Dusty Star Formation in Extreme Environments: Galaxies and Galaxy Clusters in the Distant Universe

Stacey Alberts
University of Massachusetts - Amherst

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DUSTY STAR FORMATION IN EXTREME ENVIRONMENTS: GALAXIES AND GALAXY CLUSTERS IN THE DISTANT UNIVERSE

A Dissertation Presented

by

STACEY L. ALBERTS

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

September 2014

Department of Astronomy
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To my parents, Anita and Michael, for all their love and support, and to my loving husband Andrew.
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ABSTRACT

DUSTY STAR FORMATION IN EXTREME ENVIRONMENTS: GALAXIES AND GALAXY CLUSTERS IN THE DISTANT UNIVERSE

SEPTEMBER 2014

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Directed by: Professor Alexandra Pope

In this thesis, we present a comprehensive study of the dust-obsured star formation (SF) activity in galaxy clusters out to high redshift using infrared (IR) imaging. Using hundreds of galaxy clusters and wide-field far-IR imaging across nine square degrees, we quantify the average star formation rates (SFRs) out to the distant Universe for mass-limited cluster galaxy samples using stacking. We compare the evolution of this SF activity to field galaxies, finding that the evolution in clusters occurs more rapidly than in the field and clusters have field-like SF approximately nine billion years ago, during an epoch before SF quenching becomes effective in massive clusters.

Building on this result, we present new, deep far-IR imaging of 11 spectroscopically-confirmed clusters at high redshift, which allows us to examine the SFRs of individual IR-luminous cluster galaxies as a function of environment. We find a transition from field-like SF to quenching of IR-luminous galaxies in the cluster cores over the redshift range probed. We present the first UV-to-far-IR spectral energy distributions (SEDs)
of high redshift cluster galaxies, quantify the cluster-to-cluster variations in SF properties, and compare cluster galaxies to star forming galaxies in the field. In addition, we examine the SEDs of cluster galaxies with measurable emission from black hole accretion and quantify the fraction of these galaxies as a function of environment and redshift, finding an excess at high redshift in the cluster cores. Lastly, we compare dust-obscured SFRs from far-IR to unobscured SFRs from optical emission lines.

In the last section, we present new submillimeter imaging of a massive cluster in the distant Universe. We characterize the FIR/submillimeter SED of IR-luminous cluster galaxies, finding dust temperatures similar to that in field galaxies in the same epoch. We use imaging of dust emission in the optically thin regime to derive the interstellar medium (ISM) masses of cluster galaxies. Through this analysis, we determine that IR-luminous cluster galaxies at high redshift have comparable ISM masses, gas fractions, and gas depletion timescales as field galaxies.
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One of the main challenges being addressed by modern astronomy and cosmology is the build up of structure over cosmic time, as the baryon content of the Universe develops from an almost perfectly uniform distribution as observed in the Cosmic Microwave Background (CMB; Penzias & Wilson, 1965; Bennet et al., 2013) to a collection of discrete galaxies inhabiting the varied environments - voids, filaments, groups, clusters - which make up the large scale structure (LSS) of the Universe. The evolution of galaxies (e.g. Giavalisco, 2002; Renzini et al., 2006; Shapley, 2011; Silk & Mamon, 2012), driven internally by processes such as star formation, is almost certainly tied to the surrounding environment; however, a coherent and complete description connecting evolution on the scales of galaxies to the large-scale environment remains elusive. One approach, facilitated by modern observations, is to trace galaxy properties in the most extreme environments, massive galaxy clusters, across cosmic time. Following this approach, we can then begin to place galaxies within the paradigm of modern astronomy by addressing the following fundamental questions:

- How do the properties of galaxies in the largest bound structures - galaxy clusters - compare to galaxies not in clusters, referred to as field galaxies, as a function of cosmic time?

- How do potential internal drivers of galaxy evolution - such as star formation (SF), gas content, and the growth of black holes - depend on the surrounding environment?
• What processes shape galaxy properties in galaxy clusters, leading to the different distribution of galaxy types across environment as seen in the local Universe?

• At what epoch do galaxies in clusters assemble the bulk of their baryonic mass and what are the implications for galaxy evolution in overdense environments?

Answering these questions provides a framework to address the full range of effects of environment across all LSS and across cosmic time, connecting the growth of structure in the early Universe to the distinct populations we see today.

1.1 Galaxies in the Local Universe

Studies of galaxy properties such as stellar mass, color, and morphology in the local Universe have revealed that galaxies can be roughly divided into three galaxy types that make up the Hubble Sequence (Hubble, 1926; de Vaucouleurs, 1959). Disk, or late-type, galaxies are characterized by well-defined spiral structure and typically host a mixture of young, newly formed stars and cold molecular gas primarily found in the disk as well as an old stellar population, which tends to be concentrated in a central bulge (see review by Kennicutt, 1998). Early-type (elliptical or lenticular) galaxies are well characterized by their lack of ongoing star formation and relative dearth of cold gas. Though ellipticals do not dominate galaxy number counts, they tend to represent the most massive systems locally, indicating that they underwent intense star formation and mass build-up during an earlier epoch (see review by Renzini et al., 2006). Finally, irregular galaxies make up the remaining systems, displaying no coherent structure.

In the standard cosmological model, hierarchical structure formation begins with small density perturbations in the early Universe and, through the influence of gravity, structures form from the “bottom-up” (Larson et al., 1969; Press & Schechter, 1974). This process is primarily based on the amalgamation of cold dark matter particles
(e.g. Peebles, 1982), which eventually combine to form the dark matter haloes which host baryonic components such as stars, gas, and galaxies, and eventually galaxy groups and clusters. This model of structure formation would seem to suggest that the Hubble Sequence is in fact an evolutionary track, with the most massive elliptical galaxies forming through the mergers of less massive disk galaxies. The merging of two gas-rich disks can produce a short period of intense star formation which can build up stellar mass (e.g. Barnes et al., 1991, 1992; Genzel et al., 1998; Narayanan et al., 2010); however, this track has not been observed as the most prominent mode of local galaxy evolution. Only one local population, (Ultra-)Luminous Infrared Galaxies ((U)LIRGs; Soifer et al., 1987), are observationally connected to the signatures of major mergers (see Sanders & Mirabel, 1996, for a review). LIRGs (ULIRGs) are characterized by high total infrared luminosities ($L_{\text{IR}} = L[8 - 1000\mu\text{m}]$) of greater than $10^{11} L_\odot$ ($10^{12} L_\odot$) and thus high star formation rates (SFRs), however, (U)LIRGs are relatively rare compared to Milky Way-type systems at $z \sim 0$ and are thought not to contribute significantly to the local star formation rate density (SFRD) (e.g. Le Floc’h et al., 2005). LIRGs and ULIRGs are more common at high redshift; however, the connection between this high redshift population and its local counterpart remains unclear, leaving open the question of what processes dominate galaxy evolution across cosmic time.

1.2 Star Formation and Active Galactic Nuclei in Galaxies

In the very early Universe, the evolution of matter is dominated by the physics associated with dark matter, which has been extensively and accurately modeled with detailed simulations (e.g. Moore et al., 1999; Springel et al., 2005, 2008; Diemand et al., 2008; Klypin et al., 2011). As structures form, however, processes involving baryonic physics become important, creating a complicated picture of star formation, chemical enrichment, feedback, inflows, outflows, and other regulatory processes.
which govern the evolution of the galaxies within dark matter haloes. In particular, the process of star formation, the conversion of cold, molecular gas to stars, is a direct probe of the evolutionary history of a galaxies. Together with stellar mass, the star formation rate is a fundamental process describing galaxies.

Star formation can be observed in galaxies through several different SFR indicators ranging from X-ray to infrared/submillimeter emission (see reviews by Kennicutt, 1998; Kennicutt & Evans, 2012; Calzetti et al., 2012; Madau & Dickinson, 2014). Young, massive stars emit strongly in the ultraviolet (UV) and optical emission lines, providing a direct probe of recent star formation as these massive stars have short lifetimes \((\lesssim 10 \text{ Myr})\). In galaxies containing significant amounts of dust, however, this emission can be attenuated as the high energy photons are absorbed by dust and re-radiated at longer wavelengths, in the mid- and far-infrared. This dust attenuation can render entire galaxy populations invisible in the traditional UV and optical surveys, as discovered in 1983 by the Infrared Astronomical Satellite (IRAS; Neugebauer et al., 1984), which revealed the obscured star formation of previously unknown galaxies through an all sky infrared survey (Saunders et al., 1990). Later observations by the Cosmic Background Explorer (COBE; Mather et al., 1990) first mapped the cosmic infrared background (CIB; Puget et al., 1996; Hauser et al., 1998; Fixsen et al., 1998), revealing that the total integrated infrared background of the Universe is roughly equal to the optical background.

Following on this result, recent studies have quantified the integrated star formation rate density of the Universe out to high redshift (Figure 1.1; Le Floc’h et al., 2005; Magnelli et al., 2009; Elbaz et al., 2011; Murphy et al., 2011a; Reddy et al., 2012) and firmly established the importance of the dust-enshrouded star formation component, which dominates the star formation energy budget of galaxies at \(z \sim 1 – 3\) (\(\sim 8 – 11\) billion years ago). This epoch coincides with the peak in the star formation density of the Universe, during which about half of the stars in the present day Universe form
at characteristic SFRs of tens to hundreds of solar masses per year (e.g. Reddy et al., 2008; Shapley, 2011), highlighting the importance of LIRG and ULIRG populations during the epoch of mass build-up in galaxies. A complete and accurate census of star formation during this epoch of galaxy assembly, then, requires infrared observations and a detailed understanding of the portion of the galaxy spectral energy distribution (SED) dominated by dust emission, from which dust-obscured SFR can be measured.

![Figure 1.1](image.png)

**Figure 1.1** The total infrared luminosity density coming from star formation as a function of redshift (Murphy et al., 2011a). The open stars show the total for all galaxies, corrected for completeness. Also shown are low-luminosity infrared galaxies (diamonds), LIRGs (squares), and ULIRGs (triangles). At high redshift, LIRGs and ULIRGs become increasingly important to the total SFRD of the Universe. Figure is adapted from Murphy et al. (2011a).

The efficiency of star formation is likely, at least in part, regulated by feedback, from processes such as supernova, stellar winds (e.g. Ceverino & Klypin, 2009), or the activity of active galactic nuclei (e.g. Di Matteo et al., 2005; Schawinski et al., 2006). In the local Universe, black holes are now considered a ubiquitous feature in massive
galaxies ($\gtrsim 10^{11} M_\odot$; Alexander & Hickox, 2012), with a tight correlation between black hole mass and the velocity dispersion of the host galaxy’s bulge (Ferrarese & Merritt, 2000; Gebhardt et al., 2000). Black holes that are actively accreting matter, known as Active Galactic Nuclei (AGN), are indirectly connected to star formation in that they are both predominately driven by a galaxy’s cold gas supply, however, the direct relation between these two processes remains unclear (see Alexander & Hickox, 2012, for a review). The orders of magnitude differences in the physical scales on which SF and AGN operate, plus the time variability of AGN (see Hickox et al., 2014), make establishing a causal link between SF and AGN challenging. Recent observations have found a strong correlation between the cosmic average black hole growth rate and star formation, with both processes peaking at $z \sim 2$ (Chen et al., 2013; Hickox et al., 2014; Delvecchio et al., 2014). Simulations have long predicted that, in the short-lived high-luminosity quasar phase, AGN are capable of generating galactic outflows and quenching star formation (e.g. Di Matteo et al., 2005). However, the effectiveness of this process has yet to be observationally established and the effect of low- to moderate-luminosity AGN on the host galaxy is still an open question.

1.3 The Fuel for Star Formation: the Interstellar Medium in Galaxies out to High Redshift

Fundamental to star formation and its subsequent quenching is the available fuel supply. Stars form from reservoirs of cold, molecular gas within the interstellar medium (ISM) of galaxies (e.g. Young & Scoville, 1991). The relation between the gas supply and star formation (Schmidt, 1959) provides vital information about the star formation efficiency (SFE) and the timescales for gas depletion (e.g. Daddi et al., 2010a,b; Tacconi et al., 2010, 2013, and references therein). Until recently, observations of the ISM at high redshift have been limited to small galaxy samples; however, new facilities such as the Atacama Large Millimeter/Submillimeter Array (ALMA;
Wooten et al., 2009) and the Large Millimeter Telescope (LMT; Hughes et al., 2010) are currently rapidly expanding our ability to observe the ISM of galaxies out to high redshift. Recent results have found that, mirroring the cosmic star formation rate density (Figure 1.1) and rising characteristic SFRs, the fraction of gas relative to a galaxy’s stellar mass also increases with redshift (see Carilli & Walter, 2013, for a review), with the disks of galaxies near the peak of the SFRD possibly dominated by their gas mass. Despite the increase in available gas in galaxies, however, the gas depletion timescales in $z = 1 – 3$ galaxies have been found to be somewhat shorter than that of local galaxies (e.g. Tacconi et al., 2013). High redshift galaxies would therefore quickly quench their star formation in the absence of a new gas accretion. Understanding the relationship between star formation and gas content and gas accretion history in galaxies is vital to understanding their evolution and may have important implications for galaxy evolution as a function of environment.

### 1.4 Galaxies in Galaxy Clusters

Galaxy clusters, as the most massive gravitationally bound structures in the Universe, represent an environmental extreme, with thousands of galaxies co-inhabiting dark matter haloes with total masses of $10^{14–15} M_\odot$ (see Boselli & Gavazzi, 2006, for a review). Clusters in the local Universe are characterized by massive, quiescent elliptical and lenticular (S0) galaxy populations, with few late-type spirals, in stark contrast to the field (Dressler, 1980). This morphological segregation clearly indicates that galaxy properties and evolution are dependent on environment, however, whether this dependence arises through nurture or nature has long been controversial. On the nurture side, several mechanisms specific to overdense environments have been proposed which may drive galaxy evolution. Galaxies in dense environments may experience increased galaxy interactions, from small perturbations (galaxy harassment; Moore et al., 1999) to tidal forces which strip loosely bound halo gas (starvation;
Larson et al., 1980; Balogh et al., 2000; Bekki et al., 2002) to galaxy-galaxy major mergers, which can trigger intense star formation and/or AGN activity and feedback (e.g. Croton et al., 2006; Narayanan et al., 2010; Bell et al., 2012). Interactions with the hot gas in the intracluster medium (ICM) can likewise heat or strip gas from galaxies, preventing further star formation (strangulation or ram pressure stripping Larson et al., 1980; Gunn & Gott, 1972; Bekki et al., 2009, 2014).

Though instances of these processes have been observed in local clusters (e.g. Boselli et al., 2014), the overall effectiveness of cluster-specific mechanisms is still unclear. Quiescent galaxies in general have been observed across all environments, suggesting that star formation can be extinguished through internal (non-environmental) means (e.g. Balogh et al., 2004). The rate of evolution of galaxy properties such as star formation has also been observed to correlate with galaxy mass, with more massive systems evolving faster in a process termed “downsizing” (e.g. Gavazzi et al., 1993). In a process that is more nature than nurture, more massive haloes may simply host more massive galaxies (Kauffmann et al., 2004), which has led some to propose that the dominant cause of the perceived environmentally-driven galaxy evolution is in fact the intrinsic masses of the galaxies in overdense environments. This nurture versus nature debate, in terms of galaxy clusters, is further complicated by evidence that some galaxies undergo “pre-processing”, whereby they experience accelerated evolution in galaxy groups (\( \sim 10^{13} M_\odot \)), prior to falling into massive clusters (e.g. Zabludoff & Mulchaey, 1998).

Untangling the dominant processes that drive galaxy evolution in cluster environments requires tracing the history of cluster galaxies through cosmic time. The quiescent, massive early-type galaxies so ubiquitous in today’s clusters must have formed sometime in the past, likely through intense star formation, which was subsequently quenched. Multiple studies have now shown that clusters up to \( z \sim 1 \) (\( \sim 8 \) billion years ago) still host predominately early-type galaxy populations, with little
to no star forming galaxies in the cluster cores (e.g. Muzzin et al., 2012). Predictions based on observations of quiescent cluster populations have suggested a model wherein cluster galaxies form at high redshift ($z \geq 2 - 3$) in an intense burst of star formation, followed by passive evolution to the present day (Stanford et al., 1998; Eisenhardt et al., 2008). Challenges to this model were first uncovered in statistical analyses (Mancone et al., 2010) and in individual cluster systems at $z > 1$ (Tran et al., 2010; Hilton et al., 2010; Hayashi et al., 2011; Fassbender et al., 2011; Tadaki et al., 2012; Bayliss et al., 2013; Santos et al., 2014), with the discovery of increasing star formation with increasing galaxy density in the centers of clusters.

Though studies of individual clusters are a necessary first step, large, homogenous cluster samples are vital to perform a statistical analysis and avoid bias due to cluster-to-cluster variations (e.g. Geach et al., 2006). Recently, the IRAC Shallow Cluster Survey (ISCS; Eisenhardt et al., 2008) has discovered over 300 massive ($\sim 10^{14} M_\odot$) galaxy clusters out to $z \sim 2$ in the nine square degree Boötes field. Using accurate photometric redshifts (Brodwin et al., 2006), these clusters were identified as near-infrared overdensities (Figure 1.2). This provides an ideal sample to examine the star formation properties of cluster galaxies over time as this selection method is independent of the presence of a quiescent galaxy population. Extensive spectroscopic campaigns have subsequently confirmed a subset of the ISCS clusters, which are being studied using the wealth of multi-wavelength imaging available in the Boötes field. A follow-up survey, the IRAC Distant Cluster Survey (IDCS), based on deeper near-infrared data, has identified hundreds of additional cluster candidates at higher redshifts, including the most distant spectroscopically confirmed, massive cluster at $z = 1.75$ (Stanford et al., 2012; Brodwin et al., 2012; Gonzalez et al., 2012).

Statistical studies with the ISCS have expanded on the studies of individual clusters, revealing that clusters at $z > 1$ are far more complex than previously thought. Studies of the infrared luminosity function of ISCS cluster galaxies found a sharp
deviation from passive evolution models at $z \sim 1.3$, in sharp contrast with predicted formation redshifts at $z \geq 2 - 3$ (Figure 1.3 Mancone et al., 2010). ISCS cluster galaxies at these redshifts have also been observed to have substantial star formation (Brodwin et al., 2013) and increased AGN activity over local clusters (Galametz et al., 2009; Martini et al., 2013). These results point to an epoch of active evolution and star formation in massive clusters, followed by a transition toward the quenched populations characteristic of local clusters. Following the evolution of galaxy properties, particularly star formation and AGN activity, within this cluster sample provides a unique opportunity to constrain the relation between environment and galaxy evolution and is the focus of this thesis.
Figure 1.3 The characteristic magnitude of the 3.6µm luminosity functions of cluster galaxies as a function of redshift (upper panel). The solid, dashed, and dotted lines show the best-fitting model for passively evolving stellar populations for different stellar population synthesis models and formation redshifts, $z_f$. The two highest redshift bins were not used during the fitting process and clearly deviate from what passive evolution models would predict at high redshift. The bottom panel shows the residuals. Figure adapted from Mancone et al. (2010).

1.5 Guide to this Thesis

In this thesis, we study the properties of galaxies in galaxy clusters across cosmic time, utilizing extensive multi-wavelength data and the ISCS/IDCS cluster samples to trace galaxy evolution in dense environments to high redshift. In Chapter 2, we present a statistical study comparing the dust-obscured star formation activity in cluster galaxies to field galaxies from $z = 0.3 - 1.5$ using Herschel SPIRE imaging at 250µm. Our cluster sample consists of 274 ISCS clusters, allowing us to establish the
evolution of star formation in cluster galaxies over a long redshift baseline. Through a stacking analysis of stellar-mass limited samples of thousands of cluster galaxies and tens of thousands of similarly-selected field galaxies, we quantify the average star formation rate and specific-star formation rate (SSFR=SFR/$M_\star$) as a function of cosmic time. We find a clear indication that the average SF activity in cluster galaxies is evolving more rapidly than in the field, rising to match field SF levels at $z \gtrsim 1.2$ in the cluster cores ($r < 0.5$ Mpc). We quantify this evolution and, though comparisons with simulations, suggest that ram pressure stripping is a process likely occurring in the cluster environment. Chapter 2 was published in the Monthly Notices of the Royal Astronomical Society (MNRAS) in 2014, reference Alberts S., et al., 2014, MNRAS, 437, 437.

In Chapter 3, we take a more detailed look at the star formation and AGN activity in 11 spectroscopically-confirmed, massive clusters at $z = 1 - 1.8$ using new, deep *Herschel* PACS imaging. This study presents the first UV-to-far-infrared (FIR) spectral energy distributions (SEDs) of cluster galaxies at high redshift, for both star forming galaxies (SFGs) and galaxies with a measurable AGN contribution. We find that the optical-FIR SEDs of cluster galaxies can be well described, on average, by empirically-derived field galaxy templates (Kirkpatrick et al., 2012, Kirkpatrick et al., in prep.). Adopting a SFG and AGN template, we characterize the SF properties of cluster galaxies as a function of cluster-centric radius and stellar mass, including, for the first time, the SF contribution from high redshift cluster galaxies with significant AGN emission. Using stacking, we compare the trends of the IR-luminous cluster galaxies to a full mass-limited cluster galaxy sample and quantify the cluster-to-cluster variations in total SFR per area and the halo mass-normalized SFR. As in Chapter 2, we find that clusters at high redshift have significant star formation in their cores, which quenches significantly over the epoch from $z \sim 1.5$ to $z \sim 1.2$, though with significant cluster-to-cluster variation. Through comparisons with the
Main Sequence (MS; Elbaz et al., 2011), we constrain the fraction of galaxies on and off the MS in clusters. In addition, using a selection technique based on fitting the UV-to-mid-infrared SED, we characterize our galaxies by AGN content and examine the fraction of AGN as a function of cluster-centric radius and redshift. Finally, we compare our dust-obscured SFRs from PACS to unobscured SFRs from Hα line emission. This chapter also presents the data reduction of the new PACS cluster maps and the first analysis of the star formation in IDCS J1426.5+3508, a massive cluster at \( z = 1.75 \).

In Chapter 4, we present new SCUBA-2 850\( \mu \)m imaging of IDCS J1426.5+3508. Combining Herschel PACS, Herschel SPIRE, and SCUBA-2 photometry, we analyze the FIR/submillimeter SED of star-forming cluster galaxies at \( z = 1.75 \), quantifying their dust temperatures and comparing to field galaxies at similar redshifts. We additionally present the first measurements of ISM mass in \( z = 1.75 \) cluster galaxies, using dust mass as a proxy for the ISM. Comparing to field galaxies at similar redshifts, we find comparable dust temperatures, ISM masses, gas fractions, and gas depletion timescales. Chapter 3 and Chapter 4 have been drafted into two papers to be submitted to the Astrophysical Journal and MNRAS in the immediate future. Finally, in Chapter 5, we present a summary and future directions for research on galaxy evolution as a function of environment.
CHAPTER 2

THE EVOLUTION OF DUST-OBSCURED STAR FORMATION ACTIVITY IN GALAXY CLUSTERS RELATIVE TO THE FIELD OVER THE LAST 9 BILLION YEARS

2.1 Introduction

It is well established that in the local Universe galaxy properties are strongly correlated with both their local environment and their stellar mass (e.g., Peng et al., 2010). Local clusters host strong red sequences of passively evolving galaxies with little to no star formation, while the lower density field contains the bulk of star forming galaxies (see Blanton & Moustakas, 2009, for a review). Similarly, massive galaxies tend to be redder, with old galaxy populations and low star formation rates (SFRs; e.g., Bower et al., 1992; Baldry et al., 2006; Weinmann et al., 2006; Thomas et al., 2010; Peng et al., 2010). Massive galaxies are also known to reside preferentially in denser environments (Kauffmann et al., 2004; Baldry et al., 2006). So while it is clear that environment plays a prominent role in galaxy evolution, it is still controversial whether the role of environment is direct, operating through processes external to individual galaxies and specific to dense regions, or indirect, with galaxy density tracing specific galaxy populations (such as massive galaxies) whose evolution is dominated by their own internal mechanisms. Given that environmental effects are also likely strongly dependent on cosmic time in an evolving Universe, it is important to quantify the transition epoch from active star formation and mass assembly to passive evolution in the densest environments.
Cluster studies have determined that the local SFR-density correlations are in place at $z \sim 1$ (e.g., Patel et al., 2009; Muzzin et al., 2012). Recently, Scoville et al. (2013) analyzed a large dynamical range of environments in the COSMOS field and determined that the strong correlation between red, passive galaxies and dense environments becomes much weaker at $z > 1.2$. Though Scoville et al. (2013) and other studies (Patel et al., 2009; Cucciati et al., 2010; Bolzonella et al., 2010) did not observe a reversal of the local SFR-density relation (where SF decreases with increasing galaxy density up to group scales) as found previously (Elbaz et al., 2007, see also Cooper et al. 2008), multiple high redshift studies of galaxy clusters have presented tantalizing evidence of increased star formation activity toward the densest regions. Infrared (IR) studies have noted increasing fractions of Luminous Infrared Galaxies (LIRGs; $1 \times 10^{11} \, L_\odot < L_{\text{IR}} < 1 \times 10^{12} \, L_\odot$) and Ultra-Luminous Infrared Galaxies (ULIRGs; $L_{\text{IR}} > 1 \times 10^{12} \, L_\odot$) in clusters out to $z \sim 0.8$ (Coia et al., 2005; Geach et al., 2006; Marcillac et al., 2007; Muzzin et al., 2008; Koyama et al., 2008; Haines et al., 2009; Smith et al., 2010; Chung et al., 2011). Studies of the evolution of cluster galaxies up to $z \sim 1$ have found increasing fractions of star forming galaxies in cluster cores (Saintonge et al., 2008; Webb et al., 2013; Haines et al., 2013) and the total SFR per unit halo mass in clusters has been found to be evolving as fast or faster than the field with a redshift dependence of roughly $(1+z)^{5-7}$ (Kodama et al., 2004; Bai et al., 2009; Popesso et al., 2012; Webb et al., 2013; Haines et al., 2013). At higher redshifts, individual cluster studies have revealed increased star formation activity down into the cluster cores ($z > 1.4$; Tran et al., 2010; Hilton et al., 2010; Hayashi et al., 2011; Fassbender et al., 2011; Tadaki et al., 2012). Small cluster samples, however, are susceptible to large variations in clusters properties (Geach et al., 2006) and these works highlighted the need for evolutionary studies of large, uniform cluster samples over a long redshift baseline. Recently, such studies have shown active mass assembly in clusters (Mancone et al., 2010), stochastic star
formation histories (Snyder et al., 2012), and a transition to active star formation in clusters at high redshift (Brodwin et al., 2013).

The mechanisms which drive the majority of cluster galaxies from actively star forming to passively evolving have not yet been fully identified. Multiple interpretations have been put forth as to the environment’s role in the suppression of star formation. Peng et al. (2010) found that the effects of environment and the stellar mass of galaxies are largely separable at $z \sim 1$, with the environment playing no substantial role in the quenching process for massive galaxies, whose evolution is dominated by internal self-quenching (so-called mass-quenching). Muzzin et al. (2012) found that the specific star formation rates ($SSFR=SFR/M_\star$) of star forming galaxies appear independent of environment and interpreted the environment’s primary function as controlling the fraction of star forming to quiescent galaxies through quenching on rapid timescales. This is further supported by differences found in the stellar mass distributions of cluster and field galaxy populations (van der Burg et al., 2013). Studies of the 3.6 and 4.5$\mu$m luminosity function in clusters found evidence for mass assembly at high redshift (Mancone et al., 2010), which is consistent with the two order of magnitude increase in AGN activity in cluster galaxies from $z = 0 - 1.5$ (Galametz et al., 2009; Martini et al., 2013) and may indicate a prominent role for mergers in cluster environments. More long redshift baseline studies of large, uniform cluster catalogs are necessary to quantify the relative importance of mass-versus environmental-quenching as well as what cluster-specific processes may drive the evolution of cluster populations.

In addition to needing large cluster samples over a range of redshifts, studies have shown that the prominence of dust-obscured star formation increases with redshift, with the majority of star formation enshrouded by dust at $z > 1$ (e.g., Bouwens et al., 2009; Magnelli et al., 2013). Infrared observations of clusters are therefore necessary to get a complete census of star formation over a large redshift range.
Current mid-IR studies of clusters (e.g. Webb et al., 2013; Brodwin et al., 2013) have analyzed detected infrared sources and have thus probed relatively bright IR galaxy populations. Complimentary to this, a stacking analysis can measure average star formation properties by probing farther down the luminosity function, including relatively quiescent galaxies, for a look at the full population of cluster galaxies.

In this chapter, we quantify the average star formation properties of cluster galaxies over a long baseline of cosmic time out to $z = 1.5$ ($\sim 9$ billion years ago) using a uniform, stellar mass-selected sample of 274 clusters over the 9 square degree Boötes field. This is the first study to measure the star formation properties in stellar mass-limited cluster and field galaxy samples over such a long redshift baseline. Our cluster sample is identified as three-dimensional near-infrared overdensities in photometric redshift space; as such, we do not rely on the presence of absence of a red sequence and thus are not biased against actively forming clusters. Cluster membership is determined using spectroscopic and photometric redshifts and we perform a robust, statistical removal of contaminating field galaxies. The cluster SF properties are compared to those of a field galaxy sample drawn from the same 4.5µm-selected catalog. Stellar masses are available for our entire catalog enabling us to construct stellar mass-limited galaxy samples. SFRs and SSFRs are obtained by a stacking analysis performed on *Herschel* SPIRE 250µm imaging. By stacking thousands of cluster galaxies and tens of thousands of field galaxies, we derive robust measurements of the average 250µm flux, from which we derive accurate estimates of the $L_{\text{IR}}$ and dust-obscured SFR. Our stacking analysis accounts for the contribution from both star forming and quiescent galaxies. Given our large samples of cluster and field galaxies, we are able to break our analysis down into subsets by stellar mass and galaxy color. By quantifying the rate of evolution out to high redshift, we constrain which processes might dominate the change in cluster galaxy properties and present arguments for specific quenching mechanisms in the clusters.
In Section 2.2, we present our cluster sample, cluster and field membership selection, and describe the Herschel SPIRE imaging and other ancillary data used. In Section 2.3, we lay out the stacking analysis, including the stacking procedure at 250µm and our method for stacking clusters members including corrections for source blending/clustering bias and field contamination. We discuss the procedure for stacking field galaxies, and our report on possible complications from projection effects and AGN. This section also includes the procedure for stacking at 70µm, a check on possible systematics introduced during the conversion of 250µm flux to L_{IR}. In Section 2.4, we detail the conversion of 250µm fluxes to galaxy properties (L_{IR} and SFR) and present the results of the stacking analysis for cluster and field galaxy samples. In Section 2.5, we discuss our results in terms of environmental and internal quenching mechanisms, place our results in the context of other studies. Section 2.6 contains our conclusions. Throughout this work, we adopt a WMAP7 cosmology with \((\Omega_{\Lambda}, \Omega_{M}, h) = (0.728, 0.272, 0.704)\) (Komatsu et al., 2011).

### 2.2 Data

#### 2.2.1 ISCS Cluster Sample

The IRAC Shallow Cluster Survey (ISCS; Eisenhardt et al., 2008) is a sample of 335 clusters over the redshift range \(0 < z < 2\) (106 at \(z > 1\)) in the Boötes field. Clusters were identified via a wavelet search algorithm which determined statistically significant rest-frame near-infrared overdensities in three-dimensional redshift slices using the photometric redshift probability distribution functions of 4.5µm-selected galaxies across the field. The photometric redshifts used for cluster identification (Brodwin et al., 2006) were calculated using deep \(B, R\), and \(I\) band optical data from the NOAO Deep, Wide-Field Survey (NDWFS; Jannuzi & Dey, 1999) and Spitzer IRAC 3.6 and 4.5µm imaging from the IRAC Shallow Survey (ISS; Eisenhardt et al., 2004), with a uncertainty of \(\sigma = 0.06(1+z)\). As the ISS is 4.5µm flux-limited (8.8µJy
at \(5\sigma\), this cluster sample is essentially stellar mass selected and does not require nor preclude the presence of a strong red sequence in the clusters. Spectroscopic confirmation of dozens of the ISCS clusters at low redshifts (\(z \leq 0.9\)) was obtained through the AGN and Galaxy Evolution Survey (AGES; Kochanek et al., 2012) and Keck/LRIS spectroscopy (Stern et al., 2010). Additionally, over 20 of the clusters at \(z > 1\) have been spectroscopically confirmed via Keck or HST spectroscopy (Stanford et al., 2005, 2012; Elston et al., 2006; Brodwin et al., 2006, 2011; Eisenhardt et al., 2008; Zeimann et al., 2012; Brodwin et al., 2013; Zeimann et al., 2013). Overall, this cluster sample is expected to have a \(\sim 10\%\) false detection rate due to chance projections (Eisenhardt et al., 2008).

In order to characterize the ISCS cluster masses as a function of redshift, we perform a halo mass ranking simulation following the procedure in Lin et al. (2013). We determine the median mass of the \(N\) most luminous clusters, as determined from their total 4.5\(\mu m\) luminosity, in redshift bins with width 0.2 from \(z=0.3-1.5\) (see Table 2.2.1.2). We find a range of median cluster masses of \(M_{200} \sim 5 \times 10^{13} - 8 \times 10^{13} \, M_\odot\) with no significant evolution with redshift. This is consistent with measurements of individual ISCS clusters of the dynamical (Stanford et al., 2005; Elston et al., 2006; Brodwin et al., 2006; Eisenhardt et al., 2008) and X-ray (Brodwin et al., 2011) masses, as well as an analysis of the galaxy cluster autocorrelation function for the ISCS sample (Brodwin et al., 2007) which found the characteristic cluster mass to be \(\sim 10^{14} \, M_\odot\). Mass estimates from weak lensing are also available for six ISCS clusters at \(z > 1\) (Jee et al., 2011).

In this study, we analyze the star formation properties of the 274 clusters that fall within the coverage of the SPIRE Boötes maps (Section 2.2.2), presenting the evolution of a uniform cluster sample with cosmic time and redshift. These clusters span the redshift range \(0.3 < z < 1.5\), over which the photometric redshifts have a uniform accuracy as described in the next section.
2.2.1.1 The Boötes Field: Photometric Redshifts and Stellar Mass Estimates

Photometric redshifts are available across the 9 square degree NDWFS Boötes field, which includes the SPIRE Boötes imaging. The photometric redshifts used in this study were updated from the original work in Brodwin et al. (2006) to incorporate infrared data from the Spitzer Deep, Wide-Field Survey (SDWFS; Ashby et al., 2009), which repeated the 90 second exposure of the ISS three more times. This resulted in a factor of two increase in the catalog depth, a significantly more robust catalog with regards to cosmic rays and instrumental effects, and a greater sensitivity to distant galaxies in the 5.8 and 8.0µm bands. Photometric redshifts for 434,295 galaxies were determined by fitting a subset of models (late types: Sb, Sc, Sd, Spi4, M82; early types: Ell5, Ell13, S0 and Sa) from Polletta et al. (2007) to rest-frame wavelengths \( \sim 0.1 - 8\mu m \) over \( 0 < z < 2 \). These models were chosen over the original models used in Brodwin et al. (2006) as they span the full wavelength range probed by the NDWFS+SDWFS filters (see Brodwin et al., 2013, for more details). A comparison with available spectroscopic redshifts shows that the precision of these photometric redshifts is \( \sigma \sim 0.06(1+z) \) for 95% of the galaxies over the redshift range \( 0 < z < 1.5 \) (Brodwin et al., 2013). To be conservative, we further limit our lower redshift bound to \( z \geq 0.3 \), below which the 4000Å break is blueward of the NDWFS filters.

Estimates of the stellar masses for galaxies in the photometric redshift catalog were calculated using iSEDfit (Moustakas et al., 2013), a Bayesian spectral energy distribution (SED) fitting code. The data are fit using the Bruzual & Charlot (2003) population synthesis models and assuming the Chabrier (2003) initial mass function (IMF) from 0.1-100 M\( \odot \). We adopt a stellar mass cutoff of \( M_* = 1.3 \times 10^{10}M_\odot \) throughout this work, which corresponds to the mass limit of our sample at \( z=1.5 \) (see Figure 3 in Brodwin et al., 2013). Though the statistical uncertainties in the stellar masses are typically \( \ll 0.2 \) dex, we adopt a conservative error of 0.3 dex on all

20
stellar masses to account for systematic uncertainties (see Appendix A Moustakas et al., 2013, for a more in-depth discussion of how our stellar masses are derived).

### 2.2.1.2 Cluster Membership

Cluster membership is first determined through available spectroscopic redshifts. As in Eisenhardt et al. (2008), if a spectroscopic redshift is within 2000 km s\(^{-1}\) of the systemic cluster velocity and lies within a 2 Mpc radius of the projected cluster center, it is considered to be a cluster member. The cluster centers are taken from the density peaks identified by the wavelet search algorithm.

Galaxies with only photometric redshifts are assigned membership based on a constraint of the integral of their normalized photometric redshift probability distributions:

\[
\int_{z_{cl} - 0.06(1+z_{cl})}^{z_{cl} + 0.06(1+z_{cl})} P(z) dz \geq 0.3
\]

(2.1)

where \(z_{cl}\) is the redshift of the cluster, calculated by iteratively summing up the \(P(z)\) function for potential cluster members within 1 Mpc and re-identifying cluster members until convergence. Galaxies which satisfy Eqn 2.1 and are within 2 Mpc of the projected cluster center are photometric redshift cluster members. The numbers of spectroscopic and photometric cluster members for \(r \leq 1\) Mpc (approximately the virial radius) can be seen in Table 2.2.1.2 and the stellar mass distribution of cluster galaxies at all redshifts \((z = 0.3 - 1.5)\) can be seen in Figure 2.1, normalized by the total number of cluster galaxies.

Constraining the integral of \(P(z)\) provides both an indication of whether a given galaxy is a cluster member or a foreground/background source and a cut on the quality of the photometric redshifts used throughout this study. We expect that some fraction of the galaxies identified as cluster members will actually be contaminating field galaxies due to the width of the redshift probability distribution functions. We
Table 2.1. ISCS Cluster Statistics at $z = 0.3 - 1.5$.

<table>
<thead>
<tr>
<th>Redshift Bin</th>
<th>Number of Clusters</th>
<th>Number of Spectroscopic Members</th>
<th>Number of Photometric Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3-0.5</td>
<td>60</td>
<td>160</td>
<td>1539</td>
</tr>
<tr>
<td>0.5-0.7</td>
<td>55</td>
<td>112</td>
<td>1956</td>
</tr>
<tr>
<td>0.7-0.9</td>
<td>52</td>
<td>24</td>
<td>2423</td>
</tr>
<tr>
<td>0.9-1.1</td>
<td>49</td>
<td>20</td>
<td>2482</td>
</tr>
<tr>
<td>1.1-1.3</td>
<td>30</td>
<td>58</td>
<td>1383</td>
</tr>
<tr>
<td>1.3-1.5</td>
<td>28</td>
<td>47</td>
<td>1320</td>
</tr>
</tbody>
</table>

Figure 2.1 The stellar mass distribution of our cluster (black diamonds) and field (blue circles) galaxy samples as described in Sections 2.2.1.2 and 2.2.1.3. Each distribution includes galaxies from $z = 0.3 - 1.5$ and is normalized by the total number of galaxies in each sample. The cluster sample has not been corrected for field contamination (see Section 2.3.1.2). Given the uncertainties, the stellar mass distributions of cluster and field galaxies are similar over most masses, with slightly fewer cluster galaxies in the lowest mass bin and correspondingly more cluster galaxies at higher masses.
mitigate this effect on our stacking analysis in two ways: 1) we test the effect of raising the integrated $P(z)$ threshold on our results, and 2) we estimate and subtract the field contamination directly using our field galaxy population. We find that raising the integrated $P(z)$ threshold has little effect on our overall conclusions and is likely removing real cluster members from our sample. Our field contamination correction, based on a statistical analysis, is described in Section 2.3.1.2.

