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THE EFFECT OF A GROWING BLACK HOLE ON THE INFRARED EMISSION OF DUSTY GALAXIES IN THE DISTANT UNIVERSE

A Dissertation Presented
by
ALLISON KIRKPATRICK

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

May 2016
Astronomy
THE EFFECT OF A GROWING BLACK HOLE ON THE INFRARED EMISSION OF DUSTY GALAXIES IN THE DISTANT UNIVERSE

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by

ALLISON KIRKPATRICK

Approved as to style and content by:

________________________________________
Alexandra Pope, Chair

________________________________________
Daniela Calzetti, Member

________________________________________
Stella Offner, Member

________________________________________
Benjamin Brau, Member

________________________________________
Stephen Schneider, Department Chair
Astronomy
To my patient and immensely supportive husband, Charles.
ACKNOWLEDGMENTS

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ABSTRACT

THE EFFECT OF A GROWING BLACK HOLE ON THE INFRARED EMISSION OF DUSTY GALAXIES IN THE DISTANT UNIVERSE

MAY 2016

ALLISON KIRKPATRICK
B.Sc., UNIVERSITY OF FLORIDA
Ph.D., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Alexandra Pope

The buildup of stellar and black hole mass peaked during $z = 1 - 3$. Infrared (IR) luminous galaxies, which are massive and heavily dust obscured ($L_{\text{IR}} > 10^{11}L_\odot$), dominate the stellar growth during this era, and many are harboring a hidden active galactic nucleus (AGN). We have quantified the contribution of AGN heating to the infrared emission of a large sample of dusty, luminous galaxies from $z = 0.5 - 4$ using Spitzer mid-IR spectroscopy, available for every source. We classify sources as star forming galaxies, AGN, or composites based on the presence of mid-IR continuum emission due to a dusty torus. 60% of our sample shows signs of some dust heating emanating from an AGN, and that an AGN is clearly linked with increasing dust temperatures. We quantify the far-IR emission using deep Herschel imaging and find that the strength of mid-IR AGN emission is tightly correlated with the total contribution of an AGN to $L_{\text{IR}}$, which has important consequences for calculating star formation rates in dusty high redshift galaxies. We calibrate techniques to remove the
contribution of AGN to $L_{\text{IR}}$. Because of dust obscuration, much of this AGN activity is undetected at other wavelengths, but we present new color diagnostics to effectively identify heavily obscured AGN. We discuss the role that mergers might play in fueling AGN growth and find our galaxies to be generally consistent with the picture that a major merger triggers an AGN. We test what effect an IR luminous AGN has on the star formation efficiency (the star formation rate compared with the molecular gas mass) using a pilot sample of 24 galaxies at $z < 0.4$. We find AGN have slightly lower star formation efficiencies, consistent with the AGN quenching star formation. These signatures are missed completely when an obscured AGN is undiagnosed, as all of the infrared luminosity is wrongly attributed to star formation. Finally, we compare high redshift IR luminous galaxies with a local sample. Despite some similarities in SED shape, we find that the dust emission from local IR luminous galaxies is largely inconsistent with the dust emission we observe in their high redshift counterparts.
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CHAPTER 1
INTRODUCTION

Fully understanding the growth, life, and death of galaxies is a major goal in modern astronomy. Internally, galaxy evolution is driven by two processes: 1) the birth and death of stars and 2) the growth of a supermassive black hole. The effect of each of these processes can be difficult to distinguish as observational astronomy is limited by the sizes of objects that telescopes can resolve. We can see individual stars only in galaxies close to the Milky Way, and even in our own galaxy, we do not yet have the resolving power to image the supermassive black hole at the center. Therefore, astronomers must infer how star formation and supermassive black hole growth changes a galaxy by looking for evidence of physical transformations using different wavelengths of light, which each probe distinct components of a galaxy. This thesis details how each process, star formation and supermassive black hole growth, influences the observed dust emission in galaxies during a key epoch of galaxy evolution 7 – 11 billion years ago.

1.1 Galaxy Evolution

Galaxy evolution is frequently quantified by an empirical relationship called the “galaxy main sequence.” There is a tight observed correlation between a galaxy’s star formation rate (SFR) and stellar mass ($M_*$) (Noeske et al., 2007; Elbaz et al., 2011). This main sequence can be understood physically if we think of the stellar mass as the integrated SFR over the lifetime of the galaxy. Then, the ratio of SFR to $M_*$ measures whether a galaxy is currently forming stars at the average rate it has
always formed stars. Galaxies that lie above the main sequence, that is, galaxies that have an enhanced SFR for a given stellar mass, are designated “starbursts” as they are thought to be undergoing a short-lived burst of star formation. Starbursts are commonly triggered by a major merger of two galaxies of comparable masses (the mass ratio is typically between 1:1 and 1:4). In the classical picture of galaxy evolution, a starburst phase gives way to an active galactic nuclei (AGN) phase, where energy released from material accreting onto the central supermassive black hole dominates the bolometric luminosity of a galaxy (Sanders et al., 1988; Sanders & Mirabel, 1996). An AGN then dramatically influences the internal evolution of a galaxy by heating the dust, expelling the gas, and ultimately quenching the star formation through feedback mechanisms (e.g., Alexander & Hickox, 2012). A quenched galaxy has a very low ratio of SFR/$M_*$ and lies below the main sequence. After the AGN phase, the galaxy then evolves into a passive elliptical. Figure 1.1 shows a schematic of a major merger and location on the main sequence.

This “merger life cycle” may also be observed by comparing the SFR with the amount of gas present to form new stars ($M_{\text{H}_2}$). The ratio of SFR/$M_{\text{H}_2}$ is known as the star formation efficiency. Galaxies with a high SFR for a small amount of molecular gas are said to be forming stars very efficiently. This high efficiency is observed in starbursts, possibly triggered by a major merger funnelling gas towards the inner regions of a galaxy and simultaneously providing fuel for an AGN (Downes & Solomon, 1998; Solomon & Vanden Bout, 2005; Daddi et al., 2010b; Genzel et al., 2010). There is also a “normal” rate of star formation measured in undisturbed disk galaxies for a given amount of molecular gas. There is clear evidence of an enhanced star formation efficiency in starbursting galaxies relative to main sequence galaxies (Bolatto et al., 2013; Carilli & Walter, 2013). However, measuring the star formation efficiency can be affected by an undetected AGN. The infrared luminosity, $L_{\text{IR}}$, is often used to calculate SFR, but $L_{\text{IR}}$ can have a significant contribution from AGN.
Early-type galaxy star formation quenching schematic

Figure 1.1: Illustration of the major merger sequence. Two main sequence galaxies (top, left) undergo a merger which induces a starburst (top, right). The AGN phase follows the starburst phase and quenches star formation by expelling the gas in the galaxy and preventing any new gas from collapsing onto the galaxy (bottom, left). With star formation quenched, after the AGN ceases to be active, the galaxy becomes a passive elliptical (bottom, right). Reprinted from Schawinski et al. (2014).
emission that is difficult to detect. If an AGN is unaccounted for, a galaxy’s SFR will be artificially high, indicating an enhanced star formation efficiency when in fact there is none. This has been observationally confirmed in Evans et al. (2001), where the authors measure high SFR/\( M_{H_2} \) ratios in luminous AGN and infer that these ratios might be boosted by the AGN contribution to \( L_{IR} \).

Finding AGN and accounting for the amount of dust heating due to the AGN is necessary in order to calculate correct SFRs and accurately measure star formation efficiencies. Both of these parameters are used to quantify how a galaxy evolves—that is, how efficiently the galaxy is forming stars, whether it might be merging, whether it is in the process of quenching, and if an AGN is responsible for that quenching. We demonstrate in this thesis techniques for detecting hidden AGN and ways to remove AGN contribution to \( L_{IR} \) before deriving SFRs.

1.2 High Redshift Dusty Galaxies

The rate at which galaxies in the Universe form stars has not been constant since the Big Bang, 14 Gyr ago. In fact, if we measure the star formation rate density (that is, the number of new stars formed over a given time in a given volume), we find that the peak era of star formation occurred at 7 – 11 billion years ago (\( z = 1 – 3 \)) (see Figure 1.2; Madau & Dickinson, 2014, and references therein). This is an era when 50% of the stellar mass we see today was formed. In addition to the SFR density increasing as we look back into the past, the types of galaxies forming the most stars also changes. In the local Universe, normal star forming galaxies dominate the SFR density (Murphy et al., 2011a). These are galaxies with SFR < 10 \( M_\odot \) yr\(^{-1} \) which they sustain for long periods (> 1 Gyr). On the other hand, 7 Gyr ago (\( z = 1 \)), Luminous Infrared Galaxies (LIRGs; \( L_{IR} = 10^{11} – 10^{12} L_\odot \)) dominate the stellar growth, and 10 Gyr ago (\( z = 2 \)), Ultra Luminous Infrared Galaxies (ULIRGs; \( L_{IR} > 10^{12} L_\odot \)) dominate. LIRGs and ULIRGs are massive (\( M_* > 10^{10} M_\odot \)), dusty galaxies with
SFRs $> 100 \, M_\odot \, yr^{-1}$. Newly formed stars emit strongly in the UV/optical portions of the spectrum, but if a galaxy is sufficiently dusty, dust grains absorb the bulk of the UV/optical light, and the heated dust emits strongly in the IR. Because the bulk of the star formation in the distant Universe is occurring behind dust (Figure 1.2), if we want to understand galaxy evolution, studying IR emission is fundamental.

Every massive galaxy hosts a supermassive black hole at its center, and the growth of this black hole is linked with the buildup of stars in the galaxy, as evidenced by the tight relationship between the mass of the black hole and a galaxy’s stellar mass (Ferrarese & Merritt, 2000). These supermassive black holes go through an AGN phase, where they actively accrete material to grow in size. A proposed schematic of an AGN is illustrated in Figure 1.3. The central black hole is surrounded by an accretion disk and a broad line region, where gas is moving at relativistic speeds (Urry & Padovani, 1995). The broad line region is observable at optical wavelengths,
Figure 1.3: Schematic of an active galactic nucleus. Matter accretes onto a black hole, and gas surrounding the black hole can move at relativistic speeds, producing what is termed the broad line region. Crucially for IR studies, the accretion disk is surrounded by a dusty torus which absorbs energy and radiates in the IR. Original figure is from Urry & Padovani (1995).

and when gas in the accretion disk loses angular momentum, it emits X-ray and UV photons. A dusty torus encloses the accretion disk. The torus is heated to $\sim 1000 \text{ K}$ and radiates in the IR. An AGN can also produce strong winds and jets, and this feedback is predicted to eventually shut down star formation in a galaxy (Hopkins et al., 2006).

We can pinpoint when the Universe was most actively forming supermassive black holes by measuring the accretion rate density, that is, the amount of mass a supermassive black hole is “consuming” in a given time in a given volume of the Universe. It turns out that, for the most luminous AGN, the accretion rate density of mass onto these central black holes also peaked at $z \sim 1 - 3$, in the same era that the SFR density peaked (Figure 1.4) (Smolčić et al., 2009). The dual pinnacles of cosmic black hole and stellar growth make galaxies in the distant Universe (called “high redshift”
Figure 1.4: The coevolution of black hole growth and star formation over cosmic time. The accretion rate density onto black holes peaks at $z = 1 - 3$, similar to the SFR density (black line). This indicates that there may be a physical link between the growth of a black hole and star formation, and both processes should be studied in tandem to properly understand galaxy evolution. Reprinted from Madau & Dickinson (2014).

Galaxies) quintessential for disentangling how the growth of an AGN impacts the interstellar medium (ISM) of an actively star forming galaxy. The majority of the black hole activity in this time period is occurring behind dust screens as well, as evidenced by the largely unresolved cosmic X-ray background at energies $> 6\,\text{keV}$ (Hickox & Markevitch, 2007). In addition, a significant portion of high redshift (U)LIRGs, which are actively star forming, show signs of concurrent AGN growth (Sajina et al., 2007; Pope et al., 2008a; Menéndez-Delmestre et al., 2009; Coppin et al., 2010), providing an attractive option for studying the simultaneous assembly of black hole and stellar mass.

### 1.3 The Infrared Spectral Energy Distribution

A galaxy’s ISM is composed of gas and dust particles and can be described by two main regions: star forming regions, which contain clouds of molecular hydrogen to form new stars, and the diffuse ISM, which fills the space between older stars and
Figure 1.5: Infrared spectral energy distribution of a star forming galaxy and AGN. The star forming galaxy (SFG) is shown in blue, while the AGN is the red curve. SEDs are from Kirkpatrick et al. (2012). The SFG exhibits a stellar bump in the near-IR, PAH features in the mid-IR, and significant cold dust emission from the diffuse ISM in the far-IR. In contrast, an AGN has power-law emission due to the dusty torus, although the cold dust emission from the host galaxy is still visible.

star forming regions. The dust in the ISM is the product of several evolutionary processes. It is formed in the winds and ejecta of dying stars and supernova, and is further processed in the ISM before being incorporated into a new generation of stars. The dust is heated by photons from young stars, the old stellar population, and an AGN, if present. Dust reradiates this absorbed light at infrared and submillimeter wavelengths. In recent decades, infrared space-based observatories have enabled detailed studies of dust emission that are not possible from the ground because of atmospheric absorption. Astronomers refer to the intensity of emitted light from a source as a function of wavelength as the spectral energy distribution (SED). The particular shape of an SED can inform observers about the intrinsic properties of the galaxy. Sample IR SEDs of an AGN and star forming galaxy are illustrated in Figure 1.5. Below, we discuss each portion of the IR SED in detail.
In the near-IR (\( \lambda = 0.7 - 3 \mu m \)) , the H- ion has a minimum opacity at 1.6 \( \mu m \), which results in increased emission from cooler stars. This 1.6 \( \mu m \) “stellar bump” is visible in stellar populations older than 10 Myr (e.g., Bruzual & Charlot, 2003). However, if an AGN is present, the dusty torus surrounding the AGN can reach temperatures \( T \gtrsim 1000 \) K, radiating into the near-IR and obscuring the stellar bump (Donley et al., 2012).

The mid-IR spectrum (\( \lambda = 3 - 20 \mu m \)) is the most rich for disentangling AGN from star formation, as it contains dust and gas emission/absorption lines and an underlying continuum. The most prominent dust emission complexes are produced by polycyclic aromatic hydrocarbons (PAHs, \( \lambda = 6.2, 7.7, 11.3, 12.7 \mu m \)) which are abundant in galaxies with metallicity close to solar, such as high redshift (U)LIRGs (Magdis et al., 2012). These molecules are preferentially located in the photodissociation regions surrounding star forming (H\( \text{II} \)) regions (Helou et al., 2004). As such, PAHs are good tracers of ongoing star formation in a galaxy (Peeters et al., 2004). The presence of certain forbidden gas emission lines, such as [Ne\( \text{V} \)], categorically signal the presence of an AGN, since the amount of energy required for ionization is too large to be produced by young, hot (OB) stars (Armus et al., 2004). Unfortunately, detections of [Ne\( \text{V} \)] are difficult at high redshift. This line is much fainter than PAHs, so a detection requires high spectral resolution and good sensitivity. However, the mid-IR spectrum will also exhibit continuum emission due to the torus enveloping the AGN. In this case, the PAH features from the host galaxy may not be visible, either because the harsh radiation field from the AGN has destroyed them, or because the torus emission is bright enough to outshine the PAH features. Mullaney et al. (2011) find that, on average, the torus emission can be represented as a steep power-law (\( \nu^{-2} \)) at \( \lambda < 20 \mu m \). This power-law flattens out at longer wavelengths and falls off steeply beyond 40 \( \mu m \). The final main features observed in the mid-IR spectra are silicate absorption at 9.7 \( \mu m \) and, to a lesser extent, at 18 \( \mu m \). The 9.7 \( \mu m \)
absorption feature is caused by a dust screen surrounding a hot emission region and can arise either from an optically thick dusty torus (Spoon et al., 2007) or the host galaxy itself (Goulding et al., 2012). The depth of the silicate feature, below the expected galaxy continuum, can be difficult to measure in star forming galaxies because prominent PAH features lie on either side, making it hard to distinguish the intrinsic continuum emission. In principle, one should be able to disentangle the PAH features, silicate features, gas emission lines, host galaxy continuum, and torus emission from the mid-IR spectrum. In practice, this is a difficult task, and many dust models and decomposition techniques exist to measure each of these features (e.g., Draine & Li, 2007; Smith et al., 2007; Pope et al., 2008a; Hernán-Caballero et al., 2015).

The bulk of IR luminosity is emitted in the far-IR (λ = 20–500 µm), which can be categorized into warm dust (T ~ 40–100 K) and cold dust (T ~ 20 K) components. If no AGN is present, newly formed stars are primarily responsible for heating the warm dust which radiates at wavelengths λ < 70 µm (Engelbracht et al., 2010; Bendo et al., 2010). However, a prominent warm dust component signals increased dust heating by an AGN (Kirkpatrick et al., 2012). Cooler temperatures are associated with a dust component heated by the diffuse interstellar radiation field, so the cold dust traces the diffuse ISM (Draine, 2003; Tuffs & Popescu, 2005; Stevens et al., 2005). Photons produced in star forming sites heat the dust surrounding HII regions, and recent studies have demonstrated that energetic photons must leak out of these HII regions, so young stars are indirectly responsible for heating the diffuse cold dust component as well (Wood et al., 2010; Clemens et al., 2013; Hughes et al., 2014; Kirkpatrick et al., 2014a). This means that the emission from dust, trace by the infrared luminosity L_{IR}, can be converted directly to a star formation rate, since the bulk of the dust is heated by young stars. The location and heating sources of the warm and cold dust have been studied extensively in local galaxies, but we must extrapolate these
results to higher redshift galaxies since we can cannot currently resolve such galaxies at far-IR wavelengths.

1.3.1 Modeling the Far-IR Emission

We now discuss briefly our approach to measure dust temperatures in a galaxy, since the choice of model is non-trivial, and the resulting dust temperatures play a big role in the conclusions drawn about how an AGN is affecting the host galaxy. Complex models of dust emission attempt to take into account a heterogenous grain population and multiple temperature components (Dale & Helou, 2002; Draine & Li, 2007; da Cunha et al., 2008), but these are difficult to apply to observations when only limited data are available. The modified blackbody (MBB) is a particularly appealing model due to its simplicity and in most cases gives a cold dust temperature and $L_{\text{IR}}$ similar to more complex modeling or template fitting (Galametz et al., 2012; Casey, 2012; Magdis et al., 2012). It has very few parameters, allowing a determination of temperature when only a few data points are available. Dust at far-IR wavelengths primarily radiates thermally as a blackbody modulated by the dust grain emissivity. If far-IR emission is modeled as a single blackbody, in the simplistic assumption of a homogenous optically thin grain population, the frequency dependence is a power law with a spectral emissivity index, $\beta$, such that

$$S_{\nu} \propto B_{\nu}(T_c)\nu^\beta$$ (1.1)

MBB modeling is limited in its appeal by the interpretation of the derived parameters. The derived dust temperature is the average of a dust population, while each galaxy will in actuality have a distribution of dust temperatures depending on the size and location of the dust relative to the heating sources. MBB fitting does not provide information about the full range of dust temperatures in the ISM. Moreover, when fitting this relationship to data points in order to determine $T_c$ and $\beta$, 

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the temperature of the blackbody and $\beta$ are anti-correlated and possibly degenerate (Shetty et al., 2009; Paradis et al., 2010; Planck Collaboration, 2011; Juvela & Ysard, 2012). To avoid uncertainties introduced by the anti-correlation, published studies commonly advocate holding the emissivity fixed to a standard value in the range $\beta = 1 - 2$ (Yang & Phillips, 2007; Xilouris et al., 2012; Bianchi, 2013). Many local star forming galaxies and ULIRGs have been shown to require at least two dust temperature components to accurately reproduce the shape of the far-IR SED (Dunne & Eales, 2001, e.g.). We follow this convention and adopt a two-temperature MBB fitting approach in this work.

1.4 Guide to This Thesis

In this thesis, we explore the effect of a buried, luminous AGN on the observed infrared spectral energy distribution of galaxies from $z = 0.04 - 4$. In Chapter 2, we create empirical infrared templates from 151 galaxies at $z > 0.5$. We compare these templates with several local galaxy templates and find that the high redshift templates are universally colder than their local counterparts. We also explore the location of AGN and star forming galaxies on the main sequence. In Chapter 3, we discuss how broadband infrared photometry can be combined to separate AGN from star forming galaxies and apply this technique to a large survey to quantify the AGN fraction. In Chapter 4, we revisit techniques introduced in Chapter 2 by doubling the sample size and creating three libraries of empirical templates. These libraries are better able to explore the change in shape of the SED with incremental AGN growth, and are also able to constrain if and how the SED evolves with $L_{\text{IR}}$ and redshift. In Chapter 5, we examine the visual morphologies of this sample in order to determine whether a merger is responsible for triggering AGN growth. In Chapter 6, we utilize a low redshift sample of dusty galaxies to test if there is a correlation between AGN emission and a galaxy’s star formation efficiency. Finally, in Chapter 7, we directly compare
our high redshift (U)LIRGs with (U)LIRGs in the local Universe to determine if there are local counterparts to our high redshift IR galaxies. We summarize the main results and discuss ideas for future work in Chapter 8. Throughout this thesis, we assume a standard cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$. 
CHAPTER 2
THE IMPACT OF ACTIVE GALACTIC NUCLEI AND STAR FORMATION ON INFRARED SPECTRAL ENERGY DISTRIBUTIONS AT HIGH REDSHIFT

In this chapter, we explore the effects of AGN and star formation activity on the infrared (0.3 – 1000 µm) spectral energy distributions of luminous infrared galaxies from $z = 0.5$ to 4.0. Based on mid-IR classification of AGN emission, we divide our full sample into four sub-samples: $z \sim 1$ star-forming (SF) sources; $z \sim 2$ SF sources; AGN with clear 9.7 µm silicate absorption; and AGN with featureless mid-IR spectra. From our large spectroscopic sample and wealth of multi-wavelength data, we create a composite SED for each sub-sample and compare the dust properties between the four sub-samples.

2.1 Data
2.1.1 Sample Selection

Our sample consists of 151 high redshift galaxies from the Great Observatories Origins Deep Survey North (GOODS-N) and Extended Chandra Deep Field Survey (ECDFS) fields. We include all sources in these fields that were observed with the Spitzer IRS (for details on the instrument, see Houck et al., 2004). While this sample contains a diverse range of sources, depending on the goals of each individual observing program, the overlying selection criterion is that each source is bright enough at 24 µm to be observable with the IRS in a reasonable amount of time (< 10 hours).

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1 This chapter is published as Kirkpatrick et al. (2012).
Figure 2.1: Distribution of IRS sample compared with the full 24 µm population. For the full 24 µm population, we use the MIPS 24 µm GOODS sample with $S_{24} > 100$ µJy and $S_{250} > 3\sigma$. We plot the distributions in a colorspace combining far-, mid-, and near-IR fluxes (left) and in the color $S_{250}/S_{24}$ (right). The IRS sample follows a similar distribution of colors as the full 24 µm population with $S_{24} > 100$ µJy.

As a result, 93% of the sources have $S_{24} > 100$ µJy, 80% have $S_{24} > 200$ µJy and 60% have $S_{24} > 300$ µJy.

It is important to determine how representative the IRS sample is of the full MIPS 24 µm population. Within GOODS-N, the IRS sources make up ~ 20% of all 24 µm sources above 200 µJy and ~ 30% above 300 µJy. If we limit ourselves to only 24 µm sources with spectroscopic redshifts greater than 0.5, then the IRS sources make up ~ 40% above 200 µJy and ~ 60% above 300 µJy. In Figure 2.1, we show that our IRS sample spans the same distribution in Herschel+Spitzer colors as the full MIPS population with $S_{24} > 100$ µJy indicating that our IRS sample is representative within these parameters. As an additional test, we can determine if the fraction of AGN-dominated sources (defined using the mid-IR spectrum, see Section 2.1.3) within our IRS sample is proportionate to that of all 24 µm sources. In Chapter 3, we develop new color-color diagnostics to separate AGN and SF sources at high redshift calibrated
using this IRS sample. Using our new color cuts, we determine which 24 µm sources from the full MIPS samples are AGN dominated in the mid-IR. The AGN dominated sources in our IRS sample have a flux density distribution consistent with the mid-IR color-selected AGN in the full MIPS sample above \( S_{24} > 100 \mu Jy \). This gives us confidence that the IRS sample is providing fair and unbiased sampling of the full 24 µm population above these flux limits.

Furthermore, it is important to determine the overlap between 24 µm and 100 µm selected galaxy samples to determine how representative our 24 µm selected sample is of the greater population of IR luminous galaxies at high redshift. When looking at a blind catalog of sources selected at 100 µm in GOODS-N with \( S_{100} > 1.1 \) mJy (the detection limit for this survey, see Elbaz et al. 2011), we find that 97% of PACS 100 µm are detected at 24 µm (see also Magdis et al., 2011), and 67% of PACS 100 µm sources have \( S_{24} > 100 \mu Jy \). Therefore, while we are selecting sources at 24 µm in this study with \( S_{24} > 100 \mu Jy \), we are getting a representative sampling of the bulk of the PACS 100 µm selected sources. Given the large beam sizes at SPIRE wavelengths, which make robust counterpart identification challenging, we are unable to perform a similar simple test of the overlap of 24 µm sources with those selected in SPIRE. However, we do note that the bulk of submm sources selected at even longer wavelengths, 850 µm, are detected at 24 µm and most of these detections are brighter than \( S_{24} = 100 \mu Jy \) (Pope et al., 2006). It is important to keep in mind that in this paper, we focus on sources that have mid-IR spectra and PACS and/or SPIRE photometry. Therefore, our sample is representative of sources that are detected both in the mid-IR and far-IR and may not cover the parameter space of sources fainter than our flux limits or sources detected in either the mid-IR or the far-IR.

The low resolution \( R = \lambda/\Delta \lambda \sim 100 \) Spitzer IRS spectra were reduced following the method outlined in Pope et al. (2008a). Specifically, since many of these are long integrations, we take care to remove latent build-up on the arrays over
Table 2.1. Basic properties of our four sub-samples.

<table>
<thead>
<tr>
<th>Sub-sample</th>
<th>No. of Sources(\text{a})</th>
<th>Median Redshift</th>
<th>Median (S_8)(\text{b}) (µJy)</th>
<th>Median (S_{24})(\text{b}) (µJy)</th>
<th>Median (S_{100})(\text{b}) (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(z \sim 1) SF galaxies</td>
<td>39</td>
<td>1.0</td>
<td>42</td>
<td>370</td>
<td>7.9</td>
</tr>
<tr>
<td>(z \sim 2) SF galaxies</td>
<td>30</td>
<td>1.9</td>
<td>17</td>
<td>270</td>
<td>3.2</td>
</tr>
<tr>
<td>Silicate AGN</td>
<td>17</td>
<td>1.9</td>
<td>64</td>
<td>470</td>
<td>5.3</td>
</tr>
<tr>
<td>Featureless AGN</td>
<td>9</td>
<td>1.2</td>
<td>288</td>
<td>1520</td>
<td>9.5</td>
</tr>
</tbody>
</table>

\(\text{a}\)We list the number of sources in each sub-sample that are used to create the composite SEDs as well as the number of sources we have rejected in each subsample in Section 2.2.

\(\text{b}\)Observed frame flux densities.

...time, and we create a ‘supersky’ from all the off-nod observations to remove the sky background. One dimensional spectra are extracted using the Spitzer IRS Custom Extraction (SPICE) in optimal extraction mode. For each target a sky spectrum is also extracted to represent the uncertainty in the final target spectrum.

2.1.2 Multi-Wavelength Data

The GOODS fields have been extensively surveyed and are rich in deep multi-wavelength data, including: Chandra 2 Ms X-ray observations (Alexander et al., 2003; Luo et al., 2008; Xue et al., 2011); 3.6, 4.5, 5.8, and 8.0 µm imaging from the Infrared Array Camera (IRAC) on Spitzer; IRS peak-up observations at 16 µm (Teplitz et al., 2011); and MIPS imaging at 24 and 70 µm (Magnelli et al., 2011).

Recently, GOODS-N and GOODS-S have been surveyed with the GOODS-Herschel Open Time Key Program (P.I. David Elbaz, Elbaz et al., 2011) using both the PACS (Poglitsch et al., 2010) and SPIRE (Griffin et al., 2010) instruments, providing deep photometry at five far-IR and submm wavelengths: 100, 160, 250, 350, and 500 µm.

For the Herschel imaging, flux densities and the associated uncertainties were obtained by point source fitting using 24 µm prior positions, allowing us to probe deeper limits...
in the *Herschel* images. In addition, the GOODS-*Herschel* catalog is only comprised of sources with a clean detection, based on the 24 µm prior position having no bright neighbors in a given passband (for further details, see Elbaz et al., 2011).

We combine this space-based imaging with ground-based imaging in the near-IR (*J* and *K* bands) from VLT/ISAAC (Retzlaff et al., 2010) and CFHT/WIRCAM (Wang et al., 2010; Lin et al., 2012). At the longest (sub)mm wavelengths we use available data from LABOCA on APEX (Weiβ et al., 2009) and the combined AzTEC+MAMBO mm map of GOODS-N (Penner et al., 2011).

### 2.1.3 Mid-IR Spectral Decomposition

We perform spectral decomposition of the mid-IR spectrum (5−15 µm rest frame) for each source in order to disentangle the AGN and SF components. We follow the technique outlined in detail in Pope et al. (2008a) which we summarize here. We fit the individual spectra with a model comprised of three components: (1)
star formation component is represented by either the local starburst composite of Brandl et al. (2006) or simply the mid-IR spectrum of the prototypical starburst M 82 (Förster Schreiber et al., 2003) – with the SNR, wavelength coverage, and spectral resolution of our high redshift spectra, both give equally good fits to the SF component of our galaxies; (2) the AGN component is determined by fitting a pure power-law with the slope and normalization as free parameters; (3) an extinction curve from the Draine (2003) dust models is applied to the AGN component. The extinction curve is not monotonic in wavelength and contains silicate absorption features, the most notable for our wavelength range being at 9.7 \( \mu m \). The local starburst composite and the M 82 template already contain some intrinsic extinction. We tested applying additional extinction to the SF component beyond that inherent in the templates and found this to be negligible for all sources (although we do include an extra extinction component in Chapter 4). We fit all three components simultaneously and integrate under the starburst spectrum and power-law continuum to determine the fraction of the mid-IR luminosity (\( \sim 5 - 15 \mu m \) depending on the redshift of the source) from SF and AGN activity, respectively. For each source, we quantify the strength of the AGN in terms of the percentage of the total mid-IR luminosity coming from the power-law continuum component. Based on this mid-IR spectral decomposition, we find that 38 (25%) out of our sample of 151 galaxies are dominated (\( \geq 50\% \)) in the mid-IR by an AGN. Figure 2.2 shows examples of the best fit models (red dashed line) for an SF-dominated galaxy and two AGN-dominated galaxies, with and without prominent 9.7 \( \mu m \) extinction. The extincted power law component is shown by the blue dashed line, and the PAH template is the green dashed line.

To more thoroughly compare the mid-IR spectral properties and far-IR SEDs within our sample, we divide our galaxies into four sub-samples based on the results of the mid-IR spectral decomposition. First, each galaxy is classified as either SF- or AGN-dominated, based on having \(< 50\% \) or \( > 50\% \) AGN contribution to the mid-IR
luminosity, respectively. We further divide the SF galaxies into two bins: $z \sim 1$ ($z < 1.5$); and $z \sim 2$ ($z > 1.5$). For AGN, the mid-IR spectral features have been predicted to reveal the shape of the torus surrounding the AGN. A clumpy torus produces a power-law spectrum, while silicate absorption indicates a thick obscuring torus. We therefore classify the AGN according to the shape of their mid-IR spectrum; those with measurable 9.7 $\mu$m silicate absorption (hereafter referred to as silicate AGN), and those without (hereafter referred to as featureless AGN), which we have classified by eye. We have a much smaller number of AGN sources, so separating further according to redshift would not produce a meaningful sample with which to determine the average properties. We are unable to classify four AGN sources as they lack spectral coverage in the relevant range (9–10 $\mu$m), so we are incapable of determining whether they exhibit silicate absorption. We refer to these as unclassifiable AGN in the relevant figures. Our four sub-samples are listed in Table 2.1, along with their median redshifts and 8, 24, and 100 $\mu$m flux densities.

While the majority of our sources that are classified as SF-dominated, based on the mid-IR spectra, have a negligible ($< 20\%$) contribution from an AGN, the AGN-dominated sources exhibit varying degrees of concurrent SF activity. Figure 2.3 shows the distribution of mid-IR AGN fraction for the silicate (top panel) and featureless AGN (bottom panel). The featureless AGN (lacking silicate absorption) have a very strong AGN continuum, accounting for 80–100% of the mid-IR emission, whereas the silicate AGN have a more uniform distribution of AGN fraction, with some silicate AGN also having weak PAH features. The broad range of AGN fraction for the silicate sources is partly a reflection of the difficulty in disentangling PAH features from the 9.7 $\mu$m silicate absorption feature in low SNR spectra.
Figure 2.3: Distribution of the strength of mid-IR AGN emission in our sample. Sources whose mid-IR spectrum is dominated by an AGN continuum are further divided according to whether they exhibit significant 9.7 $\mu$m silicate absorption. The majority of the sources completely dominated by AGN emission (> 95%) exhibit a featureless power-law spectrum (bottom panel), whereas sources with a silicate absorption feature are more uniformly distributed according to the strength of the AGN in the mid-IR (top panel).
2.1.4 Spectroscopic Redshifts

We determine redshifts for the majority of our sample by fitting the positions of the main PAH features (see Pope et al., 2008a). In the case of featureless spectra (only 9/151 sources), we adopt available optical spectroscopic redshifts with the exception of one source for which we only have a photometric redshift (Szokoly et al., 2004; Barger et al., 2008; Popesso et al., 2009). We compare our redshifts derived from the IRS spectrum with the optical spectroscopic redshifts using the parameter $\Delta z/(1 + z_{\text{IRS}})$. We find the mean value to be 0.008 with a standard deviation of 0.07. Therefore, we conclude that our IRS redshifts are good to $\sim 0.07$.

The redshift distribution of our sources is illustrated in Figure 2.4. The redshift distribution exhibits a bimodality with two peaks at redshifts of around 1 and 2. The bimodality of the redshift distribution is a result of the 24 $\mu$m selection (e.g., Desai et al., 2008). At $z \sim 2$, the 24 $\mu$m observed frame flux density corresponds to the 8 $\mu$m flux density in the source’s rest frame. Galaxies with intense star formation will have an enhanced 8 $\mu$m flux density due to prominent PAH complexes at 7.7 and 8.6 $\mu$m. Similarly at $z \sim 1$, observed frame wavelength 24 $\mu$m corresponds to a rest frame wavelength of 12 $\mu$m. The strong PAH emission features at 11.3 $\mu$m and 12.7 $\mu$m, present in SF galaxies, will boost the observed 24 $\mu$m flux density. Figure 2.4 shows that our sources at the highest redshifts are all dominated by an AGN in the mid-IR. While the featureless AGN are distributed roughly equally across our redshift range, there is a slight dearth of silicate AGN at $z \sim 1.5$ due to the 9.7 $\mu$m absorption feature falling into the 24 $\mu$m band.

In the sections that follow, we use the median redshift for each subsample (listed in Table 2.1) to compare general properties of the subsamples and investigate evolutionary connections between the populations. For our SF galaxies, Figure 2.4 illustrates that the median redshifts of 1.0 and 1.9, respectively, are accurate for each subsample. The median redshift for the silicate AGN is 1.9, and again, the distribution is peaked
Figure 2.4: Redshift distribution of GOODS-N and ECDFS sources. The distribution appears to be bimodal with peaks at $z \sim 1$ and $z \sim 2$ reflecting the 24$\mu$m selection criterion. At redshifts 1 and 2, the observed frame 24$\mu$m band corresponds to the rest-frame 12$\mu$m and 8$\mu$m band, respectively. In SF galaxies, those wavelengths are dominated by prominent PAH features if they lie at these particular redshifts, causing them to appear more luminous at 24$\mu$m. The sources have been separated according to four sub-samples based on the mechanism driving the mid-IR luminosity. Our three highest redshift sources are all AGN, though due to lack of coverage at 9.7$\mu$m, we are unable to classify them.

around this value. However, the featureless AGN have a fairly uniform redshift distribution with the mean and median redshifts both giving $z = 1.2$. It is important to keep in mind that as we did not separate the AGN based on redshift, we are not claiming that our subsamples are representative of all AGN at each of the median redshifts.

2.1.5 Stellar Masses

We use optical and near-IR photometry to estimate the galaxy stellar masses in our sample, and compute the median stellar mass for each sub-sample (see Table 2.3). The stellar masses for the current sample are part of a larger catalog of stellar masses, photometric redshifts, and multi-wavelength data for galaxies in the GOODS fields (Santini et al., 2015; Pannella et al., 2015). In the following, and for the sake of completeness, we will briefly describe the sources of the photometry used to calculate the stellar masses and the procedures used.
We have built a PSF-matched multi-wavelength catalog with 10 passbands from $U$ to 4.5 $\mu$m. The optical, near-IR, and IRAC data used to calculate the stellar masses in GOODS-N are presented in Capak et al. (2004); Wang et al. (2010); Lin et al. (2012), respectively. A $K_s$-band selected catalog has been built using SExtractor (Bertin & Arnouts, 1996) in dual image mode, closely following the procedure described in Pannella et al. (2009b) and Strazzullo et al. (2010). For the ECDFS sources we have used photometry from both the GOODS-MUSIC (Santini et al., 2009) and the GOODS-MUSYC (Cardamone et al., 2010) surveys to estimate stellar masses.

Stellar masses are estimated for both fields using the SED fitting code described in detail in Drory et al. (2004, 2009). We parametrize the possible star formation histories by a two-component model, consisting of a main, smooth component described by an exponentially declining star formation rate ($\psi(t) \propto \exp(t/\tau)$), linearly combined with a secondary burst of star formation. The main component time-scale $\tau$ varies in $[0.1, 20]$ Gyr, and its metallicity is fixed to solar. The age of the main component, $t$, is allowed to vary between 0.01 Gyr and the age of the Universe at each object’s redshift. The secondary burst of star formation, which cannot contain more than 10% of the galaxy’s total stellar mass, is modeled as a 100 Myr old constant star formation rate episode of solar metallicity. We adopt a Salpeter (1955) initial mass function for both components, with lower and upper mass cutoffs of 0.1 and 100 $M_\odot$, respectively. Adopting the Calzetti et al. (2000) extinction law, both the main component and the burst are allowed to exhibit a variable amount of attenuation by dust with $A_V \in [0, 1.5]$ and $[0, 2]$ for the main component and the burst, respectively. We confirmed our masses by also fitting without the secondary burst component and find consistent results.

A significant fraction ($\sim 66\%$) of our sources that are AGN-dominated in the mid-IR do not display a prominent stellar bump. For these objects, we do not expect the photometry to diverge from the best-fit results until after 1.5 $\mu$m, at which point the
stellar bump becomes diluted. Based on our fitting method, we find that this should produce a bad fit rather than a biased one. We test our fitting method for power-law sources on an individual basis by removing the IRAC photometry to ensure we were only fitting wavelengths bluer than the $1.6\mu m$ bump. The results are consistent with the results produced when the IRAC data is included. A recent study by Hainline et al. (2012) found that for IRAC power-law sources, the stellar mass can be a factor of 1.4 higher when an AGN component is not accounted for in the SED modeling. In this study, we use the stellar masses to calculate specific star formation rates to assess whether our sources lie on the main sequence (see Section 2.4.2.1). The possible bias of 1.4 introduced by not including an AGN component in the stellar fitting will not greatly affect the discussion in that section given the spread in the main sequence.

In Section 2.4, we compare with stellar masses presented in Elbaz et al. (2011). Our stellar masses were calculated using the stellar population synthesis models from Bruzual & Charlot (2003), while Elbaz et al. (2011) use templates from PEGASE.2 (Fioc & Rocca-Volmerange, 1999). As a result, our masses are a factor of $\sim 2$ lower (see also Bell et al., 2011).

## 2.2 Composite Spectral Energy Distributions

As described in detail above, we divide our full sample into the four sub-samples listed in Table 2.1. For each sub-sample, we create a composite SED from 0.3 to $600\mu m$ rest-frame by combining data from: ground-based near-IR; Spitzer IRAC, IRS, and MIPS (24$\mu m$, 70$\mu m$); Herschel PACS and SPIRE; and ground-based 870$\mu m$ and 1.15 mm.

For sources lacking a detection at the Herschel wavelengths, we extract a measurement of the flux density and associated uncertainty for each source directly from our images using the prior position at 24$\mu m$. This is not just an upper limit but rather an actual best estimate of the flux of the source even if it not formally detected. We
take measurements from the image to avoid biasing our SEDs high in the submm by including only detections. We do not take a measurement when a source looks too blended on the image; we have rejected 26 sources from our composite SEDs due to blending in the Herschel images.

Since spectroscopic redshifts are known for all sources in our sample, we begin by shifting all spectra and photometry to the rest frame. We then examine the full IR SED of each galaxy; sources which lack a sufficient amount of data in the far-IR/submm (< 3 measurements beyond a rest wavelength of 25 µm) are not used in creating the composite SEDs to avoid biasing our results. By requiring sources to have measurements (not necessarily detections) at longer wavelengths, we have only rejected a limited number of sources (26, or 17%) which are severely blended with other sources in the large SPIRE beams. Our rejected sources have the same redshift distribution as our full sub-samples, ensuring that we have not introduced a redshift bias.

When combining the spectra and photometry for the composite SEDs, we normalize the data for each source to the mid-IR spectrum over the wavelength range 6.4 to 7.5 µm (with the exception of the featureless AGN), chosen because it is free of prominent PAH features, and because the majority of our sources have spectral coverage in this range. Any sources with exceptionally noisy data over this range (such that we are unable to reliably decompose the AGN and SF components) or without continuous data from 6.4 – 7.5 µm are excluded from the composite SEDs. The featureless AGN have mid-IR spectra that are free of PAH and silicate features, so we choose to normalize over a longer wavelength range, 6.4 – 11.4 µm.

For clarity, we now state exactly how many sources are rejected from the creation of the composites in each subsample. In the $z \sim 1$ SF galaxies subsample, we begin with 69 sources; we reject 13 due to blending in the far-IR and 17 that lack coverage in the mid-IR normalization range; this leaves 39 sources. For the $z \sim 2$ SF galaxies, we
begin with 44 sources; we reject 7 sources due to far-IR blending, 5 sources that lack coverage in the mid-IR normalization range, and 2 sources with exceptionally noisy mid-IR spectra; this leaves 30 sources. For the silicate AGN, we begin with 22 sources; we reject 4 due to blending in the far-IR and 1 because it lacks spectral coverage in the mid-IR normalization range, leaving us with 17 sources. Finally, in the case of the featureless AGN, we initially have 12 sources, from which we reject two that are blended in the far-IR and one because it lacks coverage in the mid-IR normalization range; we therefore have 9 sources which we use to create the composite. The number of sources comprising each composite are listed in Table 2.1. The remaining 95 sources are representative of our full IRS sample: 82% have $S_{24} > 200 \mu$Jy, and 60% have $S_{24} > 300 \mu$Jy. For all four subsamples, the redshift distributions are the same for the full subsample and the limited subsample used to create the composite.

We determine the median $L_\nu$ for each source over this wavelength range. Within each sub-sample, we also determine the median $L_\nu$ for all sources, and we normalize the rest-frame data of each source to the median $L_\nu$ of that sub-sample in order to preserve the intrinsic average luminosity of each sub-sample.

