

Multiwavelength Study of Submillimeter Galaxies toward Understanding of Galaxy-Supermassive Black Hole Co-evolution

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Abstract

The evolutionary connection between galaxies and the supermassive black holes (SMBHs) at their centers is an important topic in modern astronomy. Numerous studies have suggested that galaxies and SMBHs co-evolve, inspired by the tight correlation between bulge mass and SMBH mass, as well as by the similar cosmic evolution of the star-formation rate density and the SMBH accretion rate density. However, the main process driving the co-evolution is still under debate. In this thesis, I tackle this mystery by focusing on two observationally outstanding populations: submillimeter galaxies (SMGs), and active galactic nuclei (AGNs) at their centers. SMGs are a cosmologically significant population of high-redshift galaxies that are very luminous at submillimeter wavelengths. They exhibit intense star-formation activities and are the observed manifestation of rapidly growing galaxies. In contrast, AGNs are the compact regions at the center of galaxies that emit significant amount of energy, fueled by intense accretion onto the central SMBHs. AGNs thus represent a specific phase during which SMBHs are actively growing. Therefore, comprehensive studies of both AGNs and SMGs are crucial to understand the mechanisms behind the co-evolution of galaxies and SMBHs.

First, I focus on the X-ray-detected AGNs in the SMGs from the ALMA Lensing Cluster Survey (ALCS). ALCS is an extensive survey of well-studied lensing clusters, that achieves the highest sensitivity in the source plane across mildly wide area. Since X-rays are well-established tracer of AGNs, these sources provide a secure sample of AGNs within faint SMGs. I examine the evolutionary phase of the galaxies and SMBHs for these sources. The X-ray spectral analysis shows that two of the AGNs are not significantly absorbed ($\log N_{\text{H}}/\text{cm}^{-2} < 23$), while the other shows signs of

moderate absorption ($\log N_{\text{H}}/\text{cm}^{-2} \sim 23.5$). From the X-ray to millimeter spectral energy distribution (SED) modelling, I find that the three X-ray AGNs show both high mass accretion rates (intrinsic 0.5–8 keV X-ray luminosities of $\sim 10^{44-45} \text{ erg s}^{-1}$) and high star-formation rates ($\gtrsim 100 M_{\odot} \text{ yr}^{-1}$). This demonstrates that a wide-area survey with ALMA and CXO can selectively detect intense growth of both galaxies and SMBHs in the high-redshift universe.

Next, I analyze the overall properties of the ALCS sample, including the X-ray undetected sources. From the optical to millimeter SED modelling, I find that the majority of the ALCS sources lie on the star-forming main sequence, with a smaller fraction showing intense starburst activities. In addition, ALCS sample contains high infrared-excess sources ($\text{IRX} = \log(L_{\text{dust}}/L_{\text{UV}}) > 1$), including two extremely dust-obscured galaxies ($\text{IRX} > 5$). For the dust properties, ALCS sample is confirmed to probe a broader range in lower dust mass than conventional SMG samples in the same redshift range, thanks to the deep millimeter selection. I also identify six AGN candidates from the SED analysis that are not detected in the archival CXO data. The X-ray upper bounds indicate that these sources are Compton thick or have unusually weak X-ray emission. This implies that a significant number of AGNs in SMGs are “hidden”, and not detected in previous X-ray observations below 10 keV.

Finally, I turn to the ALMA/SCUBA-2 COSMOS Survey (AS2COSMOS), which is a follow-up observation of the brightest SMGs in the Cosmic Evolution Survey (COSMOS) field. Since the COSMOS field has rich multi-wavelength data, it is an ideal field to study the properties of AGNs, including the “hidden” population presented in ALCS. From the SED analysis, I identify 24 AGN-host galaxies. Supplemented by 23 X-ray-detected AGNs, we construct an overall sample of 40 AGN-host galaxies. The X-ray luminosity upper bounds indicate that the X-ray undetected SED-identified AGNs are likely to be nearly Compton thick or have unusually suppressed X-ray emission. In the SFR versus AGN luminosity plane, the X-ray undetected SED-identified AGNs are distributed in the AGN-dominant phase, while X-ray AGNs are distributed around the simultaneous evolution lines. This suggests that in the AGN-dominant phase, AGNs tend to be heavily obscured or have anomalously suppressed X-ray emissions. From visual classification, we identify $25^{+6}_{-5}\%$ of the SMGs without AGNs as major merger candidates. This fraction is almost consistent with the general galaxy population at $z \sim 2$, suggesting that major mergers are not necessarily required for the enhanced star formation in SMGs. We also identify $47^{+16}_{-15}\%$ of the AGN hosts as major merger candidates, which is about twice as high as that in the SMGs without AGNs. This suggests that major mergers

play a key role in triggering AGN activity in bright SMGs.

A series of these results highlight two key insights into the co-evolution of galaxies and SMBHs in the high-redshift universe. First, during the rapid growth phase of SMBHs in SMGs, AGNs tend to be heavily obscured or exhibit anomalously suppressed X-ray emissions, making them difficult to detect with conventional X-ray observations below 10 keV. Such incompleteness could bias our estimates of the cosmological evolution of SMBH accretion rate density. Second, major mergers are not the principal driver of enhanced star formation in bright SMGs, but might play a key role in triggering AGN activity in those systems. This suggests that the galaxy-SMBH co-evolution at high redshift cannot be explained by a simple merger-driven evolutionary scenario.

Declaration

The work in this thesis is based on research carried out at Department of Astronomy, Kyoto University, Japan. The content presented in Chapter 2, Chapter 3, and Chapter 4 have been published in journals, which are listed below.

Publications

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Nomenclature

SMBH	Supermassive Black Hole
DSFG	Dusty Star-Forming Galaxy
LIRG	Luminous Infrared Galaxy
ULIRG	Ultra-Luminous Infrared Galaxy
SMG	Submillimeter Galaxy
AGN	Active Galactic Nucleus
SED	Spectral Energy Distribution
SFR	Star Formation Rate
SFH	Star Formation History
ALMA	Atacama Large Millimeter/submillimeter Array
CXO	Chandra X-ray Observatory
ACIS	Advanced CCD Imaging Spectrometer
HST	Hubble Space Telescope
ACS	Advanced Camera for Surveys
WFC3	Wide Field Camera 3
Spitzer	Spitzer Space Telescope
IRAC	Infrared Array Camera
MIPS	Multiband Imaging Photometer for Spitzer

Herschel	Herschel Space Observatory
PACS	Photodetector Array Camera and Spectrometer
SPIRE	Spectral and Photometric Imaging Receiver
VLA	Very Large Array
ALCS	ALMA Lensing Cluster Survey
AS2COSMOS	ALMA SCUBA-2 COSMOS Survey

Dedication

I dedicate this thesis to all taxpayers, who have not only funded my education but also my parents' salaries. Thank you for helping me grow!

CHAPTER 1

General Introduction

1.1 Galaxy-Supermassive Black Hole Co-evolution

In 2020, the Nobel Prize in Physics was awarded to Roger Penrose, Reinhard Genzel, and Andrea Ghez for their discoveries about the black hole. The prize was shared between Penrose for the theoretical discovery, and Genzel and Ghez for the observational discovery of a supermassive compact object at the center of our galaxy. This object is called as a supermassive black hole (SMBH), which has about four million solar mass in the case of our galaxy (Sagittarius A*). From their findings, a lot of effort was made to investigate the nature of SMBHs, and now the existence of SMBHs at the centers of galaxies is widely accepted (e.g., Kormendy & Richstone 1995; Richstone et al. 1998).[†] However, the history of SMBH growth is still an open question in modern astronomy.

One of the clues to solve this question is the evolutionary connection between galaxies and SMBHs. From 1990s, a lot of studies have shown the observational evidence of

[†]The first discovery that a dense stellar population could not explain the observed kinematic motion around a galactic center was made by Miyoshi et al. (1995), which utilized a rotating H₂O maser disc around the nucleus of NGC 4258.

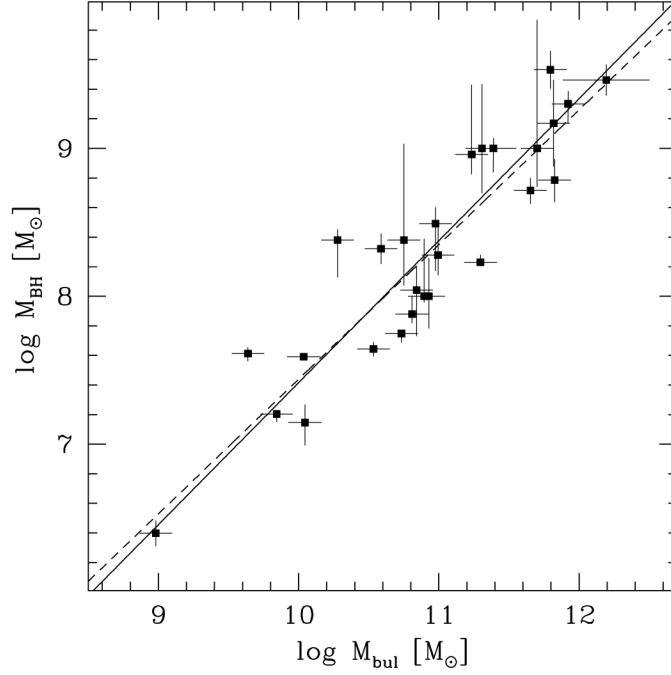


Figure 1.1: Correlation between bulge mass and SMBH mass. The solid lines are obtained with the bisector linear regression algorithm, while the dashed lines are ordinary least square fits. (Marconi & Hunt, 2003)

the tight correlation between the masses of SMBHs and the masses of the bulges of their host galaxies (Figure 1.1; e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000; Magorrian et al. 1998; Marconi & Hunt 2003). Although there are significant gaps in size and mass, but they can become energetically comparable. Therefore, it has been suggested that galaxies and SMBHs are co-evolving, by mutually regulating each other's growth (e.g., Kormendy & Ho 2013). This idea is also supported by the similarity in the cosmological evolution of the star-formation rate (SFR) density and the SMBH mass accretion rate density (Figure 1.2; e.g., Madau & Dickinson 2014; Ueda et al. 2014, 2003). However, the mechanism of the coevolution is still unclear.

1.2 Galaxy Merger

Galaxy merger is a promising process driving the co-evolution of galaxies and SMBHs. Numerical simulations have suggested that galaxy mergers can first trigger starburst activity, and then induce intense mass accretion at the centers of galaxies (Figure 1.3; Hopkins et al. 2008). At this phase, the compact regions of galactic centers emit enormous energy in wide wavelength, which can reach or exceed the luminosity of their host galaxies. These objects are called as active galactic nuclei (AGNs; see

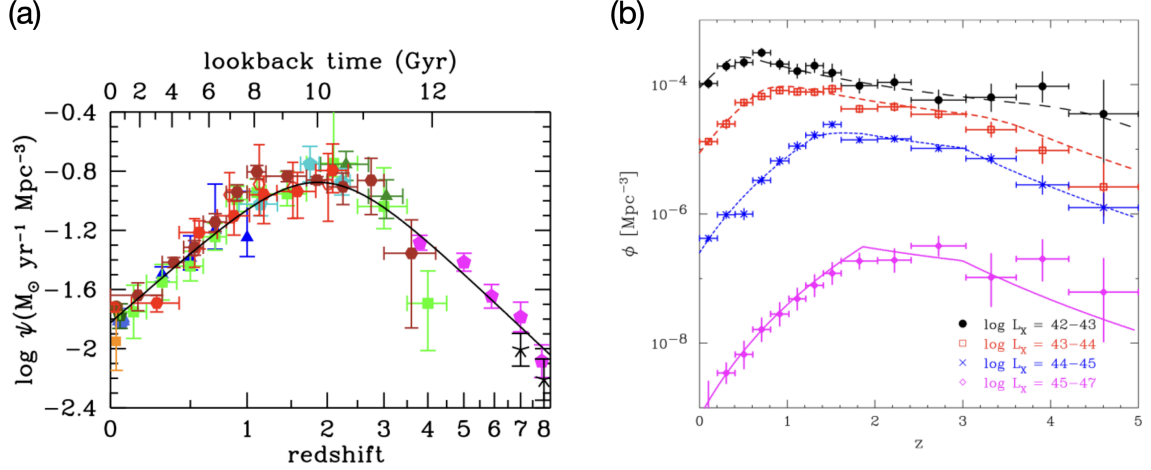


Figure 1.2: Cosmological evolution of the SFR density (a; Madau & Dickinson 2014) and the active galactic nucleus number density, which is a proxy of the SMBH mass accretion rate density (b; Ueda et al. 2014).

Section 1.4). After the emergencies of AGNs, the feedback from AGNs is supposed to quench the starburst activity in the host galaxies through outflowing material via winds and/or relativistic jets (Fabian, 2012). Hereafter, we call this scenario as the “merger-driven evolutionary scenario”.

This scenario is supported by many observations in the nearby universe, where the redshift (z) is lower than ~ 0.5 . For instance, several studies have shown the enhancement of star formation activity in merging galaxies (Armus et al., 1987; Ellison et al., 2013, 2008; Kennicutt et al., 1987; Knapen et al., 2015; Sanders & Mirabel, 1996; Scudder et al., 2012; Xu & Sulentic, 1991). The increase in the number fraction of AGNs is also observed in interacting systems (Araujo et al., 2023; Canalizo & Stockton, 2001; Comerford et al., 2024; Ellison et al., 2019; Pierce et al., 2023; Villar-Martín et al., 2011). However, the details of each process, such as the mechanism for subtracting sufficient amount of angular momentum from gas or the feedback from AGNs that quenches the star-formation activity in the host galaxies, are still unclear.

Over the past decade, surveys have started to test this scenario in the high-redshift universe ($z \geq 0.5$). For example, Schreiber et al. (2015) reported that the fraction of galaxies lying above the star-formation main sequence grows more slowly with redshift than the merger rate (Figure 1.4). In other surveys, Pearson et al. (2019) shown that the SFRs of merging galaxies are not significantly different from the SFRs of non-merging systems in the high-redshift universe. These results suggest that high-redshift mergers are statistically inefficient at triggering starburst, indicating the

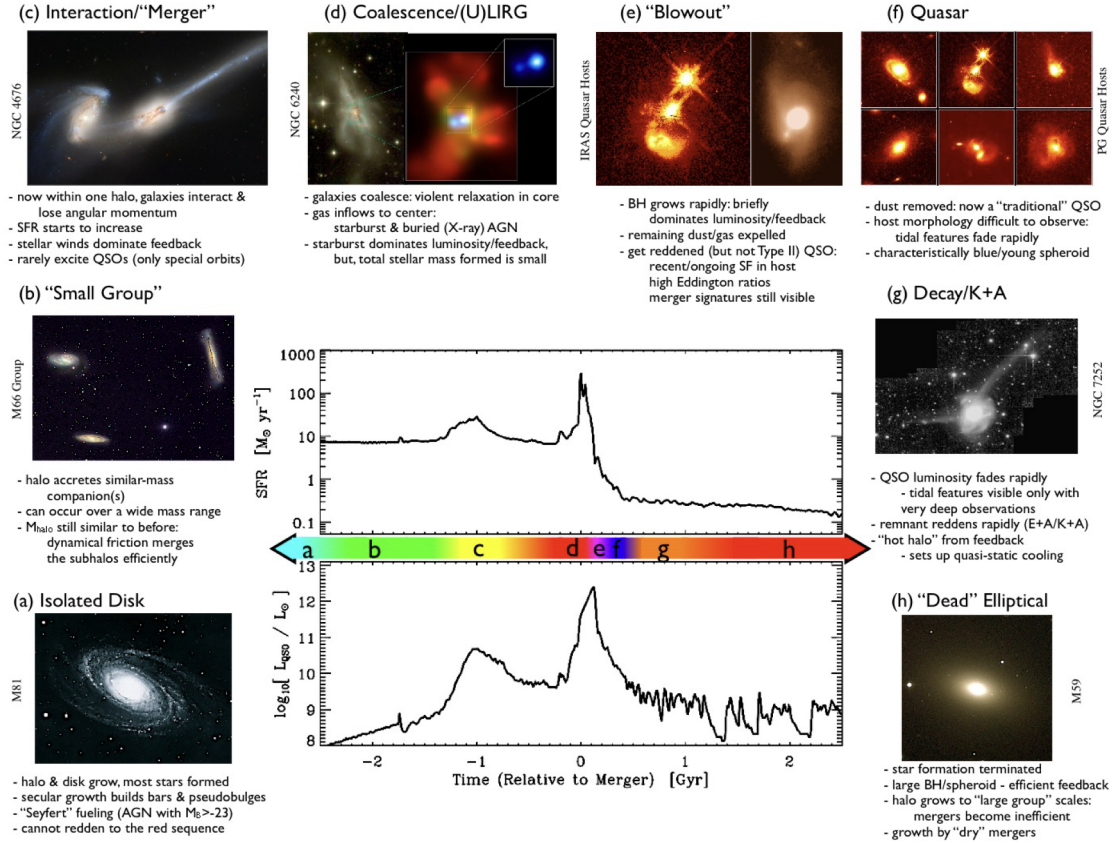


Figure 1.3: Schematic outline of the phases of growth in a "typical" galaxy undergoing a gas-rich major merger. Image credit: (a) NOAO/AURA/NSF; (b) REU program/NOAO/AURA/NSF; (c) NASA/STScI/ACS Science Team; (d) optical (left): NASA/STScI/R. P. van der Marel & J. Gerssen; X-ray (right): NASA/CXC/MPE/S. Komossa et al.; (e) left: J. Bahcall/M. Disney/NASA; right: Gemini Observatory/NSF/University of Hawaii Institute for Astronomy; (f) J. Bahcall/M. Disney/NASA; (g) F. Schweizer (CIW/DTM); (h) NOAO/AURA/NSF. (Hopkins et al., 2008)

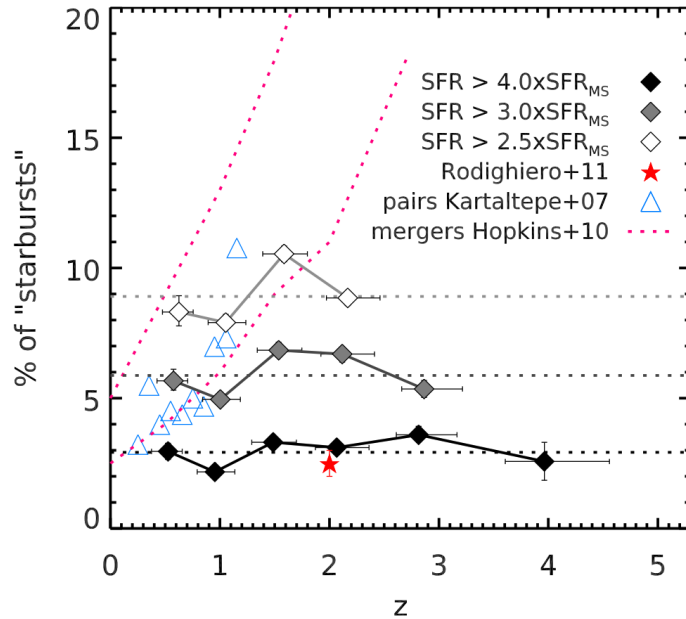


Figure 1.4: Evolution of the observed “starburst” fraction with redshift. Starbursts galaxies are defined as having an SFR enhanced by at least a factor X_{SB} compared to the SFR on the main sequence. Here, $X_{\text{SB}} = 4, 3$, and 2.5 are shown as diamonds (black, gray, and white, respectively), slightly offset in redshift for clarity. The observed value at $z = 2$ from Rodighiero et al. (2011) is shown as a filled red star, where $X_{\text{SB}} = 4$ was used. These figures are compared qualitatively to the observed pair fraction reported by Kartaltepe et al. (2007) as open blue triangles, and the range of major merger fractions predicted by Hopkins et al. (2010) is shown with dashed purple lines. (Schreiber et al., 2015)

existence of other mechanisms that drove the co-evolution of galaxies and SMBHs in the high-redshift universe. These studies are still ongoing, and the James Webb Space Telescope (JWST) will provide a new opportunity to investigate the high-redshift universe in more detail.

1.3 Submillimeter Galaxy

1.3.1 Dusty Star-forming Galaxy

Dusty star-forming galaxies (DSFGs) are a key population to tackle the puzzle of galaxy-SMBH co-evolution. These galaxies are characterized by their strong far-infrared (FIR) emission, implying intense star-formation activities. The brightest of DSFGs have infrared luminosities in excess of $L_{\text{IR}} = 10^{13} L_{\odot}$, which correspond to an SFR of $\sim 1000 M_{\odot} \text{ yr}^{-1}$. These systems are seen back to $z \sim 7$ (~ 800 Myr

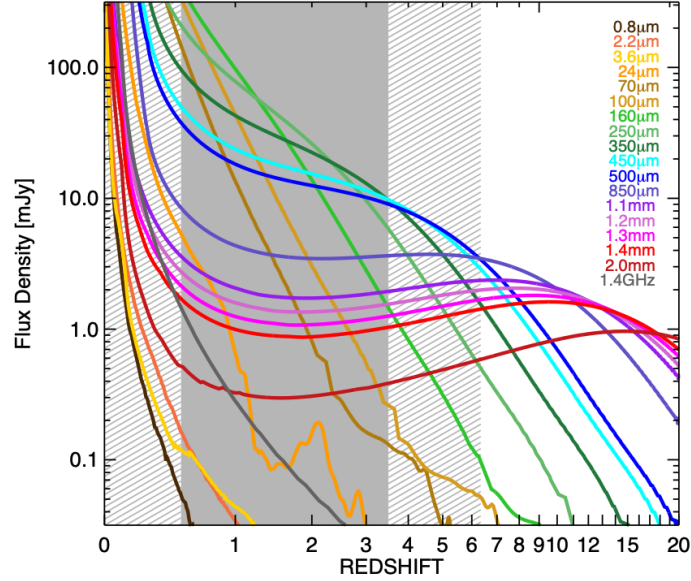


Figure 1.5: The observed flux densities for a typical DSFGs with an infrared luminosity of $L_{\text{IR}} = 10^{12.5} L_{\odot}$. The Pope et al. (2008) composite SMG spectrum is used to generate the flux evolution, or K -correction, at wavelengths 24 μm –2 mm, and at 1.4 GHz. An Arp 220 spectrum, adjusted to have a luminosity of $L_{\text{IR}} = 10^{12.5} L_{\odot}$, is used to generate optical and near-IR K -corrections. The peak epoch of DSFG discovery is highlighted in solid gray, from $0.5 < z < 3.5$, where redshift follow-up and characterization has been efficient, particularly for 850 μm -selected SMGs. The shaded areas, at $0 < z < 0.5$ and $3.5 < z < 6.4$ highlight redshift space where $L_{\text{IR}} = 10^{12.5} L_{\odot}$ galaxies are perceived to be rare. At $0 < z < 0.5$ this is because they have a very low volume density, attributable to cosmic downsizing (Cowie et al., 1996), whereas at high-redshift ($3.5 < z < 6.4$) it is unknown whether or not the volume density of DSFGs is much lower since galaxies are much more difficult to spectroscopically confirm. (Casey et al., 2014)

after the Big Bang), and are thought to be the most intense stellar nurseries in the universe. They are categorized based on their infrared luminosities: luminous infrared galaxies (LIRGs; $L_{\text{IR}} = 10^{11}\text{--}10^{12} L_{\odot}$), ultraluminous infrared galaxies (ULIRGs; $L_{\text{IR}} = 10^{12}\text{--}10^{13} L_{\odot}$), or hyperluminous infrared galaxy (HyLIRGs; $L_{\text{IR}} \geq 10^{13} L_{\odot}$).

The first systematic study of this population was performed with the Infrared Astronomical Satellite (IRAS; Neugebauer et al. 1984). During the short lifetime in 1983, IRAS logged $\sim 250,000$ extragalactic sources, and the bright subset of 629 sources became the most well-studied infrared sources (Revised Bright Galaxy Sample; RBGS; Sanders et al. 2003). Careful morphological analysis of these galaxies indicates that almost all the ULIRGs appear to be in advanced mergers (e.g., Sanders & Mirabel 1996). This demonstrates that galaxy mergers are a key process to trigger intense star formation in DSFGs in the local universe.

1.3.2 Submillimeter Survey

Submillimeter observations are a powerful tool to study high-redshift DSFGs. Thanks to the negative K -correction, submillimeter flux densities of DSFGs remain relatively constant or even increase with redshift up to $z \sim 10$ (Figure 1.5; Casey et al. 2014), which allows an efficient survey of DSFGs in submillimeter wavelengths. This population is often referred to as submillimeter galaxies (SMGs). The first deep submillimeter survey was performed by Smail et al. (1997). This survey utilized the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope (JCMT) and targeted two massive, concentrated clusters, A370 at $z = 0.37$ and Cl 2244-02 at $z = 0.33$, at wavelengths of 850 and 450 μm (Figure 1.6). Due to the limited sensitivity, only a few sources were detected in this survey. However, the observed source counts required a significant increase in the number density of strongly star-forming galaxies in the high-redshift universe and indicated that previous optical surveys substantially underestimated the star formation density in the distant Universe.

Since their pioneering work, many submillimeter surveys have been performed to study SMGs. Table 1.1 summarizes the key submillimeter (and millimeter) surveys (Wang et al., 2020). Although these surveys covered wide areas, their sensitivities remain limited. One critical issue is the low angular resolution of single-dish telescopes at submillimeter wavelengths. For example, JCMT has a beam size of ~ 13 arcsec at 850 μm , which is much larger than the typical angular resolution of ground-based

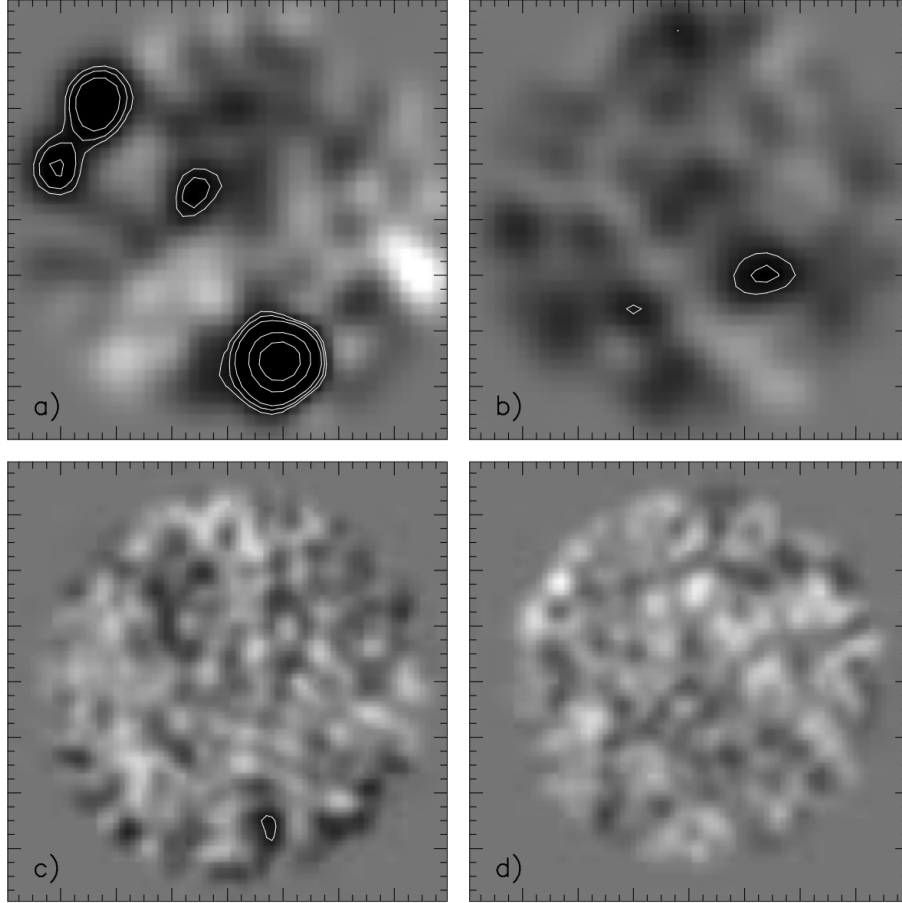


Figure 1.6: The 450 and 850 μm maps of the two fields: a) A370, 850 μm ; b) Cl 2244-02, 850 μm ; c) A370, 450 μm ; d) Cl 2244-02, 450 μm . The maps are smoothed to the instrumental resolution at each wavelength and have had their boundaries apodized to remove regions on the outskirts with low effective exposure times resulting from the rotation of the field-of-view during our long exposures. They are displayed as a grayscale from -4σ to 4σ , the contours are positive and show 3, 4, 5, 10, 15 σ for each field. The major tick marks are 20 arcsec in all panels. (Smail et al., 1997)

optical telescopes (~ 0.5 arcsec). Consequently, it cannot resolve individual faint SMGs that are more numerous than bright SMGs, and the observed flux densities are the sum of the emission from multiple sources. This phenomenon is known as the “confusion limit” (Helou & Beichman, 1990). At this limit, sensitivity does not improve by increasing the exposure time, and the only solution is to improve angular resolution. The low angular resolution also causes problems in identifying the counterparts of SMGs in other wavelengths. Since the positional accuracy of SMGs is subjected to the beam size, single-dish surveys cannot accurately locate the positions of SMGs, making the identification of counterparts at other wavelengths often ambiguous. This issue is also crucial for understanding the nature of SMGs.

