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2018

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UNIVERSITY OF CALIFORNIA

Los Angeles

Multiwavelength Analyses of Mid-Infrared Selected Active Galactic Nuclei

A dissertation submitted in partial satisfaction

of the requirements for the degree

Doctor of Philosophy in Astronomy and Astrophysics

by

Anson Chengsong Lam

2018

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ABSTRACT OF THE DISSERTATION

Multiwavelength Analyses of Mid-Infrared Selected Active Galactic Nuclei

by

Anson Chengsong Lam

Doctor of Philosophy in Astronomy and Astrophysics

University of California, Los Angeles, 2018

Professor Edward L. Wright, Chair

Traditional methods of identifying active galactic nuclei (AGNs) rely on UV and optical color criteria, but these methods exclude AGNs that are highly optically obscured by surrounding dust. This underestimates the number of obscured AGNs in the Universe, and is problematic for our understanding of galaxy evolution and computing luminosity functions. Since much of the radiation absorbed by dust is re-radiated in the IR, mid-IR color selection provides a much more robust method of identifying AGNs that is not biased against highly dust obscured galaxies. The Wide-field Infrared Survey Explorer (WISE) provides all-sky mid-IR survey in four bands, and this photometry can be used to identify AGN candidates. We select AGNs from the catalog using a $W1 - W2 > 0.8$ color cut, and perform optical spectroscopy with Keck DEIMOS for redshift and emission line measurements. We confirm that mid-IR color selection does indeed identify obscured AGNs that are missed by the largest existing optical surveys, and targeted observations are necessary to find these objects. Combining WISE data with the AKARI far-IR all-sky catalog, we also perform SED analysis to characterize the physical properties of dusty AGNs and their surrounding obscuring medium. Using only photometry, we are able to extract physical properties (ex. dust temperature and masses). Finally, we test the effects of using different SED and color criteria to select different populations of AGNs from the 3D-HST catalog and compute their luminosity functions. We find that SED fitting can identify a large number of AGNs that are missed by traditional color selection methods, and this increases the sample size of AGNs available for analysis by several factors.

The dissertation of Anson Chengsong Lam is approved.

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2018

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ACKNOWLEDGMENTS

I owe a debt of gratitude to a number of individuals who have supported and encouraged me along this journey.

- My thesis advisor, Ned, for his mentorship, honest critiques, and humor over the course of my PhD career. I started off my first year of graduate school fumbling around with order-of-magnitude problems on a whiteboard (still happens), but over the years I've developed a confidence and intuition that I wouldn't have found otherwise without my advisor.
- My thesis committee. I'm particularly lucky to have worked with group of faculty who have supported me so enthusiastically throughout my entire PhD career. Matt, for all the discussions and paper revisions we've done together, and for encouraging me to extend my research networks abroad. Alice, for our discussions about MOSDEF and 3D-HST, and for giving me ideas for the final portions of my thesis. Steve, for that fateful phone call letting me know that I've been admitted to the department, and for supervising me during my second year research project.
- All my fellow graduate students in the UCLA astronomy department. Whether it's debugging code or just hanging out during our weekly socials, I'm thankful to be among a group of like-minded peers who have provided me with so much support and company.
- My coaches and teammates on the UCLA Triathlon team, for inspiring me with their performances and commitment and challenging me to be a better athlete. Among the countless number of adventures we've had together, I won't forget the $3 \times (8 \times 100)$ yard swim sets, epic training camps in Oregon, or standing on the podium at nationals with the rest of you.
- The innumerable friends I've met during my time at UCLA, both here and abroad. I've learned a tremendous amount meeting so many people from different departments and backgrounds, and I prior to my graduate school career I never would have imagined that I would find adventures and company in so many different parts of the world.

- My parents, for all the love and support they’ve provided me throughout my academic journey and beyond. They’ve been with me every step of the way through all of my undertakings and exploits, and I wouldn’t have made it this far without them.

Portions of this thesis is adopted from published works. Chapter 1 is based a version of “*Far-IR dust properties of highly dust obscured AGNs from the AKARI and WISE all-sky surveys*¹” (A. Lam, M. Malkan, E. Wright, 2019, Publications of the Astronomical Society of Japan, AKARI Special Issue). Chapter 2 is based on a version of “*DEIMOS Observations of WISE-Selected, Optically Obscured AGNs*²” (A. Lam, E. Wright, M. Malkan, 2018, Monthly Notices of the Royal Astronomical Society, 480, 451).

¹<http://doi.org/10.1093/pasj/psy081>

²<http://doi.org/10.1093/mnras/sty1844>

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PUBLICATIONS

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A. Lam, E. Wright, M. Malkan “DEIMOS Observations of WISE-Selected, Optically Obscured AGNs” 2018, Monthly Notices of the Royal Astronomical Society, 480, 451

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INTRODUCTION

According to the unified model, active galactic nuclei (AGNs) can be classified into two types based on their orientation and dust obscuration properties (Antonucci 1993; Urry & Padovani 1995). Type 1 AGNs have their nuclei visible along our line of sight, and are characterized by both narrow and broad emission lines. Type 2 AGNs are obscured, with photons being scattered and absorbed by gas and dust surrounding the central black hole. This may be due either to the viewing angle or some intrinsic difference in structure. One distinguishing feature between the two types of AGNs is the ratio of optical to IR emission, as Type 2 AGNs have high IR to optical luminosity ratios due to optical flux being absorbed and converted into heat. These objects have been identified through a variety of methods in the radio (McCarthy 1993), hard x-ray (Stern et al. 2014), optical (Zakamska et al. 2003), and mid-infrared (Lacy et al. 2013).

In the unified AGN model, obscuration is caused by a dusty torus surrounding the accretion disk. Obscured AGNs (see Hickox & Alexander (2018) for a review) are more difficult to identify not only because of the diminished flux radiating from the accretion disk, but also due to the increased fraction of emission coming from the host galaxy that can overpower the AGN emission component. Unobscured AGNs with little dust content are easily identified by UV and optical selection criteria since the accretion disk radiates most strongly in these wavelengths. This is not the case for obscured AGNs, not only because of obscuring dust that blocks out the accretion disk along the line of sight, but also due to the increased radiation contribution from the host galaxy that results from star formation. Previous studies have shown that majority of the AGN population is obscured, which suggests that these objects make up the majority of the number density of AGNs in the Universe (Ueda et al. 2014; Aird et al. 2015)

The obscured AGN fraction has been shown to be a function of luminosity and redshift (Lawrence 1991), and understanding AGN evolution and the physical nature of the obscuring medium requires us to understand this dependence. The mass fraction of gas in galaxies increases with redshift, so this suggests that obscuration may also follow the same trend. Chen et al. (2015) shows that there is a relationship between degree of obscuration and far-IR luminosity, which suggests that the ob-

scuring medium is on a galactic scale and not localized to certain regions in the galaxy. However, optical reddening and extinction can also result internally within the host galaxy, and perhaps also depends on the orientation of the galaxy relative to the line of sight (ex. galaxies viewed edge-on being more optically thick compared to galaxies viewed face-on).

AGNs are selected and identified based on various different multi-wavelength criteria (see Padovani et al. (2017) for a review). X-ray observations are one of the most reliable ways to identify AGNs since this directly samples the high energy emission coming from the AGN, and the X-ray emission from other processes in the galaxy is relatively small in comparison (which helps reduce the level of host galaxy contamination). However, this part of the spectrum is also subject to high levels of dust extinction, causing the most highly obscured objects to be completely missed by surveys operating in this waveband. Optical AGN selection criteria are often used instead, but the optical portion of a galaxy's spectral energy distribution (SED) tends to be very different between obscured and unobscured AGNs due to varying levels of reddening.

In comparison, the behavior of mid-IR emission between different types of AGNs is relatively similar. There are other sources of strong mid-IR emission (ex. dust-obscured star formation from the host galaxy), but the shape of the SED in the mid-IR is different for these different processes and can be easily distinguished from an AGN. WISE has provided all-sky coverage over multiple epochs of various types of astrophysical IR sources, and the data from this telescope provides a plethora of photometry from which AGNs can be selected and analyzed. Mid-IR diagnostics are useful because the emission from the AGN is largely separate from the host galaxy in this waveband. At these wavelengths, obscuration effects are relatively low and light emitted near a supermassive black hole produces a characteristic power law spectrum, making AGNs easier to identify due to their distinctively red WISE colors. In addition to mid-IR color diagnostics and AGN emission in the mid-IR SED, one can use high-excitation emission lines (ex. [NeV] and [NeVI]) from high energy accretion disk radiation as a basis for AGN identification.

A complete study of AGN activity over the history of the universe requires us to reliably identify both obscured and unobscured sources. Currently, optical and X-ray sky surveys are biased towards detecting unobscured AGNs. These objects are inherently easier to identify and follow

up spectroscopically, and thus account for most of the identified types of AGNs relative to their obscured counterparts. However, obscured AGNs are expected to be the dominant type, but these are under represented in surveys due to selection biases. This is especially problematic for understanding galaxy evolution if AGN activity peaks at a redshift of $z \sim 2$ (Boyle et al. 1988). Having a complete sampling of these types of AGNs is important for models of AGN formation and galaxy feedback, as dust obscuration has been proposed to be an evolutionary phase in AGNs (Hopkins et al. 2006). For example, quasars are thought to be driven by the mergers of galaxies with high gas content, which is also responsible for any obscuration that occurs (Kauffmann & Haehnelt 2000). Additionally, the number counts of obscured AGNs are expected to be high in order to account for the energy distribution of the cosmic X-ray background radiation (Ueda et al. 2003). Understanding the physical properties of these AGNs can also provide insight into how the masses of supermassive black holes correlate to total amount of radiation produced by the central engine.

One particularly important application of performing a complete AGN census is measuring the AGN contribution to the cosmic infrared background (CIB). The CIB (Hauser & Dwek 2001; Lagache et al. 2005; Franceschini et al. 2008; Cooray 2016) represents the IR energy density of all the galaxies and AGNs emitted over the history of the universe. Half of all the energy emitted by stars and black hole accretion is absorbed by dust and re-radiated in the IR. A number of high redshift sources have most of their energy emitting in the IR, which suggests that star formation and AGN activity is present in heavily obscured systems (Burgarella et al. 2013; Madau & Dickinson 2014). Compton thick AGNs are responsible for most of the accretion power in the Universe so these objects represent an important phase of galaxy evolution (Gilli et al. 2007; Comastri et al. 2015). Faint, Compton-thick AGNs are not detectable by the deepest X-rays surveys, but due to absorption and reemission by the dusty AGN torus these are expected to be detectable in the IR.

This thesis is composed of three projects involving the analysis of AGN photometry and spectra in order to identify highly dust obscured AGNs and characterize their physical properties. Chapter 1 contains an analysis of optical spectra of WISE-selected obscured AGN candidates. This study makes use of Keck DEIMOS for high-resolution optical spectroscopy of obscured AGNs selected

using a WISE $W1 - W2 > 0.8$ color cut. From these spectra, we are able to identify a number of AGNs that are missed by traditional AGN selection methods and surveys. Using SED modeling, we are also able to quantify the amount of optical extinction present and show that these are indeed AGNs with varying degrees of obscuration.

Chapter 2 presents the analysis of multi-wavelength data to model the emission characteristics of dusty AGNs selected using the WISE and AKARI all-sky IR catalogs. We use SED modeling to characterize the extinction and dust properties of these AGNs, and compute bolometric corrections, and estimate AGN dust masses and temperature using simple analytic models. Even without spectroscopic data, we can determine a number of AGN dust properties only using SED analysis without the need for resource-intensive spectroscopy. These methods, along with the abundance of publically available archival photometric data, will be valuable for large-scale studies of dusty, IR-luminous AGNs.

Chapter 3 shows the results of computing $8\mu\text{m}$ luminosity functions for mid-IR selected AGNs and galaxies. This makes use of the DEIMOS spectra described in Chapter 1, using z_{spec} values when available and computing z_{photo} values for the objects that did not produce usable spectra. One of the limitations of AGN color selection criteria is that weak AGN components are not easily selected through these methods, so we use SED fitting to identify a broader sample of AGNs from the 3D-HST data set with a range of AGN fractions. We use photometric and redshift data from this catalog to identify different samples of AGNs based on mid-IR color criteria and SED fitting, and examine the different effects of AGN selection on computing luminosity functions. From these luminosity functions, we compute the total IR energy density Ω_{TIR} for all of our galaxy and AGN samples over a range of redshifts.

Chapter 4 provides a summary of the impact and applications of the work presented in this thesis to future telescopes and missions. We focus our discussion on the Keck FOBOS (a fiber-based optical spectrograph at Keck Observatory with multiplexing capacity exceeding that of DEIMOS), SPHEREx (an all-sky spectroscopic IR sky survey), and SPICA (a mid-IR space telescope with photometry and spectroscopy capabilities). The unique capabilities of these instruments will allow us to identify a larger sample of obscured AGNs (especially at higher redshifts) and study their

physical properties through a combination of photometric and spectroscopic data.

CHAPTER 1

DEIMOS Observations of WISE-Selected, Optically Obscured AGNs

While there are numerous criteria for photometrically identifying active galactic nuclei (AGNs), searches in the optical and UV tend to exclude galaxies that are highly dust obscured. This is problematic for constraining models of AGN evolution and estimating the AGN contribution to the cosmic X-ray and IR backgrounds, as highly obscured objects tend to be underrepresented in large-scale surveys. To address this, we identify potentially obscured AGNs using mid-IR color colors from the Wide-field Infrared Survey Explorer (WISE) catalog. This paper presents the results of optical spectroscopy of obscured AGN candidates using Keck DEIMOS, and their physical properties derived from these spectra. We find that a $W1 - W2 > 0.8$ color criterion effectively selects AGNs with a higher median level of $E(B - V)$ extinction compared to the AGNs found in the SDSS DR7 survey. This optical extinction can be measured using SED modeling or by using $r - W1$ as a measure of optical to IR flux. We find that specific, targeted observations are necessary to find the most highly optically obscured AGNs, and that additional far-IR photometry is necessary to further constrain the dust properties of these AGNs.

1.1 Introduction

Active galactic nuclei (AGNs) are powered by their central supermassive black holes (SMBH), and their properties are governed by the SMBH's mass and accretion rate. Type 1 AGNs have their nuclei visible along our line of sight, and are characterized by both narrow and broad emission lines. Type 2 AGNs are obscured, with photons being scattered and absorbed by gas and dust

surrounding the central black hole. This may be due either to the viewing angle or some intrinsic difference in structure. One feature distinguishing the two types of AGNs is the ratio of optical to IR emission, as Type 2 AGNs have high IR to optical luminosity ratios due to optical flux being absorbed and converted into heat. These objects have been identified through a variety of methods in the radio (McCarthy 1993), hard x-ray (Lansbury et al. 2017), optical (Zakamska et al. 2003), and mid-infrared (Lacy et al. 2013).

Currently, optical and X-ray sky surveys are biased towards detecting unobscured AGNs. These objects are inherently easier to identify and follow up spectroscopically, and thus account for most of the identified types of AGNs relative to their obscured counterparts. However, obscured AGNs are expected to be the dominant type in order to account for the energy distribution of the cosmic X-ray background radiation (Ueda et al. 2003), but these are under-represented in X-ray/optical surveys due to selection biases. Having a complete sampling of these types of AGNs is important for models of AGN formation and galaxy feedback, as dust obscuration has been proposed to be an evolutionary phase in AGNs (Hopkins et al. 2006). For example, AGNs are thought to be driven by the mergers of galaxies with high gas content (Sanders et al. 1988), which is also responsible for any obscuration that occurs (Kauffmann & Haehnelt 2000). Understanding the physical properties of these AGNs can also provide insight into how the masses of SMBHs correlate with the total amount of radiation produced by the central engine, as well as constrain the growth of black holes, the black hole-host galaxy connection, and AGN accretion efficiency.

The Wide-field Infrared Survey Explorer (*WISE*) (Wright et al. 2010; Mainzer et al. 2011) has provided all-sky coverage in the mid-IR of various types of astrophysical IR sources. Mid-IR color selection using *WISE* photometry provides an effective way to identify obscured AGN candidates with good reliability and completeness (Stern et al. 2012; Assef et al. 2013, 2018). The *WISE* dataset has led to the discovery of hot, Dust Obscured Galaxies (HotDOGs), which contain a large proportion of hot dust and are likely hosts for AGNs as shown by their high dust temperatures (Wu et al. 2012; Eisenhardt et al. 2012; Tsai et al. 2015). At mid-infrared wavelengths, obscuration effects are relatively low and light emitted near a supermassive black hole produces a relatively flat power-law spectrum that is distinct from the SEDs of other types of objects (ex. stars, which

behave like blackbodies and have flux densities decrease significantly at wavelengths above a few microns.). The IR obscuration makes these AGNs easier to find owing to their dustiness and redness, as heavily obscured AGNs will have very red *WISE* band colors. This is especially true compared to UV AGN selection, in which AGN sampling can be incomplete due to Lyman dropouts, etc. The highest redshift AGNs have their Lyman-alpha features shifted into the IR, and are thus invisible to UV and optical searches. While these mid-IR color criteria have been defined using known samples of obscured AGNs, there have been relatively few observations utilizing these criteria as the basis for follow-up observations. The Keck DEIMOS spectrograph (Faber et al. 2003) is ideal for obtaining high quality optical spectra of these AGNs due to its high resolution and wide field of view, and its capabilities are powerful for probing the physical properties of highly obscured AGNs that are identified from the *WISE* catalog.

In this paper, we present the results of selecting obscured AGN candidates using mid-IR *WISE* photometry and observing these objects using the Keck DEIMOS optical spectrograph. We describe our observations and target selection criteria in Section 2. Section 3 discusses the data reduction, flux calibration, and line measurement methods we used on our quasar spectra. In Section 4, we discuss our results regarding sample completeness, redshift distributions, SED modeling and virial black hole mass measurements. We also discuss plans for future observations and suggestions for performing obscured AGN searches. We assume a Λ CDM cosmology using the parameters from the Planck collaboration: $\Omega_m = 0.3089$, $\Omega_\Lambda = 0.6911$, $H_0 = 67.74$ km/s/Mpc.

1.2 Observations

DEIMOS (DEep Imaging Multi-Object Spectrograph) is an optical, multi-object imaging spectrograph located at the W.M. Keck Observatory capable of simultaneously obtaining spectra of 100+ objects in a single slitmask, with a spectral resolution of up to $R \sim 6000$ and spectral coverage of 5000 Å. Here, we describe our AGN target selection process and telescope configuration.

1.2.1 Target selection criteria

To determine potential obscured AGN targets, we selected AGN candidates from the AllWISE data release, which contains photometry for ~ 750 million different objects in the mid-IR. The *WISE* survey is an all-sky mid-IR survey at 3.4, 4.6, 12, and 22 μm ($W1$, $W2$, $W3$, and $W4$, respectively), with respective angular resolutions of 6.1", 6.4", 6.5", and 12.0". We first applied a color cut across the first two *WISE* bands such that $W1 - W2 \geq 0.8$. This color selection criterion has been shown to select mid-IR AGN candidates to a high level of completeness and reliability (Stern et al. 2012), and includes both unobscured (type 1) and obscured (type 2) AGNs (Edelson & Malkan 2012). *WISE* objects that satisfy $W1 - W2 \geq 0.8$ have a sky density of 61.9 ± 5.4 AGN candidates per square degree to a depth of $W2 \sim 15.0$ (the AllWISE catalog has a density of $\sim 18,000$ objects per square degree, averaged across the entire sky). A few AGN candidates selected using this color cut do not have corresponding magnitudes in the Sloan Digital Sky Survey Data Release 12 (SDSS DR12, Alam et al. (2015)) despite being in the survey footprint, which may be due to high levels of optical extinction. However it is important to note that SDSS is highly flux limited due to its relatively short exposure time. We expect that these color-selected AGNs not observed by SDSS (either photometrically or spectroscopically) are likely to be detectable with DEIMOS using a longer exposure time. To eliminate any potential complications arising from Galactic extinction and reddening, we select fields around the North Galactic cap.

We narrow down the list of potential targets by choosing those that are maximally clustered within a region of the sky that falls within the boundary of a DEIMOS field of view. This is done to maximize the efficiency of multi-AGN observations per field. That is, we make efficient use of the exposure time per slitmask by minimizing the number of different fields and pointings that have to be made. Each DEIMOS field contains a $16.7' \times 5'$ area, with a total coverage of 68.3 arcmin^2 after accounting for the region of each mask which is lost to vignetting. There are 3-4 million *WISE*-selected AGN across the entire sky (Stern et al. 2012), which works out to an expected number of 1.7 in a randomly placed DEIMOS field of view. For a Poisson distribution with this mean, the probability of getting 6 or more AGNs in a random field of view is 0.1%, but there are 1.7 million fields of view around the sky. After systematically tiling a region of the sky with rectangles the size

of a DEIMOS field of view, and counting the number of color cut candidates that lie within each field, we find that the largest clusters within a field of view appear most frequently as groupings of 6.

1.2.2 DEIMOS Observations

We used the DSIMULATOR slitmask software to design DEIMOS slitmasks centered around the six AGN candidates we targeted per field. We then populated the remaining area in each slitmask with additional bright *WISE* -selected sources that fall within the field of view, providing an additional 60–70 secondary targets per mask (not included for analysis in this paper). We estimate the optical band magnitudes of these AGNs with *WISE* W1 and W2 magnitudes by assuming a power law spectrum and extrapolating into the optical r band, which yields average magnitudes of $r \sim 20$. This is well below the $r > 15$ saturation limit of the DEIMOS detector, so we were not concerned about any possibility of overexposure. Prior to designing our slitmasks, we visually inspected the *WISE* images for each AGN target using the IRSA finder chart tool, to ensure that these clusters were indeed resolvable point sources in mid-IR, and not the result of artifacts produced by bright sources (ex. PSFs of bright stars).

We observed a total of 15 disjoint fields over a 1.5 nights in May 2015 and October 2016 on the DEIMOS spectrograph, in which we selected 90 *WISE*-selected AGN candidates using the $W1 - W2$ color cut and the clustering criteria described above. Each mask was observed for a total of 45 minutes using the 600ZD grating, and with a central wavelength of 7500 Å. We estimated the required exposure time for each field based on a minimum signal to noise ratio of around ~ 15 . The online DEIMOS Exposure Time Calculator provides an exposure time of 2700 seconds provides a good SNR for Z band magnitude of 22 (AB) using a 1'' slitwidth, a 600 l/mm grating, and a central wavelength of 7500 Angstroms. To account for cosmic ray subtraction, we took three 900-second exposures for each field and co-add them to create the final spectrum. We measured redshifts for a total of 66 targets, with the remaining spectra being either too noisy for reliable emission line identification or being empty spectra.

1.3 Data reduction and analysis

We reduced our raw DEIMOS spectra using the DEEP2 data reduction pipeline (Newman et al. 2013; Cooper et al. 2012). This reduction package performs wavelength calibration, sky line subtraction, co-adding, cosmic ray subtraction, and outputs the corresponding 1D and 2D spectrum for each object.

1.3.1 Flux calibration

To perform flux calibration, we use a standard DEIMOS photon throughput function¹ to correct the reduced 1D spectra. Figure 1.1 shows the throughput functions for the GG495 and OG550 filters. Our observations were done using the GG495 filter, and the dips at $\sim 6800 \text{ \AA}$ and $\sim 7600 \text{ \AA}$ of the throughput function correspond to the atmospheric B and A absorption bands (which have not been properly corrected). The sharp rise around $\sim 1\mu\text{m}$ is a result of 2nd order leakage from emission at $\sim 5000 \text{ \AA}$. In contrast, the OG550 filter blocks out this leakage and does not show this behavior at $\sim 1\mu\text{m}$. These features produce obvious distortions in the spectra, but we avoid performing line measurements in these affected regions. After correcting the 1D spectra, we then renormalize the spectra such that the integrated r band magnitude (taking into account the SDSS r band transmission curve) matches the observed r magnitude from SDSS. We note however, that the absolute flux calibration of our spectra do not affect our results or conclusions. Specifically, our equivalent width and FWHM measurements of emission lines do not change with respect to flux calibration, and the continuum luminosities we use are derived from SED fitting instead of the spectra.

1.3.2 Redshift and emission line measurements

For initial redshift measurements and object classification, we used the SpecPro software package (Masters & Capak 2011) to visually inspect each of our DEIMOS spectra. SpecPro computes a

¹<http://www.ucolick.org/~ripisc/results.html>

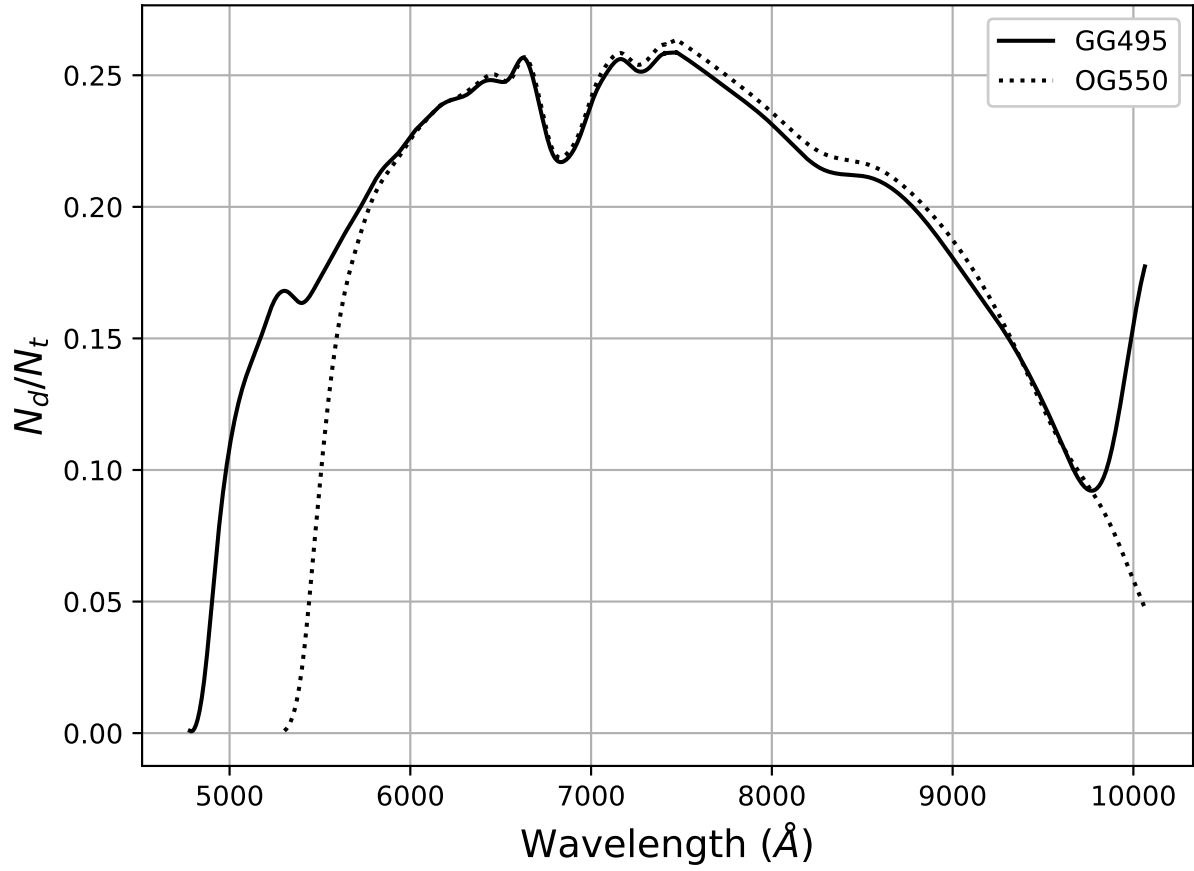


Figure 1.1: DEIMOS throughput functions for the GG495 and OG550 filters, with a 600 l/mm grating, and 7500 Å central wavelength. The throughput is given by N_d/N_t , where N_d is the number of photons detected and N_t is the number of photons reaching the primary mirror.

best fit to a given 1D spectrum by cross correlating various galaxy and spectral templates to provide redshift estimates. In addition to 1D spectra, we also use the corresponding 2D spectra for each object to visually aid in identifying any bright emission lines (ex. [OIII]) that may not be distinct in the reduced 1D spectra due to low signal to noise. We require that a spectrum have at least two identifiable line features in order to assign it a secure redshift value.

We identify 66 DEIMOS targets (out of 83 targets, a 80% success rate) to be probable AGNs with secure redshifts based on distinguishable spectral features and the presence of broad lines. We show examples of our spectra in Figure 1.4 at the end of the paper. This shows that the $W1 - W2 > 0.8$ color cut criterion in Stern et al. (2012) is indeed efficient in selecting AGN targets. The median redshift of our AGN sample is $\langle z \rangle = 0.95$, which lies between the obscured quasar sample in Hainline et al. (2014) with $\langle z \rangle \sim 0.35$ and Banerji et al. (2015) with $\langle z \rangle \sim 2$. One target (WISE J111735.43+291640.4; RA=169.3976364, DEC=29.2779092) had a spectrum with strong Balmer absorption features (indicative of a large population of type A stars) and narrow line emission. There is no clear broad line emission visible, so it is possible that this may be a Seyfert 2 object. The spectrum of this object is shown in the last panel of Figure 1.4, but since this galaxy is markedly different from the other AGNs in our sample we’ve excluded it from our analysis. The remaining failed spectra were too noisy to produce any clearly identifiable spectral features, or yielded blank spectra. We label these failures as “noisy” if there is an object evident in the 2D spectrum, but the 1D spectrum does not show prominent emission lines suitable for redshift measurements. We label spectra as “empty” if there is no object visible in either the 1D or 2D spectrum. Figure 1.2 shows a plot of $W1$ and r magnitudes for our targets that successfully produced redshifts and those that failed (excluding the objects with no r band photometry). Even though we prioritized selecting $W1$ bright objects, neither the $W1$ nor r magnitude seems to indicate whether or not an object would yield a spectrum with a measurable redshift. After visually inspecting the corresponding WISE and SDSS images for each target, we do not see any signs that these failures were due to astrometry issues with the slitmasks given that the majority of slits did yield spectra. However, given that the size of the WISE PSF ($\sim 6''$) is larger than the $1''$ width of a DEIMOS slit, some of the blank or noisy spectra may have been the result of the slits being

slightly offset from the target. We calculate the astrometry offsets between the WISE and SDSS coordinates, and Figure 1.3 shows that only four failed spectra had a offset larger than $1''$. Only one object (J111714.53+291313.3, RA=169.3105733, DEC=29.220385) had a SDSS spectrum (with $z=0.893$), and this object was offset by $> 1''$. Increasing the size of the slit is not necessarily beneficial, since this also increases the level of sky noise. Out of the six objects with no r band photometry and not visible in SDSS images, four were empty spectra and two were noisy. This suggests that objects without SDSS photometry are unsuitable as targets (being too faint, or perhaps being WISE photometric artifacts) for our given observing configuration. This 20% failure rate of spectra is somewhat high, but it's possible that some of these sources are variable in nature (characteristic of AGNs), and the reported magnitudes from WISE and SDSS may have changed since their initial observations.

Out of the 66 AGNs in our DEIMOS sample, 14 objects had spectroscopy in SDSS DR14 catalog and were correctly identified as AGNs. The SDSS redshift values are also in good agreement with ours (see Tables 1.1, 1.2, and 1.3). The remaining objects in our sample had neither SDSS spectra nor object classification. This demonstrates that our mid-IR selection does find a significant number of quasars that large optical surveys such as SDSS do not. Our survey was optimized for the DEIMOS spectrograph by locating spatial clusters (i.e. line-of-sight alignments) of very red mid-IR objects, but there is a much larger number of reddened AGNs distributed across the sky that are not as tightly clustered together. This implies that the majority of highly reddened AGNs are missed by these sorts of large-scale optical surveys.

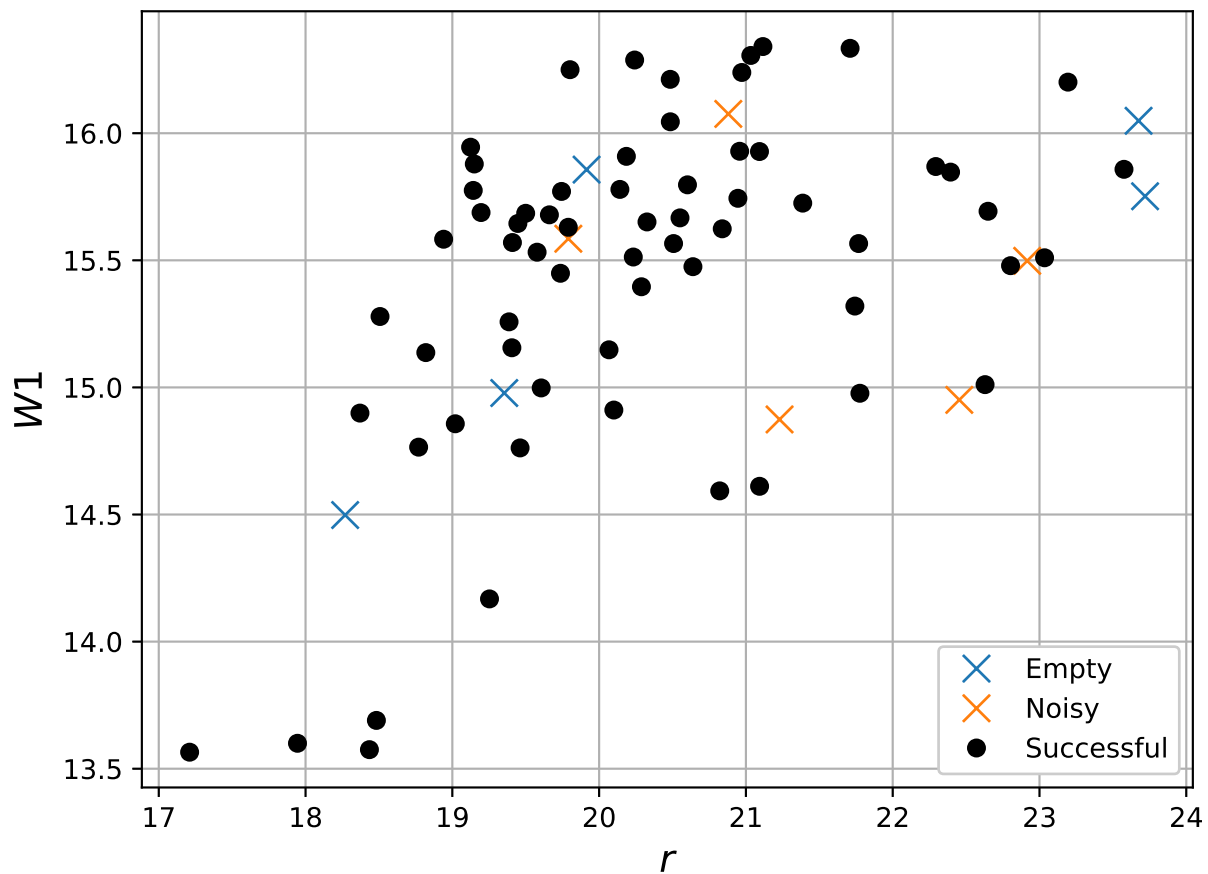


Figure 1.2: $W1$ and r magnitudes for our observed targets. Black dots show objects with successful redshift measurements. Crosses indicate spectra that were too noisy (orange) or were empty (blue).

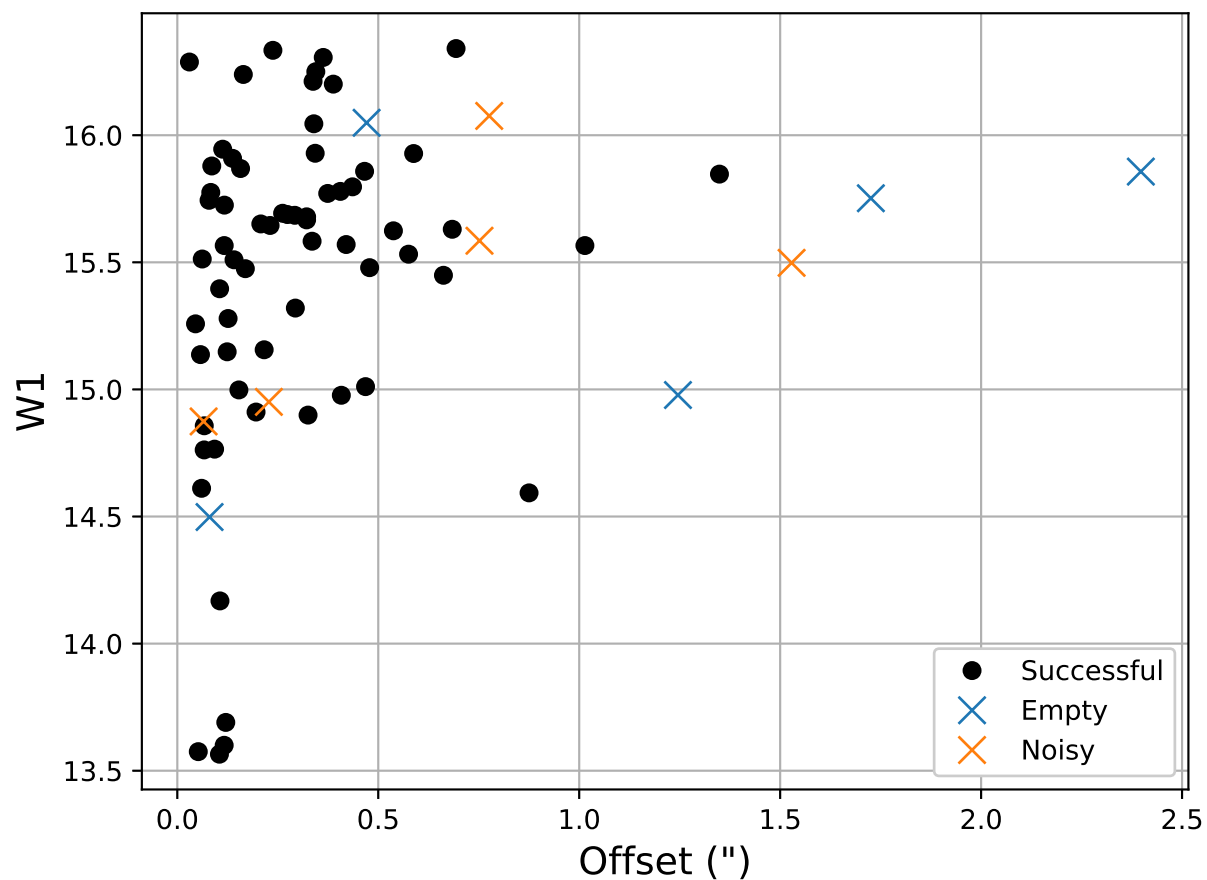


Figure 1.3: $W1$ and astrometry offsets (between WISE and SDSS) for our observed targets. Black dots show objects with successful redshift measurements. Crosses indicate spectra that were too noisy (orange) or were empty (blue).

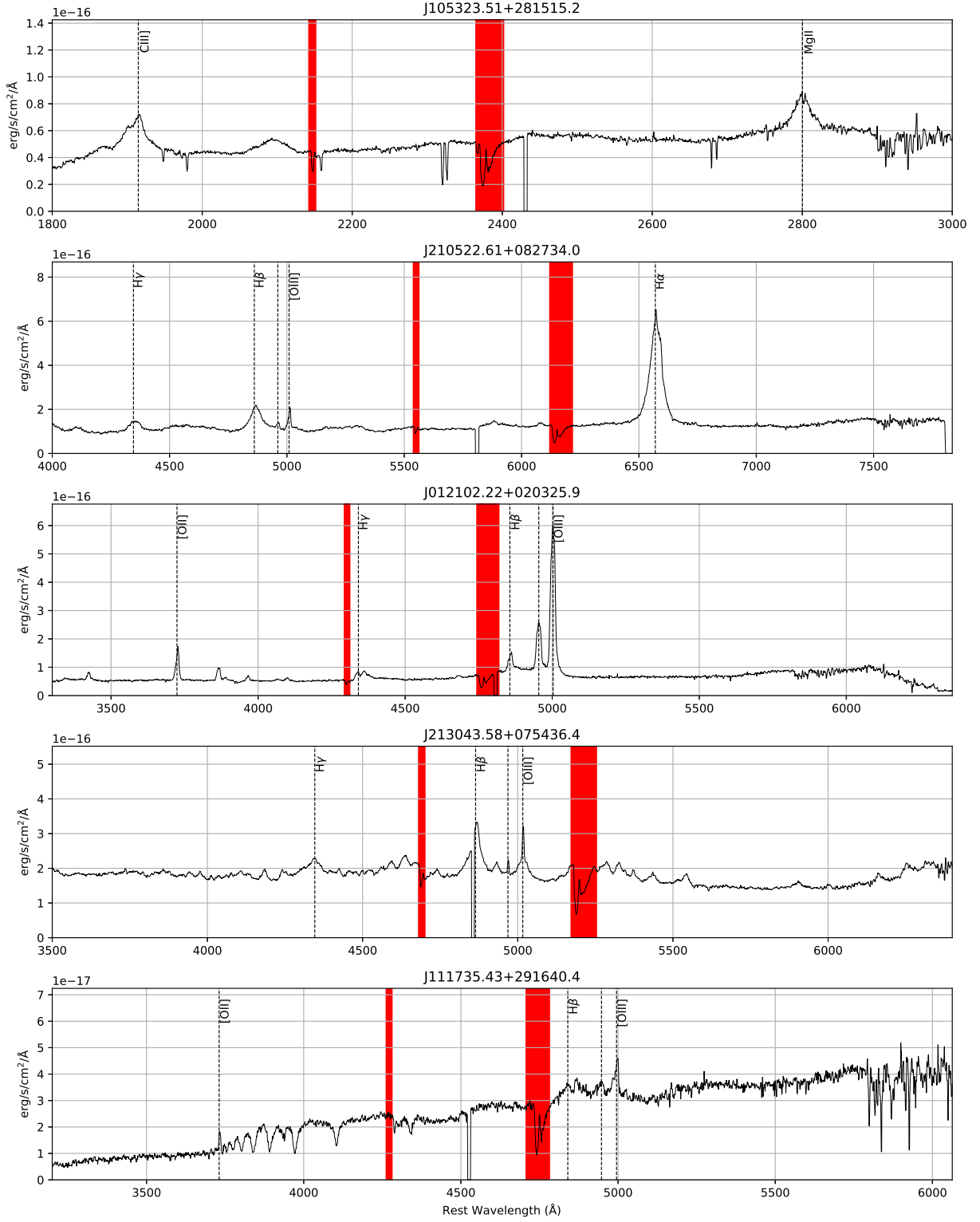


Figure 1.4: Examples of some of our DEIMOS AGN spectra. Emission lines are indicated, and the red regions show the A and B atmospheric bands. The bottommost spectrum is the spectrum of the potential Seyfert 2 galaxy we identified in our sample.

WISE Designation	z	z_{SDSS}	$E(B - V)$	AGN %	α_{opt}	Galaxy template	$\log\left(\frac{M_{\text{BH}}}{M_{\odot}}\right)$	$\log\left(\frac{L_{\text{bol}}}{\text{erg/s}}\right)$	$\log\left(\frac{L_{\text{bol}}}{L_{\text{Edd}}}\right)$
J012024.91+020238.0	1.001	1.003	0.00	0.93	-0.93	E	-	46.64	-
J012102.22+020325.9	0.597	-	0.29	0.93	-1.28	E	8.89	46.35	-0.64
J012102.56+020314.0	1.336	1.337	0.00	0.95	-0.72	Im	9.91	47.06	-0.95
J012113.17+020444.8	0.351	-	0.21	0.99	-1.45	E	-	44.98	-
J012114.71+020254.1	0.596	-	0.12	0.92	-1.20	E	-	45.95	-
J013127.45-021810.9	1.512	1.509	0.00	0.89	-0.80	E	9.49	46.82	-0.77
J013138.37-021729.5	1.179	1.182	0.08	0.88	-1.12	Sbc	8.93	46.56	-0.47
J013203.35-021800.4	0.255	-	0.60	0.92	-1.73	E	-	45.15	-
J013204.11-021742.1	0.907	-	0.66	0.99	-2.34	Im	-	46.27	-
J021256.88-013436.1	1.598	1.599	0.00	1.00	-0.73	E	9.13	47.04	-0.19
J021303.16-013004.6	1.380	1.378	0.00	0.74	-0.87	Sbc	-	46.75	-
J021315.94-013114.7	0.642	-	0.53	0.90	-1.90	Sbc	-	45.99	-
J021320.76-013021.8	0.565	-	0.11	0.90	-1.07	E	-	45.57	-
J025831.97+015719.7	1.243	1.247	0.02	0.88	-0.80	Im	8.37	46.48	0.02
J025849.39+015936.6	1.351	-	0.04	0.88	-0.91	Sbc	9.93	46.71	-1.32
J025905.91+015922.5	0.709	-	0.28	0.89	-1.24	E	8.39	45.90	-0.59
J025914.06+015742.6	1.134	-	0.08	0.93	-1.13	E	-	46.36	-
J034829.35+011629.2	0.236	-	0.28	0.64	-1.31	Sbc	-	44.93	-
J034857.28+011854.7	0.709	-	0.46	0.86	-1.11	Sbc	-	46.03	-
J034913.95+011551.0	0.890	-	0.14	0.90	-1.27	Sbc	8.50	46.13	-0.47
J034918.43+011614.2	1.130	-	0.14	0.80	-1.28	Im	9.89	46.40	-1.59
J105230.92+281707.4	0.708	-	0.64	0.95	-2.21	Sbc	-	46.07	-
J105237.91+281628.0	1.787	-	0.35	0.75	-1.93	Sbc	-	46.93	-
J105239.12+281458.1	0.532	-	0.17	0.91	-1.14	E	8.02	45.69	-0.43

Table 1.1: SED properties of the DEIMOS sample. “AGN %” indicates the contribution of the AGN template to the total template, and α_{opt} is the optical power law index.

WISE Designation	z	z_{SDSS}	$E(B - V)$	AGN %	α_{opt}	Galaxy template	$\log\left(\frac{M_{\text{BH}}}{M_{\odot}}\right)$	$\log\left(\frac{L_{\text{bol}}}{\text{erg/s}}\right)$	$\log\left(\frac{L_{\text{bol}}}{L_{\text{Edd}}}\right)$
J105301.75+281345.3	0.255	-	0.27	0.72	-1.23	Sbc	7.66	45.16	-0.60
J105323.51+281515.2	2.239	2.220	0.07	0.94	-0.86	Sbc	9.17	47.45	0.18
J111729.59+291330.8	0.631	-	0.47	0.98	-1.96	Im	-	46.10	-
J111749.37+291619.4	1.304	1.272	0.01	0.90	-0.71	Im	9.06	47.10	-0.05
J111759.97+291435.8	1.477	-	0.54	0.99	-2.12	Im	9.69	47.12	-0.67
J111801.15+291629.8	0.919	-	0.07	0.95	-1.08	E	9.17	46.08	-1.19
J113715.83+183920.9	0.464	-	0.38	0.85	-1.58	Sbc	-	45.75	-
J113726.28+183931.6	0.396	0.409	0.05	0.98	-1.09	E	8.17	45.94	-0.33
J113742.73+183928.2	0.195	-	0.09	0.63	-1.03	Sbc	-	44.72	-
J113753.73+184042.7	0.979	0.995	0.00	0.93	-0.78	Im	9.21	46.66	-0.65
J114606.80+324348.8	1.698	-	0.34	0.92	-1.50	Sbc	-	46.96	-
J114614.93+324247.6	1.377	-	0.22	0.94	-1.36	Sbc	-	46.63	-
J114643.89+324354.6	1.228	-	0.03	0.83	-0.67	Im	9.87	46.72	-1.25
J114644.21+324616.4	0.642	0.641	0.05	0.94	-0.93	E	-	46.05	-
J114658.54+324418.4	1.418	-	0.15	0.89	-1.15	Sbc	8.76	46.81	-0.06
J210522.61+082734.0	0.238	-	0.05	0.92	-0.99	E	8.30	45.38	-1.01
J210554.75+082803.4	0.431	-	0.39	0.97	-1.80	Im	-	45.42	-
J210556.31+082716.2	0.517	-	0.06	0.86	-1.15	Sbc	7.82	45.51	-0.41
J210600.72+083016.3	0.243	-	0.11	0.33	-1.87	Sbc	-	45.05	-
J210601.46+082820.6	1.178	-	0.04	0.87	-1.00	E	9.58	46.35	-1.32
J212354.75+075116.8	0.758	-	0.59	0.96	-2.02	Sbc	-	46.25	-
J212403.27+075505.8	0.460	-	0.60	0.94	-1.76	Sbc	-	45.80	-
J212415.85+075342.1	0.620	-	0.24	0.97	-1.33	E	8.21	45.78	-0.53
J212419.78+075517.9	1.308	-	0.23	0.90	-1.49	Im	9.63	46.71	-1.02
J212634.11+084107.7	2.018	-	0.00	0.98	-0.63	E	9.49	47.29	-0.30

Table 1.2: SED properties of the DEIMOS sample. “AGN %” indicates the contribution of the AGN template to the total template, and α_{opt} is the optical power law index. (Continuation of Table 1.1)

WISE Designation	z	z_{SDSS}	$E(B - V)$	AGN %	α_{opt}	Galaxy template	$\log\left(\frac{M_{\text{BH}}}{M_{\odot}}\right)$	$\log\left(\frac{L_{\text{bol}}}{\text{erg/s}}\right)$	$\log\left(\frac{L_{\text{bol}}}{L_{\text{Edd}}}\right)$
J212638.72+083850.8	1.724	-	0.00	0.78	-0.49	Im	-	47.07	-
J212652.34+083953.8	1.726	-	0.44	0.82	-2.22	Sbc	-	47.17	-
J212657.82+084053.1	1.700	-	0.33	0.84	-1.71	E	-	46.84	-
J213043.12+075239.8	1.106	-	0.00	0.97	-0.82	Im	9.60	47.32	-0.38
J213043.58+075436.4	0.466	-	0.08	0.89	-1.04	E	-	46.19	-
J213111.02+075102.4	0.651	0.652	0.16	0.92	-1.21	E	-	45.74	-
J213133.95+075415.7	0.326	-	0.47	0.91	-1.68	Sbc	-	45.17	-
J230849.95+014036.0	1.214	-	0.06	0.93	-0.97	Im	8.55	46.63	-0.02
J230849.99+014338.5	0.908	-	0.03	0.92	-1.02	Sbc	8.86	46.46	-0.49
J230850.31+014253.0	0.963	-	0.05	0.93	-1.05	Sbc	8.26	46.50	0.13
J230850.70+014201.6	0.689	-	0.47	0.99	-2.29	Im	-	46.30	-
J230924.01+014046.0	0.550	-	0.00	0.78	-0.68	Im	8.44	45.94	-0.60
J231514.63-015651.0	0.572	0.573	0.17	0.90	-1.04	E	-	45.60	-
J231521.53-015613.7	0.162	-	0.00	0.79	-1.02	Im	-	44.32	-
J231524.02-015852.7	1.585	-	0.11	1.00	-1.05	E	-	47.17	-
J231542.28-015737.1	1.675	-	0.01	0.81	-0.63	Im	8.92	47.14	0.13
J231542.85-015817.0	1.675	-	0.07	0.87	-0.83	Im	9.41	47.18	-0.32

Table 1.3: SED properties of the DEIMOS sample. “AGN %” indicates the contribution of the AGN template to the total template, and α_{opt} is the optical power law index. (Continuation of Table 1.2)

We perform equivalent width and FWHM measurements of emission line features using Gaussian fitting. Most of the narrow lines in our sample are easily fit using a single three-parameter Gaussian and a two-parameter linear continuum. The centroids of these line fits also allow us to refine our initial redshift measurements more precisely. Since the wavelength calibration is done separately for the red and blue sides of the spectra within the data reduction pipeline, there are small discrepancies in the redshift values obtained from lines lying on different halves of a spectrum. We account for this by taking the average redshift value from different lines, and the redshift errors for our AGNs are on the order of $\sigma_z \sim 0.001$ or better. For broad line features, we use two Gaussians to fit a single line (with the centers, widths, and amplitudes of each Gaussian as free parameters). For $H\beta$, we take these two Gaussians to be the narrow and broad components of the line. Some emission lines that are particularly broad or asymmetric are poorly fit with Gaussians, but we are still able to obtain equivalent width measurement by integrating over the measured data points instead of the Gaussian model. The difference between the equivalent widths derived from integrating over the data points versus integrating over a Gaussian model is negligible ($\sim 0.1\text{\AA}$).

For the $H\alpha$ / [NII] complex, we reduce the number of free parameters such that: 1. the central wavelength of the [NII] doublet are fixed relative to the $H\alpha$ peak, 2. the [NII] doublet amplitude ratio is 1:3 and, 3. the doublet has the same width. We apply the same constraints for the $H\beta$ / [OIII] complex. To ensure that our $H\alpha$ measurements are reliable and not affected by strong blending with [NII], we only do individual line measurements if the forbidden [NII] line is narrower than the $H\alpha$ line and $H\alpha$ has a $\text{FWHM} < 1200 \text{ km s}^{-1}$. Even if the signal-to-noise ratio is high, it is difficult to measure equivalent widths for highly blended lines if the line wings are not easily distinguishable. For the two spectra in our sample with highly blended emission lines, we instead measure the total $H\alpha$ + [NII] equivalent width.

Figures 1.5 and 1.6 show the equivalent width and FWHM measurements we obtained from our spectra of AGN candidates. We only include the strongest emission lines that appear most frequently in our sample, and in particular those that are directly applicable for AGN classification and black hole mass measurements.

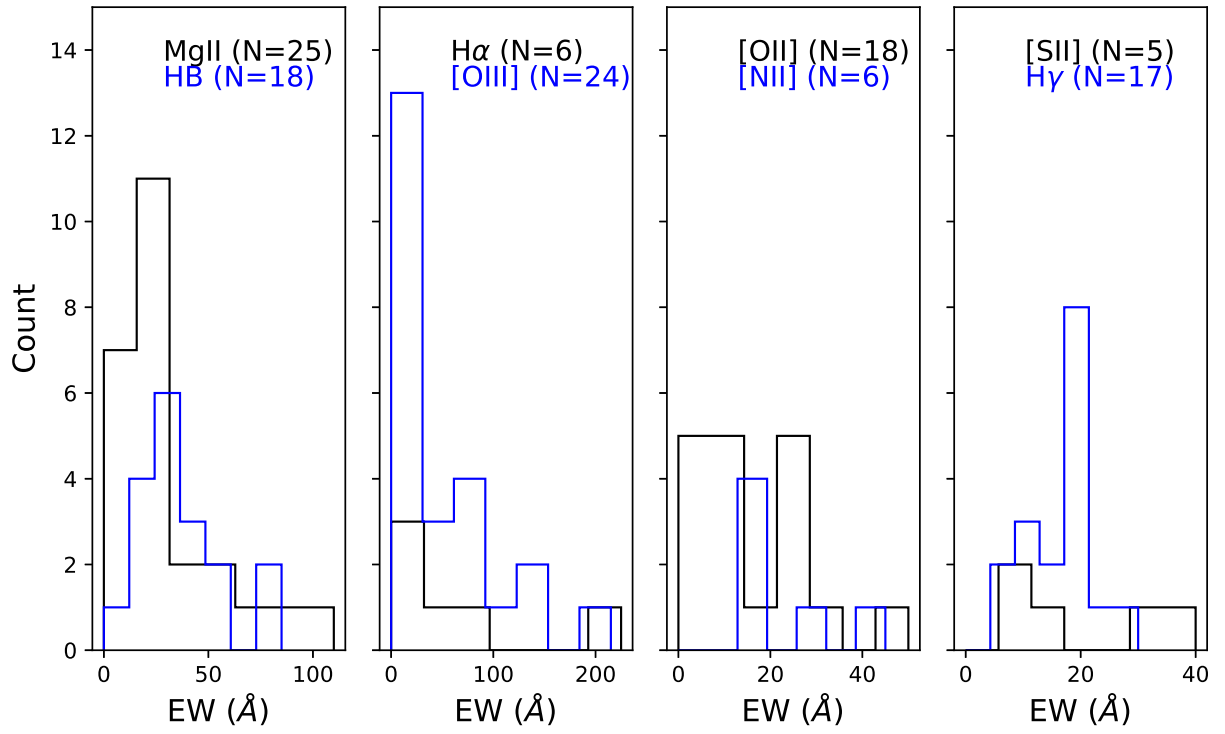


Figure 1.5: Histograms of emission line equivalent width measurements from the DEIMOS AGN sample.