We also expect some of our galaxies to host AGN. Using shallow X-ray observations across the field (see Section 2.2.4) and IRAC color selection (Stern et al., 2005; Kirkpatrick et al., 2013), we identify AGN in a small fraction of our cluster galaxies, $\sim 1 - 3\%$ from low to high redshift. More thorough studies of AGN in the ISCS, using deeper X-ray data, have shown that the fraction of AGN in cluster galaxies is as much as 10 per cent at $z > 1$, an increase of two orders of magnitude from local AGN fractions (Galametz et al., 2009; Martini et al., 2013). Given a constraint of $\lesssim 10\%$ and the fact that we are primarily probing with the cold dust regime which has been found to be dominated by heating from star formation even in known AGN (e.g., Mullaney et al., 2012a), we choose to leave AGN in our sample for our main analysis. We examine the impact of AGN on our SPIRE stacking analysis separately in Section 2.3.2.

2.2.1.3 Field Galaxies

Our field galaxy set is drawn from the Boötes field using the same 4.5µm-selected galaxy catalog as the cluster members. In order to get a clean field sample, we discard any galaxies that are within a radius of 2.5 Mpc and 0.2(1+$z$) in redshift space of known clusters. We further restrict our field sample by requiring that each galaxy have an integrated $P(z) \geq 0.3$ at its best-fit redshift, which places a similar cut in the quality of the photometric redshifts as our cluster member sample. This ensures that we are looking at similar galaxy populations in terms of our ability to assign
an accurate photometric redshift. The stellar mass distribution of our field galaxy sample at all redshifts can be seen in Figure 2.1, normalized to the total number of field galaxies. Though a more careful analysis of the stellar mass function is beyond the scope of this work, we can see that, within the uncertainties, the mass distributions for cluster and field galaxies are similar, with a suggestion of a small difference in the normalized fraction of galaxies in each environment in the low and high mass ends. We find the same relative mass distributions of cluster and field galaxies when we split out galaxy samples into $z < 1$ and $z > 1$ bins.

### 2.2.2 Far-Infrared: SPIRE Imaging

The Boötes field was observed with Herschel SPIRE (250, 350, and 500$\mu$m; Griffin et al., 2010) as part of the Herschel Multi-tiered Extragalactic Survey (HerMES; Oliver et al., 2012). The observations covered 8 square degrees of the NDWFS/Boötes field, centered on 14:32:06 +34:16:48, which was surveyed with four pointings. The central two square degrees of the field were then observed with an additional 5 pointings. We will refer to the smaller, deep area as the “inner” region and the shallower, wider area as the “outer” region throughout this work. In order to optimize these data for point source recovery, we reduced and mosaiced the publicly available AORs using the Herschel Interactive Processing Environment version 7 (HIPE; Ott, 2010), focusing on the removal of striping through high order polynomial baseline removal, the correction of astrometry offsets through the stacking of the positions of known MIPS 24$\mu$m sources, and the removal of glitches missed by the standard pipeline reduction. The final maps have a 5$\sigma$ depth in the inner (outer) region of 14mJy (26mJy) at 250$\mu$m. The confusion noise for SPIRE observations is discussed in Nguyen et al. (2010) and is 5.8±0.3 mJy at 250$\mu$m. We generated 5$\sigma^1$ point source catalogs at 250, 350, and 500$\mu$m, both for the original unfiltered maps and after using a matched-

\footnote{confusion noise is not included in the S/N estimates for the catalog sources}
filter technique, a method developed to optimize the signal-to-noise ratio (S/N) for confusion-dominated submillimeter maps (see Chapin et al., 2011). Completeness simulations indicate that our source catalog is 90% complete in the inner (outer) region down to 20mJy (33mJy) at 250µm for the unfiltered map and down to 18mJy (25mJy) for the matched-filter map. A more detailed description of the reduction of the 250, 350, and 500µm SPIRE maps, their catalogs, and the completeness tests performed can be seen in Appendix A.

The large full width at half maximum (FWHM) of the SPIRE imaging (18″.1, 24″.9, and 36″.6 at 250, 350, and 500µm; Swinyard et al., 2010) presents challenges for both detected sources and for stacking analyses. Clustering and source blending will result in flux boosting within the large beams, particularly at the longer wavelengths. For detected sources, we address this by simulating the flux boosting as a function of flux (see Appendix A). The bias introduced into SPIRE stacking analyses due to clustering has recently been examined in two studies. Béthermin et al. (2012) found that boosting due to clustering of sources ranges from ~7% at 250µm to ~20% at 500µm for typical galaxy densities in the field, however Viero et al. (2013) showed that this bias factor increases dramatically with increasing source density and increasing beamsize (see their Figure 4). In addition, the typical region examined in this study (0.5 Mpc or 1 arcminute radius at z=1), will be covered by <2 beams at 500µm. For these reasons, we limit our stacking analysis to the 250µm waveband and apply a correction for clustering bias by determining the baseline signal in the map through a random sampling of pixels both in the field and in the areas of our map which contain clusters (see Section 2.3.1.2).

2.2.3 Mid-Infrared: MIPS Imaging

To constrain any evolution in the SEDs of cluster galaxies relative to coeval field galaxies, we also stack the MIPS AGN and Galaxy Evolution Survey (MAGES; Jan-
nuzzi et al., in prep) 70µm images at the positions of our cluster and field galaxies (see Section 2.3.3 for details on the stacking of the 70µm images).

MAGES imaged the Boötes field to a depth two times greater than the original GTO survey of the Boötes field in each of the three MIPS bandpasses (Rieke et al., 2004). The MAGES data also added three additional spacecraft roll angles, which allow for improved rejection of 1/f noise in the resulting maps. The flatter backgrounds in the 70µm and 160µm MAGES images compared to the original survey allow reliable stacking in these bands.

The MAGES data were reduced using the MIPS-GTO pipeline (Gordon et al., 2005), and source catalogs were generated from the resulting image mosaics with DAOPhot (Stetson et al., 1987). The MAGES point-source catalogs reach 3σ sensitivities of 0.122, 18.6 and 110 mJy in the 24µm, 70µm, and 160µm images, respectively.

2.2.4 X-ray: Chandra Photometry

X-ray data is available across a 9.3 square degree field as part of XBoötes, a mosaic of 126 short (5ks) Chandra ACIS-I images covering the entirety of NDWFS (Murray et al., 2005; Kenter et al., 2005). The XBoötes catalog contains 2,724 point sources with energies of 0.5-7 keV, which is sufficient to detect unobscured moderate to luminous AGN (Ranalli et al., 2003).

2.3 Stacking Analyses

Stacking is a statistical process by which the signal from multiple individually undetected sources is combined in order to increase the overall S/N and obtain a representative (commonly mean or median) flux density of a population in some waveband (e.g., Dole et al., 2006; Marsden et al., 2009; Béthermin et al., 2012). The details of the stacking process depend on the map and the spread in the properties of
the population being stacked. Stacking will allow us to probe much deeper down the infrared luminosity function than requiring detections, as most of the ISCS cluster galaxies will be undetected given the 250µm flux limit (14mJy or L_{IR} \sim 5 \times 10^{11}L_\odot).

We describe our stacking procedure at 250µm and our main stacking analysis of cluster and field galaxies in this section. In addition, we describe stacking procedure at MIPS 70µm, which will be used to verify our results at 250µm.

2.3.1 Stacking at 250µm

2.3.1.1 Procedure

Stacking at 250µm is performed on the unfiltered map, which has a zero mean and is calibrated in Jy beam^{-1}. The latter fact greatly simplifies the stacking process as the peak pixel value provides the best estimate of the total flux density of a given source at that position (in the absence of clustering or source blending). The signal of a stack is therefore obtained by combining the pixels in which the sources being stacked are located. Given that our map has two regions with differing noise properties, we choose to combine the pixel values at the locations of the sources in each stack using a variance-weighted mean. Stacking tests on fake sources inserted into the map (see Appendix A), however, show that both variance-weighting and unweighted schemes provide equally good estimates of the true stacked flux.

The uncertainties associated with each stacked flux density are obtained via the bootstrap method, during which random subsamples (with replacement) of sources are chosen and re-stacked. The number of sources in each subsample is equal to the original number of sources in the stack. This process is repeated 10 000 times in order to determine the representative spread in the properties of the population being stacked. The bootstrap uncertainty \( \sigma_{\text{boot}} \) can be expressed by

\[
\sigma_{\text{boot}} = \sqrt{\frac{\sigma_{\text{instr}}^2 + \sigma_{\text{conf}}^2 + \sigma_{\text{pop}}^2}{N_{\text{stack}}}}
\]

(2.2)
where $\sigma_{\text{instr}}$ is the instrument noise, $\sigma_{\text{conf}}$ is the confusion noise, $\sigma_{\text{pop}}$ is the intrinsic spread in the flux density of the population being stacked, and $N_{\text{stack}}$ is the number of sources in the stack. As discussed in Béthermin et al. (2012), though $\sigma_{\text{conf}}$ and $\sigma_{\text{pop}}$ are most likely not Gaussian, $\sigma_{\text{boot}}$ can be approximated as a Gaussian via the central limit theorem given a large number of stacking iterations. Bootstrapped uncertainties are advantageous as they provide an indication of the scatter in a population, which may include extreme outliers which are otherwise not obvious in a straight measurement of the mean and the standard deviation.

The process of stacking in general is best understood for sources below the detection limit, where each individual measurement is dominated by Gaussian noise. We test the contribution from detected sources by matching our cluster members to the 250$\mu$m matched-filter catalog. The large beamsize and relatively low S/N of the SPIRE observations creates large offsets between the true position of the submillimetre flux and where it is detected in the maps due to random noise peaks. We characterize these positional uncertainties as part of our completeness simulations (see Appendix A) and determine that a search radius of 8” is appropriate to identify the vast majority of 250$\mu$m counterparts. We find that $\lesssim$10% of our cluster members ($r < 0.5$ Mpc) have a 250$\mu$m counterpart within 8” of their position. This is not unexpected, given that the deep inner region of the 250$\mu$m map has a flux limit of 14 mJy, which corresponds to $L_{\text{IR}} \sim 5 \times 10^{11} L_\odot$ at $z=1$. A test of random positions across the 250$\mu$m map indicates that we expect a chance encounter with a detected source in an 8” search radius at a rate of $\sim 3\%$. Given that only a small fraction of our cluster sample is detected at 250$\mu$m, we treat all of our cluster members as undetected and stack them accordingly. We verify this approach by examining the distribution of flux values that go into each stack, which should be Gaussian due to the noise properties of the undetected sources and have a well-defined mean.
2.3.1.2 Stacking Cluster Members

Cluster members identified as described in Section 2.2.1.2 are stacked in redshift bins with a width of 0.2 over the redshift range $z = 0.3 - 1.5$ and radial bins as described below. The mean redshift of each bin is calculated as the mean of the best-fit redshifts of the constituent galaxies. As discussed in Section 2.2.1.1, to obtain a complete mass-limited sample over our redshift range, we impose a stellar mass limit of $M_* = 1.3 \times 10^{10} M_\odot$.

In order for the average flux values of our cluster member stacks to be meaningful, we need to remove any signal that is unrelated to real cluster members. There are two potential sources of contaminating signal in our stacks: 1) an underlying, baseline signal, mainly due to source blending and clustering, (with a possible minor contribution from dust in the intracluster medium contributing a few percent to the IR luminosity Giard et al. (2008)), and 2) contamination by field galaxies which are mistaken for cluster members due to the width of the photometric redshift probability distribution functions.

First, we test the 250$\mu$m map for a baseline signal towards the clusters. SPIRE maps are normalized such that they have a zero mean baseline, which we verify by stacking on 100,000 random pixels across the 250$\mu$m map. This indicates that there is no overall baseline signal that needs to be removed and boosting from clustering bias of all galaxies across the map is negligible. The increased source density inherent in the clusters themselves, however, can cause a underlying signal due to source blending and the strong clustering of galaxies in clusters. To examine this signal, we split the clusters into the redshift bins described above and stack random pixels in projected radial bins originating at the cluster centers. Figure 2.2 (top) shows the average 250$\mu$m flux densities recovered from these random stacks as a function of radius and redshift. At all redshifts, the baseline signal in clusters is strong out to $r = 0.5$ Mpc, indicating clustering bias and source blending. At larger radii, where the number
density of cluster members drops (bottom panel), the baseline signal is significantly reduced. Stacking beyond the virial radius ($\sim 1$ Mpc) recovers no signal.

In addition to redshift bins, we choose projected radial bins such that we get good number statistics in each cluster galaxy stack. The baseline signal of cluster galaxies (Figure 2.2, top) as a function of radius suggest a division at $r = 0.5$ Mpc, which is approximately half the virial radius given the expected masses and velocity dispersions of these clusters (Stanford et al., 2005; Elston et al., 2006; Brodwin et al., 2006, 2007; Eisenhardt et al., 2008; Brodwin et al., 2011). We stack all cluster members in six redshifts bins and two radial bins: $r < 0.5$ Mpc and $0.5 < r < 1$ Mpc, which we will refer to as the cluster “core” and “outskirts” throughout this work. We re-calculate the baseline signal as described above for the larger radial bins and subtract the baseline signal from the cluster stacked flux densities in the appropriate redshift/radial bins.

The second correction is for contamination of the cluster member catalog by field galaxies. Due to the nature of our criteria for cluster membership, we expect that some fraction of our cluster members are actually field galaxies which are spatially coincident with one of the ISCS clusters and whose photometric redshift probability distribution function satisfies Equation 2.1. Given that the width of a cluster in redshift space will be sharply peaked compared to the cumulative width of the photometric redshift probability distribution functions, this contribution can be determined in a statistical fashion by calculating the “background” total 250$\mu$m flux per unit area of field galaxies which would satisfy Equation 2.1 if the cluster was not present. To accomplish this, we mask out a 2.5 Mpc area around all known clusters within the Boötes field and use the remaining area to identify galaxies which have an integrated $P(z) \geq 0.3$ at discrete redshifts, ranging from $z = 0.3 - 1.5$ in steps of 0.05. The galaxies which satisfy integrated $P(z) \geq 0.3$ at each redshift step are stacked to determine the mean flux level of field galaxies, $\langle S_{fc}(z) \rangle$, which we additionally smooth
Figure 2.2 The baseline flux density at 250\(\mu\)m and source density of cluster members as a function of cluster-centric radius. (Top) The average 250\(\mu\)m flux density in randomly-selected pixels as a function of projected radius for ISCS clusters separated into redshift bins. This baseline signal is due to the increased source density toward clusters (resulting in source blending and clustering signal) and must be removed from the stacking signal in the areas of the SPIRE map that have clusters. (Bottom) The source surface density of cluster members after correcting for field contamination. The density of cluster members at \(r \lesssim 0.5\) Mpc dominates over the background field level, while at \(r \gtrsim 0.5\) Mpc the corrected source density of cluster members is only a small enhancement over the field source density.
with a boxcar filter with a width of 0.1 to remove noise introduced by the binning in redshift space. Multiplying by the number of field galaxies per unit area, \( \Sigma_{fc}(z) \), we find the total 250\(\mu m \) flux per unit area that we can expect to contaminate our cluster stacks.

The field correction is applied by subtracting the total flux per unit area of field galaxies (Figure 2.3, red squares) from the total flux per unit area of our contaminated cluster stacks (Figure 2.3, blue diamonds) via:

\[
\langle S_{cl}(z) \rangle \Sigma_{cl}(z) = \langle S_{total}(z) \rangle \Sigma_{total}(z) - \langle S_{fc}(z) \rangle \Sigma_{fc}(z) \quad (2.3)
\]

where \( z \) is the mean redshift of cluster members in a given bin, \( \langle S_{total}(z) \rangle \) and \( \Sigma_{total}(z) \) are the stacked fluxes and the number of sources per unit area in the contaminated cluster stacks, \( \langle S_{cl}(z) \rangle \) is the true flux density of cluster galaxies and \( \Sigma_{cl}(z) \) is found via

\[
\Sigma_{cl}(z) = \Sigma_{total}(z) - \Sigma_{fc}(z). \quad (2.4)
\]

The field corrected total 250\(\mu m \) flux per unit area of cluster galaxies can be seen in Figure 2.3 as the filled black points for the cluster cores \( (r < 0.5 \text{ Mpc}; \text{ top}) \) and outskirts \( (0.5 < r < 1 \text{ Mpc}; \text{ bottom}) \). In the cluster cores, the corrected total 250\(\mu m \) flux per unit area exceeds that in the field at high redshift \( (z > 0.8) \). In the outskirts, only two of the redshift bins are detected at \( \geq 3\sigma \); however, the highest redshift bin shows that the total flux per unit area of cluster galaxies is approaching the level of the field. This is significant given that the number of cluster galaxies per unit area (see Figure 2.2), corrected via Equation 2.4, is only a small enhancement over the field source density at these redshifts, indicating that the average activity in cluster members will be higher than in the field in this high redshift bin (see Figure 2.4).

The corrected mean flux density of cluster galaxies, after the baseline and field corrections described above are applied, can be seen in Figure 2.4 (black diamonds)
Figure 2.3 The total 250$\mu$m flux per unit area as a function of redshift for cluster members and field galaxies in radial bins $r < 0.5$ Mpc (top) and $0.5 < r < 1$ Mpc (bottom). This quantity is obtained by multiplying the average stacked flux density, $\langle S(z) \rangle$, with the number density of sources, $\Sigma(z)$. The blue, open diamonds are the field-contaminated cluster galaxy stacks (after correction for baseline signal due to source blending/clustering), denoted “total” in Equations 2.3-2.4. The black, filled diamonds show the total 250$\mu$m flux per unit area of cluster galaxies denoted “cl”, after both baseline and field contamination corrections have been applied. The red, open squares indicate the total flux per unit area of field galaxies which satisfy Equation 2.1, denoted “fc”. No stacked signal above the field contamination was detected for cluster galaxies at $r > 1$ Mpc in any of the redshift bins. Upper limits are 3$\sigma$. 
Figure 2.4 The average stacked 250µm flux density for cluster members after baseline and field contamination corrections (cl; black diamonds) as compared to field galaxies (fc; red squares) which satisfy Equation 2.1 as a function of redshift. The top panel shows cluster members for $r < 0.5\,\text{Mpc}$, the middle panel for $0.5 < r < 1\,\text{Mpc}$ and the bottom panel combines the two for an $r < 1\,\text{Mpc}$ bin to maximize detections. In addition, we combine the two lowest redshift bins into a bin spanning $z=0.3-0.7$ (indicated by green circles). The average 250µm flux densities of field galaxies which satisfy Equation 2.1 are consistent with the average fluxes of all field galaxies in our mass-limited sample (Section 2.2.1.3). The dotted lines show the 250µm k-correction for a typical dusty, star-forming galaxy of constant luminosity and normalized to the field level at $z=0.3$. Upper limits are $3\sigma$. Some lower redshift bins are poorly constrained and their upper limits are outside the plot ranges.
compared to the average flux of field galaxies per redshift (red squares) for \( r < 0.5 \) Mpc (top) and \( 0.5 < r < 1 \) Mpc (middle). No stacked signal above the field was found at \( r > 1 \) Mpc. Four out of six redshift bins are detected at \( \geq 3\sigma \) for \( r < 0.5 \) Mpc and two out of six are detected for \( 0.5 < r < 1 \) Mpc. In order to maximize the number of detected stacked signals we have to work with, we make two changes for the subsequent analysis. 1) we combine the two lowest redshift bins, and 2) we combine the core and outskirts bins into one “core+outskirts” \( r < 1 \) Mpc radial bin (Figure 2.4, bottom), which we will compare with the \( r < 0.5 \) Mpc radial bin. The two radial bins are combined as a weighted mean after applying the baseline correction.

To verify that these trends are not a product of our binning scheme, we shifted the redshift bins by 0.1 and re-stacked and re-corrected our cluster galaxy stacks. We find that these trends are robust against the exact redshift bins chosen.

The shape of the average 250\( \mu \)m flux of field galaxies in Figure 2.4 is relatively flat, which reflects that the average infrared luminosity of field galaxies is increasing with redshift, compensating for the k-correction (dotted curve). It should be noted that there are several submillimetre emission lines which will be sampled by the 250\( \mu \)m band over this redshift range. The brightest, CII (rest-frame 158\( \mu \)m), has been measured to contribute \( \sim 4 \) per cent to the 250\( \mu \)m flux for \( z < 1 \) for a typical SMG and may contribute more in sub-ULIRG galaxies, though this has not been well quantified to date (Smail et al., 2011). These emission lines may contribute to the wiggles in the 250\( \mu \)m flux as a function of redshift for the field. The (corrected) average 250\( \mu \)m flux of cluster galaxies, on the other hand, clearly rises as a function of redshift. We examine these results in terms of physical properties in Section 2.4.

### 2.3.1.3 Stacking Field Galaxies

We stack field galaxies in the Boötes field, the selection of which is described in Section 2.2.1.3, in two ways. First, we stack them in redshift bins with width
0.1 to take full advantage of the large numbers of field galaxies at our disposal in order to examine the evolution of their infrared properties as a function of redshift. Second, we bin them in the same redshift bins as our cluster galaxies for a direct comparison. For the latter, we take \( N_{stack} \) (see Equation 2.2) from the corresponding cluster stack rather than the total number of field galaxies in the stack, which is typically an order of magnitude larger than the number of cluster members. This will provide comparable uncertainties. We find that the average 250\( \mu \)m flux densities of field galaxies stacked in this way are consistent with the values found for the field correction. We test that this holds even if we remove the restriction on the integrated \( P(z) \) for the field stacks. This indicates that the cluster membership criteria does not introduce a bias based on the restriction of the integrated \( P(z) \) parameter at a given redshift.

### 2.3.1.4 Projection Effects and Verifying the Baseline Correction

In this section, we briefly discuss (i) projection effects due to selecting cluster members based on their 2D cluster-centric radius and (ii) our tests to verify our baseline correction procedure.

1. Since we are using projected cluster-centric radii, we are stacking cluster galaxies in cylinders rather than spheres and will suffer some contamination to our signal from projection effects. A recent study by Noble et al. (2013) examined contamination due to projection effects by separating infalling galaxies from older cluster populations using caustic diagrams. They found that recently accreted, star forming galaxies contaminate at all projected radii and that this effect may be responsible for recent studies claiming no environmental dependence for star forming galaxy properties as a function of radius. As our radial bins are quite large, we expect our susceptibility to this to be minimized, however, we can quantify these effects in the following way. For the \( r < 1 \) Mpc bin, we argue...
that projection effects are not significant as we found no stacked signal above our field contamination outside 1 Mpc. The \( r < 0.5 \) Mpc bin most likely contains some signal from cluster galaxies at larger radii. Stacking at \( 0.5 < r < 1 \) Mpc found that only 2/5 redshift bins are detected, with the strongest signal in the outskirts at \( \langle z \rangle = 1.4 \). By comparing the field-corrected source density of cluster members in the core and outskirts in our highest redshift bin and using the average stacked flux from each to determine their relative contribution to the total flux and source densities, we estimate that the outskirts are contributing \( \sim 30\% \) of the average flux in the \( r < 0.5 \) Mpc \( \langle z \rangle = 1.4 \) bin.

2. We test our general stacking technique and method for extracting the baseline signal due to galaxy clustering and source blending by re-stacking our \( r < 0.5 \) Mpc cluster members and field galaxies using SIMSTACK from Viero et al. (2013), which was developed to account for clustering bias in stacking analyses. We find that SIMSTACK yields consistent results with our stacking method, indicating that any clustering bias in the full field population is negligible, as our baseline test in the field determined, and that we are correctly removing the signal from clustering bias in our \( r < 0.5 \) cluster stacks. The Viero et al. (2013) code is designed to stack populations of galaxies with similar clustering properties and so we do not test our outer radial bin, as they mix cluster and field galaxies in similar proportions.

2.3.2 Testing the Contribution of Active Galactic Nuclei at 250µm

As discussed in Section 2.2.1.2, a small fraction (\( \leq 10\% \)) of the galaxies in our field-contaminated cluster stacks are expected to host AGN, which we expect to have a minimal contribution to the cold dust regime as probed at 250µm over our redshift range. To confirm this is true for the bright AGN we can detect across our galaxy samples, we remove all galaxies which 1) have an X-ray detection and/or 2) fall in
the IRAC color selection “wedge” for AGN as described in Kirkpatrick et al. (2013) and repeat our stacking analysis as described in Sections 2.3.1.2 and 2.3.1.3. We find that removing these AGN makes no statistically significant difference in the measured stacked fluxes for either our cluster or field galaxy samples.

2.3.3 Stacking at 70 $\mu$m

The MAGES 70 $\mu$m flux maps differ from the 250 $\mu$m maps described above in several respects, including larger spatial variations in sensitivity, the units of the image mosaic, and the relative importance of confusion noise. As a result, we treat the 70 $\mu$m stacks slightly differently than the 250 $\mu$m stacks. In this section, we describe the procedures we used to stack the MAGES 70 $\mu$m image for both the field and cluster galaxy samples and the corrections that we applied to photometry measured from stacks of cluster galaxies.

2.3.3.1 Procedure

The MIPS 70 $\mu$m bandpass is more sensitive to the presence of warm and hot dust than the SPIRE 250 $\mu$m bandpass. This is especially true in our higher-$z$ bins, in which the 70 $\mu$m band probes rest-frame wavelengths $\lambda \lesssim 30 \mu$m. As a result, the $L_{\text{IR}}$ inferred at $\lambda_{\text{obs}} = 70 \mu$m can be more strongly influenced by a small population of galaxies with unusually warm dust than can $L_{\text{IR}}$ inferred at 250 $\mu$m.

Since detected sources contribute more at 70 $\mu$m than at 250 $\mu$m where confused sources dominate, we use a residual image for stacking to avoid contribution from the wings of unrelated bright sources near the target positions. The 70 $\mu$m residual image is constructed by PSF-subtracting all sources detected at 5$\sigma$ significance from the 70 $\mu$m science image using DAOPhot. Stacked images constructed from the residual image yield a flatter background that is consistent with the intrinsic background in the 70 $\mu$m science image. This allows more reliable photometry of the stacked images; however, our use of the residual image requires that we add back the flux from target
positions with detected 70µm counterparts to the flux measured from the stacked image. We determine the mean flux of galaxies in each redshift bin as,

\[
S_{70\mu m} = \frac{(N_{\text{stack}} - N_{\text{det}})S_{\text{stack}} + N_{\text{det}}\langle S_{\text{det}} \rangle}{N_{\text{stack}}}
\] (2.5)

where \(S_{\text{stack}}\) is the flux measured from the stacked image, and \(\langle S_{\text{det}} \rangle\) is the mean flux of detected galaxies. The numbers of sources \(N_{\text{stack}}\) and \(N_{\text{det}}\) indicate the total number of galaxies in the appropriate redshift bin and the number of targets in the stack with detected counterparts, respectively. We tested whether spatial variations in the uncertainties of individual pixels require variance weighting in the mean-combined stacks and found that weighting the stacked images makes no difference in our ability to recover the mean fluxes of galaxies in our source lists. In order to determine the uncertainties associated with each stack, we also generate 2500 mean-combined, bootstrap-sampled image stacks from the residual image.

We use aperture photometry to measure fluxes from the mean-combined images. We measure fluxes in radii of 16′′, equal to the FWHM of the 70µm PSF, and we use annuli extending from \(r = 18′′\) to \(r = 39′′\) to measure the sky flux. The measured fluxes are aperture-corrected to \(r = \infty\) using a multiplicative factor of 1.21\(^2\). The uncertainties are obtained from the RMS dispersion about the mean bootstrapped flux.

### 2.3.3.2 Stacking Cluster Members at 70µm

The most important difference between the analysis applied to stacked images at 70µm and 250µm is the absence of an additional baseline correction to the 70µm fluxes. The requirement to use aperture photometry to measure 70µm fluxes, as opposed to the direct measurement of flux from the brightest pixel in the 250µm

images, means that the fluxes have already been corrected for the elevated background in the clusters. No additional background correction is required. The field correction is applied to the 70µm fluxes as described in Section 2.3.1.2.

2.4 Stacking Results

2.4.1 Deriving the Total L_{IR}, SFRs, and SSFRs from Stacking at 250µm

Using the stacked 250µm flux densities, we infer the average physical properties of our cluster galaxies and field galaxies as a function of redshift and cluster radius, including the total infrared luminosity (L_{IR}), defined over the rest-wavelengths 8-1000µm, star formation rate (SFR), and specific star formation rate (SSFR=SFR/M_\star). Over our redshift range, the 250µm waveband probes the far-infrared portion of a galaxy SED, which is dominated by emission from cold dust heated by star formation. We derive these quantities by comparing to an empirical template developed in Kirkpatrick et al. (2012). This template was formulated using a sample of star forming galaxies at 0.4 < z < 1.4 (L_{IR} \sim 10^{11}L_\odot) selected at 24µm and identified as star forming through IRS spectroscopy. Using deep Herschel imaging over the 100-500µm wavelength range, the dust properties of the template were modeled using a two-component blackbody.

The choice to represent the average properties of star forming galaxies with one template is appropriate given that we are measuring the average flux of similar populations and is consistent with our goal of comparing the average star formation properties of cluster galaxies versus field galaxies as a function of redshift. Template-to-template variations in the far-infrared will be driven by differences in the dust properties of star forming galaxies, which will, to first order, contain a cold dust component from star formation heating of the ISM and warm dust components originating from young star forming regions or AGN emission. In terms of the SED, these details determine the location of the peak of the dust emission and the shape of the
Rayleigh-Jeans tail. Before *Herschel*, only templates from local starbursting galaxies were available for fitting high redshift star forming galaxies; however, these local templates often lacked data spanning 160-850µm and so had difficulty constraining cold dust emission. Multiple studies have shown that high redshift star forming galaxies at the LIRG and ULIRG level may have colder dust than their local counterparts, making the application of local templates to high redshift galaxies problematic (Rowan-Robinson et al., 2004, 2005; Pope et al., 2006; Symeonidis et al., 2009; Seymour et al., 2010; Muzzin et al., 2010; Elbaz et al., 2010; Nordon et al., 2010; Rujopakarn et al., 2011). Using an empirical template with well-sampled far-infrared data and based on high redshift galaxies mitigates some of these concerns; however, we must still address whether it is appropriate to apply one template over the redshift range in this study. Chen et al. (2013) examined the dependence of the scatter in $S_{250}/L_{\text{IR}}$ on differing SED shapes for a sub-set of star-forming $z \sim 1$ galaxies from Kirkpatrick et al. (2012), finding that the deviations in the far-infrared SED shape are reasonably small and the estimation of $L_{\text{IR}}$ from the monochromatic 250µm flux is appropriate for representative star-forming populations. In addition, Hwang et al. (2010a) examined the dust properties of galaxies out to $z=3$ using *Herschel* PACS and SPIRE data and found the relation between the total infrared luminosity and dust temperature to be fairly constant at sub-LIRG luminosities, with a small rise of $\sim 5$K in galaxies with $10^{11} < L < 10^{12} L_\odot$. Based on previous studies (Brodwin et al., 2013) and the rate of detection of cluster members in our shallow SPIRE data, we expect the typical luminosities of our galaxies to be significantly $< 10^{12} L_\odot$. The Hwang et al. (2010a) results then suggest that our galaxies should have fairly consistent dust properties over the redshift range probed. While a different choice in templates may affect the absolute level of the physical properties inferred in this study, it should not affect the differences we quantify between cluster and field galaxies, if the templates are applied consistently. We further test this assumption by stacking the same galaxies at 70µm
in Section 2.4.2. A comparison between the Kirkpatrick et al. (2012) LIRG template and the commonly used Chary & Elbaz (2001) templates can be found in Kirkpatrick et al. (2012).

In the following analysis, we estimate the total L$_{\text{IR}}$ by normalizing the Kirkpatrick et al. (2012) SED template to the stacked 250µm flux densities of our cluster and field galaxy samples. The error associated with the SED template is 40%, which accounts for the spread in the SEDs of high redshift star forming galaxies. From the L$_{\text{IR}}$, we obtain the SFR via the Murphy et al. (2011a) relation

$$\text{SFR}[M_\odot yr^{-1}] = 1.47 \times 10^{-10} L_{\text{IR}}[L_\odot]$$

which assumes a Kroupa IMF (Kroupa, 2001), providing a similar normalization to the Chabrier IMF used to calculate the stellar masses. Specific star formation rates are calculated from the average SFR (obtained from stacking) multiplied by the number of sources stacked divided by the sum of the masses of the galaxies in the stack. The number of sources and total mass are corrected for field contamination in the same manner as the stacked fluxes, by subtracting the total number or mass per unit area of field galaxies from the field-contaminated cluster samples. The error on the total mass in any given bin is determined by bootstrapping.

2.4.2 Evolution of Star Formation in Clusters and Field Galaxies with Cosmic Time

In this section, we examine the average dust-obscured star formation activity in cluster galaxies as a function of environment by comparing cluster galaxies in two projected radial bins, $r < 0.5$ Mpc (core) and $r < 1$ Mpc (core+outskirts), to our field galaxy sample. We examine trends in physical galaxy properties as a function of cosmic time and redshift, to better connect our results to the characteristic timescales of different cluster processes.
In the cluster cores, the average $L_{IR}$ and SFR of our mass-limited sample of cluster galaxies (Figure 2.5, left, black diamonds) rises rapidly as a function of redshift, drawing even with the field activity (blue circles) at $z \gtrsim 1.2$. Our low redshift bin ($\langle z \rangle = 0.5$) has an average SFR $\sim$ few $M_\odot$ yr$^{-1}$, quenched to $\sim$ 30% of the field level. In our highest redshift bin, $\langle z \rangle = 1.4$, the average cluster galaxy SFR is consistent with the field at $\sim 30 M_\odot$ yr$^{-1}$. The $\langle SSFR \rangle$ (Figure 2.5, right) shows a similarly rapid trend, with the ratio of SSFR in the clusters to the field doubling over this redshift range. The clusters are suppressed to $\sim$ 30% of the field level at $\langle z \rangle = 0.5$ versus $\sim$ 75% of field level at $\langle z \rangle = 1.4$. Over our redshift range ($z=0.3$-1.5 or $\sim$ 6 Gyr), the SSFR in cluster galaxies increases an order of magnitude from $\sim$ 0.05 to 0.5 Gyr$^{-1}$.

Including all cluster galaxies out to $r < 1$ Mpc (Figure 2.6) dramatically raises the average SFR in the highest redshift bin to $\sim 60 M_\odot$ yr$^{-1}$. In the radial bin $0.5 < r < 1$ Mpc (not shown), the $\langle z \rangle = 1.4$ bin is detected at the $5\sigma$ level with $\langle SFR \rangle \sim 90 M_\odot$ yr$^{-1}$, three times the $\langle SFR \rangle$ in the cluster cores and the field level, with a $\langle SSFR \rangle \sim 2$ Gyr$^{-1}$.

As a check of our measured average field SFR, we compare our field values to 250$\mu$m stacks of K-band selected field galaxies from the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al., 2007) in the Ultra-Deep Survey (UDS). This field galaxy sample extends down to the same stellar mass limit as used in this work and was stacked using SIMSTACK (M. Viero, private communication; Viero et al., 2013). We convert the average 250$\mu$m of the UDS sample into a $L_{IR}$ and SFR as described in Section 2.4.1 and the results are in good agreement with our field values (Figures 2.5-2.6, yellow squares).
2.4.2.1 Evolution as a Function of Cosmic Time

In order to quantify the evolution of the average SFRs and SSFRs for galaxies in clusters versus the field, we fit both the cluster galaxy stacks (Figure 2.5, black diamonds) and high resolution field galaxy stacks (small blue circles) with a function of the form \( y = \beta e^{\alpha t} \), where \( t \) is cosmic time. The fits were performed using MPFIT (Markwardt, 2009). Table 2.4.2.1 provides a summary of the fit coefficients, where the coefficient uncertainties are the 1\( \sigma \) errors from the covariance matrix as determined by MPFIT and the reduced \( \chi^2 \) values indicate the goodness-of-fit. The average SFRs of cluster galaxies is decreasing with time as \( \langle \text{SFR} \rangle_{\text{cl}} \propto e^{(-0.66\pm0.08)t} \) for the cluster cores versus \( \langle \text{SFR} \rangle_{\text{field}} \propto e^{(-0.42\pm0.005)t} \) in the field. These correspond roughly to e-folding times of 1.5 and 2.4 Gyr, with the star formation in cluster galaxies decreasing \( \sim 2 \) times faster than the field. This e-folding time for field galaxies is consistent with that found to be the median H\(_2\) consumption time for local spiral galaxies (Bigiel et al., 2011). Following this evolution, the average cluster galaxy has SF on par with the average field galaxy at \( z \gtrsim 1.2 \). The \( \langle \text{SSFR} \rangle \) does not quite draw even with the field at the highest redshift that we probe in this study, which may indicate a difference in the stellar mass distributions between cluster and field galaxies, as is hinted at in our stellar mass distributions for cluster and field galaxies (Figure 2.1) and was measured in clusters at \( z \sim 1 \) in van der Burg et al. (2013). We note, however, that the evolution in the \( \langle \text{SSFR} \rangle \) with cosmic time is consistent within the errors with that of the \( \langle \text{SFR} \rangle \) and statistically distinct from the evolution of star formation in field galaxies. This indicates that differences in the stellar mass distributions between cluster and field galaxies cannot be wholly responsible for driving these trends. The fit to \( y = \beta e^{\alpha t} \) for cluster galaxies at \( r < 1 \) Mpc (core+outskirts) is less well constrained, due to the lack of a \( \gtrsim 3\sigma \) detection in the lowest redshift bin, but still shows a significantly faster decline than in the field galaxy population with \( \langle \text{SFR} \rangle_{\text{cl}} \propto e^{(-0.76\pm0.10)t} \).
The reduced $\chi^2$ values for the fit to the high resolution field galaxies stacks indicate that a single exponential function is not a good fit to the data. Fitting two exponential functions to the field galaxies with an break at $z \sim 0.8$ greatly improves the goodness-of-fit and we find that the best-fit $\langle\text{SFR}\rangle$ slopes are significantly different, with $\alpha = -0.53 \pm 0.01$ at $z < 0.8$ and $\alpha = -0.28 \pm 0.01$ at $z > 0.8$. This break is reminiscent of the differential ramp up of LIRGs and ULIRGs in the field with time and the general form of the star formation rate density of the Universe (see Murphy et al., 2011a; Magnelli et al., 2013). Though we are unable to repeat this analysis for our cluster sample due to poorer redshift sampling in the cluster stacks, we note that the cluster galaxy evolution is still distinct from the field at both low and high redshift. A more in-depth look at the evolution of field galaxies as a function of cosmic time is reserved for a future paper.

