsing into stars without destroying the molecular gas itself (Martig et al., 2009). While it is likely that this quenching mechanism naturally works alongside other environmental quenching mechanisms, it crucially does not require gas removal or suppression and so naturally explains the large depletion timescales at the high stellar mass end (Martig et al., 2009). At the low stellar mass end, Saintonge et al. (2011b) suggest a preferential enhancement of star formation in lower mass galaxies through mild starburst events triggered by, for example, distant tidal encounters or variations in the accretion rate of the intergalactic medium, rather than the more massive starbursts triggered by major mergers.

In Figure 2.17 we present the distribution of Antlia cluster members in our optically-selected sample in the  $t_{\text{dep}}-\text{sSFR}$  plane, alongside the ALLSMOG sample of main sequence field galaxies. We find that, while our galaxies probe a larger range of stellar masses and SFRs than Saintonge et al. (2011b), those Antlia cluster members residing close to the main sequence fall close to the field relation and well within the scatter of the field star-forming galaxies, indicating that galaxies within the Antlia cluster have similar star formation efficiencies to their counterparts in the field. Given their large molecular gas reservoirs and assuming in the simplest case that molecular gas is depleted only by star formation, we infer that galaxies in the Antlia cluster will be able to sustain star formation for timescales similar to galaxies residing in the field.

Moreover, Figure 2.17 demonstrates that Antlia cluster members residing below the main sequence typically have lower depletion timescales than star-forming galaxies with comparable stellar masses, primarily driven by their reduced reservoirs of molecular gas, as demonstrated in Figure 2.14. We therefore conclude that these galaxies are well on their way to becoming quenched: not only do they have reduced SFRs with respect to the main sequence, but additionally their molecular gas reservoirs are significantly reduced, implying depletion timescales of between 100 Myr and 1 Gyr.

### 2.7.5 Quenching in the Antlia Cluster

#### Evidence of Quenching from Optical Morphologies and non-Gaussian Emission Line Profiles

From the above discussions, we infer that there is significant evidence of ongoing quenching within the Antlia cluster. Firstly, Figure 2.1 demonstrates that our optically-selected sample breaks up into two effectively distinct populations, those lying slightly below the main sequence and following the trend of the ALLSMOG sample reasonably well, and those scattered well below the main sequence, representing a population with little ongoing star formation compared to their counterparts in the field with similar stellar masses. From Figure 2.14, we additionally infer that those sources residing below the main sequence have molecular gas reservoirs that

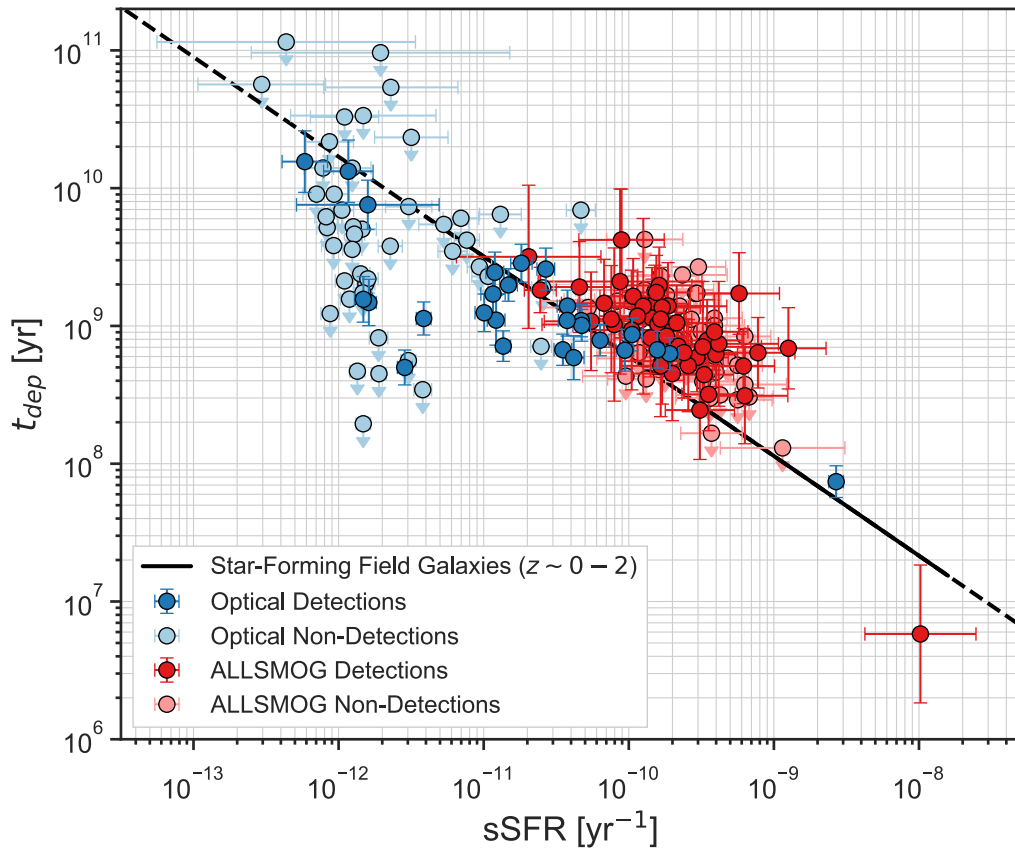


Figure 2.17: The molecular gas depletion timescale as a function of sSFR, with molecular gas masses calculated based on a conversion factor of  $\alpha_{\text{CO}} = 4.3 \text{ M}_{\odot}/(\text{K km s}^{-1} \text{ pc}^2)$ . We show both our optically-selected Antlia cluster members, which probe the entire  $M_{\star}$ –SFR plane, as well as main sequence field galaxies from the ALLSMOG survey (Cicone et al., 2017). Both the Antlia cluster and the ALLSMOG field star-forming galaxies follow the relationship derived for star-forming, HI-rich field galaxies at  $z \sim 0 - 2$  (Saintonge et al., 2011b). Cluster and field galaxies at  $z \sim 0.01$  of similar mass, SFR, and consequently specific SFR, have similar depletion timescales, pointing to similar molecular gas reservoirs. Extrapolating the relation to lower values of sSFR, we see a significant spread in the depletion timescales for Antlia cluster members of a given sSFR, primarily driven by our non-detections and sources residing below the main sequence. Cluster galaxies located below the main sequence have on average lower molecular gas reservoirs and shorter depletion times compared to star-forming galaxies of similar masses. This indicates that these lower-SFR cluster galaxies have already used up most of their molecular gas and their star formation will be shut down in 100 Myr to 1 Gyr.

are significantly reduced compared to the more ‘normal’ star-forming galaxies within the Antlia cluster and in the field. We therefore believe that, while Cicone et al. (2017) uniformly select star forming field galaxies residing on the main-sequence, the galaxies we find in the Antlia cluster are either on their way to becoming quenched, placing them just below the main-sequence, or have already become quenched, placing them far below it.

There are numerous different environmental and stellar-mass quenching mechanisms, each of which can affect the morphology of a galaxy in different ways. Hydrodynamical stripping processes, such as ram pressure stripping, could produce a visible tail of material behind the quenching galaxy or a structure reminiscent of a shock on one side, while processes such as harassment can make the galaxy look irregular in morphology. We therefore attempt to determine the main physical processes driving the observed quenching in the Antlia cluster members residing well below the main sequence by studying their morphologies (Figures 2.6 and 2.7). We can further compare these morphologies to the observed CO(2 – 1) emission line profiles for these galaxies to evaluate whether there is any evidence of unusual gas kinematics, another crucial indicator of ongoing quenching, with asymmetric or non-Gaussian line profiles indicative of, for example, rapidly rotating galaxies or hydrodynamical stripping.

We infer that there are a number of galaxies with non-Gaussian CO(2 – 1) emission line profiles that additionally show evidence of quenching in their optical images. Eleven sources in our optically-selected sample are classified as irregular galaxies which could be the result of galaxy-galaxy interactions or hydrodynamical stripping processes within the cluster. Additionally, of the eleven sources that display CO(2 – 1) emission line profiles that deviate from a single-peaked Gaussian, five ( $\sim 45\%$ ) show some evidence of disturbance in their optical morphology, while a further 8/64 ( $\sim 13\%$ ) of the remaining galaxies in the optically-selected sample show evidence of a disturbance in their optical morphology. Most notably, J103152 shows evidence of a large shock front on one side of its disc, as does the source J103124, although the disturbance in this galaxy is somewhat less pronounced. The source J103152 additionally has a strong, asymmetric double-Gaussian profile and is the most star-forming galaxy in our sample, providing tentative evidence that interactions between galaxies and the surrounding ICM can produce both disturbed gas kinematics and enhanced SFRs in our sample. J103019 and J102722 are asymmetric, possibly due to material being dragged out of the galaxies via ram pressure stripping. These sources also show unusual profiles in their CO(2-1) emission lines, with the Gaussian profile of J102722 offset by  $\sim 1000 \text{ km s}^{-1}$  and the CO(2-1) emission line of J103019 being best fit by a double-Gaussian. These galaxies have a range of SFRs and so, if they are becoming quenched, they are likely at different stages in this quenching process.

Although we only have a small number of galaxies in our optically-selected sample with non-Gaussian CO(2 – 1) emission line profiles, Figure 2.15 demonstrates that 8/11 or  $\sim 72\%$  reside between  $\sim 200 - 600$  kpc from the core of the Antlia cluster, where the evolving ICM is likely to be dense enough to begin acting significantly on the cluster members. This conclusion is evidently somewhat tenuous given the small number statistics and large error bars shown in Figure 2.15, but if these sources do represent a population of galaxies that are currently undergoing quenching, then we infer that this quenching preferentially occurs between  $\sim 400 - 800$  kpc from the cluster centre.

### How Strong is Ram Pressure in the Antlia Cluster?

Clearly, based on their optical morphologies and CO(2 – 1) emission line profiles, it is not unreasonable to suggest that a number of galaxies within the Antlia cluster show evidence that they are undergoing hydrodynamic stripping, but it remains unclear whether ram pressure within the Antlia cluster would actually be strong enough to produce this stripping in our optically-selected sample. In order to test this in more detail, we estimate upper limits on the ram pressure within the Antlia cluster.

Generally, the ram pressure acting on a galaxy traversing through a cluster can be approximated as  $P_r \approx \rho v^2$  where  $\rho$  is the mass density of the intra-cluster medium (ICM) and  $v$  is the velocity of the galaxy relative to the ICM (Gunn and Gott, 1972). We estimate the density of the ICM using the electron number density profile determined by Wong et al. (2016) for the Antlia cluster, converting the number density at a given projected cluster-centric radius into a mass density. We estimate an upper limit on the velocity by assuming that the galaxies are on highly elliptical orbits, in which case their velocities are given by the cluster’s escape velocity at the given cluster-centric radius ( $v = \sqrt{2GM/r}$ ) where we use the Antlia cluster virial mass ( $M \sim 5 \times 10^{14} M_\odot$ ). Using this albeit simplistic approximation, we estimate that ram pressure in the Antlia cluster can reach  $\sim 10^{-12}$  ergs cm $^{-3}$  within the central  $\sim 150$  kpc of the Antlia cluster, falling exponentially to  $\sim 10^{-15}$  ergs cm $^{-3}$  at  $\sim 1000$  kpc from the cluster core. Simulations by Abadi et al. (1999) suggest that a typical spiral galaxy moving through an ICM of similar

density to that of the Coma cluster can feel a ram pressure force of  $\sim 10^{10} \text{ M}_{\odot} (\text{km s}^{-1}) \text{ kpc}^{-3}$  (corresponding to a ram pressure of  $\sim 7 \times 10^{-12} \text{ ergs cm}^{-3}$ ), resulting in the stripping of  $\sim 80\%$  of its diffuse gas mass. It is therefore likely that ram pressure will be strong enough, particularly in the central regions of the Antlia cluster, to strip a significant fraction of the molecular gas from the member galaxies, although it is worth noting that this is a somewhat crude estimate of the ram pressure in the Antlia cluster.

## 2.8 Conclusions

We carried out CO(2 – 1) measurements with the APEX telescope, tracing the molecular gas reservoirs of galaxies in the nearby, disturbed Antlia cluster, based on two distinct samples, one focused on obtaining a broad selection of stellar mass and SFR, and the second focused on those galaxies with significant reservoirs of atomic gas as traced by previous HI measurements. This survey is therefore unique in its selection of a wide range of galaxy types (including spirals, ellipticals and irregular galaxies, as well as both star-forming and quenched galaxies down to a limiting stellar mass and SFR) as well as its choice of target: a disturbed cluster still in the process formation. The primary goals of this study were to investigate how the differences in the molecular gas reservoirs and star formation evolution of galaxies within a merging cluster environment, compared to massive and dynamically evolved clusters that are more well-studied in the literature.

Our cluster members were split into two samples: an optically-selected sample targeting 72 galaxies over a wide range of stellar mass ( $10^8 \text{ M}_{\odot} < M_{\star} < 10^{10} \text{ M}_{\odot}$ ) and SFR ( $0.0005 \text{ M}_{\odot} \text{ yr}^{-1} < \text{SFR} < 10 \text{ M}_{\odot} \text{ yr}^{-1}$ ) and hence populating a large fraction of the  $M_{\star} - \text{SFR}$  plane, and a second sample comprising 20 sources within the Antlia cluster with previous HI detections. However, we infer from a comparison of those sources detected in both samples that the HI detections are highly offset from the CO(2 – 1) detections, which themselves are highly co-spatial with the stellar light. We conclude that we cannot infer any robust conclusions from the HI-selected sample.

Focusing on the optically-selected sample, we report a CO(2 – 1) detection rate of  $\sim 37.5\%$ , rising to 86% for star-forming galaxies within 1 dex of the main sequence. We compared the resulting molecular gas measurements from our optically-selected sample to a comparison sample of main sequence field galaxies from the ALLSMOG survey (Cicone et al., 2017), finding that our optically-selected sample itself effectively splits into two distinct sub-samples: a population of galaxies residing just below the main sequence and roughly following the trends of their field counterparts, and a population residing well below the main sequence. We infer that these two populations may represent galaxies that are undergoing quenching, and those that have already been quenched. Our detection rate remains roughly constant with projected cluster-centric distance (excluding a small number of star-forming detections outside of  $R_{200}$ ), and the detections also cluster towards the high stellar mass and high SFR end of our sample, with no observable relation between the CO(2 – 1) detection rate and redshift (nor stellar or HI mass). A number of our galaxies have non-Gaussian CO(2 – 1) emission line profiles, or single Gaussian profiles significantly offset from their expected position. These profiles could be indicative of sources with unusual gas kinematics, and this is supported by the optical images of these galaxies which, in some cases, show tentative signatures of quenching (e.g. shocks, tails).

Our main finding is that the member galaxies of the Antlia cluster have comparable molecular gas reservoirs to their counterparts in the field with similar stellar masses and SFRs, contrary to what is observed in more massive and dynamically evolved clusters such as Coma and Virgo. This implies that the member galaxies within disturbed and/or merging cluster environments can retain a significant fraction of their molecular gas which, in turn, can fuel high SFRs. We infer that the Antlia cluster may represent the intermediate step between the field, containing many star-forming galaxies, and dense clusters in which the majority of their members have been quenched. The gentler ICM of disturbed cluster environments may allow their member galaxies to retain their reservoirs of molecular gas, which can in turn fuel high SFRs. In this scenario, the evolving ICM may just be beginning to interact with the member galaxies, and hence we expect a number of galaxies in our sample to be undergoing quenching.

Further research must be completed in order to confirm that the members of the Antlia clus-

ter are indeed undergoing quenching and to determine the processes that are contributing to this quenching process. While we have proven that galaxies residing in disturbed cluster environments are capable of holding on to their reservoirs of molecular gas, spatially resolved observations of these molecular gas reservoirs with ALMA are required to securely quantify the relationship between the disturbed cluster environment and its member galaxies.



# Chapter 3

## The Nature of Sub-mm Faint $500\ \mu\text{m}$ Risers

*The majority of the content within this chapter is based upon a paper submitted to MNRAS (<https://doi.org/10.48550/arXiv.2203.01049>).*

### 3.1 Introduction and Motivation

Over the last few decades we have witnessed a dramatic shift in our understanding of the nature of DSFGs and, more specifically, sub-millimeter galaxies (SMGs: Blain et al., 2002), which were first detected with SCUBA in the late 1990s (e.g. Smail et al., 1997; Barger et al., 1998; Hughes et al., 1998). It is now well understood that these sources primarily lie at moderate redshifts ( $z \sim 2 - 3$ : Chapman et al., 2005; Wardlow et al., 2011; Simpson et al., 2014; Koprowski et al., 2014; Smith et al., 2017; Danielson et al., 2017; Stach et al., 2019) and are massive ( $M_{\star} \sim 10^{10} - 10^{11} M_{\odot}$ : Swinbank et al., 2004; Hainline et al., 2011; Michałowski et al., 2012; Gruppioni et al., 2013; Simpson et al., 2014; Dudzevičiūtė et al., 2020; Pantoni et al., 2021), extremely luminous, with total infrared luminosities of  $L_{\text{IR}} \sim 10^{11} - 10^{13} L_{\odot}$  (Magnelli et al., 2012; Swinbank et al., 2014; Gruppioni et al., 2015; MacKenzie et al., 2017; Michałowski et al., 2017; Rowan-Robinson et al., 2018; Hill et al., 2018; Cheng et al., 2019; Greenslade et al., 2020)

and contain significant reservoirs of dust and gas (Smail et al., 2002; Greve et al., 2005; Kovács et al., 2006; Tacconi et al., 2006, 2008; Carilli et al., 2010; Clements et al., 2010a; Bothwell et al., 2013; Dudzevičiūtė et al., 2020; Pantoni et al., 2021), allowing them to reach dust-obscured SFRs of hundreds to thousands of solar masses per year. SMGs are therefore understood to provide an enormous contribution to the total energy density emitted by galaxies at ‘Cosmic Noon’, at which time the Cosmic Star Formation Rate Density (CSFRD) of the Universe itself peaks, representing a vital stage in galaxy formation and evolution (see, for example, reviews from Madau and Dickinson 2014, and Casey et al. 2014).

However, a complete understanding of the nature of the SMG population remains illusive, particularly for those at  $z > 4$ , where small and inhomogeneously selected samples, as well as a lack of spectroscopic confirmations, hinders further progress. The *Herschel Space Observatory* provides a simple but powerful method of selecting candidate  $z > 4$  DSFGs based on their colours in the  $250\mu\text{m}$ ,  $350\mu\text{m}$  and  $500\mu\text{m}$  bands of the SPIRE instrument. Sources with a rising SED in these three *Herschel* SPIRE bands, known as  $500\mu\text{m}$  risers, must have had the peak of their dust component shifted to wavelengths greater than  $\sim 500\mu\text{m}$ , making them natural  $z > 4$  DSFG candidates (Dowell et al., 2014; Asboth et al., 2016; Ivison et al., 2016). Based on these selection criterion, *Herschel* discovered many more extremely luminous, candidate  $z > 4$  DSFGs than expected ( $3.3 \pm 0.8 \text{ deg}^{-2}$ ), numerous examples of which have subsequently been confirmed as high redshift sources (e.g. Cox et al., 2011; Riechers et al., 2013, 2017, 2021; Fudamoto et al., 2017). These systems are found to be extreme examples of the DSFG population, typically with FIR luminosities  $> 10^{13} L_{\odot}$  and corresponding star formation rates in excess of  $1000 M_{\odot} \text{ yr}^{-1}$ , potentially lying at the high luminosity end of a more significant population of DSFGs at these redshifts (Greenslade et al., 2020).

It remains challenging to place these extreme DSFGs within the context of our current understanding of galaxy formation and evolution, particularly as theoretical models and simulations have significant difficulties in reproducing this population whilst simultaneously satisfying other observational constraints. These studies typically attempt to recover the observed SMG number counts by combining hydrodynamic simulations or semi-analytic models (SAMs) with appropriate dust radiative transfer models to predict the sub-mm flux densities of the SMG population.

Early attempts at this kind of analysis were typically based on SAMs with simple radiative transfer calculations or empirical galaxy SED templates, but these studies underestimated the true SMG number counts by as much as  $\sim 20 - 30$  times (Granato et al., 2000; Fontanot et al., 2007; Somerville et al., 2012). Other studies, have been more successful in recreating the observed number counts of sub-mm bright galaxies, but either incorrectly predict, or are unable to predict, the observed properties of the SMG population, such as SFR, redshift distribution, stellar mass function or multi-wavelength photometry (see e.g. Granato et al., 2004; Baugh et al., 2005; Davé et al., 2010; Shimizu et al., 2012). Alternatively, zoom-in simulations of individual systems, such as those performed by Narayanan et al. (2015), can provide valuable insights into the detailed processes that produce the observed SMGs, but cannot be used to recover the observed population density. More recent attempts have been made using large-volume cosmological hydrodynamic simulations such as **EAGLE** (Schaye et al., 2015; Crain et al., 2015), **IllustrisTNG** (Pillepich et al., 2018; Marinacci et al., 2018; Naiman et al., 2018; Nelson et al., 2018; Springel et al., 2018; Nelson et al., 2019; Pillepich et al., 2019) and **SIMBA** (Davé et al., 2019), but these simulations still have difficulty in recreating the observed number counts of SMGs. McAlpine et al. (2019) use mock sub-mm flux densities estimated based on a radiative transfer model applied to the **EAGLE** simulations to reproduce the observed sub-mm population finding that, while they can recover many of the main properties of the population, they significantly underestimate the observed number counts of SMGs brighter than 3 mJy at  $850\mu\text{m}$  (Wang et al., 2019; Cowley et al., 2019). Lovell et al. (2021) provide a similar analysis of the **SIMBA** simulations, finding that their SMG number counts are more realistic, but still underestimate the observed counts by up to a factor of 10, while Hayward et al. (2021) find that the **IllustrisTNG** simulations underpredict the observed SMG number counts by more than 1 dex for SMGs with  $S_{850\mu\text{m}} \gtrsim 4\text{ mJy}$ .

While accumulating observations of these  $500\mu\text{m}$  riser sources will be a significant step in constraining our current theories of galaxy formation and evolution, there remain gaps in our observational understanding. Very few studies have focused on investigating the nature of significant samples of  $500\mu\text{m}$  risers and, as such, the majority of their properties remain poorly constrained. As well as selecting intrinsically red, extremely luminous, high redshift DSFGs,

the  $500\mu\text{m}$  riser criterion is expected to pick out some fraction of multiple systems at more moderate redshifts ( $z \sim 2$ ), with *Herschel* SPIRE colours artificially reddened by the effects of blending. The *Herschel* SPIRE beam increases in size across the  $250\mu\text{m}$ ,  $350\mu\text{m}$  and  $500\mu\text{m}$  bands (to  $17.6''$ ,  $23.9''$  and  $35.2''$  respectively<sup>1</sup>), and so any multiple systems will be more effectively blended at longer wavelengths. For example, Ma et al. (2019) and Montaña et al. (2021) estimate that  $\sim 20\%$  and  $\sim 25\%$  of their samples of  $500\mu\text{m}$  risers respectively would not pass the  $500\mu\text{m}$  riser selection criterion after accounting for the effects of blending. Moreover, Montaña et al. (2021) find that the photometric redshift distribution of  $500\mu\text{m}$  risers that resolve into multiple components in higher resolution imaging is skewed towards lower redshifts ( $z_{\text{med}} = 3.5$  vs.  $z_{\text{med}} = 3.8$ ), with a higher fraction lying at lower redshifts ( $27\%$  at  $z_{\text{phot}} < 3$  vs.  $10\%$ ) compared to isolated systems.

The fraction of  $500\mu\text{m}$  risers that are comprised of multiple individual galaxies is still a topic of debate. Simulations suggest that  $\sim 40\%$  of faint ( $S_{500} < 60\text{ mJy}$ ) *Herschel* sources should be comprised of multiple DSFGs, while the brightest should be exclusively strongly lensed single galaxies (Béthermin et al., 2017). Additionally, some fraction of these multiple systems will be chance line-of-sight arrangements of DSFGs, rather than physically associated structures. Oteo et al. (2017) provide follow-up observations of a sample of 44  $500\mu\text{m}$  risers with the Atacama Large Millimeter Array (ALMA: Brown et al., 2004), finding that  $\sim 61\%$  resolve into a single sub-mm bright source, while the remainder break up into multiple DSFGs (four break up into  $\geq 3$  sources, with one resolving into five separate sources in the synthesised  $\sim 0.12''$  ALMA beam). Additionally, 18 of their sources show some evidence of gravitational lensing. Greenslade et al. (2020), selected a sample of thirty-four  $500\mu\text{m}$  risers from the *Herschel* Multi-tiered Extragalactic Survey (HerMES: Oliver et al., 2012), and carried out interferometric follow-up observations with the Submillimeter Array (SMA: Ho et al., 2004) between 2010 and 2015. They found that 4 break up into two individual sources and 18 resolve into a single source, with the remaining 12 maps containing no apparent SMA counterpart. Greenslade et al. (2020) suggested that non-detections were likely a result of the bright *Herschel* sources breaking up into multiple faint counterparts clustered within the *Herschel* SPIRE beamsizes ( $\sim 17.6''$  for

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<sup>1</sup><https://www.cosmos.esa.int/documents/12133/1035800/QUICK-START+GUIDE+TO+HERSCHEL-SPIRE>

the  $250\,\mu\text{m}$  band) but separated by distances greater than the SMA beamsize ( $\sim 2''$ ) and lying below its detection threshold, with simple flux calculations indicating that these multiple systems should contain  $\geq 3$  individual DSFGs. Based on this assumption, Greenslade et al. (2020) estimated that  $\sim 60\%$  of faint ( $S_{500} < 60\,\text{mJy}$ )  $500\,\mu\text{m}$  risers and  $\sim 35\%$  of bright ( $S_{500} > 60\,\text{mJy}$ )  $500\,\mu\text{m}$  risers should be blends, indicating that this population is likely much more diverse than predicted. Similarly, based on LMT/AzTEC  $1.1\,\text{mm}$  follow-up observations of their sample of bright *Herschel*  $500\,\mu\text{m}$  risers, Montaña et al. (2021) find that 45/93 have no counterpart in the higher resolution imaging, with some of these non detections expected to be multiple systems and others expected to be individual, resolved sources that are faint at  $1.1\,\text{mm}$  due to a large dust spectral emissivity index  $\beta$ . The multiplicity of their sample could therefore be  $\sim 9\%$  in the most conservative scenario, or  $\sim 50 - 60\%$  in the most extreme scenario. Any systems with high multiplicities would naturally be candidate high redshift protocluster cores containing numerous DSFGs, structures discovered in only a handful of studies to date (e.g. Miller et al., 2018; Oteo et al., 2018).

Therefore, before we are able to attempt to place these  $500\,\mu\text{m}$  risers within the context of our current models of galaxy formation and evolution, we must be able to more robustly determine the true multiplicity fractions for the population, and a key step in this process will be determining the nature of those  $500\,\mu\text{m}$  risers without apparent counterparts in higher resolution, interferometric observations. Are these systems with extremely high multiplicities, such as the high redshift protocluster cores discovered by Miller et al. (2018) and Oteo et al. (2018)? Or are they instead faint in the available sub-mm observations due to some inherent property of the sources themselves, or alternatively some observational effect? In order to address these questions, we aimed to build on the work of Greenslade et al. (2020), targeting four of their  $500\,\mu\text{m}$  risers without an apparent SMA counterpart for additional, deeper FIR/sub-mm observations. Given the significant improvements to the SMA since 2015 (particularly in terms of the improved bandwidth provided by the SWARM correlator), we were able to obtain much deeper, high-resolution SMA  $345\,\text{GHz}$  continuum imaging of these  $500\,\mu\text{m}$  risers. We additionally obtained complementary observations at  $850\,\mu\text{m}$  with the SCUBA-2 instrument on JCMT, which provided an integrated flux density with a coarser resolution at a similar

wavelength.

In Section 3.2 we describe the selection of the  $500\mu\text{m}$  riser sample, followed by a discussion of the observations and data reduction in Section 3.3. The resulting multi-wavelength photometry is discussed in detail in Section 3.4 and in Section 3.5 we estimate properties for the sources in our sample. In Section 3.6 we use the SCUBA-2 observations to investigate the environments in which our  $500\mu\text{m}$  risers are placed, before providing a discussion and the conclusions of our results in Sections 3.7 and 3.8. Throughout this work, we adopt the standard flat  $\Lambda\text{CDM}$  cosmology:  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ , and  $H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$ .

## 3.2 Sample Selection

This work focuses on a small sub-sample of  $500\mu\text{m}$  risers from the larger sample assembled by Greenslade et al. (2020) based on *Herschel* SPIRE flux densities and colours from the *Herschel* Multi-Tiered Extragalactic Survey (HerMES: Oliver et al., 2012). Their sample includes 34 bright *Herschel* sources, all of which are detected to  $> 4\sigma$ , with  $S_{250} < S_{350} < S_{500}$  and  $500\mu\text{m}$  flux densities in the range  $27\text{ mJy} < S_{500} < 160\text{ mJy}$ . They extract positions and flux densities for their *Herschel* sources from the HerMES DR4 maps based on the method outlined in Wang et al. (2014). This method makes use of two separate algorithms, which are discussed briefly below.

In order to build a catalogue of source positions in each *Herschel* SPIRE band, sources are first detected using the **STARFINDER** algorithm, an IDL-based iterative source finding and fitting program optimised for crowded stellar fields (Diolaiti et al., 2000). **STARFINDER** iteratively searches for local maxima above a defined signal-to-noise threshold (after subtracting those that had already been identified in previous iterations), cross-correlates each detected source with a Gaussian point response function with a FWHM matching the beamsize of the *Herschel* SPIRE instrument in the given band, and adds sources with correlation coefficients larger than a given threshold to a list of accepted sources (Wang et al., 2014). **STARFINDER** then iteratively repeats this process with successively lower signal-to-noise thresholds.

Based on accurate positions from **STARFINDER**, photometry was then extracted using the **DESPHOT** algorithm developed for the second HerMES data release (Roseboom et al., 2010, 2012; Wang et al., 2014) which, unlike **STARFINDER**, is optimised for images in which the background noise is confusion-dominated. The **DESPHOT** algorithm first splits the *Herschel* SPIRE map into ‘segments’ based on regions in which all neighbouring pixel values are above a defined signal-to-noise threshold, before extracting photometry for each source based on the assumption that the distribution of pixel values in the map can be described as the sum of the flux densities of each source multiplied by a Gaussian point response function, plus a fixed background value and an unknown noise term (Wang et al., 2014). The non-negative, weighted **LASSO** algorithm (Tibshirani, 2011; Zou, 2006; Braak et al., 2010; Roseboom et al., 2012) is used to find the maximum likelihood solution, which imposes the condition that all flux densities must be positive and iteratively finds the flux density of each individual source that reduces the overall  $\chi^2$  value of the map the most whilst maintaining a good solution to the other sources in the map (Wang et al., 2014). The fixed background level is estimated by subtracting the resulting flux density model from the SPIRE map, and the confusion noise is estimated based on the standard deviation of the pixel intensities in the residual map (Wang et al., 2014).

It is worth noting that there have been numerous refinements to the *Herschel* SPIRE data reduction process in more recent data releases such that the flux densities of the sources in the sample vary somewhat in the most up-to-date maps and catalogues. Greenslade et al. (2020) find that 7 of their  $500\,\mu\text{m}$  risers can no longer be strictly classed as such based on these revised flux density estimates, but keep them in the sample as literature results suggest that there can be significant contamination of the  $500\,\mu\text{m}$  riser sample based on flux boosting, particularly for those sources with  $S_{500} \sim S_{350}$  (B  thermin et al., 2017; Donevski et al., 2018), and typical star-forming SED shapes suggest that these sources may still lie at high redshifts.

Greenslade et al. (2020) then carried out interferometric follow-up observations on their sample of  $500\,\mu\text{m}$  risers with the SMA. These observations were taken between 2010 and 2015 using various configurations (typically Compact, but SubCompact, Extended and Very Extended configurations were also used), numbers of antennas (between 6 – 8), frequencies (typically either  $\sim 265\,\text{GHz}$  or  $\sim 345\,\text{GHz}$ ) and under a range of weather conditions (with median opac-

ities between  $0.03 - 0.13$ ). The observing strategies also varied somewhat, with a mixture of full tracks, partial tracks and track sharing resulting in different sampling of the  $uv$  plane (Greenslade et al., 2020). The SMA observations were reduced using the standard IDL-based reduction package **MIR**<sup>2</sup> and imaged using the data analysis package **MIRIAD** (Sault et al., 2011). The SMA reduction and source extraction process will be discussed in more detail in Section 3.3. Based on the ALESS (da Cunha et al., 2015) average SED redshifted to  $z \sim 4 - 6$  and normalised to  $S_{500} = 60$  mJy, Greenslade et al. (2020) estimated that, assuming a single source is responsible for the entirety of the *Herschel* SPIRE flux density, their  $500\mu\text{m}$  risers should have flux densities of  $\sim 24 - 38$  mJy at 345 GHz. However, despite reaching detection thresholds of  $\sim 7 - 10$  mJy, twelve of their SMA maps showed no detections. Greenslade et al. (2020) suggested that non-detections were likely a result of the bright *Herschel* sources breaking up into multiple faint counterparts clustered within the *Herschel* SPIRE beamsize ( $\sim 17.6''$  for the  $250\mu\text{m}$  band) and hence contributing to a large integrated FIR flux density, but separated by distances greater than the SMA beamsize ( $\sim 2''$ ) and lying below their detection threshold. Assuming in the most conservative case that any multiple systems are comprised of sources with similar flux densities, Greenslade et al. (2020) predicted that these  $500\mu\text{m}$  risers must break up into  $\geq 3$  individual sources, and are therefore potential indications of forming compact cluster cores at  $z > 4$  similar to those discovered by Oteo et al. (2018) and Miller et al. (2018). In order to investigate these non-detections in more detail, we targeted the three brightest sources at  $500\mu\text{m}$  from the Greenslade et al. (2020) sample without SMA counterparts for deeper FIR/sub-mm follow-up observations, all of which lie within the Bootes field (Bootes15, Bootes24 and Bootes27). Additionally, a fourth  $500\mu\text{m}$  riser, XMM-M5, which was also undetected in the SMA observations of Greenslade et al. (2020), was observed as part of a separate SMA project (2019A-S004, PI: D. L. Clements) and is also presented in this work. Positions and *Herschel* SPIRE photometry for our sources are presented in Table 3.1, and in Figure 3.1 we show their *Herschel* SPIRE colours. We infer from these properties that our four  $500\mu\text{m}$  risers are reasonably typical of the global  $500\mu\text{m}$  riser population, although potentially lying towards the less extreme end.

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<sup>2</sup><https://github.com/qi-molecules/sma-mir>



| Source   | RA<br>J2000 | Dec<br>J2000 | $S_{250\mu m}$<br>mJy | $S_{350\mu m}$<br>mJy | $S_{500\mu m}$<br>mJy |
|----------|-------------|--------------|-----------------------|-----------------------|-----------------------|
| Bootes15 | 14:40:09.66 | +34:37:55.70 | $51.2 \pm 6.0$        | $68.3 \pm 7.0$        | $66.1 \pm 8.0$        |
| Bootes24 | 14:36:21.30 | +33:02:29.00 | $28.7 \pm 6.0$        | $49.7 \pm 7.0$        | $55.8 \pm 8.0$        |
| Bootes27 | 14:38:45.14 | +33:22:31.80 | $37.8 \pm 6.0$        | $44.2 \pm 7.0$        | $52.2 \pm 8.0$        |
| XMM-M5   | 02:18:56.74 | −04:35:44.90 | $26.6 \pm 6.0$        | $44.0 \pm 7.0$        | $46.1 \pm 8.0$        |

Table 3.1: Positions and *Herschel* SPIRE flux densities (taken from Greenslade et al., 2020) for the four  $500\mu m$  risers.

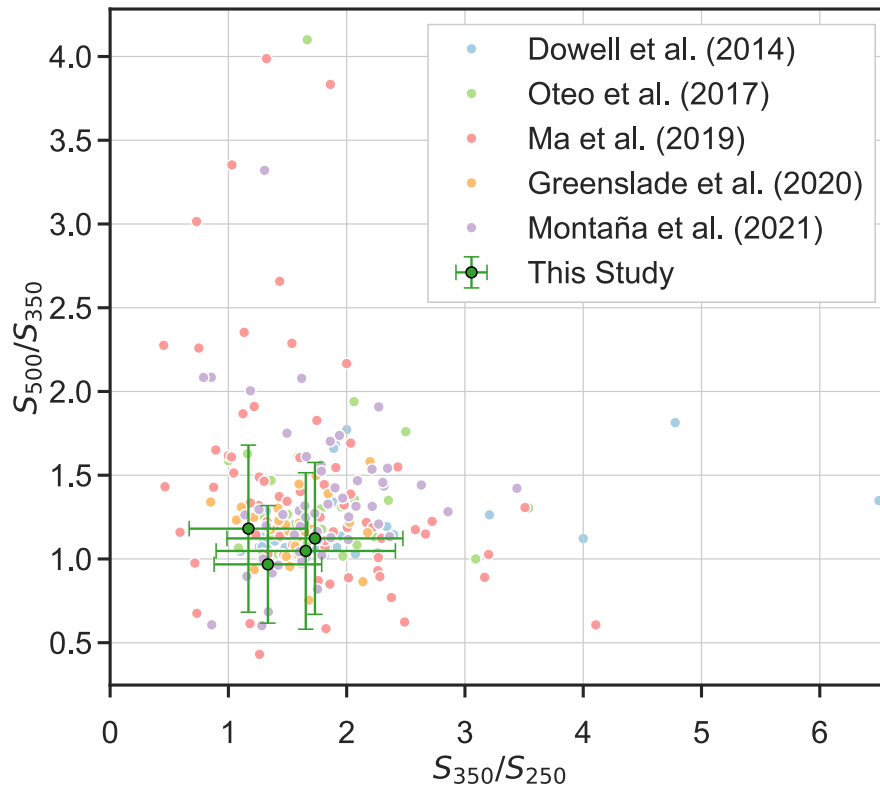


Figure 3.1: *Herschel* SPIRE colours for our  $500\mu m$  risers alongside those from a selection of studies in the literature. Note that the Ma et al. (2019) and Montaña et al. (2021) colours are based on deblended *Herschel* photometry using high resolution follow-up observations and so contain a number of sources that are no longer strictly  $500\mu m$  risers. We find that our  $500\mu m$  risers are towards the less extreme end of the global  $500\mu m$  riser population.

### 3.3 Observations and Data Reduction

In this section, we present the observing strategy and data reduction process for our deep FIR/sub-mm observations with the SMA and the SCUBA-2 instrument on the James Clerk Maxwell Telescope (JCMT).

### 3.3.1 SMA Observations

The SMA observations were taken in three tracks between 31<sup>st</sup> January and 26<sup>th</sup> February 2020 as part of the SMA program 2019B-S016 (PI: J. Cairns), with total integration times of 10.9 hours on Bootes15, 4.6 hours on Bootes24 and 3.6 hours on Bootes27. These integration times are an improvement over the follow-up observations of Greenslade et al. (2020), who targeted these sources for 3.9 hours, 3.7 hours and 2.2 hours, and they compare favourably to the average integration time of 4.1 hours across the Greenslade et al. (2020) follow-up observations. The conditions for these observations were exquisite, with  $\tau$  values of  $\sim 0.02 - 0.04$ . We used the SMA in its Compact configuration with 7 antennas. At the time the observations were taken the SMA used two receivers (referred to as RxA and RxB respectively), each with a total bandwidth of 16 GHz split between two 8 GHz bandwidth sidebands separated by an 8 GHz gap. Each of the four 8 GHz sidebands was further comprised of four spectral chunks, labelled **s1–s4**. We configured the observations such that the **s1** spectral chunk of the lower sideband (LSB) was tuned to 337 GHz and 345 GHz for each receiver respectively. This configuration produced 32 GHz of continuous bandwidth with a central frequency of 345 GHz, and resulted in a  $\approx 1.7'' \times 2.1''$  elliptical beam. At 345 GHz, the primary beam of the SMA can be described as a Gaussian function with a FWHM of  $0.53'$ .

We reduced our SMA maps using the standard IDL-based SMA data reduction package **MIR**. We firstly completed a manual inspection of the data, flagging any regions that contained phase jumps and fixing any channels that showed significant noise spikes, as well as the  $\approx 300$  channels on the edge of each chunk to maintain data quality. We then applied the system temperature correction, before a second manual inspection to ensure that the amplitude values were reasonable. The passband calibration aims to ensure that there are no variations in phase or amplitude with frequency. We used a number of standard quasars for this step, including 3c454.3, 3c279, 0927+390 or 3c84. Gain calibration on the SMA is carried out by periodically observing a bright quasar with a known flux density alternately to the target source in order to ensure there are no variations in phase or amplitude with time. For this process, we used the quasars 1506+426 and 3c345. Finally, flux calibration sets the flux density value, typically

based on a Solar System object (or quasar) with a well-characterised flux density, for which we used either 0854+201 or Callisto. The error for this calibration process is estimated to be  $\sim 10\%$  (see e.g. Liu et al., 2018).

Following the calibration process, we used the Common Astronomy Software Applications package<sup>3</sup> (CASA: McMullin et al., 2007) to complete the imaging of our SMA observations. Each chunk of each sideband on each receiver was individually exported into CASA before being concatenated together to produce one large visibility dataset. Following the calibration process, we ensured that the  $\approx 300$  channels on the edge of each chunk were flagged in order to avoid including poor data in the final image, and we inspected the result to ensure that we had flagged enough of the edge channels and that there were no spikes or strong lines in the data. We generated the continuum image by averaging all of the remaining spectral channels together.

In order to clean the SMA maps, we identified the positions of likely sources based on the dirty maps. We first identified a detection threshold for each of our SMA maps following the method of Greenslade et al. (2020). For each map we generated 1,000 fake noise maps with the same dimensions containing Gaussian random noise. Each of these maps was then convolved with the SMA beam for that observation and scaled to match the noise characteristics of the real SMA map. We extracted sources from each of these fake noise maps based on a range of signal-to-noise thresholds from 2 to 5 in steps of 0.05, considering as detections any source with a peak pixel value greater than the given signal-to-noise threshold, with any other surrounding pixels within the SMA beamsize meeting the signal-to-noise criteria considered part of the same source. For each signal-to-noise threshold value, we averaged the number of fake sources extracted across the 1,000 realisations. The optimal signal-to-noise threshold will be low enough to allow us to extract sources deep into the SMA maps, but high enough to minimise the number of fake sources extracted from the fake noise maps. Following Greenslade et al. (2020), we selected a signal-to-noise cut-off corresponding to an average of 0.1 extracted fake sources across all 1,000 realisations, yielding a detection threshold of  $4.1\sigma$  for the three maps in the Bootes field, slightly higher than the average value of  $3.75\sigma$  found for the Greenslade et al. (2020) observations.

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<sup>3</sup><https://casa.nrao.edu/index.shtml>

We therefore found all sources above this  $4.1\sigma$  detection threshold in the dirty maps and considered them to be real sources. We used the CASA task `tclean` to complete interactive CLEANing of the SMA maps. Given the much smaller beamsize of the SMA observations compared to the *Herschel* SPIRE observations, we expect the individual SMA detections to be well resolved, and hence we select natural weighting which maximises the signal-to-noise. We used less than a hundred CLEAN iterations for each map, placing CLEAN windows in the images to preferentially select flux from the positions of the  $> 4.1\sigma$  detections. The resulting CLEANed maps reached  $1\sigma$  rms values of 0.17, 0.29 and 0.27 mJy/beam for Bootes15, Bootes24 and Bootes27 respectively, around an order of magnitude deeper than the maps obtained by Greenslade et al. (2020).

As discussed in Section 3.2, XMM-M5 was observed separately as part of the SMA project 2019A-S004 (PI: D. L. Clements). As such, the details of the observations differ slightly from those of the three sources in the Bootes field. While the SMA was similarly used in Compact configuration, the two receivers were instead tuned to 198 GHz and 206 GHz respectively, resulting in a beamsize of  $\approx 3.6'' \times 3.2''$ . The resulting observations were reduced using a similar process to our three  $500\mu\text{m}$  risers in the Bootes field, resulting in a  $1\sigma$  rms sensitivity of  $\sim 0.28$  mJy/beam. In Figure 3.2, we present both the dirty and CLEANed SMA maps, as well as the beamshape of the observations.

We then test the completeness of our SMA maps. For each SMA map, we insert five fake sources with a given peak flux density value into the dirty map at random positions, where each fake source is based on a Gaussian kernel matching the beamshape of the observations as defined in the header information. We then determine how many of these fake sources are recovered when we extract sources from the dirty map based on the defined detection threshold. We complete 1,000 iterations of this process for each peak flux density value of the inserted fake sources, ranging from 0 mJy to 2.5 mJy in steps of 0.1 mJy. The final completeness value for each map and peak flux density value is simply the median of the completeness distribution from the 1,000 runs.

In Figure 3.3, we present the result of these completeness calculations for each of our four

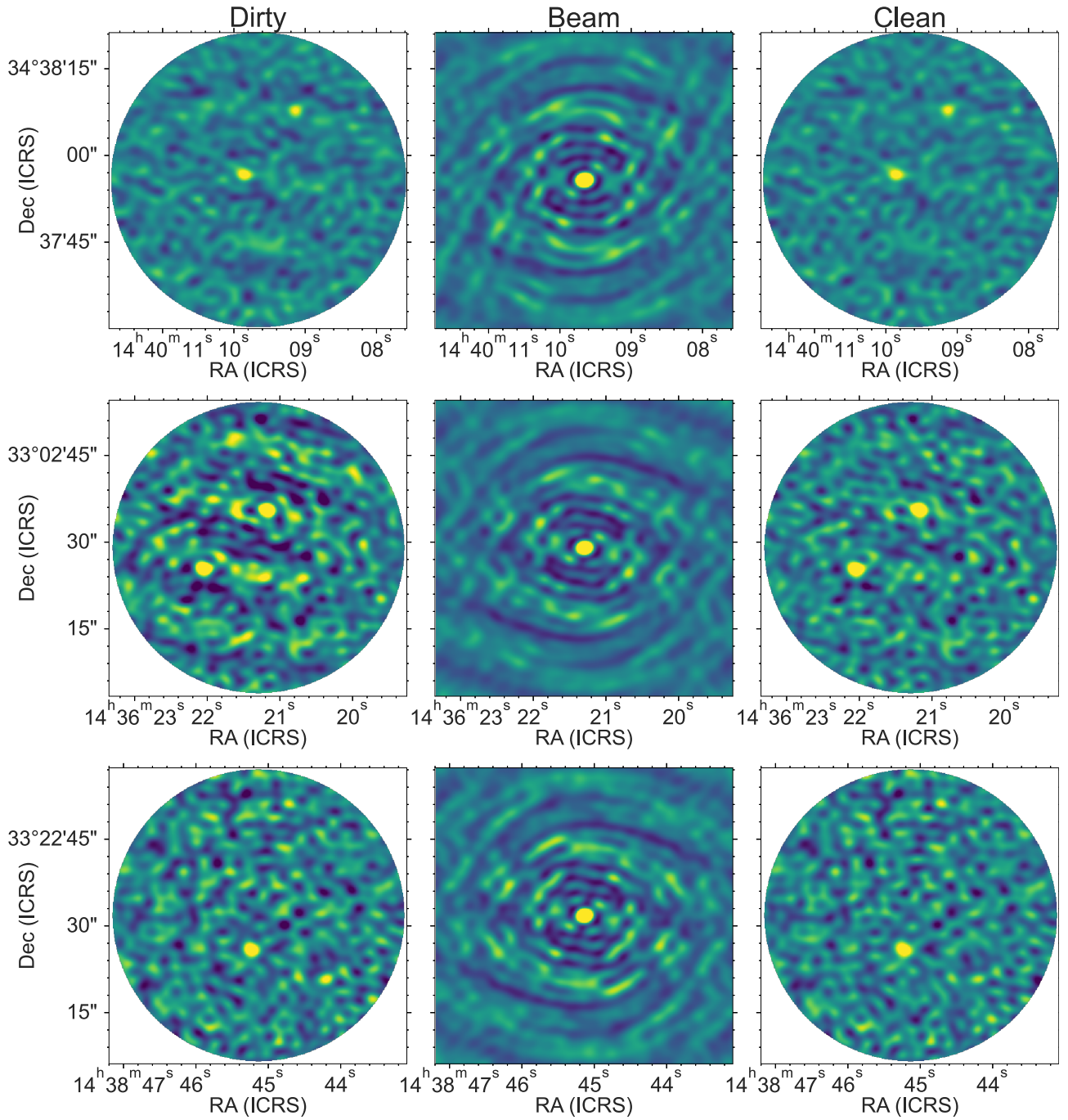


Figure 3.2: The dirty (*left*) and CLEANed (*right*) SMA maps for our 500  $\mu\text{m}$  risers, as well as the beamshape of the observations (*middle*). All extracted sources are well detected in both the dirty and CLEANed SMA maps, excluding the fainter detection associated with Bootes27, which is only marginally detected in the CLEANed SMA map.

targets. We find that Bootes15 performs significantly better than the other maps, reaching 100% completeness for sources with flux densities  $\geq 1.1$  mJy. Bootes24 and Bootes27 reach a completeness of 50% at 1.6 mJy and 1.2 mJy, 80% at 1.9 mJy and 1.4 mJy and up to 100% at 2 mJy and 1.7 mJy respectively. XMM-M5 reaches 50% completeness at 1.3 mJy, but does not

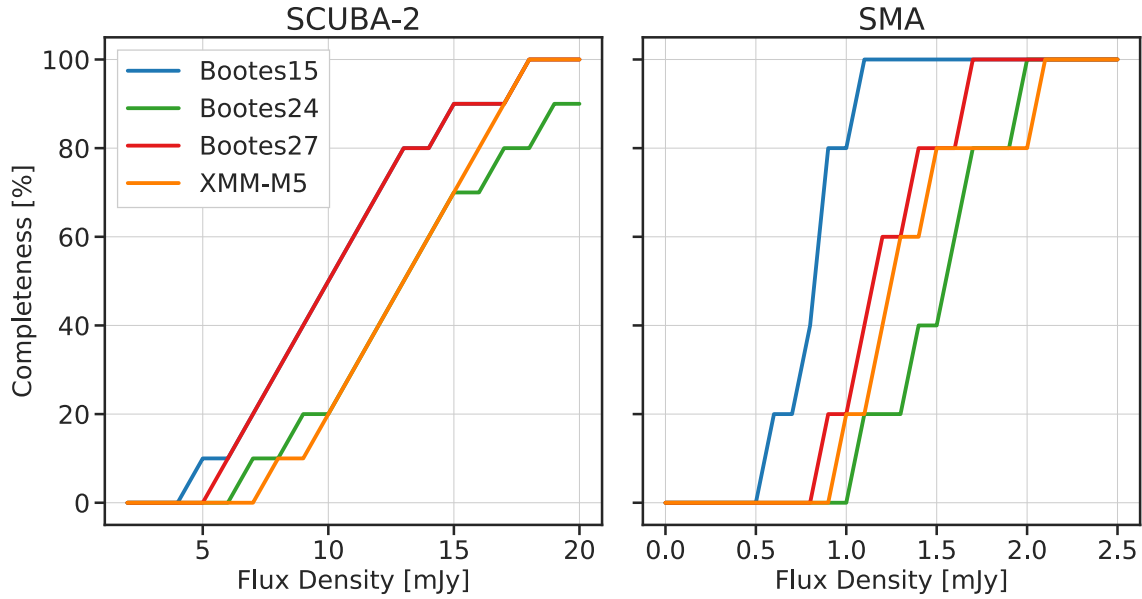


Figure 3.3: The completeness estimates for the SCUBA-2 maps (*left*) and SMA maps (*right*) associated with our four  $500\mu\text{m}$  risers. We find that in the SCUBA-2 maps, Bootes15 and Bootes27 reach a completeness of  $\sim 50\%$  at 10 mJy, and rise to a completeness of  $\sim 80\%$  at 14 mJy. Bootes24 and XMM-M5 reach a  $\sim 80\%$  completeness at 17 mJy and 16 mJy respectively. For the SMA maps, Bootes15 reaches 80% completeness at 1 mJy and 100% at 1.1 mJy. Bootes24 and Bootes27 reach 80% completeness at 1.7 mJy and 1.4 mJy respectively, while XMM-M5 reaches 80% completeness at 2 mJy.

reach 100% completeness until 2.1 mJy.

### 3.3.2 SCUBA-2 Observations

#### Reduction and Calibration

The JCMT/SCUBA-2  $450\mu\text{m}$  and  $850\mu\text{m}$  observations for Bootes15, Bootes24 and Bootes27 were taken between 1<sup>st</sup> December 2020 and 20<sup>th</sup> January 2021 as part of the SCUBA-2 program M20BP036 (PI: J. Cairns). For these observations we used the CV Daisy mode with numerous pointings on each source, resulting in a total on-source time of 2.7 hours on Bootes15, 1.4 hours on Bootes24 and 4.1 hours on Bootes27. The weather conditions for the observations were reasonably good, with  $\tau_{225}$  values in the range 0.08 – 0.14, resulting in  $1\sigma$  rms sensitivities of 2.2, 2.8 and 1.7 mJy/beam in our SCUBA-2  $850\mu\text{m}$  maps of Bootes15, Bootes24 and Bootes27 respectively. We completed three separate reductions of the SCUBA-2 data, with each reduction based on standard methods using either the Sub-Millimetre User Reduction Facility (SMURF)

package (Chapin et al., 2013) or the **ORAC-DR** data reduction pipeline (Economou et al., 1999).

For the first method, we reduced the SCUBA-2 data manually, based on the process discussed in Cheng et al. (2019). We first used the **MAKEMAP** command on the individual scans from SCUBA-2, with the **METHOD** parameter set to the default **ITERATE** method, which uses an iterative technique to fit a number of models for noise and instrumental behaviour. We then used the **PICARD** recipe **MOSAIC\_JCMT\_IMAGES**, which co-adds the individual scans to produce a single map, as well as removing a number of contaminant signals. For this first reduction, we assumed that the individual sources detected in the SMA images would be contained within the much larger SCUBA-2 beam, such that each of the  $500\ \mu\text{m}$  risers would appear as a single, point-like source comprised of the unresolved SMA sources. We applied therefore a matched filter using the **PICARD** recipe **SCUBA2\_MATCHED\_FILTER**, which subtracts the background by convolving the maps and the PSF with a  $30''$  FWHM Gaussian kernel, before convolving the maps with the PSF to produce the matched-filtered signal map. This process gives an effective beam FWHM of  $14.6''$  surrounded by a shallow negative ring. The signal maps produced using this method are in units of pW, and so must be calibrated using a Flux Correction Factor (FCF). We used the standard FCF value<sup>4</sup> of  $537 \pm 43\ \text{Jy beam}^{-1}\ \text{pW}^{-1}$ .

For the second data reduction method, we made use of the **ORAC-DR** data reduction pipeline. We used the **REDUCE\_SCAN\_FAINT\_POINT\_SOURCES** recipe which employs a similar method to our manual data reduction process above. Each of the individual, uncalibrated scans are passed to the map maker to produce scans calibrated in mJy/beam. The pipeline then estimates the rms noise in each image, as well as the Noise Equivalent Flux Density (NEFD). Once all the individual observations have been processed, the pipeline co-adds scans together, which it then similarly convolves with a matched filter to enhance the signal-to-noise ratio of point sources. The rms noise and NEFD are calculated for this co-added image, and a signal-to-noise map is produced. As expected, we find that the pipeline produces essentially identical results to our manual data reduction.

For the final data reduction, we again make use of the **ORAC-DR** pipeline, but this time using the

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<sup>4</sup><https://www.eaobservatory.org/jcmt/instrumentation/continuum/scuba-2/calibration/>



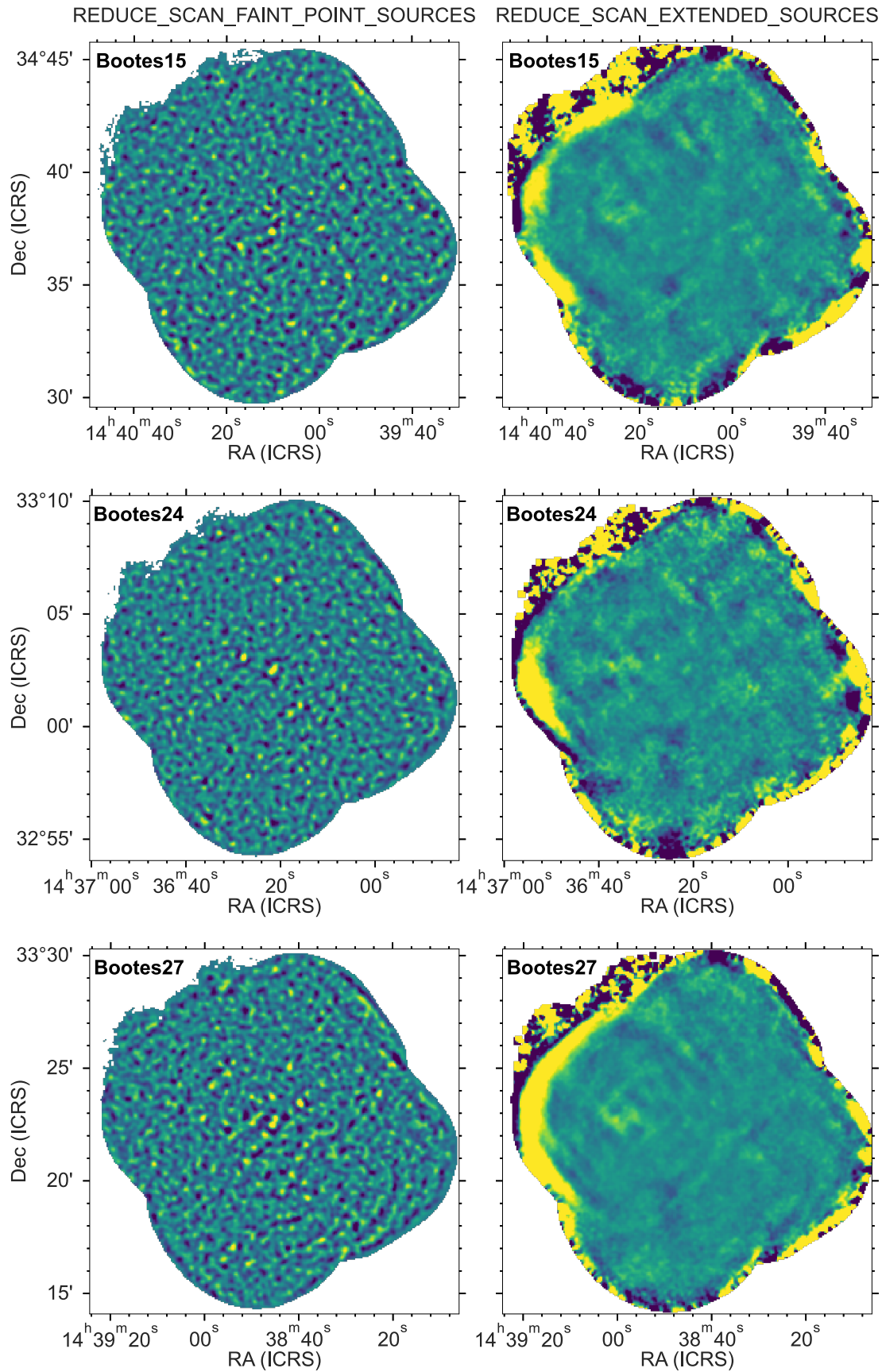


Figure 3.4: Reduced SCUBA-2  $850\mu\text{m}$  maps for our  $500\mu\text{m}$  risers based on the `REDUCED_SCAN_FAINT_POINT_SOURCES` recipe (*left*) and the `REDUCED_SCAN_EXTENDED_SOURCES` recipe (*right*). In order to aid visualisation, the extended source maps are slightly smoothed.



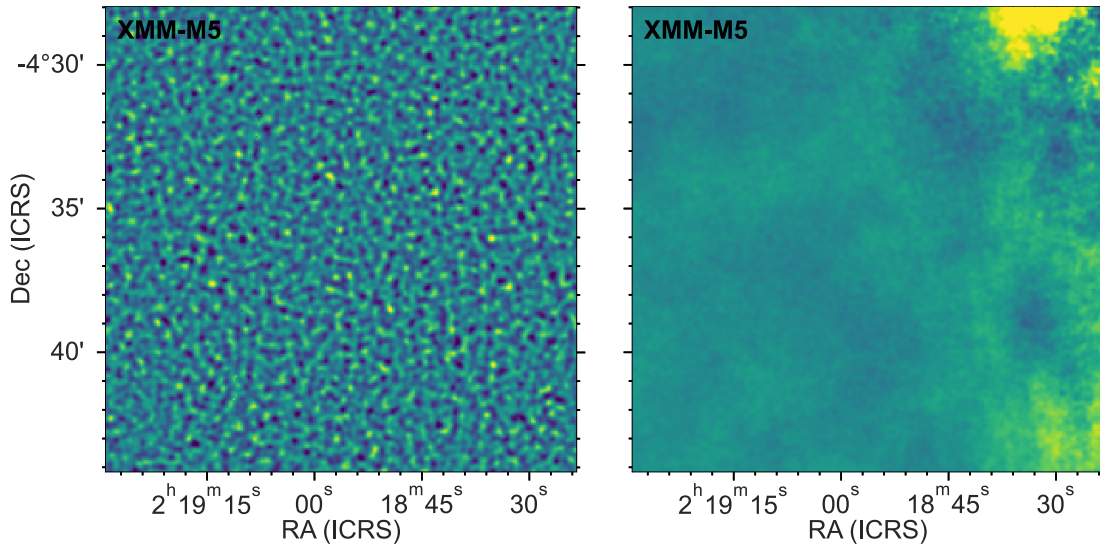


Figure 3.4: Continued.

`REDUCE_SCAN_EXTENDED_SOURCES` recipe. Given the intermediate beamsizes of SCUBA-2 which is larger than that of the SMA but smaller than that of *Herschel* SPIRE, any  $500\,\mu\text{m}$  risers that are multiple systems could feasibly be partially resolved in the resulting SCUBA-2 maps. If this were the case, then observations with the matched filter could miss significant amounts of flux lying outside of the SCUBA-2 beam and hence underestimate the true flux density of the system. Flux density estimates should instead be calculated based on SCUBA-2 maps reduced without the matched filter in these cases. The `REDUCE_SCAN_EXTENDED_SOURCES` recipe similarly passes the individual, uncalibrated scans to the map maker, but this time the scans are calibrated in units of  $\text{mJy/arcsec}^2$ . Individual scans are then similarly co-added together and the noise properties of this image are calculated.

In the following analysis, we focus on the SCUBA-2 maps produced by the two pipeline reductions. We note that, while the SCUBA-2 instrument simultaneously provides  $450\,\mu\text{m}$  and  $850\,\mu\text{m}$  photometry, the noise levels in the  $450\,\mu\text{m}$  maps are too large to detect our  $500\,\mu\text{m}$  risers based on their *Herschel* SPIRE flux densities.

We additionally used archival  $850\,\mu\text{m}$  SCUBA-2 maps for XMM-M5 from the Canadian Astronomy Data Center<sup>5</sup>. XMM-M5 was observed as part of the SCUBA-2 Large eXtragalactic Survey (S2LXS<sup>6</sup>: Geach et al. M17BL001) and is located within two overlapping pointings. We

<sup>5</sup><https://www.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/en/>

<sup>6</sup><https://www.eaobservatory.org/jcmt/science/large-programs/s2lxs/>

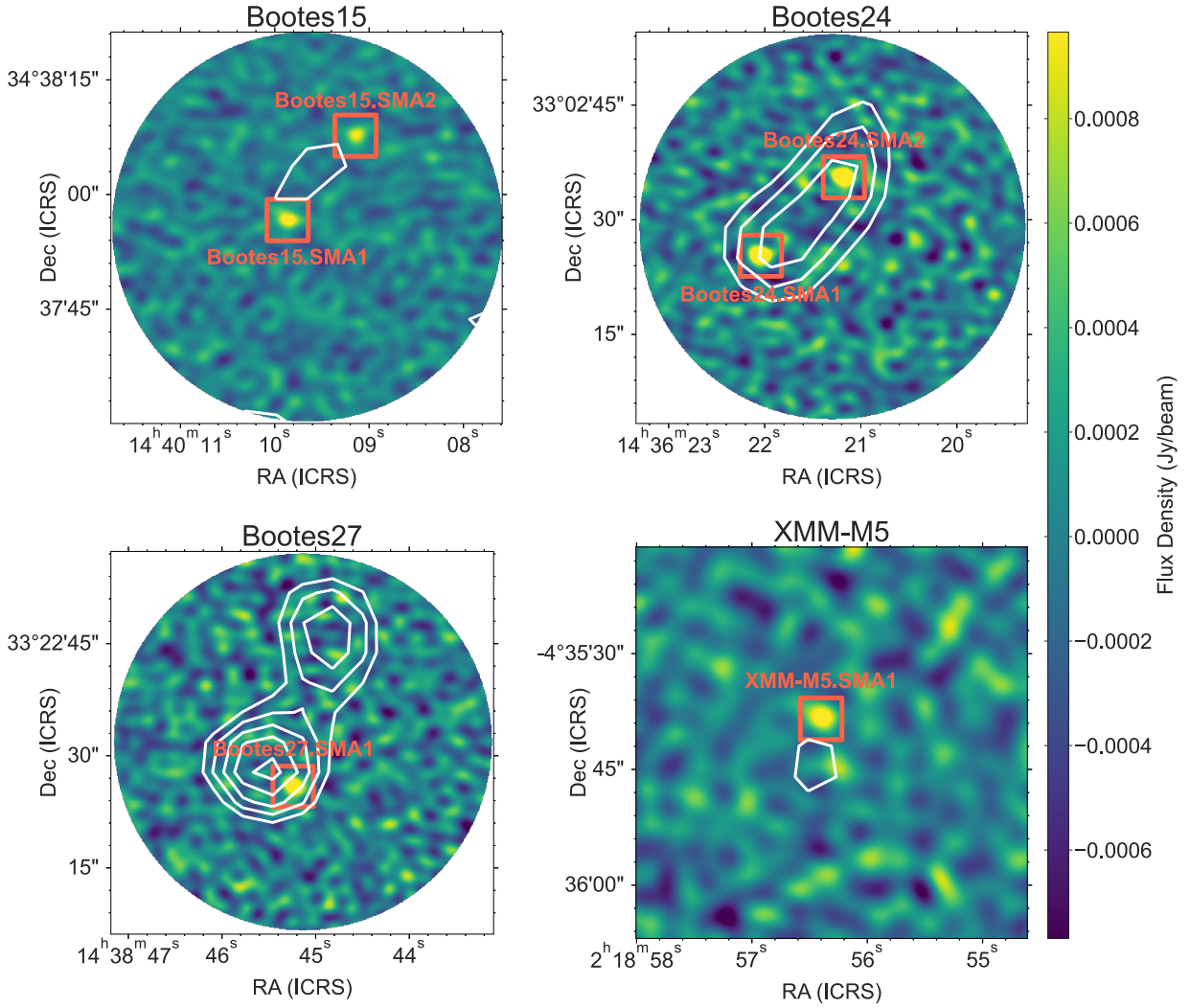


Figure 3.5: SMA maps overlaid with SCUBA-2  $850\mu\text{m}$  contours from  $3\sigma$  to  $7\sigma$  significance for the four  $500\mu\text{m}$  risers. Bootes15 and Bootes24 each break up into two individual sources in the SMA maps, while Bootes27 and XMM-M5 resolve into one faint source. Bootes24 and Bootes27 are well detected by SCUBA-2, while Bootes15 and XMM-M5 are marginally detected to  $\sim 3\sigma$  significance.

re-reduce each of these pointings using the two ORAC-DR pipeline reduction methods outlined above, and co-add the two pointings to obtain a deeper SCUBA-2  $850\mu\text{m}$  image of XMM-M5. This reduction process results in a  $1\sigma$  rms noise of  $\sim 3.3\text{ mJy/beam}$  within an aperture of radius  $350''$  centred on the SMA position of XMM-M5. In Figure 3.4, we show the reduced SCUBA-2 maps based on the two pipeline reductions.