The Atacama Large Millimeter/submillimeter Array (ALMA) is a game changer in submillimeter surveys. Utilizing the interferometric technique, ALMA achieves an unprecedentedly high angular resolution (< 1 arcsec at $870\ \mu\text{m}$), which allows us to resolve faint SMGs and perform much deeper surveys than the conventional single-dish surveys. Since its first scientific observation in 2011, ALMA has been utilized for many submillimeter surveys. Table 1.2 summarizes the key submillimeter and millimeter surveys performed with ALMA. These surveys achieved more than one order of magnitude deeper sensitivities than previous single-dish surveys, and detected more general population at high redshift. Combination survey with ALMA and single-dish telescopes is also an effective strategy. Since ALMA has a small field of view, it is difficult to cover wide areas with ALMA alone. On the other hand, single-dish telescopes have a wide field of view, but the angular resolution is limited. Thus, follow-up observations with ALMA of bright sources detected with single-dish telescopes can resolve the individual SMGs and construct secure SMG catalogs in wide areas. This strategy has been successfully applied to several surveys.

1.3.3 Representative ALMA Surveys

In this section, I introduce some examples of representative ALMA surveys that are treated as the comparison samples in thesis (see also Table 1.1 and Hodge & da Cunha 2020 for a recent review). The ALMA LABOCA E-CDFS Submillimeter Surveys (ALESS; Chen et al. 2015; da Cunha et al. 2015; Danielson et al. 2017; Decarli et al. 2014; Hodge et al. 2013; Karim et al. 2013; Simpson et al. 2014; Swinbank et al. 2012a, 2014, 2012b; Thomson et al. 2014; Wang et al. 2013) is an ALMA cycle 0 program to follow up ~ 100 SMGs that were previously detected by the single-dish LABOCA $870\ \mu\text{m}$ survey in the extended Chandra Deep Field South (LESS; Weiß

Table 1.1: Summary of single-dish submillimeter and millimeter surveys (Wang et al., 2020) (edited).

Survey	Sky Area [deg ²]	Wavelength [μm]	1σ rms [mJy beam ⁻¹]	Reference
SCUBA/JCMT SHADES	0.2	850	2	Coppin et al. (2006)
SCUBA/JCMT HDF	0.0025	850	0.45	Hughes et al. (1998)
SUPER GOODS	0.125	850/450	0.28/2.6	Cowie et al. (2017)
Hawaii SCUBA-2 Lensing Cluster Survey	0.137	450	4.4 ^c	Hsu et al. (2016)
S2CLS	5	850	1.2	Geach et al. (2017)
S2COSMOS/eS2COSMOS	2	850	0.9	Simpson et al. (2019)
STUDIES	0.08	450	0.55	Wang et al. (2017)
S2LXS	10	850	2	^a
HerMes	380	250/350/500	5.2~12.8	Oliver et al. (2012)
H_ATLAS	570	250/350/500	9	Eales et al. (2010)
HerS	79	250/350/500	13.0/12.9/14.8	Viero et al. (2014)
BGS-Wide	10	250/350/500	36/31/20	Chapin et al. (2011)
BGS-Deep	0.9	250/350/500	11/9/6	Chapin et al. (2011)
LESS	0.25	870	1.2	Weiß et al. (2009)
AzTEC GOODS-S	0.075	1100	0.48~0.73	Scott et al. (2010)
AzTEC GOODS-N	0.068	1100	0.96~1.16	Perera et al. (2008)
AzTEC SHADES	0.7	1100	0.9	Austermann et al. (2010)
AzTEC COSMOS	0.72	1100	1.26	Aretxaga et al. (2011)
SPT	2500	1400/2000/3000	4/1.2/2	Mocanu et al. (2013); Vieira et al. (2013)
IRAM/GISMO survey	0.07	2000	0.23	Magnelli et al. (2019)
NIKA2 GOODS-N ^d	0.04	1200/2000	0.2~0.6/0.1~0.3	Désert et al. (2016)
NIKA2 COSMOS ^d	0.4	1200/2000	0.1/0.07	Désert et al. (2016)
Planned Survey				
ToITeC Ultra-Deep Galaxy Survey	1	1100/1400/2000	0.026/0.024/0.018	^b
ToITeC Large Scale Structure Survey	100	1100/1400/2000	0.26/0.24/0.18	^b

^a Geach et al. M17BL001

^b http://toltec.astro.umass.edu/science_legacy_surveys.php

^c Before lensing amplification correction.

^d See also Beelen et al. <https://lpsc-indico.in2p3.fr/Indico/event/1765/session/9/contribution/52>

Table 1.2: Summary of submillimeter and millimeter surveys with ALMA.

Survey	Sky Area [arcmin ²]	Wavelength [mm]	1 σ rms [μ Jy beam ⁻¹]	Reference
SXDF-ALMA	2.0 (PB > 0.5)	1.1	55	Hatsukade et al. (2016)
HUDF	4.5	1.3	35	Dunlop et al. (2017)
ALMA Frontier Fields	26 (PB > 0.3)	1.1	55–71 ^a	González-López et al. (2017a); Muñoz Arancibia et al. (2023)
ADF22	6	0.63/0.87/1.1	230/21/12	Umehata et al. (2015, 2017, 2024)
ASAGAO	26 (PB > 0.2)	1.2	61	Hatsukade et al. (2018)
ASPECS	2.9 (PB > 0.5)	1.2	9.3	Aravena et al. (2016a); González-López et al. (2020)
	4.6 (PB > 0.5)	3.0	3.8	González-López et al. (2019)
GOODS-ALMA	72.42 (PB > 0.2)	1.1	68.4	Franco et al. (2018); Gómez-Guijarro et al. (2022a)
ALCS	133 (PB > 0.3)	1.2	40–92 ^a	Fujimoto et al. (2024); Kohno et al. (2023)
DUALZ	24	1.2	32.7	Fujimoto et al. (2023)

^a These surveys covered several clusters, and the rms depths varied from field to field.

et al. 2009). It was able to separate unresolved multiple sources that were confused in the previous single-dish survey, and successfully yielded a reliable catalog of SMGs.

In order to search for rare populations and to improve statistics, Stach et al. (2019) performed ALMA imaging follow-up of the SCUBA-2 UDS survey (AS2UDS) in cycles 1, 3, 4, and 5. This survey observed 716 SMGs in the UKIDSS Ultra Deep Survey (UDS) field that were previously detected by the SCUBA-2 Cosmology Legacy Survey (S2CLS: Geach et al. 2017), and yielded the largest homogeneously-selected SMG sample to date (see also Algera et al. 2020; Cooke et al. 2018; Dudzevičiūtė et al. 2020; Gullberg et al. 2019; Koprowski et al. 2020; Smail et al. 2021; Stach et al. 2018).

To search for fainter, hence more numerous sources, Dunlop et al. (2017) performed an ALMA deep survey in the GOODS-S/Hubble Ultra Deep Field (HUDF; Beckwith et al. 2006). It covered an area of ~ 4.5 arcmin² and detected 16 secure sources with a flux limit of 0.1 mJy at 1.3 mm.

The ALMA twenty-Six Arcmin² survey of GOODS-S At One-millimeter (ASAGAO; Fujimoto et al. 2018; Hatsukade et al. 2018, 2020; Ueda et al. 2018; Yamaguchi et al. 2019, 2020) was designed to fill the gap between the ALESS and HUDF surveys. This survey covered an area of 26 arcmin² (primary beam sensitivity of PB > 20%) and detected 25 sources at $\geq 5.0\sigma$ (45 sources at $\geq 4.5\sigma$) with a flux limit of 0.2 mJy (1.2 mm).*

To simultaneously search for blank-field CO line and dust continuum, the large program called ALMA Spectroscopic Survey in the HUDF (ASPECS) was performed in cycle 4 (Aravena et al., 2016a,b, 2019, 2020; Boogaard et al., 2019, 2020; Bouwens et al., 2016; Carilli et al., 2016; Decarli et al., 2016a,b, 2019, 2020; González-López et al., 2020; Inami et al., 2020; Magnelli et al., 2020; Popping et al., 2019, 2020; Uzgil et al., 2019, 2021; Walter et al., 2016). This survey covered 2.9 arcmin² (PB > 50%) and detected 35 secure sources with a flux limit of ~ 0.04 mJy at 1.2 mm, which is the deepest ALMA survey unbiased in the image plane conducted to date.

*The GOODS-S area is also covered by an extensive survey at 1.1 mm called GOODS-ALMA (Ciesla et al., 2023; Franco et al., 2018, 2020a,b; Gómez-Guijarro et al., 2022a,b; Zhou et al., 2020).

1.4 Active Galactic Nucleus

1.4.1 Unified Picture of AGN

In contrast to DSFGs, which represent a population of rapidly growing galaxies, AGNs are phases during which SMBHs actively grow. AGNs are the compact regions at the center of galaxies that emit significant amounts of energy (bolometric luminosity of $\log L_{\text{bol}}/\text{erg s}^{-1} \sim 42\text{--}47$), powered by intense mass accretion onto the central SMBHs. AGNs are classified into two categories based on their optical spectrum: type-1 and type-2. Type-1 AGNs have broad ($1000\text{--}20000 \text{ km s}^{-1}$) permitted and semi-forbidden emission lines, whereas type-2 AGNs show only narrow ($300\text{--}1000 \text{ km s}^{-1}$) emission lines (see Netzer 2015 for a review). Today, this difference is understood as an orientation effect of AGNs (Antonucci, 1993; Antonucci & Miller, 1985; Urry & Padovani, 1995). Assuming a toroidal obscuring materials around the central SMBH, a type-1 AGN is interpreted as seen from a face-on view, where the fast moving gas near the SMBH can be observed. This region is called the broad line region (BLR). By contrast, a type-2 AGN corresponds to an edge-on view, where the obscuring torus blocks the direct view of the BLR. Since their findings, this unified picture of AGNs has been tested and is known to explain a lot of observed features of AGNs (Figure 1.7; Beckmann & Shrader 2012).

The basic idea of the unified picture is widely accepted, and many updates have been made. Some studies have suggested that the torus is not a simple structure with smooth gas, but a complex one with clumpy materials (e.g., Elitzur & Shlosman 2006; Krolik & Begelman 1988; Nenkova et al. 2008a,b; Tristram et al. 2007). Recent interferometric observations in the mid-infrared bands have also revealed the presence of an extended component elongated in the polar direction (e.g., Asmus 2019; Hönig & Kishimoto 2017; Hönig et al. 2012; Tristram et al. 2014). From a theoretical point of view, Wada (2012) proposed a “radiation-driven fountain” model, in which the radiation pressure from the accretion disk drives biconical outflows, and the falling back of failed winds and inflows naturally form a geometrically thick torus-like shape. This model is known to successfully reproduce the observed properties of AGNs (Izumi et al., 2018, 2023; Ogawa et al., 2022; Uzuo et al., 2021; Wada et al., 2016).

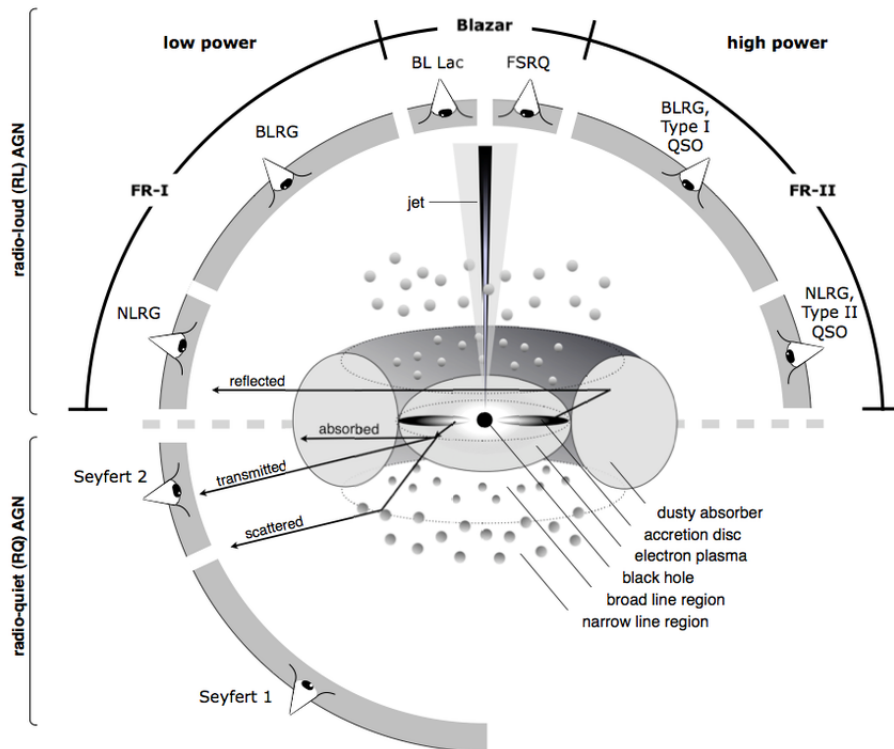


Figure 1.7: Schematic representation of our understanding of the AGN phenomenon in the unified scheme. The type of object we see depends on the viewing angle, whether or not the AGN produces a significant jet emission, and how powerful the central engine is. Note that radio loud objects are generally thought to display symmetric jet emission. Graphic by Marie-Luise Menzel (Beckmann & Shrader 2012; https://www.researchgate.net/figure/Schematic-representation-of-our-understanding-of-the-AGN-phenomenon-in-the-unified_fig2_231205857).

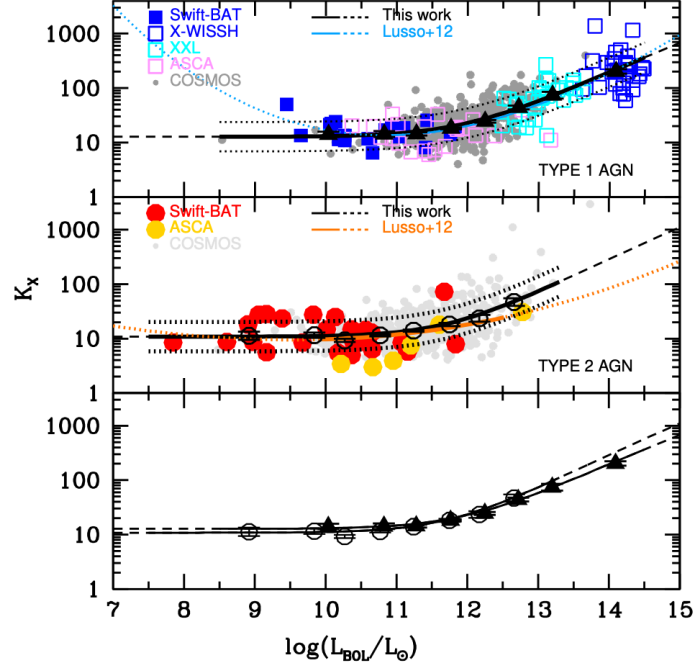


Figure 1.8: Hard X-ray bolometric correction in the 2–10 keV band as a function of the bolometric luminosity for type 1 (upper panel) and type 2 (central panel) AGN. Symbols are as in the legend. Black filled triangles and open circles show the average values for type 1 and type 2 sources, respectively (directly compared in the lower panel), in bins of bolometric luminosity. The black solid and dashed lines show the best-fit relations and their extrapolations. (Duras et al., 2020)

1.4.2 Growth Rate of SMBH

The mass accretion rate onto a central SMBH is a key parameter, as it directly reflects the growth rate of SMBHs. This value is thought to be tightly correlated with the luminosities of AGNs (Shakura & Sunyaev, 1973). In the case of a moderate Eddington ratio, the mass accretion rate is calculated as:

$$\dot{M}_{\text{BH}} = L_{\text{bol}}(1 - \eta)/\eta c^2 \quad (1.1)$$

where c is the speed of light and η is the radiative efficiency (Ueda et al., 2018). η depends on the spin of the SMBHs, and the typical value is $\eta \sim 0.05$ (Ueda et al., 2014). L_{bol} is the bolometric luminosities of AGNs, which is calculated by integrating the observed luminosity over the entire wavelengths. Accurate measurements of the bolometric luminosities of AGNs are sometimes challenging, particularly in the case of type-2 AGNs, because a large fraction of the energy is emitted in the ultraviolet (UV) wavelengths, where it is easily absorbed by surrounding gas and dust.

X-ray observations are powerful tools to measure the bolometric luminosities of

AGNs. Since X-rays have strong penetrating power, they are less affected by the obscuring materials. In addition, in the X-ray bands (0.5–10 keV), the opacity of gas varies significantly with energy, which enables us to measure the line-of-sight hydrogen column density of the obscuring materials by an X-ray spectral analysis. X-ray luminosity is known to be correlated with the bolometric luminosity of AGNs. Thus, we can estimate the bolometric luminosity of AGNs from an X-ray spectral analysis. Many studies have investigated the X-ray properties of AGNs (e.g., Fabian et al. 2000; George & Fabian 1991; Nandra & Pounds 1994; Reynolds & Nowak 2003; Tanaka et al. 1995; Turner & Miller 2009), and the correlation between the X-ray luminosities and the bolometric luminosities has also been studied intensively, utilizing less obscured AGNs where the bolometric luminosities are securely estimated (e.g., Elvis et al. 1994; Lusso & Risaliti 2016; Lusso et al. 2012; Marconi et al. 2004; Steffen et al. 2006; Vasudevan & Fabian 2007).

Figure 1.8 shows a recent calibration of hard X-ray (2–10 keV) to bolometric correction factor ($K_X = L_{\text{bol}}/L_X$) by Duras et al. (2020). As shown in the figure, the hard X-ray to bolometric correction factor is known to become larger with increasing bolometric luminosity. Although a clear explanation for this trend remains elusive, some studies suggest it may be linked to the changes in the X-ray corona in the most powerful AGNs (Martocchia et al., 2017; Nardini et al., 2019; Zappacosta et al., 2020). Finally, if the line-of-sight hydrogen column density exceed $N_H > 1.7 \times 10^{24} \text{ cm}^{-2}$, it is specially referred to as Compton thick. In such cases, the direct emission is almost completely blocked by the obscuring materials, making it difficult to estimate the intrinsic X-ray luminosity.

1.5 Thesis Outline

In this thesis, I investigate the properties of AGNs in SMGs identified by two recent ALMA surveys-ALMA Lensing Cluster Survey (ALCS) and ALMA/SCUBA2 COSMOS Survey (AS2COSMOS)-as a step toward understanding the co-evolution of galaxies and SMBHs in the high-redshift universe. ALCS is an ALMA Cycle 6 large program that conducted an unbiased study of 33 lensing clusters, covering a relatively wide area for an ALMA survey. While its overall sensitivity is moderate, ALCS achieved an exceptionally high sensitivity within strongly magnified regions. This survey detected 180 faint SMGs with $S_{1.2\text{mm}} = 0.007\text{--}5.6 \text{ mJy}$ in the source planes. AS2COSMOS is an ALMA cycle 4 program that followed up 160 of the

brightest SCUBA-2 850- μm sources from the S2COSMOS survey. AS2COSMOS is effectively complete for SMGs brighter than $S_{850\mu\text{m}} = 6.2\text{ mJy}$, and identified 260 SMGs with $S_{870\mu\text{m}} = 0.7\text{--}19.2\text{ mJy}$. While ALCS provides an ultra-deep, lensing-boosted view of faint SMGs, AS2COSMOS offers a bright SMG sample across a wider area. Combining these complementary surveys enables a more comprehensive study of the SMG population across a broad luminosity range.

In Chapter 2, I briefly summarize the properties of X-ray-detected AGNs in the ALCS sample. Since X-rays are well-established tracer of AGNs, this provides a study of secure AGN sample in faint SMGs. In Chapter 3, I investigate the properties of all the SMGs in the ALCS sample, including X-ray undetected SMGs. This provides a general view of a faint SMG population. In Chapter 4, I study the properties of SMGs in the AS2COSMOS sample. Here I also perform a morphological analysis to directly test the impact of major mergers on galaxy and SMBH growth in bright SMGs. In Chapter 5, I summarize the thesis and provide a future prospect.

CHAPTER 2

ALMA Lensing Cluster Survey: Properties of Millimeter Galaxies Hosting X-ray-detected Active Galactic Nuclei

We report the multi-wavelength properties of millimeter galaxies hosting X-ray-detected AGNs from the ALCS sample. ALCS is an extensive survey of well-studied lensing clusters with ALMA, covering an area of 133 arcmin^2 over 33 clusters with a 1.2 mm flux-density limit of $\sim 60 \mu\text{Jy}$ (1σ). Utilizing the archival data of Chandra X-ray observatory (CXO), we identify three AGNs at $z = 1.06$, 2.09, and 2.84 among the 180 millimeter sources securely detected in the ALCS (of which 155 are inside the coverage of CXO). The X-ray spectral analysis shows that two AGNs are not significantly absorbed ($\log N_{\text{H}}/\text{cm}^{-2} < 23$), while the other shows signs of moderate absorption ($\log N_{\text{H}}/\text{cm}^{-2} \sim 23.5$). We also perform spectral energy distribution (SED) modeling of X-ray to millimeter photometry. We find that our X-ray AGN sample shows both high mass accretion rates (intrinsic 0.5–8 keV X-ray luminosities of $\sim 10^{44-45} \text{ erg s}^{-1}$) and star-formation rates ($\gtrsim 100 M_{\odot} \text{ yr}^{-1}$). This demonstrates that a wide-area survey with ALMA and CXO can selectively detect intense growth of both galaxies and SMBHs in the high-redshift universe.

2.1 Introduction

X-ray properties of SMGs have been intensively studied so far. For example, Wang et al. (2013) found 10 X-ray counterparts to 99 SMGs of ALESS (Hodge et al., 2013), from which 8 sources were identified as AGNs; hereafter we refer to these X-ray AGNs as “ALESS-XAGN” sample. Moreover, Rujopakarn et al. (2016) found 6 X-ray AGNs from 16 SMGs of GOODS-S/UDF survey (Dunlop et al., 2017); hereafter “UDF-XAGN”. Furthermore, Ueda et al. (2018) identified 13 X-ray AGNs in a sample consisting of 25 SMGs from the ASAGAO sample (Hatsukade et al., 2018), supplemented by the UDF survey (6 X-ray AGNs are the same as UDF-AGN); hereafter, we refer to those X-ray AGNs that are not in the UDF region as “ASAGAO-XAGN”. Finally, Stach et al. (2019) identified 23 X-ray AGNs from 274 SMGs of AS2UDS (Stach et al., 2018) falling within the CXO footprint; hereafter “AS2UDS-XAGN”. However, these studies are still limited in parameter space (depth and area). In shallow surveys, the results are biased for intensively star-forming galaxies, whereas rare populations are missed in narrow area surveys. It is important to conduct deep and wide area surveys to carry out a complete census of the whole sub/millimeter populations.

Lensing fields are excellent targets to perform deep surveys efficiently. Using ALMA in cycle-6, our team conducted an extensive survey in high magnification regions of 33 lensing clusters, called the ALMA lensing cluster survey Fujimoto et al. 2024; Kohno et al. 2023. The sample comes from the best-studied clusters of galaxies observed with the Hubble Space Telescope (HST) treasury programs, i.e., CLASH (Postman et al., 2012), HFF (Lotz et al., 2017; Steinhardt et al., 2020), and RELICS (Coe et al., 2019). The total survey area is 133 arcmin^2 and the depth is $\sim 60 \mu\text{Jy}$ (1.2 mm, 1σ). The ALCS achieves, after correcting for lensing, one of the widest and deepest millimeter surveys among ALMA unbiased surveys conducted to date (Fujimoto et al., 2024).

In this chapter, we investigate the properties of the three X-ray-detected AGNs in the ALCS, using the archival data of CXO. We estimate the X-ray luminosities (or mass-accretion rates), star-formation rates, and stellar masses of this sample, and discuss their evolutionary stages in comparison with other X-ray-detected samples. The structure of this chapter is as follows. In Section 2.2, we describe the details of sample selection and data reductions. Section 2.3 presents the X-ray spectral analysis and the SED modeling. Section 2.4 and 2.5 are the discussion and conclusion, respectively. Throughout the chapter, we assume a flat universe with $H_0 = 70.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$

and $\Omega_M = 0.272$ (Komatsu et al., 2011). The Chabrier initial mass function (IMF, Chabrier 2003) is adopted.

2.2 Observations and Data Reduction

2.2.1 Observations and Source Detection with ALMA

ALMA Band-6 observations of the 33 lensing clusters were conducted between 2018 December and 2019 December through the program 2018.1.00035.L (PI: K. Kohno; Kohno et al. 2023) with a 15 GHz total bandwidth covering 250.0–257.5 GHz and 265.0–272.5 GHz. Two compact array configurations (C43-1 and C43-2) were used to obtain a moderate synthesized beam size (~ 1 arcsec) to avoid losing sensitivity for spatially extended sources, which can be expected for highly magnified cases. For five Hubble Frontier Fields, we also combined the existing ALMA data from 2013.1.00999S and 2015.1.01425.S (PI: F. Bauer; González-López et al. 2017a,b).

All the ALMA data were calibrated and reduced with the Common Astronomy Software Applications package (CASA; McMullin et al. 2007) with the pipeline script in the standard manner. Different pipeline versions were used for observations obtained in different cycles, i.e., v5.4.0 for 26 clusters observed in Cycle 6 and v5.6.1 for the remaining clusters in Cycle 7. The natural-weighted 1.15 mm continuum images have a typical noise level of $\sim 60 \mu\text{Jy beam}^{-1}$ with a native beam size of ~ 1 arcsec with the natural weighting. We also produced lower resolution maps by applying a uv -taper, yielding a typical beam size of ~ 2 arcsec, which is better suited for spatially elongated, low surface brightness emission.

The source detection was performed with the SEXTRACTOR in native and tapered maps with natural weighting. First, in a blind search, 141 sources were detected with a signal-to-noise ratio (SNR) over 5.0 in the natural maps or over 4.5 in the tapered maps, which corresponds to a false-detection rate of $< 1\%$. Second, in a prior-based approach, 39 sources are detected with $5.0 \geq \text{SNR} \geq 4.0$ (a false-detection rate of $< 50\%$) in the natural maps associated with $4.5 \mu\text{m}$ detection ($\text{SNR} \geq 5.0$). Details of the ALMA data analysis, source extraction processes, and the ALCS 1.2 mm continuum source catalog is presented in a separate paper (Fujimoto et al., 2024).

2.2.2 CXO Counterparts

CXO (Weisskopf et al., 2002) observed the ALCS fields on multiple occasions since 1999 with the Advanced CCD Imaging Spectrometer (ACIS: Garmire et al. 2003). It covers all the ALCS fields except for RXC J0032.1+1808 and RXC J0600.1-2007, with a median exposure of ~ 80 ksec. 155 sources out of the 180 secure ALCS sources are covered by the existing CXO data. We processed all the data obtained by 2017, following the standard analysis procedures with the Chandra interactive analysis of observations (CIAO v4.12) software and calibration database (CALDB v4.9.1). The products were combined by using MERGE_OBS and sources were detected by running WAVDETECT (Freeman et al., 2002) in the 0.5–7.0 keV band. In the detection, the false-positive probability threshold was set to 10^{-8} and the wavelet scales were set to “ $\sqrt{2}$ sequence” (i.e., 1, $\sqrt{2}$, 2, $2\sqrt{2}$, 4, $\sqrt{2}$, 8, $8\sqrt{2}$ and 16 pixels), which are the same settings as in Luo et al. (2008). We cross-matched the CXO detected sources with the secure ALCS source list comprising of 180 millimeter detected galaxies (see Fujimoto et al. 2024). The X-ray counterpart of an ALMA source was identified if the position coincides with the ALMA position within the CXO positional uncertainty, for which we adopt the root sum square of the 3σ statistical error and the 99% absolute astrometry uncertainty of CXO (1.4 arcsec).^{*} We ignored the positional uncertainty of ALMA, which is much smaller than that of CXO. The cluster center regions are excluded because of the difficulty in identifying point sources.

The three X-ray counterparts were found in the cluster fields of Abell370, MACSJ0416.1-2403, and MACS0329.7-0211, where the total exposure times of the CXO observations are 96.3 ks, 328 ks, and 77.5 ks, respectively. The source names are A370-ID110, M0416-ID117, and M0329-ID11 (hereafter “ALCS-XAGN”). Their coordinates are summarized in Table 2.1. We extracted the X-ray spectra from circular regions with radii of 1.5 arcsec for A370-ID110 and of 2.0 arcsec for M0416-ID117 and M0329-ID11. Since the point spread function (PSF) sizes at M0416-ID117 and M0329-ID11 are slightly larger than that at A370-ID110, we adopted a little larger aperture for M0416-ID117 and M0329-ID11. centered at the X-ray source positions, and subtracted the backgrounds taken from source-free regions around the objects.