2.4.2.2 Evolution as a Function of Redshift

Multiple studies have examined cluster properties, such as the star-forming galaxy fraction, number of LIRGs, and total SFR per halo mass (e.g., Bai et al., 2009; Haines et al., 2009; Popesso et al., 2012; Webb et al., 2013), and quantified their evolution as a function of redshift. Though the cluster properties, quantities measured, and sample selection vary greatly between cluster studies, including this work, it is instructive to assume that all of these quantities are related on some level. As such, we compare our average SFR as a function of redshift by fitting the commonly adopted form $y = y_0(1 + z)^n$ to the cluster members and high resolution field stacks, as above.

In the cluster cores ($r < 0.5\,\text{Mpc}$), we find that the evolution of the average SFR goes as $n = 5.6 \pm 0.6$, while in the core+outskirts ($r < 1\,\text{Mpc}$), $n = 5.9 \pm 1.0$. This is statistically distinct from the field, where $n = 3.9 \pm 0.04$. The evolution of the SSFR is similar, with $n = 5.1 \pm 0.7$ (core) and $n = 5.3 \pm 1.1$ (core+outskirts), compared to $n = 4.0 \pm 0.05$ for field galaxies. The coefficients and their reduced $\chi^2$ values are
Table 2.2. Fit coefficients for the \langle SFR \rangle and \langle SSFR \rangle of cluster and field galaxies as a function of cosmic time

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>$\beta^a$</th>
<th>$\alpha^b$</th>
<th>Reduced $\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = \langle SFR \rangle$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clusters ($r &lt; 0.5$ Mpc)</td>
<td>810±400</td>
<td>-0.66±0.08</td>
<td>1.1</td>
</tr>
<tr>
<td>Clusters ($r &lt; 1$ Mpc)</td>
<td>1540±1100</td>
<td>-0.76±0.10</td>
<td>1.0</td>
</tr>
<tr>
<td>Field</td>
<td>267±9</td>
<td>-0.42±0.005</td>
<td>14.0</td>
</tr>
<tr>
<td>Field ($z &lt; 0.8$)</td>
<td>630±60</td>
<td>-0.53±0.01</td>
<td>3.2</td>
</tr>
<tr>
<td>Field ($z &gt; 0.8$)</td>
<td>124±10</td>
<td>-0.28±0.01</td>
<td>1.1</td>
</tr>
<tr>
<td>$y = \langle SSFR \rangle$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clusters ($r &lt; 0.5$ Mpc)</td>
<td>11±6</td>
<td>-0.59±0.08</td>
<td>0.9</td>
</tr>
<tr>
<td>Clusters ($r &lt; 1$ Mpc)</td>
<td>15±12</td>
<td>-0.66±0.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Field</td>
<td>6.4±0.2</td>
<td>-0.45±0.005</td>
<td>16.0</td>
</tr>
<tr>
<td>Field ($z &lt; 0.8$)</td>
<td>17±2</td>
<td>-0.56±0.01</td>
<td>3.5</td>
</tr>
<tr>
<td>Field ($z &gt; 0.8$)</td>
<td>2.8±0.2</td>
<td>-0.30±0.01</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Note. — Fit coefficients for \langle SFR \rangle and \langle SSFR \rangle of galaxies with the functional form $y = \beta e^{\alpha t}$, where $t$ is cosmic time in Gyr. For the field, we fit both the entire range and allow for a break at $z \sim 0.8$. The reduced $\chi^2$ values for each fit are shown in the last column.

$^a\beta$ has units of $M_\odot$ yr$^{-1}$ for $y = \langle SFR \rangle$ and Gyr$^{-1}$ for $y = \langle SSFR \rangle$.

$^b\alpha$ has units of Gyr$^{-1}$. 

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Table 2.3. Fit coefficients for the $\langle \text{SFR} \rangle$ and $\langle \text{SSFR} \rangle$ of cluster and field galaxies as a function of redshift

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>$n$</th>
<th>Reduced $\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = \langle \text{SFR} \rangle$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clusters ($r &lt; 0.5 \text{ Mpc}$)</td>
<td>$5.6 \pm 0.6$</td>
<td>1.8</td>
</tr>
<tr>
<td>Clusters ($r &lt; 1 \text{ Mpc}$)</td>
<td>$5.9 \pm 1.0$</td>
<td>0.6</td>
</tr>
<tr>
<td>Field</td>
<td>$3.9 \pm 0.4$</td>
<td>39.0</td>
</tr>
<tr>
<td>$y = \langle \text{SSFR} \rangle$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clusters ($r &lt; 0.5 \text{ Mpc}$)</td>
<td>$5.0 \pm 0.7$</td>
<td>1.33</td>
</tr>
<tr>
<td>Clusters ($r &lt; 1 \text{ Mpc}$)</td>
<td>$5.3 \pm 1.1$</td>
<td>1.6</td>
</tr>
<tr>
<td>Field</td>
<td>$4.0 \pm 0.05$</td>
<td>32.5</td>
</tr>
</tbody>
</table>

Note. — Fit coefficients for $\langle \text{SFR} \rangle$ and $\langle \text{SSFR} \rangle$ of the functional form $y \sim (1 + z)^n$. The reduced $\chi^2$ values for each fit are shown in the last column.

summarized in Table 2.4.2.2. For further discussion and a comparison with other cluster studies, see Section 2.5.2.

2.4.2.3 Verification at 70$\mu$m

To verify our procedure of choosing a single SED template to measure $L_{\text{IR}}$ and probe the importance of galaxies with unusually warm dust, we have constructed stacks of our galaxy samples at 70$\mu$m. By measuring the $L_{\text{IR}}$ of our galaxy samples using one template, we have made two assumptions: 1) that the SEDs of the galaxies in our samples, in particular their dust properties, do not vary significantly over the redshift range we probe, and 2) that the dust properties of our cluster galaxies do not differ systematically from those of our field galaxies. We outlined some of our
Figure 2.5 Evolution of the average $L_{\text{IR}}$, SFR, and SSFR in cluster galaxies relative to the field. (Left) The top panel shows the $\langle L_{\text{IR}} \rangle$ and $\langle \text{SFR} \rangle$ of cluster galaxies (black diamonds) within a projected radius of 0.5 Mpc versus field galaxies (blue circles) as a function of redshift, while the bottom panel shows the ratio of $\langle L_{\text{IR}} \rangle$ for cluster to field galaxies. The large blue circles are the field stacked in the same redshift bins as cluster galaxies while the smaller blue circles are field galaxies in higher resolution redshift bins with width 0.1. We fit the cluster member and high resolution field galaxy stacks with the function $y = \beta e^{\alpha t}$ (black and blue solid lines respectively) to quantify the rapid rise of the SF activity in cluster members as a function of redshift as compared to the field. The shaded regions show the 1σ errors on the fits. The dashed purple line shows that the high resolution field stacks are better fit by two $y = \beta e^{\alpha t}$ functions, broken at $z=0.8$. The filled yellow squares are field galaxies from UDS, stacked using SIMSTACK (Viero et al., 2013). (Right) The same for $\langle \text{SSFR} \rangle$, which shows that the differences in average SF properties between cluster and field galaxies cannot be fully accounted for with mass differences between the two populations. The green, dashed-dot lines denote the boundaries of the infrared Main Sequence as defined in Elbaz et al. (2011). The large error bar represents the uncertainties associated with the Kirkpatrick et al. (2012) template SED and stellar mass estimates.
justifications for these assumptions in Section 2.4.1 and here we further test them by repeating our stacking analysis at 70µm, a waveband which probes the warm dust component of a galaxy’s SED (see Section 2.3.3 for the 70µm stacking procedure).

Figure 2.7 shows the ratio of the L_{IR} as derived from the average 70µm and 250µm fluxes as a function of redshift for cluster galaxies (red) and field galaxies (purple). The red shaded region shows the scatter associated with the (Kirkpatrick et al., 2012) SED template, which was derived from a field galaxy population. The 70µm data slightly overpredicts the L_{IR} as compared to 250µm at z > 0.8, which may be due to increased warm dust caused by AGN activity, which is known to increase with redshift (e.g., Ueda et al., 2003; Richards et al., 2006; Galametz et al., 2009; Martini et al., 2013). We verified that the removal of AGN identified in our X-ray and mid-IR data did not significantly change the 70µm stacked flux measurements. However, given the uncertainties in the 70µm fluxes and our AGN selection, this does not necessarily rule out the contributions from lower luminosity AGN. At low redshift, the 70µm data slightly underpredicts the L_{IR} relative to 250µm, which may indicate that our chosen template has insufficient cold dust to represent the average low redshift galaxy at the low IR luminosities we are probing (L_{IR} \sim 10^{10}L_\odot) (e.g., Hwang et al., 2010a; Symeonidis et al., 2013). All points, however, fall within the expected scatter of the SED template, for both cluster and field samples. This indicates that our use of one SED template to compare cluster and field galaxies as a function of redshift is robust. When the cluster and field galaxy L_{IR}^{70\mu m} are used to calculate SFRs and SSFRs as a function of cosmic time as in Figure 2.5, we find that the general trends are preserved, with cluster galaxies in the cluster cores showing a rapid evolution relative to the field.
Figure 2.6 The same as Figure 2.5, but with a projected radius of 1 Mpc (cluster core+outskirts).

Figure 2.7 The ratio of the $L_{IR}$ for cluster (red stars) and field galaxies (purple triangles) derived from stacking at 70$\mu$m and 250$\mu$m. The red, shaded band shows the scatter associated with the Kirkpatrick et al. (2012) SED template used to calculate the $L_{IR}$. All points fall within the expected scatter of the SED template, indicating that the template represents both the average warm and cold dust properties of the cluster and field galaxy samples as a function of redshift.
2.4.3 Evolution of Cluster and Field Galaxies with Respect to Stellar Mass

We examine the average $L_{\text{IR}}$, SFR, and SSFR as a function of stellar mass by breaking our cluster and field samples into two stellar mass bins: $1.3 \times 10^{10} < M_\star < 6.3 \times 10^{10} M_\odot$ and $M_\star > 6.3 \times 10^{10} M_\odot$, chosen as roughly the middle value in the mass range we probe. The results are as follows. In the cluster cores, we find that the $\langle \text{SSFR} \rangle$ of the higher mass galaxies (Figure 2.8, upper right) is suppressed at $\sim 70\%$ of the field SSFR but otherwise shows no strong differential evolution with respect to the field as a function of redshift. Conversely, in the cores+outskirts, the higher mass galaxies show a stronger evolution relative to the field galaxies (lower right). This suggests that multiple mechanisms may be responsible for the evolution of high mass galaxies in the cores versus the outskirts. The lower mass cluster galaxies (left), on the other hand, are the primary drivers of the field-like star formation activity in the full galaxy population at high redshift (Figure 2.5). This is true in both the cores (upper left), where the lower mass galaxies show field-like star formation in the $\langle z \rangle = 1.2 - 1.4$ bins, and in the core+outskirts (lower left), where the low mass galaxies are experiencing enhanced star formation above the field level. The average $L_{\text{IR}}$ and SFRs in these stellar mass bins show the same trends as the $\langle \text{SSFR} \rangle$.

2.4.4 The Evolution of Star-Forming, Blue Galaxies in Clusters vs. the Field

In this section, we separate out star forming galaxies in order to analyze whether the evolutionary trends we see are due to a change in the properties of currently star forming galaxies. As part of the process of deriving photometric redshifts, each galaxy is matched to a best fit template chosen to represent late-type galaxies (Sb, Sc, Sd, Spi4, and M82) and early-type galaxies (Ell5, Ell13, S0, and Sa) from Polletta et al. (2007) using optical and near-infrared photometry (see Section 2.2.1.1). Whether a
Figure 2.8 The \( \langle \text{SSFR} \rangle \) for cluster (black diamonds) and field (blue circles) galaxies as in Figure 2.5, but for mass bins \( 1.3 \times 10^{10} < M_* < 6.3 \times 10^{10} M_\odot \) (left) and \( M_* > 6.3 \times 10^{10} M_\odot \) (right). The top panels show cluster members out to projected radius of 0.5 Mpc (core) and the bottom panels show out to 1 Mpc (core+outskirts). In the cluster cores, the evolution in star formation activity seems to be dominated by the lower mass galaxies, as the higher mass galaxies show no strong differential evolution with respect to the field, though they are suppressed below the field level at all redshifts. When the outskirts are included we see that all cluster galaxies are on average evolving more rapidly than the field, with the lower mass galaxies showing enhancement over the field in the highest redshift bin. The green, dashed-dot lines denote the boundaries of the infrared Main Sequence as defined in Elbaz et al. (2011).
galaxy is best-fit to a late-type or early-type template depends predominantly on the strength of its 4000Å break. This allows us to roughly separate our galaxy samples into “blue” (late-type) and “red” (early-type) sub-samples. This selection is similar to traditional methods of using rest-frame optical colors which bracket the 4000Å break to separate galaxies into star forming and quiescent categories. The process of matching the best-fit template for deriving photometric redshifts is applied in the same way to both cluster and field galaxies, meaning that we can consistently compare blue or red galaxies in the cluster to those in the field using this selection.

We note that, using this selection technique, galaxies fit to early type templates may be truly passive or may be star forming galaxies that are so heavily dust-obscured as to look red. By matching to MIPS 24µm, we find that 15-30% of galaxies best-fit by early-type templates have a corresponding MIPS detection within 4″. Unfortunately, the MIPS catalog is too shallow to detect the characteristic L_{IR} of our sample at z \gtrsim 1 and so gives an incomplete census of contamination as well as introducing complications from AGN contamination. As such, we focus on the blue galaxies as a representative sample of star forming galaxies with non-extreme dust properties and determine their average L_{IR}, SFR, and SSFR properties, with the caveat that we are likely missing some fraction of heavily dust-obscured star formation, a fraction which will grow more significant with increasing redshift.

In Figure 2.9, we compare the average SFR (left) and SSFR (right) of blue galaxies in the cluster cores versus the field. We find that the evolution of \langle SFR \rangle shows an increase with redshift compared to the field, as we saw with the full sample in Figure 2.5; however, when the stellar mass of the blue galaxies is taken into account for the \langle SSFR \rangle, the star forming galaxies no longer show a strong evolution relative to the field over time, though they are suppressed at \sim 70% of the field SSFR. At \langle z \rangle = 1.4, the average SFR in the cluster cores is consistent with the field, but the average SSFR is lower. This may be an indication that the stellar mass function of
blue, star forming galaxies is different in clusters versus the field at these redshifts. At lower redshifts, on the other hand, the average SFR and SSFR are both quenched below the field level. Taken together, these two plots indicate that both the SFRs and stellar mass distributions in cluster galaxies relative to the field may be different over our redshift range. In the core+outskirts (not shown), the average SFR and SSFR behave in the same manner with the exception of the $\langle z \rangle = 1.4$ bin, which again has enhanced star formation of 1.7 times the field SFR and 1.2 times the field SSFR.

We compare our results to a recent study which looked at the average SSFRs in star forming cluster galaxies from $z = 0.15 - 0.3$. Haines et al. (2013) too found that the SSFR does not show a strong differential evolution relative to the field, but that the average SSFR is suppressed below the field level. We show the Haines et al. (2013) results in Figure 2.9 (right), where we also indicate the region which corresponds to the infrared Main Sequence (Elbaz et al., 2011). Our star-forming galaxy samples, both cluster and field, fall on the Main Sequence at all redshifts.

2.5 Discussion

As cluster studies push to higher and higher redshifts, the challenge becomes not just to explain the signature properties of local clusters – the strong, red sequence of passively evolving galaxies – but to constrain the epoch in which clusters were engaging in active mass build-up, with the star formation necessary to assemble present-day massive ellipticals. Using a uniform sample of clusters ($\approx 10^{14} M_\odot$), we have demonstrated that the average $250 \mu$m flux (and by extension the dust-obscured SFR) of cluster galaxies is quenched below the field level across most of cosmic time, $\approx 8$ Gyr, but with a rapid evolution in which the average SFR of cluster galaxies draws even with the field in the cluster cores at $z \gtrsim 1.2$, with enhanced SF above the field level in the cluster outskirts. We measure an e-folding time for the evolution in the cluster cores of $\approx 1.5$ Gyr over $0.3 < z < 1.5$. This is consistent with the findings
Figure 2.9 The evolution of star forming galaxies in cluster cores versus the field. The average $L_{\text{IR}}$ and SFR (left) and average SSFR (right) for cluster galaxies (black diamonds) versus field galaxies (blue circles) as in Figure 2.5 for blue galaxies only. Though the average SFR shows a rapid decline with cosmic time compared to the field, the average SSFRs show no strong differential evolution with respect to the field. The blue and black lines show the evolution of all galaxies with cosmic time, as seen in Figure 2.5. In the bottom panels, the filled, gray diamonds show the ratio of $L_{\text{IR}}$ for all cluster to field galaxies as in Figure 2.5. The dashed-dot green lines show the region of SSFR as a function of redshift denoted the infrared Main Sequence (Elbaz et al., 2011). The blue and black squares are average SSFRs for star forming cluster (open squares) and field (filled squares) galaxies at $z = 0.18 - 0.22$ (Haines et al., 2013).
of (Brodwin et al., 2013), who looked at cluster members detected at 24µm from 1.0 < z < 1.5 and found a sharp transition from active to quenched SF. Here we explore what mechanisms might be responsible for the evolution we observe.

### 2.5.1 Quenching Mechanisms

Several pieces of evidence presented here give us clues about the processes involved in the quenching of star formation activity in cluster galaxies. We find that in the cluster cores (r < 0.5 Mpc), the full population of cluster galaxies (Figure 2.5) shows significant quenching over the redshifts we probe, starting with field-like SF activity at z ∼ 1.2 and quenching with an e-folding time of ∼ 1.5 Gyr. This is considerably faster than the e-folding time of SF in field galaxies, ∼ 2.4 Gyr, where galaxy evolution is likely driven by mass-quenching, gas accretion, and/or AGN (Mo, van den Bosch, & White, 2010). This rapid evolution is seen in both the average SFR and SSFR, the latter suggests that these trends cannot be fully explained by a different stellar mass functions for cluster and field galaxies.

When broken into sub-populations, our cluster galaxies suggest that multiple processes are likely operating in these clusters. High mass cluster galaxies (M > 6.3×10^{10}) in the cores show no strong evolution relative to the field, which may indicate that their evolution is dominated by mass-quenching. This is consistent with the results of Peng et al. (2010), who found that galaxies of these masses are dominated by internal evolution regardless of environment. High mass galaxies in the cluster outskirts, however, do show a more rapid evolution relative to the field. Lower mass galaxies show a more rapid evolution at all redshifts and radii, with field-like star formation in the cores at high redshift and enhanced star formation in the outskirts.

Blue, star forming galaxies show a strong evolution relative to the field in their SFRs, but no strong evolution in their SSFRs. Unlike the full galaxy populations, this suggests that the evolution in blue galaxy SFRs could be fully explained by different
stellar mass functions between cluster and field for blue galaxies specifically. This would be consistent with studies of low redshift massive clusters, where measures of the Hα luminosity function (Kodama et al., 2004) and mid-IR SFRs (Bai et al., 2009; Haines et al., 2009) were found to be largely independent of environment. Haines et al. (2013) found a similar trend with the SSFR in low redshift clusters (see Section 2.5.2).

Taken together, these observations suggest that multiple cluster-specific processes may be driving the evolution of sub-populations of cluster galaxies in different cluster regions, while other dusty galaxies (high mass, core galaxies) may be dominated by mass-quenching. If the trends seen in the SFRs of blue, star forming galaxies can be explained as differences in the stellar mass distribution of cluster galaxies, then the evolution of the full population may be driven by the rapid transition of star forming galaxies to the quiescent galaxy population through the effective shut down of SF. This is supported by Brodwin et al. (2013), who found a strong transition to lower SFRs below $z \sim 1.3 - 1.4$ in $z > 1$ ISCS clusters using MIPS 24µm observations and concluded that these trends can be explained by merger-driven star formation followed by rapid AGN quenching in $z \gtrsim 1.5$ clusters. These observations further support Muzzin et al. (2012), who found a lack of correlation between SSFR and $D_n(4000)$ in star forming galaxies with environment at $z \sim 1$ and a high post-starburst fraction. They concluded that star forming galaxies are transitioning to the quiescent population on rapid timescales at higher redshifts. This transition would require that the cold gas which fuels star formation in galaxies be consumed, heated, or removed. In this work, we have observed evidence for the previously suggested mergers at high redshifts in the cluster outskirts; however, we do not see enhanced star formation on average at lower redshifts and radii (though this does not rule out dry mergers). A more likely scenario for ongoing quenching at lower redshifts and in the cluster cores may involve the removal of gas. This is supported by local observations, which have found cluster galaxies to be increasingly deficient in HI gas close to cluster
centers (Haynes, Giovanelli, & Chincarini, 1984; Solanes et al., 2001; Hughes et al., 2009) as well as cluster galaxies with truncated gaseous disks (e.g., Koopmann & Kenney, 2004; Koopmann, Haynes, & Catinella, 2006) and long extra-galactic tails of HI gas (Chung et al., 2007). The two main processes that remove gas in galaxies in dense environments are strangulation (Larson et al., 1980) and ram pressure stripping (Gunn & Gott, 1972). For a review of cluster processes in general, see Boselli & Gavazzi (2006).

Strangulation, the removal of loosely-bound hot halo due to the intracluster medium (ICM) and global tidal field of the clusters, is capable preventing the refueling of galaxies over several Gyr. Unlike their analogues in the field, cluster galaxies can no longer accrete fresh, cold gas once they enter a region with a hot, dense ICM. This lack of fresh gas may lower their SFR relative to field galaxies on long timescales and we suggest this may be responsible for the lower SSFRs of high mass galaxies in the cluster cores.

Ram pressure stripping (RPS), the removal of the ISM by the hot ($\sim 10^7 - 10^8$ K), dense ($\sim 10^{-3} - 10^{-4}$ atoms cm$^{-3}$) ICM, can operate efficiently on galaxies with high orbital velocities ($\sim 1000$ km s$^{-1}$), loosely bound ISMs such as in intermediate to low mass galaxies, and in clusters with short crossing times. Hydrodynamical simulations of individual galaxies using the Gunn & Gott (1972) RPS estimation found the timescale for gas removal to be $\sim 10 - 100$ Myr (Abadi et al., 1999; Quilis, Moore, & Bower, 2000; Marcolini, Brighenti, & D’Ercole, 2003; Roediger & Bruggen, 2006, 2007; Kronberger et al., 2008). As such, lower mass galaxies near the cluster cores may see their gas stripped away on short timescales, stopping their SF and adding them to the passively evolving galaxy fraction.
2.5.1.1 A Back-of-the-envelope Calculation for Gas Depletion

By making some simplifying assumptions, we can link our measured $\langle L_{IR} \rangle$ for cluster and field galaxies to the fraction of galaxies which retain gas between $z=1$ and $z=0.5$. We first assume that if a galaxy has gas, then it contributes a fixed amount to the average $L_{IR}$, $\ell_{IR,g}$; if it contains no gas, it contributes nothing. If the fraction of galaxies that retain their gas is given by $f_g(z)$ and the total number of galaxies is $N_g(z)$ then

$$\langle L_{IR}(z) \rangle = \frac{\Sigma L_{IR}(z)}{N_g(z)} \approx \frac{f_g(z)N_g(z)\ell_{IR,g}(z)}{N_g(z)} = f_g(z)\ell_{IR,g}(z).$$

(2.7)

Consider the field-normalized ratio of the average $L_{IR}$ of cluster galaxies at $z=1$ to $z=0.5$, $Q$,

$$Q = \frac{\langle L_{IR}^{cl}(z = 1) \rangle}{\langle L_{IR}^{cl}(z = 0.5) \rangle} / \frac{\langle L_{IR}^{field}(z = 1) \rangle}{\langle L_{IR}^{field}(z = 0.5) \rangle}$$

(2.8)

We further assume that the fraction of galaxies with gas in the field does not change significantly, $f_g^{field}(z=1) = f_g^{field}(z=0.5) = 1$, and that, in the absence of gas stripping, the contribution to the total IR luminosity for cluster galaxies which retain their gas is equal to contributions from field galaxies: $\ell_{IR,g}^{cl}(z) = \ell_{IR,g}^{field}(z)$ (this assumption breaks down on the timescales of strangulation). This simplifies $Q$ to a simple ratio of the fraction of galaxies that retain gas in clusters at $z=1$ to at $z=0.5$: $Q \approx \frac{f_g^{cl}(z=1)}{f_g^{field}(z=0.5)}$. From
Equation 2.8, the ratio of our average $L_{IR}$ for cluster and field galaxies across $z=0.5-1$ is then approximately the fraction of galaxies which retain gas over the same redshift range. We calculate $Q \approx 1.8 \pm 0.7$ from our observations at $r < 0.5 \, \text{Mpc}$ (Figure 2.5).

2.5.1.2 Comparison to a Ram Pressure Stripping Simulation

Tecce et al. (2010) performed a self-consistent estimation of the effects of ram pressure stripping in moderate to high mass clusters using a semi-analytic model of galaxy formation combined with hydrodynamical simulations of galaxy clusters. They calculated the fraction of galaxies which have been stripped of their gas as a function of cluster-centric radius and redshift, finding that out to the virial radius of $\sim 10^{14} \, M_\odot$ clusters, this fraction increases by a factor of 2 from $z=1$ to $z=0.5$. Their simulations consider galaxy velocities of 700-3000 km s$^{-1}$ and note that the ICM density increases an order of magnitude from $z=1$ to the present day (with $\rho_{ICM} \sim 10^{-6} - 10^{-3}$ atoms cm$^{-3}$ at $z=1$).

From Tecce et al. (2010), we determine the simulated fraction of cluster galaxies that retain their gas from $z=1$ to $z=0.5$ at a radius of 0.5 Mpc for $\sim 10^{14} \, M_\odot$ clusters is $Q = 1.5 \pm 0.3$ (Tecce et al., 2010), while our observations show $Q \approx 1.8 \pm 0.7$. Given this simple calculation, our observations are consistent with ram pressure stripping playing a prominent role in the removal of gas from star forming galaxies in the ISCS cluster cores. Currently, similar theoretical predictions do not exist for strangulation, though it too may play a role in SF quenching. In addition to the simplifying assumptions we’ve made, we note two caveats: 1) the velocity dispersions of the ISCS clusters are $\sim 700$ km s$^{-1}$ (Brodwin et al., 2011), lower than the typical velocities at which RPS is thought to be efficient. As the scatter for the individual galaxy velocities within the ISCS is unknown, the fraction of galaxies for which RPS may be relevant is also unknown. And 2) hydrodynamical simulations have found that $\sim 30$
per cent of a galaxy’s hot halo gas may remain intact even 10 Gyr after the initial infall (McCarthy et al., 2008).

2.5.1.3 Mergers and Active Galactic Nuclei

In Figure 2.6, we see a striking increase in the average SFR and SSFR of cluster galaxies over the field at high redshift when we examine the cluster outskirts. Detected at the 5σ level, the 250µm flux in the \( \langle z \rangle = 1.4, 0.5 < r < 1 \) Mpc bin reveals a \( \langle \text{SFR} \rangle \) (\( \langle \text{SSFR} \rangle \)) of \( \sim 3 \) (~ 2) times the field level at the same redshifts (though the average SSFR is still within the infrared Main Sequence; Elbaz et al., 2011). One possible explanation for this enhanced activity is galaxy mergers, which operate in dense environments where galaxy velocities are moderate. Mergers have been observed at high redshift (Bridge et al., 2010; Lotz et al., 2011) and a recent study of a \( z=1.4 \) cluster using Herschel found that ULIRGs were primarily residing in the cluster outskirts \( (r > 250 \) kpc), with half of the PACS detected sources showing the disturbed morphologies indicative of merger activity (Santos et al., 2013).

Mancone et al. (2010) presented statistical evidence for rapid mass assembly in the ISCS (consistent with merger activity) by examining the rest-frame 3.6 and 4.5µm luminosity functions for cluster galaxies over the redshift range \( z = 0.3 - 2 \), finding that the characteristic magnitude \( m^* \) was well described by passive evolution models up until \( z \sim 1.4 \), above which \( m^* \) is abruptly fainter. This shift in the characteristic 3.6 and 4.5µm magnitudes, a proxy for the characteristic stellar mass, can be explained by an increase in the merger rate. These results are corroborated by a study of the SSFR in 16 ISCS clusters between \( z=1-1.5 \) using MIPS 24µm imaging, which finds substantial star formation occurring at all cluster-centric radii and a transition epoch from passively evolving to actively star forming at \( z \sim 1.4 \) (Brodwin et al., 2013). Mergers can both greatly enhance star formation and quickly quench it, as simulations show that mergers often trigger substantial AGN feedback that expels the
remaining gas and ends star formation; this process operates on timescales of $\sim 100$ Myr (Springel et al., 2005; Hopkins et al., 2006; Narayanan et al., 2010). The fraction of AGN has been found to increase by two orders of magnitude within the ISCS sample over $z=0-1.5$ (Galametz et al., 2009; Martini et al., 2013). In our sample, we see that the enhanced star formation is occurring primarily in lower mass galaxies, consistent with the Mancone et al. (2010) results and with studies of the merger rate which find that higher mass galaxies ($\gtrsim 5 \times 10^{10} M_\odot$) are undergoing fewer mergers than low mass galaxies (Bridge et al., 2010; Lotz et al., 2011). We note that there may also be minor or dry mergers, even at radii or redshifts where we don’t see enhanced star formation activity.

Though the accretion of galaxy groups onto clusters has also been posited to enhanced star formation and lead to the rapid consumption of gas (Miller & Owen, 2003; Poggianti et al., 2004; Coia et al., 2005; Ferrari et al., 2005), this process is expected to be more or less continuous over the last 10 billion years (Berrier et al., 2009), which would not explain the abrupt transition from enhanced to quenched that we see in the cluster outskirts (Figure 2.6). Multiple lines of evidence are pointing toward a prominent role for mergers in the evolution of the ISCS clusters. Deep Herschel PACS imaging will be used to take a closer look at the radial dependence of the (U)LIRG population in high redshift ISCS clusters in Chapter 3.

2.5.2 Comparison of the Evolution of the SFR in Clusters to Other Studies in the Literature

The most direct comparison to our study is a recent work by Haines et al. (2013), who looked at the average SSFRs of massive ($M \gtrsim 10^{10} M_\odot$) star forming galaxies out to $r_{200}$ in 30 galaxy clusters from $0.15 < z < 0.3$. Though their clusters are on average more massive than ours ($\sim 10^{14} - 10^{15} M_\odot$), we probe to similar depths in $L_{IR}$ ($\sim 1 \times 10^{10} L_\odot$). We find remarkable agreement in that their star forming
cluster galaxies also show little differential evolution with respect to the field, but
are suppressed below the field level by 28 per cent (see Figure 2.9 for comparison).
They further determine that this holds for fixed stellar mass, indicating it is caused
by changes in the SFRs at these redshifts. Haines et al. (2013) concludes that this
systematic reduction of the SFRs in cluster galaxies is due to long timescale (∼1 Gyr)
quenching, such as strangulation or ram pressure stripping. Combined, our results
suggest that the suppression of the SSFRs in star forming cluster galaxies exists over
a long redshift baseline (0.15 < z < 1.5), which may indicate a common quenching
mechanism in low and high redshift clusters.

In Section 2.4.2.2, we quantified the evolution of the average SFR and SSFR as a
function of redshift in order to compare to other work in the literature. We found that,
when quantified via the function \( y = y_0 (1 + z)^n \), the average SFR of cluster galaxies
goes as \( n = 5.6 \pm 0.6 \) in the cluster cores and \( n = 5.9 \pm 1.0 \) in the core+outskirts. We
compare the evolution of the average SFR to two popular quantities in the literature:
the total SFR per halo mass, \( \Sigma(\text{SFR})/M_{\text{halo}} \), which is particularly useful measurement
for comparing systems of different mass, and the fraction of star-forming galaxies, \( f_{\text{SF}} \).
Several studies have found that the redshift dependence of the total SFR per halo
mass goes as \( n \sim 5-7 \) (Kodama et al., 2004; Finn et al., 2004, 2005; Geach et al., 2006;
Bai et al., 2009; Chung et al., 2010; Koyama et al., 2010; Hayashi et al., 2011; Popesso
et al., 2012; Webb et al., 2013; Haines et al., 2013). Given that our cluster sample
is uniform in mass across our redshift range, we can fairly compare the evolution of
our average SFR to this quantity. The evolution of \( f_{\text{SF}} \) is somewhat less constrained
with \( f_{\text{SF}} \propto (1 + z)^{2-7} \) (Kodama et al., 2004; Geach et al., 2006; Saintonge et al.,
2008; Bai et al., 2009; Haines et al., 2009; Webb et al., 2013; Haines et al., 2013).
Comparing to this quantity is interesting, however, given the suggestion that the
evolution we see in the SF activity in our full cluster galaxy population is dominated
by the changing fraction of star forming galaxies. Comparisons between our results
and these literature results are complicated as we are measuring different quantities and have different cluster masses, cluster selection, galaxy selections, SFR tracers, and redshift ranges. Nevertheless, we find good agreement between our measured evolution of the average SFR and the measured evolution of both $\Sigma$(SFR)/$M_{\text{halo}}$ and $f_{\text{SF}}$ from previous works. In particular, we note the high redshift cluster studies of Webb et al. (2013), who looked at IR-luminous ($L_{\text{IR}} > 2 \times 10^{11}L_\odot$) galaxies in 42 red-sequence selected cluster from $0.3 < z < 1$. They found evolutions of $n = 5.4 \pm 1.5$ for the total SFR per halo mass and $n = 5.1 \pm 1.9$ for the star forming fraction. Given this consistent evolution between these quantities and between our studies (and others), this indicates that the total SFR per halo mass in cluster galaxies could be tightly correlated with the star forming fraction in clusters over a range of luminosities and that different cluster samples may be experiencing similar quenching mechanisms over a range of redshifts.

At $z > 1$, our findings provide important direct support for conclusions drawn from previous investigations of the ISCS clusters. In particular, we have shown field-level star formation rates, indicating ongoing stellar mass assembly, at $z > 1.2$, matching the inference based on the near-IR luminosity function evolution of cluster members by Mancone et al. (2010). In addition, we have shown that, at $z \lesssim 1.2$, one or more processes are rapidly halting star formation in some of these cluster galaxies (Figure 2.5-2.6). In combination, these scenarios can explain the nearly constant color of the optically defined quiescent galaxies in ISCS clusters (Snyder et al., 2012): at any given time, the population of red cluster galaxies reflects the extended star formation histories of the previous star forming galaxies that have been very rapidly quenched in their past, possibly in a stochastic manner. Therefore we conclude that there is broad agreement between the scenarios implied by the stellar mass build-up of cluster galaxies, the apparent stellar age evolution of cluster ellipticals, and the SFRs of cluster galaxies as measured directly (this work; Brodwin et al., 2013).
2.6 Conclusions

In this work, we have used a large, uniform cluster sample over a long redshift baseline (z=0.3-1.5) in order to analyze the star formation activity in cluster galaxies relative to the field as a function of cosmic time. Through a stacking analysis, we have probed to low infrared luminosities and determined the average $L_{IR}$, SFRs, and SSFRs by measuring the average $250 \mu m$ flux of mass-limited samples of thousands of cluster galaxies and tens of thousands of field galaxies. Using robust, statistical methods, we have accounted for source blending/clustering bias and field galaxy contamination (due to photometric redshift uncertainties) in our cluster galaxy stacking. Our main results are as follows.

1. Our full (star-forming and quiescent) cluster galaxy sample exhibits rapid evolution with cosmic time as compared to the field. We quantify this evolution as an exponential function of time and find that cluster galaxies in the cluster cores ($r < 0.5 \text{ Mpc}$) have an e-folding time of $\sim 1.5 \text{ Gyr}$, as compared to $\sim 2.4 \text{ Gyr}$ for field galaxies. The average SFR in the cluster cores is quenched below the field level for much of cosmic time ($\sim 9 \text{ billion years}$) but draws even with the field at $z > 1.2$. When accounting for stellar mass by measuring the SSFR, the core cluster galaxies don’t quite draw even with the field up to $z \sim 1.5$, but still show a statistically faster evolution than the average SSFR of field galaxies (see Table 2.4.2.1). In the cluster outskirts ($0.5 < r < 1 \text{ Mpc}$), we see enhanced SFRs (SSFRs) of $\sim 3 \sim 2$ times the field level at $\langle z \rangle=1.4$, likely due to increased merger activity among the infalling galaxy population. These results confirm the transition epoch toward active star formation and mass assembly at $z \sim 1.4$ seen in previous studies.

2. When divided into lower and higher mass bins, we see that the SSFRs of the higher mass galaxies ($M_* > 6.3 \times 10^{10} M_\odot$) in the cluster cores are quenched
below the field level, but otherwise show no strong differential evolution relative to the field. We suggest that strangulation from the hot cluster ICM is responsible for the lower level of star formation, but that the overall evolution with time of the higher mass cluster galaxies is dominated by the same mechanism as higher mass field galaxies, i.e. mass-quenching. Lower mass galaxies ($1.3 \times 10^{10} < M_* < 6.3 \times 10^{10} M_\odot$) seem to be driving the differing evolution from the field galaxies in the cluster cores with SSFRs that begin reaching the field level at $z > 1.2$. In the outskirts, both mass bins show a more rapid evolution in the clusters than the field, with lower mass galaxies showing enhanced SF at $\langle z \rangle = 1.4$, which may suggest that lower mass galaxies are preferentially experiencing major mergers which trigger starbursts.

3. We find that though the $\langle SFR \rangle$ of blue, star forming galaxies decreases faster than blue galaxies in the field, the SSFR of blue galaxies shows the same behavior as high mass galaxies (suppressed below the field but with no strong differential evolution). The exception is the the cluster outskirts at $\langle z \rangle = 1.4$, where blue galaxies show enhanced SF activity. This suggests that environment could be strongly effecting the SFRs and/or stellar mass distributions of blue, star forming galaxies in clusters.

4. We suggest that our results are consistent with both strangulation and ram pressure stripping operating in these clusters, and increased merger activity occurring in the cluster outskirts at high redshift. Strangulation, a long timescale process, may particularly be affecting high mass galaxies in the cluster cores. Ram pressure stripping, a shorter timescale process, may control our fraction of star forming to quiescent galaxies, driving the trend that we see in the full cluster sample. Mergers and AGN provide a natural explanation for enhanced star
formation activity and quenching on short timescales in the cluster outskirts at $\langle z \rangle = 1.4$.