In Figure 3.5 we show the SMA maps for the  $500\mu\text{m}$  risers with  $850\mu\text{m}$  contours based on the REDUCE\_SCAN\_FAINT\_POINT\_SOURCES reduced SCUBA-2 maps. The SCUBA-2 maps with the matched filter were chosen for Figure 3.5 as this reduction maximises the signal-to-noise ratio

in the map.

### False Detection Rates and Completeness

We calculate the reliability of our SCUBA-2 maps using two separate methods. The first method is predicated on the assumption that there are roughly equal numbers of positive and negative spurious peaks in the SCUBA-2 maps. Therefore, by simply inverting the map and finding the ratio of the number of negative  $\text{SNR} > 4$  spurious peaks to the number of positive  $\text{SNR} > 4$  peaks, we can make a simple estimate of how many positive sources we expect to be spurious. Based on this method, we find that the Bootes15 and XMM-M5 maps have reliabilities greater than  $\sim 80\%$  at  $4\sigma$  significance, similar to other analyses of this nature (MacKenzie et al., 2017; Cheng et al., 2019). By comparison, we are more likely to find spurious sources in the Bootes24 and Bootes27 fields, with reliabilities of  $\sim 60\%$  and  $\sim 50\%$  respectively. However, given that this method assumes that the noise across the SCUBA map is reasonably uniform with equal numbers of positive and negative spurious peaks, we propose that a more robust method of estimating the reliability would be to make use of ‘jackknife’ maps (e.g. Cheng et al., 2019; Simpson et al., 2019). We use the `MAKEMAP` command in the `SMURF` package to create a map for each scan on each  $500\mu\text{m}$  riser. For each region, we invert half of these scans before co-adding all scans together to produce a single map. This map should therefore have all signals from astronomical sources effectively removed, leaving a map containing just the instrumental noise. We then followed the reduction method outlined in Section 3.3.2, applying a matched filter and subsequently producing a signal-to-noise map for each region. Given that this map should contain only instrumental noise, any  $\text{SNR} > 4$  detections must be spurious, giving a more robust estimate of the false-detection rate. Based on these jackknife maps, we find that the SCUBA-2 maps for the Bootes15 and Bootes24 regions have 100% reliability at  $4\sigma$ , while Bootes27 and XMM-M5 have somewhat lower reliabilities of  $\approx 88\%$  and  $60\%$  respectively. We note that we calculated the reliabilities for various combinations of the available SCUBA-2 integrations in order to exclude scans with significantly higher RMS noise, with the aforementioned and following analysis applied to the combination of integrations that provides the highest reliability for each region.

As an independent estimate of the quality of our observations, we also calculate the completeness of the SCUBA-2 maps. For each of our SCUBA-2 maps, we inserted fake sources within the  $700''$  diameter circular region, where each fake source was defined as a simple 2D Gaussian with a random position, a given peak flux density and a width  $\sigma = 6.2''$  (corresponding to the FWHM of the SCUBA-2  $850\mu\text{m}$  beam). We then ran our source extraction method (which will be discussed in more detail in Section 3.3.4) on the map and identified how many fake sources had been recovered. For each run we calculate the completeness based on ten fake sources, all with the same flux density, and we repeated the process 1,000 times for each peak flux density value, starting from 2 mJy and increasing in steps of 1 mJy up to 20 mJy. The final completeness value for each source and peak flux density value is the median of the completeness distribution from the 1,000 runs. In Figure 3.3 we present the result of this completeness calculation for each of our four SCUBA-2 maps. We find that Bootes15 and Bootes27 both reach a completeness of  $\sim 50\%$  at  $\sim 10$  mJy, and rise to a completeness of  $\gtrsim 80\%$  at 14 mJy. Bootes24 and XMM-M5 have a poorer completeness, reaching  $\sim 80\%$  at  $\sim 17$  mJy and  $\sim 16$  mJy respectively.

### 3.3.3 Ancillary Data

In order to further investigate the properties of our  $500\mu\text{m}$  riser systems and their component galaxies, we made use of the available archival data at optical to MIR wavelengths. However, due to their position towards the edge of the Bootes field, Bootes15, Bootes24 and Bootes27 are only observed sporadically in the available ancillary data.

All three are covered by the DESI Legacy Imaging Surveys<sup>7</sup> which combines the Dark Energy Camera Legacy Survey, the Beijing–Arizona Sky Survey, and the Mayall  $z$ -band Legacy Survey, mapping  $\sim 14,000\text{ deg}^2$  of the sky using the Blanco telescope at the Cerro Tololo Inter-American Observatory, as well as the Mayall and 2.3m Bart Bok Telescopes at the KPNO down to AB magnitudes of 23.72, 22.87 and 22.29 in the  $g$ ,  $r$  and  $z$  bands respectively (Dey et al., 2019). The Infrared Bootes Imaging Survey (IBIS: Gonzalez et al., 2010) provides deep NIR images and catalogues in the  $J$ ,  $H$  and  $K_s$  bands, down to limiting AB magnitudes of 22.0,

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<sup>7</sup><http://legacysurvey.org/>

21.5, and 20.8 respectively, and we extract 3.4, 4.6, 12, and 22  $\mu\text{m}$  *Wide-Field Infrared Survey Explorer* (*WISE*: Wright et al., 2010) images and catalogues from the ALLWISE database, which combines the WISE cryogenic and NEOWISE (Mainzer et al., 2011) post-cryogenic phases.

Additionally, the *Spitzer* Deep Wide-Field Survey (SDWFS: Ashby et al., 2009) provides deep 3.6, 4.5, 5.8 and 8.0  $\mu\text{m}$  imaging for 10 deg<sup>2</sup> in the Bootes field. Bootes24 lies just within the footprint of SDWFS, although it only benefits from data at 4.5 and 8.0  $\mu\text{m}$ . For Bootes15 and Bootes27, we rely on archival IRAC imaging. Bootes15 is covered at 3.6 and 4.5  $\mu\text{m}$  as part of *Spitzer* Program 80156 (PI: A. Cooray) aiming to study lensed sub-mm galaxies from the *Herschel*-ATLAS (H-ATLAS: Eales et al., 2010) and HerMES surveys. Additionally, Bootes27 is covered at 4.5 and 8.0  $\mu\text{m}$  as part of *Spitzer* Program 30134 (PI: G. Fazio) aiming to study a statistically complete sample of star-forming dwarf galaxies.

By contrast, XMM-M5 benefits from a wealth of multi-wavelength data, including ‘forced photometry’ at optical and NIR wavelengths from Nyland et al. (2017). This includes photometry in the  $u$ ,  $g$ ,  $r$ ,  $i$  and  $z$  bands from the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS: Gwyn, 2012), in the  $Z$ ,  $Y$ ,  $J$ ,  $H$  and  $K_s$  bands from the VISTA Deep Extragalactic Observations (VIDEO: Jarvis et al., 2013) survey, and in the 3.6 and 4.5  $\mu\text{m}$  IRAC bands from the *Spitzer* Extragalactic Representative Volume Survey (SERVS: Mauduit et al., 2012). The reader is directed to Nyland et al. (2017) for a description of how this photometry was extracted. XMM-M5 is also included in the Subaru XMM Deep Survey (SXDS: Furusawa et al., 2008) which covers five broadband filters reaching limiting AB magnitudes of  $B = 28.4$ ,  $V = 27.8$ ,  $R_c = 27.7$ ,  $i' = 27.7$ , and  $z' = 26.6$ , as well as the Hyper Suprime-Cam Subaru Strategic Program (HSC SSP: Aihara et al., 2018a) Survey which, in its ‘Deep’ layer, reaches limiting AB magnitudes of 27.5, 27.1, 26.8, 26.3 and 25.3 in the  $g$ ,  $r$ ,  $i$ ,  $z$  and  $y$  bands respectively. A more comprehensive, multi-wavelength analysis of XMM-M5 will be presented in a separate paper (Clements et al. in prep), and hence will not be discussed further in this study.

### 3.3.4 Extracting Flux Densities

#### SMA

Greenslade et al. (2020) tested numerous methods for extracting photometry from SMA continuum observations. For the case of point-like SMA detections, they found that the most robust method for extracting flux densities is to simply take the peak flux density for each source from the CLEANed SMA maps. Given that each resolved source is well detected and point-like in the SMA maps of our  $500\mu\text{m}$  risers, we extract the peak flux density from the CLEANed SMA maps for each source identified with  $\text{SNR} > 4.1\sigma$  in the dirty SMA maps. The flux density of each detection was subsequently corrected for the primary beam response which, for the SMA, can be modelled as a simple Gaussian with a FWHM determined by the wavelength of the observations<sup>8</sup>, such that

$$\theta_{\text{FWHM}} \approx \frac{\lambda}{D} \quad (3.1)$$

where  $\theta_{\text{FWHM}}$  is the FWHM of the primary beam,  $\lambda$  is the central wavelength of the observations and  $D$  is the diameter of each SMA antenna. We use the MIRIAD task `pbplot` to determine  $\theta_{\text{FWHM}}$ , finding values of  $\theta_{\text{FWHM}} = 0.57'$  for the three  $500\mu\text{m}$  risers in the Bootes field observed at 345 GHz, and  $\theta_{\text{FWHM}} = 0.87'$  for XMM-M5 observed at 210 GHz. Based on this Gaussian model, we then estimated the correction factor for the primary beam response at the position of each detection in the SMA continuum maps and divided the extracted flux density by this correction factor, propagating the errors accordingly. In Table 3.2 we present the corrected SMA photometry alongside the corresponding correction factor for the primary beam response, where the uncertainties include the 10% calibration error added in quadrature with the rms noise in the SMA map. As a final test, we extract flux densities based on the aforementioned method for each source from their SMA dirty continuum maps, finding that these values differ by no more than  $\sim 3\%$  from those extracted from the CLEANed maps.

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<sup>8</sup><https://lweb.cfa.harvard.edu/sma/miriad/manuals/SMAguide/smauserhtml/node130.html>

| Source        | RA<br>J2000 | Dec<br>J2000 | $S_{870\mu m}$<br>mJy | Primary Beam<br>Response |
|---------------|-------------|--------------|-----------------------|--------------------------|
| Bootes15.SMA1 | 14:40:09.86 | +34:37:56.65 | $1.4 \pm 0.2$         | 0.98                     |
| Bootes15.SMA2 | 14:40:09.13 | +34:38:07.84 | $1.8 \pm 0.3$         | 0.60                     |
| Bootes24.SMA1 | 14:36:22.04 | +33:02:25.30 | $3.4 \pm 0.5$         | 0.76                     |
| Bootes24.SMA2 | 14:36:21.17 | +33:02:35.53 | $3.4 \pm 0.5$         | 0.88                     |
| Bootes27.SMA1 | 14:38:45.24 | +33:22:25.92 | $1.9 \pm 0.4$         | 0.91                     |
| XMM-M5.SMA1   | 02:18:56.39 | −04:35:38.32 | $1.3 \pm 0.3^\dagger$ | 0.99                     |

<sup>†</sup> SMA observations tuned to 210 GHz rather than 345 GHz.

Table 3.2: Positions, corrected SMA flux densities and primary beam response values for the resolved SMA sources associated with each  $500\ \mu\text{m}$  riser.

## SCUBA-2

We then extracted  $850\ \mu\text{m}$  flux densities for each  $500\ \mu\text{m}$  riser from their SCUBA-2 maps. From Figure 3.5, it is clear that the larger beamsize of the SCUBA-2 instrument has blended the multiple systems observed in the SMA maps into one detection. For the three sources observed in the Bootes field, this integrated flux is clearly significantly extended. We therefore extracted two separate flux densities for the SCUBA-2 observations, one for each of the two pipeline reductions, such that we could evaluate whether the reduction based on the extended sources recipe recovers significantly more flux than the reduction based on the point source recipe. For the  $850\ \mu\text{m}$  map reduced using the point source recipe, we located the highest signal-to-noise pixel associated with each  $\text{SNR} > 4$  detection and simply extracted the corresponding flux density. For the  $850\ \mu\text{m}$  map reduced using the extended source recipe, we laid down a series of apertures in the image with increasing radii from  $0''$  to  $10''$ , and calculated the sum of the pixel values within these apertures. This produced a flux density in units of  $\text{mJy arcsec}^{-2}$ , which we then multiplied by 16 in order to convert to mJy (based on the  $4''$  pixel size of the SCUBA-2  $850\ \mu\text{m}$  images). For the final flux density measurement, we selected the aperture with the largest flux density value, as this aperture should contain the maximum amount of flux density from the source without including too much contaminating background. We also manually checked each final aperture to make sure that it is a reasonable size.

SCUBA-2 850  $\mu\text{m}$  photometry must additionally be corrected for flux boosting. Geach et al. (2017) investigated the effects of flux boosting in the SCUBA-2 Cosmology Legacy Survey (S2CLS), finding that the level of flux boosting is consistent across the whole survey and well described by the power law

$$B = 1 + 0.2 \left( \frac{\text{SNR}}{5} \right)^{-2.3} \quad (3.2)$$

where  $B$  is the flux boosting factor and SNR is the signal-to-noise ratio of the detection. We estimated errors for our SCUBA-2 flux density measurements based on the combination of instrumental noise, confusion, a typically assumed 5% calibration error and the uncertainty in the flux boosting, which we define as the different between the extracted and deboosted flux densities. The resulting SCUBA-2 flux densities estimated from both reduction processes are presented in Table 3.3.

The wider area of the SCUBA-2 850  $\mu\text{m}$  observations compared to the high-resolution SMA observations allow us to look in more detail at the regions in which our 500  $\mu\text{m}$  risers are placed. For this purpose, we use the SCUBA-2 850  $\mu\text{m}$  maps reduced using the faint source recipe, as this reduction provides the highest signal-to-noise and so is better suited to detecting potentially faint sources in the surrounding field. We crop our SCUBA-2 maps to a circle of diameter 700'' centred on the position of the SCUBA-2 detection, which effectively removes the edges of the map where the variance becomes much larger (these regions can be seen most clearly in the extended reductions in Figure 3.4). We start by taking each signal-to-noise map and find any pixels with  $\text{SNR} > 4$ , with connected pixels considered part of the same source. We then manually examine each of these sources to ensure that each detection is robust and that there is no evidence of shredding (i.e. individual sources detected as multiple sources in the map). For each of these sources, we then extract deboosted flux densities and associated errors based on the method outlined in Section 3.3.4. In Figure 3.6, we present the positions of each of the  $\text{SNR} > 4$  detected SCUBA-2 sources in the field (as well as the 500  $\mu\text{m}$  risers themselves) overlaid on the SCUBA-2 850  $\mu\text{m}$  point source reduced maps.



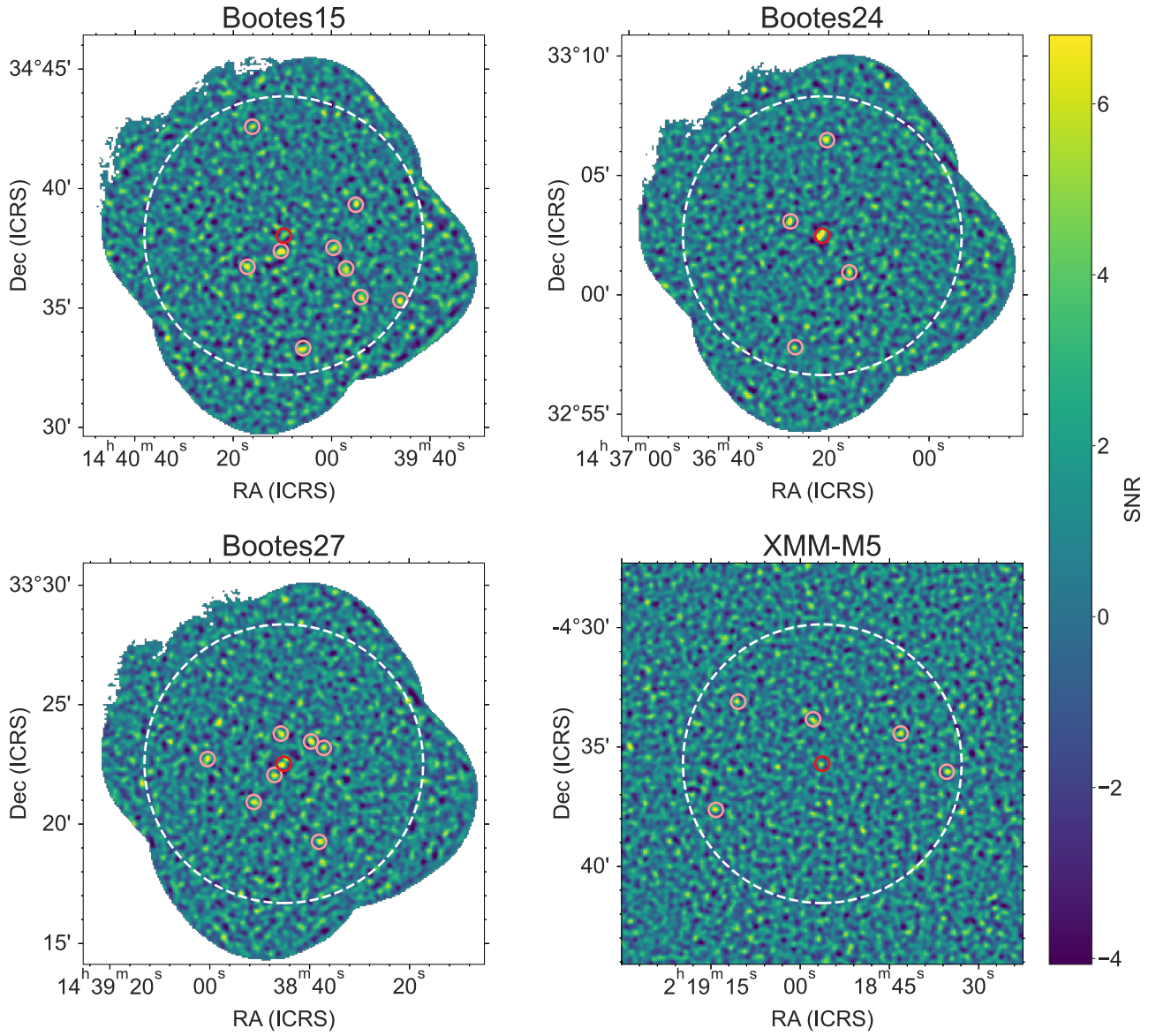


Figure 3.6: SCUBA-2 850  $\mu\text{m}$  maps overlaid with the positions of our 500  $\mu\text{m}$  risers (dark circles) and other SNR  $> 4$  detected sources in the wider field (light circles).

| Source                  | RA<br>J2000 | Dec<br>J2000 | $S_{850\mu\text{m}}$<br>Point Source<br>mJy | $S_{850\mu\text{m}}$<br>Extended<br>mJy | Aperture Radius<br>arcsec |
|-------------------------|-------------|--------------|---------------------------------------------|-----------------------------------------|---------------------------|
| Bootes15                | 14:40:09.66 | +34:38:03.75 | $2.9 \pm 1.8$                               | $2.6 \pm 1.5$                           | 14.0                      |
| Bootes24                | 14:36:21.62 | +33:02:28.87 | $9.7 \pm 2.2$                               | $11.3 \pm 2.6$                          | 19.2                      |
| Bootes27                | 14:38:45.00 | +33:22:38.29 | —                                           | $10.1 \pm 1.6$                          | 20.0                      |
| Bootes27.1 <sup>†</sup> | 14:38:45.46 | +33:22:27.75 | $6.9 \pm 1.3$                               | —                                       | —                         |
| Bootes27.2 <sup>†</sup> | 14:38:44.82 | +33:22:47.82 | $5.6 \pm 1.3$                               | —                                       | —                         |
| XMM-M5                  | 02:18:56.51 | −04:35:45.97 | $8.1 \pm 3.3$                               | —                                       | —                         |

<sup>†</sup>Partially resolved components

Table 3.3: Positions and extracted SCUBA-2 850  $\mu\text{m}$  flux densities for the four 500  $\mu\text{m}$  risers. Positions are based on the brightest pixel in the SCUBA-2 maps.

## Optical/NIR Ancillary Data

The catalogues from the DESI Legacy Survey provide photometry in the  $g$ ,  $r$  and  $z$  bands, as well as the four *WISE* bands, in units of “nanomaggies” (nMgy). The nMgy is a convenient linear unit of flux density often used in SDSS photometry, related to the apparent magnitude via the equation

$$m = 22.5 \text{ mag} - 2.5 \log_{10}(f), \quad (3.3)$$

such that  $1 \text{ nMgy} \approx 3.631 \times 10^{-6} \text{ Jy}^9$ . For those sources detected in the DESI catalogues, we simply convert these values into flux densities in  $\mu\text{Jy}$  or  $\text{mJy}$ . For those sources that remain undetected in the DESI catalogues, we extract  $3\sigma$  upper limits on the three optical bands based on  $1.9''$  apertures placed at their positions in the DESI maps. We additionally tested different aperture sizes, finding that the radius made little difference to the extracted rms noise value. The IBIS catalogue provides photometry in the  $J$ ,  $H$  and  $K_s$  bands in units of Vega magnitudes. We therefore convert these values into flux densities using standard conversion factors, including small colour corrections in order to match the Vega magnitude zeropoint<sup>10</sup>.

While the three  $500\mu\text{m}$  risers in the Bootes field are covered by archival *Spitzer* imaging, they do not sit within the footprint of any of the available catalogues, and we must therefore extract photometry for these sources directly from the maps themselves. In order to extract flux densities in the available IRAC bands, we first carry out a simple background subtraction on the maps and convert them from  $\text{MJy/sr}$  into units of  $\mu\text{Jy/pixel}$ . We extract photometry from the IRAC maps by laying down a series of apertures of different radii, as well as a surrounding annulus from which we can estimate a local measurement of the noise in the maps. We apply various corrections to the extracted photometry, including a colour correction accounting for the fact that the IRAC maps are calibrated based on the nominal spectral slope of a calibrator source<sup>11</sup>, and an aperture correction accounting for the difference in our aperture sizes compared

<sup>9</sup><https://www.sdss3.org/dr8/algorithms/magnitudes.php#nmgy>

<sup>10</sup>[http://hedam.lam.fr/HELP/dataproducts/dmu0/dmu0\\_IBIS/readme.md](http://hedam.lam.fr/HELP/dataproducts/dmu0/dmu0_IBIS/readme.md)

<sup>11</sup>[https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/15/#\\_Toc82083614](https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/15/#_Toc82083614)

those used to extract the flux densities for the calibrator source<sup>12</sup>. As a consistency check, we test this extraction method across a section of the Bootes field covered by the SDWFS survey, finding good agreement between our extracted flux densities and those listed in the *Spitzer* catalogues. Based on this comparison, we find that the best configuration for extracting IRAC photometry is a  $2.9''$  radius aperture with a  $2''$  radius annulus around it to estimate the local background. We estimate a conservative uncertainty of 10% in the extracted photometry. The resulting optical/NIR photometry will be discussed in Section 3.4.2.

## 3.4 Photometry

### 3.4.1 SMA and SCUBA-2 Detections

In Figures 3.5 and 3.7 we present the SMA  $870\,\mu\text{m}$  continuum maps for our four  $500\,\mu\text{m}$  risers overlaid with SCUBA-2  $850\,\mu\text{m}$  contours, and the *Herschel* SPIRE  $250\,\mu\text{m}$  maps overlaid with both the SMA and SCUBA-2 contours. We note that the SMA maps and contours are based on the CLEANed continuum maps.

#### SMA

In Figure 3.5, the location of the  $\text{SNR} > 4.1$  detections identified from the SMA dirty maps are denoted by red boxes, indicating that Bootes15 and Bootes24 each break up into two resolved sources in the SMA images. These resolved sources are well detected to  $> 5\sigma$  in both the dirty and CLEANed maps. For Bootes27, one source is similarly well detected, and there are numerous lower significance detections in the surrounding field, too faint to be classified as robust detections based on our calculated detection threshold. Most notably, these include a marginal  $\sim 3.3\sigma$  detection in the SMA dirty map associated with the partially resolved Northern component of Bootes27, and a second  $\sim 3.9\sigma$  detection offset by  $\sim 10''$  from the SCUBA-2 contours and lying to the South West of Bootes27. At these flux density levels,

<sup>12</sup>[https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/17/#\\_Toc82083617](https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/17/#_Toc82083617)

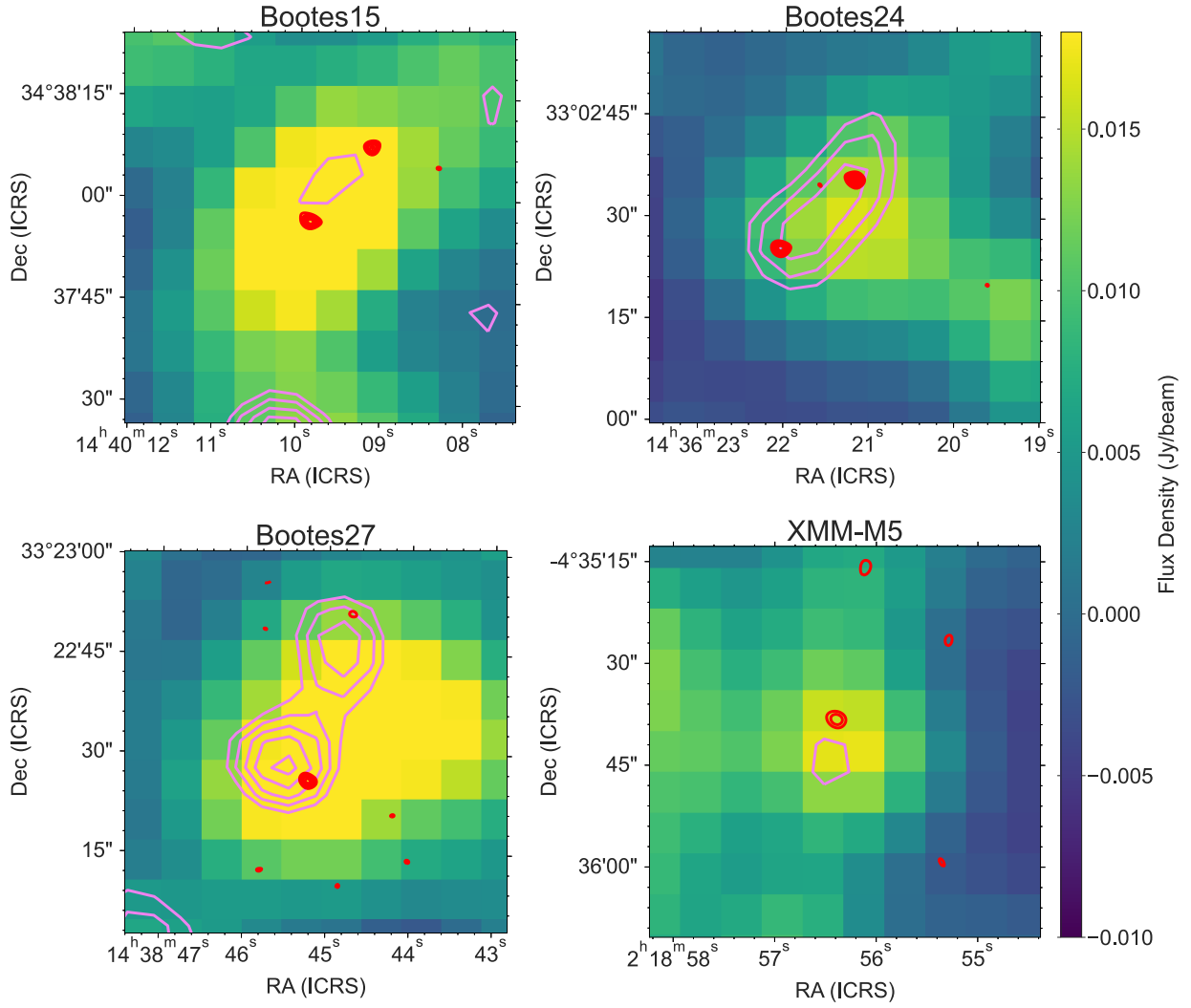


Figure 3.7: *Herschel* SPIRE  $250\mu\text{m}$  maps with SCUBA-2  $850\mu\text{m}$  (pink) and SMA (red) contours from  $3\sigma$  to  $7\sigma$  significance for the four  $500\mu\text{m}$  risers. Bootes15 and Bootes24 each break up into two individual sources in the SMA maps, while Bootes27 and XMM-M5 resolve into one faint source. Bootes24 and Bootes27 are well detected by SCUBA-2, while Bootes15 and XMM-M5 are marginally detected to  $\sim 3\sigma$  significance. Bootes27 shows two partially resolved SCUBA-2 sources associated with the bright *Herschel* source.

the Bootes27 SMA dirty map has completenesses of  $\approx 20\%$  and  $\approx 60\%$  respectively, and so we would not necessarily expect to observe these sources above our nominal signal-to-noise threshold, even if they were real. As neither of these sources meet our  $4.1\sigma$  detection threshold, we do not consider them to be robust detections and hence they are not considered in the forthcoming analysis. The SMA map for XMM-M5 shows a single  $\sim 4.7\sigma$  peak coincident with the bright *Herschel*  $500\mu\text{m}$  riser (Figure 3.7).

## SCUBA-2

In the SCUBA-2  $850\,\mu\text{m}$  maps, we find that Bootes15 is marginally detected with a signal-to-noise ratio of 3.06, and is likely to be extended as the SCUBA-2 flux density peaks between the two SMA detections and is elongated along the direction of their separation. Bootes24 and Bootes27 also appear to be extended, but are both well detected to  $> 5\sigma$ . In particular, Bootes27 is clearly partially resolved and comprised of two sources, one of which has no apparent SMA cross-match. Like Bootes15, XMM-M5 is only marginally detected with a signal-to-noise ratio of 3.65, although it is clearly detected as a point-like source. In Table 3.3, we present the  $850\,\mu\text{m}$  flux densities of our  $500\,\mu\text{m}$  risers based on each of the two reduction pipelines, although we note that no reliable flux density could be extracted for XMM-M5 based on the extended reduction due to the low signal-to-noise of the archival observations. This does not affect the following analysis as XMM-M5 is clearly detected as a point-like source and hence we use the flux density estimated based on the `REDUCE_SCAN_FAINT_POINT_SOURCES` recipe. For Bootes15 and Bootes24, which appear to be extended in the SCUBA-2  $850\,\mu\text{m}$  maps, we use the flux density estimates based on the `REDUCE_SCAN_EXTENDED_SOURCES` recipe, and we note that the flux density estimates from the two pipeline reduction methods agree within their respective errors. For Bootes27, which is clearly partially resolved, there is a significant difference between the flux density estimates for the two pipeline reduction methods. When considering the total Bootes27 system, we use the `REDUCE_SCAN_EXTENDED_SOURCES` recipe, but in places we consider these two components separately. In these cases we use the flux density estimates from the `REDUCE_SCAN_FAINT_POINT_SOURCES` recipe. We additionally note that, while Bootes15 and XMM-M5 are detected to  $> 3\sigma$ , after including the instrumental, confusion and calibration uncertainties, the photometry is constrained to an accuracy of  $\sim 1.7\sigma$  and  $\sim 2.5\sigma$  respectively.

## Integrated FIR/sub-mm Photometry

In Table 3.4, we assemble the integrated FIR/sub-mm photometry for each of our  $500\,\mu\text{m}$  risers, where we have estimated the total SMA flux density for each source by adding together the flux densities of the resolved sources in the SMA continuum maps from Table 3.2. Despite

| Source   | $S_{250\mu\text{m}}$<br>mJy | $S_{350\mu\text{m}}$<br>mJy | $S_{500\mu\text{m}}$<br>mJy | $S_{850\mu\text{m}}$<br>mJy | $S_{870\mu\text{m}}$<br>mJy | $S_{1.4\text{mm}}$<br>mJy |
|----------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|---------------------------|
| Bootes15 | $51.2 \pm 6.0$              | $68.3 \pm 7.0$              | $66.1 \pm 8.0$              | $2.6 \pm 1.5$               | $3.2 \pm 0.4$               | —                         |
| Bootes24 | $28.7 \pm 6.0$              | $49.7 \pm 7.0$              | $55.8 \pm 8.0$              | $11.3 \pm 2.6$              | $6.8 \pm 0.6$               | —                         |
| Bootes27 | $37.8 \pm 6.0$              | $44.2 \pm 7.0$              | $52.2 \pm 8.0$              | $10.1 \pm 1.6$              | $1.9 \pm 0.4$               | —                         |
| XMM-M5   | $26.6 \pm 6.0$              | $44.0 \pm 7.0$              | $46.1 \pm 8.0$              | $8.1 \pm 3.3$               | —                           | $1.3 \pm 0.3$             |

Table 3.4: Integrated FIR/sub-mm photometry for the four  $500\mu\text{m}$  risers. *Herschel* SPIRE flux densities are taken from Greenslade et al. (2020). The integrated  $870\mu\text{m}$  flux density is calculated by summing the SMA flux densities (corrected for primary beam response) of all sources associated with each  $500\mu\text{m}$  riser in Table 3.2.

being observed at similar wavelengths, we find that the integrated  $850\mu\text{m}$  flux densities are significantly larger than the combined  $870\mu\text{m}$  flux densities for Bootes24 and Bootes27 (XMM-M5 is observed at a lower frequency and so we exclude it from this analysis). This disparity is particularly evident in Bootes27, for which we measure integrated flux densities of  $10.1 \pm 1.6$  mJy and  $1.9 \pm 0.3$  mJy from the SCUBA-2 and SMA maps respectively, indicating a  $> 4\sigma$  disparity between the two measurements.

We investigate this discrepancy in more detail in Figure 3.8, where we plot the SCUBA-2  $850\mu\text{m}$  flux density against the combined SMA  $870\mu\text{m}$  continuum flux density for the three  $500\mu\text{m}$  risers in the Bootes field. Alongside our  $500\mu\text{m}$  risers, we plot two additional samples from the literature that similarly obtained both interferometric and single-dish sub-mm photometry. Hill et al. (2018) targeted 70 of the brightest  $850\mu\text{m}$  sources from S2CLS down to a limiting flux density of  $S_{850} \sim 8$  mJy with high-resolution SMA follow-up observations at  $860\mu\text{m}$ . Similarly, Stach et al. (2019) present the ALMA survey of the SCUBA-2 Cosmology Legacy Survey UKIDSS/UDS field (AS2UDS), providing high resolution, ALMA Band 7 follow-up observations of SCUBA-2  $850\mu\text{m}$  sources in the UKIDSS/UDS field. We combined the SMA, ALMA and SCUBA-2 photometry from these surveys and, for any SCUBA-2 sources which break up into multiple components in the higher resolution interferometric observations, we combined the flux densities of the resolved sources together to aid comparison with our own photometry. While the interferometric and single-dish sub-mm flux densities are consistent for Bootes15, we find that Bootes24 is  $\sim 1.7$  times fainter in the SMA maps than the SCUBA-2 maps, lying

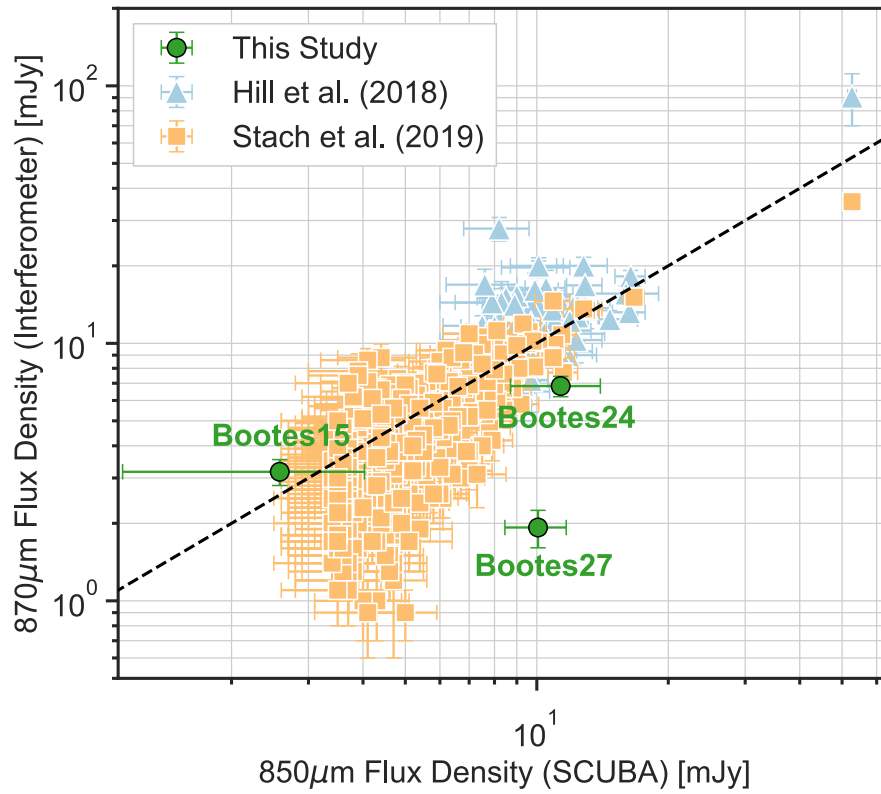


Figure 3.8: The combined  $870\,\mu\text{m}$  flux density for the resolved sources in either SMA or ALMA maps as a function of their integrated  $850\,\mu\text{m}$  flux density from SCUBA-2. Orange squares and blue triangles show the Stach et al. (2019) and Hill et al. (2018) samples respectively, while the green points show our sample of  $500\,\mu\text{m}$  risers. The black dashed line shows where the two flux density measurements are equal. We do not include XMM-M5 in this plot as the SMA observations are tuned to a shorter wavelength (210 GHz rather than 345 GHz).

towards the edge of the region probed by the Hill et al. (2018) and Stach et al. (2019) samples in Figure 3.8, but agreeing at the  $3\sigma$  level and hence not representing a significant tension. For Bootes27, the single resolved SMA source coincident with the SCUBA-2 contours is roughly five times fainter than the  $850\,\mu\text{m}$  flux density, placing it well outside the region probed by the Hill et al. (2018) and Stach et al. (2019) samples. We interpret this disparity as evidence of additional faint sources lying below the SMA detection limit, but contributing to the integrated flux density at  $850\,\mu\text{m}$ . This will be discussed further in the following Sections.

In Figure 3.9, we show the *Herschel* SPIRE  $500\,\mu\text{m}$  flux densities of our  $500\,\mu\text{m}$  risers as a function of their SCUBA-2  $850\,\mu\text{m}$  flux densities alongside samples from S2CLS and the SCUBA-2 Ultra Deep Imaging EAO Survey (STUDIES: Wang et al., 2017) samples. We find that Bootes24, Bootes27 and XMM-M5 are all reasonably consistent with the brighter end of

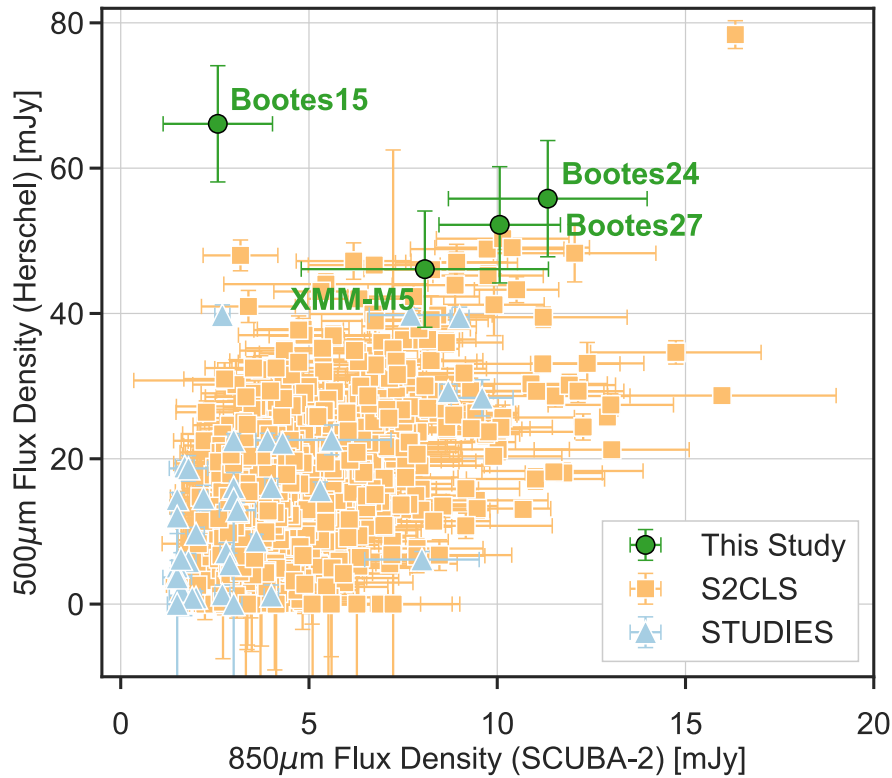


Figure 3.9: SCUBA-2  $850\mu\text{m}$  flux density vs. *Herschel* SPIRE  $500\mu\text{m}$  flux density for our  $500\mu\text{m}$  risers (green points) as well as for the S2CLS (orange squares) and STUDIES (blue triangles) surveys. Bootes15 is significantly fainter than expected at  $850\mu\text{m}$  based on its  $500\mu\text{m}$  flux density.

these two samples. By comparison, Bootes15 is significantly fainter at  $850\mu\text{m}$  based on its *Herschel*  $500\mu\text{m}$  flux density (peculiarly, it is the brightest source in our sample at  $500\mu\text{m}$  but the faintest at  $850\mu\text{m}$ ). We additionally note that a broad range of  $850\mu\text{m}$  flux densities are found for sources in the comparison samples with similar flux densities at  $500\mu\text{m}$  to the other three  $500\mu\text{m}$  risers (e.g. sources in S2CLS with  $S_{500} \sim 40 - 50$  mJy at  $500\mu\text{m}$  can have  $850\mu\text{m}$  flux densities of  $\sim 3 - 12$  mJy at  $850\mu\text{m}$ ). We conclude that our SCUBA-2 observations for Bootes15 could miss some fraction of the integrated  $850\mu\text{m}$  flux density, either in the form of diffuse, extended flux density that is resolved out in our observations, or individual, point-like sources below our SCUBA-2 detection threshold, or, alternatively, there may be additional sources that are blended within the  $500\mu\text{m}$  *Herschel* SPIRE beam, but do not contribute to the SCUBA-2 flux density.

We can estimate the potential effects of blending within the *Herschel* SPIRE images by comparing them with the SCUBA-2 maps. This comparison is presented in Figure 3.10. We find



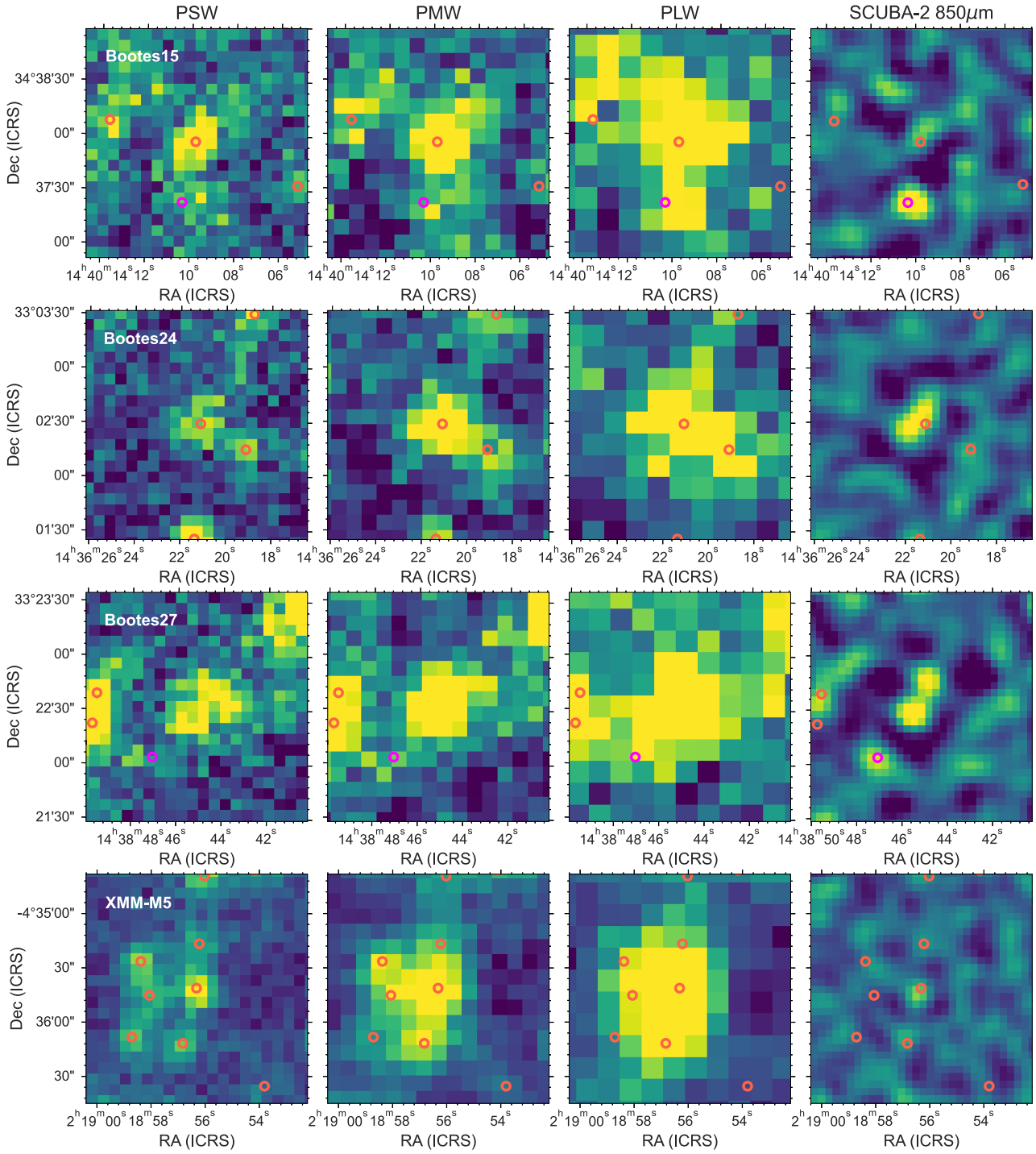


Figure 3.10: Comparison of the *Herschel* SPIRE maps (where PSW, PMW and PLW refer to the 250, 350 and 500  $\mu$ m bands respectively) and their SCUBA-2 850  $\mu$ m point source maps from this study. Plotted as red points are the positions of 250  $\mu$ m-selected sources from the HerMES catalogue, while the magenta points show the positions of potential contaminating sources.

that one of the  $\text{SNR} > 4$  SCUBA-2 detections lies within  $\sim 31''$  to the South of the Bootes15  $500\mu\text{m}$  riser, placing it just within the FWHM of the *Herschel* SPIRE beamsizes at  $500\mu\text{m}$  ( $35.2''$ ) but outside of the  $250\mu\text{m}$  ( $17.6''$ ) and  $350\mu\text{m}$  ( $23.9''$ ) beamsizes. This SCUBA-2 source does not have a separate counterpart in the HerMES catalogues, indicating that it may contribute to making Bootes15 artificially red. Similarly, we find a SCUBA-2 detection towards the South East of Bootes27 within the  $500\mu\text{m}$  beamsizes which may contribute to making this source artificially red. For Bootes24 and XMM-M5, all  $\text{SNR} > 4$  SCUBA-2 detections lie well outside of the *Herschel* SPIRE  $500\mu\text{m}$  beamsizes, and all nearby potential  $250\mu\text{m}$  sources are detected as separate objects in the HerMES catalogue, indicating that they have been de-blended and hence likely do not contribute to artificially reddening these  $500\mu\text{m}$  risers. We make a simple estimate of the likely effect of these contaminating sources on the  $350\mu\text{m}$  and  $500\mu\text{m}$  flux densities of Bootes15 and Bootes27. We first extract a flux density estimate at  $250\mu\text{m}$  for the contaminating sources from the *Herschel* SPIRE maps by simply extracting the peak flux density within the SPIRE beamsizes centred on the brightest pixel in the SCUBA-2  $850\mu\text{m}$  maps. We conservatively estimate the likely peak flux of these contaminating sources by linearly interpolating between their  $250\mu\text{m}$  flux densities from the *Herschel* SPIRE maps, and their deboosted  $850\mu\text{m}$  flux densities from SCUBA-2. In each of the  $350\mu\text{m}$  and  $500\mu\text{m}$  bands, we construct a Gaussian function with a peak matching the interpolated flux density, and a FWHM matching the beamsizes of the SPIRE instrument in that band. Finally, based on these Gaussian functions, we estimate the likely contaminating flux density at the position of the brightest pixel in the *Herschel* SPIRE images at  $350\mu\text{m}$  and  $500\mu\text{m}$ . We find that the contaminating source associated with Bootes15 could conservatively contribute  $\sim 1.1\text{ mJy}$  and  $\sim 3.6\text{ mJy}$  at  $350\mu\text{m}$  and  $500\mu\text{m}$  respectively. The contamination for Bootes27 is  $\sim 0.3\text{ mJy}$  and  $\sim 2.8\text{ mJy}$  at  $350\mu\text{m}$  and  $500\mu\text{m}$  respectively. We therefore expect the contamination from these nearby sources to be small relative to the errors on the *Herschel* SPIRE photometry.

Finally, we additionally note, in Figure 3.9, the possible presence of two diverging trends, a steeper gradient traced by our  $500\mu\text{m}$  risers, and a second, shallower trend at lower  $500\mu\text{m}$  flux densities. While based on small numbers of sources, this could suggest that the brighter end of the  $850\mu\text{m}$  population splits into two distinct populations with significantly different

SED shapes in the FIR/sub-mm, potentially caused by different multiplicities, dust properties or redshifts. Such a trend would require additional sources probing this rather sparse region, and follow-up observations to reveal the properties of DSFGs in these two distinct regions.

### 3.4.2 Optical and Near-Infrared Photometry

We aim to investigate the resolved sources in more detail, making use of the archival optical/NIR data discussed in Section 3.3.3. Here we discuss only the three  $500\,\mu\text{m}$  risers in the Bootes field, as an in-depth multi-wavelength analysis of XMM-M5 will be presented as part of a separate study (Clements et al. in prep).

In the DESI catalogues, there is an optical detection  $\sim 1.6''$  from Bootes15.SMA1, with a flux density of  $0.95 \pm 0.21\,\mu\text{Jy}$ ,  $1.62 \pm 0.36\,\mu\text{Jy}$  and  $5.90 \pm 0.62\,\mu\text{Jy}$  in the  $g$ ,  $r$  and  $z$  bands respectively. This detection has an irregular morphology that changes significantly across the three optical bands, becoming significantly extended in the  $z$  band, such that the brightest component of the optical detection in the  $z$  band is offset from the SMA position. Bootes15.SMA1 is also well detected in the archival  $3.6\,\mu\text{m}$  and  $4.5\,\mu\text{m}$  IRAC maps, although it is possible that this bright IRAC source is a blend of two individual sources identified in the DESI catalogues. The IRAC detection is elliptical in shape and significantly extended, with a semi-major axis length of  $\sim 8''$ . In order to extract a flux density in these bands, we carry out a simple background extraction of the archival IRAC maps, convert the map units from MJy/sr to mJy/pixel, lay down an elliptical aperture covering the source in the  $3.6\,\mu\text{m}$  and  $4.5\,\mu\text{m}$  images and estimate the flux density based on the sum of the pixel values within the aperture. We estimate a conservative 10% error on the flux density estimate. Bootes15.SMA1 therefore has a flux density of  $0.15 \pm 0.02\,\text{mJy}$  and  $0.14 \pm 0.01\,\text{mJy}$  in the  $3.6\,\mu\text{m}$  and  $4.5\,\mu\text{m}$  bands respectively. Unfortunately, Bootes15 lies outside of the footprint of the IBIS catalogues, so no photometry in the  $J$ ,  $H$  and  $K_s$  bands can be recovered. Bootes15.SMA2 remains undetected in all available optical/NIR ancillary data.

There is also an optical detection  $\sim 1.8''$  from Bootes24.SMA1 in the DESI catalogue, although it appears that this source is physically distinct from the SMA detection, and there is no

detection associated with Bootes24.SMA2. At longer wavelengths, there are bright sources associated with both Bootes24.SMA1 and Bootes24.SMA2 in the IRAC  $4.5\mu\text{m}$  maps as well as the  $8.0\mu\text{m}$  maps, although in the latter these detections are somewhat offset from the SMA detections and we therefore do not consider them to be robust counterparts. Based on the aforementioned source extraction method, we estimate  $4.5\mu\text{m}$  flux densities of  $12 \pm 1\mu\text{Jy}$  and  $10 \pm 1\mu\text{Jy}$  for Bootes24.SMA1 and Bootes24.SMA2 respectively. While the IBIS catalogue does cover the Bootes24 region, there are no infrared detections associated with either of the resolved SMA sources.

The Bootes27 region, by comparison, provides a much more complicated picture. There are no obvious optical sources coincident with either of the resolved SMA sources in the DESI catalogues or images. However, there are numerous bright IRAC sources lying within the extended SCUBA-2 contours for Bootes27, although none of them are convincing counterparts to either of the SMA detections. Moreover, a number of these sources are either brighter at  $8\mu\text{m}$  than at  $4.5\mu\text{m}$  or, in some cases, remain undetected at  $4.5\mu\text{m}$  altogether, indicating that they must have red IRAC colours. We identify potentially interesting sources in this region as those with peak flux densities greater than  $3\sigma$  in the IRAC  $8\mu\text{m}$  image (where  $\sigma$  represents the local background noise estimated from the  $2''$  annulus in the  $8\mu\text{m}$  map) lying roughly within the SCUBA-2 contours. We extract flux densities at these positions using the methods outlined in Section 3.3.4 for the IRAC  $4.5\mu\text{m}$  and  $8\mu\text{m}$  data. For those sources detected in the IRAC  $8\mu\text{m}$  image but not in the  $4.5\mu\text{m}$  image, we estimate informative  $3\sigma$  upper limits based on the local background noise within the  $2''$  annulus. We additionally find that two of these IRAC sources have counterparts in the IBIS catalogues. In Figure 3.11 we show the Bootes27 region in the IRAC  $4.5\mu\text{m}$  and  $8.0\mu\text{m}$  bands.

We additionally note that, while there is *WISE* data available for these regions, they have a significantly poorer spatial resolution and brighter flux limits compared to the IRAC maps, and as a result are more likely to suffer from blending. We therefore do not discuss the *WISE* observations any further in this work. From this discussion, we find that no useful conclusions can be drawn from the optical/NIR data for Bootes15.SMA2 or Bootes24.SMA2, as well as the two resolved SMA sources associated with Bootes27. While Bootes24.SMA1 is detected

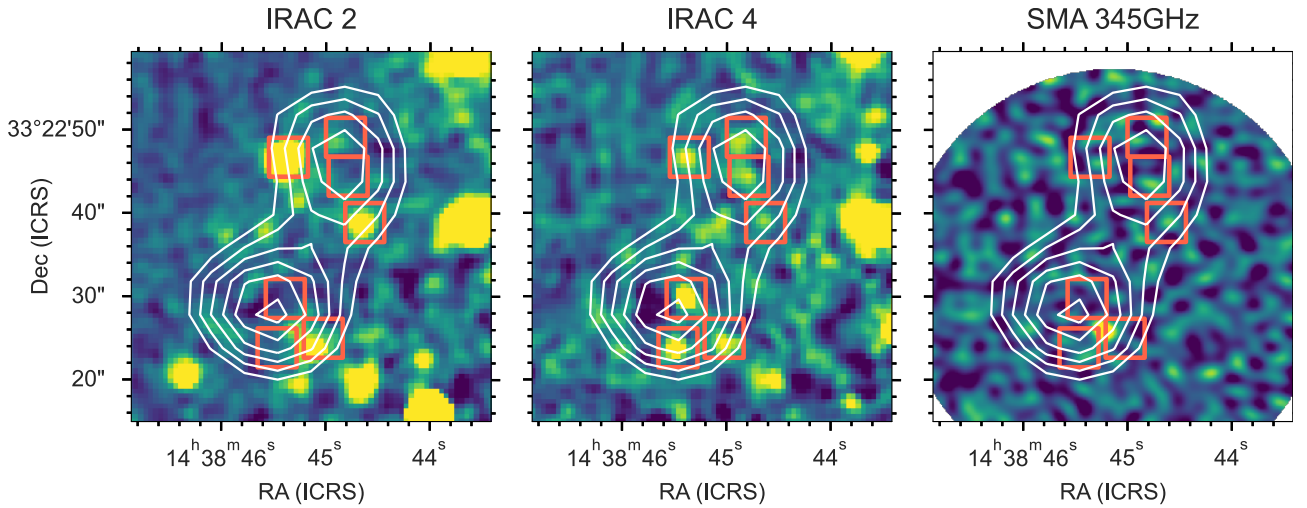


Figure 3.11: Near-infrared images of the Bootes27 region at  $4.5\,\mu\text{m}$  (*left*) and  $8\,\mu\text{m}$  (*centre*) alongside the CLEANed SMA continuum map (*right*). Red squares indicate the positions of  $\text{SNR} > 3\sigma$  detections in the IRAC  $8\,\mu\text{m}$  image lying approximately within the SCUBA-2 contours for the Bootes27  $500\,\mu\text{m}$  riser (white contours). We infer that there are seven bright IRAC sources clustered within the Bootes27 SCUBA-2 contours, four of which are either much fainter or remain undetected in the  $4.5\,\mu\text{m}$  IRAC image.

at  $3.6\,\mu\text{m}$ , it remains undetected in all other available optical/NIR bands, and so we similarly cannot make any significant conclusions based on this data. The only resolved source associated with any of the three  $500\,\mu\text{m}$  risers in the Bootes field with counterparts detected in the optical/NIR is Bootes15.SMA1. In Section 3.5.3, we attempt to use this multi-wavelength photometry to determine properties for Bootes15.SMA1, and in Section 3.5.4, we discuss the IRAC sources associated with the Bootes27 region.

### 3.5 Galaxy Properties

In this Section, we estimate the properties of the total  $500\,\mu\text{m}$  systems based on the integrated FIR/sub-mm photometry assembled in Table 3.4. We additionally estimate the properties of the resolved sources that comprise the  $500\,\mu\text{m}$  risers based on the higher angular resolution optical/NIR photometry wherever possible.

### 3.5.1 Fitting the Integrated FIR SEDs

In order to estimate galaxy properties for the combined  $500\mu\text{m}$  riser systems, we combined the *Herschel* SPIRE and SCUBA-2 photometry to build their integrated FIR/sub-mm SEDs. We use the `emcee`<sup>13</sup> package (Foreman-Mackey et al., 2013), a python-based Affine Invariant Markov Chain Monte Carlo (MCMC) Ensemble sampler, to fit a modified blackbody function to the integrated FIR/sub-mm SEDs of our  $500\mu\text{m}$  risers. We follow the literature (Blain et al., 2002; Magnelli et al., 2012; Casey, 2012; Bianchi, 2013; Casey et al., 2014; Greenslade et al., 2020), fitting a blackbody function of the form

$$S_\nu \propto (1 - \exp(-\tau_\nu)) B_\nu(T), \quad (3.4)$$

where  $S_\nu$  is the flux density at the rest frame frequency  $\nu$  (such that  $\nu = \nu_{\text{obs}}(1+z)$ ) in units of mJy and  $\tau_\nu$  is the optical depth of the dust defined as  $\tau_\nu = (\nu/\nu_0)^\beta$ , where  $\nu_0$  is the frequency at which  $\tau_\nu = 1$  and  $\beta$  is the dust emissivity index.  $B_\nu(T)$  is the Planck function for a given temperature  $T$ , defined as

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(\frac{h\nu}{k_B T}) - 1}. \quad (3.5)$$

Given that we are fitting to only four photometric data points, we reduce the number of degrees of freedom by fixing  $c/\nu_0 = 200\mu\text{m}$  following Conley et al. (2011) and Casey (2012). This leaves us with four parameters for our fit - the photometric redshift  $z$ , the dust temperature  $T_d$ , the dust emissivity index  $\beta$  and the normalisation factor  $a$ . We estimate initial best fit parameters for each source through a simple, non-linear least squares fit to the data, which we then visually inspect to ensure a reasonable fit. We use the `emcee` Ensemble Sampler with the following uninformative priors;  $-20 < \log(a) < -10$ ,  $10\text{ K} < T_d < 80\text{ K}$ ,  $1 < \beta < 6$  and  $0 < z < 12$ . We then initialise 250 walkers in a small gaussian ball around our initial best fit parameters and allow 50,000 steps in our MCMC chains. Following the `emcee` documentation and Goodman and Weare (2010), we use the integrated autocorrelation time ( $\tau$ ) to evaluate the robustness of our MCMC analysis, where typically chain lengths of  $> 50\tau$  should result in

<sup>13</sup><https://emcee.readthedocs.io/en/stable/>

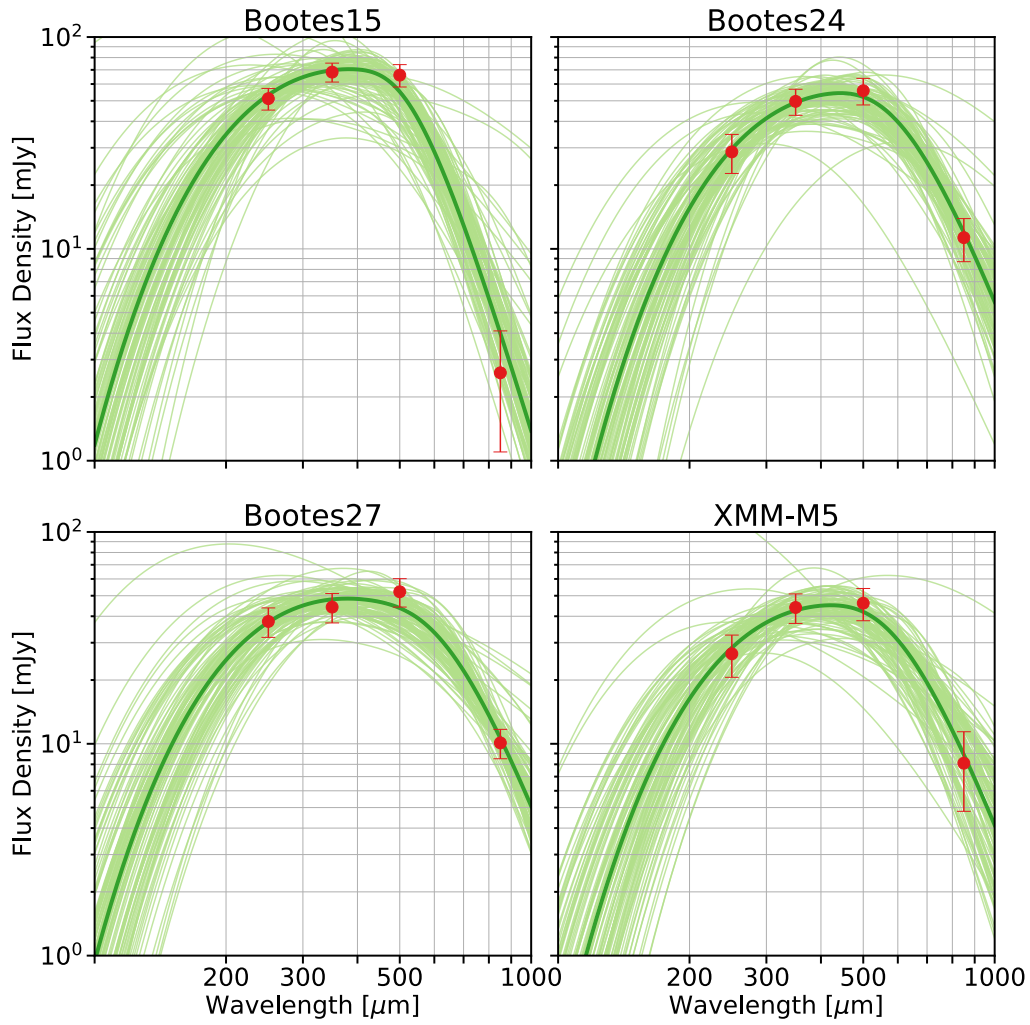


Figure 3.12: Resulting SED fits from the `emcee` ensemble sampler. Light green lines show 100 random samples while the dark green line shows the best fitting SED. Red points show the integrated FIR photometry from *Herschel* SPIRE and SCUBA-2.

convergence. We calculate typical integrated autocorrelation times of  $\tau \sim 500$  steps, indicating that we should obtain convergence in our analysis. Additionally, we throw away the first  $\sim 5\tau$  (equivalent to 2,500 steps) as a “burn-in” phase. In Figure 3.12, we show the SEDs of 100 random samples alongside the best fitting SED model, and in Figure 3.13, we show the resulting corner plots from the MCMC fitting. We find that the FIR properties we obtain from this process are broadly well constrained, with single-peaked probability density functions well within the uninformative priors, demonstrated by the corner plots. The exception to this is the dust spectral emissivity index  $\beta$ , where the probability distribution clearly bumps up against the upper limit of the priors ( $\beta < 6$ ). We discuss the implications of these results in Section 3.7.2.