It should be noted that these AGNs were also reported in previous studies. A370-ID110 was first discovered by the submillimeter survey of Abell 370 using the

^{*}<https://cxc.harvard.edu/cal/ASPECT/celmon/>

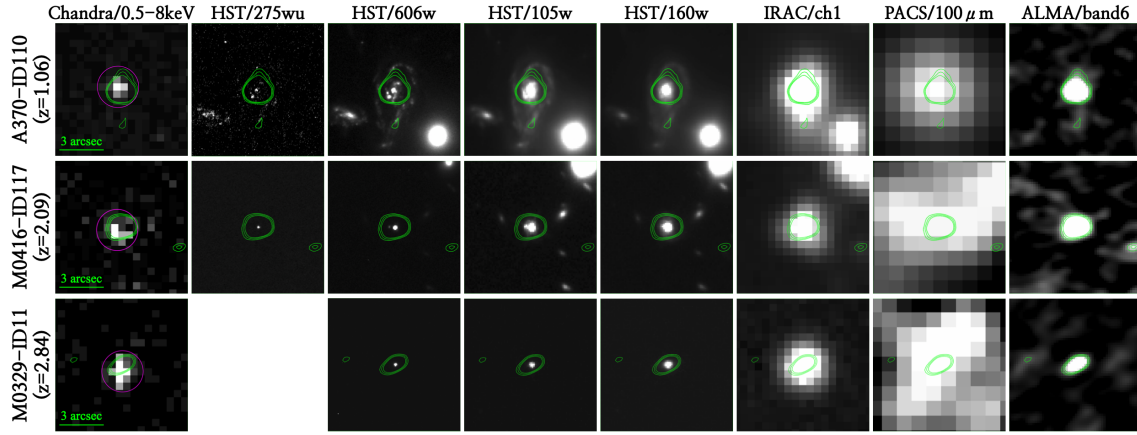


Figure 2.1: Multi-wavelength images of the ALCS-XAGNs. The green contours show the intensity in the ALMA band drawn at 1σ intervals from 3σ to 5σ . The magenta circles in the CXO images show the absolute astrometry uncertainty of CXO (1.4 arcsec). For the three sources, the statistical error of CXO is much smaller than the absolute one (<0.3 arcsec). The Herschel/PACS images are smoothed with 2D Gaussians of σ radii of 1.5 pixels.

Submillimeter Common-User Bolometer Array (SCUBA) (Smail et al., 1997), and was subsequently detected in X-rays by a CXO follow-up (Bautz et al., 2000). Its properties were discussed in several papers (e.g., Alexander et al. 2005; Smail et al. 2002; Soucail et al. 1999). M0416-ID117 was previously detected with ALMA in González-López et al. (2017a), and its physical properties were discussed in Laporte et al. (2017). M0416-ID117 and M0329-ID11 were detected in blind X-ray surveys using CXO archival data by Wang et al. (2016a) and Gilmour et al. (2009), respectively. In this chapter, we reanalyze the X-ray spectra and then perform X-ray to millimeter SED analyses utilizing the newly obtained ALMA data.

2.2.3 HST, Spitzer, and Herschel Counterparts

Optical, near-infrared, and mid-infrared images of these three clusters were taken using HST Advanced Camera for Surveys (ACS*) and Wide Field Camera 3 (WFC3[†]), and Spitzer Space Telescope (Spitzer) Infrared Array Camera (IRAC; Fazio et al. 2004). The images and source catalogs were built by reprocessing of available archival HST and Spitzer IRAC 3.6 μm and 4.5 μm mosaics of ALCS fields (Kokorev et al., 2022). All three ALCS-XAGN sources have counterparts in ACS, WFC3, and IRAC

*<https://www.stsci.edu/hst/instrumentation/acs>

[†]<https://www.stsci.edu/hst/instrumentation/wfc3>

(channel 1 and 2) images as shown in Figure 2.1. We also utilized IRAC (channel 3 and 4) and Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) photometric data from the Spitzer Enhanced Imaging Products (SEIP; SSC And IRSA 2020). Only the counterpart of A370-ID110 was found in the SEIP catalog within 1.5 arcsec. M0416-ID117 and M0329-ID11 were found outside the coverage of IRAC ch3, ch4 and MIPS.

Herschel Space Observatory (Herschel) Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) images at 100–500 μm bands have been obtained for the ALCS fields mostly through the Herschel Lensing Survey (Egami et al., 2010; Sun et al., 2021). One of the fields, Abell 370 was observed as part of the PACS Evolutionary Probe (PEP, Lutz et al. 2011). Although some of the ALCS fields have only shallow (“snap-shot”) SPIRE coverages without PACS observations, all three ALCS-XAGN containing fields have deep SPIRE and PACS images. The PACS 100 μm images of these 3 ALCS-XAGN sources are also presented in Figure 1. Details of the Herschel data in ALCS fields are described in Sun et al. (2022).

2.3 Spectral Analysis and Results

2.3.1 X-ray Spectral Analysis

We fit the observed (magnification not corrected) X-ray spectra with a simple absorbed power-law model. This model is represented as follows in the XSPEC (Arnaud, 1996) terminology:

$$\text{phabs} * \text{zphabs} * \text{zpowerlaw} \quad (2.1)$$

The first term (**phabs**) represents the galactic photoelectric absorption and the second term (**zphabs**) an intrinsic absorption at the source redshift. All the parameters are left as free parameters except for the galactic absorption column density and the redshift. The former is fixed at the values estimated by the method of Willingale et al. (2013). The redshifts are fixed at the spectroscopic ones obtained by Canada-France-Hawaii Telescope in A370-ID110 ($z = 1.06$; Soucail et al. 1999) and the Grism Lens-Amplified Survey from Space in M0416-ID117 ($z = 2.09$; Hoag et al. 2016), and at the photometric one estimated by the optical to near-infrared SED analysis with

the EAZY code in M0329-ID11 ($z = 2.84^{+0.10}_{-0.11}$; Kokorev et al. 2022).

We are able to adequately reproduce the X-ray spectra of the AGNs, with reduced chi-square values of less than 1 ($\chi^2/\text{d.o.f.} < 1$). The left panels of Figure 2.2 show the result of the X-ray spectral fitting. The best fit parameters are summarized in Table 2.1. A370-ID110 shows a significant absorption in the X-ray spectrum. This is consistent with the previous X-ray study by Bautz et al. (2000). We note that A370-ID110 and M0329-ID11 show especially high X-ray luminosities ($\log L_X/\text{erg s}^{-1} \gtrsim 44.5$) compared with normal AGNs.

2.3.2 SED modeling with cigale

We perform multi-component SED modeling of the X-ray to millimeter photometry, where we use the magnification-corrected photometries. We employ the latest version of Code Investigating GALaxy Emission (CIGALE v2022.0; Boquien et al. 2019; Burgarella et al. 2005; Noll et al. 2009; Yang et al. 2020, 2022) to conduct X-ray to millimeter SED modeling by self-consistently considering the energy balance between the UV/optical and IR. The SED modules used for the fitting are as follows. We employ a delayed star-formation history (SFH) model, assuming a single starburst with an exponential decay. The simple stellar population (SSP) is modeled with the stellar templates of Bruzual & Charlot (2003), where we assume the Chabrier (2003) IMF. We apply a modified Calzetti starburst attenuation law (Calzetti et al., 2000), where we also allow steeper curve than the original one. The standard nebular emission model (see Inoue 2011) is also added. For the AGN emission, we adopt the SKIRTOR model (Stalevski et al., 2012, 2016), a clumpy two-phase torus model. The dust emission is modeled by the dust templates of Jones et al. (2017). We assume an isotropic X-ray radiation from an AGN, where we fix the photon index of 1.9 as a common value, which is well within the errors derived by the X-ray spectral analysis. Here, we use the 2–8 keV absorption corrected flux derived by the X-ray spectral analysis.* The redshifts are fixed at the values noted in Section 2.3.1. The free parameters are summarized in Appendix A.1. The physical properties are estimated by the Bayesian method, where we adopt log-uniform distributions for the prior probability distributions of SFR[†], stellar mass (M_*), dust luminosity (L_{dust}), and

*We adopt the average of the upper and lower errors as the flux error.

[†]In this chapter, the term “SFR” refers to the average SFR in the last 10 Myr.

dust mass (M_{dust}^*), while uniform distributions are assumed for those of minimum radiation field of interstellar dust (U_{min}), infrared excess ($\text{IRX} = \log L_{\text{dust}}/L_{\text{UV,SF}}$), and power-law index of observed UV slope (β).

We confirm that CIGALE successfully reproduces the SEDs from millimeter to X-ray of all the sources ($\chi^2/\text{d.o.f.} < 5$).[†] The right panels of Figure 2.2 show the results of SED modeling. The physical properties are summarized in Table 2.1. The SED modeling suggests that A370-ID110 is a type 2 AGN, whereas M0416-ID117 and M0329-ID11 are type 1 AGNs. This result is consistent with the AGN types suggested by the X-ray absorption hydrogen column-densities (type 1: $\log N_{\text{H}}/\text{cm}^2 \lesssim 22$, type 2: $\log N_{\text{H}}/\text{cm}^2 \gtrsim 22$). We also confirm that the near infrared spectrum of A370-ID110 (Takata et al., 2006) shows no clear broad emission lines. We find that all the sources are classified as ULIRGs ($L_{\text{IR}}/L_{\odot} > 10^{12}$) and show high star-formation rates ($\text{SFR} \gtrsim 100 M_{\odot} \text{yr}^{-1}$). This is consistent with the results presented in Sun et al. (2022). We also confirm that the physical properties of A370-ID110 and M0416-ID117 are consistent with those reported in the previous studies (Laporte et al., 2017; Smail et al., 2002).

2.4 Discussions

We discuss our results in comparison with other ALMA and CXO selected AGN samples (i.e., ALESS-XAGN, UDF-XAGN, ASAGAO-XAGN, and AS2UDS-XAGN) at $z=1-3$. We also compare our results with X-ray-selected broad line AGNs at $z=1.18-1.68$ in the SXDF (hereafter SXDF-XAGN; Ueda et al. 2008) as a sample with a different selection method. The stellar masses and SFRs of ALESS-XAGNs, UDF-XAGNs, ASAGAO-XAGNs, and AS2UDS-XAGN are estimated by the MAGPHYS code (da Cunha et al., 2015; Dudzevičiūtė et al., 2020; Yamaguchi et al., 2020), while those of SXDF-XAGNs are estimated by the X-CIGALE code (Setoguchi et al., 2021). The X-ray luminosities of ALESS-XAGNs, UDF-XAGNs and ASAGAO-XAGNs, and AS2UDS-XAGNs are taken from Wang et al. (2013), Ueda et al. (2018), and Kocevski et al. (2018), respectively. We also extract the X-ray luminosities of

*In this chapter, we use the terms “dust luminosity” and “dust mass” to describe those of interstellar dust (i.e., not including those in the AGN torus).

[†]Although this threshold is much larger than in an ordinary chi-square test, we adopt a conservative value by considering the over simplification of the SED model, such as the SFH profile, ignorance of time-variability in AGN, and uniform distribution of interstellar dust among stars (see e.g., Toba et al. 2022).

Table 2.1: (1) Source names. (2)&(3) ALMA source position. (4) Redshift. Those of A370-ID110 and M0416-ID117 are the spectroscopic redshifts, while that of M0329-ID11 is the photometric redshift (see Section 2.3.1 for more detail). (5) Magnification factor due to the lensing effect (Fujimoto et al., 2024). (6) X-ray absorption hydrogen column density in units of 10^{22} cm^{-2} . (7) Photon index. (8) Intrinsic X-ray luminosity in the rest-frame 0.5–8.0 keV band. (9) Star-formation rate. (10) Stellar mass. (11) Total infrared emission from interstellar dust. (12) Dust mass. (13) Minimum radiation field illuminating the interstellar dust. (14) Infrared excess ($\text{IRX} = \log L_{\text{dust}}/L_{\text{UV}}$). In CIGALE, IRX is calculated from the GALEX FUV filter and dust luminosity. (15) Power-law index of observed UV slope, which is measured in the same way as Calzetti et al. (1994). (16) Fraction of AGN IR luminosity to total IR luminosity, where we use the rest-frame 8–1000 μm luminosities. (17) IR luminosity in the rest-frame 8–1000 μm band, which is measured by integrating the best-fit SED over a wavelength of 8–1000 μm . Errors attached in (6)–(8) correspond to the 90% confidence regions, whereas those in (9)–(16) show the 1σ confidence regions. All physical quantities in this table are corrected for the lensing magnification; possible uncertainties in the magnification factors are ignored. Because of the poor far-infrared data of M0329-ID11, the IR luminosity may have a large uncertainty.

name	R.A. [degree]	Decl. [degree]	z	μ	N_{H} [10^{22} cm^{-2}]	Γ	$\log L_{\text{X}}$ [erg s^{-1}]	$\log \text{SFR}$ [$M_{\odot} \text{ yr}^{-1}$]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	$\log M_*$	$\log L_{\text{dust}}$	$\log M_{\text{dust}}$	U_{min}	IRX	β	f_{AGN}	$\log L_{\text{IR}}$
	[$M_{\odot}$]	[$L_{\odot}$]	[$M_{\odot}$]					[$L_{\odot}$]
	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
A370-ID110	39.985689	-1.5739784	1.06	1.19	$32.8^{+11.7}_{-10.6}$	$2.5^{+0.8}_{-0.8}$	$45.0^{+0.7}_{-0.5}$	2.43 ± 0.02
	11.81 ± 0.06	12.51 ± 0.02	8.80 ± 0.02	25.0 ± 0.4	2.14 ± 0.02	0.49 ± 0.13	0.23 ± 0.09	12.68
M0416-ID117	64.0449843	-24.0798771	2.09	1.57	$2.4^{+8.6}_{-2.4}$	$2.1^{+0.9}_{-0.6}$	$43.8^{+0.6}_{-0.3}$	1.93 ± 0.05
	10.81 ± 0.16	12.01 ± 0.03	7.98 ± 0.11	51.2 ± 12.5	0.84 ± 0.03	-1.85 ± 0.02	0.05 ± 0.01	12.07
M0329-ID11	52.4239873	-2.1824407	2.84	2.46	$0.1^{+5.9}_{-0.1}$	$1.7^{+0.6}_{-0.4}$	$44.4^{+0.3}_{-0.2}$	2.18 ± 0.08
	10.74 ± 0.21	11.77 ± 0.15	8.63 ± 0.15	7.3 ± 3.7	-0.03 ± 0.14	-2.03 ± 0.08	0.55 ± 0.22	12.40

SXDF-XAGNs from Nobuta et al. (2012), where we convert the 2–10 keV luminosity to 0.5–8 keV luminosity, assuming a power-law spectrum with $\Gamma = 1.9$. Here we note that all the X-ray luminosities of AS2UDS-XAGNs and ALESS-AGNs are estimated at their spectroscopic redshifts, while the stellar masses and SFRs are estimated at their photometric ones. In this chapter, we only plot the sources whose photometric redshifts are close to their spectroscopic ones within $-(z_{\text{photo}} - z_{\text{spec}})/(1 + z_{\text{spec}}) < 0.3$. Hence, the systematic errors in stellar masses and SFRs are estimated to be ~ 0.3 dex, which does not affect our discussions.

Recently, Hunt et al. (2019) investigated the systematic differences among the three SED models: GRASIL (Silva et al., 1998), MAGPHYS, and CIGALE, utilizing the far-ultraviolet to submillimeter SEDs of the 61 galaxies from the KINGFISH sample (Kennicutt et al., 2011). They showed that galaxies with high specific SFRs ($\log \text{sSFR}[\text{yr}^{-1}] > -10.6$) show good agreement in their stellar masses and SFRs among the three models, whereas those with low sSFRs sometimes show large differences in their SFRs. The sSFRs of the ALESS-XAGNs, UDF-XAGNs, ASAGAO-XAGNs, and AS2UDS-XAGNs are adequately high ($\log \text{sSFR}[\text{yr}^{-1}] > -9.6$), and hence we ignore the systematic difference between CIGALE and MAGPHYS as an approximation.

2.4.1 Stellar Mass versus SFR

The left panel of Figure 2.3 shows stellar masses versus SFRs for our 3 sources and other AGN samples (ALESS-XAGN, UDF-XAGN, ASAGAO-XAGN, AS2UDS-XAGN, and SXDF-XAGN). We also show the star-forming “main sequence” at $z=1.0$, $z=2.0$, and $z=3.0$ given by Speagle et al. (2014). Our sample is distributed close to the main sequence lines (within 0.2 dex along the SFR axis). This indicates that our sources are normal star-forming galaxies at $z=1-3$, i.e. galaxies with no clear evidence for negative feedback by the AGNs. We note that the ALCS-XAGN sample contains a massive star-forming galaxy (A370-ID110; $M_* > 10^{11} M_\odot$) and that the SFRs of ALCS-XAGN tend to be smaller than those of the compared SMG samples (see the next section).

2.4.2 X-ray luminosity versus SFR

The right panel of Figure 2.3 shows X-ray luminosities versus SFRs. We also show the relation of galaxy-SMBH simultaneous evolution for the local $M_{\text{BH}}\text{-vs-}M_{\text{bulge}}$ and $M_{\text{BH}}\text{-vs-}M_{\text{stellar}}$ relations. This relation is given as

$$\text{SFR} * (1 - R) = A \times \dot{M}_{\text{BH}} \quad (2.2)$$

where R is the return fraction ($R = 0.41$ for a Chabrier IMF), and A is the mass ratio ($M_{\text{bulge}}/M_{\text{BH}} = 200$ and $M_{\text{stellar}}/M_{\text{BH}} = 400$; see Ueda et al. 2018 for more details). The mass-accretion rate can be estimated by the X-ray luminosity as

$$\dot{M}_{\text{BH}} = \kappa_{0.5-8} L_{\text{X}} (1 - \eta) / (\eta c^2) \quad (2.3)$$

where $\kappa_{0.5-8}$ is the bolometric correction factor ($\kappa_{0.5-8} = 13$ or $\kappa_{2-10} = 20$ assuming a photon index of 1.9; Vasudevan & Fabian 2007), η is the radiation efficiency ($\eta = 0.05$), and c is the speed of light. ALCS-XAGNs are located on the “simultaneous evolution” line or in the AGN dominant phase, while the other ALMA and CXO selected samples belong to the SF-dominant phase. This is a unique feature of our ALCS-XAGN sample among sub/millimeter selected galaxies, realized by the following selection effects. Since the X-ray data of ALCS are shallower but cover a wider area than those of the UDF survey and ASAGAO, high X-ray luminosity (hence rare) AGNs can be efficiently selected in the ALCS sample. On the other hand, because ALCS is much deeper than the parent sample of ALESS and AS2UDS*, whose median SFRs are $\sim 250 M_{\odot} \text{ yr}^{-1}$, ALCS can detect AGNs in the AGN-dominant phase, which are relatively faint in the millimeter band with SFRs $\lesssim 250 M_{\odot} \text{ yr}^{-1}$. Besides, since the ALCS-XAGNs are selected by millimeter observations, they are more biased to higher SFRs compared with purely X-ray selected AGN samples (e.g., SXDF-XAGNs whose median SFR is $\sim 30 M_{\odot} \text{ yr}^{-1}$). Page et al. (2012) showed that SMGs containing AGNs with high mass-accretion rates show relatively low SFRs, implying negative feedback by the AGNs. Given this trend, A370-ID110 and M0329-ID11, which show both high SFRs ($\text{SFR} > 100 M_{\odot} \text{ yr}^{-1}$) and high X-ray luminosities ($\log L_{\text{X}}/\text{erg s}^{-1} \gtrsim 44.5$), may be a rare population that is difficult to be detected in previous sub/millimeter surveys.

*Since ALESS and AS2UDS are follow-up observations of the single-dish surveys LESS (Weiß et al., 2009) and S2CLS (Geach et al., 2017), respectively, their properties are basically determined by the selection bias of the parent samples.

According to the merger-driven evolutionary scenario proposed by many authors (e.g., Hopkins et al. 2008; Sanders & Mirabel 1996; Yamada et al. 2021; Yutani et al. 2022), the galaxies and SMBHs “co-evolve” during major mergers being deeply embedded by gas and dust, and then evolved to the AGN dominant phase with quenched SFRs by AGN feedback. If this scenario is applicable, our sources may correspond to the transition stage where the merging has finished, but the star formation is not yet quenched. The smaller obscuration in our AGNs than that in late-stage mergers (Ricci et al., 2017a, 2021; Yamada et al., 2021) is also consistent with this picture.

We note, however, that it is not clear whether the AGNs and star-formation activities in our sample are indeed triggered by merger processes or not. Some studies argue that a significant fraction of AGNs at $z \sim 1-3$ are triggered by secular mechanisms (e.g., Draper & Ballantyne 2012; Kocevski et al. 2012; Schawinski et al. 2011), where star-formation activities may inject turbulence in the gas disks and make the gas fall into the nuclear regions (Hobbs et al., 2011). Given the high SFRs of ALCS-XAGNs, the AGN activities might be triggered by the intense star-formation activities in their host galaxies.

Fujimoto et al. (2018) studied the morphology of DSFGs detected in ASAGAO at $z=1-3$. They found that the ULIRGs at $z=1-3$ showed larger fractions of irregular and merging galaxies than less luminous galaxies, implying the significant contribution of ongoing merger process in high-redshift ULIRGs, although the fraction of disk galaxies is the largest even in the ULIRG sample. In our X-ray AGN sample, only A370-ID110 is confirmed to have disk-like structure, while M0416-ID117 and M0329-ID11 are too faint to examine their morphology. Future investigation of host galaxy morphology with James Webb Space Telescope or Thirty Meter Telescope would be helpful to reveal the origins of the high mass accretion rates and SFRs in our sample.

2.5 conclusions

We report the multi-wavelength properties of millimeter galaxies hosting AGNs detected in the ALCS. The main conclusions are summarized as follows:

1. Utilizing the archival data of CXO, we identified 3 AGNs out of the 180 millimeter galaxies securely detected in the ALCS, which are found in the fields of Abell370, MACSJ0416.1–2403, and MACS0329.7–0211 at spectroscopic

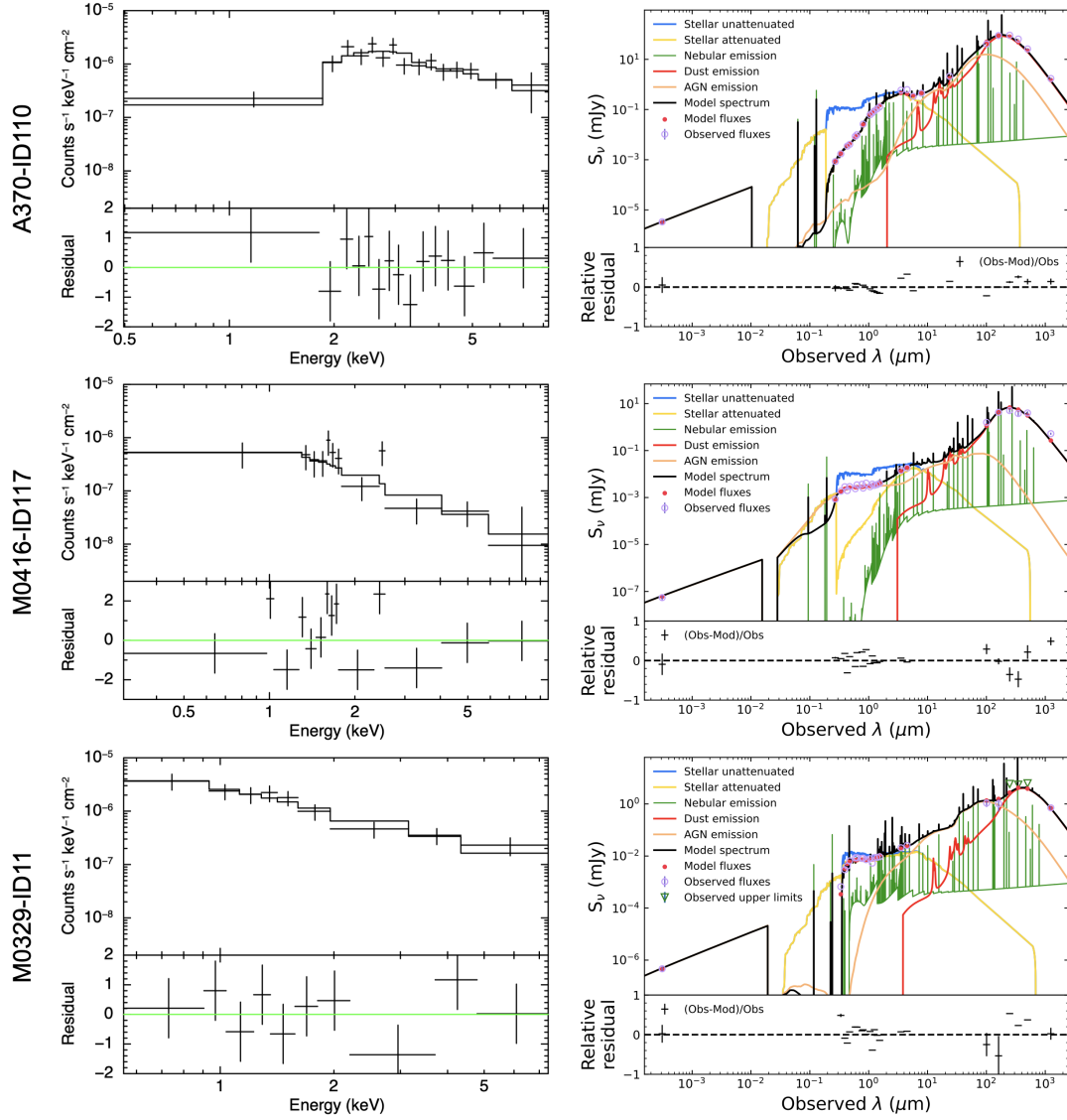


Figure 2.2: Left: folded X-ray spectra corrected for the effective area and the best fit models of the ALCS-XAGNs. The lower panel shows the residuals. Right: results of the SED modeling. The solid black line represents the best-fit SEDs. The lower panel shows the residuals. The X-ray spectra are not corrected for lensing magnification, while the X-ray to millimeter SEDs are corrected.

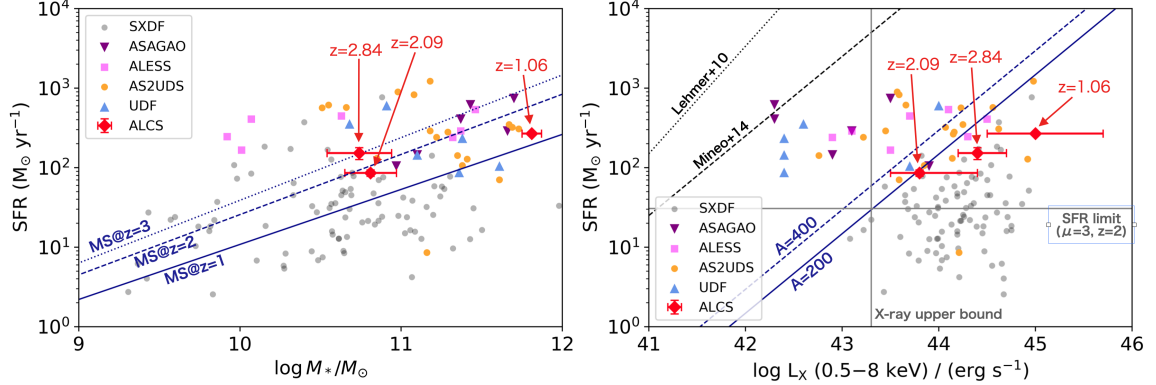


Figure 2.3: Left: stellar masses (M_*) versus SFRs. The blue lines represent the star-forming “main sequence” at $z=1.0$ (solid), $z=2.0$ (dashed), and $z=3.0$ (dotted), respectively (Speagle et al., 2014). Right: de-absorbed X-ray luminosities versus SFRs. The solid and dashed blue lines represent the relation of galaxy-SMBH simultaneous evolution for $A=200$ and $A=400$, respectively (Section 2.4.2). All the physical quantities in this figure are corrected for lensing magnification. For comparison, we show the X-ray contribution from star-formation activity with dotted (Lehmer et al., 2010) and dashed (Mineo et al., 2014) black lines. We also show the median X-ray upper bounds of CXO non-detected ALCS sources with vertical grey line, where we assume an intrinsic X-ray absorption of $\log N_{\text{H}}/\text{cm}^{-2} = 23$ (Uematsu et al., 2024). Moreover, we show the detection limit of SFR with horizontal grey line. The SFR limit is converted from the infrared luminosity limit by assuming the Kennicutt law (Kennicutt, 1998a), where we multiply 0.63 to correct Salpeter IMF to Chabrier IMF. The infrared luminosity limit is estimated from the observed flux limit at 1.2 mm ($\sim 300 \mu\text{Jy}$; 5σ) by assuming a single greybody with an emissivity index of 1.8 and temperature of 35 K at $z = 2$, using a typical magnification factor of 3.

redshifts of 1.06 and 2.09, and photometric redshift of 2.84, respectively.

2. The X-ray spectral analysis shows that two AGNs are not significantly absorbed ($\log N_{\text{H}}/\text{cm}^{-2} < 23$), while one shows signs of moderate absorption ($\log N_{\text{H}}/\text{cm}^{-2} \sim 23.5$).
3. We performed SED modeling of the X-ray to millimeter photometry with the CIGALE code. We find that our sources have both high mass-accretion rates (intrinsic 0.5–8 keV X-ray luminosities of $\sim 10^{44-45}$ erg s $^{-1}$) and star-formation rates ($\gtrsim 100 M_{\odot} \text{ yr}^{-1}$).
4. We find that ALCS-XAGNs show higher mass-accretion rates than other ALMA selected X-ray AGN samples. We also confirm that ALCS-XAGNs show higher SFRs than a purely X-ray-selected AGN sample. This can be explained by the selection bias, showing that a wide and deep survey with ALMA, combined with medium-depth X-ray data, can efficiently detect intense growth stage of both galaxies and SMBHs in high-redshift universe.