This study has probed the average star formation properties of cluster galaxies relative to the field using a large cluster sample over a wide range in redshift. Individual cluster galaxy SF properties will be examined for high redshift ($z=1-2$) ISCS clusters using deep Herschel PACS (PI: Alexandra Pope) imaging in Chapter 3.
CHAPTER 3
THE RISE OF STAR FORMATION AND AGN ACTIVITY IN $z = 1 - 2$ GALAXY CLUSTERS: A MULTI-WAVELENGTH ANALYSIS FEATURING DEEP HERSCHEL PACS IMAGING

3.1 Introduction

A detailed and complete understanding of galaxy evolution requires placing galaxies in a cosmological context, describing their properties in relation to their environment over cosmic time. Studies of galaxy clusters locally show a strong anti-correlation between star formation rate (SFR) and galaxy density, with the highest density environments containing massive, red, passively evolving early-type galaxies (ETGs). Star-forming galaxies (SFGs) avoid the dense cores of local clusters, residing primarily on the outskirts and in the field where they are likely experiencing pre-processing as infalling galaxies or groups (e.g. Bai et al., 2009; Chung et al., 2010; Cybulski et al., 2014). Environmental quenching is highly efficient at low redshift, observed as far from the cluster cores as three times the virial radius (Chung et al., 2011). Optical and near-infrared (NIR) analyses of the color and luminosity function of cluster galaxies at $z < 1$ favor cluster formation models with high formation redshifts ($z \gtrsim 2 - 3$), in which clusters form in a burst of intense star formation activity and then passively evolve to $z \sim 0$ (e.g. Stanford et al., 1998; Blakeslee et al., 2006; Eisenhardt et al., 2008; Mei et al., 2009). Recent analyses of clusters at $z = 1 - 2$, however, are challenging this model by presenting evidence of an epoch of active star formation in cluster galaxies (Brodwin et al., 2013, Chapter 2).
Direct observations of star formation in clusters at \( z \lesssim 1 \) support both predictions of a high formation redshift and a rapid evolution of cluster populations. The fractions of Luminous Infrared Galaxies (LIRGs; \( 1 \times 10^{11} \, L_\odot < L_{\text{IR}} < 1 \times 10^{12} \, L_\odot \)) and Ultra-Luminous Infrared Galaxies (ULIRGs; \( L_{\text{IR}} > 1 \times 10^{12} \, L_\odot \)) are known to be steadily increasing in cluster environments up to \( z \sim 0.8 \) (Coia et al., 2005; Geach et al., 2006; Marcillac et al., 2007; Muzzin et al., 2008; Koyama et al., 2008; Haines et al., 2009; Smith et al., 2010; Chung et al., 2011; Webb et al., 2013). Measurements of the integrated star formation rate (SFR) per unit halo mass in clusters have also been found to be evolving as fast or faster than the field, \((1 + z)^{5-7}\) up to \( z \sim 1 \) (Saintonge et al., 2008; Webb et al., 2013; Haines et al., 2013). Despite this evolution in star forming populations, however, dense cluster cores are still characterized by significant quenching up to \( z \sim 1 \) (e.g. Patel et al., 2009; Muzzin et al., 2012), consistent with the local SFR-density relation.

Studies at \( z \gtrsim 1 \) are presenting a different picture. Evidence for a departure from passive evolution models at high redshift was presented in Mancone et al. (2010), which demonstrated that the NIR luminosity function of cluster galaxies deviates from the predicted models at \( z > 1.3 \), much lower than the expected formation redshift. In the field, Scoville et al. (2013) analyzed a large dynamical range of environments, finding that the correlation between ETGs and density becomes much weaker at \( z > 1.2 \). More recently, as more clusters are identified at \( z > 1 \), studies of individual clusters have found examples of increasing star formation as a function of galaxy density, right into cluster cores (Tran et al., 2010; Hilton et al., 2010; Hayashi et al., 2011; Fassbender et al., 2011; Tadaki et al., 2012; Bayliss et al., 2013; Santos et al., 2014).

Most of the emission from star formation is re-processed by dust in high redshift galaxy populations (e.g. Murphy et al., 2011a; Magnelli et al., 2013), making infrared observations necessary to account for the bulk of the SFR. Brodwin et al. (2013) and
Chapter 2 presented the first statistical studies of dust-obscured star formation in clusters at high redshift. Using Spitzer MIPS imaging, Brodwin et al. (2013) identified a transition epoch from active star formation in the cores of $\sim 10^{14} M_\odot$ clusters to passive evolution at $z \gtrsim 1.4$ using $z = 1 - 1.5$ clusters from the IRAC Shallow Cluster Survey (ISCS; Eisenhardt et al., 2008). Using the full ISCS cluster sample and stacking on Herschel SPIRE observations, Chapter 2 quantified the evolution of the average SFR in clusters relative to the field over the redshift range $z = 0.5 - 1.5$ for mass-limited galaxy samples. This analysis demonstrated that the average evolution of SF in these clusters occurs more rapidly than in the field and that cluster galaxies have field-like SFRs, on average, at $z \gtrsim 1.2$.

This epoch of active star formation in galaxy clusters coincides roughly with the peak in in the global SFR density in the Universe ($z \sim 1 - 3$; Murphy et al., 2011a; Magnelli et al., 2013) as well as the peak in the black hole growth in galaxies (e.g. Silverman et al., 2008). In the field, the link between SF and black hole growth (i.e. AGN activity) is still poorly understood. Several theoretical simulations predict that AGN activity can be associated with major mergers of gas-rich galaxies, which can trigger black hole growth, fuel SF, and eventually quench star formation through AGN feedback (Hopkins et al., 2006; Somerville et al., 2008; Narayanan et al., 2010). If so, then AGN could be a prominent driver of rapid ($\lesssim 100$ Myr) quenching in high redshift clusters where galaxy densities are high, but velocity dispersions are still low enough to permit galaxy interactions. Recent observations of field galaxies, however, find only weak or no correlation between SF and nuclear activity for low- to moderate-luminosity AGN (Shao et al., 2010; Mullaney et al., 2012a; Santini et al., 2012; Rosario et al., 2012). Studies show that AGN are primarily hosted in SFGs rather than quenching or quenched galaxies (Rosario et al., 2013), and that high fractions ($\sim 80\%$) of AGN are hosted in disk or spheroidal galaxies with no evidence for the disturbed morphology associated with mergers (Kocevski et al., 2012;
Schawinski et al., 2014). Conversely, studies of the link between SF and the average black hole accretion rate find a tight correlation (Chen et al., 2013). Hickox et al. (2014) argues that AGN variability mimics the weak correlation between SF and AGN at high redshift observed in some studies. The growth of super massive black holes have also been found to correlate strongly with stellar mass, closely paralleling the SFR-M_\star relation (i.e. the Main Sequence) up to z \sim 2, suggesting co-evolution (Mullaney et al., 2012b). The addition of environment only complicates an already unclear picture; however, what is clear is that the AGN fraction rises rapidly in clusters with redshift, reaching field levels at z \sim 1.5 (Galametz et al., 2009; Martini et al., 2013) and that tracking AGN activity alongside SF in high redshift clusters provides an important constraint on cluster galaxy evolution.

Currently, studies of cluster evolution must contend with the challenges presented by the relatively small number of clusters confirmed at high redshift (z > 1.5) as well as controlling for differences in cluster selection and a wide range of analysis techniques at all redshifts. Additionally, intrinsic cluster properties such as cluster halo mass and dynamical state, which are often unknown, likely have a strong effect on the SF properties of cluster galaxies, shifting the transition epoch for individual clusters even within similarly selected cluster samples. These variations from cluster-to-cluster have been noted at both moderate redshift (z \sim 0.5; Geach et al., 2006) and in statistical cluster samples at z = 1 − 1.5 (Brodwin et al., 2013). Among individual clusters and proto-clusters at z \sim 1.5 − 2, there are examples of both highly star forming systems (Bayliss et al., 2013; Zeimann et al., 2012; Santos et al., 2014; Mei et al., 2014; Fassbender et al., 2014, this work) and seemingly evolved systems (Koyama et al., 2014; Newman et al., 2014). These comparisons are further complicated by different star formation tracers, i.e. obscured versus unobscured, and different observation depths. When deep FIR data is not available, corrections need to be made to account for the bulk of the star formation budget, which can introduce large uncer-
tainties. As an illustrative example, Wylezalek et al. (2014) recently presented new evidence for cluster downsizing, in which higher mass clusters evolve earlier and more rapidly than lower mass clusters (e.g. Neistein et al., 2006). They examined the MIR luminosity function of $z > 1.3$ cluster candidates and found the luminosity function to be consistent with passive evolution models, seemingly at odds with the Mancone et al. (2010) analysis. Given their selection around radio-loud AGN, however, these cluster candidates are expected to reside in extremely massive haloes, making these two studies consistent given a framework in which clusters experience downsizing. Understanding cluster-to-cluster variation both in terms of selection and analysis techniques and in the broader context of intrinsic cluster properties is necessary to create a unified picture of cluster evolution.

In this chapter, we present new, deep *Herschel* PACS imaging of a uniformly selected sample of 11 galaxy clusters at $z = 1–1.8$ from the IRAC Shallow and Distant Cluster Surveys (ISCS/IDCS Eisenhardt et al., 2008). This epoch is characterized by both the transition from active star formation to passive evolution in clusters (Mancone et al., 2010; Brodwin et al., 2013, Chapter 2) and the peak in the global star formation rate density of the Universe, which is dominated by dust-obscured SF in LIRGs and ULIRGs (e.g. Murphy et al., 2011a; Magnelli et al., 2013). Our PACS imaging probes near the peak of the dust emission in the galaxy spectral energy distribution (SED; 36-80µm over $z = 1 – 1.8$), allowing us to localize dust-obscured SF to cluster galaxies selected using spectroscopic and robust photometric redshifts. AGN emission in cluster galaxies is identified by examining the optical-MIR SED using extensive multi-wavelength photometry and template fitting (Chung et al., 2014). This information is used to incorporate the contribution of AGN host galaxies to the global cluster SF as well as we examine the evolution of AGN as a function of environment in parallel with the evolving SFR.
In Section 3.2, we provide details on our cluster sample, spectroscopy and photometry, photometric redshifts, and describe our procedure for identifying cluster members. In Section 3.3, we present the SF properties of PACS-selected cluster members, including the first UV-to-FIR SEDs of high redshift cluster galaxies for both SFGs and AGN. We examine the IR-luminous galaxy population in these clusters as a function of cluster-centric radius and redshift and in relation to the Main Sequence (Elbaz et al., 2011). Then, using stacking on the PACS images, we expand our analysis to mass-limited galaxy samples to probe the average SF in all cluster galaxies and quantify cluster-to-cluster variations for IR-luminous cluster members and in the total (stacked) SF per unit area and per cluster halo mass. In Section 3.4, we utilize the full ISCS/IDCS sample from $z = 0.5 - 2$ to trace the evolution of the AGN fraction in galaxies as a function of environment and redshift. Finally, in Section 3.5, we examine the relation between unobscured and obscured SFR tracers as a function of environment using $HST$ grism spectroscopy in the cluster cores. Section 3.6 presents our discussion and Section 3.7 our summary and conclusions. Throughout this work, we adopt a WMAP7 cosmology with $(\Omega_\Lambda, \Omega_M, h) = (0.728, 0.272, 0.704)$ (Komatsu et al., 2011). A Kroupa IMF (Kroupa, 2001) is assumed unless otherwise stated.

### 3.2 Data

#### 3.2.1 IRAC Shallow and Distant Cluster Surveys

The IRAC Shallow Cluster Survey (ISCS Eisenhardt et al., 2008) consists of over 300 infrared-selected galaxy cluster candidates over the redshift range $0.1 < z < 2$. Spanning the 8.5 deg$^2$ Boötes field in the NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey, 1999), clusters were identified as 3-D overdensities in (RA, Dec, photometric redshift) space using a wavelet detection algorithm and photometric redshifts (Elston et al., 2006; Brodwin et al., 2006, 2013) derived from deep optical
$B_{VI}$ imaging from NDWFS and Spitzer IRAC imaging from the IRAC Shallow Survey (ISS; Eisenhardt et al., 2004). The ISCS includes >100 cluster candidates at $z > 1$, over 20 of which have been spectroscopically confirmed (Stanford et al., 2005; Brodwin et al., 2006, 2011, 2013; Elston et al., 2006; Eisenhardt et al., 2008; Zeimann et al., 2012). A follow-up survey, the IRAC Distant Cluster Survey (IDCS), was conducted using deeper IRAC data from the Spitzer Deep, Wide-Field Survey (SDWFS; Ashby et al., 2009).

Given the cluster mass function and the flux-limited nature of the ISS ($8.8 \mu$Jy, 5$\sigma$ at 4.5$\mu$m), the ISCS cluster sample is essentially mass selected, with a typical halo masses of $\sim 10^{14} M_{\odot}$, near the survey detection limit. This has been verified in several ways: a subset of ISCS clusters have been observed in X-ray (Brodwin et al., 2011) and weak lensing (Jee et al., 2011), from which halo masses in the range $M_{200} = (1 - 5) \times 10^{14} M_{\odot}$ were measured. These direct measurements are consistent with the mean mass derived from a statistical analysis of the clustering of the full ISCS sample (Brodwin et al., 2007). More recently, a statistical study of the ISCS cluster masses using halo mass ranking simulations (Lin et al., 2013) found median cluster masses of $M_{200} \sim (5 - 8) \times 10^{13} M_{\odot}$, with no significant redshift evolution (Alberts et al., 2014). Given these masses, the ISCS clusters have a characteristic virial radius of 1 Mpc at $z > 0.5$ which we will adopt as the value for $r_{200}$ throughout this study.

Though this work will primarily focus on ISCS clusters, we additionally include in our study one cluster from the IDCS, which has a halo mass of $M_{200} \approx 5 \times 10^{14} M_{\odot}$ from X-ray and Sunyaev-Zel’dovich Effect measurements (Stanford et al., 2012; Brodwin et al., 2012), comparable to the ISCS clusters.

In this work, we concentrate our analysis on 11 spectroscopically confirmed clusters from the ISCS/IDCS which we observed with Herschel/PACS. These clusters, which span the redshift range $1 < z < 1.8$, are listed in Table 3.2.1, including available halo mass measurements and additional references. In Section 3.3.3, we utilize all
ISCS/IDCS clusters at $z > 0.4$ for an analysis of the AGN fraction in cluster galaxies in order to improve our statistics and cover a wider redshift range.
<table>
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<tr>
<td>ISCS J1432.4+3332^a</td>
<td>ISCS1</td>
<td>14:32:29.18</td>
<td>33:32:36.0</td>
<td>1.113</td>
<td>30</td>
<td>$4.9^{+1.6}_{-1.2}$</td>
<td>1, 2, 3, 4</td>
</tr>
<tr>
<td>ISCS J1434.5+3427^a</td>
<td>ISCS2</td>
<td>14:34:30.44</td>
<td>34:27:12.3</td>
<td>1.238</td>
<td>24</td>
<td>$2.5^{+2.2}_{-1.1}$</td>
<td>1, 3, 4, 5</td>
</tr>
<tr>
<td>ISCS J1429.3-3437^a</td>
<td>ISCS3</td>
<td>14:29:18.51</td>
<td>34:37:25.8</td>
<td>1.262</td>
<td>19</td>
<td>$5.4^{+1.6}_{-1.2}$</td>
<td>2, 3, 4</td>
</tr>
<tr>
<td>ISCS J1432.6+3436^a</td>
<td>ISCS4</td>
<td>14:32:38.38</td>
<td>34:36:49.0</td>
<td>1.350</td>
<td>16</td>
<td>$5.3^{+2.6}_{-1.7}$</td>
<td>2, 3, 4</td>
</tr>
<tr>
<td>ISCS J1434.7+3519^a</td>
<td>ISCS5</td>
<td>14:34:46.33</td>
<td>35:19:33.5</td>
<td>1.374</td>
<td>14</td>
<td>$2.8^{+2.9}_{-1.4}$</td>
<td>2, 3, 4</td>
</tr>
<tr>
<td>ISCS J1432.3+3253^a</td>
<td>ISCS6</td>
<td>14:32:18.31</td>
<td>32:53:07.8</td>
<td>1.396</td>
<td>12</td>
<td>...</td>
<td>3, 4</td>
</tr>
<tr>
<td>ISCS J1425.3+3250^a</td>
<td>ISCS7</td>
<td>14:25:18.50</td>
<td>32:50:40.5</td>
<td>1.400</td>
<td>10</td>
<td>...</td>
<td>3, 4</td>
</tr>
<tr>
<td>ISCS J1438.1+3414^a</td>
<td>ISCS8</td>
<td>14:38:08.71</td>
<td>34:14:19.2</td>
<td>1.413</td>
<td>19</td>
<td>$2.3^{+2.4}_{-2.1}$</td>
<td>2, 3, 4, 6, 7</td>
</tr>
<tr>
<td>ISCS J1431.1+3459^a</td>
<td>ISCS9</td>
<td>14:31:08.06</td>
<td>34:59:43.3</td>
<td>1.463</td>
<td>10</td>
<td>...</td>
<td>3, 4</td>
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<tr>
<td>ISCS J1432.4+3250^a</td>
<td>ISCS10</td>
<td>14:32:24.16</td>
<td>32:50:03.7</td>
<td>1.487</td>
<td>13</td>
<td>$2.5^{+1.5}_{-0.9}$</td>
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<td>IDCS11</td>
<td>14:26:32.95</td>
<td>35:08:23.6</td>
<td>1.75</td>
<td>7</td>
<td>$5.3 \pm 1.6$</td>
<td>8, 9, 10</td>
</tr>
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</table>

Note. — ^1Elston et al. (2006); ^2Eisenhardt et al. (2008); ^3Brodwin et al. (2013); ^4Zeimann et al. (2013); ^5Brodwin et al. (2006); ^6Stanford et al. (2005); ^7Brodwin et al. (2011); ^8Brodwin et al. (2012); ^9Gonzalez et al. (2012); ^10Stanford et al. (2012)

^aCluster has H\alpha measurements from HST grism spectroscopy (Section 3.2.2) and targeted, deep MIPS imaging (Section 3.2.4.1).

^bWeak lensing mass measurement from Jee et al. (2011).

^cX-ray mass measurement from Brodwin et al. (2011); Stanford et al. (2012).
3.2.2 Spectroscopic Redshifts and Hα Emission

The AGN and Galaxy Evolution Survey (AGES; Kochanek et al., 2012) provides optical spectroscopy and spectroscopic redshifts in the Boötes field and consists primarily of galaxies at $z < 1$ and AGN at $z < 3$. Targeted follow-up spectroscopic campaigns obtained spectroscopic redshifts for galaxies/AGN in $z > 1$ clusters using multi-object Keck optical spectroscopy and Wide Field Camera 3 (WFC3) slitless near-IR grism spectroscopy from *HST* (Kimble et al., 2008). The reader is directed to Brodwin et al. (2013) and Zeimann et al. (2013) for a detailed description of the targeted spectroscopy. Spectroscopic confirmation of a cluster is based on detection of at least five galaxies within a radius of 2 Mpc and with spectroscopic redshifts in the range $\pm 2000(1 + \langle z_{\text{spec}} \rangle)$ km s$^{-1}$. The number of spectroscopic redshifts in the main cluster sample for this work can be seen in Table 3.2.1.

In addition to spectroscopic redshifts, the WFC3 grism data was also used to obtain measurements of the Hα emission of cluster and field galaxies at $1 < z < 1.5$ (Zeimann et al., 2013). Hα emission is a tracer of recent (unobscured) star formation and/or AGN activity. Hα measurements were obtained for ten of the clusters in this study with *Herschel* PACS (and *Spitzer* MIPS) observations, allowing us to compare the direct, unobscured component of star formation to the dust-obscured, re-radiated component as a function of environment (see Section 3.3.4). The WFC3 grism observations cover a field-of-view (FOV) of $136'' \times 123''$ ($\sim 1$ square Mpc at $z \sim 1$) and reach 50% completeness at an Hα flux of $\sim 1 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, corresponding to (attenuation-corrected) SFR$_{\text{H}} > 4 M_\odot$ yr$^{-1}$ (see Zeimann et al., 2013, for more details).

3.2.3 New Herschel PACS Imaging

We present new targeted imaging from the *Herschel Space Observatory* (Pilbratt et al., 2010) Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al.,
which was obtained at 100 and 160µm as part of Open Time 2 observing (PID: OT2_apollo_3). Integration times range from 270 – 4050 s over 2-4 pointings per map in order to provide a uniform intrinsic depth for 10 maps. The PACS maps are approximately centered on 11 spectroscopically confirmed clusters from 1 < z < 1.8 with the exception of ISCS6 and ISCS10, which were observed in one map due to their small angular separation (~4 arcmin). Each map covers a FOV of 7′×7′, a physical size of 2-3 Mpc in radius around each cluster. 5′×5′ of this area is uniform in depth, with a small loss in sensitivity toward the edges of the map (see Appendix B).

Data reduction was performed using Unimap v5.4.0 (Traficante et al., 2011; Piazzo et al., 2012), a generalized least-squares (GLS; Lupton, 1993) mapmaker. The individual astronomical observation requests (AORs) were processed up to Level 1 in HIPE v10 (Ott, 2010) and converted to a Unimap usable format using UniHIPE. Pre-processing, which removes offsets, jumps and spikes due to cosmic rays, as well as baseline drift, preceded the GLS mapmaker. Astrometry was corrected by stacking on the 5σ MIPS 24µm catalog and removing any offsets in the stack. Final PACS maps are in Jy pix⁻¹ with 1″ and 2″ pixel sizes for 100 and 160µm, respectively.

Given the resolution of PACS (FWHM~ 6.7″ at 100µm and 11″ at 160µm), we expect the majority of sources and all cluster galaxies in our maps to be point sources and we extracted their flux densities using PSF fitting. We constructed PACS 100µm source catalogs based on the positions of isolated sources in the SDWFS 5σ 4.5µm catalog. Though it is more common in the literature to use MIPS 24µm sources as priors (e.g. Magnelli et al., 2013), deep MIPS imaging is not available for IDCS11 and the IRAC source catalog results in a more complete catalog as some PACS sources may not be detected by MIPS. Given the depth of our IRAC catalog, there is typically one IRAC source per PACS beam and we use visual inspection to identify cases of blending. Using a prior catalog for source extraction allows us to extract a flux measurements or limits for all IRAC sources. PACS 160µm catalogs were constructed
using priors based on the PACS 100µm source catalogs. The local background was estimated in postage stamps around each prior and flux density uncertainties were measured from the residual map. We tested the robustness of our catalogs using Monte Carlo simulations and determined that we can measure accurate flux densities at the 2σ level through the use of priors and so we consider 100µm sources at ≥ 2σ to be detected. For more details about the observations, source extraction, and completeness simulations, see Appendix B.

3.2.4 Ancillary Multi-wavelength Photometry

The Boötes field contains a wealth of multiwavelength observations, with photometry from the X-ray to the radio. The reader is referred to Chung et al. (2014) for a full description of the UV-to-MIR photometry used to derive the photometric redshifts used in this work (Section 3.2.5). Optical-NIR photometry for the WFC3 grism sources was obtained separately using PyGFit (Mancone et al., 2013) to obtain measurements directly from the NDWFS B_W RI, SDWFS, and Infrared Boötes Imaging Survey (IBIS; Gonzalez et al., 2010a) JHK_S images (see Zeimann et al., 2013, for more details). In the following, we describe the MIR-FIR photometry, including new PACS imaging, as well as the X-ray observations used.

3.2.4.1 Spitzer IRAC and MIPS Observations

The IRAC Shallow Survey was followed up with three more observations as part of the SDWFS (Ashby et al., 2009), providing a deeper catalog by a factor of two, with an aperture-corrected 5σ limit of 5.2µJy at 4.5µm ([4.5] = 18.83 mag). Spitzer MIPS observations are available from the MIPS AGN and Galaxy Evolution Survey (MAGES; Jannuzi et al., 2010) over the Boötes field to a 3σ depth of 0.122 mJy at 24µm. In addition, ten of the clusters in this work were targeted for deep MIPS 24µm observations, with 3σ depths of 156 µJy at z = 1 to 36 µJy at z = 1.5, providing uniform detection of star-forming galaxies with SFR ≥ 45 M⊙ yr⁻¹ over a 5’x5’ FOV.
For a complete description of the data reduction of the targeted MIPS observations and an analysis of MIPS-derived star formation properties of cluster galaxies, see Brodwin et al. (2013).

### 3.2.4.2 Herschel SPIRE Observations

**Herschel** Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al., 2010) observations at 250, 350, and 500$\mu$m are available in Boötes from the **Herschel** Multi-tiered Extragalactic Survey (HerMES; Oliver et al., 2012). The SPIRE observations are confusion-limited, reaching a 5$\sigma$ depth of 14 mJy at 250$\mu$m in the inner two square degrees of the Boötes field and 26 mJy over the remaining 8 square degrees. For a detailed description of the Boötes SPIRE imaging and our reduction of the data, the reader is referred to Chapter 2.

### 3.2.4.3 Chandra X-ray Observations

Targeted X-ray observations of ten of the clusters in this study were obtained as a Cycle 10 **Chandra** program to a uniform exposure time of 40 ks. In addition to identifying bright AGN, these X-ray observations were used to measure the X-ray emission of the intracluster medium (ICM), from which cluster halo masses can be derived. For a full description of the X-ray data reduction and ICM measurements, see Brodwin et al. (2011). The eleventh cluster, IDCS1, was observed as part of the XBoötes Survey (Murray et al., 2005; Kenter et al., 2005) with an exposure time of 9.5 ks (see Stanford et al., 2012). XBoötes is available across the Boötes field with exposure times of 5-15 ks, sufficient to detect unobscured moderate to luminous AGN (Ranalli et al., 2003).

### 3.2.5 Photometric Redshifts

New photometric redshifts are available for the Boötes field from Chung et al. (2014) and briefly described here. Using up to 17 photometric bands from the ul-
traviolet to mid-IR, empirically derived SED templates were fit using the publicly available code from Assef et al. (2010), which uses non-negative linear combinations of templates to fit available photometry. An $R$-band luminosity prior from the Las Campanas Redshift Survey (Lin et al., 1996) was used to avoid unphysical fits. The templates include a characteristic elliptical, spiral, and irregular (starburst), as well as an AGN template, which is introduced with a variable amount of internal reddening. Each source was fit first with galaxy templates only. Then they were fit with galaxy+AGN templates and an F-test was used to check if the addition of an AGN component improved the goodness-of-fit (see Chung et al., 2014, for a detailed discussion). Stellar and brown dwarf templates were also fit in order to identify Galactic sources.

For the purposes of this work, we limit our photometric redshift catalog to sources with $4.5\mu m$ fluxes greater than $5.2\mu Jy \ (5\sigma)$. After removing stars and brown dwarfs, this catalog contains 281,779 sources.

### 3.2.5.1 The Contribution from AGN: $F_{gal}$

Following Chung et al. (2014), the influence of AGN in a given source is quantified through the ratio of its UV-to-MIR luminosity that is coming from host galaxy component to the total: $F_{gal} = L_{gal}/L_{total}$, with $F_{gal}=0.5$ providing a useful dividing line between sources whose luminosity is dominated by an AGN ($F_{gal} < 0.5$) versus those whose luminosity is dominated by the (host) galaxy ($F_{gal} > 0.5$). This parameter provides an AGN selection that takes advantage of a broad wavelength range from UV to mid-IR, in principle providing a more sensitive selection than indicators of AGN activity that use only limited wavelength windows or colors, as well as a greater sensitivity to composite objects that have significant contributions from both the host galaxy and AGN (Hickox et al., 2009; Mendez et al., 2013; Chung et al., 2014). Checking against spectroscopic redshifts, Assef et al. (2010) found that the
Figure 3.1 The IRAC colors of galaxies in the photometric redshift catalog broken into four subsets by \( F_{\text{gal}} = \frac{L_{\text{gal}}}{L_{\text{tot}}} \). This parameter measures the relative fraction of luminosity in the UV-MIR which is accounted for by galaxy templates versus the total, measured by galaxy+AGN templates, during SED fitting. The contours show the number density of each subset in IRAC color space. The dashed line shows the Lacy et al. (2004) criteria for MIR AGN selection, while the solid line shows the more conservative AGN selection from Kirkpatrick et al. (2013). As \( F_{\text{gal}} \) increases, sources move from the region of IRAC color space associated with AGN to the region associated with non-AGN sources. Star symbols denote X-ray AGN, which can be seen in all regions of IRAC color space. The fraction of X-ray AGN in each \( F_{\text{gal}} \) subset, \( F_{\text{X-ray}} \), decreases with increasing \( F_{\text{gal}} \).

ability of this SED fitting technique to measure \( F_{\text{gal}} \) is not dependent on measuring an accurate photometric redshift. Photometric redshift uncertainties, however, increase dramatically for sources dominated by the AGN component (\( F_{\text{gal}} < 0.5 \)), as outlined in the next section.

How does \( F_{\text{gal}} \) compare to other AGN indicators? Common indicators of AGN include X-ray emission from the AGN accretion disk, spectral features, and mid-IR colors (e.g. Lacy et al., 2004; Stern et al., 2005). The correlation between X-ray detections and \( F_{\text{gal}} \) was tested in Chung et al. (2014). They found that X-ray detected sources have a large range of \( F_{\text{gal}} \), with a tighter correlation for sources that are compact based on their \( I \)-band stellarity index from SExtractor (Bertin & Arnouts, 1996). This is similar to the large scatter in the MIR colors of X-ray AGN which can lie outside the color space of MIR-identified AGN, and is likely due to soft X-
ray observations being sensitive to the host galaxy contribution and lower luminosity AGN (Gorjian et al., 2008; Cardamone et al., 2008; Mendez et al., 2013). AGES AGN identified through optical spectral features, at \( z > 1 \), on the other hand, show a stronger correlation with \( F_{\text{gal}} \), with \( \sim 80\% \) of AGES AGN having a corresponding \( F_{\text{gal}} < 0.5 \).

Sources with an AGN luminosity comparable or larger than the host galaxy luminosity will resemble a power-law in the MIR and occupy a particular region of MIR color space (e.g. Lacy et al., 2004; Stern et al., 2005; Donley et al., 2012; Kirkpatrick et al., 2013). Chung et al. (2014) looked at unambiguous AGN in IRAC color space, finding that 75\% were recovered by the Lacy et al. (2004) AGN selection and 32\% by the more conservative Donley et al. (2012) selection. It has been shown that star-forming submillimeter galaxies occupy parts of the IRAC color space sometimes associated with AGN (Yun et al., 2008; Alberts et al., 2013) and that the more conservative selection is necessary to remove high redshift, dusty SFG interlopers from AGN samples selected by IRAC colors (Donley et al., 2012; Kirkpatrick et al., 2013). In Figure 3.1, we show the IRAC colors of galaxies in the photometric redshift catalog in the redshift range \( 1 < z < 1.8 \) broken into four categories: \( F_{\text{gal}} < 0.3 \) (“AGN-dominated”), \( 0.3 < F_{\text{gal}} < 0.5 \) (“AGN-composite”), \( 0.5 < F_{\text{gal}} < 0.7 \) (“galaxy-composite”), and \( F_{\text{gal}} > 0.7 \) (“galaxy-dominated”). Throughout this work, we refer to galaxies with significant contribution from both the host galaxy and AGN in the optical-MIR SED as “composites”. In general, sources trend from the region of IRAC color space traditionally associated with AGN to that of star forming galaxies as a function of increasing \( F_{\text{gal}} \), with significant scatter. The Lacy et al. (2004) and Kirkpatrick et al. (2013) AGN selections are shown for reference. We note that X-ray detections are found throughout IRAC color space, though the fraction decreases with increasing \( F_{\text{gal}} \).
Throughout this work, we use the $F_{\text{gal}}$ parameter as a measure of the AGN contribution to individual sources, allowing us to examine the star formation properties of sources that contain an AGN and examine the role of AGN and composite objects as a function of environment.

### 3.2.5.2 Photometric Redshift Uncertainties: Pair Statistics

Photometric redshift uncertainties are typically measured through comparisons with spectroscopic redshifts. Splitting the photometric redshift catalog into unambiguous galaxy and AGN subsets, Chung et al. (2014) reported redshift dispersions of $\sigma/(1+z) = 0.040$ for galaxies and $\sigma/(1+z) = 0.169$ for AGN, with 5% outlier rejection. Here we expand this comparison in order to quantify the photometric redshift uncertainties for all sources, including composites. We match good quality spectroscopic redshifts (“A” or “B” quality) to IRAC sources with a measured photometric redshift within $1^\prime\prime$ and compare spectroscopic and photometric redshifts. We find that the uncertainty for galaxies and galaxy composites ($F_{\text{gal}} > 0.5$) is $\sigma/(1+z) = 0.040$ (Figure 3.2), consistent with Chung et al. (2014), while for AGN and AGN composites ($F_{\text{gal}} < 0.5$), we measure $\sigma/(1+z) = 0.214$.

Though the above results indicate accurate photometric redshifts for galaxies and galaxy composites, which we expect to dominate our cluster members, we note that our spectroscopic redshift sample for non-AGN is sparse at the redshifts of interest ($1 < z < 1.8$). Therefore we show here the results of an alternative method for measuring photometric redshift uncertainties: pair statistics (Quadri & Williams, 2010; Huang et al., 2013; Dahlen et al., 2013). Pair statistics takes advantage of the fact that some fraction of galaxies pairs with small angular separations will actually be physically associated (i.e. at the same redshift), in excess of a random distribution of projected pairs. Figure 3.3 (left) shows the distribution of $\Delta z_p/(1 + z_p)$ for pairs of galaxies ($F_{\text{gal}} > 0.5$; black histogram) within $30^\prime\prime$ of each other, where $\Delta z_p$ is the dif-
Figure 3.2 Comparison of spectroscopic and photometric redshifts for galaxies ($F_{\text{gal}} > 0.5$) in the photometric redshift catalog. After 5% outlier rejection, we find a photometric redshift uncertainty of $\sigma/(1+z) = 0.040$. The red line represents a one-to-one relation.

The difference in their photometric redshifts. This is compared to a random distribution (red histogram) where the same set of photometric redshifts are assigned random positions over the same area. The resulting excess (right) is fit with a gaussian distribution and the standard deviation is measured (and divided by $\sqrt{2}$ to remove double-counting). Using this technique, we measure $\sigma/(1+z) = 0.054 \pm 0.001$ for all $F_{\text{gal}} > 0.5$ photometric redshifts. To check that the photometric redshift uncertainties do not degrade as a function of redshift, we further split the photometric redshift catalog into broad
Figure 3.3 Analysis of the photometric redshifts using pair statistics. Left: The distribution of $\Delta z_p/(1 + z_p)$ for close galaxy pairs ($r < 30''$, black histogram) and for a random distribution (red histogram), where $z_p$ is the photometric redshift. Right: The residual excess from subtracting the random distribution from the distribution of galaxy pairs. The blue line is a Gaussian fit. The width of the Gaussian, divided by $\sqrt{2}$ to correct for double counting, gives the photometric redshift uncertainty for these sources, which is measured to be $\sigma/(1+z) = 0.054$.

redshift bins and repeat this analysis. We find that the uncertainties are stable up to $z \sim 2$.

3.2.6 Stellar Masses

Stellar mass estimates are available for sources in the SDWFS IRAC catalog (see Brodwin et al., 2013), derived with optical and MIR photometry using iSEDfit (Moustakas et al., 2013), a Bayesian SED fitting code which assumes Bruzual & Charlot (2003) population synthesis models and a Chabrier (2003) initial mass function (IMF). Though individual mass errors are typically reported by iSEDfit to be $< 0.2$ dex, a mass error of 0.3 dex is adopted in this work for all stellar mass estimates in order to account for systematic uncertainties. At $z > 1$, this stellar mass catalog is 80% complete above $\log(M_\star/M_\odot) = 10.1$ (see Figure 3 in Brodwin et al., 2013), with a higher
completeness expected in the clusters given the high masses of typical cluster galaxies and the flat NIR luminosity function measured for high redshift clusters (Mancone et al., 2012). Stellar masses for the WFC3 grism sources were also measured using iSEDfit and the photometric bands $B_WRIJHK_S[3.6][4.5]$ (see Zeimann et al., 2013, for more details).

3.2.7 Cluster Membership

Sources with spectroscopic redshifts are assigned cluster membership following the criteria from Eisenhardt et al. (2008), which defines a cluster member given a spectroscopic redshift within 2000 km s$^{-1}$ of the systemic cluster velocity and within 2 Mpc of the cluster center. In addition, in order to compare to the Zeimann et al. (2013) Hα analysis, we consider an additional 30 sources with $HST$ grism spectroscopy as potential cluster members satisfying the criteria $-0.03 < z_{\text{spec}} - z_{cl} < 0.03$, where $z_{cl}$ is the redshift of the cluster. These sources account for $\lesssim 20\%$ of potential spectroscopic cluster members. As a final criteria, we cut on the quality of the spectroscopic redshift, accepting only “A” or “B” quality.

Photometric redshift cluster members are determined based on constraining the integral of their normalized photometric redshift probability distribution function (PDF) given the measured photometric redshift uncertainties (see Section 3.2.5). For sources with $F_{gal} > 0.5$, we adopt the photometric redshift uncertainties derived through pair statistics. Cluster members are thus identified within 2 Mpc of a cluster center and satisfying the following criteria:

$$\int_{z_{cl}-0.054(1+z_{cl})}^{z_{cl}+0.054(1+z_{cl})} P(z) \, dz \geq 0.3 \quad . \quad (3.1)$$

Studies of X-ray and MIR-selected AGN in galaxy clusters have established their importance at high redshift, finding a two orders of magnitude increase in the AGN fraction from low to high redshift and field-like AGN fractions at $z > 1$ in clusters.
(Galametz et al., 2009; Martini et al., 2013). In order to account for the contribution of AGN-dominated and AGN-composite galaxies in clusters, we opt to identify cluster members from the $F_{\text{gal}} < 0.5$ population instead of rejecting all AGN. Rather than identify all possible AGN cluster members by recasting Eqn 3.1 with the full photometric redshift uncertainties for $F_{\text{gal}} < 0.5$ sources, which would produce a sample strongly contaminated by field AGN, we require $F_{\text{gal}} < 0.5$ sources to satisfy Eqn 3.1 with the uncertainties measured for the galaxy population, placing an artificial constraint on the quality of the measured photometric redshift. This conservative approach gives us a better census of the total SF and AGN activity of cluster galaxies with minimal contamination; however, we note that our $F_{\text{gal}} < 0.5$ cluster member sample likely suffers from incompleteness and bias toward composite AGN, as it is more difficult to measure photometric redshifts for SEDs completely dominated by AGN power law emission.

Clusters ISCS6 ($z = 1.396$) and ISCS10 ($z = 1.487$) have an angular separation of only 4 arcmin ($\sim 2$ Mpc) between their centers. Given the photometric redshift uncertainties, some galaxies satisfy cluster membership for both clusters in the overlapping regions. In order to avoid double-counting, we assign galaxies to the cluster for which they have the highest integrated photometric redshift PDF at the redshift of that cluster.