In creating the composite SEDs, we treat the near/mid-IR data separately from the far-IR/submm data. This is because in the far-IR the individual photometric uncertainties dominate the noise, whereas in the near/mid-IR the scatter between different sources in each composite is a larger source of error. After normalization, we average the near-IR and mid-IR data by determining the median $L_\nu$ and wavelength in bin sizes $\geq 0.1$ $\mu$m (larger than the spectral resolution of the IRS spectra), chosen so that each bin is well-populated ($> 10$ data points). We bootstrap the sample to estimate the errors on our composite in the mid-IR and near-IR, since in this regime the uncertainty in the composites is dominated by the scatter between different sources. For each sub-sample, we randomly draw sources with replacement and recalculate the normalized median SED 10,000 times. Because we normalize in
the range $6.4 - 7.5 \mu m$, the resulting SEDs exhibit little scatter in and around these wavelengths.

We fit all of the normalized far-IR ($> 18 \mu m$) data in each sub-sample with a two temperature component modified blackbody function of the form

$$M_\nu = a_1 \times \nu^\beta \times B_\nu(T_{\text{warm}}) + a_2 \times \nu^\beta \times B_\nu(T_{\text{cold}}) \quad (2.1)$$

where $B_\nu$ is the Planck function. We keep the emissivity fixed at $\beta = 1.5$. Since the photometric uncertainty is large in the far-IR, we use a Monte Carlo simulation to determine the parameters and errors of the blackbody model. We randomly sample each data point within its error and refit the model 10,000 times. We fit for the normalization factors $a_1$ and $a_2$ together with $T_{\text{warm}}$ and $T_{\text{cold}}$, the temperatures of the warm and cold dust components, simultaneously using a $\chi^2$ minimization technique. The final parameters for each composite are the mean values determined through the Monte Carlo simulations, and the errors on each parameter are the standard deviation. We then propagate the standard deviation on each parameter, along with the correlations between parameters, which we find to be much less than the standard deviations, to obtain the error bars on the far-IR SED model. The degeneracies between the parameters are illustrated in Appendix A. We do find a degree of degeneracy between the warm and cold dust temperatures, but the temperature ranges spanned by each component do not overlap, giving us confidence that we are measuring two distinct temperatures.

We settled on a two temperature model after finding very poor fits (high reduced $\chi^2$ values, a factor of $\sim 6$ higher) to a single component modified blackbody. The introduction of a second dust component produces a significantly better fit, with lower $\chi^2$ values. Since the individual photometric uncertainties dominate the noise in the far-IR composites, each data point is weighted by its associated variance in our fits. In the case of the SF SEDs, both sets of data lack photometry from $\sim 18 - 30 \mu m$. The
Figure 2.5: Illustration of the creation of our four empirical composite spectral energy distributions. The corresponding subsamples are detailed in Table 2.1. In each panel we show photometric (black points) and spectroscopic data (black lines) for the sub-sample in the rest frame with our composite SED overplotted in red and the uncertainty of the composite shown as the shaded region. The near-IR and mid-IR data were averaged to obtain the composite while the far-IR data were fit with a two temperature modified blackbody model. The blue and green dashed lines illustrate the modified blackbody curves of the individual warm and cold dust components, respectively. The open triangles in the upper panels are the stacked (sub)mm detections at observed frame 870 $\mu$m and 1.15 mm. In the absence of stacked detections, we plot the 3$\sigma$ upper limit. In all cases, the (sub)mm detections and upper limits are consistent with our composites.
warm modified blackbody overlaps with the mid-IR stacking in the \( z \sim 1 \) SF SED, so we use this modified blackbody to fill in the gap in the SED we were unable to fit. For the \( z \sim 2 \) SF SEDs, the warm modified blackbody does not overlap with the stacked mid-IR spectrum, so we linearly interpolate between the stacked photometry and fitted far-IR photometry to fill in the area with no photometry. Both of these regions are indicated with the dashed lines in Figure 2.5. We verify the far-IR fits by calculating the medians in differential bin sizes for the far-IR data using the same techniques described for the near-IR data, and in all cases, our model fits match the binned medians. Our composite SEDs for each of the four sub-samples are shown in Figure 2.5.

We use longer ground-based (sub)mm measurements to verify the accuracy of our composite SEDs. Most of our sources are not individually detected in the LABOCA and AzTEC+MAMBO maps, and therefore we stack all sources in each sub-sample to obtain an average flux density at 870 \( \mu \)m and 1.15 mm, respectively. We follow the (sub)mm stacking method outlined in Pope et al. (2008b). The stacking of the SF sub-samples results in several > 4\( \sigma \) detections which we plot on the composite SEDs in Figure 2.5 as the triangles. When the stacking results in a non-detection, we plot a 3\( \sigma \) upper limit. The (sub)mm detections lie right on the composite SEDs for the two SF sub-samples, confirming our modified blackbody model fits. For the AGN composites, the upper limits from stacking are also consistent with our composite SEDs.

In Section 2.3 we discuss the key features of our new high redshift SEDs. Given that we report the average luminosity, redshift, and stellar mass of the sources that go into these templates, they may be useful for fitting other high redshift sources, though it is important to bear in mind that we created the composites from sources
that are bright in the mid-IR \((S_{24} > 200 \mu Jy)\). We make these new empirical high redshift SED templates publicly available\(^2\).

### 2.3 Features of Composite SEDs

#### 2.3.1 Mid-IR Spectral Features

We perform mid-IR spectral decomposition on our composites as we did for the individual galaxies (see Section 2.1.3). Since the majority of the sources comprising both composite SF SEDs are completely dominated by star formation, we naturally find that our SF composites both have negligible (< 10%) AGN contribution in the mid-IR. The featureless AGN composite SED is 100% dominated in the mid-IR by an AGN power-law component. The silicate AGN SED is arguably the most interesting, since it contains both weak PAH features and a strong continuum component. Upon decomposition, we find the silicate AGN composite to have an 84% AGN contribution in the mid-IR. Both the SF SEDs and the featureless AGN SED have negligible silicate absorption at 9.7 \(\mu m\), while \(\tau_{9.7} = 0.4\) for the silicate AGN composite SED. The silicate AGN SED has a power-law slope of \(\alpha = 1.5\) from 4 – 15\(\mu m\), and the featureless AGN SED has a power-law slope of \(\alpha = 1.6\) in the same wavelength range. Both numbers are consistent with what is derived from local AGN in Mullaney et al. (2011).

#### 2.3.2 Dust Temperature and Infrared Luminosity

Our full composite SEDs are shown together in Figure 2.6. All SED composites peak at approximately the same wavelength in the far-IR \((\sim 100 \mu m)\) which implies that each sub-sample has cold dust at approximately the same temperature. However, the full SEDs clearly show a difference in the relative amounts of warmer dust, which we quantify by fitting a two temperature modified blackbody model (see Table 2.2 for the dust temperatures for each sub-sample). A two temperature model can be

\(^2\)http://www.astro.umass.edu/~pope/Kirkpatrick2012/
Figure 2.6: Comparison of far- and mid-IR emission of composite SEDs created from the four sub-samples of galaxies.  

*Top panel –* No additional normalization has been applied; the SEDs represent the average intrinsic luminosities of sources in each sub-sample. The shaded regions in the mid-IR and near-IR correspond to the 1σ spread of sources around the median luminosities. In the far-IR, the shaded regions are computed by propagating the errors on each parameter present in the blackbody fitting routine. The $z \sim 2$ SF SED is the most luminous at $\lambda > 100 \mu m$, while the featureless AGN SED is the weakest at the longest wavelengths. The AGN SEDs are the most luminous at $20 \mu m$ where the warm dust component dominates the spectrum.  

*Middle panel –* Composite SEDs have been normalized at 100 $\mu m$, allowing for more direct comparison of the near and mid-IR. No variation of PAH features is seen between SF composite SEDs. The featureless AGN SED has the highest mid-IR to far-IR ratio.  

*Bottom panel –* Composite SEDs have been normalized at 7 $\mu m$. The weak PAH features of the silicate AGN composite are visible in direct comparison to the SF SEDs.
physically understood as follows: the cold dust ($\gtrsim 100 \mu$m) is due to the diffuse interstellar medium, heated by the underlying stellar population, whereas the warm dust originates in SF regions and traces the younger stellar population (e.g., Bendo et al., 2012). In the case of an AGN, as the AGN becomes luminous the dust surrounding it heats up and can radiate in the mid-IR and far-IR. Therefore, we might expect to see warmer dust in our AGN SEDs than in our SF SEDs. Naturally, a multi-temperature model is even more ideal, as the AGN is not the only heating source for the dust. In an AGN still actively forming stars, there should a be a third dust temperature that arises from the SF regions. Unfortunately, even for our large amount of photometric data in the far-IR, fitting more than two dust temperatures becomes degenerate and produces poor $\chi^2$ values. Therefore, we use two temperatures with the assumption that these represent the dominant sources of dust radiation, but there are likely more sources of heating that we are unable to separately quantify.

For the AGN composites, there is a degree of uncertainty as to where the power-law spectrum ends and the warm dust component begins. Due to limited spectroscopic data, we are only able to stack spectra below $\sim 18 \mu$m, and we fit our dust temperatures using only far-IR data (above $18 \mu$m). Recent work has suggested that the power-law portion of the AGN spectrum continues to $20 \mu$m, flattens, and then falls off after $40 \mu$m (Mullaney et al., 2011). In this case, assigning a single temperature to this portion of the spectrum is misleading, since it is composed of many dust temperatures. However, our primary motivation is to compare our AGN composite SEDs directly with our SF SEDs, so we choose to fit a single blackbody to the warm dust emission around $\sim 20 - 60 \mu$m. Since the AGN is also radiating into the mid-IR power-law portion of the spectrum, the IR luminosity we derive from the warm dust component only will be a lower limit on the AGN emission.

There is a known degeneracy between the dust emissivity, $\beta$, and temperature, such that if we fix $\beta$ to a higher value, it will produce lower temperatures. We chose
to fix $\beta$ rather than fit it along with the temperatures, but it is important to keep the degeneracy of the two parameters in mind when interpreting the temperatures. There is evidence that $\beta$ is universal on galaxy-wide scales (Dunne & Eales, 2001), and as we fix it to the same value for every sub-sample, we do not expect that there is any bias created between the sub-samples in this study.

From our fitting we find that the two AGN composites have cold dust temperatures of $\sim 33$ K, while the SF galaxies are only slightly colder at $\sim 27$ K. However, the AGN possess a significantly hotter warm dust component ($\sim 99$ K) in comparison to the warm dust component for the SF galaxies ($\sim 57$ K). This makes sense if the warm dust emission is predominantly heated by the AGN as opposed to star formation in dense HII regions.

To quantify the relative contributions of the hot and cold dust components, we calculate $L_{\text{IR}}$ for each component separately by integrating over each modified blackbody model (see Table 2.3). We compare $L_{\text{IR}}^{\text{warm}}$ and $L_{\text{IR}}^{\text{cold}}$ to the total IR luminosity (integrated over 8 to 1000 $\mu$m), $L_{\text{IR}}$, to determine the fraction of $L_{\text{IR}}$ attributed to each dust component. We then calculate a luminosity-weighted average temperature by multiplying each luminosity fraction by the respective temperature and combining to obtain an effective temperature, $T_{\text{eff}}$ (Table 2.2). $T_{\text{eff}}$ for the AGN SEDs is more than 20 K hotter than $T_{\text{eff}}$ for the SF galaxies, demonstrating the bolometric significance of the warm dust component in AGN-dominated sources. The two SF composites have almost the same $T_{\text{eff}}$, indicating little evolution in $T_{\text{dust}}$ with redshift in SF galaxies.

The $L_{\text{IR}}$ values computed by integrating each composite SED from 8 to 1000 $\mu$m are listed in Table 2.3; differences between the sub-samples are largely due to our flux-limited sample. $L_{\text{IR}}$ for the composite SED created from $z \sim 2$ SF galaxies is five times greater than $L_{\text{IR}}$ for the $z \sim 1$ SF composite; these luminosities qualify the $z \sim 1$ and $z \sim 2$ SF SEDs to be LIRGs and ULIRGs, respectively. The silicate
Table 2.2. Dust temperatures derived for each sub-sample.

<table>
<thead>
<tr>
<th>Sub-sample</th>
<th>Effective Temperature(^a)</th>
<th>(T) (warm dust)(^b)</th>
<th>(T) (cold dust)(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(z \sim 1) SF galaxies</td>
<td>37 ± 3 K</td>
<td>55 ± 6 K</td>
<td>25 ± 2 K</td>
</tr>
<tr>
<td>(z \sim 2) SF galaxies</td>
<td>40 ± 3 K</td>
<td>59 ± 5 K</td>
<td>28 ± 2 K</td>
</tr>
<tr>
<td>Silicate AGN</td>
<td>58 ± 2 K</td>
<td>98 ± 2 K</td>
<td>35 ± 3 K</td>
</tr>
<tr>
<td>Featureless AGN</td>
<td>65 ± 2 K</td>
<td>100 ± 1 K</td>
<td>33 ± 1 K</td>
</tr>
</tbody>
</table>

Note. — See Table 2.3 for IR luminosities.

\(^a\)Calculated from a luminosity-weighted average of the warm and cold dust components. See text for details.

\(^b\)Temperatures are the mean values determined from Monte Carlo simulations (see Section 2.2), with the errors being the respective standard deviations.

AGN possess a notably larger \(L_{\text{IR}}\) \((1.7 \times 10^{12} L_\odot)\) than the featureless AGN \((L_{\text{IR}} = 8 \times 10^{11} L_\odot)\), though this is likely due to the different redshift distributions of the two sub-samples and not any intrinsic evolution of \(L_{\text{IR}}\). The luminosities of the individual dust components (listed in Table 2.3) quantify the relative importance of each dust component in the different SEDs. For the featureless AGN, the warm dust component is more luminous than the cold dust component by a factor of \(> 2\). Though the warm dust does not dominate the far-IR SED of any other sub-sample, it does contribute at a level of \(\sim 50\%\) of the total IR luminosity.

This is an important result, since it demonstrates that single temperature blackbody models or templates derived using only longer wavelength SPIRE data will miss the importance of this warm dust component. For example, Smith et al. (2012) derive composite SEDs for \(z < 0.5\) galaxies primarily using SPIRE data, which we can compare with our composite SEDs. The median SED of galaxies with \(L_{\text{dust}} > 10^{11} L_\odot\) from Smith et al. (2012) is consistent with our SF composite SEDs in the mid-IR and beyond the peak in the submm, but it is a factor of \(\sim 2\) lower than our SF composites.
in the wavelength range 20 – 60 µm, where the warm dust dominates. The discrepancy arises from the fact that Smith et al. (2012) do not possess PACS data for the majority of their sources and so they may miss a significant warm dust component. This comparison underscores the importance of full photometric coverage when modeling far-IR SEDs. The optimal strategy is to combine deep PACS and SPIRE data to obtain a full census of the dust emission.

If, instead of a two temperature modified blackbody, we fit our full suite of far-IR data above ∼ 20 µm with a one temperature modified blackbody, we get a poor χ² fit (reduced χ² a factor of ∼ 6 higher than the reduced χ² values for the 2 temperature fits, due to the fact that data > 70 µm is not fit well), and we calculate an $L_{\text{IR}}$ that is ∼ 30% lower for our SF composites and silicate AGN composite. For the featureless AGN composite, using a one temperature modified blackbody lowers the $L_{\text{IR}}$ by ∼ 20%. We also derive temperatures that are ∼ 20 K hotter than the cold dust temperatures (see Table 2.2) for all four sub-samples, with the temperatures of the SF composites comparable to that of the AGN composites. This underscores the importance of the two temperature approach, since data points in the range 24 – 100 µm can bias any one-temperature fit to a warmer dust temperature and lower $L_{\text{IR}}$.

On the other hand, when photometry spanning the range 24 – 100 µm are missing, the dust emission will likely be biased to colder temperatures and lower luminosities. For our SF composites, only using the cold dust for calculations lowers both the $L_{\text{IR}}$ and star formation rates by a factor of ∼ 2. The biggest discrepancy arises from the featureless AGN, where the warm dust is more important than for the other SEDs. There, the warm dust accounts for 60% of the total IR luminosity. When dealing with individual galaxies, often there are not enough data points to unambiguously fit both the warm and cold dust components. As not accounting for any warm dust may
significantly bias results, it is perhaps best to use templates which account for both important dust components as observed in high redshift galaxies.

2.3.3 Overall SED Shape

In the top panel of Figure 2.6, which compares the intrinsic luminosities of the sources going into each composite, the AGN SEDs have more emission than the SF SEDs in the range 15 to 30 µm. At $z \sim 2$, the MIPS 70 µm passband covers this wavelength range. In fact, for our high redshift sources ($z > 1.5$), 64% of those detected at 70 µm are AGN dominated. For our lower redshift sources ($z < 1.5$), only 19% of 70 µm-detected sources are dominated by an AGN in the mid-IR. At the peak of the SED, the most luminous sources are the $z \sim 2$ SF galaxies and silicate AGN, reflecting their higher total IR luminosities listed Table 2.3.

We normalize the composite SEDs to 100 and 7 µm in the middle and bottom panels of Figure 2.6, respectively, to allow a more direct comparison of the mid-IR spectral features. The mid-IR slopes of the AGN SEDs are remarkably similar, despite the absence/presence of features, but the featureless AGN have a much larger mid-IR to far-IR ratio. In fact, the featureless AGN SED effectively flattens out at $\lambda > 20$ µm. Both AGN SEDs lack a visible stellar bump at 1.6 µm, indicating that the rest-frame near-IR emission is also dominated by the AGN. The SF and silicate AGN SEDs all exhibit PAH features, though they are much weaker for the silicate AGN SED.

In the middle and bottom panels of Figure 2.6, we can directly compare our two SF composite SEDs to look for any evolution in SED shape with redshift and/or $L_{\text{IR}}$. The PAH features of the two SF SEDs are nearly identical in strength and shape. There appears to be no evolution of PAH features between LIRGs at $z \sim 1$ and ULIRGs at $z \sim 2$. The far-IR part of the SF SEDs are also remarkably similar in shape, as quantified in the average dust temperatures (Table 2.2). The stellar bump
at 1.6 µm is more prominent relative to the IR emission for the $z \sim 1$ SF SED than for the $z \sim 2$ SF SED, reflecting the higher average specific star formation rate of galaxies at $z \sim 2$ compared to $z \sim 1$, which we discuss in the next section.

2.3.4 Star Formation Rates

We calculate the star formation rate (SFR) for each composite SED according to the formula

$$\left( \frac{\text{SFR}}{M_\odot \, \text{yr}^{-1}} \right) = 1.72 \times 10^{-10} \left( \frac{L_{\text{IR}}^{\text{SF}}}{L_\odot} \right)$$

(2.2)

which assumes a Salpeter IMF (Salpeter, 1955) and continuous star formation (Kenneicutt, 1998). Note that we only want to use the portion of $L_{\text{IR}}$ that is heated by SF activity when using this equation, otherwise we will over-predict the SFR. For the SF composite SEDs, we assume that both the cold and the warm ($\sim 60$ K) dust components are heated by star formation, since there is no evidence of AGN activity in the composites based on the mid-IR spectrum.

We calculate the fraction of the AGN SED that can be accounted for by the SF SED template when both are normalized at 200 µm, beyond which all the dust emission is presumed to be due to SF. We calculate the $L_{\text{IR}}$ of the normalized SEDs and take the ratio of $L_{\text{IR}}$ for the $z \sim 1$ SF SED and featureless AGN SED, and for the $z \sim 2$ SF SED and silicate AGN SED. We use the SF composite SED that most closely matches the total $L_{\text{IR}}$ of the respective AGN composite when determining the $L_{\text{IR}}$ ratios. We find that SF activity accounts for 56% of the $L_{\text{IR}}$ for the silicate AGN SED and 21% of the featureless AGN SED. We therefore scale the $L_{\text{IR}}$ by 56% and 21% for the silicate and featureless AGN, respectively, when calculating the SFR.

Unsurprisingly, our $z \sim 2$ SF composite SED has the highest SFR: $344 M_\odot \, \text{yr}^{-1}$. The $z \sim 1$ SF composite SED has an SFR of $73 M_\odot \, \text{yr}^{-1}$. The silicate AGN SED has an average SFR of $159 M_\odot \, \text{yr}^{-1}$, whereas the featureless AGN SED has a much lower
average SFR of 28 M⊙ yr⁻¹. If we instead assume that all of the $L_{\text{IR}}$ in the AGN composites is heated by SF, we would over-predict the SFR by a factor of $\sim 2 - 4$.

As a consistency check, for the two AGN SEDs, we conservatively attribute the warm dust at 100 K to the AGN and the cold dust to the SF activity and recalculate the SFR using $L_{\text{IR}}^{\text{cold}}$ instead of the scaled $L_{\text{IR}}$; naturally, this conservative estimate should provide a lower limit on the actual SFR, since there is likely some portion of warmer dust emission that arises from SF. Using just the cold dust component, we find the same SFR of 28 M⊙ yr⁻¹ for the featureless AGN, and an SFR of 141 M⊙ yr⁻¹ for the silicate AGN, which are very similar to the SFRs we calculated above, so most of the SF activity in each AGN composite is accounted for by the cold dust component.

There is a tight correlation between stellar mass and SFR which evolves with redshift (Daddi et al., 2007; Dunne et al., 2009; Pannella et al., 2009a; Elbaz et al., 2011; Lin et al., 2012), and as such, an interesting comparison is given by the specific star formation rates (sSFR), defined as: $\text{sSFR} = \frac{\text{SFR}}{M_*}$. We list the median stellar mass (see Section 2.1.5) and sSFR of each composite SED in Table 2.3. For the SF composites, which have comparable median stellar masses, we see an increase in the sSFR from $z \sim 1$ to $z \sim 2$, consistent with what is observed for all SF galaxies (e.g., Elbaz et al., 2011). The silicate AGN and $z \sim 2$ SF SEDs have comparable stellar masses and redshifts, but the sSFR for the $z \sim 2$ SF SED is more than a factor of 2 higher. Similarly, the featureless AGN composite has a higher stellar mass and $\sim 4$ times lower sSFR than the $z \sim 1$ SF composite. As we will discuss in Section 2.4, these values are consistent with a scenario in which the AGN sources are in a later phase in the evolution of IR luminous galaxies, after the active period of star formation has been quenched.
Table 2.3. Luminosities and other parameters derived for each sub-sample.

<table>
<thead>
<tr>
<th>Subsample</th>
<th>$L_{\text{IR}}$</th>
<th>$L_{\text{IR}}$</th>
<th>$L_{\text{warm}}^a$</th>
<th>$L_{\text{cold}}^a$</th>
<th>$L_{\text{IR}}^\text{cold}$</th>
<th>$L_8^b$</th>
<th>$L_{\text{IR}}$</th>
<th>$M_*$</th>
<th>SFR</th>
<th>sSFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z \sim 1$ SF</td>
<td>0.42±0.17</td>
<td>2.0±0.5</td>
<td>2.0±0.6</td>
<td>0.46</td>
<td>0.65</td>
<td>6.57</td>
<td>0.74</td>
<td>73±29</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>$z \sim 2$ SF</td>
<td>2.00±0.71</td>
<td>8.7±1.9</td>
<td>10.2±2.1</td>
<td>0.51</td>
<td>2.53</td>
<td>7.92</td>
<td>1.17</td>
<td>344±122</td>
<td>2.94</td>
<td></td>
</tr>
<tr>
<td>Sil. AGN</td>
<td>1.65±0.54</td>
<td>7.0±0.5</td>
<td>8.5±2.4</td>
<td>0.50</td>
<td>2.60</td>
<td>6.35</td>
<td>1.15</td>
<td>159±52$^c$</td>
<td>1.38</td>
<td></td>
</tr>
<tr>
<td>Feat. AGN</td>
<td>0.76±0.07</td>
<td>4.4±0.2</td>
<td>1.6±0.3</td>
<td>0.21</td>
<td>1.94</td>
<td>3.94</td>
<td>1.23</td>
<td>28±3$^c$</td>
<td>0.23</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Determined by integrating under the modified blackbody curve for the warm and cold components separately.

$^b$In units of $10^{11}L_\odot$. Measured by integrating under the IRAC 8 $\mu$m filter for each composite SED.

$^c$Calculated using a scaled $L_{\text{IR}}^\text{SF}$ for the AGN SEDs (shown in italics to distinguish).

2.3.5 Comparison of New High $z$ SEDs to Local Templates

Prior to the era of $Herschel$, far-IR (40 – 200 $\mu$m) data sampling the peak of the SED were rare, particularly for high redshift sources. Estimates of bolometric luminosity were performed by fitting locally derived templates to mid-IR and/or submm data and extrapolating to the far-IR. With our wealth of far-IR data from $Herschel$, we are in a position to compare the commonly applied locally derived templates with our new empirical high-redshift SEDs.

In Figure 2.7 we compare our SF composite SEDs to the SEDs of local galaxies often used as standard templates in the literature. These local templates come from combining all known data on known sources including available IRAS (12, 25, 60, 100 $\mu$m), $Spitzer$ (24, 70, 160 $\mu$m), and SCUBA (850 $\mu$m) photometry as well as mid-IR spectroscopy (e.g., Förster Schreiber et al., 2003; Armus et al., 2007). The local templates lack photometry from 160 – 850 $\mu$m, making it difficult to constrain the cold dust emission.
In the top panel of Figure 2.7, we compare our $z \sim 1$ composite SF SED to the SED of local starburst M 82. Though M 82 has a lower $L_{\text{IR}}$ ($\sim 4 \times 10^{10} L_\odot$) than our $z \sim 1$ SED, it is worthwhile to compare the two SEDs, since our mid-IR classification is based on the M 82 template. We normalize M 82 to our composite SED at 7.0 $\mu$m. Our $z \sim 1$ composite SED almost exactly reproduces the shape and strength of the PAH features of M 82, affirming the reliability of comparing the mid-IR PAH features of this local galaxy with the mid-IR spectra of high redshift sources. However, M 82 has less far-IR emission, and it is weighted towards warmer dust than our $z \sim 1$ SF composite, indicating that any mid-IR similarities do not carry over into the far-IR.

The bottom panel of Figure 2.7 shows our $z \sim 2$ composite SF SED compared to two local prototypical (U)LIRGs, Arp 220 ($L_{\text{IR}} = 1.4 \times 10^{12} L_\odot$) and NGC 6240 ($L_{\text{IR}} = 6.3 \times 10^{11} L_\odot$), both normalized to our composite SED at 7.0 $\mu$m. While the mid-IR spectrum of NGC 6240 is very close to that of our high redshift composite, Arp 220 shows substantially more silicate absorption. The prominent absorption feature at 9.7 $\mu$m is possibly attributable to AGN activity in Arp 220 (e.g., Armus et al., 2007), while our $z \sim 2$ composite SF SED has a negligible AGN contribution. Neither of these local (U)LIRGs match our $z \sim 2$ SED in the near or far-IR; specifically, Arp 220 and NGC 6240 peak at shorter wavelengths in the far-IR, indicating much more warm dust emission. It is possible the difference in warm dust emission arises from the fact that local ULIRGs are merger-induced, triggering AGN activity, while our sample of high redshift ULIRGS may not be (see Section 2.4.2.1). These local ULIRG templates differ significantly from our $z \sim 2$ ULIRG composite, and in fact, there are not even any individual sources that go into the composite that fit the local ULIRGs from 20 – 80 $\mu$m (see the gray points showing all galaxies that go into the composite). This illustrates the difficulty of applying such local templates to high redshift systems.

We compare our silicate AGN composite SED with the SEDs of local AGN Mrk 231 ($L_{\text{IR}} = 3.2 \times 10^{12} L_\odot$) and NGC 1068 ($L_{\text{IR}} = 1.6 \times 10^{11} L_\odot$) in Figure 2.8. Both Mrk 231
Figure 2.7: Comparison of our sources and composite SEDs with local templates. We also overplot the photometric (gray points) and spectroscopic (gray lines) data for a given SF sample. Top – $z \sim 1$ SF composite SED compared to the SED of M 82 (normalized at 7.0 $\mu$m). M 82 is in excellent agreement with our $z \sim 1$ composite SED in the mid-IR, but is weighted towards warmer dust temperatures and underpredicts the luminosity in the far-IR/submm. Bottom – $z \sim 2$ SF composite SED compared to the SEDs of Arp 220 and NGC 6240 (both normalized at 7.0 $\mu$m). The local and high $z$ ULIRG SEDs show fairly good agreement in the range 5 – 11 $\mu$m, but both local SEDs are too luminous in the far-IR, particularly at the shortest wavelengths, indicating more warm dust. In addition, Arp 220 has stronger silicate absorption than our composite SED.
Figure 2.8: Comparison of our silicate AGN composite SED with the local AGN Mrk 231 and NGC 1068. The templates are overplotted on the photometric (gray points) and spectroscopic (gray lines) data for the silicate AGN sample. Both Mrk 231 and NGC 1068 have been normalized to the silicate AGN SED at 7.0 µm. Mrk 231 peaks at shorter wavelengths in the far-IR than our template, while NGC 1068 falls off sharply below 3 µm.

and NGC 1068 have been normalized to our composite at 7.0 µm. Our composite and Mrk 231 appear to have a similar 9.7 µm silicate absorption feature and a similar slope in the mid-IR, but Mrk 231 peaks at shorter far-IR wavelengths than our composite SED, indicating more warm dust. NGC 1068 looks fairly similar in shape in the far-IR to our composite, though it is intrinsically less luminous. Furthermore, NGC 1068, a local Compton-thick AGN, has less silicate absorption in the mid-IR and falls off sharply below 3 µm, differing from both our high redshift SED and Mrk 231.

With the emerging abundance of *Herschel* photometry, recent studies have begun to demonstrate the unsuitability of locally-derived templates in fitting high redshift galaxies using longer wavelength PACS and SPIRE data (Dannerbauer et al., 2010; Elbaz et al., 2010, 2011; Nordon et al., 2010). These previous results fit templates from Chary & Elbaz (2001, CE01) to individual galaxies with far-IR photometric data points, which each have significant uncertainty. In this study, we are able to compare the locally-derived CE01 templates to templates derived from high-redshift data for a statistical sample of galaxies. We plot the CE01 templates with the $L_{\text{IR}}$ corresponding to each of our SF composite SEDs in Figure 2.9, with no renormalization. For the
$z \sim 1$ SF composite (top panel), the CE01 template reproduces fairly well the near and mid-IR portions of the composite SED. However, it peaks at slightly shorter far-IR wavelengths and has less cold dust emitting at (sub)mm wavelengths. For the $z \sim 2$ SF composite (bottom panel), the CE01 template fails to reproduce any portion of our $z \sim 2$ composite SED. The mid-IR spectrum of the CE01 template has a strong continuum component and weaker PAH features than we observe in the average $z \sim 2$ ULIRG of similar luminosity. Again the far-IR emission peaks at shorter wavelengths, corresponding to warmer dust emission, than our $z \sim 2$ SF SED. The stacked (sub)mm points (plotted as the triangles) are also inconsistent with the CE01 templates, confirming that our high redshift sample has more cold dust emission than the CE01 templates.

Overall, we find that most local templates fail to accurately reproduce both the dust temperatures and mid-IR spectral features of our high redshift composite SEDs. It is possible that things will be more consistent once Herschel data are incorporated to create more complete SEDs of local galaxies and better constrain the cold dust emission. Otherwise, this is evidence that the SEDs of IR luminous galaxies evolve with redshift. The disparity of the locally derived templates from our high redshift composites illustrates the need for caution when applying local templates to high redshift galaxies.

2.4 Discussion

In Sections 2.2 and 2.3, we presented our high redshift composite SEDs and outlined key differences and similarities between the SF- and AGN-dominated IR luminous galaxies. We also compared our new high redshift SED templates to those of local galaxies of similar luminosities and found them to be significantly different. We now discuss what these results might tell us about the evolution of IR luminous galaxies.
Figure 2.9: Comparison of our $z \sim 1$ and $z \sim 2$ SF composite SEDs with the locally-derived CE01 templates of the same luminosity. The templates are overplotted on the photometric (gray points) and spectroscopic (gray lines) data for a given SF sample. For the $z \sim 1$ SF galaxies (top panel), the CE01 template traces the composite SED in the near and mid-IR but differs in the far-IR. For the $z \sim 2$ SF galaxies (bottom panel), the CE01 template fails to reproduce any portion of the composite SED.
2.4.1 Quantifying the AGN Component

We begin by exploring the X-ray and mid-IR properties of the AGN comprising our composite SEDs. Though an in-depth X-ray analysis of our AGN sample is beyond the scope of this paper, we briefly discuss two important X-ray parameters commonly used to interpret AGN: X-ray detection fraction and X-ray luminosity. Our entire sample of AGN sources (38) have a 58% X-ray detection fraction. When we classify our sources into silicate and featureless AGN, only 9/22 (41%) silicate AGN are individually detected in the deep Chandra X-ray imaging, whereas 11/12 (92%) featureless AGN are detected in the X-ray. The four unclassifiable AGN have a detection fraction of 50%.

We calculate the intrinsic X-ray luminosity, $L_{2-10\text{ keV}}$, using Equation 4 of Mullaney et al. (2011).

$$\log \left( \frac{L_{\text{IR}}^{\text{AGN}}}{10^{43} \text{ erg s}^{-1}} \right) = 0.53 + 1.11 \log \left( \frac{L_{2-10\text{ keV}}}{10^{43} \text{ erg s}^{-1}} \right)$$  \hspace{1cm} (2.3)

To disentangle the luminosity due to the AGN from the host galaxy, we follow the same method used to calculated the SFR (see Section 2.3.4). We normalize all composite SEDs to 200 $\mu$m and calculate the ratio of the normalized $L_{\text{IR}}$ for the $z \sim 1$ SF SED and featureless AGN SED, and for the $z \sim 2$ SF SED and silicate AGN SED. We find that AGN activity accounts for 44% of the $L_{\text{IR}}$ for the silicate AGN SED and 79% of the featureless AGN SED, and accordingly we scale each respective $L_{\text{IR}}$ by these amounts when calculating $L_{2-10\text{ keV}}$. This gives an intrinsic X-ray luminosity of $L_{2-10\text{ keV}} = 5.30 \times 10^{44} \text{ erg s}^{-1}$ for the silicate AGN and $L_{2-10\text{ keV}} = 4.46 \times 10^{44} \text{ erg s}^{-1}$ for the featureless AGN.

We look for evolution between our high redshift AGN and local AGN by comparing to the sample of moderate luminosity ($L_{2-10\text{ keV}} \sim 10^{42} - 10^{44} \text{ erg s}^{-1}$) AGN in Mullaney et al. (2011). By cross-matching the Swift-BAT sample (Tueller et al., 2008) of X-ray AGN with the Spitzer-IRS archive, Mullaney et al. (2011) identified
a sample of nearby (i.e., $z < 0.1$) galaxies whose mid-infrared spectra are strongly AGN-dominated. By carefully subtracting any contribution from the host galaxy at far-IR wavelengths, they were able to empirically define the infrared emission due solely to the AGN in these local galaxies and derive an average, intrinsic AGN SED at $6 - 100 \mu m$. In Figure 2.10, we plot the mean AGN SED and the high and low luminosity AGN SEDs from the local population along with our high redshift AGN composite SEDs. The high and low luminosity AGN SEDs were derived by averaging the SEDs of $\log(L_{2-10\text{keV}}) > 42.9$ and $\log(L_{2-10\text{keV}}) < 42.9$ AGN, respectively. The low luminosity AGN template and the mean AGN template turn over around $40 - 50 \mu m$ whereas the high luminosity AGN template turns over at $32.0 \mu m$. In both of our high $z$ AGN composites, the warm dust component, which we attribute to the AGN, turns over at approximately the same wavelength ($29 \mu m$) as the high luminosity local AGN template.

The mid-IR spectral decomposition of our AGN composite SEDs resulted in an 84% contribution of the AGN to the mid-IR luminosity for the silicate AGN SED and a 100% contribution for the featureless AGN SED (see Section 2.3.1). If we make the simplifying assumption that the warm temperature component is due entirely to the AGN and the cold component to the host galaxy, then we can quantify the contribution of the AGN to the total IR luminosity by subtracting the contribution of $L_{\text{IR}}^{\text{cold}}$ from $L_{\text{IR}}$ (see Table 2.3). For the silicate AGN SED, we find an IR contribution of 50%, and for the featureless AGN, a contribution of 79%, in good agreement with what we find when we remove the host component by scaling the SF composite SEDs. Both SEDs exhibit a lower overall contribution from the AGN component to $L_{\text{IR}}$ than that indicated by the mid-IR alone, since the SF component dominates at the longest IR wavelengths. As a check on the validity of our simple assumptions about the two temperature components, we also compare the $L_{\text{IR}}^{\text{AGN}}$ that we derive from the Mullaney et al. (2011) mean AGN templates (Figure 2.10). Fitting the Mullaney et
Figure 2.10: High z AGN SEDs compared to local AGN SEDs. We plot our composite AGN SEDs (solid lines) along with the average AGN SEDs derived in Mullaney et al. (2011), normalized at 7 µm. The blue dashed line shows the mean AGN SED, while the green and orange dot-dashed lines show the high and low luminosity AGN SEDs, respectively, which have been created using the SEDs of local AGN. We overplot the warm dust component for each of our composite SEDs as the dotted line. The warm dust emission peaks at the same wavelength as the high luminosity AGN SEDs, which is consistent with the high $L_{2-10\text{ keV}}$ values we derive for our composites.
al. (2011) mean AGN templates to the mid-IR of our AGN SEDs, we find an AGN contribution to $L_{\text{IR}}$ of 62% and 83% for the silicate and featureless AGN, respectively. These results are remarkably consistent with our modified blackbody fits, which is reassuring. With our blackbody fits, we are able to attach physical parameters, namely dust temperatures, to each population which eases comparisons between our samples and with other galaxy populations at low and high redshift.

### 2.4.2 Evolution of Infrared Luminous Galaxies

In the local Universe, all ULIRGs and most LIRGs are observed to be caught in the act of a major merger (Sanders & Mirabel, 1996), where the interaction is the trigger for the intense infrared luminosity (Murphy et al., 1996; Bushouse et al., 2002). A popular scenario for linking IR luminous galaxies dominated by SF and AGN activity is outlined in Sanders et al. (1988). During the early stages of a merger of two disk galaxies a dusty starburst is triggered, but as the black holes merge together and are fed by the disrupted gas, an AGN begins to dominate the IR emission and destroys or blows away the dust and gas, quenching the star formation. Eventually the AGN runs out of fuel, and the galaxy settles down as a massive elliptical galaxy. This scenario is a plausible explanation for local ULIRGs.

At $z \sim 1 - 3$, the situation is different. While some high redshift ULIRGs are major mergers (e.g., Engel et al., 2010), many high redshift ULIRGs show no evidence for any merger or interaction, from studies of their morphology or dynamics (e.g., Daddi et al., 2010a; Tacconi et al., 2010). The higher gas fractions and longer gas consumption timescales suggest that the intense star formation in these galaxies is fueled continuously, perhaps through cold gas streams (e.g., Dekel et al., 2009). Several recent studies (e.g., Schawinski et al., 2011; Mullaney et al., 2012) have found that many moderate luminosity AGN are found in high redshift IR luminous galaxies that
are not necessarily undergoing a major merger, suggesting that internal instabilities could be the primary mechanism fueling the AGN.

We found significant differences in the IR SED between our mid-IR identified SF and AGN galaxies; specifically, the AGN sources have effective dust temperatures $\sim 20$ K higher, indicating that the luminous AGN is not only responsible for heating the hot dust in the mid-IR, but also has an impact on the warmer far-IR dust and can even dominate the bolometric luminosity (e.g. our featureless AGN in Table 2.3, see also Díaz-Santos et al., 2010). It is tempting to try to place our SF- and AGN-dominated galaxies into an evolutionary sequence, where the SF galaxies represent an early phase of active star formation, and the AGN galaxies represent a later phase once the black hole has been fueled and is able to heat the dust to warmer temperatures and quench the star formation. This evolutionary sequence may or may not be triggered by a major merger at high redshift. Any direct evolutionary comparison can only be tentatively drawn between our $z \sim 2$ SF SED and our silicate AGN SED, since these two SEDs are comparable in $L_{\text{IR}}$ and stellar mass, and both are primarily composed of galaxies with a redshift of $\sim 2$. There is some tentative evidence that a major merger produces more warm dust emission than normal SF activity (Hayward et al., 2012). Our $z \sim 2$ SF SED exhibits much less warm dust emission than the local ULIRG SEDs, indicating high redshift ULIRGs are not analogs to local ULIRGs and may follow a different evolutionary path in which they are normal SF galaxies until the AGN at the center begins to dominate the bolometric luminosity. Our silicate AGN composite SED is luminous in the X-ray ($L_{2-10\text{keV}} \sim 5 \times 10^{44}$ erg s$^{-1}$) and has a lower sSFR than the $z \sim 2$ SF composite SED. The AGN properties of our silicate AGN SED are consistent with a later evolutionary stage than our $z \sim 2$ SF galaxies, regardless of whether the evolution is driven by major mergers or some other process.
2.4.2.1 Main Sequence of Star Forming Galaxies

One way that has been proposed to determine if a high redshift galaxy is undergoing a starburst event triggered by a merger is using the ratio of SFR to stellar mass. Several recent studies have found a tight correlation between SFR and stellar mass which has been called the ‘main sequence’ for star-forming galaxies (e.g., Noeske et al., 2007; Elbaz et al., 2007; Daddi et al., 2007; Magdis et al., 2010). Furthermore, this main sequence shifts to higher SFR from $z = 0 – 3$, leading to an increase in the average sSFR with redshift (e.g., Elbaz et al., 2011). If galaxies on the main sequence are undergoing continuous star formation then starburst galaxies will lie above the main sequence, their SFRs possibly boosted by a merger or interaction.

Both of our SF composites and our silicate AGN composite have sSFRs that place them on the sSFR-redshift main sequence defined by Eqns. 13 and 24 in Elbaz et al. (2011) and Eqn. 2 in Pannella et al. (2009a). The featureless AGN, however, lie decidedly below both of these relations, though not in the regime designated as “quiescent” ($< 10\%$ of the average sSFR at a given redshift, Mullaney et al., 2012). Our stellar masses are a factor of $\sim 2$ lower than those in Elbaz et al. (2011) due to different stellar population models (see Section 2.1.5), so if we increase our stellar masses by this amount, our sSFRs will consequently be a factor of 2 lower, placing them even further away from the SB regime.

Elbaz et al. (2011) discovered another tight correlation between the $8 \mu m$ luminosity, $L_{8\mu m}$, and $L_{\text{IR}}$, mimicking the SFR-$M_*$ main sequence, and defined an alternate main sequence using the parameter $\text{IR}8 = L_{\text{IR}}/L_{8\mu m}$. IR8 is calibrated to distinguish between starbursting and main sequence SF galaxies, but it has been shown to be useful when applied to AGN as well. We calculate the $8 \mu m$ luminosity of our SF and AGN sources by applying the IRAC $8 \mu m$ passband to each composite SED in the rest frame. We calculate IR8 = $L_{\text{IR}}/L_{8\mu m}$ for each composite and list the values in Table 2.3. We do not distinguish between main sequence and starburst galaxies for
individual sources since we are interested in the average properties of our sub-samples. Using a large sample of GOODS-\textit{Herschel} galaxies, Elbaz et al. (2011) define the main sequence to be IR8 = 2.7 to 7.8 (range is the 68% dispersion around the mean IR8 value of 4.9). Interestingly, IR8 for both of our AGN composites fits comfortably within this range. The $z \sim 1$ SF SED has an IR8 of 6.6, which is well within the main sequence, while the $z \sim 2$ SF SED, with an IR8 of 7.9, lies just above the main sequence range. Although most of the galaxies in our $z \sim 1$ SF sub-sample are main sequence galaxies, the $z \sim 2$ SF sub-sample may contain a mix of both main sequence galaxies and starbursts, according to the IR8 parameter.