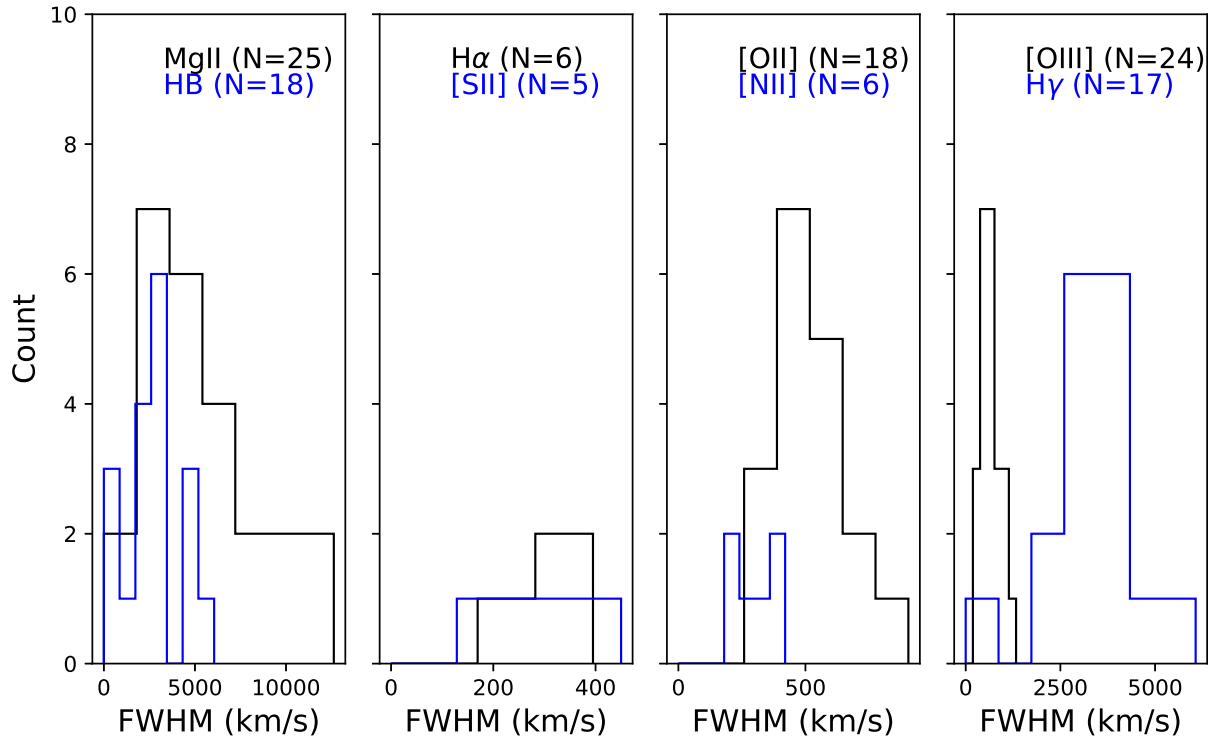


Figure 1.6: Histograms of emission line FWHM measurements from the DEIMOS AGN sample.

1.4 Results and discussion

1.4.1 Galaxy clustering and biasing

Since we have selected our AGN targets based on their spatial clustering, it is possible that this may lead to a biased sample of galaxies if they are actually physically clustered in space. To determine if this biasing is significant, we examine the AGN redshifts to distinguish between actual 3D clustering and chance line of sight alignments. At a redshift of $z \sim 1.25$, the angular scale of physical clustering corresponds to a spread of $\Delta z \sim 0.01$ if the sources are clustered within a few arcminutes on the sky. Given the σ_z of redshifts within each field, we conclude that this clustering is due to line-of-sight alignments and not actual physical clustering.

1.4.2 SDSS AGN control sample

The SDSS data set contains a significant number of quasars for which spectroscopic data is available, and is useful as a control sample to compare the properties of our observed quasars. Shen et al. (2011) provides an extended catalog of properties for 105,783 objects in the SDSS DR7 Quasar Catalog (Schneider et al. 2007) that includes emission line measurements (for $H\alpha$, $H\beta$, $MgII$, and CIV) and virial black hole mass estimates based on these line measurements.

We divide the SDSS catalog into two samples based on the Stern et al. (2012) *WISE* color cut: a mid-IR bluer ($W1 - W2 < 0.8$) sample and a mid-IR redder ($W1 - W2 > 0.8$) sample. 95% of the AGNs in this catalog lie above the $W1 - W2 > 0.8$ color cut, which is expected since the rest frame H and K band emission at $\sim 2\mu m$ is a defining characteristic of AGNs and is preferentially selected using this color criteria. Table 1.4 summarizes the properties of these samples, along with our DEIMOS sample. Figure 1.7 shows a mid-IR vs. optical color-color diagram of these different AGN samples. Our sample of DEIMOS AGNs seems to have a similar distribution of $W1 - W2$ colors as the red SDSS AGN sample, but also has a larger fraction of AGNs with redder $u - g$ optical colors. As we discuss in Section 1.4.4, this difference is likely due to the different degrees of optical obscuration represented in each sample.

Sample	N	z	$\log\left(\frac{M_{\text{BH}}}{M_{\odot}}\right)$	$\log\left(\frac{L_{\text{bol}}}{\text{erg/s}}\right)$	$E(B - V)$	α	$W1 - W2$	$r - W1$
DEIMOS	66	0.96 ± 0.51	8.95 ± 0.64	46.25 ± 0.71	0.19 ± 0.20	-1.25 ± 0.46	1.11 ± 0.20	4.87 ± 1.18
SDSS (W1-W2;0.8)	41856	1.37 ± 0.56	8.89 ± 0.70	46.82 ± 0.54	0.04 ± 0.06	-0.81 ± 0.23	1.19 ± 0.18	3.72 ± 0.60
SDSS (W1-W2;0.8)	2989	1.30 ± 0.76	8.64 ± 1.03	46.42 ± 0.76	0.04 ± 0.07	-0.76 ± 0.31	0.64 ± 0.16	4.13 ± 0.78

Table 1.4: Summary of the different DEIMOS and SDSS AGN samples

Using a mid-IR color selection criteria tends to select AGNs peaking around a redshift of $z \sim 1.5$, and excludes AGNs at the high and low tail ends of the redshift distribution (see the top histogram of Figure 1.9). There are two main reasons for this. At lower redshifts, a lower fraction of AGN emission compared to host galaxy emission causes these AGNs to be bluer in $W1 - W2$ due a larger fraction of starlight in $W1$ (Secrest et al. 2015), causing these galaxies to fall in the $W1 - W2 < 0.8$ region. At higher redshifts ($z \sim 2$), the characteristic SED features of AGNs lie outside of the $W1$ and $W2$ bands, and are not selected using a $W1 - W2 > 0.8$ criterion.

1.4.3 Virial black hole mass estimates

We follow the approach of Shen et al. (2011) and use common broad emission lines to estimate the virial BH masses using empirical calibrations of $H\beta$ from Vestergaard & Peterson (2006) (VP06) and MgII from Vestergaard & Osmer (2009) (VO09), who follow a similar emission line fitting procedure as the one we use (see also McGill et al. (2008) for similar virial BH mass calibrations). For $H\beta$, we fit the line using two concentric Gaussians (with the same central λ_0), and use the FWHM of the broad component to estimate the black hole mass. For MgII, we use the FWHM of a single Gaussian fit. The virial black hole mass inferred from $H\beta$ and MgII line measurements is given by:

$$\log \left(\frac{M_{\text{BH, vir}}}{M_{\odot}} \right) = a + b \log \left(\frac{\lambda L_{\lambda}}{10^{44} \text{erg/s}} \right) + 2 \log \left(\frac{\text{FWHM}}{\text{km/s}} \right), \quad (1.1)$$

$$(a, b) = (0.910, 0.50), \quad \text{VP06; } H\beta \quad (1.2)$$

$$(a, b) = (0.860, 0.50), \quad \text{VO09; MgII.} \quad (1.3)$$

For the continuum luminosity L_{λ} , we use $\lambda = 3000\text{\AA}$ for MgII and $\lambda = 5100\text{\AA}$ for $H\beta$. These relations assume that the AGN broad-line region (BLR) is virialized, that the continuum luminosity parameterizes the BLR radius, and that the FWHM is a reliable measure of the virial velocity. We decide not to use CIV measurements as a mass estimator, due to the lack of prominent CIV emission lines in our DEIMOS sample, and that CIV-based mass estimates tend to have larger scatter and are in general less consistent compared to $H\beta$ and MgII-based measurements due to the

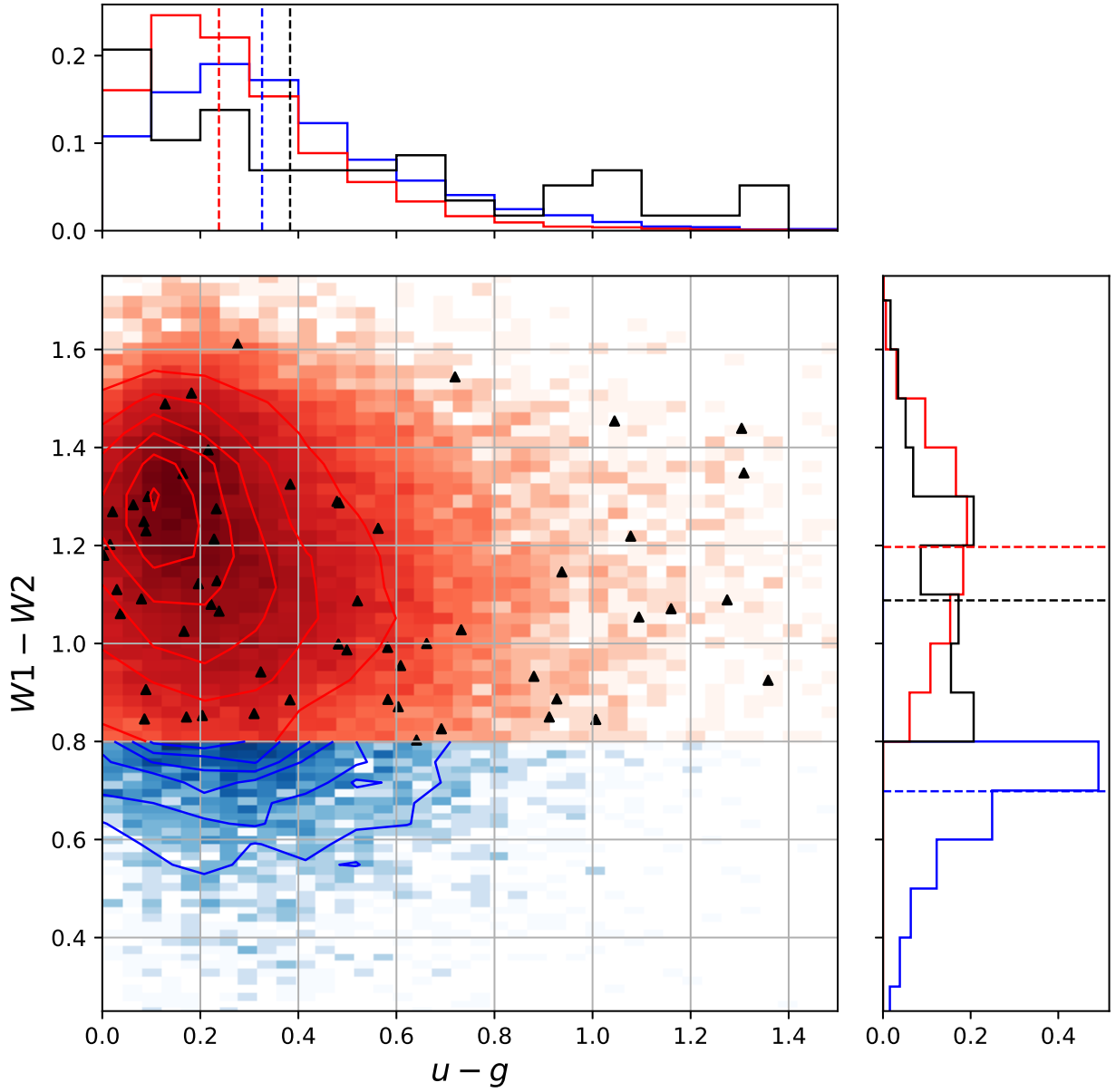


Figure 1.7: Mid-IR vs optical color-color diagram from *WISE* and SDSS photometry. Red and blue points represent the SDSS AGN samples with $W1 - W2 > 0.8$ and $W1 - W2 < 0.8$, respectively. Black triangles correspond to our DEIMOS AGN sample. The side panels show area-normalized histograms of their respective axes, with the dashed line indicating the median of the distributions.

presence of absorption features. We also choose not to use $H\alpha$ for BH mass estimates, since $H\alpha$ only appears in a few of our DEIMOS spectra. Additionally, occasional line blending with [NII] and potential host contamination (especially in lower luminosity, low redshift objects) complicates using $H\alpha$ measurements as a mass estimator.

To estimate the continuum luminosity at 3000 Å and 5100 Å (corresponding to MgII and $H\beta$, respectively), we fit the SDSS *griz* band photometry with a power law and interpolate in the rest frame wavelengths. Since some of these AGNs are heavily extinguished in the optical wavelengths, we correct the observed continuum luminosity with the extinction values that are obtained from SED fitting (see Section 1.4.4). Since the *u* band tends to capture the UV bump in the AGN SED, we exclude that band from the power law fit, as the flux tends to be higher than the other SDSS bands and deviates from a simple power law. The optical *griz* bands are well described by a power law fit, with no notable curvature or significant deviations across our sample. To check the reliability of this estimate, we estimate λL_{3000} of the objects in the SDSS quasar catalog using the optical photometry provided therein. Comparing this with the corresponding λL_{3000} obtained directly from the spectrum, the median $|\log \lambda L_{3000,SED} - \log \lambda L_{3000,spec}|$ difference is on the order of ~ 0.1 dex, which is comparable to the size of the median error $|\log \lambda L_{3000,spec}|$ values provided within the catalog. This error is also comparable to the expected time variability of the continuum. Berk et al. (2001) points out that the AGN continuum is not always well characterized by a single power law due to effects such as host-galaxy contamination at lower redshift. Thus, the optical power law index cannot be extrapolated to longer wavelengths as there is significant curvature in the spectrum between the optical and IR.

We measured masses for 25 spectra using MgII, and for 15 spectra using $H\beta$, with the requirement that these are broad lines with a FWHM > 2000 km/s. No spectra contained both a measurable broad Mg and $H\beta$ component. Figure 1.9 shows the black hole masses of our DEIMOS sample as a function of redshift, along with the SDSS AGN sample. The redder SDSS sample has a larger median black hole mass compared to the bluer sample by about ~ 0.25 dex, as a result of the objects having higher z . The distribution of BH masses in the DEIMOS sample is fairly consistent with the SDSS samples, and Figure 1.8 shows that there is no correlation between $E(B - V)$ extinction

(see Section 1.4.4) and the measured black hole mass. Contours represent 2d-histogram bins.

12 AGNs in our DEIMOS sample also have reliable broad line $H\gamma$ FWHM measurements, with insignificant contamination from neighboring [OIII] and iron emission. Although $H\gamma$ is not traditionally used to estimate black hole virial masses, there should be in principle a calibration between $H\gamma$ FWHM and black hole mass if we assume that this line emission originates from the BLR and reliably traces the virial velocity. To obtain virial mass parameters corresponding to $H\gamma$ in Eq. 1.1, we find the values for a and b that provide the best match with the black hole masses derived from $H\beta$ and MgII. For the $H\gamma$ continuum luminosity, we use L_{4100} . Using linear least-squares regression to find the best fit parameters, Figure 1.10 shows that there is visible trend between the $H\gamma$ line parameters and measured black hole mass. The scatter in this correlation is large and the small sample size makes it difficult to accurately constrain the fit parameters, but this shows that it is in principle possible to use $H\gamma$ as a BH mass estimator. Given a value of $r = 0.63$ and $N = 12$, this produces a p-value of $p = 4.8 \times 10^{-3}$ that this correlation is due to random chance.

1.4.4 SED modeling

To estimate the relative contribution of the quasar and galactic emission components, we use the low-resolution spectral templates given in Assef et al. (2010) and model each quasar as a linear combination of an AGN template and a single galaxy template. Assef et al. (2010) presents two AGN templates, and three galaxy templates (representing spiral, elliptical and irregular galaxy types). One AGN template is derived from a set of theoretical and observational assumptions regarding the SED behavior of AGNs, and the other is the average SED of Richards et al. (2006). Despite their different derivations, these two AGN templates are nearly identical in shape. Following the method in Hainline et al. (2014), we model each quasar using a linear combination of a single AGN and a single galaxy template that provides the best least-squares fit.

Since these templates do not include the effects of optical extinction produced by dust, we apply an extinction curve to the AGN template to simulate the effects of optical obscuration. The extinction curves that we use are described in Gordon & Clayton (1998) and Cardelli et al. (1989),

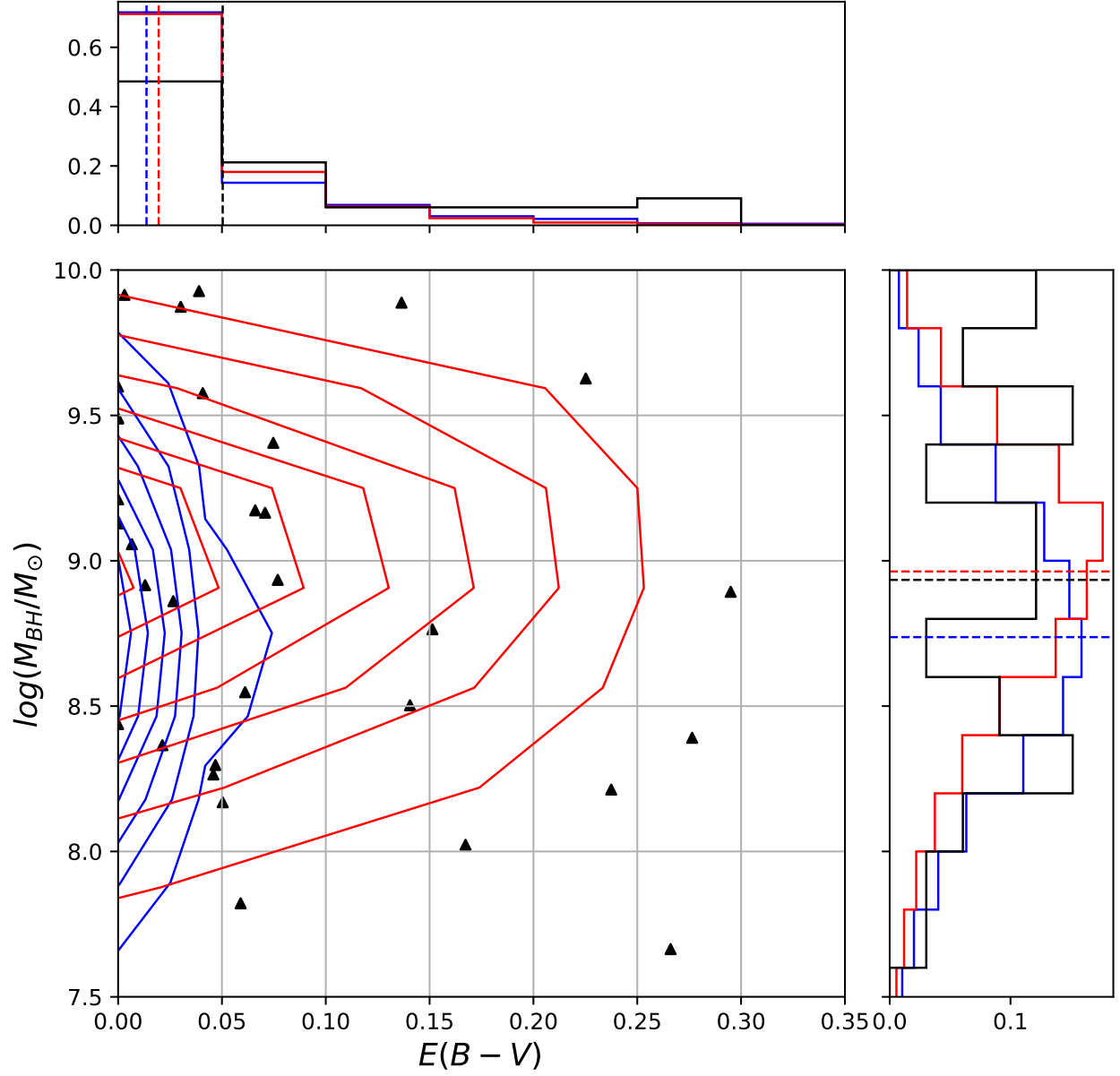


Figure 1.8: Virial black hole mass as a $E(B-V)$ extinction. Red and blue contours represent the SDSS AGN samples with $W1 - W2 > 0.8$ and $W1 - W2 < 0.8$, respectively. Black triangles correspond to our DEIMOS AGN sample. Contours represent 2d-histogram bins.

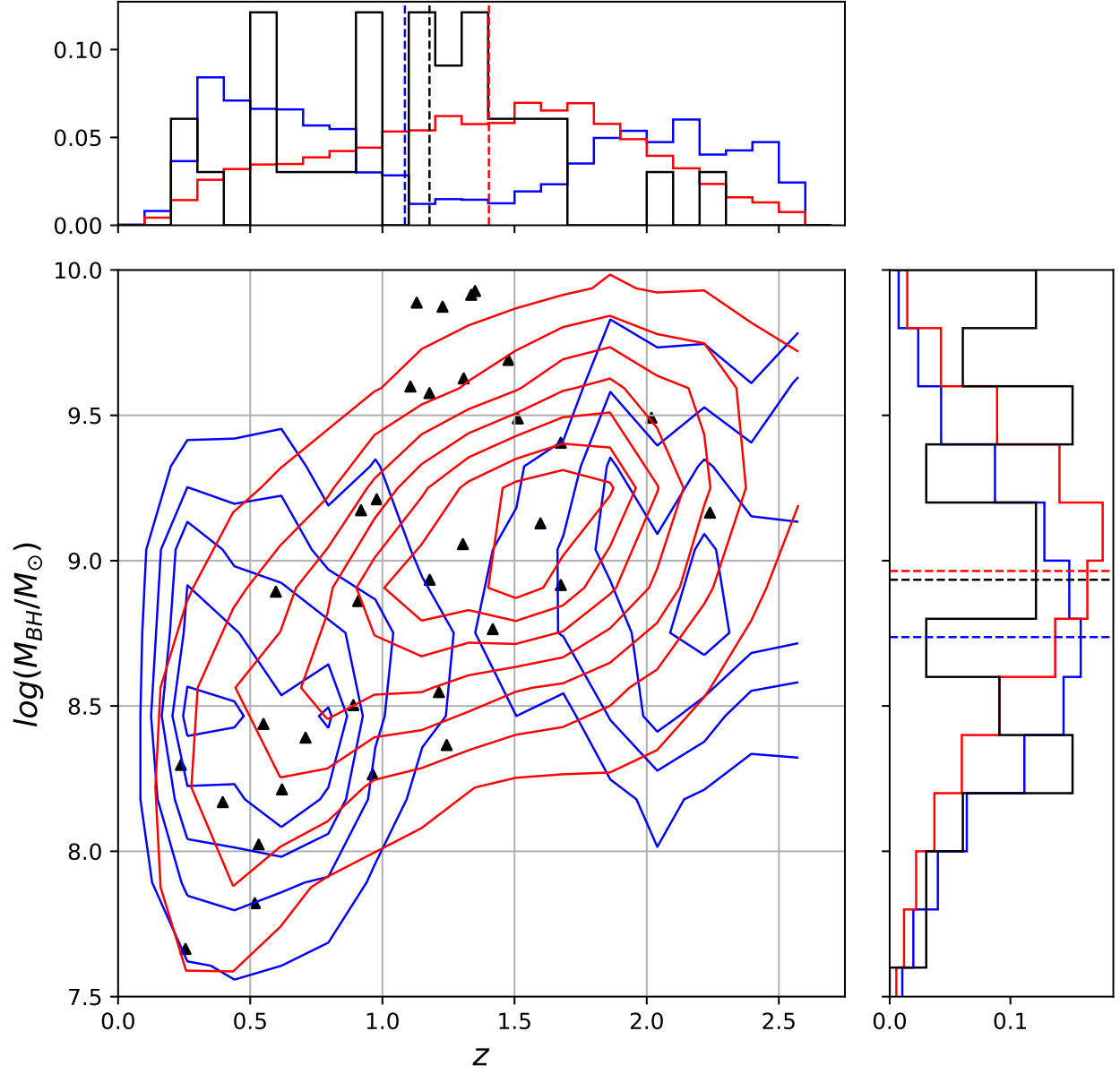


Figure 1.9: Virial black hole mass as a function of redshift. Red and blue contours represent the SDSS AGN samples with $W1 - W2 > 0.8$ and $W1 - W2 < 0.8$, respectively. Black triangles correspond to our DEIMOS AGN sample. Contours represent 2d-histogram bins.

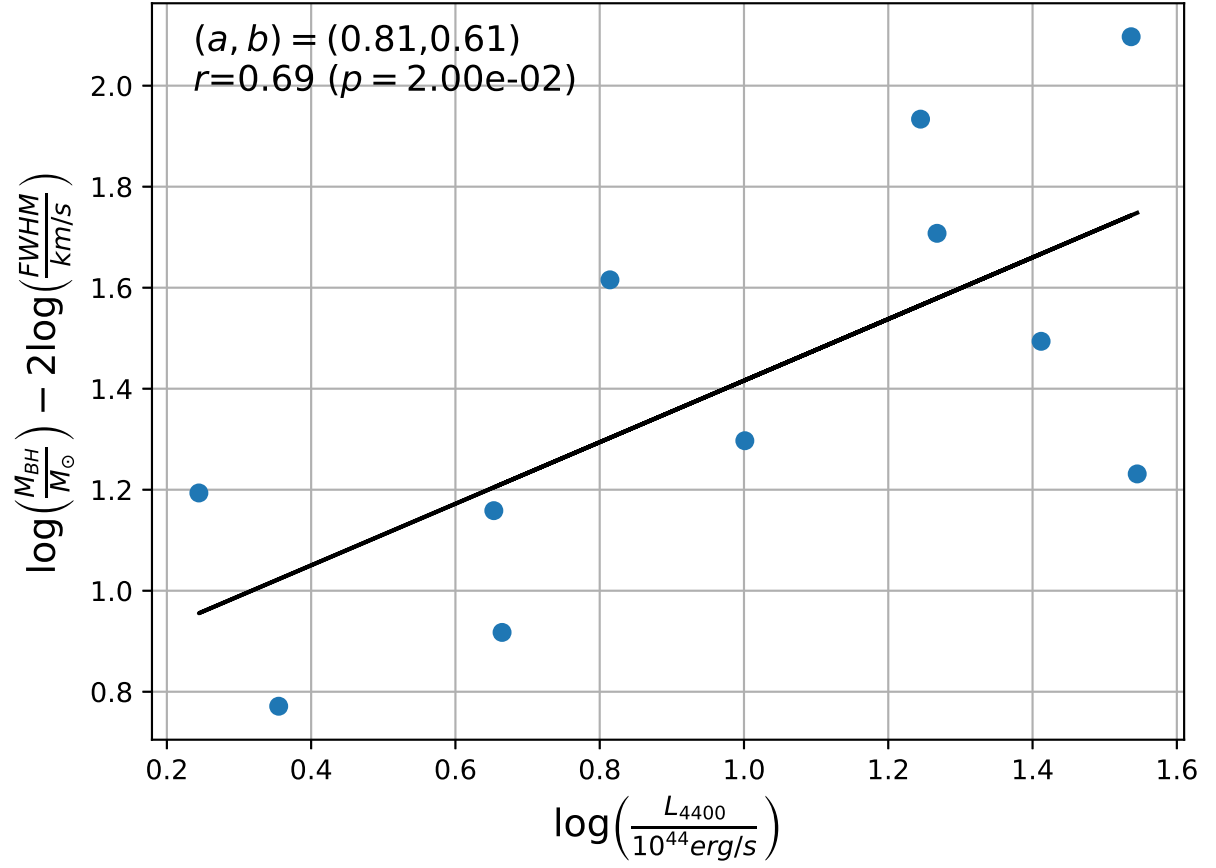


Figure 1.10: Virial black hole mass relation for $H\gamma$, with the y-intercept and slope of the linear fit corresponding to a and b in Eq. 1.1, respectively.

which we use to model the dust obscuration for wavelengths $\lambda < 3000 \text{ \AA}$ and $\lambda > 3000 \text{ \AA}$, respectively. In the canonical torus model one usually assumes that only the AGN component is extinguished, so we only apply the extinction curves to the AGN template. All but one of the objects in the DEIMOS sample have an AGN contribution (defined as the contribution of the AGN template to the total flux for $< 30 \mu\text{m}$) of greater than 60%. We are also implicitly assuming that the origin of this extinction is due to dust absorption and re-emission. It is possible that internal reddening in the host galaxy also plays a role here, but there is no practical way to distinguish these two effects with our given data. A more detailed and precise treatment of extinction is beyond the scope of this paper.

We use the available optical and infrared photometry from SDSS, UKIDSS, and *WISE* to perform SEDs fits on our DEIMOS sample and the SDSS DR7 quasar catalog. The SDSS model magnitudes are AB magnitudes, and we convert the *WISE* Vega magnitudes into the AB system for the purposes of flux comparison. We disregard any additional color corrections to the *WISE* magnitudes, as these account for only percent level errors. The majority of the objects in our DEIMOS sample have reliable ($\text{SNR} > 3$) *W3* measurements, but most do not have *W4* detections. Only 3.5% of all the entries in the AllWISE catalog have $> 2\sigma$ measurements for all four *WISE* bands, and 13% have a *W1/W2/W3* band combination.

Tables 1.1, 1.2, and 1.3 shows the AGN properties we derive from SED fitting. In Figures 1.11, 1.12, and 1.13, we show the SED fits of our AGNs, arranged in order of increasing $E(B - V)$ extinction (only one object is excluded from SED fitting due to a lack of optical photometry). In each plot, the solid line shows the sum of the AGN and galaxy templates with extinction added, while the dotted line shows the result with extinction removed. We calculate the $E(B - V)$ reddening value by interpolating the *B* and *V* magnitudes from these two curves. We also account for galactic dust reddening along the line of sight using the estimates described by Schlafly & Finkbeiner (2011), and subtract the corresponding $E(B - V)_{\text{gal}}$ from the $E(B - V)$ value measured from the SED. A number of the AGNs in our sample have optical power law indices that are steeper than $\alpha_\nu = 1$, where α is defined as $F_\nu \propto \nu^\alpha$. Our SED fits seem to show that these steep power indices are due to dust extinction instead of a significant stellar contribution. For the majority of

our objects, the integrated luminosity due to the AGN component makes up $> 85\%$ of the flux contained within the spectral range of our SED templates ($0.03 < \lambda < 30$ microns). In addition to the broad emission features we’ve observed in the DEIMOS spectra, these AGN-dominated SEDs serve as further proof that our observed DEIMOS sample is composed of AGNs.

Figure 1.14 shows that there is a strong correlation between the optical power law index α and the $E(B - V)$ extinction value above $|\alpha| > 1$, suggesting that optical photometry can be used as an indicator of the degree of optical obscuration for more highly reddened objects. A change in the power law slope of $\Delta\alpha = 1$ should change $E(B - V)$ by $2.5 \log(\nu_B/\nu_V) = 0.24$, and the distribution of the SDSS objects in these figures seem to reasonably agree with this order of magnitude estimate. We find that our DEIMOS sample has a broader distribution of obscuration levels compared to the SDSS samples, with a larger fraction of AGNs having higher extinction and steeper values of α . 56% of the DEIMOS AGNs show an optical slope of $\alpha > 1$, which is substantially higher than the percentage found in the “red” (26%) “blue” (13%) SDSS samples. This demonstrates that our mid-IR selection criteria tends to select both the low-reddening sources found in optical surveys, as well as a significant fraction of sources with high levels of optical reddening. We expect the dust obscured AGNs to exhibit a steeper power law index compared to less obscured AGNs, since some portion of the radiated luminosity from the central engine from the former is being absorbed by dust and re-radiated in the infrared.

Figure 1.15 shows there is also a strong correlation between $E(B - V)$ extinction and optical to infrared flux ratio (represented as $r - W1$), which is the result we would expect if the optical flux is heavily suppressed by dust and re-radiated in the IR. This shows that the optical to infrared flux ratio is a good measure of optical obscuration, consistent with what other papers in the literature have suggested (Fiore et al. 2008; Richards et al. 2006). Figure 1.16 shows that there is no significant correlation between $W1 - W2$ color and $E(B - V)$ extinction. This shows that while the $W1 - W2 > 0.8$ criterion is useful for identifying objects with potentially higher levels of optical obscuration, it does not indicate the degree of optical extinction that is actually present. That is, this selection criteria selects AGNs with a wide range of obscuration levels, but it is distinct from other optical AGN selection methods in that it is unbiased against heavily reddened objects.

We find that there is no apparent correlation between redshift and $E(B - V)$ extinction. Any trend between the two would indicate that dust fraction evolves over time, which would be an important clue in constraining how AGNs evolve with time and whether obscuration is just a temporary phase in AGN evolution. Other papers have suggested that there should be higher degrees of obscuration at high z due to increased molecular gas fraction in high z galaxies (Daddi et al. 2007; Tacconi et al. 2010). The absence of a trend between the two might suggest that other factors (ex. dust distribution and orientation) play a role in determining how obscuration manifests in the optical regime, although this result could be impacted by selection effects due to our mid-IR color criteria and the 20% of AGNs for which we had no redshifts.

1.4.5 Bolometric luminosity estimates

For obscured AGNs, the bolometric luminosity of AGNs is generally inferred from the [OIII] emission line luminosity $L_{[\text{OIII}]}$ (Heckman et al. 2004; Malkan et al. 2017), since optical extinction prevents us from reliably using bolometric corrections to the observed optical luminosity. However, since strong [OIII] lines only appear within a subset of our DEIMOS sample, we instead use SEDs to estimate the bolometric luminosity. For objects with high levels of optical extinction, the short wavelength end of the SED converges rapidly to zero. The largest uncertainty in estimating the bolometric luminosity lies in the far-IR contribution of the SED. Since the templates in Assef et al. (2010) do not extend beyond 30 microns, it is difficult to ascertain if we can make a reasonable estimate how much of the bolometric luminosity is represented by emission at $< 30 \mu\text{m}$.

As a very rough estimate of the fraction of L_{bol} represented by the $< 30 \mu\text{m}$ (i.e. the wavelength range spanned by our SED fits) and $> 30 \mu\text{m}$ portions of the SED, we estimate the IR $> 30 \mu\text{m}$ emission using the AGN templates provided by Mullaney et al. (2011), which captures the far-IR peak of the SED out to $\sim 1000 \mu\text{m}$. The two sets of templates overlap in the $\sim 5\text{-}20 \mu\text{m}$ wavelength range, and we scale the far-IR AGN templates such that the average flux in this mid-IR range is equal to that of our SED fit. Integrating over the combined templates, we find that the far-IR portion of the SED at $> 30 \mu\text{m}$ typically contributes anywhere from $\sim 50\text{-}90\%$ of the bolometric luminosity. In other words, $L_{<30\mu\text{m}}$ typically only underestimates L_{bol} by a factor of

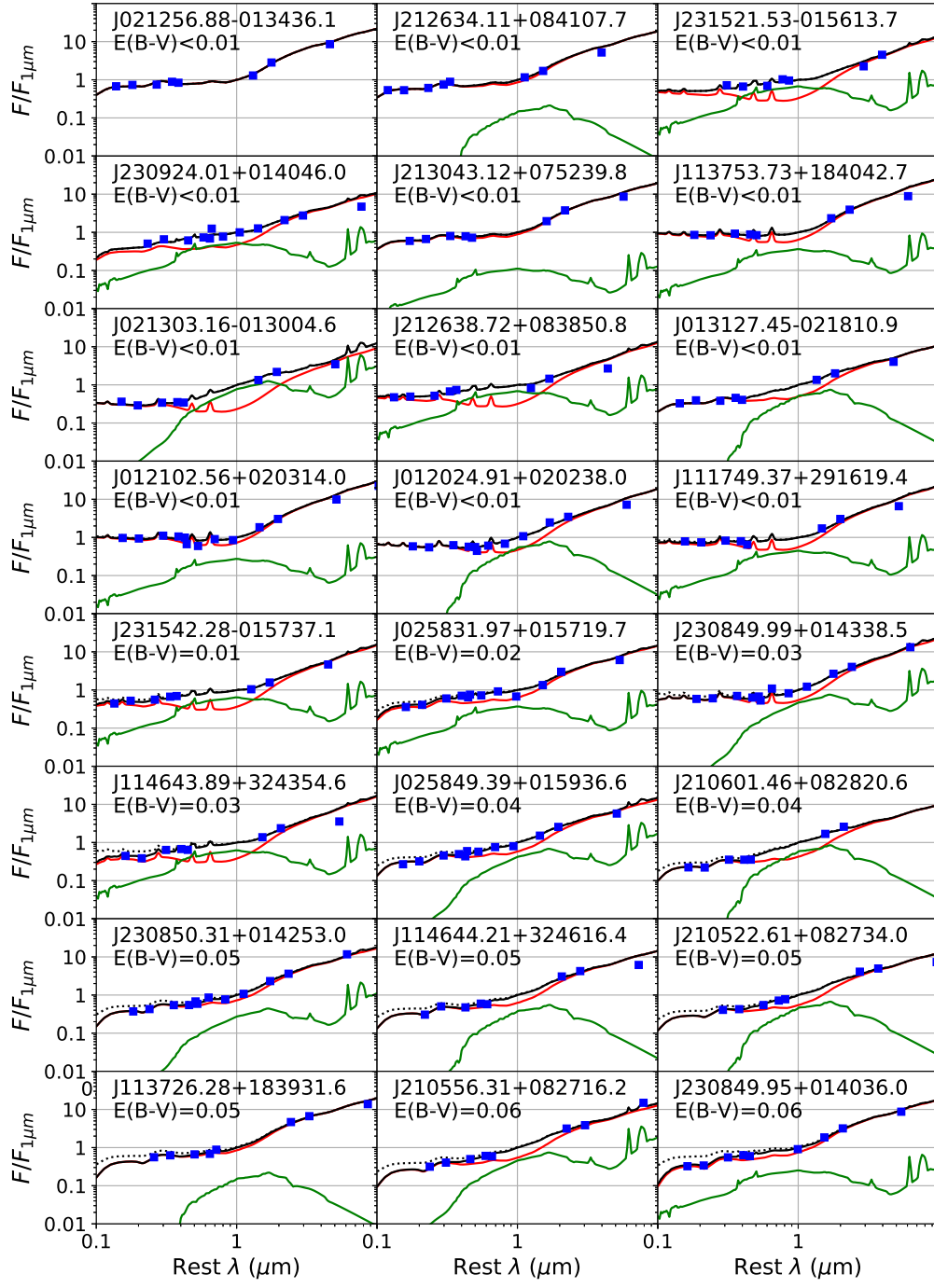


Figure 1.11: SED fits of the AGNs in the DEIMOS sample, arranged in order of increasing $E(B - V)$ extinction. Blue points represent photometry from *WISE*, *SDSS*, and *UKIDSS* (when available). The red and green curves show the AGN and host galaxy templates respectively, which sum to the black curve. The dotted curve shows the fit without extinction applied. The SEDs are normalized with respect to the flux at $1\mu\text{m}$.

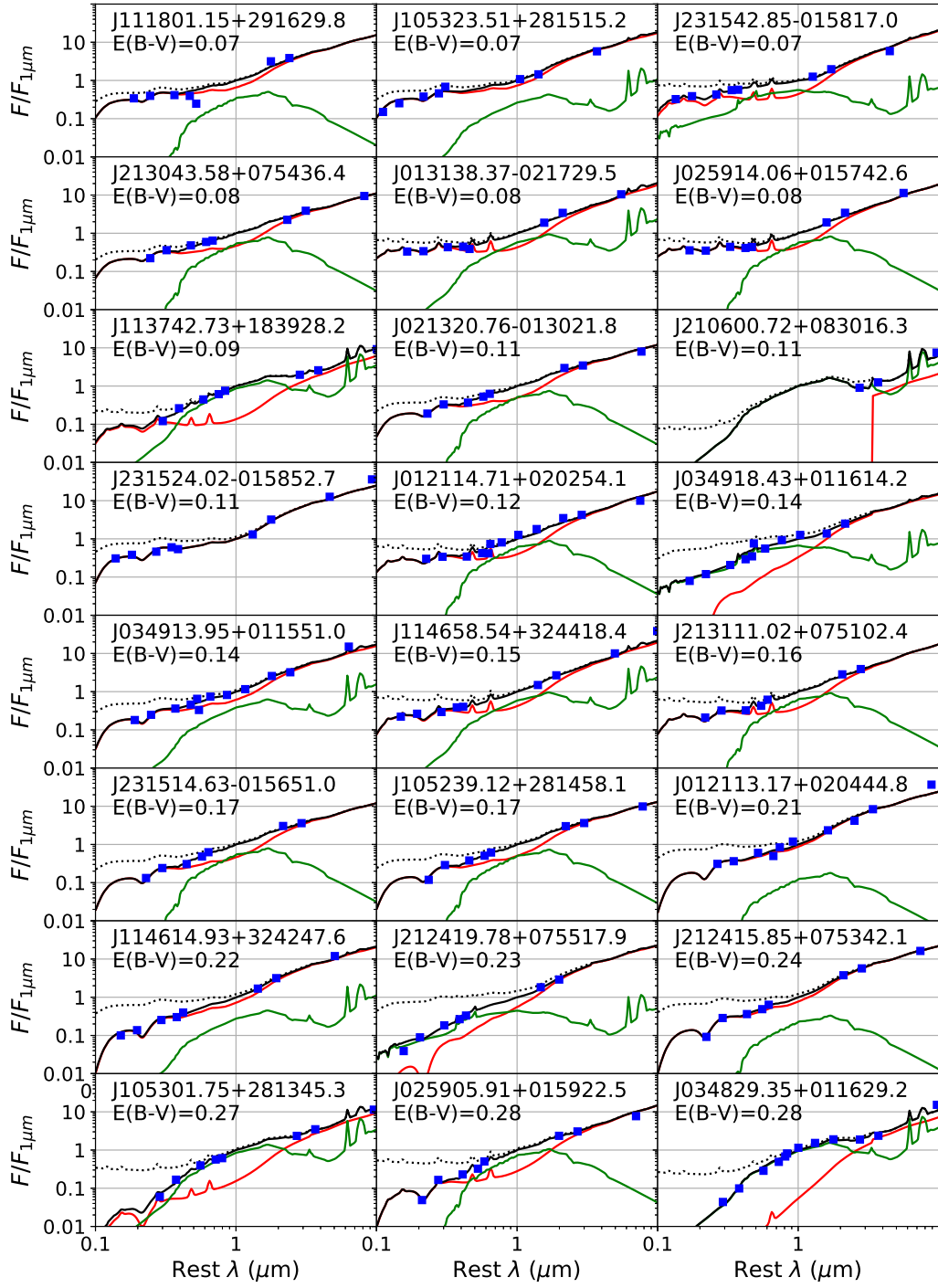


Figure 1.12: SED fits of the AGNs in the DEIMOS sample, arranged in order of increasing $E(B-V)$ extinction (continuation of Figure 1.11).

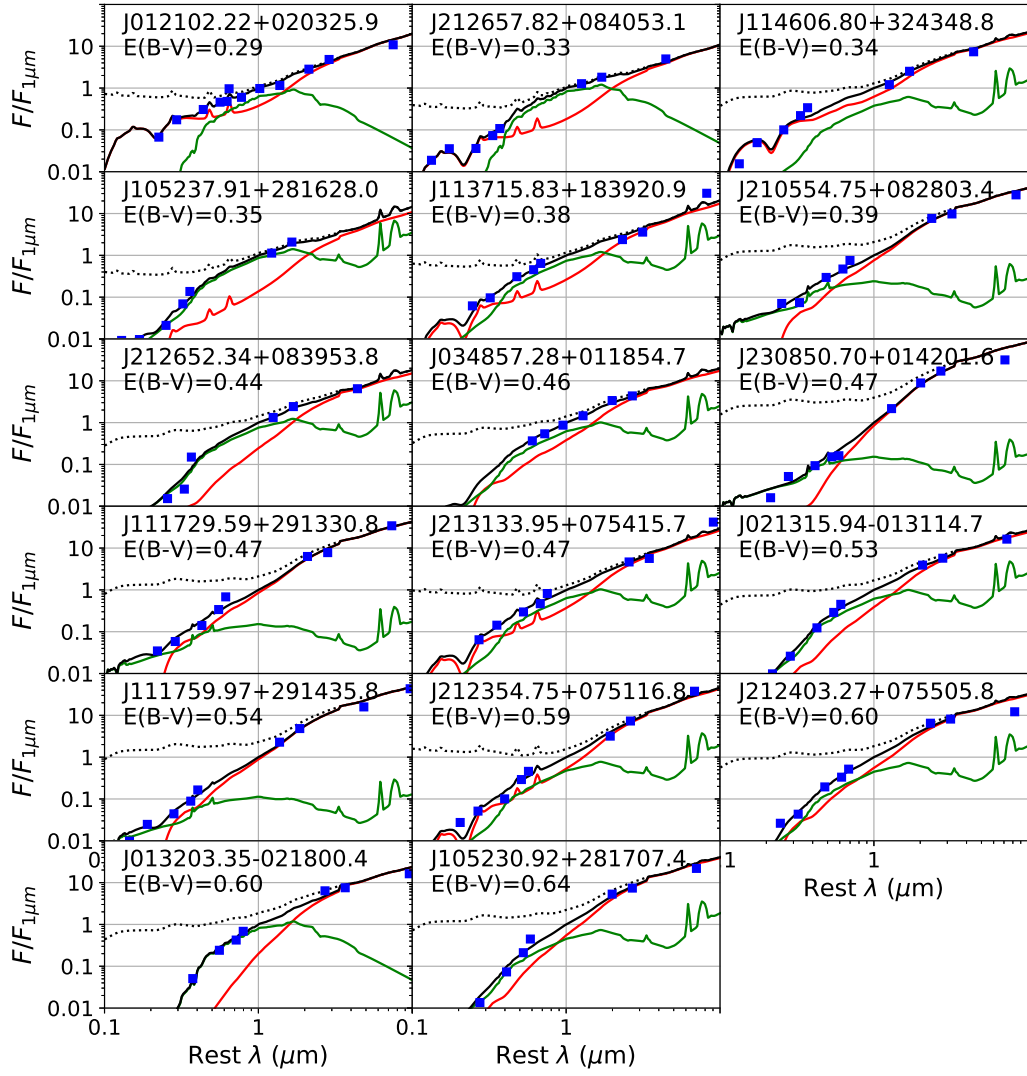


Figure 1.13: SED fits of the AGNs in the DEIMOS sample, arranged in order of increasing $E(B - V)$ extinction (continuation of Figure 1.12).

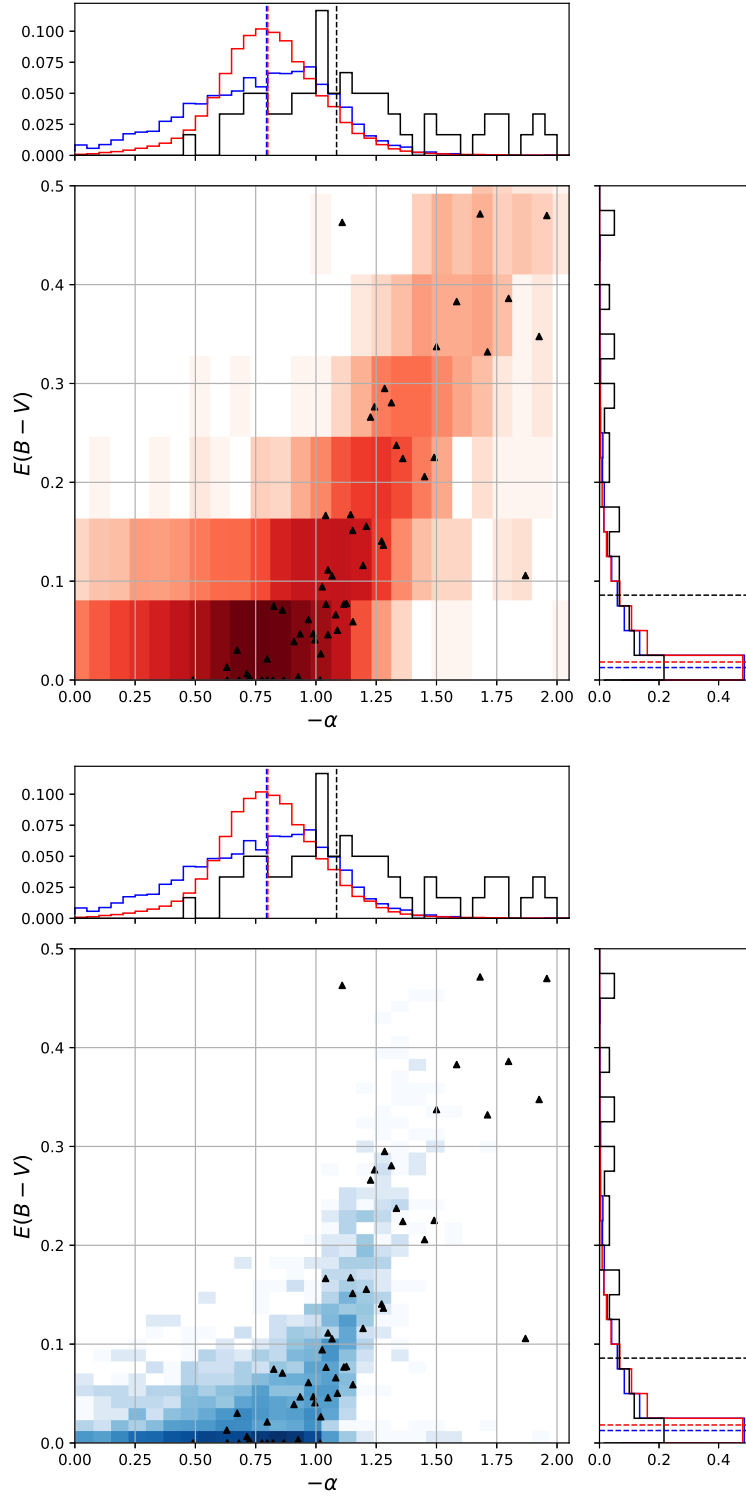


Figure 1.14: $E(B-V)$ extinction plotted against the optical power law index. The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue) and our *WISE* -selected DEIMOS AGNs (black triangles).

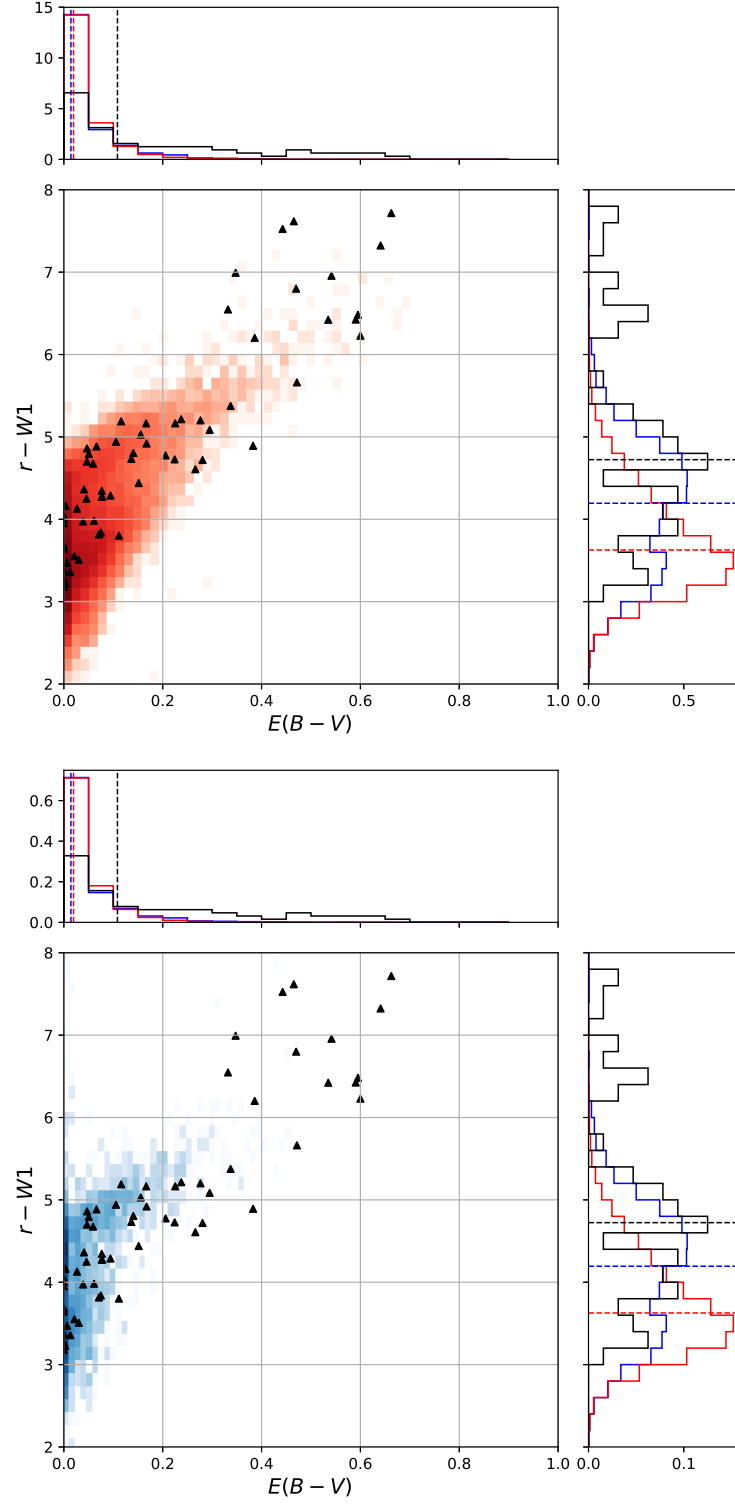


Figure 1.15: Optical to mid-IR flux ratio ($r - W1$) plotted against $E(B - V)$ extinction. The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue) and our *WISE* -selected DEIMOS AGNs (black triangles).

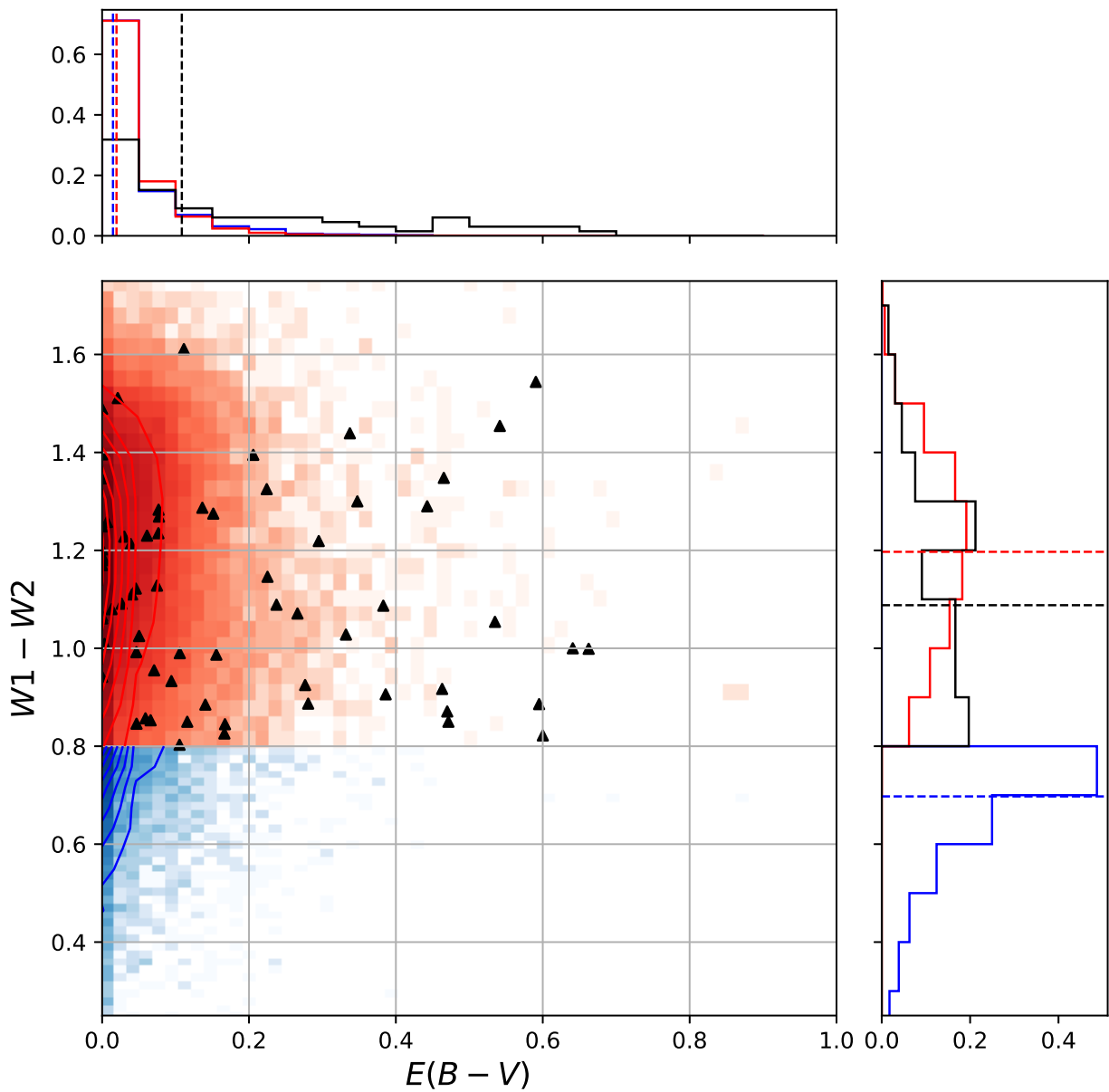


Figure 1.16: $W1 - W2$ WISE colors plotted against $E(B - V)$ extinction. The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue) and our WISE-selected DEIMOS AGNs (black triangles).

less than an order of magnitude, and is at the very least a reasonable order of magnitude estimate and lower limit for L_{bol} . We obtain $L_{<30\mu\text{m}}$ by integrating over the extinction corrected models derived from the SED fits.

Of course, this rough estimate assumes that the far-IR emission of all the AGNs is reasonably well approximated by the same far-IR template, or that the bolometric correction is the same for all AGNs. This is probably not realistic, since we would expect redder AGNs (particularly those selected by the *WISE* selection criteria) with substantial amounts of dust to have higher IR luminosities. This would cause the discrepancy between $L_{<30\mu\text{m}}$ and L_{bol} to be even larger. In the absence of far-IR photometry, it's difficult to quantify this directly through SED fitting. Spinoglio et al. (1995a) finds that L_{bol} is most closely proportional to the $12\mu\text{m}$ luminosity, and we use the relation given therein to estimate L_{bol} from the $L_{12\mu\text{m}}$ value interpolated from the SED fits:

$$\log L_{12\mu\text{m}} = 1.09 \log L_{\text{bol}} - 5.19. \quad (1.4)$$

Figure 1.17 shows that $L_{<30\mu\text{m}}$ typically only differs from L_{bol} within a factor of ~ 2 or less, which is consistent with our own SED estimates. For consistency, we use Equation 1.4 as our definition of L_{bol} for the remainder of this paper.