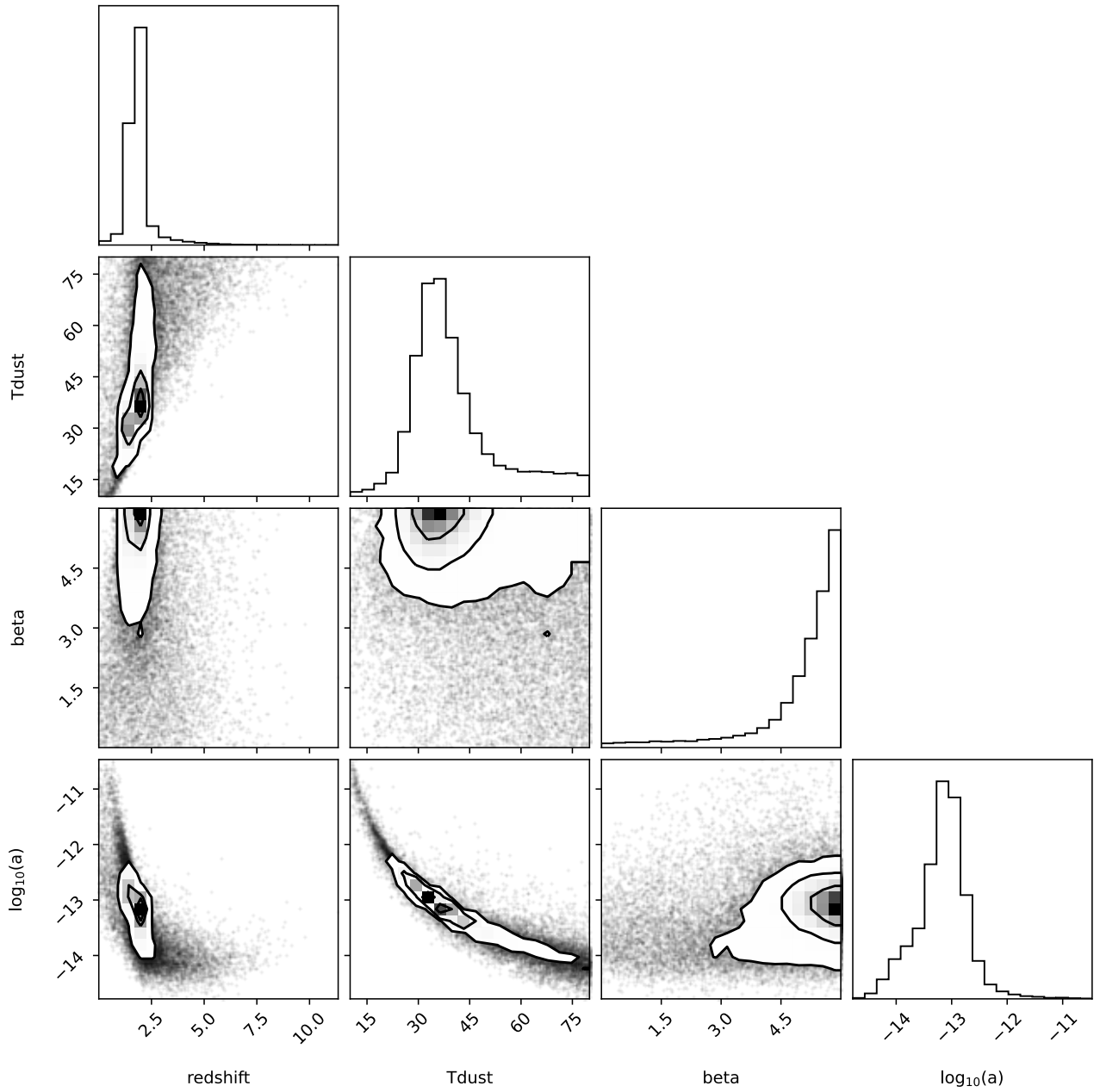


Figure 3.13: Corner plot showing the samples and marginalised posterior distributions for each of the parameters in the MCMC SED fitting for Bootes15. The photometric redshift, characteristic dust temperature and normalisation constant are well constrained, while the dust spectral emissivity index  $\beta$  bumps up against the upper limits of our uninformative priors ( $\beta < 6$ ).



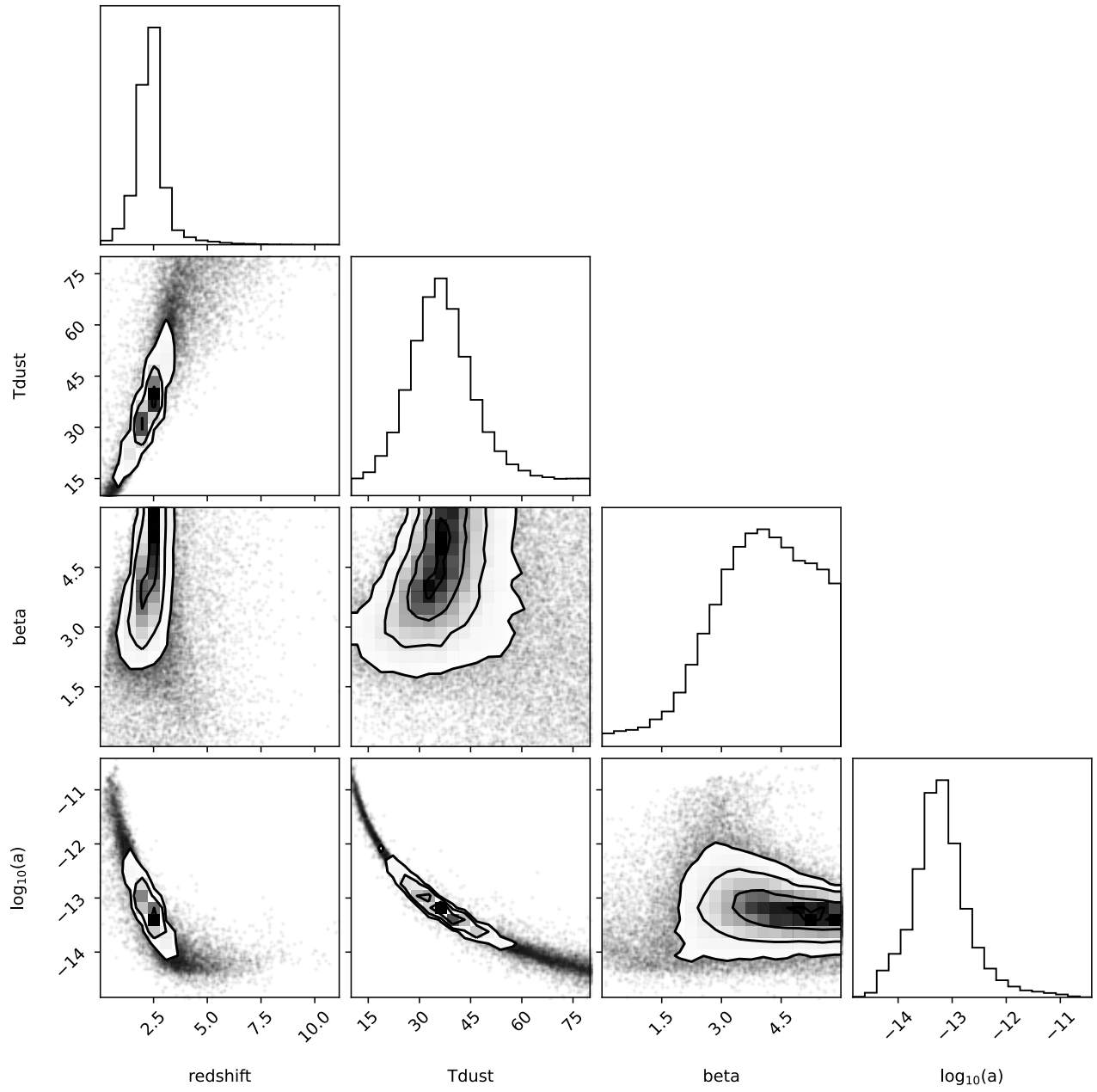


Figure 3.13: Continued: Bootes24.

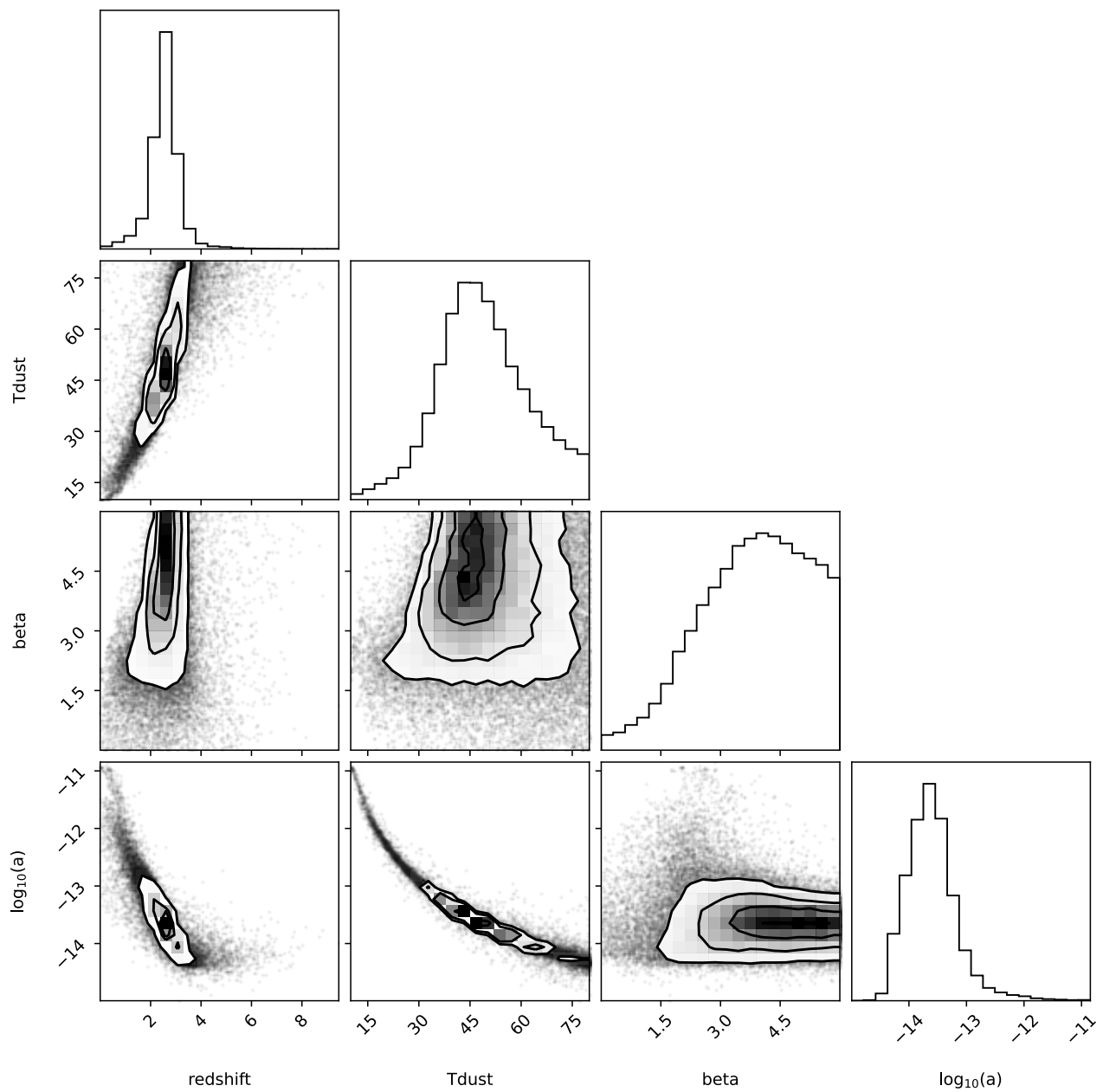


Figure 3.13: Continued: Bootes27.

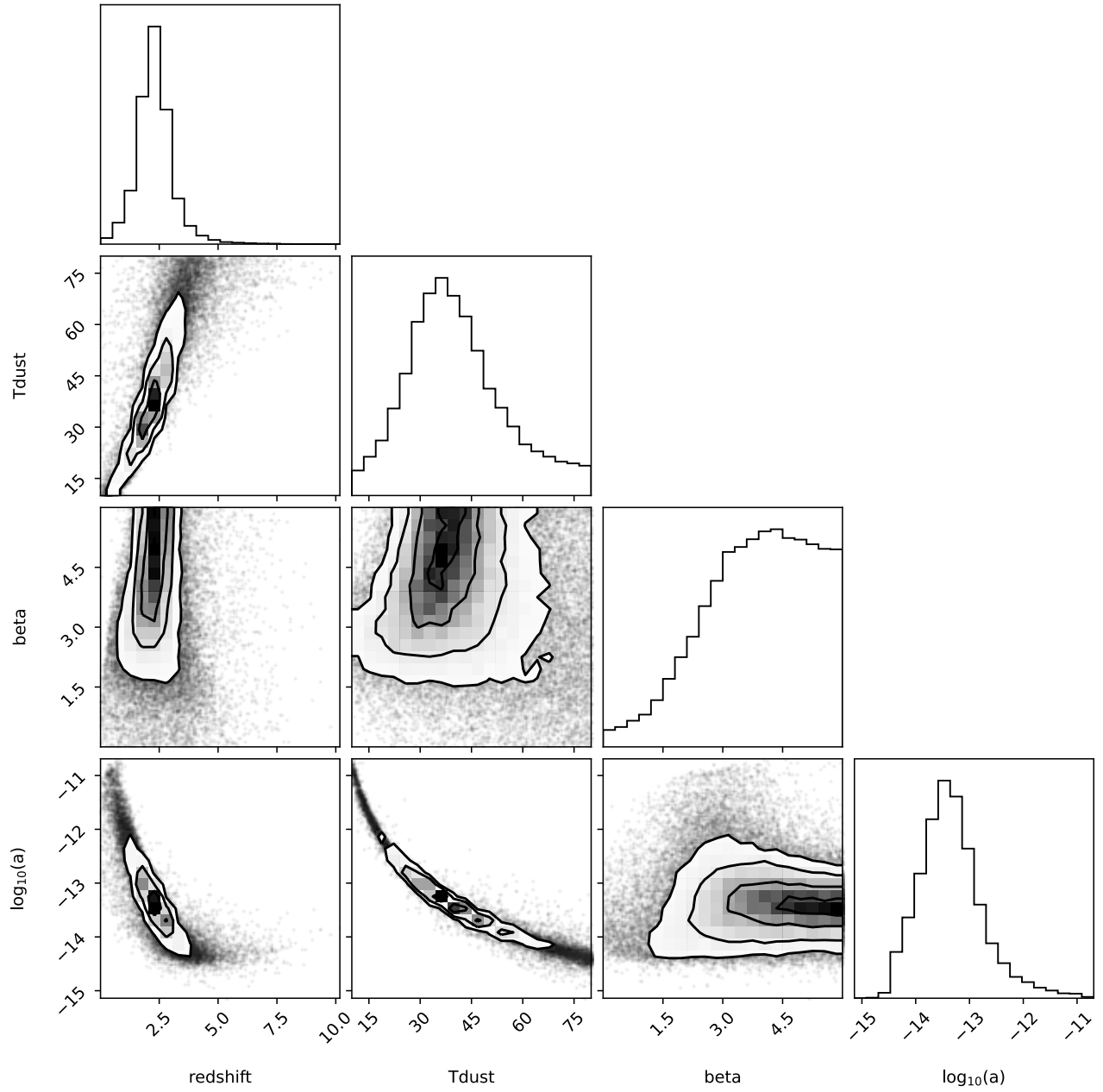


Figure 3.13: Continued: XMM-M5.

We then estimate the dust mass, FIR luminosity ( $L_{\text{FIR}}$ ) and associated dust-obscured SFR for each source in our sample. We estimate the dust mass via the equation

$$M_d = S_\nu D_L^2 [(1+z)\kappa_\nu B_\nu(T)]^{-1} \tau_\nu [1 - \exp(-\tau_\nu)]^{-1}, \quad (3.6)$$

where  $S_\nu$  is the flux density at rest-frame  $125\mu\text{m}$ ,  $D_L$  is the luminosity distance and  $\kappa_\nu$  is the dust opacity coefficient which is assumed to be  $2.64\text{m}^2\text{kg}^{-1}$  at  $125\mu\text{m}$  (Dunne et al., 2003b; Riechers et al., 2013; Greenslade et al., 2020). Given that we have SCUBA-2 photometry at  $850\mu\text{m}$ , we additionally calculate the dust mass using a second method which takes advantage of the fact that the FIR SED can be approximated as an optically thin modified blackbody at wavelengths longer than  $450\mu\text{m}$  where  $\tau \ll 1$  (Casey et al., 2014). We use the equation

$$M_d = \frac{S_{850} D_L^2}{\kappa_d(\nu) B_\nu(T)}, \quad (3.7)$$

where  $S_{850}$  is the  $850\mu\text{m}$  flux density from our SCUBA-2 observations and  $\kappa_\nu$  is assumed to be  $0.15\text{m}^2\text{kg}^{-1}$  at  $850\mu\text{m}$  (Weingartner and Draine, 2000; Dunne et al., 2003a; Casey, 2012; Clements et al., 2010a; U et al., 2012). We find that this second method generally produces slightly higher dust masses but, although the different dust estimates for Bootes27 are in slight disagreement ( $\log_{10}(M_d/M_\odot) = 9.55_{-0.44}^{+0.35}$  and  $10.10_{-0.11}^{+0.10}$  for the first and second methods respectively), the different estimates for Bootes15, Bootes24 and XMM-M5 agree within their respective error bars. For the remainder of the analysis, we follow Greenslade et al. (2020) and use the dust masses estimated using the first method. The FIR luminosity is defined as the integrated luminosity from  $42.5 - 122.5\mu\text{m}$  (Greenslade et al., 2020), and we calculate the dust-obscured SFR from this FIR luminosity based on the conversion factor from Riechers et al. (2013), assuming a Chabrier IMF (Chabrier, 2003a).

In Table 3.5 we present estimates for the photometric redshift, characteristic dust temperature and dust spectral emissivity index for our sources, as well as the dust mass, FIR luminosity and corresponding dust-obscured SFR. These estimates are based on the 16th, 50th and 84th

| Source   | $z$                    | $T_d$<br>K                | $\beta$                | $M_d$<br>$\times 10^9 M_\odot$ | $L_{\text{FIR}}$<br>$\times 10^{13} L_\odot$ | SFR<br>$M_\odot \text{yr}^{-1}$ |
|----------|------------------------|---------------------------|------------------------|--------------------------------|----------------------------------------------|---------------------------------|
| Bootes15 | $1.80^{+0.30}_{-0.25}$ | $37.02^{+14.88}_{-7.07}$  | $5.40^{+0.44}_{-1.18}$ | $11.75^{+9.63}_{-8.44}$        | $0.83^{+0.91}_{-0.42}$                       | $832^{+906}_{-424}$             |
| Bootes24 | $2.34^{+0.49}_{-0.54}$ | $36.84^{+12.40}_{-9.61}$  | $4.06^{+1.26}_{-1.32}$ | $8.51^{+9.69}_{-5.42}$         | $1.20^{+2.43}_{-0.85}$                       | $1202^{+1428}_{-847}$           |
| Bootes27 | $2.56^{+0.43}_{-0.48}$ | $48.06^{+14.84}_{-11.28}$ | $3.94^{+1.33}_{-1.51}$ | $3.63^{+4.50}_{-2.31}$         | $2.04^{+1.59}_{-1.15}$                       | $2042^{+1589}_{-1150}$          |
| XMM-M5   | $2.28^{+0.64}_{-0.63}$ | $38.80^{+16.19}_{-11.72}$ | $3.99^{+1.34}_{-1.51}$ | $5.50^{+8.31}_{-3.80}$         | $1.05^{+1.64}_{-0.80}$                       | $1047^{+1644}_{-796}$           |

Table 3.5: Photometric redshifts, characteristic dust temperatures and  $\beta$  values, as well as derived dust masses, FIR luminosities and corresponding SFRs based on the integrated FIR/sub-mm photometry for our  $500 \mu\text{m}$  risers.

percentiles of samples in the marginalised distributions. We note that there is a well known degeneracy between the redshift and dust temperature in this blackbody model and so, while we show all properties from our SED fitting routine in the interests of completeness, these values will not be used in the analysis. By contrast, the FIR luminosity, dust-obscured SFR and dust mass are known to be more robust to these degeneracies. We infer that our  $500 \mu\text{m}$  risers are typically HLIRGs, with FIR luminosities in excess of  $10^{13} L_\odot$ , and with corresponding SFRs of hundreds to thousands of solar masses per year. Our  $500 \mu\text{m}$  risers also have large dust masses, towards the higher end of the Greenslade et al. (2020) sample. This SED fitting routine typically predicts unrealistically high  $\beta$  values, well outside of the expected range from the literature and bumping up against the upper limits of our uninformative priors  $\beta < 6$ . The implications of these results will be discussed in more detail in Section 3.5.5, but we expect that these high  $\beta$  values are a natural consequence of their observed multiplicities.

### 3.5.2 Photometric Redshifts

Using the FIR/sub-mm photometry presented in Table 3.4, we can make simple estimates of their approximate photometric redshifts based on FIR/sub-mm colour-colour plots. This model-independent approach to estimating photometric redshifts is outlined in Cheng et al. (2019). By estimating the  $S_{250}/S_{350}$  and  $S_{350}/S_{850}$  colours for various template SEDs (including the local ULIRG Arp220, the average SED from the ALESS sample, the high redshift DSFG HFLS3 and the Cosmic Eyelash) at different redshifts in the range  $z = 0 - 4.5$ , Cheng et al. (2019)

define two distinct regions in the  $S_{250}/S_{350}$  vs.  $S_{350}/S_{850}$  colour-colour plot, one most likely populated by galaxies at  $z \geq 2$ , and the other most likely populated by galaxies at  $1 < z < 2$ . In Figure 3.14 we present the  $S_{250}/S_{350}$  vs.  $S_{350}/S_{850}$  colour-colour diagram for our  $500\mu\text{m}$  risers, with purple and blue regions indicating the likely positions of  $z \geq 2$  and  $1 < z < 2$  DSFGs respectively. For Bootes27, we calculate the FIR/sub-mm for both the total system, and for each of the partially resolved sources associated with the SCUBA-2  $850\mu\text{m}$  detection by dividing the *Herschel* SPIRE flux density proportionally between the two components. These two components are shown as lighter red shapes in Figure 3.14, but we find that both inhabit a similar space in the FIR/sub-mm colour-colour diagram to the total system. We find that Bootes24, Bootes27 and XMM-M5 are all consistent with them lying at  $z \geq 2$  based on their FIR/sub-mm colours, while the photometric redshift of Bootes15 remains poorly constrained, primarily driven by the poor SCUBA-2  $850\mu\text{m}$  photometry.

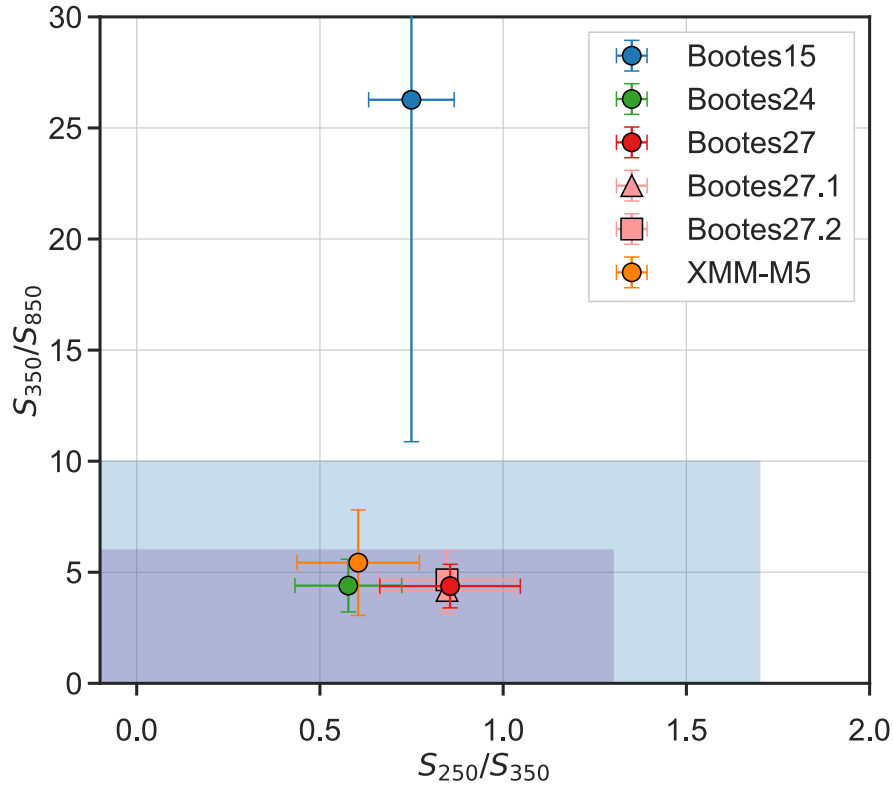


Figure 3.14:  $S_{250}/S_{350}$  vs.  $S_{350}/S_{850}$  colour-colour diagram for our four  $500\mu\text{m}$  risers. The purple and blue regions indicate likely colours for  $z \geq 2$  and  $1 < z < 2$  DSFGs respectively. Bootes24, Bootes27 and XMM-M5 are all consistent with  $z \geq 2$ , while Bootes15 remains unconstrained due to the poor SCUBA-2 photometry.

As an independent estimate of the photometric redshift, we additionally run the MMPZ al-

gorithm<sup>14</sup> (Casey, 2020) which estimates redshifts by determining where the FIR/mm SED is most consistent with the observed  $L_{\text{IR}} - \lambda_{\text{peak}}$  relation (Lee et al., 2013; Strandet et al., 2016; Casey et al., 2018; Casey, 2020; Casey et al., 2021b). We use the integrated FIR photometry for each source, including the *Herschel* SPIRE and SCUBA-2 photometry, and obtain a photometric redshift PDF for each of our  $500\,\mu\text{m}$  risers, which we present in Figure 3.15. Based on the upper and lower 68% credible intervals, we find likely photometric redshifts of  $1.83^{+1.33}_{-1.80}$  for Bootes15,  $3.03^{+1.02}_{-0.90}$  for Bootes24,  $2.53^{+0.83}_{-0.70}$  for Bootes27,  $2.88^{+1.02}_{-0.90}$  for XMM-M5. These values are in good agreement with the FIR/sub-mm colours, and we infer that Bootes24, Bootes27 and XMM-M5 likely lie at  $z \gtrsim 2$ . We note that, similarly to the results of the FIR/sub-mm colours discussed in the previous section, the photometric redshift of Bootes15 remains essentially unconstrained due to the poor SCUBA-2 photometry. We note that subtracting off the likely additional flux density contributed at  $350\,\mu\text{m}$  and  $500\,\mu\text{m}$  by the contaminating sources for Bootes15 and Bootes27 discussed in Section 3.4.1 makes no significant difference to the FIR/sub-mm colours or the results from MMPZ.

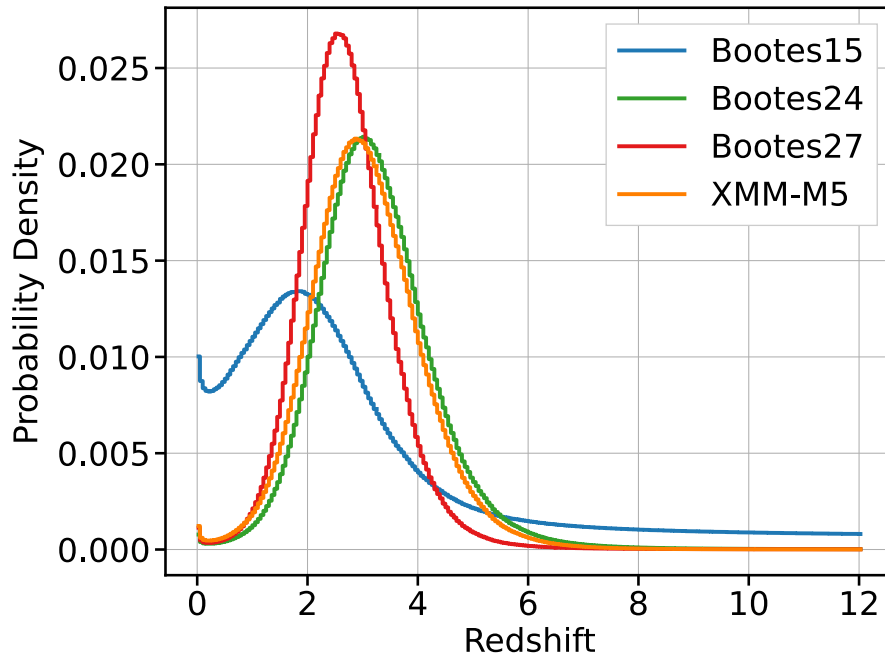


Figure 3.15: The full probability density functions for the photometric redshifts of our four  $500\,\mu\text{m}$  risers estimated by MMPZ. We find that, similarly to our results based on their FIR/sub-mm colours, Bootes24, Bootes27 and XMM-M5 are all reasonably well constrained, and likely lie at  $z \sim 2 - 4$ . Bootes15 remains poorly constrained, primarily due to a lack of quality SCUBA-2  $850\,\mu\text{m}$  photometry.

<sup>14</sup><http://www.as.utexas.edu/~cmcasey/mmpz.html>

We also attempt a simple deblending, using MMPZ to provide a rough estimate of the photometric redshift of the resolved sources associated with each  $500\mu\text{m}$  riser. For Bootes15 and Bootes24, we divide the *Herschel* SPIRE and SCUBA-2 photometry for the total systems proportionally based on the flux densities of the resolved SMA sources. For Bootes27, we divide the *Herschel* SPIRE flux proportionally between the two partially resolved components of the SCUBA-2 detection. We then run MMPZ once more on this naively deblended photometry. For the two deblended Bootes15 sources, we estimate photometric redshifts of  $1.53^{+1.86}_{-1.50}$  and  $1.53^{+1.95}_{-1.50}$ , while for the two SCUBA-2 components associated with Bootes27, we estimate photometric redshifts of  $2.78^{+0.65}_{-0.75}$  and  $2.78^{+0.70}_{-0.75}$ . The SMA flux densities of the two sources associated with Bootes24 are equal, and so we estimate a photometric redshift of  $2.88^{+0.90}_{-0.90}$  for each. We additionally note that the full photometric redshift PDFs for these deblended sources are very similar to those based on the integrated flux densities of the  $500\mu\text{m}$  risers, and so they are not included in Figure 3.15.

### 3.5.3 Multi-wavelength SED Fitting for Bootes15.SMA1

We build up the multi-wavelength SED for Bootes15.SMA1 based on optical data from the DESI Legacy Survey in the  $g$ ,  $r$  and  $z$  bands,  $3.6\mu\text{m}$  and  $4.5\mu\text{m}$  photometry extracted from archival IRAC maps and the 345 GHz SMA continuum flux density. We run this photometry through the SED fitting code **CIGALE** (Boquien et al., 2019). The primary benefits of **CIGALE** compared to other SED modelling programs are its ease of use and the variety and flexibility of its models, producing FUV to radio SED templates based on composite stellar populations produced by a variety of star formation histories, as well as the emission from ionised gas, both of which can be attenuated by a range of dust attenuation models (Boquien et al., 2019). Moreover, **CIGALE** is based on an ‘energy-balance’ principle, such that the stellar light is self-consistently absorbed and re-emitted at infrared wavelengths (Boquien et al., 2019). In Table 3.6 we outline our choice of modules for the **CIGALE** SED fitting, as well as the parameter ranges chosen within those models.

In Figure 3.16, we present the best fitting model SED and the full photometric redshift PDF



| Module                     | Parameter          | Parameter Range                        |
|----------------------------|--------------------|----------------------------------------|
| sfhdelayedbq               | tau_main [Myr]     | 100, 200, 500, 1000, 1500              |
|                            | age_main [Myr]     | 100, 200, 500, 1000, 1500              |
|                            | age_bq [Myr]       | 10, 20, 50, 100                        |
|                            | r_sfr              | 0.1, 0.3, 0.5, 0.8, 1.0, 1.5, 2.0, 5.0 |
| bc03                       | imf                | Chabrier                               |
|                            | metallicity        | 0.02                                   |
| nebular                    | logU               | -2.0                                   |
|                            | lines_width [km/s] | 300.0                                  |
| dustatt_modified_starburst | E_BV_lines         | 0.2, 0.4, 0.6, 0.8                     |
|                            | E_BV_factor        | 0.2, 0.4, 0.6, 0.8                     |
|                            | Rv                 | 3.1                                    |
| dale_2014                  | fracAGN            | 0.0                                    |
|                            | alpha              | 0.065, 1.0, 2.0, 3.0, 4.0              |
| redshifting                | redshift           | $z = 0 - 6$ in steps of 0.1            |

Table 3.6: List of the modules and the main parameters (with associated parameter ranges) allowed in the CIGALE SED fitting for Bootes15.SMA1.

for Bootes15.SMA1 produced by CIGALE. From this SED fitting, we infer that Bootes15.SMA1 lies at  $z \sim 1 - 2$ , with a best fit redshift of  $z = 1.65 \pm 0.39$  based on the marginalised likelihood distribution. Unfortunately, the SFR and stellar mass of Bootes15.SMA1 remain essentially unconstrained, likely due to the small number of photometric bands to which we fit the SED model. This is demonstrated by the extremely low reduced chi-squared value of  $\chi^2_\nu = 0.036$ , indicating significant overfitting caused by the large number of possible models compared to the small number of photometric points. Assuming that the photometric redshift estimate for Bootes15.SMA1 is representative of the  $500 \mu\text{m}$  riser system, this results indicates that Bootes15 may lie at a somewhat lower redshift than the other sources in our  $500 \mu\text{m}$  riser sample. We additionally note that if we divide the observed *Herschel* SPIRE and SCUBA-2 flux density equally between the two resolved SMA detections associated with Bootes15, the resulting best fit SED from CIGALE predicts similar results, with a slightly lower photometric redshift estimate of  $z = 1.41 \pm 0.22$ .

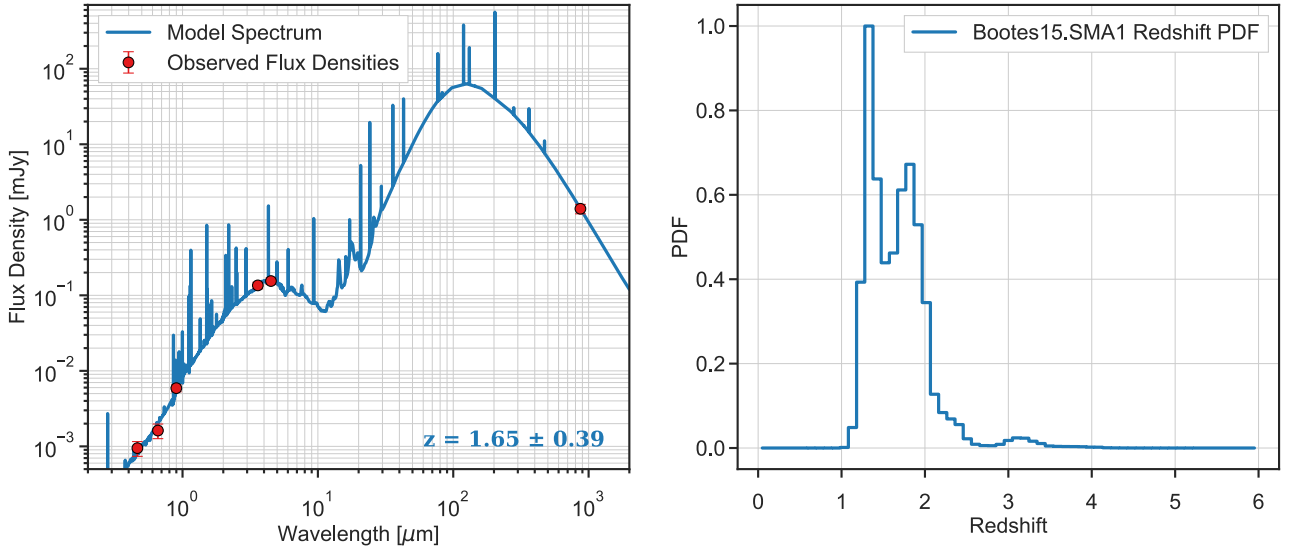


Figure 3.16: The best fitting SED model (*left*) and the full photometric redshift PDF (*right*) estimated by **CIGALE** for Bootes15.SMA1. This SED fitting indicates that Bootes15.SMA likely resides at  $z = 1 - 3$ , with a best fitting photometric redshift of  $z = 1.65 \pm 0.39$ . Assuming that the redshifts of the resolved sources are representative of the photometric redshifts estimated for the total  $500\mu\text{m}$  systems, we infer that Bootes15 likely lies at a somewhat lower redshift than the other  $500\mu\text{m}$  risers in the sample.

### 3.5.4 IRAC Sources Associated with Bootes27

Finally, we focus on the numerous bright and apparently red IRAC sources coincident with Bootes27. Section 3.4.2 outlines the IRAC and IBIS photometry extracted for the seven IRAC sources within the SCUBA-2  $850\mu\text{m}$  contours. None of these sources were detected in the  $g$ ,  $r$  and  $z$  band images or catalogues, and so we extracted  $3\sigma$  upper limits at these wavelengths. We then followed the same SED fitting method as discussed in the previous section, with the **CIGALE** modules and parameter ranges presented in Table 3.6.

In Figure 3.17 we show the positions and best fitting photometric redshifts from **CIGALE** for each of the IRAC sources, as well as their full photometric redshift PDFs. The four IRAC  $8\mu\text{m}$  sources with multi-peaked photometric redshift PDFs are only detected at  $8\mu\text{m}$  in the optical/NIR ancillary data. This results in significant degeneracies in the best fitting photometric redshift, due to multiple different galaxy spectra at different redshifts being well fit to the single photometric data point and upper limits. While the IRAC source with the highest estimated redshift has  $z = 5.71 \pm 0.69$ , the best fitting SED model for this source has a redshift of  $z = 1.6$ , and so it is likely that **CIGALE** has trouble fitting a plausible SED model to the

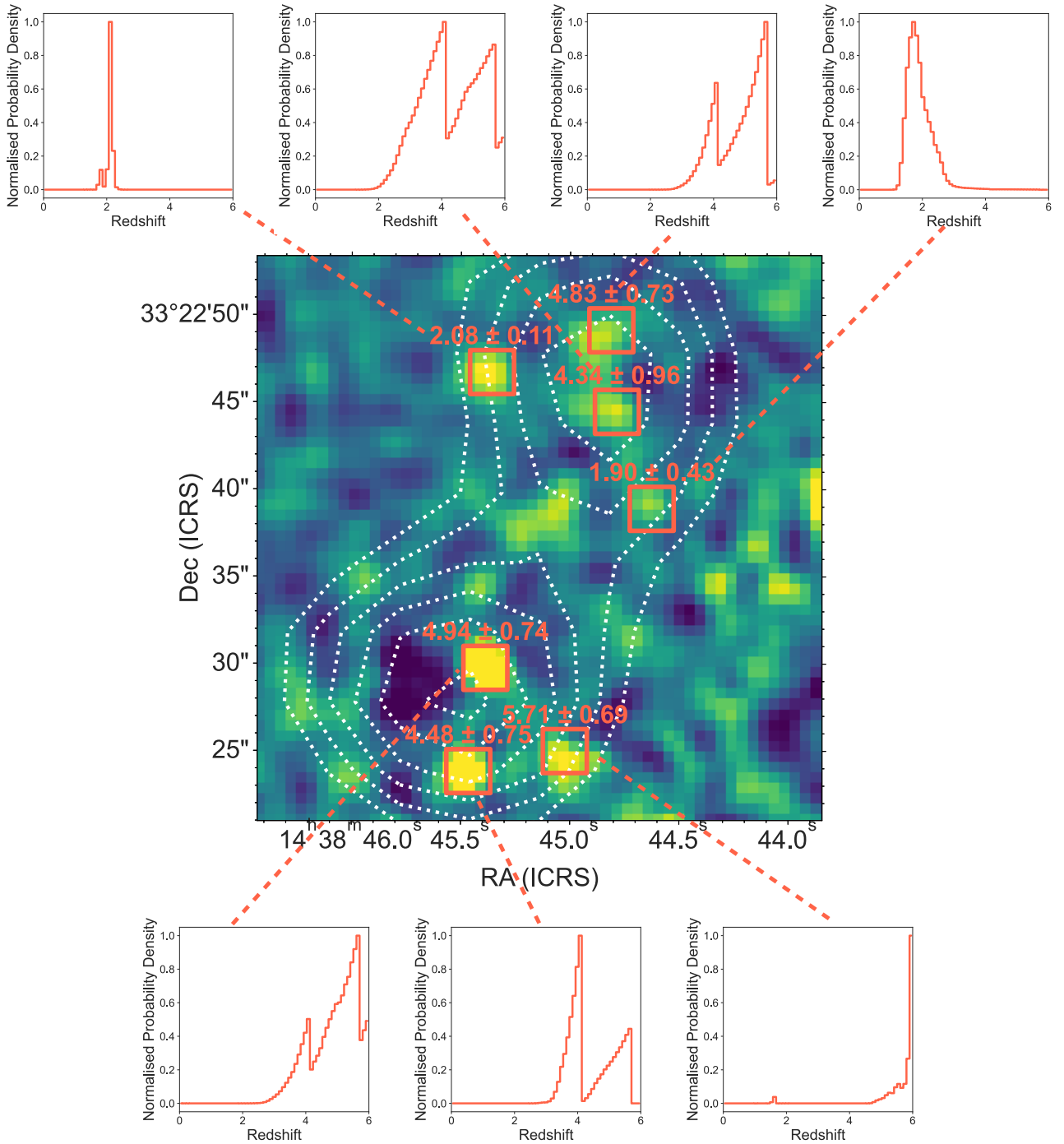


Figure 3.17: The positions and corresponding best fitting photometric redshifts estimated by CIGALE for the seven IRAC sources lying within the SCUBA-2 850  $\mu\text{m}$  contours of Bootes27. For each source, we additionally show the full photometric redshift PDFs. These PDFs demonstrate that there is significant uncertainty in the true photometric redshift, but there is a clear preference for these IRAC sources to reside at  $z \sim 2$  or higher.

available photometry for this source (which includes  $J$ ,  $H$  and  $K_s$  flux densities from IBIS as well as detections in both IRAC bands). For the remaining two sources, **CIGALE** estimates redshifts of  $z \sim 2$ . While there is significant variation and uncertainty in the exact photometric redshift estimates from **CIGALE** for these sources, we infer that all of them are more likely to lie at higher redshifts ( $z \gtrsim 2$ ) than lower redshifts. These estimates are in line with the photometric redshift estimates for the total Bootes27 system based on the FIR/sub-mm colour-colour diagram ( $z \geq 2$ ) and the results from MMPZ ( $z \sim 2 - 3.5$ ). Clearly, additional photometric or spectroscopic follow-up observations will be required to better constrain the redshifts of these bright IRAC  $8\mu\text{m}$  sources.

### 3.5.5 Summary and Caveats

Before moving on to investigate the wider environments surrounding our  $500\mu\text{m}$  risers, there are numerous caveats to the aforementioned SED fitting analysis that are worthy of note. Our FIR/sub-mm observations have revealed that 3/4 of our  $500\mu\text{m}$  risers resolve into two individual sources, and additional analysis comparing the SMA and SCUBA-2 flux densities and morphologies suggests that there may be additional, faint sources which we are currently unable to detect. We infer that our sources are typically multiple systems, and this multiplicity likely affects the total, integrated SEDs of the  $500\mu\text{m}$  risers in numerous ways.

First and foremost, we find that, rather than being intrinsically red, high redshift sources, our  $500\mu\text{m}$  risers are representative of the population lying at more moderate redshifts that have been artificially reddened due to the successively larger beamsizes of the *Herschel* SPIRE instrument at  $250\mu\text{m}$ ,  $350\mu\text{m}$  and  $500\mu\text{m}$  exacerbating the effects of blending at longer wavelengths compared to shorter wavelengths (see e.g. Bussmann et al., 2015; Duivenvoorden et al., 2018). This effect is clearly demonstrated by Ma et al. (2019) and Montaña et al. (2021), who find that  $\sim 20\%$  and  $\sim 25\%$  of their samples respectively would no longer be strictly defined as  $500\mu\text{m}$  after the effects of blending have been accounted for. Moreover, as discussed in Section 3.4.1, we find that our SCUBA-2 observations likely miss some fraction of the integrated  $850\mu\text{m}$  flux density associated with Bootes15, as it is much fainter at  $850\mu\text{m}$  than other sources

with similar flux densities in the *Herschel* SPIRE bands. We predict that the combination of undetected flux at  $850\mu\text{m}$  and exacerbated blending within the large *Herschel* beamsize at  $500\mu\text{m}$  would produce an artificially steep Rayleigh-Jeans tail, leading to significant difficulties in interpreting the resulting galaxy properties. Indeed, Table 3.4 and Figure 3.13 demonstrate that the integrated FIR/sub-mm SEDs of our  $500\mu\text{m}$  risers are best fit by unrealistically high  $\beta$  values, resulting from the extremely steep Rayleigh-Jeans tails shown in the best-fit SEDs in Figure 3.12.

For a more robust SED analysis, we would therefore need to carry-out accurate de-blending of the resolved sources within the *Herschel* SPIRE beam. However, as outlined in Section 3.4.2, there is a dearth of quality multi-wavelength ancillary data available for our  $500\mu\text{m}$  risers due to their positions towards the edge of the Bootes field. We also expect there to be additional faint sources contributing to the integrated FIR/sub-mm flux density that remain undetected in even our deeper SMA observations, particularly for Bootes24 and Bootes27, and so it is possible that de-blending based on our current understanding of the resolved nature of these sources would lead to misleading results. Moreover, the simple de-blending completed in Section 3.5.2 made no significant difference to the estimated photometric redshift estimate for the resolved sources. Given these difficulties, we do not attempt a more rigorous SED fitting based on de-blended *Herschel* and SCUBA-2 photometry. Moreover, in the following analysis, while we discuss the results of the modified blackbody SED fitting procedure in the interests of completeness, we rely primarily on the FIR/sub-mm colours when discussing the photometric redshift estimates for our  $500\mu\text{m}$  risers, and we do not make any significant conclusions based on their rather uncertain galaxy properties.

## 3.6 The Wider Environment

### 3.6.1 Overdensities of SMGs

Based on the SCUBA-2 detected sources in the surrounding field (see Figure 3.6), we aim to investigate whether our  $500\mu\text{m}$  risers are placed within overdensities of sub-mm bright galaxies by constructing cumulative number counts in each region. We construct these cumulative number counts in steps of 1 mJy before applying an effective area correction accounting for the variable noise across the SCUBA-2 maps. In order to calculate the effective area correction for each source, we use their extracted flux densities prior to deboosting and find the threshold RMS noise value above which the source would no longer be detected to  $\text{SNR} > 4$ . We find the number of pixels in the map with a standard deviation below this threshold value, multiply by the area of one pixel to find the effective area ( $A_e$ ) over which the source could be detected in the SCUBA-2 map, before converting into units of ‘map size’, where one map is equal to the area of the  $700''$  diameter circular region over which sources were extracted. Each source then effectively contributes  $1/A_e$  to the cumulative number counts (Wang et al., 2017). We note that the  $500\mu\text{m}$  risers themselves are excluded from the cumulative number count calculations as they were selected to lie within the SCUBA-2  $850\mu\text{m}$  maps.

We then calculate the overdensity values in each map based on the expected cumulative number counts in field regions from S2CLS. We multiply the cumulative number counts per square degree presented in Table 4 in Geach et al. (2017) by our map area in square degrees to match our units of cumulative number counts per map size. In Figure 3.18, we then compare the cumulative number counts in the regions of our  $500\mu\text{m}$  risers to the expected number of field counts from S2CLS. We estimate quantitative overdensity values at each flux density level using Poisson statistics following Cheng et al. (2019). The probability of observing a given number of sources based on an expected number of sources can be calculated using the Poisson probability mass function

$$f(k) = \exp(-\mu) \frac{\mu^k}{k!}, \quad (3.8)$$

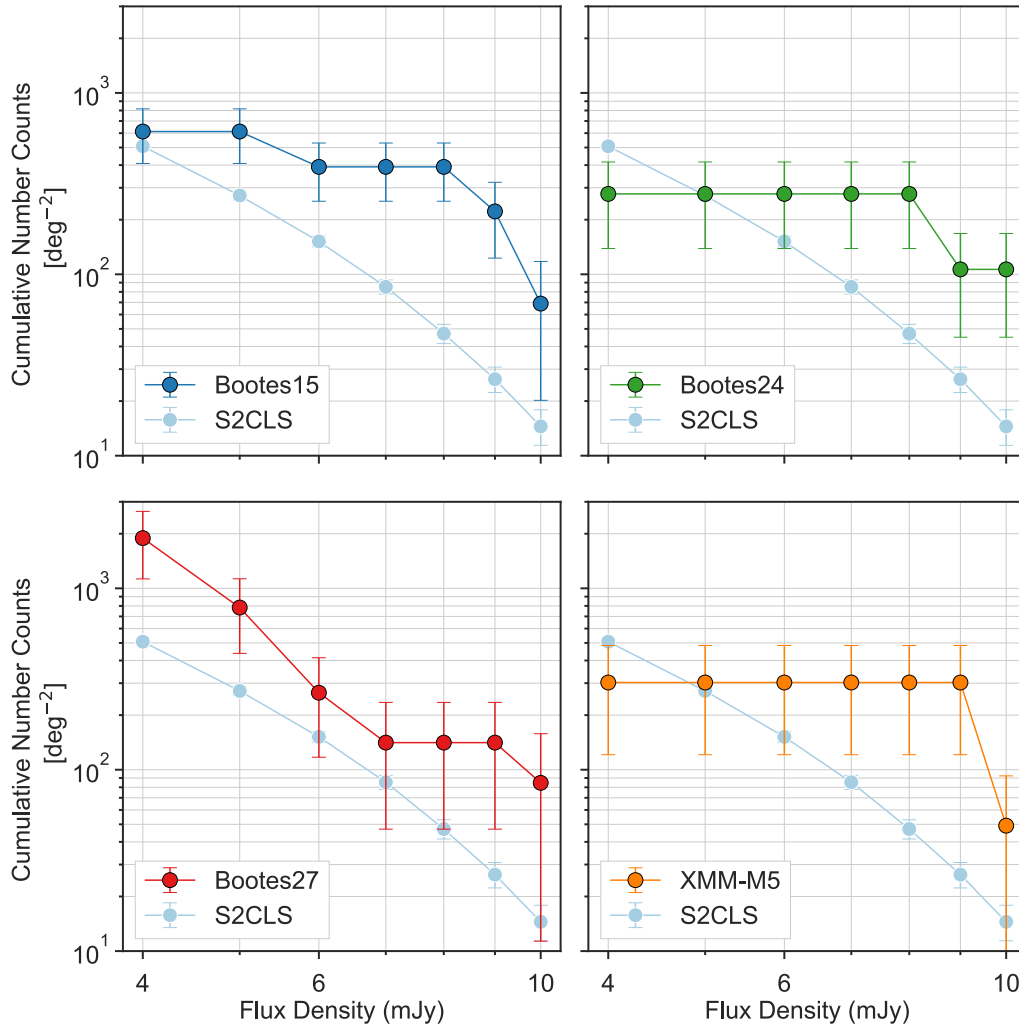


Figure 3.18: Cumulative number counts for the four 500  $\mu\text{m}$  riser fields, plotted alongside the expected cumulative number counts in the field from S2CLS. The Bootes15, Bootes24 and XMM-M5 fields are overdense in bright ( $S_{850} \gtrsim 8 \text{ mJy}$ ) sub-mm sources.

where, in our case,  $k$  is the number of observed counts and  $\mu$  is the expected number of counts from S2CLS. The overdensity level itself is then calculated via the equation

$$\delta = \frac{k - \mu}{\sqrt{\mu}}, \quad (3.9)$$

and we propagate Poissonian errors on the observed and expected number of counts to estimate errors on these overdensity values, additionally folding in the uncertainties due to the reliability in the observed maps based on the jackknifing analysis discussed in Section 3.3.2.

Based on our cumulative number counts analysis, we infer that Bootes15, Bootes24 and XMM-

M5 are all consistent with residing in regions overdense in SMGs. We find that Bootes15 hosts an overdensity of  $8.6 \pm 3.5$  of SMGs brighter than 8 mJy, Bootes24 hosts a more moderate overdensity of  $5.8 \pm 3.5$  of SMGs brighter than 8 mJy, and XMM-M5 hosts an overdensity of  $9.3 \pm 6.5$  of sources brighter than 9 mJy. The probabilities of observing these numbers of sources in a random field are  $2.8 \times 10^{-7}$ ,  $1.1 \times 10^{-4}$  and  $1.8 \times 10^{-6}$  respectively. By comparison, Bootes27 does not appear to show any reliable evidence of an overdensity. While there appears to be a significant overdensity of sources brighter than 4 mJy at  $850\mu\text{m}$  in the Bootes27 region, this is driven entirely by a single source with a deboosted flux density of  $\sim 4.9$  mJy that would only be detected to  $\text{SNR} > 4$  over less than 5% of the total map area. This results in a large effective area correction producing an artificially high overdensity value. If this single source is removed from the Bootes27 region, we find no significant overdensity.

### 3.6.2 Cross-Matching with HerMES Sources

In order to further investigate the sources that make up these potential overdensities, we cross-match the  $\text{SNR} > 4$  detected sources in the SCUBA-2  $850\mu\text{m}$  maps with the HerMES (Oliver et al., 2012) catalogues. Based on a similar analysis, Cheng et al. (2019) identified an optimal search radius for cross-matching SCUBA-2 and *Herschel* SPIRE sources of  $9''$ , or approximately half of the FWHM of the *Herschel* SPIRE beam at  $250\mu\text{m}$ , such that any *Herschel* source within  $9''$  of a SCUBA-2 detection were considered robust counterparts. Based on this cross-matching process, we find that 3/9 (33%), 2/4 (50%), 3/7 (43%) and 3/5 (60%) of the SCUBA-2 detections have *Herschel* counterparts for the Bootes15, Bootes24, Bootes27 and XMM-M5 regions respectively, excluding the  $500\mu\text{m}$  riser sources themselves. In Table 3.7, we assemble the FIR/sub-mm photometry from SCUBA-2 and *Herschel* for these SCUBA-2 detected sources in the surrounding field.



| Source       | RA<br>J2000 | Dec<br>J2000 | $S_{250\mu m}$<br>mJy | $S_{350\mu m}$<br>mJy | $S_{500\mu m}$<br>mJy | $S_{850\mu m}$<br>mJy |
|--------------|-------------|--------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Bootes15.SC1 | 14:39:46.10 | +34:35:18.74 | $0.0 \pm 3.5$         | $15.0 \pm 2.3$        | $13.4 \pm 2.7$        | $11.7 \pm 3.1$        |
| Bootes15.SC2 | 14:40:17.23 | +34:36:45.19 | $6.8 \pm 2.8$         | $24.1 \pm 3.0$        | $0.0 \pm 4.4$         | $6.0 \pm 1.7$         |
| Bootes15.SC3 | 14:39:54.99 | +34:39:24.67 | $25.0 \pm 2.3$        | $40.1 \pm 2.3$        | $32.9 \pm 3.0$        | $9.1 \pm 2.1$         |
| Bootes24.SC1 | 14:36:27.67 | +33:03:05.02 | $46.1 \pm 2.2$        | $48.2 \pm 2.6$        | $28.7 \pm 4.1$        | $15.3 \pm 2.5$        |
| Bootes24.SC2 | 14:36:20.49 | +33:06:29.46 | $73.7 \pm 2.3$        | $79.5 \pm 2.4$        | $57.0 \pm 3.2$        | $18.7 \pm 4.8$        |
| Bootes27.SC1 | 14:38:51.21 | +33:20:55.74 | $19.6 \pm 2.3$        | $26.8 \pm 2.3$        | $29.0 \pm 2.7$        | $5.7 \pm 1.4$         |
| Bootes27.SC2 | 14:38:37.17 | +33:23:12.26 | $47.9 \pm 2.3$        | $25.4 \pm 2.3$        | $26.5 \pm 3.2$        | $6.5 \pm 1.6$         |
| Bootes27.SC3 | 14:38:39.71 | +33:23:27.66 | $564.2 \pm 4.6$       | $219.7 \pm 10.2$      | $83.8 \pm 17.8$       | $11.3 \pm 1.6$        |
| XMM-M5.SC1   | 02:19:14.18 | −04:37:38.09 | $25.7 \pm 1.0$        | $37.7 \pm 1.1$        | $37.9 \pm 1.4$        | $10.5 \pm 3.5$        |
| XMM-M5.SC2   | 02:18:35.31 | −04:36:02.25 | $15.4 \pm 1.1$        | $14.6 \pm 1.0$        | $7.7 \pm 1.3$         | $13.7 \pm 3.9$        |
| XMM-M5.SC3   | 02:18:57.87 | −04:33:51.44 | $81.5 \pm 1.1$        | $70.7 \pm 1.2$        | $40.9 \pm 1.9$        | $10.0 \pm 3.4$        |

Table 3.7: Positions and integrated FIR/sub-mm photometry for the  $\text{SNR} > 4$  SCUBA-2 detections with HerMES counterparts. *Herschel* SPIRE flux densities are taken from the corresponding HerMES catalogue.

### 3.6.3 Properties of the Surrounding SMGs

For each SCUBA-2 detected source in the surrounding field, we then carry out a similar analysis as for the  $500\mu m$  risers, in which we attempt to estimate the properties of each system based on their integrated FIR/sub-mm photometry. We first fit a modified blackbody function to the integrated FIR/sub-mm photometry for each source using the same methods outlined in Section 3.5.1. In Figure 3.19 we show the best fitting model SEDs for the SCUBA-2 detected sources and in Table 3.8 we present the resulting properties estimated from the SED fitting. We note that, for some of the SMGs, the modified blackbody SED fitting technique resulting in somewhat longer integrated autocorrelation times than for our  $500\mu m$  riser sources and so, where appropriate, we increase the number of steps used in `emcee` in order to ensure that the chain is always longer than  $50\tau$ , and hence that we will likely obtain convergence in the MCMC fitting.

As well as the SED fitting procedure, we estimate the photometric redshifts for these SMGs using the same methods as for the  $500\mu m$  risers. In Figure 3.20 we show the positions of

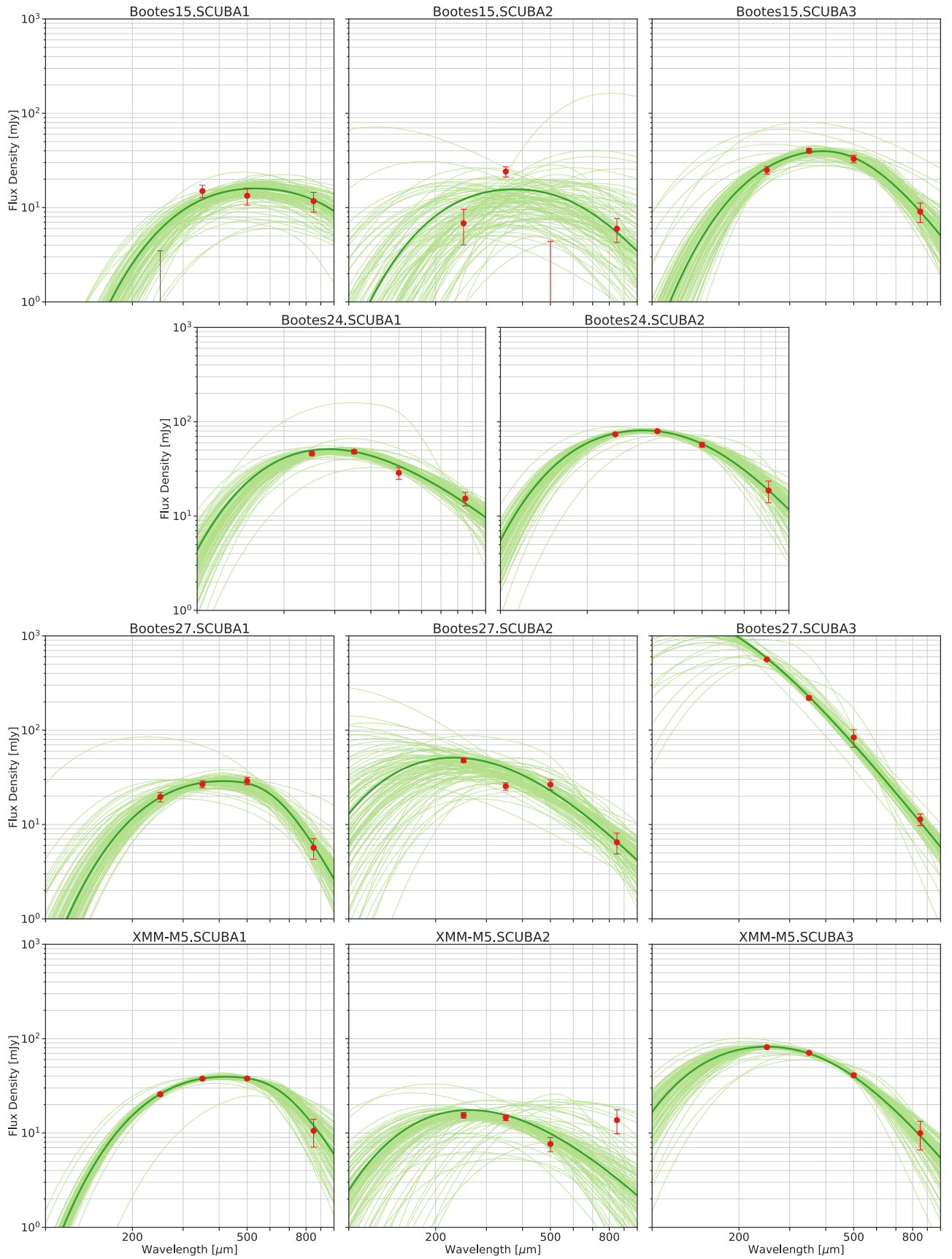


Figure 3.19: Resulting SED fits from the `emcee` ensemble sampler for the SMGs in the wider field. Light green lines show 100 random samples while the dark green line shows the best fitting SED. Red points show the integrated FIR photometry from *Herschel* SPIRE and SCUBA-2.

| Source       | $z$                    | $T_d$<br>K                | $\beta$                | $M_d$<br>$\times 10^9 M_\odot$ | $L_{\text{FIR}}$<br>$\times 10^{13} L_\odot$ | SFR<br>$M_\odot \text{yr}^{-1}$ |
|--------------|------------------------|---------------------------|------------------------|--------------------------------|----------------------------------------------|---------------------------------|
| Bootes15.SC1 | $5.29^{+1.72}_{-1.90}$ | $60.08^{+14.13}_{-21.13}$ | $2.64^{+2.26}_{-1.86}$ | $1.23^{+2.08}_{-0.74}$         | $4.47^{+5.31}_{-3.44}$                       | $4467^{+5306}_{-3444}$          |
| Bootes15.SC2 | $3.24^{+2.10}_{-1.59}$ | $57.57^{+16.21}_{-24.41}$ | $2.41^{+2.29}_{-1.68}$ | $0.55^{+2.08}_{-0.41}$         | $1.05^{+3.12}_{-0.92}$                       | $1047^{+3122}_{-924}$           |
| Bootes15.SC3 | $2.16^{+0.72}_{-0.78}$ | $38.01^{+13.75}_{-13.25}$ | $2.84^{+1.48}_{-0.80}$ | $3.31^{+2.85}_{-1.65}$         | $0.78^{+1.46}_{-0.67}$                       | $776^{+1462}_{-667}$            |
| Bootes24.SC1 | $2.80^{+0.69}_{-1.33}$ | $63.27^{+12.66}_{-24.01}$ | $1.02^{+1.38}_{-0.62}$ | $0.56^{+0.53}_{-0.19}$         | $3.39^{+2.64}_{-2.95}$                       | $3388^{+2637}_{-2952}$          |
| Bootes24.SC2 | $2.69^{+0.63}_{-0.86}$ | $59.83^{+12.88}_{-18.35}$ | $2.03^{+1.75}_{-0.81}$ | $1.66^{+1.36}_{-0.66}$         | $4.79^{+3.73}_{-3.47}$                       | $4786^{+3725}_{-3468}$          |
| Bootes27.SC1 | $2.45^{+0.34}_{-0.36}$ | $42.38^{+8.30}_{-6.94}$   | $4.38^{+1.08}_{-1.29}$ | $3.55^{+2.62}_{-1.85}$         | $0.93^{+0.58}_{-0.44}$                       | $933^{+580}_{-443}$             |
| Bootes27.SC2 | $1.95^{+0.86}_{-1.16}$ | $62.60^{+12.74}_{-21.32}$ | $1.57^{+2.24}_{-1.12}$ | $0.35^{+0.88}_{-0.24}$         | $1.12^{+1.57}_{-1.01}$                       | $1122^{+1570}_{-1012}$          |
| Bootes27.SC3 | $0.22^{+0.22}_{-0.15}$ | $61.54^{+12.97}_{-17.61}$ | $1.96^{+0.29}_{-0.21}$ | $0.22^{+0.42}_{-0.19}$         | $0.24^{+0.81}_{-0.22}$                       | $240^{+807}_{-223}$             |
| XMM-M5.SC1   | $2.82^{+0.50}_{-0.41}$ | $46.22^{+6.88}_{-5.82}$   | $3.94^{+1.36}_{-1.49}$ | $3.80^{+3.28}_{-1.90}$         | $2.04^{+1.43}_{-0.89}$                       | $2042^{+1426}_{-894}$           |
| XMM-M5.SC2   | $2.28^{+1.25}_{-1.02}$ | $60.65^{+14.16}_{-21.78}$ | $1.39^{+2.25}_{-1.01}$ | $0.18^{+0.42}_{-0.09}$         | $0.65^{+1.17}_{-0.55}$                       | $646^{+1174}_{-550}$            |
| XMM-M5.SC3   | $1.90^{+0.36}_{-0.65}$ | $58.63^{+10.86}_{-19.92}$ | $2.13^{+0.98}_{-0.57}$ | $0.98^{+0.50}_{-0.30}$         | $2.09^{+0.66}_{-1.61}$                       | $2089^{+665}_{-1611}$           |

Table 3.8: Photometric redshifts (estimated from our modified blackbody fit and from MMPZ), characteristic dust temperatures and  $\beta$  values, as well as derived dust masses, FIR luminosities and corresponding SFRs for the  $\text{SNR} > 4$  SCUBA-2 detections with HerMES counterparts.

these sources on the FIR/sub-mm colour-colour plot, along with the positions of the  $500 \mu\text{m}$  risers themselves. We additionally run the integrated FIR/sub-mm photometry for each source through MMPZ, and in Figure 3.21 we present the resulting photometric redshift estimates and associated uncertainties. In the interests of completeness, we additionally present in Figure 3.22 the full photometric redshift PDF for each of the SCUBA-2 detected SMGs, as well as for the  $500 \mu\text{m}$  risers themselves.