CHAPTER 3

ALMA Lensing Cluster Survey: Full Spectral Energy Distribution Analysis of $z \sim 0.5\text{--}6$ Lensed Galaxies Detected with Millimeter Observations

Sub/millimeter galaxies are a key population for the study of galaxy evolution because the majority of star formation at high redshifts occurred in galaxies deeply embedded in dust. To search for this population, we have performed an extensive survey with ALMA, called the ALMA Lensing Cluster Survey. This survey covers 133 arcmin^2 area and securely detects 180 sources at $z \sim 0.5\text{--}6$ with a flux limit of $\sim 0.2 \text{ mJy}$ at 1.2 mm (Fujimoto et al., 2024). Here we report the results of multi-wavelength SED analysis of the whole ALCS sample, utilizing the observed-frame UV to millimeter photometry. We find that the majority of the ALCS sources lie on the star-forming main sequence, with a smaller fraction showing intense starburst activities. The ALCS sample contains high infrared-excess sources ($\text{IRX} = \log(L_{\text{dust}}/L_{\text{UV}}) > 1$), including two extremely dust-obscured galaxies ($\text{IRX} > 5$). We also confirm that the ALCS sample probes a broader range in lower dust mass than conventional SMG samples in the same redshift range. We identify six AGN candidates from the infrared diagnosis in the SED modeling that are not detected in the archival CXO data. The X-ray upper bounds indicate that these sources are Compton thick or have unusually weak X-ray emission. This implies that a significant number of

AGNs in SMGs are “hidden” by gas and dust, and not detected in previous X-ray observations.

3.1 Introduction

In this chapter, we discuss the overall properties of the ALCS sample. We perform multi-component SED modeling for the whole ALCS sample, utilizing the UV-to-millimeter photometry obtained by ALMA, HST, Spitzer, and Herschel. In Section 3.2, we summarize the observations and data reduction. In Section 3.3, we explain the SED modeling and comparison samples. In Section 3.4, we show the results of the SED modeling. In Section 3.5, we discuss the dust properties and the nature of AGNs in our sample. Finally, we provide a summary and conclusions in Section 3.6. Throughout the chapter, we assume a flat universe with $H_0 = 70.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_M = 0.272$ (Komatsu et al., 2011). The Chabrier initial mass function (IMF, Chabrier 2003) is adopted. If not specifically mentioned, errors correspond to 1σ confidence.

3.2 Observations and data reduction

3.2.1 Observations and source detection with ALMA

We use the same 1.2 mm continuum source catalog as in Chapter 2, which was built by Fujimoto et al. (2024).

3.2.2 HST, Spitzer, and Herschel counterparts

The ALCS fields were observed with HST, Spitzer, and Herschel previously. The images and photometric catalogs of optical and near-infrared bands were built by Kokorev et al. (2022) by reprocessing the best-available data from HST and Spitzer IRAC channels 1 and 2. Sun et al. (2022) produced the far-infrared images and catalogs, utilizing the archival data of Herschel/PACS and SPIRE. The quality of the multi-wavelength photometry is summarized in Section 3.2.4. We note that the photometric data of Spitzer IRAC channel 2 is sometimes inconsistent with the other

photometries, which may be due to remaining blending effects or oversubtraction of nearby sources. For this reason, the photometric data of Spitzer IRAC channel 2 in M0416-ID120, M1206-ID60, ACT0102-ID11, M1115-ID34, and ACT0102-ID224 are not used in the SED modeling.*

In addition to these catalogs, we utilize the photometric data of Spitzer IRAC channels 3 ($5.8 \mu\text{m}$) and 4 ($8.0 \mu\text{m}$), and those of Spitzer MIPS channel 1 ($24 \mu\text{m}$), taken from the Spitzer Enhanced Imaging Products (SEIP; SSC And IRSA 2020). Those sources are cross-matched with the ALMA source positions within 1.5 arcsec. Since IRAC and MIPS have large beam sizes (full-width half maximum of 1.8, 1.9, and 5.9 arcsec at $5.8 \mu\text{m}$, $8.0 \mu\text{m}$, and $24 \mu\text{m}$, respectively), the measured photometric data can be contaminated by nearby sources. To evaluate this effect, we compare the flux densities of IRAC channel 2 extracted from the SEIP (f_{SEIP}) with those in the catalog by Kokorev et al. (2022) (f_{ALCS}), who de-blended the photometric data utilizing the HST source positions. If $0.5 < f_{\text{ALCS}}/f_{\text{SEIP}} < 2.0$, we use the photometric data from the SEIP for our SED modeling. If $f_{\text{ALCS}}/f_{\text{SEIP}} < 0.5$, we treat the SEIP data as upper limits. In the case of $f_{\text{ALCS}}/f_{\text{SEIP}} > 2.0$, we conservatively do not utilize the data from the SEIP, considering the possibility of mismatching with the ALMA source.

3.2.3 CXO observations

Uematsu et al. (2023) detected three AGNs among the lensed ALCS sources, utilizing the archived data of CXO; hereafter, we refer to these AGNs as “ALCS-XAGNs”. In this chapter, we derive the 3σ upper bounds[†] of the X-ray luminosities for the rest of the sources. First, we reprocessed all the data obtained with CXO by 2021, following the standard procedures with the Chandra interactive analysis of observations software (CIAO v4.12) and the calibration database (CALDB v4.9.1). Next, we combined the products by using `MERGE_OBS`. Then, we ran `SRCFLUX` to the combined data and obtained the 3σ upper bounds of the 0.5–7 keV count rates for each source. For the source and background regions, we employed circular regions with radii of 1.5 arcsec and annuli with inner and outer radii of 2 arcsec and 4 arcsec, respectively, after masking obvious X-ray point sources. Then, we converted the

*We note that these sources were not detected in the Spitzer IRAC channel 3, 4 and Spitzer MIPS channel 1 in the SEIP catalog.

[†]In this chapter, we refer to the upper edge of a confidence interval as “upper bound” (see Kashyap et al. 2010 for more details).

Table 3.1: Classification of the ALCS sources. (1) Class. (2)–(4) The quality of the data. If a source is detected above 2σ in at least one band, the corresponding column is checked by the symbol ($\checkmark$). (5) The number of ALCS sources that meet the criteria. The number in parentheses shows the number of sources that belong to the MAIN sample. In this classification, BCGs (11 sources), a possible mismatched source, a possible contaminated source, and a spectroscopically-confirmed member galaxy of a cluster are excluded. The multiply-imaged sources are counted individually.

Tier	HST	Spitzer	Herschel	N
(1)	(2)	(3)	(4)	(5)
1	$\checkmark$	$\checkmark$	$\checkmark$	99 (79)
2	$\checkmark$	$\checkmark$	...	28 (16)
3	...	$\checkmark$	$\checkmark$	21 (20)
4	...	$\checkmark$	...	10 (7)
5	$\checkmark$	...	$\checkmark$	3 (3)
6	$\checkmark$	...	...	1 (0)
7	...	...	$\checkmark$	2 (2)
8	...	...	...	2 (2)

count rates to the intrinsic X-ray luminosities, assuming typical X-ray spectra of AGNs. Since there are no CXO observations in RXC0032 and RXC0600, the X-ray luminosity upper bounds in those fields are not given. We excluded the brightest cluster galaxies (BCGs) from the catalog because of the difficulty in separating the X-ray point sources from the diffuse X-ray emission of the galaxy clusters. Details of the X-ray spectral models and the results are summarized in Appendix B.1.

3.2.4 Data quality, sample selection, and magnification

We classify the ALCS sources into eight groups based on the quality of the multi-wavelength photometry. The criteria are summarized in Table 3.1. In this classification, BCGs (11 sources*; A383-ID40, M0159-ID46, M0429-ID19, M1115-ID36, M1206-ID58, M1423-ID50, M1931-ID41/42, R0032-ID162, R1347-ID75, R2129-ID20), a possible mismatched source (R0600-ID67), and a possible contaminated source (R0600-ID164) are excluded. A370-ID31 is also excluded because it is spectroscopically confirmed as a member galaxy of the foreground cluster (Abell 370). We note that this classification is independent of the one that is based on the source detection (either blind [MAIN] or prior-based [SECONDARY]) in the ALMA band (see Section 3.2.1).

The magnification factors are extracted from Fujimoto et al. (2024), where the

*We follow the classification in Sun et al. (2022).

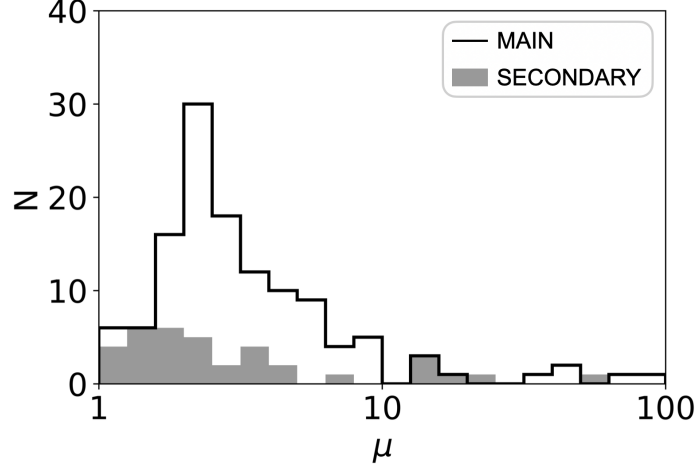


Figure 3.1: Distribution of the magnification factor in the ALCS tier-1/2/3/4/5/6 samples. One source belonging to the SECONDARY sample lies off the plot with $\mu = 0.15$ ($z = 0.63 \pm 0.10$). The multiply-imaged sources are counted individually.

lens model of GLAFIC (Oguri, 2010) is adopted as a fiducial. Figure 3.1 shows the histogram of the magnification factors in the tier-1/2/3/4/5/6 samples. Here we note that the uncertainties in the lens models and magnification factors are not considered in this chapter. Such uncertainties can affect the physical quantities of each source, however, they do not change the qualitative discussion. We spectroscopically confirm six multiply-imaged sources (ACT0102-ID118/215/224; $z = 4.32$, MACS0417-ID46/58/121; $z = 3.65$, MACS0553-ID133/190/249; $z = 1.14$, M1206-ID27/55/60/61; $z = 1.04$, R0032-ID32/53/55/57/58; $z = 3.63$, R0032-ID208/281/304; $z = 2.98$). We also regard R0032-ID127/131/198 and ACT0102-ID223/294 as multiple images of single sources at $z = 2.391$ and $z = 4.0 \pm 0.5$, based on the source positions, the lens models, and the similarities in their SEDs. Moreover, A2537-ID24/66 and R0032-ID63/81 are also treated as multiple images at $z = 3.2$ and $z = 3.0$, which are used to construct the lens models in the literature (see Fujimoto et al. 2024 for details).

3.3 Analysis

3.3.1 SED modeling with cigale

We conduct multi-component SED modeling to the UV to millimeter photometry of the ALCS tier-1/2/3/4/5/6 samples, except for the three ALCS-XAGNs, whose SEDs are already analyzed by Uematsu et al. (2023). The tier-7/8 samples are not

analyzed in this chapter because it is challenging to derive the physical properties from their limited photometric data. Although these sources are located within the coverages of HST and Spitzer, they are too faint to be detected with these observatories. This suggests that those sources are heavily obscured galaxies in high-redshift universe. We use CIGALE, incorporating modifications to the dust emission model. CIGALE assumes energy balance between UV/optical absorption and infrared re-emission, which enables us to self-consistently model the SED of each galaxy. Moreover, CIGALE can simultaneously treat AGN and galaxy components, which enables us to assess the contribution of AGN in the SED.

The SED modules assumed in this study are described in the following subsections. The free parameters are summarized in Appendix B.2. In the SED modeling, the multiply-imaged sources are treated individually. The redshifts are fixed at the values reported in Fujimoto et al. (2024) (69/180 sources have spectroscopic redshifts). The uncertainties of the photometric redshifts are not considered in the main part of this chapter. The redshift uncertainties and their impact on the estimation of the physical properties are discussed in Appendix B.3, where we treat photometric redshifts utilizing MAGPHYS (Battisti et al., 2020, 2019; da Cunha et al., 2008, 2015).

3.3.1.1 Stellar emission, dust attenuation, and nebular emission

In our CIGALE SED modeling, we employ a delayed SFH, assuming an additional burst with exponential decay. The simple stellar population (SSP) is modeled with the stellar templates of Bruzual & Charlot (2003), assuming the Chabrier (2003) initial mass function. The dust attenuation is modeled with the Calzetti starburst attenuation law (Calzetti et al., 2000), where we allow slightly steeper or flatter curves than the original one (see Appendix B.2 for the parameter range). We also add nebulae emission according to Inoue (2011).

3.3.1.2 AGN emission

We employ the Skirtor model (Stalevski et al., 2012, 2016) for the optical and infrared emission from an AGN. The Skirtor model assumes anisotropic radiation from an accretion disk and a dusty torus composed of two-phase matter. We also add a polar dust emission modeled by a single graybody, where we assume an emissivity index of 1.6, temperature of 150 K, and opacity of unity at 200 μm . To identify whether a

galaxy hosts an AGN or not, we utilize the Bayesian Information Criterion (BIC; Schwarz 1978). The BIC is calculated as $\text{BIC} = \chi^2 + k \times \ln(n)$, where χ^2 is the non-reduced chi-square, k is the number of degrees of freedom (dof), and n is the number of the photometric data points. If the addition of an AGN component reduces BIC by more than 10 ($\Delta\text{BIC} = \text{BIC}_{\text{noAGN}} - \text{BIC}_{\text{AGN}} > 10$), we consider that the AGN component is needed for the SED (see Toba et al. 2020). For the tier-2/3/4/5/6 samples, the AGN component is always excluded, because it is challenging to identify the presence of an AGN from the limited photometry of those samples.

3.3.1.3 Dust emission from host galaxy

Recent studies have shown that some SMGs and local ULIRGs exhibit higher dust temperatures compared to typical local galaxies (Clements et al., 2018; Cortese et al., 2014; da Cunha et al., 2021). Currently, the physically-based dust emission models implemented in CIGALE cannot properly account for these populations due to the limited range of dust temperatures. This limitation in the higher temperature regimes may result in an overestimation of AGN contribution, particularly that of polar dust emission from the AGN, or an underestimation of infrared luminosity from star-formation activity. Therefore, we develop a new dust emission model by extending the parameter range of the THEMIS model (Jones et al., 2017), which is the latest dust-emission model implemented in CIGALE.

We use the DUSTEM code (Compiègne et al., 2011) to extend the THEMIS model. Dust temperature is characterized by the minimum radiation field illuminating the interstellar dust (U_{min}). In the current version of the THEMIS model, U_{min} is limited to 0.1–80, which corresponds to 12–39 K.* We extend it to $U_{\text{min}} = 0.1\text{--}6309$ ($10^{-1}\text{--}10^{3.8}$) with a step size of 0.2 in logarithmic space. This parameter range corresponds to $T_{\text{dust}} = 12\text{--}83$ K ($T_{\text{dust}}^{\text{peak}} = 20\text{--}141$ K; see Section 3.3.3), which is almost equivalent to the likelihood distribution of dust temperature in the ALESS sample (20–80 K; da Cunha et al. 2015). We confirm that the extended model successfully reproduces the original THEMIS model by covering high dust temperature cases. Figure 3.2 compares the original THEMIS model and our new model, which we hereafter call ETHEMIS (Extended THEMIS).

*Here, we use T_{dust} to refer to the intrinsic temperature of interstellar dust illuminated with $U = U_{\text{min}}$ ($T_{\text{dust}} = 18.3 U_{\text{min}}^{1/5.79}$ K; Nersesian et al. 2019).

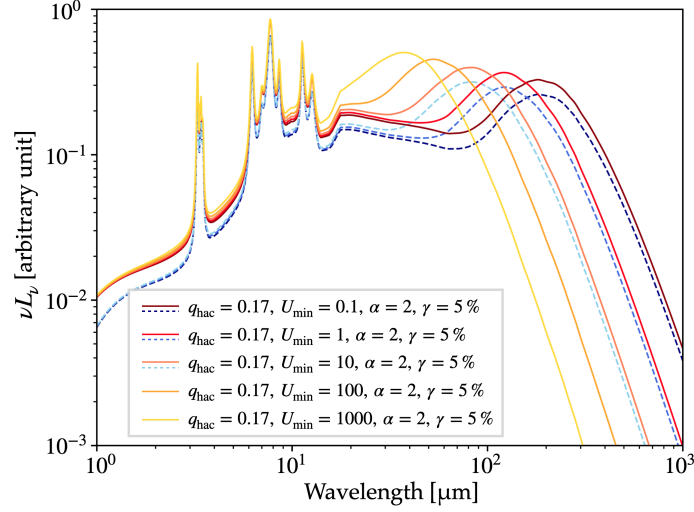


Figure 3.2: Example of SEDs in the THEMIS (dashed lines) and the ETHEMIS model (solid lines) spanning a wide range in dust temperature. All the SEDs in this figure are normalized by the total luminosity, while a small systematic offset is imposed in the THEMIS model to improve visibility.

3.3.2 Estimation of physical properties

For the estimation of physical properties, we calculate the likelihood-weighted mean of all the models on the grid as a Bayesian estimation, where we treat the following parameters in a logarithmic space:

- Star-formation rate (SFR). In this chapter, we employ 10 Myr averaged values.
- Stellar mass (M_*).
- Dust luminosity (L_{dust}) and mass (M_{dust}). In this chapter, we use the terms “dust luminosity” and “dust mass” to describe those of interstellar dust (i.e., not including those in the AGN torus).

while the following parameters are treated in a linear space:

- Dust temperature (T_{dust}).
- Color excess of stellar continuum attenuation ($E(B - V)$).
- Infrared excess ($\text{IRX} = \log(L_{\text{dust}}/L_{\text{UV}})$).
- Power-law index of observed UV slope (β), which is measured in the same way as Calzetti et al. (1994).

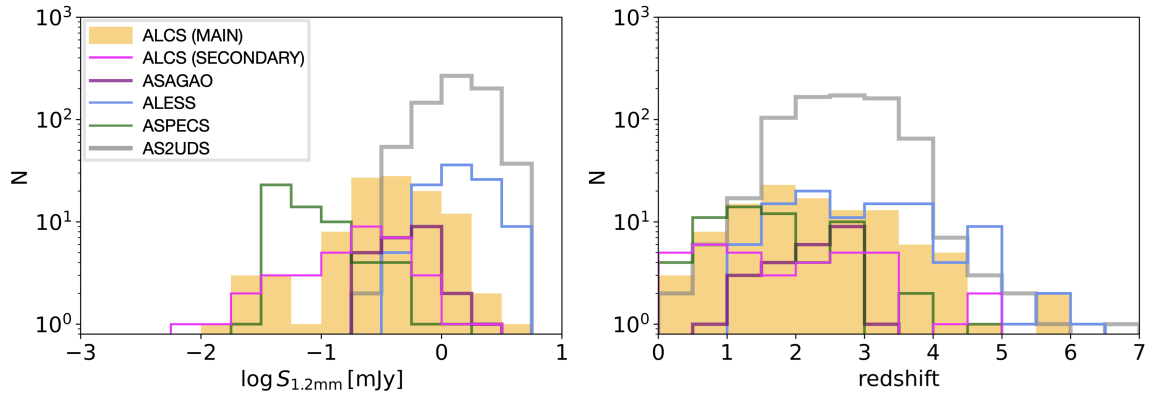


Figure 3.3: (Left) Flux-density distribution of sources detected in major ALMA surveys. (Right) Their redshift distribution. In these histograms, only the ALCS tier-1/2/3/4/5/6 samples are counted for the ALCS sample. For each set of multiple images, we include only one image which is selected with priorities given to a higher tier sample and to an image with a smaller magnification factor. The flux densities of the ALCS sources are corrected for lensing magnification.

- Power-law index to modify the attenuation slope (δ) (see Equation (8) in Boquien et al. (2019)).
- Bolometric AGN luminosity ($L_{\text{AGN, bol}}$)

This means that we calculate the likelihood-weighted mean of the marginalized PDF with a log-uniform prior for the former parameters and with a uniform prior for the latter, respectively. The specific star-formation rates ($\text{sSFR} = \text{SFR} / \text{stellar mass}$) are derived from the stellar masses and the SFRs, where the confidence intervals of the sSFRs are calculated by propagating the uncertainties associated with the stellar masses and the SFRs. We correct all the quantitative variables for the lensing effect by dividing the observed values by the magnification factors.

3.3.3 Characteristic dust temperature

The definition of the term “dust temperature” varies from study to study. For example, Nersesian et al. (2019) employ the term to denote the intrinsic temperature of interstellar dust illuminated by the minimum radiation field ($U = U_{\text{min}}$), which is the same definition employed in our ETHEMIS model. By contrast, Sun et al. (2022) define the term as the luminosity-weighted average of the intrinsic temperature of two optically thin graybodies. Furthermore, the measured dust temperature is also highly dependent on the assumptions of models, e.g., the assumption of dust opacity

(Casey, 2012; da Cunha et al., 2021; Dudzevičiūtė et al., 2020). Therefore, to properly compare different studies, the dust temperature in each study should be converted according to a common definition. One way is to use the inverse “peak wavelength” temperature ($T_{\text{dust}}^{\text{peak}}$), which is calculated from the peak wavelength of the far-infrared dust emission using the Wien’s displacement law*:

$$T_{\text{dust}}^{\text{peak}} [\text{K}] = 5099 / \lambda^{\text{peak}} [\mu\text{m}] \quad (3.1)$$

Since this value directly reflects the shape of the dust SED, it is less affected by the assumptions of models and hence is useful for comparing different studies. Therefore, we use the inverse peak-wavelength temperature to compare different samples; hereafter we refer to this temperature as “characteristic dust temperature”. However, it should be noted here that the characteristic dust temperature does not denote the intrinsic temperature of dust, and one should be careful when interpreting this value.

3.3.4 Comparison samples

We discuss our results in comparison with previous ALMA surveys (e.g., ASAGAO, ASPECS, ALESS, AS2UDS, and ALPINE). The flux densities and the redshifts of the ASAGAO, ASPECS, ALESS, and AS2UDS samples are extracted from Yamaguchi et al. (2020), Aravena et al. (2020), Hodge et al. (2013), and Dudzevičiūtė et al. (2020), respectively. The other physical properties discussed in this chapter are taken from Yamaguchi et al. (2020), Aravena et al. (2020), da Cunha et al. (2015), and Dudzevičiūtė et al. (2020), respectively. We also utilize the results from da Cunha et al. (2021), which discussed the dust properties of the well-sampled subset of the ALESS sample utilizing 2mm observation with ALMA. In addition, the physical properties of the ALPINE sample are extracted from Boquien et al. (2022).

Figure 3.3 shows the histograms of 1.2 mm flux densities.[†] We confirm that the ALCS basically fills the gap between ALESS/AS2UDS and ASPECS, although the ALCS detects especially faint sources that were not detected in the previous surveys

*Since far-infrared photometry is often given in the dimension of “Jy”, we utilize the peak wavelength in the dimension of “Jy” ($\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$) to calculate the characteristic dust temperature.

[†]The flux densities of the ALESS and AS2UDS samples are converted from those at 870 μm , assuming an optically thin graybody with an emissivity index of 1.8 and an intrinsic temperature of 35 K (e.g., Coppin et al. 2008; Planck Collaboration et al. 2011).

thanks to the lensing effect. The right panel of Figure 3.3 shows the histograms of redshifts. We see that the ALCS sample contains mainly high-redshift ($z > 1$) galaxies like the other sub/millimeter selected samples (ALESS, ASAGAO, ASPECS, AS2UDS), reflecting the effect of negative K -correction.

The SEDs of the ALESS, ASAGAO, ASPECS, and AS2UDS samples were analyzed with MAGPHYS (da Cunha et al., 2008, 2015), while those of the ALPINE and ALCS samples are analyzed with CIGALE. To check the systematic difference between these codes, we also analyze the SEDs of the ALCS sample with MAGPHYS. This results are summarized in Appendix B.4. Accordingly, we impose a systematic offset of -0.37 dex in the stellar mass of the AS2UDS, ASAGAO, ALESS, and ASPECS samples. The SFRs, dust luminosities, and dust masses are not corrected, because we did not find obvious systematic differences for these parameters. Moreover, we use the characteristic dust temperature to compare the dust temperature among different studies. The conversion methods of dust temperature among different definitions are summarized in Appendix B.5.

3.4 Results

We successfully reproduce the SEDs of the ALCS tier-1/2/3/4/5/6 samples with a fit quality of $\chi^2/\text{dof} < 5$. Figure 3.4 shows the example SED of the ALCS sample. The fit quality is shown in Figure 3.5. All the SEDs and the best-fit models are summarized in Appendix B.2.

3.4.1 Overall properties of ALCS sample

Figure 3.6 shows the distribution of the ALCS sample across nine parameter spaces. We confirm that the MAIN sample comprises galaxies with higher dust luminosities, dust mass, and SFRs. We also confirm that the SECONDARY sample tends to contain galaxies with lower $E(B - V)$ and lower IRX. These differences can be explained by the selection effects. Since the MAIN sample is selected by higher significance in the ALMA band, it contains galaxies that are brighter in the millimeter band. This results in the higher dust luminosities, dust mass, and SFRs of the MAIN sample. By contrast, since the IRAC/ch2 band can suffer from dust attenuation in high-redshift universe, the IRAC selection of the SECONDARY sample might cause

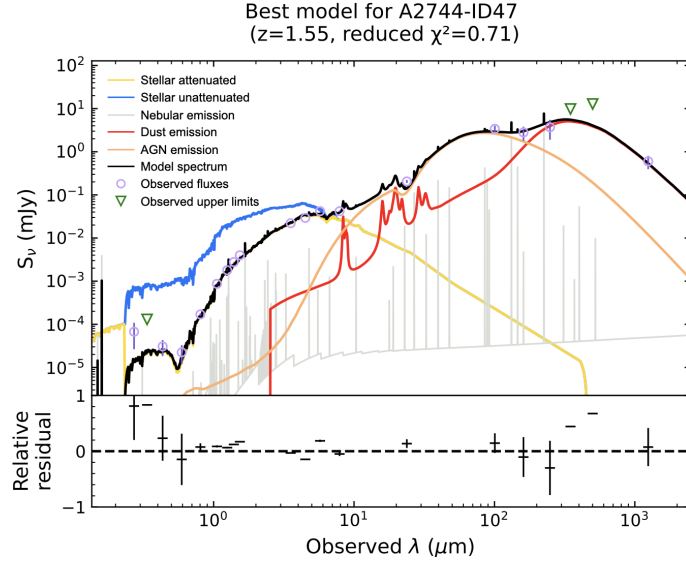


Figure 3.4: The SED and the best-fit model of A2744-ID47. Lensing magnification is NOT corrected in this figure. The black solid line represents the composite spectrum of the galaxy. The yellow line illustrates the stellar emission attenuated by interstellar dust. The blue line depicts the unattenuated stellar emission for reference purpose. The orange line corresponds to the emission from an AGN. The red line shows the infrared emission from interstellar dust. The gray line denotes the nebulae emission. The observed data points are represented by purple circles, accompanied by 1σ error bars. The bottom panel displays the relative residuals.

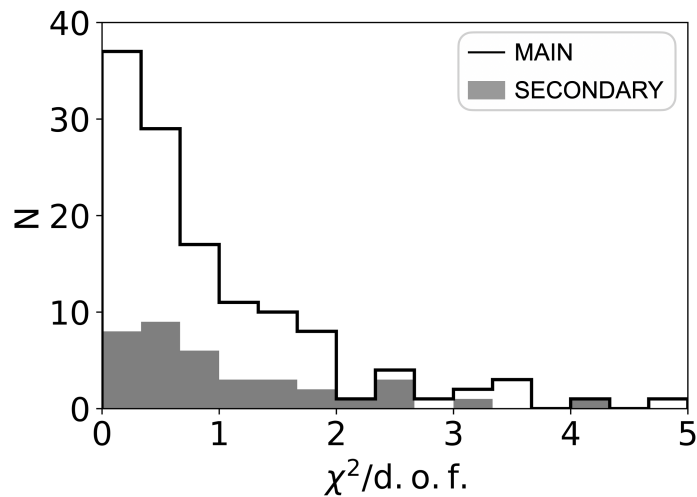


Figure 3.5: Histogram of fit quality of the ALCS tier-1/2/3/4/5/6 samples. The multiply-imaged sources are counted individually.