During the active stages of a major merger, the AGN produced is likely to be heavily obscured. As our present study does not rely on X-ray detection to identify AGN, we are not biased towards unobscured AGN. Therefore, if AGN at high redshift primarily reside in (U)LIRGs triggered by a major merger, our main-sequence/starburst classification should reflect this. As neither the silicate AGN nor featureless AGN lie in the starburst regime, according to the IR8 criterion and the sSFR-$z$ relation, our findings are in agreement with recent studies that suggest the majority of AGN at high redshift ($z \sim 1 - 3$) reside in normal, main sequence galaxies (e.g., Lutz et al., 2010; Mullaney et al., 2012; Xue et al., 2010). However, two caveats must be taken into consideration. First, a compact starburst and an AGN can, in effect, wash each other out in the IR8 parameter. The starburst can increase the ratio of the far-IR to the mid-IR, but the AGN will increase the amount of mid-IR luminosity. Together, these effects act to produce a main-sequence IR8 value. Second, both main sequence criteria may be limited in usefulness when discussing AGN. A major merger may immediately trigger a starburst, but may take more time to funnel material to the AGN, and this can produce a delay between starburst activity and a luminous AGN on the order of $\sim 10^8$ yrs. It is possible that any signatures of a merger have disappeared before the galaxy displays strong AGN signatures.
Figure 2.11: Our $z \approx 1$ and $z \approx 2$ SF SEDs compared against the main sequence and starburst templates derived in Elbaz et al. (2011). Top—$z \approx 1$ SF SED (purple) along with the main sequence template (orange) and starburst template (green), which have been normalized at 7.0 $\mu$m. Bottom—same, but with the $z \approx 2$ SF SED plotted in purple. Both the main sequence and starburst templates overpredict emission at far-IR/submm wavelengths ($\gtrsim 200 \mu$m).

Based on the IR8 parameter, most of our AGN and SF galaxies do not show enhanced IR luminosity and may not be a phase of the popular local ULIRG major merger scenario, although they might still be linked in some other evolutionary sequence (e.g. involving minor mergers or cold gas accretion). Naturally, our findings are only for the average of all of our high redshift sub-samples of galaxies and do not necessarily apply on an individual basis.

Elbaz et al. (2011) present templates for typical main sequence and starbursting galaxies, computed by stacking photometry for main sequence and starburst galaxies at $z < 2.5$ from 3 – 350 $\mu$m. We compare both of our SF SEDs to the main sequence
and starburst templates in Figure 2.11. Upon comparison to our SF templates, we find that both the Elbaz et al. (2011) main sequence and starburst templates overpredict the amount of emission at wavelengths greater than 200 $\mu$m rest-frame exhibited by both our $z \sim 1$ and $z \sim 2$ SF templates, indicating even more cold dust emission. This is possibly due to a difference in the average intrinsic IR luminosity or redshifts for each of these templates. In addition, there are differences in the way the templates were created, which could also account for some of the variation in cold dust emission. Elbaz et al. (2011) only fit the long wavelength SPIRE photometry when there is a detection in the prior catalog whereas we include a measurement for every galaxies regardless of if it is a formal detection (see Section 2.2). Furthermore, Elbaz et al. (2011) fit the far-IR data for individual sources with a CE01 templates to calculate each $L_{\text{IR}}$, and then normalized every source to the same $L_{\text{IR}}$ before stacking, whereas we normalize all sources in the mid-IR using the IRS spectra. The amplitude and shape of our SEDs at these longer wavelengths is validated by our stacked submm measurements (see triangles in Figure 2.11). Most of the mismatch between the Elbaz et al. (2011) templates and ours in the submm is likely due to the fact that we are comparing sources at different redshifts and luminosities; the Elbaz et al. (2011) SEDs include all galaxies at $z < 2.5$ and will be weighted towards galaxies at $z \lesssim 1$ with lower average $L_{\text{IR}}$, which may indeed be intrinsically cooler, than our SF composite SEDs. As shown earlier in Section 2.3.5, local templates do not fit the $z \gtrsim 1$ galaxies, and we expect the SEDs of star forming galaxies to start to evolve somewhere between $z \sim 1$ and $z \sim 0$. A more in depth study of the SEDs of star forming galaxies at $z < 1$ is needed to determine when the SED shapes begin to differ from local templates.

2.4.2.2 Silicate Absorption in AGN

An understanding of the role of AGN in the evolution of IR luminous galaxies is further complicated by the silicate absorption feature at 9.7 $\mu$m. Our AGN sources
are clearly split into two sub-samples, those with a prominent silicate feature and those without, and the same is seen in samples of local AGN. The 9.7 $\mu$m absorption feature is understood to be sensitive to the geometry of the dust, presumably emitted from the compact torus region surrounding the AGN. Sources with absorption have an optically thick, smooth dust distribution, whereas clumpy dust produces only shallow absorption (e.g., Spoon et al., 2007; Nenkova et al., 2008). It is possible that one dust distribution transforms into the other, or that we are seeing identical AGN at different viewing angles with and without silicate absorption.

Silicate absorption has been linked with the most heavily obscured, Compton-thick AGN (e.g., Sales et al., 2011; Georgantopoulos et al., 2011). Interestingly, in our sample only 41% of silicate AGN are individually detected in the deep Chandra X-ray imaging, whereas 92% of featureless AGN are detected in the X-ray. This supports the idea that the silicate AGN are more heavily obscured, maybe even Compton thick, while the featureless AGN are less obscured and can have a stronger effect on the host galaxy, as evidenced by a larger fraction of $L_{\text{IR}}$ coming from the warm dust component. A more detailed study of the individual X-ray properties of our IRS sample is reserved for a future paper.

Broadly speaking, silicate AGN may represent the transition stage from a star formation dominated galaxy to an unobscured AGN, following the Sanders et al. (1988) prescription for creating luminous quasars. For our AGN sources, we assume the mid-IR emission arises from the hot dust torus surrounding the AGN, while the emission at $\gtrsim 60\,\mu$m arises from the cold dust heated by star formation in the host galaxy. The persistence of significant cold dust observed in our silicate AGN suggests that these nuclei are heavily obscured and therefore may not yet have a strong effect on the star formation occurring in the host galaxy. Currently, a precise picture of AGN feedback has not been proven, but one prominent line of thought is that as the AGN becomes more powerful, the feedback from the AGN is responsible for heating
the dust and actively shutting down star formation. We can speculate that this feedback is evidenced by the lack of any SF features or silicate absorption in the mid-IR, the suppression of cold dust emission, and the much lower SFR observed in our featureless AGN compared to our silicate AGN. Of course, while these scenarios are possible in general, based on the average properties of our sub-samples of galaxies, it is impossible to state that this is the case for every galaxy within each sub-sample, since we are probing a range of redshifts and $L_{\text{IR}}$.

### 2.4.3 A Closer Look at Our High Redshift SEDs

Looking only at the high redshift SF sources, we might ask whether there is evidence for evolution in the SEDs between $z \sim 1$ and $z \sim 2$. We showed in Figure 2.6 that when normalized in the mid-IR or far-IR, our two SF composite SEDs are indistinguishable over 3 – 500 µm; the only difference is seen in the near-IR, where the $z \sim 1$ SF SED is a factor of a few higher than the $z \sim 2$ SF SED. This region of the SED is probing the stellar bump and is a rough proxy for stellar mass. When we compare the average sSFR = SFR$/M_\ast$ of our $z \sim 1$ and $z \sim 2$ SF galaxies, we find an increase of a factor of $\sim 2.5$, consistent with the observed increase in the sSFR with redshift (e.g., Elbaz et al., 2011). In addition, galaxies with more dust emission (as evidenced by a higher IR luminosity) will have more extinction of the stellar bump. Beyond these two effects, there is no evidence from our analysis that the SEDs of IR luminous SF galaxies evolve between $z = 1$ and 2, though we are comparing LIRGs at $z \sim 1$ with ULIRGs at $z \sim 2$. The lack of any strong differences between our $z \sim 1$ and $z \sim 2$ SF SEDs is especially interesting, since the former are primarily normal main sequence galaxies, while the latter contain a mix of main sequence and starburst galaxies according to the IR8 parameter. This suggests that mergers either might not significantly alter the distribution of dust and gas in high redshift ULIRGs, or might not be as prevalent as they are in local ULIRGs. Recently, Díaz-Santos et al.
(2011) analyzed the extended mid-IR emission for a large sample of local LIRGs and ULIRGs, and found that once the central component of the galaxy is removed, the average SEDs of LIRGs and ULIRGs are all remarkably similar in shape to the local starburst template of Brandl et al. (2006). Their results imply that the differences between LIRG and ULIRG SEDs are due to processes taking place in the cores. High redshift ULIRGs are more extended than their local counterparts, so the extended emission could be dominating the shape of the SED, causing little difference between the $z \sim 1$ and $z \sim 2$ SEDs.

On the other hand, we do see an evolution in the SEDs of SF galaxies when we compare our high redshift composite SEDs to those of local ULIRGs. The general trend is that we find more of the IR luminosity is coming from colder dust at high redshift, whereas local ULIRGs have more shorter wavelength far-IR emission from warmer dust. This was originally observed for high redshift submillimeter selected galaxies (e.g., Pope et al., 2006), and we now show that it extends to a larger high redshift ULIRG population selected in the mid-IR. We argue that this result would not be as robust without modeling the IR emission with multiple dust components since a single dust component would bias the far-IR peak to slightly shorter wavelengths, and would fail to properly account for all of the substantial warmer dust. The presence of more cold dust in high redshift ULIRGs is likely to be in part because they are more extended than local ULIRGs (even major mergers at high redshift are more extended) allowing for a larger fraction of the dust to remain at cooler temperatures (Daddi et al., 2010a; Engel et al., 2010; Ivison et al., 2011). An interesting test of our empirical SED templates would be to compare them to the expected SEDs from radiative transfer models that take into account the larger sizes of high redshift ULIRGs.
Chapter Summary

We have combined deep photometry from 3.6 to 500 μm with Spitzer mid-IR spectroscopy for 151 high redshift (z > 0.5) (U)LIRGs in order to explore the relative contribution of AGN and SF activity to the total IR emission. Our sources bright in the mid-IR (93% have $S_{24} > 100 \, \mu Jy$), and we have shown that they are representative of the full 24 μm population above this flux limit. We perform spectral decomposition on the mid-IR spectrum of each source to determine whether the mid-IR luminosity is dominated by continuum emission from an AGN or PAH emission from ongoing star formation.

Based on the mid-IR spectral decomposition, we divide our sample into 4 sub-samples ($z \sim 1$ SF, $z \sim 2$ SF, silicate AGN, featureless AGN) and create composite SEDs over the full IR range for each sub-sample. We fit a two temperature component modified blackbody model to our composite SEDs and calculate the dust temperatures and IR luminosities. By comparing the properties of the SEDs, we conclude the following:

1. We find no significant difference in the SEDs (PAH features, dust temperatures) between SF systems with similar stellar masses at $z \sim 1$ (average $L_{\text{IR}} = 4.2 \times 10^{11} L_\odot$) and $z \sim 2$ (average $L_{\text{IR}} = 2.0 \times 10^{12} L_\odot$).

2. AGN dominated galaxies with a pure power law spectrum are dominated by a warm ($\sim 100$ K) dust component in the IR, whereas AGN with silicate absorption have a strong warm dust component and show a significant cold dust component.

3. We find warmer ($\sim 20$ K) effective average dust temperatures for our AGN SEDs than for our SF SEDs.
4. We find that a single temperature model is a poor fit to the data and neglects significant emission at shorter far-IR wavelengths leading to inaccurate $L_{\text{IR}}$s and SFRs.

We compare our composite SEDs created from high redshift (U)LIRGs with local templates, including the library of Chary & Elbaz (2001), and find that the local templates differ significantly from our SEDs, particularly at far-IR wavelengths where ULIRGs at high redshift contain a higher fraction of cool dust than local ULIRGs. The difference in warm dust emission between local and high redshift SEDs could be attributed to different evolutionary paths. As the local SEDs used in this work are extrapolated from 160 – 850 $\mu$m, far-IR Herschel photometry is needed for stronger comparisons to be made between the cold dust emission in local and high redshift galaxies.

We use the criteria presented in Elbaz et al. (2011) to assess the ‘starburstiness’ of our sub-samples and find, according to either the IR8 parameter or sSFR-$z$ relation, that most of our sources lie on the main sequence of star formation. The properties of our SF and AGN sub-samples are consistent with scenarios which link the evolution of star formation and rapid black hole growth in galaxies at high redshift.
CHAPTER 3
SEPARATING HIGH REDSHIFT ACTIVE GALACTIC NUCLEI AND STAR FORMING GALAXIES USING INFRARED COLOR DIAGNOSTICS

In this chapter\(^1\), we demonstrate how effective different IR color combinations are at separating our mid-IR spectroscopically determined AGN from our star forming galaxies. We look in depth at existing IRAC color diagnostics, and we explore new color-color diagnostics combining mid-IR, far-IR, and near-IR photometry, since these combinations provide the most detail about the shape of a source’s IR spectrum. An added benefit of using a color that combines far-IR and mid-IR photometry is that it is indicative of the power source driving the IR luminosity.

A full description of our sample and the composite SEDs we create from it is given in Chapter 2. The two SF composites SEDs are remarkably similar in shape and have most emission from cold dust. The featureless AGN composite is nearly a pure power-law until \( \sim 20 \mu m \), and then is relatively flat from \( \sim 20 - 100 \mu m \). The silicate AGN SED is a power-law in the near-IR, has weak PAH features and silicate absorption at 9.7 \( \mu m \), has warm dust emission around 20 \( \mu m \), and has a cold dust component peaking at the same wavelengths as the SF SEDs. The difference in shapes between the two AGN SEDs and the SF SEDs suggests that IR color diagnostics could be useful for separating AGN from SF galaxies.

\(^1\)This chapter is published as Kirkpatrick et al. (2013).
Figure 3.1: IRAC color selection techniques. The most popular color-color diagnostics are from Stern et al. (2005, left panel) and Lacy et al. (2004, middle panel), with the empirically defined AGN regions shown in grey. Our SF galaxies separate nicely with redshift (z < 1.5 are the filled green circles while z > 1.5 are plotted as the open green circles). The AGN sources do not separate in these color-color spaces with redshift and thus are only plotted according to whether they possess a 9.7 µm absorption feature (open blue squares) or not (filled blue triangles). The four AGN we were unable to classify as they lacked spectral coverage at 9.7 µm are plotted as the blue crosses. Overplotted are the redshift tracks calculated from our composite SEDs for z ∼ 2 SF galaxies (purple) and z ∼ 1 SF galaxies (red). In the left panel, the z ∼ 1 SF SED and z ∼ 2 SF SED diverge around z ∼ 1 due to the difference in the strength of portion of the stellar bump traced by the 3.6 µm filter. As the two AGN composites occupy the same region of colorspace for both the left and middle panels, we only plot the redshift track of the featureless AGN composite SED (in pink) on the left and the track for the silicate absorption AGN (orange) in the middle. The right panel shows the effective wavelengths of the four IRAC bands at different redshifts on each of our composite SEDs, demonstrating that at high redshift these colors sample the stellar bump region.
3.1 IRAC Color-Color Diagnostics

Some of the most well used IR color diagnostics for separating AGN and SF galaxies are presented in Lacy et al. (2004) and Stern et al. (2005) and utilize IRAC colors. The motivation behind an IRAC selection technique is that, at these wavelengths, luminous AGN should have a monotonically increasing SED, and these power-law colors will separate AGN from SF galaxies in colorspace. With our high redshift photometry and spectroscopy, we are able to apply these diagnostics to a large sample of mid-IR spectroscopically determined AGN and SF galaxies. Lacy et al. (2004) and Stern et al. (2005) define IRAC color-color regions to separate AGN based on large surveys of low redshift ($z \lesssim 0.7$) galaxies. As we move to higher redshift ($z \sim 2$), the IRAC bandwidths begin to probe the stellar bump; our composite AGN and SF SEDs exhibit different shapes in the $\lambda < 4 \mu m$ region of the spectrum, indicating that IRAC color diagnostics might also be useful at higher redshift. We apply the diagnostics of Stern et al. (2005) and Lacy et al. (2004) to our sample (Figure 3.1). Sources in our sample that we determined through mid-IR spectral decomposition to be dominated by an AGN (> 50%) in the mid-IR are plotted in blue, and sources dominated by star formation are plotted in green.

In the left panel of Figure 3.1, we plot our sources in the IRAC color-color space defined in Stern et al. (2005) with the gray shaded region being the area defined as AGN-dominated by the authors. Our SF sources separate cleanly according to redshift and largely avoid the gray shaded region. We have also overplotted the redshift tracks of our $z \sim 1$ SF composite SED and our $z \sim 2$ SF composite SED. We calculate the redshift tracks of each of our composite SEDs by convolving the SEDs with the IRAC bandpass filters (and MIPS, PACS, SPIRE, and WISE filters in Section 3.2) at the appropriate wavelengths for a given redshift. The convolution acts to smooth out much of the noise in our spectra as the individual filters span a fairly large wavelength range. The $z \sim 2$ SF track contaminates the AGN region around
Figure 3.2: More restrictive IRAC color selection criteria for separating power-law AGN. The modified criteria (shaded region) from Donley et al. (2012) do an effective job of selecting our power-law sources while avoiding contamination from SF galaxies but still miss many of our silicate AGN.

$z \sim 1$, and in fact, all of the $z \sim 1$ SF galaxies (green filled circles) occupying the shaded region have a redshift between 1 and 1.5. The divergence of the two SF tracks around $z \sim 1$ is due to the fact that the 3.6 $\mu$m filter is tracing the bluest portion of the stellar bump, which has differing strengths relative to the other IRAC filters for the two SF composite SEDs (see Figure 2.6 and the right panel of Figure 3.1). Our individual $z \sim 1$ sources have colors that are located around both the $z \sim 1$ and $z \sim 2$ tracks indicating a spread in the obscuration of the IRAC colors for these sources. The spread of the individual photometry points in relation to the composite SED is illustrated in Chapter 2.

The AGN sources (blue symbols) are not completely constrained to the gray shaded region, though our redshift track from the featureless AGN composite SED indicates they should be on average, illustrating a lack of homogeneity in the near- and mid-IR photometry among mid-IR classified AGN. Most AGN in our sample do not have a clear stellar bump in the near-IR which restricts them to the shaded region
(only 8% (2) of the AGN sources in the grey region have a visible stellar bump). Of the outlying high redshift AGN in this plot, the majority (70%) possess a weak visible stellar bump which pushes them into the regions of the color space occupied by SF galaxies. Eleven (50%) of the silicate AGN, 2 (17%) of the featureless AGN, and 1 (25%) of the unclassifiable AGN lie outside the gray region. One of the advantages of this study is that we are able to investigate how well the mid-IR power source determines the near- and far-IR power source. Clearly, our mid-IR dominated AGN do not uniformly have IRAC colors indicative of an AGN. Furthermore, 11 of the AGN contaminating the SF region do not have far-IR colors expressive of an AGN (see Section 3.2).

The middle panel of Figure 3.1 is the color space defined by Lacy et al. (2004) where the shaded region is used to identify AGN. The vast majority of our sources occupy this region, regardless of their power source diagnosed from the mid-IR spectrum (see also Donley et al., 2008, 2012). The SF sources again show a clean redshift separation as the IRAC channels sample the stellar bump. As neither subsample of AGN similarly exhibits a redshift separation, we do not plot them with different symbols according to redshift. The redshift tracks of the featureless AGN and silicate AGN composite SEDs occupy the same portion of the graph, so we only plot the silicate AGN SED track in orange; the track lies in the upper portion of the graph.

We overplot both SF SED redshift tracks ($z \sim 1$ in red and $z \sim 2$ in purple) as they show an interesting separation. At low redshifts ($z < 2$), the $z \sim 1$ SF SED track lies just outside the shaded region, while the $z \sim 2$ SF SED lies inside it, but after $z = 2$, the tracks lie on top of each other. This difference in the color tracks between our $z \sim 1$ and $z \sim 2$ composite SEDs is likely due to the different intrinsic $L_{IR}$ of each subsample. The $z \sim 1$ sources are on average LIRGs ($L_{IR} \sim 4 \times 10^{11}L_\odot$) and therefore have less dust to obscure the IRAC colors than our $z \sim 2$ ULIRG SED composite; adding more dust to a SF galaxy will cause it to shift towards the top-left
of this plot, which is exactly the shift we see between our $z \sim 1$ and $z \sim 2$ SED tracks. At $z \geq 3$, the tracks approach the area occupied by the AGN, but as none of our SF sources possess a redshift this high, we are unable to determine if our sources follow our tracks into the upper portion of the graph. Both of the SF SEDs accurately trace the redshift separation exhibited by our sources.

In the right panel of Figure 3.1, we show on our composite SEDs the effective wavelengths of each of the IRAC bandwidths at redshifts 1, 2, and 3 (blue, green, and red, respectively). These bands straddle the stellar bump over this redshift range. Both AGN SEDs have a power-law shape over these bands causing little evolution in IRAC colorspace.

The high degree of contamination in these IRAC color-color diagnostics by high redshift SF galaxies motivated Donley et al. (2012) to create more restrictive criteria than originally presented in Lacy et al. (2004) and Stern et al. (2005). Donley et al. (2012) uses a sample of AGN identified at optical and X-ray wavelengths to construct the new criteria, and now we are able to test these criteria using mid-IR spectroscopic AGN. We apply the new color cut presented in Donley et al. (2012) to our sample in Figure 3.2. The authors determined the gray shaded region was the most effective at selecting out AGN with power-law spectra in the IRAC bandwidths, and indeed, all of our sources that meet the more restrictive criteria have flux densities such that $S_{3.6} < S_{4.5} < S_{5.8} < S_{8.0}$. Based on our high redshift sources, we propose the simple IRAC color cuts of

$$
\log \left( \frac{S_{5.8}}{S_{3.6}} \right) > 0.08 \quad (3.1)
$$

and

$$
\log \left( \frac{S_{8.0}}{S_{4.5}} \right) > 0.15 \quad (3.2)
$$

(solid lines in Figure 3.2) for selecting potential power-law AGN candidates, similar to the Donley et al. (2012) criteria.
The IRAC color selection techniques, even using the more restrictive cuts presented in Donley et al. (2012), still miss a large fraction (39% of the present sample) of mid-IR spectroscopically confirmed AGN, specifically most of the more obscured silicate AGN. Furthermore, such diagnostics cannot conclusively determine if an AGN is significantly contributing to the bolometric luminosity of a galaxy. Since an IRAC color diagnostic applied at high redshift ($z > 1.3$) is necessarily based on separating sources into AGN- or SF-dominated based on the shape of the spectrum in the near-IR, such diagnostics might not be the most desirable for determining the dominate power source of dust obscured galaxies in the mid-IR and far-IR regime.

3.2 New Color-Color Diagnostics

Our large sample of high redshift SF and AGN sources, identified with deep mid-IR spectroscopy, and wealth of multiwavelength photometry allows us to define new color-color diagnostics that are well suited to uncovering galaxies harboring an AGN as revealed in the mid-IR spectrum, and galaxies with a bolometrically important AGN. We seek to combine multiple portions of the IR spectrum that are probing the physical nature of each galaxy with different pieces of information. At 3.6 $\mu$m, SF galaxies at $z \sim 1 - 2$ will have a stellar bump due to the underlying stellar population, while this effect might be washed out in luminous AGN, producing a power-law shape. Similarly, at these redshifts, the 24 $\mu$m filter will straddle the PAH complexes at 7.7 and 12.7 $\mu$m, which will be weakened or absent in a bright AGN. However, there is a caveat that at $z \sim 1.5$, the silicate absorption feature present in some AGN spectra, falls into the 24 $\mu$m bandwidth which can produce colors that mimic SF galaxies. On the other hand, the bandwidth is large enough that we do not expect this to be a significant source of contamination. The far-IR should have a different shape based on the relative amounts of cold and warm dust emission present, and SF galaxies will have relatively more cold dust than AGN, while AGN have an increased amount of
Figure 3.3: $S_{250}/S_{24}$ v. $S_{8}/S_{3.6}$. Left - New color-color diagnostic combining submm wavelength Herschel/SPIRE photometry with mid-IR Spitzer data. The dark line divides the SF galaxies (green) from the AGN galaxies (blue). We plot all sources according to redshift (filled symbol: $z < 1.5$; open symbol: $z > 1.5$). We overplot the redshift tracks of our composite SEDs from $z \sim 0.5 - 4.0$ as this is the redshift range of our sources. We show with the dashed grey lines what color thresholds can be used to separate AGN from SF sources if only one color is available. Middle - Illustrates where each of the redshifted photometry points lie on the composite SEDs. Right - Same as the left panel except we overplot the SED templates of local galaxies and high redshift SMGs for comparison.

warm dust. Finally, the 8 $\mu$m filter, at $z \sim 1 - 2$, covers a relatively featureless portion of the spectrum, so when combined with filters that are tracing features, should act as a base to distinguish between AGN and SF systems.

We used available photometry from Herschel and Spitzer ranging from 3.6–350 $\mu$m (observed) and explored every possible color combination. In addition, we also look at where the composite SEDs lie to get a sense of where we should expect to find AGN and SF galaxies, on average. For color-color plots in which the AGN were well separated from the SF sources, we calculated the contamination rates of each region. We find that a color diagnostic spanning the full range of the IR spectrum does the best job of separating both AGN with pure power-law spectrum from 1 – 10 $\mu$m and AGN with silicate absorption from SF galaxies at high redshift. We define two new color-color diagnostics which, based on having a low contamination and clarity of
separation, are the optimal diagnostics to employ when a full suite of IR photometry exists.

3.2.1 $S_{250}/S_{24}$ v. $S_{8}/S_{3.6}$

We find that combining longer wavelength photometry from Herschel with mid-IR photometry from Spitzer MIPS/IRAC provides the most reliable separation between our mid-IR classified AGN and SF galaxies since they probe the widest range of dust properties affected by AGN and SF activity.

Figure 3.3 shows $S_{250}/S_{24}$ v. $S_{8}/S_{3.6}$. Both colors cause a separation of sources with the result that the SF dominated sources lie in the lower right portion of the graph (separated by the diagonal solid line). The SF sources separate weakly according to redshift (indicated by open and filled symbols) with the lower redshift sources lying slightly below the high redshift sources. The redshift tracks calculated from the $z \sim 1$ SF SED and $z \sim 2$ SF SED follow similar evolutionary paths, although again they exhibit a separation in the IRAC color, $S_{8}/S_{3.6}$, with the $z \sim 2$ SF track redder than the $z \sim 1$ SF track between $z \sim 1 - 2$. The SED redshift tracks trace out the area occupied by the SF galaxies according to the redshift separation exhibited by the sources.

The AGN are loosely separated by the presence or absence of silicate absorption at 9.7 $\mu$m in this color-color space. We plot both subsamples according to redshift (filled symbols are $z \sim 1$ and open symbols are $z \sim 2$). The featureless AGN do not contaminate the SF region and lie further to the left (lower $S_{250}/S_{24}$) than the silicate AGN, due to an excess of warm dust emission in these sources. We overplot the redshift track computed from the featureless AGN SED. The track has some slight evolution along the x-axis with redshift, consistent with the individual data points. The silicate AGN (filled and open squares, according to redshift), on the other hand, show no evolution along the x-axis with redshift but show some spread along the
y-axis. The fact that some silicate AGN sources contaminate the SF region can be attributed to two effects, namely that some individual sources possess a weak stellar bump and some sources have more relative cold dust emission in the far-IR. The silicate AGN SED redshift track exhibits no evolution in either direction and so is plotted as a star.

Both color axes produce a separation of AGN and SF sources. Based on the location of our sources, we calculate the separation line to be

$$\log\left(\frac{S_8}{S_{3.6}}\right) = 0.74 \times \log\left(\frac{S_{250}}{S_{24}}\right) - 0.78$$  \hspace{1cm} (3.3)

drawn as the bold solid line in Figure 3.3. In the absence of all four wavelengths, we find that the majority of our AGN sources satisfy either of the following color criteria shown as the dashed lines:

$$\log\left(\frac{S_{250}}{S_{24}}\right) < 1.30$$  \hspace{1cm} (3.4)

$$\log\left(\frac{S_8}{S_{3.6}}\right) > 0.32$$  \hspace{1cm} (3.5)

The separation along individual axes is particularly useful if only an upper limit for $S_{250}$ is available when searching for AGN.

We quantify the contamination of the SF and AGN regions (separated by the diagonal solid line): 10% of the sources (11 of 111 total) in the SF region are AGN and 2 of the 22 sources (9%) in the AGN region are SF dominated (Table 3.1). None of the contaminating AGN are power-law dominated. Some of the individual silicate AGN have a stellar bump (41%), causing contamination along the $S_8/S_{3.6}$ axis. Furthermore, several of our silicate AGN (8, or 42%) have significant amount of cold dust emission in the far-IR, producing $S_{250}/S_{24}$ flux density ratios greater than 1.3. The high $S_{250}/S_{24}$ flux density ratio correlates with the presence of a stellar bump in the silicate AGN, with 32% possessing both. Finally, it is worthwhile to note that...
the contaminating AGN are significantly fainter at 24 µm (median \( S_{24} = 220 \mu Jy \)) than the AGN lying in the upper region of the graph (median \( S_{24} = 1240 \mu Jy \)). Indeed, all but one of the properly identified AGN have \( S_{24} > 300 \mu Jy \). Based on our sample of 24 µm bright sources, our diagnostic is optimized to select AGN with \( S_{24} > 300 \mu Jy \), though if the physics is similar in lower luminosity AGN, they will have similar SEDs and colors, in which case our diagnostics can also be used to select out AGN dominated sources.

\( S_{250} \), in comparison with \( S_{24} \), is an indicator of the relative amount of cold dust in a galaxy. As an AGN becomes more powerful, the relative amount of warm dust increases, so that the ratio of \( S_{250}/S_{24} \) decreases. For galaxies lacking a significant amount of warm dust, the cold dust will be the dominant contributor to the \( L_{\text{IR}} \). Low \( S_{250}/S_{24} \) ratios in our mid-IR AGN indicate that the warm dust, indicative of an AGN, is significantly contributing to the far-IR emission, and accordingly, the AGN is an important contributor to the bolometric luminosity. Our diagnostic is therefore more powerful than the IRAC diagnostics presented in Section 3.1 since it selects AGN significantly contributing to the total IR emission.

Our new diagnostic is a definite improvement over the IRAC selection criteria presented in Lacy et al. (2004) and Stern et al. (2005), though photometry is scarcer. In our sample of 151 galaxies, 99% have IRAC data so both Lacy et al. (2004) and Stern et al. (2005) can be applied, while only 88% have the relevant wavelengths to satisfy our new diagnostic. We verify the more restrictive IRAC criteria of Donley et al. (2012), shown in Figure 3.2, with our IRS sample, whose mid-IR power source has been determined via spectral decomposition. Our new diagnostic is a slight improvement over the revised IRAC criteria presented in Donley et al. (2012). In the present case, 35% of our AGN sources are misclassified as SF galaxies, while according to the restricted IRAC criteria (equations (1) and (2)), 39% are misclassified. In addition, with the new criteria, we correctly identify two sources as AGN that
were misclassified using only the IRAC colors. Though the improvements gained in recovering mid-IR AGN by combining colors covering the entire IR spectrum is only slight over using IRAC colors alone, an added strength of our new criteria lies in the fact that mid-IR data from the Wide-field Infrared Survey Explorer (WISE) can be easily substituted for Spitzer data. The WISE 22 μm and 3.4 μm channels correspond to Spitzer 3.6 μm and 24 μm bandwidths. We have used the redshift tracks of our templates to determine that the WISE 12 μm channel is the optimal substitute for Spitzer 8 μm (see Section 3.2.4).

The middle panel of Figure 3.3 illustrates the different SED tracks shown on the left panel. 250 μm, 24 μm, 8 μm, and 3.6 μm at z = 1, 2, 3 are indicated on the composite SEDs. $S_{250}$ traces the far-IR peak of each template while $S_{24}$ traces the mid-IR emission – the different ratios of mid-IR to far-IR emission (or warm to cold dust) in AGN and SF sources produces the observed color separation in $S_{250}/S_{24}$. At the lower wavelengths, $S_{8}/S_{3.6}$ remains fairly constant for both high redshift AGN SED templates. As some of our individual AGN sources do show signs of weak SF activity as well as AGN activity, several of our AGN possess a noticeable stellar bump which causes a spread in $S_{8}/S_{3.6}$. Of the 11 AGN sources contaminating the SF region, 60% possess a visible stellar bump compared with only 14% of AGN sources in the AGN region. The $z \sim 1$ SF composite SED illustrates how a stellar bump would cause a change in $S_{8}/S_{3.6}$ with redshift.

In the right panel of Figure 3.3, we overplot other SED templates in our new color-color space, namely the SEDs of local galaxies and high redshift submillimeter galaxies (SMGs, Pope et al., 2008a). These local SEDs come from combining all known data on these sources including available IRAS (12, 25, 60, 100 μm), Spitzer (24, 70, 160 μm), and SCUBA (850 μm) photometry as well as mid-IR spectroscopy (e.g., Förster Schreiber et al., 2003; Armus et al., 2007). Mrk 231 (red) lies in the AGN region we defined, although contrary to our high redshift AGN SED templates,
it does exhibit some evolution along the y-axis. M 82 (blue) does not enter the SF region until \( z = 1 \) which is most likely due to the fact that its SED peaks at a lower IR wavelength than the majority of our high redshift sources (see Chapter 2). Both NGC 6240 (orange) and the high redshift SMG composite (purple) lie in the SF region except at very low redshifts \( (z \lesssim 0.5) \) and follow the same general redshift evolution as our sources, that is, increasing \( S_{250}/S_{24} \) color with increasing redshift. The SMG composite reaches even higher \( S_{250}/S_{24} \) colors than our sample which is consistent with their selection at submm wavelengths. The consistency of these other local and high redshift templates with our new color diagnostics reinforces our confidence in applying this color selection to a wider range of IR luminous, 24\( \mu \)m bright galaxies at high redshift.

### 3.2.2 \( S_{100}/S_{24} \) v. \( S_{8}/S_{3.6} \)

In the absence of longer wavelength SPIRE data, we find that we can substitute \( S_{100} \) for \( S_{250} \) and we still see a nice separation between the SF and AGN galaxies. In the left panel of Figure 3.4, we use the colors \( S_{100}/S_{24} \) and \( S_{8}/S_{3.6} \) to define a region that separates our high redshift SF and AGN dominated galaxies (diagonal solid line). The line of separation is

\[
\log(S_{8}/S_{3.6}) = 0.208 \times \log(S_{100}/S_{24}) + 0.105 \tag{3.6}
\]

where mid-IR AGN lie above the line.

We plot the uncertainties on our redshift tracks as the hashed lined regions. We opt to not to plot these uncertainties in the other plots presented in this work (Figures 3.1 and 3.3) for the sake of clarity, and the ranges covered by the uncertainties in this plot are indicative of the spread in the previous figures. As discussed in detail in Chapter 2, the uncertainties on the composites were calculated by a bootstrapping technique, which indicates how the scatter in the data points affects the calculated
Figure 3.4: $S_{100}/S_{24}$ v. $S_{8}/S_{3.6}$. Left - New color-color diagnostic combining far-IR Herschel/PACS photometry with mid-IR Spitzer data. The dark line divides the SF galaxies (green) from the AGN galaxies (blue). We plot all sources according to redshift (filled symbol: $z < 1.5$; open symbol: $z > 1.5$). We also plot the redshifts tracks of our high redshift composite SEDs from $z \sim 0.5 - 4.0$ which is the redshift range of our sources. The silicate AGN composite SED has negligible redshift evolution in this color space and is plotted as the orange star. Middle - Illustrates where each of the redshifted photometry points lie on the composite SEDs. Right - Our new color-color plot with templates from local galaxies and high redshift SMGs overplotted.

median luminosity by resampling with replacement. The uncertainties on our composites are not calculated directly from the intrinsic scatter in the data, but are the standard deviation of the calculated luminosity after resampling the data 10,000 times. Therefore, it is not surprising that uncertainties on the template tracks do not encompass the full spread of all data points, particularly the silicate AGN.

The SF region has only a 12% contamination (11 of 92 total galaxies) by AGN sources (Table 3.1). The SF dominated systems show a clear separation with redshift. We overplot the redshift track of the $z \sim 1$ SF composite SED in red, and it traces out the evolution exhibited by our individual sources. There is only one SF source that lies inside the AGN region (causing a contamination rate of 7%), and it not only has a high redshift ($z = 2.57$) but also has a 47% AGN contribution to the mid-IR. The silicate AGN exhibit no redshift evolution in this color space, but the featureless AGN display a weak separation. The AGN composite SED tracks (orange and pink)
Table 3.1: Reliability of our new color-color diagnostics.

<table>
<thead>
<tr>
<th>Color Diagnostic</th>
<th># of galaxies</th>
<th>% (#) Contamination</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SF</td>
<td>AGN</td>
</tr>
<tr>
<td>$S_{250}/S_{24}$ vs $S_{8}/S_{3.6}$</td>
<td>102</td>
<td>31</td>
</tr>
<tr>
<td>$S_{100}/S_{24}$ vs $S_{8}/S_{3.6}$</td>
<td>83</td>
<td>24</td>
</tr>
</tbody>
</table>

do not move much vertically with redshift since these sources have a simple power-law shape and lack a stellar bump in the rest-frame near-IR.

The middle panel of Figure 3.4 shows three of our composite SEDs with lines illustrating where the relevant photometry bandwidths lie at a given redshift. The featureless AGN have a relatively flat spectrum from 20 – 100 µm, so the 100 µm flux does not change with redshift whereas the 24 µm flux decreases, causing the evolution along $S_{100}/S_{24}$. This is not the case for the silicate AGN. The slope from the mid-IR to the far-IR is relatively constant, producing little change in $S_{100}/S_{24}$ at increasing redshifts.

We have presented a simple IR color-color plot that separates our high redshift AGN and SF sources. In the right panel of Figure 3.4, we test our diagnostic by overplotting the redshift tracks of local templates and a high redshift SMG SED. The local AGN Mrk 231 (red dashed line) lies well outside the SF region while the starburst M 82 (blue) and local ULIRG NGC 6240 (orange) lie inside it for the most part. The SMG redshift track (purple) also lies in the SF region as expected since most SMGs are star formation dominated (e.g., Pope et al., 2008a).

The $S_{100}/S_{24}$ vs $S_{8}/S_{3.6}$ colorspace can be used to select SF galaxies based on redshift as well as looking for AGN. The $z < 1.5$ SF galaxies have higher $S_{100}/S_{24}$ ratio since the 100 µm filter is tracing the cold dust. At redshift of 2, the 100 µm filter is now tracing the warm dust, and the 24 µm flux density is boosted by the 8 µm PAH complex, producing a lower $S_{100}/S_{24}$ ratio, similar to what is seen for the AGN. The similar $S_{100}/S_{24}$ colors for both $z \sim 2$ SF galaxies and AGN keeps this
color alone from being an accurate indicator of the bolometrically important power source, unlike $S_{250}/S_{24}$. Substituting $S_{160}$ instead of $S_{100}$ also works well for separating out the AGN (it has the same contamination rates mentioned above), but does not separate SF sources according to redshift.

### 3.2.3 Far-IR Color Selection

As an AGN becomes luminous enough to dominate the mid-IR spectrum, it can heat the dust in the host galaxy causing a shift in the SED to warmer average dust temperatures and an increased importance of warm dust to the bolometric luminosity. Based on this, we might expect that just the *Herschel* PACS and SPIRE colors can be used to preferentially select AGN sources. Hatziminaoglou et al. (2010) searched for a separation using $S_{350}/S_{250}$ and $S_{500}/S_{350}$ and found that in the SPIRE bands, their sample of AGN were indistinguishable from the non-active star forming galaxies. As many of our sources are not detected or blended at 500 µm, we instead combine $S_{350}/S_{250}$ with $S_{160}/S_{100}$ and also find that it does not separate the mid-IR classified AGN and SF sources. Figure 2.6 illustrates that at rest frame wavelengths greater than 40 µm, the far-IR portion of the silicate AGN SED and both SF SEDs are all broadly consistent in shape explaining the lack of spread in colors.

The less pronounced differences in far-IR portions of the composite SEDs is also reflected by the failure of $S_{250}$ thresholds alone to preferentially select AGN from the larger GOODS survey of galaxies (discussed below; see Table 3.2 and Section 3.3). Our AGN sources, particularly the featureless AGN, are significantly brighter than our SF sources at 24 µm and 8 µm. Therefore, it is not surprising that we found the largest separation between the AGN and SF sources when combining mid-IR with far-IR photometry. We caution that with only far-IR information it is difficult to determine the impact of the AGN on the full IR SED. The most reliable selection of
3.2.4 Mid-IR Color Selection

There is now an abundance of mid-IR photometry as a result of two prominent mid-IR space telescopes: *Spitzer* and the Wide-field Infrared Survey Explorer (WISE). Past studies have explored using *Spitzer* color combinations to separate out mid-IR selected AGN and SF systems (e.g., Ivison et al., 2004; Pope et al., 2008a), and emerging studies show that WISE colors can effectively separate IR luminous AGN (Eisenhardt et al., 2012; Stern et al., 2012; Yan et al., 2013). We are motivated by these studies to investigate how well the WISE photometry can separate our high redshift sources, particularly the SF galaxies. WISE has four transmission filters centered at 3.4, 4.6, 12, and 22µm, and though WISE photometry is less sensitive than *Spitzer* data, it has the advantage that it is an all-sky survey and can be used to search for high-redshift objects in regions of the sky not previously well-studied.

We do not have WISE photometry for our sources, but we can use the WISE transmission filters to create synthetic photometry using the IRS spectra and the appropriate transmission filters at 12 and 22µm. For the 3.4 and 4.6µm filters, we substitute the appropriate IRAC photometry. We have applied a small correction to the IRAC photometry (0.94 for the 3.6µm filter and 1.04 for the 4.5µm filter), which we have calculated by comparing the responses of our composite SEDs to each of the WISE and IRAC transmission filters. In addition, we calculate the redshift tracks of our composite SEDs by convolving with the appropriate WISE filters, and we plot our synthetic photometry and redshift tracks in Figure 3.5.

Colors combining the first three channels, 3.4, 4.6, and 12µm, are capable of selecting hyperluminous \( L_{\text{IR}} > 10^{13} L_\odot \) galaxies, particularly AGN/QSOs (Eisenhardt et al., 2012; Stern et al., 2012; Yan et al., 2013). Stern et al. (2012) found that the
Figure 3.5: Potential WISE color diagnostic to separate AGN and star forming galaxies. We used the WISE transmission filters to create synthetic 12 and 24 $\mu$m photometry for our sources which we combine with Spitzer photometry of comparable wavelengths to create WISE colors. We overplot the redshift tracks of $z \sim 1$ SF SED and silicate AGN SED. The $z \sim 2$ SF SED and featureless AGN SED occupy the same regions as the plotted redshift tracks, so for clarity we do not show them. We plot the AGN selection criterion of Stern et al. (2012) as the grey dashed line. Based on the location of our tracks and synthetic photometry, we conclude that the primary strength of this mid-IR diagnostic is in selecting $z \sim 2$ SF galaxies.
WISE color cut $[3.4]_{\text{AB}} - [4.6]_{\text{AB}} > 0.8$ separates luminous AGN, which have been classified as such based on meeting the criteria in Stern et al. (2005, see Figure 3.1). As a complement to these techniques, we would like to separate luminous SF galaxies at high redshift. We find that only combining the first three WISE channels does not effectively separate our SF sources. The strongest separation of our tracks is produced by combining all four WISE channels as shown in Figure 3.5. We overplot the AGN criterion of $[3.4]_{\text{AB}} - [4.6]_{\text{AB}} > 0.8$ as the grey dashed line. Our AGN redshift track confirms the Stern et al. (2012) criterion for AGN with $z \sim 0.5 - 1.0$ and $z \sim 3$. However, none of our sources have a power-law slope steep enough in the appropriate wavelength range to meet this criterion.