We note again that we cannot infer any reliable information from the photometric redshifts or dust temperatures from the modified blackbody SED fitting due to the well studied redshift-dust temperature degeneracy. We find that the dust spectral emissivity index that we estimate for these sources is broadly constrained within the typical values of  $\beta \approx 1 - 3$  found in the literature (Hildebrand, 1983; Dunne and Eales, 2001; Dupac et al., 2003; Yang and Phillips, 2007; Chapin et al., 2011; Casey et al., 2011; Casey, 2012; Spilker et al., 2014; Kato et al., 2018; Clements et al., 2018; Faisst et al., 2020a; Arendt et al., 2019; da Cunha et al., 2021; Casey et al., 2021b). While this does not provide any conclusive proof, we discussed in Section

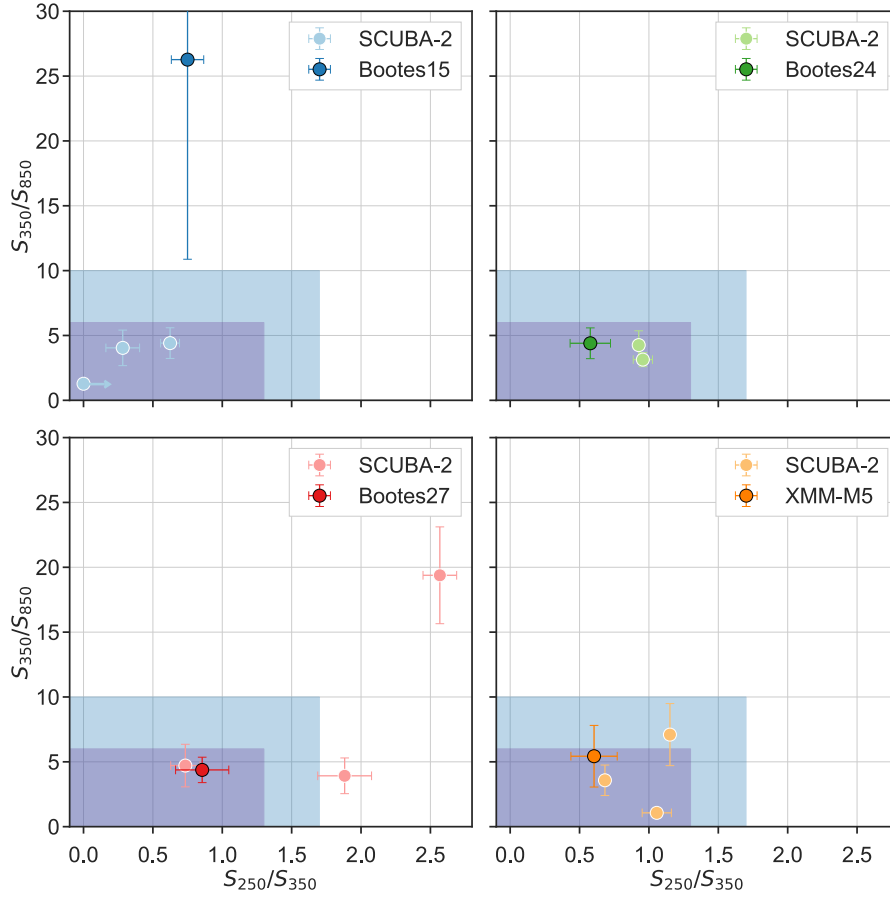


Figure 3.20:  $S_{250}/S_{350}$  vs.  $S_{350}/S_{850}$  colour-colour diagram for our four  $500\mu\text{m}$  risers. The purple region in the lower left corner, and the blue region surrounding it, indicate likely colours for  $z \geq 2$  and  $1 < z < 2$  DSFGs respectively. Bootes24, Bootes27 and XMM-M5 are all consistent with residing at  $z \geq 2$ , while Bootes15 remains unconstrained due to the poor SCUBA-2 photometry.

3.5.5 that the high  $\beta$  values for our  $500\mu\text{m}$  risers are likely driven by their multiplicities, and the lack of such high  $\beta$  values in these SCUBA-2 detected SMGs implies that the same effects are likely not affecting their integrated FIR/sub-mm photometry. The exceptions to this are Bootes27.SCUBA1 and XMM-M5.SCUBA1, both of which fulfil the  $500\mu\text{m}$  riser criterion. This could provide tentative evidence that these SMGs are also examples of multiple systems at moderate redshifts.

We find that the estimated dust masses and FIR luminosities place the sources towards the more extreme end of the DSFG population, with most satisfying the HLIRG criterion ( $L_{\text{FIR}} > 10^{13} L_{\odot}$ ), implying SFRs of thousands of solar masses per year. In terms of their photometric redshifts, we infer from the FIR/sub-mm colours that the three SMGs in the Bootes15 field with HerMES counterparts likely lie at  $z \geq 2$ , although MMPZ has significant difficulty in

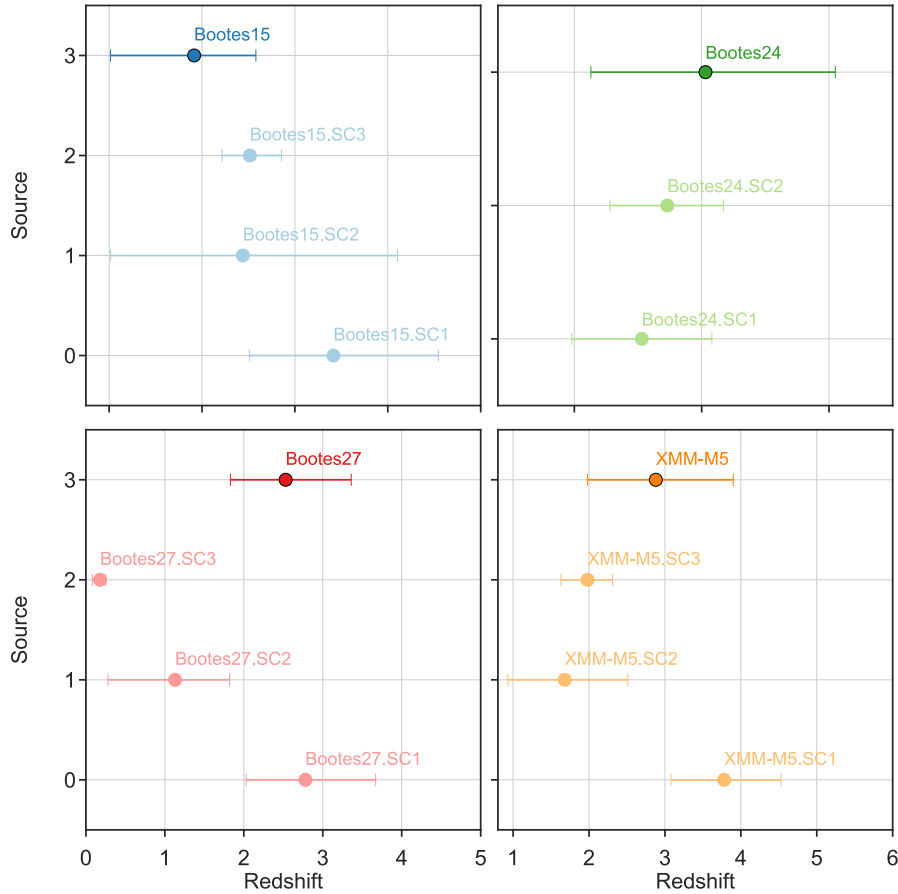


Figure 3.21: The photometric redshifts for our  $500\,\mu\text{m}$  risers and SCUBA-2 SNR  $> 4$  detected sources estimated by MMPZ. Similarly to the FIR/sub-mm colours, we find that the Bootes24 region is consistent with containing a physically associated overdensity of bright DSFGs, with well constrained photometric redshifts placing the surrounding SMGs at  $z \approx 2-3$ , and Bootes24 itself at  $z \approx 2-4$ . While the photometric redshift of XMM-M5 does overlap with those of the bright SCUBA-2 sources, there is a larger range of photometric redshifts, indicating that this region may be somewhat more complex. The DSFGs associated with Bootes15 do not have well constrained photometric redshifts, and the bright SCUBA-2 sources in the Bootes27 region are likely unassociated with each other.

estimating a reliable redshift for two of these sources. The two SMGs associated with the Bootes24 field have consistent photometric redshifts in both the FIR/sub-mm colour-colour diagram and from MMPZ, placing them at  $z \approx 2-3$ , similar to the redshift estimated for Bootes24 itself. Both methods of estimating the photometric redshift agree that the SMGs associated with the Bootes27 field are likely a line-of-sight projection, with each DSFG lying at a very different redshift. This is expected based on the very different SED shapes for these SMGs in Figure 3.19. Finally, the SMGs associated with the XMM-M5 field provide a somewhat more complicated picture. The FIR/sub-mm colour-colour diagram places two of these sources

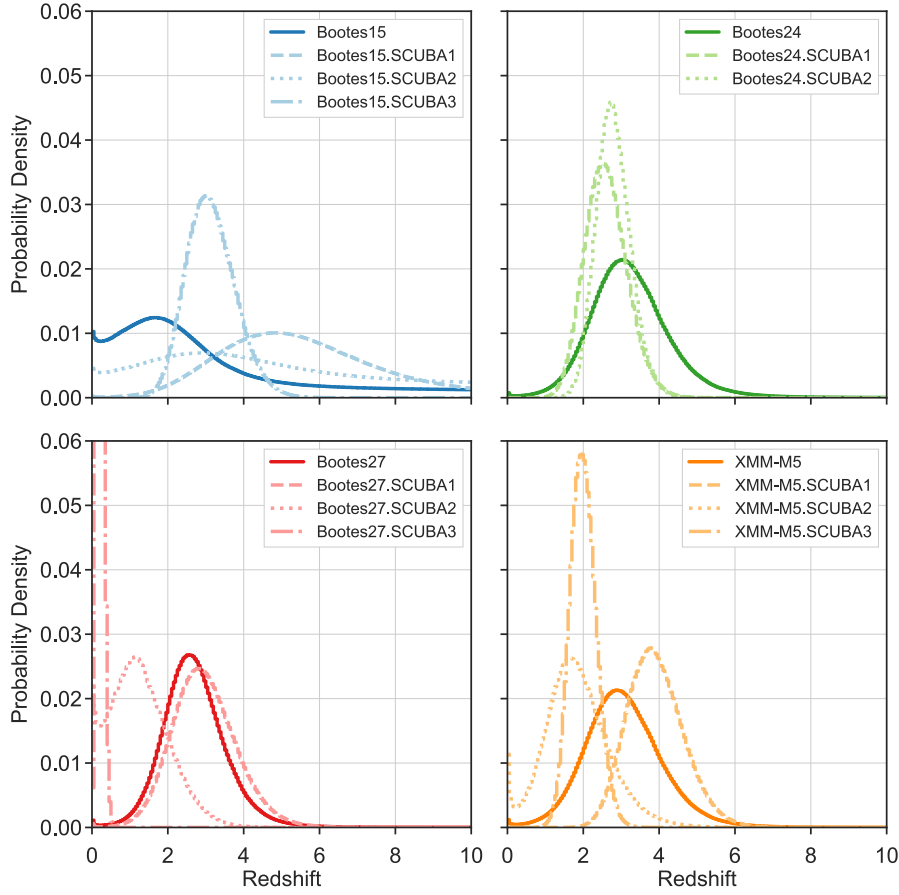


Figure 3.22: Normalised photometric redshift PDFs for our  $500\mu\text{m}$  risers and their associated  $\text{SNR} > 4$  SCUBA-2 detections estimated by MMPZ.

at  $z \geq 2$ , and the third at  $z \sim 2$ . Similarly, MMPZ places two of these SMGs at  $z \sim 2$  and the third at  $z \sim 4$ , with no crossover within the estimated error bars of their photometric redshifts. We note that both of the SMGs highlighted in the previous paragraph as meeting the  $500\mu\text{m}$  riser criterion are placed at a similar redshift to their respective  $500\mu\text{m}$  riser based on both their FIR/sub-mm colours and the results of MMPZ.

## 3.7 Discussion

### 3.7.1 Multiplicities

Of the four  $500\mu\text{m}$  risers from Greenslade et al. (2020) selected here for deeper SMA and SCUBA-2 follow-up observations, we find direct evidence of multiplicity in three of them.

Bootes15 and Bootes24 each break up into two resolved sources in the high-resolution SMA continuum images and show signs of extended emission in the SCUBA-2 maps. While resolving into a single source in the SMA maps, Bootes27 is clearly comprised of two partially resolved components in the SCUBA-2 map. We therefore suggest that a significant fraction of these  $500\mu\text{m}$  risers without counterparts in high resolution follow-up observations are indeed multiple systems. It is worth noting that we currently observe no direct evidence for the large multiplicities ( $\geq 3$ ) predicted by Greenslade et al. (2020) for these  $500\mu\text{m}$  risers although, given the discrepancies between the *Herschel* SPIRE, SCUBA-2 and SMA photometry and the significantly different resolutions probed by these three sets of observations, we cannot rule out the possibility of additional faint counterparts lying below our current detection limits. This is particularly true for Bootes15 and Bootes27, which we next discuss individually.

### Bootes15

We infer from Figures 3.8 and 3.9 that, while the SMA and SCUBA-2 photometry for Bootes15 agree quite well within the (rather large) error bars (with flux densities of  $2.6 \pm 1.5$  mJy and  $3.2 \pm 0.4$  mJy respectively), the SCUBA-2 photometry is much fainter than we would expect based on the *Herschel* SPIRE  $500\mu\text{m}$  flux density when compared to the S2CLS and STUDIES samples (see Figure 3.9). This discrepancy is likely due, at least in part, to the SCUBA-2 observations missing some fraction of the total sub-mm flux density from Bootes15, either in the form of extended, diffuse emission or additional faint, point-like sources lying below our detection threshold. Based on Figure 3.9, we suggest that a SCUBA-2  $850\mu\text{m}$  flux density of  $\sim 10 - 15$  mJy would make Bootes15 more consistent with the other  $500\mu\text{m}$  risers in this study, as well as the sources in the STUDIES and S2CLS samples. We therefore require an additional  $\sim 7 - 12$  mJy of undetected flux density to bring Bootes15 more in line with the observed samples and, with a  $1\sigma$  RMS noise in the  $850\mu\text{m}$  SCUBA-2 map of 2.2 mJy/beam, this additional flux density could be comfortably provided by 1 – 2 undetected sources, assuming a  $\text{SNR} > 3$  detection threshold.

However, if we assume that the true flux density of Bootes15 is  $\sim 10 - 15$  mJy at  $850\mu\text{m}$ , then

this would introduce a significant discrepancy between the SMA and SCUBA-2 photometry, similar to the discrepancy we observe in Bootes27. This is not necessarily surprising: if the additional flux is in the form of undetected point-like sources then we do not observe any SMA counterparts to these sources, and if the additional flux is in the form of undetected diffuse emission, the SCUBA-2 source is likely much more extended than we currently observe, and so the SMA counterparts that we have detected would be unlikely to be able to account for the significantly extended nature of the source.

We therefore suggest that the photometry that we have measured for Bootes15 is best explained by undetected sub-mm flux density in both the SCUBA-2 and SMA images. If this additional flux density were in the form of faint, point-like sources lying below our current SMA/SCUBA-2 detection thresholds, then we would also expect these additional sources to contribute to artificially reddening the *Herschel* SPIRE photometry. For example, Bussmann et al. (2015) find that blending can have a significant effect on the FIR/sub-mm colours of bright *Herschel* sources, with blends of three sources boosting the  $S_{500}/S_{350}$  colours by as much as  $\sim 1.8$  times the deblended colours. Our interpretation can therefore simultaneously account for the bright *Herschel* SPIRE source associated with Bootes15, its red *Herschel* colours and its unexpectedly faint SCUBA-2 and SMA photometry.

## Bootes27

For Bootes27, the bright *Herschel* SPIRE detection resolves into a single, faint SMA source. The SCUBA-2 contours clearly show two partially resolved regions of sub-mm emission, with the Northern component showing no apparent SMA counterpart. However, even focusing on the Southern component coincident with the SMA detection, the deboosted  $850\mu\text{m}$  flux density of  $6.9 \pm 1.3\text{ mJy}$  is significantly larger than the SMA continuum flux density of  $1.9 \pm 0.3\text{ mJy}$ . At shorter wavelengths, there are  $\sim 7$  bright IRAC  $8.0\mu\text{m}$  detections associated with the SCUBA-2  $850\mu\text{m}$  contours and, while the photometry for these sources remains limited, their photometric redshift PDFs suggest that they lie at  $z \gtrsim 2$ , very roughly placing them in line with the photometric redshift estimates for the whole system from MMPZ ( $z \sim 2-3.5$ ) and the



FIR/sub-mm colours ( $z \geq 2$ ). We note that none of these IRAC sources are coincident with the SMA detection in the Southern component, indicating that they are likely additional sources that potentially contribute to the large *Herschel* SPIRE flux density. We interpret the tension between the *Herschel*, *Spitzer*, SCUBA-2 and SMA observations for this source as evidence that there may be additional faint sources that remain undetected in the sub-mm continuum observations. We make a simple estimate of the number of sources that likely remain undetected, assuming that they would appear point-like in the SMA maps. The dirty SMA map used for source extraction has a  $1\sigma$  RMS noise of 0.29 mJy/beam, meaning that any source with a flux density of less than  $\sim 1.2$  mJy would fall below the required  $4.1\sigma$  detection threshold. Based on the flux density of the single resolved SMA source ( $1.9 \pm 0.3$  mJy) and the integrated SCUBA-2 flux density ( $10.1 \pm 1.6$  mJy) we find that, in order to avoid a  $3\sigma$  tension between the two measurements, we require at least 2.2 mJy of additional, undetected flux density in the SMA continuum maps, corresponding to at least three point-like sources fainter than 1.1 mJy. Alternatively, if we consider the flux density measurements at face value, we require an additional  $8.2 \pm 1.6$  mJy of flux density in our SMA continuum maps, corresponding to 6 – 9 SMA sources with  $S_{870\mu\text{m}} \lesssim 1.1$  mJy. This discrepancy could therefore be fully accounted for if all of the  $\sim 7$  IRAC  $8.0\mu\text{m}$ -detected sources have  $870\mu\text{m}$  flux densities of  $\sim 1$  mJy. Alternatively, it is possible that some combination of the IRAC sources and additional undetected sources are required. Such high multiplicities would naturally make Bootes27 a candidate protocluster core at  $z \geq 2$ , potentially similar to those discovered by Miller et al. (2018) and Oteo et al. (2018), albeit at a lower redshift.

### 3.7.2 Properties

Before undertaking any discussion of the properties of our  $500\mu\text{m}$  risers and the resolved components of which they are comprised, the reader is directed to the caveats outlined in Section 3.5.5.

## Dust Masses, FIR Luminosities and SFRs

Based on our integrated FIR SED fitting, we find that the  $500\mu\text{m}$  risers have FIR luminosities  $L_{\text{FIR}} \sim 10^{13.1} L_{\odot}$  and dust masses of  $M_d \sim 10^{9.8} M_{\odot}$ . These results therefore identify our  $500\mu\text{m}$  risers as HLIRGs, with corresponding dust-obscured SFRs of thousands of solar masses per year. In Figure 3.23 we compare these results to those of Greenslade et al. (2020) for their sample of  $500\mu\text{m}$  risers. We find that our  $500\mu\text{m}$  risers have dust masses towards the higher end of the Greenslade et al. (2020) sample, but with lower FIR luminosities and inferred SFRs. Our dust-obscured SFRs are broadly in line with those found by Cheng et al. (2019) who fit four typical DSFG template SEDs to *Herschel* and SCUBA-2 photometry to estimate dust properties for their candidate protoclusters. We note that our dust mass estimate has a  $\beta$  dependence through the optical depth term  $\tau_{\nu} = (\nu/\nu_0)^{\beta}$  and so will be affected by our unusual  $\beta$  values. Estimating the dust mass with  $\beta \approx 2.2$  (see e.g. Casey et al., 2021b), we would expect the dust mass of Bootes15 to be  $\sim 4.1\times$  smaller, and the dust masses of Bootes24, Bootes27 and XMM-M5 to be  $\sim 2.2\times$  smaller than their respective values in Table 3.5. For Bootes24, Bootes27 and XMM-M5, this smaller value would be well within the errors quoted in Table 3.5, while the dust mass for Bootes15 would be reduced to  $\sim 10^{9.45} M_{\odot}$  compared to the  $1\sigma$  lower limit of  $10^{9.61} M_{\odot}$  from Table 3.5. Therefore, while the dust masses of Bootes24, Bootes27 and XMM-M5 are reasonably robust to changes in  $\beta$ , the high dust mass of Bootes15 is certainly linked to its higher  $\beta$  value. These results suggest that, while our  $500\mu\text{m}$  risers may represent a sample of high redshift DSFGs experiencing an intense burst of star formation, they appear to be somewhat less extreme than those in the Greenslade et al. (2020) sample.

## High Dust Spectral Emissivity Index

We find that, based on the FIR/sub-mm blackbody SED fitting routine, our  $500\mu\text{m}$  risers typically require SEDs with  $\beta \sim 4$  (with even the lower limit of Bootes15 and Bootes27 requiring  $\beta > 3$ ), in tension with the typical values of  $\beta \sim 1.5$  found in the literature (Hildebrand, 1983; Dunne and Eales, 2001; Dupac et al., 2003; Yang and Phillips, 2007; Chapin et al., 2011; Casey et al., 2011; Casey, 2012; Spilker et al., 2014; Kato et al., 2018; Clements et al., 2018; Faisst

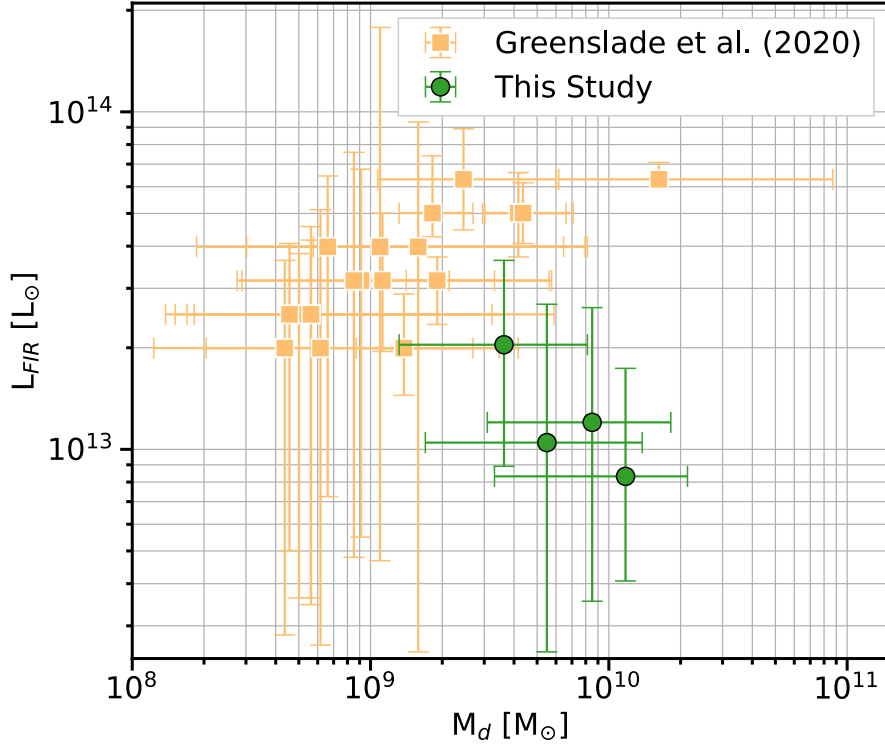


Figure 3.23: FIR luminosity against dust mass for the four  $500\,\mu\text{m}$  risers in this study, as well as those from the Greenslade et al. (2020) sample. Our  $500\,\mu\text{m}$  risers have lower FIR luminosities than Greenslade et al. (2020), indicating that they are either somewhat less extreme or lie at lower redshift, with broadly higher dust masses.

et al., 2020a). More recent works suggest that high redshift DSFGs may skew towards higher values of  $\beta \approx 2$  (Arendt et al., 2019; da Cunha et al., 2021; Casey et al., 2021b) similar to the values we find for Bootes27 and XMM-M5. Due to the degeneracies in our modified blackbody fitting, we are unable to deduce reliable estimates for dust temperature and/or redshift which are required to identify the reason for our high  $\beta$  values. We discussed in Section 3.5.5 that the combination of missing flux in the FIR/sub-mm observations and the exacerbated effects of blending in the  $500\,\mu\text{m}$  *Herschel* SPIRE band would manufacture an artificially steepened Rayleigh-Jeans tail which would manifest in the SED fitting as a large  $\beta$  value. We therefore suggest that the multiplicities of our  $500\,\mu\text{m}$  risers are likely the cause of these high  $\beta$  values but, in the interests of completeness, we can also rule out some other effects that could potentially be responsible.

Firstly, we investigate whether multiple sources with different SED shapes could produce unrealistically high  $\beta$  values. We use different template SEDs (ALESS, Arp220 and HFLS3), testing

redshifts in the range  $0 \leq z \leq 5$  in steps of 0.2 and normalisations of the  $500\mu\text{m}$  flux density of the template SED from 1 mJy to 75 mJy in steps of 5 mJy. For Bootes15 and Bootes24, each of which is made up of two resolved SMA sources, we sum two template SEDs with different combinations of redshift and normalisation within this parameter space, fit the resulting SED to the integrated SCUBA-2 and *Herschel* photometry and calculate chi-squared values (note that only one of the SMA detections associated with Bootes27 is coincident with the SCUBA-2 emission, and so we exclude it from this analysis). We additionally extract the flux densities of the individual component SEDs at 345 GHz and compare to the measured flux densities of the resolved SMA sources. We repeated this analysis for the ALESS, Arp220 and HFLS3 templates. We find that there are no combinations of redshift and normalisation of typical template SEDs that can simultaneously produce a good fit to the integrated FIR photometry and agree with the resolved SMA photometry.

Additionally, for Bootes15 and Bootes24, we divide the *Herschel* SPIRE flux density between the two SMA sources and repeat the modified blackbody SED fitting procedure with the naively de-blended *Herschel* SPIRE photometry, but now with the SMA flux densities rather than the integrated SCUBA-2  $850\mu\text{m}$  flux density. We first test dividing the *Herschel* SPIRE flux density equally between the two SMA sources, and we then test assigning the *Herschel* SPIRE flux density proportionately based on the ratio of the SMA flux densities of the two sources. We find that in both cases, the SED fitting suggests similarly high  $\beta$  values ( $\beta \gtrsim 4$ ).

We then test whether the definition of the dust opacity in our modified blackbody fit could result in unusually high  $\beta$  values. Rather than fixing  $\nu_0$  (the frequency at which the dust opacity  $\tau_\nu = 1$ ), Greenslade et al. (2020) leave this as a free parameter in their blackbody fit and, given that  $\nu_0$  is related to  $\beta$  through the dust opacity relation, it is possible that a different value of  $\nu_0$  might ease the tension in our  $\beta$  values. We re-run the modified blackbody SED fit to all four  $500\mu\text{m}$  risers, fixing the  $\nu_0$  parameter to different values within the priors defined in Greenslade et al. (2020) ( $c/\nu_0 = 1, 5, 10, 50, 100, 200, 500, 1000\mu\text{m}$ ). We find that, while more reasonable  $\beta$  values can be obtained if  $c/\nu_0 \lesssim 10\mu\text{m}$ , the resulting SED fits are much poorer, with  $\chi^2$  values  $\gtrsim 2$  orders of magnitude larger than when  $c/\nu_0$  is fixed at  $200\mu\text{m}$ .

We interpret these results as evidence that the high  $\beta$  values in our  $500\mu\text{m}$  risers cannot be explained simply by some effect of the currently observed multiplicities or the SED fitting procedure. This conclusion is further supported by the fact that, as demonstrated in Table 3.8, the other sub-mm bright sources detected in the SCUBA-2 maps with cross-matched *Herschel* photometry tend to have much more reasonable  $\beta$  values. Instead, it is likely that these high  $\beta$  values are the result of additional  $850\mu\text{m}$  flux density that is undetected in our SCUBA-2 observations. We test how much additional  $850\mu\text{m}$  flux density would be required in each of our  $500\mu\text{m}$  risers to obtain more reasonable  $\beta$  estimates. Although the error bars for  $\beta$  remain rather large we find that, by adding flux density to the  $850\mu\text{m}$  photometry for each of our  $500\mu\text{m}$  risers and repeating the MCMC SED fitting,  $850\mu\text{m}$  flux densities of  $\sim 15 - 20\text{ mJy}$  are required to reach  $\beta < 3$ . More specifically, an additional 18 mJy, 8 mJy, 6 mJy and 7 mJy is required in order to obtain  $\beta < 3$  for Bootes15, Bootes24, Bootes27 and XMM-M5 respectively. If this flux density is divided into resolved sources then, based on the rms noise in our SCUBA-2 maps, we would require an additional  $\approx 8, 3, 4$  and 2 undetected sources in our SCUBA-2 maps. However, given the large error bars for our  $\beta$  estimates, much lower multiplicities could be obtained should we simply require that our  $\beta$  values agree within the errors of the Casey et al. (2021b) value of  $\beta = 2.2^{+0.5}_{-0.4}$ . In this case, Bootes27 and XMM-M5 are already in agreement with this value, and we would require just  $\sim 8\text{ mJy}$  and  $< 5\text{ mJy}$  of additional flux density for Bootes15 and Bootes24 respectively, corresponding to  $\sim 4$  and  $\sim 1 - 2$  additional resolved sources. We also note that an additional  $\sim 8\text{ mJy}$  of flux would bring the  $850\mu\text{m}$  flux density of Bootes15 up to  $\sim 10.6\text{ mJy}$ , in much better agreement with the expected SCUBA-2 flux density based on its *Herschel* SPIRE photometry compared to the STUDIES and S2CLS samples in Figure 3.9. Additionally, it is possible that there is some extended flux density associated with our  $500\mu\text{m}$  risers that our SCUBA-2 observations are not sensitive enough to detect, which would further ease the tension in these  $\beta$  values.

### Photometric Redshifts

We then estimated the photometric redshifts of our  $500\mu\text{m}$  risers based on their integrated FIR/sub-mm photometry. Considering first the FIR/sub-mm colour-colour plot in Figure 3.14,

we find that our  $500\mu\text{m}$  risers are likely at  $z \geq 2$ , excluding Bootes15 which has an essentially unconstrained photometric redshift due to the poor SCUBA-2 photometry. We note that, if our SCUBA-2 observations miss  $\sim 8\text{ mJy}$  of flux density from the Bootes15 system at  $850\mu\text{m}$  (the most conservative estimate from the previous section), then we expect that Bootes15 would lie near the boundary of the  $z \geq 2$  and  $1 < z < 2$  regions in Figure 3.14, with  $S_{350}/S_{850} \sim 6.4$ . We find that MMPZ produces similar results, placing Bootes24, Bootes27 and XMM-M5 at  $z \approx 2 - 4$ . These results are consistent with the interpretation that the  $500\mu\text{m}$  selection criterion can effectively select both intrinsically red, individual DSFGs at  $z > 4$ , as well as some fraction of multiple systems, artificially reddened by the exacerbated effects of blending towards the longer wavelength *Herschel* SPIRE bands and lying at more moderate ( $z \sim 2$ ) redshifts. We find that our  $500\mu\text{m}$  risers fall into the latter of these two categories. This is in line with similar studies, such as Montaña et al. (2021), who find in their sample of  $\sim 100$   $500\mu\text{m}$  risers that the photometric redshift distribution of those that resolve into multiple components is skewed towards lower redshifts, with a slightly lower median redshift ( $z_{\text{med}} = 3.5$  vs.  $z_{\text{med}} = 3.8$ ) and a higher fraction residing at lower redshifts (27% at  $z_{\text{phot}} < 3$  vs. 10%) compared to single systems.

### 3.7.3 Environments

While the primary aim of our observations was to study the  $500\mu\text{m}$  riser sources in more detail, the SCUBA-2  $850\mu\text{m}$  maps also give a much wider-field view, allowing us to investigate the  $> 10'$  region around each source in our sample. Numerous examples of DSFGs clustered on the sky have been found with a range of scales, from compact protocluster cores extended over several arcseconds such as those discovered at  $z > 4$  by Miller et al. (2018) and Oteo et al. (2018), to overdensities at more moderate redshifts extended over tens of arcminutes (see e.g. Casey et al., 2015). Therefore, while  $850\mu\text{m}$  observations with SCUBA-2 may not be able to capture the full extent of the most massive overdensities of DSFGs, the majority would be well contained within the map size. We therefore used our SCUBA-2 observations to determine the environments in which our  $500\mu\text{m}$  risers lie.

Based on the cumulative number counts constructed in Section 3.6.1, we found that Bootes15, Bootes24 and XMM-M5 are all consistent with residing in overdensities of SMGs brighter than  $\sim 8$  mJy at  $850\,\mu\text{m}$ . In particular, Bootes15 appears to have a robust  $8.6 \pm 3.5$  overdensity of sources brighter than 8 mJy at  $850\,\mu\text{m}$ , whereas the overdensities for Bootes24 and XMM-M5 are more moderate, with extremely marginal overdensities at the lower end of their associated error bars. This result is interesting as we would not necessarily expect our  $500\,\mu\text{m}$  risers to be effective tracers of high-redshift galaxy overdensities - based on the clustering analysis of SMGs from the ALESS survey, García-Vergara et al. (2020) find that only the brightest SMGs ( $S_{870} > 5 - 6$  mJy) should trace massive structures at  $z \sim 2$ , while our sources are significantly fainter than this in the resolved SMA maps. Without spectroscopic redshifts for the SCUBA-2 sources we cannot say with certainty whether these overdensities are physically associated structures or simply chance line of sight projections of bright sub-mm sources. In the absence of spectroscopic data, we must rely on photometric redshifts estimated from FIR/sub-mm colour-colour diagrams and the MMPZ algorithm. From Figures 3.20 and 3.21, we infer that the marginal overdensity associated with Bootes24 could be physically associated, with the FIR/sub-mm colours placing the sources at  $z \geq 2$ , and MMPZ placing them at  $z \sim 2-4$ . For the Bootes15 field, improvements in the FIR/sub-mm photometry are required to better constrain the photometric redshifts of the detected sources, while the sources in the Bootes27 field likely lie at very different redshifts. The SCUBA-2 detections in the XMM-M5 field could represent an overdensity of SMGs, and their colours suggest that they are all at  $z \geq 2$ , but MMPZ places two of these sources at  $z \sim 1.5-2$ , and the third at  $z \sim 4$ . This overdensity is therefore less likely to be a physically associated structure than Bootes24. Additional observations providing improved photometry and/or spectroscopic redshifts for these sources will be required to conclude with certainty whether they are physically associated structures.

### 3.7.4 Comparison to Predictions for Bright *Herschel* Sources

In this section, we place our results within the context of observations and simulations of similar samples of  $500\,\mu\text{m}$  risers from the literature, with a particular focus on the multiplicity fraction,

the brightest galaxy fraction and the flux density distribution of the resolved sources associated with each  $500\mu\text{m}$  riser.

### Multiplicity Fraction

Our results support the conclusions of Greenslade et al. (2020), who find that  $\sim 35\%$  of bright ( $S_{500} > 60\text{ mJy}$ )  $500\mu\text{m}$  risers, and  $\sim 60\%$  of faint ( $S_{500} < 60\text{ mJy}$ )  $500\mu\text{m}$  risers are multiples, although we note that these observations were somewhat inhomogeneous, making use of a variety of frequencies (ranging from 231 GHz to 346 GHz) and configurations, with a mixture of full tracks, partial tracks and track sharing, resulting in a range of angular resolutions (with an average beam FWHM of  $2.5 \pm 0.8$  arcseconds) and depths ( $0.5 - 2.9\text{ mJy/beam}$ ).

Oteo et al. (2017) provide high-resolution ( $\sim 0.12''$ ) ALMA follow-up observations at  $870\mu\text{m}$  for 44 ultra-red DSFGs from HerMES and H-ATLAS with  $S_{500}/S_{250} > 1.5$  and  $S_{500}/S_{350} > 1.0$ , reaching  $1\sigma$  RMS sensitivities of  $0.1\text{ mJy/beam}$ . They find that, in total,  $\approx 39\%$  resolve into multiple components and, more specifically,  $\approx 22\%$  of bright ( $S_{500} > 60\text{ mJy}$ ) and  $\approx 65\%$  of faint ( $S_{500} \leq 60\text{ mJy}$ ) sources in their sample resolve into multiple components.

B  thermin et al. (2017) produce a FIR to sub-millimeter simulation of the extragalactic sky based on a galaxy evolution model with two star-formation modes. They extract sources from maps based on these observations to investigate the effects that the limited angular resolution of single-dish instruments has on observations in the FIR/sub-mm. They predict that all *Herschel* sources brighter than  $60\text{ mJy}$  at  $500\mu\text{m}$  should be individual, lensed sources, while  $\sim 40\%$  of sources fainter than  $60\text{ mJy}$  at  $500\mu\text{m}$  should be blended.

In their compilation of 63  $500\mu\text{m}$  risers, Ma et al. (2019) estimate a multiplicity fraction of  $\sim 27\%$  based on numerous follow-up observations with NOEMA, ALMA and the SMA, although these studies reach various depths and angular resolutions, as well as probing much fainter  $500\mu\text{m}$  flux densities. This multiplicity fraction rises to  $\sim 39\%$  when sources showing evidence of strong gravitational lensing are removed.

Monta  a et al. (2021) carry out  $1.1\text{ mm}$  LMT/AzTEC observations of  $\sim 100$   $500\mu\text{m}$  risers with



$S_{500} \approx 35 - 80$  mJy, achieving an average beam FWHM of  $9.6 \pm 0.5$  arcseconds and  $1\sigma$  RMS sensitivities of  $\approx 0.7 - 2.8$  mJy. They find that  $\sim 9\%$  show direct evidence of multiplicity, rising to  $\sim 23\%$  if  $500\mu\text{m}$  risers which display evidence of multiplicity but are slightly below their detection threshold are included, and up to  $\sim 50\%$  if  $500\mu\text{m}$  risers without counterparts in their higher resolution observations are assumed to be multiple sources. This is considered an extreme scenario as a higher dust spectral emissivity index  $\beta$  could also render some of their sources undetectable at  $1.1$  mm, but our observations of  $500\mu\text{m}$  risers without counterparts in previous, high resolution follow-up observations indicate that a significant fraction of these non-detections could be multiple systems. For the twelve sources in their sample with  $S_{500} > 60$  mJy, two break up into multiple components and three show no counterparts in their higher resolution images, indicating a multiplicity of  $\approx 17 - 42\%$ . However, the larger beamsize of their observations compared to Oteo et al. (2017) and Greenslade et al. (2020) probe multiplicity on a significantly different scale, such that smaller scale multiplicities would likely be classified as individual sources. They estimate a correction factor of  $\sim 10\%$  accounting for multiple systems separated by distances much smaller than their  $9.6 \pm 0.5$  arcsecond beamsize, bringing the multiplicity fraction up to  $\gtrsim 18\%$  in the conservative case and  $\sim 60\%$  in the extreme case.

We find that our three Bootes sources all show some evidence of multiplicity. This result supports the conclusions of Greenslade et al. (2020) and, by extension, is in good agreement with the multiplicity fractions for  $500\mu\text{m}$  risers quoted by Oteo et al. (2017), despite their ALMA observations achieving significantly better sensitivities and angular resolutions. These results are also in reasonably good agreement with the more extreme scenario in Montaña et al. (2021), and well within the range of potential multiplicity fractions of the brightest ( $S_{500} > 60$  mJy) sources in their sample. These multiplicity fractions indicate that  $500\mu\text{m}$  risers are a much more diverse population than previously predicted.

### Brightest-Galaxy Fraction

We can also compare the flux distributions of the resolved SMA sources in our  $500\mu\text{m}$  risers to the literature. Béthermin et al. (2017), based on their simulations, predict that the brightest

galaxy should contribute  $\sim 60\%$  of the total  $500\mu\text{m}$  flux density. Similarly, Donevski et al. (2018) find that the brightest galaxy inside the *Herschel* beam for their simulated SPIRE data contributes on average  $75\%$  and  $64\%$  at  $250\mu\text{m}$  and  $500\mu\text{m}$  respectively. Montaña et al. (2021) find that the brightest component contributes on average  $50 - 75\%$  of the total flux density at  $1.1\text{ mm}$ , while Ma et al. (2019) find that the brightest ALMA source contributes on average  $41 - 80\%$  of the total ALMA flux density and  $15 - 59\%$  of the total SCUBA-2/LABOCA flux density at a similar wavelength.

We find that the brightest SMA component in Bootes15 contributes  $56 \pm 12\%$  to the total SMA flux density, and  $69 \pm 41\%$  of the integrated SCUBA-2  $850\mu\text{m}$  flux density. For Bootes24 the brightest SMA component contributes  $50 \pm 9\%$  to the total SMA flux density, but just  $30 \pm 8\%$  to the integrated SCUBA-2 flux density at a similar wavelength. For these two  $500\mu\text{m}$  micron risers that resolve into multiple SMA components, the brightest galaxy fraction is in good agreement with the values of  $\approx 50 - 60\%$  found by Greenslade et al. (2020) for the four  $500\mu\text{m}$  risers in their sample that break up into multiple SMA components.

For Bootes27, the single resolved SMA component contributes just  $19 \pm 4\%$  of the integrated SCUBA-2  $850\mu\text{m}$  flux density. These values are in good agreement with Ma et al. (2019), and indicate that for Bootes24 and Bootes27, we may not recover the total sub-mm flux density.

### Comparison to Known Protocluster Cores

We can also compare these values to the flux density distributions of known high- $z$  protocluster cores, such as the Distant Red Core (DRC: Oteo et al., 2018) and SPT2349-56 (Miller et al., 2018). For the DRC, we focus on the ALMA  $2\text{ mm}$  follow-up observations carried out by Oteo et al. (2018), reaching depths of  $\sim 6\mu\text{Jy/beam}$  with a synthesised beam FWHM of  $1.68'' \times 1.54''$ . For SPT2349-56, we use the flux densities extracted from the ALMA  $850\mu\text{m}$  continuum maps based on the [CII] map channels with no line emission (Hill et al., 2020). In Figure 3.24, we then plot the contribution of each of the ten brightest resolved sources associated with the protocluster cores to the total flux density in the aforementioned bands. For our  $500\mu\text{m}$  risers, we plot the contribution of each of the resolved SMA sources to the integrated SCUBA-2  $850\mu\text{m}$

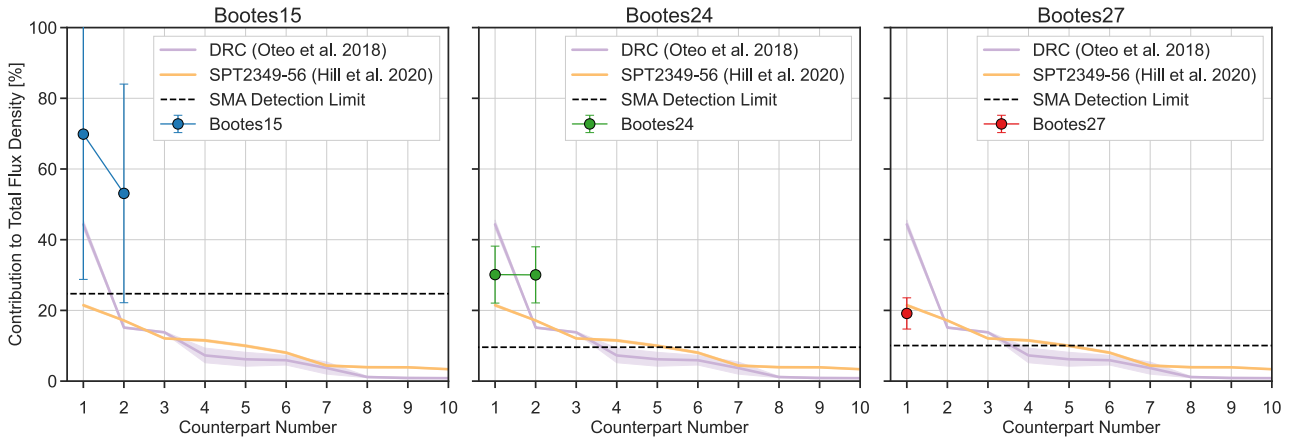


Figure 3.24: The relative contributions of each of our SMA detections to the total integrated SCUBA-2  $850\,\mu\text{m}$  flux density. The orange and purple lines show the flux density distributions of the DRC and SPT2349-56 protoclusters respectively, while the black dashed lines show the  $4.1\sigma$  detection limits in our dirty SMA maps. The contribution of each SMA source to the integrated SCUBA-2 flux density of Bootes15 remains poorly constrained. The SMA sources associated with Bootes24 and Bootes27 recover  $60 \pm 15\%$  and  $19 \pm 4\%$  of the total integrated SCUBA-2 flux density and so there may be additional sources residing below our SMA detection limits. However, if further sources do lie below our detection threshold, they likely follow a different flux density distribution to the DRC and SPT2349-56 protoclusters.

flux density, and estimate the uncertainties in these contributions by adding in quadrature the errors in the resolved SMA and integrated SCUBA-2 flux densities. Note that we exclude XMM-M5 from this plot, as the SMA and SCUBA-2 observations were taken at very different wavelengths.

For Bootes15, the contribution of each SMA source to the total SCUBA-2 flux density is poorly constrained, primarily due to the large uncertainties in the  $850\,\mu\text{m}$  photometry. In total, we estimate that the SMA observations recover  $123 \pm 73\%$  of the SCUBA-2 observations. However, as previously discussed, it is likely that some fraction of the total SCUBA-2 flux density is missed by our observations. The two SMA sources associated with Bootes24 recover  $60 \pm 15\%$  of the total SCUBA-2 flux density, shared equally between the two resolved sources. Therefore, the combined contribution from the two brightest sources is in good agreement with the two brightest sources in the DRC, which similarly contribute  $\sim 60\%$  to the total flux density of the system. However, the flux density is shared much more unequally between the two brightest sources in the DRC. If there were additional sub-mm sources contributing to Bootes24, we would expect to detect one extra source in our SMA observations if they were to follow a

DRC-like flux density distribution. Alternatively, we would expect to detect the brightest 4 – 5 sources if they were to follow a SPT2349-56-like flux density distribution. For Bootes27, the single resolved SMA source associated with the observed SCUBA-2 emission contributes just  $19 \pm 4\%$  to the integrated  $850\mu\text{m}$  flux density. This is similar to the  $\sim 22\%$  contribution to the total system from the brightest source in SPT2349-56. However, if Bootes27 were to represent a protocluster core with a similar flux density distribution to SPT2349-56, we would similarly expect to detect the brightest 4 – 5 components, whereas we only detect a single source associated with the  $850\mu\text{m}$  emission.

We infer that Bootes24 and Bootes27 may contain additional, faint sources lying below our SMA detection threshold that contribute to the total integrated SCUBA-2 flux density. However, it seems that this flux density must be distributed between its members differently to known high redshift protocluster cores, with each of the fainter members individually contributing significantly less to the total sub-mm flux density than expected. This is potentially to be expected in our systems, as we have identified that these sources are artificially reddened blends of multiple sources lying at lower redshifts, likely making them somewhat older than the DRC and SPT2349-56 structures.

### 3.8 Conclusions

We have presented *Herschel*, SMA and SCUBA-2 observations of four  $500\mu\text{m}$  risers from the HerMES survey. These sources were selected based on their red *Herschel* SPIRE colours, but remained undetected in previous high-resolution follow-up observations conducted by Greenslade et al. (2020). The previous results indicated that they were likely comprised of multiple DS-FGs that individually were faint enough to remain undetected in their high resolution SMA observations, but each contributing to a large integrated flux density when smoothed over the *Herschel* SPIRE beamsize. We confirm that these  $500\mu\text{m}$  risers do indeed tend to be comprised of multiple sources. Bootes15 and Bootes24 each breaking up into two faint sources in the high-resolution SMA images and are extended in the SCUBA-2 maps. By comparison

Bootes27 resolves into a single SMA source, but appears as two partially resolved sources in the SCUBA-2 maps, one of which has no apparent SMA counterpart. XMM-M5 resolves into a single source in both the SMA and SCUBA-2 observations. By confirming the nature of these multiple systems, our results corroborate the main findings of Greenslade et al. (2020) who estimated (by assuming that their  $500\,\mu\text{m}$  risers without SMA counterparts are sources with high multiplicities) that  $\sim 35\%$  of bright ( $S_{500} > 60\,\text{mJy}$ )  $500\,\mu\text{m}$  risers and  $\sim 60\%$  of faint ( $S_{500} < 60\,\text{mJy}$ )  $500\,\mu\text{m}$  risers are multiples.

We investigated the properties of our  $500\,\mu\text{m}$  risers through numerous methods. We estimated photometric redshifts using their FIR/sub-mm colours, as well as the MMPZ algorithm. While the photometric redshift of Bootes15 remains poorly constrained, Bootes24, Bootes27 and XMM-M5 all likely lie at  $z \geq 2$ . This is consistent with the interpretation that the  $500\,\mu\text{m}$  riser selection criterion recovers both intrinsically red sources at  $z > 4$  and artificially red, multiple systems at more moderate redshifts. Additionally, there is sufficient optical/NIR ancillary data available for one of the resolved SMA sources associated with Bootes15 to attempt a more rigorous SED fitting with **CIGALE**, and we estimate a photometric redshift for this source of  $z = 1.65 \pm 0.39$ , indicating that Bootes15 may lie at a somewhat lower redshift than our other  $500\,\mu\text{m}$  risers. We additionally estimate dust masses, FIR luminosities, SFRs and dust spectral emissivity indices for each of our  $500\,\mu\text{m}$  risers based on a simple modified blackbody fitting to the integrated FIR/sub-mm photometry. We find that our  $500\,\mu\text{m}$  risers are typically less extreme than those in Greenslade et al. (2020), with FIR luminosities of  $\sim 10^{13.1} L_{\odot}$  (placing them as HLRGS) and associated dust-obscured star formation rates of  $\sim 800 - 2000 M_{\odot}\text{yr}^{-1}$ . Their dust masses are towards the higher end of the Greenslade et al. (2020) sample with an average dust mass of  $\sim 10^{9.8} M_{\odot}$ . We find that our  $500\,\mu\text{m}$  risers favour  $\beta \gtrsim 3$  due to the steep Rayleigh-Jeans tail resulting from the faint  $850\,\mu\text{m}$  photometry. It is likely that these high  $\beta$  values are a direct result of the multiplicities of our  $500\,\mu\text{m}$  risers and, for Bootes15 in particular, due to undetected  $850\,\mu\text{m}$  flux density.

By comparing the cumulative number counts of  $\text{SNR} > 4$  detections in the SCUBA-2  $850\,\mu\text{m}$  maps with the expected number of field counts from the SCUBA-2 Cosmology Legacy Survey, we find that Bootes15, Bootes24 and XMM-M5 lie within galaxy overdensities of  $8.6 \pm 3.5$ ,

$5.8 \pm 3.5$  and  $9.3 \pm 6.5$  of bright ( $\gtrsim 8$  mJy) SMGs respectively. For those SCUBA-2 detections that have *Herschel* SPIRE counterparts, we estimate photometric redshifts based on their FIR/sub-mm photometry. We find that the overdensity associated with Bootes24 could feasibly be physically associated, while Bootes15 and XMM-M5 are more likely to be chance line-of-sight arrangements of sources.

We then compared the properties of our sample to similar studies of  $500\mu\text{m}$  risers from the literature. In terms of multiplicity fraction, our results support the conclusions of Greenslade et al. (2020), whose estimated multiplicity fractions are, in turn, in good agreement with Oteo et al. (2017) and with the more extreme scenarios in Montaña et al. (2021). We also find that the brightest SMA component of Bootes24 and Bootes27 contributes a similar amount to the total integrated SCUBA-2 flux density as the brightest resolved source associated with the  $500\mu\text{m}$  risers in the Ma et al. (2019) sample. For the three  $500\mu\text{m}$  risers in the Bootes field, we estimate that our SMA observations recover  $123 \pm 73\%$ ,  $60 \pm 15\%$  and  $19 \pm 4\%$  of the integrated SCUBA-2 flux density respectively indicating that, for Bootes24 and Bootes27, there may be additional, faint sources below the current SMA detection limit, but contributing to the integrated SCUBA-2 flux density. We additionally expect to miss some fraction of the SCUBA-2  $850\mu\text{m}$  flux density for Bootes15 and Bootes27 in particular, and so our current SMA observations may not recover the true sub-mm flux density of the system. These results indicate that Bootes24 and Bootes27 could be examples of dense, protocluster cores of DSFGs, only a handful of which have been discovered to date.

For Bootes27, we calculate that we would require 6 – 9 additional undetected sources in the SMA continuum maps to fully recover the SCUBA-2 flux density. We note that there are  $\sim 7$  bright, IRAC  $8.0\mu\text{m}$  detected sources coincident with the SCUBA-2 emission and, based on rather sparse optical/NIR photometry, we estimate that these sources likely lie at  $z \geq 2$ . If these IRAC  $8.0\mu\text{m}$  sources all contribute to the SCUBA-2 and *Herschel* SPIRE flux density, then the disparity between the interferometric and single-dish photometry would be comfortably resolved.

Finally, we compare the flux density distributions of our resolved SMA sources to those of

known protocluster cores. We find that, while the SMA sources associated with Bootes24 and Bootes27 only recover a fraction of the total sub-mm flux density, we would have expected to detect the brightest 4 – 5 components if the multiple systems followed a similar flux density distribution to SPT2349-56, or the brightest three components if they followed a similar flux density distribution to the DRC. Therefore, if these  $500\ \mu\text{m}$  risers are examples of dense protocluster cores, they likely follow a different flux density distribution to known, high- $z$  protocluster cores.

We therefore find that our  $500\ \mu\text{m}$  risers are typically comprised of multiple DSFGs and may represent examples of high redshift protocluster cores similar to those found by Miller et al. (2018) and Oteo et al. (2018). However, additional follow-up observations will be required to confirm the nature of these sources, and there are a number of available avenues that these observations could take. Deeper sub-mm continuum/spectroscopic observations with NOEMA will likely be required to determine if there are any additional, faint, point-like sources below our current SMA detection limits that contribute to the integrated SCUBA-2 flux (and if these sources are physically associated), particularly for Bootes24 and Bootes27 where our SMA observations currently only recover a fraction of the total  $850\ \mu\text{m}$  flux density. Alternatively, deep optical/NIR follow-up observations would allow us to accurately deblend the *Herschel* SPIRE flux density, from which we could attempt a rigorous SED fitting for each of the resolved components and estimate galaxy properties such as SFR and stellar mass. Finally, additional spectroscopic follow-up observations for sources in the wider field would allow us to conclude whether any larger scale overdensities in these regions represent physically associated structures.

# Chapter 4

## Star Formation in SpARCS-0330

### 4.1 Introduction and Motivation

The large-scale structures in our universe are arranged into the ‘cosmic-web’ (Bond et al., 1996), comprised of sheets, voids and filaments. In the  $\Lambda$ CDM model, these large-scale structures are thought to have built up hierarchically from small density perturbations superimposed onto the isotropic and homogeneous background. Galaxy clusters form at the intersections of these filaments, and both observations (e.g. Zabludoff and Franx, 1993; Ebeling et al., 2004; Cortese et al., 2006; Kartaltepe et al., 2008) and simulations (e.g. Colberg et al., 2000; Evrard et al., 2002; Acreman et al., 2003; Ceccarelli et al., 2005) suggest that they grow primarily via the accretion of galaxies and galaxy groups, and through galaxy cluster mergers (e.g. Springel et al., 2005). As the largest and most dense structures in the universe, galaxy clusters provide an ideal laboratory for studying both the assembly of large scale structure over cosmic time, as well as the effect of local environment on the formation and evolution of individual galaxies.

At high redshifts ( $z > 2$ ), a number of studies have identified “protoclusters”: overdensities of galaxies which typically span tens of Mpc in size and host some of the most vigorous star-formation observed in the universe to date. Hundreds of protocluster candidates have been discovered and/or confirmed using spectroscopy and imaging in the UV, optical and near-infrared, primarily searching for overdensities of Ly $\alpha$ -emitters, H $\alpha$ -emitters, or Lyman Break



Galaxies (e.g. Steidel et al., 1998; Pentericci et al., 2000; Kurk et al., 2004; Steidel et al., 2005; Verhamme et al., 2008; Tanaka et al., 2011; Toshikawa et al., 2012; Hayashi et al., 2012; Mawatari et al., 2012; Yuan et al., 2014; Lee et al., 2014; Diener et al., 2015; Casey et al., 2015; Toshikawa et al., 2016; Balmaverde et al., 2017; Cai et al., 2017; Jiang et al., 2018; Darvish et al., 2020; Zheng et al., 2021; Hu et al., 2021; Koyama et al., 2021; Endsley and Stark, 2022). Numerous high- $z$  protoclusters (and candidates) have also been identified via overdensities of sources bright in the far-infrared (e.g. Walter et al., 2012; Ivison et al., 2013; Dannerbauer et al., 2014; Clements et al., 2014, 2016; Kato et al., 2016; Greenslade et al., 2018; Oteo et al., 2018; Miller et al., 2018; Cheng et al., 2019; Gómez-Guijarro et al., 2019; Polletta et al., 2021; Wang et al., 2021a; Cairns et al., 2022). By contrast, local and dynamically evolved galaxy clusters are typically massive, virialised and abundant in quiescent, elliptical galaxies (Dressler, 1980; Balogh et al., 1998; Goto et al., 2003) growing primarily via dry mergers (e.g. Laporte et al., 2013; Kormendy and Ho, 2013), and as such show strikingly different properties to their high redshift counterparts, although there do exist low redshift examples of disturbed galaxy clusters, such as the Antlia cluster discussed in Chapter 2. Despite these differences, it is predicted that protoclusters will evolve into massive clusters at  $z = 0$  (e.g. Shimakawa et al., 2014; Cooke et al., 2015). Therefore, at  $z \lesssim 1$ , there must be some rapid, environmentally-driven quenching of star formation that transforms the high- $z$  star-forming protoclusters into  $z = 0$ , quiescent galaxy clusters. However, the exact nature of this evolution from protocluster to cluster remains poorly understood.

Part of the reason for this lack of understanding is that, historically, protoclusters and clusters have been studied completely separately, typically due to the difference in the redshift ranges at which they are observed ( $z < 1$  for galaxy clusters,  $z > 2$  for protoclusters). Therefore, in order to understand the evolution from high- $z$  protoclusters to  $z = 0$  galaxy clusters, we must look for overdensities of galaxies at the onset of cluster formation ( $z \sim 2$ ), at which time we are able to observe the full range of activity: the assembly of a collapsed cluster core feeding on the star-forming filamentary material that resides in the protocluster web. As a result, the study of galaxy clusters at this epoch has seen a surge of interest in recent years, and indeed we have progressed our knowledge of this stage in galaxy cluster evolution significantly. Observations

suggest that  $z \sim 2$  galaxy clusters harbour a significant amount of star formation (Brodwin et al., 2013; Fassbender et al., 2014; Bayliss et al., 2014; Webb et al., 2015a,b), but also contain a significant ‘red sequence’, indicating that environmental quenching processes start to play a role at this epoch (Kodama et al., 2007; Bauer et al., 2011; Quadri et al., 2012; Gobat et al., 2013; Strazzullo et al., 2013; Andreon et al., 2014; Newman et al., 2014; Balogh et al., 2016; Cooke et al., 2016). Indeed, studies aiming to quantify the efficiency with which galaxy clusters truncate star formation in their member galaxies have found that there is a decrease in this efficiency from  $z < 1$  up to  $z \sim 2$  (e.g. Darvish et al., 2016; Nantais et al., 2016, 2017, 2020).

The *Spitzer* Adaptation of the Red-Sequence Cluster Survey (SpARCS<sup>1</sup>; Muzzin et al. 2009; Wilson et al. 2009b) has been invaluable for the study of high- $z$  galaxy clusters. SpARCS is a deep  $z'$ -band imaging survey ( $z' = 24$  AB) of the *Spitzer* SWIRE fields, using MegaCam at CFHT for the Northern fields and MOSAICII at CTIO for the Southern fields (Wilson et al., 2009b). High redshift galaxy cluster candidates are selected using an adaptation of the “cluster red-sequence” (CRS) selection method developed by Gladders and Yee (2000, 2005). The CRS method relies on the assumption that all rich clusters contain a “red-sequence” of quiescent elliptical galaxies, which is largely supported by observations (see e.g. Kravtsov and Borgani, 2012), that follow a reasonably strict colour-magnitude relation (Gladders and Yee, 2000). Selections based on overdensities of galaxies in the red-sequence have numerous advantages over other galaxy cluster identification techniques. First and foremost, the red-sequence appears to be homogeneous, both within individual galaxy clusters and between galaxy clusters, and is comprised of galaxies which likely assembled the majority of their stellar mass at  $z > 2$  which should reliably trace galaxy clusters out to reasonably high redshifts (Gladders and Yee, 2000). Additionally, the CRS method allows the simple exclusion of contaminating foreground sources as, if filters are chosen to straddle the 4000Å break, the cluster red-sequence is at least as red as other galaxies at the same redshift and all lower redshifts, producing a strong contrast with contaminating foreground galaxies and leaving blue galaxies at higher redshifts as the only remaining contaminants in a given colour slice (Gladders and Yee, 2000). Numerous studies have hence employed the CRS method for galaxy cluster identification, finding that it produces

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<sup>1</sup><https://faculty.ucr.edu/~gillianw/SpARCS/>

accurate photometric redshifts and low false positive rates (e.g. Bahcall et al., 2003; Gilbank et al., 2004; Gladders and Yee, 2005; Barkhouse et al., 2006; Gilbank et al., 2007; Yee et al., 2007; Koester et al., 2007; Muzzin et al., 2008, 2009; Wilson et al., 2009b).