Figure 1.18 shows L_{bol} plotted against redshift. The trend between L_{bol} and z demonstrates that the sample is flux limited, and that the most luminous objects are rarer (i.e. found in larger volumes) due to the AGN luminosity function. Figure 1.19 shows that there is a correlation between L_{bol} and the optical power law index. This is consistent with the finding in Dietrich et al. (2002) that the mean UV-IR slope is a function of luminosity. While the SDSS AGNs show a slight trend, the AGNs from the DEIMOS sample seem to deviate significantly from this. The DEIMOS sample contains a larger fraction of AGNs with higher degrees of obscuration (which produces steeper optical power laws), and these objects are perhaps not well represented in large-scale surveys such as SDSS due to their faintness. It is possible that this apparent correlation between power law slope and luminosity only appears in flux-limited surveys in which highly obscured objects are not included to any significant extent.

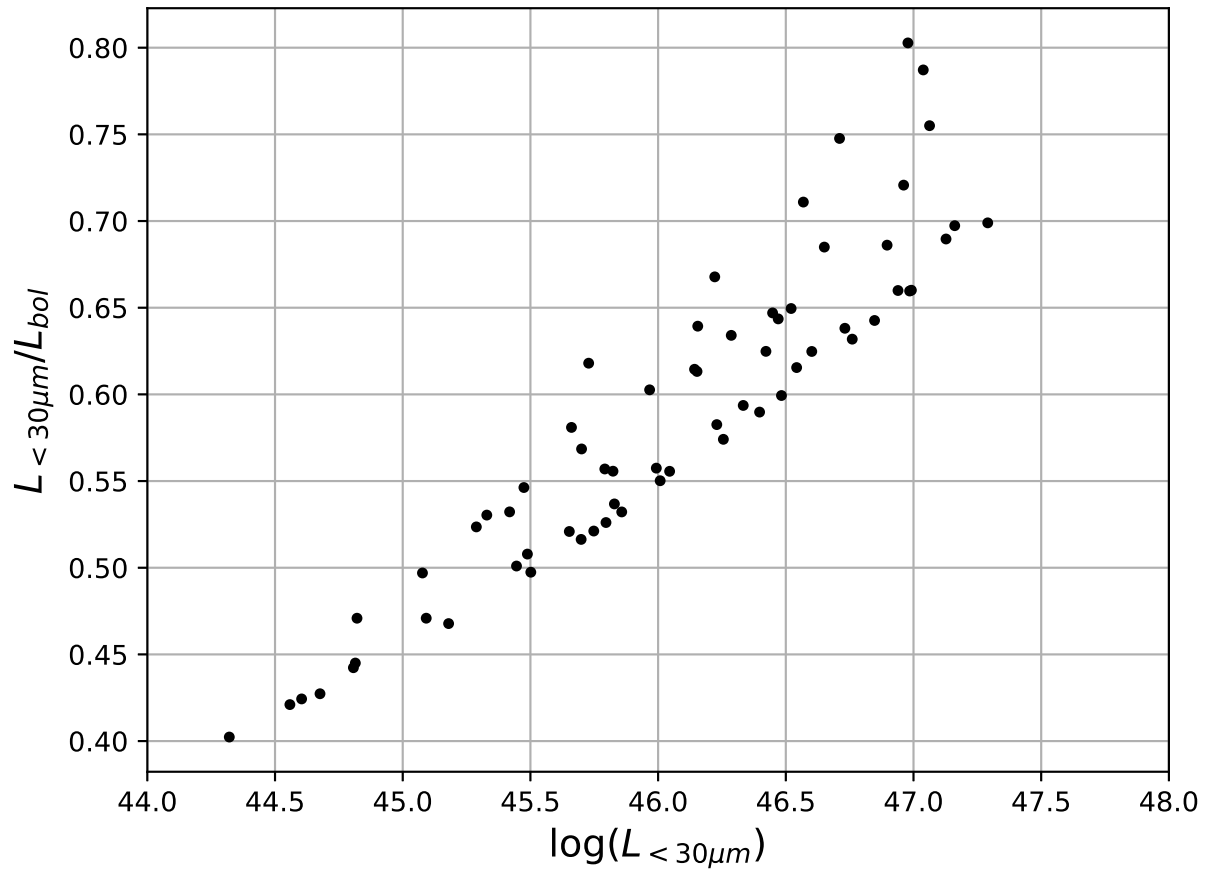


Figure 1.17: $L_{30\mu m}/L_{bol}$ as a function of $\log(L_{30\mu m})$ for our *WISE* -selected DEIMOS AGNs.

Figure 1.20 shows a scatterplot of $\log(L_{\text{bol}})$ and $\log(M_{\text{BH}})$ of our DEIMOS sample and AGNs from the SDSS DR7 catalog for which BH mass measurements are available. There is not a well defined correlation between the two quantities as the scatter is relatively large, but the L_{bol} and M_{BH} values of our DEIMOS AGNs fall generally within the locus occupied by the SDSS AGNs. Since we were able to measure black hole masses for only a subset of the DEIMOS AGNs, the DEIMOS AGNs in Figure 1.20 is a subset of the points shown in Figure 1.19. We note that the FWHM values used to calculate M_{BH} in Eq. 1.1 generally tend to be around a constant value of ~ 4000 km/s, so M_{BH} is mostly determined by the value of L_{λ} . In Figure 1.20 we plot contours of constant FWHM to illustrate this relation. All the samples generally follow the slope of these constant FWHM contours, suggesting that M_{BH} is largely determined by the luminosity.

These plots show that the AGN samples are generally consistent with each other and don't appear to have any notable differences in terms of how the optical and mid-IR luminosities relate to other physical properties. A significant fraction of the total luminosity lies in the far-IR, but unfortunately our DEIMOS sample of AGNs does not appear in far-IR catalogs such as AKARI or Herschel. The estimated peak far-IR flux density (based on far-IR SED templates) of our DEIMOS sources are ~ 0.1 Jy or less, which is just below the detector limits of Herschel SPIRE (~ 0.1 Jy for the 250/350/550 μm bands) and AKARI (~ 0.5 Jy for 90 μm band). Indeed, our targets are not detected in either of those catalogs.

1.4.6 Eddington ratios

The Eddington luminosity represents the maximum possible luminosity of an AGN powered by spherical accretion (for stable, equilibrium conditions) and is given by $L_{\text{Edd}} = 1.26 \times 10^{38} (M_{\text{BH}}/M_{\odot})$ erg/s (Rees 1984). However, an AGN's luminosity can exceed this value if the accretion is not spherically symmetric (Begelman 2002). Since the total luminosity is proportional to the black hole accretion rate, the Eddington ratio is also an indirect measure of accretion. The Eddington ratio redshift distribution can offer insights into the fueling mechanism and evolution of obscured AGNs. Kollmeier et al. (2006) shows that the Eddington ratio is nearly constant ($L_{\text{bol}}/L_{\text{Edd}} \sim 0.25$) across a range of z , suggesting that accretion flows around black holes are self-regulating. On the

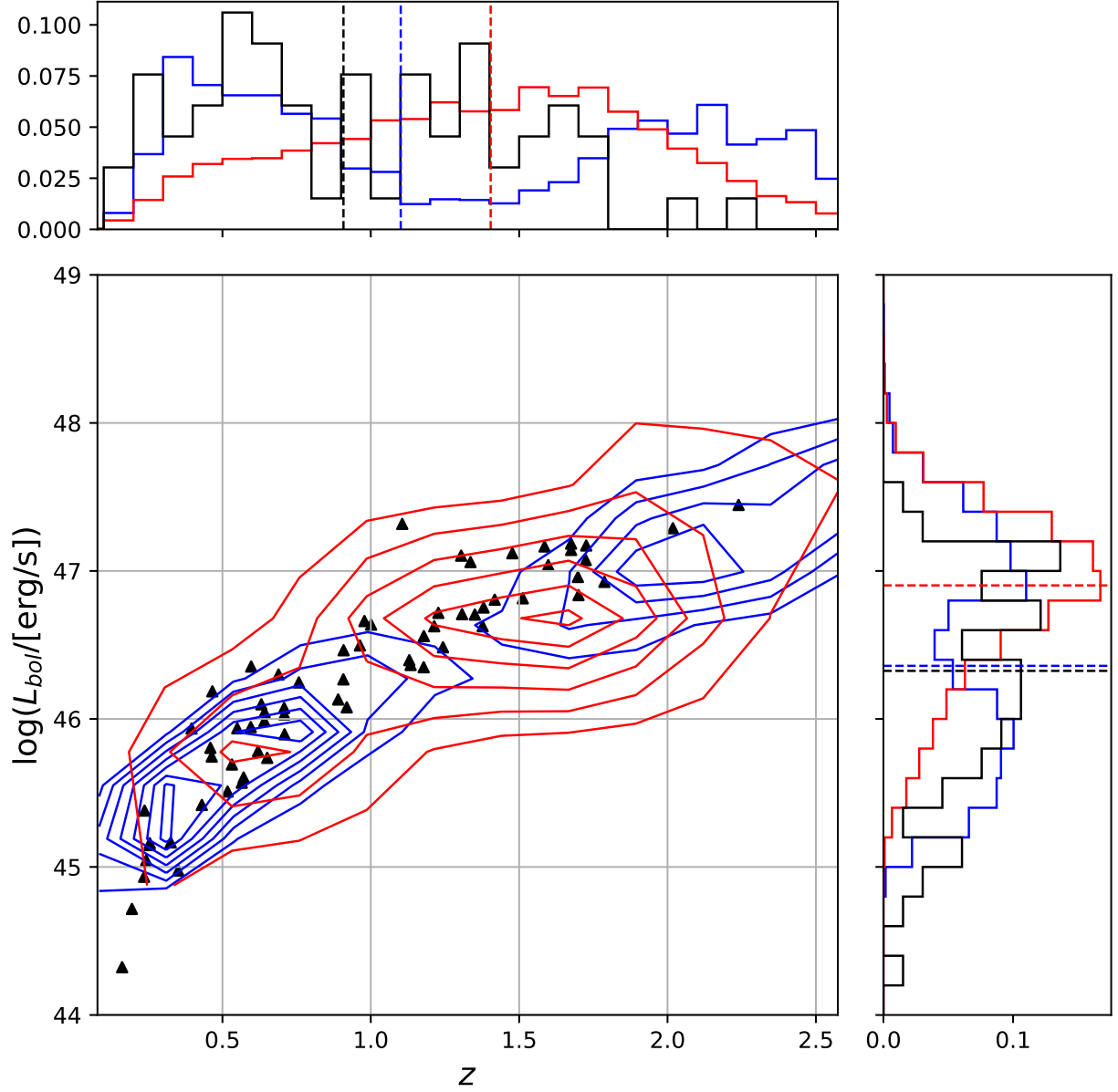


Figure 1.18: L_{bol} as a function of z . The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue) and our *WISE*-selected DEIMOS AGNs (black triangles). Contours represent 2d-histogram bins.

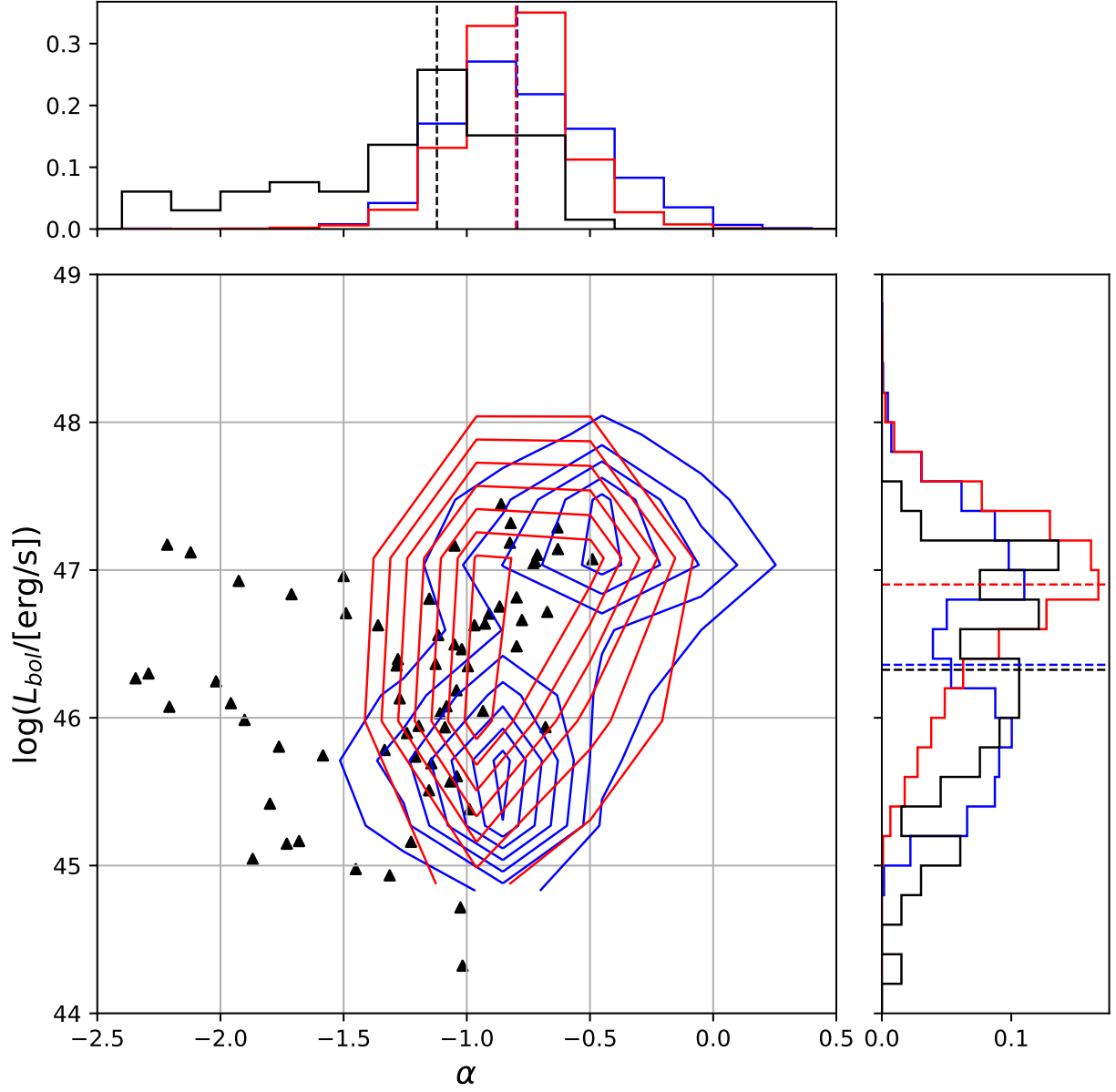


Figure 1.19: L_{bol} as a function of optical power law index α . The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue) and our *WISE*-selected DEIMOS AGNs (black triangles). Contours represent 2d-histogram bins.

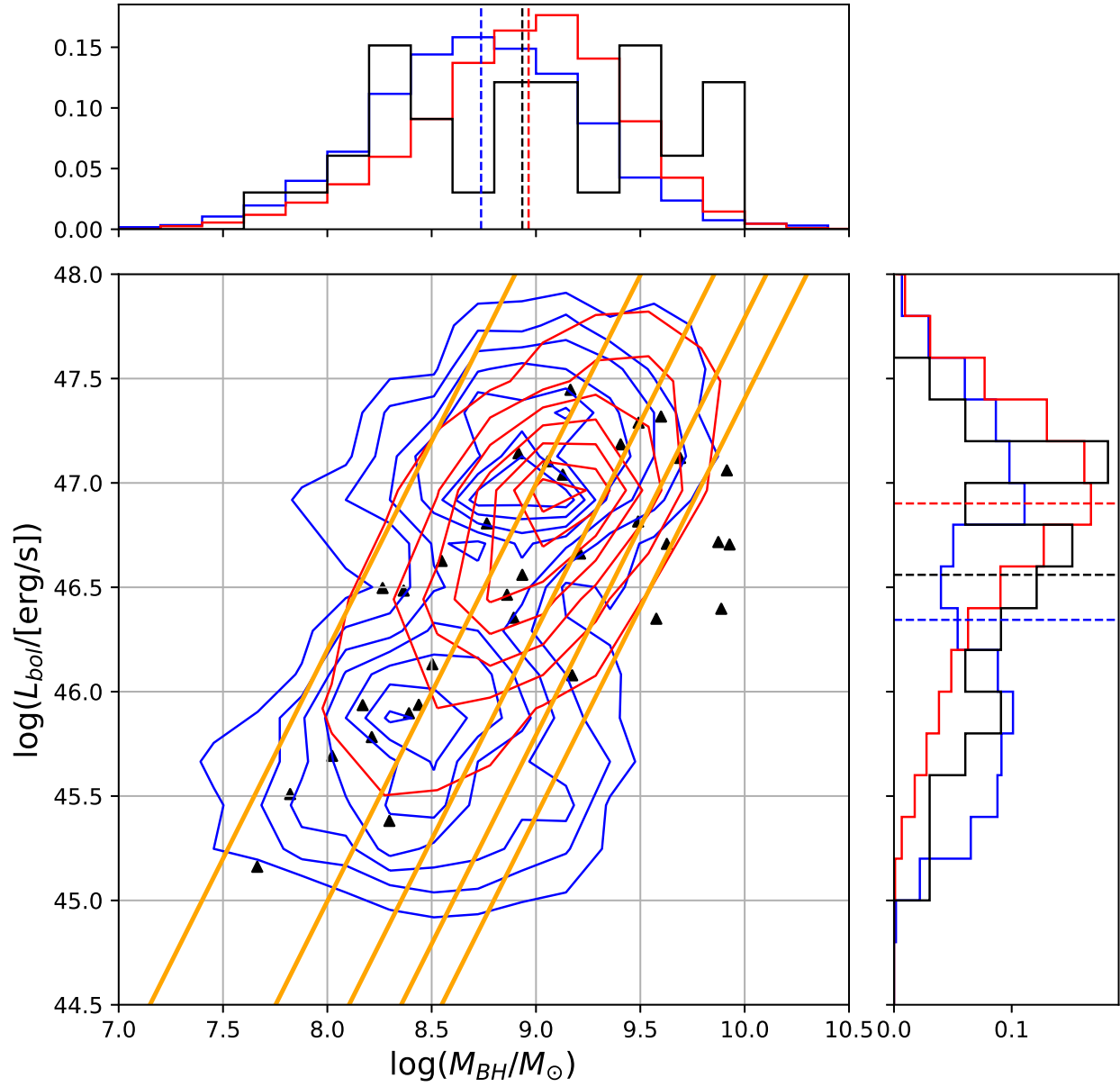


Figure 1.20: L_{bol} plotted against virial black hole mass. Red and blue contours represent the SDSS AGN samples with $W1 - W2 > 0.8$ and $W1 - W2 < 0.8$, respectively. Black triangles correspond to our DEIMOS AGN sample. The orange contours show the relation in Eq. 1.1 with the FWHM held constant (from left to right: 1000, 2000, 3000, 4000, 5000 km/s). Contours represent 2d-histogram bins.

other hand, Netzer et al. (2007) suggests the Eddington ratio distribution varies as function of both M_{BH} and z , which may be more indicative of large scale dynamical disturbances.

In the top plot of Figure 1.21, we show L_{bol}/L_{Edd} as a function of z . The blue SDSS sample seems to show a slightly broader distribution towards the lower tail end of the Eddington limit distribution, which is probably the result of the lower luminosity AGNs present in that sample. Roughly 30% of the objects in the SDSS samples show super-Eddington luminosities (in comparison Woo & Urry (2002) finds that only $\sim 10\%$ of the AGNs in their sample are super-Eddington). This high percentage of super-Eddington AGN is likely a result of the flux-limited nature of our samples, in which particularly bright objects are over-represented at higher redshift. The L_{bol}/L_{Edd} values for our DEIMOS AGNs are listed in Tables 1.1, 1.2, and 1.3.

The bottom plot of Figure 1.21 shows a linear regression of the trend between Eddington ratio and redshift. The SDSS samples show a significant non-zero slope (with the red $W1 - W2 > 0.8$ sample being steeper). The error on the slope for the DEIMOS sample is too large to determine if the non-zero slope is significant, but given that the SDSS AGNs show such a strong trend we would expect the DEIMOS AGNs to show similar behavior. Since we are using flux-limited samples, these slopes do not necessarily indicate an increase in accretion activity over time. L_{Edd} directly scales with M_{BH} , and as we've demonstrated in Figure 1.20 M_{BH} is primarily determined by the continuum luminosity ($M_{BH} \propto L^{1/2}$) rather than the emission line FWHM. If the continuum luminosity scales directly with L_{bol} , then implies that the Eddington ratio is roughly proportional to $L_{bol}^{1/2}$. In other words, we are preferentially sampling the most luminous AGNs at high redshift. If we were to include the fainter AGNs at high redshift in these samples, then this slope would likely be more shallow. Given this selection effect, we are unable to make any definitive statements about the redshift evolution of the Eddington ratio with these data.

Warner et al. (2004) mentions that there are certain correlations between the equivalent width of certain line species and the Eddington ratio. Figure 1.22 shows the equivalent width plotted against the Eddington ratio for MgII and $H\beta$, and we find similar results. The DEIMOS sample shows a strong anti-correlation for MgII, while the SDSS samples do not show such a strong relationship. Neither the DEIMOS nor SDSS samples show any significant trend for $H\beta$.

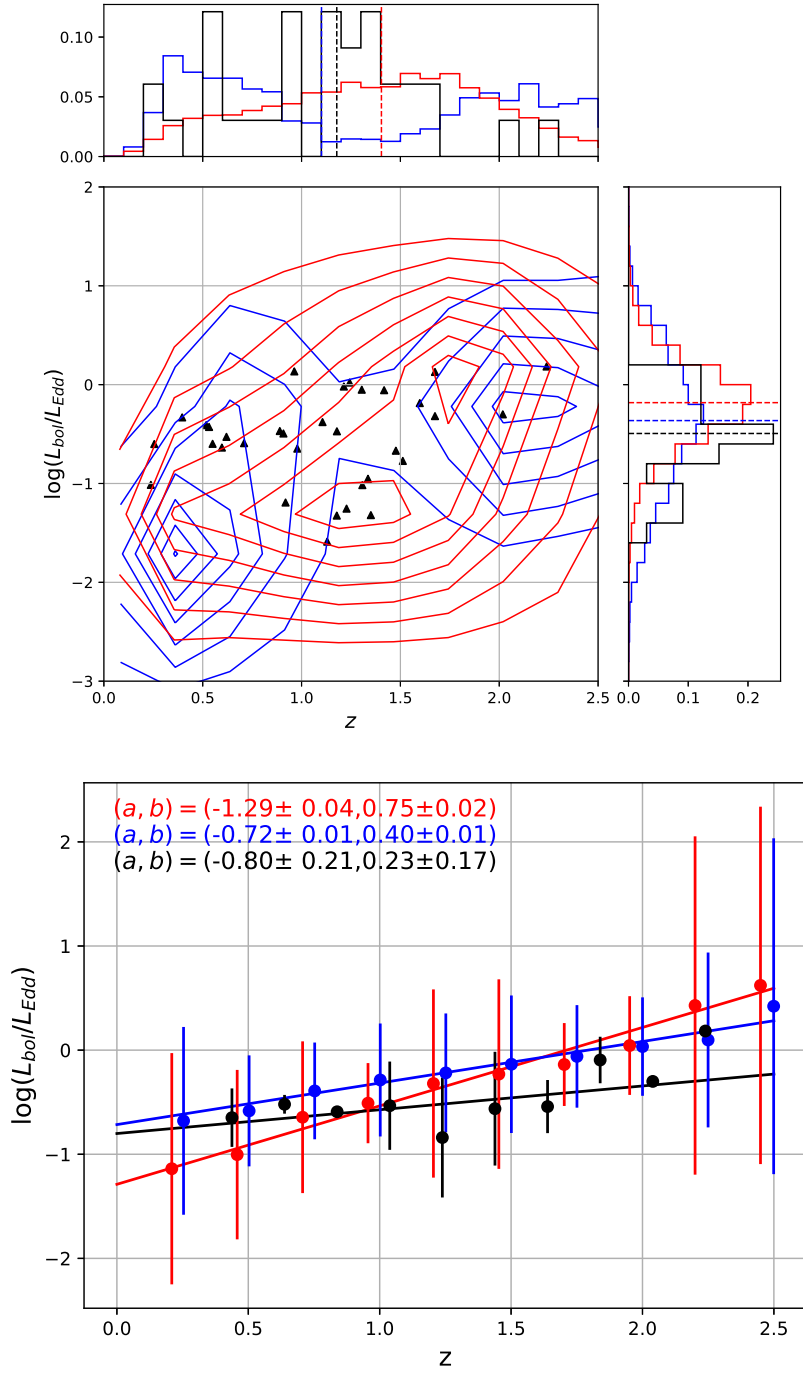


Figure 1.21: [Top] Eddington ratio plotted against redshift. The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue) and our $WISE$ -selected DEIMOS AGNs (black triangles). Contours represent 2d-histogram bins.[Bottom] Linear regression fits of the form $\log(L_{\text{bol}}/L_{\text{Edd}}) = a + bz$, with binned averages and $1-\sigma$ error bars.

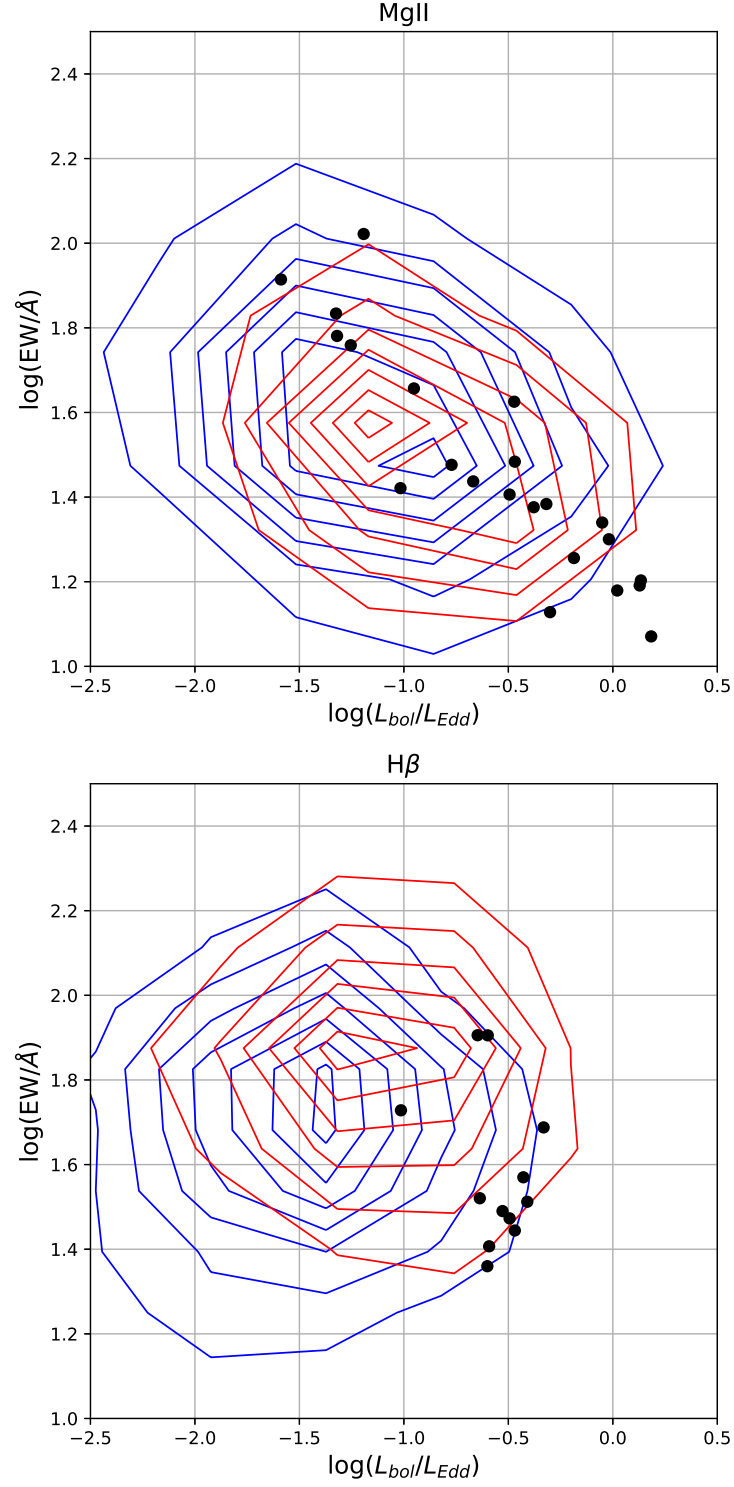


Figure 1.22: Equivalent width plotted against Eddington ratio for MgII and H β . The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue) and our *WISE*-selected DEIMOS AGNs (black triangles). Contours represent 2d-histogram bins.

1.4.7 Baldwin Effect

Baldwin (1977) shows that there is an anti-correlation between the equivalent width of CIV and its corresponding continuum luminosity. Figures 1.23, 1.24, and 1.25 show the monochromatic continuum luminosities plotted against equivalent width for CIV, MgII, and H β respectively. Since our DEIMOS sample did not contain a significant number of CIV emission lines, we have omitted those from the plot. As expected, the correlation between equivalent width and continuum luminosity is more apparent for lines with higher ionization energies. In Figure 1.24, we can see that our DEIMOS sample tends to have smaller MgII equivalent widths compared to the SDSS samples.

1.5 Conclusions

We have selected a sample of potentially dust obscured AGNs from the mid-IR *WISE* catalog using a $W1 - W2 > 0.8$ mid-IR color cut, and obtained spectra using the DEIMOS spectrograph. We have identified 66 targets (80% success rate) to be AGNs based on their spectral features with a median redshift of $z \sim 1$. Our observations show that the $W1 - W2 > 0.8$ color cut described in Stern et al. (2012) is indeed good for identifying AGNs with varying degrees of optical obscuration. Since a large number of our AGNs observed with DEIMOS were not previously classified as AGNs by SDSS, this suggests that there is an enormous population of dusty AGNs that are excluded by these large-scale surveys. Using the SDSS DR7 quasar catalog as a control sample, and dividing this into two samples using the $W1 - W2 > 0.8$ color cut, we also show that one of the largest differences between these two samples is their redshift distributions. This is a direct result of *WISE* mid-IR color selection preferentially selecting redder galaxies around the peak of AGN activity around $z \sim 1.5$. This color criterion is thus suited for sampling the era in which AGNs contribute the most to the cosmic X-ray and IR backgrounds.

Using H β and MgII to measure virial BH masses, we find that the redder SDSS AGN sample has a slightly higher median $\log(M_{BH}/M_{\odot})$ compared to the bluer sample by ~ 0.25 dex, but the DEIMOS sample has a BH mass distribution that roughly coincides with the two SDSS popula-

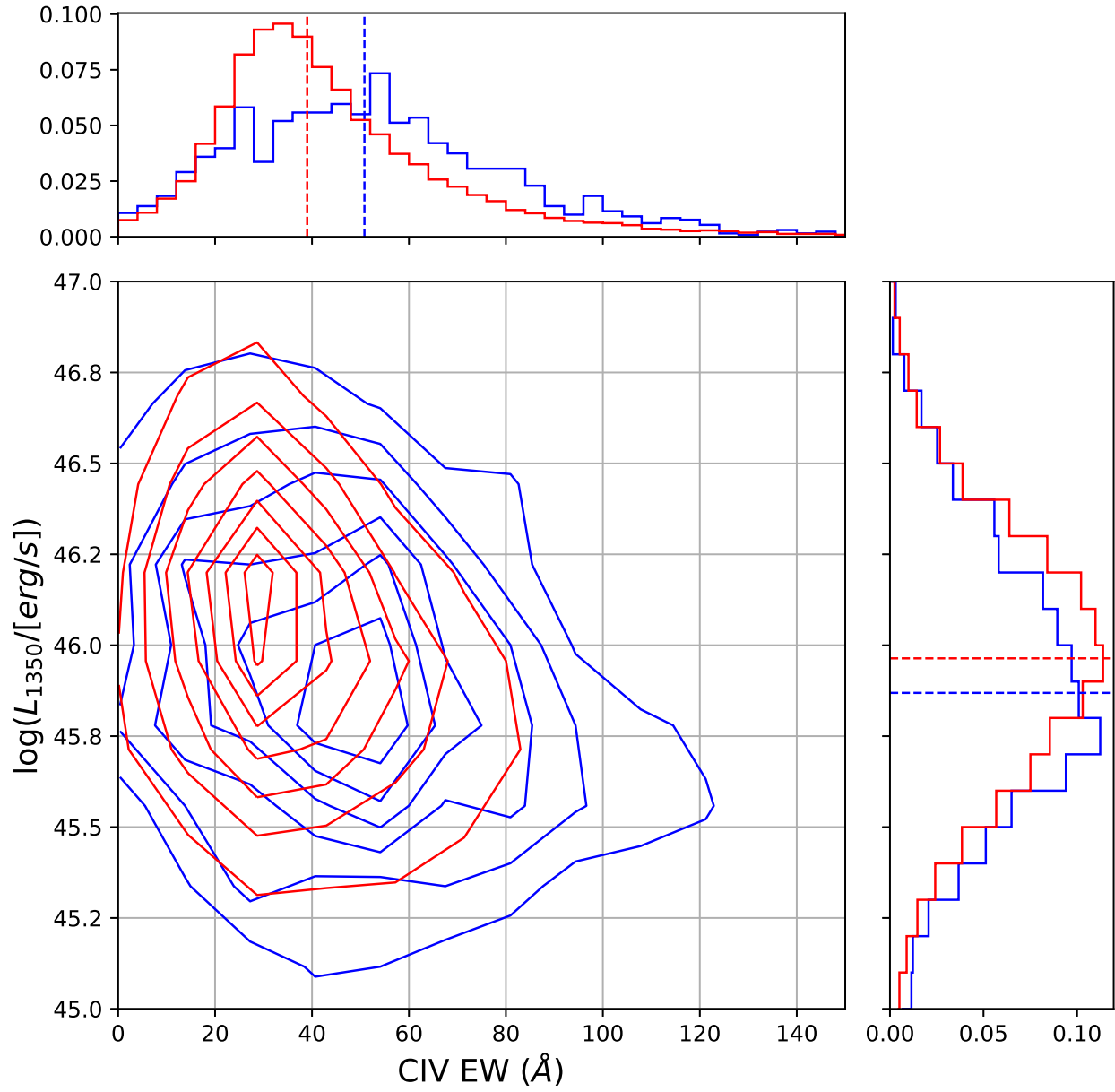


Figure 1.23: 1350 $\text{\AA}$ continuum luminosity vs. equivalent width for CIV. The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue). Since only two of our DEIMOS spectra contained clear CIV emission lines, we exclude these from this diagram. Contours represent 2d-histogram bins.

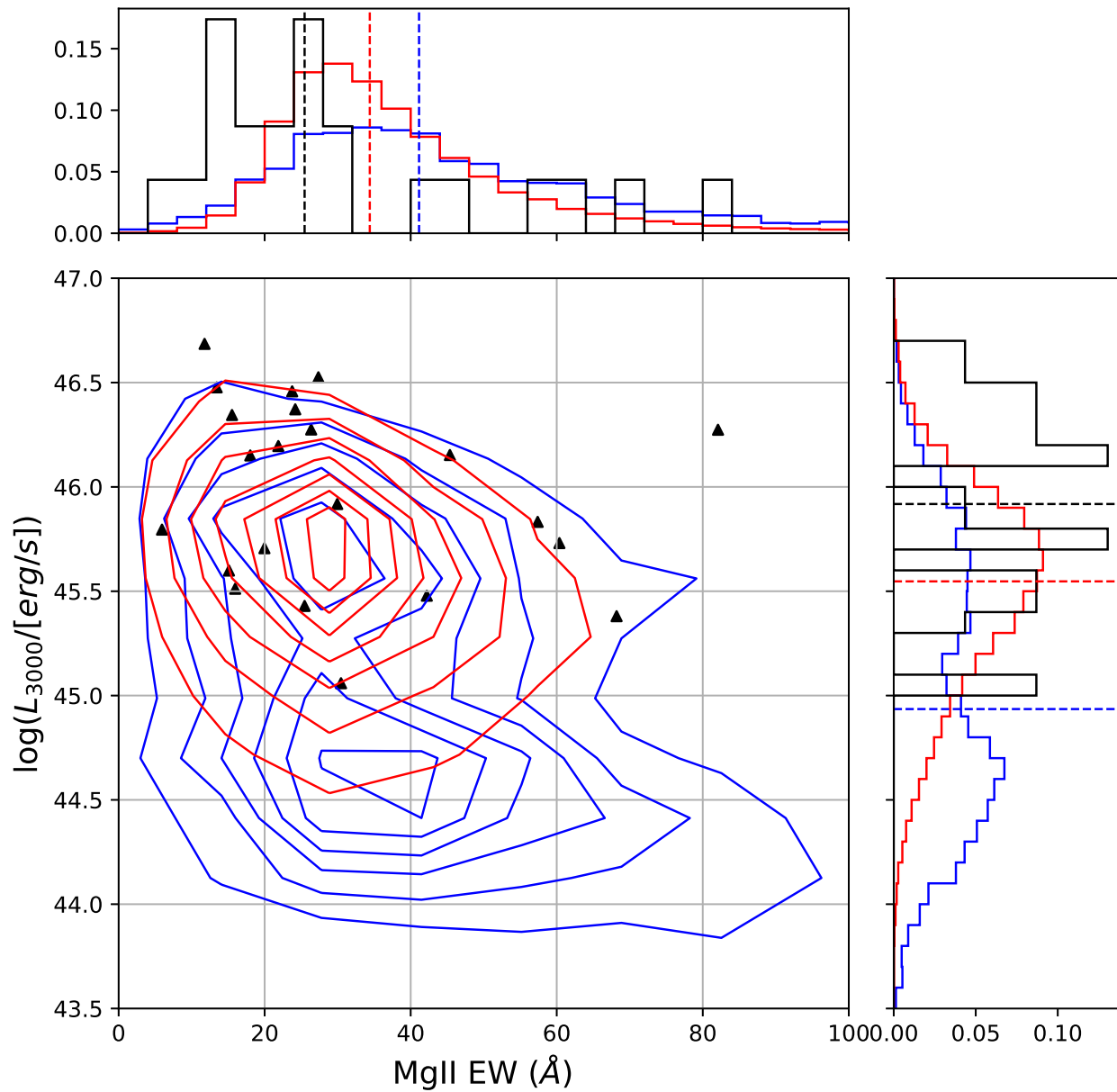


Figure 1.24: 3000 Å continuum luminosity vs. equivalent width for MgII. The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue) and our *WISE*-selected DEIMOS AGNs (black triangles). Contours represent 2d-histogram bins.

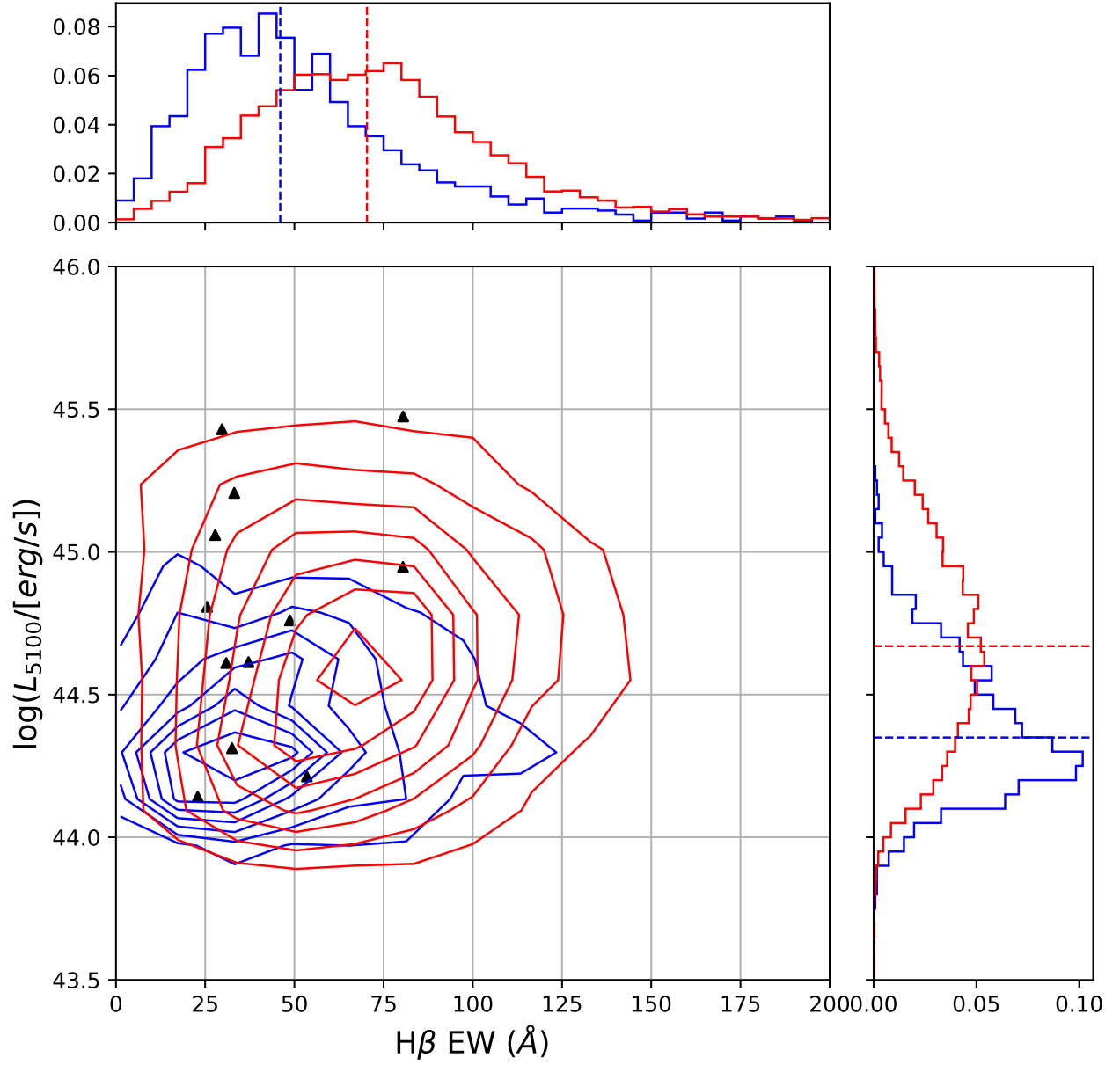


Figure 1.25: 5100 $\text{\AA}$ continuum luminosity vs. equivalent width for $H\beta$. The colors indicate SDSS AGNs with $W1 - W2 > 0.8$ (red), $W1 - W2 < 0.8$ (blue) and our *WISE*-selected DEIMOS AGNs (black triangles). Contours represent 2d-histogram bins.

tions. There appears not to be any obvious physical difference in BH mass that is correlated with obscuration. From fitting these virial BH masses against the $H\gamma$ equivalent width in our DEIMOS sample, we also find that $H\gamma$ shows a strong enough correlation to be useful as a potential BH mass indicator. However, our small sample size makes it difficult to accurately determine fit parameters for Eq. 1.1, so there needs to be a larger set of $H\gamma$ measurements for this relationship to be better established. Having a secondary estimator for BH mass is useful in the event that lines such as $H\beta$ and $MgII$ are not easily measured due to issues such as blending and atmospheric absorption.

Using the low-resolution spectral templates presented in Assef et al. (2010), we have fitted the rest frame SEDs of these AGNs up to $30\ \mu m$. In the absence of spectroscopy, SED fitting is a powerful tool for identifying objects as AGNs. The DEIMOS sample shows a significantly broader and higher range of $E(B - V)$ values compared to the SDSS samples, showing that specific, targeted surveys are necessary in order to find the most highly obscured objects. In addition, the $r - W1$ values of the DEIMOS AGNs show a strong correlation with $E(B - V)$, which shows that this optical to IR flux ratio is a good indicator of optical obscuration. This demonstrates that in addition to the $W1 - W2$ color cut, $r - W1$ color is also a good metric to use in order to select galaxies based on their *degree* of optical obscuration. We also find that there is no visible correlation between $E(B - V)$ and z , which is at odds with the idea that higher redshift galaxies tend to have a higher gas and dust content.

Estimating bolometric luminosities is difficult without a complete wavelength range of photometric data, but we've shown that SED modeling and scaling relations (ex. between $L_{12\mu m}$ and L_{bol}) can yield reasonable estimates. More detailed modeling using far-IR photometry is required in order to more precisely constrain the relationship between dust content, obscuration, and the far-IR fractional contribution to the L_{bol} . This is especially crucial when comparing the luminosity properties of different populations of AGNs, since redder AGNs generally tend to have higher IR luminosities, and population differences may not be apparent if the far-IR luminosity is excluded. Quantifying this difference requires obtaining SEDs with adequate far-IR photometry that captures the IR peak out to a few hundred microns, but even the largest far-IR sky surveys (ex. AKARI, Herschel, etc.) to date are not sensitive enough to detect the AGNs that we observed with

DEIMOS. The flux-limited nature of our survey makes it difficult to draw conclusions regarding the luminosity and accretion activity of AGNs at high redshift, since most of the fainter objects are not represented in our sample. Future work should account for these selection effects in order to properly understand the redshift evolution of black hole accretion.

In this paper, we have primarily focused on the optical to mid-IR properties of obscured AGNs. Since these AGNs are dust obscured, this naturally leads to the question of how to characterize the physical properties of this dust, which predominantly produces emission in the mid to far-IR wavelengths. In a future paper, we intend to explore the dust properties for these obscured AGNs and how it relates to observable quantities (ex. photometry) by examining SEDs that includes the far-IR dust emission. We also intend to examine how the bolometric correction changes with mid-IR color and the presence of dust emission, since this is directly applicable to estimating bolometric luminosities for AGNs without far-IR photometry. In this paper, we have not made a distinction between the intrinsic reddening of an AGN and the reddening produced due to dust absorption and re-emission. These represent two different underlying physical scenarios, but it is difficult to definitively rule out which mechanism is responsible for producing the observed reddening. In order to better understand the population of AGNs which are being identified by mid-IR color criteria, we need reliable methods of observationally distinguishing between intrinsic and extrinsic reddening so that it is possible to make definitive statements regarding the dust content of these AGNs.

From these results, we have shown that the optical and IR photometry from SDSS and *WISE* are powerful in not only identifying obscured AGN candidates, but also their degree of optical obscuration. While large scale surveys such as SDSS have produced large AGN catalogs for statistical studies, the most highly obscured AGNs are not necessarily identified or included due to their lower optical fluxes and lack of spectroscopy. To obtain a more complete picture of the total AGN population and account for any “missing” AGNs, targeted spectroscopic observations need to be done in the future of highly obscured objects, which can be easily selected from publically available photometric catalogs.

CHAPTER 2

Far-IR dust properties of highly dust obscured AGNs from the AKARI and WISE all-sky surveys

The combination of the AKARI and WISE infrared all-sky surveys provides an unique opportunity to identify and characterize the most highly dust obscured AGNs in the universe. Dust-obscured AGNs are not easily detectable and potentially underrepresented in extragalactic surveys due to their high optical extinction, but are readily found in the WISE catalog due to their extremely red mid-IR colors. Combining these surveys with photometry from Pan-STARRS and Herschel, we use SED modeling to characterize the extinction and dust properties of these AGNs. From mid-IR WISE colors, we are able to compute bolometric corrections to AGN luminosities. Using AKARI's far-IR wavelength photometry and broadband AGN/galaxy spectral templates, we estimate AGN dust mass and temperature using simple analytic models with 3-4 parameters. Even without spectroscopic data, we can determine a number of AGN dust properties only using SED analysis. These methods, combined with the abundance of archival photometric data publically available, will be valuable for large-scale studies of dusty, IR-luminous AGNs.

2.1 Introduction

Galaxies that are optically faint but bright in the mid-IR tend to be high redshift, dusty galaxies (Hwang & Geller 2013; Dey et al. 2008; Yan et al. 2004; Toba & Nagao 2016). Due to their optical faintness, these dust-obscured galaxies (DOGs) are easily missed by optical galactic surveys, but are readily found in IR catalogs. These galaxies show heavy extinction in their spectra, as inferred from the Balmer decrement ($H\alpha/H\beta$) (Brand et al. 2007). IR luminous sources tend to dominate

the bolometric luminosity function of galaxies in the local universe (Soifer et al. 1986), and the most luminous sources are thought to be powered by active galactic nuclei (AGNs) (Sanders et al. 1988). Understanding the physical mechanisms underlying the emission from dusty galaxies and AGNs can help to determine their role in galaxy evolution.

Far-IR photometry is relatively sparse compared to photometry at shorter wavelengths, and it is difficult to get a complete picture of the physical properties of an AGN if we only have a portion of the full SED available. The far-IR emission from dusty galaxies can represent the bulk of the bolometric luminosity, but without far-IR data we need to rely on bolometric corrections to luminosity measurements at shorter wavelengths. Toba et al. (2017) and Mullaney et al. (2011) show that IR photometry can be used to reliably estimate total IR luminosity of a galaxy. However, even with monochromatic mid-IR luminosity measurements, bolometric estimates can be highly skewed due to the presence of mid-IR PAH features.

Additionally, targeted spectroscopic observations are highly time and resource intensive. The largest spectroscopic surveys represent only a small fraction of the objects contained in photometric surveys, and analyzing these spectroscopic data sets tends to be significantly more time-consuming compared to SED analysis. Even when spectroscopy is necessary to achieve certain science goals, we need to know *a priori* with a reasonably high level of confidence that our objects of interest (ex. AGNs with high dust content) are indeed the objects being targeted.

The all-sky coverage of WISE (Wright et al. 2010) and AKARI (Murakami et al. 2007) makes it possible to identify large samples of AGNs and examine their dust emission properties in the mid and far-IR (Mateos et al. 2012, 2013). The wavelength range spanned these photometric surveys also represent the bulk of the bolometric luminosity for dusty galaxies. Additionally the deep FIR sky data from the AKARI satellite combined with the longer wavelength coverage of Herschel (Pilbratt et al. 2010) allows us to study the full IR SED of dusty AGNs. Mid-IR color selection from photometric catalogs has been shown to identify AGNs with a high degree to completeness and reliability due to emission from heated dust grains (Stern et al. 2012; Hickox et al. 2007; Spinoglio & Malkan 1989). This is a significantly easier and more efficient method of identifying AGNs compared to using emission line diagnostics from spectroscopic data.

By using archival data to perform SED analysis, we can identify and analyze the physical properties of dust obscured AGNs without the additional effort required to perform spectroscopic analysis of these objects. With SED modeling, it is possible to quantify the degree of dust obscuration and understand the basic properties of the obscuring dust using archival data that is already publicly available. Dust modeling in the IR is complicated by the fact that dust emission is highly dependent on factors such as dust composition, emissivity, orientation, and distribution. However, we show that it is possible to describe the main IR dust components using relatively simple parametric models with a minimal number of parameters.

In this paper, we present our results of modeling the dust properties of obscured AGNs selected from the WISE and AKARI photometric catalogs. In Section 2.2, we discuss the photometric data sets that we use and AGN selection criteria. Section 2.3 describes the SED fitting using broadband galaxy and AGN templates from the UV to the far-IR. Section 2.4 discusses the distribution of the total integrated luminosity across the AGN SED and how bolometric corrections can be made to the integrated flux of shorter wavelength photometry. Section 2.5 outlines our procedure in modeling AGN dust temperatures and masses, and their relationships with different AGN properties. We summarize our conclusions in Section 2.6. Throughout this paper we assume a Λ CDM cosmology with the parameters $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 67.74$ km/s/Mpc.

2.2 Data and AGN selection

2.2.1 Photometric catalogs

The WISE catalog contains photometry of over 747 million objects in 4 MIR bands (3.4, 4.6, 12, and 22 μ m), with respective detection limits of 0.08, 0.11, 1, and 6 mJy in each band. We identify AGN candidates from the AllWISE data release (Mainzer et al. 2011; Wright et al. 2010) by applying a color cut across the first two WISE bands such that $W1 - W2 \geq 0.8$. This color selection criterion has been shown to select mid-IR AGN candidates to a high level of completeness and reliability (Stern et al. 2012), and includes both unobscured (type 1) and obscured (type 2) AGNs. WISE objects that satisfy $W1 - W2 \geq 0.8$ which have a sky density of 61.9 ± 5.4 AGN

candidates per square degree to a depth of $W2 \sim 15.0$ (the AllWISE catalog has a density of $\sim 18,000$ objects per square degree, averaged across the entire sky). The AllWISE catalog also contains entries from the 2MASS extended source catalog (Jarrett et al. 2000; Skrutskie et al. 2006), which provides J , H , and K band photometry when available.

There are a number of AGN selection criteria available in the literature, but we choose to use the Stern et al. (2012) color cut because it is less restrictive in the WISE color space and only uses the $W1$ and $W2$ bands. 83% of the objects in the WISE catalog contain a detection greater than 2σ in both the $W1$ and $W2$ bands (which are more sensitive compared to $W3$ and $W4$), while only 3.5% have detections in all four WISE bands. The color criteria described in Jarrett et al. (2011) and Mateos et al. (2012) use both $W1 - W2$ and $W3 - W4$ colors, and this severely limits the number of potential AGNs that can be identified. In Figure 2.1, we show the sample of AGNs that we use for SED fitting plotted in the $W1 - W2$ and $W3 - W4$ color space and a comparison of different WISE AGN color selection criteria. Since our sample has heavy Malmquist bias and contains particularly bright objects (see Section 2.4), we are able to get detections in all four WISE bands. The majority of our AGNs fall within the common overlap of all these criteria, so the choice of color selection criteria does not substantially affect our sample.

The AKARI/FIS all-sky survey Bright Source Catalog (Kawada et al. 2007) contains far-IR photometry (65, 90, 140, and 160 μm) of $\sim 427,000$ objects, with respective 5σ sensitivities of 2.4, 0.55, 1.4, 6.3 Jy in each band. We cross-correlate the AKARI Bright Source Catalog with the WISE catalog using a 20'' matching radius (determined by the 40'' PSF of the AKARI 90 μm data), which yields 32,523 matches. Out of these matches, there are 2,700/3,006/9,053/2,769 detections in the 65/90/140/160 μm bands, respectively. Out of these sources, 2,609 (96.6%)/29,577 (98.2%)/8,722 (96.3%)/2,630 (94.9%) objects have reliable photometry (i.e. a flux density quality flag of 3 in the catalog) in the 65/90/140/160 μm bands, respectively. 2551 (7.8%) of the matched WISE-AKARI sources satisfy the $W1 - W2 > 0.8$ color cut.

To perform broadband SED fitting, we add additional optical photometry from Pan-STARRS and far-IR photometry from Herschel to the objects in our sample when available. The SPIRE sub-millimeter camera (Griffin et al. 2010) on Herschel provides 250, 350, and 500 μm photometry.

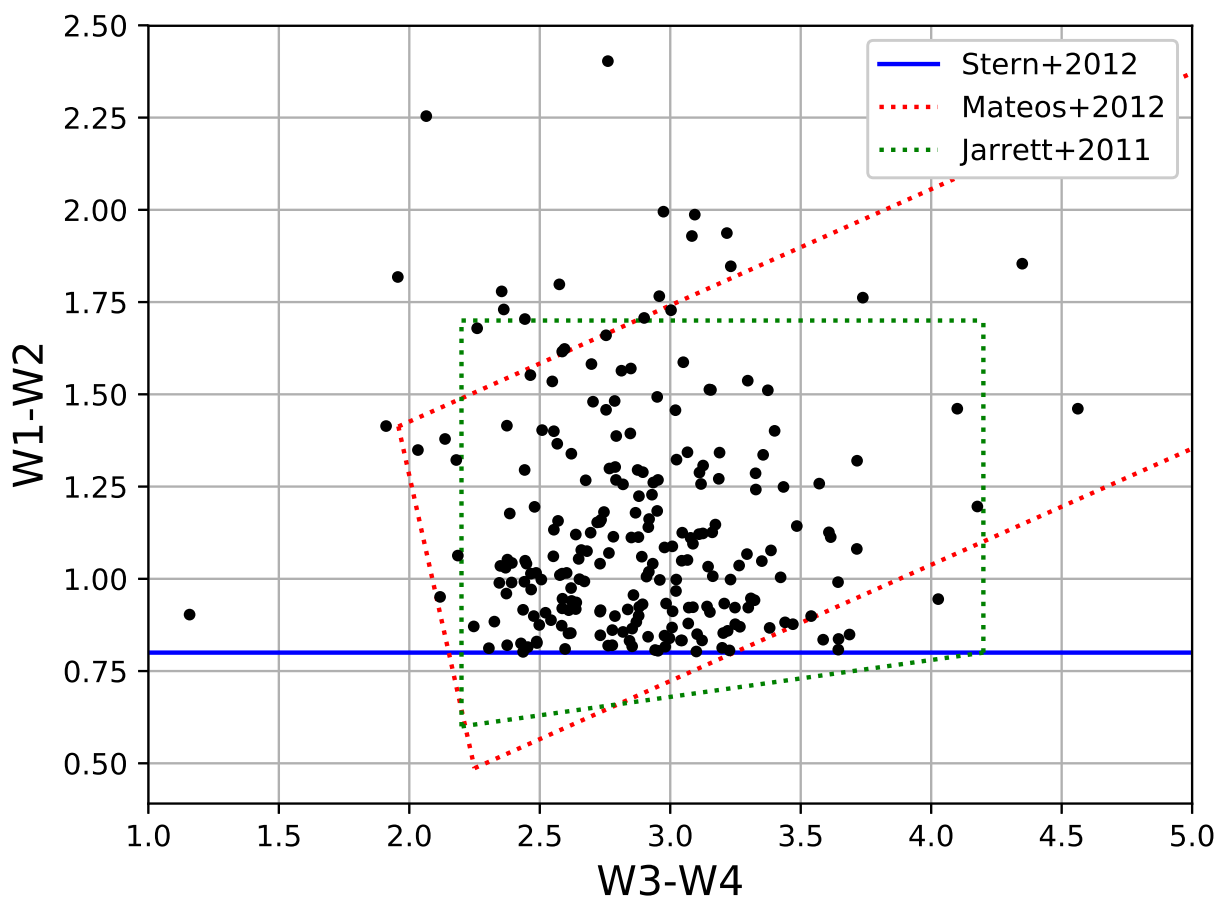


Figure 2.1: $W1 - W2$ and $W3 - W4$ color diagram of the AGNs selected for SED analysis. Dotted lines show the WISE AGN selection criteria given by Stern et al. (2012), Mateos et al. (2012), and Jarrett et al. (2011)

The majority of the objects in the WISE-AKARI sample do not have SPIRE detections in the FIR, perhaps as a result of the SEDs being dominated by a AGN dust component that peaks in the MIR bands instead of the FIR (Hwang & Geller 2013). The IRAS catalog (Neugebauer et al. 1984) is often used for IR studies due to its all-sky coverage, but we find that this data does not improve our sample size of objects. The WISE $W3$ and $W4$ bands are much more sensitive than the corresponding IRAS bands and contain roughly twice as many detections. Among the catalog objects with photometric redshifts (see Section 2.2.2), AKARI has roughly twice as many detections in the 65 and 90 μm bands compared to the IRAS 60 and 100 μm bands. For these reasons, we have not included IRAS data in our analysis. For optical photometry we use the Pan-STARRS 3π Steradian Survey (Chambers et al. 2016), which covers the *grizy* bands. Pan-STARRS is not an all-sky survey like WISE or AKARI, but we find there are 50-60% (depending on the Pan-STARRS filter) of the $\sim 32,000$ WISE+AKARI objects included in the catalog. In order to perform optical extinction measurements, we only include objects that contain Pan-STARRS photometry in our sample. Figure 2.2 show a flowchart summarizing our selection process and final number counts.