Figure 3.5 illustrates that the strongest separation of our sources and redshift tracks is for SF galaxies at $z \sim 2$ due to prominent PAH features lying in the 22$\mu$m transmission filter. The sensitivity depths at 12 and 22$\mu$m are $\sim 1$ and $\sim 6$ mJy, respectively (Wright et al., 2010). Given the sensitivity limits, at a redshift of $\sim 2$, a SF galaxy would need to be at least a ULIRG and probably even a hyper-LIRG ($L_{\text{IR}} > 10^{13} L_\odot$) to be detected by WISE. A benefit of this color selection technique is that few, if any, extragalactic sources with luminosities less than the ULIRG threshold should occupy the same region as the $z \sim 2$ ULIRGs. Therefore, our WISE color selection method is useful for selecting the brightest SF galaxies at $z \sim 2$. In the absence of WISE photometry, Spitzer photometry can be used in similar combinations, with either 8$\mu$m or 16$\mu$m substituting for $S_{12}$ (e.g., Ivison et al., 2004; Pope et al., 2008a).

### 3.2.5 X-ray Emission in AGN

One of the motivating reasons for IR diagnostics of a galaxy’s power source is to search for moderately to heavily obscured AGN missed by X-ray surveys. We use Chandra surveys of the GOODS fields (Alexander et al., 2003; Luo et al., 2008)
to determine if our diagnostics select galaxies that are obscured and lack an X-ray
detection. For $S_{250}/S_{24} \text{ v. } S_{8}/S_{3.6}$, the X-ray detection fraction is 75% for AGN lying
above the solid line and drops to 36% for AGN lying in the region dominated by SF
galaxies. For $S_{100}/S_{24} \text{ v. } S_{8}/S_{3.6}$, the X-ray detection fraction for AGN above the
solid line is 79%, comparable to the detection fraction for the $S_{250}/S_{24} \text{ v. } S_{8}/S_{3.6}$
diagnostic. However, in the SF region, the X-ray detection fraction of AGN sources
is 60%. Approximately 40% of the X-ray undetected AGN lie above the solid lines
in both diagnostics, making our color selection criteria useful for selecting galaxies
dominated by an AGN in the IR regardless of the level of obscuration. It is interesting
to note that $\sim 23\%$ of our mid-IR dominated AGN would not be classified as such
based on either X-ray data or the $S_{250}/S_{24}$ and $S_{8}/S_{3.6}$ colors. The AGN embedded
in these galaxies are not having a strong enough effect on the far-IR and near-IR
portions of the spectrum to distinguish them from SF galaxies on the basis of colors,
although the AGN are having an effect on the mid-IR emission. This could be a
product of viewing angle, or possibly even an evolutionary sequence where as the
AGN grows more luminous, it will be reflected in its IR colors (see Chapter 2 for a
full discussion).

### 3.3 Application to GOODS-\textit{Herschel} Galaxies

We now apply our new diagnostics defined above to broadly separate SF and AGN
dominated galaxies in the whole GOODS-\textit{Herschel} survey (Elbaz et al., 2011). We
plot all galaxies in GOODS-N and GOODS-S detected in all four bands on our two
new color-color plots in Figure 3.6. We use the color cuts derived in Sections 3.2.1 and
3.2.2 (equations (3) and (6)) to separate sources dominated by AGN and SF activity
in the mid-IR. Using the $S_{250}/S_{24} \text{ v. } S_{8}/S_{3.6}$ plot (top panels), we have a total of
665 galaxies with detections in all four bandwidths in GOODS-N and GOODS-S, of
which 58 (9\%) lie in the AGN region. For $S_{100}/S_{24} \text{ v. } S_{8}/S_{3.6}$ (bottom panels), we
Figure 3.6: Our new color diagnostics applied to the full GOODS-Herschel catalogs. We plot the full sample of MIPS 24\,\textmu m selected galaxies in the GOODS fields, which have Herschel photometry, in our diagnostics originally presented in Figs. 3.3 and 3.4 (top and bottom panels, respectively). In the left panels, we shade galaxies according to their 250\,\textmu m flux density (or 100\,\textmu m flux density); in the middle panels, according to 24\,\textmu m flux density; and in the right panels, according to 8\,\textmu m flux density. The region below the solid lines are the same as we defined in Figs. 3.3 and 3.4; a source lying above the line we label as AGN-dominated in the mid-IR (based on our extensive mid-IR spectroscopic sample). Our new diagnostics indicate that roughly \(\sim\)10\% of the GOODS-Herschel galaxies have an AGN dominating the mid-IR luminosity. Breaking things down as a function of flux density, we find that sources with the brightest \(S_{24}\) and \(S_8\) are predominantly AGN, whereas \(S_{250}\) and \(S_{100}\) do not preferentially select AGN at brighter flux densities (see Tables 3.2 and 3.3).
Table 3.2: Percentage of AGN and SF field galaxies according to $S_{250}$, $S_{24}$, and $S_8$ strength.

<table>
<thead>
<tr>
<th>Range</th>
<th>$S_{250}$ (mJy)</th>
<th>$S_{24}$ (µJy)</th>
<th>$S_8$ (µJy)</th>
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</thead>
<tbody>
<tr>
<td>&lt; 15</td>
<td>5 (25)</td>
<td>95 (480)</td>
<td></td>
</tr>
<tr>
<td>15-30</td>
<td>12 (21)</td>
<td>88 (150)</td>
<td></td>
</tr>
<tr>
<td>&gt; 30</td>
<td>26 (12)</td>
<td>74 (35)</td>
<td></td>
</tr>
</tbody>
</table>

Note. — Data corresponds to the top panels of Figure 3.6. AGN are those lying above the solid line indicated on the plot. In this table, we calculate the percentage of AGN and SF sources in a given flux density range for $S_{250}$, $S_{24}$, and $S_8$. The actual number of each type of source is listed in the parentheses.

have 988 sources with detections in all four bandwidths, of which 94 (10%) lie in the AGN region. Both diagnostic plots lead to a similar fraction of GOODS-Herschel sources being AGN dominated in the mid-IR.

It has been found that bright 24 µm flux density correlates with mid-IR AGN indicators at high redshift and in local ULIRGs (Desai et al., 2007; Dey et al., 2008; Donley et al., 2008, respectively). Given this trend, we look to quantify the fraction of galaxies that are AGN dominated in the mid-IR as a function of flux density using our new color-color plots. In Figure 3.6, we plot all GOODS-Herschel galaxies with different colored symbols depending on their flux density (see legend for each panel). Our diagnostic was determined using 24 µm bright sources, and applied to our own sample, the diagnostic primarily recovered AGN with $S_{24} > 300$ µJy. Furthermore, the contribution of the AGN to the mid-IR has been shown to increase with increasing 24 µm flux density, particularly at higher redshift ($z > 0.6$, Brand et al., 2006). It is clear that a larger fraction of sources are in the AGN region of the color-color plot for the brightest 24 µm and 8 µm flux densities, whereas the 250 µm and 100 µm flux densities do not make as much of a difference to the AGN fraction. We quantify the fraction of sources in each flux bin that are classified as AGN and SF dominated based
Table 3.3: Percentage of AGN and SF field galaxies according to $S_{100}$, $S_{24}$, and $S_{8}$ strength.

<table>
<thead>
<tr>
<th>Range ($S_{100}$ µm)</th>
<th>% AGN (#)</th>
<th>% SF (#)</th>
<th>Range ($S_{24}$ µJy)</th>
<th>% AGN (#)</th>
<th>% SF (#)</th>
<th>Range ($S_{8}$ µJy)</th>
<th>% AGN (#)</th>
<th>% SF (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5</td>
<td>5 (40)</td>
<td>95 (779)</td>
<td>&lt; 200</td>
<td>3 (22)</td>
<td>97 (613)</td>
<td>&lt; 40</td>
<td>3 (21)</td>
<td>97 (741)</td>
</tr>
<tr>
<td>5-15</td>
<td>15 (29)</td>
<td>85 (165)</td>
<td>200-600</td>
<td>9 (35)</td>
<td>91 (337)</td>
<td>40-200</td>
<td>13 (33)</td>
<td>87 (222)</td>
</tr>
<tr>
<td>&gt; 15</td>
<td>36 (25)</td>
<td>64 (44)</td>
<td>&gt; 600</td>
<td>49 (37)</td>
<td>51 (38)</td>
<td>&gt; 200</td>
<td>62 (40)</td>
<td>38 (25)</td>
</tr>
</tbody>
</table>

Note. — Data corresponds to the bottom panels of Figure 3.6. AGN sources (94 total) are those lying above the solid line indicated on the plot. In this table, we calculate the percentage (number) of AGN and SF sources in a given flux density range for $S_{100}$, $S_{24}$, and $S_{8}$.

on these color-color plots in Tables 3.2 and 3.3. Our results show that the presence of an AGN is only visible as an excess in the mid-IR, while the far-IR photometry alone is largely insensitive to the physics of the nuclear power source. We therefore conclude that the flux limit of a mid-IR survey has a big effect on the fraction of sources which have a significant AGN whereas far-IR/submm fluxes correlate less strongly with AGN fraction.

Using the data in Table 3.2, we plot the percentage of galaxies which are classified as AGN and SF greater than a given 24 µm flux density in Figure 3.7. The fraction of AGN sources shows a steady increase with 24 µm flux density. Above $S_{24} \sim 750$ µJy, the majority of galaxies selected at this wavelength will be AGN dominated.

3.4 Chapter Summary

We have combined deep photometry from 3.6 – 500 µm with Spitzer mid-IR spectroscopy for 151 high redshift ($z > 0.5$) (U)LIRGs in order to explore the relative positions of high redshift mid-IR AGN and SF galaxies in IR colorspace. We start by applying color-color diagnostics based on IRAC colors alone (Lacy et al., 2004; Stern et al., 2005) to our high redshift sample and find that there is significant contami-
Figure 3.7: Cumulative distribution of $S_{24}$ for AGN and star forming galaxies. We calculate the percentage of AGN and SF sources (with Poisson error bars) greater than a given $24 \mu m$ flux density. Sources are taken from the GOODS fields and defined as an SF or AGN galaxy based on their position in $S_{250}/S_{24}$ v. $S_{8}/S_{3.6}$ color space (see top panels of Figure 3.6). The brightest flux densities are dominated by AGN, illustrating that applying a flux density cut in $S_{24}$ is useful for selecting a population with a large percentage of AGN.

nation of SF sources in the AGN regions; however, our mid-IR spectroscopic sample confirms the new IRAC color diagnostics from Donley et al. (2012). Adding $24 \mu m$ photometry does not effectively separate all of the AGN, but it does produce a separation of the SF galaxies according to redshift. The same separation of SF galaxies is produced by plotting our redshifted SED tracks in color-color graph using the WISE transmission filters.

Our high redshift AGN and SF sources exhibit different spectral features and SED shape in the near-, mid-, and far-IR/submm wavelengths. We explore combining photometry from all three IR ranges for an optimal selection technique. In addition to photometry, we explore where AGN or SF sources should lie on average in different color combinations by using redshift tracks of our composite SEDs. We present two new color-color diagnostics combining Spitzer mid-IR and Herschel far-IR photometry that can be used to estimate whether a galaxy harbors an AGN in the absence of IRS spectroscopy. The optimal color diagnostics for bright $S_{24}$ sources spanning the full IR spectrum are $S_{250}/S_{24}$ v. $S_{8}/S_{3.6}$ and $S_{100}/S_{24}$ v. $S_{8}/S_{3.6}$. These diagnostics
have a low contamination rate of \( \sim 10\% \) in each of the SF and AGN occupied regions, and the contaminating AGN chiefly have \( S_{24} < 300 \mu \text{Jy} \). Moreover, the \( S_{250}/S_{24} \) color estimates if an AGN is significantly contributing to the bolometric output of a galaxy. The mid-IR photometry from WISE can also be used in conjunction with \textit{Herschel} photometry to separate out AGN. When only limited data is available, either of the colors \( S_{250}/S_{24} \) or \( S_8/S_{3.6} \) can be used alone to select AGN.

We apply our new color-color diagnostics to the entire GOODS-\textit{Herschel} survey to determine the fraction of sources which are dominated by AGN and SF activity. We find roughly 10\% of GOODS-\textit{Herschel} galaxies have a significant AGN. We also confirm that a higher fraction (\( \gtrsim 50\% \)) of the brightest sources, \( S_8 > 200 \mu \text{Jy} \) or \( S_{24} > 600 \mu \text{Jy} \), have colors indicative of a bolometrically significant AGN. The 100 \( \mu \text{m} \) and 250 \( \mu \text{m} \) fluxes show a much weaker dependence on AGN fraction, though when combined with \( S_{24} \), \( S_{250} \) effectively separates out the AGN, indicating that the amount of cold dust emission relative to mid-IR emission is a good indicator of the IR power source. We conclude then that far-IR fluxes or colors alone cannot be used to determine the nature of the IR power source, and the most effective method is to combine mid-IR and far-IR data.
CHAPTER 4

THE ROLE OF STAR-FORMATION AND AGN IN DUST HEATING OF $z = 0.3$-2.8 GALAXIES - EVOLUTION WITH REDSHIFT AND LUMINOSITY

In this chapter\(^1\), we extend the results of Chapters 2 and 3 by combining our GOODS-N and GOODS-S sources with 192 sources from the Spitzer First Look Survey (Sajina et al., 2012). We characterize infrared spectral energy distributions of 343 (Ultra) Luminous Infrared Galaxies from $z = 0.3 - 2.8$. With this combined sample, we are able to probe the effect of a growing AGN on the observed SED by classifying sources as SFGs, AGN, and composites. We are also able to quantify changes in the dust emission as a function of redshift and $L_{\text{IR}}$.

4.1 Sample and Observations

4.1.1 Sample Description

We have assembled a multi-wavelength data set for a sample of 343 high redshift ($z \sim 0.3 - 2.8$) (U)LIRGs in the Great Observatories Origins Deep Survey North (GOODS-N), Extended Chandra Deep Field Survey (ECDFS), and Spitzer Extragalactic First Look Survey (xFLS) fields. All sources are selected to have mid-IR spectroscopy from the Spitzer Space Telescope Infrared Spectrograph (IRS), necessary to concretely quantify the IR AGN emission in each galaxy. Our sample contains a range of sources from individual observing programs, each with differing selection criteria. However, the overarching selection criterion is that each galaxy must be bright

\(^1\)This chapter is published as Kirkpatrick et al. (2015).
enough at 24 µm (observed frame) to be detectable in (< 10 hours). More specific properties of the different fields are outlined below.

The xFLS sample is comprised of archival sources with IRS spectroscopy (complete sample details can be found in Sajina et al., 2012). The sources were selected to have an observed 24 µm flux density greater than 0.9 mJy and to have an R magnitude of $m_{R,\text{Vega}} \geq 20$. Spitzer Program IDs and references are listed in Table 4.1. The xFLS IRS sample contains just under half of the xFLS sources that meet the above photometric criteria; however, Sajina et al. (2012) find that the IRS sample has the same $S_{24}/S_8$ color distribution as the parent sample and is representative of a 24 µm-selected sample ($> 0.9$ mJy) at $z \sim 1$. The $m_{R,\text{Vega}} > 20$ criteria removes the $z \sim 0.2$ peak found in the redshift distribution of a purely 24 µm-selected sample.

The GOODS-N and ECDFS samples include all sources in these fields that were observed with Spitzer IRS (complete details are in Chapter 2). All of these sources were selected at 24 µm (observed), and 93% of have $S_{24} > 100$ µJy. The IRS sources occupy the same regions in $S_{250}/S_{24}$ and $S_8/S_{3.6}$ colorspace as the parent MIPS 24 µm GOODS sample with $S_{24} > 100$ µJy, and they have a similar redshift distribution as those MIPS sources in GOODS for which we have redshift estimates ($\sim 750$ sources).

We illustrate the representativeness of the combined sample in Figure 4.1. We plot the distribution of $S_{24}/S_8$ for our IRS sources, and we compare with the full distribution of GOODS-N, GOODS-S, and xFLS sources. We are limited by the choice of color due to the different wavelength coverage and depths of the xFLS and GOODS fields. We combine $S_8$ with $S_{24}$ as this color traces the relative amount of PAH emission or silicate absorption compared with warm continuum emission, both of which we use to diagnose the presence of an AGN. The xFLS field (2.7 deg$^2$) is much larger than the GOODS fields (0.09 deg$^2$), so we have weighted the distribution of the xFLS sources by the ratio of the field areas. The distributions are not consistent, which is a natural result of our combining several samples with different selection
criteria. However, our IRS sample is generally representative of the GOODS and xFLS fields in the $S_{24}/S_8$ color, although there is a subset of sources with low $S_{24}/S_8$ ratios that we are missing. It is important for the reader to bear in mind that for this study, we are interested in sources that have mid-IR spectroscopy and PACS or SPIRE photometry. Sources with low $S_{24}/S_8$ ratios are likely to be very faint at longer wavelengths. This sample is representative of sources that are detected both in the mid-IR and far-IR and may not cover the parameter space of sources fainter than our flux limits in either IR regime.

An additional result of our different $S_{24}$ selection criteria for fields of different sizes is that we have biased our redshift distribution of SFGs and AGN. Our selection of SFGs is predisposed towards strong PAH emitters at redshifts $z \sim 1$ and $z \sim 2$, where the PAH features fall in the 24 $\mu$m bandpass. Strong AGN are intrinsically brighter at $S_{24}$ (Kirkpatrick et al., 2012); due to the smaller area of the GOODS fields, our brightest AGN are found in the xFLS field at $z > 2$. However, owing to the bright detection limits, no SFGs are found at similar redshifts in xFLS. We use the IRS spectrum to determine redshifts (Section 4.2.2), and this introduces a bias as well, since we require coverage of PAH features or the 9.7 $\mu$m silicate absorption feature. In our sample, 60% of sources have coverage of the 6-8 $\mu$m PAH complexes, 64% have coverage of the 11.2-12.7 $\mu$m complexes, and 82% have coverage of the 9.7 $\mu$m silicate absorption feature. We have 36 sources with a featureless spectrum that have optically available redshifts, but we have rejected a further $\sim 10\%$ of sources that meet our selection criteria because they have featureless spectra and no reliable optical redshift.

4.1.2 Spectroscopy and Photometry

Full details on the IRS observations and data reduction of the xFLS sources are discussed in Dasyra et al. (2009). Here we only present a brief summary. The data
Table 4.1: *Spitzer* Program IDs for IRS sample.

<table>
<thead>
<tr>
<th>PID</th>
<th># of Sources(^a)</th>
<th>References</th>
</tr>
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\(^a\)A few programs resulted in so-called bonus sources indicated with a “+” sign.
Figure 4.1: Representativeness of the IRS supersample. We plot the distribution in $S_{24}/S_8$ (observed) for our IRS sample (black) compared with the full xFLS and GOODS fields (red). We have down-weighted the distribution of xFLS sources (each source is assigned a weight of 0.03) to account for the difference in the sizes of the GOODS and xFLS fields. The IRS sample is representative of the full fields except for very blue sources ($\log S_{24}/S_8 < 0.1$) which are likely undetected in the far-IR.

reduction starts with the Spitzer Basic Calibrated Data (BCD). We removed the residual median sky background from each IRS low-resolution order (the short-low (SL) order covering 5.2-14.7 $\mu$m, and the long-low (LL) order covering 14.3-35.0 $\mu$m). We did a mixture of automatic and manual bad pixel removal, replacing their values with interpolations from their neighbors. The 1D spectra for each nod position and each spectral order were extracted using the Spitzer Science Center package SPICE, adopting the “optimal” extraction technique which in essence is a weighted PSF-fitting and is recommended for faint sources. Aperture and slit-loss corrections are applied. Finally, the two nod positions are averaged and the different orders merged using linear interpolation in the overlap region. The flux calibration was found to be consistent between the orders and consistent with the broadband IRAC 8 $\mu$m and MIPS 24 $\mu$m flux densities.

The low resolution ($R = \lambda/\Delta\lambda \sim 100$) Spitzer IRS spectra in the GOODS-N and ECDFS fields were reduced following the method detailed in Pope et al. (2008a). Specifically, since many of these are long integrations, we take care to remove latent
build-up on the arrays over time, and we create a supersky from all the off-nod observations to remove the sky background. One-dimensional spectra are extracted using SPICE in optimal extraction mode. For each target, a sky spectrum is also extracted to represent the uncertainty in the final target spectrum. The target spectrum flux calibration was found to be consistent with the broadband MIPS $24\,\mu m$ flux densities.

The xFLS field was observed with Herschel SPIRE as part of the HerMES survey, while the GOODS-N and ECDFS fields were imaged with Herschel PACS and SPIRE as part of the GOODS-Herschel Open Time Key Program. All Herschel photometric flux densities are extracted using the MIPS $24\,\mu m$ prior positions. For sources that are blended with another galaxy based on $24\,\mu m$ prior positions, we deblend by fitting two Gaussians. If a source is blended with two or more other galaxies, we reject the photometry at this wavelength. We also reject sources that result in a $\leq 1\sigma$ detection. For the xFLS sources, we have rejected the $250\,\mu m$ photometry for 23 sources, the $350\,\mu m$ photometry for 36 sources, and the $500\,\mu m$ photometry for 46 sources due to being too blended or too faint. In the GOODS-N and ECDFS fields, we reject 26 sources at all SPIRE wavelengths for being too blended. The sources rejected span the full redshift distribution.

We combine Herschel and Spitzer photometry and spectroscopy with ground-based near-IR and submillimeter imaging to obtain excellent coverage of the full IR spectrum from $z = 0.3-2.8$. Specifically, for the GOODS-N and ECDFS sources, we have $J$ and $K$ band photometry from VLT/ISAAC (Retzlaff et al., 2010) and CFHT/WIRCAM (Wang et al., 2010; Lin et al., 2012); Spitzer IRAC 3.6, 4.5, 5.8, 8.0 $\mu m$, IRS 16 $\mu m$, and MIPS 24, 70 $\mu m$ imaging; Herschel PACS 100, 160 and SPIRE 250, 350, 500 $\mu m$ imaging; and 870 $\mu m$ photometry from LABOCA on APEX (Weiβ et al., 2009) and the combined AzTEC+MAMBO 1.1mm map of GOODS-N (Penner et al., 2011). For the xFLS sources, we have Spitzer IRAC 3.6, 4.5, 5.8, 8.0 $\mu m$, and MIPS 24, 70, 160 $\mu m$ imaging; Herschel SPIRE 250, 350, 500 $\mu m$ imaging; and MAMBO 1.2 mm
Figure 4.2: We show the available photometry and spectroscopy for each source in our sample. We redshift the observed photometric wavelengths for individual sources to the rest frame. We plot a filled circle if a source has a photometric detection at a given wavelength, and we indicate the rest frame coverage of the IRS spectra with a blue shaded region. We show an IR SED in grey to better illustrate the coverage of our photometry and spectroscopy. Our spectroscopic and photometric coverage is exceptional, and there are no significant gaps in any particular bandpass due to increasing redshift.

imaging (Lutz et al., 2005; Sajina et al., 2008; Martínez-Sansigre et al., 2009). We illustrate the wavelength coverage of our data in Figure 4.2.

4.2 Mid-IR Spectral Decomposition

4.2.1 AGN Strength

We perform spectral decomposition of the mid-IR spectrum ($\sim 5 - 18 \mu$m rest frame) for each source in order to disentangle the AGN and star forming components. Pope et al. (2008a) explain the technique in detail, and we summarize here. We fit the
individual spectra with a model comprised of four components: (1) the star formation component is represented by the mid-IR spectrum of the prototypical starburst M 82 (we verified the choice of template by comparing with the low redshift starburst template from Brandl et al. (2006), which produced the same results); (2) the AGN component is determined by fitting a pure power-law with the slope and normalization as free parameters; (3,4) extinction curves from the Draine (2003) dust models for Milky Way (MW) type dust is applied to the AGN component and star forming component. The full model is then

\[ S_\nu = N_{AGN} \lambda^\alpha e^{-\tau_{AGN}} + N_{SF} S_\nu(M82)e^{-\tau_{SF}} \]  

We fit for \( N_{AGN}, N_{SF}, \alpha, \tau_{AGN}, \tau_{SF}, \) and redshift simultaneously.

The extinction curve is not monotonic in wavelength and contains silicate absorption features, the most notable for our wavelength range being at 9.7 \( \mu m \). It is important to note that the assumption of MW dust has a non-negligible effect on the normalization of the AGN component, and a lower metallicity dust could lower the overall contribution of an AGN to \( L_{IR} \) (Snyder et al., 2013). The M 82 template already contains some intrinsic extinction. We allow additional extinction to the SF component beyond that inherent in the template and find this to be necessary for 24% of the sources.

For each source, we quantify the strength of the AGN, \( f(AGN)_{MIR} \), as the fraction of the total mid-IR luminosity coming from the extincted power-law continuum component. We classify the sources as SFGs (\( f(AGN)_{MIR} < 0.2 \)), composites (\( f(AGN)_{MIR} = 0.2 - 0.8 \)), and AGN (\( f(AGN)_{MIR} > 0.8 \)). Figure 4.3 illustrates the sample’s \( f(AGN)_{MIR} \) distribution, with colors corresponding to redshift. There are roughly equal numbers of SFGs (30%), composites (34%), and AGN (36%). This high percentage of AGN is a selection effect due to the different field sizes and flux limits. Throughout the paper, we refer to these mid-IR spectroscopically identified
AGN simply as AGN, though the reader should bear in mind that they may not be identified as such at other wavelengths.

Assessing the reliability of our decomposition technique is of utmost importance for interpreting the results in this paper. We have tested the soundness of our $f(\text{AGN})_{\text{MIR}}$ in three ways: 1) The most serious concern is between dust extinction and AGN fraction. We find that if we remove the extinction component, 70% of our sample would have $\Delta f(\text{AGN})_{\text{MIR}} < 0.1$, while 21% would lie within $\Delta f(\text{AGN})_{\text{MIR}} < 0.2$. In general, not including the extinction component scatters to lower $f(\text{AGN})_{\text{MIR}}$. 2) We create synthetic spectra, where we know the input AGN fraction, and add noise. We then run our decomposition code on our synthetic spectra. We can recover $f(\text{AGN})_{\text{MIR}}$ within 0.1 even at a signal to noise ratio of three. 3) We test our results by comparing to another decomposition method, deblendIRS, presented in Hernández-Caballero et al. (2015). The deblendIRS technique decomposes IRS spectra into a stellar, PAH, and AGN component using a library of 19 stellar, 56 PAH, and 39 empirical AGN templates. This allows for variation in the PAH features. When comparing the two techniques, we find on average $\Delta(f(\text{AGN})_{\text{MIR}} - f(\text{AGN})_{\text{deblendIRS}}) = 0$ with a standard deviation of 0.15. These three techniques underscore the reliability of the $f(\text{AGN})_{\text{MIR}}$ values presented here.

4.2.1.1 Comparison of AGN Indicators

We briefly address how our AGN quantification technique compares with two other AGN selection methods often used at high redshift. Our GOODS-N and ECDFS sources have *Chandra* 2 Ms and 4 Ms (respectively) X-ray observations (Alexander et al., 2003; Luo et al., 2008; Xue et al., 2011). Of our AGN in these fields, 73% are detected in the X-ray. We estimate that our AGN all have comparable intrinsic X-ray luminosities, indicating that those AGN that are not detected might be Compton thick (Alexander et al., 2008; Bauer et al., 2010). Of our composite sources, 35%
Figure 4.3: The distribution of mid-IR AGN fraction, determined from the mid-IR spectral decomposition. The colors correspond to redshift. A large portion (30%) are SFGs with little AGN contribution, but there is also a sizeable population of AGN (36%). We indicate our $f(\text{AGN})_{\text{MIR}}$ classifications below the x-axis.

have an X-ray detection. Eleven of our AGN are included in a study by Brightman et al. (2014) that measures column density for sources in GOODS-S. Eight of these AGN have column densities of $N_H \approx 10^{22} - 10^{23}\text{ cm}^{-2}$, but the remaining 3 have $N_H > 10^{24}\text{ cm}^{-2}$, indicating Compton thickness. Much more limited X-ray data exists for the xFLS field. Specifically, Bauer et al. (2010) target 20 AGN sources with *Chandra* 150 ks observations. Only two sources are detected, and the remaining sources are estimated to be Compton thick. Overall, there is broad agreement between our mid-IR spectral AGN indicators and X-ray AGN indicators, although we stress that our technique will not be biased againsty obscured AGN which are much more prevalent at high redshift (e.g., Treister et al., 2010).

*Spitzer* IRAC color selection is also commonly used to cull AGN from a sample (Lacy et al., 2004; Stern et al., 2005; Donley et al., 2012). The criteria in Donley et al. (2012) is based on colors ($S_8/S_{4.5}$ and $S_{5.8}/S_{3.6}$) that distinguish whether a galaxy has power-law emission in the near- to mid-IR, and this power-law emission is indicative of an AGN. However, in Chapter 3, we demonstrated that AGN residing in high redshift (U)LIRGs do not universally display power-law emission in these colors.
due to contamination from the host galaxy. 75% of the AGN in this sample have colors indicative of an AGN according to Donley et al. (2012), while only 29% of composites meet these criteria. The benefit of our mid-IR spectral decomposition is that we can identify heavily obscured AGN and quantify the strength of the AGN emission.

4.2.2 Spectroscopic Redshifts

We determine redshifts for the majority of our sample by fitting the positions of the main PAH features (6.2, 7.7, 11.2, 12.7 µm complexes). Out of our sample, 36 sources have a featureless mid-IR spectrum. In these cases, we adopt available optical spectroscopic redshifts for the GOODS/ECDFS sources (e.g., Szokoly et al., 2004; Barger et al., 2008; Popesso et al., 2009; Stern et al., 2012). Optical redshifts for the xFLS sources were determined with targeted Keck and Gemini follow-up observations (e.g., Choi et al., 2006; Yan et al., 2007; Sajina et al., 2008). Redshifts derived from fitting the PAH features have typical uncertainties of $\Delta z = 0.01 - 0.03$ (Dasyra et al., 2009) while redshifts based only on the 9.7 µm silicate feature (as is the case for many of our strong AGN) have uncertainties of $\Delta z = 0.1 - 0.2$ (Sajina et al., 2007).

The redshift distribution is illustrated in Figure 4.4, where we separate sources according to $f(\text{AGN})_{\text{MIR}}$. The redshift distribution is largely bimodal, with peaks around $z \sim 1$ and $z \sim 2$, which reflects the overarching 24 µm selection criterion. At $z = 1, 2$, prominent PAH features fall within the 24 µm bandpass causing an increase of detected sources with intense star formation. Conversely, at $z \sim 1.5$, the 9.7 µm silicate absorption feature falls within the 24 µm bandpass, resulting in a dearth of sources. The highest redshift sources ($z > 2.5$) are predominantly AGN; this is also a byproduct of the 24 µm selection criterion since AGN activity boosts mid-IR emission. We have relatively more composites at $z \sim 2$ than SFGs because the composites tend to be more luminous at 24 µm due to AGN emission and are more easily detected.
Figure 4.4: The redshift distribution of our sample where we have separated sources by $f(\text{AGN})_{\text{MIR}}$. The top panel shows the fraction of SFGs in each redshift bin, the middle panel shows the fraction of composites, and the bottom panel shows the fraction of AGN per bin. The highest redshift sources are mainly AGN, which reflects the 24 $\mu$m selection criterion, since AGN are typically brighter at this wavelength than SFGs. The bimodal distribution which peaks at $z \sim 1$ and $z \sim 2$, particularly evident for the SFGs and composites, is also a byproduct of the 24 $\mu$m selection, since at these redshifts prominent PAH features fall in the 24 $\mu$m bandpass.
4.3 A New Public Library of Empirical Infrared Templates

The spectral energy distributions of dusty high redshift ULIRGs are seen to differ from the SEDs of local ULIRGs (e.g., Pope et al., 2006; Elbaz et al., 2011; Sajina et al., 2012; Kirkpatrick et al., 2012). In light of this, a library of templates designed specifically for high redshift galaxies is required. Our large spectroscopic sample and wealth of multiwavelength data is ideally suited for this purpose. However, our individual mid-IR spectra are noisy, and many of our sources lack complete coverage of the peak of the SED emission in the far-IR, due to confusion limits from Herschel. Therefore, we can better study the dust emission at high redshift by considering the average SED. We combine our sources to create three libraries of publicly available\(^2\) empirical SED templates:

1. MIR-based Library. This is a user-friendly library suited for sources with mid-IR spectroscopy.

2. Color-based Library. This is a user-friendly library ideal for sources with only IR photometry.

3. Comprehensive Library. This library best represents the intrinsic properties \((f(\text{AGN})_{\text{MIR}}, L_{\text{IR}})\) of our sources.

Within each template library, we divide our sources into subsamples using criteria outlined in Sections 4.3.1-4.3.3. Table 4.2 describes the basic properties of the subsamples comprising each template. We begin by shifting all spectra and photometry to the rest frame. Within each subsample, we determine the median mid-IR luminosity \((5 - 15 \mu\text{m})\) and scale the individual rest frame SEDs using this value. We choose to normalize by the mid-IR luminosity because it minimizes the scatter

\(^2\)http://www.astro.umass.edu/~pope/Kirkpatrick2015
in $L_\nu$ between galaxies at all IR wavelengths while preserving the intrinsic average luminosity of each subsample.

After normalization, we average the IR data by determining the median $L_\nu$ and wavelength in differential bin sizes, chosen so that each bin is well-populated (> 5 data points). In the near-IR and far-IR, where data is scarcer, we calculate rolling medians, and we treat photometric data points and spectroscopic data points the same. For each subsample, we randomly draw sources with replacement and recalculate the normalized median 1000 times; the uncertainty on the template is then the standard deviation around the median. Because we normalize in the mid-IR, the resulting templates exhibit little scatter in and around these wavelengths.

We fit a two temperature modified blackbody (2T MBB) to the bootstrapped far-IR data (> 20 $\mu$m) and uncertainties in order to characterize the shape of the far-IR in terms of physical parameters. The 2T MBB has the form

$$S_\nu = a_w \times \nu^\beta \times B_\nu(T_w) + a_c \times \nu^\beta \times B_\nu(T_c)$$

where $B_\nu$ is the Planck function, and $T_w$ and $T_c$ are the temperatures of the warm and cold dust components, respectively. We keep the emissivity fixed at $\beta = 1.5$, assuming optically thin dust. The choice of model is non-trivial, and we discuss alternate far-IR models in Appendix B. We fit for the normalization factors, $a_w$ and $a_c$, and the temperatures, $T_w$ and $T_c$, simultaneously using a $\chi^2$ minimization technique. The error bars in this regime reflect the uncertainty of the fitted parameters, including both the intrinsic scatter among sources and the photometric uncertainties in the data. We then verify the 2T MBB fit by overplotting photometry from 850 – 1100 $\mu$m, observed frame. The submillimeter data is not included in the fit because it is not available for the majority of sources and would therefore bias the derived cold dust temperature. For all templates, the available submillimeter data agrees with the template within the photometric uncertainties. Our fitting technique is illustrated for one subsample.

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Table 4.2: Categories of template SEDs.

<table>
<thead>
<tr>
<th>Name</th>
<th>Number of Sources</th>
<th>Median $z$</th>
<th>Median $f(\text{AGN})_{\text{MIR}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MIR-based Templates (Figure 4.5)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIR0.0</td>
<td>68</td>
<td>0.94</td>
<td>0.00</td>
</tr>
<tr>
<td>MIR0.1</td>
<td>24</td>
<td>0.94</td>
<td>0.09</td>
</tr>
<tr>
<td>MIR0.2</td>
<td>21</td>
<td>1.10</td>
<td>0.20</td>
</tr>
<tr>
<td>MIR0.3</td>
<td>16</td>
<td>1.38</td>
<td>0.28</td>
</tr>
<tr>
<td>MIR0.4</td>
<td>18</td>
<td>1.39</td>
<td>0.38</td>
</tr>
<tr>
<td>MIR0.5</td>
<td>21</td>
<td>0.96</td>
<td>0.49</td>
</tr>
<tr>
<td>MIR0.6</td>
<td>15</td>
<td>1.59</td>
<td>0.60</td>
</tr>
<tr>
<td>MIR0.7</td>
<td>23</td>
<td>1.50</td>
<td>0.70</td>
</tr>
<tr>
<td>MIR0.8</td>
<td>31</td>
<td>1.52</td>
<td>0.80</td>
</tr>
<tr>
<td>MIR0.9</td>
<td>51</td>
<td>1.80</td>
<td>0.90</td>
</tr>
<tr>
<td>MIR1.0</td>
<td>54</td>
<td>1.18</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>Color-based Templates (Figure 4.8)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COLOR1</td>
<td>75</td>
<td>1.10</td>
<td>0.14</td>
</tr>
<tr>
<td>COLOR2</td>
<td>57</td>
<td>0.94</td>
<td>0.23</td>
</tr>
<tr>
<td>COLOR3</td>
<td>41</td>
<td>1.17</td>
<td>0.39</td>
</tr>
<tr>
<td>COLOR4</td>
<td>26</td>
<td>0.95</td>
<td>0.77</td>
</tr>
<tr>
<td>COLOR5</td>
<td>29</td>
<td>1.52</td>
<td>0.81</td>
</tr>
<tr>
<td>COLOR6</td>
<td>25</td>
<td>1.09</td>
<td>0.96</td>
</tr>
<tr>
<td>COLOR7</td>
<td>24</td>
<td>1.97</td>
<td>0.87</td>
</tr>
<tr>
<td>COLOR8</td>
<td>23</td>
<td>1.83</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>Comprehensive Templates (Figure 4.10)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SFG1</td>
<td>38</td>
<td>0.92</td>
<td>0.00</td>
</tr>
<tr>
<td>SFG2</td>
<td>23</td>
<td>0.91</td>
<td>0.00</td>
</tr>
<tr>
<td>SFG3</td>
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<td>1.75</td>
<td>0.07</td>
</tr>
<tr>
<td>Composite1</td>
<td>24</td>
<td>0.85</td>
<td>0.38</td>
</tr>
<tr>
<td>Composite2</td>
<td>27</td>
<td>0.94</td>
<td>0.60</td>
</tr>
<tr>
<td>Composite3</td>
<td>18</td>
<td>1.89</td>
<td>0.43</td>
</tr>
<tr>
<td>Composite4</td>
<td>29</td>
<td>1.96</td>
<td>0.57</td>
</tr>
<tr>
<td>AGN1</td>
<td>22</td>
<td>0.80</td>
<td>1.00</td>
</tr>
<tr>
<td>AGN2</td>
<td>23</td>
<td>1.03</td>
<td>0.93</td>
</tr>
<tr>
<td>AGN3</td>
<td>21</td>
<td>1.65</td>
<td>0.94</td>
</tr>
<tr>
<td>AGN4</td>
<td>31</td>
<td>1.95</td>
<td>0.93</td>
</tr>
</tbody>
</table>
in Figure 2.5, and we show all subsamples and corresponding templates in Appendix C. Table 4.3 lists \( T_e, T_w, \) and \( L_{IR} \) of each template.

Other popular models for fitting the full IR SED include a power-law combined with a MBB (e.g., Casey, 2012) and a hot torus model combined with a 2T MBB (e.g., Sajina et al., 2012). We opt not to use these models because we do not include near- and mid-IR data in our fits as this portion of each template is created through stacking the data. We tested what effect these different models have on measuring \( L_{IR} \) and \( T_e \) and find no significant change in these parameters.

### 4.3.1 Mid-IR Based Templates

Our sample is unique in that we have mid-IR spectroscopy for every source, allowing us to classify a large sample of galaxies in a similar manner. Therefore, we create a library of eleven templates by separating sources according to \( f(\text{AGN})_{\text{MIR}} \), in order to assess what effect a mid-IR luminous AGN has on the full IR SED. Each subsample is chosen so that it contains at least 15 sources and so that the median \( f(\text{AGN})_{\text{MIR}} \) increases by \( \sim 0.1 \), spanning the range \( f(\text{AGN})_{\text{MIR}} = 0.0 - 1.0 \). We list the subsample properties in Table 4.2 and show the library of MIR-based Templates in Figure 4.5. These user-friendly templates are ideal for inferring far-IR dust properties when little or no far-IR information is available. In particular, this template library will be useful to derive \( L_{IR} \) and estimate SFRs when mid-IR spectroscopy from the forthcoming MIRI instrument on the James Webb Space Telescope becomes available.

In Figure 4.5, we have ordered the templates by the median \( f(\text{AGN})_{\text{MIR}} \) of the sources that comprise each template. PAH features are visible in all but the MIR1.0 template. The MIR0.8-MIR1.0 templates all exhibit silicate absorption, although this may be a selection effect since some pure power-law spectra were excluded from the final xFLS sample. In general, the MIR0.3-MIR0.7 subsamples contain fewer
Table 4.3: Properties of template SEDs.