Rather than targeting clusters at  $z \sim 1$  by using the  $R - z'$  colours to pick out the galaxy cluster red-sequence as proposed in Gladders and Yee (2000) and employed in the Red-Sequence Cluster Surveys (RCS-1 and RCS-2: Gladders and Yee, 2005; Yee et al., 2007), the SpARCS survey adapted the CRS method, using *Spitzer* IRAC data to target rich clusters at high redshift by selecting galaxies based on their  $z' - 3.6\mu\text{m}$  colours which should span the  $4000\text{\AA}$  break at  $z > 1$ , a method previously demonstrated by Muzzin et al. (2008). Particularly high redshift cluster candidates within the SpARCS sample were selected using the “Stellar Bump Sequence” (SBS) method outlined in Muzzin et al. (2013a). The SBS method is necessary to pick out the highest redshift clusters in the SpARCS survey because, as demonstrated by Muzzin et al. (2013a), the  $z' - 3.6\mu\text{m}$  colours of red-sequence galaxies at  $z > 1.4$  become extremely red, reaching the limiting depth of the  $z'$  observations in the SpARCS survey. The SBS method effectively combines the  $z' - 3.6\mu\text{m}$  colour cut, which excludes foreground interlopers, with the  $3.6\mu\text{m} - 4.5\mu\text{m}$  cluster detection method presented by Papovich (2008) which, at  $z > 1.3$  is spanned by the  $1.6\mu\text{m}$  stellar bump (Muzzin et al., 2013a). The  $1.6\mu\text{m}$  stellar bump has long been a popular choice for photometric redshift estimation as it is caused by a natural minimum in the wavelength-dependent opacity of the Hydrogen anion  $\text{H}^-$  (Sawicki, 2002) which is primarily produced as metals in the stellar atmosphere are photoionised, providing electrons which can in turn be captured by the Hydrogen atom (Millar et al., 2017). As a result, the  $1.6\mu\text{m}$  stellar bump is essentially ubiquitous and easily identified in galaxies containing stellar populations  $\gtrsim 100$  Myr old (Sawicki, 2002), and hence provides an excellent method for estimating photometric redshifts for red-sequence galaxies within galaxy clusters, provided that low redshift ( $0.2 < z < 0.4$ ) interlopers, which can show similar  $3.6\mu\text{m} - 4.5\mu\text{m}$  colours, can be eliminated (Muzzin et al., 2013a; Nantais et al., 2016).

With a total effective area of 41.9 square degrees and hundreds of candidate galaxy clusters, SpARCS is the largest completed  $z > 1$  cluster survey to date, and has produced the first large, homogeneously-selected sample of  $z > 1$  galaxy clusters (Muzzin et al., 2009). Many of

the SpARCS clusters have been directly studied in the literature (e.g. Demarco et al., 2010; Muzzin et al., 2012, 2013a; Lidman et al., 2012, 2013; Noble et al., 2013; Webb et al., 2015a,b; Nantais et al., 2016; Noble et al., 2016, 2017; Bonaventura et al., 2017; Nantais et al., 2017; Willis et al., 2018; Foltz et al., 2018; Noble et al., 2019; Pintos-Castro et al., 2019; Castignani et al., 2020; Nantais et al., 2020; Dunne et al., 2021), and additionally provide the basis for other spectroscopic follow-up surveys such as the Gemini Cluster Astrophysics Spectroscopic Survey (GCLASS: Muzzin et al., 2012) and the Gemini Observations of Galaxies in Rich Early Environments (GOGREEN: Balogh et al., 2017) survey.

In this study, we present an investigation into the star-forming properties of SpARCS-0330 (RA=03:30:55.87, Dec=−28:42:59.5), one of the most massive, high- $z$  galaxy clusters ever discovered. SpARCS-0330 lies in the Chandra Deep Field South (CDFS) at a redshift of  $z = 1.626$ . SpARCS-0330 was first discussed in Lidman et al. (2012), who used photometry from SpARCS and the literature (Stott et al., 2008, 2010) to investigate how the stellar masses of Brightest Cluster Galaxies (BCGs) change with redshift between  $0.03 < z < 1.63$ . Lidman et al. (2012) estimate the dynamical mass of SpARCS-0330 based on the line-of-sight stellar velocity dispersion to be  $2.4^{+1.0}_{-1.5} \times 10^{14} M_{\odot}$  and, evolving this value to  $z = 0$  by integrating the mean mass accretion rates in the Millennium and Millennium-II simulations (Fakhouri et al., 2010), estimate a present day cluster mass of  $2.1^{+1.1}_{-1.4} \times 10^{15} M_{\odot}$ , similar to massive galaxy clusters in the local Universe such as Coma. SpARCS-0330 has subsequently been investigated in numerous studies. Most pertinent to this work, Nantais et al. (2016) compiled multi-wavelength photometry and spectroscopy for SpARCS-0330, as well as three other SpARCS clusters, to analyse the stellar mass functions and environmental quenching efficiencies of galaxy clusters at  $1.37 \leq z \leq 1.63$ , finding evidence for a reduction in the quenching efficiency in galaxy clusters at high redshift. In the process, Nantais et al. (2016) spectroscopically confirmed  $\approx 40$  cluster members and many more candidate members based on their photometric redshifts. Nantais et al. (2017) additionally used fourteen SpARCS clusters at  $0.6 < z < 1.6$ , including SpARCS-0330, to demonstrate that there is indeed a strong evolution in the environmental quenching efficiency of galaxy clusters, falling from  $\approx 88\%$  at  $z < 1.1$  to  $\approx 42\%$  at  $z \sim 1.6$ . More recently, Nantais et al. (2020) presented H $\alpha$  observations of three SpARCS clusters, including SpARCS-

0330, finding similar  $H\alpha$ -based SFRs as contemporaneous field galaxies with similar masses, indicating that high redshift galaxy clusters may not be as effective at quenching their member galaxies as more local clusters, either due to the galaxies themselves being accreted too recently, or due to the cluster environment not yet being dynamically evolved enough to effectively truncate star formation. Aside from the works of Nantais et al. (2016, 2017, 2020), studies involving SpARCS-0330 have focused on mergers between massive galaxy cluster members (Delahaye et al., 2017), quenching timescales in high redshift galaxy clusters (Foltz et al., 2018) and the growth of Brightest Cluster Galaxies (BCGs) and Intracluster Light (DeMaio et al., 2020). We aim to build on this work by combining the photometric catalogues for SpARCS-0330 compiled by Nantais et al. (2016) with FIR photometry from *Herschel* to build catalogues of up to 20-band photometry for galaxies within  $\approx 3$  Mpc of the nominal cluster centre. We additionally construct a complementary sample of galaxies in the wider field (within 15 Mpc of the core) based on archival observations. Using these catalogues, we define samples of likely cluster candidates and attempt to map out star formation and quenching across the SpARCS-0330 cluster by estimating galaxy properties with the CIGALE and EAZY SED fitting codes, and hence bridging the gap between studies of distant protoclusters and present day massive galaxy clusters.

In Section 4.2 we outline the various observations and ancillary data associated with the SpARCS-0330 cluster and in Section 4.3 we discuss the construction of the final catalogues. In Section 4.4 we estimate photometric redshifts and select our samples. In Section 4.5 we discuss the properties of the galaxies in our samples and in Section 4.6 we use these properties to investigate star formation activity and quenching within the SpARCS-0330 cluster. In Section 4.7 we provide a discussion of the main findings of this study, before summarising our conclusions and discussing avenues for future work in Section 4.8. We assume a standard  $\Lambda$ CDM cosmology with  $H_0 = 67.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_\Lambda = 0.685$  and  $\Omega_m = 0.315$  (Planck Collaboration et al., 2014). At the average redshift of SpARCS-0330 ( $z = 1.626$ )  $1''$  corresponds to 6.3 kpc.

| Photometric Band               | Central Wavelength ( $\mu\text{m}$ )   | Instrument            |
|--------------------------------|----------------------------------------|-----------------------|
| $u, g, r, i, z$                | 0.3543, 0.4770, 0.6231, 0.7635, 0.9134 | IMACS                 |
| $Y, J, K_s$                    | 1.021, 1.258, 2.146                    | HAWK-I                |
| F105W, F140W, F160W            | 1.0552, 1.3923, 1.5369                 | HST                   |
| IRAC-1, IRAC-2, IRAC-3, IRAC-4 | 3.6, 4.5, 5.8, 8.0                     | <i>Spitzer</i> IRAC   |
| MIPS-1, MIPS-2                 | 24, 70                                 | <i>Spitzer</i> MIPS   |
| PACS Green, PACS Red           | 100, 160                               | <i>Herschel</i> PACS  |
| PSW, PMW, PLW                  | 250, 350, 500                          | <i>Herschel</i> SPIRE |

Table 4.1: Summary of the photometry available for the SpARCS-0330 galaxy cluster

## 4.2 Observations, Data Reduction and Ancillary Data

SpARCS-0330 benefits from a wealth of ancillary data which we discuss in the following subsections. While the spectroscopic data is not directly used in this work, the data used to spectroscopically confirm the  $\approx 40$  cluster members is described below, along with the photometric data that is studied in this paper. Much of the photometry and spectroscopy was assembled by Nantais et al. (2016) in their study of the stellar mass functions of four SpARCS galaxy clusters, and we simply outline the available photometry here. A summary of the photometry used in this paper can be found in Table 4.1.

### 4.2.1 Spectroscopy

The most useful spectra for constraining the redshifts of the members of the SpARCS-0330 cluster were taken with the Focal Reduction and Imaging Spectrograph (FORS2: Appenzeller and Rupprecht, 1992) on the European Southern Observatory’s (ESO) 8.2m Very Large Telescope (VLT) Unit Telescope 1 (UT1: Antu). FORS2 is a multi-mode instrument capable of imaging, polarimetry and both long-slit and multi-object spectroscopy, primarily working in the optical with a wavelength range of 330 – 1100 nm. The instrument was used in Mask Exchange Unit (MXU) mode which can use up to ten masks, each allowing up to 470 slits, to obtain spectra of large numbers of objects in a single observation, yielding spectral resolutions of  $\approx 260 - 2600$  down to limiting magnitudes of 24.2 – 23.3 in the  $R$  band. The spectral data from FORS2 was reduced by Nantais et al. (2016) using software customised for FORS2 MXU reduction out-

lined in Nantais et al. (2013). In addition to the FORS2 spectra, NIR multi-object spectroscopy was taken with MOSFIRE (McLean et al., 2010, 2012), the NIR spectrograph mounted at the Cassegrain focus of the Keck Telescopes (PI: G. Wilson). MOSFIRE has a 6.14 square arcminute field of view allowing up to 46 slits at a time, providing NIR spectra in the wavelength range  $0.97 - 2.45 \mu\text{m}$  with a spectral resolution of  $R \sim 3270$  (assuming a  $0.7''$  slit width) down to limiting AB magnitudes of 21.5, 21.3, 21.5 and 20.5 in the  $Y$ ,  $J$ ,  $H$  and  $K$  bands respectively (McLean et al., 2010).

In addition to these spectroscopic observations, the Australian Dark Energy Survey (OzDES: Yuan et al., 2015) produced spectra in the region of SpARCS-0330, although typically probing sources at lower redshift. OzDES was a long term spectroscopic survey on the 4m Anglo-Australian Telescope (AAT) at Siding Spring Observatory, running for one hundred nights between 2013 and 2019. Observations made use of the AAOmega Spectrograph with the Two Degree Field multi-object fibre positioner, producing spectra from  $370 - 880 \text{ nm}$  with a spectral resolution of  $R \sim 1400$  and down to a limiting  $r$  band magnitude of 25 (Yuan et al., 2015). This data was primarily used to check photometric redshifts and improve their quality.

In total, these observations identified 40 spectroscopically confirmed members of the SpARCS-0330 galaxy cluster within  $\sim 7'$  of the cluster core and in the redshift range  $1.612 < z < 1.641$ , placing them within  $\Delta z \sim 0.015$  of the nominal cluster redshift of  $z = 1.626$  as defined by Lidman et al. (2012).

## 4.2.2 Photometry

### Optical/NIR

The optical and NIR photometry were taken with both ground and space-based observatories. From the ground, optical imaging was completed with the  $f/2$  camera on the Inamori-Magellan Areal Camera and Spectrograph (IMACS: Dressler et al., 2011), mounted on the 6.5m Magellan-Baade Telescope at the Las Campanas Observatory in Chile. The  $f/2$  camera provides a  $27.4'$  FoV with a pixel size of  $0.2''$ . IMACS has the capacity for 15 filters, and observations were

taken in the Sloan  $u$ ,  $g$ ,  $r$ ,  $i$  and  $z$  bands, reaching limiting AB magnitudes of 22.7, 21.6, 20.7, 20.0 and 18.4 respectively<sup>2</sup>. Observations were taken by Nantais et al. (2016) in two runs in September 2011 and December 2012 and reduced using their bespoke scripts.

SpARCS-0330 was additionally observed with the High Acuity Wide-field  $K$ -band Imager (HAWK-I: Pirard et al., 2004; Casali et al., 2006) installed at the Naysmith A focus of the Unit Telescope 4 (UT4: Yepun) on the VLT. HAWK-I provides a 7.5 square arcsecond FoV with a pixel scale of  $0.106''$  and offers 10 different filters in the wavelength range  $0.85 - 2.5 \mu\text{m}$ , including both broad band ( $Y$ ,  $J$ ,  $H$  and  $K_s$ ) and narrow band (Bracket gamma, CH4, H2,  $1.061 \mu\text{m}$ ,  $1.187 \mu\text{m}$  and  $2.090 \mu\text{m}$ ) filters. Under average conditions, HAWK-I can reach limiting magnitudes of 24.8, 23.9 and 24.2 in the  $J$ ,  $H$  and  $K_s$  bands respectively<sup>3</sup>. Observations were similarly carried out by Nantais et al. (2016) over three ESO periods and were reduced by Nantais et al. (2016) using a similar method as discussed in Lidman et al. (2008, 2012). Nantais et al. (2016) calculate that the observations of SpARCS-0330 go down to a limiting  $K_s$  magnitude of 23.4, with a maximum completeness of 99% at  $K_s < 21$  mag. The image quality varies from  $0.3''$  FWHM for HAWK-I  $K_s$  band data to  $1.1''$  FWHM for IMACS  $u$  band data.

The central region of SpARCS-0330 out to a projected cluster-centric radius of  $\approx 750$  kpc benefits from archival *HST*/WFC3 observations from the See Change Survey (programs GO-13677 and GO-14327) which, by targeting twelve  $z > 1$  clusters, was designed to efficiently detect high redshift Type Ia supernovae (Hayden et al., 2021). SpARCS-0330 benefits only from observations in the F105W, F140W and F160W filters from the WFC3/IR camera (Delahaye et al., 2017; Noble et al., 2017). The observations made use of a 5-point dither pattern and were reduced using a data reduction pipeline which carried out the charge-transfer efficiency correction before aligning and co-adding the images using the standard **AstroDrizzle** software<sup>4</sup>. The reader is directed to Hayden et al. (2021) for a more detailed discussion of the observations and data reduction.

<sup>2</sup><http://www.lco.cl/technical-documentation/imacs-user-manual/>

<sup>3</sup><https://www.eso.org/sci/facilities/paranal/instruments/hawki/overview.html>

<sup>4</sup><https://drizzlepac.readthedocs.io/en/latest/astrodrizzle.html>



## MIR, FIR and Sub-mm

SpARCS-0330 was imaged with the Infrared Array Camera (IRAC: Fazio et al., 2004) and the Multiband Imaging Photometer (MIPS: Rieke et al., 2004) instruments on *Spitzer* as part of the *Spitzer* Wide-area Infrared Extragalactic Survey (SWIRE: Lonsdale et al., 2003) covering all seven *Spitzer* bands (four IRAC bands at 3.6, 4.5, 5.8 and  $8.0\,\mu\text{m}$  and three MIPS bands at 24, 70 and  $160\,\mu\text{m}$ ). However, due to the large beamsize of the  $160\,\mu\text{m}$  observations, only the 24 and  $70\,\mu\text{m}$  bands are used in our analysis. We also use the publicly available SWIRE catalogues retrieved from the NASA/IPAC Infrared Science Archive<sup>5</sup>. In addition to the SWIRE catalogues, the CDFS field was also covered as part of the *Spitzer* Extragalactic Representative Volume Survey (SERVS: Mauduit et al. 2012), an  $18\,\text{deg}^2$  *Spitzer* survey reaching  $\sim 2\,\mu\text{Jy}$  depth in the 3.6 and  $4.5\,\mu\text{m}$  IRAC bands.

We made use of publicly available 250, 350 and  $500\,\mu\text{m}$  *Herschel* SPIRE imaging and catalogues for the CDFS field from HerMES (Oliver et al., 2012). We use the XID+24 catalogues, which are created by taking the positions of sources in the CDFS field from the higher-resolution  $24\,\mu\text{m}$  catalogues produced by the SWIRE survey, and using these positions as priors for the probabilistic de-blending tool XID+ (Hurley et al., 2017). XID+ is used to obtain the full posterior probability distribution on flux estimates in the three *Herschel* bands for the sources detected in the SWIRE survey. As well as the archival SPIRE imaging, we obtained deep *Herschel* PACS at 100 and  $160\,\mu\text{m}$ . The observations were conducted in a similar manner to the PACS observations described in Noble et al. (2016) and the data reduction process made use of the Unimap pipeline (Piazzo et al., 2015). Unimap is a generalised least-squares map maker for *Herschel*. We ran Unimap with the default parameters to produce a map with final pixel sizes of  $1.6''$  and  $3.2''$  for the 100 and  $160\,\mu\text{m}$  maps respectively. The resulting PACS maps are presented in Figure 4.1

In order to extract flux densities from these deep *Herschel* PACS maps, we carried out aperture photometry based on replicated maps produced by XID+ to build up a full posterior probability distribution for the flux density estimates. For the positional priors, we used the same  $24\,\mu\text{m}$

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<sup>5</sup><https://irsa.ipac.caltech.edu/data/SPITZER/SWIRE/>

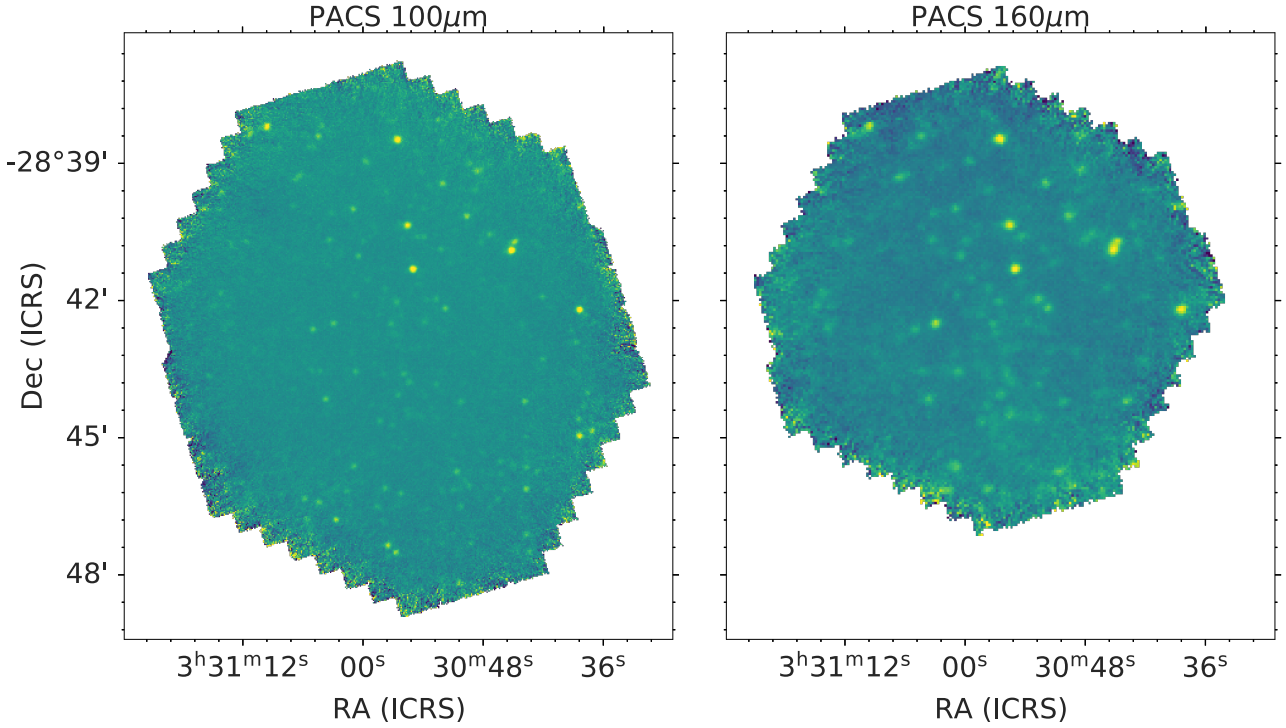


Figure 4.1: The *Herschel* PACS  $100\,\mu\text{m}$  (left) and  $160\,\mu\text{m}$  (right) maps reduced using the Unimap generalised least-squares map maker.

positions from the SWIRE survey that were used for the publicly available HerMES catalogue, allowing us to simply attribute a PACS  $100\,\mu\text{m}$  and  $160\,\mu\text{m}$  flux density to each source in the HerMES catalogue (provided that it is coincident with the map areas of the PACS observations). We extracted aperture photometry with 7 different apertures from a  $2''$  radius to a  $5''$  radius, and for each aperture size we define the flux density and its associated errors as the median and the 16th and 84th percentiles of the posterior probability distribution estimated by XID+. From this analysis, we produced a single FIR/sub-mm catalogue containing *Herschel* SPIRE and PACS photometry for sources in the region of the SpARCS-0330 cluster.

## 4.3 Assembling the Catalogues

### 4.3.1 The Photometric Catalogue

Nantais et al. (2016) used the optical/NIR data discussed in Section 4.2 to create a photometric catalogue from  $u$ -band through to  $8.0\,\mu\text{m}$ . This process will be summarised here and the reader

is directed to Nantais et al. (2016) for a more in depth discussion of the production of this catalogue.

All objects were extracted originally from the HAWK-I  $K_s$  image using Source Extractor<sup>6</sup> version 2.19.5 (Bertin and Arnouts, 1996). In order to ensure that no legitimate, low-surface brightness sources were missed, at least 5 pixels at  $1\sigma$  or higher were required for a detection. The total flux was derived from Source Extractor’s FLUX\_AUTO, which estimates the total flux density by integrating the pixel values within an adaptively scaled aperture<sup>7</sup>. Optical and NIR images were PSF-matched using the IRAF<sup>8</sup> task `wiener` to the  $u$ -band PSF ( $1.02''$ ).

Aperture photometry was obtained using Source Extractor in dual image mode, with the  $K_s$  band image as the detection image and the PSF-matched colour image as the measurement image. For optical and NIR images, an aperture diameter of  $2.2''$  was selected, as it was shown to minimise the scatter in the photometric redshifts for objects with spectroscopic redshifts. For IRAC images, an aperture diameter of  $3.7''$  was used. Although this aperture contains a considerably smaller fraction of the light in the IRAC bands than the  $2.2''$  optical aperture, it was used to avoid adding large amounts of noise and increasing scatter in the photometric redshifts due to large uncertainties in the first two IRAC channels.

For  $u$  through  $K_s$ , all uncertainties were set equal to the quadrature sum of the background RMS and a 1% uncertainty associated with PSF size variation and positioning errors. For IRAC channel 1 through to IRAC channel 4, the background RMS was added in quadrature to an uncertainty of 5% of the flux (or, in the case of negative fluxes, an absolute value of 5% of the flux) following UltraVISTA to account for systematic errors in the IRAC zeropoints. Reddening corrections for the Milky Way foreground dust were applied to the photometry based on Schlafly and Finkbeiner (2011) maps, and the zeropoints in all bands were adjusted (by a maximum of  $\pm 0.1$  mag and usually within their error range) to match the stellar loci of UltraVISTA.

<sup>6</sup><https://www.astromatic.net/software/sextractor/>

<sup>7</sup><https://sextractor.readthedocs.io/en/latest/Photom.html>

<sup>8</sup>IRAF is distributed by the National Optical Astronomy Observatories which are operated by the Association of Universities for Research in Astronomy, Inc., under the cooperative agreement with the National Science Foundation

For the sources in the photometric catalogue, photometric redshifts were estimated using the SED fitting code **EAZY** (Brammer et al., 2008), while stellar masses and star formation rates were estimated with **FAST** (Kriek et al., 2009). A discussion of the parameters used for these fitting codes can be found in Nantais et al. (2016) and van der Burg et al. (2013). In particular, **FAST** stellar mass outputs were based on the Bruzual and Charlot (2003) models. Each source was additionally given a flag showing whether the source has a spectroscopic redshift and, if so, whether it resides inside or outside the SpARCS-0330 cluster. Where both were available, Nantais et al. (2016) compared the spectroscopic redshifts to the photometric redshifts estimated by **EAZY** for galaxies within 1 Mpc of the cluster centre, finding that the scatter is small and comparable to similar analyses of this nature (e.g. van der Burg et al., 2013).

## FIR Crossmatching

At this point we have two separate catalogues - the optical/NIR catalogue compiled by Nantais et al. (2016) containing photometry from  $u$ -band through to  $8\mu\text{m}$  and either spectroscopic or photometric redshifts, alongside an infrared catalogue with six-band photometry from  $24 - 500\mu\text{m}$ . The difficulty in linking the two catalogues stems from the different resolutions of the instruments used for detection - sources in the FIR catalogue were selected from the  $24\mu\text{m}$  *Spitzer* SWIRE catalogue with a PSF FWHM of  $\sim 6$  arcseconds<sup>9</sup>, whereas the  $K_s$  images from HAWK-I are much higher resolution, with a PSF FWHM  $\sim 0.4$  arcseconds<sup>10</sup>. We therefore identify the most likely optical counterpart to sources in the FIR catalogue using the likelihood ratio method developed by Sutherland and Saunders (1992). The likelihood ratio,  $L$ , is defined as:

$$L = \frac{q(m)f(r)}{n(m)} \quad (4.1)$$

where  $q(m)$  and  $n(m)$  represent the normalised magnitude distributions for the true optical

<sup>9</sup><https://irsa.ipac.caltech.edu/data/SPITZER/docs/mips/mipsinstrumenthandbook/>

<sup>10</sup>[https://www.eso.org/sci/facilities/paranal/instruments/hawki/doc/VLT-MAN-ESO-14800-3486\\_v103.pdf](https://www.eso.org/sci/facilities/paranal/instruments/hawki/doc/VLT-MAN-ESO-14800-3486_v103.pdf)

counterparts and the background optical sources respectively, and  $f(r)$  represents the probability of the optical source being the true counterpart based on its offset from the FIR source. This positional probability term is typically defined as a gaussian (e.g. Smith et al., 2011; Wu et al., 2013; Seo et al., 2018):

$$f(r) = \frac{1}{2\pi\sigma_1\sigma_2} \exp\left(\frac{-r^2}{2\sigma_1\sigma_2}\right) \quad (4.2)$$

where  $\sigma_1$  and  $\sigma_2$  are the positional uncertainties for the two sources and  $r$  is the offset between them. We conservatively estimate the positional uncertainties in the *Spitzer* MIPS  $24\mu\text{m}$  and the HAWK-I  $K_s$  maps as a quarter of the PSF FWHM, resulting in values of  $\sim 1.5''$  and  $\sim 0.1''$  respectively.

To calculate  $q(m)$  we first build up the magnitude distribution of each of the optical sources lying within  $3''$  of a  $24\mu\text{m}$  source (matching the PSF size of *Spitzer* MIPS). We find that there are 127 *Spitzer* sources within the footprint of the optical/NIR catalog, with 444 potential optical counterparts. In order to recover the magnitude distribution of background optical sources, we take an equal number (127) of apertures, each with a radius of  $3''$ , lay them in random positions  $> 6''$  away from a  $24\mu\text{m}$  source (i.e. such that no potential true optical counterparts to  $24\mu\text{m}$  sources fall within the apertures), and build up the magnitude distribution of the optical sources that fall within these apertures. By subtracting these two magnitude distributions, we arrive at the magnitude distribution of the excess optical sources above the background level. This magnitude distribution is presented in Figure 4.2. Normalising this result following Seo et al. (2018) yields

$$q(m) = \frac{\text{excess}(m)}{\sum_m \text{excess}(m)} \times Q_0 \quad (4.3)$$

where  $Q_0$  is the fraction of true counterparts, defined as:

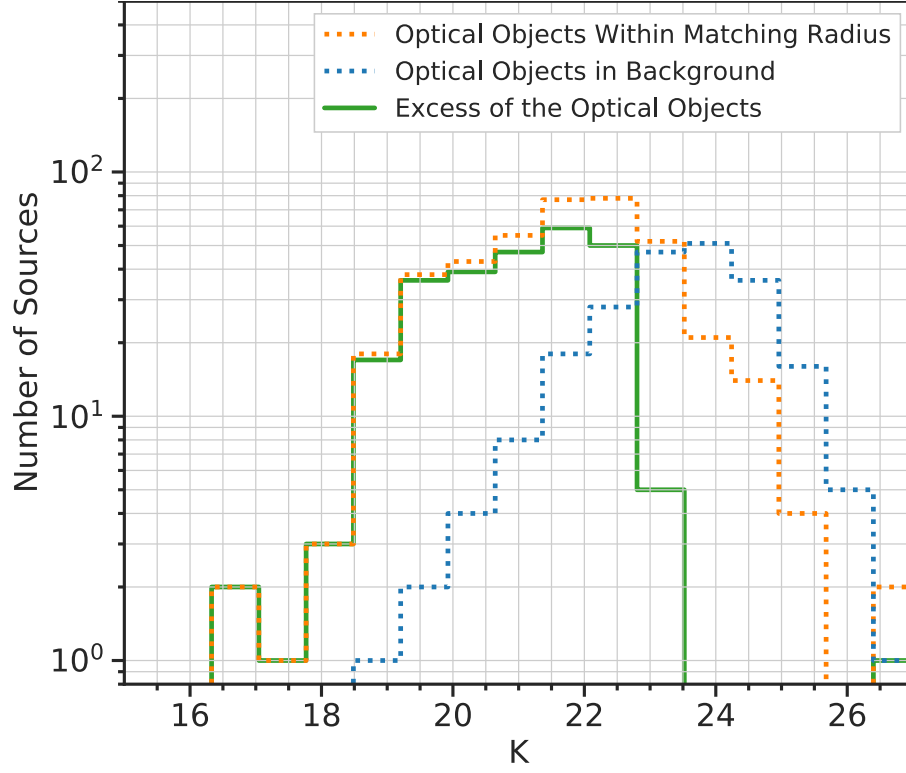


Figure 4.2: The magnitude distributions used to calculate  $q(m)$ . The orange and blue dotted lines show the magnitude distributions of optical sources within the matching radius of a  $24\mu\text{m}$  source and optical sources within our background apertures respectively, while the green line shows the excess number of optical sources above the background.

$$Q_0 = \frac{N_{\text{candidates}} - N_{\text{background}}}{N_{24\mu\text{m}}} \quad (4.4)$$

where  $N_{\text{candidates}}$ ,  $N_{\text{background}}$  and  $N_{24\mu\text{m}}$  are the total number of optical sources within  $3''$  of a  $24\mu\text{m}$  source, the total number of optical sources within the background apertures and the total number of  $24\mu\text{m}$  sources in the FIR catalogue respectively. Based on this method, we calculate  $Q_0 = 0.75$  for our sample.

After calculating the likelihood ratio  $L_j$  for each potential optical counterpart  $j$ , we assign each a reliability  $R_j$ , defined as:

$$R_j = \frac{L_j}{\sum_i L_i + (1 - Q_0)} \quad (4.5)$$

where  $\Sigma_i L_i$  represents the sum of the likelihood ratios of the  $i$  potential optical counterparts within the  $3''$  matching radius of a  $24\mu\text{m}$  source. We then carry out the cross-matching procedure in three steps. Firstly, any optical counterpart with  $R_j \geq 0.8$  are considered robust counterparts and the FIR photometry is appended to the optical/NIR photometry for that source. Of the 127 sources in the FIR photometry catalogue 85 have a single, robust optical counterpart ( $\sim 67\%$ ). Of the remaining 42 FIR sources, we find 40 have multiple potential counterparts with  $R_j < 0.8$ , while two have no viable optical counterparts (we exclude these two from the catalogue). For the 40 sources without robust optical counterparts, we first find the ratio of the reliability of each source compared to the sum of  $R_j$  for each potential optical counterpart. If this ratio comes to  $> 0.8$  for any one source, we consider this to be the most likely optical counterpart as, although it is not robust enough to make the original cut, the optical counterpart is clearly the most viable. Alternatively, if there is no obvious optical counterpart, we divide the total *Spitzer* and *Herschel* flux equally between the potential counterparts.

### Finalising the Photometric Catalogue

The primary aim of this study is to map out star formation and quenching across the SpARCS-0330 cluster. As such we must estimate the properties of its member galaxies. In order to achieve this, we select the best photometry for each source in the catalogue to pass on to the SED fitting code **CIGALE**.

The only available optical photometry in the  $u$ ,  $g$ ,  $r$ ,  $i$  and  $z$  bands comes from IMACS, while the only available  $Y$  band data comes from HAWK-I. For the  $J$ ,  $H$  and  $K_s$  bands, the high resolution HST data is used if available, otherwise photometry in the  $J$  and  $K_s$  bands is similarly added from HAWK-I. This is then followed by photometry in the four IRAC channels. If the source has MIR/FIR photometry from *Spitzer* and *Herschel* (following the discussion in Section 4.3.1), then this is used for the SED fitting. Otherwise, an aperture matching the beamsize of each instrument was laid down at the position of the  $K_s$  band source in the corresponding image and an upper limit estimated from this aperture. Finally, we include the photometric

redshift estimates from **EAZY**. From this process, we built up a photometric catalogue containing up to 20 band photometry for the sources in the cluster region, with informative upper limits in bands where no detection was present and photometric redshift estimates.

### 4.3.2 The Wider Photometric Catalogue

While this photometric catalogue provides superb photometry across 20 bands for the sources in the region of SpARCS-0330, we are limited to the central  $\approx 7'$  of the cluster due to the limited field of view of the HAWK-I instrument used for the extraction of optical sources in the photometric catalogue. In order to study star formation in the SpARCS-0330 cluster on a wider scale, we constructed an additional wide field catalogue based on archival images and catalogues. This photometry is typically shallower and does not cover as many photometric bands, but spans  $\approx 30$  Mpc across the nominal cluster centre.

We make use of the band-merged catalogue produced by the SWIRE team, containing the HerMES, SWIRE and SERVS catalogues in the CDFS, as well as optical/NIR photometry from CTIO MOSAIC2 covering the  $u$ ,  $g$ ,  $r$ ,  $i$  and  $z$  bands and two separate surveys from the 4.1m Visible and Infrared Survey Telescope for Astronomy (VISTA: Emerson et al. 2004); the VISTA Deep Extragalactic Observations (VIDEO<sup>11</sup>: Jarvis et al., 2013) survey and the VISTA Hemisphere Survey (VHS<sup>12</sup>: McMahon et al., 2013). The VIDEO Survey is a  $12 \text{ deg}^2$  survey reaching  $5\sigma$  depths in AB magnitude of  $Z = 25.7$ ,  $Y = 24.5$ ,  $J = 24.4$ ,  $H = 24.1$  and  $K_s = 23.8$  in  $2''$  diameter apertures. VHS aimed to survey the entire southern celestial hemisphere ( $\sim 19,000 \text{ deg}^2$ ) in the  $J$  and  $K_s$  bands, with an additional  $\sim 4,500 \text{ deg}^2$  of deep  $H$ -band imaging in the South Galactic Cap, and shallower  $Y$  and  $H$ -band imaging at higher galactic latitudes. For the CDFS field, VHS can reach a median  $5\sigma$  point source limit of  $J = 20.2$  and  $K_s = 18.1$ , and is hence much shallower than the VIDEO survey. In addition to the optical/NIR photometry, the catalogue contains ancillary data in the NUV and FUV bands from the *Galaxy Evolution Explorer* (GALEX<sup>13</sup>). All GALEX fluxes are aperture corrected

<sup>11</sup><http://www-astro.physics.ox.ac.uk/~video/public/Home.html>

<sup>12</sup><http://www.vista-vhs.org/>

<sup>13</sup><http://www.galex.caltech.edu/index.html>



and calibrated using zero points of 18.82 and 20.08 in the FUV and NUV bands respectively. We note that, while some sources in this SWIRE band-matched catalogue have spectroscopic redshifts (typically either from the NASA Extragalactic Database<sup>14</sup>, the first data release of the Prism Multi-Object Survey (Coil et al., 2011; Cool et al., 2013) or from Hsu et al. 2014), none are associated with SpARCS-0330.

## 4.4 Sample Selection

### 4.4.1 Photometric Redshift Estimates

A key step in assembling a sample of candidate cluster members is estimating the photometric redshifts of galaxies in the vicinity of SpARCS-0330. For the photo-z and photo-z wide samples, we pursue two complementary methods for estimating their photometric redshifts.

For the first method, all galaxy properties, including photometric redshifts, are estimated by **CIGALE**. For the photometric catalogue, we exclude any source that has a spectroscopic redshift (as discussed in Section 4.2.1) and we additionally filter by the **CLASS\_STAR** parameter<sup>15</sup> produced by Source Extractor, which represents the likelihood that the source is a star based on the  $K_s$  image used for the detection in Source Extractor. We select only those sources with **CLASS\_STAR** < 0.5, indicating a likely galaxy. We run the resulting sources in the photometric catalogue through **CIGALE**, with the modules and parameter ranges outlined in Table 4.2. For the wider photometric catalogue, we initially restrict the sample to only sources within 15 Mpc of the cluster centre and with photometry in at least 6 optical bands in order to improve the quality of the SED fitting. We also restrict the sample to include only those sources with **CLASS\_STAR** < 0.5. Similarly to the photometric catalogue, the resulting wider field sample is run through **CIGALE** based on the modules and parameters presented in Table 4.2.

For the complementary method, we first estimate photometric redshifts using the SED fitting code **EAZY**. From these photometric redshift estimates, we can then select only those sources

<sup>14</sup><https://ned.ipac.caltech.edu/>

<sup>15</sup><https://sextractor.readthedocs.io/en/latest/ClassStar.html>

| Module                     | Parameter          | Parameter Range               |
|----------------------------|--------------------|-------------------------------|
| sfhdelayedbq               | tau_main [Myr]     | 1000, 4000, 8000              |
|                            | age_main [Myr]     | 500, 1000, 1500               |
|                            | age_bq [Myr]       | 10, 50, 100                   |
|                            | r_sfr              | 0.1, 0.5, 1.0, 2.0, 5.0, 10.0 |
| bc03                       | imf                | Chabrier                      |
|                            | metallicity        | 0.02                          |
| nebular                    | logU               | -2.0                          |
|                            | lines_width [km/s] | 300.0                         |
| dustatt_modified_starburst | E_BV_lines         | 0.3, 0.5, 1.0                 |
|                            | E_BV_factor        | 0.3, 0.5, 1.0                 |
|                            | Rv                 | 3.1                           |
| casey_2012                 | temperature [K]    | 10, 20, 30, 40, 50, 60        |
|                            | beta               | 1.5                           |
|                            | alpha              | 1.0, 2.0, 3.0, 4.0, 5.0       |
| redshifting                | redshift           | $z = 0 - 6$ in steps of 0.1   |

Table 4.2: List of the modules and the main parameters (with associated parameter ranges) allowed in the full CIGALE SED fitting.

at similar redshifts to SpARCS-0330 and run the resulting samples through CIGALE with redshifts fixed to the EAZY estimate to obtain stellar masses and SFRs. This second method has significant benefits over using CIGALE to estimate all of the galaxy parameters. Firstly, fixing the photometric redshift significantly restricts the parameter space over which CIGALE has to work, making this method much less computationally expensive. This is a significant consideration, particularly for the photo-z wide sample for which we require CIGALE to find best fitting SEDs for thousands of galaxies, many of which contain upper limits on their FIR photometry. Moreover, the photometric redshift estimates from EAZY allow us to pre-select a sample of likely cluster members rather than having to run the full wider photometric catalogue through CIGALE, further reducing the computation time. In terms of the fitting routines themselves, while CIGALE is more flexible in its construction, EAZY photometric redshifts are estimated from a series of well-tested and well-calibrated empirical galaxy template SEDs and has been proven to produce robust photometric redshift estimates (Brammer et al., 2008). With a lack of quality photometry, CIGALE may also suffer from significant degeneracies between models, as there are

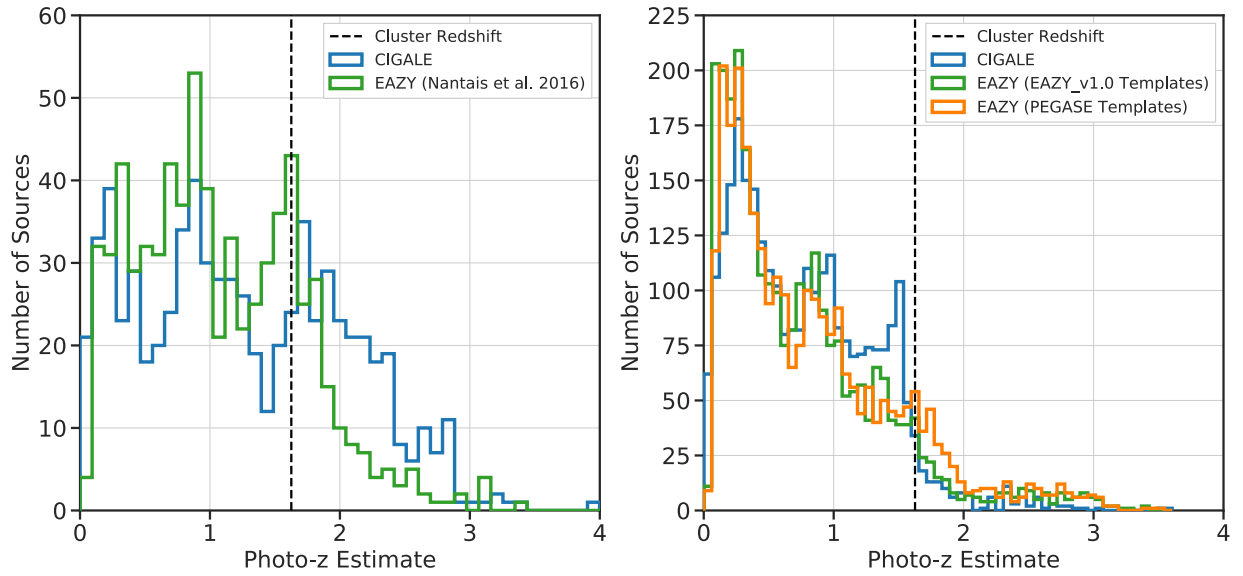


Figure 4.3: Photometric redshift histograms for the photometric catalogue (*left*) and the wider photometric catalogue (*right*) samples. In both panels, the blue line shows the photometric redshifts estimated by CIGALE. In the left panel, the green line shows the redshifts estimated by Nantais et al. (2016) using EAZY, whereas in the right panel, the green and orange lines show our photometric redshift estimates from EAZY based on the EAZY\_v1.0 and PÉGASE template sets respectively.

many more tunable parameters that can be specified by the user. However, it is worth noting that EAZY cannot easily process FIR photometry, nor include upper limits on the photometry.

Photometric redshift estimates from EAZY are already included in the original photometric catalogue assembled by Nantais et al. (2016). For the wider photometric catalogue, we run the catalogue through EAZY using both the EAZY\_v1.0 minimal template set described in Brammer et al. (2008), as well as the full library of PÉGASE (Fioc and Rocca-Volmerange, 1997) templates. The EAZY\_v1.0 template set is constructed by reducing the library of PÉGASE templates described in Grazian et al. (2006) into 5 “principal component” templates based on the Non-negative Matrix Factorisation (NMF) algorithm of Blanton and Roweis (2007). The PÉGASE templates are optimised for starbursts and evolved galaxies at  $0 < z < 2$  and should therefore be well suited to the members of SpARCS-0330 at  $z \sim 1.6$ .

In Figure 4.3, we compare the photometric redshift distributions from CIGALE and EAZY. In order to include the most reliable photometric redshift estimates, we include only those sources with  $\chi^2_\nu < 10$  from both fitting algorithms, including both of the template sets used in EAZY. Moreover, the photometric redshifts are calculated by marginalising over all models/templates.

In both panels, we find a qualitatively similar trend, with three distinct peaks at  $z < 0.5$ ,  $z \sim 1$  and  $z \sim 1.6$ . While these three peaks could be indicative of significant aliasing, we note that, for the photometric catalogue, the highest redshift peak is exactly coincident with the nominal cluster redshift of  $z = 1.626$  for the **EAZY** estimates, and only slightly offset for the **CIGALE** estimates. In the wider field, we observe a large number of sources at  $z < 0.5$  followed by another significant bump at  $0.5 < z < 1$ . There is additionally a smaller bump associated with the nominal redshift of the SpARCS-0330 cluster. This is most evident in the **EAZY** photometric redshift estimates based on the PÉGASE templates, but there is also a small increase in those based on the **EAZY\_v1.0** templates. The **CIGALE** photometric redshifts show another strong peak at  $z \sim 1.5$ , offset from the expected cluster redshift by  $\Delta z \sim 0.12$ . To investigate this offset in more detail, we run the photometry for the 40 spectroscopically confirmed cluster members through **CIGALE**, allowing **CIGALE** to estimate the photometric redshift. We then make a composite photometric redshift PDF by summing together the PDFs for each spectroscopically confirmed source and normalising the result so that it sums to unity, which we present in Figure 4.4. We find that **CIGALE** systematically underpredicts the redshift of the confirmed cluster members, with a significant offset between the redshift range of the spectroscopic confirmations and the peak of the composite photometric redshift PDF. We quantify the extent of this offset by isolating the peak of this composite photometric redshift PDF (selecting data in the range  $1.0 < z < 1.8$ ) and fitting a Gaussian function using the fitting algorithm **LMFIT** (which is discussed in more detail in Chapter 2). This Gaussian is well fit to the data ( $\chi^2 = 0.001$ ), with a best fitting central redshift of  $z = 1.52 \pm 0.01$ . From this value we estimate a systematic offset of  $\Delta z \approx 0.1$  in the photometric redshifts estimated by **CIGALE**. Adding this systematic shift to the photometric redshift distribution from **CIGALE** in Figure 4.3 would bring the **CIGALE** and **EAZY** results (based on the PÉGASE templates) into good agreement, with the peak positioned almost exactly at the nominal cluster redshift.

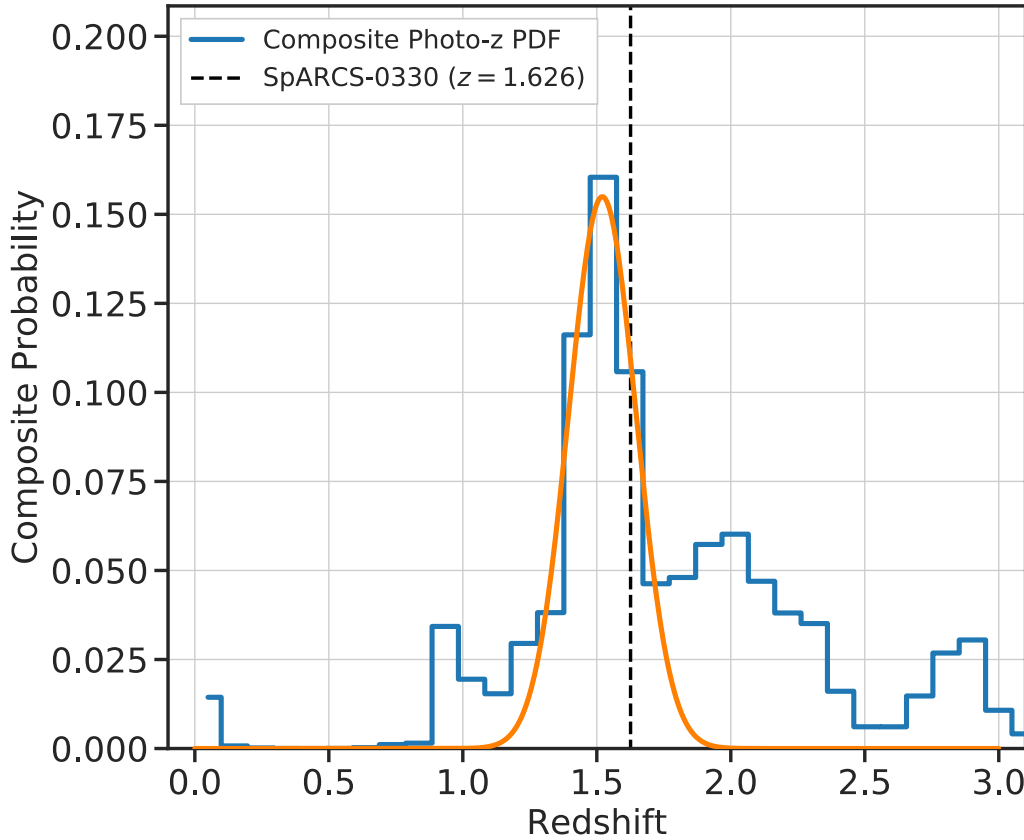


Figure 4.4: The composite photometric redshift PDF (blue) produced by summing the individual photometric redshift PDFs for each spectroscopically confirmed cluster member estimated by CIGALE. We fit a Gaussian function to the resulting composite PDF (orange line) and compare to the expected redshift based on the nominal cluster redshift (black dashed line). We find that the best fitting redshift of the peak of the composite PDF is  $z \approx 1.521$ , and is therefore offset by  $\Delta z \approx 0.105$  from the expected cluster redshift.

#### 4.4.2 The Final Samples

We use the aforementioned analysis and available photometry to select our final samples. We order our sample into three separate tiers of data quality: the spec-z, photo-z and photo-z wide samples. We note that, as well as making the necessary quality cuts outlined in the following sections, we additionally apply the  $K_s$  band magnitude cut ( $K_s < 23.40$ ) implemented by Nantais et al. (2016) to ensure a high level of completeness in the samples.

##### The Spec-z Sample

From the master catalogue discussed in Section 4.3.1, we first select our sample of spectroscopically confirmed cluster members, comprised of sources in the photometric catalogue with

| Module                     | Parameter          | Parameter Range                       |
|----------------------------|--------------------|---------------------------------------|
| sfhdelayedbq               | tau_main [Myr]     | 100, 200, 500, 1000, 2000, 5000, 8000 |
|                            | age_main [Myr]     | 100, 200, 500, 1000, 2000             |
|                            | age_bq [Myr]       | 10, 50, 100                           |
|                            | r_sfr              | 0.1, 0.2, 0.5, 1.0, 2.0, 5.0, 10.0    |
| bc03                       | imf                | Chabrier                              |
|                            | metallicity        | 0.02                                  |
| nebular                    | logU               | -2.0                                  |
|                            | lines_width [km/s] | 300.0                                 |
| dustatt_modified_starburst | E_BV_lines         | 0.2, 0.4, 0.6, 0.8                    |
|                            | E_BV_factor        | 0.2, 0.4, 0.6, 0.8                    |
|                            | Rv                 | 3.1                                   |
| casey_2012                 | temperature [K]    | 10, 20, 30, 40, 50, 60                |
|                            | beta               | 1.5                                   |
|                            | alpha              | 1.0, 2.0, 3.0, 4.0, 5.0               |
| redshifting                | redshift           | Fixed <sup>†</sup>                    |

Table 4.3: List of the modules and the main parameters (with associated parameter ranges) allowed in the CIGALE SED fitting for the sources with photometric redshifts estimated from EAZY.

spectroscopic redshifts in the range  $(z_{spec} - z_{cl})/(1 + z_{cl}) \leq 0.05$  (van der Burg et al., 2013; Nantais et al., 2016). Of the 40 spectroscopically confirmed cluster members in this sample, all have optical/NIR photometry (i.e. from  $u$  band through to IRAC channel 4) from the original photometric catalogue, 6 have  $24\mu\text{m}$  photometry from *Spitzer* MIPS, 1 has *Herschel* PACS 100 and  $160\mu\text{m}$  photometry and 6 have 250, 350 and  $500\mu\text{m}$  photometry from *Herschel* SPIRE. As discussed in Section 4.3.1, we estimate upper limits for the sources that don’t have photometry in these bands.

We then run the photometry for each source through the SED fitting code CIGALE, with the redshift fixed to their spectroscopically confirmed redshifts. In Table 4.3 we outline the modules and parameters used for the CIGALE SED fitting. We note that we test multiple different combinations of modules and parameter ranges in CIGALE, finding that these modules provided the lowest median reduced chi-squared value for each of our samples. In Figure 4.5, we show an example of the resulting best fit SED for one of the spectroscopically confirmed sources

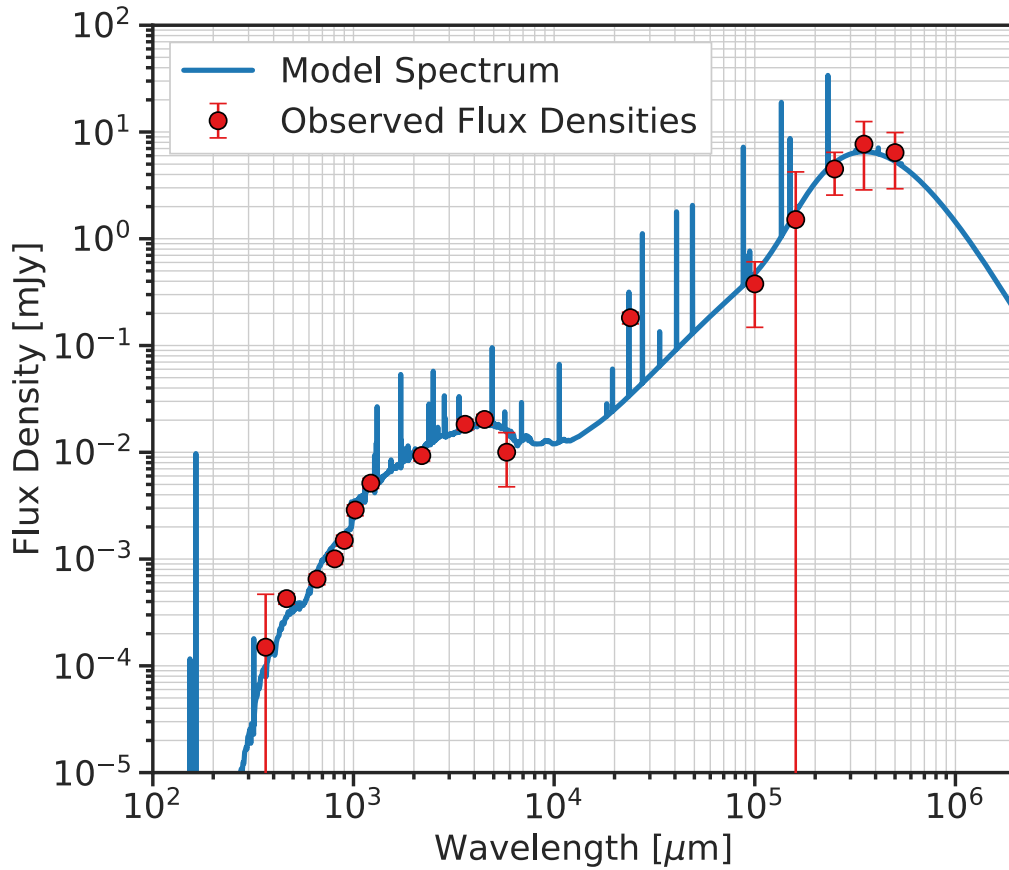


Figure 4.5: An example of a best fitting model SED produced by **CIGALE** for the source 2503 in the spec-z sample. Red points show the photometry of the source and the blue line shows the best fitting SED model. This source has a spectroscopically confirmed redshift of  $z = 1.620$ , and the **CIGALE** best fitting SED has a reduced chi-squared value of  $\chi^2_\nu = 4.4$ , indicating a reasonable fit to the data.

in SpARCS-0330. In order to ensure that our final analysis is not affected by sources whose properties were based on a poor SED fitting, we exclude any galaxy with  $\chi^2_\nu > 5$ . This leaves us with 38 spectroscopically confirmed sources in the spec-z sample.

### The Photo-z Sample

Our second sample is comprised of sources that do not have a spectroscopic redshift in the master catalogue. We select only those sources with **CLASS\_STAR**  $< 0.5$ , indicating a likely galaxy and, similar to the spec-z sample, we select likely cluster members as those with an EAZY photometric redshift in the range  $(z_{phot} - z_{cl})/(1 + z_{cl}) \leq 0.05$ . We chose to use the EAZY photometric redshift estimate rather than the **CIGALE** photometric redshift estimate in

part based on Figure 4.3 which demonstrates an excellent agreement between the position of the photometric redshift peak and the nominal cluster redshift, but also as this method is significantly less computationally expensive. As a result, we could probe a much wider parameter space in the following **CIGALE** fit, and indeed for the photo- $z$  sample, we use the same modules and parameter ranges as shown in Table 4.3. We then run the photometry for this sample through **CIGALE** with the redshift fixed to the photometric redshift estimate from **EAZY**. We exclude any sources with  $\chi^2_\nu > 5$ , leaving us with 270 sources in the photo- $z$  sample. Of those 270 sources, all have photometry in the  $u$ ,  $g$ ,  $r$ ,  $i$  and  $z$  bands, as well as the four IRAC channels, 266 have photometry in the  $Y$ ,  $J$  and  $K_s$  bands, while 17 have photometry in the  $H$  band. In total, only 7 of the 270 sources have a crossmatch to the FIR catalogue containing the *Spitzer* MIPS  $24\mu\text{m}$  and *Herschel* SPIRE data, with 5 of those sources also having *Herschel* PACS photometry due to the smaller footprint of the PACS maps compared to the HerMES and SWIRE maps. For those sources without a FIR counterpart, as discussed in Section 4.3.1, we extract upper limits directly from the *Spitzer* and *Herschel* maps.

### The Photo- $z$ Wide Sample

Finally, the third tier is the wider photometric sample, from which we aim to map out star formation in the wider cluster environment. This sample is based on the band-merged SWIRE catalogue discussed in Section 4.3.2. As discussed in Section 4.4.1, we make a number of cuts to the full band-merged catalogue in order to maintain high quality photometry for only the most likely cluster candidates. We first select only those sources within 15 Mpc of the nominal cluster centre. We also restrict the sample to include only those sources with **CLASS\_STAR**  $< 0.5$  and with photometry in at least 6 optical bands in order to improve the quality of the SED fitting. We select potential cluster candidates in the wider field by selecting just those with  $(z_{\text{phot}} - z_{\text{cl}})/(1 + z_{\text{cl}}) \leq 0.05$  and use the full optical to FIR photometry for the resulting sources for the **CIGALE** SED fitting with the redshift fixed to the photometric redshift estimate from **EAZY** based on the PÉGASE templates. We exclude any sources with  $\chi^2_\nu > 5$  in the resulting SED fits, leaving us with 681 sources in the photo- $z$  wide sample.



Of those 681 sources, 2 have NUV photometry from GALEX (there are no sources with FUV photometry). There are 477, 677, 676, 394 and 7 sources with photometry in the  $u$ ,  $g$ ,  $r$ ,  $i$  and  $z$  bands respectively. From the VISTA surveys, there are 682, 408 and 642 sources with photometry in the  $J$ ,  $H$  and  $K_s$  bands respectively (no sources have photometry in the  $Y$  band). There are 691 and 550 sources with photometry in the IRAC 1 and 2 channels, but none in the longer wavelength channels. In total, 9 of the 691 sources have a crossmatch to the FIR catalogue containing the *Spitzer* MIPS  $24\mu\text{m}$  and *Herschel* SPIRE data. For those sources without a FIR counterpart, as discussed in Section 4.3.1, we extract upper limits directly from the *Spitzer* and *Herschel* maps.

## 4.5 Properties

In Figure 4.6 we present histograms of the galaxy properties derived from the SED fitting. We find that our candidate cluster members tend to have  $\text{SFR} \sim 10^{0.8} \text{ M}_\odot \text{ yr}^{-1}$ ,  $M_\star \sim 10^{10} \text{ M}_\odot$  and  $\text{sSFR} \sim 10^{-9} \text{ yr}^{-1}$ . We note that the photo- $z$  wide sample tends towards slightly larger SFRs ( $\sim 10^{0.89} \text{ M}_\odot \text{ yr}^{-1}$ ) and slightly lower stellar masses ( $\sim 10^{9.85} \text{ M}_\odot$ ) than the photo- $z$  and spec- $z$  samples. This offset is likely due to selection biases within the two samples.

In Figure 4.7 we show the distribution of flux densities in the  $z$  band for the photo- $z$  and photo- $z$  wide samples, demonstrating that the photo- $z$  sample more effectively selects lower luminosity sources (with flux densities  $\lesssim 1 \mu\text{Jy}$  in the optical bands), while the photo- $z$  wide sample tends to select sources brighter than  $\approx 0.4 \mu\text{Jy}$ . Qualitatively similar results are found in the other optical bands. This difference is primarily due to the different depths of the surveys used in assembling the photometry for the samples: optical flux densities in the photo- $z$  sample, as discussed in Section 4.3, are taken from deep optical imaging with IMACS, while for the photo- $z$  wide sample we rely on photometry from CTIO MOSAIC2 reaching only moderate depths (Lonsdale et al., 2003). We therefore expect these two samples to pick out samples of physically distinct galaxy populations, making comparisons between the samples difficult. This caveat will be revisited throughout the forthcoming analysis.

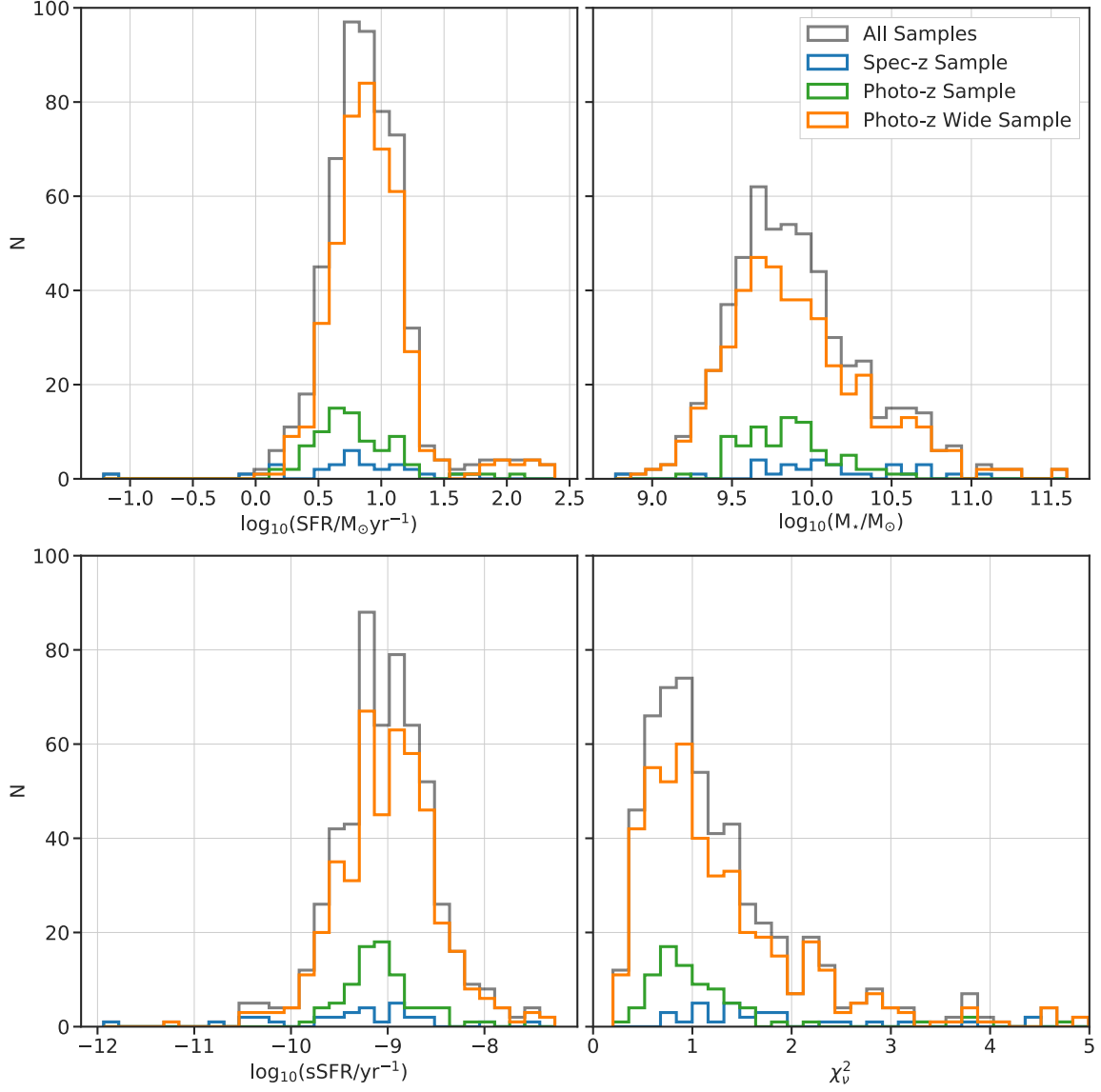


Figure 4.6: The distributions of SFR (*upper left*), stellar mass (*upper right*), sSFR (*lower left*) and reduced chi-squared value (*lower right*) for each of the three tiers of data quality, as well as for all three samples combined. We estimate median galaxy properties of  $\text{SFR} \sim 10^{0.8} \text{ M}_{\odot}\text{yr}^{-1}$ ,  $M_{\star} \sim 10^{10} \text{ M}_{\odot}$  and  $\text{sSFR} \sim 10^{-9} \text{ yr}^{-1}$ , noting that the photo-z wide sample tends towards slightly higher SFRs and slightly lower stellar masses than the photo-z sample. We additionally note that the majority of SED models produced by CIGALE fit the available photometry excellently, with typical reduced chi-squared values  $\chi^2_{\nu} \sim 1$ .