Figures 2.3 and 2.4 show color diagrams of the objects in WISE-AKARI color space. The redder WISE selected sample tend to have redder $m_{65} - m_{90}$ and $m_{90} - m_{140}$ on average, which is probably a result of band shifting effects at higher redshifts. There does not appear to be any notable correlation between the WISE and AKARI colors for individual objects.

2.2.2 Photometric redshifts

In order to identify the largest possible sample of AGNs for SED analysis, we rely on photometric redshifts derived from all sky surveys. AGNs with high levels of optical obscuration are easily missed by large scale surveys such as SDSS, so there is not always spectroscopic redshift data available. We use the 2MASS Photometric Redshift catalog (Bilicki et al. 2013), which contains a million galaxies with an accuracy of $\sigma_z = 0.015$ and a median redshift of $z \sim 0.1$. These z_{photo} values are derived using an artificial neural network applied to photometry in the 2MASS, WISE and SuperCOSMOS catalogs. Matching this redshift catalog with the AKARI-WISE catalog described above produces 6,384 matches. 238 of these objects meet the $W1 - W2 > 0.8$ color

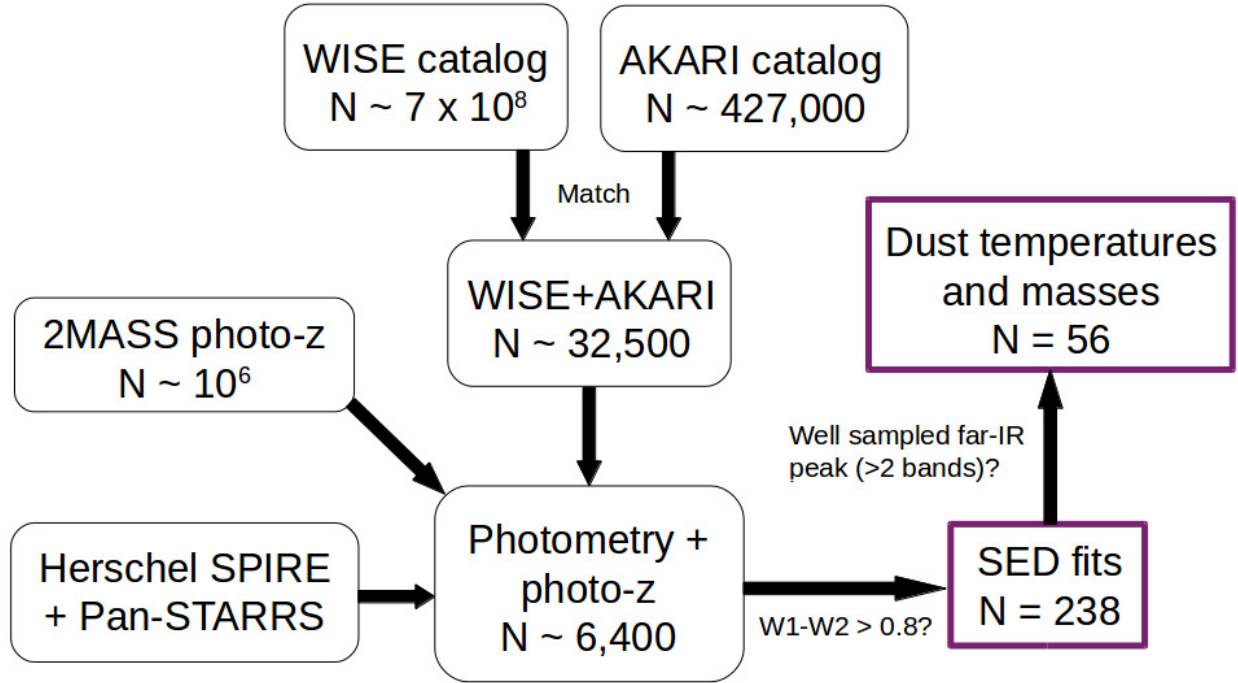


Figure 2.2: Flowchart outlining the AGN selection criteria and number of objects at each step. The purple boxes indicate the final two samples that we use for SED fitting and dust temperature/mass fitting.

cut. Figure 2.7 shows the redshift distribution of these samples.

Photometric redshifts are difficult to determine for AGNs due to their strong power law continuum and general lack of prominent emission features in the SED. This is especially true for particularly luminous AGNs, in which most of the mid-IR PAH features are absent due to photodissociation by the AGN emission. Even with WISE photometry, the width of the $W1$ and $W2$ bands and large gaps between the $W2$, $W3$, and $W4$ bands do not allow emission features to be easily visible (in contrast, Goto et al. (2015) exploits AKARI’s near-continuous filter coverage in the mid-IR for z_{photo} measurements in AKARI NEP field). Although it is possible to use the photometry that we have to estimate photometric redshifts using codes such EAZY (Brammer et al. 2008) or LEPHARE (Arnouts et al. 1999; Ilbert et al. 2006), the strong AGN power-law behavior makes it extremely difficult to reliably estimate photometric redshifts for these objects without additional photometry. To ensure that the redshift estimates that we use are consistent and to avoid introducing additional systematic errors, we do not perform additional photometric redshift fitting

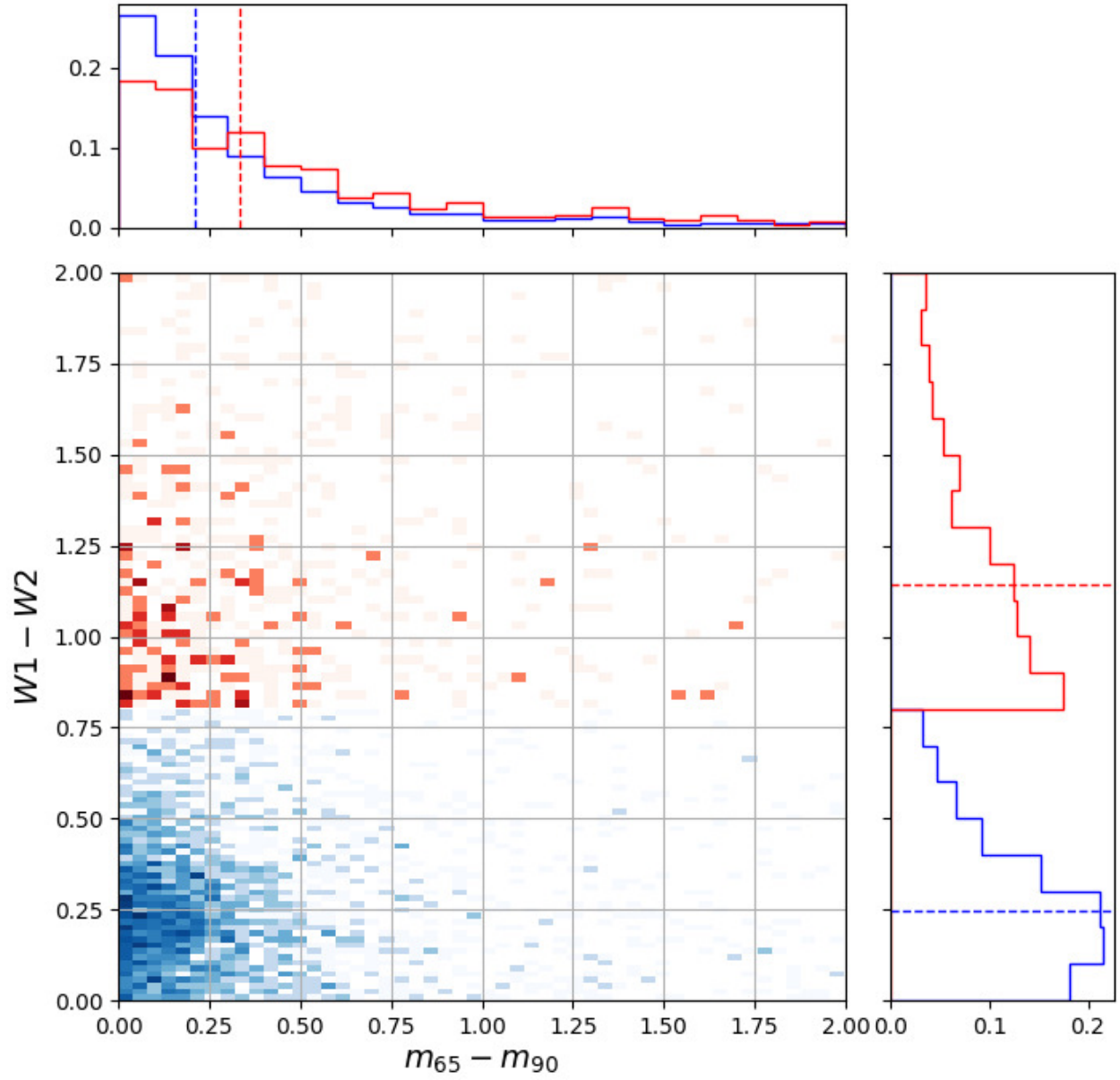


Figure 2.3: WISE-AKARI color space diagram, with $W1 - W2$ color plotted against $m_{65} - m_{90}$ color. Objects are divided into redder ($W1 - W2 > 0.8$) and bluer ($W1 - W2 < 0.8$) samples based on our AGN color selection criteria. Top and right panels show histograms of relative frequencies, with dashed lines indicating the medians of the distributions.

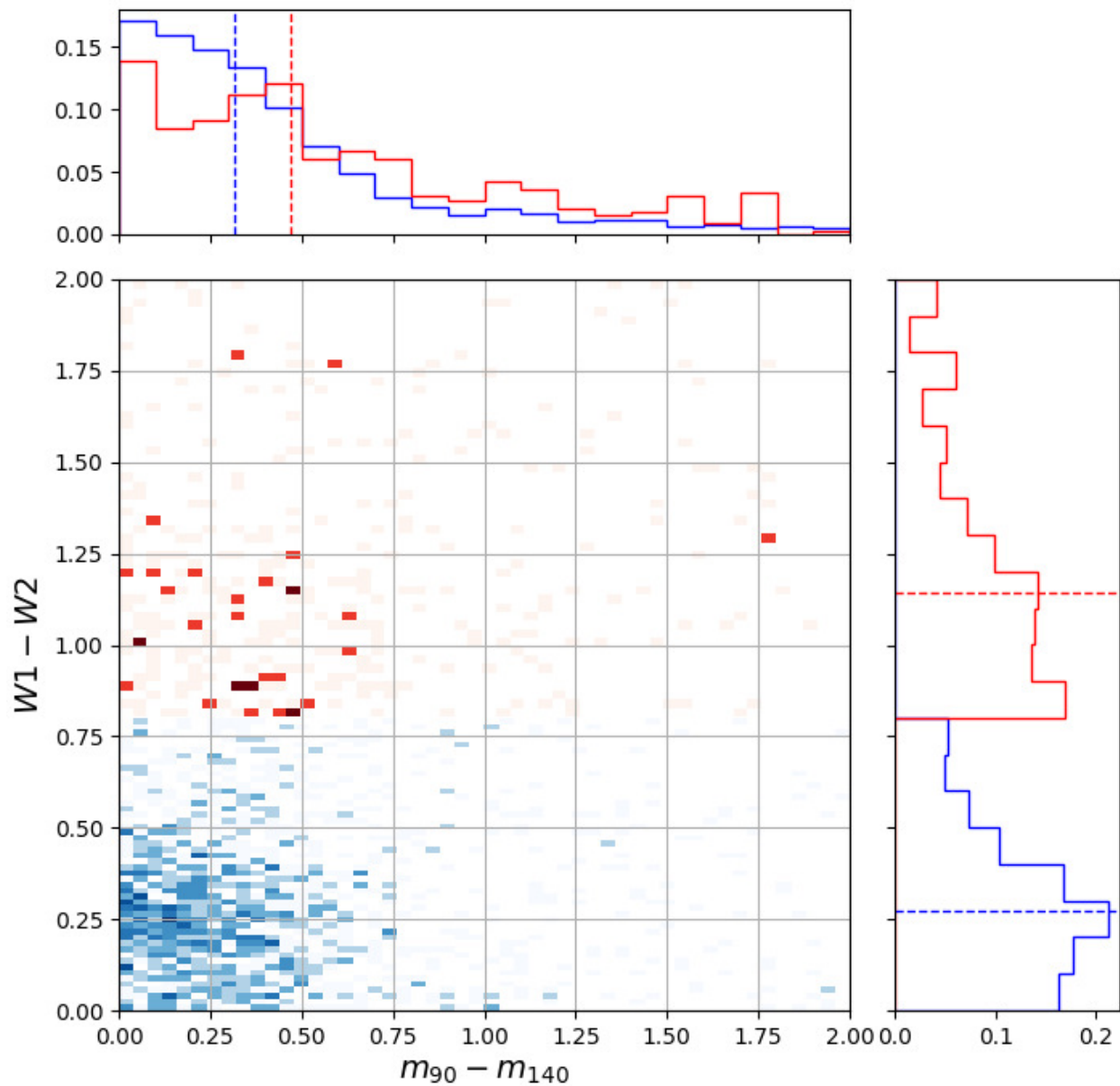


Figure 2.4: WISE-AKARI color space diagram, with $W1 - W2$ color plotted against $m_{90} - m_{140}$ color. Top and right panels show histograms of relative frequencies, with dashed lines indicating the medians of the distributions.

for the AKARI objects that lack z_{photo} values in the 2MASS Photometric Redshift catalog.

The 2MASS Photometric Redshift catalog also contains spectroscopic redshift values for a subset of its objects. 62% of the ~ 6400 matched WISE/AKARI objects with photometric redshifts have z_{spec} values. Figure 2.5 shows a comparison of z_{spec} and z_{photo} for the sample of AGNs we selected for SED analysis. 97 out of these 248 AGNs have z_{spec} values in the catalog. The bottom panel of Figure 2.5 shows that the fractional errors $\Delta z/(1+z)$ are on the order of a few percent. Ilbert et al. (2006) defines the photometric redshift error as $\sigma_{\Delta z/(1+z)} = 1.48 \times \text{median}[|\Delta z|/(1+z)]$. For our sample of AGNs, we find $\sigma_{\Delta z/(1+z)} = 0.013$, which is consistent with the $\sigma_z = 0.015$ value given by Bilicki et al. (2013).

One concern for our low redshift sample is that for a given error σ_z , this produces larger errors in the luminosity distance D_L at low z compared to higher z . Bolometric luminosity scales with the luminosity distance as $L \propto D_L^2$, so the relative difference in luminosities that result from photometric and spectroscopic redshifts is given by $L_{bol,photo}/L_{bol,spec} \propto D_L^2(z_{photo})/D_L^2(z_{spec})$. Figure 2.6 shows a plot of $D_L^2(z_{photo})/D_L^2(z_{spec})$ as a function of z_{spec} . For the lowest redshift objects at $z \sim 0.01$, z_{photo} tends to overestimate the luminosity by a factor of a few, but this factor decreases with increasing redshift. At the higher end of our redshift distribution z_{photo} underestimates the luminosity by a factor of ~ 2 . These discrepancies are within an order of magnitude, so this should not have a significant impact on our results given that L_{bol} for our sample tends to span a few orders of magnitude (see Section 2.5.4 for our results that involve IR and bolometric luminosity estimates). The bottom panel of Figure 2.6 shows a histogram of the fractional errors $[D_L(z_{photo}) - D_L(z_{spec})]/D_L(z_{spec})$, and we can see that in general z_{photo} tends to overestimate the luminosity distance for our sample of objects.

There are other catalogs of photometric redshifts in the literature that are also potentially useful for photometric studies of AGNs. DiPompeo et al. (2015) provides a catalog of quasar identifications and redshifts generated using probability density functions of over 5 million objects using a combination of WISE and SDSS photometry. The authors show that their probabilistic quasar selection is more complete than the Stern et al. (2012) WISE color-cut criteria, which tends to miss quasars that are at redshifts of $z > 3$. This is because high redshift objects tend to be too

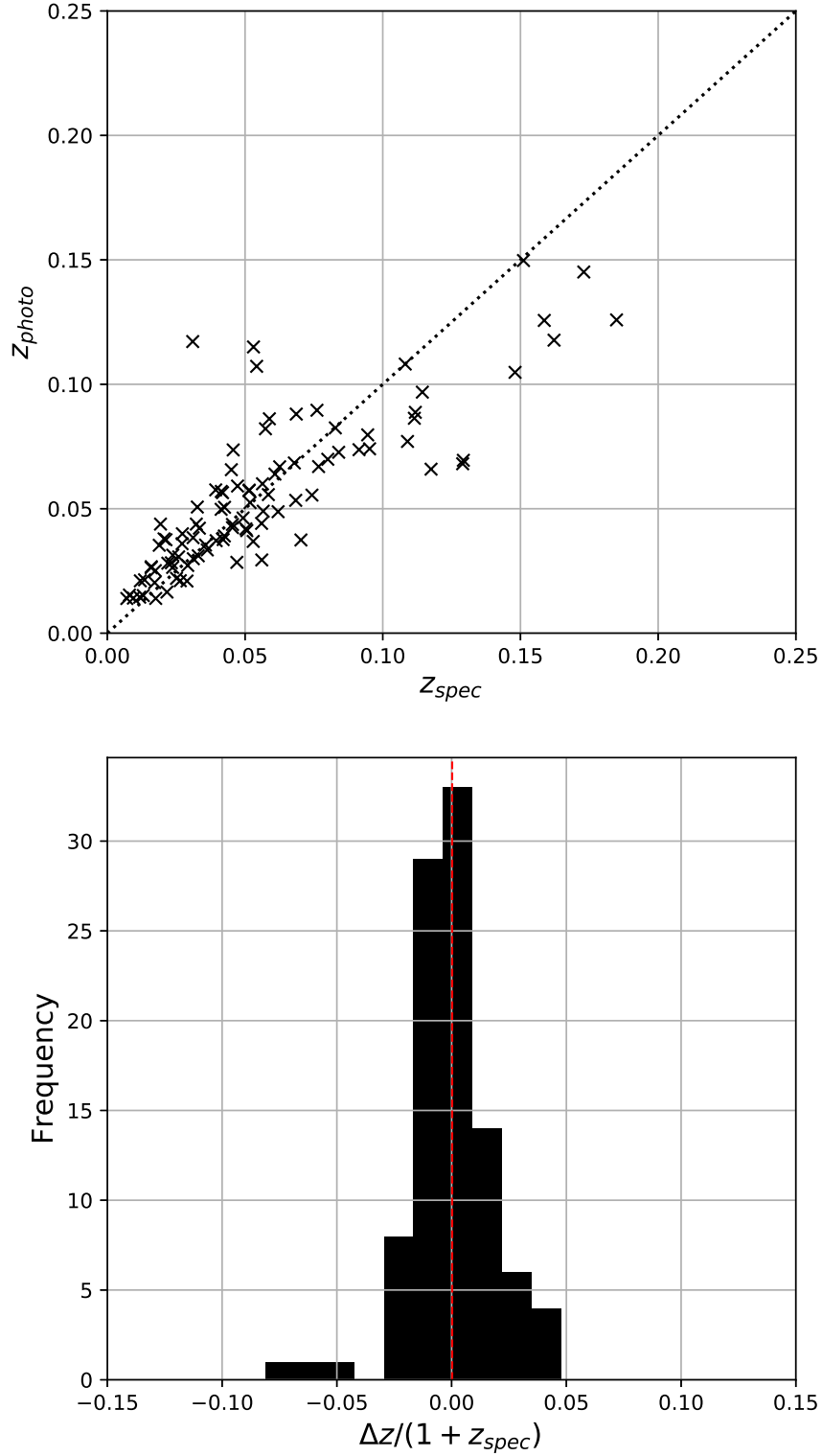


Figure 2.5: [Top] A comparison of z_{photo} vs z_{spec} values from the 2MASS Photometric Redshift catalog of AGNs we've selected for SED analysis. Dotted line denotes where $z_{photo} = z_{spec}$. [Bottom] Histogram of the fractional redshift errors $\Delta z / (1 + z)$. Red dashed line indicates the mean.

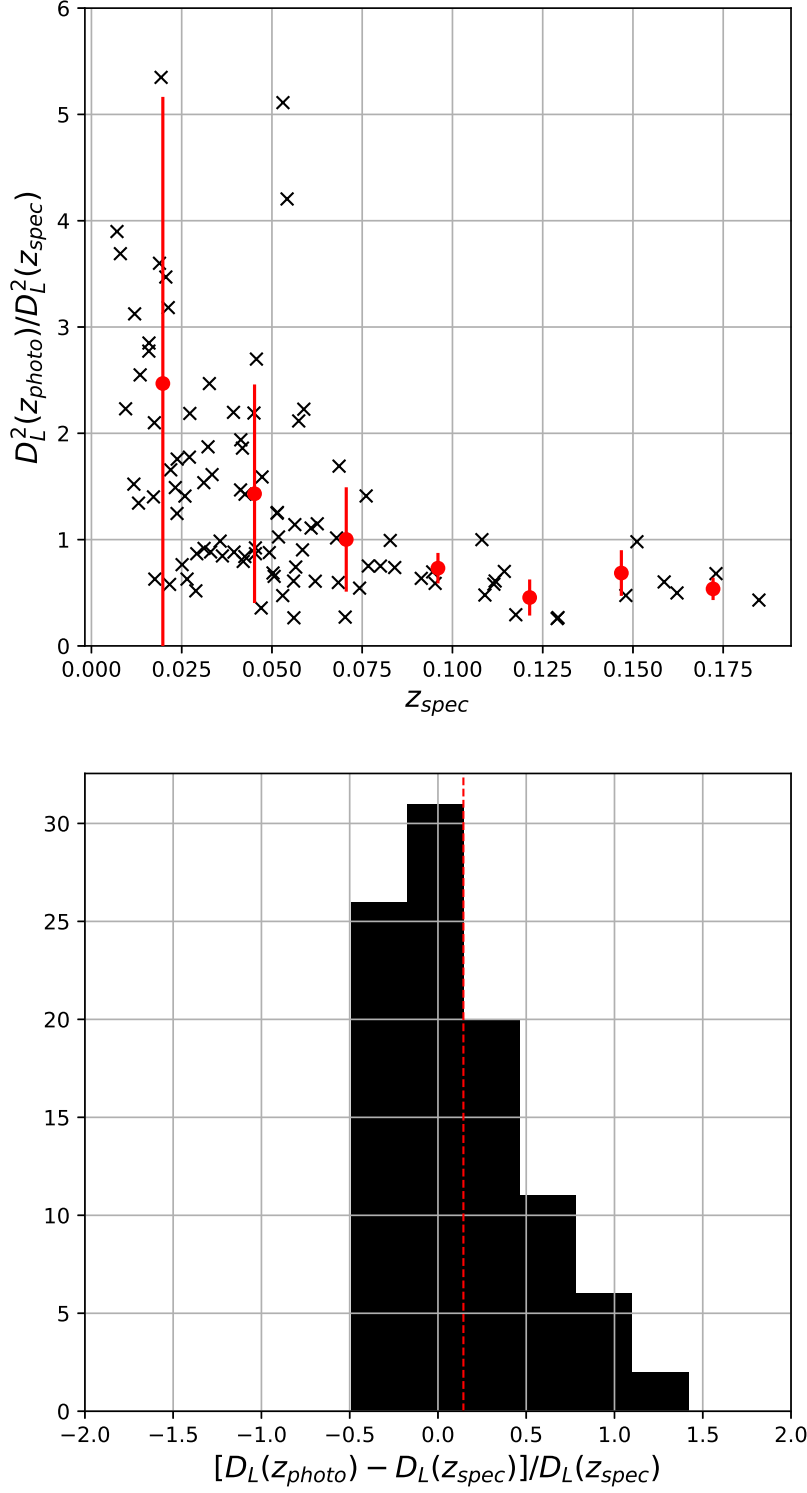


Figure 2.6: [Top] $D_L^2(z_{photo})/D_L^2(z_{spec})$ plotted against spectroscopic redshift for our sample of AGNs selected for SED analysis. Red points show binned averages and error bars. [Bottom] Histogram of the fractional errors on $D_L(z_{spec})$, given by $[D_L(z_{photo}) - D_L(z_{spec})]/D_L(z_{spec})$. Red dashed line indicates the mean.

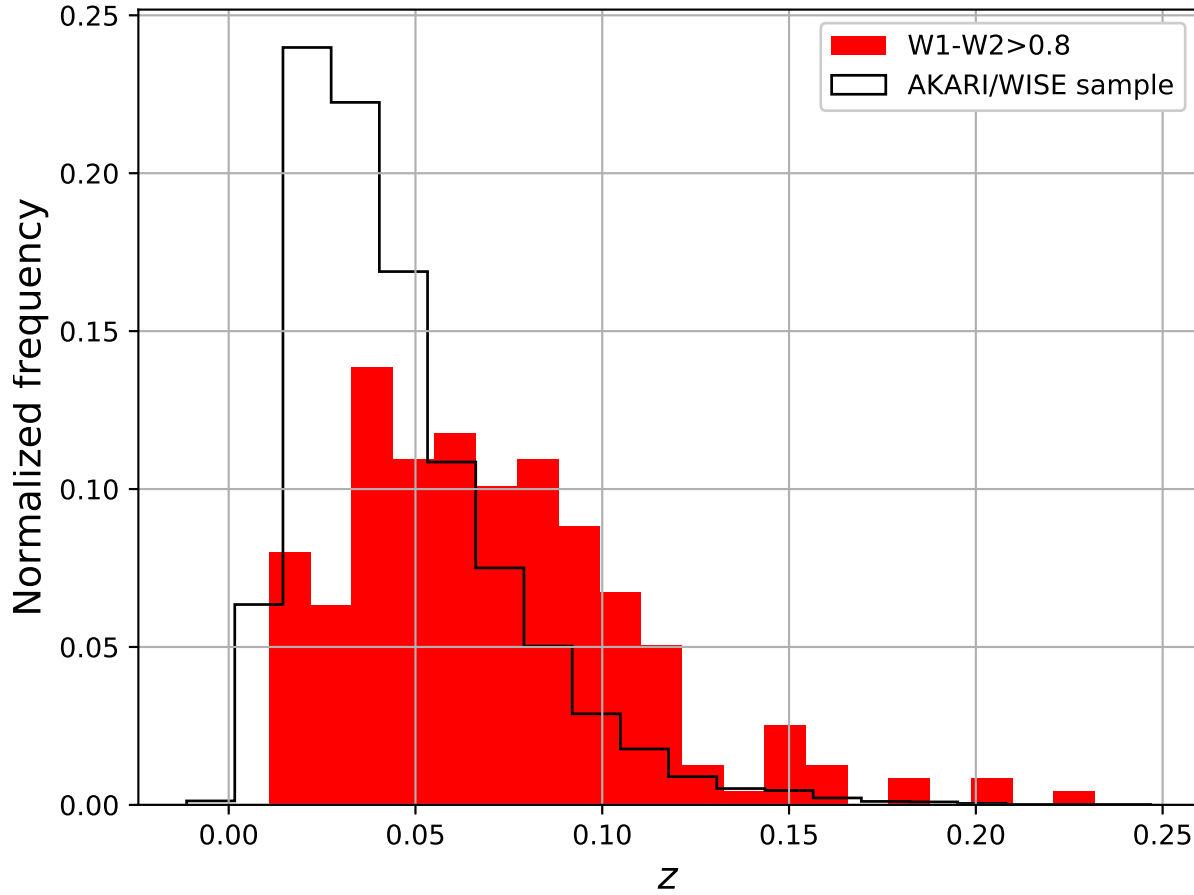


Figure 2.7: Redshift distribution of the objects in the AKARI/WISE catalog (black curve) that have corresponding photometric redshifts in the 2MASS Photometric Redshift catalog, and the objects from that sample that satisfy the $W1 - W2 > 0.8$ color cut (red).

blue in $W1 - W2$ to satisfy the color cut. Using a 20'' matching radius to match this catalog with the AKARI BSC produces 5,079 matches, which is although smaller than the number of matches with the Bilicki et al. (2013) catalog, represents a different set of objects located at a larger range redshifts. However, this catalog is probabilistic in nature and includes objects that perhaps have only a very small AGN component or multiple peaks in the redshift probability distribution. Since we are interested in examining the impact of AGN dominated galaxies on their surrounding dust to ensure consistency in photometric redshift measurements, we choose to limit our sample to the objects contained in Bilicki et al. (2013).

2.3 SED modeling

2.3.1 Optical to mid-IR SEDs ($\lambda < 10\mu\text{m}$)

We use the low-resolution spectral templates presented in Assef et al. (2010) and model each quasar as a linear combination of an AGN template and a single galaxy template (spiral, elliptical or irregular) similar to the method described in Hainline et al. (2014). We find the combination that provides the best least-squares fit, and apply the extinction curves described in Gordon & Clayton (1998) and Cardelli et al. (1989) to the AGN template to simulate the effects of optical obscuration. To ensure that our photometry is reliable enough for SED modeling, we only use WISE photometry with a signal-to-noise ratio ≥ 3 , and AKARI measurements that are marked as “high” quality. The templates provided in Assef et al. (2010) only extend to rest frame $30\mu\text{m}$, but this still encompasses all the WISE bands for the AGNs in our sample since these objects are low redshift ($z \sim 0.1$). The top panel of Figure 2.8 shows a histogram of the $E(B - V)$ extinction measured from these SED fits, which we use to quantify the degree of optical obscuration. We define the AGN fraction to be $f_{AGN, < 30\mu\text{m}} = F_{AGN, < 30\mu\text{m}} / F_{total, < 30\mu\text{m}}$, which covers the wavelength range spanned by the Assef et al. (2010) templates. The bottom panel of Figure 2.8 shows that the majority of the objects in our sample also have $> 90\%$ of their flux for $\lambda < 30\mu\text{m}$ coming from the AGN component, which gives us confidence that most of these objects are indeed AGNs. Dey et al. (2008) shows that there is a distinction between “bump” and “power-law” type DOGs, with the latter having an AGN dust component at mid-IR wavelengths. From visually inspecting the SEDs of our sample galaxies, all of our objects show strong power law behavior in the mid-IR bands as captured by WISE. However, the large wavelength gaps between each band (particularly $W2$, $W3$, and $W4$) may not capture any PAH emission that is present. Even so, there is no indication that the mid-IR portion of the SEDs have significant curvature.

2.3.2 Mid to far-IR SEDs ($\lambda > 10\mu\text{m}$)

To examine the mid to far-IR properties of these AGNs, we use the the AGN and galaxy templates in Mullaney et al. (2011), which are produced from Spitzer spectra and IRAS photometric data. We

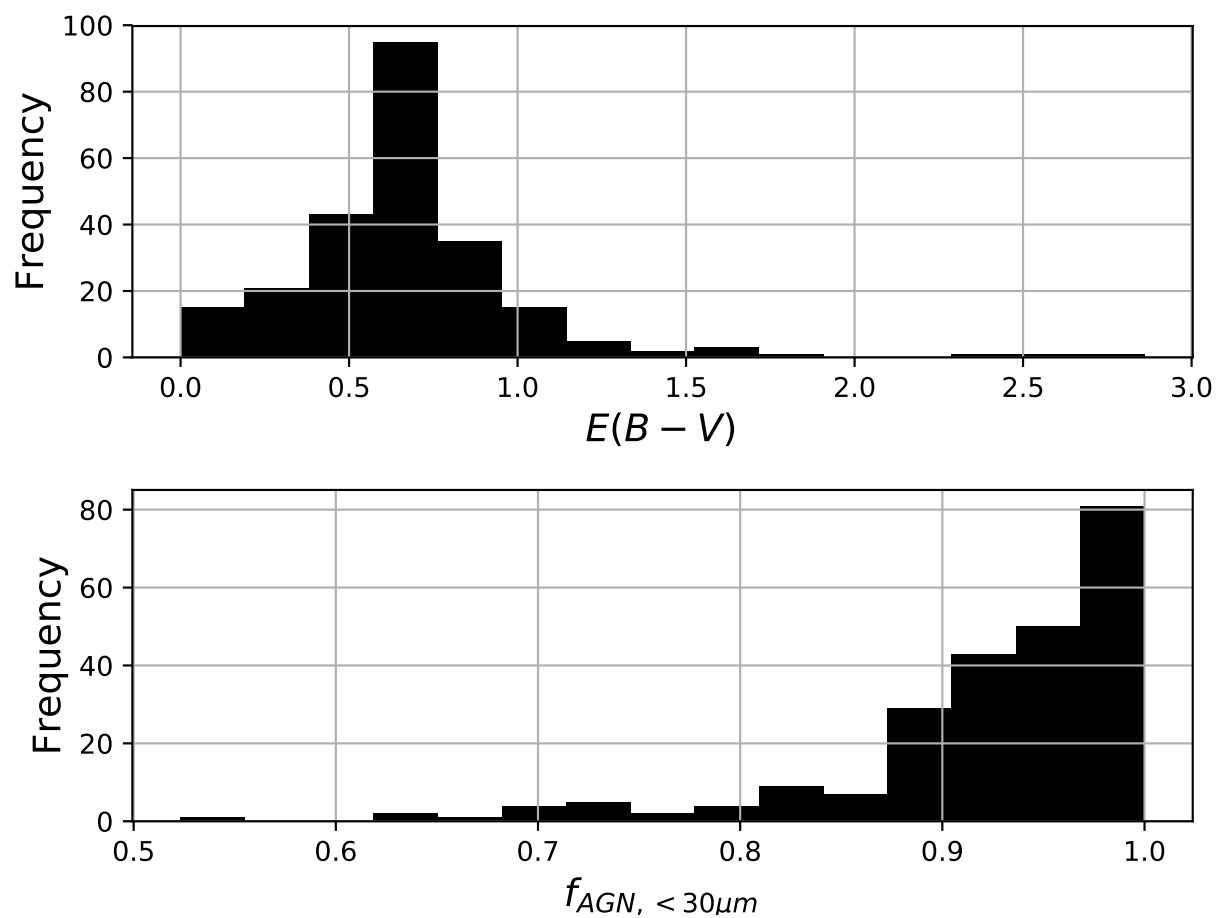


Figure 2.8: [Top] Distribution of optical $E(B - V)$ extinction values derived from SED fitting using the templates of Assef et al. (2010). [Bottom] Distribution of the fractional AGN contribution to the total integrated luminosity for $\lambda < 30\mu m$.

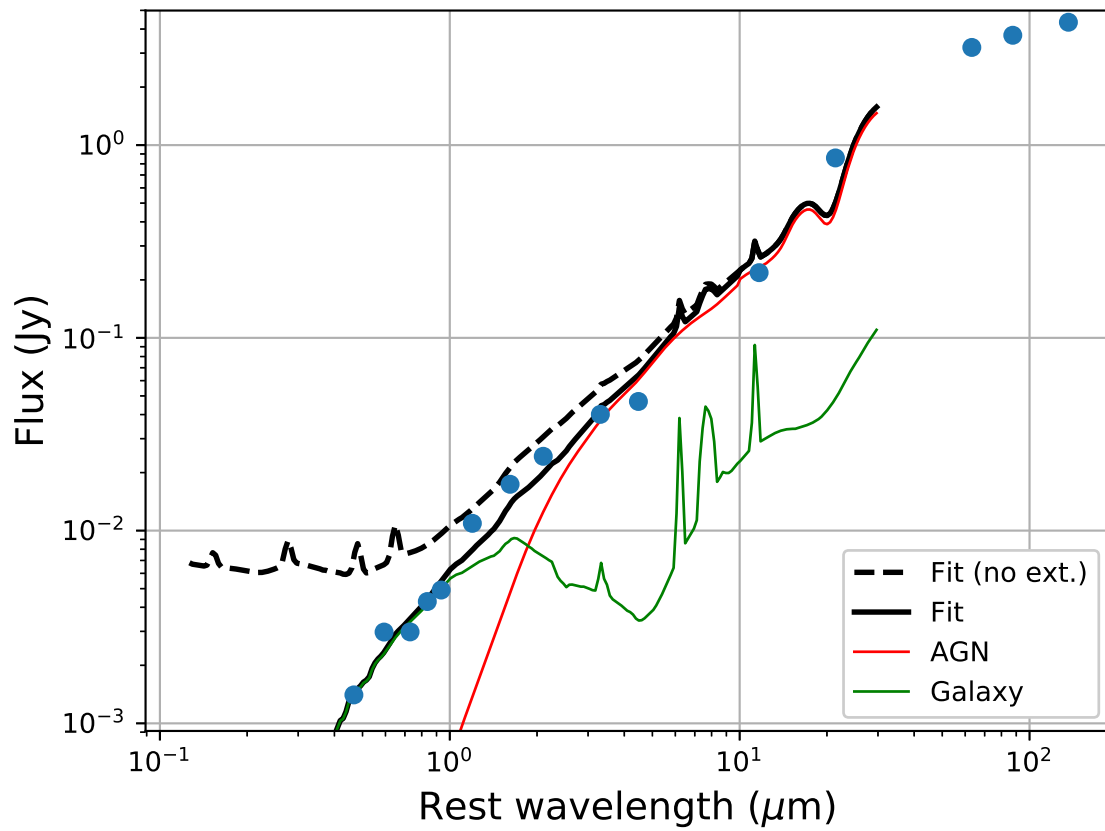


Figure 2.9: SED fit for using the templates from Assef et al. (2010) (red and green curves), which extend up to 30 μm . The solid curve shows the sum of the templates with extinction applied, while the dashed curve shows the model without extinction.

once again fit each set of photometric band with a linear combination of a AGN (out of a possible set of three templates: 'Mean', 'LowLum', 'HighLum') and host galaxy template (out of a possible set of six spiral galaxy templates, ranging from SB1 to SB5). Galaxies that lack far-IR SPIRE photometry (i.e. only containing photometry up to rest frame $\sim 100\mu\text{m}$) tend to be fit with an SED dominated by a host galaxy component. As a result, our least-squares fitting routine tends to favor the host galaxy template if there isn't a sufficient number of far-IR bands that captures both sides of the IR peak.

Since the shape of the far-IR peak for most objects can be reasonably well fit using either the AGN or host galaxy template, it is difficult to determine what is the dominant source of dust heating in the far-IR using this kind of SED fitting alone. Since we are fitting the mid and far-IR portions of the SED independently of each other, a number of our objects are fitted with objects that are inconsistent between the two halves of the SEDs (ex. an AGN dominated template below $30\mu\text{m}$, and a spiral galaxy dominated template above $30\mu\text{m}$). There is some ambiguity in choosing the appropriate template in the far-IR portion of the SED, so we choose the type of template (AGN or starburst) to match the dominant template in the mid-IR portion. The majority of our objects already have an AGN fraction greater than 90% in the $< 30\mu\text{m}$ range, so including the far-IR portion of the SED in computing AGN fraction will likely not drastically change these values. Dusty AGNs tend to have minimal extinction in the mid-IR compared to the optical, so we do not apply any reddening correction in that portion of the SED.

2.4 IR bolometric correction

Since the majority of objects in the AKARI/WISE catalog do not have far-IR photometry extending beyond the AKARI bands (ex. from Herschel SPIRE), we are unable to measure the bolometric luminosity of the AGNs by directly integrating over the entire wavelength range. This can be problematic, since a number of physical parameters (ex. Eddington ratio) that characterize an AGN depend on having an accurate estimate of F_{bol} . Even with far-IR data, bolometric corrections to far-IR photometry are not necessarily reliable. For example, Elbaz et al. (2010) shows

that extrapolations from the Herschel SPIRE bands tends to overestimate the total IR luminosity, presumably because of the lack of spectral coverage in templates at those wavelengths. Mid-IR photometry is also occasionally used to estimate L_{bol} , but highly skewed estimates result if the band in question is centered on the $7.7 \mu\text{m}$ PAH complex. Even so, mid-IR PAH features tend to be stronger in star-forming galaxies, whereas AGNs tend to be dominated by a strong continuum. To avoid this biasing, it is preferable to estimate the total luminosity using wider wavelength range of SED photometry.

Since the WISE and AKARI bands capture most of the bolometric luminosity, the bolometric correction applied to this wavelength range should be relatively small. In general, there is more photometric data available at shorter wavelengths since this is easier to obtain. The issue then is how to apply bolometric corrections to the integrated flux from the shorter wavelength portion of SEDs.

Bolometric corrections become more important for dusty galaxies, since increasing dust content generally tends to increase the far-IR luminosity. This is easily seen in the mid-IR, in which the power law continuum tends to steepen as the far-IR dust luminosity increases. By combining the templates of Assef et al. (2010) and Mullaney et al. (2011), we can see how the bolometric correction changes as a function of dust content. We use the mid-IR WISE colors to parameterize the hot dust content, since this is an observable that is generally independent of the details of any dust model.

The SED templates from Assef et al. (2010) and Mullaney et al. (2011) that we are using do not overlap perfectly well in the mid-IR, since these are empirically derived from different data sets. To reconcile the two using the WISE photometry that we have, we join the templates using a power law continuum by doing a fit between the $W2$ and $W4$ bands, and integrate over the entire SED to get F_{bol} . This power law interpolation of course leaves out any PAH emission, but the contribution of PAH emission features to F_{bol} is on the order of a few percent, with some of that emission partially canceled out by the PAH absorption at $9.7 \mu\text{m}$. An examination of the νF_{nu} vs. ν plots of these SEDs shows that the integrated flux converges within the wavelength range spanned by the templates. Figure 2.10 shows an example of an SED with an power law mid-IR continuum, and the

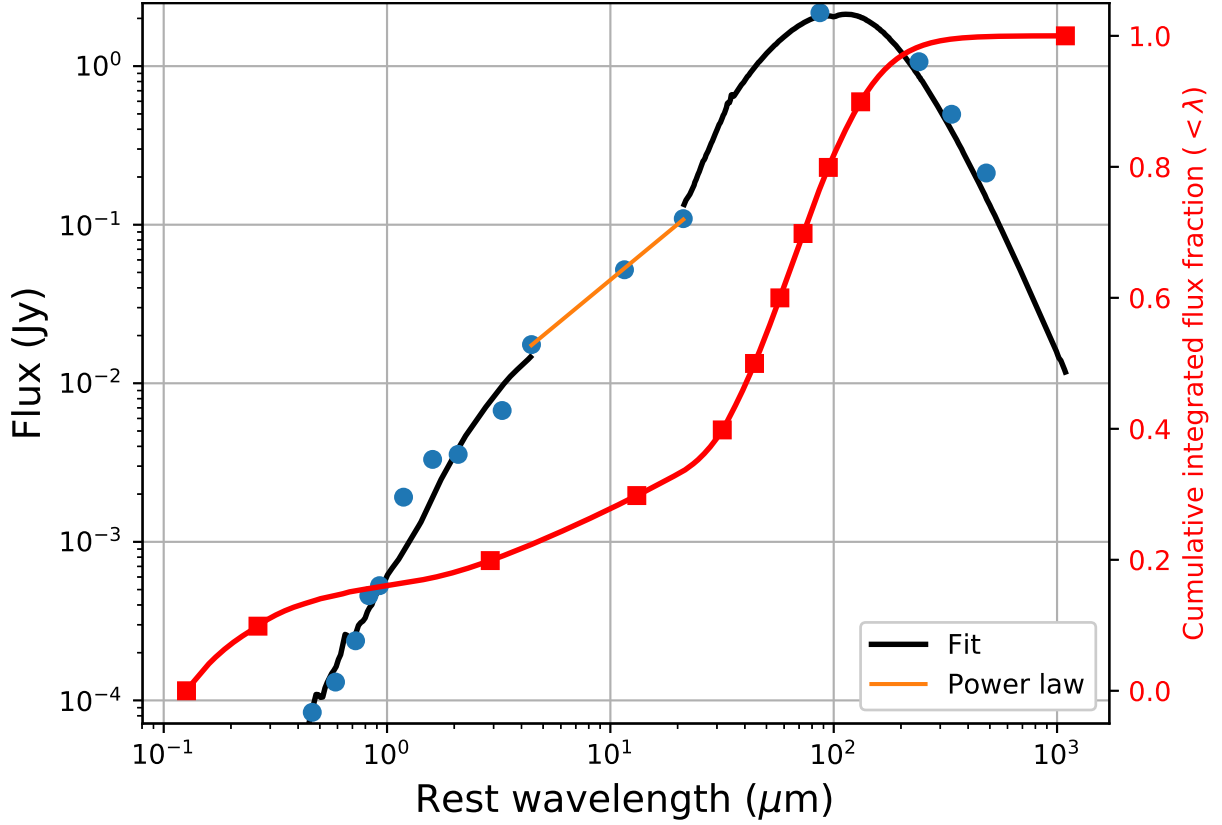


Figure 2.10: Example of a broadband SED fit. The black curve shows the best fit SED, and the yellow curve is the power law continuum that we fit between the $W2$ and $W4$ bands. The red curve shows the cumulative integrated flux (ranging from the lower limit of the SED, up to the corresponding wavelength) as a fraction of F_{bol} . Red squares denotes increments of 0.1 along the vertical axis (flux fraction).

cumulative integrated flux (expressed as a fraction of F_{bol}) plotted against wavelength. For most of these SEDs, the cumulative flux fraction increases sharply between $\sim 10 \mu\text{m}$ up to the far-IR peak at $\sim 100\text{-}200 \mu\text{m}$, and this region encompasses roughly $\sim 70\text{-}80\%$ of the bolometric flux.

Since WISE photometry is generally more abundant compared to far-IR photometry and captures a significant fraction of the bolometric luminosity, this is useful for predicting F_{bol} . Figure 2.11 shows the fraction of the bolometric flux below $25 \mu\text{m}$ (roughly the upper limit of WISE) plotted against $W2 - W4$ color for our AGN sample. From the binned averages, there is a clear trend of very red objects in the mid-IR having a smaller percentage of F_{bol} under $25 \mu\text{m}$, with the median being $F_{<25\mu\text{m}}/F_{bol} \sim 0.5$. This is consistent with our expectation that a larger fraction

of the bolometric luminosity should be found at longer wavelengths as the slope of the mid-IR continuum increases. In other words, very red, dusty objects are dominated by far-IR emission in their energy budget. Although the scatter is considerably large, it is still possible to make a rough bolometric flux correction using this relation. Since our sample is very heavily Malmquist-biased towards highly far-IR luminous AGNs, the points in Figure 2.11 probably represent upper limits to the bolometric correction.

Since the shapes of the optical and near-IR portions of the dusty AGN SEDs tend to be highly variable across objects due to different amounts of extinction, it is difficult to produce a general template in that regime that can be applied to a variety of AGNs. However, the νF_ν contribution of the shorter wavelength region tends to be substantially smaller than the mid-IR. In Figure 2.12 we show the fraction of the bolometric flux below $3\ \mu\text{m}$ (the lower limit of WISE) plotted against $W2 - W4$ color. The change in $F_{<3\mu\text{m}}/F_{\text{bol}}$ with $W2 - W4$ is smaller than the previous plot, with the median being $F_{<3\mu\text{m}}/F_{\text{bol}} \sim 0.3$.

Since the optical and UV flux that is absorbed by dust should be re-processed and re-emitted in the IR, one might expect some sort of relationship between the level of extinction and the IR dust luminosity. This requires us to make some assumptions in the physical processes of optical dust extinction, and one of the biggest assumptions is that the level of extinction (ex. $E(B - V)$) scales directly with the quantity of dust. However, we observe no apparent correlation between $E(B - V)$ and the mid or far-IR luminosity within any wavelength range. This suggests that other factors (ex. dust distribution and geometry) likely play a role in the extent of optical dust absorption. In general, dusty AGNs tend to have highly variable optical/UV SEDs, but the general shape of the mid and far-IR SED remains does not change significantly between objects.

2.5 Dust temperature and mass

2.5.1 Modified blackbody and power law fitting

There are a number of SED template models in the literature that are given as function of L_{IR} and dust temperature (Chary & Elbaz 2001; Dale & Helou 2002). However, dust temperatures

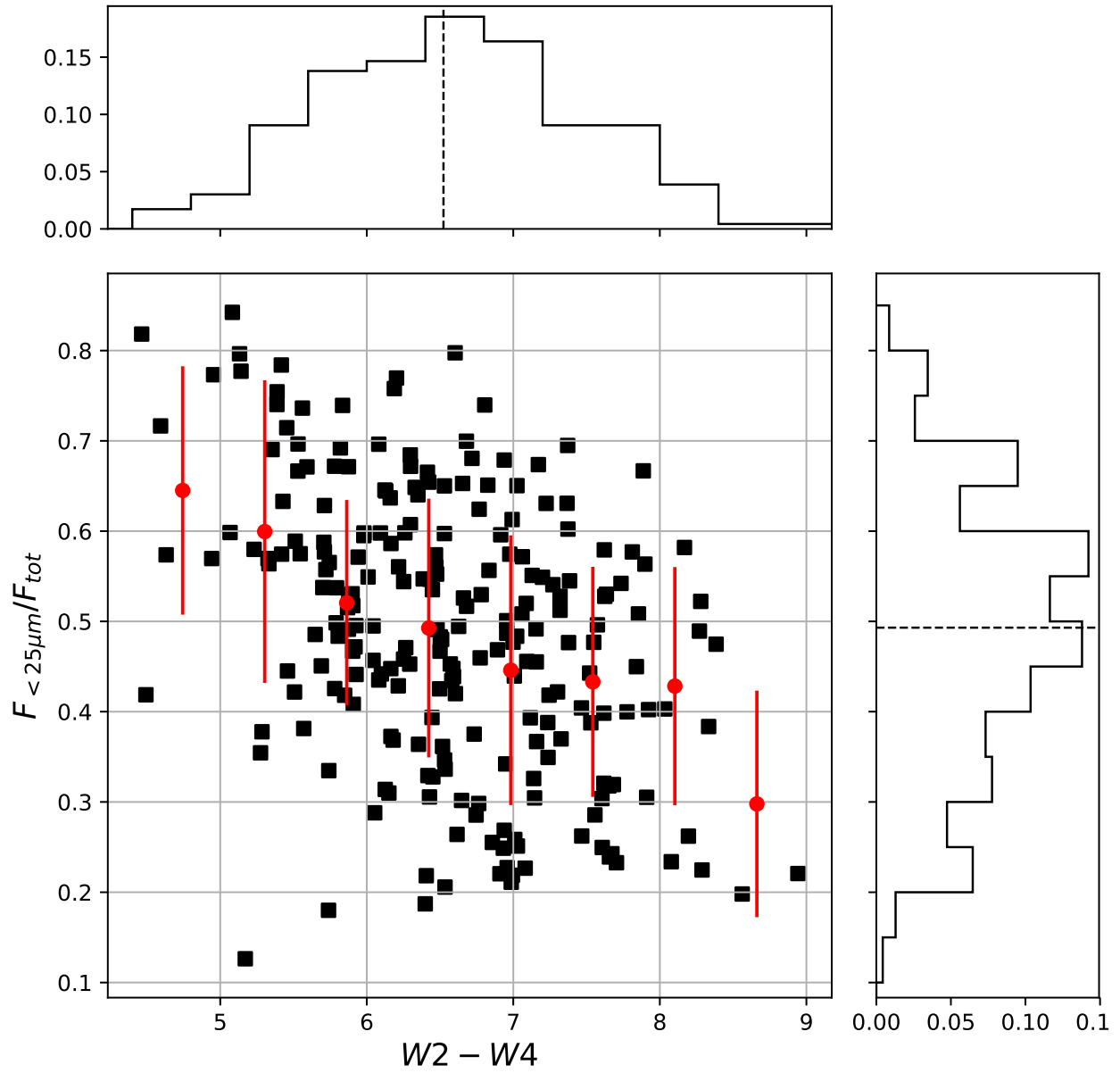


Figure 2.11: The fraction of the total luminosity below $25\ \mu\text{m}$ plotted against $W2 - W4$ color. Red points show binned averages and error bars.

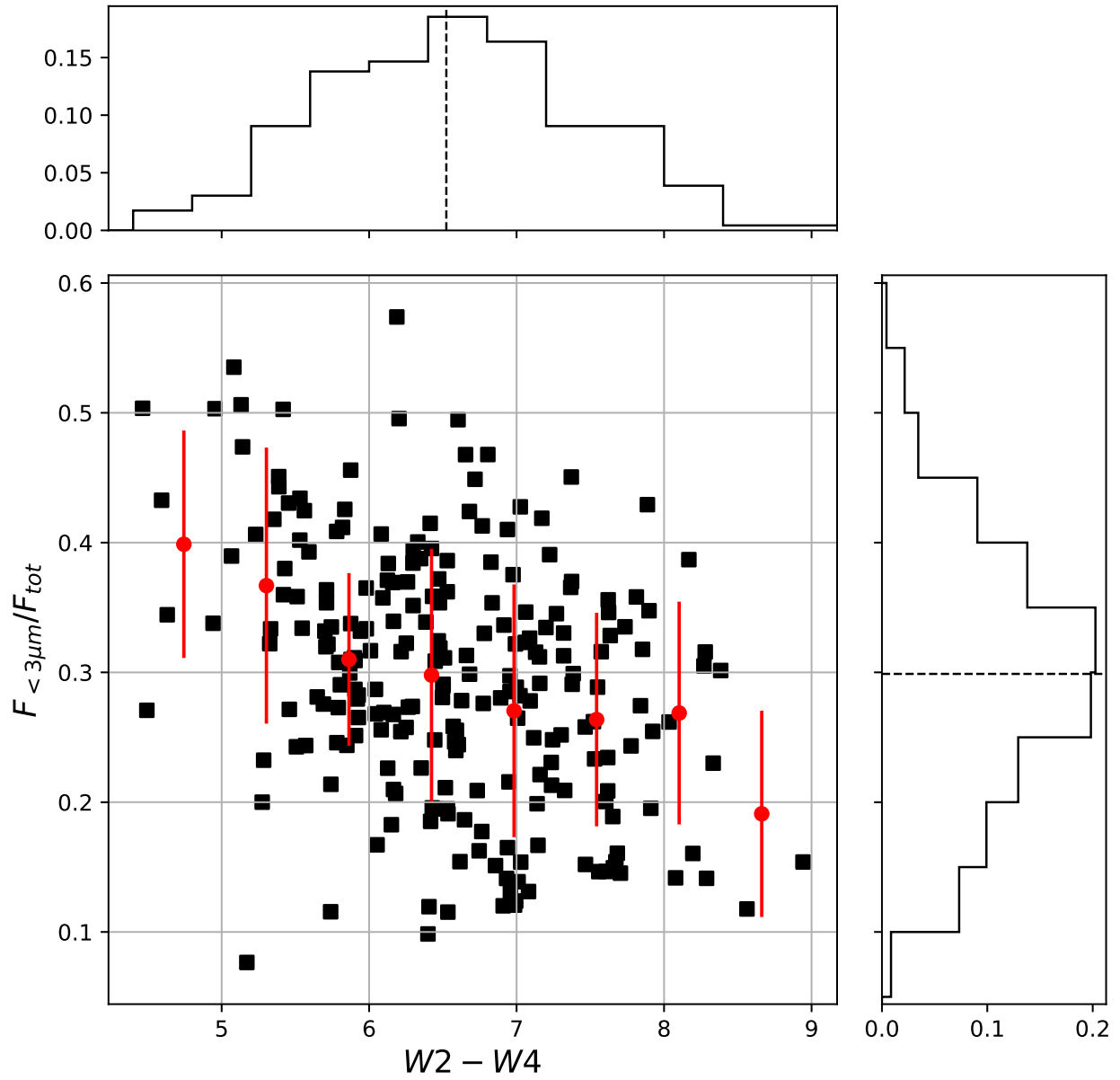


Figure 2.12: The fraction of the total luminosity below $3\ \mu\text{m}$ plotted against $W2 - W4$ color. Red points show binned averages and error bars.

corresponding to SED templates are necessarily discretized, and using galaxy template sets offers less flexibility than analytic models in choosing and constraining model parameters. For functional fits, a number of papers in the literature assume an isothermal dust model and fit the far-IR portion of the SED with a modified blackbody $S(\nu) \propto (1 - e^{-\tau(\nu)})B_\nu(T)$, where $(1 - e^{-\tau(\nu)})$ term accounts for dust opacity and emission. The optical depth τ is parameterized by $\tau(\nu) = (\nu/\nu_0)^\beta$, where ν_0 is the frequency at which $\tau = 1$ (Draine 2006). In the optically thin case $\tau \ll 1$, this reduces to $1 - e^{-\tau} \sim \tau$. Amblard et al. (2010) represents the modified blackbody with emissivity function $\epsilon_\nu \propto \nu^\beta$:

$$S_\nu = \epsilon B_\nu \propto \frac{\nu^{3+\beta}}{e^{h\nu/kT_0} - 1}. \quad (2.1)$$

There are several issues with using a single temperature model, particularly if the SED is well sampled in the far-IR. A single modified black body function captures the far-IR peak emission, but tends to systematically underpredict the observed fluxes at wavelengths longer than the peak. Dunne & Eales (2001) accounts for this by instead using a two temperature dust model with an additional low temperature dust component (typically $T \sim 15\text{K}$).