<table>
<thead>
<tr>
<th>Name</th>
<th>$T_{c}^a$ (K)</th>
<th>$T_{w}^a$ (K)</th>
<th>$L_{\text{IR}}^b$ ($10^{12} L_{\odot}$)</th>
<th>$L_{\text{IR}}^c$ ($10^{12} L_{\odot}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIR0.0</td>
<td>25.7 ± 0.6</td>
<td>66.0 ± 2.4</td>
<td>0.57 ± 0.07</td>
<td>0.57 ± 0.07</td>
</tr>
<tr>
<td>MIR0.1</td>
<td>26.8 ± 1.0</td>
<td>66.7 ± 4.5</td>
<td>0.72 ± 0.16</td>
<td>0.69 ± 0.15</td>
</tr>
<tr>
<td>MIR0.2</td>
<td>24.6 ± 1.3</td>
<td>62.4 ± 1.4</td>
<td>1.05 ± 0.17</td>
<td>0.98 ± 0.16</td>
</tr>
<tr>
<td>MIR0.3</td>
<td>27.3 ± 1.9</td>
<td>75.0 ± 11.3</td>
<td>1.22 ± 0.52</td>
<td>1.11 ± 0.47</td>
</tr>
<tr>
<td>MIR0.4</td>
<td>29.4 ± 1.6</td>
<td>70.3 ± 3.7</td>
<td>2.21 ± 0.49</td>
<td>1.88 ± 0.42</td>
</tr>
<tr>
<td>MIR0.5</td>
<td>29.4 ± 1.8</td>
<td>84.3 ± 5.6</td>
<td>1.17 ± 0.30</td>
<td>0.92 ± 0.23</td>
</tr>
<tr>
<td>MIR0.6</td>
<td>35.2 ± 3.2</td>
<td>87.7 ± 9.9</td>
<td>3.76 ± 1.43</td>
<td>2.82 ± 1.07</td>
</tr>
<tr>
<td>MIR0.7</td>
<td>26.1 ± 2.2</td>
<td>80.2 ± 3.4</td>
<td>1.95 ± 0.47</td>
<td>1.38 ± 0.34</td>
</tr>
<tr>
<td>MIR0.8</td>
<td>28.3 ± 1.3</td>
<td>85.6 ± 3.8</td>
<td>2.97 ± 0.55</td>
<td>1.81 ± 0.34</td>
</tr>
<tr>
<td>MIR0.9</td>
<td>29.0 ± 1.9</td>
<td>89.8 ± 6.1</td>
<td>3.27 ± 0.71</td>
<td>1.67 ± 0.36</td>
</tr>
<tr>
<td>MIR1.0</td>
<td>26.3 ± 2.3</td>
<td>83.4 ± 4.5</td>
<td>1.68 ± 0.33</td>
<td>0.72 ± 0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>$T_{c}^a$ (K)</th>
<th>$T_{w}^a$ (K)</th>
<th>$L_{\text{IR}}^b$ ($10^{12} L_{\odot}$)</th>
<th>$L_{\text{IR}}^c$ ($10^{12} L_{\odot}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COLOR1</td>
<td>26.4 ± 0.9</td>
<td>63.0 ± 4.2</td>
<td>1.16 ± 0.25</td>
<td>1.14 ± 0.24</td>
</tr>
<tr>
<td>COLOR2</td>
<td>24.8 ± 1.1</td>
<td>61.5 ± 3.4</td>
<td>0.66 ± 0.13</td>
<td>0.59 ± 0.12</td>
</tr>
<tr>
<td>COLOR3</td>
<td>26.9 ± 1.5</td>
<td>62.8 ± 4.7</td>
<td>1.89 ± 0.49</td>
<td>1.72 ± 0.45</td>
</tr>
<tr>
<td>COLOR4</td>
<td>20.9 ± 1.6</td>
<td>74.3 ± 7.4</td>
<td>0.81 ± 0.23</td>
<td>0.52 ± 0.15</td>
</tr>
<tr>
<td>COLOR5</td>
<td>28.5 ± 2.4</td>
<td>80.5 ± 4.6</td>
<td>3.35 ± 0.85</td>
<td>2.04 ± 0.52</td>
</tr>
<tr>
<td>COLOR6</td>
<td>27.0 ± 2.4</td>
<td>87.3 ± 4.6</td>
<td>1.62 ± 0.36</td>
<td>0.66 ± 0.15</td>
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<tr>
<td>COLOR7</td>
<td>37.0 ± 3.3</td>
<td>88.3 ± 7.7</td>
<td>4.82 ± 1.66</td>
<td>2.75 ± 0.95</td>
</tr>
<tr>
<td>COLOR8</td>
<td>24.4 ± 2.4</td>
<td>88.9 ± 4.1</td>
<td>2.46 ± 0.56</td>
<td>0.81 ± 0.19</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Name</th>
<th>$T_{c}^a$ (K)</th>
<th>$T_{w}^a$ (K)</th>
<th>$L_{\text{IR}}^b$ ($10^{12} L_{\odot}$)</th>
<th>$L_{\text{IR}}^c$ ($10^{12} L_{\odot}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFG1</td>
<td>26.3 ± 1.0</td>
<td>62.4 ± 5.9</td>
<td>0.40 ± 0.11</td>
<td>0.38 ± 0.10</td>
</tr>
<tr>
<td>SFG2</td>
<td>28.1 ± 1.3</td>
<td>64.9 ± 5.6</td>
<td>1.31 ± 0.35</td>
<td>1.27 ± 0.34</td>
</tr>
<tr>
<td>SFG3</td>
<td>26.8 ± 1.8</td>
<td>58.1 ± 6.9</td>
<td>1.35 ± 0.51</td>
<td>1.28 ± 0.49</td>
</tr>
<tr>
<td>Composite1</td>
<td>25.7 ± 0.9</td>
<td>81.0 ± 5.0</td>
<td>0.49 ± 0.09</td>
<td>0.45 ± 0.08</td>
</tr>
<tr>
<td>Composite2</td>
<td>30.9 ± 2.7</td>
<td>84.3 ± 4.6</td>
<td>1.31 ± 0.51</td>
<td>1.05 ± 0.41</td>
</tr>
<tr>
<td>Composite3</td>
<td>31.1 ± 2.8</td>
<td>72.5 ± 9.6</td>
<td>1.60 ± 0.72</td>
<td>1.02 ± 0.46</td>
</tr>
<tr>
<td>Composite4</td>
<td>38.9 ± 2.9</td>
<td>82.8 ± 15.6</td>
<td>6.96 ± 3.34</td>
<td>5.01 ± 2.40</td>
</tr>
<tr>
<td>AGN1</td>
<td>21.7 ± 2.2</td>
<td>72.7 ± 7.6</td>
<td>0.47 ± 0.17</td>
<td>0.21 ± 0.08</td>
</tr>
<tr>
<td>AGN2</td>
<td>25.3 ± 2.9</td>
<td>86.0 ± 4.4</td>
<td>2.03 ± 0.58</td>
<td>1.24 ± 0.35</td>
</tr>
<tr>
<td>AGN3</td>
<td>31.8 ± 4.1</td>
<td>78.5 ± 9.8</td>
<td>2.38 ± 1.18</td>
<td>0.90 ± 0.45</td>
</tr>
<tr>
<td>AGN4</td>
<td>33.4 ± 5.3</td>
<td>75.2 ± 5.8</td>
<td>6.57 ± 2.10</td>
<td>3.22 ± 1.03</td>
</tr>
</tbody>
</table>

$^a$See Equation 4.2.
$^b$Calculated by integrating each template from 8-1000 µm.
$^c$Fraction of $L_{\text{IR}}$ attributable to star formation. Calculated total AGN contribution to $L_{\text{IR}}$, $f(\text{AGN})_{\text{total}}$, and scaled $L_{\text{IR}}$ correspondingly to obtain $L_{\text{IR}}^{\text{SF}}$. See Section 4.4.
Figure 4.5: MIR-based template library. This library is created by grouping sources according to \( f(\text{AGN})_{\text{MIR}} \) to explore how the shape of the IR SED changes as an AGN grows more luminous. Template subsample properties are listed in Table 4.2. The templates have been arbitrarily offset in \( L_\nu \) to allow for easier comparison. Shaded regions show the uncertainties for each template. MIR0.3 has particularly large uncertainties around 20\,\mu m, but this is due to a lack of data points in this regime. As the mid-IR AGN grows stronger, the far-IR emission becomes flatter due to an increase in the warm dust emission.
sources each, and these sources show a variety of SED features which is reflected in the templates and resulting errors. The lack of uniformity in the MIR0.3-MIR0.7 templates signals that AGN emission may manifest itself in the full IR SED differently based on some property of the host galaxy, such as the spatial distribution of the dust. In contrast, the MIR0.0-MIR0.2 templates have very small uncertainties, suggesting a remarkable uniformity in shape among SFGs.

The MIR0.0-MIR0.2 templates are consistent in shape with the $z \sim 1$ SF SED and $z \sim 2$ SF SED from Chapter 2. The Silicate AGN SED from Chapter 2, created from sources with $f(\text{AGN})_{\text{MIR}} > 0.5$ that exhibited silicate absorption at 9.7 $\mu$m, is consistent with the MIR0.6 template. In contrast, the Featureless AGN SED from that chapter, created from sources with $f(\text{AGN})_{\text{MIR}} > 0.5$ with a power-law spectrum, is not consistent with any of the templates presented here. The MIR0.8-MIR1.0 templates all have more cold dust emission than we observed previously. By combining the GOODS+ECDFS sources from Chapter 2 with the xFLS sources from Sajina et al. (2012), we more than doubled the number of AGN in the sample, increasing the range of observed far-IR SEDs. We also now have proportionally more AGN with silicate absorption, rather than pure power-law AGN, and these silicate AGN tend to have more cold dust.

We characterize the shape of the far-IR using $T_c$, $T_w$, and $L_{\text{cold}}/L_{\text{IR}}$ and plot these properties as a function of $f(\text{AGN})_{\text{MIR}}$ (median of each subsample) in Figure 4.6. $L_{\text{cold}}$ is derived by integrating under the cold dust MBB from Equation 4.2, and it arises from the diffuse ISM, making $L_{\text{cold}}$ and $T_c$ secure tracers of the host galaxy (Dunne & Eales, 2001). $T_c$ varies by less than 5 K for almost all templates (grey dashed line is median $T_c$), illustrating that $T_c$, which quantifies the peak wavelength of the dust emission, is not correlated with the presence of a mid-IR luminous AGN. Since $T_c$ arises from the diffuse ISM, this indicates that on average, the galaxies in our sample all display extended dust emission. $T_c$ for MIR0.6 (light green) is a notable exception.
$T_c$ is nearly 10 K higher for this template, shifting the peak of the SED from $\sim 110 \mu m$ to $\sim 90 \mu m$. $T_c$ is higher for MIR0.6 due to a combination of the fact that there are fewer sources in this bin, and these are the most luminous sources on average in the sample. It is possible this subsample is made up of more compact galaxies, leading to warmer overall dust temperatures. We explore correlations between $T_c$ and $L_{\text{IR}}$ in Section 4.3.3.

$L_{\text{cold}}/L_{\text{IR}}$, the fraction of $L_{\text{IR}}$ due to cold dust emission, is nearly constant for the MIR0.0-MIR0.6 templates, after which it starts to decrease (middle panel of Figure 4.6). We illustrate this trend with the grey dashed line, where we join the median $L_{\text{cold}}/L_{\text{IR}}$ for MIR0.0-MIR0.6 with a simple linear fit to the MIR0.6-MIR1.0 points. Until $f(\text{AGN})_{\text{MIR}} = 0.6$, emission from the extended host galaxy is dominating the infrared luminosity, despite a growing contribution from an AGN to the mid-IR.

In contrast, $T_w$ increases until $f(\text{AGN})_{\text{MIR}} = 0.6$, and then it is fairly constant for $f(\text{AGN})_{\text{MIR}} = 0.7-1.0$ (bottom panel; dashed line is a linear fit joined to a median). $T_w$ has two possible heating sources. The first is star forming regions, either in the extended disk or in a compact starburst, although locally compact starbursts are measured to produce warmer temperatures (e.g., Díaz-Santos et al., 2011). In the MIR0.0-MIR0.1 templates, $T_w$ can be safely attributed to star formation. As the AGN grows stronger, it will contribute to $T_w$, eventually outshining any dust heated by star formation. The gas that fuels a growing AGN can fuel a compact starburst too, making it difficult to distinguish exactly what is responsible for high $T_w$ temperatures. However, the clear trend between $T_w$ and $f(\text{AGN})_{\text{MIR}}$ in our sample indicates that either the AGN progressively increases its heating contribution to the wavelength range $\lambda = 20-80 \mu m$, producing higher $T_w$s, or the growth of the AGN is directly linked with a compact starburst which is responsible for the boost in $T_w$. $f(\text{AGN})_{\text{MIR}} = 0.6$ marks a turning point in the shape of the IR SED. It is here that
$T_w$ reaches its peak temperature, and afterwards AGN-heated dust contributes more to $L_{\text{IR}}$ than the diffuse dust heated by star formation.

The warm dust component fits to the wavelength range $\sim 20 - 80 \mu$m which, for our sample, is covered by MIPS and PACS observations. The xFLS sources lack PACS detections, which could affect the reliability of the warm dust fits and the trend between $T_w$ and $f(\text{AGN})_{\text{MIR}}$. We test how reliable the trend is by fitting the 2T MBB to the far-IR data after removing all PACS and MIPS 160 (available for a few xFLS sources) photometry. The same trends between $T_w$, $L_{\text{cold}}/L_{\text{IR}}$ and $f(\text{AGN})_{\text{MIR}}$ are observed.

4.3.2 Color-Based Templates

In the MIR-based Template Library, we grouped sources according to $f(\text{AGN})_{\text{MIR}}$, but as we noted, the individual sources comprising some of the templates showed a broad range of observed SED properties. We now explore an alternative way to sort sources and create templates based only on the SED shape of each source. In Kirkpatrick et al. (2013) we created an IR color diagnostic designed to capture the full shape of the SED by combining far-, mid-, and near-IR photometry. We present this color diagnostic in Figure 4.7, where we make use of photometry from Herschel SPIRE and Spitzer MIPS/IRAC, available for 87% of our sample. $S_{250}/S_{24}(\text{observed})$ traces the ratio of far-IR emission to mid-IR emission, and this ratio is lower in AGN sources as the heating from the AGN boosts the mid-IR emission. At the redshifts of our sources, $S_8/S_{3.6}(\text{observed})$ is primarily tracing the stellar bump, and in this regime, radiation from the AGN washes this feature out, producing power-law emission.

The top panel of Figure 4.7 illustrates that $f(\text{AGN})_{\text{MIR}}$ grows larger with decreasing $S_{250}/S_{24}$ and increasing $S_8/S_{3.6}$. There is a degree of scatter, particularly among the AGN sources, and in Kirkpatrick et al. (2013) we demonstrated that much of this scatter is attributable to the broad redshift range of our sources. However, intrinsic
Figure 4.6: Far-IR properties of the MIR-based library. We show cold dust temperature (top panel), $L_{\text{cold}}/L_{\text{IR}}$ (middle panel), and warm dust temperature (bottom panel) as a function of $f(\text{AGN})_{\text{MIR}}$ where $f(\text{AGN})_{\text{MIR}}$ is the median value of the sources comprising each template. $T_w$ increases until $f(\text{AGN})_{\text{MIR}}=0.6$, while $L_{\text{cold}}/L_{\text{IR}}$ decreases after this point. In contrast, $T_c$ is roughly constant (dashed line is median $T_c$).
Figure 4.7: Distribution of our sources in IR colorspace using the observed frame colors. 

**Top panel-** Each source is shaded according to $f(\text{AGN})_{\text{MIR}}$. AGN strength increases as $S_{250}/S_{24}$ decreases and $S_8/S_{3.6}$ increases. The dark line (equation in upper right corner) shows the empirical separation between the AGN and SFGs defined in Kirkpatrick et al. (2013). **Bottom panel-** For the Color-based Templates, we group sources by their location in colorspace in order to better explore the differences in the intrinsic IR SED shapes. The sources that comprise each template are illustrated by the shaded regions.
SED shape can also produce scatter, and we have tested this effect using the library of torus models in Siebenmorgen et al. (2015). These models account for the intrinsic luminosity of the AGN, the viewing angle, the inner radius of the torus, the volume filling factor and optical depth of the toroidal clouds, and the optical depth of the disk midplane in the host galaxy. We redshift the models to $z = 1.5$ and plot their observed frame colors. We find that this library of AGN SEDs occupies the same general region as our AGN, although with a much broader distribution of colors, and varying the radius of the inner torus and the optical depth of the host disk does the best job at reproducing the observed scatter of our sources. Modeling the geometry of the torus in individual sources is beyond the scope of this work; however, the above suggests that allowing for a range of host galaxy optical depths can already account for much of the scatter in colorspace. Indeed, Roebuck et al. (2016, in prep.) uses simulations to show that our empirical IR AGN templates include not only the torus, but also the host dust-reprocessed light. We conclude that both redshift and intrinsic SED shape can account for the scatter of our sample.

To create the Color-based Templates, we divide sources according to $S_{250}/S_{24}$ and $S_{8}/S_{3.6}$, so that we can quantify differences in $T_w$ and $T_c$ as a smooth function of $S_{250}/S_{24}$ and $S_{8}/S_{3.6}$. We illustrate the color criteria for each subsample in the bottom panel of Figure 4.7. We have blindly chosen the color criteria rather than basing them on existing knowledge of the IR SED so that we can more fairly test how SED properties correlate with colors. The color bins were chosen so that each subsample has roughly the same number of sources. This template library is ideal for applying to high redshift sources that only have IR photometry available. Although created from the same sources, this library differs from the MIR-based Library in part because $S_{8}/S_{3.6}$ is sensitive to dust obscuration which is an effect missed when separating by $f(\text{AGN})_{\text{MIR}}$ alone. Furthermore, $S_{250}/S_{24}$ is sensitive to dust temperature, and when we sort sources by this color, we can test how strong the link is between the
increase in warm dust and $f(\text{AGN})_{\text{MIR}}$. This is subtly different from linking $T_w$ and $f(\text{AGN})_{\text{MIR}}$ in the MIR-based Library. In essence, with the MIR-based Library, we sorted sources by mid-IR AGN emission and looked for trends with the far-IR. Here, we begin by separating according to a far-/mid-IR color and test whether we recover the same trends with $f(\text{AGN})_{\text{MIR}}$.

In Kirkpatrick et al. (2013), we defined an empirical separation between AGN and SFGs

$$\log(S_8/S_{3.6}) = 0.74 \times \log(S_{250}/S_{24}) - 0.78$$

shown as the dark line in Figure 4.7. By dividing colorspace into eight quadrants, we can refine this AGN selection technique to include composites as well. Our color criteria can be used to estimate $f(\text{AGN})_{\text{MIR}}$ of a source, and for this purpose we list the mean $f(\text{AGN})_{\text{MIR}}$ in each color region in Table 4.4. The upper three quadrants, COLOR6, COLOR7, and COLOR8, have the smallest spread of $f(\text{AGN})_{\text{MIR}}$, so these color criteria are excellent for selecting strong AGN sources. SFGs are confined to the lower three quadrants, COLOR1, COLOR2, and COLOR3. The middle regions, COLOR4 and COLOR5, have a large population of composite galaxies, which show strong star forming and AGN signatures.

Figure 4.7 and Table 4.4 demonstrate that there is a large spread in the observed colors of AGN due to differing levels of dust obscuration, varying amounts of dust heating by the AGN, or slight differences in the intrinsic SED of the host galaxy (Mullaney et al., 2011). We have tested potential effects of heavy obscuration using the high $\tau$ AGN template from Sajina et al. (2012) and find that obscuration can account for some of the scatter in the COLOR6, COLOR7, and COLOR8 quadrants, but it will not cause an AGN to mimic the colors of an SFG or composite. The spread in our AGN SEDs is consistent with what is observed in the local Universe, where local LIRGs with a significant mid-IR AGN contribution have a larger range of
Table 4.4: Mid-IR AGN strength of IR color regions.

<table>
<thead>
<tr>
<th>Region</th>
<th>$S_8/S_{3.6}$</th>
<th>$S_{250}/S_{24}$</th>
<th>Mean $f(\text{AGN})_{\text{MIR}}$</th>
<th>$\sigma^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>COLOR1</td>
<td>$&lt; 1.3$</td>
<td>$\geq 35$</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>COLOR2</td>
<td>$&lt; 1.3$</td>
<td>$&lt; 35$</td>
<td>0.26</td>
<td>0.27</td>
</tr>
<tr>
<td>COLOR3</td>
<td>1.3-2.5</td>
<td>$\geq 20$</td>
<td>0.41</td>
<td>0.34</td>
</tr>
<tr>
<td>COLOR4</td>
<td>1.3-2.5</td>
<td>$&lt; 20$</td>
<td>0.70</td>
<td>0.26</td>
</tr>
<tr>
<td>COLOR5</td>
<td>2.5-5.0</td>
<td>$\geq 13.5$</td>
<td>0.75</td>
<td>0.27</td>
</tr>
<tr>
<td>COLOR6</td>
<td>2.5-5.0</td>
<td>$&lt; 13.5$</td>
<td>0.94</td>
<td>0.06</td>
</tr>
<tr>
<td>COLOR7</td>
<td>$\geq 5.0$</td>
<td>$\geq 14.5$</td>
<td>0.83</td>
<td>0.12</td>
</tr>
<tr>
<td>COLOR8</td>
<td>$\geq 5.0$</td>
<td>$&lt; 14.5$</td>
<td>0.91</td>
<td>0.10</td>
</tr>
</tbody>
</table>

$a$ Each region is illustrated in the bottom panel of Figure 4.7.

$b$ The color limits corresponding to each region.

$c$ The standard deviation of $f(\text{AGN})_{\text{MIR}}$ around the mean values so that the reader can understand the typical spread of $f(\text{AGN})_{\text{MIR}}$ for each region.

silicate absorption and PAH emission strengths compared with star forming LIRGs (Stierwalt et al., 2014).

We show all eight templates in Figure 4.8, where we have separated the templates into two panels for easier comparison based on $S_{250}/S_{24}$ color divisions. For consistency with the other libraries, we also truncate these templates below 2 $\mu$m, although the observed 3.6 $\mu$m photometry point falls below this threshold at $z > 0.8$. In general, there is a lot of scatter below 2 $\mu$m, and since we are not fitting this regime with any physical model, we truncate the templates to avoid over-interpreting the data. The templates in the right panel, with higher $S_{250}/S_{24}$ ratios, all have clearly visible PAH features. In the left panel, the warm dust component is clearly prominent, and the near-IR slope grows steeper as the AGN becomes stronger. The COLOR8 template still has larger errors around the cold dust component than the other templates, which is primarily attributable to selection effects. This template is comprised of the strongest AGN sources, and these sources typically lie at higher redshift, producing less photometry in the Rayleigh-Jeans tail (at the median redshift, 500 $\mu$m observed
Figure 4.8: Color-based template library. The sources have been selected by their location in IR colorspace. We have separated the eight templates into two panels to allow for easier comparison based on their far-IR colors. The templates in the left panel have lower $S_{250}/S_{24}$ ratios and a stronger warm dust contribution than the templates in the right panel.

frame corresponds to $\sim 170$ $\mu$m rest frame). The cold dust emission of this template agrees with the available submillimeter observations (Appendix C), but since submillimeter observations are necessarily biased towards colder sources, we caution against using this template to extrapolate to submillimeter wavelengths.

We explore the dust properties as a function of the IR colors in Figure 4.9. By grouping sources based on observed properties, we are able to look for correlations between observed properties and intrinsic properties such as dust temperature and $f(\text{AGN})_{\text{MIR}}$. The cold dust temperature shows no obvious correlation with $S_{250}/S_{24}$ and $S_8/S_{3.6}$. This is similar to what we observe for the MIR-based Library. $S_{250}/S_{24}$ is correlated with $T_w$ and $L_{\text{cold}}/L_{\text{IR}}$. The trend with $S_{250}/S_{24}$ is expected since this ratio covers the wavelength range that we fit the warm MBB. The trend with $L_{\text{cold}}/L_{\text{IR}}$ clearly demonstrates that $S_{250}/S_{24}$ is a good proxy for the relative amount of cold dust emission by a galaxy.

We are also able to observe the effect of the AGN on multiple portions of the IR SED when we examine the trends between $L_{\text{cold}}/L_{\text{IR}}$, $T_w$ and the near-IR color $S_8/S_{3.6}$. The prominence and temperature of the warm dust component increases as this color
Figure 4.9: Dust properties of the Color-based templates. Warm dust temperature, $L_{\text{cold}}/L_{\text{IR}}$, and $f(\text{AGN})_{\text{MIR}}$ are a strong function of the two IR colors, due to the fact that $T_w$ and $L_{\text{cold}}/L_{\text{IR}}$ are influenced by heating from the growing AGN. In contrast, the cold dust temperature comes from the host galaxy, and this property is insensitive to IR color.
The increase of $S_8/S_{3.6}$ is due to dust heating from the torus outshining the stellar bump, producing a power-law whose slope depends on the amount of dust extinction. The far-IR emission is not necessarily occurring on the same spatial scales as the near-IR emission, since dust at different temperatures is required to produce emission in each wavelength range. The correlation between $L_{\text{cold}}/L_{\text{IR}}$, $T_w$ and $S_8/S_{3.6}$ could indicate that the same mechanism is responsible for both far-IR and near-IR sources of dust heating. We can test whether an AGN or star formation is the primary driver of the warm dust temperature by comparing the warm dust temperature with the amount of $L_{\text{IR}}$ due to star formation or an AGN (calculated in Section 4.4). We find no correlation between $T_w$ and $L_{\text{IR}}^{\text{SF}}$ (listed in Table 4.3), but we see a strong relationship between $T_w$ and $L_{\text{IR}}^{\text{AGN}}$, hinting that AGN luminosity is responsible for the increase in the warm dust temperature. This AGN-heated warm dust cannot be directly associated with the torus, which is on much smaller spatial scales and much hotter, but is most likely AGN-heated dust in the host galaxy.

The bottom row of Figure 4.9 shows the trends between $f(\text{AGN})_{\text{MIR}}$ and each color. We plot the median $f(\text{AGN})_{\text{MIR}}$ and include the upper and lower quartiles to illustrate the spread in each subsample. $f(\text{AGN})_{\text{MIR}}$ is strongly correlated with $S_{250}/S_{24}$, illustrating that the ratio of far- to mid-IR emission is an excellent indicator of mid-IR AGN strength. On the other hand, $f(\text{AGN})_{\text{MIR}}$ shows a bimodality with $S_8/S_{3.6}$ rather than a linear trend. Sources with $f(\text{AGN})_{\text{MIR}}>0.8$ have a range of $S_8/S_{3.6}$ values, partially explained by differing extinction levels, while sources with $f(\text{AGN})_{\text{MIR}}<0.2$ have $S_8/S_{3.6} \leq 1$.

### 4.3.3 Comprehensive Templates

In this library, we look for evolution of the IR SED shape as a function of AGN strength, redshift, and $L_{\text{IR}}$. We initially separate our sources by $f(\text{AGN})_{\text{MIR}}$. We have three categories: (1) SFGs ($f(\text{AGN})_{\text{MIR}} \leq 0.2$); (2) Composites ($f(\text{AGN})_{\text{MIR}} = 0.2-0.8$);
Figure 4.10: Comprehensive template library. We have separated sources by \( f(\text{AGN})_{\text{MIR}} \), redshift, and \( L_{\text{IR}} \). SFGs (\( f(\text{AGN})_{\text{MIR}}<0.2 \)) are plotted in the left row, Composites (\( f(\text{AGN})_{\text{MIR}}=0.2-0.8 \)) in the middle row, and AGN (\( f(\text{AGN})_{\text{MIR}}>0.8 \)) in the right row. The top row shows our selection criteria as the shaded regions for the sources that comprise each template. We overplot the median \( L_{\text{IR}} \) and \( z \) in each subsample (symbols here correspond to symbols used in Figure 4.11). Shaded regions were selected to maximize completeness while optimizing the median redshift and \( L_{\text{IR}} \) so that we can compare templates at similar redshifts and \( L_{\text{IR}} \). The middle row shows the library of templates at the intrinsic luminosity density of each template, while in the bottom row, the templates have all been normalized at 300\( \mu \)m to allow easier comparison of the mid- and far-IR features. The large uncertainties on the far-IR emission of the AGN templates are due to the intrinsic scatter of SED shapes among these sources and a lack of data constraining the Rayleigh-Jeans tail due to the redshifts of the sources. The shape of the SFGs is remarkably consistent. The peak of the SED increases steadily for the Composites, as can clearly be seen in the bottom middle panel. The AGN1 and AGN2 templates, which are created from the lower redshift AGN, have a distinctly different far-IR shape than the AGN3 and AGN4 templates, indicating a possible temperature evolution with redshift.
(3) AGN \( (f(\text{AGN})_{\text{MIR}} \geq 0.8) \). These categories are motivated by the trends we seen in the MIR-based and Color-based Libraries. The bottom panels of Figure 4.9 demonstrate that the near-IR and far-IR colors change significantly when \( f(\text{AGN})_{\text{MIR}} > 0.8 \) and \( f(\text{AGN})_{\text{MIR}} < 0.2 \), making these natural selection thresholds.

Within these \( f(\text{AGN})_{\text{MIR}} \) categories, we further separate by redshift and by \( L_{\text{IR}} \), selected to maximize completeness in each \( L_{\text{IR}} - z \) bin. We have optimized the redshift and \( L_{\text{IR}} \) selection criteria in order to have at least two subsamples with similar median redshifts and two subsamples with similar \( L_{\text{IR}} \) values, so that we can examine the shape of the templates as a function of both redshift and \( L_{\text{IR}} \). The division of the sources is illustrated in the top rows of Figure 4.10. Our Comprehensive Library is shown in the middle rows of Figure 4.10, and in the bottom rows we have normalized the templates at 300 \( \mu m \) to allow for easier comparison. The large uncertainties in the range 15-30 \( \mu m \) for the higher redshift templates is due to a scarcity of photometric data, particularly for the SFGs due to these sources being intrinsically fainter in this regime. The high redshift Composites (blue and gold templates) have large far-IR errors as a result of few sources in this subsample. In contrast, the large uncertainties on the far-IR for the AGN templates are caused by the intrinsic scatter of SED shapes among these subsamples and a lack of data constraining the Rayleigh-Jeans tail for the high redshift templates.

The bottom panels of Figure 4.10 qualitatively illustrate a fundamental difference between our SFGs and our Composites and AGN. The SFGs have a high degree of similarity between all \( L_{\text{IR}} \)s and redshifts. Our analysis suggests that on average, the SFG SED does not evolve with redshift or luminosity for these types of massive dusty galaxies. Any evolution between \( L_{\text{IR}} \) and dust temperature is driven not by an intrinsic change in the ISM of high redshift (U)LIRGs, but by a different process, such as a growing AGN. We should note that our selection criteria is biased towards sources with strong PAH emission (which we will comment on further in Section 4.5),
and we are examining only one order of magnitude in $L_{\text{IR}}$ which is possibly too narrow of a range to expect to see any strong trend between $T_c$ and $L_{\text{IR}}$.

We quantify the far-IR dust properties of the Comprehensive Library in Figure 4.11. In the left column, we plot $T_c$, $T_w$, and $L_{\text{cold}}/L_{\text{IR}}$ as a function of the median redshift of the sources that were used to create each template. In the right column, we plot these properties as a function of template $L_{\text{IR}}$. The three SFG templates all have the same $T_c$, $T_w$, and $L_{\text{cold}}/L_{\text{IR}}$ regardless of $L_{\text{IR}}$ or redshift, effectively demonstrating the lack of evolution in these sources, on average.

In contrast, the Composites and AGN show a clear increase in $T_c$, also evident in Figure 4.10 where the peak of the SED shifts with increasing $L_{\text{IR}}$ and $z$. For the Composites, the increase in $T_c$ is correlated with $L_{\text{IR}}$, as can be seen clearly by examining the green points in the top right panel of Figure 4.11. The Composite2 and Composite4 templates (square and circle) each have $T_c$ at least 5 K higher than the Composite1 and Composite3 templates (diamond and triangle), despite lying at similar redshifts, respectively. In contrast, for the AGN, the increase of $T_c$ is more strongly correlated with redshift, although $T_c$ has large uncertainties. It is important not to overstate this distinction, since our high redshift subsamples are biased towards sources with high $L_{\text{IR}}$. Nevertheless, the clear difference between the AGN and Composites hint that different mechanisms could be driving the evolution of dust temperature. For the Composites, this change could be driven by an increase in the importance of mergers which produce compact starbursts and warmer dust (Armus et al., 2007), while for the AGN, there might be an intrinsic evolution in the effect of an AGN on the IR SED with redshift, as galaxies have higher gas fractions and clumpier ISMs. We have morphological classifications for our xFLS sample (Zamojski et al., 2011), and these data hint at an increase in the number of interacting galaxies for the higher luminosity Composite templates, but not for the AGN. We will examine the individual morphologies of our galaxies in a future work.
Figure 4.11: Far-IR properties of the Comprehensive library. We plot the derived cold and warm dust temperatures ($T_c$, $T_w$) for each of our 11 Comprehensive Templates, as well as the fraction of $L_{IR}$ due to the cold dust component. We shade the points according to $f(\text{AGN})_{\text{MIR}}$, so that SFGs are blue, Composites are green, and AGN are red; in addition, symbols correspond to redshift and $L_{IR}$ of the templates (illustrated in the top row of Figure 4.10). Here, we plot the far-IR dust parameters as a function of the median redshift of the sources used to create each template and as a function of the template $L_{IR}$. In the lower panels, we plot the median $T_w$ and $L_{\text{cold}}/L_{\text{IR}}$ for the SFGs, Composites, and AGN templates as the dashed lines. Cold dust temperature increases with $L_{IR}$ and redshift for the Composites and AGN, while the SFGs show no evolution. $L_{\text{cold}}/L_{\text{IR}}$ is significantly lower in the AGN templates because dust heated by the AGN is now outshining much of the dust heated by starlight alone. In the upper right panel, we have plotted the $L_{\text{IR}}$-$T$ relation from Casey et al. (2012).
The relationship between dust temperature and \( L_{\text{IR}} \) that we see for the Composites and AGN is consistent with what is derived for a large sample of high redshift SPIRE 250\( \mu \text{m} \) selected galaxies (Casey et al., 2012). We have over plotted the relation from Casey et al. (2012) as the black line and grey shaded region in the top right panel. Casey et al. (2012) make no attempt to separate sources into SFGs or AGN. The increase in \( T_c \) in our Composite and AGN templates is noticeably absent in our SFG templates, implying that the \( L_{\text{IR}} - T \) relation is not driven by a simple change in the ISM with redshift. However, we lack a higher luminosity SFG template, so it is impossible to say conclusively that we would not observe a trend among the SFGs if we had full coverage at high \( L_{\text{IR}} \).

The middle panels of Figure 4.11 show the warm dust temperatures. We plot the average warm dust temperatures for the SFG, Composite, and AGN templates as the dashed lines to allow for easier comparison. \( T_w \) does not evolve strongly with either \( L_{\text{IR}} \) or redshift. Furthermore, \( T_w \) is similar for the Composite templates (the average \( T_w \) for all four templates is 80 K) and AGN templates (average \( T_w = 78 \) K), while SFGs have a lower average \( T_w \) of 62 K. This suggests that the mechanism responsible for heating the warm dust component is linked with \( f(\text{AGN})_{\text{MIR}} \), and it also confirms that our threshold of \( f(\text{AGN})_{\text{MIR}} < 0.20 \) for selecting SFGs is well-founded. The middle panels are best interpreted in comparison with the bottom panels. When we examine the fraction of \( L_{\text{IR}} \) due to the cold dust component, we find that the Composites and SFGs have similar fractions (\( L_{\text{cold}}/L_{\text{IR}} \sim 0.52 \)), while the AGN only have \( L_{\text{cold}}/L_{\text{IR}} \sim 0.25 \), despite having similar warm dust temperatures as the Composites.

Taken together, these data present a picture whereby the Composites are a true mix of the SFGs and AGN. In SFGs, the warm dust arises from star-forming regions. Once an AGN significantly contributes to the mid-IR emission, warm dust heated by the AGN becomes more luminous than the warm dust located in star forming regions, producing an increase in \( T_w \). However, although a significant amount of the dust is
now heated by a central AGN in the Composite galaxies, the cold dust emission still
dominates $L_{\text{IR}}$. For the AGN, a larger fraction of the dust mass is heated by the
central AGN as indicated by the lower $L_{\text{cold}}/L_{\text{IR}}$ ratios.

4.4 Relation Between Mid-IR and Far-IR

Throughout this paper, we have been discussing the AGN strength in the mid-
IR. We now wish to explore how $f(\text{AGN})_{\text{MIR}}$ correlates with the total contribution
of the AGN to $L_{\text{IR}}$. We use the three template libraries presented in Section 4
to calculate a conversion between $f(\text{AGN})_{\text{MIR}}$ and $f(\text{AGN})_{\text{total}}$. First, we perform
mid-IR spectral decomposition, described in Section 4.2.1, on each template from
$\lambda = 5-15 \mu m$. Next, we use a similar decomposition technique for the entire template.
We fit simultaneously the $z \sim 1$ Star Forming SED and the Featureless AGN SED
from Chapter 2. We removed the cold dust component from the Featureless AGN
SED, as this component arises from the host galaxy. We have verified that the
remaining SED does not contain any host emission using the decomposition package
decompir presented in Mullaney et al. (2011). We modify the Featureless AGN SED
with the extinction curve from Draine (2003), where we hold $\tau$ fixed to the values
derived from the mid-IR spectral decomposition. The normalizations of the AGN
and Star Forming SEDs are the only free parameters, and we allow them to vary
simultaneously. Figure 4.12 illustrates two decomposition examples. We calculate
$f(\text{AGN})_{\text{total}}$ by integrating under the Featureless AGN SED to obtain the $L_{\text{IR}}$ of the
AGN component, and we express this as a fraction of the total $L_{\text{IR}}(8-1000 \mu m)$.
This simple decomposition technique works well for 80% of our templates. However,
the Composite4, AGN1, AGN4, MIR6, COLOR4, and COLOR7 templates are not
well fit, resulting in poor $\chi^2$, due to the cold dust peaking at significantly warmer
temperatures than the $z \sim 1$ Star Forming SED, and we exclude them from the
analysis below.
Figure 4.12: Illustration of our full IR SED decomposition technique. We show both a star forming template (MIR0.1, left) and an AGN template (MIR1.0, right). We find a best fit model (red dashed line) by simultaneously fitting the z ∼ 1 Star Forming SED (green dot-dashed line) and Featureless AGN SED (blue dotted line), with extinction if required, from Kirkpatrick et al. (2012). We then integrate under the AGN component (blue dotted line) to calculate $f(\text{AGN})_{\text{total}}$ which is the fraction of $L_{\text{IR}}(8-1000 \mu m)$ due to AGN heating. We have illustrated the integrated portion of the model and AGN component with the shaded regions. In the insets, we show the mid-IR decomposition (Equation 4.1), used to calculate $f(\text{AGN})_{\text{MIR}}$ from 5-15 $\mu$m.
We plot $f(\text{AGN})_{\text{MIR}}$ versus $f(\text{AGN})_{\text{total}}$ in Figure 4.13, where the filled symbols correspond to the template libraries. In the bottom panel, we quantify the relationship between $f(\text{AGN})_{\text{MIR}}$ and $f(\text{AGN})_{\text{total}}$ with a simple linear scaling (plotted as the dashed line)

$$f(\text{AGN})_{\text{total}} = (0.49 \pm 0.02) \times f(\text{AGN})_{\text{MIR}} \quad (4.4)$$

where we have weighted each template by the number of sources comprising it. We require the linear fit to have a $y$-intercept of 0, so that $f(\text{AGN})_{\text{total}}=0$ when $f(\text{AGN})_{\text{MIR}}=0$. The standard deviation around this relation is 9.6% (grey shaded region). Our composite templates lie below the dashed line while the AGN lie above it, indicating that a simple linear scaling may not be the best choice, especially if $f(\text{AGN})_{\text{MIR}}$ is well known.

In the top panel, we use a quadratic equation to quantify the relationship between $f(\text{AGN})_{\text{MIR}}$ and $f(\text{AGN})_{\text{total}}$:

$$f(\text{AGN})_{\text{total}} = (0.66 \pm 0.09) \times f(\text{AGN})_{\text{MIR}}^2 - (0.035 \pm 0.07) \times f(\text{AGN})_{\text{MIR}} \quad (4.5)$$

Again, we have weighted each template by the number of sources that comprise it, and we have forced the $y$-intercept to be 0. We plot this relationship, and the corresponding standard deviation of 5.8%, as the dark dashed line and grey shaded region, respectively. The smaller standard deviation indicates that this is a better fit for our templates.

We independently test the validity of our relation using the SEDs of individual sources with exceptional photometric coverage of the far-IR. We have already decomposed the mid-IR spectra of these sources, and we decompose the full SEDs using the same procedure as for our templates. We plot these sources as the black crosses. The scatter among the individual sources better illustrates the uncertainty associated with our decomposition methods, but in general, the trend between $f(\text{AGN})_{\text{MIR}}$ and
Figure 4.13: $f(\text{AGN})_{\text{MIR}}$ v. $f(\text{AGN})_{\text{total}}$. Typical uncertainties on each parameter are shown in the lower right corner. $f(\text{AGN})_{\text{MIR}}$ has a higher error because we have included an extinction component in this fit, while when fitting $f(\text{AGN})_{\text{total}}$, we only allow the relative normalizations to vary. We fit a quadratic equation (top panel) and a linear relation (bottom panel) to our templates (filled symbols). The standard deviation of the templates around each relation is shown as the grey shaded region. We have a handful of sources ($\sim$ 30) with exceptionally well-sampled SEDs, allowing us to decompose the entire SED into an AGN and star forming component. We plot these sources as the crosses. They are not included in the linear or quadratic fits or the standard deviation calculations, but they agree remarkably well with these relations, ensuring the reliability of our results. The quadratic relation provides a better fit to the data.
$f(\text{AGN})_{\text{total}}$ for the sources agrees remarkably well with the templates and reinforces that the quadratic relation is a better fit to the data than the linear scaling.

The quadratic relation arises because AGN-heated dust emission falls off sharply after 40 $\mu$m, so $L_{\text{IR}}$ is dominated by stellar heating after this wavelength. That is, until the AGN boosts the warm and hot dust emission enough to outshine the cold diffuse dust which Figure 4.6 indicates happens when $f(\text{AGN})_{\text{MIR}}>0.70$. This non-linear relationship supports what we found earlier, that composites are an intermediate class between SFGs and AGN where most of the far-IR emission can be attributed to star formation, although the AGN is dominating at shorter wavelengths.

Since we have determined $f(\text{AGN})_{\text{total}}$, we can scale $L_{\text{IR}}$ by $(1-f(\text{AGN})_{\text{total}})$ to obtain $L_{\text{IR}}^{\text{SF}}$, the portion of $L_{\text{IR}}$ due only to heating by stellar radiation (listed in Table 4.3). We could not decompose the full IR SED of the Composite4, AGN1, AGN4, MIR6, COLOR4, and COLOR7 templates, so we calculate $f(\text{AGN})_{\text{total}}$ using Equation 4.5. $L_{\text{IR}}^{\text{SF}}$ is a crucial quantity for obtaining accurate star formation rates. In future surveys, particularly with JWST, $f(\text{AGN})_{\text{MIR}}$ can be determined using mid-IR spectroscopy; this can then be converted into $f(\text{AGN})_{\text{total}}$ using one of our relations, and $L_{\text{IR}}$ can be scaled accordingly so as not to overestimate star formation rates. Carefully removing AGN contribution to $L_{\text{IR}}$ will provide a more accurate understanding of the buildup of stellar mass in the early Universe.

Finally, we wish to comment on how our far-IR properties relate to another commonly used measure, $L(\text{FIR})$ which is the integrated luminosity from 50 – 300 $\mu$m. $L_{\text{cold}}$ accounts for most of the emission in this wavelength regime, and we find a nearly linear relationship between $L_{\text{cold}}$ and $L(\text{FIR})$:

$$L(\text{FIR}) = 6.92 L_{\text{cold}}^{0.94}$$

$L_{\text{cold}}$ also accounts for the bulk of $L_{\text{IR}}$ attributed to star formation by our decomposition technique, and $L_{\text{cold}}$ and $L_{\text{IR}}^{\text{SF}}$ have a nearly linear relationship as well.
The strong correlation between $L(\text{FIR})$ and $L_{\text{IR}}^{\text{SF}}$ strengthens our conclusion that heating by star formation accounts for the bulk of the cold, far-IR emission.

4.5 Discussion

4.5.1 Consistency in Star Forming Galaxies Over Cosmic Time

We have carefully decomposed the mid-IR spectra of our sources, allowing us to classify galaxies harboring a buried AGN that may not be visible at other wavelengths. An additional benefit of this classification scheme is that it enables us to isolate the mid- and far-IR properties of purely star forming galaxies over a large range in redshift. Within the Comprehensive Library, we have determined the average SEDs of pure SFGs with median redshifts of $z \sim 0.8$ and $z \sim 1.7$, and these templates are indistinguishable (left column of Figure 4.10). In particular, we find that mid-IR classification is an excellent predictor of far-IR emission, and this is not a trivial result since mid-IR and far-IR emission are tracing different dust populations at different spatial locations.

Before we discuss the full IR SED, we want to comment on our mid-IR identification technique. Our technique for selecting SFGs hinges on the PAH emission, and it is possible that we could misidentify SFGs that have mid-IR emission dominated by star formation, but also have weak PAH emission. However, based on previous results in the literature, we do not think these types of galaxies are common in samples of (U)LIRGs; locally, such galaxies are low-metallicity dwarfs (e.g., Wu et al., 2006). The similarity of PAH emission among star forming galaxies is also seen in Battisti et al. (2015), which compares PAH features of local star forming galaxies ($L_{\text{IR}} \sim 10^{10} L_\odot$) and finds remarkable consistency. These galaxies have been classified as SFGs according to optical emission line ratios. Battisti et al. (2015) also compares the average
PAH emission of these local SFGs with the star forming templates from Kirkpatrick et al. (2012) and find they are consistent, showing no evolution of PAH emission features with redshift or luminosity. Petric et al. (2011) classifies local (U)LIRGs from the Great Observatories All Sky Survey (GOALS; Armus et al., 2009) as SFGs based on mid-IR flux ratios and finds that PAH emission in all SFGs is qualitatively similar. On the other hand, Polletta et al. (2008) and Bauer et al. (2010) conclude that the mid-IR continuum in high redshift ULIRGs with weak PAH features is dominated by quasar emission, although these sources can still have a significant amount of $L_{\text{IR}}$ due to star formation. Our results are consistent with these previous studies.