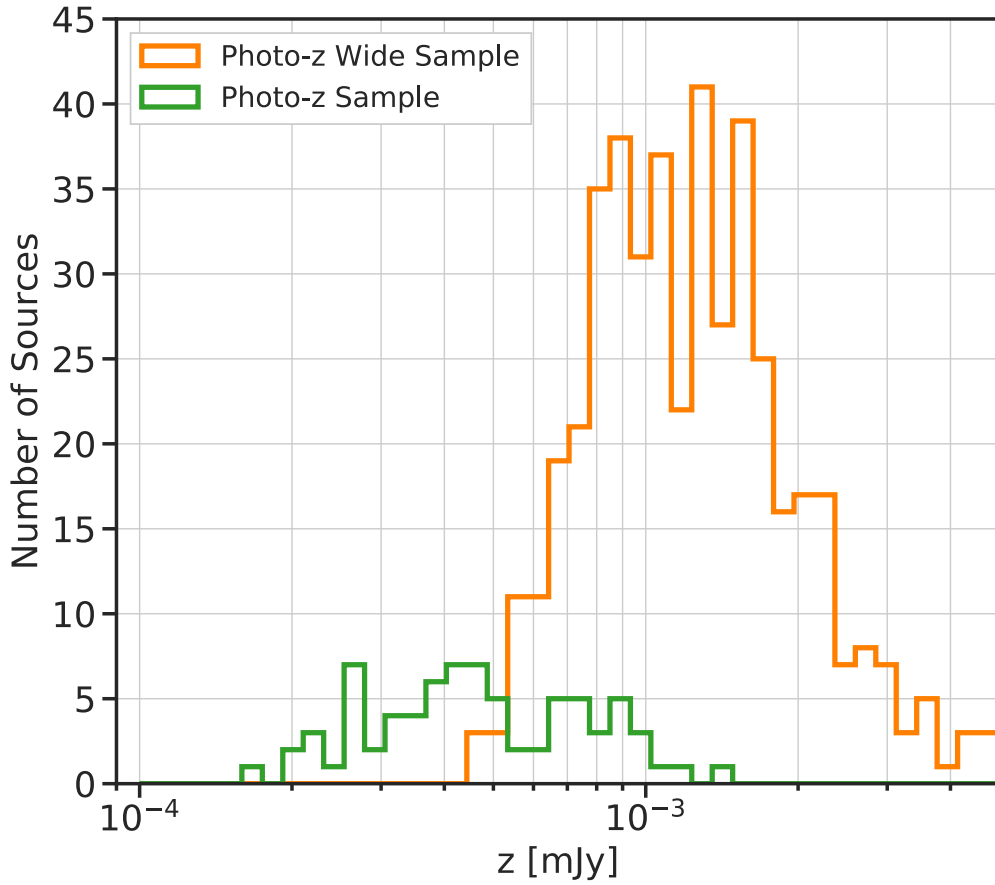


Figure 4.7: The flux density distributions of the photo- $z$  and photo- $z$  wide samples in the  $z$  band. We find that the photo- $z$  sample broadly selects lower luminosity sources compared to the photo- $z$  wide sample. Similar results are found for the  $g$ ,  $r$  and  $i$  bands.

Finally, we find that the best fitting SED models estimated by CIGALE tend to fit the available photometry excellently, with vast majority of reduced chi-squared values  $\chi^2_\nu \sim 1$ .

## 4.6 Star Formation and Quenching in SpARCS-0330

### 4.6.1 SFR – $M_\star$ Relation

In Figure 4.8, we show the location of our three samples on the SFR– $M_\star$  plane, alongside the “main sequence” (MS) relation and associated scatter from Speagle et al. (2014) normalised to a Universe age of  $t = 3.965$  Gyr ( $z = 1.626$ ). We additionally show, in a separate panel, a similar plot highlighting the galaxies in each sample with a counterpart in the MIR and FIR bands.

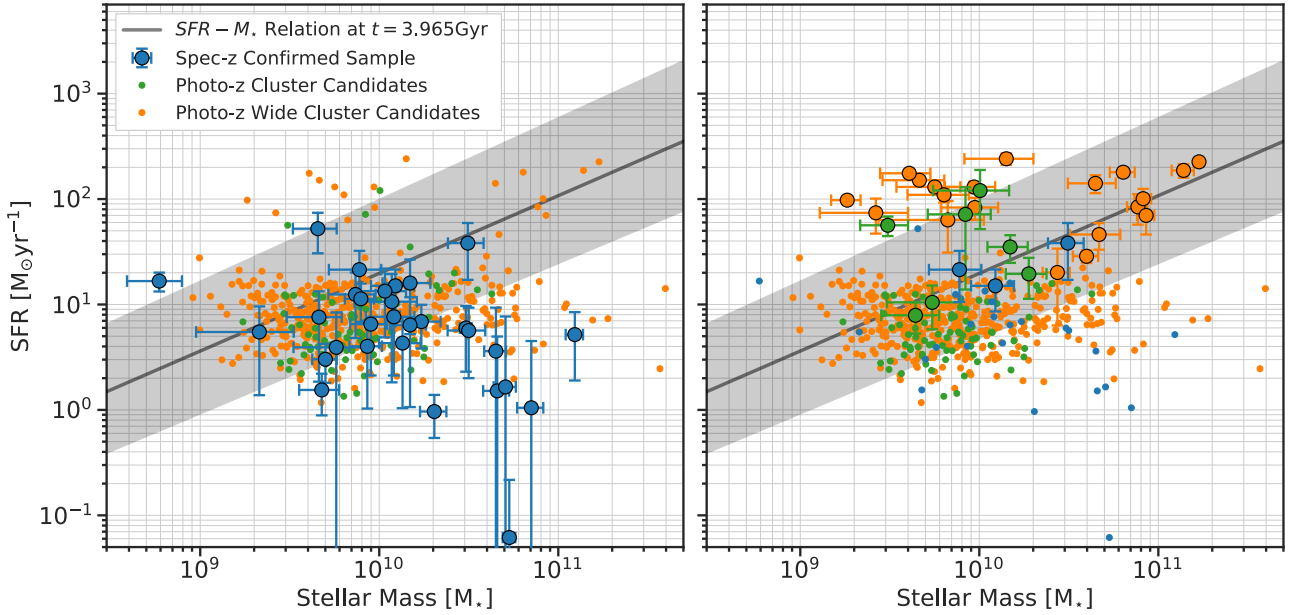


Figure 4.8: The distribution of the galaxies in the spec-z (blue), photo-z (green) and photo-z wide (orange) samples on the  $\text{SFR}-M_*$  plane, alongside the MS relation and associated scatter at  $z = 1.626$  (grey line and shaded region) from Speagle et al. (2014). In the left panel, the relation is shown for all sources, while in the right panel, we highlight with darker colours and error bars those sources that have a detection in the MIR and FIR bands from *Spitzer* and *Herschel*. The majority of sources in all three samples fall within the MS scatter, with only the more massive end of the sample ( $M_* \gtrsim 3 \times 10^{10} M_\odot$ ) lying below the main sequence, indicating that the most massive galaxies in our samples are likely already in the process of quenching (or already quenched). Sources with MIR and FIR detections tend to reside on or above the MS, indicating that these sources have significant ongoing star formation.

We find that the majority of sources lie within the scatter of this relation, indicating that, for the most part, our galaxies are consistent with undergoing sustained star formation. The more massive sources in our sample ( $M_* \gtrsim 3 \times 10^{10} M_\odot$ ) tend to lie below the scatter of the MS. This indicates that the most massive galaxies are likely in the process of quenching, or have already had their star formation quenched, having assembled the majority of their stellar mass at  $z > 1.6$ . This is consistent with the “mass downsizing” trend (Cowie et al., 1996; Cimatti et al., 2006), in which the most massive galaxies assembled the majority of their stellar mass at high redshifts, and have since evolved effectively passively, primarily through dry mergers (see e.g. Hopkins et al., 2008; Kormendy and Ho, 2013). The photo-z and photo-z wide samples additionally contain a handful of galaxies residing above (or at least towards the upper edge of the scatter of) the MS relation, indicating that they also contain galaxies potentially undergoing bursts of star formation. We infer that our samples contain a variety of galaxy types, including

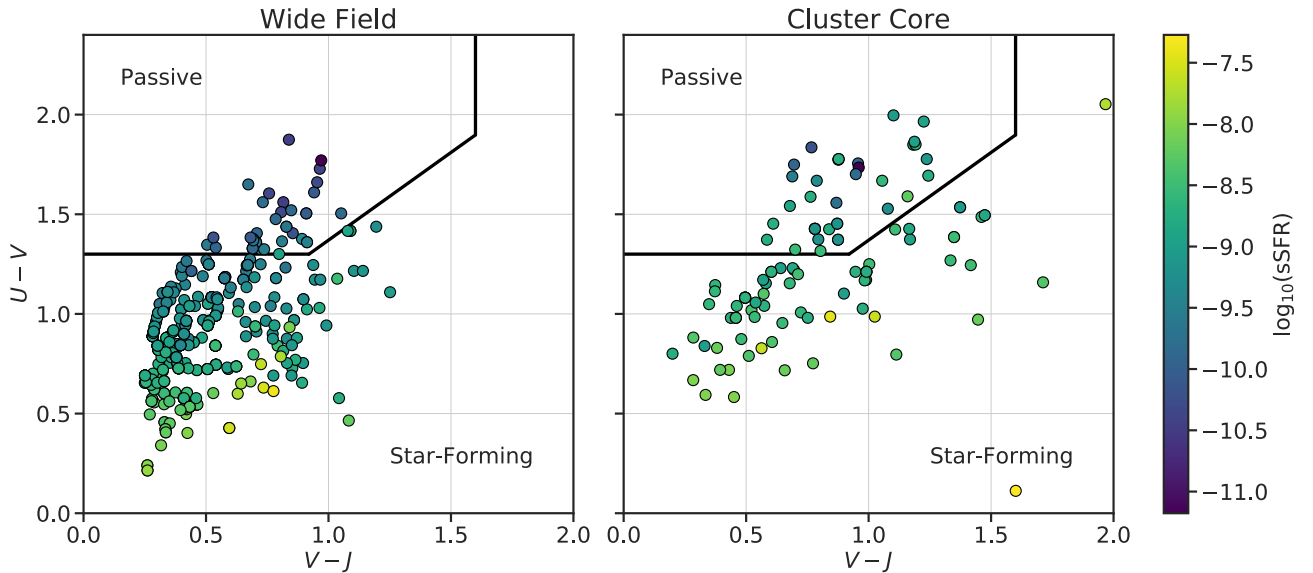


Figure 4.9: The distribution of galaxies in the photo-z wide sample (*left*) and combined spec-z and photo-z samples (*right*) on the UVJ colour diagram. Galaxies are additionally colour-coded by sSFR, and the colour selection criterion for the passive galaxy population are shown as black lines. In both samples, galaxies meeting the passive galaxy criterion tend to have lower sSFRs, particularly for the photo-z wide sample.

star-forming, passive and starbursting galaxies.

#### 4.6.2 Quenched Fraction

In order to further investigate the star formation activity in the SpARCS-0330 cluster, we aim to characterise the total quenched fraction both in the cluster core (based on the spec-z and photo-z samples) and in the wider field (based on the photo-z wide sample). We use two different methods to estimate the quenched fraction: the positions of our sources on the UVJ colour diagram and their distance from the star-forming main sequence relation described by Speagle et al. (2014). These two methods will be referred to as the UVJ and MS methods in the forthcoming analysis.

To calculate their UVJ colours, we use the best fitting SED model for each galaxy from CIGALE and their photometric redshift estimate from EAZY to estimate their magnitudes at rest frame wavelengths of 365 nm, 551 nm and 1220 nm respectively. We then plot these UVJ colours in Figure 4.9, with each galaxy colour-coded by its sSFR, characterising the strength of star formation relative to the underlying galaxy stellar mass (Guzmán et al., 1997), which is known

to correlate strongly with UVJ colour (e.g. Williams et al., 2009). To separate out our star-forming and passive galaxy samples, we rely on the following colour criteria from Williams et al. (2009) for galaxies lying in the range  $1 < z < 2$ :

$$(U - V) > 0.88 \times (V - J) + 0.49 \quad (4.6)$$

$$U - V > 1.3 \quad (4.7)$$

$$V - J < 1.6 \quad (4.8)$$

where Equation 4.6 imposes the diagonal redshift-dependent colour selection criterion, while Equations 4.7 and 4.8 effectively prevent unobscured galaxy and DSFG interlopers from contaminating the passive sample respectively. Given the much shallower depth of the photometry in the photo-z wide sample compared to the spec-z and photo-z samples, we additionally plot UVJ colours separately for the wider field and for the cluster core. We find that those galaxies classified as passive based on their UVJ colours do indeed have lower sSFRs compared to those classified as star-forming: in the wider field, those classified as passive and star-forming have median sSFRs of  $0.15 \text{ Gyr}^{-1}$  and  $1.15 \text{ Gyr}^{-1}$  respectively, while those in the cluster core classified as passive and star-forming have median sSFRs of  $0.46 \text{ Gyr}^{-1}$  and  $0.92 \text{ Gyr}^{-1}$  respectively. Based on these passive and star-forming samples, we estimate quenched fractions of  $34 \pm 6\%$  for the cluster core and  $8 \pm 1\%$  for the wider field. For the cluster core, this quenched fraction is somewhat lower than the 45% estimated by Nantais et al. (2016), but we note that their quiescent fraction was estimated from the combination of three different SpARCS clusters, and only for those lying within 1 Mpc of the cluster centre. Focusing on the UVJ colours of galaxies in their photometric catalogue from FAST for galaxies within  $\sim 3$  Mpc of SpARCS-0330 alone, we estimate a quenched fraction of  $18 \pm 3\%$ , significantly lower than the quenched fraction based on our CIGALE-based estimates. For the wider sample, the extremely low quenched fraction likely reflects the poor depth of the available photometry, which would bias our sample towards more massive, luminous and star-forming galaxy populations.

For the MS method, we define our passive galaxy sample as those lying below the scatter of the star-forming main sequence relation as defined by Speagle et al. (2014). This is essentially equivalent to a selection based on sSFR, as we select those galaxies with unexpectedly low SFRs relative to their stellar masses compared to the main sequence. Based on this definition, we estimate quenched fractions for the cluster core and the wider field of  $27 \pm 5\%$  and  $22 \pm 2\%$  respectively. For the cluster core, this value agrees with the quenched fraction estimated from the UVJ colours within their respective errors, but for the wider field this estimate is significantly larger than the estimate based on the UVJ colours. The differences between the two methods will be investigated further in Section 4.7.3.

While insights can be drawn from investigating the quenched fraction of the total samples within the cluster core and in the wider environment, we would expect to see a dependence of the quenched fraction on galaxy stellar mass. This is a natural extension of the well-known galaxy bi-modality, where more massive galaxies are found to be preferentially elliptical, quiescent and comprised primarily of older stellar populations, while lower mass galaxies tend to be star-forming and disk-like. To investigate whether we recover this trend, we split both the sample within the cluster core (i.e. the combined spec-z and photo-z samples) and the photo-z wide sample into three stellar mass bins. We then calculate the quenched fraction using both the UVJ and MS methods in each stellar mass bin and present them in Figure 4.10. Irrespective of the method used to calculate the quenched fraction, and for both the cluster core and the wider field, we find a significantly higher quenched fraction ( $\sim 60 - 80\%$ ) in galaxies with  $M_\star > 10.1 M_\odot$  than in their lower mass counterparts. These results suggest that the quenched fractions discussed above are at least in part driven by stellar mass quenching rather than environmental quenching. The interpretation of these results will be discussed further in Section 4.7.

### 4.6.3 Galaxy Properties as a Function of Cluster-Centric Radius

We investigate whether there is a radial dependence on the SFR, sSFR and quenched fraction for the different galaxy samples. Galaxy clusters are expected to continually accrete galaxies and

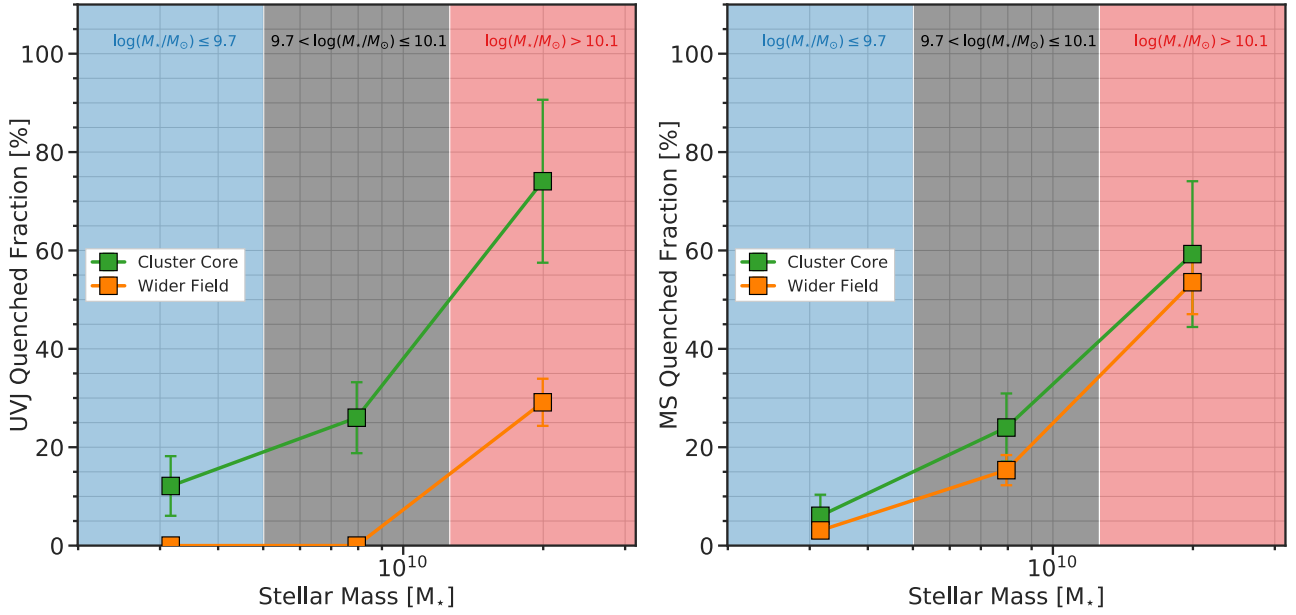


Figure 4.10: The quenched fraction within the cluster core (green) and in the wider field (orange) in three stellar mass bins based on the UVJ (*left*) and MS (*right*) methods. We find the largest quenched fractions in the most massive stellar mass bin, regardless of the method of estimating the quenched fraction and for both the cluster core and the wider field.

galaxy groups (Zabludoff and Franx, 1993; Ceccarelli et al., 2005; Cortese et al., 2006; McGee et al., 2009; Benavides et al., 2020) which can have their star formation rapidly truncated by numerous environmental quenching mechanisms in the harsh cluster environment. Observations and simulations of local galaxy clusters suggest that galaxies and galaxy groups accreted into the cluster environment are quenched following a “delayed-then-rapid” model, evolving reasonably passively for the first 2 – 4 Gyr before having star formation rapidly truncated in  $\sim 0.5 - 1.5$  Gyr (Wetzel et al., 2013; McGee et al., 2014; Bahé and McCarthy, 2015; Rhee et al., 2020). There is reported to be some variation in the quenching timescale with redshift. Balogh et al. (2016) estimate a total quenching timescale of  $t_q \sim 2 - 5$  Gyr from both the GCLASS survey and the Group Environment and Evolution Collaboration 2 (GEEC2: Balogh et al., 2011) survey, with the fastest quenching timescales witnessed in the most massive galaxies. A similar quenching timescale and stellar mass trend is observed by Fossati et al. (2017) at  $z \sim 0.7 - 1.5$  based on observations in the 3D-HST/CANDELS deep fields. Foltz et al. (2018) estimate a quenching timescale of  $t_Q = 1.24^{+0.23}_{-0.20}$  Gyr for galaxies with  $M_\star \gtrsim 10^{10.5} M_\odot$  at  $z \sim 1.5$  based on observations of four SpARCS clusters (including SpARCS-0330), with this timescale increasing to  $t_Q \approx 1.50^{0.19}_{0.18}$  Gyr for galaxies at  $z \sim 1$ . Muzzin et al. (2014) estimate a more rapid quenching



timescale of  $t_Q \approx 1$  Gyr based on the distribution of post-starburst galaxies in cluster phase space from the GCLASS survey, with a rapid fade time of  $\approx 0.5$  Gyr after the infalling galaxy first passes through  $0.25 - 0.5R_{200}$ . Given typical galaxy cluster crossing times of  $1 - 2$  Gyr (see e.g. Alberts et al., 2016), these results suggest that infalling galaxies can have their ongoing star formation significantly diminished within their first crossing of clusters at  $z \sim 1 - 2$ . If this is the case, we might expect to see increased star formation activity towards the outskirts of these clusters, where we might preferentially find satellite galaxies and groups recently accreted into the cluster, compared to the cluster core where the harsher cluster environment is more efficient at stripping gas from infalling galaxies and truncating star formation. Indeed, numerous studies at different redshifts find increased quenching efficiencies and/or quenched fractions towards the cores of massive clusters (e.g. Paccagnella et al., 2016; Jian et al., 2017; van der Burg et al., 2018)

In Figure 4.11 we show the CIGALE-estimated SFR and sSFR of each galaxy in the spec-z and photo-z samples as a function of projected cluster centric radius. We additionally plot the SFR and sSFR separated into bins of projected cluster-centric radius, after estimating the optimum bin width based on the Freedman-Diaconis rule. We estimate errors on the binned SFR and sSFR using a simple bootstrapping method. For each bin, we randomly draw samples allowing duplication until we have a number of random sources within the bin equal to the original number sources in the bin, from which we calculate a median value. This is repeated 1000 times for each bin, such that we end up with a distribution of median values based on the galaxies randomly drawn from each bin. The errors on the median values are then defined as the 16<sup>th</sup> and 84<sup>th</sup> percentiles of these median distributions in each bin. In addition to SFR and sSFR, we additionally plot the quenched fraction as a function of projected cluster-centric radius, with the combined sample binned in a similar way based on the Freedman-Diaconis rule. We estimate the quenched fraction in each bin using both the MS and UVJ methods outlined in Section 4.6.2. For the SFR, sSFR and quenched fraction in bins of projected cluster-centric radius, we additionally fit a linear model using `lmfit`, and show the corresponding best fitting model and  $1\sigma$  scatter.

We find that within the cluster core, SFR is essentially constant with respect to the projected

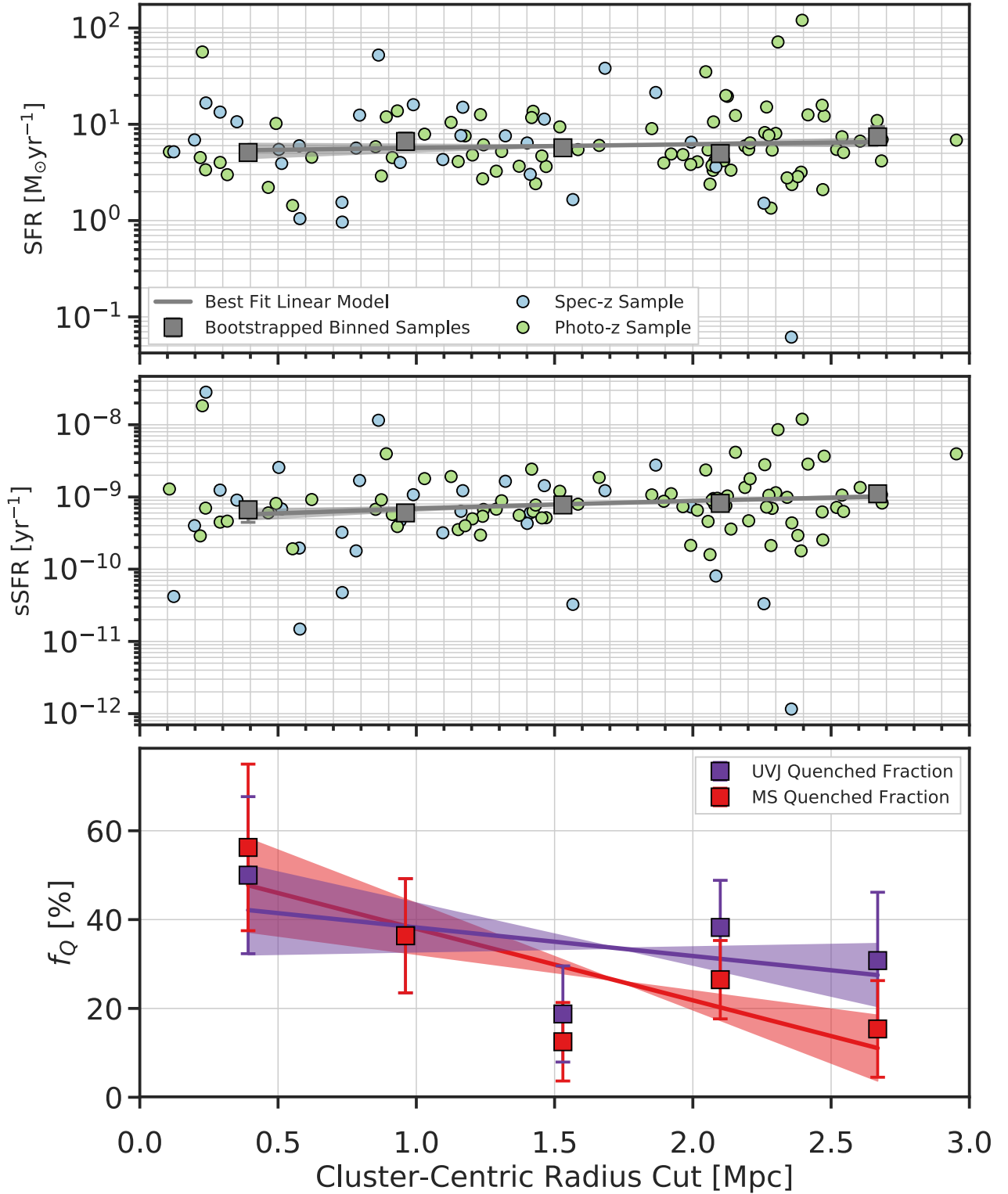


Figure 4.11: SFR (*upper*), sSFR (*centre*) and quenched fraction (*lower*) as a function of projected cluster-centric distance within the core of SpARCS-0330. In the upper two panels, the spec-z and photo-z samples are shown as blue and green points respectively, while the gray squares show the median SFR and sSFR in bins of projected cluster-centric distance with errors estimated from a simple bootstrapping method. In the lower panel, we show in red and purple the quenched fraction as a function of projected cluster-centric radius estimated from the MS and UVJ methods discussed in Section 4.6.2. In all three panels, the lines and associated shaded regions show the best fitting linear models and associated  $1\sigma$  scatter to the binned properties.

cluster-centric distance with a gradient of  $0.51 \pm 0.60 \text{ M}_{\odot}\text{yr}^{-1}\text{Mpc}^{-1}$ , while we see a gentle increase in the sSFR. We find that, irrespective of the method used, the quenched fraction decreases with projected cluster-centric radius within the core of SpARCS-0330, from  $\sim 50 - 60\%$  within 500 kpc, down to  $\sim 20 - 30\%$  at 2.5 – 3 Mpc. However, we note that for both methods, the best fitting gradient from `lmfit` is essentially consistent with no evolution at the  $3\sigma$  level and doesn't provide a particularly convincing fit to the data, with reduced chi-squared values of 128 and 140 for the UVJ and MS methods respectively, although these poor reduced chi-squared values are likely driven by a dip in the quenched fraction at  $\sim 1.5$  Mpc. We infer that, within the core of SpARCS-0330, galaxies may be preferentially quenched closer to the centre, with increasingly large star formation efficiencies further from the central regions.

In Figure 4.12, we show a similar plot, but for the wider region around SpARCS-0330 based on the photo-z wide sample. There is a gentle increase in both SFR and sSFR in the wider field with projected cluster-centric distance (with gradients of  $0.20 \pm 0.07 \text{ M}_{\odot}\text{yr}^{-1}\text{Mpc}^{-1}$  and  $(1.74 \pm 1.54) \times 10^{-11} \text{ yr}^{-1}\text{Mpc}^{-1}$ ). We note that these gradients are consistent with no evolution at the  $3\sigma$  level. For both methods of calculating the quenched fraction, we see a gentle decrease in the quenched fraction across the wider cluster environment although similarly, the estimated gradients are consistent with no evolution at the  $3\sigma$  level. Moreover, the quenched fractions estimated from the UVJ method are systematically lower than those estimated from the MS method, with values of  $\approx 20 - 25\%$  and  $\approx 5 - 10\%$  respectively. For both cases, a linear model provides a reasonable, but not excellent, fit to the data, with reduced chi-squared values of 10.3 and 20.0 for the UVJ and MS methods respectively. We infer that there is little evolution in the quenched fraction across the wider cluster environment. We note that the available photometry for the photo-z wide sample likely misses a significant proportion of the quenched population lying in the wider field, biasing our results towards more actively star-forming galaxies. It is therefore possible that there is a significant quenched population that is missed by our observations which could significantly affect these conclusions.

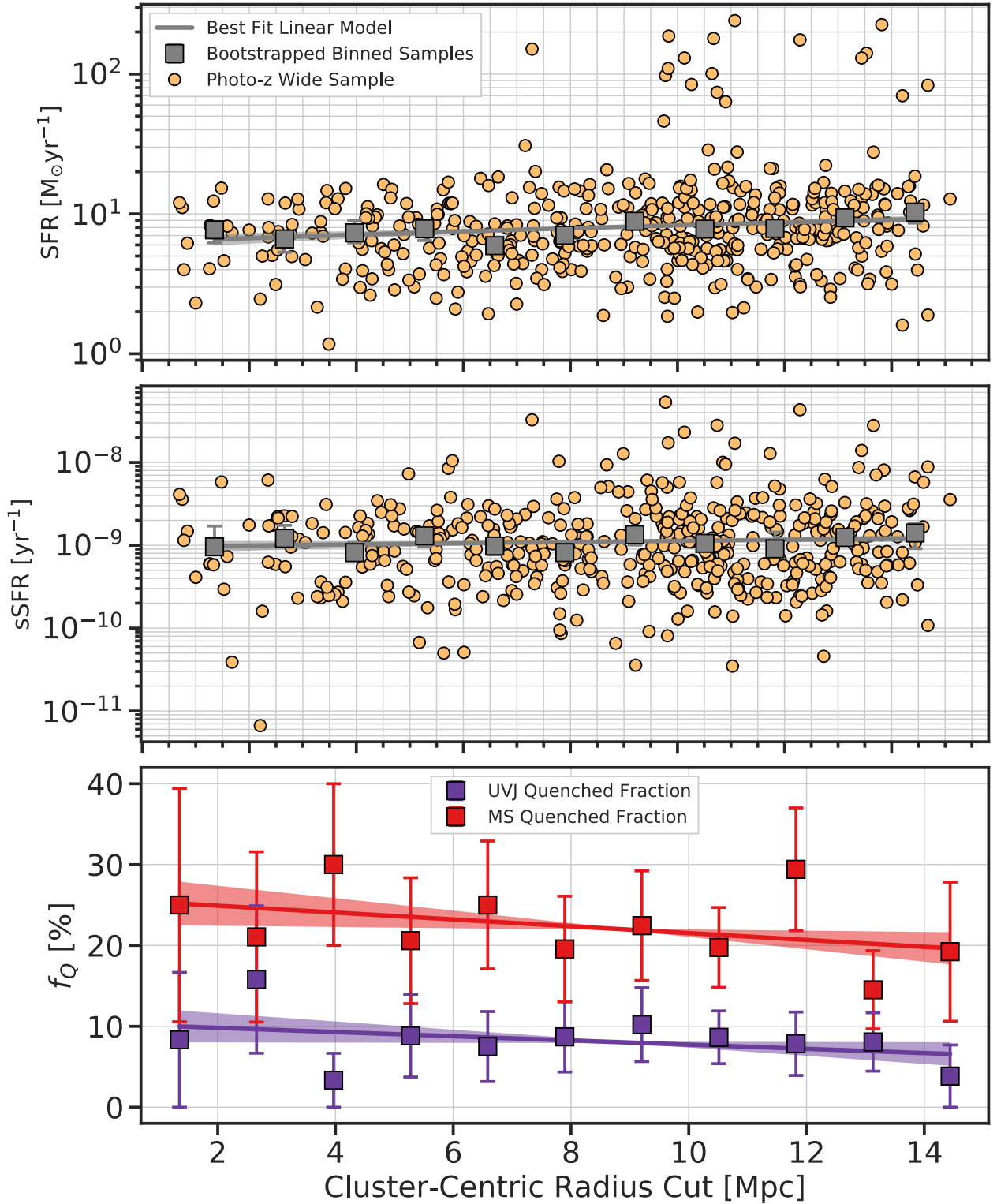


Figure 4.12: SFR (*upper*), sSFR (*centre*) and quenched fraction (*lower*) as a function of projected cluster-centric distance in the wider region of SpARCS-0330. In the upper two panels, the photo-z wide sample is shown in orange points, while the gray squares show the median SFR and sSFR in bins of projected cluster-centric distance with errors estimated from a simple bootstrapping method. In the lower panel, we show in red and purple the quenched fraction as a function of projected cluster-centric radius estimated from the MS and UVJ methods discussed in Section 4.6.2. In all three panels, the lines and associated shaded regions show the best fitting linear models and associated  $1\sigma$  scatter to the binned properties.

#### 4.6.4 Spatial Distribution of Galaxy Properties

##### Distribution of Sources on Sky

In Figure 4.13 we present the spatial distribution of galaxies in the spec-z and photo-z samples across the core of the SpARCS-0330 cluster plotted on the HAWK-I  $K_s$  band image. The candidate cluster members are colour-coded by stellar mass, and we additionally overplot contours showing the local density of galaxies with either photometric or spectroscopic redshifts placing them at the nominal cluster redshift. We find potential evidence of substructure within the cluster core, with the combined sample effectively splitting into three regions, indicative of a galaxy cluster that is not yet fully dynamically developed. The nominal cluster position, denoted by the red box, is almost exactly co-spatial with the peak of the densest of the three regions and is centred on the most massive galaxy in our combined sample with  $M_\star \sim 10^{11.1} M_\odot$ , which we infer to be the central Brightest Cluster Galaxy (BCG) of SpARCS-0330. Excluding the BCG, we do not observe any preference for the most massive galaxies within the core (i.e.  $M_\star > 10^{10.1} M_\odot$ ) to lie within the densest regions.

We have found that the quenched fraction within the cluster is a strong function of stellar mass but a much weaker function of projected cluster-centric radius. Figure 4.13 further demonstrates that, excluding the BCG, there does not appear to be a preference for the most massive galaxies within the core (i.e.  $M_\star > 10^{10.1} M_\odot$ ) to lie within the densest regions. From these results, we infer that quenching within the SpARCS-0330 cluster is primarily driven by processes that correlate with galaxy stellar mass rather than environment, and hence that SpARCS-0330 may not yet be dynamically evolved enough to effectively quench its member galaxies. The implications of these results will be discussed further in Section 4.7.

##### Segmentation Maps

Finally, we aim to investigate the spatial distribution of these galaxy properties in more detail. In particular, we have seen tentative evidence for a radial evolution in the star forming properties of galaxies, but are these trends seen similarly in all directions across the cluster? In order to

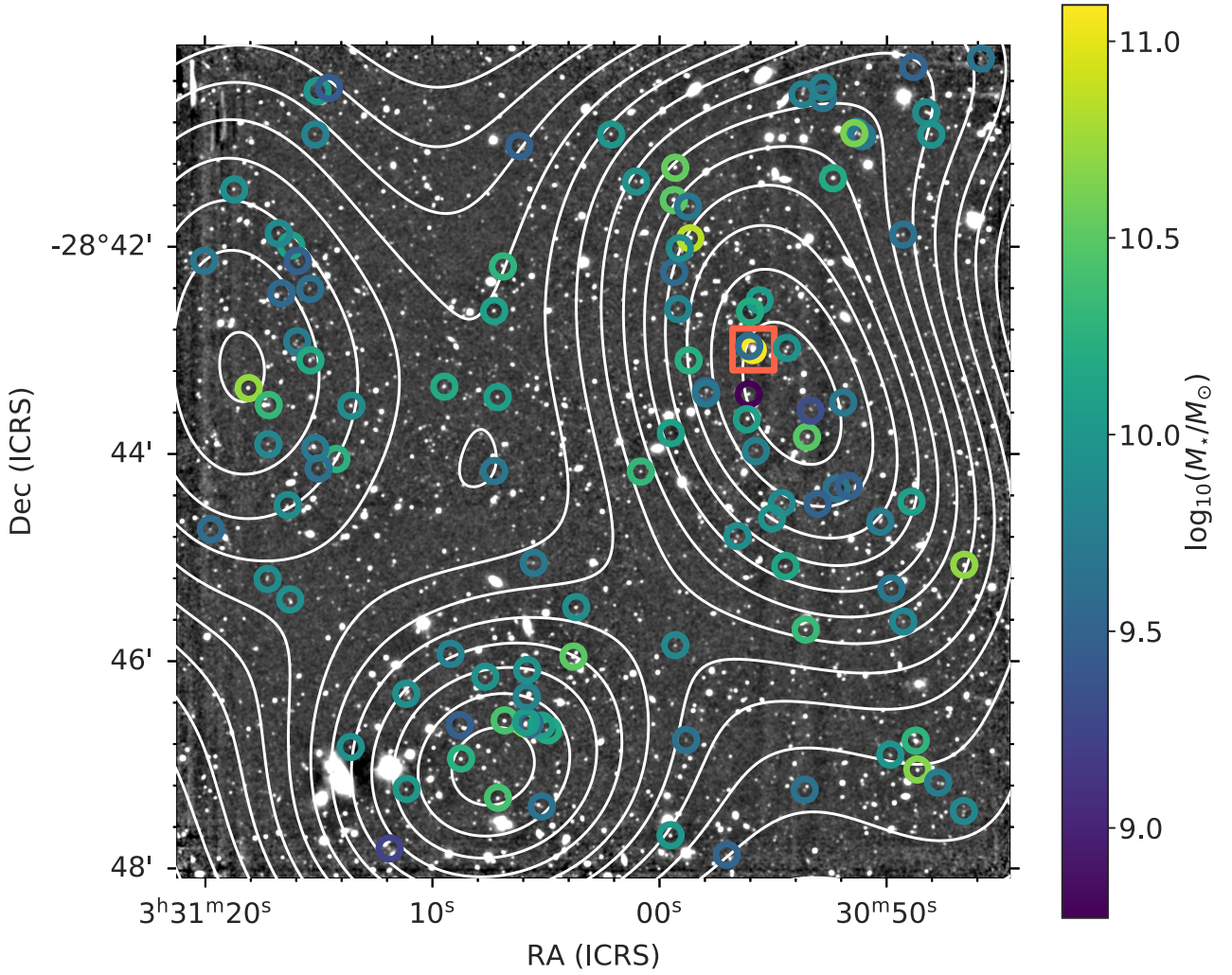


Figure 4.13: The spatial distribution of galaxies in the spec-z and photo-z samples (open circles) overplotted on the HAWK-I  $K_s$  band image of the core of the SpARCS-0330 cluster. Cluster candidates are colour-coded by stellar mass. We additionally overplot the density of cluster candidates as white contours.

evaluate these trends further, we make a series of segmentation maps, splitting the SpARCS-0330 cluster into individual cells and finding the average galaxy properties within these cells. We wish to maximise the signal in these cells to improve the robustness of our conclusions, and so rather than considering the cluster core and wider field samples separately, we combine the spec-z, photo-z and photo-z wide samples in this case. However, given the significant differences in the depths of the photometry for the different samples, we must first introduce some additional cuts to this combined sample to make it as homogeneous as possible. In other words, we aim to restrict the combined sample such that only galaxies that could be detected in all three sub-samples would be included. This effectively means excluding numerous faint

sources from the spec-z and photo-z samples that would not be detected in the shallower photo-z wide photometry. We apply a conservative cut, constructing histograms of flux density for each sample in all available bands and excluding any sources in the spec-z and photo-z samples that are fainter than the faintest galaxy in that band in the photo-z wide sample. This process leaves us with a combined sample of 397 candidate cluster members spanning  $\approx 30$  Mpc across the SpARCS-0330 cluster.

In our first attempts to map out the star formation activity across the SpARCS-0330 cluster, we simply split the combined sample into a series of segments, plotting the median galaxy properties within them separately. The resulting plot is presented in Figure 4.14 where we show the median quenched fraction (based on both the MS and UVJ methods) and sSFR in each segment. We estimate typical Poissonian errors for the quenched fractions, resulting in uncertainties of  $\approx 5 - 12\%$  for the MS method and  $\approx 3 - 6\%$  for the UVJ method. We find that the two methods used to calculate the quenched fraction follow similar trends, although, as discussed in Section 4.6.2, the MS method estimates systematically higher quenched fractions than the UVJ method. We find one segment towards the North of SpARCS-0330 with a significantly higher quenched fraction than the other segments, regardless of the method used to estimate the quenched fraction (either  $36 \pm 9\%$  or  $14 \pm 6\%$  based on the MS and UVJ methods respectively). This segment is characterised by lower SFRs ( $\sim 6 \text{ M}_{\odot} \text{ yr}^{-1}$ ) but reasonable sSFRs compared to the rest of the combined sample ( $\sim 10^{-9} \text{ yr}^{-1}$ ). We additionally test different offset angles for the segments and different numbers of segments, with all permutations recovering qualitatively similar results.

In Figure 4.15 we present a similar analysis in which we split the combined sample into shells and calculate the quenched fraction, median SFR and median sSFR in each shell. These segmentation maps recover similar results as we found in Figures 4.11 and 4.12, as they are essentially a slightly different visualisation of the same analysis. We find a high quenched fraction within the most central regions, followed by a reasonably steep decline in quenched fraction with projected cluster-centric radius within the cluster core. In the wider regions, the quenched fraction is consistent with little evolution, or at most a gentle decline, with cluster-centric radius. We similarly find slightly lower SFRs in the central regions, although

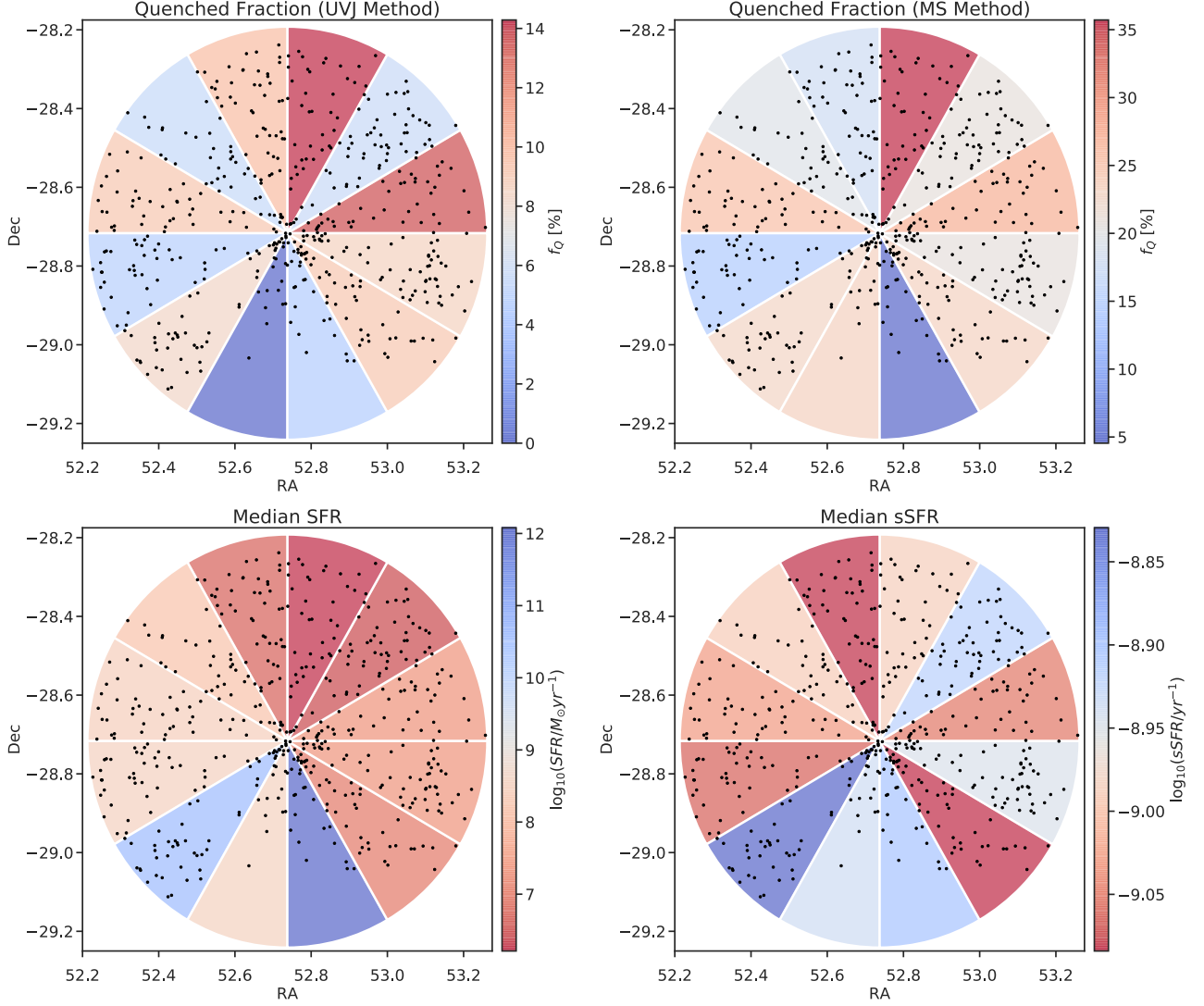


Figure 4.14: Segmentation maps showing the star-forming properties of galaxies across SpARCS-0330 in segments, including the quenched fraction based on the UVJ (*upper left*) and MS (*upper right*) methods, as well as the median SFR (*lower left*) and sSFR (*lower right*) in each segment. Red colours are indicative of quenching (i.e. high quenched fractions, low SFRs and sSFRs) while blue colours show regions of more active star formation. When quenched fractions and median SFRs are considered, we find evidence of preferential quenching in one of the Northern segments of SpARCS-0330.



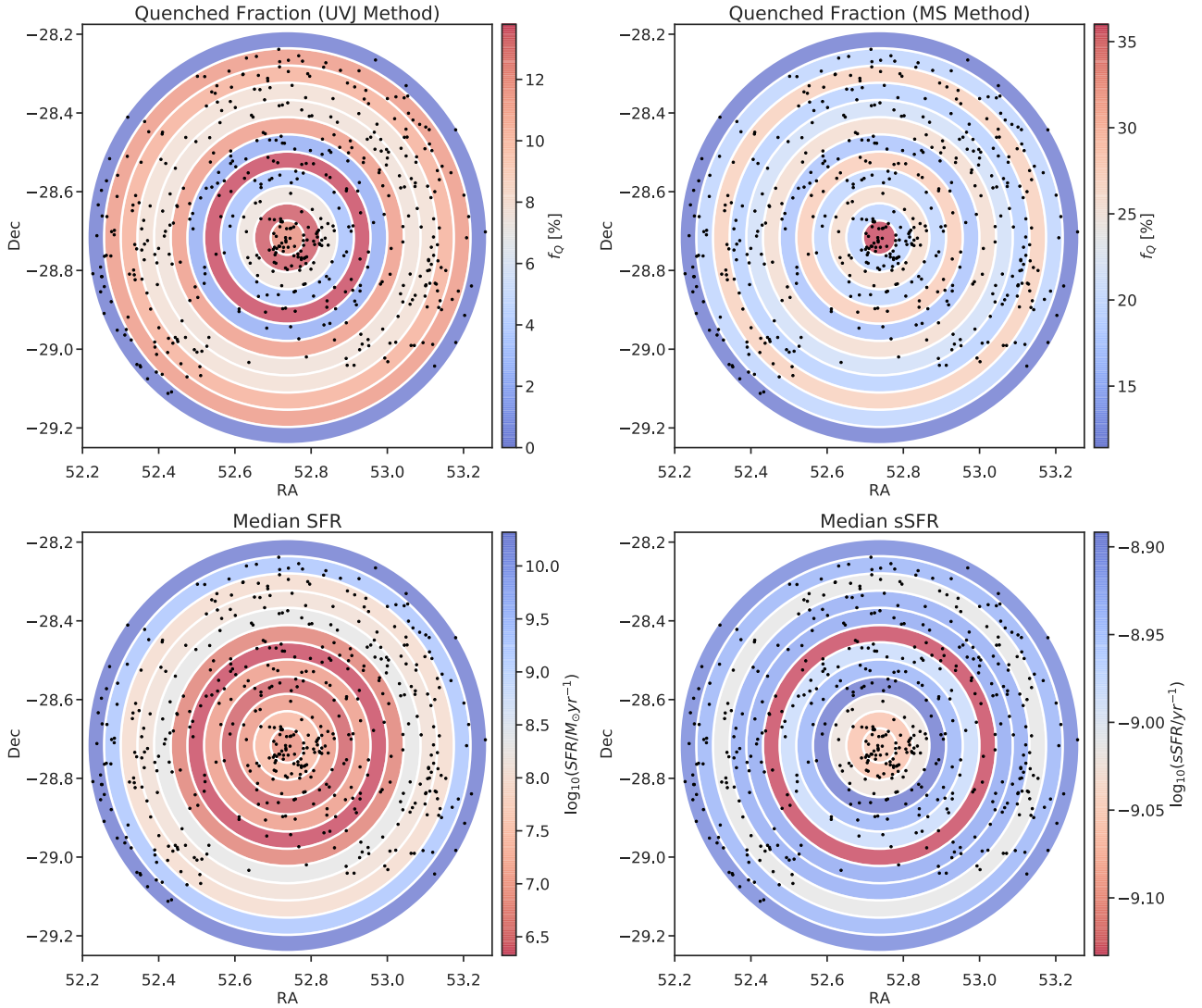


Figure 4.15: Segmentation maps showing the star-forming properties of galaxies across SpARCS-0330 in shells, including the quenched fraction based on the UVJ (*upper left*) and MS (*upper right*) methods, as well as the median SFR (*lower left*) and sSFR (*lower right*) in each segment. Red colours are indicative of quenching (i.e. high quenched fractions, low SFRs and sSFRs) while blue colours show regions of more active star formation. We recover similar trends to those found in Figures 4.11 and 4.12, including a rapid decrease in the quenched fraction with projected cluster-centric radius within the cluster core, followed by a roughly constant quenched fraction in the wider regions.

the median sSFR is only slightly lower in the cluster core than in the outer reaches of the cluster. In fact, the median sSFR is remarkably consistent across the cluster, excluding a single shell at  $\sim 5.3 - 6.7$  Mpc from the cluster centre which has a slightly reduced median sSFR compared to the surrounding shells.

In order to verify these conclusions, we must first ensure that the signals measured from the segmentation maps cannot be obtained by simple random variations in galaxy properties or positions. We therefore construct two simple tests. We first randomly shuffle the properties of the galaxies in the combined sample, including their UVJ colours, stellar masses and SFRs, and redraw the segmentation maps for the quenched fractions, median SFRs and median sSFRs. We repeat this process 1,000 times, finding the median value in each cell from these runs. As a complementary test, we also keep the properties of each galaxy the same but shuffle their positions within the segmentation maps. We then follow a similar analysis, repeating this process 1,000 times and estimating the median quenched fractions, SFRs and sSFRs we can expect based on random variations in the positions of the galaxies in the sample. We find that, for the configuration shown in Figure 4.14, quenched fractions of  $\approx 9\%$  for the UVJ method and  $\approx 23\%$  for the MS method can be obtained by randomly shuffling the properties of the galaxies in the combined sample, and similar quenched fractions of  $\approx 8\%$  for the UVJ method and  $\approx 22\%$  for the MS method can be obtained by randomly shuffling the positions of the galaxies in the combined sample. We therefore find that, for the UVJ quenched fraction, the values presented in Figure 4.14 can be comfortably reached by simple random variations in galaxy properties. For the MS method, the elevated quenched fraction in the segment to the North is  $\approx 1\sigma$  above the typical values that can be obtained by random variations in the combined sample. We therefore cannot infer a great deal of information from these segmentation maps likely either because no trend in the star-forming properties of galaxies exists with spatial location within SpARCS-0330 and/or we cannot generate statistics robust enough to test whether such a trend exists. We note that we additionally constructed segmentation maps with higher spatial resolution (i.e. split into both segments and cells rather than just one or the other), but the statistics for these maps are even less robust, as naturally we split the sample up into smaller cells each containing a much smaller number of sources.

## 4.7 Discussion

### 4.7.1 Star Formation and Quenching in the Core of SpARCS-0330

The primary aim of this study was to map out star formation across the SpARCS-0330 cluster in order to investigate how large scale structures transition from the intensely star-forming protoclusters observed at  $z > 2$  to the massive and largely quiescent galaxy clusters at  $z < 2$ . In this discussion, we first focus on the core of SpARCS-0330 where the available photometry is at its deepest. This work builds on the results of Nantais et al. (2016), who assembled the deep optical/NIR photometric catalogue for SpARCS-0330, before using the **EAZY** and **FAST** algorithms to estimate photometric redshifts, SFRs and stellar masses, as well as subsequent publications (e.g. Nantais et al., 2017, 2020). We took this photometric catalogue and used the likelihood ratio method to additionally crossmatch FIR photometry from the *Herschel* SPIRE instrument, estimating informative upper limits where no reliable crossmatch could be found, in order to build up optical-to-FIR SEDs for each cluster candidate. We then used the photometric SED fitting code **CIGALE** to estimate more informed SFRs and stellar masses for the candidate cluster members.

First and foremost, we find evidence of significant ongoing star-formation within the central  $\approx 6$  Mpc of SpARCS-0330. The majority of galaxies in our spec- $z$  and photo- $z$  samples lie either on or within the scatter of the star-forming main sequence from Speagle et al. (2014). There appears to be a significant stellar mass dependence on this star formation, with the most massive ( $\gtrsim 10^{10.1} M_{\odot}$ ) galaxies lying largely below the main sequence, and less massive galaxies lying largely on or above it, such that passive galaxies dominate at high masses, while star-forming galaxies dominate at low masses. We additionally note that all galaxies within the core with robust FIR detections lie well within the scatter of the star-forming main sequence or above it. We interpret these results as evidence that the environment within the central regions of SpARCS-0330 is not yet hostile enough to significantly disrupt the star formation activity in its member galaxies, with only the most massive galaxies lying preferentially below the star-forming main sequence at these redshifts. This mass dependence could reflect the

“mass downsizing” trend, where the most massive galaxies built up the majority of their stellar mass at  $z > 2$  before evolving reasonably passively down to  $z \sim 0$  (see e.g. Cowie et al., 1996; Cimatti et al., 2006; Hopkins et al., 2008; Kormendy and Ho, 2013), and may therefore be independent of the SpARCS-0330 cluster environment. Nevertheless, we do find some dependence of the star formation activity of candidate members within the cluster core on projected cluster-centric radius. Regardless of the method used, the quenched fraction decreases from  $\approx 50 - 60\%$  within the central  $\sim 500$  kpc to  $\approx 20 - 30\%$  at  $\sim 3$  Mpc, and is complimented by a gentle (albeit tenuous) increase in both SFR and sSFR with cluster-centric radius. Moreover, Figure 4.13 demonstrates that, while the most massive galaxy in SpARCS-0330 is coincident with the nominal cluster centre, there appears to be no preference for the most massive galaxies to lie preferentially towards the cluster centre, and in fact we find significant evidence of substructure among the cluster candidates. We infer that, while the main driver of quenching in SpARCS-0330 is likely stellar mass, there is clearly some additional, albeit weaker, environmental dependence on the quenched fraction. We interpret these findings as evidence that the evolving cluster environment may be starting to become more effective at quenching its members, particularly towards the central  $\approx 1$  Mpc where the cluster potential is at its deepest.

These results are in good agreement with a number of similar studies in the literature. In their study of fourteen galaxy clusters from the SpARCS survey, including SpARCS-0330, Nantais et al. (2016) find a significant decrease in the quenching efficiency of galaxy clusters towards higher redshifts, with quenched fractions evolving from  $88^{+40}_{-3}\%$  at  $z < 1.1$  to  $42^{+10}_{-13}\%$  at  $z \sim 1.6$ . A qualitatively similar, albeit somewhat weaker, trend was found by Darvish et al. (2016) based on  $K_s$  band selected galaxies in the COSMOS field, with photometric redshifts from the smaller COSMOS UltraVista catalogues. Lying at  $z = 1.626$ , our quenched fraction estimate within the core of SpARCS-0330 of  $34 \pm 6\%$  agrees with the value at  $z \sim 1.6$  within their respective errors. We note that this value was estimated based on the UVJ colour-colour diagram, and our slightly lower estimate of  $27 \pm 5\%$  based on the MS method, while still in agreement within the errors, is somewhat lower. Similarly, our value is in reasonable agreement with the  $z = 1.62$  galaxy cluster case study in Quadri et al. (2012), with a quenched fraction of  $43 \pm 14\%$ . Moreover, based on  $H\alpha$  observations of galaxies within  $z \sim 1.6$  clusters, both Nantais et al.

(2020), based on three SpARCS clusters including SpARCS-0330, and Tran et al. (2017), based on the ZFIRE (Nanayakkara et al., 2016) spectroscopic survey, find no statistical differences in the star-forming properties of contemporaneous field and cluster galaxies, indicating that high redshift clusters are not yet effective at quenching their member galaxies. We note that, similarly to Nantais et al. (2017), our current observations cannot identify the main reasons for the inefficiencies in environmental quenching at high redshifts, but likely processes are either the member galaxies having not spent enough time within the cluster environment to yet be effectively quenched, or the cluster environment itself not yet becoming virialised and hence not being hostile enough to effectively truncate star formation. The latter is tentatively supported by our observations of the cluster core which show significant substructure, including three distinct regions of high galaxy density within a radius of  $\sim 3$  Mpc from the cluster centre.

#### 4.7.2 Star Formation and Quenching in the Wider Field

We then focus on the wider field surrounding the SpARCS-0330 cluster within a radius of  $\sim 15$  Mpc. In terms of SFR and sSFR, we find a qualitatively similar trend to the cluster core, a gentle increase with cluster-centric distance that is consistent with essentially no evolution at the  $3\sigma$  level. Quenched fractions in the surrounding region are lower, with estimates of  $8 \pm 1\%$  and  $22 \pm 2\%$  based on the UVJ and MS methods respectively. We note that the UVJ and MS methods produce significantly different estimates, and we investigate this discrepancy further in the following section. Both methods, however, produce a much weaker dependence of quenched fraction on cluster-centric radius, indicating that there is little change in the quenched fraction across the wider field. By comparison, we find a similarly strong dependence of the quenched fraction on stellar mass in the wider field, with quenched fractions of  $0 - 5\%$  for galaxies with  $M_\star \leq 9.7 M_\odot$ , rising to  $30 - 60\%$  for galaxies with  $M_\star \geq 10.1 M_\odot$  (with the higher values in each range corresponding to the MS method). We infer that, in the wider field, quenching is dominated by internal processes that scale with stellar mass, rather than environmental processes, which should scale with cluster centric radius. Additionally, while Figure 4.14 suggests that there could be a region of preferential quenching towards the North

of SpARCS-0330, these results are tentative at best, with quenched fractions only  $\approx 1\sigma$  larger than could be obtained by random variations of position or properties within the cluster (as discussed in Section 4.6.4). We conclude that there is no evidence that the wider environment surrounding SpARCS-0330 has a significant effect on the star-forming properties of galaxies lying in these regions.

We do, however, note that the photometry available for the wider field is significantly shallower than for the cluster core, as demonstrated in Figure 4.2 and, as such, these observations could miss a significant population of quenched galaxies in the wider field. For example, we find that  $\approx 50 - 60\%$  of galaxies in the combined spec-z and photo-z samples that are too faint in the optical bands to be detected in the photo-z wide sample are defined as quenched based on their UVJ colours. Such a population could therefore significantly change our conclusions for galaxies in the wider field.

### 4.7.3 Quenched Fractions

Finally, we investigate the reasons behind the significantly different quenched fraction estimates based on the UVJ and MS methods, particularly for the photo-z wide sample. In Figure 4.16, we present the properties of galaxies classed as quenched or star-forming using the different methods within the cluster core. We find that the MS method effectively provides a stricter cut on the star forming properties of galaxies in the cluster core, particularly in sSFR, while the UVJ method allows galaxies with slightly higher SFRs and sSFRs through the selection process. The sSFR cut for the MS method occurs at  $\sim 10^{-9.3} \text{ yr}^{-1}$ , while there is significant overlap in the sSFRs of the quenched and star-forming populations based on the UVJ method. As a result the quenched population from the MS method has a lower star formation efficiency compared to the UVJ method, with median sSFRs of  $10^{-9.6} \text{ yr}^{-1}$  and  $10^{-9.3} \text{ yr}^{-1}$  respectively, and the stricter sSFR cut in the MS method means that fewer galaxies are defined as quenched, hence driving the lower quenched fraction estimate for this population compared to the UVJ method. Moreover, we find that galaxies defined as quenched based on the UVJ method tend to be slightly more star-forming than those defined as quenched based on the MS method, with

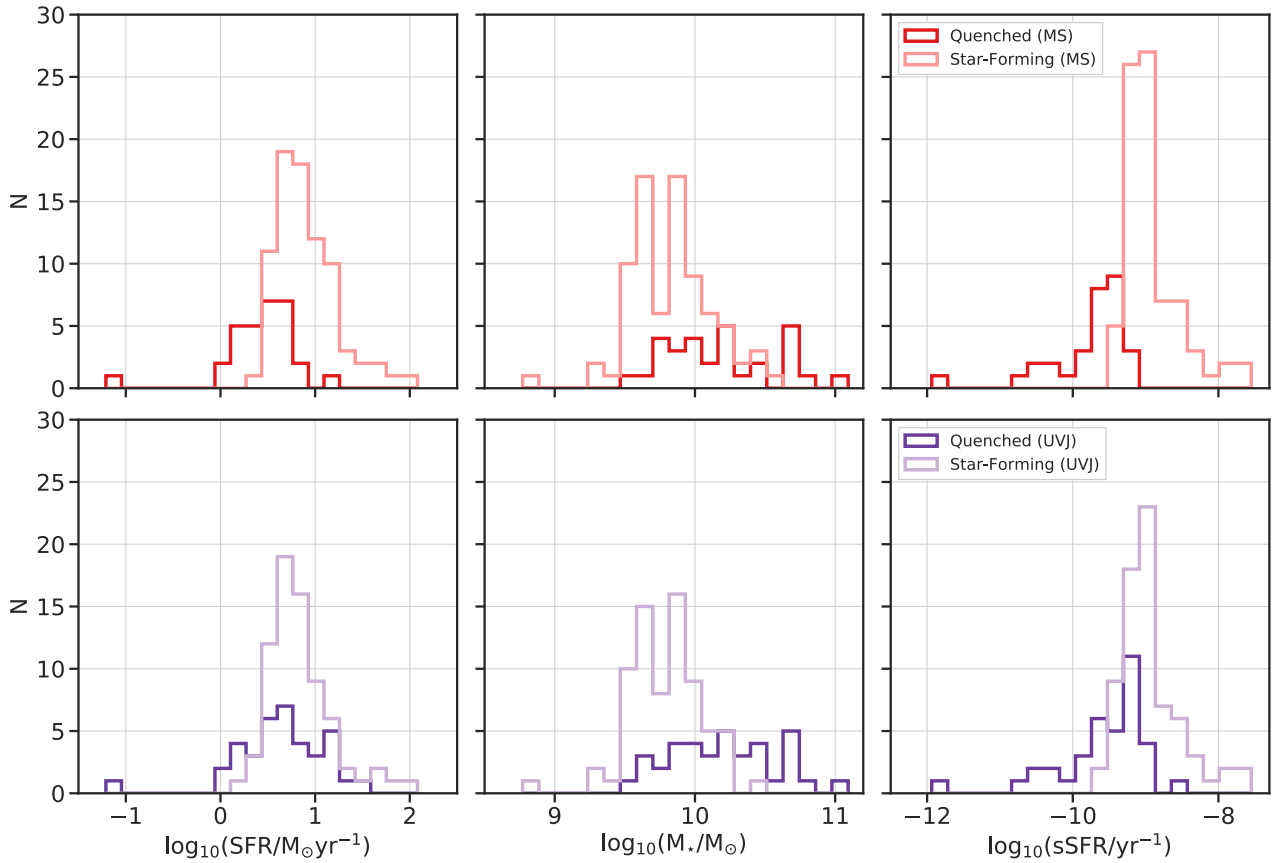


Figure 4.16: Histograms of SFR (*left*), stellar mass (*centre*) and sSFR (*right*) for the quenched and star-forming galaxies in the combined spec- $z$  and photo- $z$  samples. The top and bottom rows show the quenched and star-forming galaxies classified by their position with respect to the main sequence and by their UVJ colours respectively.

median SFRs of  $10^{0.7} \text{ M}_{\odot} \text{ yr}^{-1}$  and  $10^{0.5} \text{ M}_{\odot} \text{ yr}^{-1}$  respectively. Similar results are found for the photo- $z$  wide sample.

## 4.8 Conclusions

In this work, we have used multi-band photometry to investigate how star formation proceeds in the massive,  $z \sim 1.6$  galaxy cluster SpARCS-0330. We combined the optical/NIR photometric catalogue compiled by Nantais et al. (2016) with FIR observations from *Herschel* to map out star formation within  $\approx 3 \text{ Mpc}$  of the cluster core. We additionally compiled a shallower but wider field photometric catalogue from ancillary data in the field, reaching up to  $\approx 15 \text{ Mpc}$  from the cluster centre. For those sources without spectroscopic redshifts in the catalogues, we

used the photometric fitting code **EAZY** to estimate photometric redshifts which allowed us to select three samples representing three tiers of data quality: the spec-z sample comprised of spectroscopically confirmed cluster members, the photo-z sample comprised of galaxies benefiting from deep photometry within the cluster core but without spectroscopic redshifts, and the photo-z wide sample, comprised of galaxies in the surrounding field with photometric redshift estimates based on somewhat shallower archival photometry. We ran each of these samples through **CIGALE** to estimate galaxy properties, including stellar mass and SFR, which we then used to map out star formation across the SpARCS-0330 cluster.