There is also emission in the mid-IR that is not accounted for by a single or two temperature model (Casey 2012). This mid-IR excess is due to hotter dust components (with several temperature components) that is heated by a central AGN. This requires additional blackbody components to be added, usually three or more to adequately describe the smooth power law nature of the mid-IR emission (da Cunha et al. 2008). Thus, an accurate fit of IR dust emission requires an arbitrary number of blackbody components, each with their own set of parameters. Fitting such a large set of parameters becomes unwieldy, especially if there are only a limited number of data points available. It is possible in principle to represent the dust emission as a temperature distribution convoluted with a modified blackbody function, but this is a computationally expensive procedure.

As a compromise, we use a single modified blackbody with a mid-IR power law component as described in Casey (2012):

$$S_\nu(\lambda) = A_{BB} \frac{\lambda^{-(\beta+3)}}{e^{hc/\lambda kT} - 1} + A_{PL} \lambda^\alpha e^{-(\lambda/\lambda_0)^2}. \quad (2.2)$$

$S_\nu(\lambda)$ is in units of Jy, and α is the mid-IR power law index. Since the power-law dominates in the mid-IR and the blackbody component dominates at longer wavelengths, λ_0 is the wavelength at which the power law turns over and exponentially attenuates.

Most of our SEDs have a limited number of far-IR bands available for fitting, so we need to reduce the number of free parameters in Eq. 2.2. That is, an SED with N photometry bands allows for $N - 1$ degrees of freedom in the fit. We first fit the mid-IR portion between $3 < \lambda < 50 \mu\text{m}$ with a power law to obtain values for A_{PL} and α . A number of papers assume an emissivity parameter of $\beta = 1.5$, which is empirically derived using from fitting modified blackbody functions to dusty emission (Gordon et al. 2010). Here, we assume that $\beta = 2$, which is the limiting value expected for dust grains in the Rayleigh regime, as constrained by the Kramers-Kronig relation (Li 2005). The precise value of β does not significantly affect the total integrated IR luminosity or the dust temperature T (Casey 2012). However, a larger value of β increases the Rayleigh-Jeans portion of the far-IR emission such that it is in better agreement with the measured fluxes, and makes it unnecessary to add an additional cold dust temperature component. Fixing these values in Eq. 2.2, we fit the rest of the parameters to the SED. To ensure that the two components of Eq. 2.2 transition smoothly, we fit the blackbody and power law components independently of each other to the photometry points with $\lambda > 40 \mu\text{m}$ and $\lambda < 40 \mu\text{m}$, respectively. We then set λ_0 to be wavelength at which slopes are equal: $d \log B(\lambda)/d \log \lambda = \alpha$. Figure 2.13 shows an example of an SED fit done using Eq. 2.2.

We require that there be at least three FIR band measurements to perform fitting of the FIR peak. To avoid any possible biasing in peak fitting and temperature measurements, we require that there be photometry measurements on both sides of the FIR peak for the fit to be considered reliable. Since there is a partial degeneracy between β and T , we set $\beta = 2$ to be a fixed parameter. There is a complete degeneracy between T and z , so it is critical that we have accurate redshift values in order to accurately estimate the dust temperature. As discussed in Section 2.2.2, the z_{photo} errors are sufficiently small that this will not significantly affect our dust temperature measurements. An error of $\sigma_z \sim 0.01$ produces an error of $\sigma_\lambda \sim 1 \mu\text{m}$ for a typical far-IR peak wavelength of $\sim 100 \mu\text{m}$. This corresponds to an error of $\sigma_T \sim 0.3\text{K}$ in Wien's displacement law,

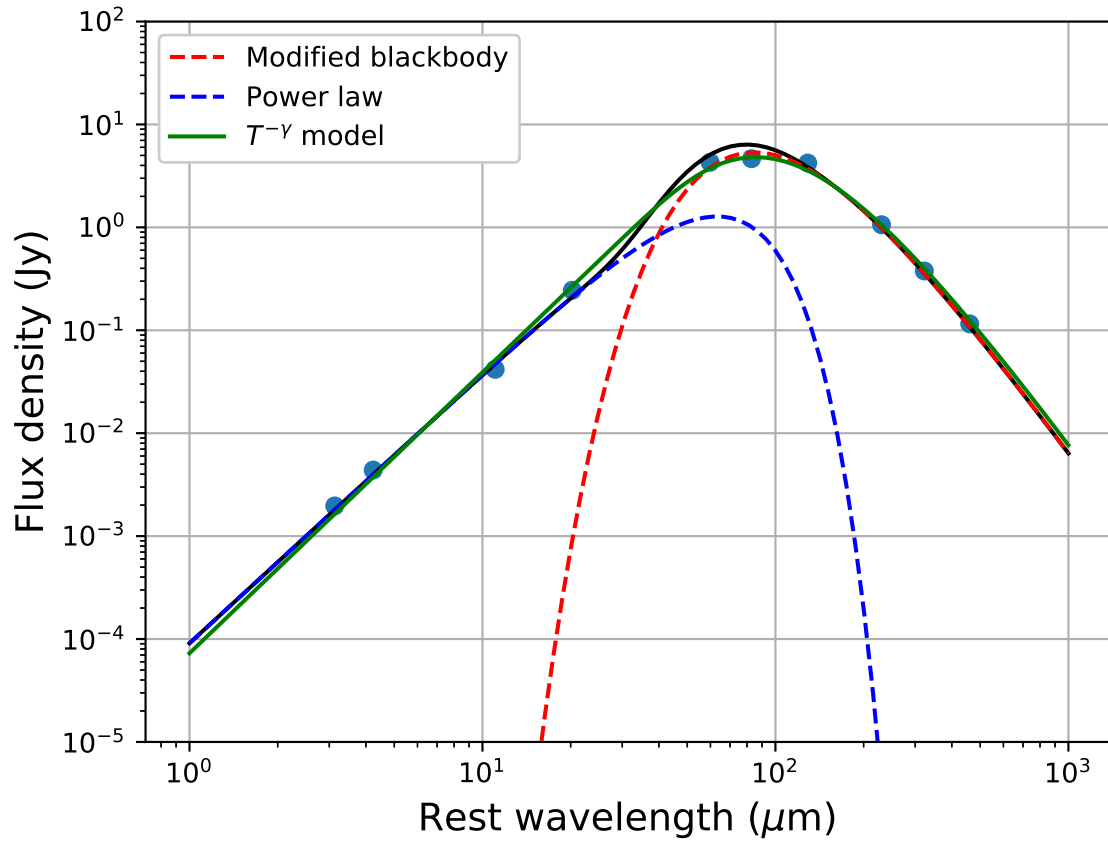


Figure 2.13: An example of an SED with the far-IR emission fit using a single temperature blackbody (red dashed curve) and a mid-IR power law (blue-dashed curve) that turns over and exponentially attenuates when the blackbody component dominates. The green curve shows the model in Eq. 2.3.

which is typically comparable or an order of magnitude smaller than the errors due to the modified blackbody fit itself. Our final sample contains 54 objects that have adequate photometry for far-IR dust fitting (see Figure 2.2). This small sample size is likely the result of extreme Malmquist bias, since our requirements select the most IR luminous galaxies that are detectable with AKARI and Herschel SPIRE photometry. Since the majority of L_{bol} comes from the far-IR dust peak of the SED, high levels of dust reddening might suggest that our sample is more heavily reddened than the usual population of dusty AGNs.

Since different papers tend to use different values of β (or even allowing β to be a free parameter), it can be difficult to compare the values of T_{BB} obtained from different studies with our results. However, we find that value of β does not significantly impact the value of T_{BB} , and only changes the slope of the long-wavelength portion of the fit. Riguccini et al. (2015) fits a single temperature model to far-IR dust emission from a sample of DOGs in the COSMOS field, and finds a median temperature of $T \sim 40\text{K}$ with $\beta = 1.5$. This is higher than the median temperature of our sample ($T_{BB} \sim 28\text{K}$), but the range of temperatures generally agrees. If the central AGN engine is indeed responsible for heating the dust, then we would expect the blackbody dust temperature to increase with the AGN fraction. As shown in Figure 2.14, we do not find any significant trend between the AGN fraction $f_{AGN, < 30\mu m}$ and the blackbody temperature T_{BB} in Eq. 2.2. It is possible that a trend exists, but our small sample size prevents us from seeing this since we are selecting a smaller subset of objects from our SED analysis sample. The sample of DOGs in Riguccini et al. (2015) contains a wide range of AGN fractions, and the authors shows that the AGN fraction is positively correlated with the dust temperature using a single temperature model. Unfortunately the lack of objects with lower AGN fractions ($f_{AGN, < 30\mu m} < 0.8$) in our sample makes it difficult to determine if there is such a trend.

2.5.2 Temperature power law distribution

A more physical way to characterize dust emission is by using a temperature distribution, since there is no single characteristic T that adequately describes the emission across the entire IR wavelength range. Kovacs et al. (2010) uses a power distribution of temperatures to ($dM_d/dT \propto T^{-\gamma}$)

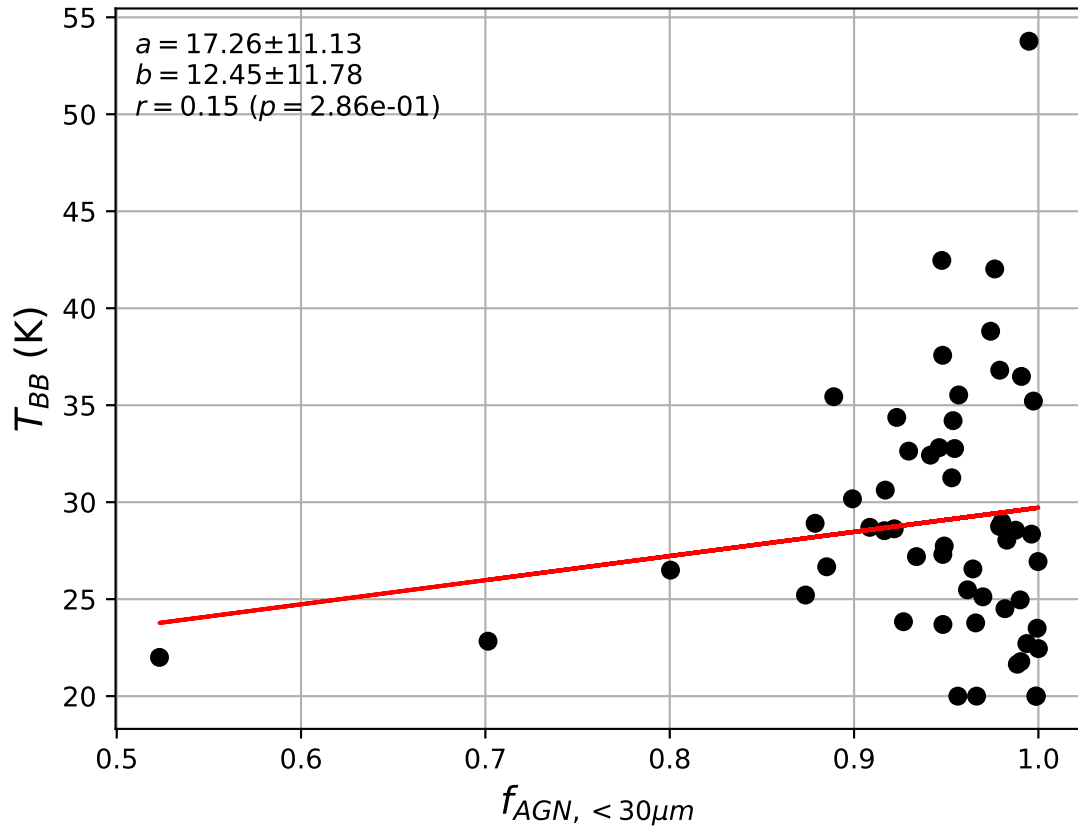


Figure 2.14: Correlation between AGN fraction $f_{AGN, < 30\mu m}$ and the blackbody temperature T_{BB} in Eq. 2.2. Red line shows the best fit.

parameterize the mid-IR emission, which in effect is very similar to using a power law parameterization of the flux. This temperature distribution dM_d/dT is used to weight the modified blackbody function $\nu^\beta B_\nu(T)$. The total flux S_ν is given by:

$$S_\nu(\gamma, T_c) = (\gamma - 1)T_c^{\gamma-1} \int_{T_c}^{\infty} \nu^\beta B_\nu(T) T^{-\gamma} dT. \quad (2.3)$$

This relation provides another two-parameter model to fit the dust emission. γ determines the relative contribution of the hot dust temperature components, and thus determines the shape of the mid-IR emission. Since the mid-IR can be represented as a combination of multiple temperature components (modified blackbody functions) of decreasing amplitude, T is well approximated by a power law distribution. For the purpose of numerical integration, we take $< 10,000\text{K}$ as the upper limit for the integral in Eq. 2.3, since we are only concerned with the mid-IR emission. T_c represents the coldest temperature dust component and this parameter governs the shape of the far-IR Rayleigh tail of the dust emission. Since both γ and α parameterize the mid-IR continuum, Figure 2.15 shows that the two are tightly correlated. Figure 2.16 shows that γ is also tightly correlated with WISE colors, and therefore this allows us parameterize the temperature distribution of hot dust using only WISE $W2 - W4$ colors. This relation is not necessarily trivial, as γ depends on a combination of both AKARI and WISE photometry.

The top histogram in Figure 2.15 shows the distribution of the mid-IR power law index α . The tight relation between α and γ shows that the mid-IR photometry can be used to constrain the radial density profile of the warm, compact dust producing the mid-IR emission. Blain (2002) measures range of $1.7 < \alpha < 2.2$ from a sample of dusty IRAS galaxies. Our measurements are centered around the same interval, but span a wider range ($1 < \alpha < 3$). Smaller values of α (i.e. flatter spectrum) are consistent with lots of warm dust, while a steep slope indicates very little dust.

The temperature distribution depends on the geometry and distribution of the emitting dust. $6.5 < \gamma < 7.5$ corresponds to emission from sources within a diffuse medium, while $4 < \gamma < 5$ corresponds to emission from a dense medium at a distance from a heating source. The side histogram in Figure 2.15 shows that γ has distribution with a median of $\langle \gamma \rangle \sim 8$, which indicates a

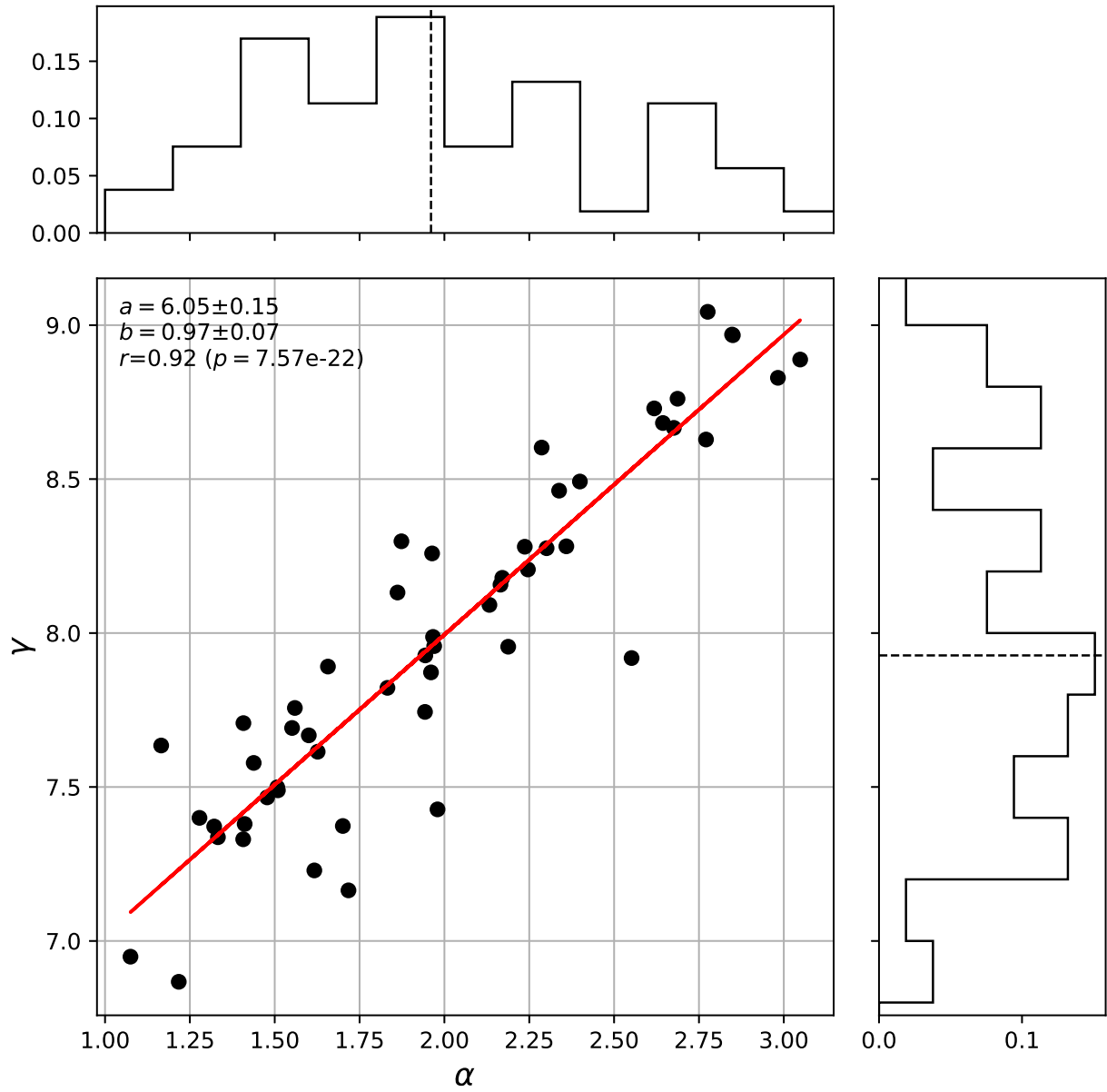


Figure 2.15: Correlation between α (mid-IR continuum power law index in Eq. 2.2) and γ (temperature distribution power law index in Eq. 2.3). Red line shows the best fit.

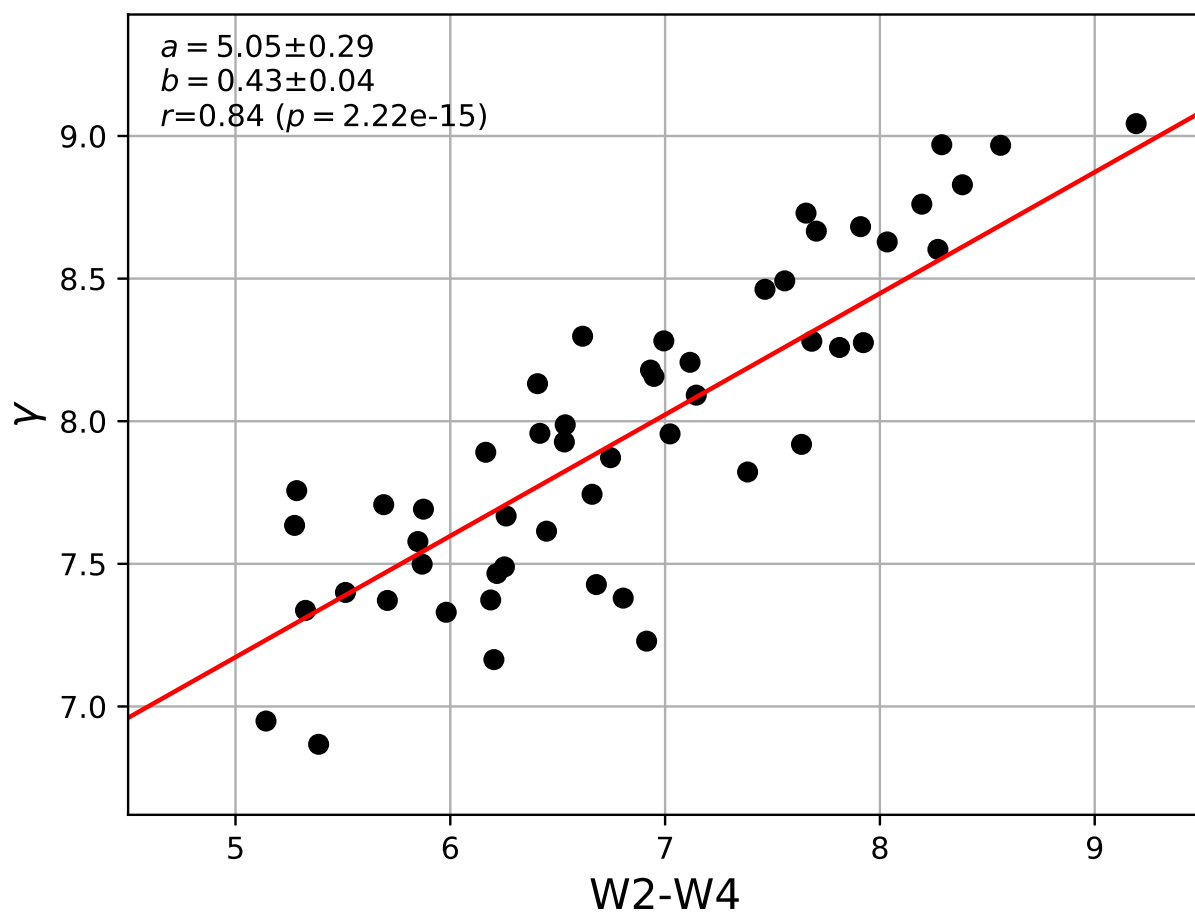


Figure 2.16: Correlation between γ (temperature distribution power law index in Eq. 2.3) and $W2 - W4$ WISE color. Red line shows the best fit.

small warm dust fraction and spatially diffuse dust distributed at farther distances from the central engine. This is not necessarily inconsistent with the compact torus model of AGN emission, since a compact dust torus can be embedded within a spatially larger, more diffuse dust mass distribution. In other words, the hot dust torus near the central AGN is heated to high temperatures (producing the mid-IR continuum), but there is also significant emission from dust at larger radii that represents the bulk of the dust mass.

Figure 2.17 shows that T_{BB} and T_c also have a tight linear correlation, and that T_c is systematically lower than T_{BB} by $\sim 8\text{-}10\text{K}$. This shows that even in the Rayleigh tail of the dust peak, multiple temperature components are required to capture the shape of the far-IR emission. Even though T_{BB} corresponds to the blackbody component centered around the far-IR peak and represents most of the far-IR emission, it does not represent the bulk of the dust *mass* in the $dM/dT \propto T^{-\gamma}$ model. Therefore, dust mass measurements using an isothermal blackbody model can potentially lead to underestimates if the coldest temperature dust components are not taken into account.

2.5.3 Correlation between AKARI fluxes and T_{BB}

Since AKARI photometry samples the far-IR peak of the SED, we can use AKARI fluxes to predict the blackbody dust temperature based on the relative flux densities in different bands. This is potentially useful for estimating the dust temperature for galaxies that have a known redshift, but lack sufficient far-IR photometry to fit an emission model to its SED. Figure 2.18 shows that the AKARI flux density ratios $\log(S_{65}/S_{140})$ and $\log(S_{90}/S_{140})$ are correlated with the blackbody temperature T_{BB} in Eq. 2.1. The linear fits are given in the form:

$$T_{BB} = a + b \log \left(\frac{S_X}{S_Y} \right), \quad (2.4)$$

where X and Y correspond to different wavelength AKARI bands. The correlation is weaker for $\log(S_{65}/S_{140})$, since the $S_{65} \mu\text{m}$ flux tends to be dominated by the mid-IR power law component of the dust model. The median power law turnover wavelength occurs at $\langle \lambda_c \rangle \sim 75 \mu\text{m}$ (representing the transition between the warm and cold dust components), so S_{90} is a better probe

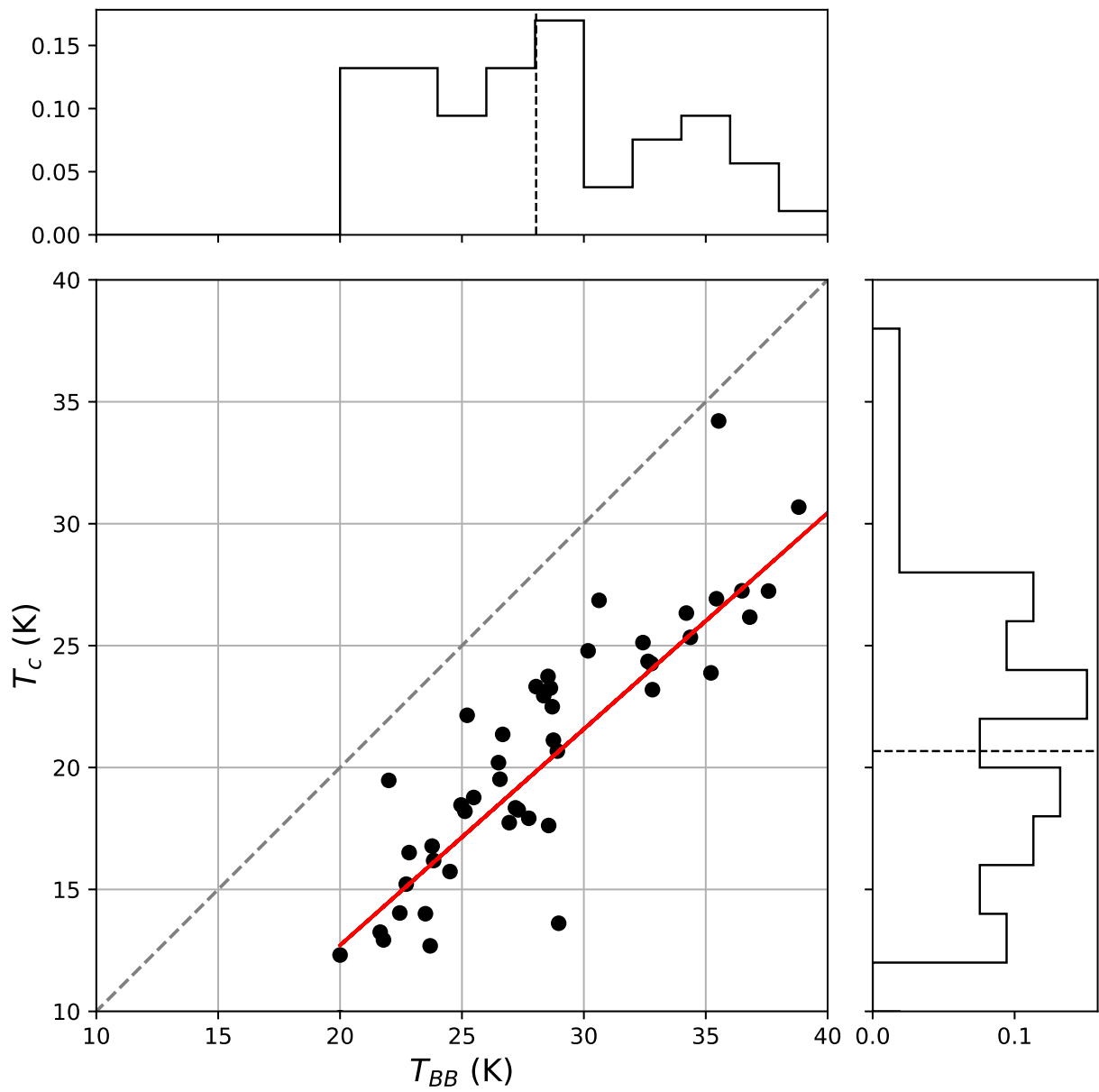


Figure 2.17: Correlation between T_{BB} (modified blackbody temperature in Eq. 2.2) and T_c (cold cutoff temperature in Eq. 2.3). The grey dashed line indicates where $T_{BB} = T_c$. Red line shows the best fit.

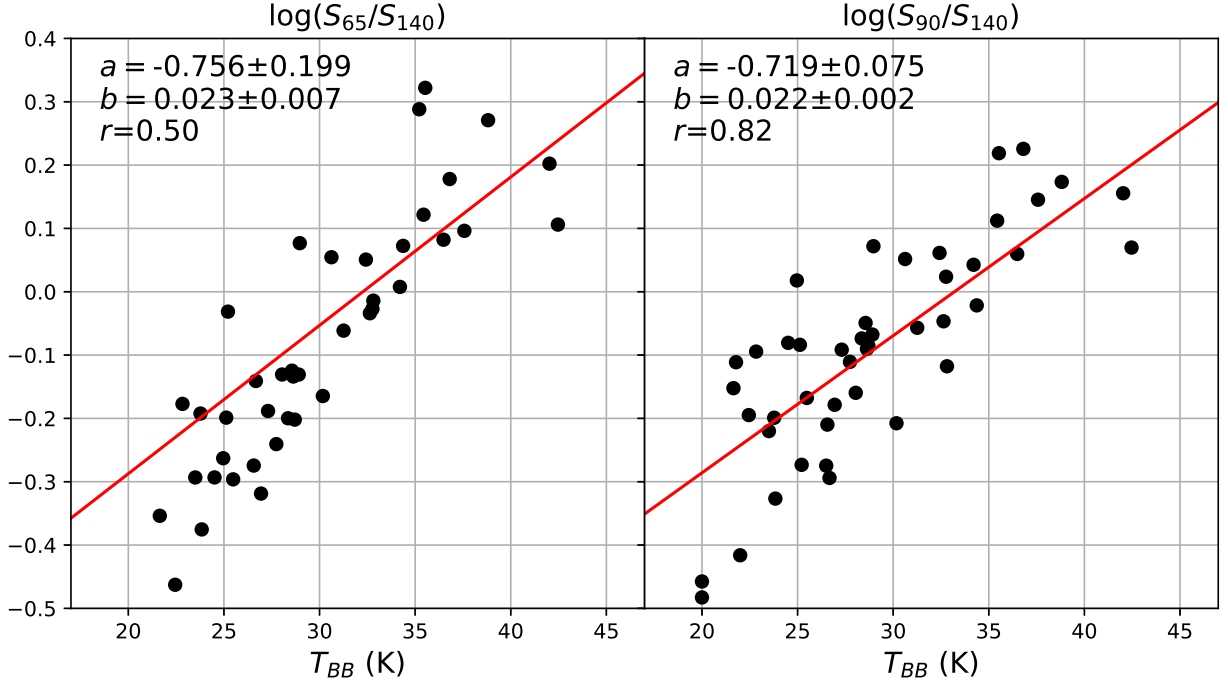


Figure 2.18: Correlation between AKARI flux ratios vs. the modified blackbody temperature in Eq. 2.1. Red line shows the best fit.

of the blackbody emission. There is also a positively correlated trend between these flux ratios and the cutoff temperature T_c in Eq. 2.3, but the scatter is large enough such that a linear regression fit is not useful for predicting T_c to any reasonable accuracy. This is not surprising, since T_c parameterizes the far-IR emission far beyond the wavelength range of AKARI. Even if AKARI flux ratios are not useful for predicting T_c , the photometry can be fit directly with Eq. 2.3 to place constraints on the parameters even if longer wavelength photometry (ex. from Herschel SPIRE) is not available.

It's important to note that our AGN sample spans a relatively narrow range of redshifts ($z < 0.15$), so the tightness of the correlation and fit parameters will likely change for a different redshift range. At higher z , this correlation will be less robust and perhaps disappear entirely since the AKARI bands will be sampling the mid-IR power law dominated region of the SED. This corresponds to $z > 0.9$, at which S_{160} falls below the characteristic power law turnover wavelength $\lambda_c \sim 75 \mu\text{m}$.

There are $N \sim 2,500$ objects in our original sample of WISE-selected AGN candidates with $W1 - W2 > 0.8$, while only $N = 56$ objects ($\sim 2\%$) have adequate far-IR photometry for direct temperature model fitting. We can use the relations in Figure 2.18 to estimate T_{BB} for the remainder of these objects. The two regression fits have nearly identical fit parameters, but we choose to use S_{90}/S_{140} since it has less scatter, and S_{90} is less likely to fall into the mid-IR power law region at higher redshifts compared to S_{65} . Figure 2.19 shows a comparison of the T_{BB} values derived from S_{90}/S_{140} for different subsets of our AGN sample. All of the distributions roughly coincide at the same T_{BB} peak. In our temperature fitting procedure, there tends to be a lack of objects with $T_{BB} < 20$ since there is less available photometry beyond the far-IR peak for most objects (likely biasing the temperature upwards). The larger WISE+AKARI sample lacking z_{photo} measurements peaks at a slightly lower T_{BB} . The primary difference between this sample and the 2MASS photometric catalog sample (with $\langle z \rangle \sim 0.1$) is that the former presumably represents objects from a higher, wider range of redshifts (i.e. beyond $z > 0.1$). At higher redshifts, the AKARI bandpasses are shifted in a way such that S_{90}/S_{140} measurements are biased towards lower temperatures.

2.5.4 IR luminosity

Using the SEDs we computed in Section 2.3, we examine the relationships between L_{IR} and other dust parameters. We adopt the convention in Jr. (1998) and define the IR luminosity to be between 8-1000 μm . Since this wavelength range represents around 70-80% of L_{bol} , most of the trends applicable to L_{IR} also holds for L_{bol} .

Figure 2.20 shows that there is a tight correlation between L_{bol} and $L_{60\mu\text{m}}$ (as well as $L_{100\mu\text{m}}$). If we assume that the far-IR portion of the SED across different objects has a consistent shape and is well modeled by the same template, then this relation is trivial. The scatter in the correlation arises from the UV to mid-IR emission that is not included in the far-IR template. Figure 2.20 also shows the fits derived by Spinoglio et al. (1995b) from a sample of $12\mu\text{m}$ selected IRAS galaxies, which are in excellent agreement with our fits. The empirical data in Spinoglio et al. (1995b) show a larger scatter, so some caution is required when applying these luminosity correlations

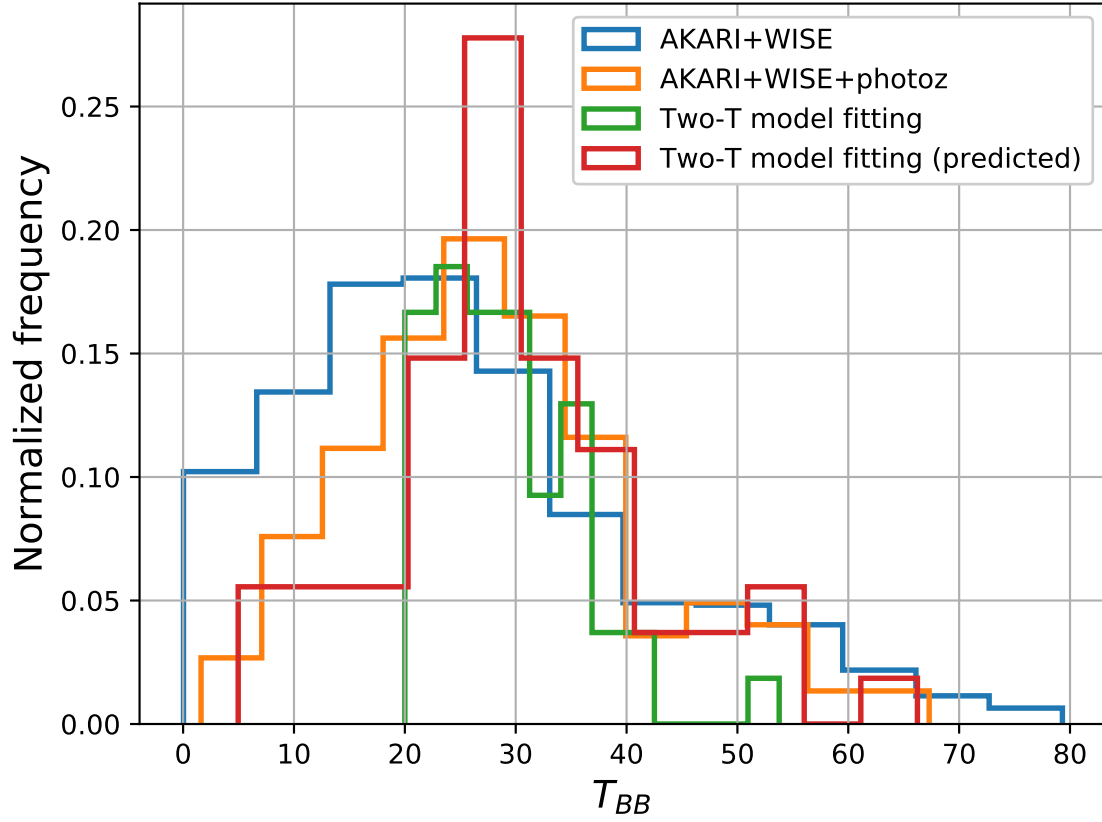


Figure 2.19: Histograms of T_{BB} values as estimated from Eq. 2.4 and the relations in Figure 2.18. The orange and blue curves show the temperatures for the AKARI-WISE AGN sample ($W1 - W2 > 0.8$) with and without 2MASS z_{photo} values, respectively. The green curve represents the temperatures fit directly to the SED with Eq. 2.2, and the red curve shows the values computed from Eq. 2.4 for the same objects.

to individual objects. Since all of our AGNs are generally well fit with the far-IR templates of Mullaney et al. (2011), it is possible that this consistency in far-IR spectral shape is a result of our sample being limited to a narrow range of redshifts and luminosities (i.e. Malmquist bias), so we need to examine a more diverse set of objects to determine to whether such a relation holds more generally.

Even though dust temperatures are best modeled by a distribution instead of a single blackbody, a single temperature cold dust component captures the bulk of the emission in the far-IR. We would then expect there to be some sort of relation between this cold dust temperature and L_{IR} , since the bolometric luminosity of a blackbody increases monotonically with T . Figure 2.21 shows the dust temperature T_{BB} (from Eq. 2.1) increases with increasing IR luminosity, consistent with trends found by Hwang et al. (2010), Elbaz et al. (2010), Amblard et al. (2010). However, our linear regression parameters do not agree with those obtained by other studies. We stress that the meaning of a dust temperature such as T_{BB} is highly dependent on the model being used (ex. number of temperature components, availability of photometry, etc) and number of photometric bands available for fitting, so comparisons with the results of other studies are difficult.

Figure 2.22 shows that there is a statistically significant positive correlation between the AGN fraction $f_{AGN, < 30\mu m}$ and the IR luminosity, which is consistent with the idea that the dust emitting in the IR is being heated by the AGN engine. Hwang & Geller (2013) also finds the same behavior for DOGs, and Veilleux et al. (2009); Lee et al. (2012); Riguccini et al. (2015) find that in general AGN contribution increases with increasing L_{IR} .

2.5.5 Warm dust mass fractions

We can integrate the power law temperature distribution $dM_d/dT \propto T^{-\gamma}$ to compute the dust mass:

$$M_d \propto \frac{A_d}{\kappa} \int_{T_c}^{\infty} T^{-\gamma} dT, \quad (2.5)$$

where A_d is the effective radiative dust area and κ is the effective dust opacity. Computing

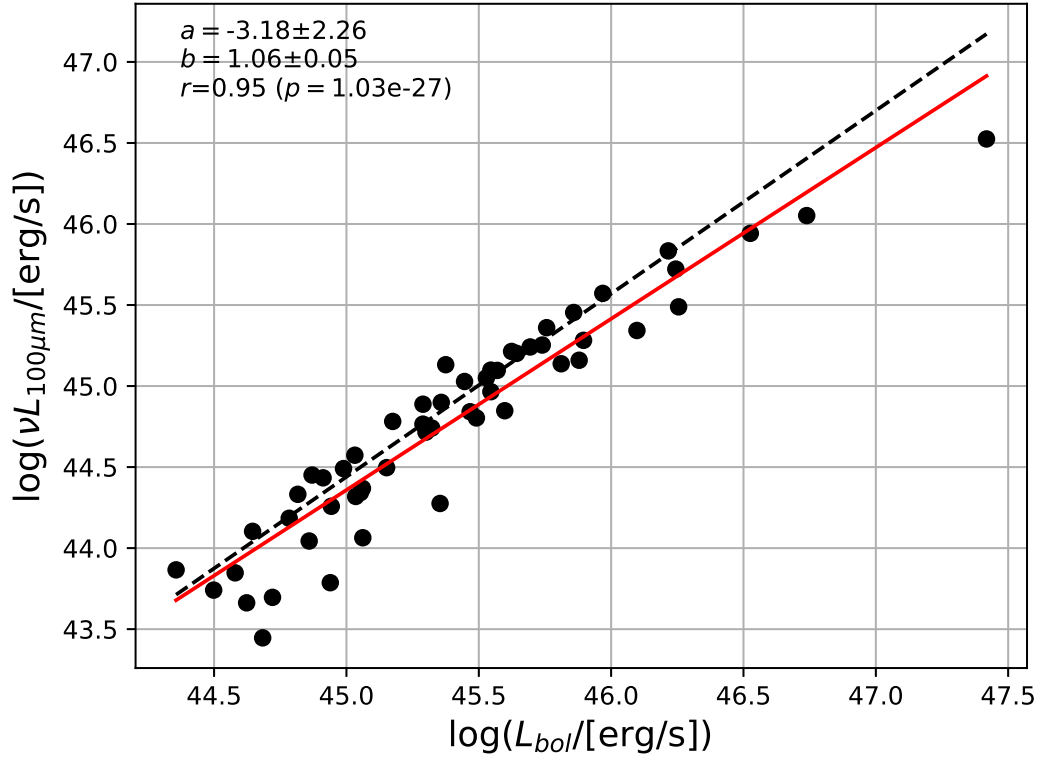
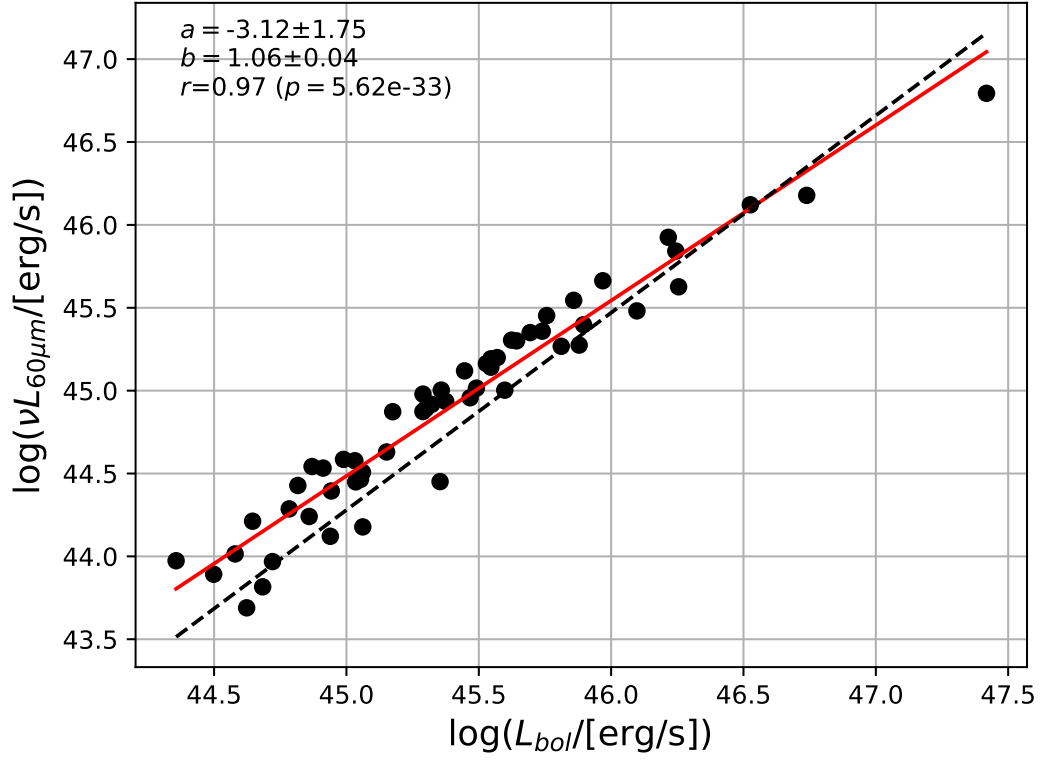


Figure 2.20: $\log(\nu L_{60\mu m})$ and $\log(\nu L_{100\mu m})$ plotted against L_{bol} . Red lines show the best fit, and the dashed lines are the relations derived in Spinoglio et al. (1995b).

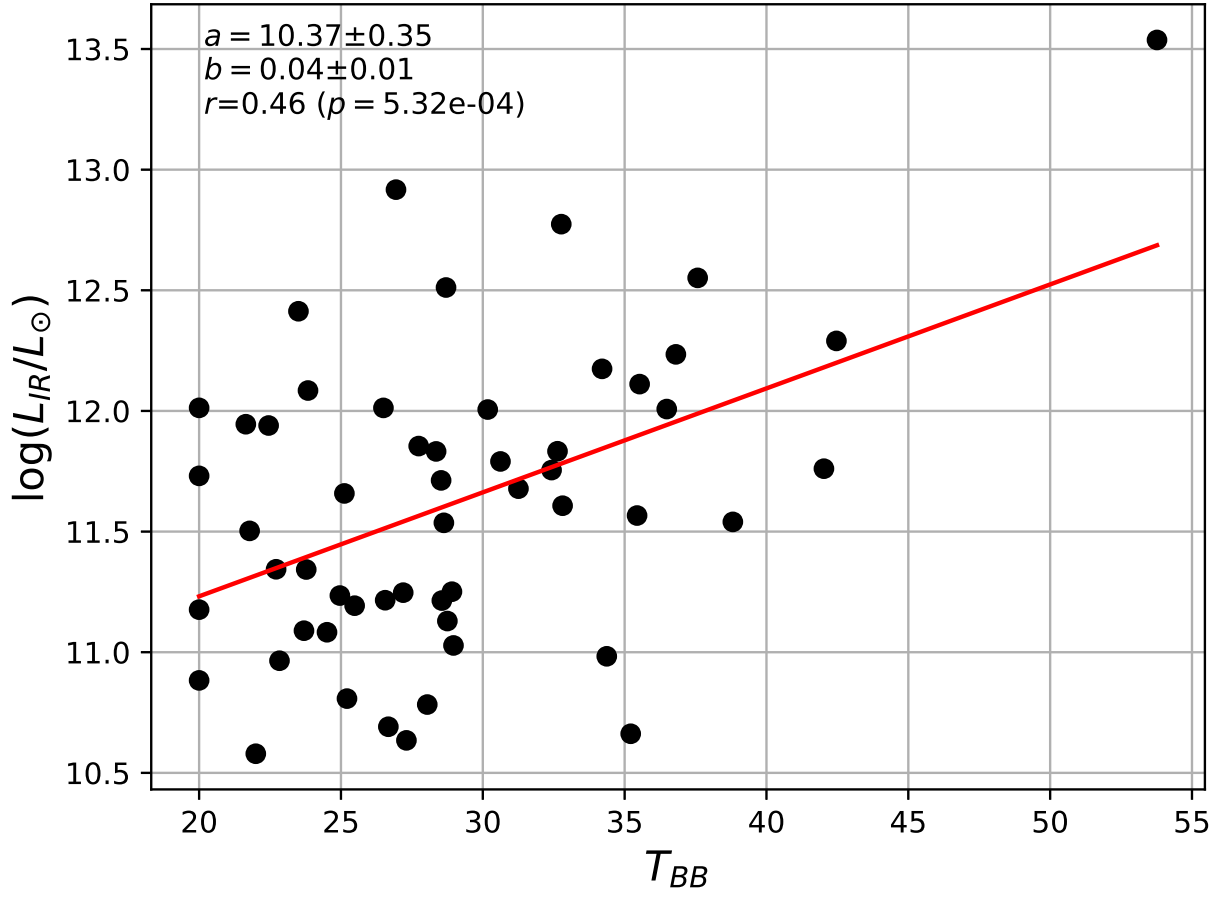


Figure 2.21: $\log(L_{IR})$ plotted against the blackbody temperature T_{BB} in Eq. 2.2. Red line shows the best fit.

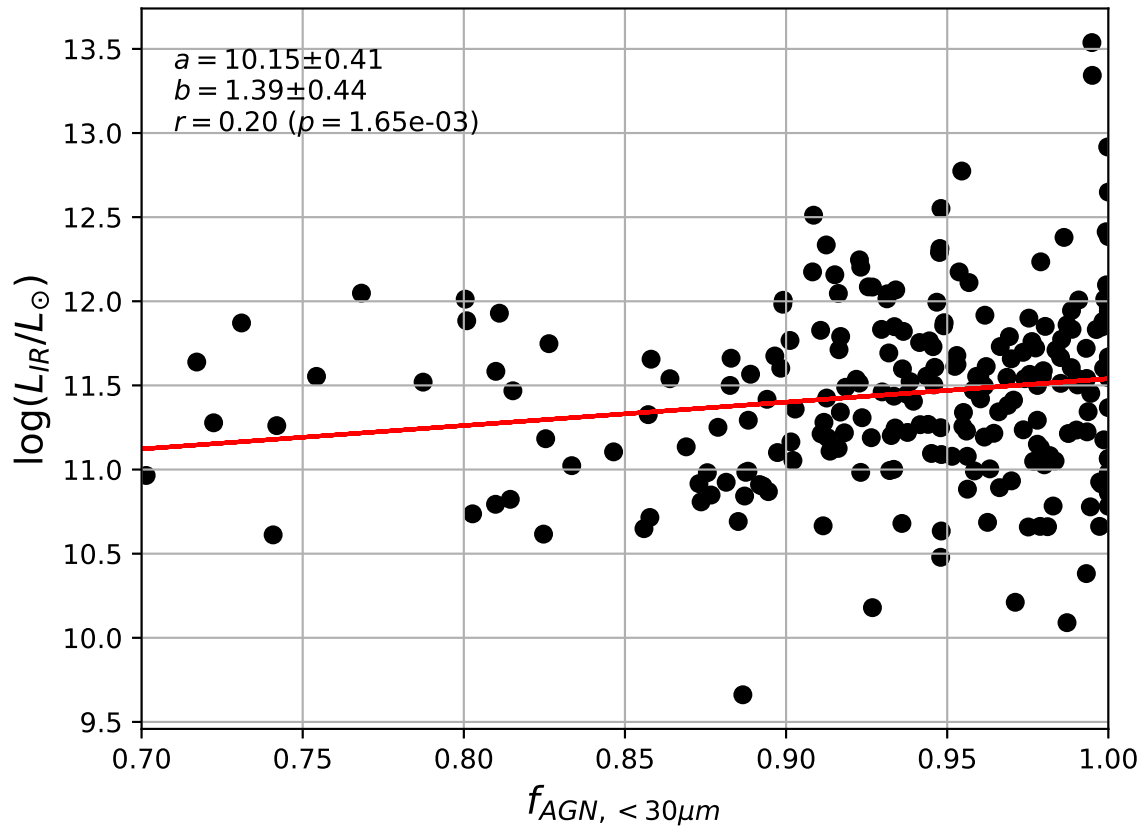


Figure 2.22: Fractional contribution of the AGN template to the total integrated SED luminosity at $< 30\mu m$, plotted against the IR luminosity. Red line shows the best fit.

absolute values for M_d is difficult because values of κ for dust tend to be highly uncertain and dependent on wavelength. There are various parameterizations for κ_ν (Scoville & Kwan 1976), but a detailed discussion of this is beyond the scope of this paper. Since we are primarily interested in seeing how the dust mass is dependent on AGN parameters and observables, we instead compute dust mass ratios, which only depend on the SED fit parameters T_c and γ . This allows for easy comparisons between individual objects and AGN populations without any assumptions regarding dust opacity models. However, this does assume that the effective dust area A_d is relatively constant across objects.

Dust mass estimates that rely on a single temperature blackbody component tend to be highly sensitive to the value of T_{BB} (Draine et al. 2007). This is even more so in the case of using a temperature power law distribution, in which the cold temperature dust masses increase without bound with T_c . Since the total mass scales with T_c as $M_d \propto 1/T_c^{-\gamma+1}$, a typical value of $\gamma \sim 8$ causes the dust mass to be highly sensitive to the measured value of T_c . This extreme dependence makes computing the total dust mass difficult, since a small uncertainty in T_c can change the mass estimate by a few orders of magnitude. Additionally, it is difficult to precisely define what the total dust mass content actually means, since the far-IR SED emission represents the dust that is heated and detectable, and does not include any colder dust that does not contribute to the emission.

Rather than estimating the total dust mass at all temperatures, we instead compute the relative fraction of warm and cold dust components given fixed temperature ranges. This leaves γ as a free parameter, which has relatively low uncertainties since the mid-IR continuum is well sampled and well fit by a power law. If we assume that each temperature corresponds to a different radius from the central AGN, knowing the relative masses of the different temperature components provides information about the radial mass distribution.

We define the warm dust mass to be $T > 50\text{K}$, and the total dust emission to be all the mass with $T > 15\text{K}$. Since the integral in Eq. 2.5 is just a simple power law, the distribution only depends on γ . The choice of temperature bounds is somewhat arbitrary, since the bounds do not affect the distribution of dust mass fractions and only shifts the fractions by a constant multiplicative factor.

Figure 2.23 shows that L_{IR} is negatively correlated with the warm dust mass fraction. In other

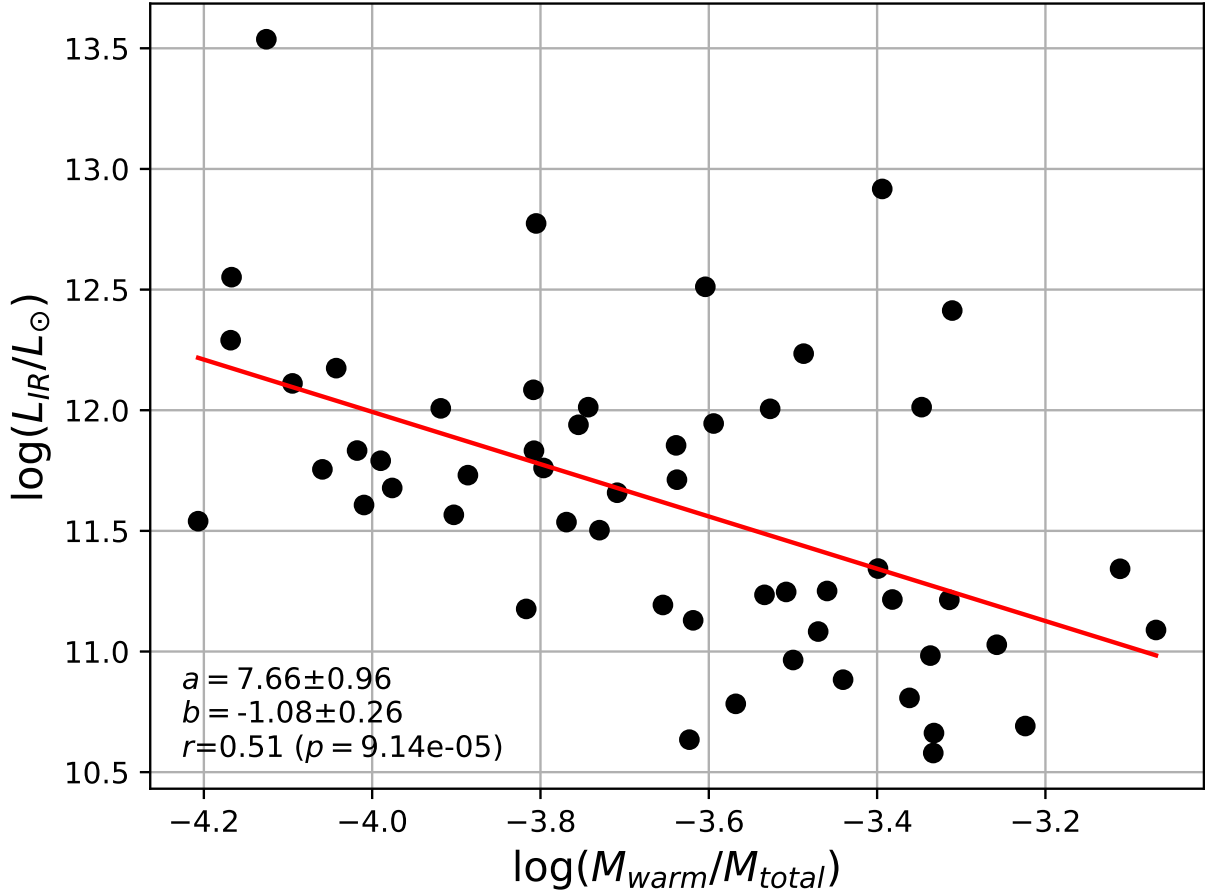


Figure 2.23: $L_{IR}/L_{\odot}$ plotted against the warm dust fraction $\log(M_{warm}/M_{total})$. Red line shows the best fit.

words, this implies that the cold dust mass fraction is *positively* correlated with L_{IR} . This supports the idea that the bulk of the IR luminosity is dominated by cold dust due to its significantly larger mass compared to warm dust. We also observe no correlation between the optical extinction $E(B - V)$ and dust mass. As discussed earlier, this is not too surprising given that the extinction likely depends on factors (ex. geometry, covering fraction, etc.) other than the total dust content. Since we have a very narrow range of AGN fractions ($f_{AGN < 30\mu m}$), we were unable to find any significant relationship between warm mass dust fraction and AGN fraction. Such a positive correlation would give support to the idea that the AGN is responsible for heating the warm dust located closer to the central engine. As was the case for AGN fraction and T_{BB} (see Figure 2.14), we would need a sample of AGNs with a wider range of AGN fractions to demonstrate this relation.