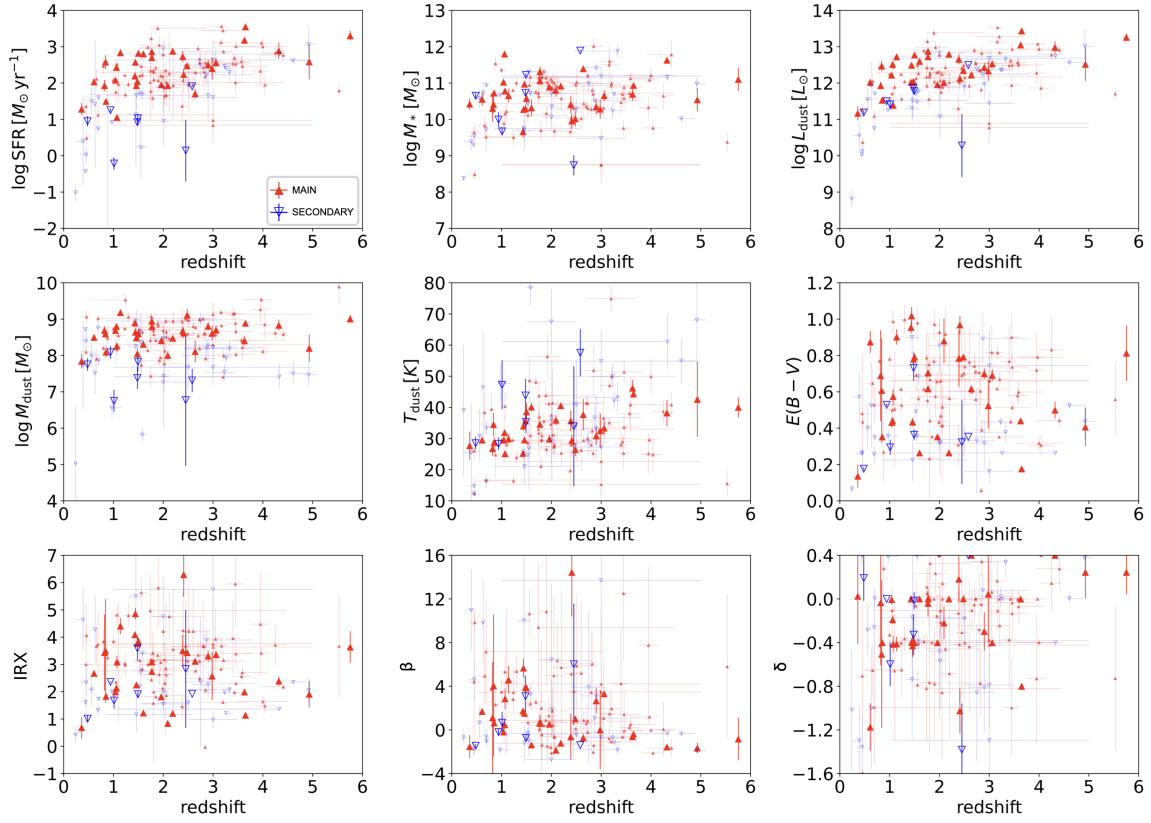


Figure 3.6: Distribution of the ALCS tier-1/2/3/4/5/6 samples in nine parameter spaces. The physical properties of ALCS-XAGNs are extracted from Uematsu et al. (2023). The filled red triangles represent the MAIN sample and the blue open triangles the SECONDARY sample. The large symbols show the galaxies that have spectroscopic redshifts, while the small symbols show those with photometric redshifts. For each set of multiple images, we include only one image, which is selected with a priority given to a higher tier sample and to an image with a smaller magnification factor, whose uncertainty is expected to be smaller. All the physical quantities in this figure are NOT corrected for lensing magnification.

a selection bias against heavily attenuated sources.

Adhering to the methodology outlined in Section 3.3.1.2, we identify six AGN candidates within the tier-1 sample (excluding ALCS-XAGNs); hereafter, we refer to these AGN candidates as “ALCS-nonXAGNs”. Figure 3.7 shows the histogram of ΔBIC . Here we note that R0032-ID57 is also classified as an AGN with the BIC selection ($\Delta\text{BIC} = 13.3$). However, the other multiple images (R0032-ID32/53/55/58) are not classified as AGNs, and no obvious signs of AGN are found in the SED of R0032-ID57. Therefore, we do not consider R0032-ID57 as a host of an AGN.

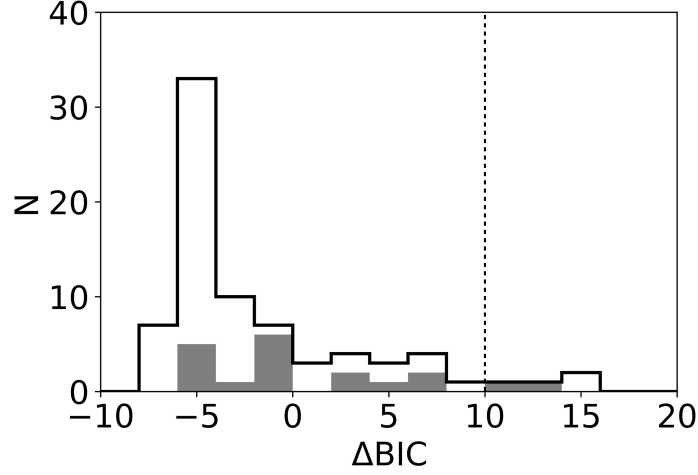


Figure 3.7: Distribution of ΔBIC in the ALCS tier-1 samples (ALCS-XAGNs are excluded). One source belonging to the SECONDARY sample lies off the plot with $\Delta\text{BIC} = 118$. The vertical dotted line shows $\Delta\text{BIC} = 10$. The multiply-imaged sources are counted individually.

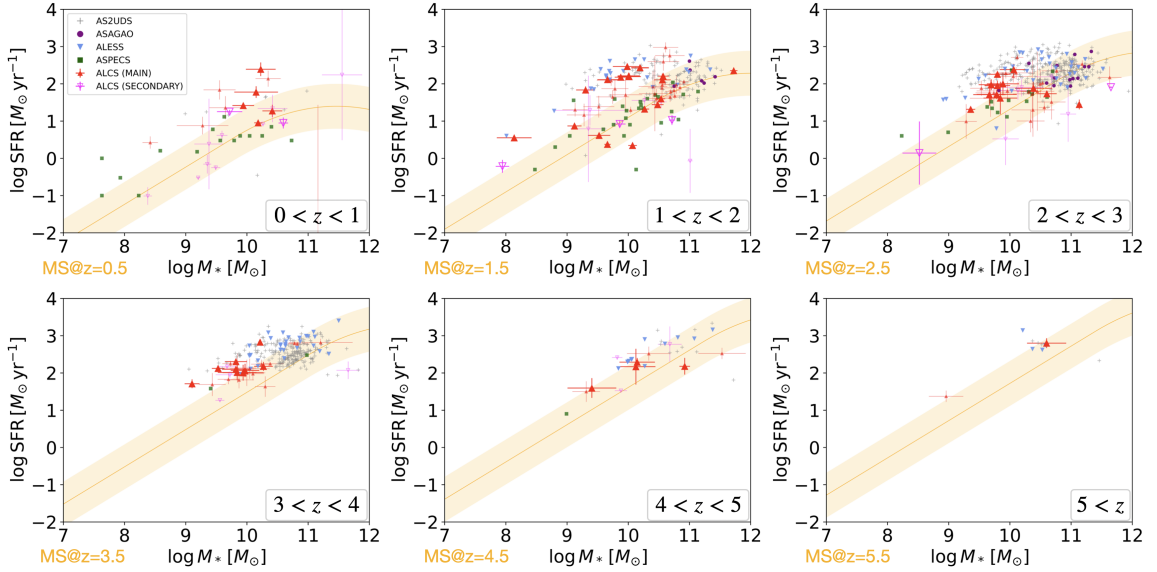


Figure 3.8: Relation between stellar mass (M_*) and SFR for galaxies detected in major ALMA surveys. The orange solid lines represent the star-formation main sequence at each redshift (Schreiber et al., 2015). The light orange areas show the ranges four times above or below the main sequence. The large symbols show the galaxies with spectroscopic redshifts, while the small symbols show those with photometric redshifts. The multiply-imaged sources are plotted individually. The stellar masses and the SFRs of the ALCS sources are corrected for lensing magnification.

3.4.2 SFR versus stellar mass

Figure 3.8 plots the relation between stellar mass and SFR. For comparison, we plot the star-forming “main sequence” given by Schreiber et al. (2015). This figure shows that the majority of the ALCS sources are in the star-forming main sequence (82/162 [51%] sources are in the ranges four times above or below the star-forming main sequence), while some of them show intense starburst activities (69/162 [43%]) and the others (11/162 [7%]) are below the main sequence. This trend is similar to what is seen for the ALESS, AS2UDS, and ASAGAO samples, although the ALCS sample contains sources with even lower SFRs and stellar masses. On the other hand, the ALCS sample shows higher SFRs compared to the ASPECS sample. These differences simply reflect the different sample selections. Since the effective depth of ALCS is deeper than those of ALESS, AS2UDS, and ASAGAO due to the lensing effect, ALCS was able to detect galaxies with lower SFRs (M_* is typically lower, according to the star-forming main sequence). At the same time, because the survey area with strong lensing effects is limited, the ALCS sample generally has higher SFRs compared with ASPECS, which is a homogeneously deep survey with ALMA.

3.4.3 IRX versus stellar mass

The left panel of Figure 3.9 shows the relation between stellar mass and IRX. For comparison, we plot the conventional relationship of optical or UV selected galaxies at $z \sim 2-3$ studied by Reddy et al. (2010), Whitaker et al. (2014), and Álvarez-Márquez et al. (2016), as compiled by Bouwens et al. (2016). We see that the ALCS sample has higher IRXs than the conventional relationship, implying that these galaxies are more deeply enshrouded by dust than optical- or UV-selected galaxies. We also find two extremely dusty-obscured galaxies that have especially high IRX (A2744-ID7 [IRX = 6.3 ± 0.8] and R0600-ID111 [IRX = 5.6 ± 0.6]). Figure 3.10 shows the SEDs of the two sources. These galaxies have steeper attenuation curves than the average (the steepness of the attenuation slopes are -1.0 ± 0.2 and -0.8 ± 0.1 , respectively), which may result in more UV absorption and thus larger IRX. Recently, Kokorev et al. (2023) found a potential major merger at $z = 2.58$ that is deeply enshrouded by dust utilizing James Webb Space Telescope (JWST) observations. This might suggest that high-IRX sources in SMG samples are important targets for JWST to reveal the evolutionary stages of distant galaxies and SMBHs. We note that there still remain some sources that potentially have high IRXs (R0032-ID281 [6.3 ± 1.8]),

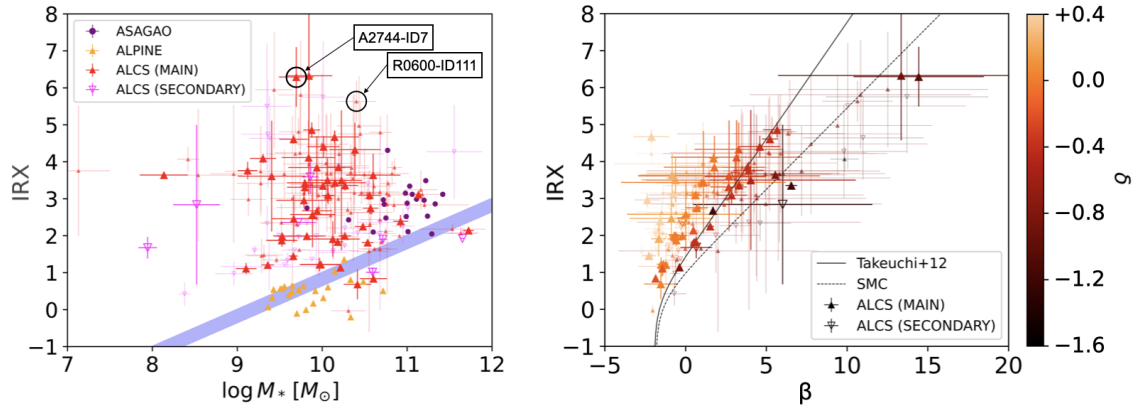


Figure 3.9: (Left) Relation of IRX versus stellar mass in major ALMA surveys. The blue line shows the conventional relation of optical or UV-selected galaxies at $z \sim 2-3$ compiled by Bouwens et al. (2016). (Right) Relation of IRX versus observed UV slope (β) in the ALCS sample. The color map shows the power-law index to modify the original Calzetti law (δ). The black solid and dashed lines show the local relationship derived by Takeuchi et al. (2012) and the so-called SMC IRX- β relationship, respectively. In these figures, the ALCS tier-1/2/3/4/5/6 samples are plotted. The large symbols show the galaxies with spectroscopic redshifts, while the small symbols show those with photometric redshifts. The multiply-imaged sources are plotted individually. The stellar masses of the ALCS sources are corrected for lensing magnification.

ACT0102-ID22 [6.0 ± 1.6], A3192-ID131 [5.8 ± 1.5], R0032-ID245 [5.7 ± 1.5], and R0949-ID14 [5.5 ± 1.7]), which belong to the tier-3/4 samples. Moreover, the tier-7/8 samples may also contain such a population, although they are not analyzed in this study. Deeper observations in optical and near-infrared bands are needed to confirm the nature of these sources.

3.4.4 IRX versus observed UV slope

The right panel of Figure 3.9 shows the relation between IRX and observed UV slope. For comparison, we plot the local relation derived by Takeuchi et al. (2012) and the so-called SMC IRX- β relation, which is based on the observational results of Lequeux et al. (1982), Prevot et al. (1984), and Bouchet et al. (1985) (see also Pei 1992; Pettini et al. 1998; Smit et al. 2016). The color map shows the steepness of the attenuation slopes. We see that the ALCS sample is distributed above the local relation at $\beta \lesssim 3$, while it is close to the SMC IRX- β relation at $\beta \gtrsim 3$. This can be explained by the sample selection. Since the ALCS sample is selected by millimeter observations, it is more sensitive to high-IRX sources than UV/optical

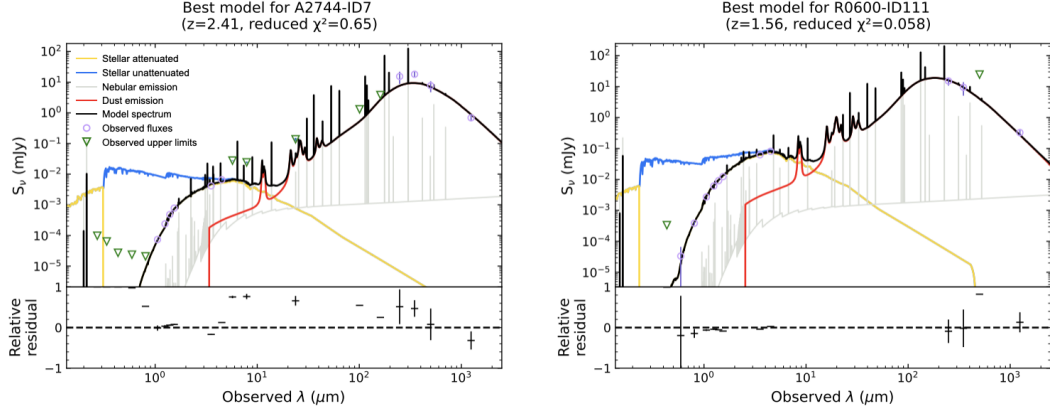


Figure 3.10: The SEDs of the galaxies that have especially high IRX. The SEDs are NOT corrected for lensing magnification. The colors and the symbols are the same as those in Figure 3.4.

selected samples. On the other hand, since the tier-1/2/3/4/5/6 samples are also selected by HST or IRAC observations, those samples miss sources that have both high IRX and small β , which are faint even in the near-infrared band.

We also confirm a large scatter in the steepness of attenuation slopes, which strongly affects the IRX– β relation, i.e., galaxies with flatter attenuation slopes (high δ) tend to show bluer UV spectrum (low β). As will be discussed in Section 3.5.1.1, the steepness of the attenuation slope is weakly correlated with the stellar mass. This might account for the differences in the IRX– β relation for different stellar masses reported in recent studies (e.g., Bouwens et al. 2020). However, the IRX– β relation can also be strongly affected by the geometry of dust and stellar components (e.g., Fudamoto et al. 2020; Narayanan et al. 2018; Popping et al. 2017). Spatially-resolved SED modeling with high-resolution observation will be helpful to reveal the dust properties in high-redshift star-forming galaxies.

3.5 Discussion

3.5.1 Dust properties

In this subsection, we discuss the dust properties of the ALCS sample. We focus on the dust attenuation law, dust temperature, and dust mass.

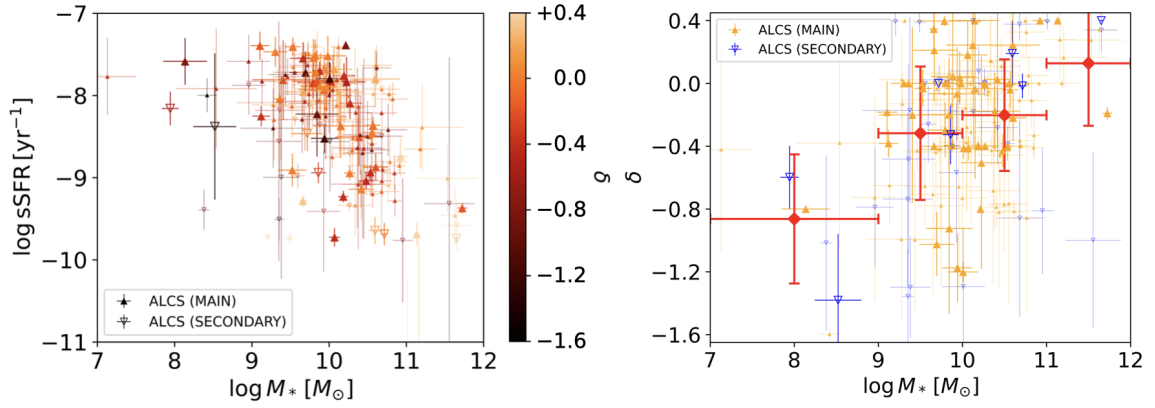


Figure 3.11: (Left) The color-coded plot of δ (power-law index to modify the original Calzetti law, representing the steepness of the attenuation curve) on the sSFR versus stellar mass plane. (Right) Relation between δ and stellar mass. The red points show the mean values and standard deviations of δ in different stellar-mass bins. In these figures, the ALCS tier-1/2/3/4/5/6 samples are plotted. The large symbols show the galaxies that have spectroscopic redshifts, while the small symbols show those with photometric redshifts. The multiply-imaged sources are plotted individually, but they are counted only once in deriving the average values. The stellar masses are corrected for lensing magnification.

3.5.1.1 Dust Attenuation Law

The dust attenuation law is critical to study the stellar populations and thus the evolutionary scenario of galaxies. Over time, numerical studies have revealed the extensive variation in attenuation curves among different galaxies and even within a single galaxy depending on the line of sight (e.g., Nandy et al. 1980, 1975; Rocca-Volmerange et al. 1981). The main features to characterize an attenuation curve are the steepness of the curve and the depth of the 2175 Å bump (UV bump). Unfortunately, it is challenging to measure the depth of UV bumps with the poor photometric data of high-redshift galaxies. Therefore, in this chapter, we focus only on the steepness of the attenuation curves of the ALCS sample.

In the modified Calzetti starburst attenuation law, the steepness of the attenuation curve is quantified by δ , the power-law index to modify the original Calzetti law (Calzetti et al., 2000). The left panel of Figure 3.11 gives a color-coded plot of δ on the sSFR versus stellar mass plane. We confirm that no strong correlation exists between δ and sSFR. The right panel of Figure 3.11 plots the relation between stellar mass and δ . A weak correlation is noticed between the steepness of attenuation curve and stellar mass, i.e., galaxies with high stellar masses tend to have flatter attenuation curves. This is consistent with the trend observed in local galaxies (Salim

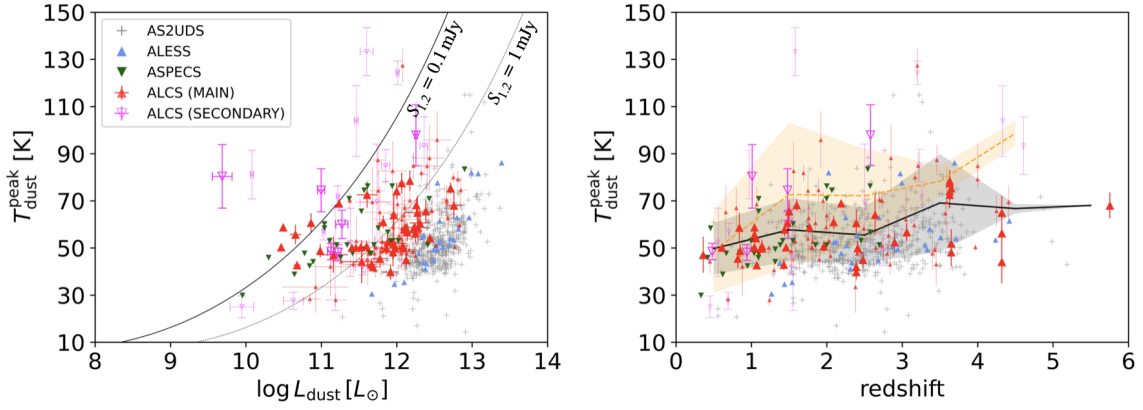


Figure 3.12: (Left) Characteristic dust temperature versus dust luminosity. The black solid and dotted lines represent the flux limit at 1.2 mm, where we assume an optically-thin graybody with an emissivity index of 1.8 at $z = 3$. (Right) Characteristic dust temperature versus redshift. The black solid and orange dashed lines show the mean characteristic dust temperature of the MAIN and the SECONDARY samples in each redshift bin, respectively. The semi-transparent regions show the standard deviations (i.e., $\pm 1\sigma$) from the mean values. In these plots, the ALCS, ASPECS, and AS2UDS samples are limited to the sources that are detected with Herschel over 2σ . The ALESS sample is also limited to the well-sampled subset reported in da Cunha et al. (2021). The large symbols show the galaxies that have spectroscopic redshifts, while the small symbols show those with photometric redshifts. The multiply-imaged sources are plotted individually, but they are counted only once in deriving the average values. The dust luminosities are corrected for lensing magnification.

et al., 2018).

3.5.1.2 Dust temperature

The cosmological evolution of dust temperature is a key issue for understanding star-formation activity in the high-redshift universe, as assumptions regarding dust temperature can significantly impact dust luminosity estimations and, consequently, SFRs. Some studies have claimed a global increase in dust temperature with redshift across $z = 0-9$ (c.f., Schreiber et al. 2018; Viero et al. 2022). On the other hand, other studies have pointed out that the increase of dust temperature only arises from the sample selection bias, and no cosmological evolution in dust temperature at a given far-infrared luminosity is required (e.g., Drew & Casey 2022; Dudzevičiūtė et al. 2020). For the ALCS sample, this issue has already been discussed in Sun et al. (2022). They conclude that no evolution has been found in the dust temperatures of LIRGs at $z \leq 2$ and ULIRGs at $z \simeq 1-4$. In this chapter, we just discuss the robust

properties of dust temperature in the ALCS sample and compare them with other SMG samples.

Figure 3.12 compares the dust temperatures obtained from major ALMA surveys. For a conservative discussion, we only plot the sources that are detected with Herschel over 2σ for the ALCS, ASPECS, and AS2UDS samples, where the dust temperatures are more reliably constrained than the other sources. For the same reason, the ALESS sample is limited to the well-sampled subset reported in da Cunha et al. (2021). One should be aware that these selections can cause biases and the subsamples might not reflect the averaged properties of the whole samples. The left panel plots characteristic dust temperature versus dust luminosity. We confirm that the galaxies that have higher dust luminosities tend to have higher dust temperatures. This can be explained by the selection bias, that galaxies with colder dust are brighter in the sub/millimeter band in the same luminosity range. We also confirm that, thanks to the lensing effect, the ALCS sample probes a broader range in lower dust luminosities than the conventional SMG samples (ALESS and AS2UDS) in the same temperature range. The right panel plots characteristic dust temperature versus redshift. The black solid and orange dashed lines show the average characteristic dust temperatures of the ALCS MAIN and the SECONDARY samples in each redshift bin, respectively. We confirm good agreement between the ALCS and the ASPECS samples, whereas a small systematic offset is found between the ALCS and the ALESS/AS2UDS samples. This discrepancy can also be attributed to the selection, showing that the ALCS sample includes sources with higher dust temperatures than the conventional SMG samples in the same redshift range.

We note that M0416-ID156 and A2537-ID24/66 (a multiply-imaged source) exhibit especially high dust temperatures ($T_{\text{dust}} > 70$ K, corresponding to $T_{\text{dust}}^{\text{pead}} > 119$ K). These results might suggest an intense star-formation activity in a compact morphology (Burnham et al., 2021) or a “dubbed starburst” as shown in Gómez-Guijarro et al. (2022b). However, we should be cautious about the potential uncertainty of the SED fitting. For instance, the far-infrared SED of M0416-ID156 is not well-fitted by the ETHEMIS model. This may be attributed to the oversimplification of the model, and can cause large uncertainty in dust temperature and dust luminosity. Conversely, the SEDs of A2537-ID24/66 are fairly well-fitted. Nevertheless, there remains a possibility that their high dust temperatures are actually caused by the remaining blending effect of low-redshift sources. Future multi-band observation with ALMA will be helpful to confirm the nature of these sources.

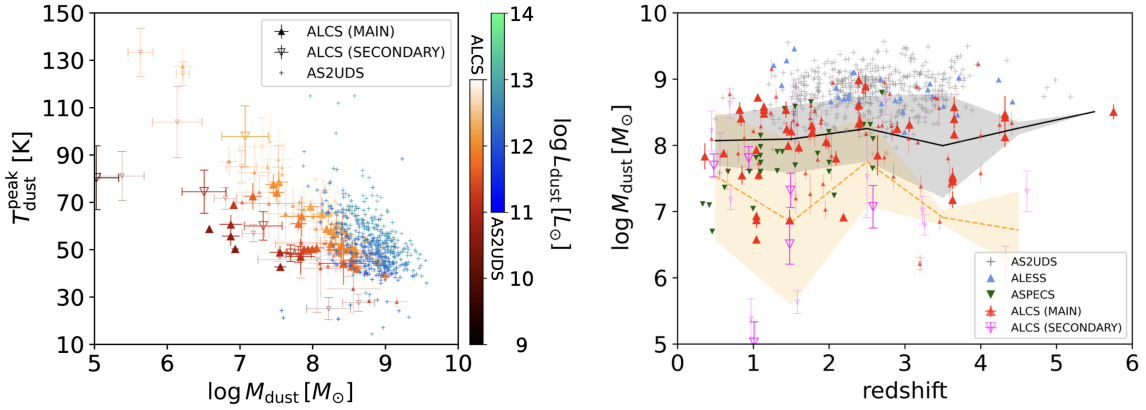


Figure 3.13: (Left) Characteristic dust temperature versus dust mass. The color bars show the dust luminosities. (Right) Dust mass versus redshift. The black solid and orange dashed lines show the mean dust mass for the MAIN and the SECONDARY samples in each redshift bin, respectively. The standard deviations are shown by the semi-transparent regions. In these plots, the ALCS, ASPECS, and AS2UDS samples are limited to the sources that are detected with Herschel over 2σ . The ALESS sample is also limited to the well-sampled subset reported in da Cunha et al. (2021). The large symbols show the galaxies that have spectroscopic redshifts, while the small symbols show those with photometric redshifts. The multiply-imaged sources are plotted individually. The dust masses and dust luminosities are corrected for lensing magnification.

3.5.1.3 Dust mass

The dust mass of a galaxy is also an essential parameter because dust is an efficient catalyst of molecular hydrogen formation in the interstellar medium (e.g., Cazaux & Spaans 2009; Cazaux & Tielens 2004; Gould & Salpeter 1963) and plays as a possible enhancer of star-formation activities in high-redshift universe (Hirashita & Ferrara, 2002). Since the dust mass of a galaxy is dominated by cold interstellar dust, submillimeter observations are suited for establishing a dust-mass-selected sample. Recently, Dudzevičiūtė et al. (2020) suggested that the dust mass of AS2UDS sample is tightly correlated with the flux density at $870 \mu\text{m}$. Moreover, Dudzevičiūtė et al. (2021) showed that $870 \mu\text{m}$ selection (AS2UDS) provides a more uniformly selected dust mass sample across $z = 1\text{--}6$ than $450 \mu\text{m}$ selection (STUDIES; Wang et al. 2017). Since the ALCS sample is selected by longer wavelengths than those of AS2UDS, it is expected to provide a uniformly selected dust mass sample like AS2UDS. However, the estimation of dust mass is sensitive to dust temperature and dust opacity da Cunha et al. (2021). Deep multi-wavelength observations in far-infrared bands are needed to solve these degeneracies.

The left panel of Figure 3.13 compares the dust temperature, dust mass, and dust

luminosity in the ALCS and the AS2UDS samples. For conservative discussion, we again impose the same far-infrared selections as those in Figure 3.12. We confirm that the ALCS sample contains galaxies with lower dust masses than the AS2UDS sample in the same dust temperature range. This can be attributed to the selection effect, showing that the ALCS sample is able to probe galaxies that have lower dust mass than the conventional SMG samples. The right panel plots dust mass versus redshift. The black solid and orange dashed lines show the average dust mass of the ALCS MAIN and the SECONDARY samples in each redshift bin, respectively. This figure shows that there is no obvious evolution in the mean dust mass of the ALCS sample but the ALCS sample spreads widely in a lower dust mass range than the conventional SMG samples. Actually, as shown in the middle panel of Figure 3.6, ALCS MAIN sample behaves as a dust-mass-selected sample ranging $\log M_*/M_\odot = 8-9$ across $z=1-6$ before lensing correction. Therefore, the large scatter found in the dust mass of the ALCS sample just arises from the variation in the magnification factors.