Finally, the spectroscopic and photometric cluster member lists are checked for overlap. Roughly 60% of the spectroscopic redshift cluster members have a match in the photometric redshift catalog and therefore a measurement of $F_{\text{gal}}$. The total number of cluster members identified is 658, with 167 spectroscopic redshift members and 371 (120) photometric redshift members with $F_{\text{gal}} > 0.5$ ($F_{\text{gal}} < 0.5$).
3.2.8 Matching Multi-wavelength Catalogs

Optical-MIR ($B_wRIJHK_S[3.6][4.5][5.8][8.0]$) photometry and stellar masses of cluster members (and field galaxies) with $HST$ grism spectroscopy were measured directly as described in Zeimann et al. (2013). Grism sources with an IRAC counterpart that is not included in the SDWFS IRAC catalog are added to the IRAC priors in order to extract PACS photometry at 100 and 160$\mu$m at the position of these sources (see Section 3.2.4.2). Non-grism spectroscopic cluster members are matched to the SDWFS IRAC catalog (search radius $r_s = 1''$) to determine stellar masses, IRAC, and PACS counterparts. The non-grism spectroscopic cluster members are also checked for a counterpart in the photometric redshift catalog; if found, then UV-MIR is available through matched photometry catalogs (see Chung et al., 2014, for more details). MIPS 24$\mu$m counterparts are search for in the deep MIPS catalogs, using $r_s = 1''$ as the source extraction is based on IRAC priors (Brodwin et al., 2013). If a MIPS detection is not available from the deep imaging because of incompleteness or being outside the FOV of the deep MIPS images, then the MAGES catalog is searched for a $> 3\sigma$ detection within 3$''$ of the IRAC position.

Photometric redshift cluster members automatically have matches to the full UV-MIR matched photometry catalogs used in (Chung et al., 2014) and to the stellar mass catalog. MIPS counterparts are determined as described above and PACS counterparts come directly from the IRAC priors. X-ray detections are matched to all sources within 2$''$. All cluster members are visually inspected for blending with nearby bright sources in the PACS 100$\mu$m maps.
3.3 Analysis

3.3.1 Spectral Energy Distributions of Herschel-selected Cluster Galaxies

Utilizing all available UV-to-FIR photometry, we examine the spectral energy distributions of Herschel-selected cluster galaxies, constructing average SEDs in order to compare their overall SED shape to that of field galaxies found at similar redshifts. Our sample, which consists of all cluster galaxies detected in at least the 4.5\(\mu\)m and 100\(\mu\)m bands with \(\log (M/M_\odot) \geq 10.1\), is broken into five subsamples according to membership (spectroscopic or photometric), radius, and AGN contribution.

Figure 3.4 UV-to-FIR SED of PACS-selected spectroscopic cluster members within \(r < 0.7\) Mpc of the cluster cores. Small symbols show individual cluster members, while the large, black circles are the weighted average of all sources. Photometry at rest wavelengths longward of 100\(\mu\)m were obtained by stacking on the SPIRE 250, 350, and 500\(\mu\)m images. All sources were normalized to the median observed-frame 4.5\(\mu\)m luminosity. AGN, either with a measured \(F_{\text{gal}} < 0.5\) or power law emission in the MIR as determined by visual inspection, are not included. The average SED of these cluster members is consistent with an empirically derived SED template for field galaxies at \(z \sim 1\) (Kirkpatrick et al., 2012), as shown by the black line, with template uncertainties denoted by the shaded region.
In order to examine our most conservative cluster sample, we start with spectroscopic redshift members within 0.7 Mpc of the cluster centers (roughly the FOV of the HST grism spectroscopy). After removing sources with a measured $F_{\text{gal}} < 0.5$ or an SED dominated by power-law emission as determined by visual inspection, there are fifteen spectroscopic SFG cluster members detected at PACS 100\,µm. Each source is shifted into the rest-frame using its spectroscopic redshift and normalized at observed-frame 4.5\,µm to the median 4.5\,µm luminosity of the subsample (Figure 3.4). We quantify the noise weighted average luminosity in the IRAC, MIPS, and PACS bands as shown in the large, black circles. The average luminosity in the SPIRE bands is determined through stacking following the procedure outlined in Chapter 2, with errors determined by bootstrapping. Because of the small number of stacked objects, we do not attempt to correct for boosting in the SPIRE bands due to source confusion and clustering (see Viero et al., 2013, Chapter 2), so these points are formally upper limits even if the stack is detected.

For comparison to field galaxies, we overlay an empirically-derived average SED, normalized at 2\,µm rest (observed 4.5\,µm at $z \sim 1.25$), developed for IR-luminous ($L_{\text{IR}} \sim 5 \times 10^{11} L_\odot$) star-forming field galaxies at $z \sim 1 - 2$ using Spitzer IRS spectroscopy and full Herschel PACS+SPIRE coverage (Kirkpatrick et al., 2012). This comparison shows that, on average, vigorously star-forming spectroscopic cluster members have an overall NIR-FIR SED shape comparable to that of field galaxies at similar redshifts. In order to derive total infrared luminosities for each galaxy, we adopt this SFG template and normalize by the PACS 100\,µm flux, calculating $L_{\text{IR}} = L[8-1000\mu m]$. Though we do not have longer wavelength submillimeter data to show that the SED is fully consistent, $L_{\text{IR}}$ is dominated by the shorter wavelength FIR emission where we have good coverage of the SED. Using this template, we find our spectroscopic cluster members span a range of $L_{\text{IR}} = (4 - 22) \times 10^{11} L_\odot$. Following the relation from Murphy et al. (2011b)
SFR [$M_\odot \text{yr}^{-1}$] = 1.47 \times 10^{-10} L_{4R}^{SF} [L_\odot],  
(3.2)

where $L_{4R}^{SF}$ is the contribution to the $L_{IR}$ coming from SF only (see below), this range corresponds to $\sim 60 - 300 M_\odot \text{yr}^{-1}$. This $L_{IR}$ to SFR conversion assumes a Kroupa IMF, which has a similar normalization as the Chabrier IMF assumed for our stellar mass estimates (see Speagle et al., 2014).

Figure 3.5 As in Figure 3.4, but for photometric redshift cluster members. Small, colored symbols are individual galaxies, while the large, black circles show the weighted average of all galaxies. Upper left: PACS-selected star forming cluster galaxies ($F_{\text{gal}} > 0.5$) within the virial radius of the clusters ($r < 1 \text{Mpc}$). Upper right: Star forming cluster galaxies beyond the virial radius ($1 < r < 2 \text{Mpc}$). The solid line and gray shaded region in the upper panels shows the SFG galaxy template from Kirkpatrick et al. (2012). Lower left: PACS-selected AGN ($F_{\text{gal}} < 0.5$) within the virial radius. Lower right: PACS-selected AGN beyond the virial radius. The solid line and shaded region in the lower panels show a representative AGN template from Kirkpatrick et al., in prep. IR-luminous cluster galaxies at all radii have UV-to-FIR SEDs that are consistent, on average, with field galaxy templates.

We repeat this analysis for our larger samples of photometric redshift cluster members (Figure 3.5) in two radial bins ($r < 1 \text{Mpc}$ and $1 < r < 2 \text{Mpc}$) in addition to splitting the sources into SFG and AGN subsamples. Again, for our star-forming
sample (F_{gal} > 0.5), we overlay the average SED for field galaxies from Kirkpatrick et al. (2012), normalized in the NIR, and find good agreement between the overall SED shapes of cluster and field galaxies, with no dependence on projected radius from the cluster centers. These comparisons indicate that dust properties, such as dust temperature, are relatively stable for star-forming cluster galaxies, as has been found for field galaxies up to z ∼ 3 (Hwang et al., 2010a; Kirkpatrick et al., 2012). This suggests that processes which may heat or strip gas and dust from the disk of galaxies in dense environments are either not significant in these massive, IR-luminous galaxies or may occur on timescales shorter than the star-formation timescale as traced by the IR, on order ∼100 Myr (Murphy et al., 2011b). Additional detections in the Rayleigh-Jeans tail of the dust distribution are required to further quantify these properties (see Chapter 4). Our star-forming photometric redshift cluster members span the infrared luminosity range (4-40) \times 10^{11} L_\odot (60-575 M_\odot yr^{-1}) with the 50% completeness limit at \sim 5 \times 10^{11} L_\odot (\sim 80 M_\odot yr^{-1}).

AGN templates are available for the LIRG and ULIRG field galaxy sample from Kirkpatrick et al. (2012), developed by separating SFGs from AGN using decomposition of the MIR (5-15\mu m) IRS spectra (Pope et al., 2008) into components from SF, characterized by PAH emission, and AGN, characterized by power-law emission. An AGN is defined as any source with > 40% of the MIR luminosity coming from power-law emission. IR color-color diagnostics, found to correlate with AGN strength (Kirkpatrick et al., 2013), are used to characterize the shape of the AGN SED and a set of AGN templates was developed by applying color cuts and then combining sources with similar NIR-FIR colors to create average AGN SED templates (Kirkpatrick et al., in prep.) following the procedure outlined in Kirkpatrick et al. (2012).

Comparing to this set of AGN templates, we find that our F_{gal} < 0.5 sources can be well described, on average, by one template (Figure 3.5, bottom panels) with a MIR (5-15\mu m) AGN fraction of 63% (Kirkpatrick et al., in prep). We measure the L_{IR}
for our $F_{\text{gal}} < 0.5$ sources using this representative AGN template. This $L_{\text{IR}}$ is then corrected for the contribution by warm dust heating from the AGN to determine the component from SF only. The relative SF and AGN contributions for the AGN template are determined through decomposition of the NIR-FIR SED into representative star-forming and AGN components and verified through spectral decomposition of available IRS observations following the technique detailed in Pope et al. (2008). The contribution from SF to the $L_{\text{IR}}$ of the AGN template best representing our AGN sources is 55% (Kirkpatrick et al., in prep.), and we calculate the SFR for sources with significant AGN emission using $L_{\text{IR}}^{\text{SF}} = 0.55 \times L_{\text{IR}}^{\text{tot}}$ and Equation 3.2. Our AGN sample has $L_{\text{IR}}^{\text{tot}} = (4 - 30) \times 10^{11} L_\odot$, corresponding to SFRs of $\sim 30 - 265 M_\odot \text{yr}^{-1}$.

3.3.2 Star Formation Properties of High Redshift Cluster Members

The distribution of SFRs and specific-SFRs ($\text{SSFR} = \text{SFR}/M_*$) as a function of stellar mass and radius can be seen in Figure 3.6 for all Herschel-selected cluster members. The dotted line denotes the stellar mass cutoff, $\log (M/M_\odot) \geq 10.1$, which is adopted in the following analyses. The dot-dash line indicates the 50% SFR completeness level for star-forming galaxies ($\sim 80 M_\odot \text{yr}^{-1}$), based on the PACS completeness and the SFG template. This SFR completeness limit will be lower by approximately a factor of two for $F_{\text{gal}} < 0.5$ sources, marked by red dots, as their PACS flux (and thus $L_{\text{IR}}$) includes a contribution from AGN emission. This AGN contribution to the $L_{\text{IR}}$ is removed to determine the SFRs seen in Figure 3.6, as described in Section 3.3.1. For reference, the Main Sequence (MS) of galaxies is shown at $z = 1$ and $z = 1.5$ (dashed lines). In this work, we adopt the MS relation from Elbaz et al. (2011), corrected to a Kroupa IMF (Kroupa, 2001) and the Murphy et al. (2011b) $L_{\text{IR}}$ to SFR conversion:

$$\text{SSFR}_{\text{MS}} [\text{Gyr}^{-1}] = 36.2 \times t_{\text{cosmic}}^{-2.2}$$ (3.3)
where $t_{\text{cosmic}}$ is the cosmic time since the Big Bang. It should be noted that our sample is SFR-limited and so does not probe the MS for the full range of $M_\star$ above our mass cutoff. Assuming a scatter around the MS of two (Elbaz et al., 2011), we lose sensitivity to MS galaxies for $\log (M/M_\odot) < 10.8$ [$\log (M/M_\odot) < 10.5$] at $z = 1$ [$z = 1.5$]. In Section 3.3.2.4, we address this by incorporating MIPS 24$\mu$m detections into our analysis.

Figure 3.6 demonstrates that *Herschel*-selected cluster galaxies in general follow the same trends as have been established in *Herschel*-selected field galaxies up to $z \sim 2$ (e.g. Rodighiero et al., 2010; Elbaz et al., 2011), namely that SFR increases with increasing stellar mass with the corresponding negative correlation between SSFR and $M_\star$. This relation implies that massive cluster galaxies, like field galaxies, form earlier and more rapidly than lower mass cluster galaxies and is in good agreement with studies of MIPS-selected SFGs in this cluster sample which probed to lower SFRs (Brodwin et al., 2013) and with other high redshift clusters selected as overdensities of red sequence galaxies (Santos et al., 2014).

### 3.3.2.1 Star Formation as a Function of Cluster-centric Radius

To begin our analysis of the impact of environmental on IR-luminous galaxies, we first look at the fraction of PACS 100$\mu$m detected cluster members as a function of projected radius and with our cluster sample split into two redshift bins: $1 < z < 1.38$ and $1.38 < z < 1.75$ (Figure 3.7, top). In order to highlight environmental trends, we make the assumption that our outermost radial bin is a good approximation of the field and normalize by this value. Only photometric redshift cluster members are considered when determining this fraction, as the spectroscopic sample completeness is a strong function of cluster-centric radius. In Figure 3.7 (top), we find that there is a significant difference between the trends of the fraction of IR-luminous galaxies with projected radius between our two redshift bins: in the higher redshift clusters,
Figure 3.6 Left: The SFR of IR-luminous cluster galaxies as a function of stellar mass in three radial bins. AGN (F_{gal} < 0.5) are marked by red dots. Right: The SSFR=SFR/M_⋆ of the same galaxies as a function of stellar mass. The dot-dashed lines in both panels show the 50% completeness limit in SFR (\sim 80 M_⊙ yr^{-1}) for SFGs. The vertical dotted lines in both panels indicates the 80% mass completeness limit, log (M_⋆/M_⊙) = 10.1. The dashed lines show the Main Sequence (MS) at z = 1, 1.5, and 2 (Elbaz et al., 2011). The large error bars show the systematic uncertainties on the SFR, SSFR, and M_⋆.

the IR-luminous fraction is consistent with being flat into the cluster cores. In the lower redshift clusters, on the other hand, we see a decline in the fraction of \sim 25% into the cluster cores relative to the field. Within the cluster centers (r < 250 kpc), \sim 50% of the cluster galaxies are PACS-detected at z > 1.38, versus \sim 16% in the low redshift clusters. This result demonstrates that 1) IR-luminous cluster galaxies at z > 1.38 are present in the cluster cores in similar numbers to the field and 2) that, over a relatively short timescale (\lesssim 1 Gyr), a significant fraction of these galaxies must be quenched below our detection limit, in excess of the normal evolution of field galaxies along the MS as a function of redshift. We repeat this analysis for cluster members with log (M/M_⊙) > 10.8 only and confirm that these trends are not driven by our sensitivity to the MS as a function of redshift.

The middle and lower panels of Figure 3.7 show the average SFR and SSFR as a function of projected radius and redshift. Since these measures are not as sensitive
Figure 3.7 The fraction of star-forming galaxies (upper panel), average SFR (middle panel), and average SSFR (bottom panel) of IR-luminous cluster galaxies as a function of projected radius. Clusters were split into two redshift bins with median redshifts of 1.26 (blue) and 1.46 (red). The star-forming fraction, $f_{\text{SF}}$, has been normalized to the outermost radial bin, which is representative of the fraction in the field at $\sim 2x$ the virial radius ($\sim 1$ Mpc). The $\langle SFR \rangle$ and $\langle SSFR \rangle$ are not normalized, but the dashed lines show the representative field values for each redshift bin. The average trends for the higher redshift ($1.38 < z < 1.75$, red) clusters are flat as a function of radius, consistent with no environmental quenching. The lower redshift clusters (blue), conversely, show significant decreases in $f_{\text{SF}}$ and $\langle SSFR \rangle$, indicating quenching in excess of what is observed in the field. All quantities are cumulative with radius.
to completeness as the IR-luminous fraction, we include all spectroscopic and photometric redshift cluster members, though we verify that spectroscopic members are not driving any of the following trends. Errors are determined using bootstrapping and thus represent the spread in the SF properties of the full population. For the average SFR, we also show the error on the measured average as the inset error bar. Though the average SFR is relatively flat with projected radius for both redshift bins, we do see weak (1σ) trends (Figure 3.7, middle). In the higher redshift clusters, ⟨SFR⟩ is boosted by ∼8% relative to the field (red dashed line), while the ⟨SFR⟩ in the lower redshift clusters decreases by approximately the same amount at small projected radii. In the bottom panel, the ⟨SSFR⟩ of the higher redshift clusters is flat or possibly increasing with decreasing radius, while the lower redshift clusters show a significant decline in the average SSFR relative to the field, albeit with a large scatter as indicated by the bootstrapped errors. These trends hint at an epoch in which the cluster environment serves to boost star formation in IR-luminous galaxies, a process which rapidly becomes ineffective as we move to lower redshifts.

When broken down by stellar mass (Figure 3.8), we find that lower mass galaxies (10.1 < log(M/M⊙) < 10.8) show an increasing ⟨SFR⟩ into the cluster cores, in excess of the field, and an increasing ⟨SSFR⟩ as a function of projected radius. This suggests that it is galaxies with stellar masses in this range or below which are susceptible to their SF being boosted by the cluster environment at high redshifts. The higher mass galaxies [log (M/M⊙) > 10.8] show a flat ⟨SFR⟩ and decreasing ⟨SSFR⟩ into the cluster cores. This decrease is driven by our lower redshift clusters, which we verify by placing this high mass cut on our 1.38 < z < 1.75 bin only, which yields a flat trend for ⟨SSFR⟩ with projected radius.

To briefly summarize, we find that there is little evidence for environmental quenching of the IR-luminous galaxy population at z > 1.38, as seen in the flat trends of the IR-luminous fraction and ⟨SSFR⟩ with projected radius. We do, however, see
Figure 3.8 The average SFR (upper panel), and average SSFR (lower panel) of IR-luminous cluster galaxies as a function of projected radius with galaxies split into two mass bins. The dashed lines show the representative field values, taken as the outermost radial bin. The $\langle \text{SFR} \rangle$ and $\langle \text{SSFR} \rangle$ of higher mass galaxies ($\log M_*/M_\odot \geq 10.8$, yellow) show a weakly decreasing trend with increasing radius, while the lower mass galaxies ($\log M_*/M_\odot \leq 10.8$, orange) increase with increasing radius, suggesting that the cluster environment is enhancing the SFRs of low mass cluster galaxies. A weak boosting of the $\langle \text{SFR} \rangle$ in the cluster cores, which may be environmentally-driven. This epoch of active star formation is in sharp contrast to our $z = 1 - 1.38$ clusters, which show a decreasing fraction of IR-luminous galaxies, as well as decreasing $\langle \text{SFR} \rangle$ and $\langle \text{SSFR} \rangle$ into the cluster cores, consistent with local SFR-density
relation. These results are consistent with and verify those of previous works which uncovered this era of star formation in galaxy clusters. Looking at ISCS cluster galaxies to a deeper SFR limit with Spitzer MIPS, Brodwin et al. (2013) found not only a flattening of the fraction of SFGs, but an increasing fraction above the field level into the cluster cores at $z \sim 1.38$. This is suggestive of the increase in the average SFR we see at high redshift, though the subtlety of this effect in this work may indicate that galaxies with lower SFRs than our limit may be more strongly affected. This is supported by a fully mass-limited analysis of galaxies in the ISCS cluster was carried out in Chapter 2 using a stacking analysis on Herschel SPIRE imaging. That study also observed this epoch of active star formation and found a $\sim 30\%$ boosting of the $\langle SFR \rangle$ of cluster galaxies over the field at $z \gtrsim 1.4$. This effect was found to be driven by lower mass galaxies, $10^{10.1} < \log(M/M_\odot) < 10^{10.8}$, and predominantly in the radial range 0.5 to 1 Mpc.

### 3.3.2.2 Probing Deeper: Stacking on the PACS Maps

In order to examine the star formation properties of the full cluster galaxy population, a mass-limited sample ($\log M_* \geq 10.1 M_\odot$), we stack on the PACS maps to quantify the average SFR per cluster galaxy. As each cluster map has a different depth, stacking is performed on each map separately by combining cutouts centered on the positions of each cluster member and then extracting the stacked flux using the same source extraction outlined in Section 3.2.4.2. Because we are interested in the properties of the full population, we do not remove detected sources from the stack. Sources are additionally separated by $F_{\text{gal}}$ during stacking in order to determine the contribution from SFGs vs AGN and then the SFRs are obtained through applying the SFG and AGN templates to the appropriate portion of the stacked flux. The combined stacked SSFRs of all clusters in two redshift bins can be seen in Figure 3.9 as a function of projected radius. In the lower redshift clusters, we again see
a significant decrease in average SSFR in the cluster cores relative to the field, with \( \langle \text{SFR} \rangle = 15 \pm 3 \, \text{M}_\odot \, \text{yr}^{-1} \) at \( r < 0.5 \, \text{Mpc} \). Since we are stacking on a mass-limited galaxy sample, this decrease could be due to a decrease in the average SFR of SFGs and/or an increase in the fraction of quenched galaxies. In the higher redshift clusters, we measure \( \langle \text{SFR} \rangle = 42 \pm 7 \, \text{M}_\odot \, \text{yr}^{-1} \) in the cluster cores, indicating a weak trend toward decreasing \( \langle \text{SFR} \rangle \) below the field value.

We compare these trends to those measured for mass-limited galaxy samples through stacking SPIRE imaging for the full ISCS cluster sample (Alberts et al., 2014). Though this decrease as a function of redshift is consistent with the evolution of the average SFR found in that study \( (\langle \text{SFR} \rangle \sim (1+z)^{5.6}) \), that analysis found that the average SFRs of cluster galaxies at \( \langle z \rangle = 1.2 \) are comparable to the stacked \( \langle \text{SFR} \rangle \) of field galaxies at the same redshifts \( (\langle \text{SFR} \rangle \sim 25 \, \text{M}_\odot \, \text{yr}^{-1}) \), while here we find a decrease below the field value. This apparent discrepancy can be resolved if the clusters in this work \( (M_{200} \sim 10^{14} \, \text{M}_\odot) \) are on the high end of the halo mass distribution of the full ISCS/IDCS sample, as is suggested by halo mass ranking simulations which found median cluster masses of \( M_{200} \sim (5 - 8) \times 10^{13} \, \text{M}_\odot \) for the ISCS (Alberts et al., 2014). In addition, the SPIRE stacking analysis found an enhancement in the \( \langle \text{SFR} \rangle \) of cluster galaxies over the field at \( 0.5 < r < 1 \) in clusters at \( \langle z \rangle = 1.4 \). This result is not reproduced here, though we do see increased \( \langle \text{SFR} \rangle \) and \( \langle \text{SSFR} \rangle \) for the IR-luminous galaxy population at \( r < 1 \, \text{Mpc} \). We suggest that these differences between the cluster subsample in this work and the analysis of the full ISCS sample are due to downsizing effects where more massive clusters, preferentially targeted for additional study in this work, quench SF earlier.

### 3.3.2.3 Cluster-to-Cluster Variations

Given the difficulties in identifying and analyzing statistical samples of clusters during the epoch of active star formation, multiple studies to date have relied on
Figure 3.9 The average SFR (upper panel) and SSFR (lower panel) derived from stacking on PACS maps for mass-limited samples of cluster galaxies as a function of projected radius. As in Figure 3.7, the clusters are divided into two redshift bins. The higher redshift \((1.38 < z < 1.75, \text{ red})\) cluster galaxies show a roughly flat \(\langle \text{SFR} \rangle\) and \(\langle \text{SSFR} \rangle\) into the cluster cores, with a weak \((< 1\sigma)\) trend toward declining with decreasing radius, indicating that the full, mass-limited cluster galaxy sample largely mirrors the SFR and \(M_*\) distribution of the field on average. In the lower redshift clusters, we see a decrease in the \(\langle \text{SFR} \rangle\) and \(\langle \text{SSFR} \rangle\) as quenching and/or mass assembly occurs, in excess of what we expect for field galaxy populations.

observations of individual clusters. Here we look at variations in the star formation properties from cluster-to-cluster within our sample in order to quantify the diversity of high redshift clusters with a uniform selection and with similar halo masses.
Figure 3.10 shows the stacked average SFRs of cluster galaxies with \( \log (M,/M_\odot) \geq 10.1 \) for each cluster in two radial bins: \( 0 < r/Mpc < 1 \) and \( 1 < r/Mpc < 2 \). In general, most clusters show a flat or slightly decreasing average SFR from the outer to the inner radial bin when considering the full, mass-limited population. In several clusters we see a significant decrease, which may reflect decreasing average SFRs in currently SFGs and/or a significantly increased fraction of passive galaxies toward the cluster cores. In several cases, the decrease is dramatic, an order of magnitude, and can be seen in both low (e.g. ISCS3, blue, \( z = 1.262 \)) and high (e.g. ISCS7, orange, \( z = 1.400 \)) redshift clusters. The highest redshift cluster in our sample, IDCS11 at \( z = 1.75 \), shows a 3\( \times \) decrease in the average SFR toward the cluster core, indicating a relatively evolved state even at this high redshift, which is consistent with its high mass (\( M_{\text{halo}} = 5.4 \times 10^{14} M_\odot \)), given cluster downsizing. By contrast, ISCS6 shows a dramatic increase of the average SFR in the cluster core.

This decrease (or increase) can be due to the changing fraction of actively star forming to passively evolving galaxies and/or the changing properties of current SFGs. In Figure 3.9, we look at the total SFR per area for both PACS detected cluster members and for all cluster members, derived by multiplying the stacked \( \langle SFR \rangle \) by the total number of stacked sources. We find a large dispersion (\( \Sigma \) SFR per area = \( \sim 20 - 200 M_\odot \text{ yr}^{-1} \text{ arcmin}^{-2} \)) in cluster properties within the virial radius (\( \lesssim 1 \text{ Mpc} \)), with some clusters showing very little total SFR in the central 1 Mpc while others show up to 7 times the amount of SF as in the outer 1-2 Mpc. By contrast, we find less variation in the total SFR in the outer radial bin, with \( \Sigma \) SFR per areas of \( \sim 20 - 50 M_\odot \text{ yr}^{-1} \text{ arcmin}^{-2} \). Comparing the total SFR from detected PACS sources to the total SFR from stacking within the virial radius, we find that the median value of this ratio is \( \sim 90\% \), ranging from 65\% at the 25\textsuperscript{th} percentile to 100\%. For clusters such as IDCS11, the bright, detected cluster members are consistent with providing the bulk of the SFR. Given that we saw no decrease in the \( \langle SFR \rangle \) of PACS-detected
Figure 3.10 The stacked average SFRs of each individual cluster in two radial bins: within the virial radius ($0 < r < 1$ Mpc) and outside the virial radius ($1 < r < 2$ Mpc). The majority of the clusters show a small dynamic range in terms of the change in their average SFR with radius, consistent with the weak trends of the $\langle SFR \rangle$ found for PACs-detected cluster members (Figure 3.7). A few clusters, on the other hand, show drastic changes in the $\langle SFR \rangle$ into the cluster cores, both increasing and decreasing with decreasing projected radius. This highlights the large cluster-to-cluster variations in cluster properties possible even in uniformly-selected clusters at similar redshifts and halo masses. The radial bins are offset for clarity.

Cluster galaxies (Figure 3.7), this indicates that the $3\times$ decrease in the stacked $\langle SFR \rangle$ seen in Figure 3.10 is likely due to a rapid build up of the red sequence, with actively SFGs having their SF quenching on short timescales, rather than a slow decrease in the SFR of currently star forming galaxies.

In Figure 3.12, we take a look at the $\Sigma$SFR per halo mass to determine the relation between the SF properties of a cluster and its total mass.
Figure 3.11 The total SFR per area for each cluster in two radial bins, within the virial radius \( (0 < r < 1 \text{ Mpc}, \text{top}) \) and outside the virial radius \( (1 < r < 2 \text{ Mpc}, \text{bottom}) \), for both PACS-detected cluster members (light blue) and mass-limited cluster galaxy samples (dark blue), determine through stacking on the PACS maps. Within the virial radius (top), the clusters show a large dispersion in the total SFR, ranging from \( \sim 20 - 200 \text{ M}_\odot \text{ yr}^{-1} \text{ arcmin}^{-2} \). In more than half of the clusters, the total SFR from PACS-detected sources is consistent with the total from stacking, indicating that the IR-luminous galaxies are dominating the SFR budget. This is not true for all the clusters, however, again displaying variations between individual clusters. Beyond the cluster radius, the total SFR per area is much more uniform across our sample, with \( \sim 20 - 50 \text{ M}_\odot \text{ yr}^{-1} \text{ arcmin}^{-2} \).

for our clusters are listed in Table 3.2.1. Though masses are sometimes available from multiple sources, we adopt mass values from X-ray observations (circles) where available and weak lensing-derived masses (diamonds) otherwise. Three of our clusters have no independent mass measurement and are assigned \( M_{\text{halo}} = 2.5 \times 10^{14} \text{ M}_\odot \) (squares), the median value of our X-ray masses. The total SFR is calculated from our stacking measurements within the cluster virial radii \( (r < 1 \text{ Mpc}) \). We choose to derive the total SFR from our stacking rather than from PACS-detected sources.
Figure 3.12 The halo mass-normalized total SFR, $\Sigma \text{SFR} / M_{\text{halo}}$, for our clusters as a function of redshift. Total SFRs were measured using stacking on mass-limited cluster galaxy catalogs within the cluster virial radius ($\sim 1$ Mpc). Halo masses were measured using X-ray (circle) or weak lensing measurements (diamond). Clusters without individual mass measurements are assigned the median of our X-ray masses, $M_{\text{halo}} \sim 2.5 \times 10^{14} M_\odot$ (squares). Upper limits are shown for three clusters that were not detected at $> 3\sigma$ in the stacks. We compare to three relations measured for clusters at $z < 1$ in the literature: Geach et al. (2006) (dashed line), Webb et al. (2013) (dotted line), and Popesso et al. (2012) (dash-dot line). In addition, we compare to the general evolution of field galaxies (Behroozi et al., 2013, solid line). Our cluster sample generally agrees with the consensus in the literature that the mass-normalized SFR in cluster goes as $(1 + z)^{5-7}$ (e.g. Geach et al., 2006; Webb et al., 2013, Chapter 2), though with at least one example that falls well off this relation. This evolution is consistent with the mass-normalized SFR in clusters drawing even with the SFR seen in typical haloes in the field at $z \gtrsim 1$, keeping in mind the large uncertainties in both cluster and field studies at these redshifts.

as up to 50% of SF is below our PACS detection limit (see Figure 3.9). Only $> 3\sigma$ stacked detections are shown; for the clusters undetected in the stacking, $3\sigma$ upper limits are shown (ISCS3, ISCS8, and ISCS9).
The relation between $\Sigma SFR/M_{\text{halo}}$ and redshift has been measured up to $z \sim 1$ in the literature and generally goes as $(1 + z)^{5-7}$ (e.g. Geach et al., 2006; Koyama et al., 2011; Popesso et al., 2012; Webb et al., 2013; Haines et al., 2013, Chapter 2). We compare here to three relations, keeping in mind that such comparisons are complicated given differences in cluster selection, cluster masses, galaxy selection, SFR tracers, and redshift range, which we make no attempt to correct for. We find that the majority of our clusters are in good agreement with trends found in Geach et al. (2006) and Webb et al. (2013). The Geach et al. (2006) trend, $\Sigma SFR/M_{\text{halo}} \propto (1 + z)^7$, is based on $z \sim 0.5$ cluster galaxies and closely follows the evolution of infrared galaxies in the field as seen in Cowie et al. (2004) up to $z \sim 1.5$. The Webb et al. (2013) relation, $\Sigma SFR/M_{\text{halo}} \propto (1 + z)^{5.4}$, was measured for similar mass, red sequence-selected clusters from $0.3 < z < 1$. Though the Webb et al. (2013) relation was derived using IR-luminous ($L_{\text{IR}} > 2 \times 10^{11} L_\odot$) galaxies, we note that the evolution they measure is in good agreement with the trend seen for mass-limited cluster galaxy samples in Chapter 2 and in this work, providing further evidence that IR-luminous galaxies dominate the SFR budget of cluster galaxies at moderate to high redshift ($z \gtrsim 0.3$). Most of our clusters do not agree with the Popesso et al. (2012) relation; however, this is not surprising given that the cluster sample in Popesso et al. (2012) had typical masses of $\sim 10^{15} M_\odot$. It is interesting that our highest redshift cluster, which has already built up an X-ray mass of $5.3 \times 10^{14} M_\odot$ by $z = 1.75$, falls closest and even below the Popesso et al. (2012) relation, suggesting that its galaxy population is more similar to those of $\sim 10^{15} M_\odot$ clusters at $z \lesssim 1$ than the other massive clusters in our sample.

The solid line and gray shaded region in Figure 3.12 show the evolution of the $\Sigma SFR/M_{\text{halo}}$ of all galaxies up to $z \sim 2$, quantified as the observed SFR density presented in Behroozi et al. (2013) divided by the mean comoving density of the Universe. Given dark matter halo mass functions (Jenkins et al., 2001), the dark
matter budget is dominated by haloes of $10^{11} - 10^{12}\, M_\odot$ at all redshifts, so this quantity is a good representation of the evolution of massive field galaxies. In good agreement with our other indications that cluster galaxies are experiencing field-like or enhanced SF, we find that $\Sigma\text{SFR}/M_{\text{halo}}$ of clusters is similar to that in the field at $z \gtrsim 1$, albeit with a large scatter and at least one example of a more evolved system that does not follow this trend.

3.3.2.4 Evolution in Cluster Galaxies Relative to the Main Sequence

The MS of galaxies defines the relation between SFR and stellar mass, which has been found to have a tight correlation, with outliers potentially representing different modes of star formation, such as starbursts (e.g. Elbaz et al., 2011). In Figure 3.6, we saw that PACS-selected cluster galaxies show no obvious deviation from the general trends of the MS. In this section, we attempt to quantify this more carefully. As we saw in Section 3.3.2, however, our PACS imaging does not reach a sufficient depth to fully sample the MS over our entire redshift range. To compensate for this, we derive SFRs for sources that are detected with MIPS $24\, \mu m$ in addition to our PACS-detected sources, effectively lowering our SFR limit to $\sim 30\, M_\odot\, yr^{-1}$. Studies have shown that SFRs can be obtained from MIPS $24\, \mu m$ up to $z \sim 1.5$ (e.g. Elbaz et al., 2011) and we verify that SFRs derived from PACS $100\, \mu m$ versus MIPS $24\, \mu m$ for galaxies in our sample are consistent within a factor of two. This analysis is limited to our clusters in the redshift range $1 < z < 1.5$ as we do not have deep imaging for our highest redshift cluster and MIPS-derived SFRs are unreliable at $z \gtrsim 1.5$.

Figure 3.13 shows the SSFRs, derived from PACS $100\, \mu m$ where available and MIPS $24\, \mu m$ otherwise, of our cluster galaxies with $\log (M_*/M_\odot) \geq 10.1$ as a function of redshift and in relation to the MS, which we assume has a scatter of $\sim 2\, \times$ (Elbaz et al., 2011). Cluster galaxies are divided into radial bins and we calculate $R_{SB} = \text{SSFR}/\text{SSFR}_\text{MS}$, which is the ratio of the SSFR of any given source to the MS at
Figure 3.13 The SSFRs of PACS and MIPS-detected cluster galaxies up to \( z \sim 1.5 \) as a function of redshift, shown in relation to the Main Sequence (solid line). Cluster galaxies are broken into radial bins and AGN and AGN-composites are marked as in Figure 3.6. The dash-dot lines denotes 2\( \times \) above and below the MS, based on the definition of starbursts in Elbaz et al. (2011).

that source’s redshift (Figure 3.14, top). We have removed any spectroscopic cluster members that are not in the photometric redshift catalog, since the spectroscopic completeness is a strong function of radius. We also remove \( F_{\text{gal}} < 0.5 \) sources, since most MS studies in the literature do not account for AGN (for a review of the MS in the literature, see Speagle et al., 2014). We examine the fraction of cluster galaxies off the MS in Figure 3.14 (bottom) in two redshift bins, where \( R_{\text{SB}} > 2 \) is considered to be a starburst following Elbaz et al. (2011) and \( R_{\text{SB}} < 0.5 \) is considered to be a galaxy that is being quenched off the MS. These dividing lines are somewhat arbitrary.
Figure 3.14 SFG cluster members in relation to the MS, as represented by $R_{SB} = \text{SSFR/SSFR}_{MS}$, as a function of projected radius. Top: The three symbols denote the three radial bins as seen in Figure 3.13. Sources with $R_{SB} = 1$ (solid line) are on the MS; off the MS is defined here as $2\times$ above and below, following Elbaz et al. (2011). Bottom: (a) The fraction of sources $2\times$ above the MS, $F_{\text{starburst}}$, as a function of projected radius. Galaxies with SSFRs in the region relative to the MS were found to be primarily compact starbursts in Elbaz et al. (2011). We find that the fraction of starbursts decreases into the cluster cores at all redshifts. (b) The fraction of sources $2\times$ below the MS, $F_{\text{quenching}}$, as a function of projected radius. These sources have lower SFRs relative to their stellar mass and are likely experiencing quenching. This fraction is flat with radius for the higher redshift clusters, but increases significantly in the cores of the lower redshift clusters in our sample. The radial bins are offset for clarity and the dashed lines correspond to the outermost radial bin, for reference.

(though see Elbaz et al., 2011, for a discussion about starbursts), but should serve to illustrate any strong trends with radius. We find that the fraction of starbursts
(i.e. galaxies more than 2× the MS) decreases with decreasing projected radius by $\sim 10 - 15\%$ for clusters at all redshifts. As the region above the MS is often attributed to merger activity (Elbaz et al., 2011), this suggests there is not an enhancement of gas-rich major mergers in the cluster cores (though this does not rule out dry or minor mergers). The fraction of quenching galaxies is flat for our high redshift ($1.38 < z < 1.75$) clusters, consistent with the flat trends in the average SFR and SSFR seen earlier. In the lower redshift ($1 < z < 1.38$) clusters, however, we see a sharp increase in the fraction of quenching galaxies, from $\sim 10 - 40\%$ with decreasing projected radius.

3.3.3 Growing AGN: Composite Galaxies from $z = 0.5 - 2$

Studies of X-ray, MIR, and radio-selected AGN in the ISCS cluster sample have established that the AGN fraction increases dramatically within cluster environments to high redshift, climbing to field-like AGN fractions at $z \sim 1.25$ (Galametz et al., 2009; Martini et al., 2013), a two order of magnitude increase over local clusters. These AGN may play a central role in the fueling and quenching of star formation in dense environments. In the scenario where star formation quenching occurs on rapid timescales in clusters, as suggested by the evolution of the SFRs in $z > 1$ clusters (e.g. Muzzin et al., 2012; Brodwin et al., 2013, Chapter 2, this chapter) and studies of the stellar mass function at $z \sim 1$ (van der Burg et al., 2013), starbursts and AGN feedback triggered galaxy interactions such as mergers could serve to rapidly remove and/or deplete gas from galaxies and quench remaining star formation on the order of $\sim 100$ Myr (Springel et al., 2005; Hopkins et al., 2006; Narayanan et al., 2010). Evidence for such merger-driven growth has been observed statistically by Mancone et al. (2010, 2012), who found that the rest-frame NIR luminosity functions of cluster galaxies in Boötes is inconsistent with passive evolution models at $z > 1.3$. This departure from passive evolution in the NIR luminosity function (a proxy for
stellar mass), combined with the simultaneous ramp up of star formation and AGN activity, supports the idea that mergers and subsequent feedback are important in cluster evolution at high redshift. For a more detailed discussion of this scenario, see Brodwin et al. (2013).