2.6 Conclusion

Using only archival photometric data and simple SED models, we have demonstrated that we can identify dust-obscured AGNs and understand their physical properties. SED analysis allows us to efficiently identify obscured AGNs without the need for time-intensive spectroscopy. Even without far-IR photometry, we have shown that mid-IR data from WISE can be used to estimate bolometric luminosities and using simple analytical models with only 3-4 parameters, we can quantify dust temperature, mass, and spatial distribution using only SED analysis. This approach greatly increases the number of AGNs we can analyze given the abundance of photometry relative to spectroscopic data, without the time and expense of obtaining the latter.

The majority of our findings regarding the nature of dusty AGNs are consistent with generally accepted AGN models. Objects that are very red in the mid-IR are dominated by an AGN component (i.e. power law behavior), and this emission due to warm dust (which is only a few percent of the total dust mass) represents a significant fraction of the bolometric flux. We find that AGNs generally have the same shape in their far-IR SEDs across different objects, which validates one of the assumptions in applying bolometric corrections to mid-IR luminosities. We have shown trends suggesting that the central AGN is responsible for heating its surrounding dust, but to demonstrate this more definitively we need to examine a sample of AGNs that have a wider range of AGN fractions. The spatial dust distribution that we infer from our dust temperature models shows that the dust is diffuse and extended, which is somewhat at odds with the standard AGN compact torus model. To examine this further, we would need to examine resolved imaging of these objects.

For future work, we should conduct this analysis on a sample of AGNs with a wider range of redshifts to see if our results hold for galaxies located beyond those in the nearby Universe. One question that remains is whether the dust temperature or warm dust fraction systematically changes with redshift. This analysis should also be performed on a sample of less luminous galaxies that we were not able to examine due to Malmquist-biased nature of our catalog. Future surveys and deeper redshift catalogs (ex. all-sky spectroscopic redshifts from the SPHEREx mission) will allow us to answer these questions.

CHAPTER 3

Mid-IR Luminosity Functions of WISE-selected Galaxies and AGNs from DEIMOS and 3D-HST

3.1 Introduction

The luminosity function (LF) is a tool to examine the distribution and evolution of galaxies over the history of the Universe. One of the key goals of studying AGNs is to understand their redshift and luminosity evolution (Croom et al. 2009; Boyle et al. 2000, 1988; Richards et al. 2006), as early studies have indicated that AGNs show strong evolution with redshift (Schmidt & Green 1983). Previous LF measurements of AGNs have been done across different wavelength bands such as the infrared (Babbedge et al. 2006; Brown et al. 2006; Matute et al. 2006) and optical (Fan et al. 2001; Wolf et al. 2003; Croom et al. 2004; Richards et al. 2006; Fontanot et al. 2006), but most of these surveys rely on optical selection criteria and potentially miss targets that are highly optically obscured.

Dust-Obscured Galaxies (DOGs, Dey et al. (2008)) and Hot Dust-Obscured Galaxies (Hot-DOGs, Eisenhardt et al. (2012); Wu et al. (2012)) are the result of dust absorbing and thermally re-emitting emission from star formation and AGN activity. IR luminous galaxies generally become more numerous at higher redshifts around $z \sim 1$ and represent a major contribution to the IR luminosity function (Calanog et al. 2013; Rodighiero et al. 2010; Caputi et al. 2007; Floc'h et al. 2005; Perez-Gonzalez et al. 2005). DOGs are classified as “bump” (star formation) or “power-law” (AGN-dominated) types depending on their SED behavior, and this spectral shape reflects the underlying mechanisms heating the surrounding dust.

AGN accretion is triggered by the merger of gas rich galaxies, and during this time the AGN

may be obscured by dust. Mid-IR emission arises from the reprocessing of gas and dust that is heated by black hole accretion, and observations of IR emission at high redshifts show strong evolution in IR luminosity density (Babbedge et al. 2006; Magnelli et al. 2009; Gruppioni et al. 2010). It has been proposed that the host galaxy of an AGN influences the growth and accretion of the central black hole (Matteo et al. 2005). The AGN LF can provide constraints on SMBH evolution (Haiman & Loeb 2001). X-ray observations show that faint and luminous AGN populations peak at different redshifts, a phenomenon known as cosmic downsizing (Barger et al. 2005; Hasinger et al. 2005). This effect seems to hold true for galaxies as well, suggesting that star formation is dependent on host galaxy mass.

The AllWISE data release (Kirkpatrick et al. 2014; Wright et al. 2010) has all-sky coverage of various types of astrophysical IR sources. Mid-IR color selection using WISE photometry provides an effective way to identify obscured AGN candidates with good reliability and completeness (Stern et al. 2012). At mid-infrared wavelengths, obscuration effects are relatively low and AGN emission produces a characteristic power law spectrum. Studies of the cosmic infrared background show that at least half the luminous energy generated by stars has been reprocessed into IR emission by dust grains (Franceschini et al. 2008). X-ray studies have shown that obscured AGNs may outnumber their unobscured counterparts by a factor of two (Bauer et al. 2010; Polletta et al. 2008).

Observational selection effects introduce different types of biases into LF measurements. In particular optical and X-ray sky surveys are biased towards detecting unobscured AGNs, which are easier to identify spectroscopically relative to their obscured counterparts. SDSS color selection identifies mostly Type 1 quasars using UV excess or Lyman break methods, but these tend to miss reddened and obscured objects since the highest redshift AGNs have their Lyman-alpha features shifted into the IR. BPT diagrams (Baldwin 1977) are also useful for separating low luminosity AGNs from starbursts based on emission line features, but it is not always easy or practical to obtain spectra that show the relevant emission lines. Having a complete sampling of dust obscured AGNs is important for models of AGN formation and galaxy feedback, as dust obscuration has been proposed to be an evolutionary phase in AGNs (Kauffmann & Haehnelt 2000). Even though mid-IR color selection has numerous advantages over other wavelengths in optimizing the completeness

and reliability of AGN samples, occasionally a lack of longer wavelength mid-IR photometry or overly restrictive photometric criteria impact the completeness of the AGN sample. Instead of looking at a single wavelength range, we can use multi-wavelength photometry to estimate the AGN contribution to the entire SED as a means of identifying AGNs in photometric data sets. Previous studies have computed mid-IR AGN luminosity functions (Goto et al. 2015; Goto et al. 2011; Caputi et al. 2007; Babbedge et al. 2006; Sanders et al. 2003; Rush et al. 1993), but the samples examined by these papers potentially miss a large number of AGNs due to their choice of selection criteria.

In this paper, we present luminosity function measurements of WISE-selected galaxies obtained from Keck DEIMOS (DEep Imaging Multi-Object Spectrograph) observations. This study uses the multi-object capacity and large field of view of DEIMOS for a high efficiency survey to obtain redshift measurements of dusty AGNs and galaxies. We also use photometric and redshift data from the 3D-HST data set to identify different samples of AGNs based on mid-IR color criteria and SED fitting, and examine the different effects of AGN selection on computing luminosity functions. In Section 3.2, we present the details of our observations of WISE-selected galaxies and AGNs using the Keck DEIMOS spectrograph. Section 3.3 details our method for computing mid-IR luminosity functions for our sample of galaxies using the $1/V_{max}$ method. Section 3.4 explains our approach in selecting different samples of AGNs based on mid-IR color criteria and SED fitting, and the luminosity functions that we compute from these samples. In Section 3.5 we show the results of computing the total IR energy density Ω_{TIR} for all of our galaxy and AGN samples. Our conclusions are presented in Section 3.6.

3.2 DEIMOS Target Selection and Observations

As detailed in Lam et al. (2018), we used Keck DEIMOS (Faber et al. 2003) for a survey of mid-IR selected obscured AGNs. We selected AGN candidates from the AllWISE photometric catalog (Mainzer et al. 2011) by choosing objects with $W1 - W2 \geq 0.8$. Mid-IR color selection effectively selects AGN candidates with good reliability and completeness, as heavily obscured AGNs

will have very red $W1 - W2$ band colors (Stern et al. 2012). We deliberately chose AGN candidates clustered within a region of the sky that falls within the area corresponding to a DEIMOS field of view ($16.7 \times 5 \text{ arcmin}^2$). The maximum number of obscured AGN candidates per DEIMOS field occur most frequently in clusters of six, and any larger clusters containing objects that satisfy the color cut are likely photometric artifacts. We also visually examined the WISE images corresponding to these selected targets to verify that they are indeed point sources.

To make full use of the multi-object capabilities of DEIMOS and obtain additional galaxy spectra, we used the remaining space in each DEIMOS slitmask to observe other WISE-selected extragalactic sources. Since the number of WISE sources contained within a DEIMOS field far exceeds the number of possible slits, we prioritized targets by their $W1$ brightness. This is to increase the likelihood that these objects will yield spectra that have a sufficient signal to noise ratio. From our initial set of observations in October 2014, we found that 75% of the sources without strong identifiable lines also do not have corresponding SDSS magnitudes. Hence, we only selected secondary WISE targets with corresponding SDSS photometry (but no pre-existing spectroscopy). We observed a total of 15 slitmasks, in which we identified 90 AGN candidates and a total of ~ 1000 WISE-selected secondary targets.

Based on the DEIMOS exposure time calculator available online, we observed each slitmask with an exposure time of 2700 seconds. This provides a good SNR for Z band magnitude of ~ 20 (AB) using a $1''$ slitwidth, 600 l/mm grating, and a central wavelength of 7500 Angstroms. To account for cosmic ray subtraction, we took three 900 second exposures for each field and combined them to create the final spectra. The data reduction was performed using the DEEP2 DEIMOS data reduction pipeline (Newman et al. 2013), which automatically performs stacking, cosmic ray subtraction, sky line subtraction, and outputs the resultant 1D and 2D spectra.

3.2.1 Redshift measurements and object classification

We used the SpecPro software package (Masters & Capak 2011) to measure redshifts and classify each object according to their spectral features. We determined the redshifts by first fitting the 1D spectra with spectral templates to identify the most probable redshift value, and visually confirming

the locations of the most prominent emission lines using the associated 2D spectrum.

In Lam et al. (2018) we presented the results of our analysis with the WISE-selected obscured AGN sample, and in this paper we focus on the secondary targets that make up the majority of our spectra obtained from that survey. Figure 3.1 shows the distribution of the $W1$ and r band magnitudes of these secondary targets. From this distribution, we find the optical flux limit for spectroscopically identifiable galaxies is $r < 24$. The brightest objects with $r < 18$ in our fields are spectroscopically confirmed stars. Since our target selection was prioritized by $W1$ brightness, this has a tendency to include a large proportion of stars. We find that as expected, galaxies with brighter optical magnitudes tend to be more likely to yield quality spectra suitable for redshift measurements. We classify objects as “unknown” if there is a detection visible in the 2D spectrum, but the 1D spectrum is too noisy to identify the object’s classification and redshift. Objects are classified as “empty” if there is no visible detection in both the 1D and 2D spectrum. The distribution of “unknown” and “empty” objects are roughly coincident in the $W1$ vs r color space. The majority of the galaxies observed in our set of secondary targets are not AGNs, since they do not appear to show any emission features indicative of AGN activity. Out of 991 DEIMOS spectra, 306 (30%) of these are galaxies/AGNs that have reliable spectroscopic redshifts.

In Lam et al. (2018), we discussed the possibility that these failures are the result of random astrometry offsets, which cause the target to be offset or misaligned from the DEIMOS slit. Our astrometry is sourced from the AllWISE catalog which has a PSF of 6” (larger than the 1” slitwidth of our DEIMOS masks), but in general the WISE astrometry has sub-arcsecond accuracy. Using a larger slitwidth to minimize slit losses is not necessarily helpful, since doing so also increases the level of sky noise in the spectrum. We found that there is no significant relationship between the astrometric offset and $W1$ magnitude. There are a few objects that have offsets $> 1''$ relative to SDSS coordinates and were likely outside the DEIMOS slit, but most of the targets were contained within their respective slits. Figure 3.1 shows that the majority of our failures occur for $r > 20$ and $W1 > 16$, although this region is also coincident with the majority of our successful detections. This indicates that source brightness is not the main factor in determining whether or not a spectrum is successfully observable. Lake et al. (2012) performed a similar survey of WISE-selected objects

using the DEIMOS spectrograph, and was able to classify $> 90\%$ of the targets with $W1 < 16$ and $i < 20.75$, and $> 50\%$ for $W1 < 18$ and $i < 23$. We find these success rates to be virtually the same for our survey.

Figure 3.2 shows a WISE color-color diagram for $W1 - W2$ vs $W2 - W3$. This distribution of objects in this WISE color space is in general agreement with the WISE color diagram presented in Wright et al. (2010). Most of the objects in our catalog do not have reliable $W3$ or $W4$ measurements ($\text{SNR} < 3$), so the objects in this plot only represent the brightest objects for which a reliable $W3$ measurement ($\text{SNR} > 3$) is available. For our sample of galaxy and AGN spectra that allow for spectroscopic redshift measurements, Fig. 3.3 shows their redshift distributions. The majority of the AGNs in our sample were selected using the $W1 - W2 > 0.8$ color cut, which tends to select AGNs with a fairly broad range of redshifts centered around $z \sim 1$. The fact that nearly all of our galaxies with z_{spec} values are at $z < 1$ is likely due to a lack of emission lines observable within the spectral range of DEIMOS for galaxies with $z > 1$.

3.2.2 SED fitting

Using available optical to mid-IR photometry from SDSS, UKIDSS, 2MASS and WISE, we fit the SEDs of each of the DEIMOS targets to determine their monochromatic IR luminosities and AGN fractions. Lam et al. (2018) shows the results of SED fitting with the DEIMOS AGN sample, and we apply this procedure to the secondary targets in the DEIMOS sample using the broadband spectral templates from Assef et al. (2010). We model each quasar as a linear combination of an AGN template and a galaxy template. We also use the extinction curves from Gordon & Clayton (1998) and Cardelli et al. (1989) to simulate the effects of optical extinction in the AGN template (see Figure 3.14 for an example of an SED fit done using this procedure using data from the 3D-HST catalog). We use spectroscopic redshifts for the fitting procedure if they are available, and photometric redshifts (see Section 3.2.3) if not. To ensure that these galaxies and AGNs have well fit SEDs, we require that there be rest-frame photometry above a $2.5\mu\text{m}$ threshold (see Section 3.4.2 for a more detailed discussion). The AGN fraction is defined to be the fraction of the integrated flux from the AGN template below $30\mu\text{m}$ (the upper limit of our spectral templates). Figure 3.4 shows

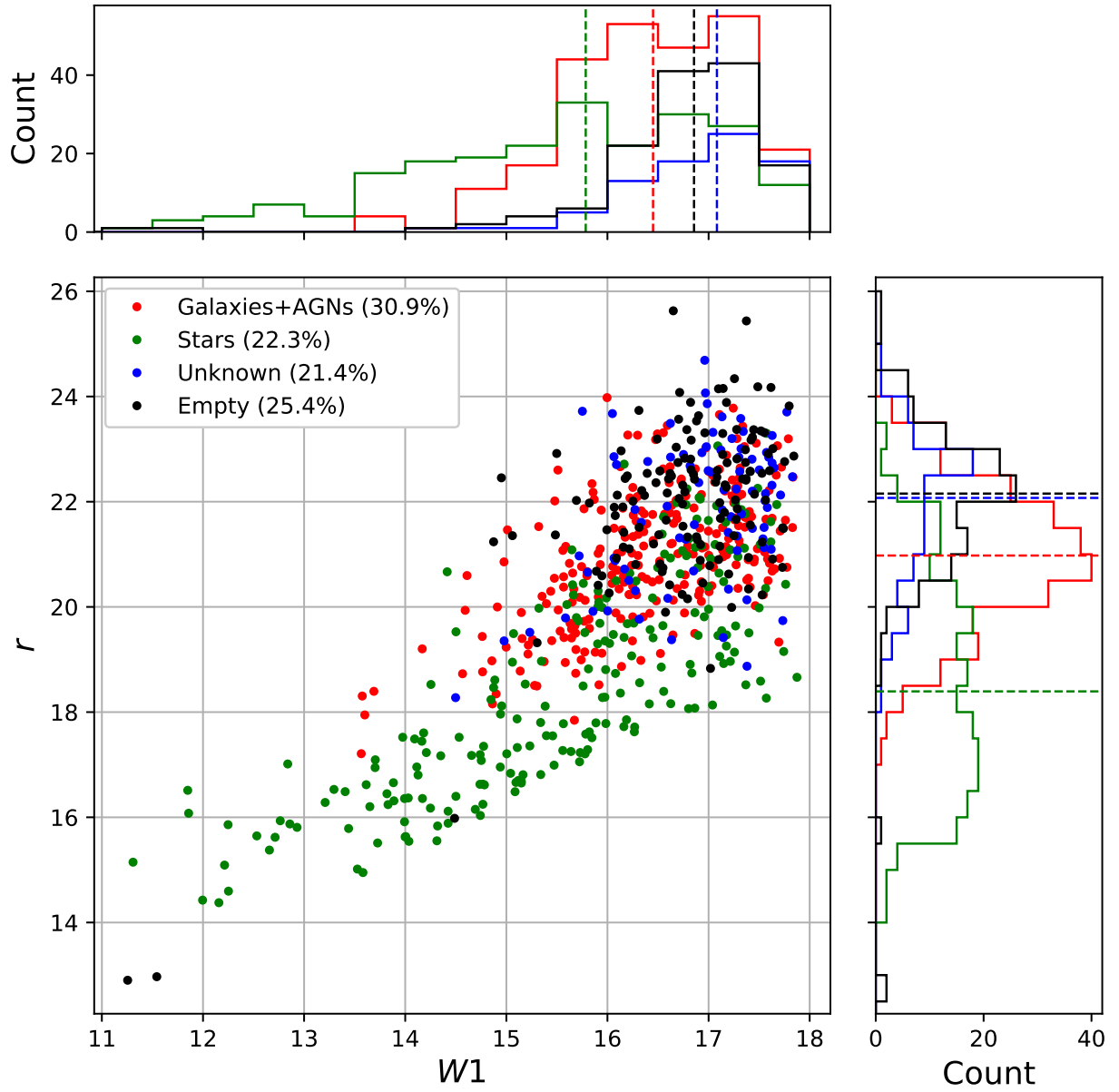


Figure 3.1: Optical r band magnitude plotted against $W1$ magnitude for our DEIMOS targets. Spectroscopically identifiable objects are classified as either stars (green), galaxies/AGNs (red). Objects with spectra too noisy for identification are labeled “unknown” (blue), and targets that are not detected are labeled as “empty” (black). The histograms on the top and side panels show the number counts of each of these populations, with the dashed line indicating the medians.

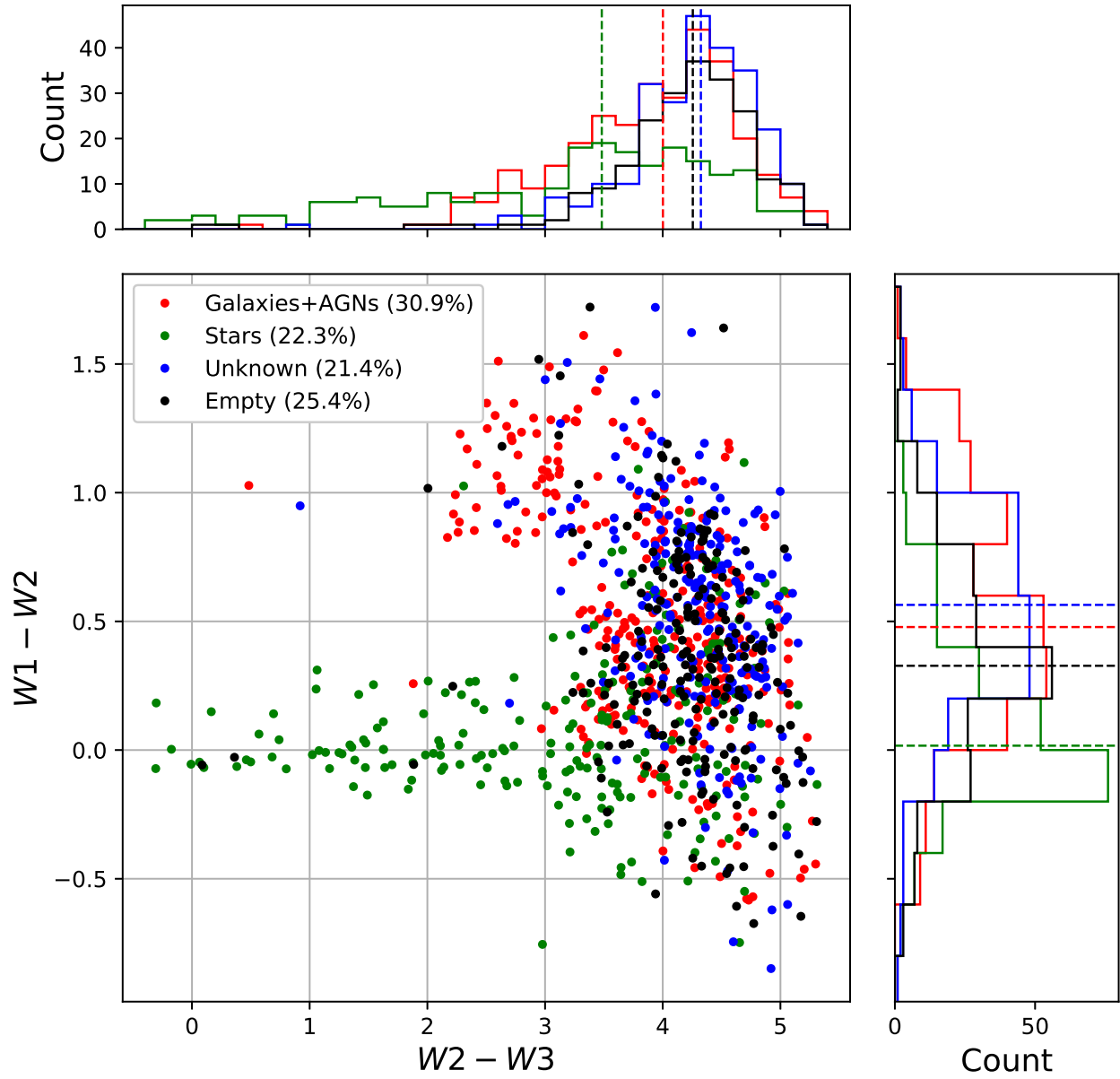


Figure 3.2: WISE $W1 - W2$ colors plotted against $W2 - W3$ colors for our DEIMOS targets. Spectroscopically identifiable objects are classified as either stars (green), galaxies/AGNs (red). Objects with spectra too noisy for identification are labeled “unknown” (blue), and targets that are not detected are labeled as “empty” (black). The histograms on the top and side panels show the number counts of each of these populations, with the dashed line indicating the medians.

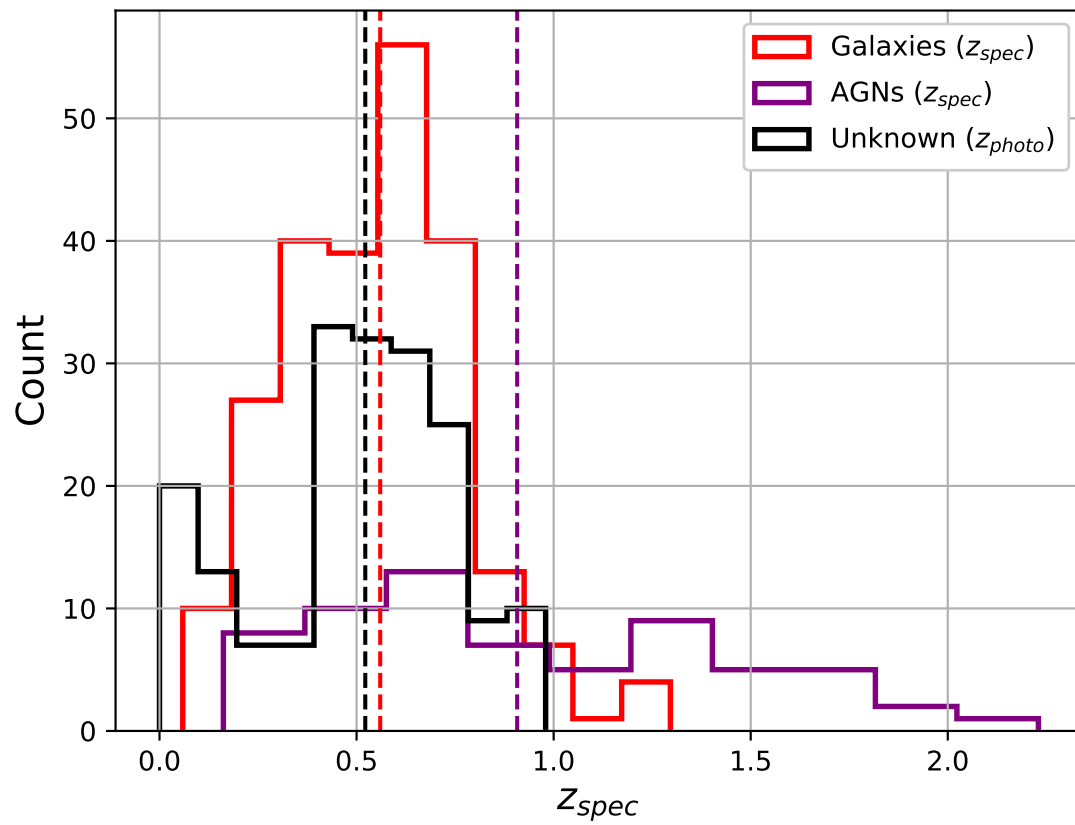


Figure 3.3: Spectroscopic redshift distribution of the galaxies (red) and AGNs (purple) in our DEIMOS sample. The black histogram denotes the photometric redshift distribution for unknown DEIMOS objects. The dashed vertical lines indicate the medians of the distributions.

the AGN fraction distribution of these galaxies and AGNs. As mentioned in Lam et al. (2018), the Stern et al. (2012) color selection tends to select objects with high AGN fractions (mostly $> 80\%$). These AGN fractions are consistent with the broad-line emission characteristic of AGNs that appear in their spectra. Since there are a number of objects in the galaxy sample that also have high AGN fractions, this seems to imply that the Stern et al. (2012) criterion is incomplete with respect to this metric as these secondary targets all had mid-IR colors with $W1 - W2 < 0.8$. Some amount of incompleteness is to be expected, since this color cut prioritizes reliability and was shown to identify 78% of a “truth” sample of Spitzer mid-infrared AGN candidates. It is also possible that there is a number of false positive AGNs in the galaxy sample due to poor SED fits that overestimate the AGN contribution if the mid-IR portion of the SED is poorly constrained. There are a number of objects that barely meet the rest-frame $2.5\mu\text{m}$ photometry threshold criterion, and some of these probably have questionable SED fits. In the absence of longer wavelength photometry in the mid-IR, it is difficult to assess this even by visually inspecting the SED. Increasing this threshold to $3\mu\text{m}$ or higher would increase the reliability of the sample by reducing the number of false positive AGNs, but this would also drastically decrease the sample size of galaxies.

We examine the spectra of the secondary targets that have high AGN fractions ($> 80\%$) to see if there are any indications of AGN spectral features (ex. broad-line emission). The majority of these spectra are noisy and do not show any clearly identifiable emission features, and as a result we are unable to obtain spectroscopic redshift measurements for most of these. The galaxies that do have redshift measurements show weak, narrow [OII] emission lines, so perhaps these may be Seyfert 2 galaxies. For objects with AGN fractions $> 50\%$, we also do not observe any clear broad-line features in the spectra that are available. Perhaps there are a number of objects that do have broad-line emission, but a large fraction of these spectra are too noisy for us to see this.

Since the Stern et al. (2012) criterion was designed to simultaneously optimize the completeness and reliability of the selected AGN sample, it should not be surprising that there is some degree of incompleteness. Indeed, the authors mention that this color cut selects 78% of Spitzer mid-infrared AGN candidates with 95% reliability. To explore this further, we examine the changes in the AGN fraction distribution of the *combined* DEIMOS AGN and galaxy sample as a function

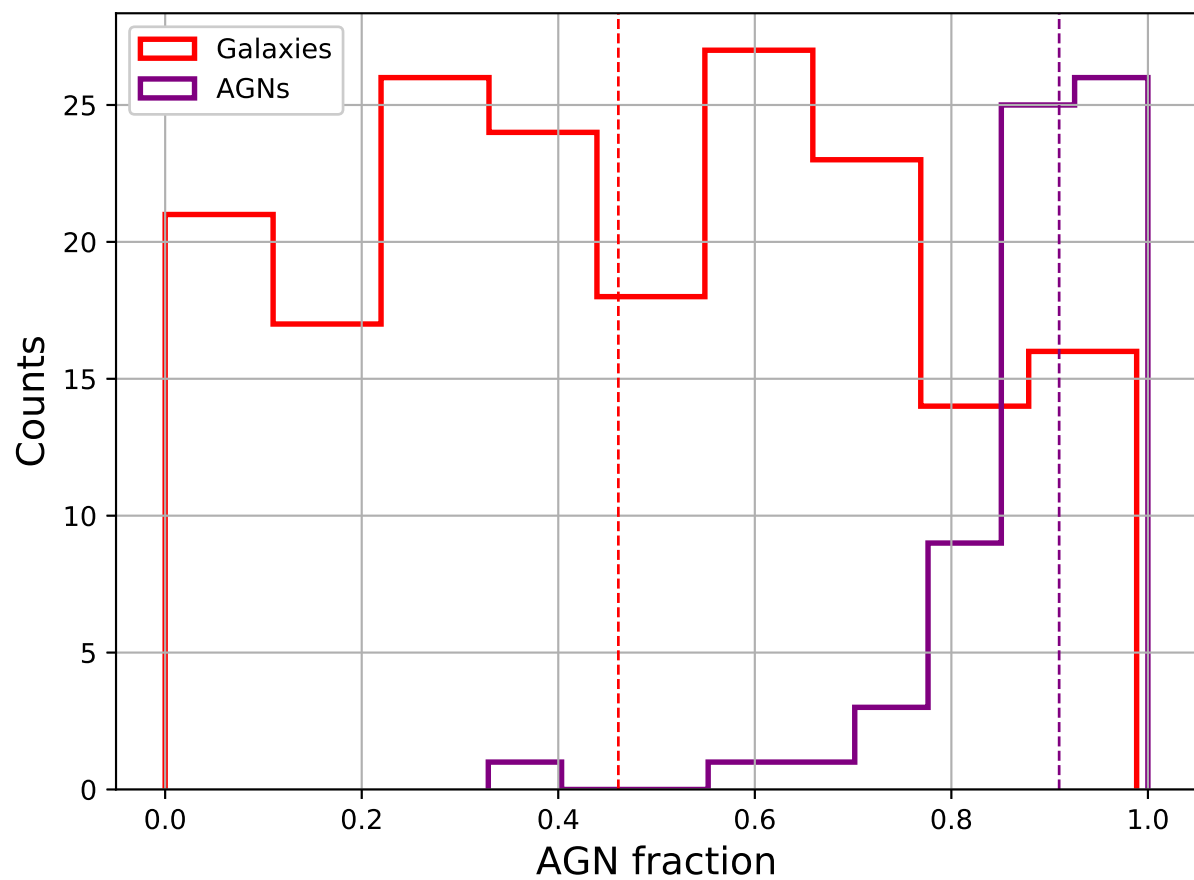


Figure 3.4: AGN fraction distributions for the AGNs (purple) and galaxies (red) in our DEIMOS sample. The dashed vertical lines indicate the medians of the distributions.

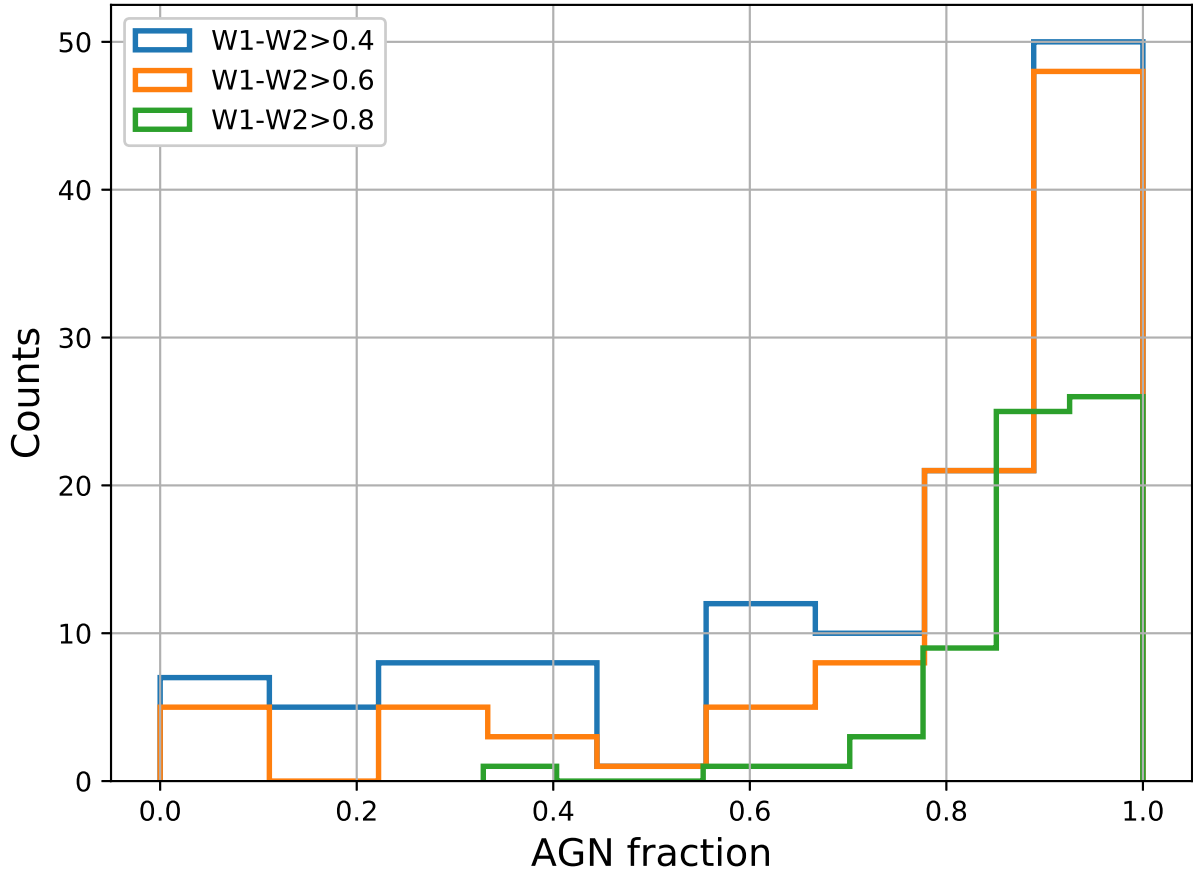


Figure 3.5: AGN fraction distribution of the combined DEIMOS AGN and galaxy sample, selected by different $W1 - W2$ color thresholds. Blue denotes $W1 - W2 > 0.4$, orange denotes $W1 - W2 > 0.6$, and green denotes $W1 - W2 > 0.8$.

of $W1 - W2$ color. Figure 3.5 shows the AGN fraction distribution of this combined sample with different $W1 - W2$ color cut thresholds. By definition, the galaxies (secondary DEIMOS targets in our survey) do not meet the $W1 - W2 > 0.8$ threshold so the green histogram in the figure represents the DEIMOS AGN sample. The histograms corresponding to the $W1 - W2 > 0.4$ and $W1 - W2 > 0.6$ thresholds show a notable increase in the number of objects with AGN fraction $> 80\%$, but also an increase in star-forming galaxy contamination. This suggests that the $W1 - W2 > 0.8$ criteria is suitable for selecting a very pure sample of AGNs, but potentially at the expense of excluding other AGNs that have bluer mid-IR colors. We elaborate more on using SED fitting to select AGNs in the 3D-HST data set in Section 3.4.2.

3.2.3 Photometric redshifts

For a large number of objects in our DEIMOS spectra, the 2D spectra indicate the presence of an object, but the 1D spectra do not show spectral absorption/emission features with a sufficiently high signal to noise ratio that allows for reliable spectroscopic measurements. To obtain redshifts for the rest of these objects, we use the LEPHARE code (Ilbert et al. 2006) to measure photometric redshifts. We run LEPHARE using the default parameters and input SDSS, UKIDSS, and WISE photometry corresponding to each of the objects. Since the majority of these galaxies are not AGNs (which are usually characterized by a featureless, mid-IR power-law continuum), the emission features in their SEDs make it easier to obtain photometric redshifts.

We use the SED templates from Coleman et al. (1980) (Ell, Sbc, Scd, Irr) and Kinney et al. (1996) (starburst) as input spectra in the LEPHARE code. We first check the reliability of photometric redshift fitting by computing z_{photo} for the sample of DEIMOS objects for which we were able to obtain spectroscopic redshifts. Fig. 3.6 shows z_{photo} plotted against z_{spec} , as well as the distribution of $\Delta z/(1+z)$ values with a catastrophic error rate of $\eta \sim 10\%$. In our initial fit, $\eta = 27\%$ of our photometric redshift measurements showed catastrophic errors (which we define to be objects with $|\Delta z|/(1+z) > 0.15$). Following the convention in Ilbert et al. (2006), we measure the accuracy $\sigma_{\Delta z/(1+z)}$ using the normalised median absolute deviation: $1.48 \times \text{median}(|\Delta z|/(1+z))$. We find that galaxies with very strong optical emission lines tend to yield poor photometric redshift fits, which is a result of the emission lines skewing the flux upwards within a single optical filter. Excluding these galaxies drastically reduces the number of outliers in our sample.

According to Ilbert et al. (2006), galaxies with especially high rates of star formation tend to account for the majority of outlier z_{photo} values. To assess the best SED template fit and classification for each galaxy, we first perform the fitting using the assigned z_{spec} . The majority of the galaxies are best fit with E/Sbc/Scd/Im templates. Fig. 3.7 shows the distribution of galaxies with “good” and “bad” z_{photo} values. The outliers have a higher fraction SB type galaxies compared to the “good” group, but otherwise show a similar distribution for the other templates. Fainter objects tend to account for a larger fraction of poorly fit z_{photo} values. Although we find that nearly 1/3 of the catastrophic outliers are fainter than $i > 21.5$, so is a significant fraction of the objects with

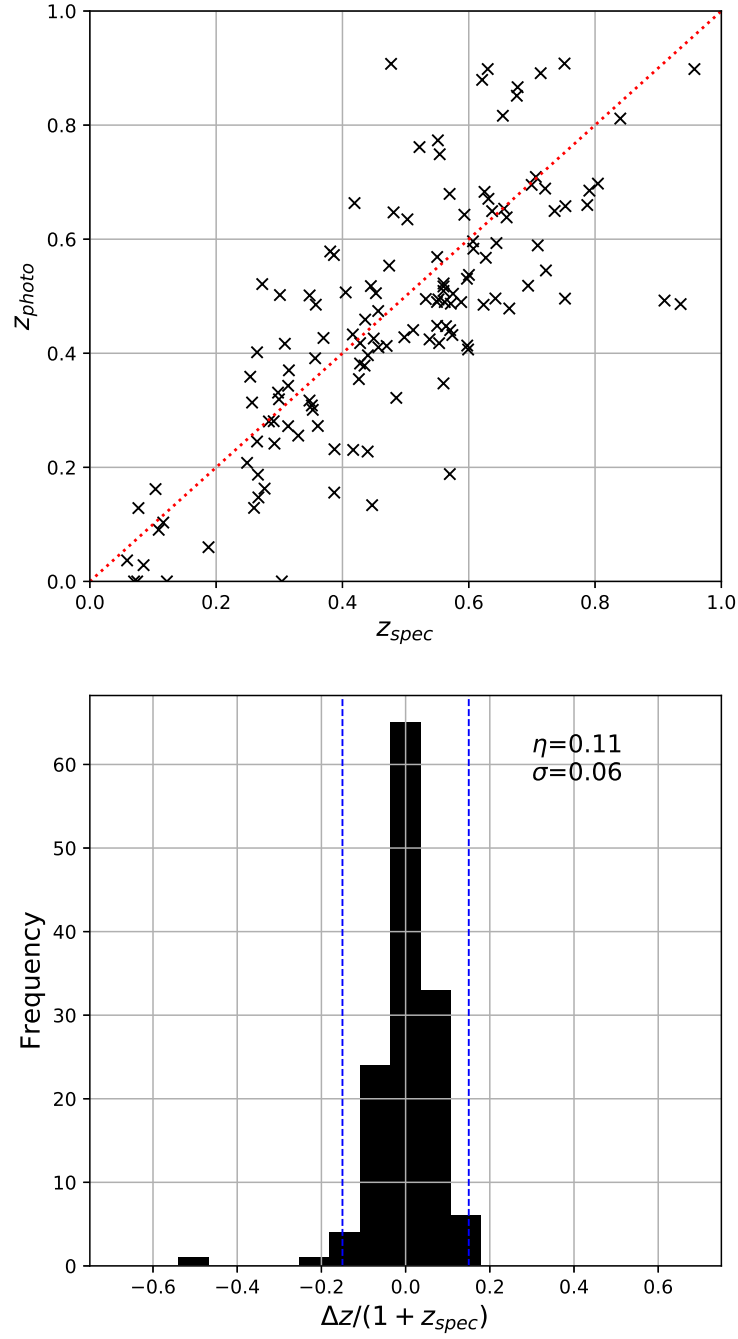


Figure 3.6: [Top] z_{photo} as measured from LEPHARE plotted against z_{spec} values from the DEIMOS galaxy sample. Red dotted line corresponds to $z_{photo} = z_{spec}$. [Bottom] Histogram of $\Delta z / (1 + z_{spec})$ values of photometric redshift measurements of the DEIMOS galaxy sample. Blue dashed lines correspond to $\Delta z / (1 + z_{spec}) = \pm 0.15$.

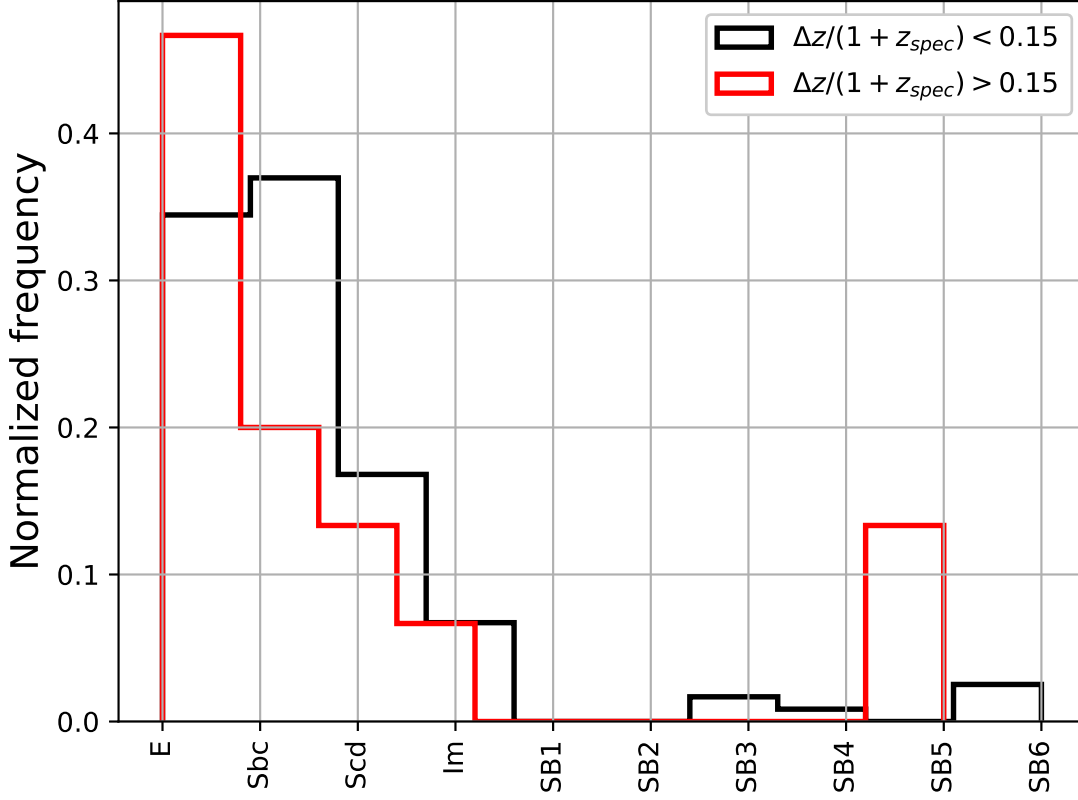


Figure 3.7: Distribution of the dominant SED templates obtained using LEPHARE for “good” ($\Delta z/(1+z) < 0.15$; in black) and “bad” (red) photometric redshift measurements based on our galaxy sample.

good z_{photo} values. Thus, making a magnitude cut will not improve the reliability of our z_{photo} sample.

We place additional constraints on the z_{photo} fitting procedure by using a $N(z)$ prior computed from the VVDS survey in the I band from Ilbert et al. (2006). Since our photometric catalog does not contain the I band we use SDSS g band for this prior instead, but the wavelength range of the two filters are sufficiently similar such that using the g band also produces a significant improvement in z_{photo} accuracy. This drastically reduces the number of catastrophic errors down to $\eta \sim 10\%$. Figure 3.3 shows the result of computing photometric redshifts for the remaining objects designated as “unknown”. Since z_{photo} tends to be unreliable for objects with $z > 1$, we discard any z_{photo} values that lie above that limit. The redshift distributions of the DEIMOS

spectroscopic galaxy sample and the photo-z sample are roughly coincident, which shows that there is no substantial biasing in using one type of redshift measurement over another.

3.3 DEIMOS Galaxy and AGN Luminosity functions

3.3.1 Computation method

We use the $1/V_{max}$ method as presented in Schmidt (1968) for luminosity function (LF) computation. This method has the advantage of computing the LF directly from data, and does not require any assumptions involving models. The LF ϕ is given by

$$\phi = \frac{1}{\Delta L} \sum_i \frac{1}{V_{max,i}} w_i, \quad (3.1)$$

where V_{max} is the comoving volume over which a galaxy is observable, ΔL is size of the luminosity bin, and w_i is the completeness correction factor. For simplicity we set $w_i = 1$ for all the luminosity bins in our calculation, although we will show that there are indeed incompleteness problems for the lower luminosity tail of the LF. Mid-IR target selection generally has a high completeness and since we are prioritizing the brightest $W1$ objects for inclusion in our survey, the higher luminosity tail of the LF tends to suffer less from incompleteness problems. We set the minimum redshift to be $z = 0.1$, since these objects represent a relatively large contribution to the LF and the errors associated with fitting z_{photo} would produce a large error in ϕ . z_{max} is the maximum redshift at which a given galaxy is detectable for a given flux limit. For a given redshift bin $z_0 < z < z_1$, $V_{max} = V(z_{max}) - V(z_0)$. In the case that z_{max} exceeds the upper limit of the redshift bin, we set $V_{max} = V(z_1) - V(z_0)$, which is the volume enclosed by the redshift bin. The DEIMOS sample of objects was selected using their $W1$ and $W2$ colors, so z_{max} is determined by the flux limit of $W2$ (the less sensitive band, with a flux limit of 0.08 mJy). The volume corresponding to an object at redshift z is given by

$$V(z) = \frac{4\pi}{3} \frac{\Omega_s}{\Omega_{sky}} d^3(z), \quad (3.2)$$

where Ω_s is the area of the sky covered by our survey, $\Omega_{sky} = 4\pi$ is the area of the entire sky, and $d(z)$ is the comoving distance to the object

We use the results of our SED fits to interpolate the $8\mu\text{m}$ luminosity for the galaxies in our sample. The $8\mu\text{m}$ luminosity is commonly used for LF measurements, as it also correlates with other AGN properties such as central black hole mass (Weedman et al. 2012) and total IR luminosity (Babbedge et al. 2006; Huang et al. 2007; Goto et al. 2011). The $8\mu\text{m}$ LF has also been computed from samples of galaxies in other fields of the sky that have been sampled by multi-wavelength observations (ex. the GOODS field by Caputi et al. (2007), and the SWIRE field by Babbedge et al. (2006)). Since computing the $8\mu\text{m}$ luminosity requires the mid-IR portion of the SED to be well sampled, we exclude any objects that lack $W2$ band measurements in our LF computation. That is, we are assuming that the $8\mu\text{m}$ flux can be reliably inferred through SED fitting based on the $W1$ and $W2$ photometry, as the majority of our objects do not have $W3$ photometry.

We divide our galaxy sample into two redshift bins ($z < 0.55$, $z > 0.55$) split into roughly equal sample sizes. Since our total galaxy sample size is relatively small and we are primarily interested in looking at the luminosity evolution of our sample, we choose a relatively large redshift bin such that the number of objects in each bin is roughly the same. Figure 3.8 shows the $8\mu\text{m}$ luminosity function divided into the z_{spec} and z_{photo} samples. Within each redshift bin, the general shape of the LF between the z_{spec} and z_{photo} samples are in good agreement with each other. Since the sample sizes are relatively small, the errors in the high luminosity bins are very large and does not necessarily imply that there is any significant discrepancy in the slopes of the blue curves. As a result, we do not expect there to be any significant biases introduced by combining the two subsets of galaxies into one sample for the purposes of LF computation. Figure 3.9 shows the $8\mu\text{m}$ luminosity function for the combined (spectroscopic and photometric redshift) galaxy sample.

The turnover in the upper redshift bin in Figure 3.8) suggest that our sample suffers from incompleteness at lower luminosities. This can be due to several factors. In the $1/V_{max}$ method, a very obscured galaxy would have a detectable volume of zero, and therefore would not be included in the LF. However, since our targets are mid-IR selected we do not expect obscuration to affect our LF computation to the extent that it affects optical LF surveys. Since we are including both the z_{spec}

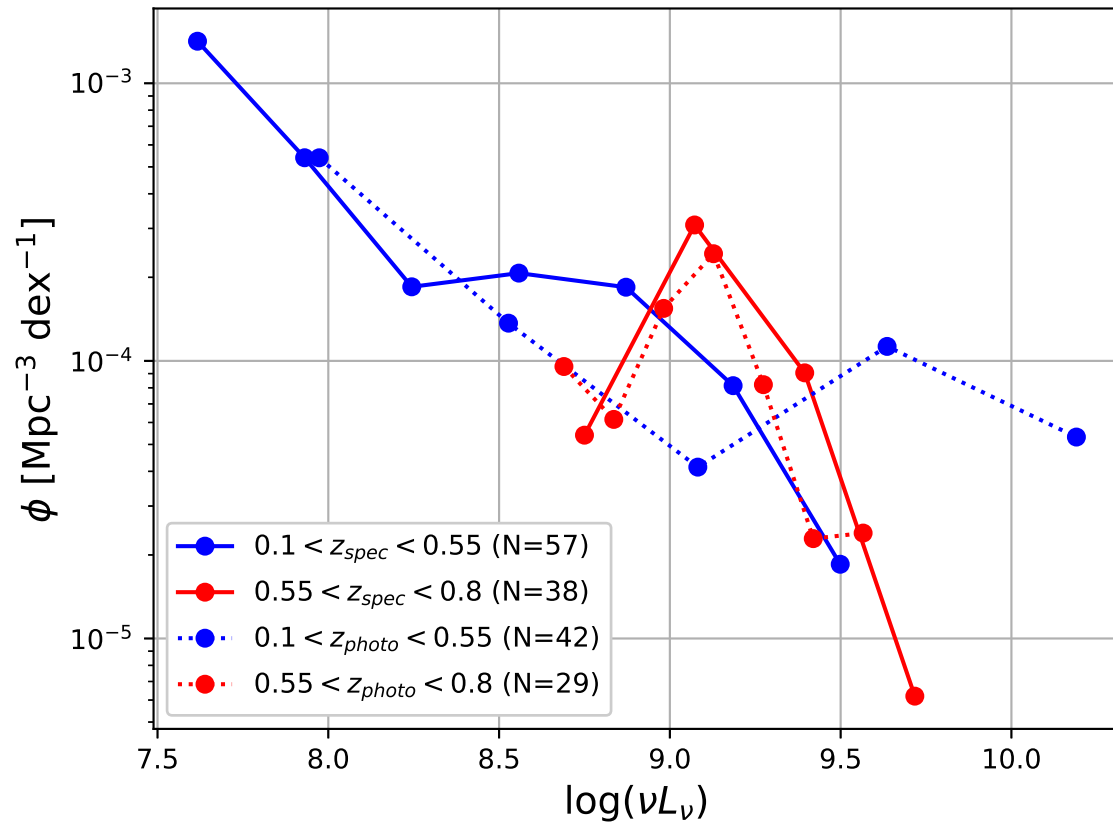


Figure 3.8: Comparison of the 8 μ m luminosity function between the z_{spec} (solid line) and z_{photo} (dotted line) DEIMOS galaxy samples, divided into two redshift bins (indicated by blue and red).

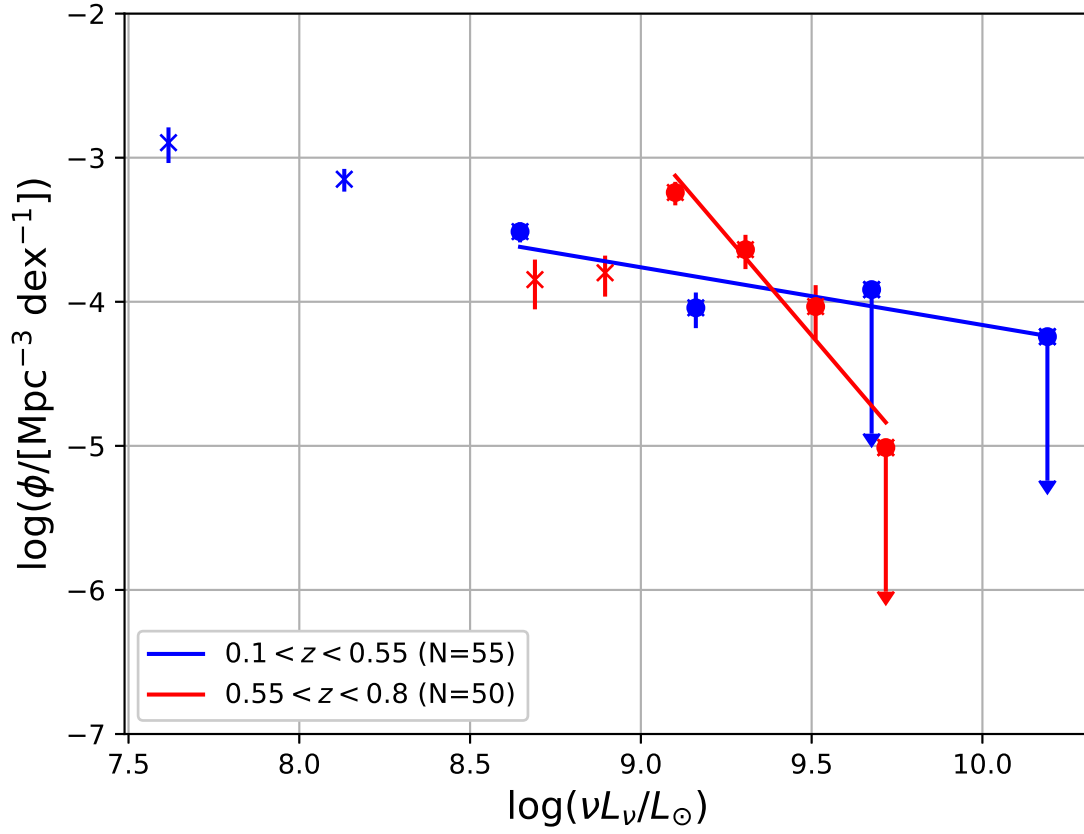


Figure 3.9: 8 μm luminosity function derived from combining the z_{spec} and z_{photo} DEIMOS galaxy samples, divided into two redshift bins (blue and red curves). Solid points indicate points used in the LF fitting, while crosses indicate the points that were excluded from the fits. Vertical bars show the $1/\sqrt{N}$ Poisson errors. Arrows are marked on bins with $N < 4$ objects and indicate that the point is an upper limit.

and z_{photo} , there are no objects being excluded due as a result of non-detections by DEIMOS. In other words, the flux limit of the DEIMOS spectrograph is not the limiting factor here. Instead, the main limiting factor is likely the density of sources that can be fit on a DEIMOS slitmask, since the number density of WISE sources is a few times larger than the density of sources that we were able to observe per mask. Since we were prioritizing targets by $W1$ brightness, the faintest IR sources were not selected for inclusion in our final target list. Sources with extremely red mid-IR colors that result in a low $W1$ flux were probably not included as well. For a more complete survey with DEIMOS that better samples the faint end of the LF, it would be better to use a smaller slitlength (ex. $1'' \times 7''$ instead of the default $1'' \times 10''$) to accommodate more targets per slitmask. At high luminosity end of the galaxy LF, we would normally expect that there be a steep decline typical of a Schechter function. This lack of a steep drop-off could be due to contamination from luminous AGNs, since we were not able to spectroscopically classify a large number of the objects and some of these could be AGNs that have not been identified. Figure 3.10 shows the $8\mu\text{m}$ luminosity function for the AGN sample. As we expect the error bars are particularly large for these samples since they have relatively small sample sizes.