Our cluster candidate galaxies tend to have  $\text{SFR} \sim 10^{0.8} \text{M}_{\odot} \text{yr}^{-1}$  and stellar masses of  $M_{\star} \sim 10^{10} \text{M}_{\odot}$ , resulting in typical sSFRs of  $\sim 10^{-9} \text{yr}^{-1}$ , with the photo-z wide sample tending towards slightly larger SFRs and lower stellar masses. This is likely a result of the shallower photometry which will naturally bias the sample towards brighter, star-forming galaxies rather than more massive but ultimately fainter quiescent ones. Their SFRs and stellar masses place the majority of our three samples on the star-forming main sequence relation at  $z \sim 1.6$ , with a small amount of scatter both above and below this relation. For those galaxies scattering below the main sequence, the vast majority are more massive, with  $M_{\star} > 10^{10.1} \text{M}_{\odot}$ . Additionally, all sources detected in the FIR *Herschel* maps lie on or significantly above the main sequence, indicating that those detected in the FIR are likely highly star-forming.

We estimated the quenched fraction in our samples based on both their UVJ colours and their positions relative to the scatter of the star-forming MS relation. We find that the MS method provides a much stricter cut on sSFR, while there is significantly more overlap in the star-forming properties of galaxies defined as quenched and star-forming based on the UVJ method. The UVJ method yields total quenched fractions of  $34 \pm 6\%$  within  $\sim 3 \text{Mpc}$  of the cluster core, and  $8 \pm 1\%$  in the wider field. For the MS method these estimates are  $27 \pm 5\%$  within the cluster core and  $22 \pm 2\%$  in the wider field. As inferred from the  $M_{\star} - \text{SFR}$  relation, there is a strong stellar mass dependence on these values, with quenched fractions of  $\sim 5 - 10\%$  in lower mass ( $M_{\star} < 10^{9.7} \text{M}_{\odot}$ ) galaxies rising to  $\sim 60 - 70\%$  in more massive ( $M_{\star} > 10^{10.1} \text{M}_{\odot}$ ) galaxies within the cluster core. A qualitatively similar trend is found for the wider field.



We then aim to determine the relation between a galaxy's star forming properties and its position within the cluster. To this end, we plot SFR, sSFR and quenched fraction as a function of projected cluster-centric radius for both the cluster core and the wider field. For both sets of samples, we find only a weak increase in the SFR and sSFR with cluster-centric radius, consistent with no dependence at the  $3\sigma$  level. We infer that galaxies towards the very centre of the cluster may be less star-forming, but only marginally so. By comparison, the relation between the quenched fraction and cluster-centric radius is comparatively strong, although weaker than the observed stellar mass dependence, falling from  $\approx 50 - 60\%$  within 500 kpc of the cluster centre to  $\approx 20 - 30\%$  at cluster centric radii of  $\sim 3$  Mpc. In the wider field, the dependence of quenched fraction on cluster centric radius is even weaker, consistent with no dependence at all. We additionally show that, while the most massive galaxy in the cluster, which we infer to be the BCG, is coincident with the nominal cluster centre and the most densely populated region of the cluster, there is no apparent preference for the most massive galaxies to lie in the densest regions of SpARCS-0330. While we aim to map out star formation in more detail using segmentation maps, the signals we recover are not strong enough to make any robust conclusions, as reasonably high median quenched fractions, SFRs and sSFRs can be achieved in a given region by randomly shuffling the positions and/or properties of our samples.

We infer that quenching in this cluster is dominated by internal, secular processes that scale with stellar mass, rather than environmental quenching processes. This conclusion is consistent with a number of other studies which find that the quenching efficiency of clusters decreases significantly at higher redshifts. This is likely due to some combination of the galaxy cluster being dynamically young, with an environment not yet hostile enough to effectively truncate star formation in their member galaxies, and/or the accreted galaxies themselves having not yet spent enough time within the cluster environment for the environmental quenching processes to effectively act on them. We find some tentative evidence for the former, as we see significant substructure within the cluster core, with three distinct overdensities of galaxies within our combined spec-z and photo-z sample.

# Chapter 5

## Case Study of an Extremely Luminous Dusty Starburst at $z = 3.65$

### 5.1 Introduction and Motivation

In the last decade or so, we have seen a shift in our understanding of the comoving luminosity densities of star formation and active galactic nuclei (AGN). While previously it was thought that the bulk of star formation in the  $1 < z < 5$  Universe was confined to infrared-luminous, dusty ‘bursts’ with star formation rates (SFRs) of tens to hundreds of solar masses per year, numerous surveys with *Herschel* have demonstrated that luminous star-forming galaxies with SFRs in excess of  $1000 \text{ M}_{\odot} \text{ yr}^{-1}$  are surprisingly common. These luminous starbursts tend to lie at  $z > 3$ , where studies have found  $\sim 2 - 3$  systems with  $\text{SFR} > 1000 \text{ M}_{\odot} \text{ yr}^{-1}$  per square degree (Riechers et al., 2013; Dowell et al., 2014; Asboth et al., 2016). This population of  $z > 3$  luminous starbursts presents a profound challenge to our models of galaxy assembly during the first 2 Gyr after the Big Bang, with most galaxy formation models significantly under predicting the number density of these systems at  $z > 2$  (e.g. Guo et al., 2011; Niemi et al., 2012; Hayward et al., 2013b; Gruppioni et al., 2015). While there is evidence that at least some of this discrepancy is due to source blending (Coppin et al., 2006; Geach et al., 2017) and/or flux boosting (Donevski et al., 2018; Duivenvoorden et al., 2018), it remains difficult for

models of galaxy assembly to reproduce the observed number density of these systems. This means that individual case studies of luminous starbursts and AGN at  $z > 3$  will be vital in understanding how star formation proceeds in the early Universe and how it may be affected by the presence of AGN, as well as testing galaxy assembly physics where models find it difficult to reproduce observations.

In addition, systems harbouring intense star formation as well as AGN activity allow investigations into the coevolution of massive galaxies and their SMBHs that can be compared to models of galaxy formation (e.g. Somerville et al., 2008; Hopkins et al., 2008; Somerville and Davé, 2015). While still a matter of intense debate, a cosmological framework is emerging in which luminous, dusty starbursts harbouring both intense star formation and AGN activity may represent a crucial stage in the formation and evolution of QSO between “coalescence” (where violent relaxation drives gas towards the centre of the merger fuelling intense star formation and feeding a buried AGN) and the “quasar” phase (e.g. Hopkins et al., 2008). Observations of such systems are therefore crucial for testing the validity of this proposed evolutionary sequence.

While these high redshift luminous starbursts are therefore interesting in their own right, a number of studies have also identified protoclusters and protocluster candidates containing DSFGs, some of which have inferred SFRs of thousands of solar masses per year (Chapman et al., 2009; Daddi et al., 2009; Dannerbauer et al., 2014; Umehata et al., 2015; Casey et al., 2015; Oteo et al., 2018; Miller et al., 2018; Cheng et al., 2019). These overdensities are thought to be the progenitors to the massive and quiescent galaxy clusters that we observe in the local Universe (Shimakawa et al., 2014; Cooke et al., 2015; Contini et al., 2016; Chiang et al., 2017). Therefore, while high redshift, luminous starbursts may not necessarily faithfully trace overdensities in the early Universe, it is possible that observing case studies of these systems may lead us to primordial galaxy overdensities, which will also allow us to investigate the formation and evolution of large scale structure in the Universe.

We have been intensely studying one such object. SDSS J1607.16+533558.5 (hereafter SDSS1607) was originally identified as a quasar from SDSS DR7 with a spectroscopically confirmed redshift of  $z_{\text{spec}} = 3.652$ . It shows broad Ly $\alpha$  emission with a flux of  $2.1 \times 10^{-14}$  ergs cm $^{-2}$  s $^{-1}$ , as well as

numerous other broad quasar lines. Observations in the FIR/mm were carried out by Clements et al. (2009), including deep, single-dish photometry from SCUBA at  $450\,\mu\text{m}$  and  $850\,\mu\text{m}$ , and MAMBO at  $1.2\,\text{mm}$ , as well as interferometry from the SMA at  $850\,\mu\text{m}$ . These observations were further supplemented with multi-wavelength photometry from 2MASS and *Spitzer*. These observations indicate that SDSS1607 is extremely IR-luminous, with a total IR luminosity of  $\sim 10^{14}\,L_{\odot}$ , placing it well within the HLIRG category. Subsequent SED modelling by Clements et al. (2009) indicate that SDSS1607 likely harbours both an AGN with  $L_{\text{AGN}} \sim 10^{14}\,L_{\odot}$ , and a starburst with  $L_{\text{SB}} \sim 10^{13.5}\,L_{\odot}$ , corresponding to a  $\text{SFR} > 2000\,M_{\odot}\text{yr}^{-1}$ .

However, while most HLIRGs appear as point-like sources in similar observations, the star formation associated with SDSS1607 appears to be significantly spatially extended, making it a particularly interesting target. SMA continuum imaging from Clements et al. (2009) showed sub-mm emission extended over  $\sim 40\,\text{kpc}$ , both in a  $\sim 10\,\text{kpc}$  “blob” to the north-west of the quasar nucleus and in a  $\sim 30\,\text{kpc}$  “tail” towards the south, consistent with a very large star-forming region. SDSS1607 is also detected in CO(4-3) emission (Iono et al., 2012), placing the star formation at the same redshift as the quasar. Imaging from the Hyper Suprime-Cam instrument on Subaru further shows extended emission associated with the sub-mm blob, with colours consistent with a redshift of 3.65. Clements et al. (2009) suggested that this system is likely the result of a merger between a gas-rich galaxy and a gas-poor AGN-host galaxy, or potentially from spatially resolved, jet-induced star formation.

In this chapter, we discuss the program of multi-wavelength follow-up observations that we have undertaken to better understand this unusual system. In particular, the majority of this chapter focuses on our efforts in the FIR and radio regimes. We present new SMA and VLA continuum observations, allowing us to further investigate the morphology of this system in the FIR/sub-mm and radio, and determine its properties. At shorter wavelengths, we have undertaken observations in the NIR with the WFC3/IR instrument on *HST* in the F110W and F160W filters. These *HST* observations are the focus of complementary work by Pitchford et al. (in prep), but will also be discussed in this section. Based on this substantial multi-wavelength dataset, we aim to further investigate the nature of the SDSS1607 system.

In Section 5.2 we discuss our observational strategy and the reduction of the SMA, VLA and *HST* observations, as well as the available ancillary data. Section 5.3 outlines the PSF subtraction process for the optical and NIR observations, and in Sections 5.4 and 5.5 we discuss the properties of the SDSS1607 system and other potential companions in the surrounding field. We provide a discussion of our results in Section 5.6 and a summary of our conclusions in Section 5.7. In this chapter, we adopt the standard flat  $\Lambda$ CDM cosmology:  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ , and  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

## 5.2 Observations and Data Reduction

### 5.2.1 SMA

The SMA observations were taken as part of the SMA program 2017B-S004 (PI: D. L. Clements), split over numerous nights between the 23<sup>rd</sup> April 2018 and the 14<sup>th</sup> June 2018. The proposal originally aimed to complete 4 tracks with the SMA, with 2 tracks in Compact (COM) configuration and 2 tracks in Extended (EXT) configuration, in order to obtain both integrated line fluxes and to image the emission on scales comparable to our existing sub-mm and optical imaging. For each track, the two receivers of the SMA were tuned to 223 GHz and 408.7 GHz in order to probe the [CII] and CO(9 – 8) emission lines respectively. There were, however, a number of technical problems during the observations. One of the two tracks in COM configuration was not observed. For one night, the data from both receivers was completely corrupted and utterly unusable. On a second night, the  $T_{\text{sys}}$  measurements for the 408.7 GHz data were between 2000 - 8000 K and the gain calibrator was not detected well enough to calibrate the dataset. On a third night, one of the eight chunks of the data was corrupted and the 408.7 GHz data was observed at the wrong frequency. This unfortunately meant that a large fraction of our SMA data was unusable, particularly in the case of the 408.7 GHz tuning for which we were left just two night's of usable data. Given the typically lower atmospheric transmission at these wavelengths, the 408.7 GHz dataset is largely unusable, and we do not discuss it further here. At 223 GHz, we obtained four nights of usable data, two in COM configuration and two

in EXT configuration. The weather conditions were generally good, with  $\tau$  values typically between 0.05 and 0.15, and the observations were completed with either 7 or 8 antennae.

The SMA data was reduced using the IDL-based SMA data reduction package MIR. The data was visually inspected and any bad integrations, antennae or baselines were removed. Each band was visually inspected for spikes, and any that were found were removed. The  $T_{\text{sys}}$  data were inspected and any data showing high  $T_{\text{sys}}$  values or jumps in  $T_{\text{sys}}$  values were also flagged. Bandpass calibration was completed using the bright quasars 3c279 or 3c454.3. For the gain calibration, the quasar 3c345 was periodically observed throughout each of our night's observations. A number of well studied and commonly used Solar System objects were used for the flux calibration, including Callisto, Ganymede, Titan and Neptune. The calibration process yields a typical uncertainty of  $\sim 10\%$  in measured flux densities (see e.g. Liu et al., 2018). After the calibration process, each chunk of the SMA data was individually exported into the CASA (McMullin et al., 2007) package for imaging.

We generated a continuum image for the 223 GHz observations. For each night of observations,  $\approx 300$  channels at the edge of each chunk were flagged to improve the data quality, and the individual chunks were concatenated into one dataset for each receiver. We then collapsed the resulting spectra down into a continuum dataset for each night of observations, and concatenated each night of observations into one dataset. Finally, we ran CASA's `tclean` task to complete interactive cleaning for our maps. We created a number of different maps testing different weighting schemes, with typically  $\sim 35 - 330$  CLEAN iterations. We additionally lay down CLEAN masks on the image, allowing the `tclean` task to preferentially select flux from regions known to contain sources. SDSS1607 is well detected in the SMA maps (to  $\approx 5 - 16\sigma$  depending on the weighting used), but we additionally observe a potential companion offset from SDSS1607 by  $\approx 14''$  and detected to  $\approx 4 - 8\sigma$ . We therefore place a second CLEAN window around this companion source. In Figure 5.1 we show the 223 GHz continuum images for SDSS1607 based on three different weighting schemes (Natural and Briggs weighting with two different values for the robust parameter), including both the dirty and CLEANed images, as well as the beamshape for the observations. In the SMA maps with Natural weighting, the 223 GHz observations reached depths of 0.24 mJy/beam. We then extracted a flux density

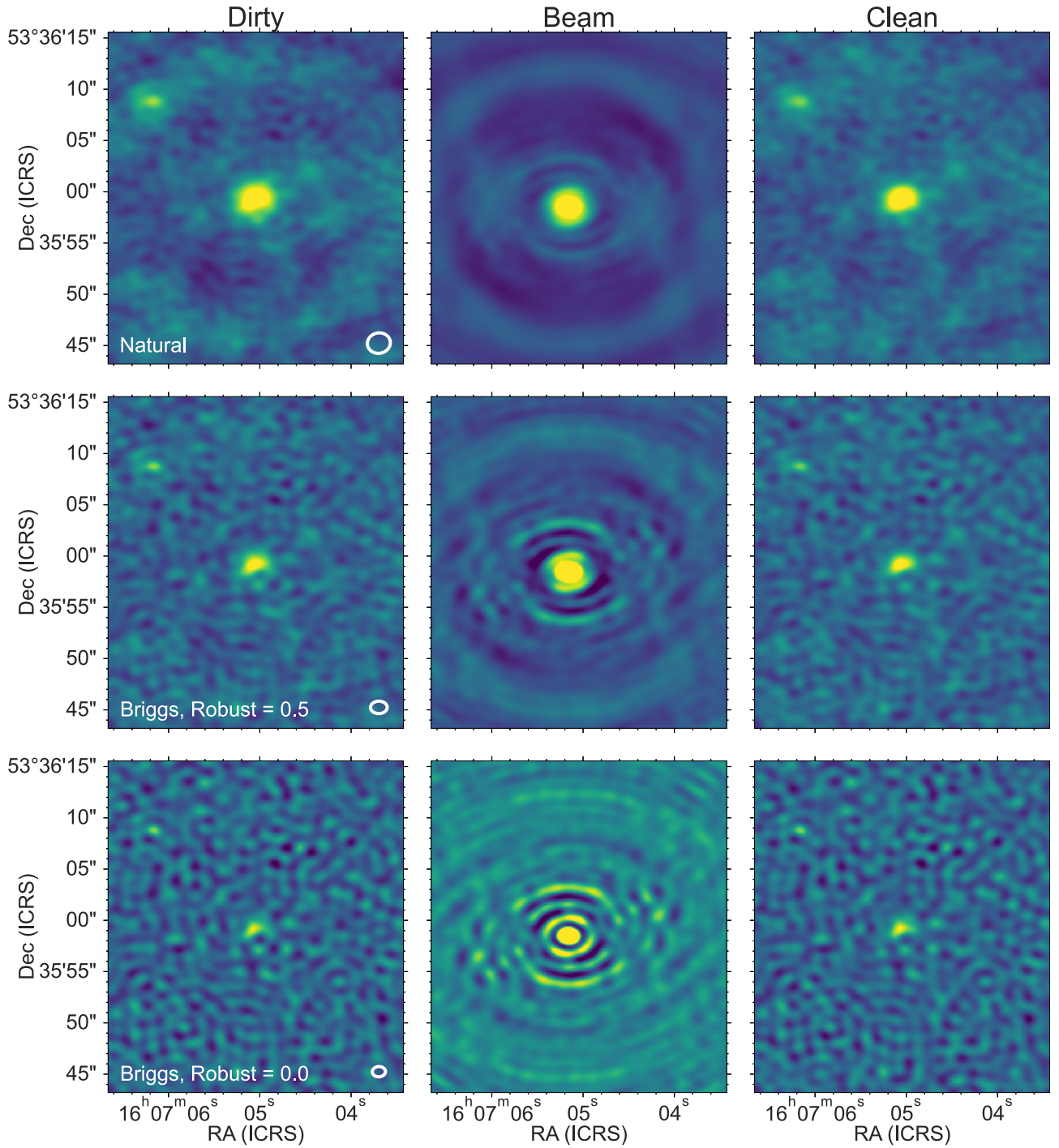


Figure 5.1: SMA continuum images at 223 GHz reduced using three different weighting schemes; Natural weighting (*top*) and Briggs weighting with the Robust parameter set to 0.5 (*middle*) and 0.0 (*bottom*). For each weighting scheme we show the dirty map (*left*), the full beamshape (*middle*) and the CLEANed map (*right*). The beamsizes are shown as a white ellipse in the bottom right corner of the dirty maps. We find that SDSS1607 and its potential companion are well detected in both the dirty and CLEANed maps for all three weighting schemes.

measurement for SDSS1607 and the potential companion from the SMA continuum images using the same methods as discussed in Chapter 4, including the correction for the response of the primary beam. Unfortunately, the data quality was not sufficient to extract any spectral information from the SMA observations and, as such, we rely only on the SMA continuum images.

### 5.2.2 VLA

VLA observations were taken as part of the VLA program 16A-025 (PI: D. L. Clements). These observations were comprised of 0.65 hours on the 22<sup>nd</sup> May 2016 tuned to X band to obtain deep, 10 GHz continuum imaging of SDSS1607, with a further 2.42 hours and 2.35 hours on the 24<sup>th</sup> and 27<sup>th</sup> May 2016 respectively, tuned to K band in order to detect the CO(1 – 0) emission line ( $\nu_{\text{rest}} = 115.271$  GHz) redshifted to  $\nu = 24.779$  GHz. All observations were taken in B configuration. The flux density and bandpass calibrator was 3C286 and the complex gain calibrator was J1549+5038.

We make use of the fully calibrated measurement sets available from the NRAO data archive<sup>1</sup>. The available datasets have been calibrated and reduced using the CASA VLA calibration pipeline<sup>2</sup> version 6.2.1, which completes the following calibration steps. The data is first imported into CASA and converted into a measurement set (`ms`) from the archival data format. The pipeline then applies Hanning smoothing, which primarily aims to reduce artefacts in the data due to the Gibbs phenomenon. In radio interferometry, the Gibbs phenomenon is a result of taking the Fourier transform of sharp features in the observations, as the Fourier series of a function containing a jump discontinuity typically produces large peaks around the discontinuity that overshoot/undershoot the true value of the function, manifesting as significant “ringing” in observations containing strong spectral line sources. Although this overshoot was described by Gibbs (1899) and hence termed the Gibbs phenomenon, the effect was actually first analysed much earlier by Wilbraham (1848). The Hanning smoothing process employed by the VLA calibration produces a running mean across the spectral axis with a triangular

<sup>1</sup><https://data.nrao.edu/portal/#/>

<sup>2</sup><https://science.nrao.edu/facilities/vla/data-processing/pipeline>



smoothing kernel, such that the central channel is weighted by 0.5 with the adjacent channels weighted by 0.25 to preserve flux<sup>3</sup>. The pipeline then applies a number of flags to the data, including observational flags, edge channels, shadowed data and other deterministic flags, before setting the flux calibrator model, which is essentially a table containing the model flux densities of the flux calibrator in each spectral window. A number of prior calibrations are completed. These include:

- Small corrections to the antenna positions if required,
- Opacity corrections accounting for the atmospheric transmission based on the frequency and elevation of the observations, as well as the weather conditions,
- Gaincurves describing how each receiver behaves as a function of elevation,
- The requantizer gain levels, which are the visibility amplitudes set as the input of the WIDAR correlator, are corrected if necessary,
- Ionospheric Total Electron Content (TEC) corrections. The two polarisations of light experience a relative delay that is proportional to the TEC and inversely proportional to the observing frequency, that is corrected using a series of images of the TEC across the sky based on data from the Global Navigation Satellite System (GNSS). Corrections are small for observations at frequencies higher than 5 GHz.

After these prior calibrations, the pipeline iteratively calculates delay, bandpass and gain calibrations, which includes carrying out flagging of likely Radio Frequency Interference (RFI) spikes in the data. Final delay, bandpass and gain calibrations are then derived on the RFI-flagged data. The calibrated data are then run through the `rflag` automatic flagging algorithm to exclude any remaining poor quality data. Finally, the visibilities are re-weighted based on the inverse square of the RMS noise within each spectral window.

We first construct continuum images in the two observed bands. For the observations in the X band, we simply split out the measurement set for SDSS1607 and carry out interactive

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<sup>3</sup><https://casa.nrao.edu/docs/taskref/hanningsmooth-task.html>

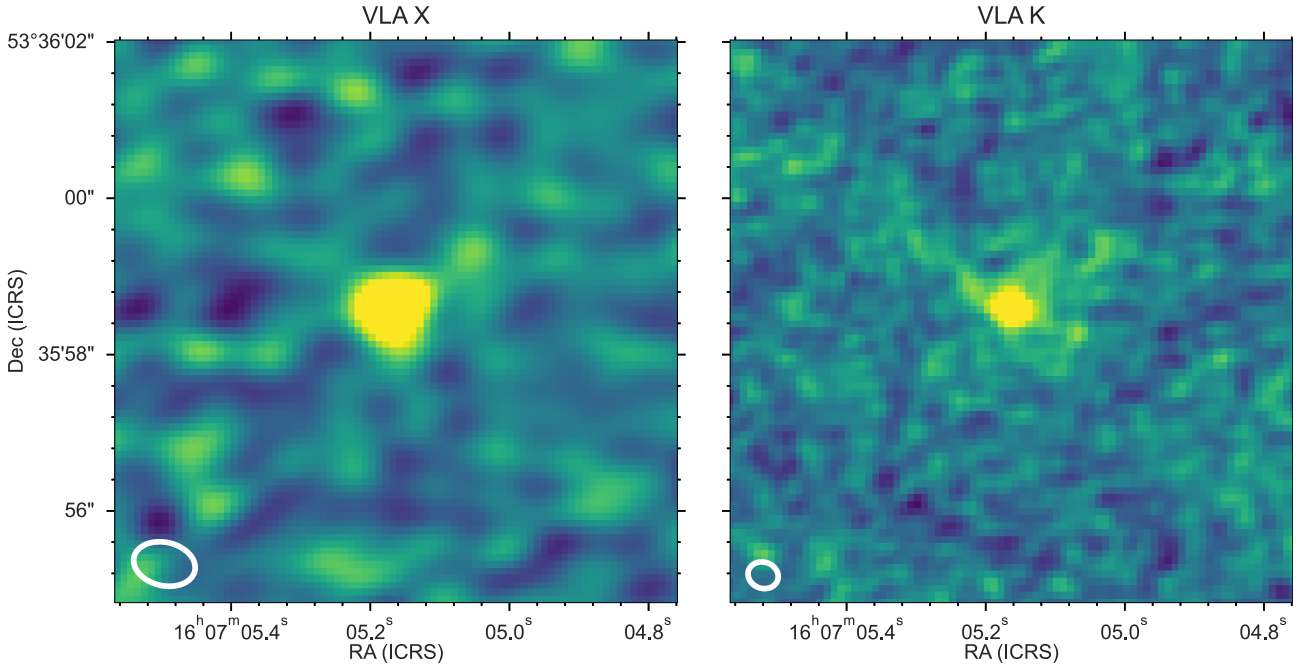


Figure 5.2: CLEANed and primary beam corrected continuum images of SDSS1607 in the X (8 GHz, *left*) and K (22 GHz, *right*) bands from the VLA. White ellipses in the bottom left corner of each frame show the beamsize of the observations. SDSS1607 is well detected in both VLA bands.

CLEANing using the `tclean` command. For the K band observations, the two individual sets of observations were calibrated separately and the SDSS1607 data were split out from the two resulting measurement sets and concatenated together to produce a single measurement set on which we carried out the CLEANing. For both frequencies, we produce continuum images with natural weighting to maximise the signal-to-noise, specifying an angular resolution of  $0.089''$  per pixel. In Figure 5.2, we present the CLEANed and primary beam corrected continuum images in the two bands.

The CASA VLA pipeline is not optimised for calibrating spectral line data, and so we additionally reduced the K band data manually. However, there were no apparent emission lines visible in the resulting spectra, and so the spectral cube data is not discussed further in this chapter.

### 5.2.3 HST

In addition to the FIR/mm observations with the VLA and SMA, we also obtained optical/NIR observations with HST. These observations were comprised of two orbits in each filter, taken as part of the HST project #15200 (PI: D. Farrah). The observations were taken in “MULTIACCUM” mode with the sampling exposure time set to every 50 s. A total of 16 MULTIACCUM samples were taken, resulting in a total exposure time of 800 s for each filter in each orbit, or a 1600 s exposure time in total for each filter. We made use of the WFC3/IR camera with the F110W and F160W filters, centred on wavelengths of  $1.153\,\mu\text{m}$  and  $1.537\,\mu\text{m}$  respectively<sup>4</sup>. At a redshift of  $z \sim 3.6$ , these two filters sample the rest frame NUV and the optical *U*-band respectively. We note that the reduction of the HST observations was done in collaboration with Pitchford et al. (in prep), and the reader is directed to this paper for a complementary discussion of the HST observations.

The WFC3/IR and UVIS detectors on HST (as well as the Wide Field Camera on ACS) are mildly undersampled. In order to fully sample the PSF, a detector is expected to have at least 2 pixels across the FWHM of the PSF (Gonzaga et al., 2012), but numerous instruments, particularly those with larger fields of view, do not approach this level of sampling and hence suffer from significant loss of information. The UVIS and IR detectors on the WFC3 camera of HST have pixel sizes comparable to the FWHM of the PSF (Gonzaga et al., 2012) meaning that, in order to fully characterise the PSF, we must sample it below the native pixel size ( $0.13''\text{ pix}^{-1}$ ) of the observations. In order to achieve this, our observations employed a four-point parallelogram dither pattern with a point spacing of  $0.572''$  and a line spacing of  $0.365''$ , ensuring a well sampled PSF. These observations therefore produced four dithered, flat-fielded images for each filter and each orbit (sixteen flat-fielded images in total), hereafter known as `flt` images. To align and combine these images, we use the standard STScI software package `DrizzlePac`<sup>5</sup>, which is the new and improved version of the previous `multidrizzle` software and makes use of the “drizzling” technique.

<sup>4</sup><https://hst-docs.stsci.edu/display/WFC3IHB/7.5+IR+Spectral+Elements>

<sup>5</sup><http://www.stsci.edu/scientific-community/software/drizzlepac.html>

The drizzling technique primarily aims to recover information that is lost due to undersampling of the Point Spread Function (PSF). Images obtained with a given telescope and detector are the result of the true distribution of light on the sky  $T$ , convolved with the Point Spread Function (PSF) of the telescope optics  $O$ , and the response function of the pixels in the detector  $E$ , which are often non-uniform, such that the final image  $I$  can be described as

$$I = T \otimes O \otimes E, \quad (5.1)$$

as outlined in Fruchter and Hook (2002). Linear Reconstruction techniques, of which drizzling is the most popular, aim to recreate the image after convolution with the PSF of the instrument in order to recover spatial resolution in the image whilst conserving the signal-to-noise ratio of the detection (Gonzaga et al., 2012). As previously mentioned, the drizzling technique required that the observations are comprised of multiple ‘dithers’, frames offset from each other so as to sample the image on different parts of the detector. There are numerous different dithering strategies (with varying numbers of frames and positions on the detector), but they can be broadly split into those with sub-pixel shifts to improve spatial sampling of the PSF, shifts by integer numbers of pixels in order to more effectively remove bad pixels and large shifts for mapping areas much larger than the size of the detector (Gonzaga et al., 2012). The former is most useful for recovering information lost to undersampling and hence is used in these observations. Each individual dither image has its pixel size shrunk by some factor defined by the user (in order to avoid re-convolving the output image with the pixel footprint of the detector), before being mapped onto a subsampled output image, with shifts and rotations between the images preserved and optical distortions of the camera taken into account (Fruchter and Hook, 2002). The total flux of each of the shrunken input pixels is divided up between the output pixels with which it overlaps, weighted proportionally to the area of overlap between the input and output pixels (Fruchter and Hook, 2002). In this way, the drizzling algorithm recovers some of the spatial resolution in the image lost to undersampling. By selecting a factor between zero and one with which to shrink the input pixel size by, the drizzle algorithm can be seen as a compromise between two more extreme Linear Reconstruction Techniques, ‘Interlacing’, in

which pixels from the independent dithers are simply interlaced onto a finer grid, and ‘Shift and Add’, in which each input pixel from the dithered image is block-replicated onto a subsampled grid before being shifted into position and added to the final image. The drizzle algorithm was first developed for co-adding dithered images in the Hubble Deep Field North (Williams et al., 1996), and has more recently been developed into the popular **DrizzlePac** package.

The drizzle algorithm in **DrizzlePac** allows us to combine our `flt` images together to improve the sampling of the PSF, but also to reduce the pixel size and produce higher resolution images. Unfortunately, the instrument was positioned at a slightly different orientation for each of the orbits which means that we cannot naturally align both the diffraction spikes and the surrounding field for the two orbits. As a result, we first produce drizzled images based on the standard set of parameters for the individual orbits and for the individual filters, yielding four drizzled images in the native *HST* pixel size.

We then correct the astrometry of these final drizzled images. Kozhurina-Platais et al. (2018) note that, based on globally accurate stellar positions from *Gaia* DR1, there are significant systematic offsets in HST WFC3 astrometry of up to 129 and -717 mas in RA and Dec respectively. In order to correct for this, we find the positions of the brightest pixel of numerous bright stars surrounding SDSS1607, and compare these positions to those of the same stars in the HSC-SSP *i* band image (see more details about the HSC-SSP observations in the following section). We take the median difference in the positions of the stars in the two images as the astrometric correction factor, resulting in values of  $\Delta\text{RA} = 207$  mas and  $\Delta\text{Dec} = -572$  mas for the F110W filter, and  $\Delta\text{RA} = 246$  mas and  $\Delta\text{Dec} = -553$  mas for the F160W filter. We subsequently correct the header information in the HST images to account for this offset and inspect the resulting images to ensure that the corrections were reasonable. We show the resulting drizzled images for one orbit in the F110W and F160W filters Figure 5.3, demonstrating the bright SDSS1607 quasar, as well as the offset blob of emission, which is resolved in the HST imaging.

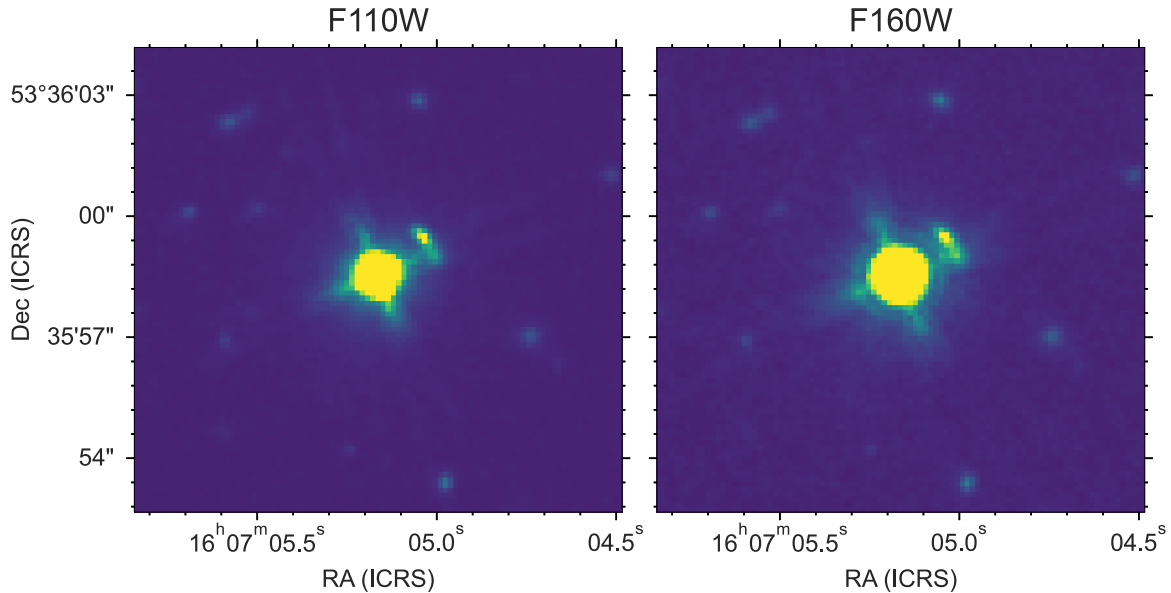


Figure 5.3: *HST* images taken with the F110W (*left*) and F160W (*right*) filters on the WFC3/IR instrument. Each image is the produce of drizzling all eight `flt` images from both orbits together for each filter. The WFC3/IR instrument was positioned with a slightly different rotation angle in the two orbit, hence the two sets of diffraction spikes in each image. In both images, the quasar and ‘blob’ of offset emission are apparent.

#### 5.2.4 Ancillary Data

SDSS1607 lies within the ELAIS-N1 (EN1) field, and as such benefits from a wealth of multi-wavelength ancillary data. At optical wavelengths, SDSS1607 is covered by the HSC SSP (Aihara et al., 2018a) survey which, in its ‘Deep’ layer, reaches limiting AB magnitudes of 27.5, 27.1, 26.8, 26.3 and 25.3 in the  $g$ ,  $r$ ,  $i$ ,  $z$  and  $y$  bands respectively. Observations in the NIR and MIR are provided by *Spitzer*, including deep  $3.6\,\mu\text{m}$  and  $4.5\,\mu\text{m}$  photometry from the *Spitzer* Extragalactic Representative Volume Survey (SERVS: Mauduit et al., 2012), as well as photometry in all IRAC and MIPS bands from the *Spitzer* Wide-Area Infrared Extragalactic Survey (SWIRE: Lonsdale et al., 2003). Additionally, the UKIRT Infrared Sky Survey (UKIDSS: Lawrence et al., 2007) provides deep  $J$  and  $K$  observations down to  $5\sigma$  point source sensitivities of 22.3 and 20.8 respectively (Vega magnitudes) as part of the UKIDSS Deep Extragalactic Survey (UKIDSS-DXS). SDSS1607 further benefits from FIR/sub-mm photometry from numerous sources, including *Herschel* and the Sub-millimeter Common User Bolometer Array 2 (SCUBA-2: Holland et al., 2013) on the James Clerk Maxwell Telescope.

## 5.3 PSF Subtraction

One of our primary science goals for this work is to investigate the properties of SDSS1607, the offset blob of emission and the potential companion source, including photometric redshifts, stellar masses and SFRs. We therefore require multi-wavelength photometry such that we can build up SEDs for the sources to be used with fitting codes such as **CIGALE** and **EAZY**. There are, however, significant difficulties in extracting the photometry for SDSS1607 and the offset blob. First and foremost, the emission from SDSS1607 itself is dominated by the quasar and so, in order to infer any information about the host galaxy, we must subtract this quasar emission. Moreover, Figure 5.3 demonstrates that, in an unfortunate coincidence, the rotation angle of the WFC3/IR camera for our observations is such that one of the diffraction spikes passes through the offset blob of emission. Simple aperture photometry is therefore impossible for this object, as this would naturally include some contamination of the flux density estimate by the PSF. It is therefore necessary for us to complete a PSF subtraction on the HST observations before we can estimate accurate photometry.

It is extremely difficult to have a perfect knowledge of the PSF from a theoretical perspective, as the PSF can change over time due to minute variations in the instrument focus, as well as across the detector due to variations in the optical distortion and the instrument thickness<sup>6</sup>. As a result, it is usually more appropriate to construct a PSF from the observations themselves. Despite this, PSF subtraction on HST observations is often completed using a purely theoretical model PSF, typically generated using the popular STScI program **Tiny Tim**<sup>7</sup> (Krist et al., 2011). We test three different methods for completing this PSF subtraction; the first involves building an empirical model PSF from our HST observations, the second uses STScI publicly available<sup>8</sup> empirically constructed model PSFs, while the final method uses **Tiny Tim** to generate a theoretical model PSF.

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<sup>6</sup><http://www.stsci.edu/hst/instrumentation/wfc3/data-analysis/psf>

<sup>7</sup><http://www.stsci.edu/software/tinytim/>

<sup>8</sup><http://www.stsci.edu/hst/instrumentation/wfc3/data-analysis/psf>

### 5.3.1 Our Empirical PSF Model

To significantly simplify the modelling of the PSF, we choose to model the “effective PSF” (ePSF), an empirical representation of the more challenging “instrumental PSF” (iPSF). A detailed discussion of ePSF modelling is presented in Anderson and King (2000), and here we simply outline the differences between the ePSF and iPSF, as well as the benefits of the former for PSF modelling.

The iPSF is effectively the two-dimensional pattern of light produced in the focal plane of an optical instrument observing a point source (Anderson and King, 2000). As such, the iPSF is extremely challenging to model accurately as it is never directly observed, only the projection of the iPSF onto the two-dimensional pixel array of the detector (Anderson and King, 2000). The observed PSF is therefore not only a function of the pixel size, the signal-to-noise ratio of the observed source and the flat field (as well as numerous other observational parameters), but critically the sensitivity profile of a pixel, which is typically not a simple square top-hat function, such that the observed PSF can vary depending on where the centre of the source falls within the boundaries of a given pixel (Lauer, 1999; Anderson and King, 2000). While we can never directly observe the iPSF, Anderson and King (2000) demonstrate mathematically that the flux from a star in a given pixel, which is the integration of the iPSF at that pixel over the two-dimensional sensitivity profile of the pixel (which is then scaled by the flux of the star and added to some background value), is equivalent to the convolution of the iPSF with the sensitivity profile of a pixel, otherwise known as the ePSF. In other words, while the iPSF effectively describes the probability distribution of where light from a point source will land on a detector, the ePSF describes the fraction of the light from the star that should fall in each of the surrounding pixels, and as such can be described as a simple array of values, making it a more practical and less abstract choice for modelling (Anderson, 2016).

The method for generating our empirical PSF was carried out by our collaborators, and is described in detail in Pitchford et al. (in prep). Here, we briefly outline this method. We first take each `flt` image and find a sample of sufficiently bright, isolated stars in the surrounding field. We use the `flt` images rather than the drizzled images as the drizzling process can intro-



duce irregularities in the sampling or correlations between the resulting pixels, and so generally it is recommended that PSF subtraction is done on the individual `flt` images. Due to a lack of sufficiently bright and isolated sources, we select a single bright star in the field to construct our model ePSF. We cut the star from the image and complete background subtraction. We use the `EPSFBuilder` class as part of the `astropy photutils` package, which uses the Anderson and King (2000) and Anderson (2016) formalisms to construct an ePSF from our stellar cutout. We generate the ePSF with an oversampling of four, allowing us to make sub-pixel shifts in the position of the ePSF relative to the `flt` image to improve the accuracy of the final subtraction. The ePSF is then scaled such that the sum of pixel values within an aperture of radius  $6''$  matches the flux of the quasar in an aperture of the same size. Once the model ePSF is generated and scaled, we start the PSF subtraction.

First, we create a  $60 \times 60$  pixel cutout centred roughly on the position of the quasar, regridding this cutout by a factor of four to match the pixel size of the oversampled ePSF. In order to align the ePSF with the position of the quasar, we make a grid of 3,600  $100 \times 100$  pixel cutouts of the regridded quasar image, centred on each pixel within a  $60 \times 60$  pixel grid around the approximate centre of the quasar. For each cutout, we calculate a simple Pearson correlation coefficient of the two arrays to obtain a rough indication of which cutout is most likely centred on the quasar. We then manually inspect a second grid of  $100 \times 100$  pixel cutouts with centres in a  $10 \times 10$  pixel box around the position with the highest correlation coefficient and look for alignment in the diffraction spikes and other features in the cutout. Once the best alignment between the ePSF and the regridded cutout of the quasar is found, we subtract the two. We “paste” the PSF-subtracted image back into the original cutout, regrid the cutout back into the native pixel size of the observations and, finally, paste the result back into the original `flt` image. We repeat this for each `flt` image, and then drizzle the results together.

### 5.3.2 The Anderson (2016) Empirical PSF Model

Our second method is effectively identical to the previous method, except that rather than building the ePSF empirically from stars within our own observations, we use empirically

constructed, oversampled ePSFs generated by STScI<sup>9</sup>. For a full description of how these PSFs are produced, the reader is directed to Anderson (2016) and Pitchford et al. (in prep), as this work was primarily carried out by our collaborators, and here we briefly summarise this process.

The STScI ePSF models were generated from observations taken as part of the calibration program CAL-13606, comprised of eight 102 second exposures for each filter in an eight-point dither pattern Anderson (2016). These observations yielded  $\approx 1,600$  stars in the field that are sufficiently bright and isolated to be considered in the generation the ePSF. Their method for constructing the ePSF relies on a virtuous cycle comprised of three steps:

1. For each star in the field, a position is determined based on a simple centroid procedure and a flux density is measured from the pixels within an aperture of radius 3.5 pixels
2. Stars in each of the eight dithered exposures are cross-matched with those in the first exposure, and the transformations required to convert their positions into the frame of the first exposure are identified, taking into account distortion in the HST optics. Stars common in 5/8 exposures are considered ‘usable’ and for each, an average position of the star in the first reference exposure is found and transformed back into each of the individual exposures. This step primarily aims to reduce pixel-phase biases; small biases in the position of the PSF due to inaccurate estimates of the position of the star in the undersampled image, which will in turn bias any estimates of position based on the resulting PSF.
3. Based on these positions and flux densities, a point estimate for the ePSF at each pixel in the region of each star is estimated via the equation

$$\psi(\Delta x, \Delta y) = \frac{P_{ij} - s_{star}}{z_{star}}, \quad (5.2)$$

where  $\Delta x$  and  $\Delta y$  are the pixel offsets in the  $x$  and  $y$  directions from the centre of the star,  $P_{ij}$  is the flux in pixel  $(i, j)$ ,  $s_{star}$  is the background sky value and  $z_{star}$  is the

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<sup>9</sup><https://www.stsci.edu/hst/instrumentation/wfc3/data-analysis/psf>

flux of the star. The resulting ePSF estimates are then subject to additional smoothing, normalisation and centring.

These three steps are then iterated, with the position and flux density in step one now determined from the resulting ePSF, until a final ePSF solution is reached (Anderson, 2016). We note that this is a somewhat brief overview of their full method, and the reader is directed to Anderson (2016) for more detail. To account for variations across the HST WFC3/IR detector, Anderson (2016) produce a  $3 \times 3$  array of ePSF models depending on where the star falls on the chip.

While it is likely that the model PSFs generated by Anderson (2016) will differ slightly from the true PSF for our observations, their model PSFs are likely better sampled and more accurate than the model PSF made from our own data, due to the eight-point dither pattern used in their observations, and the many more bright stars used to generate their PSF model. We select the ePSF model corresponding to the position of SDSS1607 on the detector and follow the methodology discussed in the previous section to complete the PSF subtraction.

### 5.3.3 The Tiny Tim PSF Model

For our final method, we generate a theoretical PSF model using the STScI program `Tiny Tim`. The construction of the `Tiny Tim` PSF model was primarily done by myself, but the method is also included in Pitchford et al. (in prep).

Since 1992, `Tiny Tim` has since been the standard PSF-modelling software for HST observers (e.g. van Dokkum et al., 2008; van der Wel et al., 2011; Krogager et al., 2013; Villforth et al., 2014; Sparks et al., 2016; Sanghi et al., 2022). One of the major benefits of the `Tiny Tim` software is its ease of use, with only three simple programs required to obtain a model ePSF. `tiny1` requires a series of user-defined inputs, including the coordinates of the source on the detector grid, the HST filter, the desired diameter of the PSF in arcseconds and the level to which the PSF model should be supersampled. `tiny2` then uses these inputs to generate a slightly oversampled and undistorted model PSF. The WFC3 and ACS instruments are located

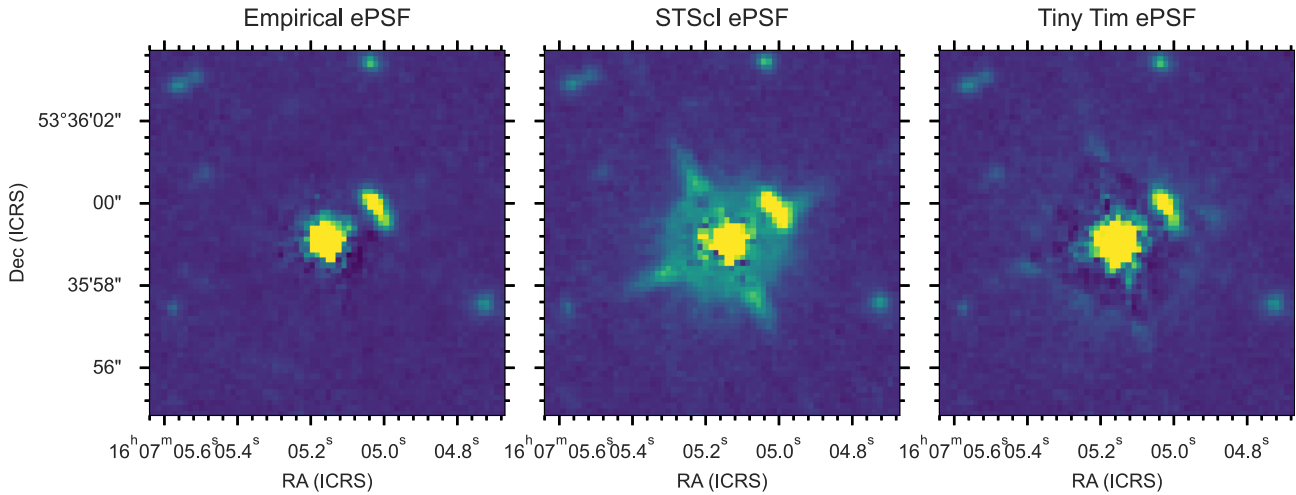


Figure 5.4: The PSF subtracted and drizzled images based on three different ePSF models;

away from the optical axis of the HST instrument and, as such, suffer from significant distortion that is not corrected for by the internal optics (Krist et al., 2011). In the final program (`tiny3`), a geometric distortion is applied to the model PSF generated by `tiny2` to account for this effect.

We generate a PSF model for each filter centred on the rough position of the quasar on the detector array, with a diameter of  $4''$ . Additionally, we follow the method of Biretta (2012, 2014) and edit the `Tiny Tim` Cold Mask parameters to their improved values. Similarly to the previous sections, we generate the final `Tiny Tim` PSF oversampled by a factor of four. We then follow the aforementioned method to complete the PSF subtraction.

### 5.3.4 Comparing PSF Subtractions

In Figure 5.4, we present the drizzled, PSF subtracted images for one orbit using the F160W filter for each of the different ePSF models. Similar PSF subtractions were found in the other orbit, and in the F110W observations. In each of the three images, we use identical scalings in order to aid comparison. We find that all three ePSF models leave significant residuals in the central regions, either due to flux from the quasar which remains unaccounted for, or due to flux from the host galaxy. Despite being based on a single star in the field, we argue that the empirically constructed ePSF provides the best PSF subtraction. While the STScI ePSF model is similarly constructed from hundreds to thousands of stars in the field based on deep HST

observations, we find that the subtraction leaves significant residuals, both in the diffraction spikes and in a faint halo surrounding the central regions. While the `Tiny Tim` ePSF model more successfully subtracts this faint emission, it seems to handle the diffraction spikes much more poorly than the empirical model, with some regions significantly over-subtracted and others showing residual flux. We additionally test whether better subtractions could be produced by small pixel or sub-pixel shifts in the alignment of the PSF with the quasar, but no significant improvements were found in this test. We also test using a  $10\times$  oversampled PSF rather than a  $4\times$  times oversampled PSF, which also produced exceedingly similar results. We therefore find that the empirical ePSF model yields the best PSF subtraction, and so we use this subtraction to obtain photometry for the system. We note that this is not necessarily a surprising result; for example, Hoffmann and Anderson (2017) find that, for HST/ACS imaging, an empirically generated ePSF based on the formalism of Anderson (2016) produces a quantitatively better fit to the globular cluster NGC 6397 than the `Tiny Tim` PSF model.

### 5.3.5 HSC PSF Subtraction

In addition to the SMA and HST observations, we find that the offset blob of emission is detectable and spatially resolved in the HSC-SSP imaging. However, we find that the Subaru PSF is large enough that emission from the quasar still infringes on the position of the blob. This can be seen most clearly in the first column of Figure 5.5, in which we present the optical images of the system. We are therefore required to complete another PSF subtraction for the HSC-SSP observations, although the HSC instrument on Subaru does not suffer from many of the PSF-related issues suffered by WFC3/IR and ACS on HST. As such, we make use of a rather more simple PSF subtraction method.

We subtract two different model PSFs from cutouts of the  $g$ ,  $r$ ,  $i$ ,  $z$  and  $y$  images from the HSC-SSP survey using the `GALFIT`<sup>10</sup> software (Peng et al., 2002, 2010), which allows the user to fit a range of models to the light profiles of astronomical objects. We use `GALFIT` to fit a simple Sérsic model to the SDSS1607 quasar, as well as fitting model Subaru HSC PSF models<sup>11</sup>

<sup>10</sup><https://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html>

<sup>11</sup><https://hsc-release.mtk.nao.ac.jp/psf/pdr2/manual.html>

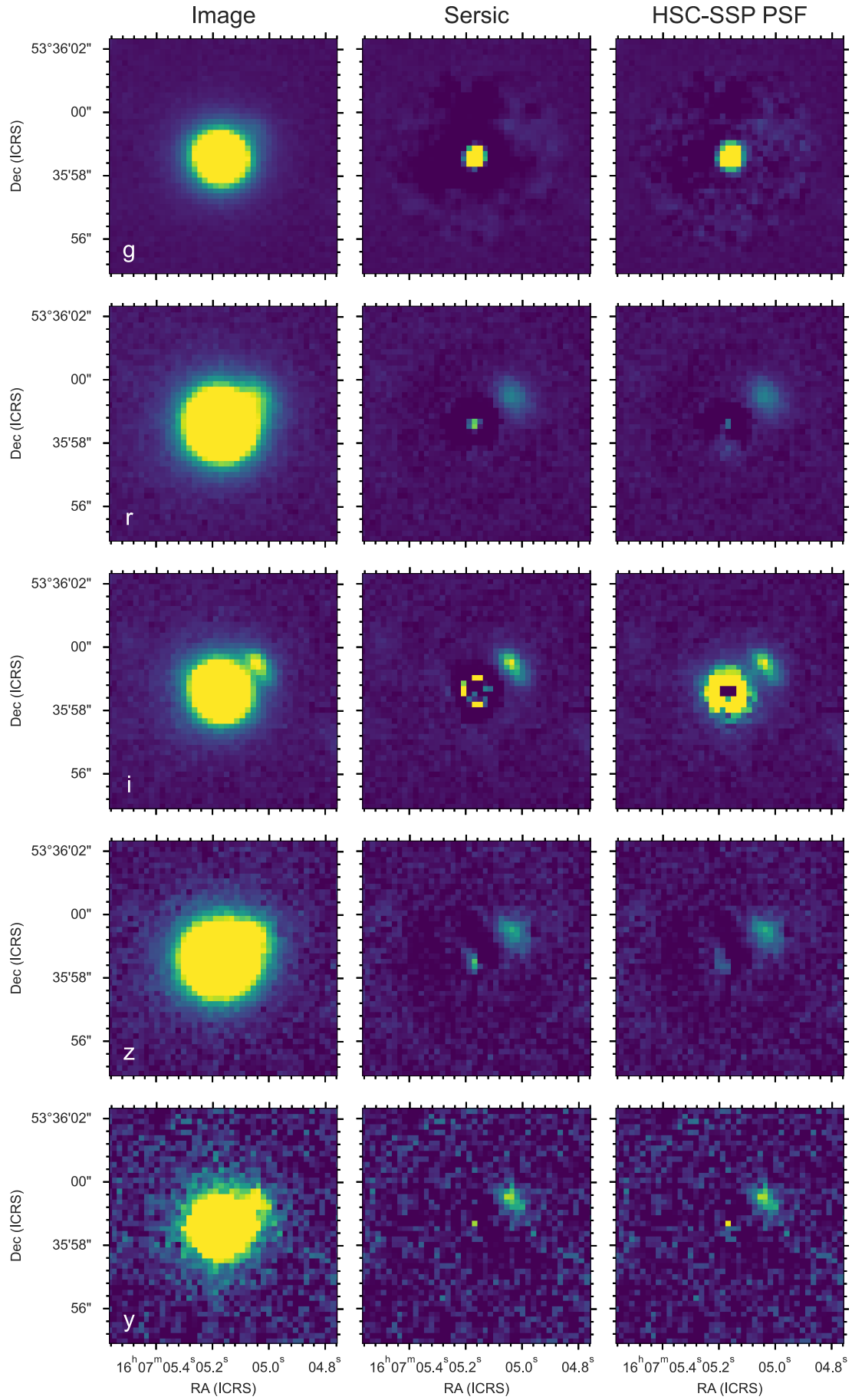


Figure 5.5: The PSF subtracted images from the HSC-SSP survey based on the two PSF models. We find that both the Sérsic model and the HSC-SSP PSF model provide a reasonably good subtraction, although the Sérsic model tends to yield slightly lower  $\chi^2_\nu$  values, indicating a slightly better fit.

available as part of the second HSC-SSP data release (Aihara et al., 2019). We allow **GALFIT** to find the optimum position and scaling for the PSF model, following which it provides the original image, the PSF model image, the residual image and a parameter file containing the best fitting positions and PSF model flux. In Figure 5.5 we show the resulting residual images for each band based on the two PSF models. We find that both PSF models fit the data well with exceedingly similar  $\chi^2_\nu$  values. The only problematic band is the  $i$  band, where the Sérsic model provides a much better subtraction than the HSC-SSP model. The offset blob of emission is clearly detected in all optical bands excluding the  $g$  band, where **GALFIT** cannot differentiate between the faint, diffuse emission towards the edge of the SDSS1607 quasar and the blob.

## 5.4 The SDSS1607 System

### 5.4.1 Morphology

Our SMA, VLA and HST observations demonstrate that SDSS1607 has an unusual morphology. In Figure 5.6, we present the HST F110W image from a single orbit, overlaid with contours from the high resolution SMA and VLA interferometry.

This Figure demonstrates in detail that the optical morphology of the system is comprised of two components; the bright central quasar and a second blob of emission, offset from the quasar centre by  $\approx 1.4''$  and extended by  $\approx 1''$ . The FIR/mm observations from the SMA demonstrate that the majority of the dust emission comes from the region of the blob rather than the quasar, although we find that the SMA detection is extended over a  $\approx 4''$  region with some overlap with the quasar centre. From the VLA observations, we find that the radio emission, as expected, is coincident with the SDSS1607 quasar. We note that, although somewhat tenuous, there are two small extensions to the radio morphology of the central quasar, consistent with the physical size of emerging radio jets. We also see a marginal  $3\sigma$  detection coincident with the blob and the peak of the SMA contours, although we note that there are similar marginal  $3\sigma$

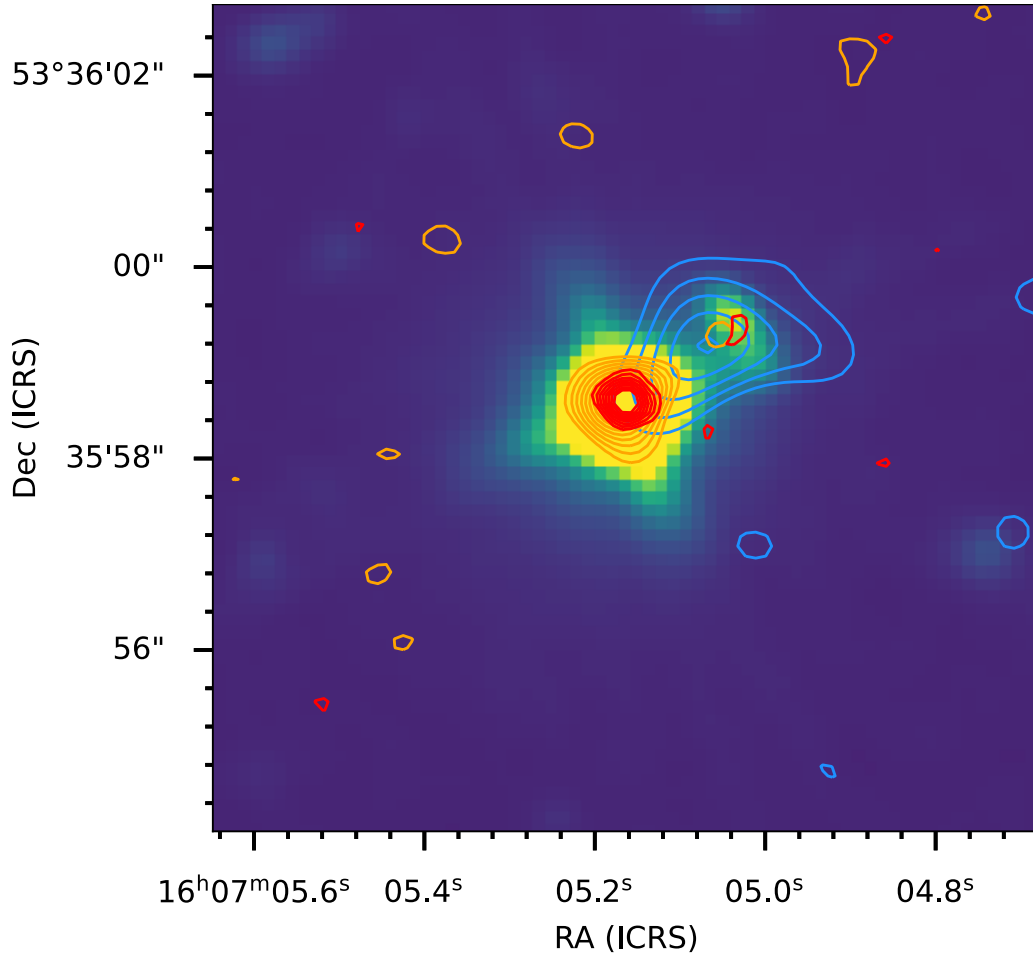


Figure 5.6: HST WFC3/IR image of SDSS1607 in the F110W filter, slightly smoothed to aid visualisation and overlaid with contours from the SMA data (blue) and the VLA 8 GHz (orange) and 22 GHz (red) data from  $3 - 10\sigma$  significance. We find that the SMA contours are coincident with the blob of offset emission but extend towards the central quasar. By comparison, both VLA continuum image demonstrate that the quasar dominates the radio emission, although we note a marginal  $\approx 3\sigma$  detection at the position of the blob. The quasar is extremely bright in the 8 GHz image with two small extensions, one of which is directed towards the offset blob of emission.

spikes surrounding the region. We discuss the interpretation of these results in more detail in Section 5.6.

### 5.4.2 Photometry

In this section, we outline our methods for extracting photometry from our observations, as well as from the available ancillary data. We do this separately for the total SDSS1607 system and the offset blob.



## The Offset Blob

We start by extracting photometry for the offset blob of emission. We infer from Figures 5.3 and 5.6 that this blob is spatially resolved and detected to high significance in the HST observations, and is coincident with a marginal  $3\sigma$  detection in the VLA 8 GHz observations. Moreover, the blob appears to be coincident with the peak of the SMA 223 GHz continuum emission. For the SMA observations, we follow Greenslade et al. (2020) and simply extract the peak flux density from the SMA maps reduced using Natural weighting, as this reduction provides the highest signal-to-noise ratio in the maps. We correct the resulting flux density for the primary beam response, although due its position near the centre of the field, this correction is small (a factor of  $\approx 0.9985$ ). The uncertainty in the SMA photometry is dominated by the  $\approx 10\%$  calibration uncertainty. While there is a marginal  $\approx 3\sigma$  detection associated with the offset blob in the VLA images, we find many spikes of similar significance throughout the VLA map. As such, we do not consider this detection robust, but continue to extract a flux density as we know that there is a source at this location. Given the physical extent of the blob of emission and the beamsize of the VLA observations in the  $K$  and  $X$  bands, we consider the blob to be a point source, and so simply extract the peak flux density. The associated uncertainty is calculated by combining the RMS noise in the image with a conservative 10% calibration uncertainty.

Flux density estimates from the HST and HSC-SSP observations are discussed in Pitchford et al. (in prep) and will be briefly outlined here. Photometry is extracted from the F110W and F160W filters from the combined, drizzled and PSF subtracted images from HST. An elliptical aperture is used covering the offset blob of emission in both bands and manually inspected to ensure that it is a good fit to the morphology of the source, before a flux density is extracted and converted into mJy using the calibration information in the image header. The uncertainty in this value is taken to be a typical 1% calibration error (Mack et al., 2021) added in quadrature with the standard deviation of the flux density of the offset blob in the four dithered frames. The latter uncertainty value should provide an uncertainty estimate relating to the PSF subtraction itself, as the diffraction spike will pass through slightly different parts of the offset blob of emission in the four dithered frames and the psf subtraction in the four

dithered frames will differ slightly due the exact position of the ePSF on the detector array. For the HSC-SSP observations, flux densities are similarly extracted from the PSF subtracted images, in this case using the HSC-SSP PSF for the  $g$ ,  $r$ ,  $z$  and  $y$  bands, and the Sérsic model for the  $i$  band where the HSC-SSP PSF has significant issues in describing the SDSS1607 quasar light profile. An elliptical aperture is used in each band, centred on the position of the offset blob, with the semi-major axis aligned with the direction in which the blob is most extended, and the size incrementally increased until the entire flux from the blob is included within the aperture. HSC-SSP maps are in units of counts per second, and so uncertainties in the extracted photometry are estimated by adding in quadrature the RMS noise in the image, the typically assumed 1% calibration uncertainty (Aihara et al., 2018a) and the Poissonian error on the extracted flux. The photometry and associated uncertainties are then converted into magnitudes using the magnitude zeropoints provided in the observation headers.

The resulting multi-wavelength photometry for the blob is presented in Table 5.1. In all other ancillary observations, the spatial resolution is too poor to accurately distinguish between the quasar and the offset blob of emission.

### The Total SDSS1607 System

Unfortunately, little information can be recovered concerning the host galaxy alone. In the HSC-SSP images, no significant residuals are left in the image after PSF subtraction, indicating that **GALFIT** cannot effectively differentiate between flux from the host galaxy and flux from the quasar itself. There are significant residuals in the PSF subtracted HST images which we take to be the host galaxy, but the actual flux density from this component is extremely sensitive to numerous aspects of the PSF subtraction process, including the alignment of the PSF and source, the drizzle parameters and the ePSF model used. As a result, we do not discuss any details of the host galaxy in this work.

We can however, proceed with a combined analysis of the total SDSS1607 system, by combining the photometry for the blob and the quasar in observations where the two are resolved, as well as including the photometry from observations in which they are not. For the SMA observations,

the total flux density was previously attributed to the blob, and so we can use the same flux density for the total system. For the VLA observations, we sum the flux density from the quasar and the marginal  $3\sigma$  detection associated with the offset blob of emission. For the quasar, as the flux is extended such that the region of emission is larger than a single beamsize, we use the CASA task `imfit`, to estimate both the flux density and associated uncertainty. The flux density is estimated by integrating over a two-dimensional elliptical Gaussian fit to the source, with associated errors estimated following the work of Condon (1997) and including the uncertainties on numerous fitting parameters, such as peak flux, FWHM of the major and minor axes of the best fit elliptical Gaussian model, and the noise-correlation beam FWHM<sup>12</sup>.