Our SFG templates have no significant change in $T_w$, $T_c$ or $L_{\text{cold}}/L_{\text{IR}}$ with redshift or $L_{\text{IR}}$, effectively demonstrating that the average dust heating in SFGs remains constant over a broad epoch. This result does not contradict observations from Béthermin et al. (2015). For a sample of main sequence galaxies spanning a redshift range of $z = 0.5 - 4$, the authors conclude that the average interstellar radiation field, measured by the parameter $\langle U \rangle$, increases as $\langle U \rangle \propto (1 + z)^{1.15}$. $\langle U \rangle$ is proportional to dust temperature, indicating that the dust temperature should be increasing and the peak of the SED should be shifting to shorter wavelengths. However, when we plot the stacked detections in Béthermin et al. (2015) in the same redshift range as our templates (0.25 < $z$ < 1.25 and 1.25 < $z$ < 2.00), we find that the stacked fluxes are consistent with our SEDs within the uncertainties. The evolution in SED peak observed in Béthermin et al. (2015) is not strong enough to be evident over the redshift range we are probing, which is more limited than that study.

Our observed lack of SED evolution is consistent with observations of the larger sample of GOODS-Herschel SFGs; the ratio of PAH to far-IR emission, as traced by $L_{8\mu m}/L_{\text{IR}}$, is constant from $z = 0 - 2.5$ providing evidence that the IR SEDs of normal, non-interacting, dusty SFGs do not evolve strongly (Elbaz et al., 2011). In contrast, local ULIRGs have a deficit of PAH emission compared with less luminous,
Figure 4.14: Color comparison of local and high $z$ sources. We plot the colors $S_{160}/S_{70}$ (rest frame) and $S_{24}/S_{8}$ (rest frame) of three samples: local star forming LIRGs from GOALS (purple squares), local normal SFGs (red triangles), and our SFGs (blue circles). The median $L_{\text{IR}}$ of each sample is listed in the legend. We have estimated the rest frame colors for our SFGs by sampling the MIR0.0-MIR0.2 templates within the template uncertainties. Average uncertainties produced by this method are illustrated by the cross in the upper right corner. Our high $z$ SFGs show a strong overlap with the GOALS LIRGs, but the less luminous local SFGs lie in a different region of colorspace. This indicates that the SEDs of local LIRGs are similar to the SEDs of high $z$ LIRGs and ULIRGs.
normal SFGs (e.g., Veilleux et al., 2009). However, at higher redshift, this deficit is seen to shift to higher $L_{\text{IR}}$, so that high redshift ULIRGs have $L_{\text{PAH}}/L_{\text{IR}}$ ratios that mimic local LIRGs, indicating that local LIRGs might be an ideal comparison sample for our high redshift LIRGs and ULIRGs (Sajina et al., 2012; Pope et al., 2013; Stierwalt et al., 2013).

We compare the IR colors of our high $z$ SFG sources with the observed frame IR colors of local LIRGs in Figure 4.14. We plot $S_{160}/S_{70}$ and $S_{24}/S_{8}$ for LIRGs from GOALS. The individual galaxies in GOALS all have mid-IR spectroscopy available allowing us to classify their mid-IR AGN emission using the same technique as for our high redshift galaxies. In Figure 4.14, we are only comparing mid-IR identified SFGs ($f(\text{AGN})_{\text{MIR}}<0.2$) in the GOALS and high $z$ samples. For the high $z$ sources, we have estimated rest frame $S_{160}/S_{70}$ and $S_{24}/S_{8}$ colors using a Monte Carlo technique to sample the MIR0.0, MIR0.1, and MIR0.2 templates within the template uncertainties at 8, 24, 70, and 160 $\mu$m. We show the typical uncertainty on this synthetic photometry in the upper right corner. We also demonstrate the portion of the SED traced by these colors in the lower left corner.

There is a strong overlap between our high $z$ SFGs and the GOALS SFGs. For comparison, we plot local less luminous ($L_{\text{IR}} \sim 10^{9} - 10^{10}$) SFGs identified through optical emission line ratios (O’Dowd et al., 2011; Battisti et al., 2015). Although a few of these sources lie in the same region as GOALS and our SFGs, in general, these sources lie below and to the right of the more luminous galaxies. $S_{160}/S_{70}$ traces the peak of the SED, while $S_{24}/S_{8}$ traces the amount of warm dust relative to the PAH emission. That we see little difference in either of these colors between the GOALS and high $z$ SFGs indicates that the average SED of high redshift LIRGs and ULIRGs is remarkably similar to local LIRGs. In other words, the SEDs of luminous dusty galaxies may not evolve strongly with redshift, if we do not consider the extreme cases of compact mergers. This result agrees with Stierwalt et al. (2013), where
the authors compared the average mid-IR spectra of the GOALS LIRGs with the average mid-IR spectra of submillimeter galaxies (SMGs) from Menéndez-Delmestre et al. (2009). Stierwalt et al. (2013) find that when all mid-IR AGN contribution is removed, the remaining spectra of local star-forming LIRGs is identical to high z star-forming SMGs. We will explore more comparisons between the GOALS survey and our high redshift sources in Chapter 7.

4.5.2 Demographics in Color Space

Our templates represent the average SEDs of our sample, but the variation among sources in the sample can be seen in Figure 4.15, where we again plot the colors $S_{250}/S_{24}$ and $S_8/S_{3.6}$ for our sample. We shade the sources according to $f(\text{AGN})_{\text{MIR}}$, so that SFGs (blue circles) have $f(\text{AGN})_{\text{MIR}} < 0.2$, composites (green squares) have $f(\text{AGN})_{\text{MIR}} = 0.2 - 0.8$, and AGN (red diamonds) have $f(\text{AGN})_{\text{MIR}} > 0.8$. Our sample is comprised of 24 µm faint galaxies from GOODS and 24 µm bright galaxies, primarily from xFLS. We illustrate the difference in these samples using filled and unfilled symbols. The filled symbols all have $S_{24} > 0.9$ mJy, and primarily lie to the upper left. AGN and SFGs lie in distinct regions in this colorspace, with AGN occupying primarily the upper left quadrant.

Because we are combining sources selected at different $S_{24}$ thresholds, we do not have a complete sample. We account for completeness using the 24 µm number counts from Béthermin et al. (2010). The authors list the number counts in 24 µm flux bins from $S_{24} = 0.035 - 100$ mJy. We divide our sources into the same flux bins, and assign a weight to each source, so that our weighted number counts match what is presented in Béthermin et al. (2010). We then divide the colors $S_8/S_{3.6}$ and $S_{250}/S_{24}$ into refined bins and count the weighted number of sources in each bin to produce the color demographic histograms on the top and right of Figure 4.15. We list the color bins and weighted percentages of SFGs, composites, and AGN in each bin in
Figure 4.15: Distribution of our sources in both $S_{250}/S_{24}$ and $S_{8}/S_{3.6}$. We shade the sources according to their mid-IR power source. SFGs (blue circles) have $f(\text{AGN})_{\text{MIR}}<0.2$, composites (green squares) have $f(\text{AGN})_{\text{MIR}}=0.2-0.8$, and AGN (red diamonds) have $f(\text{AGN})_{\text{MIR}}>0.9$. The full sample is plotted with the open symbols while sources with $S_{24} > 0.9$ mJy are plotted with the filled symbols. To the top and right, we plot the color demographics of our sources, where we have corrected for completeness effects by weighting the distributions by the 24 µm number counts presented in Béthermin et al. (2010). These distributions are useful for estimating relative numbers of SFGs and AGN when only a couple of photometric data points exist for each source.
We list the percentages of SFGs, Composites, and AGN in each color bin shown in Figure 4.15.

Table 4.5. The composites are roughly equally distributed. This is because of variable levels of AGN within the composites but may also be linked to different triggering mechanisms for an AGN growth. Major mergers are known to produce warmer SEDs, but an AGN growing in a clumpy, extended disk likely has more cold dust (Elbaz et al., 2011). AGN and SFGs separate cleanly in both $S_{8}/S_{3.6}$ and $S_{250}/S_{24}$, making each of these colors advantageous for selecting AGN and SFGs in a sample lacking spectroscopy or broad photometric coverage of the SED.

We illustrate how our color demographics can be applied to large samples, to estimate the number of pure SFGs for example, using a catalog of 10,300 BzKs with

<table>
<thead>
<tr>
<th>Min Color</th>
<th>Max Color</th>
<th>SFG</th>
<th>Composite</th>
<th>AGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{8}/S_{3.6}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>0.5</td>
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<td>37.9</td>
<td>0.0</td>
</tr>
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</tr>
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</tr>
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<td>10.0</td>
<td>70.0</td>
<td>0.0</td>
<td>22.6</td>
<td>77.4</td>
</tr>
</tbody>
</table>

| $S_{250}/S_{24}$ |
| 1.0 | 3.0 | 0.0 | 33.1 | 66.9 |
| 3.0 | 7.0 | 4.6 | 1.9 | 93.5 |
| 7.0 | 10.0 | 5.4 | 11.4 | 83.2 |
| 10.0 | 20.0 | 6.4 | 37.0 | 56.6 |
| 20.0 | 30.0 | 45.2 | 34.7 | 20.1 |
| 30.0 | 40.0 | 61.6 | 36.3 | 2.1 |
| 40.0 | 50.0 | 58.6 | 41.4 | 0.0 |
| 50.0 | 60.0 | 65.7 | 26.3 | 8.0 |
| 60.0 | 90.0 | 62.5 | 37.5 | 0.0 |
| 90.0 | 200.0 | 50.9 | 48.5 | 0.6 |
a detection in $S_8$ and $S_{3.6}$ (Lin et al., 2012). We first determine the $S_8/S_{3.6}$ distribution of BzKs using the bins listed in Table 4.5. Then, we multiply the number of BzKs in each bin by the respective percentages of SFGs in Table 4.5 to estimate the number of BzKs that are SFGs. We calculate that from the full BzK catalog, only 23% are pure SFGs. This could have implications for studies that see a redshift evolution in the shape of the SED. For example, using the same BzK catalog, Magdis et al. (2012) measure $\langle U \rangle \propto (1 + z)^{1.15}$ from $z = 0 - 2$, where $U \propto T_c$. The authors have removed X-ray luminous AGN, but according to our $S_8/S_{3.6}$ color diagnostic, it is possible that many composites hosting an obscured AGN are included in their sample.

We find a similar evolution of dust temperature with redshift for our Composites templates, but this is noticeably absent for our SFG templates (Figure 4.11). Our color demographics can help estimate the level of contamination in a large sample from galaxies that possess a mix of star formation and AGN activity. Our composites may be missed at X-ray wavelengths due to either high column densities or lower AGN X-ray luminosities. Moreover, the optical line ratios expected in composites is currently unconstrained at high redshift (Kartaltepe et al., 2015). Our IR color technique then provides a unique opportunity to identify the AGN lurking in dusty, IR luminous galaxies.

In Figure 4.16, we examine the effect that 24$\mu$m flux thresholds can have on the number of composites, SFGs, and AGN in a given sample. Again, we use the number count weights assigned to our sources, and plot the percentage of SFGs, composites, and AGN brighter than a given 24$\mu$m flux threshold (top panel). Throughout this paper, we have discussed SFGs, composites, and AGN using a mid-IR classification scheme, but in the bottom panel Figure 4.16, we classify sources according to $f(\text{AGN})_{\text{total}}$. Here, we have calculated $f(\text{AGN})_{\text{total}}$ for all sources using Equation 4.5. SFGs have $f(\text{AGN})_{\text{total}} < 0.2$, composites have $f(\text{AGN})_{\text{total}} = 0.2 - 0.5$, and AGN have $f(\text{AGN})_{\text{total}} > 0.5$, a threshold chosen because $L_{\text{IR}}$ is now dominated by AGN.
Figure 4.16: Cumulative distribution of AGN, composites, and SFGs in $S_{24}$. In the top panel, we classify sources as SFG, composite, or AGN based on $f(\text{AGN})_{\text{MIR}}$. In the bottom panel, we calculate $f(\text{AGN})_{\text{total}}$ using Equation 4.5 and then sort sources accordingly. Each point represents the percentage of SFGs, composites, or AGN brighter than a given 24$\mu$m flux. We have assigned weights to each galaxy based on its 24$\mu$m flux density in order to reproduce the number counts presented in Béthermin et al. (2010). The cumulative distribution presented here is calculated using our sources’ weights. We have attached Poisson errors to each point. AGN dominate at brighter fluxes. Composites contribute 20-30% at all flux thresholds in both panels illustrating the necessity of properly estimating or removing composites from IR samples of SFGs.
emission. Although $f_{\text{AGN}}^{\text{total}}$ is derived from $f_{\text{AGN}}^{\text{MIR}}$, we stress that the IR classifications are not the same as the mid-IR classifications. Both panels of Figure 4.16 show that AGN dominate at brighter fluxes ($S_{24} > 0.5 \, \text{mJy}$), so imposing a simple flux cut on a sample can easily remove large numbers of AGN. IR SFGs dominate the population when $S_{24} < 0.4 \, \text{mJy}$ (bottom panel), but mid-IR SFGs never do (top panel). However, IR and mid-IR composite sources contribute about 20-30% of a sample at all $S_{24}$ thresholds, so simply removing IR bright AGN or X-ray AGN does not account for all IR AGN emission.

These demographics are useful for current and future high redshift studies, particularly with JWST. The MIRI instrument on JWST will have a broadband 25.5 $\mu$m filter, so the $S_{24}$ distributions in Figure 4.16 can inform desired sensitivities of a particular project. Contamination by obscured AGN emission needs to be accounted for since Figure 4.16 demonstrates that AGN and composites are non-negligible at all $S_{24}$ thresholds. Through MIRI and NIRcam, astronomers will also be able to obtain a color very similar to $S_{8}/S_{3.6}$, and so our color demographic in Figure 4.15 and Table 4.5 can be used to estimate the number of SFGs and AGN in a given sample or select galaxies for further study.

4.6 Chapter Summary

We have decomposed mid-IR spectroscopy to robustly determine the strength of an AGN, classified as the fraction of mid-IR luminosity due to power-law continuum emission, in a sample of 343 high redshift (U)LIRGs. We define three general classifications: SFGs ($f_{\text{AGN}}^{\text{MIR}} < 0.2$), composites ($f_{\text{AGN}}^{\text{MIR}} = 0.2 - 0.8$), and AGN ($f_{\text{AGN}}^{\text{MIR}} > 0.8$). Based on these mid-IR classifications, we have created three publicly available template libraries designed for use with high redshift LIRGs and ULIRGs. The appropriate library depends on the data available to the user:
1. MIR-based Library. This is ideal if information about the mid-IR power source is available, but little far-IR data is available.

2. Color-based Library. These are ideal for high redshift sources which only have photometric data available.

3. Comprehensive Library. This library is based on comprehensive intrinsic galaxy information. We have used it to study dust emission trends with \( f(\text{AGN})_{\text{MIR}} \), redshift, and \( L_{\text{IR}} \). Choosing the appropriate template from this library requires knowledge about a source’s \( L_{\text{IR}} \) and redshift.

Using our empirical templates, we find

- SFGs are remarkably similar from \( z \sim 0.3 - 2.8 \). The shape of the mid-IR and far-IR emission is nearly identical for the three SFG templates from the Comprehensive Library, and the dust temperatures \( (T_c, T_w) \) and normalizations \( (L_{\text{cold}}/L_{\text{IR}}) \) are consistent. Furthermore, the colors of these templates are similar to colors of low redshift LIRGs from GOALS, indicating that local analogs exist for high redshift star forming LIRGs and ULIRGs, albeit at a slightly lower \( L_{\text{IR}} \). A detailed comparison of the dust emission of high redshift (U)LIRGs and their local analogs will be discussed in an upcoming study (Kirkpatrick et al. 2016, in preparation).

- For composites and AGN, the cold dust temperature, \( T_c \), changes with \( L_{\text{IR}} \) and redshift, but it is not affected by the strength of the AGN as \( T_c \) arises from the host galaxy.

- The warm dust temperature, \( T_w \), and the relative amount of cold dust emission, \( L_{\text{cold}}/L_{\text{IR}} \) are a strong function of \( f(\text{AGN})_{\text{MIR}} \). As the AGN grows more luminous, it heats more of the dust to warmer temperatures, eventually outshining
the cold dust component. \( f(\text{AGN})_{\text{MIR}} = 0.6 \) is an interesting threshold where \( T_w \) peaks and \( L_{\text{cold}}/L_{\text{IR}} \) begins to decline.

- \( f(\text{AGN})_{\text{MIR}} \) is related to the total amount of \( L_{\text{IR}} \) from AGN heating, \( f(\text{AGN})_{\text{total}} \), by a 2nd-degree polynomial. Due to the quadratic nature of the relationship, an AGN does not significantly contribute to \( L_{\text{IR}} \) until \( f(\text{AGN})_{\text{MIR}} > 0.6 \). \( f(\text{AGN})_{\text{total}} \) is useful to correct the amount of \( L_{\text{IR}} \) attributable to star formation and obtain more accurate star formation rates.

- In general, we find that composites are a true mix of SFGs and AGN, and may represent a transition between the two. A merger or other instability triggers the growth of an AGN which can heat the dust below \( \sim 40 \mu m \) and suppress PAH emission, producing higher \( f(\text{AGN})_{\text{MIR}} \) values. However, the AGN does not manifest itself on the far-IR emission until \( f(\text{AGN})_{\text{MIR}} > 0.6 \), and eventually, the AGN-heated dust outshines the diffuse dust.

- We estimate how prevalent AGN and composites are at different 24\( \mu m \) selection thresholds, and find that \( >40\% \) of a sample selected at \( S_{24} > 0.1 \text{ mJy} \) may be hosting a buried AGN. Composites and AGN have at least \( >20\% \) of \( L_{\text{IR}} \) due to AGN heating, illustrating the necessity of accounting for AGN heating when studying dust emission or IR-based SFRs at high redshift.

Our infrared analysis will be applicable for forthcoming data from JWST. MIRI will provide medium resolution spectroscopy from 5-28\( \mu m \). With the coverage of MIRI, our mid-IR decomposition technique can be used to identify mid-IR AGN out to \( z \sim 2 \). We have also demonstrated that the color \( S_8/S_{3.6} \), obtainable with JWST, can be used to separate AGN from SFGs in the range \( z = 0-2.8 \). Future observations with JWST can reach deeper 24\( \mu m \) limits to determine the prevalence of AGN and composites in these samples.
CHAPTER 5

DO MERGERS TRIGGER ACTIVE GALACTIC NUCLEI?

It is assumed that high redshift ULIRGs are analogs to local ULIRGs, which are almost exclusively undergoing a starburst phase triggered by a major merger (Sanders & Mirabel, 1996). Furthermore, at least out to \( z \approx 1.5 \), an observed interaction between disk galaxies correlates with luminous AGN signatures in the mid-infrared (Hwang et al., 2011; Zamojski et al., 2011). On the other hand, a major merger is not necessarily required to trigger the starburst phase or funnel gas onto a central supermassive black hole (Bournaud et al., 2011; Kartaltepe et al., 2012; Mullaney et al., 2012). Simple disk instabilities in galaxies with higher gas fractions and clumpy disk morphologies, like those at \( z > 1 \), can fuel star formation and an AGN without requiring a merger (Tacconi et al., 2010). An increase in the fraction of minor mergers can also provide fuel for the high specific star formation rates in \( z \sim 2 \) ULIRGs (Somerville et al., 2008). In this chapter, we explore the connection between observable merger signatures and AGN growth using the sample from Chapter 4.

5.1 AGN and the Main Sequence

An evolutionary link between our SFGs and AGN can be probed in general using the main sequence criterion (SFR/\( M_\ast \)). Recently, Elbaz et al. (2011) discovered a tight relationship between \( L_{\text{IR}} \) and \( L_{8 \mu m} \) that is insensitive to redshift and is correlated with a galaxy’s compactness. IR8=\( L_{\text{IR}}/L_{8 \mu m} \) works as a way to characterize the main sequence using the ratio of far- to mid-IR emission. Galaxies with a boosted IR8 are more compact, meaning that gas is being funneled to the center of these galaxies,
providing fuel for a warm central starburst or possibly an AGN, which reduces the photodissociation region emission (from which the PAH features arise) relative to the thermal dust emission.

The top panel of Figure 5.1 shows IR8 as a function of $f(\text{AGN})_{\text{MIR}}$ for our individual sources. The grey shaded region indicates the IR8 main sequence defined in Elbaz et al. (2011), and the starburst regime lies above it. We overplot as the large stars the mean IR8 values and the corresponding standard deviation in bins of $\Delta f(\text{AGN})_{\text{MIR}}=0.1$. As the AGN grows, it becomes visible in the mid-IR and eventually boosts the mid-IR emission relative to the far-IR, causing the galaxy to fall from the starburst region onto the main sequence. AGN feedback then possibly begins to suppress the star formation, seen as a decrease in $L_{\text{IR}}$, causing the galaxy to lie below the main sequence. Figure 5.1 demonstrates that $f(\text{AGN})_{\text{MIR}}=0.6$ is a turning point in a possible evolutionary sequence linking our sources (see also Section 4.3.1). For $f(\text{AGN})_{\text{MIR}}>0.6$, there is a visible decrease in IR8 caused by the AGN.

We explore to what degree the classical merger scenario can explain our IR8 data using IR SEDs generated from hydrodynamical simulations of equal mass mergers (the simulated SEDs will be presented in detail in Roebuck et al. 2016, in preparation). We begin with a library of model SEDs collected from studies of SMGs (Hayward et al., 2011), (U)LIRGs at $z \sim 0, 3$ (Snyder et al., 2013), and local (U)LIRGs (Lanz et al., 2014). This library is input into hydrodynamical merger simulations using the GADGET-2 SPH code (Springel et al., 2001; Springel, 2005), with additional radiative processing added using SUNRISE (Jonsson, 2006). IR SEDs are generated at different time steps and viewing angles during the merger, and we calculate $f(\text{AGN})_{\text{MIR}}$ and IR8 from the results. In the middle panel of Figure 5.1, we plot $f(\text{AGN})_{\text{MIR}}$ v. IR8 measured from the simulated SEDs of major mergers. The outcome is remarkably similar to the correlation between IR8 and $f(\text{AGN})_{\text{MIR}}$ in our observed sample. In the bottom panel of 5.1, we plot the standard deviation of the observed sources in
Figure 5.1: IR8 parameter as a function of $f(\text{AGN})_{\text{MIR}}$. We show empirical measurements for our sample in the top panel. The main sequence IR8 value and associated dispersion from Elbaz et al. (2011) is plotted at the dashed line and grey region, respectively. In the middle panel, we plot $f(\text{AGN})_{\text{MIR}}$ vs IR8 measured from SEDs produced by simulations of major mergers. The mean and standard deviation in bins of $\Delta f(\text{AGN})_{\text{MIR}}=0.1$ are over plotted as the large black stars in the top and middle panels. In the bottom panel, we plot the standard deviation of the observed sources as the red histogram, and the standard deviation of the simulated merger SEDs as the green histogram. The simulations can account for much, but not all of the intrinsic scatter.

We find that major mergers can account for much of the scatter in our sources, particularly for the composite galaxies, indicating that an ongoing merger could be triggering the growth of the AGN. However, at high $f(\text{AGN})_{\text{MIR}}$, there is a large degree of scatter in the observed IR8 not accounted for by the merger simulation suggesting that other fueling processes are at work.
5.2 Visual Identification of Mergers

The most direct way to look for merger signatures is simply to visually examine optical images of a galaxy. We now focus on the connection between AGN growth and the visual appearance of our galaxy sample. NICMOS imaging from \textit{HST} exists for 134 of the xFLS sources, and this data set has been extensively described and analyzed in Zamojski et al. (2011). Our GOODS-S sources (52) have been visually classified with \textit{HST} WFC3 imaging in Kartaltepe et al. (2015) and Rosario et al. (2015), which we adopt for this work. Cutouts of the GOODS-S sources are shown in Figure 5.2 for illustrative purposes only, as these were not the actual images used in the classification. The GOODS-S and xFLS sources have been classified according to different schemes which we unite into a single classification scheme described below.

Zamojski et al. (2011) divides the xFLS sources into seven categories based on visual appearance and the residuals when a smooth galaxy profile is subtracted. The categories are isolated disk galaxies, close pairs, triplets, first contact, early mergers, advanced mergers, old mergers, and spheroids. Here, we simplify the classification scheme into three categories: (1) Isolated galaxies, which are isolated spirals, spheroids, or old mergers; (2) Close Pair, into which we combine the close pairs with the triplets category; (3) Interacting/Merger, into which we combine first contact, early mergers, and advanced mergers. Zamojski et al. (2011) identify old mergers by looking for clumpy residuals. However, the GOODS-S galaxies were identified solely by eye, and a purely visual classification scheme is not sensitive enough to identify old mergers at these resolutions, which is why we reclassify these galaxies as Isolated. Zamojski et al. (2011) also assigns confidence intervals to each classification based on the quality of the original image. We remove completely (rather than reclassify) any galaxy in the Interacting/Merger category that has a confidence class of 4 or 5 (19 of 69 galaxies). These are galaxies where the merger can only be identified through the
Figure 5.2: *Hubble Space Telescope* images of the GOODS-S sources. We show either F105W (observed frame 1.05 μm) or F814W (observed frame 0.81 μm) images. Galaxies are sorted by $f(\text{AGN})_{\text{MIR}}$ and $L_{\text{IR}}$. Some bins have more than one galaxy, so we choose a representative example. These images are shown for illustrative purposes only and were not the images used in the classification process (see Kartaltepe et al., 2015; Rosario et al., 2015).
use of residual images, which again, the GOODS-S classification technique does not make use of.

In the GOODS-S field, all galaxies were classified by eye by at least three experts. Classifiers looked at the F160W, F125W, F606W, and F850LP images from HST and noted details about a galaxy’s shape, asymmetry, or disturbance. In this work, we use the interaction metric (Rosario et al., 2015). Initially, classifiers assigned galaxies a score based on their level of interaction: 0 (isolated), 0.25 (close pair), 0.5 (interaction beyond the cutout image), 0.75 (interaction with another galaxy within the image), or 1 (obvious late stage merger). The final interaction metric is the mean of the metrics from each individual classifier. We adopt three categories: (1) Isolated galaxies, interaction metric < 0.2; (2) Close Pair, interaction metric = 0.2 − 0.5; (3) Interaction/Merger, interaction metric > 0.5 (Rosario et al., 2015).

Figure 5.3 shows the visual merger classifications for 187 sources in our sample. We show the percentage of isolated sources, close pairs, and mergers (with Poisson error bars) for SFGs, composites, and AGN. The sample is not large enough for us to make statistically meaningful comparisons in different redshift bins or $L_{\text{IR}}$ bins as well. The percentage of isolated galaxies is roughly constant (30%) as the mid-IR classification changes. However, the percentage of close pairs drops dramatically for the composites and AGN, and the number of obvious mergers increases (67% for composites and 42% for AGN, compared with only 26% for SFGs). This could indicate that SFGs are more likely to be in the beginning phase of a merger, while composites and AGN are found in later merger stages, similar to what is seen for heavily obscured AGN at $z \sim 1 − 2$ (Kocevski et al., 2015). This supports the classical evolutionary sequence where a merger is responsible for funneling material into the center of a galaxy, fueling an AGN. The high numbers of isolated galaxies indicate that secular processes could also be responsible for AGN growth, although we note that isolated galaxies could still be the result of a merger, since we do not distinguish between disks, spheroids,
Figure 5.3: Percentage of sources undergoing a merger based on visual classifications of images as a function of mid-IR power source. Composites and AGN have a higher merger fraction than SFGs, indicating that in general, a merger triggers AGN growth according to this metric.

and old mergers in this category. Based on visual classifications, 46% of our sample is currently undergoing a merger; for GOODS-S, the merger fraction is 33%, while for xFLS it is 53%. This is lower than what is reported for the xFLS sources in Zamojski et al. (2011), where the authors estimate the percentage of merging galaxies to be $80^{+11}_{-18}\%$. The difference arises because we have reclassified old mergers as isolated galaxies and removed mergers in lower confidence classes. The merger fractions of SFGs, composites, and AGN are listed in Table 5.1.
5.3 Non-Parametric Approaches

Visual classification is highly subjective, particularly at high redshift where surface brightness dimming can greatly diminish obvious merger signatures. A complementary approach is to measure a galaxy’s morphology with a non-parametric descriptor. Non-parametric descriptors are ideal because they do not require any assumption about the underlying distribution of light, as opposed to parametric descriptors, such as the Sersic index (e.g., Blanton et al., 2003).

First, we examine the merger fraction of galaxies using two non-parametric approaches: $G - M_{20}$ and $C - A$ (Lotz et al., 2004). The Gini coefficient ($G$) measures the distribution of light in a galaxy, but is not sensitive to whether light is centrally concentrated (Abraham et al., 2003; Lotz et al., 2004). The pixels (of number $n$) in a galaxy are ranked by increasing flux values ($X_i$ at the $i$th rank) and $G$ is calculated thusly:

$$G = \frac{1}{\bar{X} n(n-1)} \sum_{i} (2i - n - 1) X_i$$

where $\bar{X}$ is the mean over all pixel flux values. If the light in a galaxy is uniformly distributed, $G = 1$, but if all the light is concentrated in one pixel, $G = 0$.

The Gini coefficient is typically coupled with $M_{20}$ to separate mergers (Lotz et al., 2004). $M_{20}$ is the second order moment of the brightest pixels in a galaxy. In effect, it measures the distance of bright knots of star formation from the galaxy center, and $G - M_{20}$ in tandem can distinguish between irregular galaxies, with bright off-center knots of star formation, and elliptical galaxies, which have centrally concentrated light profiles. The total second order moment is

$$M_{\text{tot}} = \sum_{i} M_i = \sum_{i} f_i [(x_i - x_c)^2 + (y_i - y_c)^2]$$

where $(x_c, y_c)$ marks the position of the central pixel (see definition of asymmetry below). To calculate $M_{20}$, again, pixels are ranked by flux value, and $M_{20}$ is
\[ M_{20} \equiv \log \left( \frac{\sum_i M_i}{M_{\text{tot}}} \right) \text{ while } \sum_i f_i < 0.2 f_{\text{tot}} \]  

\hspace{1cm} (5.3)

\[ G - M_{20} \] have been measured for our GOODS-N and GOODS-S galaxies in the \textit{HST} filters F814W, F105W, F125W, and F160W (Peth et al., 2015). We compare the measured \textit{rest frame} parameters of our sources (Figure 5.4). We combine the measurements in different filters for different redshift bins in order to probe the rest frame ranges $0.33 - 0.43 \mu m$, $0.43 - 0.53 \mu m$, and $0.53 - 0.63 \mu m$. The $0.33 - 0.43 \mu m$ range covers the 4000Å break and is the most heavily attenuated by dust, so it is likely the least useful, but we include it to illustrate what effect redshift might have on merger classifications, since at higher redshift, the \textit{HST} filters will image shorter wavelengths. Mergers are located above the line

\[ G > -0.14 M_{20} + 0.33 \]  

\hspace{1cm} (5.4)

This line was defined in Lotz et al. (2008) using rest-frame B-band images ($\lambda \sim 4500\AA$) of galaxies from $0.2 < z < 0.4$ from the Extended Groth Strip (EGS) field. The dividing line has not been calibrated above $z > 0.4$, although there is no strong evolution of the merger fraction of EGS galaxies out to $z = 1.2$, which could be interpreted as evidence that this merger threshold should not change (Lotz et al., 2008). Our galaxies extend beyond $z \sim 1.2$, so we attempt to investigate what effect redshift evolution could have by plotting the galaxies which have $G, M_{20}$ measurements in all three rest frame wave bins as the filled circles. In general, moving to shorter wavelengths (higher redshift) pushes galaxies closer to the merger line, and in the rest frame $0.33 - 0.43 \mu m$ bin, two galaxies would be classified as mergers that were not previously classified. However, it is not a strong effect. There is a slight separation between AGN and SFGs, with AGN tending to lie towards the upper right. We do not see any correlation between $f(\text{AGN})_{MIR}$ and preferential location in the merger region. We list the overall merger fraction in the lower right of each bin, and it is
about 21%, so this classification technique does not identify as many potential mergers as visual classification. We select as potential mergers galaxies that lie in the merger region in any of the three rest frames. Then, the merger fraction of SFGs is 21%, composites is 22%, and AGN is 33% (Table 5.1). Unlike with the visual classifications, the SFGs and composites do not have significantly different percentages of mergers.

A second popular non-parametric way to separate mergers from non-mergers is combining concentration ($C$) with asymmetry ($A$) (Abraham et al., 1994; Schade et al., 1995; Lotz et al., 2004). Concentration is defined as the ratio of the radius containing 80% of the total flux to the radius containing 20% of the total flux, where the total flux is the flux within 1.5 Petrosian radii (Bershady et al., 2000; Lotz et al., 2004):

$$C = 5 \log \left( \frac{r_{80}}{r_{20}} \right)$$  \hspace{1cm} (5.5)
Figure 5.5: Concentration v. Asymmetry, measured in three different rest frames for GOODS-N and GOODS-S galaxies. Sources found in the lower left corner are not mergers. The filled sources are the same galaxies in the three different rest bins. There is a strong evolution of where the filled circles lie, indicating this parameter is not robust against redshift.

The asymmetry parameter, $A$, quantifies how rotationally symmetric a galaxy’s light is. The galaxy image is rotated $180^\circ$ through the central pixel and subtracted from the original image (Conselice et al., 2000; Lotz et al., 2004):

$$A = \frac{\sum_{i,j} |I(i,j) - I_{180}(i,j)|}{\sum_{i,j} |I(i,j)|} - B_{180} \quad (5.6)$$

where $I$ is the original image, $I_{180}$ is the rotated image, and $B_{180}$ is the average asymmetry of the background. The central pixel is determined through an iterative process, so that it is the pixel which minimizes the value of $A$.

The $C - A$ diagnostic is shown in Figure 5.5. Again, we sort galaxies into three rest frame bins, and plot the same galaxies as the filled circles. The dotted lines separate mergers from non-mergers and were defined in Lotz et al. (2004) at rest frame 6500Å using local ULIRGs and local normal star forming galaxies. We list the merger fraction in each panel. Unlike with $G - M_{20}$, $C - A$ shows a stronger trend with decreasing wavelength (increasing redshift), so that none of the filled circles in
Table 5.1: Percentage of mergers according to different measures.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Visual (%)</th>
<th>$G - M_{20}$ (%)</th>
<th>$C - A$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFG</td>
<td>26</td>
<td>21</td>
<td>26</td>
</tr>
<tr>
<td>Composite</td>
<td>67</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>AGN</td>
<td>42</td>
<td>33</td>
<td>47</td>
</tr>
</tbody>
</table>

The right panel are found in the merger region. The merger fraction in each panel is listed in the upper right and is generally consistent with $G - M_{20}$. If we combine the classifications from all three panels, we find that SFGs have a merger fraction of 26%, composites have 30%, and AGN have 47% (Table 5.1). The $C - A$ classifications then show a stronger difference between the percentages of merger-candidate SFGs and AGN, although the percentage of SFGs and composites is similar.

5.4 Linking AGN with Morphology

In Figures 5.4 and 5.5, there is no strong trend between galaxies classified as a merger non-parametrically and $f(\text{AGN})_{\text{MIR}}$. AGN do not lie in one distinct region in either $G - M_{20}$ or $C - A$. However, we find that if we combine asymmetry with the half-light radius, $R_{50}$, we are able to separate our AGN. $R_{50}$ is the radius (in arc seconds) at which the integrated intensity is 50% of the total intensity. $R_{50}$ then should be relatively insensitive to surface brightness dimming, allowing comparison of $R_{50}$ across different redshift ranges. We show $A - R_{50}$ in the three different rest frame bins (since $A$ is not insensitive to redshift) in Figure 5.6. AGN and some composites (with higher $f(\text{AGN})_{\text{MIR}}$ values) lie in the lower left corner. This indicates that galaxies hosting an AGN tend to be more concentrated and less asymmetric, consistent with being in a later merger stage than SFGs. This parameter space could be useful for optically selecting galaxies as potential AGN but needs to be tested further through comparing the distribution of all galaxies in this parameter space.
Figure 5.6: Asymmetry v. half-light radius for GOODS-N and GOODS-S. Galaxies with a higher $f(\text{AGN})_{\text{MIR}}$ lie in the lower left corner in all three rest frame bins.

We can also combine an optical parameter, $R_{50}$, with an infrared color, $S_8/S_{3.6}$, which is sensitive to AGN growth, to better explore ways to select potential AGN. In Figure 5.7, we demonstrate that these two parameters together effectively separate our known AGN. We also plot the full sample of galaxies from the GOODS-N and GOODS-S fields in the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; P.I.s Harry Ferguson & Sandy Faber). CANDELS is an ideal comparison sample due to the wealth of multiwavelength data available. Here, we have selected only galaxies with $M_*>10^{10} M_\odot$ and $z=0.5-3.0$, similar to our sample (Pannella et al., 2015; Santini et al., 2015). Sources that have X-ray detections with Chandra 4 Ms observations are plotted as the crosses (Xue et al., 2011). Only 20% of the sources that lie in the lower right corner are detected in the X-ray, indicating that many more of the CANDELS galaxies might be AGN than are currently detectable with X-ray methods. We note that there are a lot of X-ray sources in the regions where our SFGs and composites lie. The distribution of our sources in both $S_8/S_{3.6}$ and $R_{50}$ is significantly different from the CANDELS sources, although there is no difference between the distributions of the CANDELS X-ray detected sources and
Figure 5.7: $R_{50}$ v. $S_8/S_{3.6}$. Our AGN have smaller half light radii ($R_{50}$) and a redder color ($S_8/S_{3.6}$) than the SFGs and composites, indicating this space might be useful for selecting potential AGN. We also plot the full GOODS-S and GOODS-N CANDELS catalogs, where we have selected sources with $z = 0.5 - 3$ and $M_* > 10^{10} M_\odot$. X-ray AGN candidates are marked with the crosses. We also plot the distributions of each sample in the top and right panels. CANDELS X-ray undetected sources are grey, while X-ray detected sources are black. There is no statistically significant difference in their distributions. The IRS sample is plotted in orange, and it differs from the CANDELS distributions in both $S_8/S_{3.6}$ and $R_{50}$. The different distributions are likely due to the different selection wavelengths of these sources.

undetected sources, according to a K-S test. The CANDELS galaxies were selected at near-IR wavelengths, while our IRS sources were selected at 24 $\mu$m, indicating that the different selection techniques could be culling significantly distinct populations despite similar stellar mass ranges.

5.5 Chapter Summary

We examine several merger indicators, including the IR8 main sequence indicator, visual morphologies, and non-parametric criteria. We find that composites and AGN
have a much higher fraction of visual mergers than SFGs, indicating a major merger could be triggering AGN growth. AGN do not separate strongly according to non-parametric criteria, although this could be because these criteria have not been calibrated at $z > 1.2$. The IR8 parameter depends on $f(\text{AGN})_{\text{MIR}}$. At $f(\text{AGN})_{\text{MIR}}>0.6$, the AGN component has boosted the warm and hot dust emission significantly, outshining or destroying PAHs, causing galaxies to have lower IR8 values and eventually fall below the main sequence. The simulated IR SEDs of major mergers show the same trends as our sources, and the scatter in the simulated IR8 values accounts for much of the scatter in our observed IR8s. The major merger scenario can then explain the growth of the AGN in many, but not all of our galaxies.
CHAPTER 6

EXPLORING THE EFFECT OF AGN ACTIVITY ON THE RELATIONSHIPS BETWEEN MOLECULAR GAS, DUST, AND STAR FORMATION

Star formation converts a galaxy’s molecular gas into stars through multiple complicated processes including gas accretion and the collapse and cooling of molecular clouds. Although the star formation process itself is intricate, the overall conversion of molecular hydrogen (H$_2$) into stars can be expressed simply by the Schmidt-Kennicutt (SK) law which directly relates the molecular gas content to the SFR through a power-law equation, $\Sigma_{\text{SFR}} \propto \Sigma_{\text{H}_2}^{\alpha}$, albeit with significant scatter (Schmidt, 1959; Kennicutt, 1998; Kennicutt & Evans, 2012). The rate at which a galaxy can form stars is then limited by the amount of molecular gas present and depends on the efficiency to convert this molecular gas to stars. The IR luminosity, $L_{\text{IR}}$, is an ideal measure of the SFR for dusty galaxies as it is the integrated emission from the dust, presumably heated by star formation. Molecular hydrogen is difficult to observe directly, but CO is expected to be co-spatial with H$_2$. CO is the second most abundant molecule after H$_2$, and it has transitions we can access from the ground, so CO is frequently used as a tracer of a galaxy’s molecular gas reservoir. A conversion factor, $\alpha_{\text{CO}}$, is used to relate the CO luminosity directly to the H$_2$ mass (Bolatto et al., 2013).

Star formation efficiency, which is the ratio of SFR to $M_{\text{H}_2}$, can be approximated as $L_{\text{IR}}/L'_{\text{CO}}$. Starbursts and mergers are observed to have higher $L_{\text{IR}}/L'_{\text{CO}}$ ratios than normal main sequence galaxies (Carilli & Walter, 2013, and references therein). This dichotomy has a direct effect on the calculation of the H$_2$ mass, since $\alpha_{\text{CO}}$ is proposed to be a factor of $\sim 5$ lower for starbursting galaxies, due to significant amounts of
CO residing outside of molecular clouds (the sites of star formation). However, the degree of scatter in the relationship between $L_{\text{IR}}$ and $L'_\text{CO}$, often attributed to the two different modes of star formation, is possibly affected by the contribution from an AGN to $L_{\text{IR}}$. This has been observationally confirmed in Evans et al. (2001), where the authors measure high $L_{\text{IR}}/L'_\text{CO}$ in luminous AGN and infer that these ratios might be boosted by the AGN contribution to $L_{\text{IR}}$. Finding AGN and accounting for the amount of dust heating due to the AGN is necessary in order to calculate correct SFRs and accurately measure star formation efficiencies. Linking a growing AGN with a galaxy’s star formation efficiency can also tell us whether the AGN is responsible for depleting a galaxy’s gas supply and shutting down star formation.

In this chapter, we test what effect an IR luminous AGN has on the ratio $L_{\text{IR}}/L'_\text{CO}$ in a sample of 24 intermediate redshift galaxies from the 5 mJy Unbiased Spitzer Extragalactic Survey (5MUSES). Throughout this chapter, we adopt a slightly different cosmology than in previous chapters. Here, we use a flat cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

### 6.1 Data

5MUSES is a Spitzer IRS mid-IR spectroscopic survey of 330 galaxies selected from the SWIRE and Spitzer Extragalactic First Look Survey fields (details in Wu et al., 2010). It is a flux limited sample selected at 24 $\mu$m using MIPS observations from the Spitzer Space Telescope, with $S_{24} > 5 \text{ mJy}$. Crucially, 5MUSES is a representative sample at intermediate redshift (the median redshift of the sample is 0.14, 1.8 Gyr ago) of galaxies with $L_{\text{IR}} \sim 10^{10} - 10^{12} L_\odot$, bridging the gap between large samples of local star forming galaxies, LIRGs, and ULIRGs and high redshift observations of LIRGs and ULIRGs. Complete details of the Spitzer data reduction are found in Wu

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1This chapter is published as Kirkpatrick et al. (2014b).
et al. (2010). For the present study, we make use of the Spitzer IRS short-low (SL) spectroscopy, spanning the range 5.5 – 14.5 µm.

A 24 µm selection criteria could potentially bias the sample towards warmer sources. Magdis et al. (2013) reports the far-IR observations of the 5MUSES sources with the Herschel Space Observatory. Of 188 5MUSES sources covered by the observations, 154 (82%) are detected at 250 µm. The authors also determine that the 250 µm flux densities of the whole population of galaxies in the observed field with $S_{24} > 5$ mJy (the 5MUSES detection limit) and that of the 5MUSES sample is drawn from the same distribution, indicating that the dust temperatures of 5MUSES are not significantly warmer than other IR luminous galaxies. In Section 6.2.2, we compare the 5MUSES sources to high redshift ULIRGs, also selected at 24 µm, from the GOODS-Herschel survey. For the high redshift ULIRGs, Pope et al. (2013) find no difference between 70 µm selected sources ($\sim 24$ µm rest frame) and submillimeter selected sources in terms of PAH and CO luminosities. The high redshift ULIRGs in this work are drawn from the larger parent population of Spitzer IRS sources in Chapter 2. In Chapter 2, we found that 97% of GOODS-Herschel sources with a 100 µm detection also have a 24 µm detection, ensuring that for high redshift LIRGs and ULIRGs, a 24 µm selection criteria does not bias the selection towards warmer sources.