In this section, we examine the role of AGN and SFG/AGN composite galaxies through our $F_{\text{gal}}$ parameter as a function of redshift and radius. To avoid the bias introduced by requiring photometric redshifts for cluster membership, for this analysis we opt to do a line-of-sight study with background subtraction in order to isolate clusters trends. In addition, in order to increase our statistical power and take advantage of all available data, we expand this analysis to include all ISCS/IDCS clusters between $0.5 < z < 2$.

We divide the galaxies in the photometric redshift catalog into four categories: $F_{\text{gal}} < 0.3$ (“AGN-dominated”), $0.3 < F_{\text{gal}} < 0.5$ (“AGN-Composite”), $0.5 < F_{\text{gal}} < 0.7$ (“galaxy-Composite”), and $F_{\text{gal}} > 0.7$ (“galaxy-dominated”). Note that the $F_{\text{gal}}$ parameter is not sensitive to star formation activity, so these categories should not be interpreted as star-forming versus AGN, but rather by a decreasing degree of AGN influence on the optical-MIR SED of all galaxy types, including non-star forming ellipticals. In addition, since this AGN indicator is based on SED analysis, it will include lower luminosity AGN than X-ray or IRAC indicators (see Figure 3.1). Figure 3.15 (a) shows the fraction of each category along the line-of-sight to the ISCS/IDCS cluster cores ($r < 0.5\,\text{Mpc}$) as a function of redshift. Galaxies are by far the largest component; however, we find a marked decrease in this subtype with increasing redshift, from 65% to 48% from $z = 0.5$ to $z = 1.5$. The bulk of this difference is countered by an increase in the galaxy-composites, with smaller gains in the AGN-composites and AGN. The dotted lines show the fractions for the full catalog, regardless of environment or redshift.
Next we examine the field-relative fraction of each category as a function of cluster-centric radius. We bin our cluster samples into three redshift bins: $0.5 < z < 1$ (138 clusters), $1 < z < 1.5$ (76 clusters), and $1.5 < z < 2$ (21 clusters). We then quantify the fraction of each subtype along the line of sight in radial bins, out to a projected radius of 3 Mpc, which is taken to be the field value (Figure 3.15, (b)). In the lowest redshift bin, galaxy-dominated sources are overrepresented in clusters at $\sim 110\%$ of the field value, with galaxy/AGN-composites and AGN-dominated underrepresented by $\sim 10 - 30\%$. By $z = 1$, galaxies have dropped below the field level, with galaxy composites slightly above and AGN-composites rising to $\sim 130\%$ of the field level. The fraction of AGN-dominated has also risen, though it is still below field value. For our highest redshift clusters, however, AGN-dominated, AGN-composites, and galaxy-composites are all above the field, with AGN-composites at 150\% of the field level.

These results show a substantial rise in the fraction of AGN and AGN-composites in the cluster cores, consistent with previous studies (Galametz et al., 2009; Martini et al., 2013). In addition, we demonstrate a rise in galaxy-composites, representing the hosts of relatively weak AGN, and a decline in galaxy-dominated sources with $< 30\%$ contribution to their optical-MIR SED from AGN emission. The implications of this and how it relates to the observed increase in star formation with redshift will be discussed in Section 3.4.

3.3.4 Comparison of Unobscured and Obscured Star Formation Tracers

Throughout this study, we have focused on star formation as traced by re-radiated IR emission. In this section, we compare this SFR tracer to a direct (though attenuated) measure of star formation: H$\alpha$ emission. The H$\alpha$ line is sensitive to the most massive stars ($> 10 M_\odot$), providing a more instantaneous measure of the SFR ($< 10$ Myr) than IR emission, which traces SF over $\sim 100$ Myr (Kennicutt, 1998).
Figure 3.15 All sources in the photometric redshift catalog along the line-of-sight to the cluster cores ($r < 0.5$ Mpc) for the 235 clusters in the ISCS/IDCS from $z = 0.5 - 2$. Top: Sources are separated into four subtypes by the $F_{\text{gal}}$ parameter: AGN-dominated ($F_{\text{gal}} < 0.3$, green), AGN-composite ($0.3 < F_{\text{gal}} < 0.5$, purple), galaxy-composite ($0.5 < F_{\text{gal}} < 0.7$, yellow), and galaxy-dominated ($F_{\text{gal}} > 0.7$, blue). Open symbols represent the fraction of each subtype along the line-of-sight of individual clusters as a function of cluster redshift. Closed symbols denote the weighted mean of each subtype as a function of redshift. Though galaxy-dominated sources make up the bulk of sources at all redshifts, their fraction decreases with increasing redshift in the cluster cores. Composite and AGN-dominated sources show a corresponding increase. The dotted lines show the fraction of each subtype for the full catalog, independent of redshift. Bottom: The fraction of each subtype as a function of projected radius, normalized to the field, which is taken to be the fraction at the outermost radial bin. The ISCS/IDCS are separated into redshift bins: $0.5 < z < 1$ (upper panel), $1 < z < 1.5$ (middle panel), $1.5 < z < 2$ (lower panel). For the lowest redshift clusters, galaxy-dominated sources are present in the cluster cores in slight excess of the field, with composite and AGN-dominated source fractions below the field fractions. These trends reverse with increasing redshift and for clusters at $1.5 < z < 2$, we see significantly enhanced fractions of AGN-dominated and composite sources over the field, indicating that the cluster environment is enhancing the growth of AGN in cluster galaxies.

The comparison of SF on different timescales may provide clues as to the timescales of the enhancement or quenching of SF in cluster galaxies.

First, we briefly summarize the procedure for measuring SFR$_{H\alpha}$ from $HST$ grism spectroscopy (for a full description see Zeimann et al., 2013). H$\alpha$ and [NII] are blended at the spectral resolution of WFC3 so the [NII] component is removed using
the fundamental metallicity relation (e.g. Maiolino et al., 2008) to infer each galaxy’s metallicity and derive its [NII] to Hα ratio. The total star formation is then related to the Hα luminosity, L_{Hα}, by the equation

\[ \text{SFR}^{\text{corr}}_{H\alpha} = 5.3 \times 10^{-42} \times L_{H\alpha} \times 10^{0.4 \times A_{H\alpha}} \] (3.4)

assuming continuous star formation and a (Kroupa, 2001) IMF. The last term, \(10^{0.4 \times A_{H\alpha}}\), represents the correction for attenuation due to dust extinction, which Zeimann et al. (2013) calculated following the empirical relation from Garn & Best (2010)

\[ A_{H\alpha} = 0.91 + 0.77M + 0.11M^2 - 0.09M^3 \] (3.5)

where \(M = \log M_*/10^{10}M_\odot\), assuming a Chabrier IMF (Chabrier, 2003) to match our stellar mass estimates.

Since the Hα is sensitive to much lower SFRs than the PACS imaging, we calculate SFR_{IR} using available MIPS 24µm detections for sources not detected in PACS. It should be noted that, by using the Murphy et al. (2011b) L_{IR} to SFR conversion, we are correcting our SFRs as measured in the IR for any missing, unobscured component. This means that SFR_{IR} and SFR_{Hα}^{corr} are both, assuming they are correctly calibrated, measures of the total star formation rate. We opt to include sources with a strong AGN in our analysis, having corrected for the AGN component in the IR by adopting an appropriate AGN template (see Section 3.3.1). The Hα line emission from WFC3 grism spectroscopy will also be contaminated by AGN, however, and we have NOT corrected for that contamination in calculating SFR_{Hα}, which is likely overestimated for AGN sources. All likely AGN are marked clearly in the following figures.

In Figure 3.16 (top), we examine the ratio of the unobscured star formation component, SFR_{Hα}^{uncorr}, calculated using Eqn 3.4 without the attenuation correction term,
to the total SFR\textsubscript{IR}. We find that this ratio is a strong function of SFR\textsubscript{IR}, dropping almost two orders of magnitude over the range SFR\textsubscript{IR} = 10 − 100 M\textsubscript{☉} yr\textsuperscript{−1}, demonstrating the known positive correlation between obscuration and star formation activity. Comparing cluster (black circles) to field (purple diamonds) galaxies, we find that the dependence of this ratio on SFR\textsubscript{IR} is not a strong function of environment, consistent with studies of clusters at $z \sim 0.5$ (Geach et al., 2006). The blue line shows a linear fit in log-log space to the SFGs. In Figure 3.16 (middle), we show the same ratio for the corrected SFR\textsubscript{corrHα} using Equation 3.5. The results show a definite trend whereby the mass-based attenuation correction fails to fully account for the dust-obscuration of H\textalpha emission at high SFR\textsubscript{IR} ($\gtrsim 50$ M\textsubscript{☉} yr\textsuperscript{−1}) for these $z = 1 − 1.5$ galaxies.

The extinction correction formulated based on stellar mass (Garn & Best, 2010) was developed using SDSS galaxies up to $z \sim 0.7$ with average SFR\textsubscript{Hα} $\lesssim 10$ M\textsubscript{☉} yr\textsuperscript{−1} and extinction measured through the Balmer decrement. Though Garn & Best (2010) found a correlation between extinction and SFR and metallicity as well as stellar mass, they formulated their extinction correction using stellar mass as a widely measured parameter that provided the least residuals. Our results suggest that this parameterization does not hold for dusty LIRGs and ULIRGs at high redshift and we see no strong correlation between the ratio SFR\textsubscript{uncorrHα}/SFR\textsubscript{IR} and $M_\star$. Using the linear fit from Figure 3.16 (top), we derive the following correction based on the IR luminosity

\begin{equation}
L_{\text{corrHα}} = 5.8 \times 10^{-10} \times L_{\text{uncorrHα}} \times L_{\text{IR}}^{0.9} \tag{3.6}
\end{equation}

where $L_{\text{IR}}$ is in L\textsubscript{☉}. This relation is appropriate for dusty LIRGs and ULIRG with log ($M_\star/M_\odot$) $\geq 10.1$. The SFR\textsubscript{corrHα} corrected through this relation relative to SFR\textsubscript{IR} can be seen in Figure 3.16 (bottom) with a scatter of 0.47 dex.
Figure 3.16 A comparison of the H\textalpha and IR SFR indicators. Top: The uncorrected SFR\textsubscript{H\textalpha} to SFR\textsubscript{IR} ratio as a function of SFR\textsubscript{IR} for both cluster (black circles) and field (purple diamonds) galaxies at $z = 1 - 1.5$. Outlined symbols denote sources where the SFR\textsubscript{IR} was measured using MIPS 24\textmu m, otherwise PACS 100\textmu m was used. AGN with X-ray detections (red) or $F_{\text{gal}} < 0.5$ (orange) are marked. Though the SFR\textsubscript{IR} for AGN have been corrected for the contribution from AGN emission to the FIR flux, the SFR\textsubscript{H\textalpha} was not corrected for any AGN contribution to the H\textalpha line. The line blue is the best-fit to the non-AGN galaxies. Though this ratio is a strong function SFR\textsubscript{IR}, dropping two orders of magnitude, it does a strong function of environment. Middle: The corrected SFR\textsubscript{H\textalpha} to SFR\textsubscript{IR} ratio as a function of SFR\textsubscript{IR}, using the correction based on stellar mass derived in Garn & Best (2010). This correction does not fully account for the attenuation of H\textalpha for dusty LIRGs and ULIRGs at these redshifts. Bottom: The corrected SFR\textsubscript{H\textalpha} to SFR\textsubscript{IR} ratio as a function of SFR\textsubscript{IR}, using the best-fit relation in the upper panel, parameterized in Equation 3.6. The corrected ratio has a mean of 1.07 and a scatter of 0.47 dex.

Due to the different star formation timescales probed, the comparison of unobscured starlight through the H\textalpha luminosity, $L_{\text{H\alpha}}$, and re-processed starlight through $L_{\text{IR}}$ is potentially a powerful indicator of environmentally dependent processes. Re-
cently quenched star formation may show a temporary deficit of \( L_{\text{H\alpha}} \) relative to \( L_{\text{IR}} \), while environmentally triggered starbursts may show the opposite effect. Environmental processes such as AGN feedback or tidal interactions may also strip gas and dust from cluster galaxies, leading to an elevated \( L_{\text{H\alpha}} \) during the quenching processes.

In Figure 3.17 (left), we show the ratio \( L_{\text{H\alpha}} / L_{\text{IR}} \) as a function of cluster-centric radius. AGN are not included in this analysis. We find an increasing ratio with increasing projected radius on average (red dots), which may be a sign of recent quenching at small cluster radii. The Spearman test rules out the null hypothesis that radius and the \( L_{\text{H\alpha}} / L_{\text{IR}} \) ratio are uncorrelated at the 3\( \sigma \) level. The middle panel shows a histogram of the \( L_{\text{H\alpha}} / L_{\text{IR}} \) ratios for the cluster galaxies in the lefthand panel compared to that of field galaxies (right panel). We fit both distributions with Gaussians and find that, although the mean \( L_{\text{H\alpha}} / L_{\text{IR}} \) value is similar (-3.0 for cluster galaxies and -3.2 for field galaxies in log space), the cluster galaxy distribution shows a wider dispersion of 0.4 dex versus 0.2 dex for the field. This increased scatter in the \( L_{\text{H\alpha}} / L_{\text{IR}} \) ratio may point to increasing complexity in the processes affecting the relation between SF and dust in cluster galaxies.

### 3.4 Discussion

By examining the UV-to-FIR SEDs of IR-luminous cluster galaxies, we are able to select appropriate templates from which to derive SF not only from SFGs but also separate out the contribution to cluster SF from sources with significant AGN emission. Using an updated photometric redshift catalog and our IR-luminous cluster galaxy population, we have verified the trends found in Brodwin et al. (2013, Chapter 2), finding that ISCS/IDCS clusters at \( z > 1.38 \) show field-like fractions of star-forming galaxies, as well as field-like SFRs and SSFRs in the cluster cores (\( r < 0.5 \) Mpc), indicating an era of active SF in clusters prior to the significant quenching observed at lower redshifts.
Figure 3.17 Left: The ratio of the Hα luminosity to the total IR luminosity for cluster SFGs (black circles) as a function of projected radius. Outlined symbols indicate sources whose L$_{\text{IR}}$ was derived from MIPS 24µm, all others are derived from PACS 100µm. The red symbols indicate the mean of this distribution in radial bins; the average L$_{\text{Hα}}$/L$_{\text{IR}}$ decreases with decreasing cluster-centric radius. As Hα is sensitive to shorter SF timescales than IR, this could indicate quenching in the cluster cores. Middle: The histogram of the L$_{\text{Hα}}$/L$_{\text{IR}}$ ratio for cluster galaxies (black). This ratio has a mean of -3.0 in log space with a scatter of 0.4 dex. Right: The histogram of the L$_{\text{Hα}}$/L$_{\text{IR}}$ ratio for field galaxies at 1 < z < 1.5 (purple). Field galaxies have a mean of -3.2 in log space and scatter of 0.2 dex. The increased scatter for cluster galaxies may indicate an increased complexity in the processes affecting this ratio, relative to field galaxies.

3.4.1 Variations Between Individual High Redshift Clusters

In addition to the statistical trends observed in our cluster sample, it is important to highlight the variations in galaxy properties from cluster-to-cluster. In this work, we have analyzed a statistical sample of uniformly selected clusters over a relatively small redshift range using self-consistent techniques for identifying cluster membership and measuring cluster galaxy properties. We find, nonetheless, a wide dispersion in galaxy properties across our cluster sample. This is best seen in Figure 3.9, where the total SFR per area varies by over an order of magnitude within the cluster virial radii, in sharp contrast to outside the virial radius (1 < r/Mpc < 2), where this quantity only varies up to a factor of two. This variation is seen in both the IR-luminous
galaxy population and mass-limited galaxy samples, as probed by a stacking analysis. Studies of the IR-luminous galaxies in clusters at $z \lesssim 1$ were able to link the number density and evolution of the IR galaxy population to that in the field, suggesting that cluster environments at these redshifts do not enhance SF when controlled for halo mass (Webb et al., 2013). The analysis presented here hints that we may be observing an epoch in which we do see environmentally driven enhancement, as seen in Figure 3.12. This shows a general trend in our cluster sample toward rising above the general evolution of the total SFR in halos characteristic of the field (solid line and gray shaded region), although not all of our clusters follow this trend (e.g. IDCS687). This would explain the weak trend toward increasing SFRs above the field on average seen in our high redshift clusters (Figure 3.7) and in previous studies (Chapter 2) as well as the rise in average SFR seen for ISCS6 within the virial radius (Figure 3.10). However, we note that all our clusters with individual mass measurements are consistent with the field given our uncertainties. Larger samples of clusters at higher redshifts and better constraints on both cluster and field measurements are needed to constrain this evolution.

Of particular note in our sample are the clusters ISCS6 ($z = 1.396$) and ISCS10 ($z = 1.487$). As described in Section 3.2.7, these two clusters have a small angular separation ($\sim 4'$), and given their overlap both spatially and in photometric redshift space, we have assured no double-counting of galaxies by assigning membership based on the maximum integrated PDF of the photometric redshifts. As a system and individually, these two clusters stand out among our sample, with $\Sigma$ SFR per area 2-7 times larger within the virial radius than in the surrounding regions. As seen in Figure 3.10, ISCS6 shows a significant increase in the stacked $\langle SFR \rangle$ toward smaller cluster-centric radii, a possible sign of environmentally-driven enhancement in cluster galaxy SFRs. Though their separation in redshift space (nearly 200 Mpc, comoving line of sight) makes it unlikely these clusters are currently merging, we speculate that
they may be directly connected through large scale structure, which may be enhancing their star formation. If so, then these clusters represent an important example of the effects of the dynamical state of cluster galaxies at high redshift, complimentary to lower redshift studies of more extreme merging cluster systems (e.g. Chung et al., 2010). Extensive spectroscopic follow-up of this system to more accurately map cluster membership and localize SF to the clusters and any filamentary structure in between would provide important constraints on the hierarchical growth of clusters at high redshift.

In light of the recent discoveries of massive, relatively evolved cluster systems at $z > 1.5$ (Koyama et al., 2014; Newman et al., 2014) and new evidence for cluster downsizing (Wylezalek et al., 2014), we also highlight our highest redshift, massive cluster IDCS687 at $z = 1.75$ (Stanford et al., 2012; Brodwin et al., 2012; Gonzalez et al., 2012). In Figure 3.12, we see that IDCS687 falls below the evolutionary trends predicted in previous studies (i.e. Geach et al., 2006; Webb et al., 2013, Chapter 2), agreeing more with the evolution of $\sim 10^{15} M_\odot$ haloes observed at lower redshifts (Popesso et al., 2012). In addition, we see indirect evidence that an evolved cluster population is already in place. Given the constraints placed by bootstrapping, which samples the spread in a population in addition to systematic uncertainties, we see no strong evidence for a significant decrease in the $\langle SFR \rangle$ in IR-luminous galaxies in the cluster cores in general (Figure 3.7), regardless of cluster-to-cluster variations. The IR-luminous population in IDCS687 is consistent with dominating the bulk of the SFR budget (Figure 3.9) and yet we see a drastic $3 \times$ drop in the average SFR of mass-limited cluster galaxies (Figure 3.10). This suggests that IDCS687 has already build up a population of weakly or non-star forming galaxies in its core, suggestive of an evolved system. This is not inconsistent with an era of active SF in clusters at $z \gtrsim 1.4$ given that we are not looking at progenitor sample of clusters, but rather at similar mass clusters at different snapshots in time. We caution against over-interpretation.
of such high redshift, evolved systems until statistical, uniform samples are available and suggest that the difficulties in confirming high redshift clusters may result in bias toward the most massive, and therefore through cluster downsizing the most evolved, systems. An analysis of SF in the IDCS687 Brightest Cluster Galaxy (BCG) and dust and gas properties of cluster galaxies at $z = 1.75$ will be presented in Chapter 4.

3.4.2 The Co-Evolution of Star Formation and AGN

To first order, the co-evolution of star formation and black hole (BH) growth (i.e. AGN activity) seems facile, given that both processes are driven by a common cold-gas supply, provided by the host galaxy or the host galaxy’s environment. The disparate size scales, with SF occurring in the disk and AGN growth at sub-kpc scales, however, make establishing a link between these two processes challenging. Additionally, simulations find that the physical processes that feed BH growth on small spatial scales are unlikely to be smooth or continuous and may vary on short timescales (Hopkins & Quataert, 2010; Hickox et al., 2014), making any causal connection to longer-lived SF unclear. The connection between SF and AGN is thus still heavily debated, however the parallel redshift evolution of SFGs and AGN (see Madau & Dickinson, 2014, for a review), possible observations of an AGN Main Sequence (Mullaney et al., 2012b), and the strong correlation between the average BH growth and global SFRs (Chen et al., 2013; Hickox et al., 2014) are suggestive of a direct link. AGN can be triggered by either internal secular evolution processes—disk instabilities, bars, etc— or through galaxy interactions such as harassment and mergers (see Alexander & Hickox, 2012, for a review).

Using background subtraction, we looked at the field-relative fraction of AGN-dominated and AGN-composite cluster galaxies as a function of redshift in a sample of $\sim 250$ clusters from $0.5 < z < 2$. We found that the fraction of AGN increases in the cluster cores with increasing redshift, consistent with previous studies of high
luminosity AGN (e.g. Galametz et al., 2009; Martini et al., 2013), and that AGN are present in excess of the field at $z \gtrsim 1.5$ in the cluster cores. From $z = 1.5 - 0.5$, the fraction of AGN in clusters declines rapidly. The excess of AGN above the field at these high redshifts is suggestive of either increased galaxy interaction, expected in dense environments, and/or that the cluster environment is already hosting more massive galaxies than the field, as AGN are preferentially hosted in massive galaxies (e.g. Bundy et al., 2008; Hickox et al., 2009; Xue et al., 2010). Studies find that AGN in the field primarily live in star-forming disk galaxies (e.g. Schawinski et al., 2011). If this is also true in clusters, then the latter explanation for the increased AGN fraction would suggest a difference in the stellar mass function (SMF) of currently SFGs between the cluster and field. Though SMFs of clusters at these redshifts have not yet been quantified, studies of clusters at $z \sim 1$ found no significant difference in the SMF of SFGs as a function of environment (van der Burg et al., 2013). Further observations of the SMF and the fraction of galaxy interactions in high redshift clusters are needed to explain the increase fraction of AGN. What is clear from our current results is that AGN and SFGs fractions both decline in clusters after $z \lesssim 1.5$, suggesting a co-evolution between SF and AGN in clusters.

### 3.4.3 Quenching Star Formation in High Redshift Clusters

A variety of processes have been suggested as the dominant mode of quenching in dense environments, encompassing both internal processes that induce self- or mass-quenching and externally-driven environmental quenching (e.g. Peng et al., 2010). The increased fraction of AGN and the parallel decline of AGN with SF in clusters at high redshift is suggestive of the scenario in which AGN feedback drives quenching in cluster galaxies. One particular version of this scenario, discussed in Brodwin et al. (2013), involves gas-rich major mergers triggering SF and AGN activity followed by quenching on relatively rapid ($\sim 100$ Myr) timescales. Merger activity is supported
by statistical evidence of mass assembly (Mancone et al., 2010) as well as observations of an increased merger fraction in a $z = 1.62$ (proto-)cluster (Lotz et al., 2011). Our results do not find any evidence of significant enhanced activity ($> 2 \times$ the MS) in the cluster cores across our redshift range, where we would expect to find short-lived starbursts triggered by major mergers (Daddi et al., 2010a; Genzel et al., 2010; Magnelli et al., 2013). As the triggering of AGN can be delayed by $\sim 50 - 500$ Myr (e.g. Davies et al., 2007; Schawinski et al., 2009; Wild et al., 2010), it is possible that starbursting activity is present at higher redshifts than we probe, however, it must be relatively rare as we see field-like fractions of SFGs in the cluster cores at $z > 1.4$, rather than fractions suggestive of rapid quenching at higher redshifts. Our indicators of extreme starburst activity are not sensitive to dry mergers or minor mergers, which may play an important role in mass build-up. Along similar lines, galaxy harassment may play a role in triggering SF or AGN activity in cluster galaxies at a level that may not be captured in our MS analysis. Currently, it is unclear if feedback from AGN triggered through galaxy interactions other than gas-rich major mergers, or even just internal processes, can be effective in quenching SF on galaxy scales (Alexander & Hickox, 2012).

Current facility now allow us to probe the molecular gas properties of galaxies at high redshift (see Carilli & Walter, 2013, for a review). Observations of molecular gas provide direct constraints on the fuel reservoirs available for SF and the SF efficiency in individual galaxies. Recently, Tacconi et al. (2013) surveyed MS SFGs at $z = 1 - 3$ using CO (3-2) observations to trace molecular gas. They found that the molecular-gas to SF relation is near-linear, implying a gas depletion time of $\sim 0.7$ Gyr in the absence of new accretion of cold gas (assuming a MW-like CO-H$_2$ conversion factor), consistent with previous studies (Daddi et al., 2010b; Tacconi et al., 2010; Magnelli et al., 2013). This depletion time is heavily dependent on the assumed conversion from CO luminosity to total molecular gas mass; however, adopting observed conversion
factors for ULIRGs would decrease the gas depletion time. Given the high duty cycles of SF (Reddy et al., 2005; Noeske et al., 2007; Daddi et al., 2007) and a short gas depletion time, field galaxies are expected to continually accrete new gas in order to sustain their SFRs. This suggests their star formation histories are closely linked to their history of gas accretion.

In Figure 3.7, we looked at the fraction of IR-luminous galaxies as a function of projected radius and as a function of redshift. The median redshifts of our bins, \( \langle z \rangle = 1.26 \) and \( \langle z \rangle = 1.46 \) are separated by \( \sim 0.6 \) Gyr. Over this relatively short period, we observe an average drop of \( \sim 25\% \) in the IR-luminous fraction of cluster galaxies relative to the field. Given the gas depletion timescales discussed above, if the cluster environment can suppress the accretion of new gas for a fraction of cluster galaxies, then those galaxies could quench through the consumption of the remaining gas over the timescales we observe. Simulations have found that dark matter haloes \( \gg 10^{13} \) M\(_\odot\), through the process of virialization and shock heating, can suppress the accretion of cold gas into galaxies (e.g. Cattaneo et al., 2006, 2008; Dekel & Birnboim, 2006; Kereš et al., 2009). The efficiency of this process is unclear, however, and recycled gas (Boselli et al., 2014) and/or cooling of a galaxy’s hot gaseous halo can prolong SF. Processes that strip gas from the hot halo of galaxies such as strangulation (Larson et al., 1980) have expected timescales of a few Gyr, too long to produce the rapid transition that we observe.

Ram pressure stripping (RPS; Gunn & Gott, 1972) is expected to act on timescales less than or similar to the crossing time (\( \sim 1 \) Gyr for our cluster sample, assuming velocity dispersions of 700 km s\(^{-1}\); Brodwin et al., 2011) and can therefore effectively strip tightly bound disk gas during a single passage in the most massive clusters (e.g. Abadi et al., 1999; Kapferer et al., 2009; Steinhauser et al., 2012). Though examples of this extreme RPS have been observed in local clusters (Ebeling et al., 2014), this mode of RPS requires ICM densities and galaxy velocities larger than the typical conditions.
of our high redshift clusters (e.g. Brodwin et al., 2011). When considering the gas depletion timescales, however, it is sufficient to prevent the cooling and accretion of the hot gaseous halo. Self-consistent hydrodynamical simulations have found that for a $\sim 10^{14} \text{M}_\odot$ cluster, 60-90% of outer halo gas of cluster galaxies can be stripped given velocity dispersions of $\sim 500 - 1000$ km s$^{-1}$ (Bekki et al., 2009). Given typical velocity dispersion of 700 km s$^{-1}$ for the ISCS/IDCS clusters, this suggests that RPS may play a role in the removal of hot halo gas as a reservoir for fresh gas accretion for some cluster galaxies, depending on galaxy mass, velocity, inclination, gas content, and host cluster properties.

### 3.5 Conclusions

In this work we have examined the IR-luminous population of massive cluster galaxies in a sample of 11 spectroscopically-confirmed clusters from $z = 1 - 1.8$. Using spectroscopic and robust photometric redshifts, we isolate both SF and AGN activity to individual cluster members and examine the relation between SF, AGN, and environment in both a statistical sense over our entire cluster sample and individually from cluster-to-cluster. In addition, we use a stacking analysis to probe mass-limited cluster galaxy samples and quantify the total cluster SFR in order to determine its evolution in terms of the cluster halo mass.

1. We present the first UV-to-FIR SEDs of cluster galaxies at high redshift. After splitting our cluster galaxies into SFGs and AGN, we compare to empirically derived templates of SFGs and AGN in the field at similar infrared luminosities and redshift (Kirkpatrick et al., 2012, Kirkpatrick et al., in prep). We find good agreement between the NIR-FIR SEDs of cluster galaxies and field galaxies, suggesting that cluster environment does not significantly affect the FIR SED and properties such as dust temperature.
2. We examine the average trends in SFR and SSFR of PACS-selected IR-luminous cluster galaxies as a function of projected radius and redshift. We find that our high redshift (1.38 < z < 1.75) clusters have field-like fractions of IR-luminous galaxies, \langle SFRs \rangle, and \langle SSFRs \rangle, while at lower redshifts (1.38 < z < 1.75), cluster galaxies are experiencing significant quenching. This result is in good agreement with previous studies (Brodwin et al., 2013, Chapter 2) which identified this transition epoch from active star formation to significant quenching in the cores of high redshift clusters. The mass-normalized SFRs of our cluster are generally consistent with predicted trends from previous studies (Geach et al., 2006; Webb et al., 2013, Chapter 2), with evidence for significant scatter.

3. Galaxy clusters in our sample show a wide dispersion in their star formation properties. We compare the total SFR per area within the virial radius (r < 1 Mpc) and in the outskirts (0 < r < 1 Mpc) and find both examples of significant SF activity (i.e. IDCS88) and suppressed SF activity (i.e. IDCS112) at similar redshifts. This highlights the need for statistical cluster samples.

4. Using both deep MIPS and PACS imaging, we examine our cluster galaxies in relation to the MS. We find no evidence of excess starburst activity in the cluster cores (defined as 2× the MS level, following Elbaz et al. (2011)).

5. We examine the full role of AGN in cluster environments using background subtraction. AGN are identified through their optical-MIR SED, allowing us to account for even low-luminosity AGN. We find clear evidence of an increase in galaxies with an AGN component in clusters relative to the field at the highest redshifts (z > 1.5) followed by a sharp decline with decreasing redshift and a dearth of AGN relative to the field at z ≤ 1. This trend is reminiscent of the
trends we see in the SFRs of cluster galaxies, suggesting a co-evolution between SF and AGN in clusters that may be linked to increased galaxy interactions.

6. We compare measurements of the unobscured SFR from Hα (Zeimann et al., 2013) to our IR tracer of obscured SF and find a strong dependence on the SFR\textsubscript{Hα}/SFR\textsubscript{IR} ratio on the IR luminosity. We additionally find a weak trend with projected radius, whereby the ratio of Hα to IR luminosity increases with increasing radius over the range 0 < r < 0.5 Mpc. This suggests that the cluster environment may be quenching some cluster galaxies on very rapid timescales, suppressing Hα emission, which probes SF on timescales of < 20 Myr.

7. Measurements of the gas depletion timescale in field galaxies find that SF can be quenched by the consumption of the gas reservoir on relatively rapid (∼ 0.6 Gyr) timescales and that fresh gas accretion is necessary to sustain the observed SFRs (Tacconi et al., 2013). This timescale for gas depletion is comparable to the timescale over which we see significant quenching in the cluster environment. This suggests a possible scenario for cluster galaxy evolution wherein the suppression of fresh gas accretion becomes effective at high redshift (z ≥ 1.4) in clusters, allowing a fraction of cluster galaxies to self-quench through consuming their current gas supply.
CHAPTER 4

TRACING THE INTERSTELLAR MEDIUM IN A Z=1.75 MASSIVE GALAXY CLUSTER

4.1 Introduction

Dense environments in the local Universe are dominated by a population of massive, passively evolving ellipticals, in sharp contrast to lower density field environment, which hosts the bulk of the star formation at the current epoch (see Blanton & Moustakas, 2009, for a review). The mechanisms responsible for the differences between environments are still unclear. Recent studies have traced the evolution of galaxies in the extreme environments of galaxy clusters to high redshift, finding increased star formation activity in individual clusters (Tran et al., 2010; Hilton et al., 2010; Hayashi et al., 2011; Fassbender et al., 2011; Tadaki et al., 2012) and identifying the epoch at which cluster galaxy populations transition from primarily passively evolving to actively star forming in statistical cluster samples (Brodwin et al., 2013, Chapter 2-3). This star forming era, occurring roughly at $z \gtrsim 1.4$ for typical halo masses of $\sim 10^{14} M_\odot$, provides a unique opportunity to quantify the properties of galaxies in clusters before quenching becomes prominent in the cluster environment.

At high redshift, near the peak in the star formation rate (SFR) density of the Universe ($z = 1 - 3$; Bouwens et al., 2009; Magnelli et al., 2013), the majority of star formation is dust-obscured (e.g. Magnelli et al., 2013) and the far-infrared (FIR) spectral energy distribution (SED) in star forming galaxies (SFGs) is shaped by the properties of dust grains, whose emission is primarily reprocessed light from recent star formation. Accurately measuring the SFR in high redshift galaxies therefore
requires a detailed modeling of the FIR SED, which is likely composed multiple dust components at different temperatures (e.g. Kirkpatrick et al., 2012). To date, only a few studies have placed constraints on the FIR SED in high redshift \((z > 1)\) cluster galaxies, finding that IR-luminous cluster galaxies have dust temperatures cooler on average than local IR-luminous galaxies (Smail et al., 2014) as well as similar FIR SEDs as field galaxies at similar redshifts (Chapter 3).

In addition, the FIR SED indirectly contains vital information about the gas reservoir which fuels star formation as gas and dust are linked in galaxies. The molecular gas of high redshift galaxies is typically probed through the rotational transitions of CO, which is then related back to molecular hydrogen through the use of a conversion factor. Both the time-consuming nature of detecting CO and the uncertainties in the conversion factor and the relation between different CO transitions (see Carilli & Walter, 2013) have made observations of high redshift galaxies challenging and current sample sizes are small. A complimentary method for measuring the gas mass of the ISM was recently highlighted in Scoville et al. (2014). This method uses the optically thin emission on the Rayleigh Jeans (RJ) tail of the FIR SED as a direct probe of the total dust mass. In combination with constraints on the dust emissivity (e.g. Draine & Li, 2007) and dust-to-gas abundance ratio, this can then be used to quantify the mass of the interstellar medium \((M_{\text{ISM}})\), providing an independent measure of gas properties which different assumptions and uncertainties.

Although current sample sizes are small, there is evidence that the gas fraction – the ratio of gas mass to stellar mass – increases as a function of redshift (e.g Carilli & Walter, 2013), mirroring the rise in the global SFR density of the Universe (e.g. Magnelli et al., 2013). Linking star formation and the ISM through the star formation efficiency \((\text{SFE} = \text{SFR}/M_{\text{gas}})\), or its inverse the gas depletion time, \(\tau_{\text{depletion}}\), has revealed the possibility of different modes of star formation, both a “normal” and a starbursting mode, which has an increased SFE (e.g. Daddi et al., 2010a).
Gas depletion timescales in normal SFGs have been found to be relatively short, \( \sim 0.7 \) Gyr, in \( z = 1 - 3 \) galaxy samples, far shorter than the epoch over which we observe galaxies actively forming stars. This indicates a strong connection between the SFH of a galaxy and its gas accretion history (Daddi et al., 2010b; Tacconi et al., 2010; Conselice et al., 2013).

There are several ways in which the dominant mode of star formation and the gas accretion history of a galaxy may be tied to its environment. Dense cluster environments with moderate galaxy velocities may contain an increased fraction of tidal interactions, from galaxy harassment to gas-rich mergers (Lotz et al., 2013; Brodwin et al., 2013), which may trigger starbursts which have higher SFEs than normal Main Sequence galaxies (e.g. Daddi et al., 2010b; Elbaz et al., 2011). In addition, the hot Intracluster Medium (ICM) in galaxy clusters, through the process of virialization and shock heating, may suppress the accretion of cold gas in reservoirs external to the galaxy (e.g. Cattaneo et al., 2006, 2008; Dekel & Birnboim, 2006; Kereš et al., 2009), while processes such as strangulation (Larson et al., 1980) or ram pressure stripping (Gunn & Gott, 1972; Bekki et al., 2009) may prevent the cooling of, or strip, the hot gaseous halo of a galaxy as it falls into a cluster, removing it as a future gas supply for star formation. Each of these processes have distinct timescales over which they operate and may be important at different stages of cluster evolution.

Quantifying ISM properties in cluster galaxies over a range of redshifts and cluster-centric radii will provide key insights into the dominant mode(s) of SF in clusters as well as the process of quenching. However, this field is relatively untapped, with only a handful of observations of gas in local clusters (e.g. Kenney & Young, 1989; Rengarajan & Iyengar, 1992; Boselli et al., 1997, 2014; Casoli et al., 1998; Scott et al., 2013), in clusters at intermediate redshift (\( z \sim 0.4 \) Geach et al., 2009, 2011; Jablonka et al., 2013), and in a few cluster galaxies at \( z > 1 \) (Wagg et al., 2012; Casasola et al., 2013). In this chapter, we present new SCUBA-2 imaging of a \( z = 1.75 \)...
massive ($M_{\text{halo}} \sim 5 \times 10^{14} M_\odot$) galaxy cluster (Stanford et al., 2012; Brodwin et al., 2012; Gonzalez et al., 2012), which, in conjunction with Herschel PACS and SPIRE imaging, we use to bracket the dust emission peak of cluster galaxies and constrain their FIR SED. We quantify the dust temperatures and ISM masses of cluster galaxies as a function of their SFRs and stellar masses and in comparison to field galaxy samples. In Section 2, we outline our observations and data reduction of the SCUBA-2 imaging. In Section 3, we present our analysis and results and in Section 4, we provide a discussion and Section 5 is a summary of our findings. Throughout this work, we adopt a WMAP7 cosmology with $(\Omega_\Lambda, \Omega_M, h) = (0.728, 0.272, 0.704; \text{Komatsu et al., 2011})$. A Kroupa IMF (Kroupa, 2001) is assumed unless otherwise stated.

4.2 Observations and Data Reduction

4.2.1 Cluster IDCS J1426.5+3508

First reported in Stanford et al. (2012), IDCS J1426.5+3508 was discovered as a three-dimensional overdensity using photometric redshifts and later confirmed to be at $z = 1.75$ by follow-up spectroscopy in the optical with Keck/LRIS and the infrared with HST/WFC3. To date, seven cluster members have been confirmed with robust spectroscopic redshifts. The HST spectroscopy also revealed a strong gravitational arc behind IDCS J1426.5+3508, which is described in Gonzalez et al. (2012).