Pitchford et al. (in prep) similarly assemble HST photometry for the total SDSS1607 system. This photometry is the combination of the blob photometry, the flux of the ePSF model subtracted from the image and the residual flux remaining in the PSF-subtracted image, taken to be the flux density from the host galaxy.

Rather than extracting the flux density in the optical bands from the HSC-SSP images, we find that SDSS1607 is present in the HSC-SSP catalogues, and so we simply take the value from the catalogue. For the remaining archival observations, Clements et al. (2009) assembled optical-to-mm photometry for the SDSS1607 system which we use in this work. In Table 5.1, we present the resulting photometry for the full SDSS1607 system.

### 5.4.3 Properties

We run the resulting photometry for the offset blob of emission and for the total SDSS1607 system through the SED fitting code `CIGALE` with a few notable exceptions in the case of the total system. In particular, we find that when the SCUBA  $450\mu\text{m}$  and MAMBO  $1.2\text{mm}$  flux densities are included, `CIGALE` has significant difficulties in finding a good fit to the SED of the total SDSS1607 system. Table 5.1 demonstrates that the  $450\mu\text{m}$  flux density is anomalously high compared to those in the surrounding bands of *Herschel* and are clearly very uncertain. We note that these observations were taken with the original SCUBA instrument rather than

<sup>12</sup>[https://casa.nrao.edu/casadocs/casa-5.4.1/global-task-list/task\\_imfit/about](https://casa.nrao.edu/casadocs/casa-5.4.1/global-task-list/task_imfit/about)

| Survey/<br>Instrument | Filter    | Wavelength<br>$\mu\text{m}$ | Total System<br>Flux Density   | Blob<br>Flux Density         |
|-----------------------|-----------|-----------------------------|--------------------------------|------------------------------|
| SDSS                  | $u'$      | 0.355                       | $1.31 \pm 0.07 \mu\text{Jy}$   | —                            |
|                       | $i'$      | 0.748                       | $201 \pm 10 \text{ mJy}$       | —                            |
| HSC-SSP               | $g$       | 0.479                       | $65.02 \pm 0.03 \mu\text{Jy}$  | $0.56 \mu\text{Jy}$          |
|                       | $r$       | 0.619                       | $185.81 \pm 0.05 \mu\text{Jy}$ | $2.08 \pm 0.02 \mu\text{Jy}$ |
|                       | $i$       | 0.767                       | —                              | $2.64 \pm 0.03 \mu\text{Jy}$ |
|                       | $z$       | 0.890                       | $230.05 \pm 0.05 \mu\text{Jy}$ | $2.23 \pm 0.02 \mu\text{Jy}$ |
|                       | $y$       | 0.978                       | $214.88 \pm 0.09 \mu\text{Jy}$ | $2.28 \pm 0.03 \mu\text{Jy}$ |
| HST                   | F110W     | 1.15                        | $313 \pm 9 \mu\text{Jy}$       | $3.0 \pm 0.1 \mu\text{Jy}$   |
|                       | F160W     | 1.54                        | $373 \pm 9 \mu\text{Jy}$       | $3.2 \pm 0.1 \mu\text{Jy}$   |
| 2MASS                 | $J$       | 1.24                        | $0.36 \pm 0.04 \text{ mJy}$    | —                            |
|                       | $H$       | 1.65                        | $0.31 \pm 0.06 \text{ mJy}$    | —                            |
|                       | $K_s$     | 2.16                        | $0.34 \pm 0.07 \text{ mJy}$    | —                            |
| <i>Spitzer</i>        | IRAC-1    | 3.56                        | $0.40 \pm 0.02 \text{ mJy}$    | —                            |
|                       | IRAC-2    | 4.50                        | $0.40 \pm 0.02 \text{ mJy}$    | —                            |
|                       | IRAC-3    | 5.75                        | $0.66 \pm 0.01 \text{ mJy}$    | —                            |
|                       | IRAC-4    | 7.92                        | $1.33 \pm 0.01 \text{ mJy}$    | —                            |
|                       | MIPS-1    | 23.6                        | $6.31 \pm 0.02 \text{ mJy}$    | —                            |
|                       | MIPS-2    | 70.9                        | $22.2 \pm 0.8 \text{ mJy}$     | —                            |
|                       | MIPS-3    | 155                         | $< 104 \text{ mJy}$            | —                            |
| <i>Herschel</i> SPIRE | PSW       | 250                         | $73.2 \pm 1.5 \text{ mJy}$     | —                            |
|                       | PMW       | 350                         | $87.2 \pm 1.3 \text{ mJy}$     | —                            |
|                       | PLW       | 500                         | $66.4 \pm 1.8 \text{ mJy}$     | —                            |
| SCUBA                 | SCUBA-450 | 450                         | $220 \pm 90 \text{ mJy}$       | —                            |
|                       | SCUBA-850 | 863                         | $31 \pm 3 \text{ mJy}$         | —                            |
| MAMBO                 | —         | 1200                        | $7.3 \pm 0.9 \text{ mJy}$      | —                            |
| SMA                   | RX230     | 1350                        | $3.13 \pm 0.36 \text{ mJy}$    | $3.13 \pm 0.36 \text{ mJy}$  |
| VLA                   | K         | 13,600                      | $55.8 \pm 7.2 \mu\text{Jy}$    | $8.4 \pm 2.7 \mu\text{Jy}$   |
|                       | X         | 30,000                      | $93.7 \pm 12.3 \mu\text{Jy}$   | $15.7 \pm 5.5 \mu\text{Jy}$  |

Table 5.1: Full list of photometry available for the SDSS1607 system, including both the total system and the blob individually. Photometry from SDSS, 2MASS, *Spitzer*, SCUBA and MAMBO are taken directly from Clements et al. (2009). For the SMA, the full flux density is attributed to the blob, and so the same flux density appears in both columns.

its successor SCUBA-2, which was known to be significantly less sensitive in the  $450\,\mu\text{m}$  band, and so we choose to remove this flux density point from the SED fit. Similarly, we remove the MAMBO flux density, as our deep SMA observations at 223 GHz provide improved constraints in a similar region of the SED. In Table 5.2 we present the modules and parameter ranges used for the SED fitting.

For the total system, we use the `sfh2exp` module, which models the star formation history as two decaying exponentials, the first representing the long-term star formation activity forming the bulk of the stellar population, and the second representing a more recent burst in star formation (Boquien et al., 2019), alongside the Bruzual and Charlot (2003) SSP libraries. The `dustatt_modified_starburst` module is used to model the attenuation from dust in the ISM, which is based on the Calzetti et al. (2000) law extended to shorter wavelengths using the Leitherer et al. (2002) attenuation curve. To model the emission from dust, we use the `d12014` module based on the theoretical models of Draine and Li (2007) and Draine et al. (2014). In this prescription, the emission from dust (modelled as a mixture of amorphous silicate/graphite grains and PAHs) is split into two contributions: diffuse dust heated by the stellar population and dust concentrated near star-forming regions (Boquien et al., 2019). The module requires the mass fraction of PAHs in the dust mixture (`qpah`), the radiation field produced by the general stellar population (`umin`) as well as the power law index (`alpha`) parameterising the variable radiation field illuminating dust in star-forming regions, and the mass fraction of dust within those star-forming regions (`gamma`) and, as such, probes a wider parameter range than other dust emission modules (Boquien et al., 2019). For the total system, we additionally know there is a quasar present, and as such we include the `fritz2006` AGN model to account for emission from this component, which models the AGN emission based on the theoretical models of Fritz et al. (2006). Rather than the empirical templates of Dale et al. (2014), the `fritz2006` module decomposes the AGN emission into three components: direct emission from the AGN, emission scattered by dust and thermal emission from dust (Boquien et al., 2019). Similarly to the `d12014` module, this theoretical AGN module therefore requires a large parameter space and is controlled by seven parameters, including the ratio of the maximum-to-minimum radius and the opening angle of the dusty torus (`r_ratio` and `opening_angle` respectively), the optical

| Module                     | Parameter          | Parameter Range         |
|----------------------------|--------------------|-------------------------|
| sfh2exp                    | tau_main [Myr]     | 100                     |
|                            | tau_burst [Myr]    | 100                     |
|                            | f_burst            | 0.01, 0.2, 0.5, 0.8,    |
|                            | age [Myr]          | 1000                    |
|                            | burst_age [Myr]    | 10, 100, 1000           |
| bc03                       | imf                | Chabrier                |
|                            | metallicity        | 0.02                    |
| nebular                    | logU               | -2.0                    |
|                            | lines_width [km/s] | 300.0                   |
| dustatt_modified_starburst | E_BV_lines         | 0.3                     |
|                            | E_BV_factor        | 0.44                    |
|                            | powerlaw_slope     | -0.5, 0.0, 0.5          |
|                            | Rv                 | 3.1                     |
| dl2014                     | qpah               | 0.47, 4.58, 7.32        |
|                            | umin               | 0.1, 1.0, 10.0, 50.0    |
|                            | alpha              | 1.0, 2.0, 3.0           |
|                            | gamma              | 0.0, 0.25, 0.5, 0.75    |
| fritz2006 <sup>†</sup>     | r_ratio            | 60.0                    |
|                            | tau                | 3.0, 6.0, 10.0          |
|                            | beta               | -0.75, -0.5, -0.25      |
|                            | gamma              | 2.0, 4.0                |
|                            | opening_angle      | 140.0                   |
|                            | psy                | 60.1, 70.1, 80.1, 89.99 |
|                            | fracAGN            | 0.3, 0.4, 0.5, 0.6      |
| radio                      | qir                | 0.5, 1.5, 2.5           |
|                            | alpha              | 0.2, 0.5, 0.8           |
| redshifting                | redshift           | 3.652                   |

<sup>†</sup> AGN module only included for total system fit.

Table 5.2: List of the modules and the main parameters (with associated parameter ranges) allowed in the full CIGALE SED fitting.

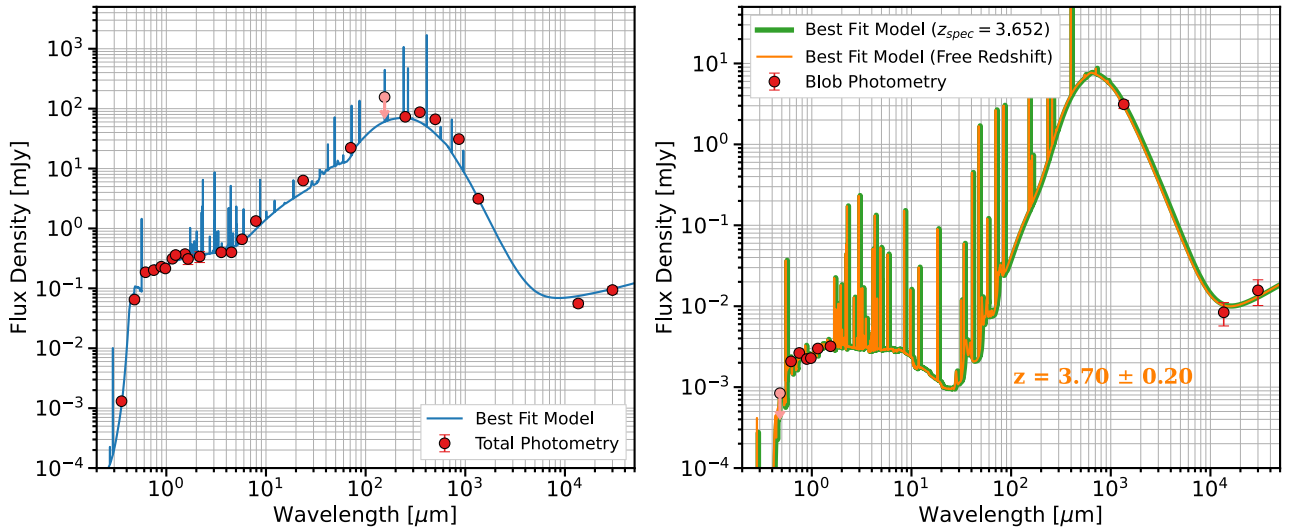


Figure 5.7: Best fitting model SEDs from **CIGALE** for the total SDSS1607 system (*left*) and for the offset blob of emission (*right*). Red points show the available multi-wavelength photometry, while the pink points show upper limits. Both sets of photometry are well fit by **CIGALE**: the total system yields a reduced chi-squared value of  $\chi^2_\nu = 4.0$  and the offset blob yields  $\chi^2_\nu \approx 0.7$ .

depth at  $9.7\ \mu\text{m}$  (**tau**), the angle between the line of sight towards the AGN and the AGN axis (**psy**) and the AGN fraction (**fracAGN**), as well as two further parameters (**beta** and **gamma**) parameterising the density distribution of dust within the torus (Boquien et al., 2019). We also make use of the **radio** module, which models the radio spectrum (assumed to be dominated by synchrotron emission at  $\lambda \approx 21\ \text{cm}$ ) based on two simple parameters, the FIR-radio correlation coefficient (**qir**) defined in Helou et al. (1985) and the power law slope **alpha** (Boquien et al., 2019). For the total system SED fitting, we fix the redshift parameter to the spectroscopic redshift of SDSS1607 while, for the blob, we complete two different SED fits, one with the SED fixed to this redshift and another with the redshift left as a free parameter. In Table 5.2, we present a full list of the modules and parameter ranges used in the **CIGALE** fitting. We note that, for the extended blob of emission, the **fritz2006** AGN module was not included, allowing us to extend the parameter ranges for the other modules to provide a better fit to the data.

In Figure 5.7 we present the best fitting SED models produced by **CIGALE** for both the total system and the offset blob of emission. For the blob, we additionally show the best fitting SED models produced when fixing the redshift to the spectroscopic redshift of the quasar, and when leaving the redshift as a free parameter. We find that, in all cases, **CIGALE** produces a good fit to the data. For the total system **CIGALE** yields a reduced chi-squared value of  $\chi^2_\nu = 4.0$ ,

while the model SEDs for the offset blob of emission benefits from much better fits, with a reduced chi-squared value of  $\chi^2_\nu \approx 0.7$  for both SED models. We additionally find that when the redshift is left as a free parameter, **CIGALE** finds a most likely redshift for the offset blob of  $z = 3.70 \pm 0.20$ , exceedingly similar to the spectroscopically confirmed redshift of  $z = 3.652$  for the quasar, indicating that the quasar and offset blob of emission are likely physically associated.

While numerous results of interest can be extracted from the **CIGALE** fits, the SDSS1607 system is complex and there is a lack of spatially resolved photometry covering the near and mid-infrared regions of the spectrum for the blob. As a result, we expect many of these results to be significantly inaccurate and/or imprecise, and so we focus only on the resulting SFRs and stellar masses of the system and the offset blob of emission. In particular, we do not attempt to extract any information from the host galaxy, primarily due to the significant difficulties in disentangling the emission from the host galaxy from that of the central engine. Based on our models, we find that the total SDSS1607 system has a SFR of  $1200 \pm 300 \text{ M}_\odot \text{ yr}^{-1}$  averaged over the past 100 Myr, and a stellar mass of  $(2.2 \pm 1.2) \times 10^{11} \text{ M}_\odot$ , while the blob has 100 Myr-averaged SFR of  $130 \pm 90 \text{ M}_\odot \text{ yr}^{-1}$  and a stellar mass of  $(3.2 \pm 4.7) \times 10^{10} \text{ M}_\odot$ , which we take to be an upper limit on the stellar mass of  $7.9 \times 10^{10} \text{ M}_\odot$ .

Based on these values of stellar mass and star formation rate, we can investigate where SDSS1607 and its components sit in relation to the star-forming main sequence at  $z = 3.65$  from Speagle et al. (2014), and to other similar systems at a range of redshifts. This is presented in Figure 5.8, where we additionally show the positions of four  $z > 6$  QSO-companion systems from Decarli et al. (2017), as well as the  $z = 4.7$  QSO-SMG system BR1202-075 (McMahon et al., 1994; Ohta et al., 1996) and the  $z = 3.8$  multiple system 4C60.07 (Greve et al., 2004; Ivison et al., 2008), both of which will be discussed in more detail in Section 5.6.3. We note that the mass estimates for BR1202-0725 and 4C60.07 are dynamical masses, rather than the stellar mass estimated for SDSS1607, and hence these values should be used as a rough guide. We find that the combined SDSS1607 system has a similar stellar mass and SFR to other comparable systems at higher redshift, excluding the 4C60.07 system, which has a much larger mass. Moreover, we find that the total system, as well as both the AGN host galaxy and the dust



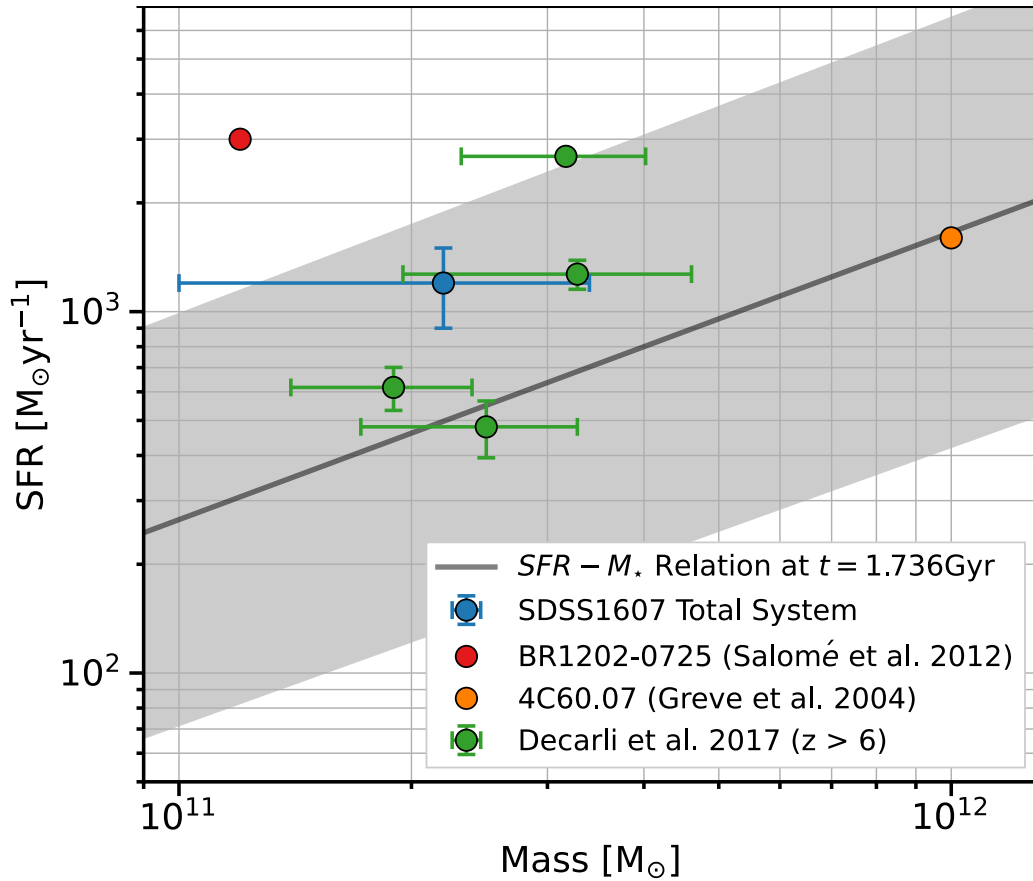


Figure 5.8: The position of the total SDSS1607 system on the SFR– $M_{\star}$  plane, alongside similar systems at a variety of redshifts. We find that SDSS1607 lies on the main sequence at  $z = 3.65$ , and has a comparable SFR and stellar mass to other systems at similar (and higher) redshifts. We note that the SFRs for BR1202-0725 and 4C60.07 are approximate estimates only, and that the masses of both are dynamical masses rather than stellar masses, and so should not be directly compared to the SDSS1607 system.

obscured blob of offset emission, are consistent with being on the main sequence at  $z = 3.65$ . These results will be discussed in more detail in Section 5.6.

## 5.5 Environment

### 5.5.1 An SMA-detected Potential Companion

In Figure 5.1, the 223 GHz SMA continuum images demonstrated that we detect a potential companion, lying  $\approx 14''$  from the SDSS1607 system. In this section, we investigate this source in more detail and discuss the likelihood that it is a true companion to the SDSS1607 system.

## Morphology

We first look for evidence of this potential companion in other bands in order to investigate its morphology. In Figure 5.9 we present cutouts of the potential companion in the five optical bands from HSC-SSP, the F110W and F160W bands from our HST observations and in the four IRAC channels. We note that this source remains undetected in the longer wavelength VLA observations, as well as in the  $J$  and  $K$  bands based on observations from the UKIDSS-UDS survey. The source is well detected in the  $3.6\,\mu\text{m}$  and  $4.5\,\mu\text{m}$  bands from the deep SERVS observations, but in the much noisier SWIRE observations, while there appears to be a source coincident in the  $8.0\,\mu\text{m}$  band, this detection is not convincing enough to appear in the catalogue. As demonstrated in Figure 5.9, the source is also not detected in the  $z$  and  $y$  band images from HSC-SSP.

The morphology of the potential companion in the HSC-SSP and HST images is clearly irregular, with multiple clumps of emission associated with the SMA detection. There additionally appear to be further clumps extending towards the lower left of the image, such that its optical morphology is much more extended than at millimetre wavelengths. Whether these extended clumps of emission that are not coincident with the SMA detection are part of the same system remains unclear. Based on its unusual morphology, we suggest that this source may be an irregular galaxy with clearly independent clumps of emission, potentially caused by some merger or tidal activity. Alternatively, it is possible that gravitational lensing could cause such an unusual morphology. The different clumps of emission appear to have quite different colours, and so it is certainly possible that the source could be comprised of a background source and a foreground lens. It remains challenging to disentangle these two cases based on our current observations.

## Photometry

The most pressing question concerning this source is whether it is a true counterpart to the SDSS1607 system. A second companion source at these high redshifts would give an indication

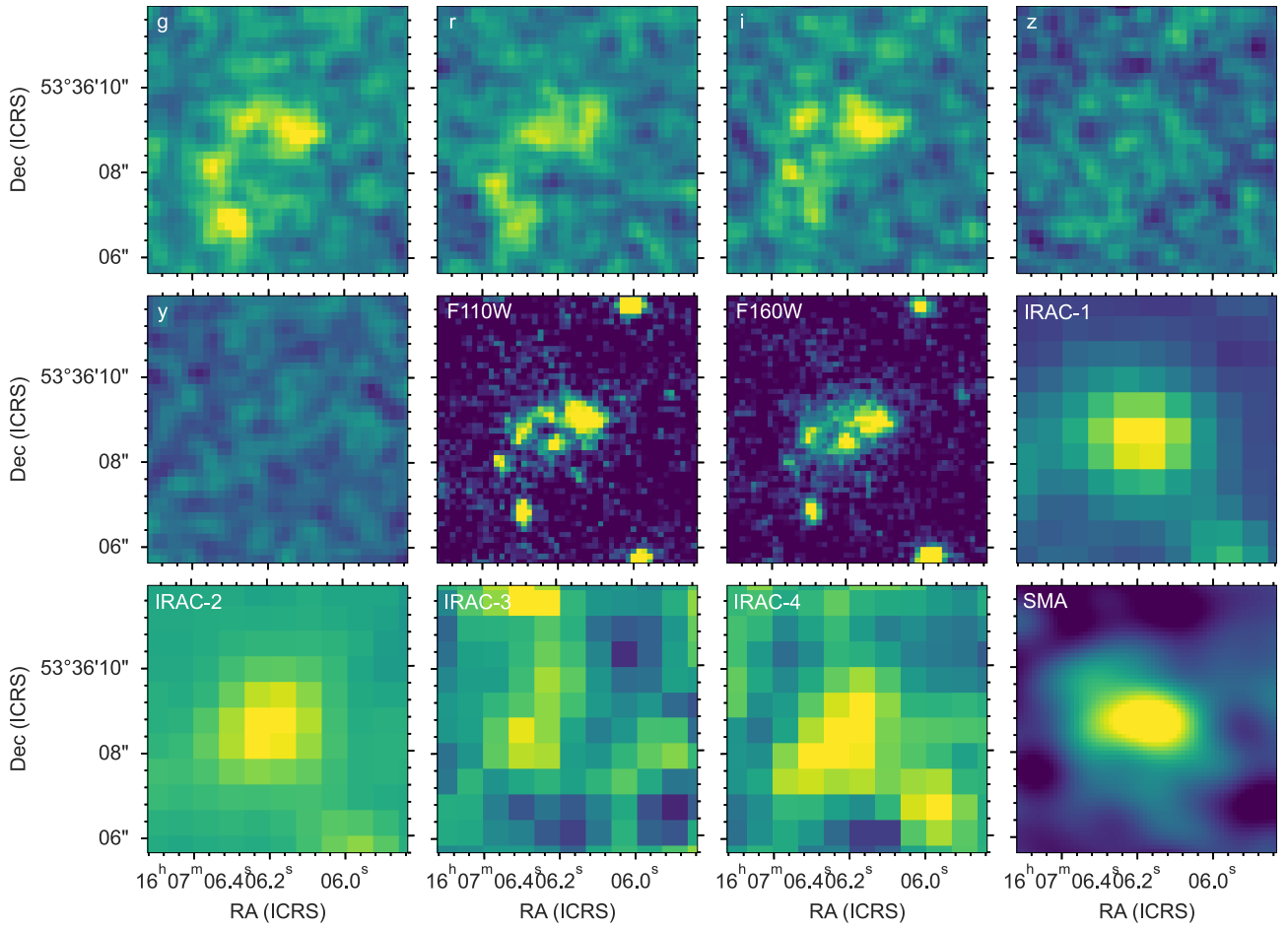


Figure 5.9: Multi-wavelength cutouts showing the irregular morphology of the potential companion to SDSS1607. This source is well detected in the  $g$ ,  $r$  and  $i$  bands from HSC-SSP, the F110W and F160W bands from our HST WFC3/IR observations, the four IRAC bands (although we note that the source is better detected in the  $3.6\,\mu\text{m}$  and  $4.5\,\mu\text{m}$  bands provided by SERVS which is somewhat deeper than the SWIRE survey) and in the sub-mm with our SMA observations. The irregular morphology is most clearly demonstrated in the HST images, where we see the source is apparently separated into numerous individual clumps of emission.

that SDSS1607 is itself part of a larger system comprising at least one other FIR luminous galaxy and extending over tens of arcseconds. In order to investigate this possibility in more detail, we assemble the optical/NIR photometry for the potential companion in the available bands and use the EAZY algorithm to obtain a photometric redshift estimate. We note that EAZY is not designed to include FIR/sub-mm and longer wavelength observations in the SED fitting process, and so we exclude the SMA photometry from this process.

To extract photometry in the F110W and F160W bands, we follow a similar process as outlined in Section 5.4.2. We first background subtract the drizzled HST images before placing an elliptical aperture in the image, which we manually inspect to ensure that it covers the irregular

| Survey/<br>Instrument | Filter   | Wavelength<br>$\mu\text{m}$ | Companion Photometry<br>$\mu\text{Jy}$ |
|-----------------------|----------|-----------------------------|----------------------------------------|
| HSC-SSP               | <i>g</i> | 0.479                       | $0.48 \pm 0.02$                        |
|                       | <i>r</i> | 0.619                       | $0.73 \pm 0.03$                        |
|                       | <i>i</i> | 0.767                       | $0.88 \pm 0.05$                        |
|                       | <i>z</i> | 0.890                       | $0.99 \pm 0.08$                        |
|                       | <i>y</i> | 0.978                       | $1.20 \pm 0.23$                        |
| HST                   | F110W    | 1.15                        | $0.88 \pm 0.03$                        |
|                       | F160W    | 1.54                        | $1.83 \pm 0.06$                        |
| <i>Spitzer</i>        | IRAC-1   | 3.56                        | $12.6 \pm 0.92$                        |
|                       | IRAC-2   | 4.50                        | $14.3 \pm 1.70$                        |
| SMA                   | RX230    | 1350                        | $1810 \pm 280$                         |

Table 5.3: Full list of photometry available for the potential companion system,. Photometry from the HSC-SSP and *Spitzer* SERVS surveys is taken directly from the catalogue, while HST and SMA photometry is obtained via aperture photometry of our observations. Note that photometry in this table is in units of  $\mu\text{Jy}$ .

morphology of the source. We note that the bright clump of emission towards the south appears to have very different colours from the more extended regions in the centre of the cutouts in Figure 5.9. We therefore assume that this clump of emission is unrelated to the potential companion source, and ensure that this region is not included within the aperture. From this aperture photometry we estimate a flux density in mJy based on the calibration information in the image header. We estimate uncertainties on this photometry by adding in quadrature the RMS noise in the image and the Poissonian error on the extracted counts.

The potential companion is detected in the catalogues of the remaining optical/NIR bands. In the HSC-SSP catalogues, the irregular nature of the source means that it is listed as two separate sources and so we combine the two to produce flux density estimates in these bands. We note that the southern clump of emission which we have considered unrelated to the system is listed as another separate source, which we do not include in the combined flux density estimate. The source is well detected and point-like in the SERVS catalogues, providing deep IRAC photometry in the  $3.6\mu\text{m}$  and  $4.5\mu\text{m}$  bands, but the source remains undetected in the longer wavelength IRAC and MIPS bands of the SWIRE survey. In Table 5.3 we present the full photometry for the potential companion source.

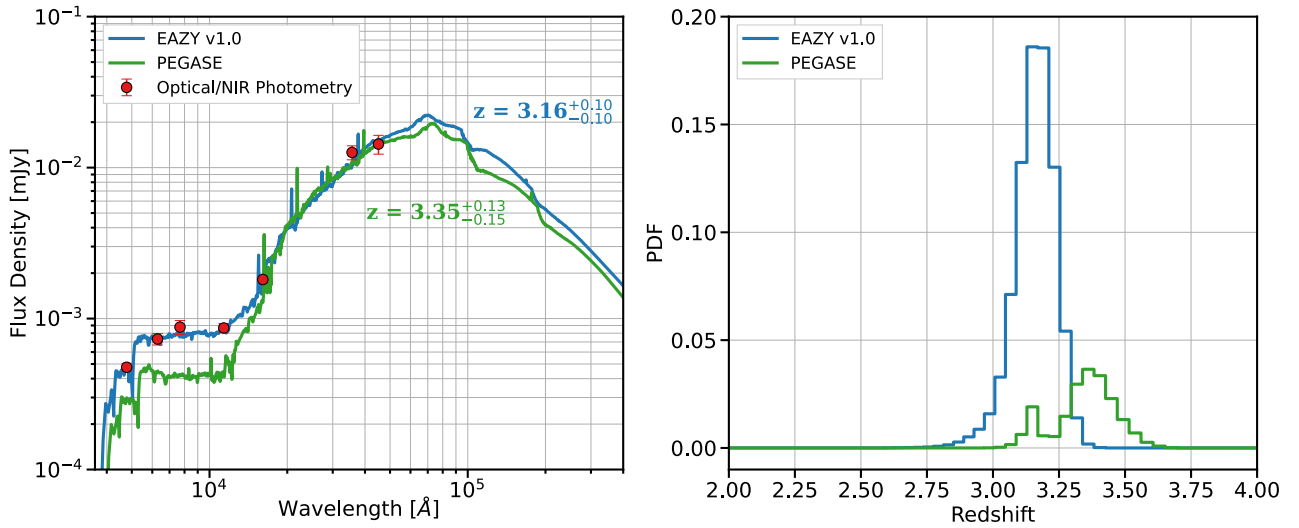


Figure 5.10: Best fitting SED models from EAZY for the available optical/NIR photometry (*left*) alongside the full photometric redshift PDFs (*right*) for both the EAZY v1.0 (blue) and PEGASE (green) template libraries. We additionally show the most likely marginalised redshift estimates from both template sets, which suggest that the potential companion lies at  $z > 3$ .

## Properties

We firstly use EAZY to estimate a photometric redshift for the companion based on our measured photometry in the optical and NIR. We use a similar method as discussed in Chapter 4, making use of both the EAZY v1.0 and PEGASE template libraries. In Figure 5.10 we show the best fitting model SEDs alongside the most likely marginalised photometric redshift estimate and the full photometric redshift PDFs for each set of templates. Both sets of templates place the potential companion at  $z > 3$ , but at a slightly lower redshift than the  $z = 3.65$  quasar. In particular, the photometric redshift PDF for the PEGASE template set shows a small overlap with  $z = 3.65$ .

We then run the full available photometry for the potential companion through CIGALE. We use a similar set of modules as listed in Table 5.2, but we exclude the `fritz2006` module, as there is no evidence of AGN activity, as well as the `radio` module, as the companion is not convincingly detected in the VLA radio images. Removing these two modules frees up computational power and, as such, we extend the parameter space probed by the `sfh2exp` and `dl2014` modules, which may help to obtain a better fit to the available photometry.

In Figure 5.11 we present the resulting best fit SED from CIGALE. The model SED fits the

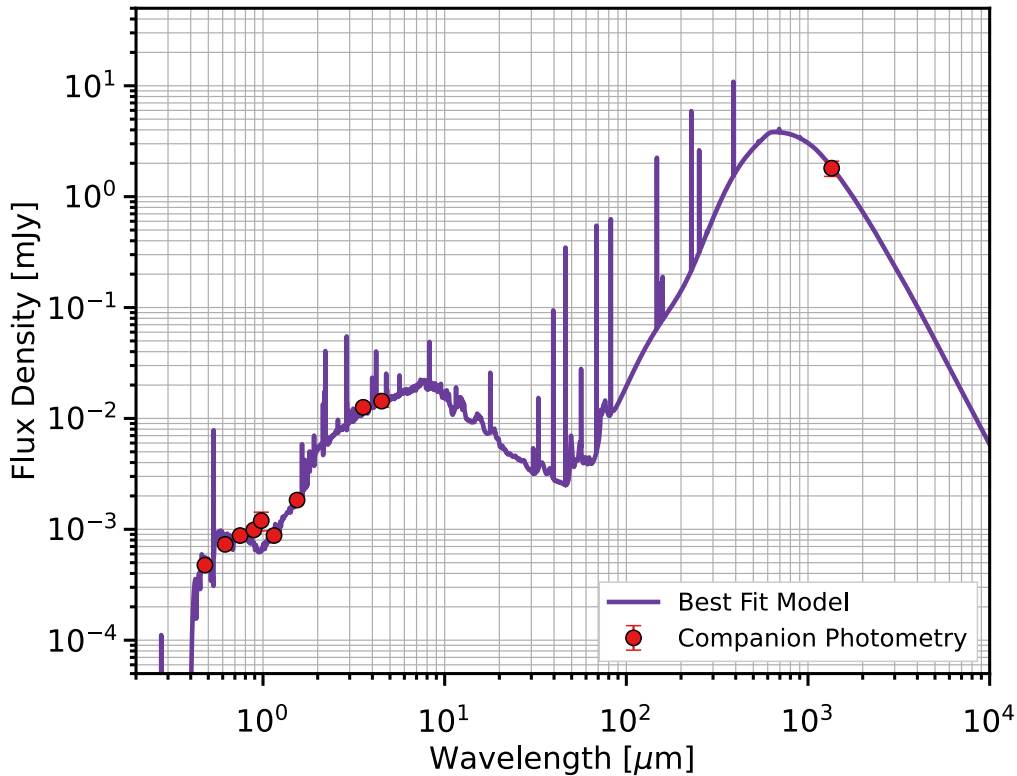


Figure 5.11: The marginalised best fit SED for the potential companion to the SDSS1607 system from **CIGALE**. The model provides an excellent fit to the available photometry, with a reduced chi-squared value of  $\chi^2_\nu = 1.4$ .

available photometry excellently, with a reduced chi-squared value of  $\chi^2_\nu = 1.4$ . **CIGALE** estimates that the potential companion has a 100 Myr averaged SFR of  $42 \pm 5 \text{ M}_\odot \text{ yr}^{-1}$  and a stellar mass of  $(2.6 \pm 0.3) \times 10^{11} \text{ M}_\odot$ , making it more massive and less star-forming than the SDSS1607 system. Interestingly, if the photometric redshift is left as a free parameter, **CIGALE** estimates a slightly higher photometric redshift of  $z = 3.51 \pm 0.14$ , consistent with the spectroscopically confirmed redshift of the SDSS1607 system. The physical interpretation of these results will be discussed in the following section.

### 5.5.2 Other Potential Candidates

We next aim to identify other potential candidates in the surrounding field. However, our ability to investigate the environment surrounding SDSS1607 for other potential companions is somewhat limited by the available data. There are no other significant detections in the SMA or VLA images in the vicinity of the *HST* images, and longer wavelength ancillary data suffers

from large beamsizes, such that intricate de-blending techniques are required to yield even reasonably accurate photometry. We are therefore limited to our *HST* observations, alongside ancillary data in the optical from HSC-SSP and in the NIR from SERVS.

For the HSC-SSP and SERVS surveys, we simply use the publicly available catalogues<sup>1314</sup>. For the *HST* images, we extract photometry from the fully reduced and drizzled images in the F110W and F160W filters (as discussed in Section 5.2.3) using the following method. First, we use **astropy** packages to estimate the background rms noise in the F110W image, followed by the **DAOSTarFinder** package from **photutils** to identify sources brighter than  $5\sigma$ . In order to ensure that our estimates for the photometry in the F110W and F160W bands are as accurate as possible, we identify sources where we see shredding, or where there are significant visible diffraction spikes, and remove them from the following analysis. We then undertake aperture photometry at the position of each source in the F110W and F160W bands using **photutils** packages. We use an aperture with a  $1''$  radius to extract a flux density in counts, using the header information in each image to convert into a flux density in Jy. We estimate an error on this value by adding in quadrature the Poissonian error on the counts, a standard 1% calibration uncertainty and the noise at the location of each source, estimated by calculating the rms value within a circular annulus from  $1''$  to  $2''$  surrounding the source.

We then crossmatch the resulting *HST*, HSC and SERVS catalogues in the vicinity of SDSS1607 to build up optical-to-NIR SEDs for each source. For the *HST* and HSC catalogues, we consider any source within  $1''$  as a good match, while for the SERVS catalogue we extend the search radius to  $2''$  to account for the slightly larger point response function of the IRAC instrument. We then aim to use **EAZY** to estimate photometric redshifts for each source based on their optical/NIR SEDs. We exclude any SED with fewer than four photometric points, as **EAZY** is not able to fit such sparsely populated SEDs. In order to estimate the best fitting model SEDs, we use the **EAZY\_v1.0** template set, as this was shown to provide a better fit to the potential companion source in the previous section. We then restrict the output of **EAZY** to only those sources where the model provides a reasonably good fit to the data, such that  $\chi^2_\nu < 10$ , and for

<sup>13</sup>[https://hsc-release.mtk.nao.ac.jp/doc/index.php/data-access\\_\\_pdr3/](https://hsc-release.mtk.nao.ac.jp/doc/index.php/data-access__pdr3/)

<sup>14</sup><http://www.mattiavaccari.net/df/pw/>

which the  $1\sigma$  error on the photometric redshift overlaps with the spectroscopically confirmed redshift of  $z = 3.652$  for SDSS1607. Through this process, we identify a second potential companion,  $\approx 26''$  from the SDSS1607 system, with a well constrained photometric redshift of  $3.50^{+0.16}_{-0.07}$ .

## 5.6 Discussion

Based on our multi-wavelength investigation, we find that the SDSS1607 system is a fascinating case study into the assembly of massive galaxies in the early Universe and the co-evolution of galaxies and their central SMBHs. Pitchford et al. (in prep) provide a thorough discussion concerning the central engine of the SDSS1607 system, and here we instead focus on the total system and the offset blob of emission, comparing them to similar sources in the literature, as well as discussing the potential companion sources.

### 5.6.1 The SDSS1607 System

Our high resolution imaging with *HST*, the SMA and the VLA have revealed that SDSS1607 is comprised of two separate components, an AGN host galaxy that is extremely luminous in the optical, near/mid- infrared and radio, and a second, heavily dust-obscured source harbouring the bulk of the emission in the FIR. This morphology is most clearly visible in the *HST* image overlaid with SMA and VLA contours in Figure 5.6, but also in the individual images in Figures 5.2 to 5.5. Spectroscopic observations from SDSS place the AGN host at  $z = 3.65$  and, while there is no spectroscopic data for the blob, the CO(4 – 3) emission line observed by Iono et al. (2012) placed the star formation at the same redshift as the quasar, and the photometric redshift estimate from CIGALE places the blob at  $z = 3.70 \pm 0.20$ . We interpret this as compelling evidence that the AGN host galaxy and the offset blob of emission are part of the same gravitationally bound system. We therefore suggest two potential explanations for this morphology.



Firstly, and possibly most likely, SDSS1607 may represent a major merger between one galaxy hosting a rapidly accreting central AGN, and another that is rich in both gas and dust. In Figure 5.8, we demonstrated that both the AGN host and the offset blob of emission have SFRs and stellar masses placing them on the star-forming main sequence relation at  $z = 3.65$ . Numerous simulations suggest that the population of massive, quiescent and extremely compact galaxies at  $z \sim 2$  may be produced by gas rich mergers at high redshifts, in which gas is driven towards the galactic centre yielding an intense starburst and a rapidly accreting central AGN (Hopkins et al., 2008; Wuyts et al., 2010; Toft et al., 2014). Given its rapidly accreting central AGN and significant ongoing star formation, SDSS1607 is a natural candidate for such a system, although it is difficult to identify at which stage of this evolution it would be placed. Has a significant stellar and black hole mass been built up from a previous merger, such that the central AGN is now working to quench ongoing star formation? And, if this is the case, is the offset blob of emission then a relic of this merger, or a separate galaxy that will eventually become a separate merging event? Or was the AGN host galaxy formed via some other mechanism, and here we are simply seeing two main sequence galaxies pre-coalescence? Additional observations will be required to investigate these possibilities further.

Alternatively, it is possible that the SDSS1607 system is an example of high-redshift, jet-induced star formation, something conclusively discovered in only a handful of objects to date (see e.g. Bicknell et al., 2000; Salomé et al., 2015). While their simulation doesn't specifically deal with jet-induced star formation outside of the galactic disk, Gaibler et al. (2012) estimate that at least  $10^9 M_{\odot}$  of disk gas, and likely significantly more, can be ejected from an AGN host galaxy while the jet is active, which could provide the fuel for the offset star formation. Bicknell et al. (2000) demonstrate that luminous star formation can be induced by an active radio jet within a few million years, well within the predicted lifetimes of such systems. Moreover, the offset blob of emission associated with SDSS1607 sits  $\approx 10$  kpc from the central engine, much closer than the examples of jet induced star formation in 3C285 and Minkowski's Object (Salomé et al., 2015). Unfortunately, we cannot currently disentangle these two interpretations, and additional spatially resolved kinematic observations probing the movement of the gas reservoir of the SDSS1607 system will be required to determine its true nature.

### 5.6.2 The Wider Environment

If the SDSS1607 system is indeed the progenitor of a massive, quiescent galaxy at  $z \sim 2$ , then observations of the surrounding environment would provide fascinating insights into the emerging structures in which such sources are thought to exist. As discussed in Section 1.4.5, while it remains unclear whether DSFGs are faithful tracers of overdense environments in the early Universe, there certainly exist examples of extremely luminous DSFGs at high redshift sitting within galaxy overdensities. This is potentially to be expected as, if these high redshift systems are indeed the progenitors of the massive ellipticals populating galaxy clusters in the local Universe, then we might expect them to populate developing protoclusters in the early Universe.

For the SDSS1607 system, there is certainly evidence for additional counterparts lying at comparable redshifts. Most convincingly, we have identified one potential companion, discovered as a separate bright source in the sub-mm imaging from the SMA, indicating that it likely hosts a significant amount of dust-obscured star formation. Indeed, subsequent SED fitting with **CIGALE** suggests this source is more massive and less star forming than the SDSS1607 system, and lies at a comparable redshift of  $z = 3.51 \pm 0.14$ . While this redshift is consistent with the spectroscopically confirmed redshift of the SDSS1607 system, we stress that the SED for this potential companion is comparably sparsely populated, with no available photometry in the  $10 - 1000 \mu\text{m}$  range, as well as a single photometric data point constraining the FIR blackbody curve. Nevertheless, the model SED constructed by **CIGALE** provides a good fit to the available photometry, and we suggest that this source makes a promising target for future follow-up observations.

Our ability to probe the surrounding environment in search of a larger structure is ultimately limited by our lack of high resolution and multi-wavelength imaging. Aside from the aforementioned potential companion, in this chapter, we have relied on model SED fitting with **EAZY**, using photometry derived from high spatial resolution optical and NIR data. This analysis has highlighted a second potential companion to the SDSS1607 system. These companions provide promising targets for future follow-up observations, aiming to investigate whether the

SDSS1607 sits within a larger scale structure at  $z = 3.65$ .

### 5.6.3 Comparison to Similar Systems

Given its high redshift, extreme luminosity throughout the electromagnetic spectrum and unusual morphology, SDSS1607 is a rare and fascinating system, regardless of whether or not it lies within a larger structure. There are, however, a handful of potentially similar systems in the literature from which we may draw comparison.

The most directly comparable system is the well studied BR1202-0725 merging galaxy system (e.g. McMahon et al., 1994; Ohta et al., 1996; Omont et al., 1996; Fontana et al., 1996; Hu et al., 1996; Petitjean et al., 1996; Benford et al., 1999; Kawabe et al., 1999; Yun et al., 2000; Carilli et al., 2002; Ohyama et al., 2004; Riechers et al., 2006; Iono et al., 2006; Leipski et al., 2010; Salomé et al., 2012; Wagg et al., 2012; Lee et al., 2019; Drake et al., 2020). The BR1202-0725 system is similarly comprised of an extremely luminous quasar (Irwin et al., 1991) and a significantly dust-obscured source (Ohta et al., 1996; Omont et al., 1996; Iono et al., 2006) offset from each other by  $\approx 3.6''$ . Subsequent observations have uncovered that BR1202-0725 is a much more complex merging system, with an additional 3 Ly $\alpha$  emitting galaxies nearby (Hu et al., 1996; Omont et al., 1996; Ohyama et al., 2004; Salomé et al., 2012; Drake et al., 2020). More recent observations with MUSE indicate a significantly extended ( $\approx 8''$ ) Ly $\alpha$  halo with high velocity winds associated with the QSO, while ALMA observations indicate a potential bridge in [CII] connecting the QSO and the dust-obscured companion (Drake et al., 2020). The combined morphological and kinematic observations across the electromagnetic spectrum rule out that the source is lensed, and rather indicate that BR1202-0725 is a system of merging galaxies, with the merging activity and tidal interactions triggering significant starbursts in the member galaxies (Salomé et al., 2012; Drake et al., 2020).

Alternatively, we can compare SDSS1607 to the multiple QSO-SMG systems at  $z > 6$  identified by Decarli et al. (2017) which, although they lie at higher redshift than SDSS1607, display similar morphological features and extreme luminosities. Two of these systems show a companion source detected in [CII]  $\approx 50$  kpc from the central quasar, while the other two show smaller

QSO-SMG separations, with one companion in particular displaying a particularly extended [CII] morphology, likely indicative of significant tidal disruption within the system (Decarli et al., 2017). The dynamical masses estimated for the companions are  $\sim 1 - 3 \times 10^{11} M_{\odot}$ , around an order of magnitude larger than the stellar mass estimated for the blob of offset emission in SDSS1607 suggesting that, while this is not a direct comparison, the offset blob is significantly less massive than the companions to the QSOs in Decarli et al. (2017).

Finally, we may compare SDSS1607 to the high redshift radio galaxy (HzRG) 4C60.07 at  $z = 3.8$ . This system is somewhat more complex, comprised of the HzRG and two additional bright sub-mm sources, one thought to be a gas-rich starburst with an associated dust-reddened AGN, and the other a plume of cold gas and dust, potentially a result of the tidal interactions in the system (Ivison et al., 2008). Greve et al. (2004) calculate a SFR of  $\sim 1600 M_{\odot} \text{yr}^{-1}$  for 4C60.07 based on its FIR luminosity, as well as estimating a dynamical mass comparable to massive ellipticals in the local Universe. Moreover, observations of the CO(1 – 0) transition indicate that 4C60.07 has a significant molecular gas reservoir, such that it may be able to sustain this prodigious SFR for 100 Myr (Greve et al., 2004). These observations therefore suggest that 4C60.07 is also a complex merger system, likely caught in its formative stages, that is the progenitor of a massive elliptical galaxy at  $z = 0$ .

Based on the nature of these similar systems, we suggest that SDSS1607 is most likely an example of a high redshift merger between an AGN host galaxy, and a gas and dust rich counterpart, that may itself sit within a larger and more complex structure. However, additional observations will be required to determine the validity of this hypothesis.

## 5.7 Conclusions

In this chapter, we have used multi-wavelength observations to constrain the nature of the SDSS1607 system at  $z = 3.652$ . Prior observations identified this source as an extremely luminous AGN with broad quasar lines, with subsequent observations in the FIR/mm placing the source securely as an HLRG, comprised of an AGN component and a starburst component

with a  $\text{SFR} > 2000 \text{ M}_{\odot}\text{yr}^{-1}$ . Our program of multi-wavelength follow-up observations included mm and radio interferometry with the SMA and VLA, as well as high resolution optical/NIR imaging with *HST*. We further leveraged additional multi-wavelength imaging and photometry from numerous publicly available surveys, from the optical through to the FIR.

For the *HST* observations, we test numerous PSF subtractions based on different models. By considering the extent to which these different PSF models successfully subtract the diffuse halo and diffraction spikes, we find that the theoretical **Tiny Tim** PSF model performs the worst, while the empirical PSF model based on our own *HST* observations performs the best. We do note, however, that significant residuals are left by all subtractions.

Our multi-wavelength observations suggest that SDSS1607 has an unusual morphology. The quasar dominates the luminosity in the optical/NIR in the *HST* images, and is coincident with the bright radio source in the VLA images. The bright FIR/mm source in the SMA images, however, is offset from the position of the quasar, and is instead centred on a small, offset blob of emission in the *HST* imaging,  $\approx 1.4''$  from the quasar centre. The offset blob of emission is extended by  $\approx 1''$  and is oriented perpendicular to a line connecting the quasar and the blob. The bright FIR/mm source is somewhat more extended ( $\approx 4''$ ) and overlapping slightly with the quasar centre.

We assembled 27-band photometry for the total SDSS1607 system, as well as 10-band photometry for the offset blob of emission, and used the photometric SED fitting code **CIGALE** to investigate the properties of these two components. The model SEDs estimated by **CIGALE** prove to be an excellent fit to the data for both the total system and the offset blob of emission, with reduced chi-squared values of  $\chi^2_{\nu} = 4.0$  and  $\chi^2_{\nu} = 0.7$  respectively. We find that the total SDSS1607 system has a SFR of  $1200 \pm 300 \text{ M}_{\odot}\text{yr}^{-1}$  averaged over the past 100 Myr, and a stellar mass of  $(2.2 \pm 1.2) \times 10^{11} \text{ M}_{\odot}$ , while the offset blob has a 100 Myr-averaged SFR of  $130 \pm 90 \text{ M}_{\odot}\text{yr}^{-1}$  and a stellar mass of  $(3.2 \pm 4.7) \times 10^{10} \text{ M}_{\odot}$ , which we take to be an upper limit on the stellar mass of  $7.9 \times 10^{10} \text{ M}_{\odot}$ . These values place both the total SDSS1607 system and the offset blob of emission on the star-forming main sequence at  $z = 3.652$ . Moreover, **CIGALE** estimates a photometric redshift of  $z = 3.70 \pm 0.20$  for the offset blob of emission, consistent

with the spectroscopically confirmed redshift of the quasar.

We additionally use the available observations to explore galaxies in the surrounding field and to determine the environment in which SDSS1607 sits. We identify another bright, potential companion in the SMA observations,  $\approx 14''$  from the centre of the SDSS1607 system. This source is also detected in the optical and NIR, and displays an irregular morphology, with multiple resolved clumps of emission associated with the SMA detection. We build up 8-band photometry for this potential companion, and estimate its properties with **EAZY** and **CIGALE**. These algorithms estimate a photometric redshift of  $z \sim 3.1 - 3.6$  for this potential companion, placing it roughly in the vicinity of the SDSS1607 system. We additionally use **CIGALE** to investigate the properties of this potential companion, finding that it is more massive and less star forming than SDSS1607, with a 100 Myr averaged SFR of  $42 \pm 5 \text{ M}_{\odot} \text{ yr}^{-1}$  and a stellar mass of  $(2.6 \pm 0.3) \times 10^{11} \text{ M}_{\odot}$ . A second potential counterpart is detected in the available *HST*, HSC and *Spitzer* SERVS maps, with **EAZY** placing this source at  $3.50^{+0.16}_{-0.07}$ . These sources make promising targets for future follow-up observations in the surrounding field.

Based on this analysis, and comparing SDSS1607 to similar sources in the literature such as BR1202-0725, 4C60.07 and the high redshift QSO-SMG systems identified by Decarli et al. (2017), we suggest that this system is most likely a high redshift merger between an AGN host galaxy and a second counterpart rich in both gas and dust. We further suggest that SDSS1607 may itself sit within a more complex structure comprised of multiple galaxies. Alternatively, it is possible that SDSS1607 represents an example of jet-induced star formation at high redshift.

Additional follow-up observations will be required to disentangle these two interpretations. First and foremost, spatially resolved, kinematic observations describing the motion of gas within the system will be vital in determining whether this system is a merger or an example of jet-induced star formation. Further spectroscopic observations in the surrounding field will also allow us to determine whether SDSS1607 sits within a larger overdensity of galaxies at high redshift.

# Chapter 6

## Conclusion

### 6.1 Summary of Thesis Achievements

This thesis aimed to investigate the properties of Dusty Star-Forming Galaxies and the structures in which they are found, building on over three decades of intense research that has seen a significant progression in our understanding of these systems. In particular, as well as focussing on individual case studies of interesting DSFGs, in this thesis we have studied the multiplicities and properties of candidate high redshift DSFG systems, and characterised the environments in which DSFGs are found and how they evolve over time based on the populations of galaxies within clusters at different stages in their evolution.

In Chapter 2 we used CO(2–1) observations to trace the molecular gas reservoirs in the members of the nearby Antlia galaxy cluster, from which we aimed to investigate how the observed high SFRs in disturbed cluster environments are fuelled. Such disturbed galaxy clusters at low redshift could prove to be useful analogues of the high redshift, rapidly evolving protoclusters which may contain early populations of DSFGs. We found that the member galaxies of the Antlia cluster have comparable molecular gas reservoirs to their counterparts in the field with similar stellar masses and SFRs, indicating that galaxies within disturbed cluster environments are able to retain their reservoirs of molecular gas. These large molecular gas reservoirs can, in turn, fuel high SFRs in the cluster members. These results indicate that the Antlia cluster is

in an intermediate evolutionary state, in which the ICM is not yet harsh enough to strip the member galaxies of their molecular gas reservoirs, as is commonly seen in more dynamically evolved local clusters.

In Chapter 3, we presented FIR/sub-mm follow-up observations of four  $500\ \mu\text{m}$  risers identified from *Herschel* SPIRE observations as part of the HerMES survey. These  $500\ \mu\text{m}$  riser sources were previously targeted with the SMA in Greenslade et al. (2020), but no counterparts were found, potentially indicating that these were systems of multiple DSFGs distant enough from each other to be resolved in their SMA observations and too faint to be detected individually, but close enough to be blended within the *Herschel* SPIRE beam. Based on deeper SMA observations, we identified that three of these  $500\ \mu\text{m}$  risers resolve into multiple components, with comparisons to simulations suggesting that the population of  $500\ \mu\text{m}$  risers may be more diverse than expected. Simple FIR/sub-mm SED modelling indicated that these systems likely lie at  $z \geq 2$ , with inferred total SFRs of  $\sim 800 - 2000\ \text{M}_{\odot}\text{yr}^{-1}$ , and have had their *Herschel* SPIRE colours artificially reddened by the effects of blending. We additionally found, based on cumulative number counts in the SCUBA-2  $850\ \mu\text{m}$  maps, that three of these systems lie in regions plausibly overdense in bright ( $\gtrsim 8\ \text{mJy}$ ) SMGs, making them candidate protoclusters at  $z > 2$ .

In Chapter 4, we used multi-wavelength photometry to investigate how star formation proceeds within  $\approx 15\ \text{Mpc}$  of the massive,  $z \sim 1.6$  galaxy cluster SpARCS-0330. Modelling the multi-wavelength SEDs of the candidate cluster members with EAZY and CIGALE, we found typical properties of  $\text{SFR} \sim 10^{0.8}\ \text{M}_{\odot}\text{yr}^{-1}$  and  $M_{\star} \sim 10^{10}\ \text{M}_{\odot}$ , resulting in typical sSFRs of  $\sim 10^{-9}\ \text{yr}^{-1}$  and placing the majority of candidate cluster members on the star-forming main sequence at  $z \sim 1.6$ . We estimated the quenched fraction in the sample using two different methods, finding a strong correlation with stellar mass (with the fraction of quenched galaxies increasing from  $\sim 5 - 10\%$  in lower mass ( $M_{\star} < 10^{9.7}\ \text{M}_{\odot}$ ) galaxies to  $\sim 60 - 70\%$  in more massive ( $M_{\star} > 10^{10.1}\ \text{M}_{\odot}$ ) galaxies) and a somewhat weaker correlation with cluster-centric radius (falling from  $\approx 50 - 60\%$  within  $500\ \text{kpc}$  of the cluster centre to  $\approx 20 - 30\%$  at cluster centric radii of  $\sim 3\ \text{Mpc}$ ). We inferred that quenching in SpARCS-0330 is dominated by secular processes that scale with stellar mass, rather than environmental processes such as hydrodynamical stripping. This is



consistent with previous studies in the literature, which suggest that the quenching efficiency of clusters decreases significantly towards higher redshifts.

In Chapter 5, we investigated the nature of the SDSS1607 system, which includes both active star formation and a broad line quasar at  $z = 3.65$ , based on NIR observations with *HST* alongside FIR/sub-mm and radio observations with the SMA and VLA. This system has an unusual morphology, comprised of a central quasar that dominates the optical, NIR and radio emission, as well as a bright FIR/mm source in the SMA images, offset from the position of the quasar by  $\approx 1.4''$  and centred on a small, extended blob of emission in the *HST* imaging. We estimated a SFR for the total system of  $1200 \pm 300 \text{ M}_{\odot}\text{yr}^{-1}$  averaged over the past 100 Myr, and a stellar mass of  $(2.2 \pm 1.2) \times 10^{11} \text{ M}_{\odot}$ . The offset blob has a 100 Myr-averaged SFR of  $130 \pm 90 \text{ M}_{\odot}\text{yr}^{-1}$ , and we placed an upper limit on the stellar mass of  $7.9 \times 10^{10} \text{ M}_{\odot}$ . We additionally identified a potential companion in the SMA maps  $\approx 14''$  from the centre of the SDSS1607 system and likely lying at  $z \sim 3.1 - 3.6$  based on SED fitting with CIGALE, as well as a second candidate companion estimated to lie at  $z = 3.50^{+0.16}_{-0.07}$  based on SED fitting with EAZY to the available optical/NIR data, hinting that the system may lie in a rich cluster environment.

## 6.2 Future Work

### 6.2.1 The Evolution of Protoclusters and Galaxy Clusters

Much of this thesis has focussed on the evolution of the environments in which DSFGs are found, from protocluster candidates at high redshift (and their potential analogues more locally) to massive galaxy clusters at more moderate redshifts, opening up numerous avenues for future research.

From our work in Chapter 4 on the SpARCS-0330 cluster, spectroscopic redshifts will be required for sources in our photo-z and photo-z wide samples in order to fully confirm our conclusions and to identify the true cluster members. Additionally, deeper photometry in the wider field would allow us to determine if we have missed a significant population of fainter and

likely quiescent galaxies in the surrounding environment. While the less effective quenching in  $z \sim 1.6$  clusters is becoming reasonably well established, the physical drivers behind this relation are not yet clear. Spatial and kinematic observations of the molecular gas reservoirs in these galaxies would shed some light on the dominant quenching mechanisms within the cluster, from which we could look for evidence of hydrodynamical stripping (e.g. tails of gas trailing accreted galaxies, disturbed molecular gas reservoirs etc.). Additionally, future work could focus on constraining the time since these galaxies were accreted into the SpARCS-0330 cluster (either through comparison with simulations or modelling of their star formation histories), which could allow us to infer whether the reason for the ineffective quenching is simply that the galaxies have not been present in the cluster for long enough. Moreover, we note that SpARCS-0330 is the most massive of the four clusters studied in Nantais et al. (2016), so a similar analysis for the remaining three clusters would provide some more robust statistics for these structures.

Chapter 3 additionally highlighted that Bootes27 is a particularly interesting source that would benefit from future follow-up observations. Evidence suggests that this system is likely comprised of multiple sources, the majority of which remain undetected in our high resolution SMA observations. In particular, the SCUBA-2 observations at  $850\,\mu\text{m}$  show two partially resolved sources. One of these partially resolved sources has no apparent SMA counterpart, and the other is much brighter at  $850\,\mu\text{m}$  than the single detected SMA source at  $870\,\mu\text{m}$ . As such, it is likely that there are least another two sources associated with this system that remain undetected in our current set of observations. Deep ancillary data from *Spitzer* SERVS have revealed that this source could be a blend of as many as seven individual sources, although a simple SED fitting suggests that it is unlikely that all of these are physically associated. However, it remains possible that Bootes27 could represent an example of a high redshift protocluster comprised of a number of FIR-luminous DSFGs. Future work will therefore likely consist of deeper, high resolution FIR/sub-mm observations aiming to detect any further sub-mm bright counterparts that remained undetected in our SMA observations, as well as multi-object spectroscopy of the IRAC sources associated with Bootes27 to determine whether or not they are physically associated within a larger structure.

### 6.2.2 The Multiplicities of Sub-mm Faint $500\ \mu\text{m}$ Risers

Based on their SMA follow-up observations of 34  $500\ \mu\text{m}$  risers selected from the HerMES survey, Greenslade et al. (2020) suggested that the population of  $500\ \mu\text{m}$  risers is likely diverse, with many more multiple systems than predicted by simulations such as those carried out by Béthermin et al. (2017). However, this conclusion was based on the assumption that the ten  $500\ \mu\text{m}$  risers that remained undetected in their SMA follow-up observations are multiple systems, individually lying below their detection threshold, but lying close enough together to be blended into one bright source in the larger *Herschel* SPIRE beamsizes. Our deeper SMA and SCUBA-2 follow-up observations of four of these sources found that three are indeed comprised of multiple sources, with the fourth resolving into a single faint source. While these results corroborate the findings of Greenslade et al. (2020), we note that this study focussed on only a small sample, such that the multiplicity of faint  $500\ \mu\text{m}$  risers, while higher than expected, could still be less than  $\sim 60\%$ . In order to obtain a more robust estimate of the multiplicities of  $500\ \mu\text{m}$  risers, similar deep, high resolution observations of the remaining six sources that were undetected in the SMA observations of Greenslade et al. (2020) should be carried out. We note that our SMA observations targeted the brightest undetected sources from Greenslade et al. (2020) at  $500\ \mu\text{m}$  and, while we achieved significantly improved sensitivities, we may not have recovered all of the sources associated with the  $500\ \mu\text{m}$  risers, particularly in the case of Bootes27. High resolution observations of the remaining six, even fainter sources should therefore aim to reach improved depths. While this problem will be somewhat eased by improvements to the SMA SWARM correlator, which is now able to reach up to 48 GHz of instantaneous bandwidth, it is unclear whether the SMA will be able to reach the sensitivities required for such observations in the near future. NOEMA may therefore provide a more realistic alternative for these future observations.

### 6.2.3 The SDSS1607 System

Our current set of data for the SDSS1607 system were unable to distinguish between the two possible interpretations concerning its nature: an example of high redshift, jet induced star

formation, or a merger between an AGN host galaxy and a second counterpart rich in both gas and dust. Such a distinction could be reasonably simply made using spatially resolved, kinematic observations, which would uncover the motion of the gas associated with the system. We attempted such an investigation with our SMA observations, but no real conclusions could be drawn from the resulting spectra due to a combination of poor weather and corrupted data, especially considering that we were already pushing the limits of the capabilities of the SMA in terms of its wavelength coverage and sensitivity. Given its position in the Northern sky, NOEMA would seem the only viable instrument to carry out such observations in the future.

### 6.3 Concluding Remarks

In the last 30 years there has been a dramatic improvement in our understanding of the nature of DSFGs and their importance in galaxy formation and evolution. We have come to understand that while the majority of light produced by star formation in the Universe is emitted in the UV and optical, around half of this light is absorbed and reprocessed into the infrared by dust within DSFGs. These galaxies can harbour star formation rates of thousands of solar masses per year, making a significant contribution to the cosmic star formation rate density, particularly at  $z > 2$  where they are significantly more common than first theorised. More recently, it has been postulated that these systems represent a single stage in galaxy evolution, and will eventually evolve into the massive, quiescent ellipticals that preferentially lie within dynamically evolved galaxy clusters in the local Universe. However, observing these objects is challenging, with the large beamsizes of FIR instruments making it difficult to distinguish between bright and individual DSFGs at high redshifts, and blends of multiple, fainter DSFGs at more intermediate redshifts. As such, there remain numerous areas in which our understanding of DSFGs is less complete, such as their total contribution to the cosmic star formation rate density, the primary mechanisms that form them and drive their observed high SFRs, and the environments in which they may preferentially form and evolve. Moreover, these questions become significantly more difficult to answer as we push to higher redshifts, regions that we must probe to better understand the formation of these systems, but in which observations

become significantly more challenging. At the time of writing, the first images and results are beginning to emerge from the recently launched James Webb Space Telescope which, along with ground based instruments such as the SMA, SCUBA-2 and ALMA, and archival data from previous space-based observatories such as *Herschel* and *Spitzer*, will likely provide the basis for future research into the nature of DSFGs.



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