From the 5MUSES sample, we selected 24 sources that span a range of PAH equivalent widths (EW; calculated for the full sample in Wu et al., 2010), as PAH EW is correlated with the mid-IR strength of an AGN (Armus et al., 2007). All 24 µm sources have spectroscopic redshifts determined from fitting the mid-IR spectral features. These sources were chosen for a pilot CO(1-0) study specifically because they exhibit a range of PAH strengths and because the spectroscopic redshifts are such that we can observe the CO(1-0) transition with the Large Millimeter Telescope (LMT). These sources were also selected according to $L_{\text{IR}}$, such that every source is observable
in a reasonable ($\lesssim 90 \text{ min}$) amount of time during the LMT Early Science phase. Our sample spans a redshift range of $z = 0.04 - 0.36$ and $L_{\text{IR}} = 1.8 \times 10^{10} - 1.3 \times 10^{12} L_\odot$. Details are listed in Table 6.1.

### 6.1.1 New LMT Observations

The LMT is a 50 m millimeter-wave radio telescope on Volcán Sierra Negra, Mexico, at an altitude of 4600 m (Hughes et al., 2010). The high elevation allows for a median opacity of $\tau = 0.1$ at 225 GHz in the winter months. For the Early Science phase, the inner 32.5 m of the primary reflector is fully operational. The primary reflector has an active surface and a sensitivity of 7.0 Jy/K at 3 mm. The pointing accuracy (rms) is $3''$ over the whole sky and 1-2" for small offsets ($< 10^\circ$) from known sources.

During March and April 2014, we observed our 24 sources with the Redshift Search Receiver (RSR; Erickson et al., 2007; Chung et al., 2009). The RSR is comprised of a dual beam, dual polarization system that simultaneously covers a wide frequency range of 73-111 GHz in a single tuning with a spectral resolution of 100 km/s. This large bandwidth combined with a high spectral resolution is ideal for measuring the CO integrated line luminosities in high redshift sources. In our intermediate redshift sample, the large bandwidth allows us to observe the CO(1-0) transition for sources spanning a wide range of redshifts. The beam size of the RSR is frequency dependent, such that $\theta_b = 1.155\lambda/32.5 \text{ m}$. The beam size depends on the frequency of the observed CO(1-0) line, and at the median redshift, $z = 0.145$, the RSR has a beam size of 22''.

Typical system temperatures ranged from $87 - 106 \text{ K}$ during our observations. Weather conditions varied over the eight nights of observations, with $\tau = 0.07 - 0.28$. All observations were taken at elevations between 40-70° where the gain curve is relatively flat. On source integration times ranged from 5 – 100 minutes and were
Table 6.1: CO(1-0) Measurements of the 5MUSES sample.

<table>
<thead>
<tr>
<th>ID</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>z\textsuperscript{a}</th>
<th>rms\textsuperscript{b}</th>
<th>FWHM (km s\textsuperscript{-1})</th>
<th>S\textsubscript{CO} ∆ν\textsuperscript{c} (Jy km s\textsuperscript{-1})</th>
<th>L\textsubscript{CO}\textsuperscript{c} (10\textsuperscript{9} K km/s pc\textsuperscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>5MUSES-200</td>
<td>16:12:50.9</td>
<td>+53:23:05.0</td>
<td>0.043</td>
<td>0.70</td>
<td>⋆</td>
<td>&lt; 2.53</td>
<td>&lt; 0.21</td>
</tr>
<tr>
<td>5MUSES-179</td>
<td>16:08:03.7</td>
<td>+54:53:02.0</td>
<td>0.053</td>
<td>0.32</td>
<td>348 ± 20</td>
<td>11.3 ± 0.93</td>
<td>1.46 ± 0.12</td>
</tr>
<tr>
<td>5MUSES-169</td>
<td>16:04:08.3</td>
<td>+54:58:13.1</td>
<td>0.064</td>
<td>0.72</td>
<td>306 ± 67</td>
<td>4.47 ± 1.08</td>
<td>0.84 ± 0.20</td>
</tr>
<tr>
<td>5MUSES-105</td>
<td>10:44:32.9</td>
<td>+56:40:41.6</td>
<td>0.068</td>
<td>0.84</td>
<td>251 ± 20</td>
<td>7.19 ± 1.27</td>
<td>1.54 ± 0.27</td>
</tr>
<tr>
<td>5MUSES-171</td>
<td>16:04:40.6</td>
<td>+55:34:09.3</td>
<td>0.078</td>
<td>0.87</td>
<td>345 ± 48</td>
<td>7.60 ± 1.45</td>
<td>2.14 ± 0.41</td>
</tr>
<tr>
<td>5MUSES-229</td>
<td>16:18:19.3</td>
<td>+54:18:59.1</td>
<td>0.082</td>
<td>0.72</td>
<td>386 ± 33</td>
<td>11.3 ± 1.48</td>
<td>3.53 ± 0.46</td>
</tr>
<tr>
<td>5MUSES-230</td>
<td>16:18:23.1</td>
<td>+54:27:21.4</td>
<td>0.084</td>
<td>0.87</td>
<td>305 ± 50</td>
<td>6.38 ± 1.25</td>
<td>2.09 ± 0.41</td>
</tr>
<tr>
<td>5MUSES-234</td>
<td>16:19:29.6</td>
<td>+54:18:41.9</td>
<td>0.100</td>
<td>0.70</td>
<td>217 ± 25</td>
<td>6.24 ± 0.69</td>
<td>2.93 ± 0.33</td>
</tr>
<tr>
<td>5MUSES-132</td>
<td>10:52:06.6</td>
<td>+58:09:47.1</td>
<td>0.117</td>
<td>1.30</td>
<td>181 ± 44</td>
<td>4.28 ± 0.92</td>
<td>2.77 ± 0.60</td>
</tr>
<tr>
<td>5MUSES-227</td>
<td>16:17:59.2</td>
<td>+54:15:01.3</td>
<td>0.134</td>
<td>0.24</td>
<td>247 ± 26</td>
<td>1.17 ± 0.34</td>
<td>1.00 ± 0.29</td>
</tr>
<tr>
<td>5MUSES-141</td>
<td>10:57:05.4</td>
<td>+58:04:37.4</td>
<td>0.140</td>
<td>0.48</td>
<td>203 ± 29</td>
<td>3.06 ± 0.62</td>
<td>2.86 ± 0.58</td>
</tr>
<tr>
<td>5MUSES-158</td>
<td>16:00:38.8</td>
<td>+55:10:18.7</td>
<td>0.145</td>
<td>0.73</td>
<td>458 ± 78</td>
<td>5.17 ± 1.23</td>
<td>5.21 ± 1.24</td>
</tr>
<tr>
<td>5MUSES-225</td>
<td>16:17:48.1</td>
<td>+55:18:31.1</td>
<td>0.145</td>
<td>0.46</td>
<td>400 ± 146</td>
<td>4.52 ± 0.57</td>
<td>4.55 ± 0.57</td>
</tr>
<tr>
<td>5MUSES-273</td>
<td>16:37:31.4</td>
<td>+40:51:55.6</td>
<td>0.189</td>
<td>0.34</td>
<td>241 ± 69</td>
<td>1.81 ± 0.40</td>
<td>3.16 ± 0.69</td>
</tr>
<tr>
<td>5MUSES-136</td>
<td>10:54:21.7</td>
<td>+58:23:44.7</td>
<td>0.204</td>
<td>0.36</td>
<td>477 ± 78</td>
<td>2.30 ± 0.55</td>
<td>4.69 ± 1.11</td>
</tr>
<tr>
<td>5MUSES-294</td>
<td>17:12:32.4</td>
<td>+59:21:26.2</td>
<td>0.210</td>
<td>0.38</td>
<td>⋆</td>
<td>&lt; 1.60</td>
<td>&lt; 3.47</td>
</tr>
<tr>
<td>5MUSES-216</td>
<td>16:15:51.5</td>
<td>+54:15:36.0</td>
<td>0.215</td>
<td>0.27</td>
<td>331 ± 60</td>
<td>1.82 ± 0.36</td>
<td>4.14 ± 0.83</td>
</tr>
<tr>
<td>5MUSES-194</td>
<td>16:11:19.4</td>
<td>+55:33:55.4</td>
<td>0.224</td>
<td>0.54</td>
<td>⋆</td>
<td>&lt; 2.62</td>
<td>&lt; 6.49</td>
</tr>
<tr>
<td>5MUSES-249</td>
<td>16:22:14.8</td>
<td>+55:06:14.2</td>
<td>0.237</td>
<td>0.41</td>
<td>⋆</td>
<td>&lt; 1.72</td>
<td>&lt; 4.80</td>
</tr>
<tr>
<td>5MUSES-250</td>
<td>16:23:13.1</td>
<td>+55:11:11.6</td>
<td>0.237</td>
<td>0.48</td>
<td>599 ± 40</td>
<td>5.56 ± 0.68</td>
<td>15.5 ± 1.89</td>
</tr>
<tr>
<td>5MUSES-275</td>
<td>16:37:51.4</td>
<td>+41:30:27.3</td>
<td>0.286</td>
<td>0.61</td>
<td>950 ± 163</td>
<td>7.77 ± 1.38</td>
<td>32.0 ± 5.68</td>
</tr>
<tr>
<td>5MUSES-313</td>
<td>17:18:52.7</td>
<td>+59:14:32.1</td>
<td>0.322</td>
<td>0.47</td>
<td>⋆</td>
<td>&lt; 2.09</td>
<td>&lt; 10.1</td>
</tr>
<tr>
<td>5MUSES-156</td>
<td>15:58:33.3</td>
<td>+54:59:37.2</td>
<td>0.340</td>
<td>0.47</td>
<td>⋆</td>
<td>&lt; 2.17</td>
<td>&lt; 12.8</td>
</tr>
<tr>
<td>5MUSES-101</td>
<td>10:41:59.8</td>
<td>+58:58:56.4</td>
<td>0.360</td>
<td>0.32</td>
<td>⋆</td>
<td>&lt; 1.34</td>
<td>&lt; 8.91</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Redshift determined by fitting center of CO(1-0) line. Redshift errors scale with S/N, with the typical error of 0.0003 corresponding to S/N \sim 5. For the sources with 3σ upper limits, we list z_{IR}.

\textsuperscript{b}The rms is determined over the entire 38 GHz spectrum.

\textsuperscript{c}3σ upper limits are listed for six sources where we were not able to detect a line.
determined by estimating $L'_{\text{CO}}$ from $L_{\text{IR}}$ using the average ratio from Carilli & Walter (2013). The integration times were estimated to obtain a $> 3\sigma$ detection of the expected integrated line luminosity in each source according to the LMT integration time calculator. We obtained $> 3\sigma$ detections of 17 out of 24 targets. With the sole exception of 5MUSES-313, where the requested on source integration time was not completed, the desired rms was reached for all sources. The rms has been calculated using the full spectrum from 73-111 GHz. We list the rms in Table 6.1 for each source. There is no correlation between rms and S/N, so low CO(1-0) emission appears to be an intrinsic property of our undetected sources.

Data were reduced and calibrated using DREAMPY (Data REduction and Analysis Methods in PYthon). DREAMPY is written by G. Narayanan and is used specifically to reduce and analyze LMT/RSR data. It is a complete data reduction package with interactive graphics. For each observation scan, four distinct spectra are produced from the RSR. After applying appropriate instrumental calibrations from the DREAMPY pipeline, certain frequencies where known instrument artifacts are sometimes present were removed. There are no known bandpass features in the spectral regions where the CO(1-0) lines are expected. For each observation, linear baselines were calculated outside the region of the CO(1-0) line, and the rms estimated from the baseline of the full spectrum is used when all data for a given source are averaged together to produce the final spectrum. The averaging is a weighted average where the weights are set to $1/\text{rms}^2$.

We checked whether aperture corrections were necessary using the empirical relation derived in Saintonge et al. (2011a) and the optical radii from NASA/IPAC Extragalactic Database. We calculated at most a 10% aperture correction for our lowest redshift galaxies which have the largest angular extent. Given the uncertainty inherent in applying a correction formula, we have opted not to apply any aperture corrections.
From the final spectrum for each source, in units of antenna temperature, we determined the locations of the CO(1-0) peak by fitting a simple Gaussian to the spectrum close to the frequency $115.271/(1+z_{IR})$, allowing for a generous 10% uncertainty in $z_{IR}$, where $z_{IR}$ was derived by fitting the mid-IR spectral features (described in Section 6.1.2). In Table 6.1, we list $z_{CO}$, the redshift determined from the peak of the CO(1-0) emission. In all cases, the redshifts derived from fitting the CO(1-0) line agree with the mid-IR redshifts within $\Delta z_{1+z_{IR}} < 0.1\%$. The RSR is designed for blind redshift searches, and we test the reliability of our CO(1-0) detections by performing blind line searches over the full 38 GHz spectra. For 94% (16/17) of the objects that we claim detections for, a blind line search identifies the correct redshift. For 5MUSES-225, known noise artifacts elsewhere in the spectrum confuse the redshift solution. However, since redshifts are known for our targets, we can nevertheless reliably measure the CO(1-0) emission at the correct redshift.

Spectra (with $T_A$ in mK) and the best fit Gaussians are shown in Figure 6.1. We integrate under the Gaussian to determine the line intensities, $I_{CO}$, in K km/s. We convert the line intensity to $S_{CO} \Delta v$ using a conversion factor of 7 Jy/K, calibrated specifically for the LMT Early Science results, and we convert to $L'_{CO}$ following the equation in Solomon & Vanden Bout (2005) after correcting for cosmology differences. The CO(1-0) luminosities are listed in Table 6.1.

6.1.2 Infrared Emission

Our analysis centers around comparing the molecular gas emission, traced by $L'_{CO}$, with the dust emission, traced primarily through $L_{IR}$. $L_{IR}(5 - 1000 \mu m)$ values are calculated in Wu et al. (2010). The authors create synthetic IRAC photometry using the Spitzer IRS spectra and then fit a library of templates to the synthetic IRAC photometry and MIPS 24, 70, and 160 $\mu$m photometry. The final spectral energy distribution (SED) for each galaxy is created by combining the mid-IR spectroscopy
Figure 6.1: LMT/RSR spectra for our 5MUSES subsample. We plot antenna temperature (mK) as a function of frequency (GHz). Here we show 14 GHz of the rest frame spectra around the CO(1-0) line (this is only a portion of the full 73-111 GHz observed with the RSR). We overplot the location of the peak of the CO(1-0) emission as the blue dotted line and the best fit Gaussian as the red dashed line for the 17 sources with a $3\sigma$ detection. Seven sources lack a $3\sigma$ detection, and for those, we show an arrow at the expected location of the CO(1-0) peak emission based on $z_{\text{IR}}$. The spectra are presented in order of increasing redshift.
Figure 6.1: Figure 6.1 continued.
with the best-fit template. Finally, the authors calculate $L_{\text{IR}}$ by integrating under the SED from 5 – 1000 µm. Twelve of the sources in our study also have photometry from SPIRE on the *Herschel Space Observatory* (Magdis et al., 2013). We test whether including this longer wavelength data changes $L_{\text{IR}}$ for these 12 sources, and find excellent agreement, such that there is less than a 3% difference between $L_{\text{IR}}$ calculated with and without SPIRE data. For the purposes of this study, we wish to use the standard definition: $L_{\text{IR}}(8 – 1000 \, \mu m)$. We correct the $L_{\text{IR}}(5 – 1000 \, \mu m)$ values from Wu et al. (2010) to $L_{\text{IR}}(8 – 1000 \, \mu m)$ by scaling by 0.948, a conversion factor which was determined using composite LIRG and ULIRG SEDs from Kirkpatrick et al. (2012). In addition, Wu et al. (2010) uses a slightly different cosmology with $H_0 = 70 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$. Over our range of redshifts, this requires an average conversion factor of 0.970 to account for the difference in cosmologies. To summarize, we calculate:

$$
L_{\text{IR}}^{\text{tot}}(8 – 1000 \, \mu m) = L_{\text{IR}}^{\text{Wu}} \times 0.948 \times 0.970
$$

(6.1)

These values are listed in Table 6.2.

When an AGN is present, $L_{\text{IR}}^{\text{tot}}$ can have a non-negligible contribution from dust heated by an AGN, and hence $L_{\text{IR}}$ does not directly translate to an SFR. We diagnose the presence and strength of an AGN through mid-IR (5 – 15 µm rest frame) spectral decomposition. We follow the technique outlined in detailed in Chapter 2. For each source, we quantify the strength of the mid-IR AGN, $f(\text{AGN})_{\text{MIR}}$, as the fraction of the total mid-IR luminosity coming from the power-law continuum component. The PAH EW from Wu et al. (2010), initially used to select our sample, directly relates to the mid-IR AGN fraction, supporting the reliability of our diagnostic. Our decomposition technique is illustrated in Figure 6.2.

We use the mid-IR AGN strength, $f(\text{AGN})_{\text{MIR}}$, to determine the total contribution of the AGN to $L_{\text{IR}}^{\text{tot}}$. To estimate the conversion between $f(\text{AGN})_{\text{MIR}}$ and $f(\text{AGN})_{\text{total}}$, we use 22 composite SEDs created from > 300 LIRGs and ULIRGs spanning a red-
Figure 6.2: Spectral decomposition of 5MUSES galaxies. We determine the presence and strength of a mid-IR AGN by decomposing the mid-IR spectrum into a star formation component (green triple-dot-dashed line) and a power-law continuum with extinction (blue dot-dashed line). We calculate $f(\text{AGN})_{\text{MIR}}$ as the fraction of the luminosity of the best fit model (red dashed line) due to the power-law component. We illustrate the spectral decomposition of a star forming galaxy (top panel), composite (middle panel), and AGN (bottom panel).
shift range of $z = 0.5 - 3$ (Chapter 4). We decompose the mid-IR portion of the composite SEDs following the technique outlined above. We then decompose the full SED, from 0.5-1000 $\mu$m, by fitting a pure AGN template and a star formation template. We find that the total IR AGN contribution is $53 \pm 12\%$ of the mid-IR AGN strength ($f(\text{AGN})_{\text{total}} = 0.53 \times f(\text{AGN})_{\text{MIR}}$). For the 5MUSES sample, where we lack enough data points to accurately decompose the full-IR SED, we scale the mid-IR AGN strength by 0.53 to estimate the total AGN contribution, $f(\text{AGN})_{\text{total}}$, to $L_{\text{IR}}^{\text{tot}}$, and we use this value to calculate $L_{\text{IR}}^{\text{SF}}$, the IR luminosity attributed to star formation. In the analysis that follows, we separate our sources according to $f(\text{AGN})_{\text{MIR}}$, resulting in three categories: (1) purely star forming galaxies have $f(\text{AGN})_{\text{MIR}} < 0.2$ ($f(\text{AGN})_{\text{total}} < 0.1$); (2) AGN have $f(\text{AGN})_{\text{MIR}} > 0.7$ ($f(\text{AGN})_{\text{total}} > 0.4$); and (3) composites have $f(\text{AGN})_{\text{MIR}} = 0.2 - 0.7$ ($f(\text{AGN})_{\text{total}} = 0.1 - 0.4$).

We are also interested in the strength of the PAH emission, since this is expected to trace star formation and photodissociation regions within molecular clouds. By comparing the PAH emission with $L_{\text{IR}}$ and CO(1-0) emission, we have three separate tracers of the dust and gas in the ISM which are expected to correlate with star formation. We quantify the PAH emission as $L_{6.2}$, the luminosity of the isolated 6.2 $\mu$m line. We fit a continuum on either side of this feature at 5.9 $\mu$m and 6.5 $\mu$m and remove the continuum component. We then integrate under the continuum subtracted emission feature to obtain $L_{6.2}$. None of our sources are extended at 8.0 $\mu$m using the Spitzer IRAC images, so aperture corrections are not necessary when comparing the Spitzer and LMT luminosities. We list $L_{6.2}$, $L_{\text{IR}}^{\text{SF}}$, $f(\text{AGN})_{\text{MIR}}$, and $f(\text{AGN})_{\text{total}}$ in Table 6.2.

### 6.1.3 Specific Star Formation Rates

The specific star formation rate (sSFR) is the ratio of SFR to stellar mass. Shi et al. (2011) determined stellar masses for the 5MUSES sample by fitting Bruzual &
Table 6.2: Infrared and star formation properties.

<table>
<thead>
<tr>
<th>ID</th>
<th>log $L_{IR}^{tot}$</th>
<th>$f(AGN)_{MIR}$</th>
<th>Type</th>
<th>log $L_{IR}^{SF}$</th>
<th>log $L_{6.2}$</th>
<th>log $M_*$</th>
<th>sSFR$^a$</th>
<th>Desig.$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5MUSES-200</td>
<td>10.36</td>
<td>0.23</td>
<td>Comp</td>
<td>10.31</td>
<td>8.04</td>
<td>10.48</td>
<td>0.09</td>
<td>MS</td>
</tr>
<tr>
<td>5MUSES-179</td>
<td>10.22</td>
<td>0.24</td>
<td>Comp</td>
<td>10.17</td>
<td>7.95</td>
<td>11.08</td>
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$^a$Calculated using $L_{IR}^{SF}$.

$^b$Main Sequence (MS) or Starburst (SB) according to Equation 6.3, where sSFR is calculated using $L_{IR}^{SF}$.
Charlot (2003) population synthesis models to optical and near-IR broadband photometry assuming a Chabrier IMF. We adopt these stellar masses, and we calculate the SFR from \( L_{\text{IR}}^{SF} \) according to

\[
\left( \frac{\text{SFR}}{\text{M}_\odot \text{yr}^{-1}} \right) = 1.509 \times 10^{-10} \left( \frac{L_{\text{IR}}^{SF}}{L_\odot} \right)
\]

assuming a Kroupa IMF and a constant star formation rate over the past 100 Myr (Murphy et al., 2011b). We do not convert between a Chabrier IMF and a Kroupa IMF for this formula, since the conversion is very small (Zahid et al., 2012).

The galaxy main sequence can be used to classify galaxies as either normal star forming galaxies or starbursts based on whether they have an enhanced SFR for a given \( M_\star \). This relationship is a slowly varying function of redshift. Elbaz et al. (2011) present a relationship between sSFR and the time since the Big Bang in Gyr, \( t_{\text{cosmic}} \), for the galaxy main sequence (see Equation 13 in Elbaz et al., 2011). The relation in Elbaz et al. (2011) is derived assuming a Salpeter IMF, an \( L_{\text{IR}} \)-SFR conversion from Kennicutt (1998), and a cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_\Lambda = 0.7 \). We convert the relation from a Salpeter IMF to a Kroupa IMF using \( M_{\star \text{Kroupa}} = 0.62 M_{\star \text{Salpeter}} \) (Zahid et al., 2012). We convert \( t_{\text{cosmic}} \) to the cosmology used in this paper by multiplying by 1.02, appropriate for our redshift range. Finally, the SFRs are related by \( \text{SFR}_{\text{Murphy11}} = 0.86 \text{SFR}_{\text{Kennicutt98}} \) (Kennicutt & Evans, 2012).

Applying all of these conversions gives the MS relation appropriate for the present work:

\[
\text{sSFR}_{\text{MS}} (\text{Gyr}^{-1}) = 38 \times t_{\text{cosmic}}^{-2.2}
\]

If a galaxy has a sSFR a factor of two greater than \( \text{sSFR}_{\text{MS}} \), it is classified as a starburst. We use \( z_{\text{CO}} \) and \( L_{\text{IR}}^{SF} \) to calculate \( \text{sSFR}_{\text{MS}} \) and list the stellar masses along with the main sequence/starburst designations in Table 6.2. We plot sSFR v. \( z \) for our sample in Figure 6.3. We show the SFR calculated using \( L_{\text{IR}}^{\text{tot}} \) (grey open symbols)
Figure 6.3: The main sequence for the 5MUSES sample, where the main sequence is sSFR v. z. The open symbols show sSFR calculated with $L_{IR}^{tot}$ while the filled symbols show sSFR calculated with $L_{IR}^{SF}$. We color the sources according to whether they are star forming galaxies (blue), composites (green), or AGN (red), according to $f(AGN)_{MIR}$. We overplot the main sequence relation from Equation 6.3 (dashed line), and the grey shaded region extends a factor of two above and below this line, consistent with the scatter measured in Elbaz et al. (2011). Removing the AGN contribution has the effect of generally lowering the sSFR and moving two sources onto the main sequence. We show the distributions of sSFRs in the histogram on the right. The grey histogram is the distribution when sSFR is calculated with $L_{IR}^{tot}$, and the cyan histogram is the distribution of sSFR calculated with $L_{IR}^{SF}$. The dashed and dot-dashed lines show the medians.

and the sSFR calculated using $L_{IR}^{SF}$ (filled symbols). We color the sources according to whether they are star forming galaxies (blue), composites (green), or AGN (red), according to $f(AGN)_{total}$ (see Section 6.1.2). Removing the AGN contribution to $L_{IR}^{tot}$, which we have done for all sources, has the effect of moving two of our sources from the starburst region onto the main sequence. Two sources, 5MUSES-136 and 5MUSES-179, lie below the main sequence, possibly indicating that they are transitioning to a more quiescent evolutionary stage. In this small sample, we observe no obvious association of AGN strength with distance from the main sequence, similar to what is seen in Elbaz et al. (2011).
6.2 Results & Discussion

6.2.1 Relationship Between Molecular Gas and Dust Emission

In the local Universe, the SK law is traditionally expressed in terms of surface densities, which necessarily require resolved measurements of star formation and molecular gas (Schmidt, 1959; Kennicutt, 1998; Shi et al., 2011; Kennicutt & Evans, 2012). At higher redshifts, resolved measurements are often not feasible, and global measurements of the SFR and molecular gas are used instead. The ratio of $L_{\text{IR}}$, directly related to a global SFR, and $L_{\text{CO}}'$ is commonly referred to as a star formation efficiency (Young & Scoville, 1991; Solomon & Vanden Bout, 2005). It is essentially the integrated version of the SK law without the uncertain conversion from CO to $\text{H}_2$ mass. This quantity is also related to the inverse of the gas depletion timescale which describes how long a galaxy could continue to form stars at the current rate if the gas reservoir is not replenished (e.g., Saintonge et al., 2011b).

In general, $L_{\text{IR}}$ correlates with $L_{\text{CO}}'$, although there is significant scatter. $L_{\text{IR}}$ is primarily measuring the reradiated light from newly formed stars (with some contribution from an older stellar population), while $L_{\text{CO}}'$ is measuring the reservoir of molecular gas available to form stars in the future; hence the dust and gas do not necessarily trace star formation on the same timescales. CO emission can also be present between molecular clouds, introducing more scatter in the relationship between $L_{\text{IR}}$ and $L_{\text{CO}}'$. To account for this scatter, many authors propose two relationships, one for starbursts, undergoing an enhanced $L_{\text{IR}}/L_{\text{CO}}'$, and one for normal star forming galaxies (e.g., Daddi et al., 2010b; Genzel et al., 2010; Carilli & Walter, 2013; Tacconi et al., 2013). If a galaxy undergoes a burst of star formation that also triggers AGN growth, this could account for some of the scatter in $L_{\text{IR}}/L_{\text{CO}}'$. Initially, as an embedded AGN grows more luminous, it heats some of the surrounding dust, but is enshrouded enough that the host galaxy is still visible (e.g., Sanders et al., 1988; Hopkins et al., 2006; Kirkpatrick et al., 2012). The increase in the amount of warm
Figure 6.4: The relationship between $L_{\text{IR}}^{\text{SF}}$ and $L_{\text{CO}}'$ for the 5MUSES sample. We also include the relationships for $L_{\text{IR}}$ and $L_{\text{CO}}'$ derived for starbursts and SFGs from Genzel et al. (2010), where the grey shaded region indicates the standard deviation. We color the points according to $f(\text{AGN})_{\text{MIR}}$, and we use different symbols to indicate the galaxies that are starbursting according to sSFR. There is no strong separation according to either $f(\text{AGN})_{\text{MIR}}$ or starburstiness, and our galaxies all lie close to the SFG relation from Genzel et al. (2010).

dust heated by the AGN will enhance $L_{\text{IR}}$ but may not yet affect $L_{\text{CO}}'$, implying an artificially high $L_{\text{IR}}/L_{\text{CO}}'$ unless the AGN contribution is accounted for (e.g., by considering $L_{\text{IR}}^{\text{SF}}$). As the AGN becomes less enshrouded, the PAH and cold dust emission from the host become less prominent because the dust heated by the AGN is outshining the dust in star forming regions, and/or because feedback from the AGN is quenching the star formation. If the AGN is quenching the star formation, this will produce lower $L_{\text{IR}}^{\text{SF}}$ values and hence lower $L_{\text{IR}}^{\text{SF}}/L_{\text{CO}}'$, unless feedback from the AGN expels CO on the same timescales.

As yet, no study has attempted to quantify the effect of the AGN on $L_{\text{IR}}/L_{\text{CO}}'$ individually in galaxies due to the difficulty in measuring the amount of $L_{\text{IR}}$ attributable to an AGN. The 5MUSES sample has mid-IR spectra that exhibit both PAH features and a strong underlying continuum, allowing us to cleanly separate out the AGN...
luminosity and calculate $L_{\text{IR}}^{\text{SF}}$. Figure 6.4 shows the relationship between $L_{\text{IR}}^{\text{SF}}$ and $L'_\text{CO}$, and the points are colored according to $f(\text{AGN})_{\text{total}}$. We overplot the relations between $L_{\text{IR}}^{\text{SF}}$ and $L'_\text{CO}$ determined for star forming galaxies (SFGs, dashed line; grey region indicates one standard deviation) and starbursts (dotted line) in Genzel et al. (2010). These relations were robustly determined using large samples of normal star forming galaxies and starbursts from $z \sim 0 - 3$, and we are interested in testing how removing the AGN component in our galaxies changes their position relative to these relations. The presence of two separate relations is discussed in depth in Carilli & Walter (2013), where the authors also present a single relation fitting all available $L_{\text{IR}}$ and $L'_\text{CO}$ measurements in the literature. We compare to the separate starburst and SFG relations to investigate any difference in $L_{\text{IR}}^{\text{SF}}/L'_\text{CO}$ according to IR power source or starburstiness.

Genzel et al. (2010) determined the relations for SFGs and starbursts using the far-IR luminosity (FIR: $50 - 300 \mu$m) as opposed to $L_{\text{IR}}$, so we scale the relationships according to $L_{\text{IR}}/\text{FIR} = 1.63$, a ratio determined using the LIRG and ULIRG templates from Chapter 2. We overplot the $1\sigma$ scatter from Genzel et al. (2010) as the grey shaded region. We plot the main sequence galaxies (determined by Equation 6.3) as filled circles and starbursts as filled stars. The starbursts on average have a factor of two higher $L_{\text{IR}}^{\text{SF}}$ and $L'_\text{CO}$ than the main sequence galaxies. We find that both the main sequence and starbursts are consistent with the SFG relationship from Genzel et al. (2010), and there is no strong separation according to IR power source.

We can look at this more simply by considering the ratio $L_{\text{IR}}^{\text{SF}}/L'_\text{CO}$. In Figure 6.5, we plot $L_{\text{IR}}^{\text{SF}}/L'_\text{CO}$ as a function of $f(\text{AGN})_{\text{total}}$. We also include $L_{\text{IR}}^{\text{tot}}/L'_\text{CO}$ as the unfilled circles and stars. The grey shaded regions illustrate the standard deviation around the average $L_{\text{IR}}/L'_\text{CO}$ calculated for starbursts and SFGs in Genzel et al. (2010). The standard deviation for the SFG region is 0.33 dex, slightly larger than the standard deviation illustrated in Figure 6.4. This is due to the fact that the
Figure 6.5: Star formation efficiency ($L^{\text{SF}}_{\text{IR}}/L_{\text{CO}}'$) v. $f(\text{AGN})_{\text{total}}$. Unfilled symbols are calculated using $L^{\text{tot}}_{\text{IR}}$. Symbols correspond to sSFR designation. The shaded regions show one standard deviation around the mean $L_{\text{IR}}/L_{\text{CO}}'$ for SFGs and starbursts from Genzel et al. (2010). Nearly all galaxies lie within the SFG region. There is no significant trend with $f(\text{AGN})_{\text{total}}$, although the AGN do have a lower average $L^{\text{SF}}_{\text{IR}}/L_{\text{CO}}'$ than the star forming galaxies or the composites. We show the distributions in the histogram on the right. The grey histogram is the distribution of $L^{\text{tot}}_{\text{IR}}/L_{\text{CO}}'$, with the mean overplotted as the dashed line, and the cyan histogram is the distribution of $L^{\text{SF}}_{\text{IR}}/L_{\text{CO}}'$, with the dot-dashed line illustrating the mean.
relation between \( L_{\text{IR}} \) and \( L'_{\text{CO}} \) is non-linear, so the standard deviation relative to the mean \( L_{\text{IR}} / L'_{\text{CO}} \) is larger.

None of our galaxies lie in the starburst region. Genzel et al. (2010) find a mean \( L_{\text{IR}} / L'_{\text{CO}} \) of 44. We calculate that the mean \( L_{\text{IR}}^{\text{tot}} / L'_{\text{CO}} \) is 59, but when we remove the AGN contribution to \( L_{\text{IR}}^{\text{tot}} \), we calculate a mean \( L_{\text{IR}}^{\text{SF}} / L'_{\text{CO}} \) of 52, closer to the mean measured by Genzel et al. (2010). Removing the AGN component only mildly reduces the scatter about the mean \( L_{\text{IR}}^{\text{SF}} / L'_{\text{CO}} \). Two galaxies, 5MUSES-179 and 5MUSES-275, lie below the SFG region. The galaxy with the lowest \( L_{\text{IR}}^{\text{SF}} / L'_{\text{CO}} \), 5MUSES-179, also lies decidedly below the main sequence region in Figure 6.3, further indicating that its star formation is highly inefficient, and this galaxy could be transitioning to a quiescent phase. We find no relationship between \( L_{\text{IR}}^{\text{SF}} / L'_{\text{CO}} \) and \( f(\text{AGN})_{\text{total}} \). For this small sample, the star forming galaxies exhibit less scatter in \( L_{\text{IR}}^{\text{SF}} / L'_{\text{CO}} \) than the composite galaxies, although both groups have the same average \( L_{\text{IR}}^{\text{SF}} / L'_{\text{CO}} \). The AGN have a lower average \( L_{\text{IR}}^{\text{SF}} / L'_{\text{CO}} \) indicating that these galaxies are not converting gas to stars at the same rate as the composite or SF galaxies; this hints that the star formation might be beginning to quench in these AGN sources.

It is interesting to note that two galaxies with very high \( L_{\text{IR}}^{\text{SF}} / L'_{\text{CO}} \) lower limits (5MUSES-249 and 5MUSES-294) show no trace of an AGN according to their mid-IR spectra. This could be illustrative of the different timescales that AGN signatures, starburst signatures, and enhanced \( L_{\text{IR}}^{\text{SF}} / L'_{\text{CO}} \) ratios are visible. Mid-IR spectroscopy and Chandra X-ray observations provide evidence that the majority of local ULIRGs and high redshift submillimeter galaxies (SMGs), which have a high merger (and hence, starburst) fraction and enhanced \( L_{\text{IR}} / L'_{\text{CO}} \), are predominately powered by star formation in the mid-IR (e.g., Alexander et al., 2005; Pope et al., 2008a; Veilleux et al., 2009; Elbaz et al., 2011). A non-negligible fraction of LIRGs and ULIRGs host a mid-IR luminous AGN, although optical morphologies of local LIRGs reveal that mid-IR AGN signatures are predominately found either in isolated disk galaxies or
coalesced nuclei at the end of a merger (Petric et al., 2011). We expect, then, that if the AGN and starburst phase do not overlap completely, AGN should have lower $L_{\text{IR}}^{\text{SF}}/L_{\text{CO}}'$ ratios, and Figure 6.5 shows that they do, for this small sample, once the AGN contribution to $L_{\text{IR}}^{\text{tot}}$ has been accounted for.

Also of interest is that we do not observe any dichotomy in $L_{\text{IR}}^{\text{SF}}/L_{\text{CO}}'$ either as a function of mid-IR power source or along the main sequence/starburst classification. Saintonge et al. (2011b) observe a clear relationship between the gas depletion timescale and the sSFR in a large, complete, sample of local galaxies as part of the COLD GASS survey. We compare our sources with the COLD GASS galaxies in Figure 6.6. Saintonge et al. (2011b) calculate the depletion timescale as $t_{\text{dep}} = M_{\text{H}_2}/\text{SFR}$, but to avoid any uncertainties due to converting $L_{\text{CO}}'$ to $M_{\text{H}_2}$ (see Section 6.2.3), we simply use the ratio $\text{SFR}/L_{\text{CO}}' \propto t_{\text{dep}}^{-1}$. We have calculated the SFRs for our galaxies using $L_{\text{IR}}^{\text{SF}}$. Figure 6.6 also includes the $z = 1 - 3$ galaxies from Genzel et al. (2010), where we have corrected the SFRs, calculated using the conversion in Kennicutt (1998), to be on the same scale as ours. The SFRs from Saintonge et al. (2011b) are calculated by fitting the SED from the UV out to 70 $\mu$m. We do not further correct for differing cosmologies as the intrinsic scatter in Figure 6.6 is larger than any shift introduced in this manner.

When looking at just our 5MUSES sample in Figure 6.6, there is no strong correlation between SFR/$L_{\text{CO}}'$ and sSFR, just as we observed no separation according to sSFR in Figure 6.5. However, when we extend the dynamical range of the plot by considering the local galaxies from Saintonge et al. (2011b) and the $z = 1 - 3$ galaxies from Genzel et al. (2010), there is a strong correlation (a Spearman’s rank test gives a correlation coefficient of $\rho = 0.72$ with a two-sided significance equal to 0.0). Our sample lies in the range expected. This suggests that we are not observing any differences between our starburst and main sequence galaxies in Figures 6.4 and 6.5 simply because we are not probing a large enough range of $L_{\text{CO}}'$ and $L_{\text{IR}}$. 
Figure 6.6: SFR/$L'_{CO}$, which is related to the inverse of the gas depletion timescale, as a function of $sSFR$. We include the local COLD GASS sources from Saintonge et al. (2011b) and the $z = 1-3$ sample from Genzel et al. (2010). There is a strong correlation between the two parameters for all galaxies, although this correlation would be missed if only considering the 5MUSES sample.

6.2.2 Comparing Different Tracers of Star Forming Regions

IR, CO, and PAH luminosities are all commonly used as tracers of star formation in dusty galaxies. PAH emission arises from PDRs surrounding young stars and has been demonstrated locally to be largely cospatial with the molecular clouds traced by CO emission (Bendo et al., 2010). If star formation is continuously fueled for $\ll 1$ Gyr, these tracers should all correlate.

For most star forming galaxies, the ratio of $L_{PAH}/L_{IR}$ is fairly constant, but there is an observed deficit of PAH emission relative to $L_{IR}$ in local ULIRGs, possibly due to an increase in the hardness of the radiation field caused either by a major merger/starburst or an AGN (Tran et al., 2001; Desai et al., 2007). This same deficit does not hold for similarly luminous galaxies at high redshift, however, where the majority of ULIRGs are observed to have strong PAH emission (Pope et al., 2008a; Menéndez-Delmestre et al., 2009; Kirkpatrick et al., 2012).
Pope et al. (2013) explored the evolution of $L_{6.2}/L_{IR}$ with redshift for a sample of ULIRGs from $z \sim 1 - 4$ as well as a sample of local ULIRGs. Specifically, the authors compare $L_{6.2}/L_{IR}$ with $L_{IR}$ and find that the deficit in $L_{6.2}$ relative to $L_{IR}$ occurs at a higher $L_{IR}$ for high redshift galaxies than is seen in the local Universe. Galaxies from $z \sim 1 - 3$ typically have higher gas fractions than local counterparts (Daddi et al., 2010a; Tacconi et al., 2010). This increase in molecular gas could be linked to the relative increase in PAH emission, since both are largely cospatial. Indeed, when Pope et al. (2013) compare $L_{6.2}/L_{IR}$ with $L_{IR}/L'_{CO}$, they find a consistent relationship for both the local and high redshift ULIRGs.

We now build on the analysis presented in Pope et al. (2013) by extending the parameter space explored to the lower luminosity 5MUSES sample. The 5MUSES galaxies combined with the local ULIRGs comprise a low redshift sample for comparison with the high redshift ULIRGs. We plot $L_{6.2}/L^\text{SF}_{IR}$ v. $L^\text{SF}_{IR}$ for our sample in the left panel of Figure 6.7. We also include the high redshift and local ULIRGs from Pope et al. (2013) where we have calculated $L^\text{SF}_{IR}$ for all ULIRGs by scaling the mid-IR AGN strength, determined by decomposing the mid-IR spectra. There is a decreasing trend between the 5MUSES sample and the local ULIRGs, but the high redshift ULIRGs are shifted from this relation. In the right panel, we plot $L_{6.2}/L^\text{SF}_{IR}$ v. $L^\text{SF}_{IR}/L'_\text{CO}$. $L'_\text{CO}$ is calculated using the estimated CO(1-0) luminosity for all galaxies (see Pope et al., 2013, for conversion details). In this panel, most galaxies follow the same decreasing trend, with a few obvious outliers. We overplot the best fit relation for the 5MUSES sample and the local and high redshift ULIRGs. The shaded region indicates one standard deviation above and below the fit. There is a decreasing correlation between $L_{6.2}/L^\text{SF}_{IR}$ and $L^\text{SF}_{IR}/L'_\text{CO}$ for most galaxies.

Figure 6.7 suggests that the relative amount of emission from small dust grains is related to $L^\text{SF}_{IR}/L'_\text{CO}$ for dusty galaxies out to $z \sim 2$. That is, weaker PAH emission is associated with a higher star formation efficiency and faster gas depletion timescales.
The decrease in $L_{6.2}$ with increasing $L_{\text{IR}}$ could indicate that PAH emission in general is suppressed for more luminous galaxies. We do not find significantly lower $L_{6.2}/L_{\text{IR}}^{\text{SF}}$ ratios for our AGN or composite galaxies as compared to our star forming galaxies, indicating that in our sample, the growing AGN is not affecting this ratio.

As discussed in Pope et al. (2013), the PAH deficit could be similar to the observed deficit in [CII] emission at high $L_{\text{IR}}$ in local galaxies (e.g., Kaufman et al., 1999; Stacey et al., 2010; Graciá-Carpio et al., 2011). Díaz-Santos et al. (2013) probe the [CII] deficit in local LIRGs and find that galaxies with compact mid-IR emission have a [CII] deficit, regardless of the mid-IR power source. For our sample, follow-up observations are required to trace the compactness of the galaxies. If our galaxies have extended dust emission, this would explain the similar $L_{6.2}/L_{\text{IR}}^{\text{SF}}$ ratios for the 5MUSES galaxies and the high redshift ULIRGs, since high redshift ULIRGs are known to have extended dust emission (e.g., Chapman et al., 2004). Based on the relative strengths of the dust emission and CO(1-0) emission, the 5MUSES sources, primarily LIRGs, seem to be more accurate counterparts for the high redshift ULIRGs than the local ULIRGs, evidencing the evolution of ISM properties with redshift. A morphological comparison of these sources could provide more insight into structure and compactness of the dust and gas emission.