The mass of IDCS J1426.5+3508 has been measured with both X-ray observations and through the Sunyaev-Zel’dovich Effect. IDCS J1426.5+3508 is detected in the shallow Chandra imaging of the Bo"{o}tes field (Murray et al., 2005) with an X-ray luminosity of $L_{0.5-2\text{keV}} = (5.6 \pm 1.2) \times 10^{44}$ erg s$^{-1}$ (Stanford et al., 2012). This corresponds to $M_{200,L_x} = (5.3 \pm 1.6) \times 10^{14} M_\odot$, assuming the scaling relations of Vikhlinin et al. (2009) and an appropriate mass-concentration relation (Duffy et
IDCS J1426.5+3508 was additionally observed in the Sunyaev-Zel’dovich decrement (Brodwin et al., 2012), with an SZ mass of $M_{200,\text{SZ}} = (4.3 \pm 1.1) \times 10^{14} M_\odot$.

The star formation properties of IDCS J1426.5+3508 were examined as part of a statistical study of ISCS/IDCS clusters at $z > 1$ (see Chapter 3). This study found that, statistically, galaxies in clusters at $z \gtrsim 1.4$ have field-like SFRs and SSFRs, with a flat fraction of SFGs to non-SFGs as a function of radius. In relation to ISCS clusters at $z \sim 1.5$, however, IDCS J1426.5+3508 appears to be more evolved, having built up a significant mass at an earlier epoch. The mass-normalized integrated SFR of IDCS J1426.5+3508 is $\Sigma \text{SFR}/M_{\text{halo}} = 61 \pm 23 \, M_\odot \text{yr}^{-1} \text{per } 10^{14} M_\odot$, a factor of 3 lower than similarly-selected cluster at $z \sim 1.5$. Nevertheless, IDCS J1426.5+3508 is not a fully quenched system, with at least four LIRGs/ULIRGs ($L_{\text{IR}} \gtrsim 5 \times 10^{11}$) detected in PACS within the central 250 kpc.

IDCS J1426.5+3508 is in the Boötes field, which has been extensively imaged, including X-ray imaging from Chandra (Murray et al., 2005), ultraviolet from GALEX, optical photometry from the NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey, 1999), NIR photometry from the Infrared Boötes Imaging Survey (IBIS; Gonzalez et al., 2010a), and MIR photometry from the Spitzer Deep, Wide-Field Survey (SDWFS; Ashby et al., 2009) and the MIPS AGN and Galaxy Evolution Survey (MAGES; Jannuzi et al., 2010). The reader is referred to Chung et al. (2014) for a description of all X-ray-to-MIR imaging available in the Boötes field. In addition, shallow Herschel SPIRE imaging is available from the Herschel Multi-tiered Extragalactic Survey (HerMES; Oliver et al., 2012). For a complete description of our reduction and analysis of the Boötes SPIRE imaging, the reader is referred to Chapter 2.
4.2.2 Redshifts, Cluster Membership, and Stellar Masses

Spectroscopic redshift cluster members are determined following the criteria from Eisenhardt et al. (2008), wherein a source is a cluster member if its spectroscopic redshift is within 2000 km s$^{-1}$ of the systemic cluster velocity and within 2 Mpc of the cluster center ($\sim 2 \times$ the virial radius). Robust photometric redshifts are available across the Boötes field using 17 photometric bands from the UV to the MIR and empirically derived SEDs (Assef et al., 2010). For a complete discussion of the photometry used and the derivation of the photometric redshifts, the reader is referred to Chung et al. (2014). The photometric redshift uncertainties for SFGs are measured to be $\sigma/(1+z) = 0.054$ up to $z \sim 2$ using pair statistics (Chapter 3).

Photometric redshift cluster membership is determined based on the integrated normalized photometric redshift probability distribution function (PDF) for each source. A source is considered a member of IDCS J1426.5+3508 if it is within 2 Mpc of the cluster center and satisfies the following criteria:

$$\int_{z_{cl}-0.054(1+z_{cl})}^{z_{cl}+0.054(1+z_{cl})} P(z) \, dz \geq 0.3 \quad \text{(4.1)}$$

where $z_{cl}$ is the redshift of the cluster.

Stellar mass estimates are measured using observed optical-to-NIR broadband photometry and iSEDfit (Moustakas et al., 2013), a Bayesian SED-fitting code which adopts the Bruzual & Charlot (2003) population synthesis models, STELIB (Le Börnje et al., 2003) stellar library, and Chabrier (2003) IMF. We adopt a mass error of 0.3 dex for all stellar mass estimates in order to account for systematic uncertainties. At the redshift of IDCS J1426.5+3508, the stellar mass catalog is $\sim 80\%$ complete above $\log(M_*/M_\odot) = 10.1$ (see Figure 3 in Brodwin et al., 2013), though we expect a higher completeness in the clusters given the high masses of typical cluster galaxies and the flat NIR luminosity function measured for high redshift clusters (Mancone et al., 2012).
4.2.3 New Herschel PACS Imaging

New, deep imaging of IDCS J1426.5+3508 is obtained from the Herschel Space Observatory (Pilbratt et al., 2010) Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al., 2010) at 100 and 160µm as part of Open Time 2 observing (PID: OT2_apope_3). IDCS J1426.5+3508 was observed with 4 pointings for a total time of 4050 s, reaching a depth of 0.5 mJy rms. Data reduction is performed using Unimap v5.4.0 (Traficante et al., 2011; Piazzo et al., 2012), a generalized least-squares (GLS; Lupton, 1993) mapmaker. Source extraction is done via PSF fitting to the positions of IRAC and spectroscopic redshift priors at both 100 and 160µm, and Monte Carlo simulations are used to assess completeness and photometric accuracy. Cluster members with PACS detections are visually inspected for blending with nearby IR sources and any potential blends are removed from the sample. For complete details on the data reduction, source extraction, and simulations, the reader is referred to Chapter 3.

4.2.4 New SCUBA-2 850µm Imaging

In this study, we present new, deep imaging of IDCS J1426.5+3508 at 850µm using SCUBA-2 (Holland et al., 2013) at the JCMT (proposal ID: M12AI01). This map consists of eight hours of on-sky integration time in $\tau_{225\text{GHz}} \lesssim 0.12$ weather using the “daisy” scan-mode, which has minimal noise increase ($\sim 20\%$) out to a radius of 2 arcminutes. Data reduction is performed using the dynamic iterative map-maker in the SMURF package (Jenness et al., 2011). A detailed description of this pipeline can be found in Chapin et al. (2013); we briefly describe the process here. Individual 30 minute scans are flat-fielded and then scaled to unit of pW. The map-maker then models the components of the signal, which are a combination of the astronomical signal, the common mode signal (atmospheric water and thermal emission) and an additional noise term, until convergence is met or a maximum number of iterations
is reached. This process results in time-streams which contain only astronomical signal, corrected for extinction, plus a noise component. The time-streams are then combined into a variance-weighted map according to the scan pattern. Filtering is done in the frequency domain and includes spike removal and DC step corrections. Bad bolometers are flagged and not used in the final map. Finally, a beam matched filter is applied in order to optimize the map for the detection of faint extragalactic point sources.

The final, combined map (Figure 4.1) is calibrated using the standard beam-matched flux conversion factor, \( F_{\text{CF}850} = 537 \pm 26 \text{ Jy beam}^{-1} \text{ pW}^{-1} \). This calibration factor is based on observations of hundreds of standard calibrators and has been found to be relatively stable (Dempsey et al., 2013). The final map reaches an rms sensitivity of 0.5 mJy beam\(^{-1}\). Blind source extraction is done by identifying isolated peaks in the map. Due to the normalization of the map in Jy beam\(^{-1}\), the peak pixel of a source gives the best estimate of its flux density. A source is considered detected at 3.5\( \sigma \), with a corresponding false detection rate of \( \sim 15\% \) (Casey et al., 2012). We detect 40 850\( \mu \)m sources within a radius of 4 arcminutes. The 20 brightest sources are stacked in order to quantify the PSF, which is found to be gaussian with a FWHM of 14.5\".

Monte Carlo simulations are performed to assess the completeness and flux boosting of 850\( \mu \)m sources, which consists of inserting and recovering fake sources in the SCUBA-2 map. The reader is referred to Appendix C for details of the simulations. Given that we are primarily concerned with sources for which the position is already known through higher-resolution IRAC imaging, we test for flux boosting in two ways. First, we measure the flux\(_{\text{out}}\) to flux\(_{\text{in}}\) ratio for sources recovered using blind source extraction and second, we measure the same ratio at the exact, known position in which the fake source was inserted (i.e. a prior). We find that the first method results in an average flux boosting of up to 1.8 for a 1.5 mJy source; this boosting is elimi-
nated on average by using the prior known position (see Figure C.2 in Appendix C). Throughout this work, we will therefore extract SCUBA-2 flux densities through the use of position of PACS detections as priors (which are themselves based on IRAC or spectroscopic priors). This will additionally result in a lower false detection rate as PACS and SCUBA-2 are both sampling IR emission to comparable depths. Emission lines are expected to contribute less than 2% of the observed 850µm flux density at $z = 1.75$ (Smail et al., 2011).

### 4.2.5 Catalog Matching, SFRs, and SSFRs

Spectroscopic and photometric cluster members are matched to FIR photometry through the use of priors. IRAC prior positions are used to extract flux densities at PACS 100µm and 160µm. If a source is detected at 100µm, but not 160µm, a limit is extracted at the position of the prior. Sources that are detected in either PACS wavebands have flux densities or limits extracted at the positions of the priors in the SPIRE 250 and 350µm maps and the SCUBA-2 850µm map. The use of priors detected in the PACS bands in extracting the SPIRE and SCUBA-2 flux densities mitigates the problem of flux boosting and the high false detection rate at low S/N (see Section 4.2.4 and Appendix C).

SFRs are measured following the procedure outlined in Chapter 3. Sources are first separated into SFGs and AGN through template fitting to their optical-MIR SEDs, which determines $F_{\text{gal}} = L_{\text{gal}}/L_{\text{total}}$, the ratio of the optical-MIR luminosity coming from the (host) galaxy to the total luminosity. Sources with $F_{\text{gal}} < 0.5$ are dominated by AGN emission in this portion of the SED. A representative empirically-derived SFG or AGN template is then used to determine the total infrared luminosity, $L_{\text{IR}} = L[8-1000\mu\text{m}]$. For the AGN template, an additional correction is made to account for the AGN contribution to the $L_{\text{IR}}$. The SFR is derived following the
Figure 4.1 SCUBA-2 850μm signal map of a $z = 1.75$, massive galaxy cluster. The red x symbols indicates IR-luminous cluster galaxies selected with *Herschel* PACS at 100 and 160μm. 850μm detections or limits are extracted from the map uses these source as priors. The black circles indicate 1 and 2× the virial radius ($\sim 1$Mpc), centered on the Brightest Cluster Galaxy. 850μm sources detected at $> 3.5\sigma$ using blind source extraction are shown in blue circles. The size of the circle indicates the FWHM~ $14.5''$ of SCUBA-2.
relations in Murphy et al. (2011b). The specific-SFR is then calculated as SSFR = SFR/M_*.

4.3 Analysis and Results

4.3.1 FIR SED Fitting and Dust Temperatures in the Cluster Environment

FIR emission in galaxies comes from two major components. The first, warm dust emission at short (∼60µm) wavelengths, is due to a combination of multiple temperature components provided by heating from compact star-forming (HII) regions and/or AGN. This component can be modeled as a power law, which approximates several successive blackbodies with different temperatures in the MIR. Cold dust emission, dominating at longer wavelengths (∼100µm), is due to the heating of the ISM on galaxy-wide scales due to the underlying stellar population (e.g. Kirkpatrick et al., 2012). This component also likely consists of multiple blackbodies, but is generally modeled as a single temperature modified blackbody. Coadding these two components allows for reasonable fits to the FIR SED in the case of limited photometric data (see Casey et al., 2012, for more details).
<table>
<thead>
<tr>
<th>ID</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>Cluster-centric Radius [Mpc]</th>
<th>$S_{100\mu m}$ [mJy]</th>
<th>$S_{160\mu m}$ [mJy]</th>
<th>$S_{250\mu m}$ [mJy]</th>
<th>$S_{350\mu m}$ [mJy]</th>
<th>$S_{850\mu m}$ [mJy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J142634.6+350548</td>
<td>14:26:34.59</td>
<td>+35:05:48.4</td>
<td>1.35</td>
<td>6.2 ± 0.6</td>
<td>15 ± 2</td>
<td>23 ± 3</td>
<td>20 ± 3</td>
<td>2.2 ± 0.8</td>
</tr>
<tr>
<td>J142635.7+350554</td>
<td>14:26:35.71</td>
<td>+35:05:54.1</td>
<td>1.32</td>
<td>3.5 ± 0.6</td>
<td>9.2 ± 2</td>
<td>2.2 ± 3</td>
<td>7.8 ± 3</td>
<td>1.4 ± 0.8</td>
</tr>
<tr>
<td>J142618.8+350618</td>
<td>14:26:18.79</td>
<td>+35:06:18.3</td>
<td>1.85</td>
<td>...</td>
<td>2.6 ± 1</td>
<td>...</td>
<td>14 ± 3</td>
<td>1.3 ± 0.9</td>
</tr>
<tr>
<td>J142645.1+350655</td>
<td>14:26:45.05</td>
<td>+35:06:55.0</td>
<td>1.48</td>
<td>3.4 ± 0.5</td>
<td>10 ± 2</td>
<td>21 ± 4</td>
<td>20 ± 3</td>
<td>3.6 ± 0.8</td>
</tr>
<tr>
<td>J142637.3+350713</td>
<td>14:26:37.34</td>
<td>+35:07:13.4</td>
<td>0.76</td>
<td>...</td>
<td>2.6 ± 1</td>
<td>6.3 ± 4</td>
<td>19 ± 3</td>
<td>1.9 ± 0.6</td>
</tr>
<tr>
<td>J142633.9+350734</td>
<td>14:26:33.91</td>
<td>+35:07:34.4</td>
<td>0.43</td>
<td>3.0 ± 0.7</td>
<td>9.3 ± 1</td>
<td>...</td>
<td>10 ± 4</td>
<td>1.7 ± 0.6</td>
</tr>
<tr>
<td>J142634.9+350833</td>
<td>14:26:34.85</td>
<td>+35:08:33.0</td>
<td>0.21</td>
<td>1.9 ± 0.5</td>
<td>3.5 ± 1</td>
<td>0.3 ± 3</td>
<td>12 ± 3</td>
<td>0.4 ± 0.6</td>
</tr>
<tr>
<td>J142645.0+350851</td>
<td>14:26:45.00</td>
<td>+35:08:51.3</td>
<td>1.29</td>
<td>1.9 ± 0.5</td>
<td>2.4 ± 1</td>
<td>...</td>
<td>3.4 ± 3</td>
<td>1.6 ± 0.8</td>
</tr>
<tr>
<td>J142632.2+350921</td>
<td>14:26:32.15</td>
<td>+35:09:20.9</td>
<td>0.50</td>
<td>2.1 ± 0.7</td>
<td>4.5 ± 1</td>
<td>7.6 ± 3</td>
<td>10 ± 4</td>
<td>1.2 ± 0.6</td>
</tr>
<tr>
<td>J142649.1+350948</td>
<td>14:26:49.09</td>
<td>+35:09:48.2</td>
<td>1.85</td>
<td>1.8 ± 0.8</td>
<td>5.0 ± 1</td>
<td>9.4 ± 4</td>
<td>12 ± 4</td>
<td>0.8 ± 0.9</td>
</tr>
<tr>
<td>J142630.3+350903</td>
<td>14:26:30.26</td>
<td>+35:11:03.5</td>
<td>1.41</td>
<td>2.6 ± 0.6</td>
<td>6.8 ± 1</td>
<td>2.7 ± 3</td>
<td>5.5 ± 3</td>
<td>1.2 ± 0.8</td>
</tr>
<tr>
<td>J142632.4+350830b</td>
<td>14:26:32.40</td>
<td>+35:08:30.8</td>
<td>0.09</td>
<td>1.6 ± 0.5</td>
<td>2.6 ± 1</td>
<td>5.3 ± 3</td>
<td>2.5 ± 3</td>
<td>1.2 ± 0.6</td>
</tr>
</tbody>
</table>

*a*Uncertainties include instrument noise only. Confusion noise is 5.8 mJy at 250\(\mu\)m and 6.3 mJy at 350\(\mu\)m (Nguyen et al., 2010).

*b*Spectroscopic member of IDCS J1426.5+3508.
To fit a cluster galaxy’s FIR SED, we require at a minimum a detection in either the 100 or 160\(\mu\)m band, a measurement at 850\(\mu\)m, and at least one additional measurement with PACS and/or the SPIRE 250 or 350\(\mu\)m bands. This results in 12 sources (Table 4.3.1), whose radial distribution can be seen in Figure 4.1. The SPIRE 500\(\mu\)m data is not used due to the large beamsize (36\arcsec). In Figure 4.2, we fit our photometry using the modified blackbody plus power law model (black solid line) as described in Casey et al. (2012), assuming general opacity, fixed emissivity \(\beta = 1.5\) (Hildebrand et al., 1983; Kovács et al., 2010), and a fixed power law slope \(\alpha = 2.0\) (e.g. Younger et al., 2009; Casey et al., 2013). The red dashed line shows the modified blackbody fit to the cold dust component. From these fits, we measure the peak of the SED, \(\lambda_{peak}\). Errors are determined by bootstrap resampling.

As discussed in Casey et al. (2014), it is important to understand that, given our current understanding of the complex parameter space needed to properly model dust (i.e. composition, dust grain type, galaxy structure, AGN, emissivity, optical depth), the real constraining power of FIR photometry lies in determining the location of the peak of the SED, \(\lambda_{peak}\). \(\lambda_{peak}\) scales inversely with the dust temperature, \(T_{dust}\), associated with the bulk (cold) dust emission, however this conversion is highly sensitive to the model parameters assumed. For example, for the same \(\lambda_{peak}\), adopting a modified blackbody model with general opacity and the theoretically predicted value for where the optical depth is unity (100\(\mu\)m; Draine, 2006) will result in a decrease of \(\sim 10\) K (see Figure 20 in Casey et al., 2014) as compared to assuming the optical depth is unity at 200\(\mu\)m (Conley et al., 2011; Rangwala et al., 2011), a value which has been observed for only a handful of extreme systems such as SMGs and Arp220 (Blain et al., 2003). Because our goal is to compare the dust temperatures of our cluster galaxies to field galaxies rather than derive absolute values, we make the simplifying assumption that the cold dust component can be modeled by an unmodified blackbody, as advocated in Casey et al. (2012, 2014). We scale \(T_{dust}\) with
$\lambda_{\text{peak}}$ through the Wien’s displacement law, $T_{\text{dust}} = b/\lambda_{\text{peak}}$ where $b = 2.898 \times 10^{-3}$ m K$^{-1}$ and $\lambda_{\text{peak}}$ is the peak of the SED (in S$_{\lambda}$). This scaling provides the least sensitivity to assumed model parameters and fitting techniques and is thus comparable across the literature. Assuming an optically thin modified blackbody with emissivity $\beta = 1.5$ will result in a similar scaling between $\lambda_{\text{peak}}$ and $T_{\text{dust}}$ as an unmodified blackbody (see Figure 20 in Casey et al., 2014).

Table 4.3.1 reports both $\lambda_{\text{peak}}$ and $T_{\text{dust}}$ for our sources. We find that these IR-luminous ($L_{\text{IR}} \sim 1 \times 10^{12} L_\odot$) cluster galaxies have a mean (median) SED peak of 99$\mu$m (97$\mu$m), corresponding to $T_{\text{dust}}$ of 31 K (32 K). In Chapter 3, we showed that the UV-to-FIR SEDs of high redshift ($z > 1$) cluster galaxies can be well represented by empirical galaxy templates derived from field galaxies with similar $L_{\text{IR}}$ and at similar redshifts (Kirkpatrick et al., 2012). Our results here are in good agreement with both the SED peak ($\sim 100\mu$m) and cold dust temperature ($28 \pm 2$ K) of the Kirkpatrick et al. (2012) SFG templates, providing additional evidence that $1 < z < 2$ cluster galaxies are well described by high redshift field galaxy templates. We additionally check that the template-derived $L_{\text{IR}}$s (Section 4.2.5) are in good agreement with the $L_{\text{IR}}$s derived through this fitting method.
Figure 4.2 The FIR SEDs for 12 IR-luminous cluster members detected at $>2\sigma$ in 
Herschel PACS at 100 or 160\(\mu\)m and a measurement in at least two additional bands.
We fit the photometry with a coupled modified blackbody plus power law (solid black line),
assuming a fixed emissivity ($\beta = 1.5$) and fixed power law slope ($\alpha = 2.0$). The
dashed red line shows the modified blackbody component of the fit. $\lambda_{\text{peak}}$ is measured
from the peak (in $S_\lambda$) of the best-fit modified blackbody plus power law model.

The cold dust temperature, $T_{\text{dust}}$, is calculated as the inverse of the peak wavelength,
$\lambda_{\text{peak}}$, assuming a simplified unmodified blackbody model and Wein’s displacement
law as the scaling between these parameters is highly model dependent (e.g. Casey et al., 2012, 2014).
This cluster sample has $\langle L_{\text{IR}} \rangle = 1 \times 10^{12} \, \mathcal{L}_\odot$ and $\langle T_{\text{dust}} \rangle = 31 \, \text{K}$,
similar to field galaxies at these redshifts.
Table 4.2. Derived Quantities of IR-luminous Cluster Members in IDCS J1426.5+3508

<table>
<thead>
<tr>
<th>ID</th>
<th>SFR ([M_\odot \text{ yr}^{-1}])</th>
<th>(M_*) ([10^{10} M_\odot])</th>
<th>(F_{\text{gal}})</th>
<th>(\lambda_{\text{peak}}) ([\mu\text{m}])</th>
<th>(T_{\text{dust}}) ([\text{K}])</th>
<th>(M_{\text{ISM}}) ([10^{10} M_\odot])</th>
<th>(f_{\text{gas}}^a)</th>
<th>(\tau_{\text{depletion}}^b) ([\text{Gyr}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>J142634.6+350548</td>
<td>170 ± 31</td>
<td>41</td>
<td>0.16</td>
<td>86 ± 9</td>
<td>34 ± 3</td>
<td>7.6 ± 3</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>J142635.7+350554</td>
<td>245 ± 42</td>
<td>13</td>
<td>0.60</td>
<td>84 ± 16</td>
<td>34 ± 17</td>
<td>5.0 ± 3</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>J142618.8+350618</td>
<td>77.7 ± 33</td>
<td>4.2</td>
<td>0.54</td>
<td>125 ± 38</td>
<td>23 ± 7</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>J142645.1+350655</td>
<td>238 ± 38</td>
<td>29</td>
<td>0.63</td>
<td>101 ± 10</td>
<td>29 ± 3</td>
<td>13 ± 3</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>J142637.3+350713</td>
<td>56.2 ± 26</td>
<td>1.5</td>
<td>0.44</td>
<td>120 ± 27</td>
<td>24 ± 5</td>
<td>6.7 ± 3</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>J142633.9+350734</td>
<td>83.8 ± 34</td>
<td>6.0</td>
<td>0.50</td>
<td>89 ± 15</td>
<td>32 ± 5</td>
<td>5.8 ± 2</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>J142634.9+350833</td>
<td>53.5 ± 24</td>
<td>32</td>
<td>0.24</td>
<td>85 ± 21</td>
<td>34 ± 8</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>J142645.0+350851</td>
<td>52.6 ± 25</td>
<td>0.2</td>
<td>0.143</td>
<td>91 ± 20</td>
<td>32 ± 7</td>
<td>5.6 ± 3</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>J142632.2+350921</td>
<td>145 ± 51</td>
<td>6.7</td>
<td>0.60</td>
<td>91 ± 22</td>
<td>32 ± 8</td>
<td>4.0 ± 2</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>J142649.1+350948</td>
<td>50.3 ± 38</td>
<td>0.2</td>
<td>0.09</td>
<td>93 ± 24</td>
<td>31 ± 8</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>J142630.3+350903</td>
<td>186 ± 45</td>
<td>6.5</td>
<td>0.77</td>
<td>83 ± 19</td>
<td>35 ± 8</td>
<td>4.3 ± 3</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>J142632.4+350830</td>
<td>45.2 ± 25</td>
<td>1.0</td>
<td>0.44</td>
<td>91 ± 20</td>
<td>32 ± 7</td>
<td>4.3 ± 2</td>
<td>0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\(^a f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_*)\) where we assume \(M_{\text{gas}} = M_{\text{ISM}}\) for our high redshift galaxy sample.

\(^b \tau_{\text{depletion}} = M_{\text{gas}}/\text{SFR}\) again assuming \(M_{\text{gas}} = M_{\text{ISM}}\).
In Figure 4.3, we plot our derived $T_{\text{dust}}$ as a function of SFR and note which sources are within the virial radius ($r < 1 \text{ Mpc}$, open circles) and on the cluster outskirts ($1 < r < 2 \text{ Mpc}$, closed circles). We contrast our finding to both local and high redshift field galaxy samples, for which individual and average dust temperatures have been derived using the procedure outlined above, assuming the simplified scaling between $T_{\text{dust}}$ and $\lambda_{\text{peak}}$, either in the original study or re-calculated for comparison with this work. We convert all reported $L_{\text{IR}}$ to SFR following Murphy et al. (2011b). No correction is made for AGN content for field galaxies, if present. The local sample (gray crosses and brown squares) comes from the Revised Bright Galaxy Sample (Sanders et al., 2003; Chapman et al., 2003), while high redshift dust temperatures have been measured for Herschel selected SFGs (Symeonidis et al., 2013, yellow) and SMGs (Casey et al., 2013, blue). Dusty SFGs at high redshift have been noted to have cooler SEDs than local galaxy samples (Pope et al., 2006; Kirkpatrick et al., 2012; Symeonidis et al., 2013; Casey et al., 2013; Lee et al., 2013), which is generally attributed to more extended dust distribution (e.g. Swinbank et al., 2013). We see in Figure 4.3 that our cluster galaxies have a similar $T_{\text{dust}}$-SFR relation as high redshift field galaxies, with no obvious trend as a function of cluster-centric radius (with the caveat that our small sample necessitates large radial bins).

Though we compare primarily to SFGs in the field, half of our cluster galaxies have optical-MIR SEDs consistent with significant AGN emission, as measured by the $F_{\text{gal}}$ parameter (see Chapter 3 and Section 4.2.5). In Figure 4.4 we look at the $T_{\text{dust}}$-$F_{\text{gal}}$ relation. We find that $T_{\text{dust}}$ is independent of the AGN activity in our cluster galaxies, even if we allow $\alpha$ to vary by incorporating MIPS 24$\mu$m photometry into our fits. This indicates that our dust temperature represents the cold dust component, as studies in the field have found no strong dependence of the bulk (cold) dust temperature on AGN activity in X-ray or MIR selected samples (Hwang et al., 2010a; Kirkpatrick et al., 2012).
Figure 4.3 The cold dust temperature, $T_{\text{dust}}$, and $\lambda_{\text{peak}}$ as a function of SFR for cluster galaxies within the virial radius ($r < 1\text{ Mpc}$, red open circles) and in the cluster outskirts ($1 < r < 2\text{ Mpc}$, red filled circles). $T_{\text{dust}}$ is assumed to scale with $\lambda_{\text{peak}}$ via the Wein’s displacement law for an unmodified blackbody. The gray x symbols and brown squares represent the individual and mean dust temperatures of local field galaxies from the Revised Bright Galaxy Survey (Sanders et al., 2003). The yellow squares show the mean $T_{\text{dust}}$-SFR relation for Herschel selected galaxies at $z = 0.8 - 1.4$ (Symeonidis et al., 2013) and the blue squares show the same for SMGs at high redshift (Casey et al., 2013). The temperatures for these field samples were calculated using the same modified blackbody plus power law model and $T_{\text{dust}}$-$\lambda_{\text{peak}}$ scaling as described in Section 4.3.1, assuming the same constraints on parameters such as emissivity, etc. These results show that cluster galaxies have similar dust temperatures as field galaxies at the same redshift, slightly offset from local populations.
Figure 4.4 The dust temperature as a function of $F_{gal} = L_{gal}/L_{total}$, the ratio of the optical-MIR luminosity coming from the (host) galaxy to the total luminosity. Open symbols are cluster galaxies within the virial radius ($r < 1$ Mpc), while close symbols are outside the virial radius ($1 < r < 2$ Mpc). $F_{gal} < 0.5$ (dotted line) indicates that the source is dominated by AGN emission in the optical-MIR. We find no dependence of $T_{dust}$ on the level of AGN activity, indicating that $T_{dust}$ represents the cold dust component of the FIR SED.
4.3.2 The Mass of the ISM in High Redshift Cluster Galaxies

As larger samples of high redshift clusters and cluster galaxies become available, we will be able to place robust constraints on the effects of environment on galaxy properties and their relation to the larger picture of galaxy evolution. One key observation will be the gas mass, which is related to the star formation efficiency ($\text{SFE} = \text{SFR}/M_{\text{gas}}$) or its corollary, the gas depletion time ($\tau_{\text{depletion}} = M_{\text{gas}}/\text{SFR}$), which may be linked to different modes of star formation (e.g. Daddi et al., 2010b), and provides vital constraints on star formation histories and quenching mechanisms.

In this section, we estimate the mass of the ISM in our cluster galaxies through our long-wavelength observations at 850$\mu$m, which directly probe the optically thin Rayleigh Jean’s tail of the dust emission, providing a robust measurement of the total dust mass. Given constraints on the dust opacity per unit mass and a constant dust-to-gas abundance ratio, the total dust can be related to the total ISM mass (Eales et al., 2012; Scoville et al., 2014). An updated derivation and calibration of this method is described in detail in Scoville et al. (2014). We briefly summarize the main points here and then present our analysis and results.

In the optically thin regime of the FIR SED, the observed flux density, $S_\nu$, is a function of the dust opacity per unit mass, $\kappa_\nu^{\text{dust}}$, $T_{\text{dust}}$, and the dust mass $M_{\text{dust}}$ though

$$S_\nu = \kappa_\nu^{\text{dust}} T_{\text{dust}} (1 + z)\nu^2 \frac{M_{\text{dust}}}{4\pi d_L^2}$$

where $d_L$ is the luminosity distance. This can be related to the total ISM mass, $M_{\text{ISM}} \approx M_{\text{HI}} + M_{\text{H}_2}$, by defining the dust opacity per unit ISM mass via $\kappa_\nu^{\text{ISM}} = \kappa_\nu^{\text{dust}} \times M_{\text{dust}}/M_{\text{ISM}}$. The ISM mass can then be quantified given photometry on the RJ tail of the dust emission, the dust temperature, and $\kappa_\nu^{\text{ISM}}$.

$\kappa_\nu^{\text{ISM}}$ is empirically determined using independent measurements of the submm flux density and ISM mass in local galaxies (Scoville et al., 2014), which find that the
relation between the luminosity at 850 µm and the ISM mass is a constant, which is related to \( \kappa_{850}^{\text{ISM}} \) and \( T_{\text{dust}} \) as

\[
\alpha_{850} \propto \frac{L_{\nu_{850}}}{M_{\text{ISM}}} \propto \kappa_{850}^{\text{ISM}} T_{\text{dust}} \tag{4.3}
\]

This constant is found to be \( \alpha_{850} = 1.0 \pm 0.23 \times 10^{20} \text{ ergs s}^{-1} \text{ Hz}^{-1} \text{ M}_\odot^{-1} \). This value is in good agreement with both Planck measurements of the Taurus cloud in the Milky Way (Planck Collaboration, 2011) and in high redshift SMGs. Combining Equations 4.2 and 4.3 and rewriting in terms of the frequency at 850 µm, the submm photometry is then related to the \( M_{\text{ISM}} \) through

\[
S_\nu = \alpha_{850} M_{\text{ISM}} (1 + z)^{\beta+3} \left( \frac{\nu_{\text{obs}}}{\nu_{850}} \right)^{\beta+2} \frac{\Gamma_{\text{RJ}}}{\Gamma_0} \frac{1}{4\pi d_L^2} \tag{4.4}
\]

where \( \beta \) is the emissivity and \( \Gamma_{\text{RJ}}(T_{\text{dust}}, \nu_{\text{obs}}, z) \) is a correction factor for the departure from the dependence on \( \nu^2 \) on the RJ tail as the observed photometry approaches the peak of the SED. \( \Gamma_0 \) is the value of \( \Gamma_{\text{RJ}} \) at \( z = 0 \). For a detailed derivation of Equation 4.4, see Scoville et al. (2014).

As before, we assume that \( \beta = 1.5 \). As seen in Equation 4.4, the dependence on \( T_{\text{dust}} \) only factors into the RJ correction factor. Nevertheless it is important to note that the \( T_{\text{dust}} \) used to measure \( M_{\text{ISM}} \) should be the characteristic temperature of the bulk of the ISM, not the effective temperature which includes the warm dust component which can dominate by luminosity, but not by mass. For the sake of comparison to field galaxy samples and given the uncertainties, we adopt the same \( T_{\text{dust}} = 25 \text{ K} \) for the calculation of \( M_{\text{ISM}} \), following Scoville et al. (2014).

In Figure 4.5, we show the ISM masses calculated for 9 PACS-detected cluster galaxies with an individual \( > 1\sigma \) measurement at 850 µm as a function of SFR. As described earlier, these 850 µm measurements are based on prior positions with PACS 100 µm detections and so are robust even at low S/N. This subset of galaxies has a mean (median) SFR of 136 (145) \( \text{M}_\odot \text{ yr}^{-1} \) and a mean (median) stellar mass of

149
1.2 \times 10^{11}(6.5 \times 10^{10})M_\odot. We measure a range in the ISM mass of \(M_{\text{ISM}} = (4 - 13) \times 10^{10}M_\odot\) with a mean (median) of \(6 \times 10^{10}M_\odot\) \((6 \times 10^{10}M_\odot)\). We see no evolution in \(M_{\text{ISM}}\) with SFR. We additionally measure \(M_{\text{ISM}}\) for all PACS-detected cluster galaxies (12 sources) by stacking on the 850\(\mu\)m flux. We find \(M_{\text{ISM}} = 3.9 \times 10^{10}M_\odot\) for the full, stacked sample. We compare our results with a sample of Herschel-detected field galaxies at \(z \sim 2\) from the COSMOS field (open squares; Scoville et al., 2013, 2014). The ISM mass for this sample was determined from continuum observations with ALMA at 850\(\mu\)m following the same procedure outlined above. Also shown are the stacked ISM masses at \(z \sim 1\) and \(z \sim 2\) for mass-limited galaxy samples (close squares). This comparison shows that our cluster galaxies roughly occupy the same \(M_{\text{ISM}}\)-SFR space as field galaxies at \(z \sim 2\).

As these field galaxies are of similar stellar mass \((\sim 10^{11}M_\odot)\) to our sample, this indicates that the gas fraction, \(f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_*)\), in cluster galaxies at these redshifts is similar to that in the field. Recent studies have begun to quantify the evolution of the gas fraction with redshift, finding that gas fraction not only increases with redshift, but that the space density of galaxies with high \(f_{\text{gas}}\) — that is, \(M_{\text{gas}}\) comparable to or larger than \(M_*\) — implies that they are the dominant population during the peak of the cosmic SFR (see Carilli & Walter, 2013, for a review). Geach et al. (2011) finds that the evolution of the gas fraction goes as \(\sim (1 + z)^2\), though we caution that currently the gas fraction has not been measured for mass-limited galaxy samples.

Here we compare \(f_{\text{gas}}\) for our cluster galaxies to those of field galaxies as a function of redshift (Figure 4.6, left), assuming \(M_{\text{gas}} \approx M_{\text{ISM}}\) (see below). We compare to the stacked average gas fraction of galaxies in COSMOS (squares; Scoville et al., 2014), derived through submm observations, and to samples of high redshift galaxies detected in CO emission (triangles; Daddi et al., 2010b; Tacconi et al., 2010, 2013). In addition, we show the predicted relation between gas fraction and redshift based on SFGs at
Figure 4.5 The mass of the ISM in IR-luminous cluster galaxies as a function of SFR, within the virial radius ($r < 1$ Mpc, red open circles) and in the cluster outskirts ($1 < r < 2$ Mpc, red filled circles). The blue open squares are field galaxies in the COSMOS field at $z \sim 2$ from Scoville et al. (2014). The filled blue squares are stacked $\langle M_{\text{ISM}} \rangle$ for mass-limited galaxies samples at $z \sim 1$ (left) and $z \sim 2$ (right).
Figure 4.6 The gas fraction and gas depletion timescale of cluster galaxies in comparison to field galaxies. Upper panel: The gas fraction, $f_{\text{gas}} = M_{\text{gas}} / (M_{\text{gas}} + M_{\text{stellar}})$, as a function of redshift for cluster galaxies within the virial radius ($r < 1$ Mpc, red open circles) and in the cluster outskirts ($1 < r < 2$ Mpc, red filled circles). For comparison, we show the stacked field gas fraction for field galaxies in COSMOS, measuring using submm imaging (Scoville et al., 2014) and the gas fraction for field galaxies as measured by CO observations (Daddi et al., 2010b; Tacconi et al., 2010, 2013). The dotted line shows the predicted evolution with redshift, $f_{\text{gas}} \propto (1 + z)^{2}$ from Geach et al. (2011). Bottom panel: The gas depletion time, $\tau_{\text{depletion}}$, as a function of SSFR. The dotted line shows the local relation from Saintonge et at. (2011). IR-luminous cluster galaxies have similar depletion times to field galaxies at similar redshifts, offset from the local relation due to increasing characteristic SSFRs and increasing gas reservoirs.
$z \sim 0.4$ (dotted line; Geach et al., 2011). Our galaxies have a mean (median) gas fraction of 0.5 (0.4) with a standard deviation of 0.3, which falls roughly along the predicted relation from Geach et al. (2011) and is in good agreement with the stacked average field gas fraction found in Scoville et al. (2014). Main sequence field galaxies at high redshift (Daddi et al., 2010b; Tacconi et al., 2010, 2013) show slightly higher gas fractions on average than both the Geach et al. (2011) prediction, the Scoville et al. (2014) observations, and our cluster galaxies, which may be a selection bias in terms of the CO detection limit. Unbiased, mass-limited statistical galaxy samples are needed to further compare the evolution of the gas fraction in clusters and the field.

A few complicating factors should be kept in mind for this and other comparisons of the gas fraction and other gas properties. Here we compare the gas mass derived from two different tracers: dust emission in the submm (Scoville et al., 2014, this work) and CO emission (i.e. Geach et al., 2011; Daddi et al., 2010b; Tacconi et al., 2010, 2013). Because dust emission is linked to the total ISM mass through the dust-to-gas abundance ratio, this measure includes both atomic and molecular hydrogen. CO emission, through the use of a conversion factor, traces only molecular hydrogen. In the local Universe, the ratio of atomic to molecular gas mass in SFGs is $\sim 1.5 - 2$ (Saintonge et al., 2011), with atomic gas dominating. The relative abundance of atomic to molecular hydrogen, however, is highly sensitive to the pressure (or column density) of the ISM (e.g Krumholz et al., 2009). As the ISM pressure increases by at least an order of magnitude from low to high redshift (e.g. Obreschkow & Rawlings, 2009; Lagos et al., 2011; Fu et al., 2012), the relative fraction of atomic hydrogen is expected to decrease in the disk, though observations of atomic hydrogen are currently limited to low redshift sources. Our comparison in Figure 4.6 (left) suggests that the ISM mass measured in high redshift galaxies (Scoville et al., 2014, this work) are dominated by molecular hydrogen, given its good agreement with the
CO measurements, modulo uncertainties in the CO conversion factor, different CO transitions, and the assumptions (dust opacity, dust-to-gas abundance) that go into measuring \( M_{\text{ISM}} \).