3.5.2 AGN

Figure 3.14 plots the X-ray luminosity upper bounds with various assumptions on line-of-sight obscuration, against bolometric AGN luminosity derived by CIGALE. For comparison, we plot the empirical bolometric-to-X-ray luminosity relation of local AGNs ($L_{\text{bol}}/L_{2-10 \text{ keV}} = 20$; Vasudevan & Fabian 2007)*. We find that most of the ALCS-nonXAGNs are consistent with their X-ray upperbands only in the heavily-obscured cases, where the line-of-sight hydrogen column density ($N_{\text{H}}^{\text{LOS}}$) is over $10^{24.5} \text{ cm}^{-2}$. This suggests that these AGNs are heavily obscured or Compton-thick AGNs. Recently, Simpson et al. (2017) reported that the gas column density inferred from the dust surface density in the AS2UDS sample is $N_{\text{H}} = 9.8_{-0.7}^{+1.4} \times 10^{23} \text{ cm}^{-2}$, which is equivalent to the heavy-obscuration case in Figure 3.14. Hence, the heavy obscuration of our AGN sample might be attributed to the host galaxies. Moreover, it has been suggested that some AGNs in local ULIRGs show “X-ray weak” features ($\kappa_{2-10 \text{ keV}} > 100$; Teng et al. 2015; Yamada et al. 2021). If this is applicable in our sample, the ALCS-nonXAGNs can be consistent with their X-ray luminosity upper bounds even in the less obscured cases ($N_{\text{H}}^{\text{LOS}} \leq 10^{23} \text{ cm}^{-2}$).

*Note that this relationship has a large scatter ($L_{\text{bol}}/L_{2-10 \text{ keV}} = 6-400$) and shows potential strong dependence on the Eddington ratio (see also Lusso et al. 2012 and Brightman et al. 2017 for other calibrations).

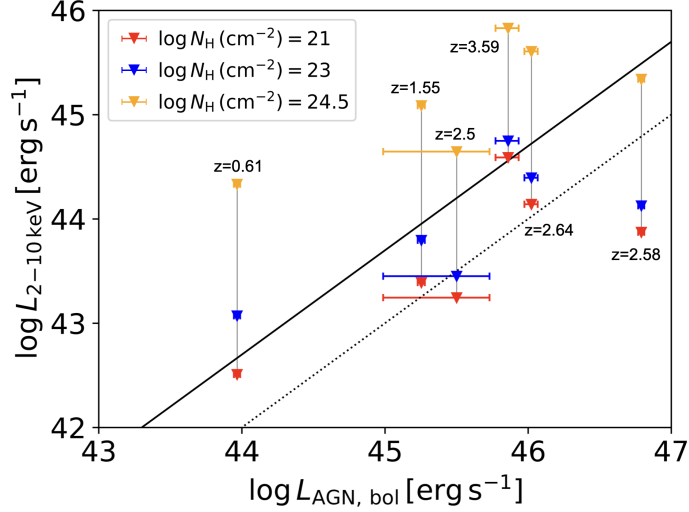


Figure 3.14: X-ray luminosity upper bound with various assumptions of line-of-sight obscuration, plotted against bolometric AGN luminosity derived by SED analysis. The colors correspond to the line-of-sight hydrogen column density assumed in calculating the X-ray luminosity upper bound. The black solid line shows the empirical bolometric-to-X-ray luminosity relation of local AGNs ($L_{\text{bol}}/L_{2-10 \text{ keV}} = 20$; Vasudevan & Fabian 2007), and the black dotted line shows the “X-ray weak” case ($L_{\text{bol}}/L_{2-10 \text{ keV}} = 100$). In this plot, the AGN luminosities and X-ray luminosity upper bounds are corrected for lensing magnification.

3.6 Summary

We report the multi-wavelength properties of millimeter galaxies detected in ALCS. The main conclusions are summarized as follows:

1. We performed UV to millimeter SED modeling of the whole ALCS sample (except for the cluster members and the ALCS-XAGNs), utilizing the photometric data obtained with HST, Spitzer, Herschel, and ALMA.
2. We confirm that the majority of the ALCS sources lie on the star-forming main sequence, while a smaller fraction shows intense starburst activities. This trend is the same as for other ALMA-detected SMG samples, e.g., ALESS, AS2UDS, and ASAGAO, although the ALCS sample contains galaxies with even lower SFRs and stellar masses thanks to the lensing effect.
3. We find two extremely dust-obscured galaxies (A2744-ID7 [$z = 2.41$] and R0600-ID111 [$z=1.56$]). These galaxies have steeper attenuation slopes than the average, which may result in more UV absorption and hence higher IRX.
4. We confirm that the ALCS sample exhibits a wider range in dust temperatures

than the conventional SMG samples (ALESS, and AS2UDS) in the same redshift range. We also confirm that the ALCS sample shows a large scatter in a lower dust mass range than the conventional SMG samples after lensing correction.

5. We identify six AGN candidates that are not detected in the archival CXO data. The X-ray upper bounds indicate that these AGNs are heavily obscured or Compton-thick AGNs. This suggests that a significant fraction of AGNs in SMGs are heavily obscured by gas and dust and might be missed in the previous X-ray observations.

CHAPTER 4

ALMA/SCUBA-2 COSMOS Survey: Properties of X-ray- and SED-selected AGNs in Bright Submillimeter Galaxies

We investigate the properties of AGNs in the brightest SMGs in the COSMOS field. We utilize the bright sample of ALMA/SCUBA-2 COSMOS Survey, which consists of 260 SMGs with $S_{870\mu\text{m}} = 0.7\text{--}19.2\text{ mJy}$ at $z = 0\text{--}6$. We perform optical to millimeter SED modeling for the whole sample. We identify 24 AGN-host galaxies from the SEDs. Supplemented by 23 X-ray-detected AGNs (X-ray AGNs), we construct an overall sample of 40 AGN-host galaxies. The X-ray luminosity upper bounds indicate that the X-ray undetected SED-identified AGNs are likely to be nearly Compton thick or have unusually suppressed X-ray emission. From visual classification, we identify $25^{+6}_{-5}\%$ of the SMGs without AGNs as major merger candidates. This fraction is almost consistent with the general galaxy population at $z \sim 2$, suggesting that major mergers are not necessarily required for the enhanced star formation in SMGs. We also identify $47^{+16}_{-15}\%$ of the AGN hosts as major merger candidates, which is about twice as high as that in the SMGs without AGNs. This suggests that major mergers play a key role in triggering AGN activity in bright SMGs.

4.1 Introduction

The properties of AGNs in SMGs have been intensely studied over the last two decades. For instance, Alexander et al. (2005) investigated the X-ray properties of SMGs in the 2 Ms Chandra Deep Field North (CDF-N), using a spectroscopically identified SCUBA 850- μm sample with radio counterparts from Chapman et al. (2005) ($S_{850\mu\text{m}} = 2.4\text{--}17.4\text{ mJy}$). They showed that the majority (15/20) of those radio-detected SCUBA galaxies host X-ray AGNs, from which the large fraction (12/15) are moderately/highly absorbed ($N_{\text{H}} \geq 10^{23}\text{ cm}^{-2}$). On the basis of ASAGAO combined with the deepest 7 Ms CXO survey, Ueda et al. (2018) found 90^{+8}_{-19} per cent and 57^{+23}_{-25} per cent of millimeter-selected galaxies with $L_{\text{IR}} > 10^{12} L_{\odot}$ and $10^{11} L_{\odot} < L_{\text{IR}} < 10^{12} L_{\odot}$ at $z = 1.5\text{--}3$ contains X-ray-detected AGNs, respectively. The GOODS fields were also studied by an ultradeep SCUBA-2 survey (a submillimeter perspective on the GOODS fields [SUPER GOODS]; Barger et al. 2019, 2022; Cowie et al. 2017, 2018). As a study in a wider field with relatively shallow X-ray observations, Wang et al. (2013) studied AGNs in the ALESS sample ($S_{870\mu\text{m}} = 1.3\text{--}9.0\text{ mJy}$). They identified eight X-ray AGNs from 91 SMGs in the shallower CXO footprints, from which six sources are moderately/highly absorbed. Similarly, Stach et al. (2019) examined the properties of SMGs in the AS2UDS sample ($S_{870\mu\text{m}} = 0.6\text{--}13.6\text{ mJy}$). They found 23 X-ray AGNs from 274 SMGs in the shallow CXO coverage. They also found 37 potential AGNs that were not detected in X-ray from 162 IRAC-selected SMGs at $z < 3$, utilizing the IRAC-color selection of Donley et al. (2012). Moreover, studies of high-density regions by Tamura et al. (2010) and Umehata et al. (2015, 2019) investigated the properties of AGNs in a protocluster at $z = 3.09$ (SSA22). Although these studies constrained the physical properties of AGNs in SMGs, the derived values vary from study to study. For a more comprehensive understanding of the nature of AGN in SMGs, it is necessary to study a larger sample and wider parameter ranges of SMGs.

The detection of AGNs in galaxy samples is always challenging. Historically, many studies used X-ray observations and/or optical spectroscopy to study the nature of AGNs. However, these methods have a bias against the most heavily obscured sources (see Hickox & Alexander 2018 for a review). In heavily obscured AGNs, X-ray and ultra-violet (UV) emission from the inner regions of the accretion disk around the SMBH is absorbed by surrounding material and is re-emitted in the mid- to far-infrared bands. Color-color diagrams in the mid-infrared wavebands are able to identify such heavily obscured systems, but are less reliable for high-redshift

sources ($z > 3$; Donley et al. 2012) and lower-luminosity AGN where the mid-IR emission can be strongly contaminated by the host galaxy (see also Pope et al. 2008). SED modeling of broad-band (rest-frame UV to far infrared) photometries is a promising method to robustly identify hidden AGNs missed at X-ray and optical energies. Although this method is dependent on the quality of the multi-wavelength photometry and model assumptions, it has successfully identified AGN candidates that are not detected in X-ray observations (e.g., Andonie et al. 2022; Chien et al. 2024; Liao et al. 2024; Uematsu et al. 2024; Yang et al. 2023).

In this study, we investigate the properties of AGNs hosted by bright SMGs in the COSMOS field, utilizing the ALMA/SCUBA-2 COSMOS Survey (Simpson et al., 2020). This survey is a follow-up of the brightest ~ 180 submillimeter sources that were detected in the SCUBA-2 COSMOS Survey (S2COSMOS; Simpson et al. 2019), and is effectively complete for S2COSMOS sources brighter than $S_{850\mu\text{m}} = 6.2\text{ mJy}$. We perform rest-frame UV to far-infrared SED modeling for the AS2COSMOS SMG sample and identify AGNs. We also perform an X-ray spectral analysis of the bright X-ray-detected AGNs. On the basis of these results, we discuss the properties of the AGNs and their host galaxies. The structure of this chapter is as follows: In Section 4.2, we describe the observations and data reduction. In Section 4.3, we describe the SED modeling and the X-ray spectral analysis. Section 4.4 presents our results and discussions. A summary is given in Section 4.5. Throughout the chapter, we assume a flat universe with $H_0 = 70.4\text{ km s}^{-1}\text{ Mpc}^{-1}$, $\Omega_{\text{M}} = 0.272$ (Komatsu et al., 2011). The Chabrier initial mass function (IMF) is adopted (Chabrier, 2003). We use the AB magnitude system (Oke & Gunn, 1983). If not specially mentioned otherwise, the quoted errors correspond to 1σ confidence.

4.2 Observations and Data Reduction

4.2.1 Submillimeter Photometry

The ALMA submillimeter source catalog that is the basis of our analysis was presented in Simpson et al. (2020). The pilot study of AS2COSMOS was performed in ALMA Cycle 4. This survey followed up 160 of the brightest SCUBA-2 $850\text{-}\mu\text{m}$ sources in the COSMOS field from the S2COSMOS survey (Simpson et al., 2019), of which 158 had deboosted/deblended $850\text{ }\mu\text{m}$ flux densities of $S_{850\mu\text{m}} > 6.2\text{ mJy}$. Observations were conducted between 2018 May 15 and 21 covering the 7.5-GHz

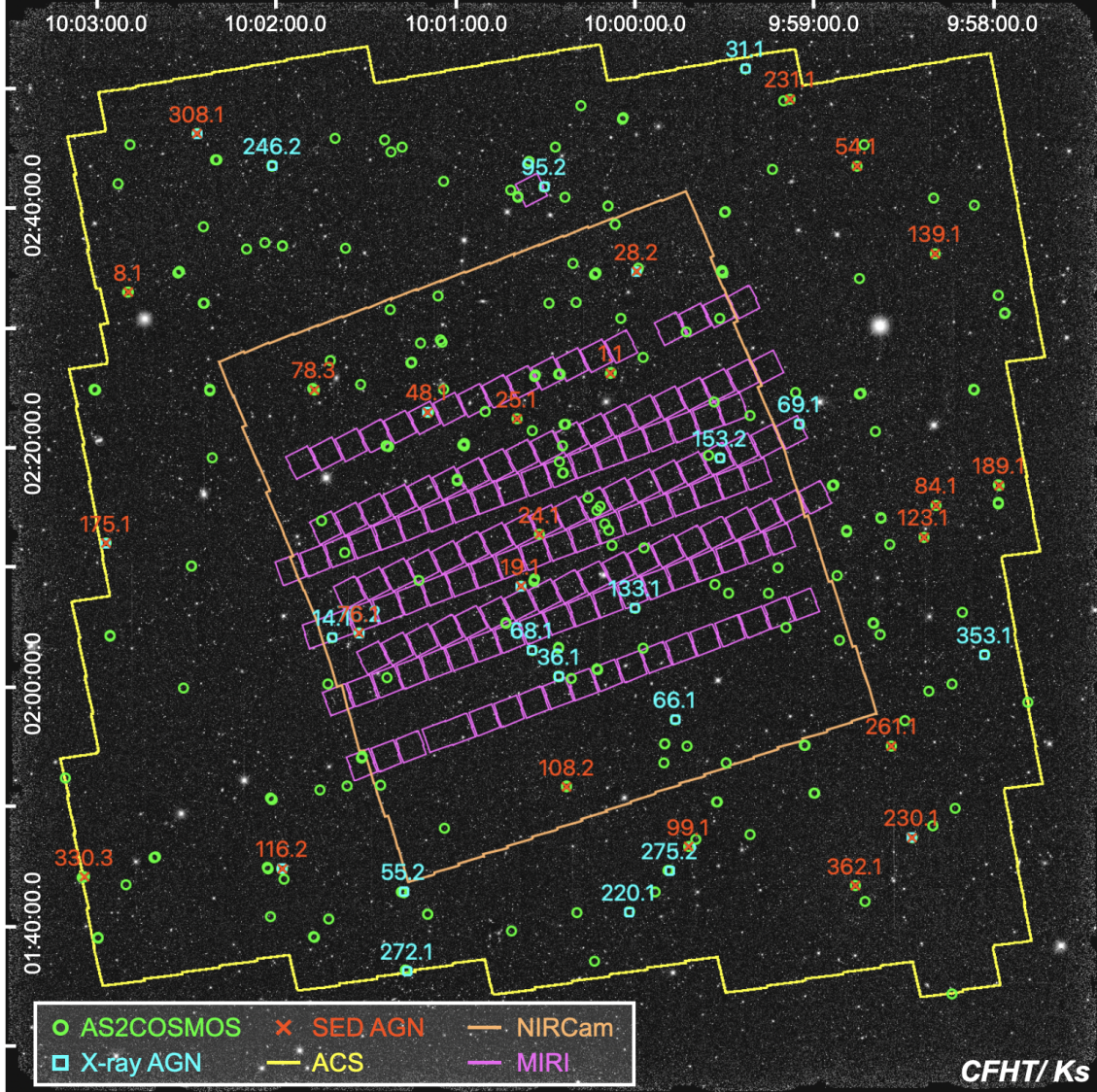


Figure 4.1: Positions of the AS2COSMOS sources. The cyan and red points correspond to the X-ray AGNs and SED AGNs, respectively (see Section 4.3.1.3 and Section 4.4.1). The background is the CFHT K_s -band image. The coverage of HST ACS, JWST NIRCам, and JWST MIRI imaging are shown in yellow, orange, and magenta, respectively.

bandwidth centered at 343 GHz ($870\ \mu\text{m}$; band 7). Supplemented by the archival ALMA band 7 imaging, Simpson et al. (2020) constructed a sample of 182 brightest S2COSMOS sources (deboosted/deblended flux densities of $S_{850\ \mu\text{m}} > 6.2\ \text{mJy}$) with ALMA band-7 imaging. All the ALMA data were calibrated and reduced with the Common Astronomy Software Applications (CASA) package (v5.1.1). The final images have a median synthesized beam size of $0.80 \times 0.79\ \text{arcsec}$ full width at half maximum (FWHM) and a median sensitivity of $\sigma_{870\ \mu\text{m}} = 0.19\ \text{mJy beam}^{-1}$.

Source extraction was performed with SEXTRACTOR. First, Simpson et al. (2020) extracted sources within the ALMA primary beams with a significance of $>4.8\sigma$ at a peak or $>4.9\sigma$ in an aperture with a $1.5\times$ FWHM of the synthesized beam. The number of false detections fell to zero with these criteria. In this step, Simpson et al. (2020) constructed a robust sample of 254 SMGs in 182 ALMA maps. Then, they extracted sources from the outer region of the ALMA primary beam with a slightly higher peak significance of $>5.1\sigma$, where the false detection rate again fell to zero. As part of this step, six additional SMGs were detected at 8.9–11.5 arcsec offsets from the phase center. The final sample contains 260 SMGs out of the 182 brightest S2COSMOS sources. This sample effectively comprises all S2COSMOS sources brighter than $S_{850\ \mu\text{m}} = 6.2\ \text{mJy}$. However, due to the influence of flux boosting on the SCUBA-2 catalog, this corresponds to an overall completeness of 50 per cent for SMGs at $S_{850\ \mu\text{m}} = 7.2\ \text{mJy}$ in the $1.6\ \text{deg}^2$ survey area. We note that Simpson et al. (2020) confirmed a small astrometric offset of $\Delta\text{R.A.} = 0.08 \pm 0.01\ \text{arcsec}$ between the AS2COSMOS and COSMOS2015 catalog (Laigle et al., 2016). In this study, we always correct the source astrometry for this offset by referring to the COSMOS2015 catalog. Figure 4.1 shows the positions of the AS2COSMOS sources on a Canada France Hawaii Telescope (CFHT) K_s -band image.

4.2.2 Spectroscopic Redshifts

Spectroscopic redshifts of AS2COSMOS sources were obtained from several studies. We utilized the following spectroscopic surveys: the Sloan Digital Sky Surveys (SDSS DR16; Ahumada et al. 2020), zCOSMOS survey (DR3; Lilly et al. 2009), the VIMOS VLT Deep Survey (VVDS final data release; Le Fèvre et al. 2013), the PRISM Multi-object Survey (PRIMUS DR1; Coil et al. 2011; Cool et al. 2013), the FMOS-COSMOS survey (version 2; Kashino et al. 2019; Silverman et al. 2015), the 3D-HST survey (Momcheva et al., 2016; Skelton et al., 2014), the Complete Calibration of the Color-Redshift Relation (C3R2) survey (DR3; Masters et al. 2019), hCOSMOS

survey (Damjanov et al., 2018), and the DEIMOS 10K spectroscopic survey (Hasinger et al., 2018). In addition to these catalogs, we used the results of the submillimeter line scan of the brightest AS2COSMOS sources performed by Chen et al. (2022) and Liao et al. (2024) (see also Birkin et al. 2021). Moreover, we utilized the spectroscopic study of a galaxy cluster performed by Wang et al. (2016b) (AS2COS0003.1, AS2COS0003.2, AS2COS0003.3, and AS2COS0003.4) and the spectroscopic study of [C II] emitters performed by Mitsuhashi et al. (2021) (AS2COS0001.1, AS2COS0001.2, AS2COS0006.1, AS2COS0034.1, and AS2COS0034.2).

We cross-matched the AS2COSMOS sources with these catalogs within 1.0 arcsec radii and only used “secure” redshifts. With priority given to the submillimeter redshifts, 80 out of 260 sources had spectroscopic redshifts ranging from 0.033 to 5.3 (hereafter “spec- z sample”). In Section 4.3.1.1 and Appendix C.3.2, we show that the original optical counterpart of AS2COS0159.1 ($z_{\text{spec}} = 0.033$) was misidentified. Therefore, the final spectroscopic redshift sample contains 79 SMGs within $z_{\text{spec}} = 0.3\text{--}5.3$. For the other sources, we calculate their photometric redshifts by utilizing CIGALE to simultaneously treat redshift uncertainties (hereafter “photo- z sample”; Section 4.3.1.2).

4.2.3 Size Measurement with ALMA

The typical synthesized beam of the ALMA 870- μm observations in AS2COSMOS from Simpson et al. (2020) was $\sim 0.8''$ FWHM. Given that the characteristic sizes of the bright dust continuum emission SMGs are believed to be $\sim 0.2''\text{--}0.3''$ FWHM (e.g., Fujimoto et al., 2018; Gullberg et al., 2019; Hodge et al., 2016; Ikarashi et al., 2015, 2017; Simpson et al., 2015), the coarse resolution of our observations would have made it challenging to measure reliable sizes for such compact sources in the image domain. However, the high S/N of our ALMA detections (median integrated S/N ~ 30 , with a range of 17–52) meant that it would be possible to obtain constraints on the size of the dust continuum emission in the brighter sources in our sample using a visibility-domain analysis, as has been demonstrated in the past (e.g., Gullberg et al., 2019; Ikarashi et al., 2015, 2017; Iono et al., 2006; Younger et al., 2008).

The ALMA dust continuum size measurements were undertaken by Ikarashi et al. (in prep.) and followed the methodology described in Ikarashi et al. (2015), with the exception that they adopted a Sersic $n = 1$ exponential disk profile (rather than a Gaussian profile used in that earlier work) as suggested by high-angular resolution

submillimetre imaging of SMGs in the literature (e.g., Fujimoto et al., 2018; Gullberg et al., 2019; Hodge et al., 2016, 2019). The first step in their analysis was to remove any other significant sources ($S/N \geq 5$) from the ALMA map of the primary source whose size was being measured. This is necessary as the visibility-domain analysis assumes there is only a single source in the map. To remove the secondary sources these were modeled using the CLEAN task in CASA employing its scratch option. This involved masking the other sources and cleaning down to $1\text{-}\sigma$ noise level, before subtracting the modeled source visibilities from the ALMA visibility data.

Then uv -amplitude plots were constructed for each source, by shifting the phase center to the position of the source and measuring the circularized, average flux in each uv -distance bin. A single exponential-disk light profile ($n = 1$) model was then fitted to the uv -amplitude plot to obtain the best-fit size as a circularized half-light radius, $R_{\text{circ},0.5}$. Ikarashi et al. (in prep.) also tested the reliability of their size measurements by performing simulations which involved injecting mock sources with known light profiles and sizes into the real ALMA visibility data and measuring their sizes in the same manner as for the real sources. This provided robust estimates of the errors in our size measurements. To determine the final size for each source, Ikarashi et al. (in prep.) assessed whether the reported size is measurable (or only provides a limit) given the claimed S/N and resulting size using these Monte Carlo simulations, which also provided appropriate uncertainties on the source size measurements.

4.2.4 Optical to Far-infrared Photometry

The optical-to-radio photometric catalog for the SMG counterparts was also constructed by Simpson et al. (2020), by updating the COSMOS2015 photometry catalog (Laigle et al., 2016) to include deeper observations in the critical optical and near-infrared bands. By cross-matching the AS2COSMOS sources with the COSMOS2015 catalog, 179/260 optical/near-infrared counterparts were identified within search radii of 0.85 arcsec, where the possibility of a false match is estimated at ~ 6.6 per cent. After that, the $YJHK_s$ band photometry was substituted with those in DR4 of the Ultravista survey (McCracken et al., 2012), which is up to ~ 0.5 mag deeper than DR2 used in the COSMOS2015 catalog. Photometry was measured using 2-arcsec diameter apertures centered at the SMG positions. In addition, the $BVriz$ photometry of COSMOS2015 catalog was replaced with the $grizY$ photometry in the second data release of the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP;

Aihara et al. 2019) if available. HSC-SSP DR2 reached ~ 1 mag deeper than the optical imaging used in the COSMOS2015 catalog, and 158/260 counterparts were identified within 0.85 arcsec. In total, 199/260 optical/near-infrared counterparts are identified in this step.

To obtain mid-infrared photometry, the 3.6–8.0 μm images of the Spitzer Large Area Survey combined with Hyper Supreme-Cam (SPLASH; Steinhardt et al. 2014) were utilized. The images were reduced with IRACCLEAN (Hsieh et al., 2012), where sources are deblended by referring to the stacked $zYJHK_s$ detection images and ALMA 870 μm source positions. The far-infrared imaging of the COSMOS field was provided by three large programs; the COSMOS-Spitzer program (24 μm ; Sanders et al. 2007), the PACS Evolutionary Probe (PEP) survey (100 and 160 μm ; Lutz et al. 2011), and the Herschel Multi-tiered Extragalactic Survey (HerMES; 250, 350, and 500 μm ; Oliver et al. 2012). The “superdeblended” catalog (Jin et al., 2018), which contains deblended 24–160- μm photometry for K_s - and 3-GHz-selected sources, was cross-matched to the SMGs to improve completeness at 24–100- μm band and photometry was also obtained by cross-matching the AS2COSMOS sources with the PACS/PEP survey catalog (Lutz et al., 2011). Finally, 250–500- μm photometry was derived following the method described in Swinbank et al. (2014), where the Spitzer 24 μm , Very Large Array (VLA) 3 GHz and ALMA 870 μm source positions were used to deblend the Herschel images.

The radio photometry was taken from the source catalog of the VLA-COSMOS 3 GHz Large Project (Smolčić et al., 2017). Cross-matching the AS2COSMOS sources with the VLA 3G-Hz catalog, 191 counterparts were identified within 1 arcsec. Since two pairs of SMGs were confused in the 3-GHz map (AS2COS0051.1/.2 and AS2COS0228.1/.2), the CASA/IMFIT routine was applied to deblend the fluxes of these sources.