### 6.2.3 Gas Fractions

The gas fraction is expressed as $f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_*)$, where $M_{\text{gas}} = \alpha_{\text{CO}} L'_{\text{CO}}$. $\alpha_{\text{CO}} = 4.6$ is a commonly adopted value for normal star forming galaxies, while in starbursts, the conversion $\alpha_{\text{CO}} = 0.8$ has been measured (Bolatto et al., 2013, and references therein). We have two observational indicators of starburstiness: $L_{\text{IR}}^{\text{SF}}/L'_{\text{CO}}$ and sSFR. To calculate $M_{\text{gas}}$, we explore two scenarios. First, we apply $\alpha_{\text{CO}} = 4.6$ to our entire sample (top panel of Figure 6.8). None of our galaxies have $L_{\text{IR}}^{\text{SF}}/L'_{\text{CO}}$ indicative of a starburst (Figure 6.5), so applying the same $\alpha_{\text{CO}}$ to the entire sample
Figure 6.7: The fraction of PAH emission for local and high z dusty galaxies. We plot $L_{6.2}/L_{\text{IR}}$ v. $L_{\text{IR}}^{\text{SF}}$ in the left panel and v. $L_{\text{IR}}^{\text{SF}}/L_{\text{CO}}$ in the middle panel. We color the points according to the power source of the mid-IR luminosity, and we use different symbols to designate starbursts and main sequence galaxies based on sSFR. We also plot as the grey points the local and high redshift ULIRGs from Pope et al. (2013). The 5MUSES galaxies combined with the local ULIRGs comprise a low redshift sample for comparison with the high redshift ULIRGs. The 5MUSES galaxies have similar $L_{6.2}/L_{\text{IR}}^{\text{SF}}$ ratios as the high redshift ULIRGs, while the local ULIRGs have a deficit, likely related to their more compact emission. When we normalize the dust emission by the molecular gas emission (middle panel), all galaxies lie in a similar region of parameter space, illustrating the consistent link between PAH emission and molecular gas over a range of $L_{\text{IR}}$ and redshifts. For clarity, we omit individual error bars and plot the typical uncertainties for all galaxies in the lower left corner. The dashed line shows the best fit relation for all galaxies (listed in the upper left corner), and the grey shaded region marks the standard deviation about this line. We show the distributions in the histogram on the right. The grey histogram is the distribution of $L_{6.2}/L_{\text{IR}}^{\text{SF}}$ for the local ULIRGs, with the median overplotted as the dashed line; the orange histogram and line show the distribution and median for the high redshift ULIRGs, and the cyan histogram and line is the distribution and median for the 5MUSES sample.
is a reasonable assumption. Second, we use $\alpha_{CO} = 0.8$ to calculate the gas mass for those galaxies with an sSFR indicative of a starburst (bottom panel of Figure 6.8). We plot the gas fractions as a function of redshift. We also plot gas fractions of normal star forming galaxies from the literature, and we have corrected the individual $\alpha_{CO}$ values used to be 4.6. The average molecular gas fraction evolves with redshift, and we plot the measured relation, $f_{gas} \propto (1 + z)^2$, determined from a stellar mass limited sample with $\log M_* > 10$ (Geach et al., 2011), similar to the masses of our 5MUSES sample.

Our gas fractions (in both panels) lie in the range expected when comparing with the best fit line and the points from Leroy et al. (2009) and Geach et al. (2011). Our CO(1-0) detection rate is high (17 out of 24 sources), producing a large range of measured gas fractions. In the top panel, our starburst galaxies are systematically higher than the main sequence galaxies, and the scatter about the $(1 + z)^2$ line is larger, which suggests that the lower $\alpha_{CO} = 0.8$ conversion factor might be more appropriate for these sources if we expect similar gas fractions for main sequence and starburst galaxies. Theoretically, the conversion factor depends on the geometry of the CO and $H_2$ distribution. When the CO emission is extended and not confined to molecular clouds, it is warmer and has a high surface density, as is the case in mergers, then the lower $\alpha_{CO}$ value is appropriate (Bolatto et al., 2013, and references therein). Magnelli et al. (2012) measure $\alpha_{CO}$ for a sample of high redshift main sequence and starburst galaxies and find an anti-correlation between $\alpha_{CO}$ and sSFR, which they interpret as evidence that the mechanisms responsible for raising a galaxy off the main sequence must also affect the physical conditions within the star forming regions. We also find that the gas fractions reproduce a similar separation between sources as the main sequence criterion, linking $\alpha_{CO}$ with the sSFR. In contrast, neither $L^{SF}_{IR}/L'_{CO}$ nor $L_{6.2}/L^{SF}_{IR}$ shows any separation between the starburst and main sequence galaxies, likely due to the limited range being probed. These ratios, then, are relatively stable.
for galaxies of a limited mass and luminosity range. Narayanan et al. (2012) argue against a bimodal $\alpha_{\text{CO}}$ conversion factor, and instead develop a fitting formula for the conversion factor that depends on the metallicity and CO line intensity. We currently lack metallicities for our sample, so we cannot directly apply the prescribed variable conversion factor. Given the continuous relationship between sSFR and SFR/$L'_{\text{CO}}$ evidenced in Figure 6.6, a continuous, rather than bimodal, conversion factor based on galactic environment may be the most appropriate choice and would mean that all galaxies in our sample obey a similar relationship between the molecular gas and the stellar mass.

### 6.3 Chapter Summary

We present new LMT/RSR CO(1-0) detections for 24 intermediate redshift galaxies from the 5MUSES sample. We use Spitzer mid-IR spectra, available for all sources, to diagnose the presence and strength of an AGN. We removed the AGN contribution to $L_{\text{IR}}^{\text{tot}}$ and probe the star formation, gas, and dust emission using $L_{\text{IR}}^{\text{SF}}$, $L'_{\text{CO}}$, and $L_{6.2}$. We find

1. Removing the AGN contribution to $L_{\text{IR}}^{\text{tot}}$ results in a mean $L_{\text{IR}}^{\text{SF}}/L'_{\text{CO}}$ for our entire sample consistent with the mean $L_{\text{IR}}/L'_{\text{CO}}$ derived for a large sample of star forming galaxies from $z \sim 0 - 3$. For our four AGN sources, removing the AGN contribution produces a mean $L_{\text{IR}}^{\text{SF}}/L'_{\text{CO}}$ lower than the mean $L_{\text{IR}}^{\text{SF}}/L'_{\text{CO}}$ for our star forming galaxies or composites. We find that $L_{\text{IR}}^{\text{SF}}/L'_{\text{CO}}$ is not strongly correlated with either the sSFR or the mid-IR power source over the range of luminosities probed.

2. The average ratio of $L_{6.2}/L_{\text{IR}}^{\text{SF}}$ in our sample is similar to what is observed in high redshift ULIRGs rather than local ULIRGs. When we plot $L_{6.2}/L_{\text{IR}}^{\text{SF}}$ as a function of $L_{\text{IR}}^{\text{SF}}/L'_{\text{CO}}$, we find all galaxies (local ULIRGs, our intermediate
Figure 6.8: Gas fractions v. $z_{CO}$. Top panel: $f_{gas}$ is calculated using $\alpha_{CO} = 4.6$ for all galaxies. Bottom panel: $f_{gas}$ is calculated using $\alpha_{CO} = 0.8$ for starburst galaxies (filled stars). We also overplot gas fractions from Leroy et al. (2009), Daddi et al. (2010b), Tacconi et al. (2010), and Geach et al. (2011). The best fit line is $f_{gas} = 0.1(1+z)^2$ (Geach et al., 2011). Our galaxies lie in the region expected from the best fit line, although there is an offset between the starbursts (stars) and main sequence sources (circles) when $\alpha_{CO} = 4.6$ is used, indicating that a lower $\alpha_{CO}$ conversion might be more appropriate for the starbursts.
redshift 5MUSES sources, and high redshift ULIRGs) are consistent with the same declining relationship.

3. Our starbursts have gas fractions that are clearly offset from the main sequence galaxies if we apply a constant $\alpha_{\text{CO}}$ to all galaxies which might indicate that the two populations require different $\alpha_{\text{CO}}$ values. However, no dichotomy between starbursts and main sequence galaxies is evident when comparing other quantities that probe the ISM ($L_{\text{IR}}^{\text{SF}}, L'_{\text{CO}},$ or $L_{6.2}$).
CHAPTER 7
COMPARISON WITH LOCAL IR LUMINOUS GALAXIES

Observations at high redshift are currently limited due to either confusion limits of telescopes or long required integration times for faint galaxies. As a result, a common technique is to apply local templates to scant photometry for distant galaxies in order to extrapolate information about their star formation rates, $L_{\text{IR}}$, or dust masses. In particular, many authors scale the appropriate Chary & Elbaz (2001) template to a 24 $\mu$m photometric point to estimate $L_{\text{IR}}$. However, this technique has been shown to overestimate $L_{\text{IR}}$ at $z > 1.5$, likely due to the changing nature of ULIRGs (Pope et al., 2006; Nordon et al., 2010; Magnelli et al., 2011; Elbaz et al., 2011). Correctly applying low redshift templates to high redshift data presents a serious problem for high redshift studies.

We now wish to further explore similarities between our high redshift (U)LIRGs and those found in the local Universe. We demonstrated in Chapter 2 that our star forming galaxies have more cold dust emission than several local galaxies, including a normal SFG (M 82), two ULIRGs (NGC 6240 and Arp 220), and the appropriate templates from Chary & Elbaz (2001). However, we also showed in Chapter 4 that the infrared colors $S_{160}/S_{70}$ and $S_{24}/S_{8}$ were similar for many of the local star forming LIRGs from the GOALS survey and our high redshift sample. In contrast, in Chapter 6, we saw that the ratio of PAH emission to $L_{\text{IR}}$ ($L_{6.2}/L_{\text{IR}}$) is lower in local ULIRGs (from GOALS) compared with ULIRGs from $z = 1 - 2$. In light of these conflicting results, we now ask, are there local analogs to our high redshift galaxies? And if so, can we learn about the high redshift galaxies by studying these local analogs?
For this study, we utilize the GOALS survey (see also Chapter 4). The GOALS sample is comprised of 180 LIRGs and 22 ULIRGs. Several of these systems are interacting, and as a result, there are 244 individual galactic nuclei with Spitzer IRS spectroscopy. These galaxies are a complete subset of the IRAS Bright Galaxy Survey and were selected at 60 µm to have $S_{60} > 5.24$ Jy. These sources cover the distance range $15 \text{ Mpc} < D < 400 \text{ Mpc}$, which corresponds to $z < 0.088$. Our high $z$ sample is the supersample presented in Chapter 4.

We have used the spectroscopy to classify each GOALS galaxy as SFG, composite, and AGN. The reader should bear in mind that the IRS spectra cover the nuclei of the GOALS galaxies, but for the high redshift sources, the spectra cover entire galaxies. In general, we have fewer AGN sources in the GOALS sample, which could make finding analogs for the AGN difficult (Figure 7.1).

### 7.1 Finding Analogs by Comparing Spectral Shapes

The GOALS galaxies have a variety of spectral shapes, particularly the ULIRGs. From the parent sample, we select local analogs purely on the basis of the shape.
of the infrared SED. For the GOALS galaxies, we have *Spitzer* MIPS 24, 70, and 160 µm imaging. The MIPS photometry covers the entire galaxy. In order to properly compare SED shapes, we do not use the IRS spectra, since it only covers the nuclear region. We do convolve the spectra with the IRAC 8 µm transmission filter to estimate $S_8$. We apply a correction factor (calculated in Stierwalt et al., 2014) so that $S_8$ covers the same emission region as the MIPS photometry. We have 190 galaxies with the required $S_8$ correction factor, so this is our parent sample.

We compare GOALS photometry with the empirical templates from the Comprehensive Library (Chapter 4); this library is ideal since it encompasses changes in the high z sources with $L_{\text{IR}}$ as well as $f(\text{AGN})_{\text{MIR}}$. We convert all GOALS photometry to $L_\nu$ and normalize at 24 µm. We then compare the photometry with the appropriate template, also normalized so that $L_{24} = 1$. We select as analogs galaxies whose $L_{70}/L_{24}$ and $L_{160}/L_{24}$ points lie within the uncertainties of the high redshift empirical template (Figure 7.2). For all of the GOALS SFGs, we compare with the SFG1, SFG2, and SFG3 templates. An analog only has to agree with one template, not all three. We follow the same procedure for the GOALS composites and AGN. Finally, we test what effect normalizing at 24 µm has by normalizing at 8 µm instead. Only three galaxies are selected as analogs with an 8 µm normalization that are not previously selected with a 24 µm normalization. In total, there are 54 GOALS analogs (out of 190). Of these, 30 are consistent with multiple templates. This method of selecting analogs is completely consistent with an alternate method of fitting the appropriate Comprehensive template to the photometry of each GOALS galaxy and calculating the reduced $\chi^2$. All analogs have reduced $\chi^2 < 2$.

We show the $L_{\text{IR}}$ distribution of the GOALS sample in Figure 7.3 and include the distribution of the analogs. The $L_{\text{IR}}$ distribution of the analogs is generally consistent with the full population; that is, there is no distinct offset in the $L_{\text{IR}}$ range of the analogs (a KS test gives a D-value of 0.1 and a probability of 75% that
the two distributions are drawn from the same parent population). In general, the analogs are more than a factor of 3 (0.5 dex) less luminous than their high redshift counterparts. This could be interpreted as being consistent with cosmic downsizing which is the idea that the majority of star formation and black hole growth shifts to less massive galaxies as time passes in the Universe, although the reason for this is not understood. Furthermore, we note that neither the Composite1 or AGN1 templates have any analogs. These are the only AGN and Composite templates with $L_{\text{IR}} < 10^{12} L_{\odot}$, demonstrating that the local LIRGs resemble high $z$ ULIRGs, rather than high $z$ LIRGs. The SFG templates are all remarkably similar in shape, so there is no distinct difference in the analogs each of those templates selects.

In Figure 7.4, we examine the IR colors of the analogs and full GOALS sample. $S_{160}/S_{24}$ and $S_{70}/S_{24}$ (left panel) show excellent agreement between the analogs and the Comprehensive templates, which is expected, since these are the ratios used to select the analogs. The left panel also demonstrates that the majority of the GOALS sample have excess far-IR emission (relative to 24 $\mu$m) than the high $z$ sources. In the right panel, we include the $S_{8}$ photometry. The right panel of Figure 7.4 shows
Figure 7.3: \( L_{\text{IR}} \) distribution of GOALS and analogs. The full GOALS sample is plotted as the black line, and the 54 analogs are the shaded purple histogram. The distributions are generally consistent according to a KS test. We also overplot the \( L_{\text{IR}} \) of SFG, composite, and AGN templates used to select the analogs.

a general offset between the full GOALS sample, including the analogs and the templates. Although the analogs are closer to the templates in the color \( S_{70}/S_8 \), they do not completely overlap. We also have 250 \( \mu \text{m} \) imaging from Herschel SPIRE for 60 sources. We plot the colors \( S_{250}/S_{70} \) and \( S_{24}/S_8 \) in Figure 7.5. Here, the majority of GOALS sources lie in the same region as the templates. This echoes what is seen in Figure 4.14 where we compare \( S_{160}/S_{70} \) with \( S_{24}/S_8 \). That is, local and high \( z \) sources are generally consistent in the colors spanning the far-IR portion of the SED or in the colors spanning the mid-IR portion of the SED. However, when we compare colors that combine mid-IR and far-IR photometry, we cannot find local galaxies that completely match the shape of our high redshift SEDs from the mid- to far-IR.

One potential reason for the discrepancy in the mid/far-IR ratios of our sources is the selection techniques of each survey. The GOALS sample is selected at 60 \( \mu \text{m} \) while the high \( z \) sources are selected at 24 \( \mu \text{m} \). 60 \( \mu \text{m} \) traces the warm dust, so it is possible that the GOALS sources are all warmer than the high \( z \) sources, explaining the offset in colorspace. We now estimate what fraction of our sources would be
Figure 7.4: Distribution of GOALS sources in IR colorspace. Left – $S_{160}/S_{24}$ v. $S_{70}/S_{24}$. Right – $S_{160}/S_{24}$ v. $S_{70}/S_{8}$. Analogs are plotted as the filled circles, and the high redshift templates are plotted as the black outlined stars. The analogs lie in the same region as the templates in the left panel, as expected, since these were the photometric ratios used to select the analogs. When we include the 8 $\mu$m data point, there is now an offset between the analogs and the templates, although there is a greater offset between the templates and the general population.

Figure 7.5: Distribution of GOALS sources in the colors $S_{250}/S_{70}$ and $S_{24}/S_{8}$. Here, we have shaded according to $L_{\text{IR}}$. Lower $L_{\text{IR}}$ sources have higher $S_{250}/S_{70}$ colors. The high z templates lie in the same region as the GOALS sources (unfilled circles) and analogs (filled circles).
selected as GOALS galaxies and what fraction of GOALS galaxies would be selected as part of the high $z$ sample. We isolate high $z$ sources in redshift ranges where either 100, 160, or 250 $\mu m$ falls in the rest frame range $\lambda = 50 - 75 \mu m$, which is approximately the bandpass of the IRAS 60 $\mu m$ filter. As this is a rough estimate, we do not apply any scaling to correct for the different wavelength ranges covered by the 100, 160, or 250 $\mu m$ bandpasses. We then calculate the threshold $L_{60}$ at $z = 0.01$ for $S_{60} = 5.24 Jy$, the selection threshold of the GOALS survey. If $L_\nu + dL_\nu$ (the observed flux and uncertainty) is greater than this threshold, we count our high $z$ source as a detection. We estimate that 48% of our sample would be selected as a GOALS galaxy. This percentage is a function of redshift, since our higher redshift sources are intrinsically brighter.

To estimate whether the GOALS sources would be included in our high $z$ sample, we use the Chary & Elbaz (2001) templates that have the same $L_{IR}$ as the GOALS galaxies. These templates are created from local galaxies, so we do not scale templates to the individual photometry. We redshift each template to $z = 1$ and $z = 2$ and convolve with the MIPS 24 $\mu m$ transmission curve. We set the selection threshold to be $S_{24} = 100 \mu Jy$. We find that 76% of the GOALS galaxies would be selected with our criteria at $z \sim 1$, but only 6% at $z \sim 2$. As for the 54 analogs, 80% would be selected at $z \sim 1$, but only one galaxy would at $z \sim 2$. We conclude that selection techniques cannot account for the difference in SED shapes of our high $z$ sources or GOALS sources. That is, galaxies with the SED shapes of our sources meet the GOALS selection criteria, and GOALS galaxies meet our selection criteria. In concept, at least, identical analogs should exist.

### 7.2 Properties of Analogs

We now examine some intrinsic properties of the GOALS analogs, the full GOALS sample, and our high $z$ SEDs. Figure 7.6 shows the ratio of $[\text{NeIII}]/[\text{NeII}]$ and
Again, we remind the reader that these lines are measured in the nuclear region for the GOALS sources, but in the entire galaxy for the high $z$ sources. These lines were measured for the GOALS galaxies in Inami et al. (2013) and for the Comprehensive templates using PAHFIT (Smith et al., 2007). $\text{[Ne}	ext{III]}/\text{[Ne}	ext{II]}$ is a strong diagnostic of the ionization (measured by the parameter $q$) in the ISM, and combining with $\text{[Ne}	ext{III]}/\text{[Ne}	ext{II]}$ can also constrain the metallicity ($Z$). In physical terms, the ionization parameter $q$ measures the number of ionizing photons per hydrogen atom. The metallicity measures the number density of metals in the ISM relative to hydrogen. By comparing $\text{[Ne}	ext{III]}/\text{[Ne}	ext{II]}$ and $\text{[Si}	ext{IV]}/\text{[Ne}	ext{II]}$ with star formation models, Inami et al. (2013) estimate that GOALS galaxies have $1 < Z[Z_\odot] < 2$. Our templates are generally offset from the GOALS sources. High $z$ (U)LIRGs are estimated to have a metallicity near solar (Magdis et al., 2011), so the offset is likely driven by an increase in the ionization parameter, indicating that high $z$ galaxies may have harsher interstellar radiation fields than their local counterparts. We note that the offset could also be caused by the fact that the IRS spectra is covering full galaxies at high $z$, but only the nuclear region of the local galaxies. Interestingly, the GOALS analogs show no offset relative to the other GOALS sources, indicating that neither metallicity or a harsh interstellar radiation field is driving the shape of the SED in these sources.

Figure 7.7 shows the fraction of $L_{\text{IR}}$ contained in the PAH emission features. Dust emission features for the GOALS galaxies were measured in Stierwalt et al. (2014) using CAFE (and the authors found that the PAH line strengths for 90% of the galaxies agreed within 10% when remeasured using PAHFIT), and the Comprehensive templates were measured with PAHFIT (Smith et al., 2007). The Comprehensive templates have slightly higher $L_{\text{PAH}}/L_{\text{IR}}$ ratios than the majority of the GOALS sources, but this reflects the fact that most of the high $z$ sources were detected on the basis of strong PAH emission. In the left panel, the equivalent width of the 6.2$\mu$m
Figure 7.6: Emission line ratios of local and high $z$ sources. We plot $[\text{NeIII}]/[\text{NeII}]$ and $[\text{SIV}]/[\text{NeII}]$ for GOALS galaxies (unfilled circles), analogs (filled circles), and Comprehensive templates (stars). There is a general offset between the templates and the GOALS galaxies, possibly due to an increase in the ionization parameter $q$. The analogs are not offset from the full sample.

A feature correlates strongly with $f(\text{AGN})_{\text{MIR}}$ as expected. Again, there is no offset in $L_{\text{PAH}}/L_{\text{IR}}$ between the analogs and the full GOALS population, as illustrated by the distributions in the right panel, indicating that strong PAH emission does not strictly correlate with the shape of the SED as traced by $S_{24}$, $S_{70}$, and $S_{160}$. The middle panel shows $L_{\text{PAH}}/L_{\text{IR}}$ as a function of $L_{\text{IR}}$. Here, we see a similar trend as in Figure 6.7 with the high $z$ templates having higher $L_{\text{PAH}}/L_{\text{IR}}$ ratios at a given $L_{\text{IR}}$. This possibly contradicts the offset indicated by the gas line fluxes in 7.6. One explanation for a low $L_{\text{PAH}}/L_{\text{IR}}$ ratio is a harsh interstellar radiation field (and indeed, the AGN have lower ratios, as would be expected). Then, the higher $L_{\text{PAH}}/L_{\text{IR}}$ ratios of the SFGs and composite templates indicate that they lack a harsh interstellar radiation field; in fact, on the basis of $L_{\text{PAH}}/L_{\text{IR}}$, it should be similar in strength to the GOALS LIRGs. On the other hand, if $L_{\text{PAH}}$ is tied to $L'_{\text{CO}}$ (as was seen in Chapter 4), then the higher $L_{\text{PAH}}/L_{\text{IR}}$ ratios in the high $z$ templates are the product of an increased gas fraction relative to the GOALS galaxies.
Figure 7.7: The fraction of $L_{\text{IR}}$ due to PAH emission at different redshifts. We plot $L_{\text{PAH}}/L_{\text{IR}}$ v. 6.2 $\mu$m equivalent width (left) and $L_{\text{IR}}$ (middle) for GOALS galaxies (un-filled circles), analogs (filled circles), and the Comprehensive library. The distribution of $L_{\text{PAH}}/L_{\text{IR}}$ for the full GOALS sample (gray) and analogs (black line) is shown in the right panel. The distributions cover the same range of $L_{\text{PAH}}/L_{\text{IR}}$. The high $z$ templates have higher $L_{\text{PAH}}/L_{\text{IR}}$ values, reflecting the 24 $\mu$m selection criterion, but possibly also due to an increased gas fraction.

Finally, we examine the merger stage of the GOALS galaxies. HCS ACS I band imaging ($\lambda = 0.814$ $\mu$m) exists for 73 of the GOALS galaxies and has been classified into six merger categories Haan et al. (2011):

1. Distinct, undisturbed disk galaxies
2. Galaxies have undergone first pass, but are still separate entities with disturbed disks or amorphous tails
3. Double nuclei encased in a common envelope
4. Double nuclei plus a tidal tail
5. Single nucleus with prominent tidal tail
6. Single nucleus with disturbed central morphology but faint tails

In Figure 7.8, we plot the number of sources in each of these categories for the 73 HST GOALS galaxies and for the analogs with HST imaging. There is a higher
Figure 7.8: Merger stages of GOALS galaxies. We have *HST* morphological images of 73 GOALS galaxies, and we plot the distribution in merger stage as the black crosses. We separate out the analogs and show their distribution as the red squares. The number 1 corresponds to the earliest merger stage, while 6 is the latest. The analogs are uniformly distributed and cover the same range of merger stages as the general population.

percentage of GOALS galaxies in the advanced merger stages (2 and 3), consistent with the picture that a merger could fuel a burst of star formation which is responsible for the enhanced IR luminosity (Sanders & Mirabel, 1996). The analogs are evenly distributed through each merger stage but cover the same range of merger stages as the full population. The distributions of the full population and the analogs differ, so that galaxies in an advanced merger (stages 3 and 4) are less likely to be selected as analogs. This could be because mergers produce different SEDs at high $z$, since our high $z$ galaxies have higher dust masses ($\sim 0.5$ dex) and likely have higher gas fractions, although this line of inquiry requires more analysis and is the subject of future work.

### 7.3 Chapter Summary

We have used the GOALS sample of local (U)LIRGs to find analogs to our high redshift sources. Based on the overall spectral shape of the $L_{24}$, $L_{70}$, and $L_{160}$, we
identify 54 local analogs. However, these analogs are consistent with our high redshift galaxies in only a few limited colors. When we compare the ratio of far-IR emission to mid-IR emission, we do not find any similar GOALS galaxies. Moreover, our high \( z \) sources are offset in the gas line ratios \([\text{Ne}^\text{III}]/[\text{Ne}^\text{II}]\) and \([\text{Si}^\text{IV}]/[\text{Ne}^\text{II}]\), which trace the metallicity and ionization parameter of a galaxy, and in the amount of \( L_{\text{IR}} \) contained in the smallest dust grains, \( L_{\text{PAH}}/L_{\text{IR}} \). The GOALS analogs are not distinct from the parent population in either of these parameters or in their observed merger stage. Most of the GOALS galaxies exhibit more emission around 70 \( \mu \)m and 160 \( \mu \)m than their high \( z \) counterparts, indicative of relatively more warm dust. This could be due to high redshift sources having more extended star formation, allowing for overall colder temperatures in the ISM. We conclude that although we can select analogs with generally consistent SED shapes in the far-IR, this does not extend to the mid-IR, and the physical processes occurring inside these galaxies appears to be dissimilar according to the gas line ratios and dust emission ratios. Mergers may play some role in the dissimilarity of the populations, since advanced mergers are not likely to be selected as analogs, despite accounting for \( \geq 50\% \) of the GOALS galaxies for which we have \( HST \) imaging. In short, we may not be able to find local LIRGs that are true analogs to high redshift LIRGs and ULIRGs.
CHAPTER 8
CONCLUSIONS

Internally, galaxy evolution is driven by ongoing star formation and an AGN. These two processes often occur simultaneously in massive, dusty galaxies. Studying star formation and AGN in tandem can provide key insights to how galaxies evolve, and IR wavelengths are fundamental, since a large portion of AGN activity and star formation is obscured by dust over cosmic time. This thesis focuses on quantifying the effect of an AGN on the dust emission in a galaxy, and it demonstrates that there is an understudied population of IR luminous galaxies hosting hidden AGN which are significantly affecting IR emission and our current understanding of star formation.

We quantify the amount of IR AGN and star formation dust heating predominantly using a sample of 343 galaxies ($z \approx 0.5 - 3$) from the Spitzer xFLS and the GOODS fields. All galaxies have Spitzer mid-IR spectroscopy, making this an unprecedented sample size. The mid-IR spectrum is rich for identifying AGN and star formation signatures. We quantify the AGN emission, $f(\text{AGN})_{\text{MIR}}$, as the fraction of mid-IR luminosity due to AGN-powered continuum emission. We define three classes of galaxies: (1) Star forming galaxies (SFGs) are dominated by PAH emission ($f(\text{AGN})_{\text{MIR}} < 0.2$); (2) AGN have negligible PAH emission ($f(\text{AGN})_{\text{MIR}} > 0.8$); (3) Composites have a mix of PAH and continuum emission ($f(\text{AGN})_{\text{MIR}} = 0.2-0.8$).

We relate the mid-IR classification to the full IR SED by creating empirical templates using data from Spitzer and Herschel. These SEDs are the first comprehensive publicly available library of IR templates specifically designed for high redshift galaxies that account for AGN emission. Templates from Kirkpatrick et al. (2012) are
already widely in use, and our expanded library in Kirkpatrick et al. (2015) can be used to better determine $L_{IR}$ and AGN contribution in high redshift sources.

The cold dust emission probes the diffuse ISM and is primarily attributable to photons leaking out of star forming regions (e.g., Kirkpatrick et al., 2014a). Our far-IR modeling shows that an AGN has no effect on this temperature ($T_c \sim 25$ K), so the cold dust can be safely attributed to star formation even if an AGN is present. On the other hand, the warm dust emission (peaking at $20 - 50 \mu$m) can arise from star forming regions, but as $f(\text{AGN})_{\text{MIR}}$ increases, the temperature of this component increases by $> 20$ K, indicating that the heating source is changing. Moreover, the contribution of the warm dust to $L_{IR}$ also increases with increasing $f(\text{AGN})_{\text{MIR}}$. We quantify this concretely by decomposing the full IR SEDs from our template library into an AGN and star formation component and relating the total contribution of AGN to $L_{IR}$ to $f(\text{AGN})_{\text{MIR}}$. We find that composite galaxies require a $20 - 50\%$ correction to $L_{IR}$ before converting to SFR, while AGN require $> 50\%$ correction, or SFRs will be overestimated by as much as a factor of 5.

Identifying dust obscured AGN at high redshift is crucial for obtaining an accurate census of black hole growth. Current Spitzer IRAC or WISE color diagnostics miss a large fraction of dust-obscured or less luminous AGN (Lacy et al., 2004; Stern et al., 2005, 2012; Donley et al., 2012). We have remedied this deficiency by creating an IR color diagnostic that captures the full shape of the SED (Kirkpatrick et al., 2013, 2015). $S_{250}/S_{24}$ (observed) traces the ratio of far-IR emission to mid-IR emission, and this is lower in AGN as the increased warm dust heating boosts $24 \mu$m emission. $S_8/S_{3.6}$ (observed) is primarily tracing near-IR emission, and in this regime, SFGs emit stellar light, while AGN have power-law emission. AGN, composites, and SFGs lie in distinct regions in this colorspace from $z = 0 - 3$ (Kirkpatrick et al., 2013). Our color diagnostic is optimized for selecting composites which are primarily missed with other techniques, such as X-ray or optical. Composites may be missed at X-ray wavelengths...
due to high column densities or lower AGN luminosities. Moreover, the optical line ratios expected in composites are unconstrained at high redshift (Kartaltepe et al., 2015). Our color technique provides a unique opportunity to identify the AGN lurking in dusty galaxies.

Star formation is fundamentally related to the amount of molecular gas present. Most galaxies form stars rather inefficiently, but some sources, referred to as “starbursts”, have an enhanced star formation efficiency. IR luminous galaxies can host a luminous AGN which contributes to $L_{\text{IR}}$. In Kirkpatrick et al. (2014b), utilizing new CO(1-0) measurements from the Large Millimeter Telescope, we demonstrated how accurately accounting for the contribution from an AGN to $L_{\text{IR}}$ can lower the measured star formation efficiency in a sample of $z < 0.4$ IR luminous galaxies, and we have extended this result to high redshift sources in the literature. Properly identifying starbursts, by accounting for AGN contribution, is of utmost importance when calculating $M_{\text{H}_2}$ or molecular gas fractions, both of which require a different proportionality between $M_{\text{H}_2}$ and $L'_{\text{CO}}$ depending on SFE. Missing dust obscured AGN could be biasing our understanding of the amount of molecular gas in high redshift galaxies.

8.1 Future Work

This thesis demonstrates how to disentangle AGN and star formation in the IR emission of dusty galaxies, and it paves the way for several future studies, particularly to answer the questions: (1) How important are composite galaxies to the buildup of stellar and black hole mass in the Universe? (2) Is a growing AGN linked with decreased star formation?

Although the majority of present day stellar and black hole mass was formed simultaneously from $z \sim 1 - 3$, no study has yet determined how much of this mass was formed within the same composite galaxy population. We plan to measure the
SFR density and black hole accretion rate (\(\dot{M}_{\text{BH}}\)) density of composites over cosmic time to demonstrate the importance of composites in the mass growth history of the Universe. We can easily identify large numbers of SFGs, composites, and AGN with our color diagnostic (Kirkpatrick et al., 2013), which will allow us to measure the SFR density and \(\dot{M}_{\text{BH}}\) density over a large redshift range. AGN are typically removed when calculating the SFR density (Murphy et al., 2011b), but based on our 343 galaxies with mid-IR spectroscopy (Kirkpatrick et al., 2015), we estimate that AGN and composites are actually dominating the buildup of stellar mass at \(z > 1.5\) and could be dominating the black hole growth in the Universe as well.

Galaxy evolution is often quantified by a galaxy’s location on the main sequence (Noeske et al., 2007; Elbaz et al., 2007). At high redshift, the SFR is typically derived from \(L_{\text{IR}}\) which overestimates SFR as much as a factor of 5 in undiagnosed composites and AGN, so our current understanding of the main sequence is incorrect. Removing AGN heating from \(L_{\text{IR}}\) causes galaxies to fall onto and below the main sequence (Kirkpatrick et al., 2014b). \(M_*\) also requires a correction for AGN contamination which is typically overlooked. \(M_*\) is determined from modeling the UV to near-IR, but the torus surrounding an AGN can also radiate in the near-IR. Hainline et al. (2012) found that \(M_*\) in AGN is overestimated as much as a factor of three if torus emission is not accounted for. Utilizing techniques in this thesis, we plan to correct both \(L_{\text{IR}}\) and \(M_*\) for large samples to accurately measure the main sequence at high redshift.

Recent work in the local Universe demonstrates that composite galaxies are located below the main sequence, suggesting quenching (Cook et al., 2014; Leslie et al., 2015). At high redshift, observations reveal a flattening of the main sequence above \(M_* = 10^{10}\, M_\odot\), possibly due to quenching (Peng et al., 2010; Whitaker et al., 2014). However, AGN hosts are systematically removed from high redshift samples, and these galaxies are predominantly more massive than \(10^{10}\, M_\odot\). If previously uniden-
tified composites and AGN are included on the main sequence, with corrected SFRs, the observed flattening could become a turnover mass above which large numbers of AGN and composites are quenching, mirroring what has been observed in the local Universe. When we compile a large sample of SFGs, composites, and AGN, with correct $L_{\text{IR}}$ and $M_*$, we will be able to test if galaxies with stronger AGN are preferentially quenching, indicating that AGN energetics could play a role in the location of galaxies relative to the main sequence.

Composites are an important class of galaxy in the overall picture of evolution, where AGN and star formation shape the same galaxy, but composites are largely neglected in current studies of the distant Universe. AGN are enshrouded in many galaxies, unobserved at X-ray and optical wavelengths, and we have honed techniques to identify their signatures in the infrared. This thesis, by demonstrating how to easily identify composites and AGN and correct $L_{\text{IR}}$ for AGN emission, paves the way for future studies measuring the coevolution of star formation and AGN within the same galaxy population over cosmic time.
Appendices
APPENDIX A

CORRELATIONS BETWEEN MODIFIED BLACKBODY PARAMETERS

In the plots below, we show the correlation between parameters when fitting our two-temperature modified blackbody model from Equation (1). We show the results from our Monte Carlo simulations (see Section 2.2) for the $z \sim 2$ SF galaxy subsample as an illustrative case (Figure A.1); the results are similar for the other three subsamples. We overplot the mean value of each parameter as the red cross. The plots below show that certain parameters are highly correlated (e.g., the temperatures of the warm and cold components) while others are not (e.g., the cold temperature and normalization). The errors we report for the dust temperatures and IR luminosities include the covariance between the parameters but we note that the error is dominated by the diagonal elements of the covariance matrix. The warm and cold temperatures, though correlated, do not overlap in their respective range of values, giving us confidence that we are clearly measuring two separate temperature components.
Figure A.1: Covariance between the parameters derived in the Monte Carlo 2T MBB fitting. $T_c$ and $T_w$ are correlated and therefore not independent.
APPENDIX B

ALTERNATE FITTING METHODS

We fit the far-IR SED with an optically thin 2T MBB to construct our templates, and we now discuss whether this fitting method is optimal for determining dust temperatures and $L_{\text{IR}}$. We use the subsamples in the Comprehensive Library to explore three alternate fitting methods:

1. Optically thick dust
2. Fixed dust temperatures
3. One temperature MBB

For each method, we follow the same fitting procedure outlined in Section 4.3, and we compare the results with the optically thin 2T MBB fits used to create our templates. We quantify the goodness of the fits with the reduced $\chi^2$ statistic, and we compare the reduced $\chi^2$ values in the left panel of Figure B.1.

$L_{\text{IR}}$ is typically a desired quantity when fitting far-IR data. We compare $L_{\text{IR}}$ calculated from each of the three alternate fitting methods with our template $L_{\text{IR}}$s (Table 4.3) in the middle panel of Figure B.1. We find no significant difference for any of the templates, showing that $L_{\text{IR}}$ is robust against these particular fitting methods. However, $L_{\text{IR}}$ is not the only useful parameter that can be derived from fitting far-IR photometry with a model; another commonly calculated quantity is ISM mass. We demonstrate how a particular far-IR fitting technique affects the derived ISM mass in the right panel of Figure B.1. For each template, we calculate the ISM mass at

200
850 µm, which is in the Rayleigh-Jeans tail of the dust emission and is a more reliable tracer of the ISM mass (Scoville et al., 2014). We use the following equation:

$$M_{\text{ISM}} = \frac{\chi^2 L_\nu}{8\pi k \kappa_{\text{ISM}} T_c}$$ (B.1)

$\kappa_{\text{ISM}}$ is the dust opacity per grain and is related to the opacity $\tau_\nu$. $\tau_{250}/N_H$ has been recently measured by the Planck Collaboration (Planck Collaboration, 2011), and from that value, Scoville et al. (2014) calculate $\kappa_{\text{ISM}}(\nu_{250})$:

$$\kappa_{\text{ISM}}(\nu_{250}) = \frac{\tau_{250}}{N_H 1.36 m_H}$$ (B.2)

where $N_H$ is the column density of hydrogen. $\kappa_{\text{ISM}}(\nu_{250})$ can then be scaled to 850 µm:

$$\kappa_{\text{ISM}}(\nu_{850}) = \kappa_{\text{ISM}}(\nu_{250}) \times \left(\frac{250}{850}\right)^{-\beta}$$ (B.3)

### B.1 Optically Thick Dust

The optically thin dust approximation is commonly adopted with a limited number of data points, but it might not be an accurate assumption at $\lambda \ll 100$ µm, particularly in starbursts. We test what effect using the full optically thick equation has on the dust temperatures by fitting to the far-IR data points of each template in the Comprehensive Library. We fit

$$S_\nu = a_1 \times (1 - e^{-\tau(\nu)}) \times B_\nu(T_{\text{warm}}) + a_2 \times (1 - e^{-\tau(\nu)}) \times B_\nu(T_{\text{cold}})$$ (B.4)

where $\tau(\nu) = (\nu/\nu_0)^\beta$. We use $\beta = 1.5$, and we assume $\nu_0 = 300$ GHz ($\lambda_0 = 100$ µm). The optically thick equation produces reduced $\chi^2$ values consistent with the optically
thin fitting. As for the physical parameters, we find that the optically thick equation has a negligible effect on $T_c$ and $L_{\text{cold}}/L_{\text{IR}}$, since the cold dust is presumably optically thin, but increases the derived $T_w$ by $\sim 20$ K. However, the exact value of $T_w$ ultimately has little effect on $L_{\text{IR}}$, and the warm dust component accounts for $\sim 1\%$ of the ISM mass. Since $\chi^2$, $L_{\text{IR}}$, and $M_{\text{ISM}}$ do not change significantly when assuming optically thin dust, we recommend using the optically thin approximation for simplicity.

**B.2 Fixed Dust Temperature**

We experiment with holding the dust temperatures fixed which is another useful technique when limited data are available. We hold the temperatures fixed to the average $T_c$ and $T_w$ values for the SFGs, Composites, and AGN, separately. In general, holding the temperatures fixed has little effect on the relative normalizations of the dust component, so the ratio $L_{\text{cold}}/L_{\text{IR}}$ is approximately constant compared with when the dust temperatures are allowed to vary. $M_{\text{ISM}}$ is significantly higher for the Composite4, AGN3, and AGN4 templates, and lower for the AGN1 and AGN2 templates. The AGN templates show the most increase of $T_c$ with $L_{\text{IR}}$ and redshift, and this is not captured by holding the temperatures fixed, producing incongruous ISM masses.

We also attempt to fit a 3T MBB, as this may be more physically appropriate, particularly for the AGN sources. In this case, the coldest dust component comes from the diffuse ISM, a warmer component is due to heating from star forming regions, and a hot component is due to heating by an AGN. In order to achieve good fits, we had to assume dust temperatures. Based on the temperatures of the diffuse component and star forming regions in the local Universe, we assumed $T_c = 20$ K, $T_w = 40$ K, and $T_h = 100$ K (e.g., Clemens et al., 2013). The results produced good reduced $\chi^2$ fits.
Figure B.1: Comparison of different far-IR fitting techniques. Left Panel– Comparison of the reduced $\chi^2$ values from our different fitting methods. Colors and symbols correspond to each template from the Comprehensive Library. Filled symbols are the reduced $\chi^2$ values derived when the two temperature components are held fixed; large open symbols are derived using the optically thick assumption; small open symbols are derived with only a one temperature MBB, instead of two temperatures. We overplot a one-to-one relation as the dashed line. The 1T MBB method produces the worst reduced $\chi^2$ values, while there is smaller difference between the reduced $\chi^2$ values using the optically thick or optically thin dust assumption. Middle Panel– We compare the $L_{\text{IR}}$ values calculated from each method. $L_{\text{IR}}$ is essentially independent of the particular far-IR fitting method. Right Panel– We compare the ISM masses derived from each fitting method. The optically thick and optically thin assumptions produce consistent ISM masses, while the one temperature fitting method results in significantly lower ISM masses.

and consistent $L_{\text{IR}}$, but we do not advocate this technique as it requires assumptions about the dust temperatures which may not hold at high redshift.

B.3 One Temperature

Finally, we test how good of a fit we can achieve with only a 1T MBB, which is commonly adopted in the literature due to incomplete photometric coverage of the far-IR. In this case, the reduced $\chi^2$ values are typically poor ($>2$). This result occurs because we are fitting the wavelength range $\lambda \sim 20 - 300 \mu\text{m}$, and a 1T MBB will necessarily be biased to warmer dust temperatures by including this much data. The 1T MBB produces consistently lower ISM masses, typically 60-70% lower than optically thin 2T MBB method, due to both the difference in $T_c$ and the extrapolated $L_{850}$. If only SPIRE data is available, we recommend adding in a warm dust component with
a fixed temperature in order to ensure the cold dust temperature is not biased to warmer wavelengths (e.g., Kirkpatrick et al., 2014a). A 2T MBB, even with a fixed warm dust component, is optimal for fitting the peak of the SED and determining $T_c$. 
APPENDIX C

TEMPLATE LIBRARIES

We present the complete data sets that comprise each template. The spectra are plotted as lines and the photometry as open circles. We plot any available sub-millimeter data as the open squares. These data were not included in the fit, since they are not available for all sources, but they are plotted to illustrate how well the Rayleigh-Jeans tails of our templates agree with observations. The templates and associated uncertainties are plotted as the thick red lines and pink shaded regions. We also plot the warm modified blackbody and cold modified blackbody from Equation 4.2 as the long dashed and dotted lines, respectively. We remind the reader that the three libraries are not independent as they all contain the same sources divided according to different criteria.
Figure C.1: MIR-based Library.
Figure C.2: Color-based Library.
Figure C.3: Comprehensive Library.
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