3.3.2 LF fitting and parameters

Since our galaxy sample size and number of luminosity bins is relatively small, we are not able to simultaneously fit several parameters for a luminosity function. Instead, use fit parameters from luminosity functions derived from other data sets and compare these with our data. We use the results of Goto et al. (2015), in which mid-IR selected galaxies from the AKARI NEP deep field are used to compute IR luminosity functions. The LFs are fit using a double power law from Babbedge et al. (2006) of the form:

$$\Phi(L)dL/L^* = \Phi^* \left(\frac{L}{L^*} \right)^{1-\alpha} dL/L^*, \quad (L < L^*), \quad (3.3)$$

$$\Phi(L)dL/L^* = \Phi^* \left(\frac{L}{L^*} \right)^{1-\beta} dL/L^*, \quad (L > L^*). \quad (3.4)$$

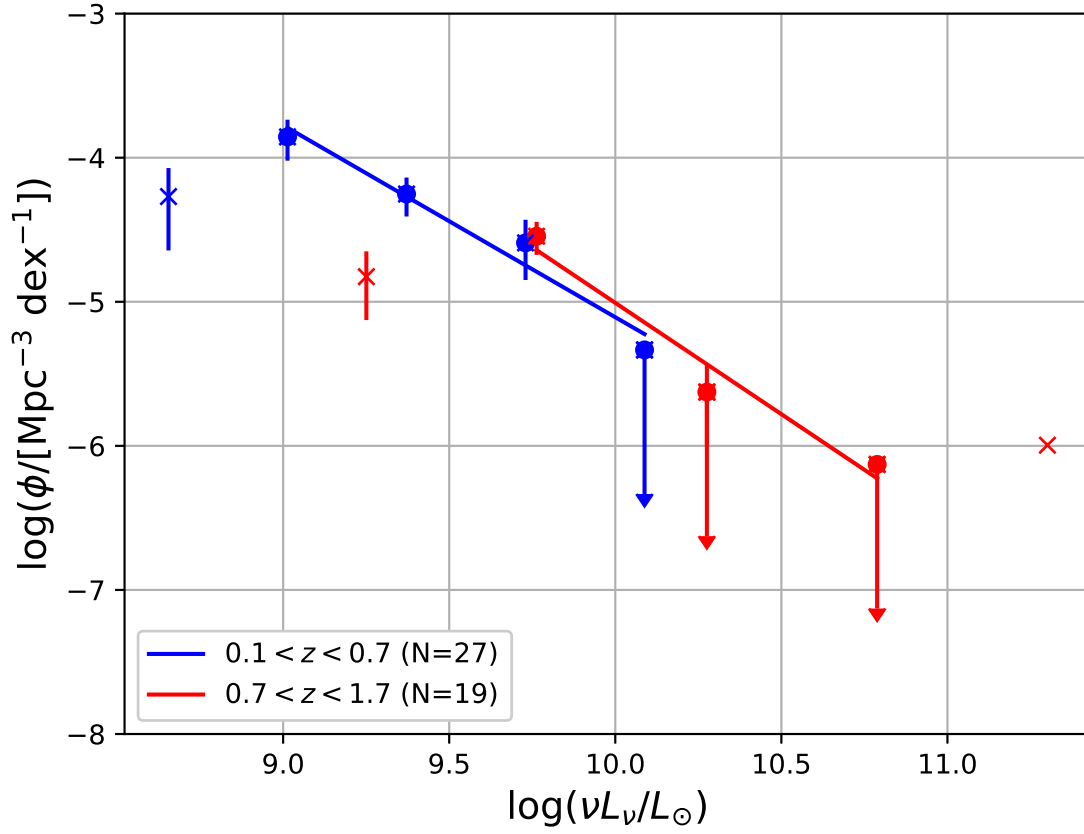


Figure 3.10: 8 μm luminosity function derived from the DEIMOS AGN sample, divided into two redshift bins (blue and red curves). Solid points indicate points used in the LF fitting, while crosses indicate the points that were excluded from the fits. Vertical bars show the $1/\sqrt{N}$ Poisson errors. Arrows are marked on bins with $N < 4$ objects and indicate that the point is an upper limit.

We take L^* to be a fixed parameter using the values given in Goto et al. (2015) since the low luminosity end of the LFs are generally not well sampled and highly incomplete, so this parameter is difficult to constrain accurately with our data. For the double power-law form of the LF, we fix $\alpha = 1.2$ but leave β and Φ^* as free parameters. Using different functional forms is useful for comparing parameters with the results of other LF studies in the literature, although the same set of data can be fit with different functions. Arguably the most important aspect is not the particular functional form, but rather being able to integrate over the shape of the LF in order to compute the total IR energy density Ω_{TIR} , which we discuss in more detail in Section 3.5. In the literature, IR LFs were fit better by a double-power law (ex. Babbedge et al. (2006)) or a double-exponential (ex. Floc'h et al. (2005)) than a Schechter function, which declines too steeply at high luminosities and underestimates the number of bright galaxies. Table 3.3 gives a summary of the LF fit parameters for the DEIMOS AGN and galaxy subsamples. As a measure of completeness, we use the V/V_{max} test. If the average ratio of V/V_{max} is $\langle V/V_{max} \rangle = 0.5$ for a sample, then the sample can be regarded to be complete (assuming a constant space density). Deviations from this value indicates incompleteness, and we list the values for each sample and redshift bin in Table 3.3.

3.3.3 Differential number counts and completeness

We define $N(m)$ to be the number of galaxies per unit apparent magnitude per unit solid angle. Figure 3.11 shows the differential number counts dN/dS for the $W1$ band for the AGNs, galaxies, and stars in our sample. To account for the proper normalization, we divide the number counts in each bin by the total area observed across all our DEIMOS slit masks ($15 \text{ slitmasks} \times 16.7' \times 5' \sim 0.35^\circ$). The AGN sample shows completeness down to a flux of ~ 0.5 mJy (with a spurious value in the highest flux bin), and the galaxy sample shows completeness down to ~ 0.04 mJy. This order of magnitude discrepancy in the completeness flux levels suggests that many faint galaxies were instead true AGNs that were misclassified. Since these faint galaxies did not yield any useful spectra, we are unable to definitively confirm if this is the case. However, this misclassification would be consistent with the high AGN fractions contained in the galaxy sample seen in Figure 3.4.

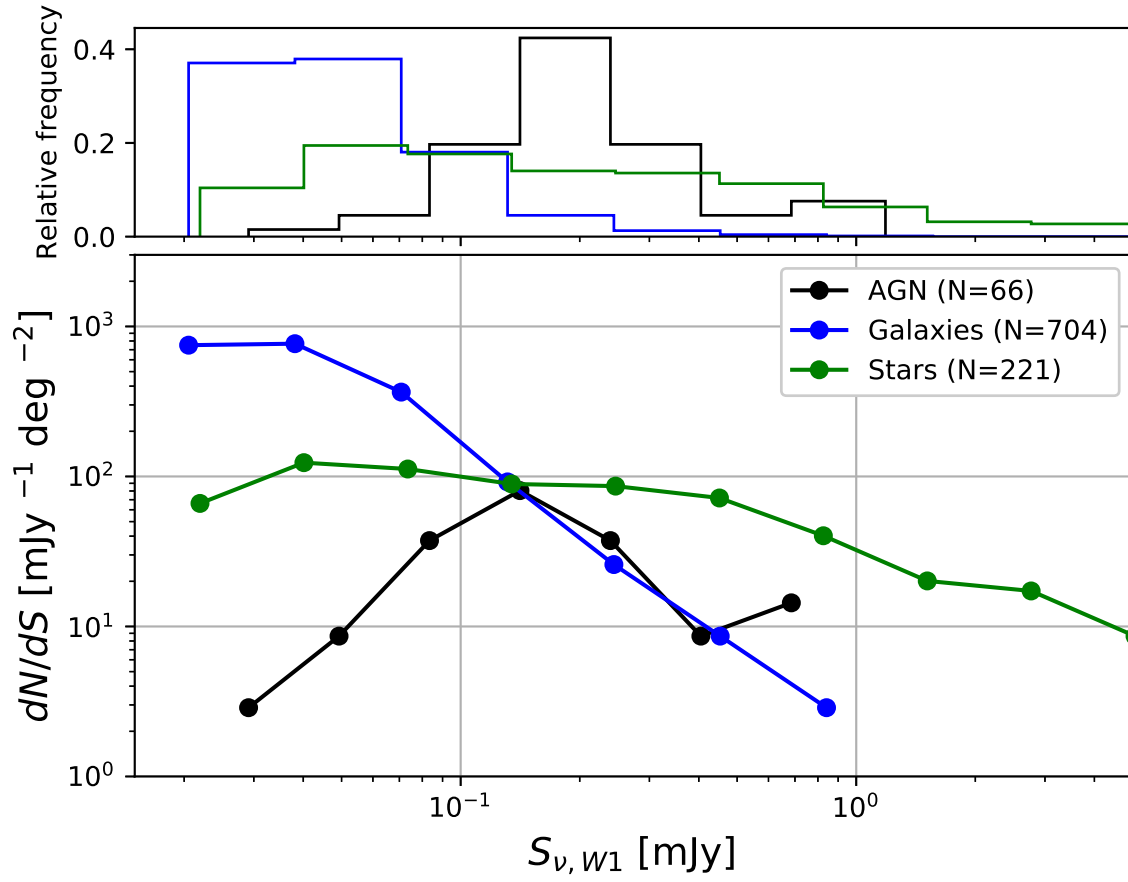


Figure 3.11: Differential number counts dN/dS of AGNs (black), galaxies (blue) and stars (green) in the WISE $W1$ band. Top panel shows a histogram of the relative frequencies of the objects in each flux bin.

3.4 3D-HST Survey: AGN and Galaxy Sample

As a comparison to our results obtained from DEIMOS survey, we use the photometric and redshift catalogs of 3D-HST survey (Skelton et al. 2014; Brammer et al. 2012) to examine the properties of the AGNs and galaxies contained therein. The combined fields (AEGIS, COSMOS, GOODS-N, GOODS-S, and UDS) have a total of $\sim 208,000$ objects over an area of 626 arcmin^2 . $\sim 100,000$ objects have spectroscopic redshifts measured from corresponding grism spectroscopy, and the catalog also includes photometric redshifts measured using the EAZY code (Brammer et al. 2008). The sky density of objects in the 3D-HST catalog is $\sim 3/\text{arcmin}^2$. In comparison, our DEIMOS survey had a sky density of $\sim 1/\text{arcmin}^2$, whereas the WISE catalog has an all-sky average density of $\sim 5/\text{arcmin}^2$. Using the larger, deeper 3D-HST catalog will allow us to estimate the completeness corrections to our DEIMOS luminosity functions.

The majority of objects in the 3D-HST catalog do not have corresponding WISE photometry since the 3D-HST survey depth extends beyond the WISE detection limits. Only $\sim 5\%$ of the sources in the catalog have corresponding $W1$ photometry. Instead of WISE, we use mid-IR photometry from the Spitzer Infrared Array Camera (IRAC). The $3.6\mu\text{m}$ and $4.5\mu\text{m}$ photometry in the 3D-HST fields come from the Spitzer Extended Deep Survey (SEDS, Ashby et al. (2013)), while the $5.8\mu\text{m}$ and $8.0\mu\text{m}$ come from the the Extended Groth Strip (EGS, Barmby et al. (2008)). The IRAC photometric bands have sensitivities of $1.6/3.1/20.8/26.9 \mu\text{Jy}$ in the $3.6/4.5/5.8/8.0 \mu\text{m}$ bands, respectively. The IRAC 3.6 and 4.5 bands are especially convenient since they are similar to the WISE $W1$ and $W2$ bands, but there are slight differences in central wavelengths and transmission curves between the two telescopes. The Stern et al. (2012) $W1 - W2 > 0.8$ color cut was originally based on an analysis of the WISE and IRAC colors for a sample of AGNs in the COSMOS field, and the authors find a median offset of $W1 - [3.6] = -0.01$ and $W2 - [4.5] = -0.07$ between the WISE and IRAC bands. The 3D-HST photometry are provided in fluxes normalized to a zero-point of AB magnitude 25, so we convert these to equivalent WISE $W1$ and $W2$ Vega magnitudes by using the offsets $W1_{AB} = W1 + 2.683$ and $W2_{AB} = W2 + 3.319$. For the purpose of selecting galaxies and AGNs, we only use objects with the `use_phot=1` flag in the catalog (see Skelton et al. (2014) for a more detailed description) to select objects that are not stars, and

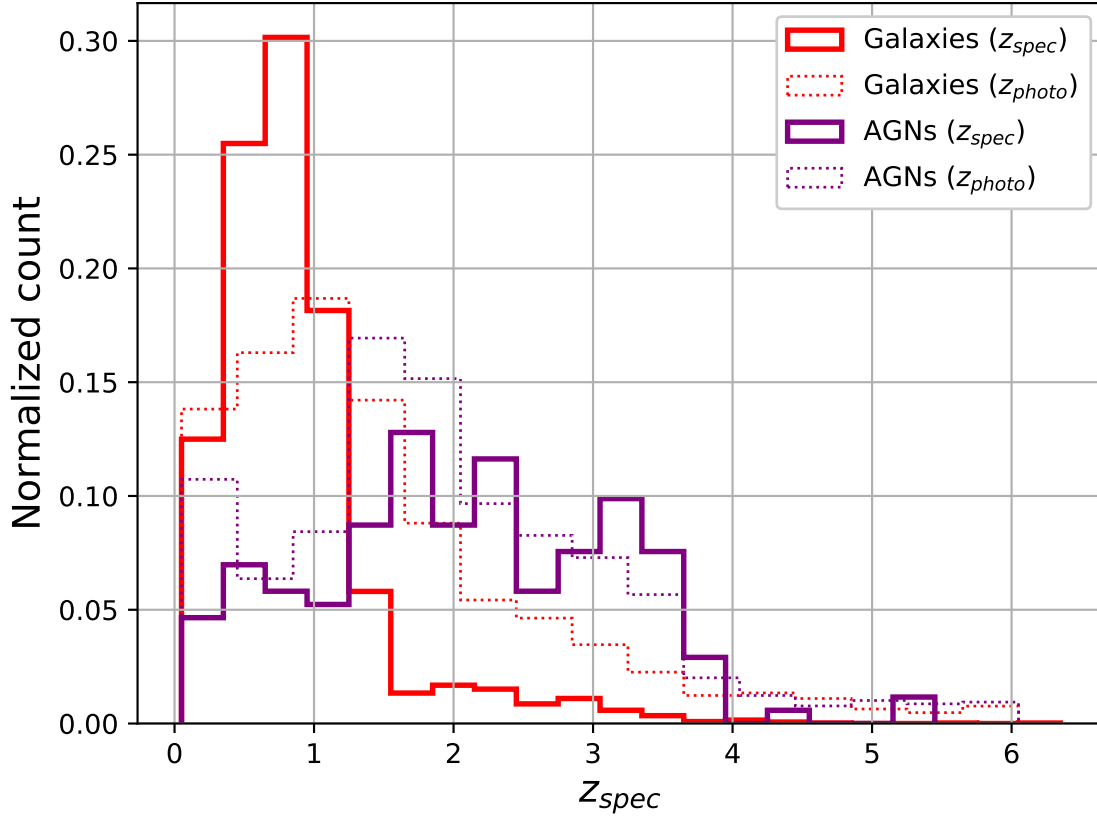


Figure 3.12: Redshift distributions of galaxies (red, $W1 - W2 < 0.8$) and AGNs (purple, $W1 - W2 > 0.8$) in the 3D-HST catalog. Solid lines show the distribution of z_{spec} values, and dotted lines show the distribution of z_{photo} values.

have a $\text{SNR} > 3$. This is not a very restrictive cut, as it still selects $\sim 85\%$ of the objects in the catalogs. Using the $W1 - W2 > 0.8$ color cut, we find a total of 27,193 objects (~ 43 AGNs/deg²) in the combined 3D-HST catalog. Figure 3.12 shows the spectroscopic and photometric redshift distributions of the galaxies and AGNs the catalog. At redshifts greater than $z \sim 1.25$, there is a sharp break in the distributions and the objects are AGN dominated.

3.4.1 IRAC AGN selection criteria

The WISE $W1 - W2 > 0.8$ criteria is suitable for identifying pure AGNs out to $z \sim 3$. At higher redshifts, the $W1 - W2 > 0.8$ color cut is less robust at selecting AGNs since the portion of the

SED sampled by the $W1$ and $W2$ bands is too blue to satisfy the criteria. For $z < 2$, the $W1$ and $W2$ bands capture the mid-IR power law portion of the rest frame SED. At higher redshifts the WISE bands fall into the rest frame optical and near-IR regimes, which can be dominated by the host galaxy component. For pure AGNs that have essentially no host galaxy component in their SEDs, the entirety of the optical to mid-IR region of the SED is essentially a continuous power law, and the rest frame optical region of the SED (i.e. observed at high redshift, $z > 2$) can still satisfy the $W1 - W2 > 0.8$ criterion. Additionally, this color cut was derived from relatively shallow Spitzer data, but for deeper catalogs such as 3D-HST there is heavy contamination from faint, high-redshift galaxies. For deep Spitzer data Stern et al. (2012) recommends using the Donley et al. (2012) IRAC selection criteria, which is specifically designed to limit the contamination from star-forming galaxies. This criteria is defined by the following conditions:

$$\begin{aligned}
x &= \log_{10} \left(\frac{f_{5.8\mu m}}{f_{3.6\mu m}} \right), & y &= \log_{10} \left(\frac{f_{8.0\mu m}}{f_{4.5\mu m}} \right), \\
x &\geq 0.08, & y &\geq 0.15, \\
y &\geq 1.21x - 0.27, & y &\leq 1.21x + 0.27, \\
f_{8.0\mu m} &> f_{5.8\mu m} > f_{4.5\mu m} > f_{3.6\mu m}.
\end{aligned} \tag{3.5}$$

Figure 3.13 shows a comparison of the AGNs in the 3D-HST catalog selected by the Donley et al. (2012) wedge ($N = 560$ AGNs) and the Stern et al. (2012) color cut ($N = 2849$ AGNs) in IRAC color space, and their redshift distributions. Nearly all of the Donley et al. (2012) wedge selected AGNs are also selected by the $W1 - W2 > 0.8$ criteria. The redshift distributions are mostly coincident, with the Donley et al. (2012) wedge having a larger fraction of AGNs at $z < 2$.

3.4.2 SED selection of AGNs

The Stern et al. (2012) color cut generally tends to select AGNs with a high AGN fraction ($> 80\%$), but this potentially misses AGNs with lower AGN fractions and have a larger contribution of flux from the host galaxy component. Additionally, the stringent constraints in color space imposed by the Donley et al. (2012) wedge excludes a large number of AGNs if there is insufficient photometry available (i.e. all four IRAC bands). Huang et al. (2017) shows that SED fitting can be used

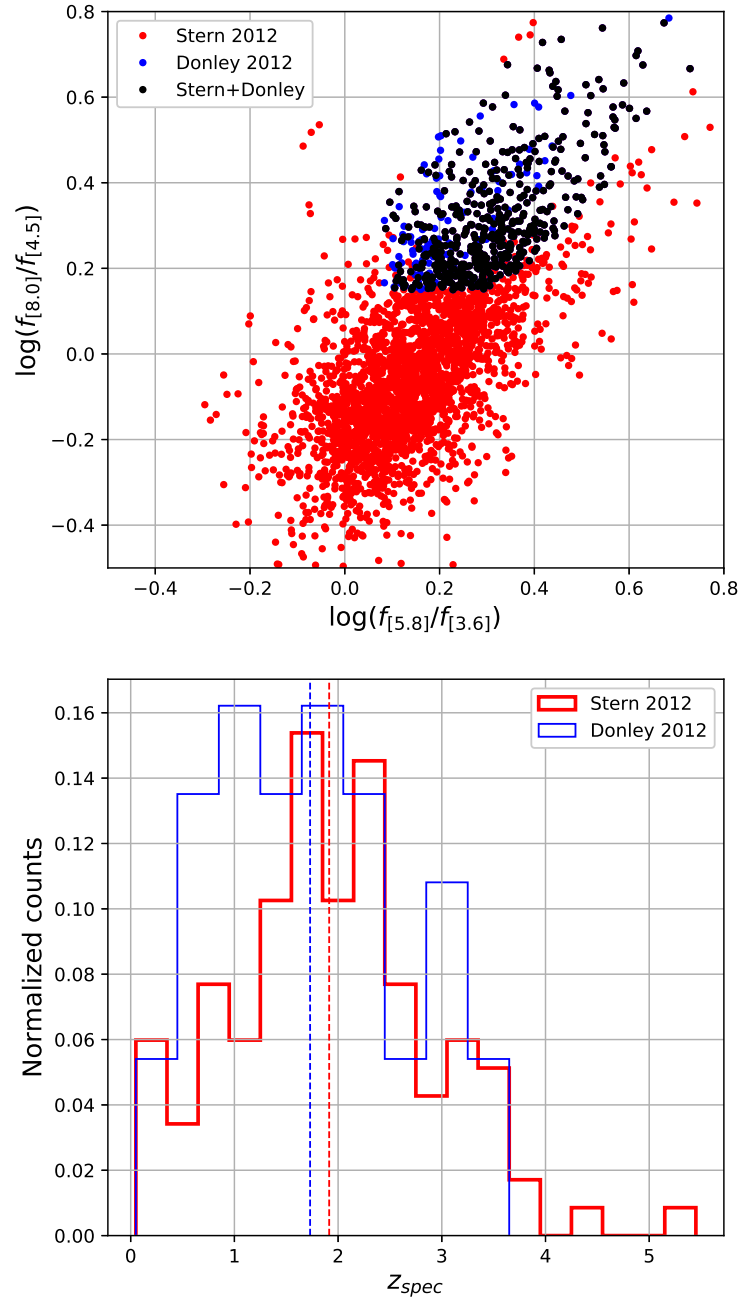


Figure 3.13: [Top] Comparison of the AGNs in the 3D-HST catalog selected by the Donley et al. (2012) wedge (blue, $N = 560$ AGNs) and the Stern et al. (2012) color cut (red, $N = 2849$ AGNs) in IRAC color space. Black points denote AGNs that satisfy both criteria. [Bottom] Redshift distributions of the Donley et al. (2012) (blue) and Stern et al. (2012) (red) selected AGNs. Dashed lines indicate the medians.

to identify galaxies with smaller AGN fractions that are missed by color-selection methods. To examine this further, we perform SED fitting on the objects in the 3D-HST catalog and measure the $< 30\mu\text{m}$ AGN fractions. To ensure that the SED is well sampled, we only include objects with at least 5 photometric bands. Additionally, we also require that the longest available photometric band for each object samples a rest wavelength of at least $2.5\mu\text{m}$ or higher so that the mid-IR emission of the SED is sampled. This is particularly important for higher redshift ($z > 2$) objects, since for these galaxies the observed IRAC bands are redshifted into the optical and near-IR. For objects that only have rest frame photometry up to the near-IR, the SED fitting procedure can be unstable and yield unphysical solutions if only a narrow wavelength range is sampled. In contrast, the mid-IR behavior of the SED is a much reliable indicator of any AGN activity, and accurately estimating the AGN fraction of galaxies requires us to have at least one data point in this regime. Figure 3.14 shows examples of SED fits done with the Assef et al. (2010) templates. The top panel shows a quality SED that has photometry sampling beyond $2.5\mu\text{m}$ and satisfies our photometry criteria, while the bottom panel shows an SED that does not meet this criteria and severely overestimates the AGN contribution due to a lack of photometric constraints in the mid-IR (which also represents the majority of the integrated flux up to $30\mu\text{m}$).

Enforcing this sort of wavelength criteria in effect also introduces a redshift cut, since high redshifts objects (particularly those lacking band 3 and 4 IRAC photometry) will not be included in our sample. Figure 3.15 shows the distribution of the longest wavelength photometric band for the objects in the 3D-HST catalog with at least $N = 5$ photometric bands. Roughly half the objects in the 3D-HST catalog have a maximum rest frame bandpass of $\sim 2.5\mu\text{m}$ or longer. For the remainder of this section, we select objects with at least one rest frame photometric band with wavelength $> 2.5\mu\text{m}$.

After narrowing our sample based on this photometry criterion, Figure 3.16 shows the distribution of AGN fractions and redshifts of the 3D-HST sample fitted with SEDs. The small peak at an AGN fraction of $\sim 90\text{-}100\%$ is a result of AGNs that are nearly entirely power-law dominated. These do not have a notable host galaxy component that can be reliably sampled with our available photometry, and being at the extreme tail end of the distribution have slightly larger errors in the

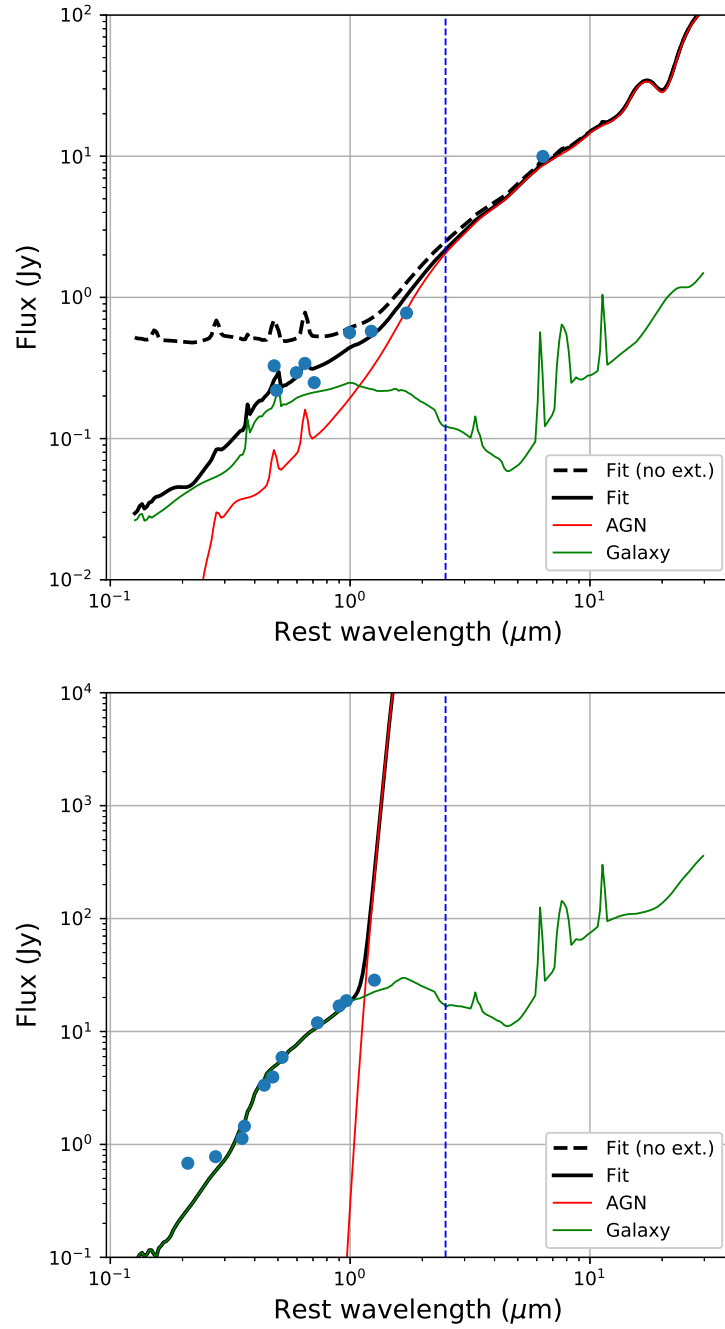


Figure 3.14: [Top] Example of a quality SED fit with an AGN template (red) and host galaxy template (green) taken from Assef et al. (2010). Solid black line shows the result of the templates added together with extinction applied to the AGN, and the dashed line shows the fit without extinction. Blue points correspond to photometry from the 3D-HST catalog, and the blue vertical dashed line indicates the $2.5 \mu\text{m}$ wavelength threshold that we require for SED fitting. [Bottom] Example of a poor SED fit that lacks rest-frame photometry past the $2.5 \mu\text{m}$ threshold, which causes the AGN component to be severely overestimated.

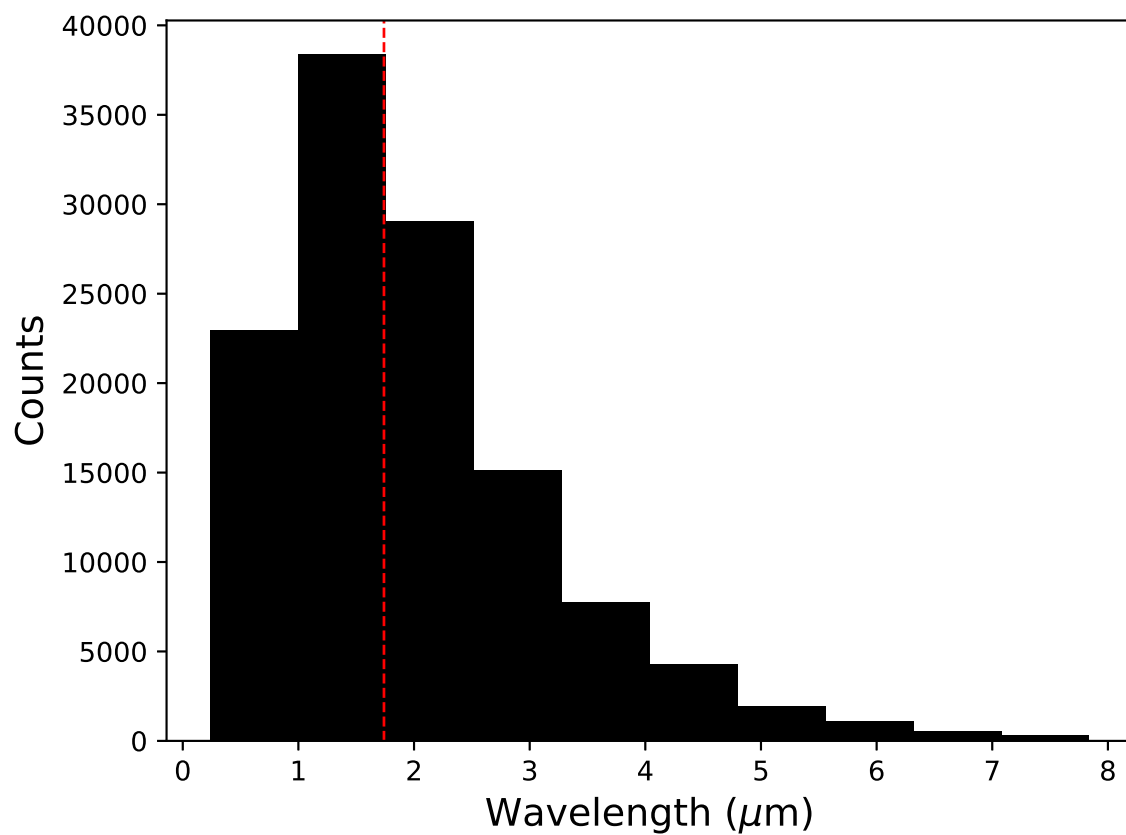


Figure 3.15: Histogram of the longest wavelength (rest frame) photometric band for each of the objects in the 3D-HST catalog with at least $N = 5$ photometric bands (with $\text{SNR} > 3$). Dashed red line indicates the median.

Sample	Size	$N(f_{AGN} > 50\%)$	$N(f_{AGN} > 80\%)$
Total 3D-HST catalog	31157	7980 (25%)	2100 (7%)
Stern+12 criterion	3077	1436 (46%)	397 (12%)
Donley+12 criterion	170	155 (91%)	69 (40%)

Table 3.1: Number of AGNs in the 3D-HST catalog identified by different color selection methods, listed by their AGN fractions. The numbers in the parentheses indicate the fraction of AGNs relative to the size of the sample.

AGN vs. host galaxy fraction. As mentioned earlier, selecting objects based on the available rest frame photometry excludes objects with $z > 2$, but the median of the distribution is still $z \sim 0.75$. Since the 3D-HST sample of galaxies has a redshift distribution that extends considerably higher than our DEIMOS sample, we check that there is reasonable agreement between the z_{photo} and z_{spec} values for these objects. As we did in Figure 3.6 for the DEIMOS sample, Figure 3.17 shows z_{photo} plotted against z_{spec} and $\Delta z/(1+z)$ values for the 3D-HST sample. The quality of the 3D-HST z_{photo} values is generally better than those of our DEIMOS sample, with only $\eta = 4\%$ of redshifts having catastrophic errors and a median scatter of $\sigma_z \sim 0.01$.

Figure 3.18 shows the distribution of AGN fractions selected by the Donley et al. (2012) wedge and Stern et al. (2012) color cut. In the 3D-HST catalog, the $W1 - W2 > 0.8$ selected objects are mostly contaminated by star-forming galaxies, with the median AGN fraction being $\sim 50\%$. The Donley et al. (2012) wedge is more restrictive and selects a far smaller number of objects, but the majority of objects show AGN fractions $> 50\%$. Table 3.1 compares summarizes the number of AGNs captured using these two methods. The Donley et al. (2012) criteria has a very high reliability in AGN selection, but the total number of AGNs selected is substantially smaller than the total number of objects available in the 3D-HST catalog. This shows that identifying AGNs through broadband SED fitting can drastically increase the sample size of AGNs within a given photometric data set several times high relative to color selection methods, consistent with the findings of Huang et al. (2017). Since we have excluded a number of high redshift objects and objects with insufficient rest-frame mid-IR photometry for reliable SED fitting, there are likely even more AGNs within the catalog that have not been included in these numbers.

Figure 3.19 shows that objects selected by the Donley et al. (2012) criteria with different AGN

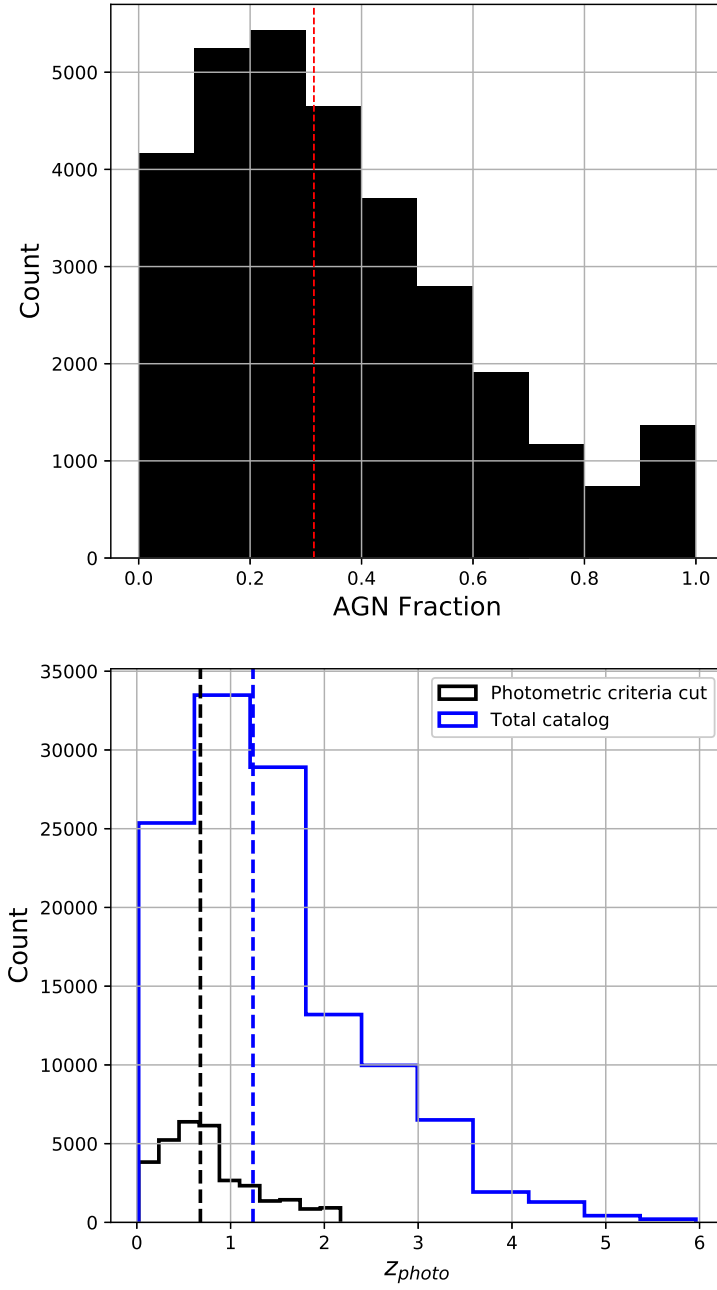


Figure 3.16: [Top] Distribution of the AGN fractions of the objects that satisfy our photometry and rest frame bandpass criteria. [Bottom] Distributions of the z_{photo} values of the objects that satisfy our photometry and rest frame bandpass criteria (black) and the total 3D-HST catalog (blue). Vertical dashed lines indicate the medians.

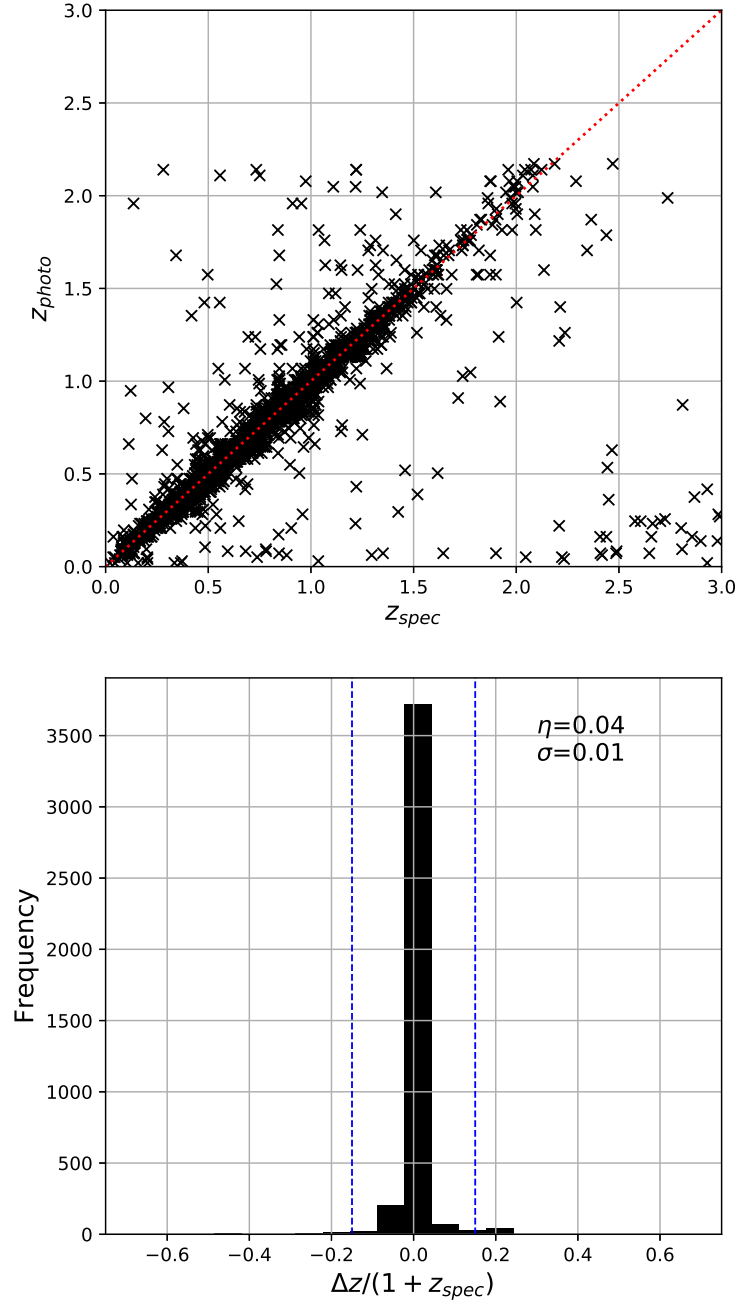


Figure 3.17: [Top] z_{photo} vs. z_{spec} values for our selected sample of 3D-HST catalog objects. Red dotted line corresponds to $z_{photo} = z_{spec}$. [Bottom] Histogram of $\Delta z / (1 + z_{spec})$ values of photometric redshift measurements. Blue dotted lines correspond to $\Delta z / (1 + z_{spec}) = \pm 0.15$.

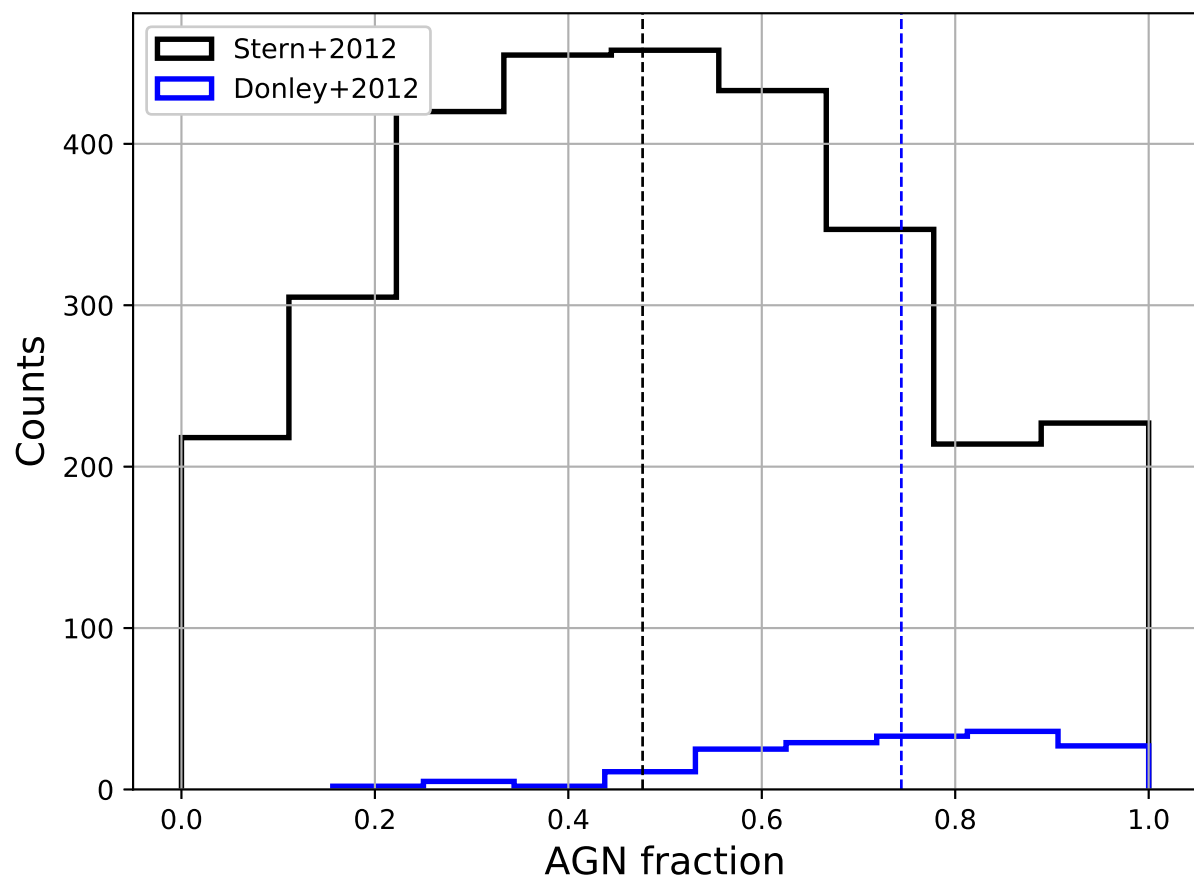


Figure 3.18: Distributions of the AGN fractions of 3D-HST objects selected by the Stern et al. (2012) (black) and Donley et al. (2012) (blue) color criteria. Dashed lines indicate the medians.

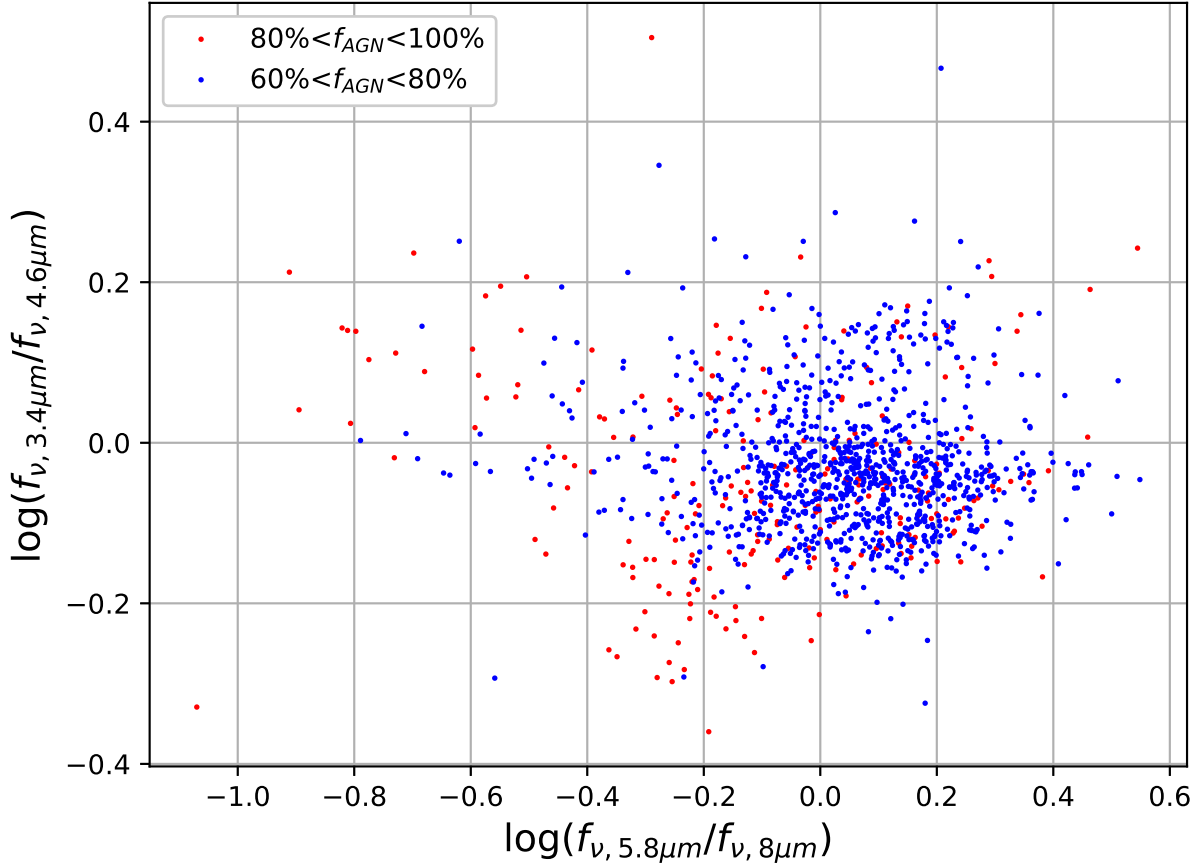


Figure 3.19: Distribution of 3D-HST galaxies with different AGN fractions in the IRAC color space. Blue indicates $60\% < f_{AGN} < 80\%$, red indicates $80\% < f_{AGN} < 100\%$.

fractions occupy essentially the same locus in the IRAC color space. This underscores the need for SED fitting in order to determine AGN fractions, since simple color criteria does not always show whether or not a sample is reliable or contaminated by star-forming galaxies.

To definitively show that these galaxies with high AGN fractions are indeed AGNs, we would need to examine their spectra for broad-line emission features (i.e. FWHM of > 2000 km/s) characteristic of Seyfert 1 galaxies. Unfortunately, the WFC3 G141 grism spectra do not have sufficiently high resolution for us to reliably measure the FWHM of these emission lines. The MOSDEF survey (Kriek et al. 2015) has obtained spectra of a subset of the targets included in the 3D-HST catalog, and an examination of these spectra would allow us to determine the correlation between AGN fraction and AGN emission features. These spectra were obtained using the

MOSFIRE spectrograph and generally yield redshifts that are more reliable than the ones obtained from the lower resolution 3D-HST grism spectra, and this would also allow us to check the quality of SED fits and AGN fraction estimates since these are also dependent on redshift accuracy. A detailed analysis of these spectra is beyond the scope of this paper.

Since SED fitting for huge data sets can be computationally expensive, we can narrow the possible set of AGNs by looking at power law behavior in the mid-IR using a very loose criteria. As shown in Figure 3.5, the number of strong AGNs (with AGN fractions $> 80\%$) does not increase significantly below a threshold of $W1 - W2 > 0.6$, so such a color cut can be used in conjunction with SED fitting to narrow down the number of potential AGN candidates.

3.4.3 Differential number counts and completeness

Similar to what we did in Section 3.3.3 for the DEIMOS sample, we compute the differential number counts for the different AGN samples selected from the 3D-HST data set. Figure 3.20 shows the differential number counts dN/dS plotted against the IRAC $3.4 \mu\text{m}$ flux for the different AGN samples. Since the 3D-HST observations go significantly deeper than WISE, these will show completeness down to far lower sensitivity limits compared to our DEIMOS samples. The $f_{AGN} > 0.5$ and $f_{AGN} > 0.8$ samples show mostly the same characteristics in the number counts, with completeness down to $\sim 5 \times 10^{-4}$ Jy. The Stern et al. (2012) selected sample shows completeness down to ~ 0.001 Jy. Since the Donley et al. (2012) selected sample requires detection in all four IRAC bands, this has the highest sensitivity limit with completeness down to ~ 0.005 Jy.

3.4.4 Luminosity functions

Since we require that there be rest-frame mid-IR photometry in the SED fits in our sample, we take this into consideration when calculating V_{max} for our luminosity functions. Unlike the approach typically used in other LF studies, we are using SED modeling instead of applying a k -correction to a single filter to determine monochromatic luminosities. This makes it more complicated than using a flux limit in a single filter to determine z_{max} , the maximum redshift below which a given

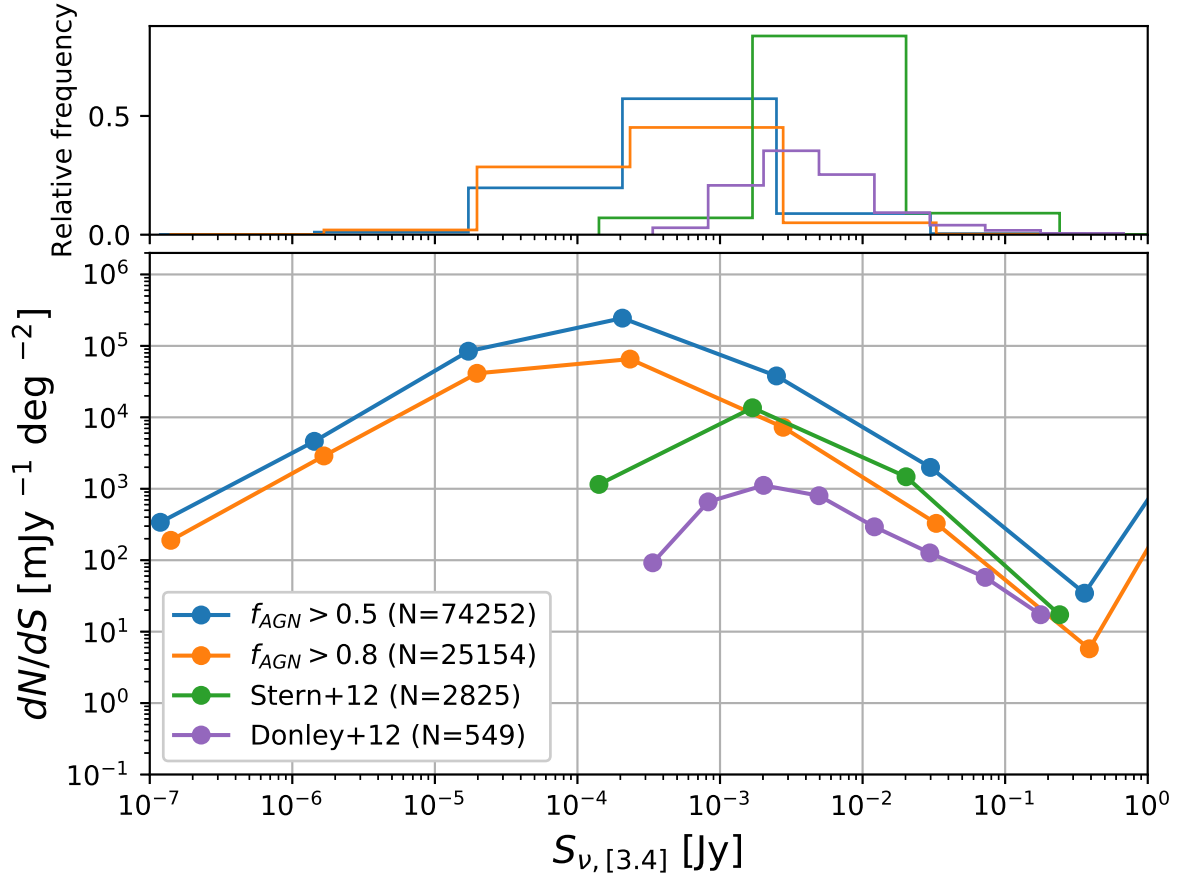


Figure 3.20: Differential number counts dN/dS of the different AGN samples selected from the 3D-HST catalog in the IRAC 3.4 μm band: $f_{AGN} > 0.5$ (blue), $f_{AGN} > 0.8$ (orange), Stern et al. (2012) criteria (green), and Donley et al. (2012) criteria (purple). Top panel shows a histogram of the relative frequencies of the objects in each flux bin.

galaxy is detectable within a certain redshift bin. Our selection criteria involves having rest-frame photometry above a $2.5\mu\text{m}$ threshold, so z_{max} is determined by a combination of 1. the flux limits of the mid-IR filters and 2. the rest wavelength of the longest wavelength photometric filter. Generally speaking it's difficult to formulate a simple, general criteria that robustly determines z_{max} for all the different SEDs that we have. Instead, we can determine this empirically by systematically shifting each SED to a higher redshift, and determining the redshift at which there is no photometry above $2.5\mu\text{m}$. This will occur as a result of 1. photometric data points “disappearing” once the corresponding luminosity distance $d_L(z)$ is large enough to decrease the observed flux below the detection limit of that particular bandpass and 2. observed bands shifting to below rest frame $2\mu\text{m}$.

Figure 3.21 shows the redshift distributions of all of these samples of galaxies and AGNs selected from the 3D-HST catalog. One feature common to all the samples is that there is a sharp break at $z \sim 1.25$, below which most of the SED selected galaxies reside and above which most of the Stern et al. (2012) and Donley et al. (2012) AGNs reside. As we will show in the following plots, this non-uniform distribution of redshifts has implications for the completeness of luminosity functions computed in different redshift bins.

To account for the highly non-uniform redshift distribution, we define our LF redshift bins to cover the redshift values where the majority of the objects are located. Figures 3.22 and 3.23 show the respective luminosity functions of objects with AGN fractions $> 80\%$ and $> 50\%$ taken from the 3D-HST sample. Objects at higher redshifts are more likely to be excluded from our SED selection criteria, since they generally have fewer bands above rest frame $2.5\mu\text{m}$ and are fainter. This causes the severity of incompleteness to increase with redshift. LF are generally expected to increase in number density with increasing redshift, so the LFs shown in the plots more likely represent lower limits rather than actual LFs. There is likely some sort of redshift evolution present in these LFs, but incompleteness in the higher redshift bins prevent us from seeing this clearly. Nonetheless, we find the best fit parameters for the LF in the lowest redshift bin, which can be used to integrate in order to find a lower limit on the total IR energy density Ω_{TIR} (see Section 3.5). We measure slopes of $\beta \sim 1.5$ for these LFs, which are substantially shallower than the values reported by Goto et al. (2015) ($\beta \sim 3.4$) for their corresponding $8\mu\text{m}$ LFs. The

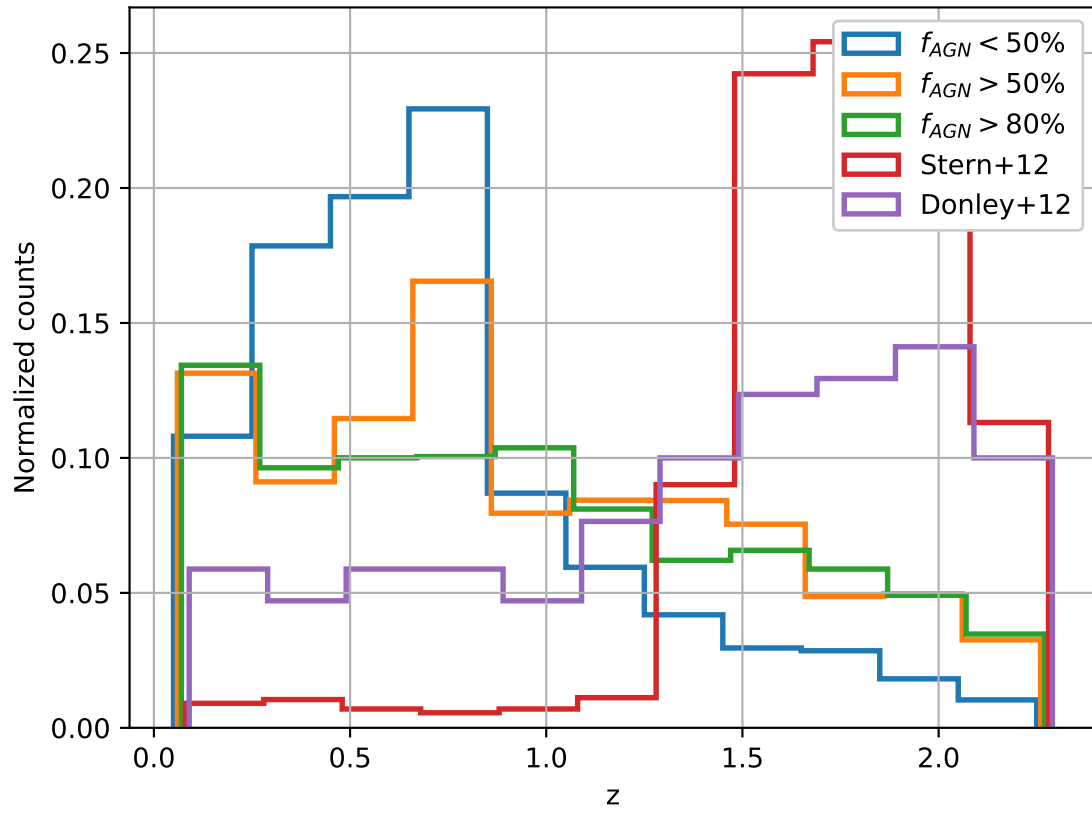


Figure 3.21: Redshift distributions of the different samples of AGNs and galaxies selected from the 3D-HST catalog.