Lastly, we look at the relation between the gas supply and current SF in these cluster galaxies. The gas depletion time, \( \tau_{\text{depletion}} = \frac{M_{\text{gas}}}{\text{SFR}} \), is the time it will take a galaxy to exhaust its gas reservoir given its current SFR, assuming no new gas supply through the accretion or cooling of additional reservoirs. Gas depletion timescales (and the SFE) have been observed to vary significantly between galaxy populations, with normal, MS SFGs having longer depletion timescales than starbursting galaxies (galaxies with enhanced SFRs relative to their stellar mass) by an order of magnitude (e.g. Daddi et al., 2010b). In the field, the gas depletion has been found to be rapid even in MS galaxies, \( \sim 0.6 \, \text{Gyr} \), necessitating the accretion of new gas to sustain the observed SF (e.g. Tacconi et al., 2013). We find similar gas depletion timescales for our cluster galaxies (Figure 4.6, right) with a range of \( \tau_{\text{depletion}} = 0.2 - 1.3 \, \text{Gyr} \) with a mean (median) of 0.7 (0.5) Gyr and a value of 0.4 Gyr for the stacked galaxy sample. This is consistent with the position in SFR-M* space of these cluster galaxies with relation to the MS and indicates that these cluster galaxies can deplete their gas supply in a relatively short period without new gas accretion or cooling. For reference, we also show the local \( \tau_{\text{depletion}}-\text{SSFR} \) relation (Saintonge et al., 2011).

### 4.4 Discussion

Analyses of the FIR SED of cluster galaxies at high redshift are still rare, limiting the potential for comparison and creating bias due to cluster-to-cluster variations (see Chapter 3). Recently, Smail et al. (2014) quantified the FIR SED of cluster galaxies in Cl 0218.3-0510, a red-sequence selected cluster at \( z = 1.62 \) (Papovich et al., 2010). Cl 0218.3-0510 is both more star-forming than IDCS J1426.5+3508 and much less massive at \( \sim 8 \times 10^{13} \, M_\odot \) (Pierre et al., 2012). Using SPIRE and SCUBA-2 observations, they
fit a modified blackbody to the FIR SED, measuring an mean $T_{\text{dust}} = 33 \pm 1.2$ K for their IR-luminous ($L_{\text{IR}} \sim 2 \times 10^{12} L_\odot$) galaxy population. Despite differences in the fitting technique and cluster masses, our results are in good agreement with the results from Smail et al. (2014), suggesting that dust temperatures are comparable across clusters of different properties, which is consistent with the result that dust temperature is not a strong function of environment at high redshift (Figure 4.3).

The cluster environment may contribute to the heating of dust as quenching becomes effective in clusters at lower redshift ($z \lesssim 1.4$; Brodwin et al., 2013, Chapter 2-3), through, for example, interactions with the hot ICM or dust stripping (Cortese et al., 2010, 2012; Rawle et al., 2012). Studies of clusters at low redshift ($z \sim 0.3$) have found that the FIR SEDs of sub-LIRG galaxies on the outskirts of clusters have excess flux blue-ward of the dust peak (not associated with AGN) when compared to similarly selected field galaxies (Rawle et al., 2010). The dust temperatures of these cluster galaxies, however, are generally found to be similar to that of field galaxies, with the exception of a small population of warm ($T \sim 40$K) galaxies in the merging Bullet cluster system (Rawle et al., 2012). An analysis of the relaxed system MS2137.3-2353 and merging cluster system Abell 2744 at similar redshifts, however, did not find a warm galaxy population, suggesting that these warmer galaxies are neither ubiquitous in low redshift clusters nor necessarily associated with the dynamical state of the cluster (Rawle et al., 2012, 2014). In local cluster galaxies, dust stripping has been observed in HI deficient systems; however, the effects of environment on dust appear to be weaker than the more effective process of stripping gas (Cortese et al., 2010, 2012). These results may indicate that (bulk) cold dust temperature is not overly sensitive to environmental processes at low redshift.

Gas studies in low redshift clusters ($z \sim 0.0 - 0.4$) have found a depletion of the molecular gas reservoir at fixed $L_{\text{IR}}$ and fixed stellar mass relative to the field (e.g. Geach et al., 2011; Jablonka et al., 2013). Recently, Boselli et al. (2014), analyzing
galaxies in Virgo relative to the field using the *Herschel* Reference Survey (HRS),
found that cluster galaxies are more likely to be deficient in atomic and molecular
hydrogen than their counterparts in the field, confirming environmental effects on
the gas properties of cluster galaxies at low redshift. Given recent evidence of dust
stripping also from the HRS (Cortese et al., 2010, 2012), Boselli et al. (2014) concludes
that cluster galaxies are undergoing ram pressure stripping (see also Vollmer et al.,
2010).

Similar to the field, the gas depletion timescale (~0.5 Gyr) of cluster galaxies at
high redshift indicate that their star formation histories (SFHs) are closely tied to
their gas accretion histories. Studies of red sequence galaxies in $z = 1 - 1.5$ clusters
indicate stochastic SFHs (Snyder et al., 2012), which may be linked to the availability
of fresh cold gas as a galaxy moves through the cluster environment, possibly through
cooling of remaining diffuse halo gas of the galaxy. Recently, observations of statistical samples of cluster galaxies have found that significant quenching occurs over a
relatively short timescale in $z = 1 - 2$ clusters (Brodwin et al., 2013, Chapter 3). Specifically, on average, the cluster environment was found to quench an excess of
~25% of IR-luminous cluster galaxies relative to similar populations in the field from
$z \sim 1.5$ to $z \sim 1.2$, a period of ~0.6 Gyr (Chapter 3). This similarity to the gas
depletion timescales suggests that it may be sufficient for the cluster environment
to suppress the fresh accretion of gas onto a fraction of cluster galaxies, which then
quench through the normal modes of star formation. This is consistent with the ob-
ervation that cluster galaxies are primarily on the MS at high redshift (Chapter 3).
The suppression of gas accretion itself may be a stochastic process and may involve
either the heating of gas reservoirs such as diffuse halo gas or the stripping of halo or
disk gas, which has been observed to be occurring in clusters at lower redshift (e.g.
Smith et al., 2010; Vollmer et al., 2010; Ebeling et al., 2014).
Gas masses have been quantified for two cluster galaxies at $z > 1$. Wagg et al. (2012) analyzed a CO detection in an ISCS cluster galaxy at $z \sim 1$. The cluster galaxy is well fit by a Seyfert 2 template and has a tentative detection of $[\text{Ne V}]$, suggesting the presence of an obscured AGN. Measurements of the CO J=2-1 line emission, assuming a ULIRG conversion factor (Downes & Solomon, 1998), indicated $M_{\text{gas}} = (1.55 \pm 0.28) \times 10^{10} \, M_\odot$. This gas mass is lower than our average gas mass by approximately a factor of 3; however, this may be a function of the assumed ULIRG conversion factor, which is lower than more typical MW conversion factor by a factor of 5 (Solomon & Vanden Bout, 2005). More recently, Casasola et al. (2013) reported the detection of CO in an AGN near the center of a cluster at $z \sim 1.4$. They similarly derived a $M_{\text{gas}} \sim 10^{10} \, M_\odot$, again assuming the ULIRG conversion factor. These comparisons outline the need for observations of gas in statistical galaxy samples with both traditional CO observations and submillimeter imaging in order to more robustly determine the appropriate conversion factor in these systems.

4.5 Summary

In this study, we present new SCUBA-2 imaging, allowing the first measurements of the dust temperatures and ISM masses in galaxies in a massive cluster at $z = 1.75$, near the peak in the cosmic SFR density of the Universe. We characterize the FIR SED of cluster galaxies using a coupled modified blackbody plus power law fit to our PACS, SPIRE, and SCUBA-2 photometry, which brackets the peak of dust emission. We address flux boosting due to the large beam sizes ($\gtrsim 15''$ for the SPIRE and SCUBA-2 observations) by requiring PACS priors, which have been visually inspected for blending with nearby IR sources, and which also probe IR emission. We show that this approach provides a better estimate of the deboosted flux of a source than blind source extraction (see Appendix C). In addition, we derive ISM masses from our
SCUBA-2 imaging following the method of Scoville et al. (2014). Our conclusions are as follows:

1. Cold dust temperatures in cluster galaxies at $z = 1.75$ are found to be, on average, $T_{\text{dust}} \sim 31 \pm 3.9$ K, comparable with field galaxies at similar masses, luminosities, and redshifts. $T_{\text{dust}}$ is not found to be a strong function of cluster-centric radius or AGN activity.

2. The ISM masses of cluster galaxies at $z = 1.75$ are similar to field galaxies at this epoch, with higher gas fractions than lower redshift galaxies.

3. The gas depletion timescales of cluster galaxies at $z = 1.75$ ($\sim 0.7$ Gyr) are consistent with those of MS field galaxies at $z = 1 - 3$ (Tacconi et al., 2013) and indicate that IR-luminous cluster galaxies are undergoing a “normal” mode of star formation rather than the more efficient starbursting mode (Daddi et al., 2010b).

4. The relatively short gas depletion timescales for cluster galaxies suggest that, as in the field, the SFH of cluster galaxies is closely tied to the gas accretion history. Based on studies which observe the quenching of, on average, 25% of IR-luminous galaxies in clusters over the redshift range $z \sim 1.5$ to $z \sim 1.2$ ($\sim 0.6$ Gyr; Chapter 3), we suggest that it may be sufficient for the cluster environment to suppress gas accretion for a fraction of cluster galaxies, which will then use up their remaining gas reservoir through normal modes of star formation. Gas stripping likely plays a role in preventing diffuse halo gas from replenishing the disk, though it is unclear if this process is effective in high redshift clusters.
CHAPTER 5
SUMMARY AND FUTURE DIRECTIONS

5.1 Summary

In this thesis, we have examined the properties of cluster galaxies across cosmic time in order to place constraints on the role of environment in galaxy evolution. We start with a statistical analysis using FIR imaging covering a large survey of almost 300 massive galaxy clusters. Using a stacking analysis, we quantify the average dust-obscured SFRs of mass-limited cluster galaxy samples over a long redshift baseline ($0.3 < z < 1.5$) and as a function of cluster-centric radius. We find that the rate of evolution in the average SFRs and SSFRs of cluster galaxies is faster than that in the field, leading to the observed local relation between SFR and galaxy density. At $z \gtrsim 1.2$, the average star formation in cluster galaxies is comparable to that of field galaxies, indicating a weakening of the SFR-density relation and an epoch of active star formation in cluster environments. This transition in massive clusters is confirmed here for the first time for mass-limited cluster galaxy samples in a large cluster survey. Further analysis reveals that the evolutionary trend seen in cluster galaxies is driven by the lower mass end of our galaxy distribution, with the most massive galaxies showing a weaker trend with redshift. We compare the timescales for cluster galaxy evolution to predictions for quenching mechanisms such as strangulation and ram pressure stripping and conclude that these processes are likely occurring in our cluster sample; however, the relative importance of these processes has yet to be established.
Following on our statistical analysis, we present new, deep targeted FIR imaging of 11 spectroscopically-confirmed clusters at $z = 1 - 2$. Using this imaging, we detect individual cluster galaxies down to $\text{SFR} \gtrsim 80 \, \text{M}_\odot \, \text{yr}^{-1}$. Combined with the extensive multi-wavelength data available, we quantify, for the first time, the UV-to-FIR SEDs of IR-luminous cluster galaxies at high redshift. We find that our cluster galaxies can be well described by empirically-derived high redshift field galaxy templates, implying that the cluster environment does not have a significant effect on the SED shape of IR-luminous cluster galaxies. We measure SFRs and SSFRs and determine that the fraction of IR-luminous cluster galaxies is flat into the cluster cores at $z > 1.4$, followed by a significant decrease in the IR-luminous population at lower redshift. This further constrains the transition epoch discovered in our statistical analysis and in studies in the literature. By stacking on mass-limited cluster galaxy samples, we quantify the contribution to the the total SFR from the IR-luminous galaxy population, finding that the IR-luminous cluster galaxies account for a majority of the total SF. Finally, we compare our cluster galaxies to the galaxy main sequence, finding that most cluster galaxies fall along or below the MS. We find no evidence for a population of cluster galaxies above the MS in the clusters, a potential signature of gas-rich major mergers.

We calculate the total SFR per area as well as the halo mass-normalized total SFR within the virial radius of our clusters. We find that in general our high redshift clusters show significantly increased SF activity over clusters at lower redshift even when normalized by halo mass, on par with the SF activity in lower mass field galaxy haloes. This is again consistent with our statistical analysis and continues the trend noted in the literature. We note, however, that we see significant variation in the total SFR from cluster-to-cluster. Given that our cluster sample is essentially mass-selected, this indicates a strong dependence of galaxy properties on other cluster properties such as dynamical state and we emphasize the need for statistical cluster samples when drawing conclusions about the evolution of cluster galaxies.
We explore the role of black hole accretion by quantifying the contribution of AGN emission to the optical-MIR SEDs of cluster and field galaxies. This technique allows us to identify even low luminosity AGN systems within our sample of cluster galaxies, and we carefully remove the AGN emission from that of the host galaxy when calculating the dust-obscured SFRs. We measure the field-relative fraction of galaxies as a function of cluster-centric radius and contribution from AGN emission, finding that the fraction of galaxies with more than 50% of their optical-MIR emission coming from AGN in the cluster cores exceeds that in the field at $z > 1$, then declines at lower redshift. This is consistent with the co-evolution of star formation and black hole accretion in cluster galaxies. AGN feedback has long been postulated as a potential mechanism for quenching star formation and this result supports the need for further study of the link between SF, AGN, and environment.

Using Hα line emission, we compare the unobscured SFR to the dust-obscured SFR from FIR. We find that using the stellar mass to correct for attenuation underpredicts the correction necessary for IR-luminous galaxies at high redshift (SFR $\gtrsim 50 \, M_\odot$ yr$^{-1}$). We determine that the ratio of the Hα to IR luminosities is a weak function of cluster-centric radius, which may imply rapid quenching in the cluster cores. Tracers of unobscured and obscured SF, which probe different timescales of star formation activity, provide a potentially powerful tool for evaluating quenching in cluster environments.

Finally, using 850$\mu$m imaging in combination with our FIR observations, we characterize the FIR SEDs of cluster galaxies at $z = 1.75$. We find that the location of the FIR peak, a proxy for dust temperature, is similar to that in field galaxies at similar redshifts. We also present the first observations of the mass of the ISM in IR-luminous cluster galaxies at $z = 1.75$. We find that IR-luminous cluster galaxies at $z = 1.75$ have comparable ISM masses as field galaxies at similar redshifts. We go on to relate the ISM mass to other galaxies properties: first, we quantify the gas fraction, which
is the ratio of the ISM mass to the total (ISM plus stellar) mass. We find that cluster galaxies have similar gas fractions as field galaxies at $z \sim 1.75$. Quantifying the gas fraction in cluster galaxies over cosmic time and comparing this evolution to that in the field will provide important constraints on the modes of galaxy evolution across different environments. Second, we calculate the gas depletion timescale, which is the timescale over which the galaxy will consume all of its (molecular) gas, assuming a continuous star formation rate. We find similar ($\lesssim 1$ Gyr) timescales for gas depletion in cluster galaxies as in field galaxies, implying that the star formation in galaxies across all environments might be tied to the availability of a fresh gas supply. Understanding how gas accretion and gas cooling occurs in the cluster environment, therefore, provides a key constraint on quenching in cluster galaxies.

In the following, we outline just a few of the many future projects which can be undertaken that build off of the work in this thesis. These projects will further illuminate the connection between environment and galaxy evolution.

### 5.2 Future Cluster Studies

#### 5.2.1 Separating “mass” quenching from environmental effects: stellar mass functions

The stellar mass function (SMF), which describes the number density of galaxies as a function of stellar mass, is a fundamental observable of galaxy populations. The shape of the SMF for field galaxies is relatively stable out to $z > 4$, with only a changing normalization (Ilbert et al., 2013; Muzzin et al., 2013). Conversely, studies of red-sequence selected clusters at $z \sim 1$ found significant differences in the SMFs of cluster and field galaxies (van der Burg et al., 2013, but see Vulcani et al., 2013), indicative of differing fractions of quiescent to star forming galaxies in the cluster environment. How are the mass distribution and the evolution of cluster galaxies related at $z > 1$? By examining the SSFRs of cluster galaxies, we showed in Chapter 2
that differences in the average galaxy mass cannot fully account for the differential evolution seen in the ISCS cluster galaxies as compared to the field; however, stellar mass may play a role in the evolution of star-forming galaxies in clusters. This is supported by our findings in Chapter 3 that most cluster galaxies are on the Main Sequence, with a tight correlation between their SF and stellar mass. Determining the role of stellar mass as a driver of cluster galaxy evolution in active cluster systems is a key component to understanding the role of environment in galaxy evolution. The comparison of the SMF in clusters versus the field using the ISCS/IDCS surveys will encompass a wide area (the 9 deg² Boötes field) and a long redshift baseline ($z = 0 − 2$). The extensive multi-wavelength imaging available, combined with techniques for measuring robust stellar mass estimates (Moustakas et al., 2013), make quantifying the SMFs of cluster and field galaxies up to the epoch of active star formation in the ISCS/IDCS clusters an important follow-up to the studies in this thesis.

### 5.2.2 Cluster Membership and the ISM: CO Spectroscopy/Imaging and Submillimeter Imaging

As discussed in Chapters 3 and 4, the relationship between star formation and gas content and accretion history may have important implications for galaxy evolution in clusters. The ISM in high redshift galaxies can be observed primarily in two ways: molecular gas can be observed through the rotational transitions of carbon monoxide (CO) and optically thin dust emission can be used to probe the total ISM mass (e.g. Scoville et al., 2014). These two methods are complimentary as both rely on an independent set of assumptions. Inferring the dominant molecular component of galaxies, molecular hydrogen, from CO emission requires the assumption of a conversion factor which may vary wildly between galaxy types. Also, depending on the observations, an additional assumption about the relation between CO excitation states may be required (see Carilli & Walter, 2013, for a review). Inferring the total ISM mass from
observations of dust requires assumptions about the dust emissivity and gas-to-dust ratio (Scoville et al., 2014). Combining these two methods provides more robust constraints on the gas content of galaxies and, we note, the only constraint on the atomic gas fraction in high redshift galaxies until future facilities come online.

With the onset of full operations for ALMA, the LMT, and the Karl G. Jansky Very Large Array (JVLA), a new era of high redshift observations of CO is beginning. Currently, galaxy samples with detections of CO emission at $z > 1$ are small (Carilli & Walter, 2013); most are blank-field galaxies, with only a handful of cluster members, as discussed in Chapter 4. CO observations can directly probe how gas reservoirs tied to SF interact with the cluster environment (i.e. gas stripping) and the mode(s) of SF which operate in cluster galaxies. In addition, detections of a CO emission line can spectroscopically confirm cluster membership for gas-rich, dusty galaxies, providing an alternative to optical/infrared spectroscopy, which can be biased against extremely dusty objects. This is a relatively new and innovative technique, having only been utilized recently to confirm galaxies in high redshift proto-clusters (Daddi et al., 2009; Aravena et al., 2012).

Submillimeter continuum observations with ALMA and the LMT provide a complimentary and lower-cost alternative to CO observations at high redshift. Deep submillimeter imaging at high resolution can obtain ISM masses (Scoville et al., 2014) through efficient mapping, providing statistical sample of cluster and field galaxies. Combining CO and submillimeter observations will provide the best calibrations for deriving gas and ISM masses and testing whether these calibrations depend on environment. Linking the star formation and AGN processes in cluster galaxies to gas content across the transition from actively star forming to passively evolving is a vital next step in constraining galaxy evolution as a function of environment.
5.3 A Complete Picture: Large Scale Structure Mapping

Ultimately, a complete understanding of the relationship between environment and galaxy evolution will require a full mapping of the LSS - voids, filaments, groups, clusters - over a wide area and a range of redshifts. Various methods have been attempted with mixed results: studies have both found a reversal of the SFR-density relation in field galaxies out to $z \sim 1$ (e.g. Elbaz et al., 2007; Cooper et al., 2008) and not found such a reversal (e.g. Bolzonella et al., 2010; Scoville et al., 2013) using techniques ranging from nearest neighbors to fixed aperture methods and relying on both spectroscopic and photometric redshifts. An study of the commonly used techniques for mapping LSS found that a combination of approaches - a nearest neighbor technique to probe inter-halo scales and a fixed aperture method to probe super-halo scales - is necessary to define a galaxy’s local environment in terms of large scale structures such as filaments or groups (Muldrew et al., 2012). Recently, Scoville et al. (2013) demonstrated the power of combined techniques by mapping the LSS in the 2 deg$^2$ COSMOS field using Voronoi tessellation and adaptive smoothing. They found that SF no longer decreases in highest density environments sampled above $z \sim 1.2$ and that the SFRD of the Universe is uniformly distributed over all environment scales at high redshift, while the dominant contribution at low redshift is found in low density environments. The COSMOS field, however, does not cover a wide enough area to be representative of the full range of densities, up to massive clusters. Recently, LSS mapping using spectroscopic redshifts, voronoi tessellation, and minimal spanning trees was used to characterize star formation across the local Coma Supercluster, encompassing a wide range in galaxy densities (Cybulski et al., 2014). They found progressively more effective environmentally-driven quenching from voids to filaments to groups to clusters, for both massive and dwarf galaxies, demonstrating the power of large scale structure mapping around massive clusters. Applying these techniques to wider fields such as Boötes – which encompass a range
of environments up to massive clusters — beyond the local Universe is a vital next step in fully characterizing galaxy properties as a function of environment.
Here we describe our reduction of the *Herschel* SPIRE observations of the Boötes field, publicly available from HerMES (Oliver et al., 2012). The Boötes field was observed with 9 AORs in SPIRE PACS Parallel Mode between December 3, 2009 and January 1, 2010. A listing of the observation IDs can be seen in Table A. Five of the AORs cover the central 2 square degrees of the field, while the other four AORs cover half of the full ∼8 square degrees centered on 14:32:06 +34:16:48. At least two AORs overlap in each area of the map. Very few cluster galaxies are detected in the SPIRE maps; because of this, this work has focused on stacking analyses in order to probe the average SF in all cluster galaxies. We describe here additional details about the source catalogs and associated simulations in order to validate the map and flux measurements used in this study.

### A.1 Data Reduction and Catalogs

Data reduction was done using HIPE version 7 (Ott, 2010). The 9 AORs were reduced separately up to Level 2 following the standard pipeline with two exceptions: 1) deglitching was performed using the more advanced sigma-kappa deglitcher rather than the default wavelet deglitcher. The sigma-kappa deglitcher uses an iterative process to reject outliers after adaptive highpass filtering of the signal timeline. The final error maps were examined for bright pixels which may indicate missed glitches and the glitch mask was adjusted accordingly. 2) Due to striping in the maps, a high order polynomial baseline removal was used instead of the default median baseline.
Table A.1. Summary of Boötes SPIRE AORs.

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<td>24748.0</td>
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<td>24748.0</td>
<td>229</td>
<td>14:31:35</td>
<td>+34:59:08</td>
</tr>
</tbody>
</table>

 removal. Final, level 2 maps of each AOR were produced using the naive mapmaker. The calibration tree used was spire_cal_7.0.

Astrometry corrections were derived from stacking bright MAGES 24µm sources on the individual, reduced AORs. The stacked images were fit with the SPIRE PSF, from which typical offsets of ~ 1 arcseconds in RA and ~ 2 arcseconds in Dec were determined. Mosaicking was performed on the Level 1 scans (which include de-glitching) of all 9 AORs for each waveband (250, 350, and 500µm) after the application of astrometry corrections and polynomial baseline removal. The error maps generated with each mosaic are the standard deviation of the data points falling into a given pixel and represent the associated instrument noise. Using the error maps, the 5σ depths of the inner (outer) portion of the 250, 350, and 500µm maps are 14.5, 11.5, and 14.5 mJy (26.5, 21.5, and 26.0 mJy). This does not include confusion noise, which is 5.8, 6.2, and 6.8 mJy beam\(^{-1}\) for 250, 350, and 500µm (Nguyen et al., 2010). These values are summarized in Table A.1.

The maps were post-processed using a matched-filter technique which optimizes the S/N ratio for confusion-dominated submillimetre maps and improves source de-
blending by convolving the maps with a Gaussian which is narrower than the PSF of the observations (see Chapin et al., 2011). Source finding was performed by identifying local maxima in both the unfiltered (UF) and matched-filtered (MF) maps. SPIRE are normalized to have a zero mean baseline and units of Jy beam$^{-1}$. This means that the flux density of the peak pixel provides an accurate estimation of the integrated flux density of a source. The instrument noise associated with each source is given by the corresponding pixel in the error map. The source detection threshold was set at 5$\sigma$, as determined by the error maps (which do not take into account confusion noise). To determine sub-pixel source locations, each detected source was weighed by the S/N in the surrounding pixels.

Extended sources were identified by eye and masked out if at least one axis exceeded 1.5 times the FWHM of the SPIRE beam. Thirteen extended sources were identified. In addition, a 4.8 square arcminute rectangular area centered on 14:33:11.8, +33:26:27 was masked in all maps due to bad pixels in the 500$\mu$m map. Point source catalogs were generated after masking out the extended sources and bad pixel region. The 5$\sigma$ catalogs for the unfiltered maps contain 14,356, 10,641, and 3,437 point sources for 250, 350, and 500$\mu$m. The 5$\sigma$ catalogs for the matched-filter maps have 21,892, 13,692, and 5,137 point sources.
## Table A.2. SPIRE Map Statistics

<table>
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<tr>
<th>Wavelength</th>
<th>FWHM [arcsec]</th>
<th>Pixel Size [arcsec] pixel(^{-1})</th>
<th>5σ Depth [mJy]</th>
<th>Confusion Noise(^a(1\sigma)) [mJy]</th>
<th>90% Comp. (UF) [mJy]</th>
<th>90% Comp. (MF) [mJy]</th>
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</thead>
<tbody>
<tr>
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<td>350μm</td>
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<td>11.5</td>
<td>6.2</td>
<td>20</td>
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<td>500μm</td>
<td>36</td>
<td>14</td>
<td>14.5</td>
<td>6.8</td>
<td>22</td>
<td>35</td>
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</table>

\(^a\text{Nguyen et al. (2010)}\)
A.2 Completeness Testing

Completeness simulations were performed on all six maps (UF and MF) for 250, 350, and 500µm in order to quantify completeness, positional uncertainties, and flux boosting. As the Herschel SPIRE PSF is nearly Gaussian, fake sources were inserted directly into the maps as Gaussians with the appropriate FWHM and with a peak value scaled to the desired flux. Inserting fake sources directly into the real map accounts for all sources of noise, including confusion noise. Given the size of the Boötes field, 100 sources can be inserted into both the inner and outer regions at a time without significantly altering the properties of the original map. We impose the restriction that no two fake sources can be placed within 100 arcseconds of each other. Fake sources were given fluxes ranging from 6-10 mJy in steps of 2 mJy, 10-80 mJy in steps of 5 mJy and 100-200 mJy in steps of 100 mJy and placed in random positions. We generated 100 simulated maps, each with 100 fake sources in both the inner and outer regions, per flux bin per wavelength for the UF and MF maps.

In order to determine the recovery search radius, 10,000 random apertures of increasing size were placed on the UF and MF maps to find the radius at which there is a 5% chance of randomly encountering a detected source in the inner region (which is more crowded due to its depth). The search radius adopted from this is 10″, 12″, and 18″ for 250, 350, and 500µm for both the UF and MF maps. In the simulated maps, fake sources are then searched for using the appropriate search radius at their original location. A source is considered to be recovered if it is detected at ≥ 5σ and its position and flux are recorded as a function of input flux.

The 90% completeness fluxes are listed in Table A.1 and an example of the completeness as a function of input flux for the 250µm unfiltered map can be seen in Figure A.1. For fake sources which are recovered, we calculate the distance between the position at which the source is recovered and its original position and determine the probability, \( P(> D; S) \), that a SPIRE source will be detected at a distance greater
Figure A.1 The completeness as a function of flux for fake sources inserted into the Boötes 250\,\mu m unfiltered map. The inner region (black diamonds) is \sim 2 times deeper than the outer region (blue triangles). The errors are Poisson errors.

than $D$ from its true position as a function of the source’s flux. The positional uncertainties for several source fluxes can be seen for the inner region of the 250\,\mu m unfiltered map in Figure A.2. For a 20 mJy source, the probability that it will be detected within 7\arcsec, 8.5\arcsec, and 13\arcsec for the 250, 350, and 500\,\mu m for the UF maps and 5.5\arcsec, 8\arcsec, and 12\arcsec for the MF maps is \geq 90\%. In addition to the positional uncertainties, we quantified flux boosting across the map due to source blending. The recovered fluxes of the fake sources were compared to their input flux as a function of input flux. We found that flux boosting is negligible for sources \geq 20 mJy for all maps and rises steeply with decreasing flux.
Figure A.2 The positional uncertainty distribution as a function of distance $D$ for the inner region of the Boötes 250$\mu$m unfiltered map. This function indicates the probability that a source will be detected at distance greater than $D$ from its true position as a function of source flux.
APPENDIX B

DESCRIPTION OF HERSCHEL PACS MAPS AND MONTE CARLO SIMULATIONS

Imaging at 100 and 160 μm is available for 11 spectroscopically-confirmed clusters from Open Time 2 observing program OT2apope3. Nine of the clusters are observed in individual maps and a tenth map contains two clusters (ISCS88 and ISCS36) due to their small angular separation. Integration times range from 270 - 4050 s, providing uniform sensitivity to IR-luminous galaxies for each cluster from $z = 1 - 1.8$. Each map is observed with at least two AORs with two different scan directions, offset by 90 degrees, in order to remove stripping effects from the 1/f noise. The observations IDs for each map can be seen in Table B. Each map covers an area of 7'x7' with uniform sensitivity into the central 5'x5'.

Data reduction and source extraction are performed as described in Section 3.2.3. PSF fitting at the location of priors is done using the empirical PSF derived from observations of the Vesta asteroid. To remove excess noise in the PSF wings, we truncate the 100μm (160μm) Vesta PSF to a size of 6 (5) pixels and apply an aperture correction of 0.660 (0.705) to extracted sources. The rms sensitivities range from $\sim0.5-3$ mJy, based on extracting the flux from 10,000 randomly placed apertures on the residual maps.

Monte Carlo simulations are performed on the 100μm maps to assess the completeness of each map and the photometric accuracy and noise properties of extracted sources. Simulated sources are inserted into the signal maps at discrete flux levels using the 100μm Vesta PSF. In order to preserve the original map statistics, 20 simulated sources at a given flux density are inserted at a time and the process is repeated.
Table B.1. Observation IDs of *Herschel* PACS Imaging

<table>
<thead>
<tr>
<th>Cluster ID</th>
<th>Short ID</th>
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<tbody>
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<td>1342257536</td>
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<td>1342257749</td>
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</tbody>
</table>

*aISCS88 and ISCS36 were observed with the same AORs.*
for a total of 5,000 simulated sources per map per flux bin. Flux bins are chosen based on the depth of each map such that we test the completeness and photometric accuracy down to uniform limits in SFR at the redshift of the cluster as determined using an empirical SFG template (Kirkpatrick et al., 2012) and the Murphy et al. (2011a) relation. Once simulated sources are inserted, source extraction is performed as described in Section 3.2.3 using the full IRAC prior list plus the known positions of the simulated sources. A simulated source is considered recovered if it is detected at $\geq 2\sigma$. We additionally split our simulated sources into radial bins from the center of the map in order to test how the completeness varies as a function of radius. The differential completeness for the central, uniform $5' \times 5'$ of each map as a function of the SFR corresponding to the input flux density of the simulated source at the redshift of the cluster can be seen in Figure B.1. The dashed (dotted) lines shows that 10 of the cluster maps are $\geq 50\%$ ($\geq 80\%$) complete at a SFR$\sim 80 \, M_\odot \, yr^{-1}$ (SFR$\sim 100 \, M_\odot \, yr^{-1}$). Our highest redshift cluster, IDCS687, has a lower completeness by $\sim 10\%$. The completeness of all maps drops by $10-15\%$ outside the uniform coverage, out to
a radius of 4 arcminutes from the center of the map. Separate completeness functions
are shown for ISCS88 and ISCS36 as they share a map but the clusters are at different
redshifts. At the same SFR, ISCS88 is $\sim 10 - 20\%$ more complete than ISCS36 due
to the depth of the ISCS88/ISCS36 map.

Due to our source extraction being based on priors, we consider sources detected
at a lower S/N than we would using blind source extraction. Following Magnelli
et al. (2013), we use our Monte Carlo simulation to test the photometric accuracy
and uncertainty estimates of simulated sources inserted into the map. Photometric
accuracy is defined as the standard deviation of $S_{\text{out}} - S_{\text{in}} / S_{\text{out}}$, where $S_{\text{in}}$ is the known
input flux of the simulated sourced and $S_{\text{out}}$ is the flux recovered. As our simulated
sources are inserted into the real signal map, this test accounts for all sources of noise
including confusion. We find that our photometric accuracy is generally better than
31%, consistent with most of our simulated sources being recovered at $\geq 3\sigma$, with
better than 50% photometric accuracy for sources recovered at $\sim 2\sigma$. In addition, we
examine the quantity $S_{\text{out}} - S_{\text{in}} / \sigma_s$, where $\sigma_s$ is the uncertainty on the flux density
measured from the residual maps. We find that the distribution of this quantity is a
gaussian with mean zero and a dispersion of one, indicating that our source extraction
does not underestimate the uncertainties associated with a given source.

Selecting sources to a lower S/N may also introduce spurious detections. Since we
are using priors, this should be minimized, however, we test the random occurrence of
$2\sigma$ peaks in our map by performing source extraction on randomized priors. We find
a $\sim 7\%$ occurrence of a $2\sigma$ peak given random priors, consistent with the gaussian
noise expectation of 5% plus a confusion noise component. Finally, we visually inspect
all PACS-detected cluster members for blending with neighboring IR sources. We
remove 10% of cluster members from our analysis due to blending. These Monte
Carlo simulations and tests provide confidence that we are able to extract sources
uses IRAC priors and accurately measure their flux densities and uncertainties for sources detected at $\geq 2\sigma$. 
APPENDIX C

MONTE CARLO SIMULATIONS OF IDCS J1426.5+3508 SCUBA-2 MAP

850μm imaging for IDCS J1426.5+3508 was obtained with SCUBA-2 (Holland et al., 2013) on the JCMT in semester 12A under proposal M12AI01. The map was reduced using the SMURF pipeline (Jenness et al., 2011) as described in Section 4.2.4. The 39 850μm sources detected through blind source extraction are listed in Table C.

Monte Carlo simulations are performed on the SCUBA-2 map in order to characterize the differential completeness, positional uncertainties, and flux boosting as a function of flux density. Simulated sources are inserted into the signal map at random positions, 20 at a time, and then blind source extraction is performed. This process is repeated 500 times for flux density bins from 1.5-5.5 mJy. The fraction of simulated sources recovered at $\geq 3.5\sigma$ gives the completeness as a function of input flux (Figure C.1). Our simulated sources are further separated into two radial bins (inner $r < 2'$ and outer $2' < r < 4'$) in order to test the completeness given increasing noise toward the edges of the map. The IDCS J1426.5+3508 map is 90% complete at $\sim2.5$ mJy in the inner region and $\sim3.5$ mJy in the outer region. We note that we use the signal map for our simulations in order to properly account for all sources of noise, including confusion noise. We use discrete flux density bins rather than observed number counts in order to avoid making any assumptions regarding the cluster population.
Table C.1. Source Catalog for the IDCS J1426.5+3508 SCUBA-2 Map

<table>
<thead>
<tr>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>$S_{850\mu m}$ [mJy]$^a$</th>
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<tr>
<td>14:26:34.66</td>
<td>+35:13:21.0</td>
<td>8.8 ± 1.0</td>
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<tr>
<td>14:26:36.46</td>
<td>+35:07:13.1</td>
<td>4.6 ± 0.6</td>
</tr>
<tr>
<td>14:26:38.40</td>
<td>+35:09:17.1</td>
<td>4.3 ± 0.6</td>
</tr>
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<td>14:26:28.14</td>
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<td>4.4 ± 0.7</td>
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<td>14:26:44.29</td>
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<td>7.2 ± 1.2</td>
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<td>4.8 ± 0.8</td>
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Table C.1—Continued

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<td>3.1 ± 0.9</td>
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*aFlux densities have not been corrected for boosting (see Figure C.2).

Positional uncertainties and flux boosting are well known to effect submillimeter observations due to the typically low S/N (< 10) of submillimeter detections and the steep, intrinsic luminosity function of submillimeter sources (e.g. Scott et al., 2006). Positional uncertainties arise when sources are near a noise peak in the map, which shifts the detected peak of emission from its true location. This error on the true position of submillimeter sources is characterized by measuring the offset between input simulated sources and where they are recovered (e.g. Scott et al., 2008). This information can then be used to determine the search radius for counterpart identification to higher resolution observations. For the IDCS J1426.5+3508, the probability that an 850\mu m source will be detected at $\geq 3.5\sigma$ within 6" of its true position is $\geq 80\%$.

Flux boosting is the systematic increase in the intrinsic flux density of faint sources. Given a large population of faint sources below a given detection limit, the probability of a faint source being boosted high by noise is substantially increased, requiring low S/N detections to be “deboosted” (e.g. Hogg & Turner, 1998). This flux boosting is characterized by measuring the ratio of the output flux recovered to the input flux of simulated sources. We measure flux boosting (Figure C.2) both for fluxes recovered from blind source extraction (closed symbols) and from extracting
Figure C.1 The 850\(\mu\text{m}\) differential completeness for IDCS as a function of the input flux. The simulated sources are analyzed separately for the central portion of the map (black diamonds, \(r < 2''\)) and the outer region (blue triangles, \(2'' < r < 4''\)).

the flux at the known position of the input source (open symbols), the equivalent of using priors for higher-resolution imaging. We find that a S/N \(\sim 3\) 850\(\mu\text{m}\) source will on average be boosted by a factor of 1.8-2.2 in a blind survey. Using priors, however, minimizes boosting, allowing for a more accurate measurement of the flux density of a known source.

Given these Monte Carlo simulation, we measure the 850\(\mu\text{m}\) flux densities of cluster galaxies in this work through the use of PACS-detected priors, which mitigates both positional uncertainties and flux boosting, as well as ensures against false detections as both PACS and SCUBA-2 sample IR emission.
Figure C.2 Flux boosting, the ratio of $\text{flux}_{\text{out}}$ over $\text{flux}_{\text{in}}$ for simulated sources inserted into the signal map for the inner ($r < 2''$, upper panel) and outer ($2'' < r < 4''$, lower panel) regions of the map. The closed symbols show the flux boosting for sources recovered through blind source extraction. The open symbols show the flux boosting for flux densities recovered at the location of priors.
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