4.2.5 High-resolution Imaging with JWST

The COSMOS field was observed with the James Webb Space Telescope (JWST) through two Cycle 1 JWST treasury programs. The first was PRIMER (Dunlop et al., 2021), which provides a contiguous 144 arcmin² with NIRCам in eight filters (F090W, F115W, F150W, F200W, F277W, F356W, F444W and F410M) and a non-contiguous 112 arcmin² with MIRI in two filters (F770W and F1800W). The second was COSMOS-Web (Casey et al., 2023), which provides a contiguous 0.54 deg² with

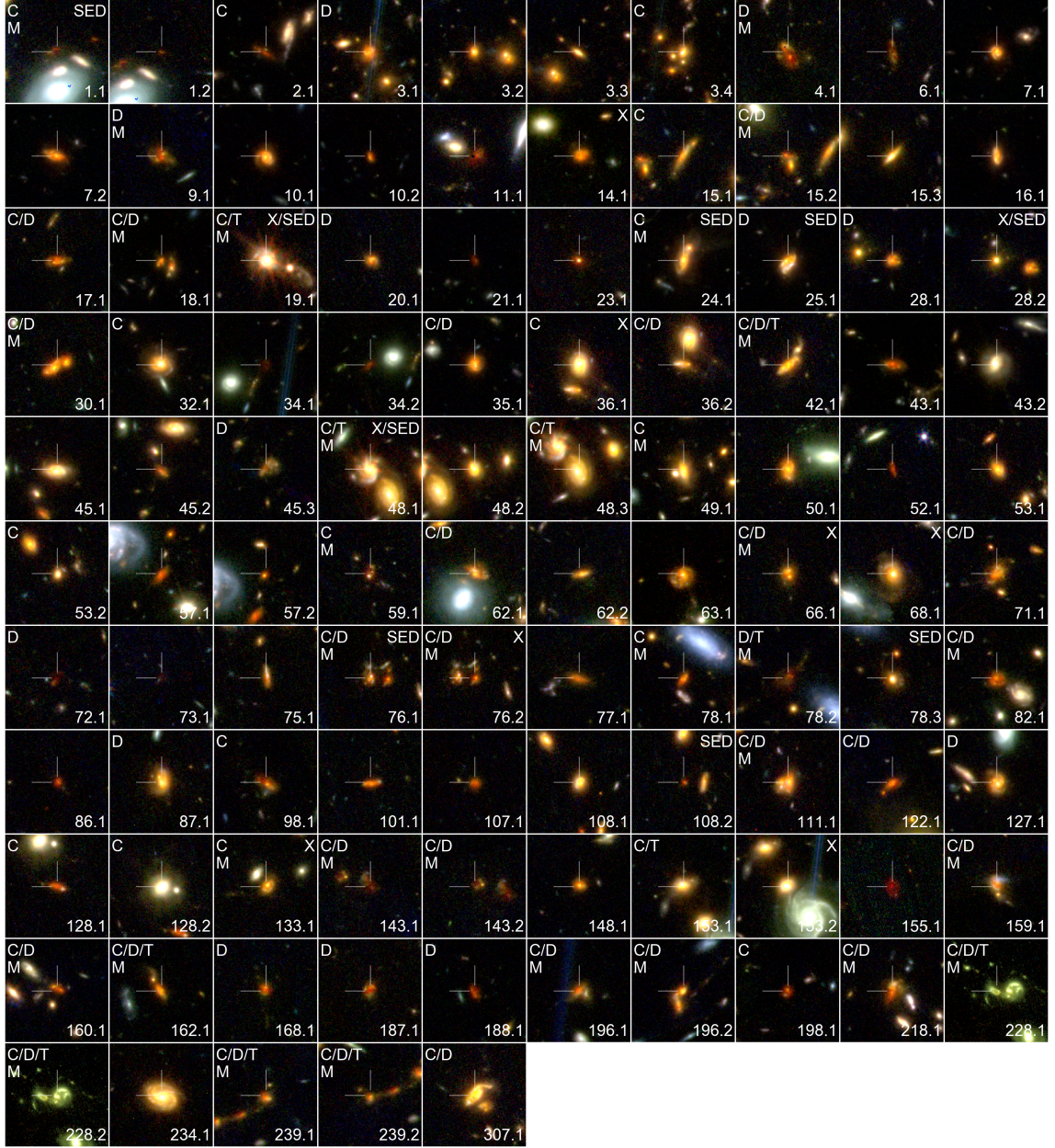


Figure 4.2: 8 arcsec $\times$ 8 arcsec JWST images of the 105 AS2COSMOS sources in the coverage of NIRCcam (AS2COS0005.1 and AS2COS0005.2 are excluded). The blue, green, and red colors correspond to the F115W+F150W, F277W, and F444W filters, respectively. We label the merger candidates, which have tidal features (T), disturbed morphology (D) or possible companions (C) (see Section 4.3.3). The major merger candidates are indicated by “M”. The X-ray AGNs and the SED AGNs are indicated by “X” and “SED” (see Section 4.3.1.3 and Section 4.4.1). Note that the images of AS2COS0107.1 and AS2COS0122.1 are constructed from F115W (blue), F277W (green), and F444W (red) filters as they are not covered by F150W. For the same reason, the image of AS2COS0155.1 is constructed from F115W (blue), F2150W (green), and F277W (red), and those of AS2COS0228.1 and AS2COS0228.2 are constructed from F115W (blue), F115W+F150W (green), and F150W (red), respectively.

NIRCam in four filters (F115W, F150W, F277W, and F444W) and a non-contiguous 0.18 deg^2 with MIRI in one filter (F770W). 107/260 AS2COSMOS sources fall within the coverage of the NIRCam imaging, whereas 43/260 sources are in the MIRI coverage (Figure 4.1). We utilized the reprocessed images provided by the DAWN JWST Archive (DJA) and constructed the color-composite images of those sources. Figure 4.2 shows the color-composite images of the 107 AS2COSMOS sources in the NIRCam coverage. The color-composite images of the 40 AS2COSMOS sources in the coverage of both NIRCam and MIRI are shown in Figure C.1 in Appendix C.1. In Section 4.3.3, we perform a morphological analysis using these images. Note that the near-infrared counterpart of AS2COSMOS0005.1 has distorted morphology, indicating it is a strong gravitational lens (Hwang et al., 2021; Jin et al., 2024; Pearson et al., 2024). This is due to gravitational lensing by a foreground galaxy. Thus, we exclude AS2COSMOS0005.1 and AS2COSMOS0005.2 in the following analysis.

4.2.6 X-ray Observations

4.2.6.1 Observation Overview and Cross Matching

The COSMOS field was observed with the CXO through two large programs. The first was the Chandra COSMOS survey (C-COSMOS; Elvis et al. 2009), which was conducted from 2006 November to 2007 June. This survey covered the central 0.5 deg^2 of the COSMOS field with an exposure time of $\sim 160 \text{ ks}$, and an outer 0.4 deg^2 area of $\sim 80 \text{ ks}$. The second program was the Chandra COSMOS-Legacy survey (Civano et al., 2016), which was carried out from 2012 November to 2014 March. During this survey, the outer region of C-COSMOS was observed to a depth of $\sim 160 \text{ ks}$, achieving an effective exposure of $\simeq 160 \text{ ks}$ over the central 1.5 deg^2 and of $\simeq 80 \text{ ks}$ in the outer 0.7 deg^2 . The whole survey detected 4016 point sources to limiting depths of $2.2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$, $1.5 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}$, and $8.9 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ in the 0.5–2.0, 2.0–10.0, and 0.5–10.0 keV bands, respectively.

Cross-matching the AS2COSMOS sources with the latest catalog by Civano et al. (2016), we identified 23 X-ray counterparts within a radius of 1.4 arcsec. Since Civano et al. (2016) reported that 95 per cent of the X-ray sources used for the astrometry correction have their optical counterparts within 1.4 arcsec, we employed this value for the cross-matching radius (the total false matching rate is ~ 0.3 across the entire field).

In this study, we performed an X-ray spectral analysis for the X-ray-detected sources to derive their X-ray luminosities and line-of-sight absorption. We also estimated the X-ray luminosity upper bounds for X-ray undetected SMGs assuming typical X-ray spectra of AGNs.* Details of the X-ray spectral analysis are described in Section 4.3.2. Here we reanalyzed all the X-ray data, consisting of 117 pointings, using the Chandra interactive analysis of observations software (CIAO v4.15; Fruscione et al. 2006) and the latest calibration database (CALDB v4.10.7). Note that AS2COS0353.2 was initially identified as an X-ray source that was later confirmed as the counterpart of AS2COS0353.1 by visual inspection (Appendix C.2).

4.2.6.2 Source Extraction

Before extracting X-ray spectra of the SMGs, we performed X-ray astrometric corrections for all the observations, following Civano et al. (2016). First, we reprocessed the data with CHANDRA_REPRO script, employing the VFAINT mode for ACIS background cleaning. Next, we performed source detection in each 0.5–7.0 keV image with WAVDETECT tool. The point spread function (PSF) maps were created at the 39.3% encircled count fraction (ECF) radius, assuming a single power-law spectrum with a photon index of 1.4 and Galactic absorption of $N_{\text{H}} = 2.6 \times 10^{20} \text{ cm}^{-2}$ (Kalberla et al., 2005). We employed a “2 sequence” of wavelet scales (i.e., 1, 1.414, 2, 2.828, 4, 5.656, 8, 11.314, and 16 pixels) and a false-positive probability threshold of 10^{-6} . Then, we corrected the astrometry using the HSC *i*-band-selected subsample (17–24 AB mag) of the COSMOS2020 catalog (Weaver et al., 2022). In this step, only secure sources whose significance is higher than 5σ and the PSF size is smaller than 2 pixels (~ 1 arcsec) were cross-matched with the reference within 1.5 arcsec. On average, 15 sources were used to perform reprojection in each image. Finally, we combined all the images using MERGE_OBS script. To confirm the astrometric accuracy, we again performed source detection in the combined image with WAVDETECT tool. In this step, the length scale was varied from $0.5''$ to $16''$ in steps of $\sqrt{2}$. The detailed analysis of the CXO astrometry is summarized in Appendix C.2.

We then extracted the X-ray spectra using circular apertures centered at the X-ray source positions. Here we determined the X-ray source positions by the frame that has the sharpest PSF at the detected position. The aperture radii were set to the

*Here we use the term “upper bound” to describe the upper boundary of confidence intervals (see Kashyap et al. 2010).

80 ECF radius in each frame, but an upper limit was set to 5.0 arcsec for sources that are detected over 3σ in the 0.5–7.0 keV band* and 4.0 arcsec for the others.[†] Background spectra were taken from annuli with inner and outer radii of 8.0 and 25.0 arcsec, respectively, by masking any X-ray sources with circular regions with radii of 8.0 arcsec. For X-ray undetected SMGs, we estimated the X-ray upper bound count rates at 99.73 per cent confidence intervals (3σ) in the 0.5–7.0 keV band, utilizing SRCFLUX script. For the source regions, we employed circular apertures with radii of 3.0 arcsec centered at the 870- μ m source positions. The background count rates were estimated by annular regions with inner and outer radii of 8.0 and 15.0 arcsec, respectively, by masking any X-ray sources with circular regions with radii of 8.0 arcsec.

4.3 Analysis

4.3.1 Optical to Submillimeter SED Analysis

4.3.1.1 SED Fitting

We perform optical to submillimeter SED modeling for the whole AS2COSMOS sample. We use CIGALE v2022.0 (Boquien et al., 2019; Yang et al., 2020, 2022), but incorporating modifications for the dust emission model as described below. The CIGALE code is designed to calculate the likelihoods of all the models on a user-defined grid and return the likelihood-weighted mean of the marginalized probability distribution function (PDF) as a Bayesian estimation. In CIGALE, users can choose several options for each SED component. We employ a delayed SFH, accompanied by a recent starburst with a constant SFR. The composite stellar populations are calculated based on the stellar template of Bruzual & Charlot (2003) and the Chabrier IMF (Chabrier, 2003). The dust extinction of the stellar component is modeled with the modified Calzetti starburst attenuation law (Calzetti et al., 2000; Leitherer et al., 2002; Noll et al., 2009). For the dust emission model, we use the ETHEMIS model (Uematsu et al., 2024), which is a high-temperature extension of the THEMIS model (Jones et al., 2017). The optical to far-infrared emission from an AGN is modeled

*Here we used the signal-to-noise ratios that were reported in Civano et al. (2016).

[†]AS2COS95.2 was detected over 3σ in the 0.5–7.0 keV band, but the upper limit on the extraction aperture was set to 4.0 arcsec to avoid contamination from a nearby source.

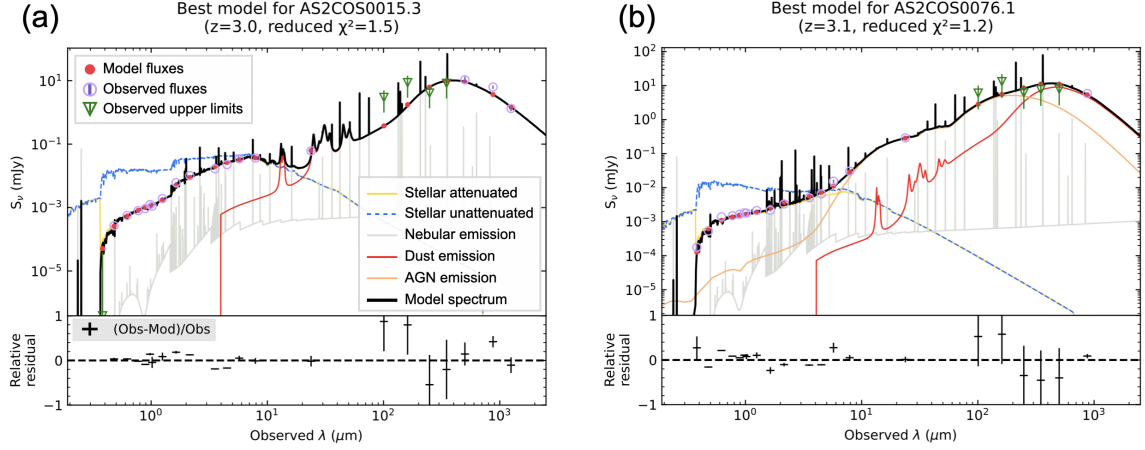


Figure 4.3: Example SEDs of a galaxy fitted (a) without and (b) with AGN templates. The black solid line represents the best-fit template SED solution. The yellow solid line illustrates the stellar emission attenuated by interstellar dust. The blue dashed line depicts the unattenuated stellar emission for reference. The orange line corresponds to the emission from the AGN. The red line shows the infrared emission from interstellar dust. The gray line denotes the nebulae emission from the host galaxy. The observed data points are represented by purple circles, accompanied by 1σ error bars. The bottom panel displays the relative residuals between the best-fitting template solution and the photometry.

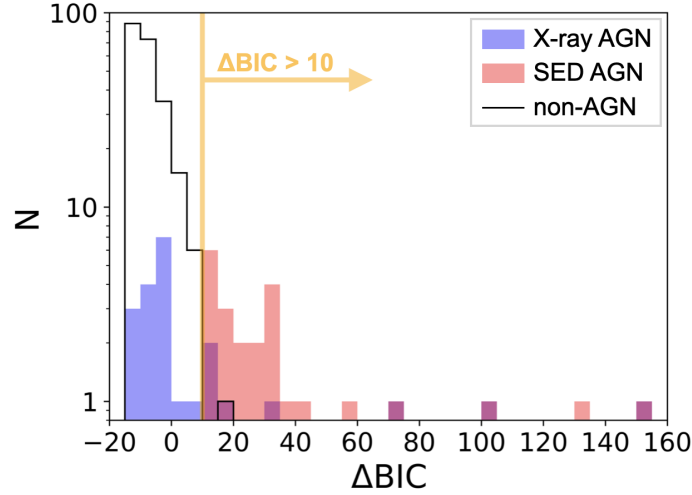


Figure 4.4: Distribution of ΔBIC of the X-ray-detected AS2COSMOS sources (X-ray AGN; see Section 4.4.1), SED AGNs, and all the AS2COSMOS sources. The vertical orange solid lines show the adopted threshold to identify an SED AGN ($\Delta\text{BIC} = 10$). Most of the X-ray-detected sources (16 out of 23) have BICs lower than 10, suggesting that the SED AGNs are the complementary sample to X-ray-detected AGNs.

with the SKIRTOR model (Stalevski et al., 2012, 2016), where a polar-dust component is implemented with a single optically-thin graybody. The UV-to-optical emission from the accretion disk is modeled by a broken power law (Schartmann et al., 2005). In the SKIRTOR model, an AGN whose inclination angle is smaller (larger) than the half-opening angle of the torus is classified as a type-1 (type-2) AGN. We employ this classification in later sections.

In CIGALE, the number of parameter grid points is often limited by computational cost. Hence, we need to optimize the parameter set to adequately reproduce the SEDs given this limitation. Moreover, there remain some possible errors in extracting photometry such as remaining blending effects or calibration issues. For these reasons, we separate the SED modeling into two steps. In the first step, we analyze all the SEDs with a robust parameter set, which is summarized in Table C.1 in Appendix C.3. In this step, we adequately reproduce most of the SEDs with reduced χ^2 values typically lower than five. Then, in the second step, we reanalyze the remaining sources by optimizing the photometry or adjusting the parameter settings. Details of these iterations are summarized in Appendix C.3. With this approach, we adequately reproduce the SEDs of the AS2COSMOS sources ($\chi^2/\text{d.o.f.} < 7$; see Figure C.4 in Appendix C.3.4). Figure 4.3 illustrates two example SEDs of AS2COSMOS sources fitted with and without AGN templates. Note that the radio component is not simultaneously treated in the SED modeling to save the computational cost.

When calculating the physical properties, we vary the following parameters logarithmically: stellar mass (M_*), star-formation rate, dust mass (M_{dust}), and infrared luminosity (L_{IR})*, while the following are varied linearly: dust temperature (T_{dust}), color excess of stellar continuum attenuation ($E(B - V)$), power-law index to modify the Calzetti attenuation slope (δ), AGN luminosity fraction in the total dust luminosity (f_{AGN}), bolometric AGN luminosity ($L_{\text{AGN, bol}}^{\text{SED}}$), and redshift (z). For SFR, we employ 10 Myr averaged values. The specific SFRs (sSFR) are calculated by dividing the SFRs by the stellar masses. The radio-IR correlation parameters (q_{IR}) are calculated by the following equation:

$$q_{\text{IR}} = \log \left(\frac{L_{\text{IR}}}{L_{\nu, 21 \text{ cm}} \times 3.75 \times 10^{12} \text{ Hz}} \right) \quad (4.1)$$

The radio luminosity density at 21 cm is converted from the radio flux density at 3

*In CIGALE, the infrared luminosity is calculated by the sum of the dust luminosity from the AGN and the dust luminosity from the host galaxy. This is almost the same as the integrated luminosity between 8–1000 μm .

GHz assuming a spectral index of 0.75 (e.g., Condon 1992; Ibar et al. 2010, 2009). Note that the spectral index was reported to have large uncertainty (a standard deviation of 0.29; Ibar et al. 2010) and care should be taken. The SFR is directly calculated from the stellar templates, and this value corresponds to the sum of UV (unobscured) and FIR (obscured) SFRs.

4.3.1.2 Treatment of the Redshift Uncertainty

In the SED modeling, the redshifts of the SMGs without spectroscopic redshifts are allowed to vary within $0.1 < z < 6.0$ (photo- z sample). Hence, the physical quantities derived by CIGALE include the redshift uncertainties. However, in the X-ray spectral analysis, redshifts are always fixed at the spectroscopic redshifts or the Bayesian-estimated photometric redshifts derived by SED modeling (Section 4.3.2). This inconsistency can cause a problem in comparing the physical properties. Therefore, we repeat the SED modeling by fixing the redshifts at either the spectroscopic ones or the Bayesian-estimated photometric ones. The values estimated in this way are used for comparison with the X-ray properties.

4.3.1.3 Identification of AGN

To identify whether a galaxy hosts an AGN or not, we utilize the Bayesian Information Criterion (BIC). The BIC is calculated as $\text{BIC} = \chi^2 + k \times \ln(n)$, where χ^2 is the non-reduced χ^2 value, k is the number of degrees of freedom, and n is the number of photometric points. In this study, we regard the sources with $\Delta\text{BIC} = \text{BIC}_{\text{w/o AGN}} - \text{BIC}_{\text{w/ AGN}} > 10$ as hosting AGNs (SED AGNs; see also Toba et al. 2020). The median number of photometric points in the SED fitting is 21, and the number of degrees of freedom for the AGN module is 4. Thus, this criterion roughly corresponds to the improvement in reduced χ^2 of 1. However, in some cases, this method gives unreasonable results, due to the limited parameter range of the SED model. Thus, we also visually examine the SEDs and conclude that there is no evidence of AGNs in the SED of AS2COS0001.2, where both mid-infrared excess and a flat far-infrared SED are not confirmed. Finally, we identify 24 SED AGNs in the AS2COSMOS sample, where seven sources are also detected in X-ray.

Figure 4.4 shows the histogram of ΔBIC . Notably, most of the X-ray-detected sources (16 out of 23) exhibit BICs lower than 10. This shows that the SED AGNs provide a

complementary AGN sample to the X-ray AGNs in our sample (see Section 4.4.1). In addition, all three type-1 SED AGNs (AS2COS0019.1, AS2COS0175.1, and AS2COS0230.1) are detected in X-ray, which is consistent with the unobscured nature of those systems. We emphasize that this method strongly depends on the quality of the multi-wavelength photometry and model assumptions. In particular, at high redshift ($z \geq 3$) or in optical(/near-infrared)-dark systems, the indicators of AGNs are sometimes limited to a slight excess at observed-frame 24- μm flux density or relatively flat SED at observed-frame 100–1000 μm , which are difficult to distinguish from the PAH emission from the host-galaxy dust or hot dust emission associated with a starburst. In our SED AGN sample, the evidence for AGNs in AS2COS0025.1, AS2COS0084.1, AS2COS0099.1, AS2COS0108.2, and AS2COS0330.3 appear to be fairly limited, and we should be careful of these sources. For sources other than the SED AGNs, we estimate the 99.73 per cent (3σ) upper bound of the bolometric AGN luminosity by integrating the marginalized PDFs with a uniform prior. Except for the SED AGNs, the physical properties of the galaxies are calculated without the AGN component.

4.3.1.4 SED Modeling Check

For a consistency check, we compare some observational properties with the physical properties derived by the SED modeling that they are expected to most strongly correlate with. Figure C.5 in Appendix C.4 presents these comparisons. We confirm a strong correlation between dust mass and 870- μm flux density as reported in Dudzevičiūtė et al. (2020). Additionally, we confirm that the 5.8 μm flux density, which corresponds to the rest-frame H-band flux density at the median redshift of $z = 2.47$, shows a positive correlation with the stellar mass. Moreover, the photometric redshifts derived by CIGALE are reasonably correlated with the spectroscopic redshifts; the median difference and the standard deviation are $\Delta z/(1+z) = (z_{\text{photo}} - z_{\text{spec}})/z_{\text{spec}} = -0.04 \pm 0.19$. Note that the photometric redshifts derived by CIGALE are also reasonably aligned with those derived by EAZY and LEPHARE, which is listed in the COSMOS2020 catalog; the median differences and the standard deviations are $\Delta z/(1+z) = (z_{\text{EAZY/LEPHARE}} - z_{\text{CIGALE}})/z_{\text{CIGALE}} = 0.14 \pm 0.62$ for EAZY and 0.09 ± 0.41 for LEPHARE, respectively. Determining the physical properties of galaxies with SED analysis are sometimes challenging or unreliable, particularly for a type-1 SED AGN where the AGN emission can mask the host-galaxy emission. To address this issue, we perform a mock analysis, which is a procedure provided by CIGALE (see Section 4.3 in Boquien et al. 2019), for all

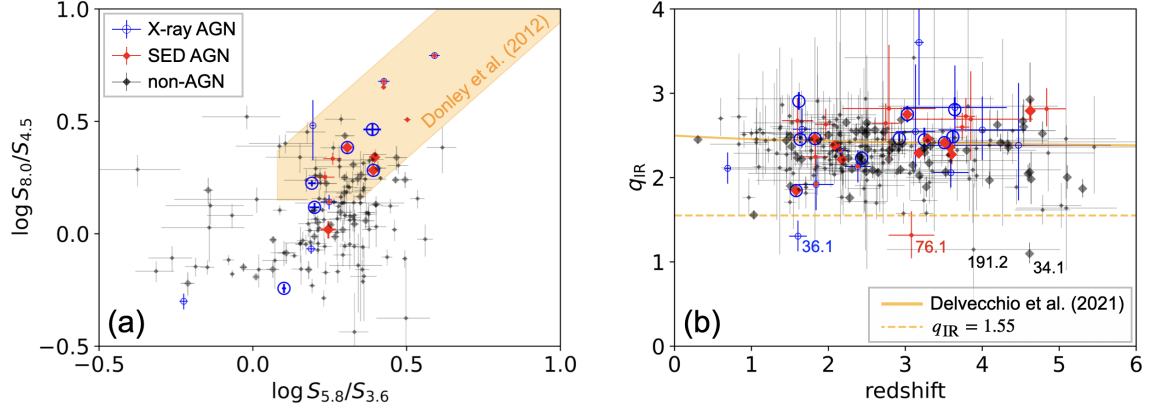


Figure 4.5: (a) Mid-infrared color-color diagram of the AS2COSMOS sources. The shaded area shows the AGN selection criteria by Donley et al. (2012). Note that only the sources that are detected in all the mid-infrared bands (Spitzer 3.6 μm , 4.5 μm , 5.8 μm , and 8.0 μm) are plotted in this figure. Moreover, the sample is limited to $z < 3$, where the selection criteria by Donley et al. (2012) are applicable. We confirm that most of the SED AGNs meet the AGN criteria by Donley et al. (2012). (b) Distribution of q_{IR} as a function of redshift. The solid line illustrates the empirical relation of star-formation galaxies at $M_* = 10^{11} M_{\odot}$ (Delvecchio et al., 2021), while the dashed line indicates $q_{\text{IR}} = 1.55$, which is used as the threshold of radio-excess AGNs in Algera et al. (2020). The large symbols show the spec- z sample, while the smaller ones show the photo- z sample. We confirm that most of the AS2COSMOS sources follow the empirical relation of star-forming galaxies, while two AGNs and two non-AGNs show radio-loud characteristics.

the AS2COSMOS sources (Appendix C.5). The median differences and the standard deviations are $\Delta \log \text{SFR} = \log \text{SFR}(\text{mock}) - \log \text{SFR} = -0.01 \pm 0.19$ and $\Delta \log M_* = \log M_*(\text{mock}) - \log M_* = 0.02 \pm 0.19$, respectively.

To validate our AGN selection, we compare the properties of our sources to the conventional AGN selection using a color-color diagram in the mid-infrared bands. Figure 4.5 (a) displays the mid-infrared color-color diagram of the AS2COSMOS sources. The orange area denotes the AGN criteria by Donley et al. (2012). Note that only the sources detected in all the mid-infrared bands (Spitzer 3.6 μm , 4.5 μm , 5.8 μm , and 8.0 μm) are plotted in this figure. We also limit the sample to $z < 3$ because the stellar emission can produce a similar shape as the AGN emission at high redshift (Donley et al., 2012). We confirm that 9/11 of the SED AGNs are located in the AGN region, while two SED AGNs (AS2COS0025.1 and AS2COS0230.1) are not. AS2COS0025.1 shows a possible excess in the Spitzer 24- μm band, which appears to drive the AGN classification. AS2COS0230.1 has a flat rest-frame optical SED, which may favor the presence of an AGN.

A significant fraction of galaxies in the AGN region (40/49) are not classified as hosting AGNs by the BIC selection. 24 out of these 40 AGN-unclassified galaxies in the AGN region have relatively high redshifts ($z \gtrsim 2.4$), which may make it difficult to distinguish AGN-host galaxies from DSFGs in the mid-infrared color-color diagram (Stach et al., 2019). The CIGALE fits for the other 13 sources with lower redshift ($1.0 \lesssim z \lesssim 2.0$) are suggested to have strong $3.3 \mu\text{m}$ PAH emission, which may caused the misidentification in the mid-infrared color-color diagram. However, we need to consider the possibility that the near-infrared AGN emission is misidentified as the $3.3 \mu\text{m}$ PAH emission in the SED fitting. The remaining three sources lie near the edge of the selection criteria. In summary, we conclude that the AGN selection by BIC provides a more conservative sample of SED AGNs than the conventional selection using the mid-infrared color-color diagram at $z < 3$.

We also check the radio loudness of the SMGs. Figure 4.5 (b) plots the radio-IR correlation factors as a function of the redshifts. The solid and dashed lines denote the empirical relation of star-formation galaxies at $z = 0\text{--}4$ (Delvecchio et al., 2021) and a criterion for radio-excess AGNs ($q_{\text{IR}} \leq 1.55$; Algera et al. 2020), respectively. We confirm that our sample mostly aligns with the empirical relation of star-forming galaxies. One X-ray-detected AS2COSMOS source and an X-ray undetected SED AGN have especially low radio-IR correlation factors ($q_{\text{IR}} = 1.3 \pm 0.2$ and 1.3 ± 0.3 for AS2COS0036.1 and AS2COS0076.1, respectively), suggesting that these sources are radio-excess AGNs. Two galaxies that are not detected in X-ray nor identified as SED AGNs also have low radio-IR correlation factors ($q_{\text{IR}} = 1.1 \pm 0.2$ and $1.1^{+0.8}_{-0.7}$ for AS2COS0034.1 and AS2COS0191.2, respectively). This might suggest that they are candidates for radio-excess AGNs. These sources are located at high redshift, which may make it difficult to identify AGNs by SED modeling. In total, the AS2COSMOS sample contains 4/258 ($1.5^{+1.2}_{-0.7}$ per cent) radio-excess sources. This fraction is consistent with the previous studies of the AS2UDS sample ($12/659$; 1.8 ± 0.5 per cent; Algera et al. 2020).

The 18 brightest and not strongly lensed AS2COSMOS sources ($S_{870 \mu\text{m}} = 12.4\text{--}19.2$) were also analyzed in Liao et al. (2024). They performed X-ray to radio SED modeling with CIGALE, and found that the luminosity fractions of AGNs in the total infrared luminosities (f_{AGN}) are always lower than $\sim 10\%$ in their sample. However, in our study, some of these sources have moderately high AGN luminosity fraction ($f_{\text{AGN}} = 0.56 \pm 0.13$, 0.38 ± 0.05 , 0.55 ± 0.13 , and 0.49 ± 0.03 for AS2COS0001.1, AS2COS0008.1, AS2COS0054.1, and AS2COS0139.1, respectively), indicating significant contributions of AGNs in those systems. These inconsistencies can be attributed

to the different parameter settings used for CIGALE. In particular, since the radio photometry of some of the AS2COSMOS sources has a high signal-to-noise ratio, the radio loudness parameter can sometimes behave as the normalization for the AGN component. In Liao et al. (2024), the radio loudness parameter was sampled at one dex intervals in the fitting. Thus, f_{AGN} might not be estimated with an accuracy of less than one dex, which might cause potential trouble in the identification of AGNs. In addition, care needs to be taken about the possible degeneracies between the parameters in SED modules. For example, the host-galaxy dust emission module have a potential degeneracy with the AGN module. Thus, if we limit parameter range of the host-galaxy dust emission module, the contribution of the AGN module can be overestimated. Currently, we are not able to calculate all the possible parameter grids and test the degeneracies between the SED modules due to the computational cost. Future studies on the SED modules themselves are needed to solve this problem.