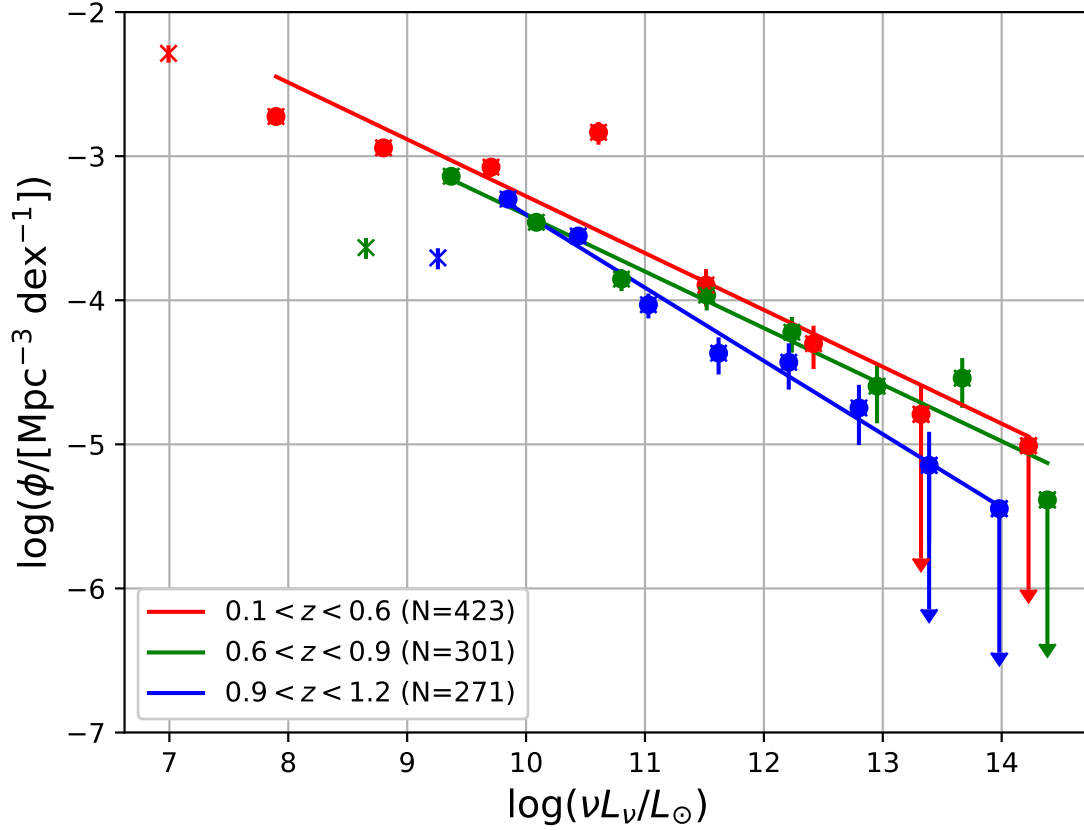


Figure 3.22: $8\mu\text{m}$ luminosity function of objects with AGN fractions $> 80\%$ taken from the 3D-HST sample. Colors correspond to different redshift bins. Solid points indicate points used in the LF fitting, while crosses indicate the points that were excluded from the fits. Vertical bars show the $1/\sqrt{N}$ Poisson errors. Arrows are marked on bins with $N < 4$ objects and indicate that the point is an upper limit.

normalization Φ^* for these LFs ($\Phi^* \sim 10^{-4}$) are also an order of magnitude smaller than the values in Goto et al. (2015).

In comparison, in Figure 3.24 we show the LFs for the sample of galaxies with AGN fractions $< 50\%$. These LFs have much better number statistics compared to the LFs of the samples with higher AGN fractions, and also show the redshift evolution typical of galaxy luminosity functions. The drop-off at the high luminosity tail is substantially steeper than the AGN LFs that we have computed so far, which is the behavior we expect as galaxies are generally less luminous than AGNs.

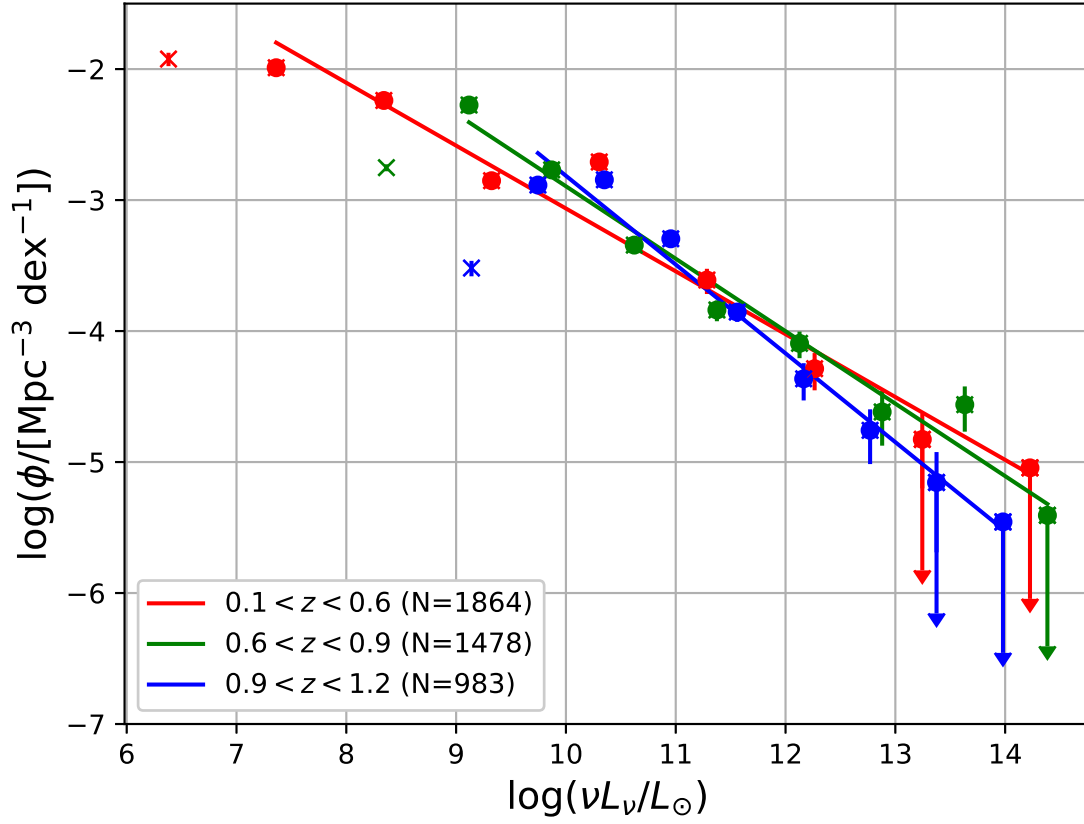


Figure 3.23: $8\mu\text{m}$ luminosity function of objects with AGN fractions $> 50\%$ from the 3D-HST sample. Colors correspond to different redshift bins. Solid points indicate points used in the LF fitting, while crosses indicate the points that were excluded from the fits. Vertical bars show the $1/\sqrt{N}$ Poisson errors. Arrows are marked on bins with $N < 4$ objects and indicate that the point is an upper limit.

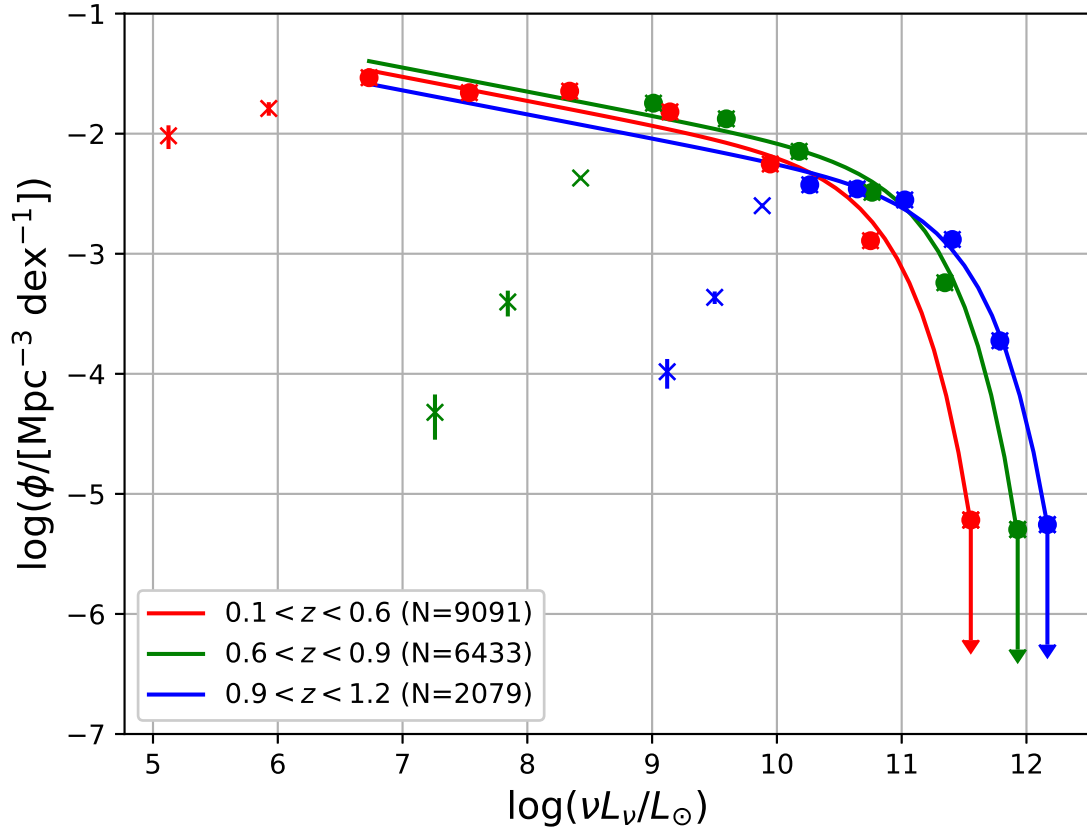


Figure 3.24: $8\mu m$ luminosity function of objects with AGN fractions $< 50\%$ from the 3D-HST sample. Colors correspond to different redshift bins. Solid points indicate points used in the LF fitting, while crosses indicate the points that were excluded from the fits. Vertical bars show the $1/\sqrt{N}$ Poisson errors. Arrows are marked on bins with $N < 4$ objects and indicate that the point is an upper limit.

Figure 3.25 shows the luminosity functions of objects that are selected by the Stern et al. (2012) color criteria from the 3D-HST sample. These LFs are generally better behaved compared to the LFs in Figures 3.22 and 3.23, in that they show the expected trend of increasing number density with redshift. The samples also appear to suffer from heavy incompleteness at the low luminosity end of the LF below $\log(\nu L_\nu/L_\odot) \sim 11$, which is seen in the turnover behavior of the curves. As mentioned earlier the Stern et al. (2012) criteria suffers from heavy host galaxy contamination at higher redshifts (see Figure 3.18), so the incompleteness seen in the LF is at least partially a result of this. The LF slope $\beta \sim 2.3$ is steeper than the slopes of the LFs in the SED-selected samples shown in Figures 3.22 and 3.23, and the normalization $\Phi^* \sim 10^{-3}$ is comparable to the values measured by Goto et al. (2015). The sample of AGNs selected by the Donley et al. (2012) criteria is far too small to yield any luminosity functions that are suitable for fitting, so we exclude this sample from this analysis.

To compare the shapes of the different LFs computed from these different samples, we fit these using the functional forms mentioned in Section 3.3.2 and adopt the same constraints on the LF parameters. The samples with $f_{AGN} > 50\%$ and $f_{AGN} > 80\%$ are better fit with a power law in Eqs. 3.3 and 3.4. The galaxy sample with $f_{AGN} < 50\%$ exhibits a sharp drop-off at the high luminosity end and is better fit with a Schechter function (Press & Schechter 1974):

$$\Phi(L)dL = \Phi^* \left(\frac{L}{L^*} \right)^\alpha e^{-L/L^*} dL/L^*. \quad (3.6)$$

The faint end of the LFs is poorly constrained, so we fix the slope to be $\alpha = 1.2$ in Eq. 3.6. Since a number of these LFs show clear signs of incompleteness in the low luminosity end, we only use the bins right of the turnover point for fitting. Table 3.3 shows a summary of the LF fit parameters for each of the samples and redshift bins.

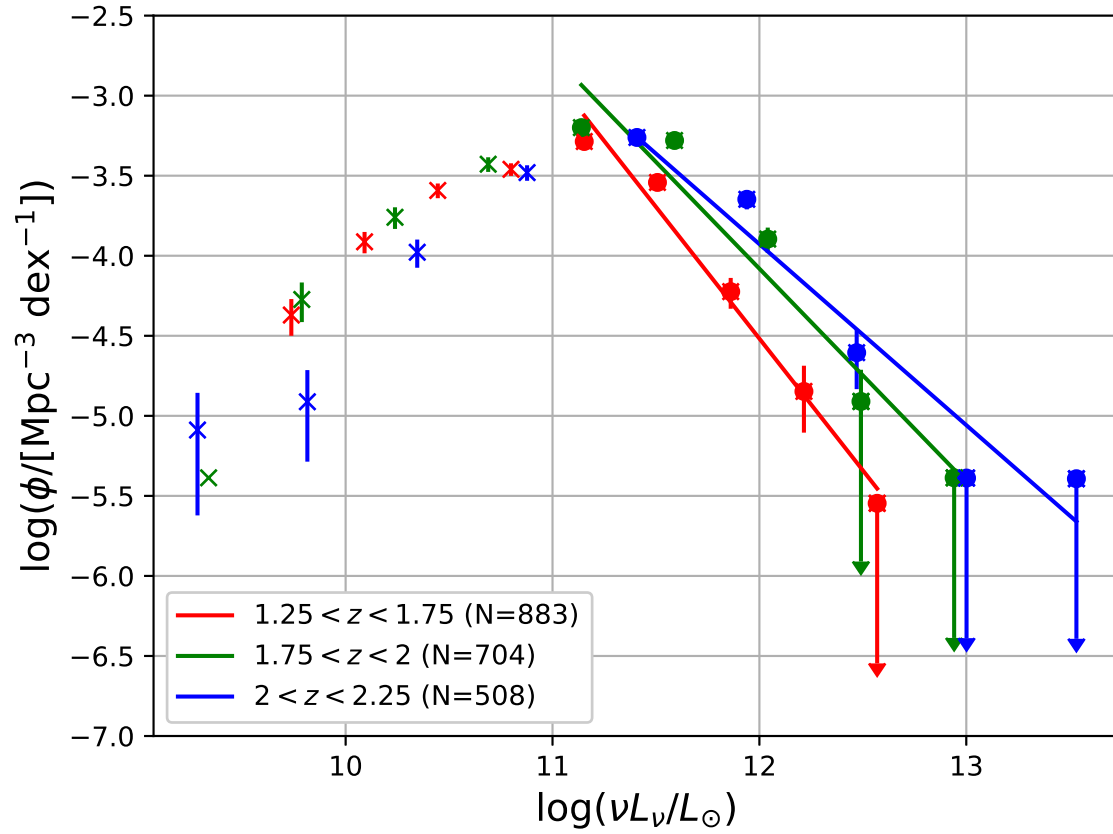


Figure 3.25: $8\mu\text{m}$ luminosity function of objects satisfying the $W1 - W2 > 0.8$ color cut from the 3D-HST sample. Colors correspond to different redshift bins. Solid points indicate points used in the LF fitting, while crosses indicate the points that were excluded from the fits. Vertical bars show the $1/\sqrt{N}$ Poisson errors. Arrows are marked on bins with $N < 4$ objects and indicate that the point is an upper limit.

3.5 IR luminosity density evolution

Using the $8\mu\text{m}$ luminosity functions derived in Section 3.4, we can estimate the IR luminosity density represented by these AGN samples. We convert between the $8\mu\text{m}$ luminosity and the total IR luminosity L_{TIR} using the following scaling relation from Goto et al. (2015):

$$L_{TIR} = (20 \pm 5) \times \nu L_{\nu, 8\mu\text{m}}^{0.94} (\pm 44\%). \quad (3.7)$$

We integrate over the total IR luminosity weighted by $\Phi(L)$ to obtain the total infrared luminosity density $\mathcal{L}_{TIR}$:

$$\mathcal{L}_{TIR} = \int L_{TIR} \Phi_{IR}(L) dL. \quad (3.8)$$

The upper and lower bounds of integration are set to be the minimum and maximum range of the luminosity bins covered by the measured LF. Figure 3.26 shows the redshift evolution of $\mathcal{L}_{TIR}$, which is generally expected to increase with redshift. For comparison, Figure 3.26 also shows the $\mathcal{L}_{TIR}$ values based on $8\mu\text{m}$ LFs computed by Goto et al. (2015). The $\mathcal{L}_{TIR}$ evolution for the Stern et al. (2012) selected sample is monotonically increasing, and the slopes of the $\mathcal{L}_{TIR}$ values from these two samples appear to be mutually consistent. If we parameterize the $\mathcal{L}_{TIR}$ evolution as $\mathcal{L}_{TIR} \propto (1+z)^\gamma$, the two samples show agreement in their slopes being $\gamma \sim 4$.

3.5.1 CIB contribution estimates

We sum up the observed $8\mu\text{m}$ fluxes (i.e. IRAC band 4) for all the objects in each sample to obtain estimates of the CIB contribution. Table 3.2 lists the $8\mu\text{m}$ intensity (in $\text{nW/m}^2/\text{str}$) for each of the AGN and galaxy samples. As expected, since the Donley et al. (2012) criteria selected sample is very small relative to the others, it has the smallest CIB contribution. It is interesting to note that the Stern et al. (2012) criteria sample and $f_{AGN} > 80\%$ sample have nearly the same CIB contribution, considering that the latter has a sample size that's a few times larger. Even with the discrepancy in sample size, the former has a large number of lower flux objects that do not contribute significantly to the $8\mu\text{m}$ intensity. The $f_{AGN} < 50\%$ galaxy sample is fairly close to

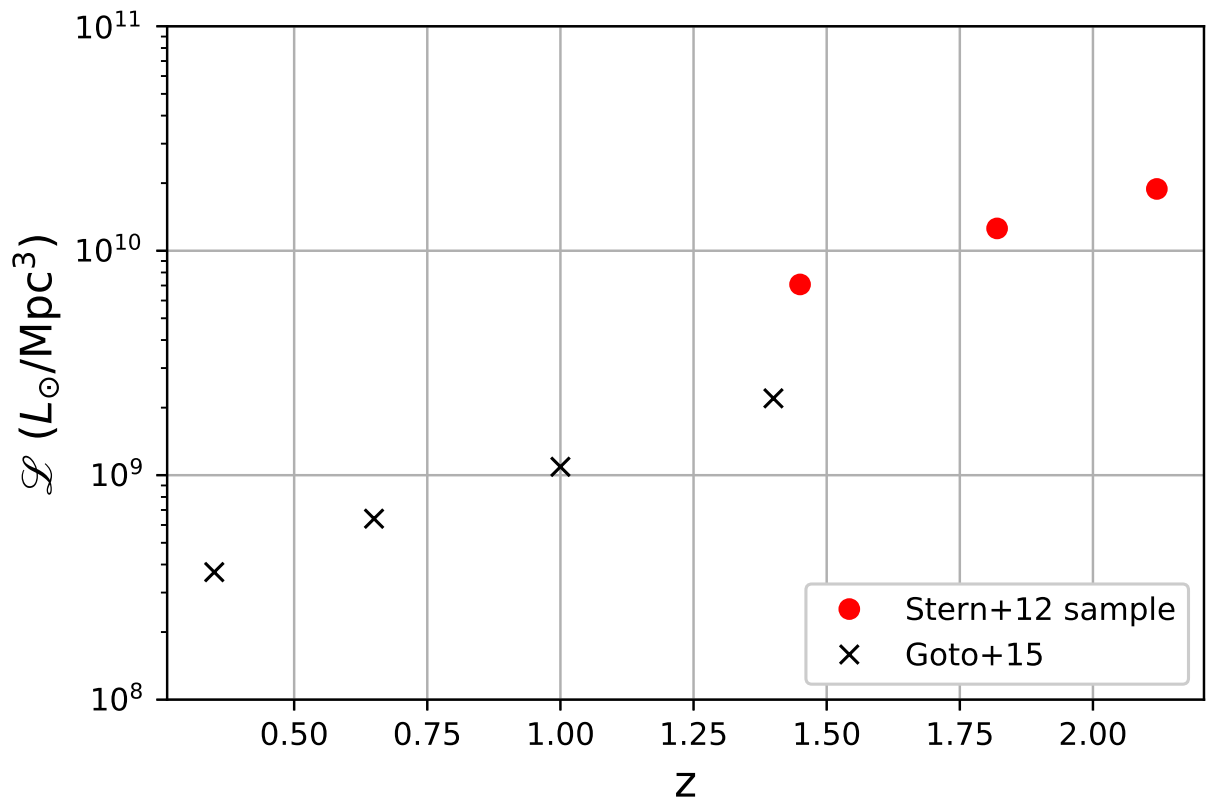


Figure 3.26: Redshift evolution of $\mathcal{L}_{TIR}$. Red points indicate values computed from the Stern et al. (2012) selected sample, and crosses show the values from Goto et al. (2015) for comparison.

Sample	$\nu I_{\nu, 8\mu m}$ [nW/m ² /str]
Stern+12	0.19
Donley+12	0.9
$f_{AGN} > 80\%$	0.17
$f_{AGN} > 50\%$	0.50
$f_{AGN} < 50\%$	1.2

Table 3.2: 8 μ m CIB contribution of each AGN and galaxy sample

measured CIB intensity values at 8 μ m (~ 3 nW/m²/str). Since a number of objects were discarded due to poor SED fits, the values in Table 3.2 should be considered to be lower limits.

3.6 Conclusions

We were able to compute luminosity functions using a spectroscopic survey of WISE-selected AGNs and galaxies, but the low-luminosity ends of the distributions could be improved by selecting more low-luminosity targets for inclusion and increasing the density of targets per slitmask. We have demonstrated that z_{photo} values computed with the LEPHARE code are largely consistent with the z_{spec} values obtained from spectral measurements. Even in the absence of usable spectra for certain targets, we are still able to include these in our LF computation due to the abundance of photometry available for SED fitting.

We have shown that mid-IR color selection can miss a substantial number of AGNs, but identifying AGNs by broadband SED fits increase the AGN sample size by at least an order of magnitude. This has the advantage of selecting a statistically robust sample of AGNs, but we are constrained by the flux limit of our catalog and the availability of longer wavelength mid-IR photometry for SED fitting. High redshift galaxies are particularly difficult to target due to their faintness, especially at the longer wavelength IRAC bands where the sensitivity is considerably lower than that of the shorter wavelength filters. In our different AGN selection criteria, the highly non-uniform redshift distribution limits the redshift range over which we are able to compute LFs. To remedy this, we would require additional longer wavelength mid-IR photometry (particularly beyond the 8 μ m limit of IRAC) and photometric/spectroscopic surveys that specifically target galaxy populations in specific redshift bins. In addition, we would need spectroscopy to determine the extent to

which SED fitting can be trusted in identifying AGNs, and to estimate the rate of false positives that result from this modeling.

The biggest challenges in computing luminosity functions is having a large enough sample size such that the error bars are small enough to make LF fitting feasible, and accounting for the sample incompleteness that occurs at low luminosities. We are able to place constraints on the IR energy density $\mathcal{L}_{TIR}$ using different galaxy and AGN samples, but accurately measuring the redshift evolution requires better sampled LFs at higher redshifts. We were also able to estimate the $8\mu\text{m}$ contribution to the CIB for our various AGN samples, but our estimates are likely lower limits due to the number of objects that we excluded on the basis of poor SED fitting. To estimate how the shape of CIB spectrum evolves with time, we would need to compare the redshift evolution of LFs at different wavelengths from the mid to far-IR. Changes in CIB spectral shape could be a result of the evolution in dust absorption and reprocessing, or a change in the AGN contribution over time. Distinguishing these two effects requires a well-constrained measure of how the IR energy density evolves with time across multiple IR wavelengths.

Sample	Function	Redshift	$L^* (10^{10} L_\odot)$	Φ^*	α	β	$\langle V/V_{max} \rangle$
DEIMOS AGN	Power law	$0.1 < z < 0.7$	1.8	$4.0 \pm 0.4 \times 10^{-4}$	1.5	2.3	0.60 ± 0.05
DEIMOS AGN	Power law	$0.7 < z < 1.7$	3.4	$3.1 \pm 0.3 \times 10^{-4}$	1.5	2.5	0.56 ± 0.05
DEIMOS galaxy	Power law	$0.1 < z < 0.55$	1.8	$4.0 \pm 0.4 \times 10^{-4}$	1.5	1.6	0.62 ± 0.02
DEIMOS galaxy	Power law	$0.55 < z < 0.8$	3.4	$3.1 \pm 0.3 \times 10^{-4}$	1.5	3.6	0.41 ± 0.03
Stern+12	Power law	$1.25 < z < 1.75$	5.8	$3.2 \pm 0.9 \times 10^{-3}$	1.5	2.6 ± 0.2	0.63 ± 0.01
Stern+12	Power law	$1.75 < z < 2$	7.5	$2.6 \pm 1.1 \times 10^{-3}$	1.5	2.3 ± 0.2	0.47 ± 0.01
Stern+12	Power law	$2 < z < 2.25$	9.4	$1.7 \pm 0.8 \times 10^{-3}$	1.5	2.1 ± 0.3	0.52 ± 0.01
$f_{AGN} > 80\%$	Power law	$0.1 < z < 0.6$	1.8	$4.1 \pm 0.6 \times 10^{-4}$	1.5	1.4 ± 0.1	0.35 ± 0.01
$f_{AGN} > 80\%$	Power law	$0.6 < z < 0.9$	3.1	$2.5 \pm 0.2 \times 10^{-4}$	1.5	1.4 ± 0.1	0.42 ± 0.01
$f_{AGN} > 80\%$	Power law	$0.9 < z < 1.2$	3.9	$1.9 \pm 0.1 \times 10^{-4}$	1.5	1.5 ± 0.1	0.46 ± 0.01
$f_{AGN} > 50\%$	Power law	$0.1 < z < 0.6$	1.8	$4.1 \pm 0.7 \times 10^{-4}$	1.5	1.5 ± 0.1	0.386 ± 0.006
$f_{AGN} > 50\%$	Power law	$0.6 < z < 0.9$	3.1	$2.5 \pm 0.7 \times 10^{-4}$	1.6	1.6 ± 0.1	0.487 ± 0.007
$f_{AGN} > 50\%$	Power law	$0.9 < z < 1.2$	3.9	$1.9 \pm 0.5 \times 10^{-4}$	1.7	1.7 ± 0.1	0.530 ± 0.009
$f_{AGN} < 50\%$	Schechter	$0.1 < z < 0.6$	1.8	$5.3 \pm 0.7 \times 10^{-3}$	1.2	-	0.421 ± 0.003
$f_{AGN} < 50\%$	Schechter	$0.6 < z < 0.9$	3.1	$5.4 \pm 0.7 \times 10^{-3}$	1.2	-	0.417 ± 0.003
$f_{AGN} < 50\%$	Schechter	$0.9 < z < 1.2$	3.9	$3.0 \pm 0.3 \times 10^{-3}$	1.2	-	0.394 ± 0.003

Table 3.3: Best fit parameters for the luminosity functions of each galaxy and AGN sample

CHAPTER 4

Future observations and telescopes

Here we discuss the capabilities of a few ground and space telescopes planned for the near future, and their impact and applications for science involving obscured AGNs.

4.1 FOBOS

Large-scale multiplexed fiber spectroscopy has proven to be a rich source of spectroscopic data, as seen from the highly successful MaNGA (Bundy et al. 2015) and eBOSS (Comparat et al. 2016) surveys on SDSS. This concept is being considered for the Keck telescope in the form of the Fiber-Optic Broadband Optical Spectrograph (FOBOS), which combines the depth allowed by Keck’s 10 meter aperture (compared to SDSS’s 2.5 meter aperture) with the multi-object capabilities of a fiber-based spectrograph. The aim is for FOBOS to be on-sky by 2024, in time for LSST and WFIRST. This instrument is still being planned, but understanding its science applications is vital for determining the final instrument specifications. In this section, we outline the planned specifications of FOBOS, and describe some of the ways in which we can utilize this spectrograph for surveys of mid-IR selected AGNs and its improvements relative to the capabilities of DEIMOS.

4.1.1 Field size and survey efficiency

One of the biggest limitations in designing an efficient redshift survey is the size of the instrument field of view. For DEIMOS, each slitmask has a $16.7' \times 5'$ area, with an total of 68.3 arcmin^2 (excluding the vignetted region of the mask). FOBOS has a diameter of ~ 15 arcminutes, which potentially offers nearly three times the multiplexing capacity of DEIMOS.

Our AGN survey described in Chapter 1 was specifically designed with DEIMOS specifications in mind in order to maximize the number of targets per field. For the DEIMOS field of view, we found that WISE-selected AGNs with $W1 - W2 > 0.8$ occur maximally as clusters of 6-7. The maximum number of AGNs per cluster is not expected not scale linearly with field size, but we do expect this number to increase with a larger field. To demonstrate this we search for clusters of WISE AGNs by using the same procedure as our DEIMOS survey, but this time we tile a region of the sky around the north Galactic Pole with FOBOS-sized fields and count the number of color-cut AGN candidates contained therein. With this search we find that the maximal clustering is 9-10 AGNs per field. This is about a 50% improvement in AGN survey efficiency compared to the DEIMOS field size. Another consideration for FOBOS is that it is best to maximize the *usable* space in the FOV for efficiency and ease of target selection. One difficulty we experienced with designing DEIMOS slitmasks is that it can be tricky to avoid placing targets on the vignetted portion of the mask, and occasionally it is impossible to fit a cluster of AGNs a slitmask without losing an target due to vignetting. For the targets contained in DEIMOS field shown in Figure 4.1, it is easy to lose a target near the long edge of the slitmask due to vignetting, or if the relative positions of the targets are arranged in a way such that slits are overlapping. Fortunately, the nature of fiber spectroscopy eliminates these problems.

In addition to observing AGNs as primary targets, the remaining area in the field can be used for spectroscopy of secondary targets. A typical DEIMOS slitmask contains around ~ 70 targets per slitmask for $1' \times 10''$ sized slits, which produces a density of ~ 1 object/arcmin². For luminosity function measurements this is relatively inefficient since the density of WISE sources far exceeds the number of available slits, which causes completeness issues. The typical sky density of WISE sources is ~ 5 objects/arcmin² averaged over the whole sky. In comparison, FOBOS has a target density of 2.5/arcmin² (~ 400 objects over a 160 arcmin² patrol field), which is more than twice that of DEIMOS. All luminosity functions tend to rise towards the faint end, and this portion can only be adequately sampled if the multiplexing capacity of the spectrograph is sufficiently large and sensitive enough to capture these objects.

One difficulty we experienced in the process of processing DEIMOS spectra is that a number

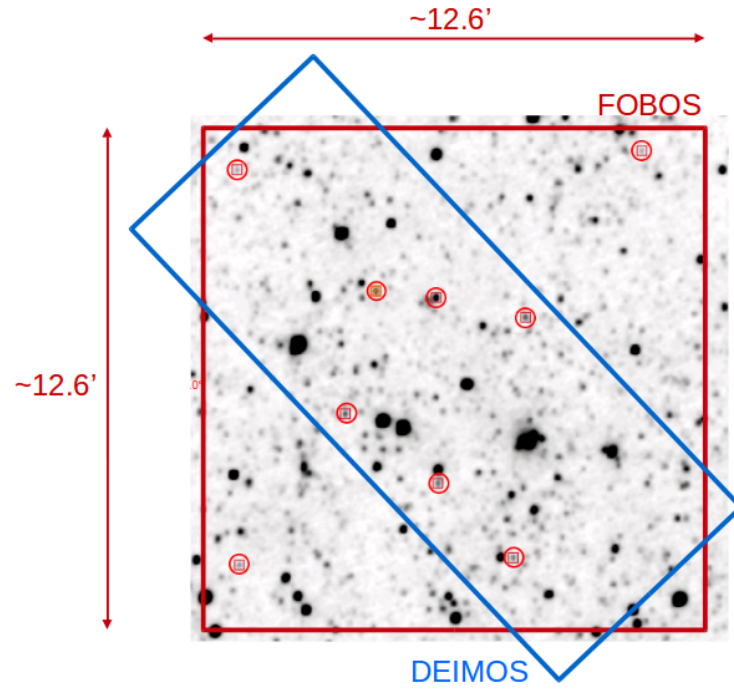


Figure 4.1: A comparison of the relative sizes of the FOBOS (red square) and DEIMOS (blue rectangle) fields of view. Red circles indicate $W1 - W2 > 0.8$ AGN candidates. In reality, the effective DEIMOS field of view is slightly smaller due to vignetting of the slitmask near the long edges of the mask, and around the corners.

of slits yielded blank or noisy spectra (i.e. too low of a SNR for any sort of emission line of redshift measurement), perhaps because there was some sort of offset between the slit center and source. This is not to be confused with systematic astrometry errors of the slitmask itself, since generally most of the slits did yield good spectra. The large PSF of the WISE catalog (FWHM of $6''$) relative to the DEIMOS slitwidth ($1''$ by default) produces some random offsets, but most of targets are contained within the slit. One could increase the size of the slit to compensate for any astrometric offsets, but this also increases the level of sky noise.

This problem can be mitigated to some extent with the integral field units (IFUs) on FOBOS. IFU bundles are useful in both good-seeing and bad-seeing conditions, and offer much better signal-to-noise compared to single fibers over a range of seeing conditions. The sky noise in spectra taken with IFU bundles can be reduced by excluding any fibers that are primarily noise dominated. FOBOS is planned to have $7 \times 0.57''$ mini-IFUs per target, and a $\sim 1.7''$ overall on-sky aperture for each target (compared to a characteristic $1'' \times 10''$ DEIMOS slit). Compared to our DEIMOS slits, this increased aperture size could mitigate the effect of slit losses in the total measured flux, and then the fraction of empty/noisy spectra due to astrometry offsets would perhaps marginally decrease as well. In addition, fibers can be repositioned within minutes, and IFU spectroscopy doesn't involve the time consuming task of creating slitmasks for each target field.

4.1.2 Spectral range and resolution

Quality spectra with identifiable emission lines will always yield good redshift measurements, but there are some factors to consider in the spectrograph design in order to maximize the productivity of redshift surveys.

Examining galaxy evolution requires us to sample galaxies over a wide range of redshifts, and high redshift galaxies are always the most difficult to observe. For optical spectroscopy, this is best achieved by pushing the red end of the spectral range to be as high as possible in order to capture any emission lines that lie in that region. The development of germanium CCDs allows for an upper wavelength limit that reaches further into the NIR, and this addition is being considered for FOBOS. Silicon-based CCDs are transparent to wavelengths greater than $1\mu\text{m}$, but the

development of germanium CCDs (with a 0.66 eV bandgap) will push the upper wavelength limit out to $\sim 1.3\mu\text{m}$. For a $1\mu\text{m}$ spectral upper limit, this corresponds to a redshift limit of $z < 1.68$ for the [OII] doublet. Increasing the red limit up to $1.3\mu\text{m}$ gives a limit of $z < 2.48$. This drastic increase in redshift range is immensely valuable for high redshift galaxy surveys and galaxy evolution studies.

The planned spectral range of FOBOS is $0.35\text{--}1\mu\text{m}$ and the spectral resolution ranges from $R \sim 2500$ at the blue end to $R \sim 4500$ in the red (DEIMOS has a resolution of $R \sim 6000$). The resolution of FOBOS will be sufficient to accurately measure the broad line emission of AGNs, but we still require high resolution in the red wavelength range in order to accurately measure lines where there are densely spaced OH sky emission lines around $1\text{--}2.25\mu\text{m}$. (Rousselot et al. (2000) provides a synthetic spectrum of the OH sky line emission in the NIR). Doublet lines such as [OII] 3727 Å are especially important for redshift determination, since having two peaks to measure gives us a more confident redshift measurement (in terms of central wavelengths and unambiguously identifying the line as [OII]) compared to singlet lines. Comparat et al. (2013) shows that a resolution of $R \sim 4500$ is capable of resolving nearly all of the [OII] doublets at $z = 1$ for a flux detection limit comparable to SDSS, but this will need to be higher for $1\mu\text{m}$ range and above. High throughput (i.e. photons detected vs. photons hitting the primary mirror) is also a necessity in the NIR region to ensure a sufficiently high SNR for measuring OH and other line emission. In addition to high resolution, one needs good methods for OH sky line subtraction for wavelengths longer than $\lambda > 8000\text{ Å}$. MaNGA can achieve sky subtraction levels of down to 0.2%, but FOBOS will need to be slightly better in order to achieve its science goals. In general, slit-based spectroscopy is superior compared to IFUs for sky lines subtraction, since fiber spectroscopy is affected by the time and spatial variability of airglow emission (Wyse & Gilmore 1992).

4.1.3 Photometric redshifts

Photometric redshifts are useful in the absence of spectroscopic data, but since they are generally less accurate the scope of applications is more limited. For example, z_{photo} values are useful for computing luminosity functions, which have more room for error since they are based on redshift

bins instead of precise redshift values (as was the case in our LF computations shown in Chapter 3). One particularly important application of accurate redshift measurements is the measurement of dust temperatures. This also requires far-IR photometric data in order to sample the far-IR dust peak, but an accurate characterization of this peak requires that the redshift is reliable, since there is a degeneracy between dust temperature and redshift. For this reason, photometric redshifts with large errors are not always suitable for this kind of analysis. This is particularly important for low redshift objects, as an error Δz at lower redshift corresponds to a relatively large error in the luminosity distance d_L , which can impact estimates of the bolometric luminosity.

Compared to star forming galaxies with strong emission lines and some degree of curvature in the mid-IR, it is particularly difficult to obtain good photometric redshifts of AGNs. This is a result of the strong mid-IR power-law continuum, and the general lack of PAH features in the SED due to AGN photo-disassociation. The bulk of publically available photometry (in terms of number of objects and number of filters) is in the UV to mid-IR wavelengths. Fortunately, this is also the part of the SED that contains useful emission features that can be used for z_{photo} estimates, whereas the mid-IR continuum is relatively unhelpful obtaining a secure redshift measurement. However, the optical and UV portion of the SED across different objects can be highly variable due to the effects of extinction. This is problematic, since photometric redshift estimates rely on template sets that do not necessarily take into account this variability, which can lead to poor z_{photo} fits. To develop better z_{photo} training sets for these dusty galaxies, we require not only a larger number of z_{spec} values for reference, but also objects of different levels of $E(B - V)$ optical extinction (i.e. different optical SED shapes). Masters et al. (2015) presents a method of mapping galaxy colors (in multidimensional color space) to redshifts, but this requires secure redshifts of faint sources for accurate calibration.

On the flip side, z_{photo} values can also serve as useful constraints in target selection for spectroscopic surveys. If we can get an initial estimate of the photometric redshift (ex. to see if a target is located at $z > 1$), then we can use this to help us select targets that are likely to yield [OII] emission lines in the red region of the spectrograph.

4.1.4 Future applications

An obvious application of FOBOS would be a larger scale survey of the DEIMOS survey presented in Chapter 1. We can apply what we learned with respect to color selection, observing configurations, percentage of successes, etc. to designing an efficient FOBOS survey once it becomes operational. Another extension of the work presented in Chapter 2 using FOBOS would be to build a redshift catalog of far-IR objects. A lot of targets in the AKARI Bright Source Catalog and Herschel catalogs don't have spectroscopic redshifts, and these would be good objects for spectroscopic follow-up with FOBOS. Accurate photometric redshifts are difficult with AGNs, and even the best z_{photo} values are only good up to around $z \sim 1$. We need to look at objects at higher redshifts in order to determine if there is any significant evolution in dust temperature and luminosities, which is one of the questions that we were unable to answer with our limited redshift range ($z \sim 0.1$) of WISE+AKARI AGNs. These far-IR objects almost all have corresponding shorter wavelength photometry, so a collection of complete, broadband SEDs and accurate redshift values would be extremely valuable for a variety of different applications beyond dust studies of galaxies and AGNs.

4.2 SPICA

The Space Infrared telescope for Cosmology and Astrophysics (SPICA; Roelfsema et al. (2018); Onaka & Nakagawa (2005)) is a proposed IR space 2.5 meter telescope (cooled below 8K) equipped with two spectrometers. The SPICA Far Infrared Instrument (SAFARI) is a spectrograph with low and mid-resolution ($R \sim 300$ and $R \sim 3000$ -1000, respectively) observing configurations covering a wavelength range of 35-230 μm . The SPICA Mid-Infrared Instrument (SMI) has three spectroscopic observing modes: large FOV ($12' \times 10'$) low-resolution ($R \sim 50$ -120) covering 17-36 μm , mid-resolution grating spectroscopy ($R \sim 2000$) covering 18-36 μm , high-resolution echelle spectroscopy ($R \sim 28000$) covering 12-18 μm domain. SPICA's wavelength coverage is beyond the wavelength range of JWST (which covers the mid-IR up to 28 μm), but offers comparable levels of sensitivity and will therefore serve as a powerful complement of IR data. The planned sensitiv-

ity (5σ of 5×10^{-20} W/m²) is more sensitive than ISO, Spitzer and Herschel by a few orders of magnitude.

The SMI/CAM instrument covering 30-37 μ m will be able to perform an efficient survey of the sky due to its large field of view ($10' \times 12'$) and high sensitivity ($\sim 9\mu$ Jy at 5σ in an hour). In comparison, the field of view on JWST is substantially smaller, making it impractical for large scale surveys. The SMI field of view is larger than the field of view for DEIMOS, but lower resolution. The longer wavelength coverage in the mid-IR will also allow for robust SED fits for galaxies up to very high redshifts by providing sufficient rest frame photometry in the mid-IR. As demonstrated in Chapter 3, we were unable to perform reliable SED fits for nearly half of the objects in the 3D-HST catalog due to a lack of sufficient rest-frame mid-IR photometry required to sample the AGN power law. This also effectively imposed a redshift cut on our 3D-HST sample to objects with $z < 3$. SPICA data will not only drastically increase the sample size of SEDs available for analysis, but the long wavelength mid-IR photometry will also eliminate these limitations imposed by redshift. The SMI/CAM wavelength coverage will also bridge the gap between JWST (0.6-20 μ m) and ALMA (350-3500 μ m). This instrument is capable of producing an IR catalog substantially deeper than WISE or IRAC, which will be valuable for high redshift target selection (i.e. through color or SED selection criteria) of AGNs. Complementary observations on previously observed fields with extensive multi-wavelength coverage (ex. 3D-HST, AKARI NEP, ADF-S) will allow us to identify and characterize AGNs that were perhaps previously missed due to insufficient mid-IR photometry (ex. lacking WISE $W3$ and $W4$ bands).

4.2.1 Dust emission

While there have been models of the dust for the SMC and our own Galaxy, we still have a limited understanding regarding the actual composition of dust grains. Since dust properties are largely based on broadband photometry, this can cause issues in estimating dust masses (van der Tak et al. 2018). In Chapter 2 we fixed the dust emissivity parameter for a modified blackbody to be $\beta = 2$, but this is only based on theoretical consideration. Studies have shown that dust temperature can affect the emissivity parameter β (Mennella et al. 1998; Ysard et al. 2015). The precise dust com-

position of galaxies is not well constrained, since these are often estimated using a small number of broadband filters, but spectroscopic analysis will help us constrain dust mass and emission properties. In Chapter 2 we’ve examined dust mass *fractions* since we didn’t have a detailed model of dust emissivity, but constraining these parameters will allow us to estimate absolute dust masses. Herschel observations showed that the dust content is a function of metallicity (Remy-Ruyer et al. 2014), and therefore a function of redshift since metallicity generally evolves with time. However, the sample that Herschel was able to observe was relatively small and incomplete with respect to low luminosity galaxies. Similarly, in examining the far IR dust properties of AGNs detailed in Chapter 2, one of the biggest bottlenecks restricting our sample size was the far-IR flux limit of Herschel and the lack of corresponding far-IR photometry that could be matched with the AKARI catalog. Even with existing data that could be used for the analysis of dust properties, the interpretation of these data is highly dependent on dust emissivity models. For example, dust emissivity has been shown to vary between galaxies (Smith et al. 2012; Tabatabaei et al. 2014). and this type of behavior can heavily impact the validity of our results regarding dust mass, temperature, etc.

4.2.2 Mid-IR emission features

Spectral observations in the mid to far-IR offer insights to the physics of dusty AGNs that are not available in optical or NIR spectroscopy. The detection of mid-IR PAH features (which have a distinct spectral signature) are easy to identify and can be used to determine redshifts for dusty galaxies. Lines from highly ionized species such as [OIV] and [NeV] trace photons emitted from the AGN provides a direct probe of the accretion rate (Spinoglio & Malkan 1992). Highly ionized species (ex. O^{3+} , Ne^{4+}) can measure the AGN accretion rate, but these lines are only accessible in the mid-IR. For AGNs, most of the surveys of accretion activity is mostly confined to $z < 3$, but SPICA can reach redshifts of $3 < z < 6$, which is substantially farther than the redshift range accessible to previous IR telescopes. Black hole accretion rate is typically estimated using the bolometric luminosities of galaxies, but the errors on these high as a result of the uncertainties in the IR luminosity and AGN fractions in the IR portion of the SED (Perez-Gonzalez et al. 2005). The AGNs that we examined in Chapter 2 have enough far-IR photometry to make L_{IR} estimates

feasible, but this is not the case for the majority of AGNs that lack this kind of photometric data. Far-IR spectroscopy can provide direct measures of black hole accretion activity through inverse P-Cygni profiles of the absorption wings of OH and [OI]63 μm lines (Falstad et al. 2015).

PAH and silicate features in the mid-IR are generally much stronger than fine structure gaseous lines, making them ideal for spectroscopic analysis. We can use the equivalent width of PAH features to measure the relative fractions of AGN and host galaxy components, which will be a way to check our AGN fraction measurements obtained through SED fitting. This is a result of PAHs being photo-disassociated by strong UV and X-ray emission from the AGN, which also causes pure AGNs to have a nearly featureless power-law continuum in their SEDs. Unlike merely checking for the *presence* of broad-line emission features in spectra, PAH feature measurements allow us to quantitatively determine these relative AGN/host component fractions. Since mid-IR emission is generally minimally affected by extinction, this will allow us to positively identify AGNs that are otherwise missed by optical spectroscopy due to heavily extinction.

Since the purest AGNs will generally lack PAH emission due to complete photodissociation, we can examine mid-IR silicate emission features instead (Hao et al. 2005; Sturm et al. 2005). Strong silicate features at 9.7 μm and 18 μm can provide us with information about the dust distribution around the central engine (Hatziminaoglou et al. 2015), which will allow us to examine the nature of extinction applied to the AGN more closely. In the previous chapters, we have assumed that AGN extinction is adequately characterized by the same extinction curve for all objects. As evidenced by the general quality of our SED fits, this seems like a reasonable assumption and is consistent with the canonical AGN torus model adopted by others in the literature. However, we have no way of rigorously testing this assumption with SED models alone. In our initial attempts at SED fitting, we found that it is possible to add arbitrary amounts of extinction to the host galaxy component and still obtain a quality χ^2 value for the fit. We would need to directly examine the dust around the central engine to distinguish the effects of AGN extinction and host galaxy extinction (and also possibly, internal reddening). Giving this kind of ambiguity regarding the nature of dust extinction in SED models, having this kind of data would also help us evaluate the validity of using more complicated dust extinction parameterizations of (ex. Salim et al. (2018)). Kaneda

et al. (2017) estimates that a wide survey with SMI would be able to detect 5×10^4 PAH galaxies, and $\sim 10^5$ dusty AGN at $z > 1$. The spectral range of JWST can detect the near to far-IR features of PAHs in the local universe, but SPICA is optimized to do this for AGNs at $z > 1$. Fine-structure lines in the IR measured from SPICA will provide an extinction-free measure of metallicity (Spinoglio et al. 2017), which will provide further clues into the physical composition of the dust. Metallicity estimates are often based on optical lines, but spectral features in this region are naturally subject to extinction. This has the effect of biased existing dust models towards low-dust and low-metallicity galaxies, which are likely not entirely representative of the AGNs found at higher redshifts.

Similar to optical spectroscopy, IR spectroscopy offers opportunities for measuring AGN strength through emission line ratios and cross-checking SED vs. spectral measures of AGN fractions. Tommasin et al. (2010) shows that both the [NeV] $14.3 \mu\text{m}$ /[Ne II] $12.8 \mu\text{m}$ line ratio and [OIV] $25.9 \mu\text{m}$ /[Ne II] $12.8 \mu\text{m}$ line ratio correlate positively with AGN strength. Additionally, the line ratios [NeIII] $15.6 \mu\text{m}$ /[NeII] $12.8 \mu\text{m}$ vs. [OIV] $25.9 \mu\text{m}$ /[OIII] $88 \mu\text{m}$ can measure the strength of an AGN in a similar way as a BPT diagram, but using extinction-free lines in the IR instead of rest-frame optical emission lines. Figure 4.2 (adopted from Figure 4 of Spinoglio et al. (2017)) shows how different classifications of objects are distributed in a diagnostic plot of these line ratios. This IR analog of a BPT diagram can be used to identify AGNs in dwarf galaxies, which have a lower AGN fraction and are easily missed by traditional AGN selection methods (ex. X-ray surveys). This diagnostic plot is based on observations of galaxies in the local universe, but SPICA can test this at higher redshift to see if the loci show any redshift evolution.

4.2.3 Surveys

Gruppioni et al. (2017) describes the different types of proposed SPICA survey strategies, which is a “wedding-cake” combination of surveys of different sizes and depths for SMI/CAM. The deeper surveys will be done in fields with existing deep, multi-wavelength photometry and will offer complementary mid-IR data absent in these legacy data sets. This will also be complementary to ALMA and JWST, which will focus on smaller regions of the sky and be ideal for follow-up

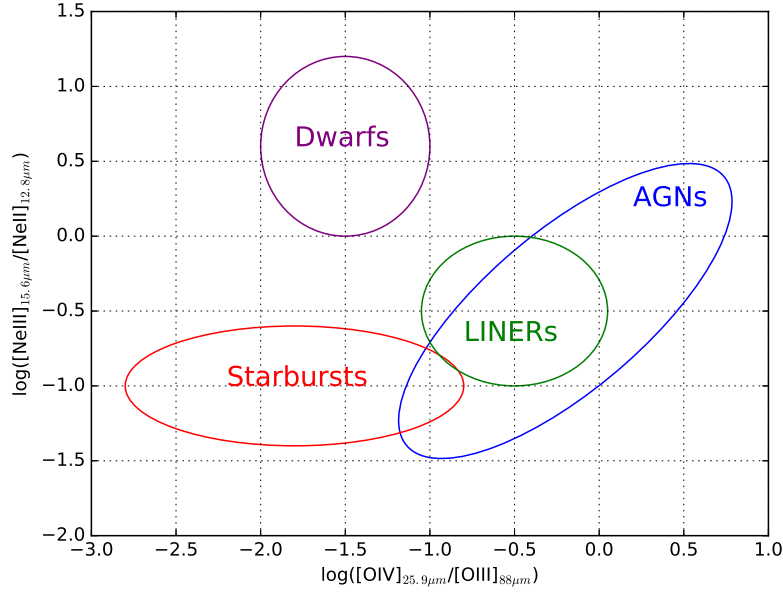


Figure 4.2: Mid-IR line ratio diagnostic plot of $[\text{NeIII}]_{15.6\mu\text{m}}/[\text{NeII}]_{12.8\mu\text{m}}$ vs. $[\text{OIV}]_{25.9\mu\text{m}}/[\text{OIII}]_{88\mu\text{m}}$. Ellipses indicate the regions corresponding to objects of different classifications: dwarf galaxies (purple), starbursts (red), LINERs (green), and AGNs (blue). Based on Figure 4 of Spinoglio et al. (2017).

observations. As shown in Chapter 3, the absence of Spitzer IRAC photometry in bands 3 and 4 effectively puts a redshift limit on the AGN SEDs we can reliably fit in the 3D-HST catalog. As we have seen in our attempts with SED fitting and measuring low luminosity AGNs, star-formation can represent a significant portion of the SED from the optical to mid-IR. At higher $6 < z < 7$ there is an increasing fraction of star forming galaxies containing an obscured AGN, and many of these are believed to still be undiscovered. The proposed Ultra-Deep Survey (UDS) can sample faint end of the luminosity function, which in Chapter 3 we’ve shown is very difficult to sample with high completeness.

A number of scaling relations between IR monochromatic luminosity and bolometric luminosity are based on the assumption that these relations hold for galaxies of different redshift ranges, but this has not been rigorously tested. In Chapter 2 we examined galaxies within a relatively narrow range of redshifts so this issue was not significant to our analysis, but extending our study of dust properties to a broader range of AGNs will require us to examine this more closely. SPICA’s SAFARI instrument also offers photometric observations at 45, 72, 100, 250, and 350 μm , which

will be powerful for additional analysis of far-IR dust properties.

4.3 SPHEREx

The Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer (SPHEREx, Dore et al. (2014, 2018)) will be the first *all-sky* near to mid-IR spectroscopic survey, planned for launch in 2023. The spectral bands covered by SPHEREx are 0.75 - 2.42 μm ($R = 41$), 2.42 - 3.82 μm ($R = 35$), 3.82 - 4.42 μm ($R = 110$), and 4.42 - 5 μm ($R = 130$). SPHEREx is expected to detect every source in the 2MASS point source catalog, as well as most of the sources in the WISE catalog. The final catalog of objects is expected to contain ~ 1 billion galaxy spectra, with ~ 100 million precision redshifts and ~ 1 million AGN spectra. This will drastically increase the number of spectroscopic redshift measurements usable for SED analysis, which will give us a larger sample size of dusty AGNs for analysis and allow for studies of redshift evolution. Our analysis of far-IR AGN dust properties was severely limited by the small number of photometric redshifts available, and we were unable to examine any dependence of these effects on redshift since our sample was primarily limited to AGNs in the local universe at $z \sim 1$. Using spectroscopic redshifts instead of photometric redshifts in SED modeling will also reduce the errors on dust temperature measurements (since there is a degeneracy between T_d and z) and L_{bol} . The spectral resolution of SPHEREx is high enough to resolve most AGN emission lines in the IR, and these will provide redshift measurements with accuracy of $\sigma_z/(1+z) \sim 0.03$ or better. This is especially important for AGNs at $z > 1$, since the lack of spectral break features above that redshift makes photometric redshift fitting highly inaccurate. The large sample size of redshifts will also be valuable for providing training sets for photometric redshift calibration.

This abundance of spectra by itself will provide a wealth of data for AGN studies, but SPHEREx is expected to have an additional impact through its synergy with other past, present, and future missions. SPHEREx is designed as an all-sky survey, and this will naturally complement the IR photometry obtained by WISE and AKARI. The low number density of objects in the AKARI Bright Source Catalog makes targeted observations inefficient with instruments such as DEIMOS

and MOSFIRE (not to mention the difficulty of obtaining observing time on a heavily oversubscribed telescope), which have a relatively small field of view despite their high multiplexing capabilities. An all-sky catalog of spectroscopic redshifts will drastically improve the usability of the AKARI data set for SED modeling and far-IR luminosity function measurements, since the relatively small number of spectroscopic redshifts in that catalog have been largely obtained through targeted spectroscopy. SPHEREx and JWST are expected to be in operation around the same time (launch delays notwithstanding), and the IR spectral coverage of the two missions are roughly coincident. JWST is intended to make deeper, targeted observations and will be useful for doing follow-up spectroscopy for any interesting objects identified in the SPHEREx catalog. Both these missions are expected to observe high redshift AGNs up to $z \sim 7$, and this deep redshift coverage will allow us to examine AGN redshift evolution far beyond what we were able to do using DEIMOS observations.

The all-sky scanning strategy of SPHEREx (similar to the scan strategy used by WISE) will provide particularly deep coverage of the ecliptic poles, and this coverage is expected to overlap with other deep fields to be covered by WFIRST and Euclid. The spectroscopic redshifts provided by SPHEREx combined with the multi-wavelength photometry in other deep surveys will allow us to perform detailed SED modeling to identify and characterization of the obscured AGN population. As we and others have demonstrated, the quantity and depth of photometry in the WISE catalog has made it significantly easier and more efficient to identify AGNs through mid-IR color selection. We expect that the redshift catalog from SPHEREx will create a similar impact by enabling large-scale AGN identification and characterization through SED modeling. Much like the WISE and AKARI surveys, the SPHEREx mission is designed for a variety of different science goals apart from AGN science and the legacy data set will be of use for years to come.

In addition to space-based telescopes, SPHEREx will also complement major ground-based spectroscopic surveys (ex. SDSS-V; Kollmeier et al. (2017)) by extending the optical wavelength coverage of ground-based observatories into the IR. One of the major components of the SDSS-V survey is the Black Hole Mapper (BHM), which is intended to examine the structure of the AGN broad-line region through reverberation mapping. Observations of the optical variability in the

spectrum captured by SDSS will complement observations of heated dust in the IR by SPHEREx. This will be useful for examining the physical relationship between the central AGN engine and surrounding dust, which is something that we had difficulty doing in detail using only photometry.

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