4.3.1.5 Selection Bias of SED AGNs

Detection of type-2 AGNs using SED modeling mostly occurs due to the dominance of AGN emission in the infrared bands. Consequently, it is more difficult to identify an AGN in a strongly star-forming galaxy because the host-galaxy emission will mask the emission from the AGN (see also Andonie et al. 2022). This selection can be characterized by the AGN luminosity fraction in the total infrared luminosity (f_{AGN}). In our sample, the type-2 SED AGNs have f_{AGN} larger than ~ 0.3 , which is considered to be the detection limit of the SED AGNs in our study. Assuming a typical SED of a type-2 AGN and the tight SFR- L_{IR} correlation, this detection limit can be expressed as follows:

$$\begin{aligned} \text{SFR} [M_{\odot} \text{ yr}^{-1}] &\gtrsim \frac{1 - f_{\text{AGN}}}{f_{\text{AGN}}} \times \kappa_{\text{IR}}^{-1} \times L_{\text{AGN, bol}} [\text{erg s}^{-1}] \\ &\times \kappa'_{\text{IR}} \\ &= 4.2 \times 10^{-44} \times L_{\text{AGN, bol}} [\text{erg s}^{-1}] \end{aligned} \quad (4.2)$$

where κ_{IR} is the infrared to bolometric correction factor of an AGN, and κ'_{IR}^{-1} is the conversion factor of infrared luminosity to SFR. Here we assume $\kappa_{\text{IR}} = 1.6$, which is calculated by the SKIRTOR model with $\tau_{9.7} = 7$, $p = 1$, $q = 1$, $\Delta = 40^\circ$, $R = 20$, $\theta = 70^\circ$, $E(B - V) = 0.1$, and $T_{\text{pol}} = 100 \text{ K}$. For κ'_{IR} , we employ the calibration by Kennicutt (1998b), where a factor of 0.63 is applied to convert Salpeter IMF to Chabrier IMF. Note that this detection limit is not as applicable to type-1 AGNs,

because type-1 AGNs can also be selected by their flat UV to optical spectra. Moreover, the detection of AGNs by SED modeling is expected to have a potential bias against high-redshift ($z > 3$) AGNs unless 24- μm flux densities are available, since the hot dust emission from an AGN is redshifted out of the mid-infrared bands (3.6–8.0 μm) and can only be identified by the 24- μm flux density.

4.3.2 X-ray Analysis

4.3.2.1 X-ray Spectral Analysis for X-ray-detected Sources

We perform an X-ray spectral analysis of the X-ray-detected AS2COSMOS sources. To appropriately treat the low-count statistics, we use the C statistic (Cash, 1979). We first construct a background model utilizing the combined background spectrum. We employ an analytical model referring to Suzuki et al. (2021), but including a simplification to avoid unreasonable fits. The background model used in this study is expressed as follows in the XSPEC terminology (Arnaud, 1996):

$$\begin{aligned}
 \text{model_back} &= \text{gaussian} + \text{gaussian} + \text{gaussian} \\
 &+ \text{gaussian} + \text{gaussian} + \text{gaussian} \\
 &+ \text{gaussian} + \text{gaussian} + \text{gaussian} \\
 &+ \text{gaussian} \\
 &+ \text{powerlaw} + \text{gabs} * \text{expdec}
 \end{aligned} \tag{4.3}$$

The nine Gaussian lines represent the fluorescence lines from the instrument: Al $K\alpha$ (1.487 keV), Al $K\beta$ (1.557 keV), Ni $K\alpha$ (7.478 keV), Ni $K\beta$ (8.265 keV), Au $M\alpha$ (2.123 keV), Au $M\beta$ (2.205 keV), Au $M\gamma$ (2.410 keV), Au $L\alpha_1$ (9.713 keV), and Au $L\alpha_2$ (9.628 keV). The widths of these lines are fixed at 1 eV. The remaining Gaussian line corresponds to the broad line component at 2.7 keV produced by the inappropriate correction of charge transfer inefficiency. The continuum background spectrum is approximated by a power-law and an exponential decay with Gaussian-profile absorption. We note that this model is not multiplied by the ancillary response file, assuming that the background spectrum is dominated by particle-induced events. We confirm that this model adequately reproduces the combined background spectrum (C-statistic = 826 for 634 degrees of freedom). The best-fit parameters are summarized in Table C.3 in Appendix C.6. In the later sections, we fix the parameters except for the normalizations of additive components, which are left as free parameters to treat the slight differences among the observations.

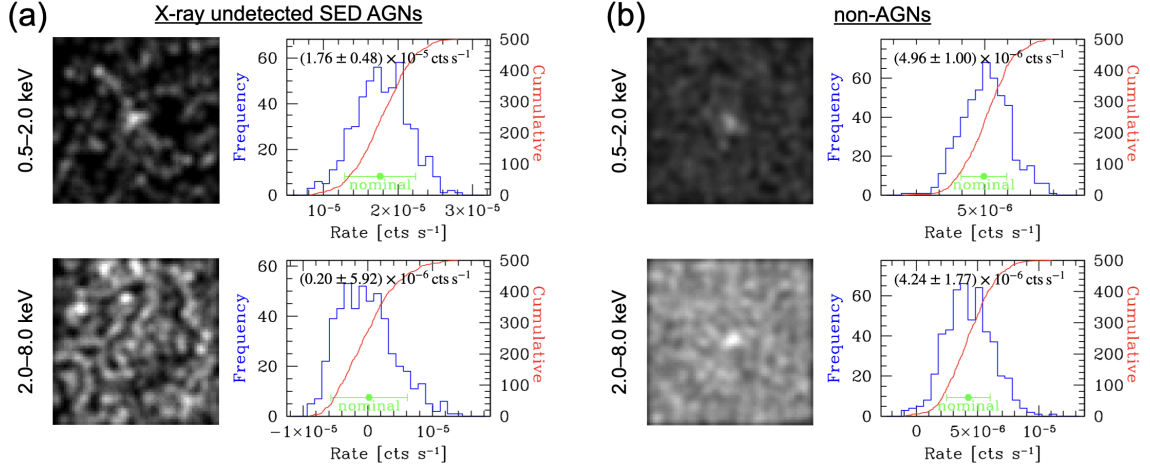


Figure 4.6: Results of X-ray stacking analysis for (a) the X-ray undetected SED AGNs and (b) the other X-ray undetected AS2COSMOS sources. The left panels show the stacked X-ray images, while the right panels show the bootstrap histograms of the net count rates. The mean count rates and the confidence intervals are shown in green and also reported in the histograms. Both samples are detected in the soft band (0.5–2.0 keV) over 3σ .

Adopting this approach, we simultaneously fit the source and the background spectra. Here, we assume that the source X-ray spectra are dominated by AGN emission. The X-ray spectrum of an AGN is approximated to three components: (1) a direct component from the nucleus, (2) reflection components from the torus and/or the accretion disk, and (3) a scattered component with emission from the photoionized plasma. The photoionized emission is usually much fainter than the direct or the reflection components at rest-frame energies above 2.0 keV. Thus, we do not consider this component in the spectral analysis. The reflection from an accretion disk is also excluded because its contribution to the X-ray spectrum is still under debate (Ogawa et al., 2021, 2019). The combined spectrum is expressed as follows in the XSPEC terminology:

$$\begin{aligned}
 \text{model_source} &= \text{phabs} * (\text{zphabs} * \text{cabs} * \text{zcutoffpl} \\
 &+ \text{const} * \text{zcutoffpl} \\
 &+ \text{atable}\{\text{xclumpy_v01_RC.fits}\} \\
 &+ \text{atable}\{\text{xclumpy_v01_RL.fits}\})
 \end{aligned} \tag{4.4}$$

The first factor represents the galactic absorption, which is calculated following the method of Willingale et al. (2013). The first term in the parenthesis represents the direct component. The second term corresponds to the unabsorbed scattered component. The third and fourth terms are the reflection component from the torus. In this study, we employ the XCLUMPY model, which reproduces the X-ray reflection

from a clumpy torus (Tanimoto et al., 2019). The photon index, cutoff energy, and normalization of the reflection and scattered components are linked to those of the direct component. The line-of-sight hydrogen column density ($N_{\text{H,X}}^{\text{LOS}}$) of the direct component is set to be consistent with the torus geometry (see Equation 3 in Tanimoto et al. 2019). Redshifts are fixed at the spectroscopic ones or the Bayesian estimated values derived by the SED modeling. Because of the modest data quality, scattered fraction, photon index, and cutoff energy are fixed at 0.01, 1.9 and 370 keV, respectively. Note that the photon index is confirmed to be unconstrained except for AS2COS0019.1, where AS2COS0019.1 has fits in which a photon index of 1.9 lies within the 90 per cent confidence interval. Moreover, the torus angular width (σ) and the equatorial hydrogen column density ($N_{\text{H,X}}^{\text{Equ}}$) are fixed at 20 degrees and 10^{25} cm^{-2} , respectively. Finally, the free parameters in the X-ray spectral fitting are the inclination angle (i ; 18–87 degrees), which is linked to the line-of-sight hydrogen column density, and the normalization of the direct component.

With this approach, we successfully reproduce the X-ray spectra of the 23 X-ray-detected sources with an AGN model (C-statistic < 1140 for 1285 degrees of freedom). The X-ray spectra and the plots of the goodness of fit as a function of the line-of-sight hydrogen column densities are summarized in Appendix C.7. We confirm that all the sources have solutions in the Compton-thin regime ($N_{\text{H,X}}^{\text{LOS}} < 10^{24.2} \text{ cm}^{-2}$), with 12/23 sources showing significant absorption ($N_{\text{H,X}}^{\text{LOS}} > 10^{22} \text{ cm}^{-2}$). Note that seven SED AGNs are detected in X-rays, from which three are classified as type-1 and four are classified as type-2 from the SED analysis. All the X-ray-detected type-2 SED AGNs show significant absorption ($N_{\text{H,X}}^{\text{LOS}} > 10^{22} \text{ cm}^{-2}$), and two of the X-ray-detected type-1 SED AGNs do not. This shows the consistency of the X-ray analysis and the SED analysis of these sources. However, AS2COS0019.1 shows significant absorption in X-rays ($\log N_{\text{H,X}}^{\text{LOS}}/\text{cm}^{-2} = 22.4_{-0.2}^{+0.1}$), while it is classified as a type-1 SED AGN. This might be attributed to the time variability of the AGN or the uncertainties associated with the model assumptions. AS2COS0036.1, AS2COS0055.2, AS2COS0066.1, AS2COS0076.2, AS2COS0095.2, AS2COS0153.2, AS2COS0220.1, and AS2COS0275.2 present alternative solutions in the Compton-thick regime which are not distinguishable from the Compton-thin solutions at a 90 per cent confidence level. In later sections, we investigate these solutions separately to consider both possibilities. For the Compton-thick case, we calculate the X-ray luminosities by fixing the line-of-sight hydrogen column density* to $N_{\text{H,X}}^{\text{LOS}} = 9.8 \times 10^{24} \text{ cm}^{-2}$. The X-ray luminosities are calculated by correcting the line-of-

*This is the hard limit of the XCLUMPY model (v1).

sight absorption and the reflection from the torus. The median X-ray luminosity is estimated as $L_{2-10\text{ keV}} = 2.6 \times 10^{44} \text{ erg s}^{-1} \text{ cm}^{-2}$ for the Compton-thin cases, while $L_{2-10\text{ keV}} = 3.1 \times 10^{45} \text{ erg s}^{-1} \text{ cm}^{-2}$ for the Compton-thick cases. Note that the X-ray spectral analysis of the sources in the COSMOS field is also performed by Laloux et al. (2023). We confirm that our estimations of the line-of-sight hydrogen column densities and the X-ray luminosities are almost consistent with those in Laloux et al. (2023) within the errors.

4.3.2.2 Upper Bound Estimation for X-ray Undetected Sources

For X-ray undetected SED AGNs (Section 4.3.1), we convert the 3σ upper bound count rates to the intrinsic X-ray luminosities by assuming a typical AGN spectrum. We employ the same model as in Section 4.3.2.1, but the inclination angle is fixed to either $i = 47$ degrees ($N_{\text{H,X}}^{\text{LOS}} = 10^{23} \text{ cm}^{-2}$) or $i = 60$ degrees ($N_{\text{H,X}}^{\text{LOS}} = 10^{24} \text{ cm}^{-2}$) assuming Compton-thin absorptions. We also calculate the Compton-thick case by fixing the inclination angle to $i = 87$ degrees ($N_{\text{H,X}}^{\text{LOS}} = 9.8 \times 10^{24} \text{ cm}^{-2}$). Note that all the type-1 SED AGNs are detected with X-rays, so the X-ray upper bounds are only calculated for type-2 AGNs. The X-ray luminosities are calculated by correcting the line-of-sight absorption and the reflection from the torus. The median X-ray luminosity upper bound is estimated as $L_{2-10\text{ keV}} = 1.5 \times 10^{44} \text{ erg s}^{-1} \text{ cm}^{-2}$ for $N_{\text{H,X}}^{\text{LOS}} = 10^{23} \text{ cm}^{-2}$, $L_{2-10\text{ keV}} = 6.5 \times 10^{44} \text{ erg s}^{-1} \text{ cm}^{-2}$ for $N_{\text{H,X}}^{\text{LOS}} = 10^{24} \text{ cm}^{-2}$, and $L_{2-10\text{ keV}} = 4.7 \times 10^{45} \text{ erg s}^{-1} \text{ cm}^{-2}$ for $N_{\text{H,X}}^{\text{LOS}} = 10^{25} \text{ cm}^{-2}$.

4.3.2.3 Stacking Analysis of X-ray Undetected Sources

We conduct an X-ray stacking analysis for the X-ray undetected AS2COSMOS sources, using CSTACK v4.5 (Miyaji et al., 2008) with default settings for the maximum off-axis angle, the source region radius, and the exclusion of obvious X-ray sources. We separately stack the 17 X-ray undetected SED AGNs and the 220 AS2COSMOS sources that are neither detected in X-rays nor identified as SED AGNs (non-AGNs). Figure 4.6 shows the results. Both samples are detected over 3σ in the soft band (0.5–2.0 keV), but not in the hard band (2.0–8.0 keV). The mean count rate of the X-ray undetected SED AGN sample is about three times higher than that of the non-AGN sample. This might show the weak X-ray emission from the X-ray undetected SED AGNs. However, given that the median far-infrared luminosity of the X-ray undetected SED AGN sample is also about three times

higher than that of the non-AGN sample, the difference does not necessarily trace the X-ray emission associated with the AGN activity. Moreover, the non-AGN sample is marginally detected in the 2.0–8.0 keV band (2.4σ), although the significance is not high. The inferred spectral shape is quite hard (photon index of ~ 1), implying a significant absorption of these sources ($N_{\text{H,X}}^{\text{LOS}} \sim 7 \times 10^{22} \text{ cm}^{-2}$ for the AGN model in Section 4.3.2.1 at the median redshift of $z = 2.45$). This provides marginal evidence for the existence of obscured AGNs in the non-AGN sample.

Utilizing the integrated count rate derived from our stacking analysis, we calculate the typical X-ray luminosity of the X-ray undetected SED AGN sample. Here, we assume the same X-ray spectral model as in Section 4.3.2.2 placed at the median redshift of the X-ray undetected SED AGN sample ($z = 3.18$). Since all these AGNs are classified as type-2 (see Section 4.3.1.1), we set the inclination angle at either $i = 47$ degrees ($N_{\text{H,X}}^{\text{LOS}} = 10^{23} \text{ cm}^{-2}$) or $i = 60$ degrees ($N_{\text{H,X}}^{\text{LOS}} = 10^{24} \text{ cm}^{-2}$) assuming Compton-thin absorption. However, considering that the stacked X-ray undetected SED AGN sample is detected only in the soft band, we explore an unobscured AGN scenario by setting the inclination angle to $i = 15$ degrees ($N_{\text{H,X}}^{\text{LOS}} = 10^{20} \text{ cm}^{-2}$). In addition, we examine a Compton-thick scenario by fixing the inclination angle to $i = 87$ degrees ($N_{\text{H,X}}^{\text{LOS}} = 9.8 \times 10^{24} \text{ cm}^{-2}$). With this recipe, we estimate the stacked X-ray luminosity of the X-ray undetected SED AGNs as $L_{2-10\text{keV}} = (1.5 \pm 0.4) \times 10^{43} \text{ erg s}^{-1}$ for $N_{\text{H,X}}^{\text{LOS}} = 10^{20} \text{ cm}^{-2}$, $L_{2-10\text{keV}} = (2.4 \pm 0.7) \times 10^{43} \text{ erg s}^{-1}$ for $N_{\text{H,X}}^{\text{LOS}} = 10^{23} \text{ cm}^{-2}$, $L_{2-10\text{keV}} = (2.4 \pm 0.6) \times 10^{44} \text{ erg s}^{-1}$ for $N_{\text{H,X}}^{\text{LOS}} = 10^{24} \text{ cm}^{-2}$, and $L_{2-10\text{keV}} = (1.1 \pm 0.3) \times 10^{45} \text{ erg s}^{-1}$ for $N_{\text{H,X}}^{\text{LOS}} = 9.8 \times 10^{24} \text{ cm}^{-2}$, respectively. Moreover, we evaluate the X-ray luminosity due to star-formation activity from the integrated count rate of the non-AGN sample. In this calculation, we employ a power-law spectrum with a photon index of 2.1 (Sazonov & Khabibullin, 2017) placed at the median redshift of $z = 2.45$. The stacked X-ray luminosity of the non-AGNs is estimated as $L_{2-10\text{keV}} = (2.3 \pm 0.5) \times 10^{42} \text{ erg s}^{-1}$.

4.3.3 Morphological Study

Utilizing high-resolution imaging with JWST, we investigate the visual morphology of the 105/258* AS2COSMOS sources in the coverage of NIRCcam imaging (see also McKinney et al. 2024 for a similar morphological study in COSMOS). We follow the same approach as the previous study of bright SMGs in the PRIMER

*The strongly lensed system (AS2COS0005.1 and AS2COS0005.2) is excluded.

Table 4.1: Physical properties of X-ray AGNs and SED AGNs in AS2COSMOS SMG sample. (1), (2)&(3) ALMA source ID and positions (same as Simpson et al. 2020); (4) redshift (three decimal digits are for spectroscopic redshifts and two are for photometric redshifts); (5) stellar mass; (6) star-formation rate; (7) luminosity fraction of AGN in total infrared luminosity (f_{AGN}); (8) change in BIC by the addition of an AGN component in the SED modeling; (9) bolometric AGN luminosity estimated by SED modeling (the uncertainties listed in this table are converted from those calculated in the linear space); (10) line-of-sight hydrogen column density (parameters that reach the model limits are indicated by “lim”); (11) X-ray luminosity (the values in the parenthesis show the X-ray luminosities assuming Compton-thick absorption; $N_{\text{H,X}}^{\text{LOS}} = 9.8 \times 10^{24} \text{ cm}^{-2}$). The redshift uncertainties are not considered for the calculation of $L_{\text{AGN,bol}}^{\text{SED}}$, $N_{\text{H,X}}^{\text{LOS}}$, and $L_{2-10\text{keV}}$. The upper bounds correspond to the 99.73 per cent confidence (3σ). Note that the reduced χ^2 values of these AGNs are lower than 5 (well fitted).

ID	R.A. [degrees]	Dec. [degrees]	z	$\text{Log}_{10} M_*$ [$M_{\odot}$]	$\text{Log}_{10} \text{SFR}$ [$M_{\odot} \text{ yr}^{-1}$]	f_{AGN}	ΔBIC	$\text{Log}_{10} L_{\text{AGN,bol}}^{\text{SED}}$ [ergs s^{-1}]	$\text{Log}_{10} N_{\text{H,X}}^{\text{LOS}}$ [cm^{-2}]	$\text{Log}_{10} L_{2-10\text{keV}}$ [ergs s^{-1}]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Only X-ray AGN										
AS2COS0014.1	150.42100	2.06802	2.921	11.50 ± 0.13	2.89 ± 0.05	...	-3.6	<46.37	$23.4^{+0.3}_{-0.4}$	$44.06^{+0.25}_{-0.26}$
AS2COS0031.1	149.84586	2.86042	3.643	11.24 ± 0.12	3.20 ± 0.05	...	-3.0	<46.24	$22.9^{+0.5}_{\text{lim}}$	$44.21^{+0.22}_{-0.23}$
AS2COS0036.1	150.10616	2.01437	1.61 ± 0.11	11.69 ± 0.07	2.43 ± 0.24	...	-0.7	<46.39	$22.5^{+0.3}_{-0.4}$	$43.63^{+0.14}_{-0.14}$
AS2COS0055.2	150.32147	1.71421	0.69 ± 0.03	11.16 ± 0.05	0.54 ± 0.31	...	-12.2	<44.45	$21.9^{+0.2}_{-0.4}$	$42.95^{+0.10}_{-0.10}$
AS2COS0066.1	149.94410	1.95418	3.247	11.07 ± 0.15	2.84 ± 0.08	...	-10.6	<46.08	$22.8^{+0.5}_{\text{lim}}$	$43.87^{+0.25}_{-0.26}$
AS2COS0068.1	150.14291	2.05061	2.433	11.39 ± 0.02	2.51 ± 0.03	...	-1.1	<46.37	$23.5^{+0.1}_{-0.2}$	$44.61^{+0.14}_{-0.13}$
AS2COS0069.1	149.77102	2.36576	3.618	10.28 ± 0.05	3.27 ± 0.02	...	-2.0	<46.40	$23.8^{+0.3}_{-0.4}$	$44.54^{+0.30}_{-0.37}$
AS2COS0076.2	150.38353	2.07446	4.47 ± 1.20	10.30 ± 0.37	3.26 ± 0.37	...	-4.1	<45.42	$23.8^{+0.4}_{-0.4}$	$44.74^{+0.37}_{-0.32}$
AS2COS0095.2	150.12596	2.69636	1.66 ± 0.12	11.37 ± 0.07	2.12 ± 0.20	...	-6.2	<46.30	$22.2^{+0.2}_{-0.3}$	$43.69^{+0.11}_{-0.11}$
AS2COS0133.1	149.99979	2.10924	3.59 ± 0.23	10.46 ± 0.31	3.07 ± 0.16	...	6.1	<45.72	$23.7^{+0.2}_{-0.2}$	$44.65^{+0.19}_{-0.20}$
AS2COS0153.2	149.88157	2.31819	1.616	10.84 ± 0.18	2.77 ± 0.08	...	-5.1	<45.96	$22.4^{+0.3}_{-0.4}$	$43.74^{+0.11}_{-0.11}$
AS2COS0220.1	150.00780	1.68614	4.00 ± 0.57	10.94 ± 0.18	3.03 ± 0.18	...	-12.4	<46.34	$23.8^{+0.3}_{-0.3}$	$44.70^{+0.27}_{-0.25}$
AS2COS0246.2	150.50454	2.72503	3.18 ± 0.06	10.35 ± 0.04	2.66 ± 0.03	...	3.2	<45.77	$22.7^{+0.4}_{\text{lim}}$	$44.28^{+0.13}_{-0.13}$
AS2COS0272.1	150.31664	1.60374	3.65 ± 0.67	11.29 ± 0.21	3.22 ± 0.23	...	-9.0	<48.01	$22.8^{+0.4}_{\text{lim}}$	$44.42^{+0.17}_{-0.17}$
AS2COS0275.2	149.95169	1.74405	1.632	10.85 ± 0.12	2.92 ± 0.04	...	-1.3	<46.25	$22.6^{+0.3}_{-0.7}$	$43.43^{+0.19}_{-0.20}$
AS2COS0353.1	149.51390	2.04452	3.13 ± 0.26	9.54 ± 0.20	2.45 ± 0.14	...	-8.3	<46.41	$23.9^{+0.3}_{-0.3}$	$44.51^{+0.32}_{-0.35}$

Table 4.1: (continued)

ID	R.A. [degrees]	Dec. [degrees]	z	$\text{Log}_{10} M_*$ [$M_\odot$]	$\text{Log}_{10} \text{SFR}$ [$M_\odot \text{ yr}^{-1}$]	f_{AGN}	ΔBIC	$\text{Log}_{10} L_{\text{AGN, bol}}^{\text{SED}}$ [ergs s $^{-1}$]	$\text{Log}_{10} N_{\text{H, X}}^{\text{LOS}}$ [cm $^{-2}$]	$\text{Log}_{10} L_{2-10 \text{ keV}}$ [ergs s $^{-1}$]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
X-ray AGN $\cap$ SED AGN										
AS2COS0019.1	150.15840	2.13955	1.825	10.37 ± 0.28	3.15 ± 0.08	0.22 ± 0.04	74.9	45.99 ± 0.04	$22.4^{+0.1}_{-0.2}$	$44.42^{+0.05}_{-0.05}$
AS2COS0028.2	149.99795	2.57821	2.15 ± 0.10	10.14 ± 0.25	2.87 ± 0.29	0.29 ± 0.17	19.0	46.42 ± 0.03	$23.9^{+0.2}_{-0.2}$	$44.48^{+0.25}_{-0.25}$
AS2COS0048.1	150.28853	2.38193	1.581	11.62 ± 0.06	1.91 ± 0.06	0.57 ± 0.05	11.0	46.25 ± 0.08	$22.6^{+0.2}_{-0.2}$	$43.76^{+0.10}_{-0.10}$
AS2COS0116.2	150.49037	1.74637	2.38 ± 0.17	10.85 ± 0.23	2.49 ± 0.14	0.61 ± 0.04	100.3	46.75 ± 0.05	$23.5^{+0.1}_{-0.1}$	$44.73^{+0.11}_{-0.11}$
AS2COS0175.1	150.73578	2.19958	3.509	12.40 ± 0.84	1.78 ± 1.34	0.30 ± 0.02	151.3	46.56 ± 0.02	$20.0^{+2.6}_{-0.6}$	$44.59^{+0.09}_{-0.09}$
AS2COS0230.1	149.61511	1.78955	1.84 ± 0.23	10.56 ± 0.30	2.71 ± 0.17	0.10 ± 0.01	14.8	45.22 ± 0.08	$22.2^{+0.6}_{-0.3}$	$43.72^{+0.15}_{-0.15}$
AS2COS0308.1	150.60879	2.76970	3.026	11.01 ± 0.06	3.22 ± 0.02	0.41 ± 0.04	33.3	46.77 ± 0.11	$22.6^{+0.3}_{-0.6}$	$44.93^{+0.06}_{-0.06}$
Only SED AGN										
AS2COS0001.1	150.03350	2.43675	4.625	10.33 ± 0.22	3.19 ± 0.12	0.56 ± 0.13	57.2	46.96 ± 0.16	...	<44.89
AS2COS0008.1	150.70497	2.54874	3.581	11.96 ± 0.07	2.27 ± 0.09	0.38 ± 0.05	15.8	46.38 ± 0.09	...	<44.93
AS2COS0024.1	150.13265	2.21184	2.176	11.25 ± 0.09	2.54 ± 0.14	0.55 ± 0.09	37.9	46.46 ± 0.07	...	<44.47
AS2COS0025.1	150.16352	2.37252	2.086	10.51 ± 0.12	2.70 ± 0.05	0.49 ± 0.03	13.3	46.42 ± 0.04	...	<44.41
AS2COS0054.1	149.69140	2.72481	3.176	10.86 ± 0.23	2.88 ± 0.15	0.55 ± 0.13	24.3	46.62 ± 0.08	...	<44.66
AS2COS0076.1	150.38388	2.07448	3.08 ± 0.30	10.04 ± 0.38	2.49 ± 0.17	0.65 ± 0.09	31.3	46.39 ± 0.03	...	<45.07
AS2COS0078.3	150.44575	2.41303	2.75 ± 0.18	10.93 ± 0.13	2.35 ± 0.16	0.46 ± 0.14	13.8	46.19 ± 0.10	...	<45.04
AS2COS0084.1	149.58108	2.25228	3.600	9.69 ± 0.12	2.64 ± 0.06	0.40 ± 0.08	21.6	46.08 ± 0.10	...	<44.90
AS2COS0099.1	149.92558	1.77732	1.60 ± 0.20	10.18 ± 0.88	2.04 ± 1.62	0.88 ± 0.04	27.2	46.89 ± 0.03	...	<44.30
AS2COS0108.2	150.09505	1.86019	3.85 ± 0.80	9.23 ± 0.23	2.16 ± 0.19	0.89 ± 0.03	14.9	46.71 ± 0.07	...	<44.81
AS2COS0123.1	149.59827	2.20781	4.84 ± 0.25	9.58 ± 0.14	2.53 ± 0.08	0.90 ± 0.02	16.4	47.03 ± 0.06	...	<45.00
AS2COS0139.1	149.58247	2.60280	3.292	10.43 ± 0.05	3.42 ± 0.02	0.49 ± 0.03	131.2	47.31 ± 0.03	...	<44.75
AS2COS0189.1	149.49363	2.28020	2.79 ± 0.61	9.78 ± 0.33	2.62 ± 0.28	0.35 ± 0.22	30.1	46.15 ± 0.73	...	<44.76
AS2COS0231.1	149.78372	2.81792	1.97 ± 0.14	11.21 ± 0.14	2.31 ± 0.14	0.69 ± 0.08	44.8	46.47 ± 0.07	...	<44.48
AS2COS0261.1	149.64308	1.91751	1.83 ± 0.16	10.93 ± 0.10	2.17 ± 0.11	0.63 ± 0.05	12.6	46.16 ± 0.06	...	<44.59
AS2COS0330.3	150.76551	1.73478	3.74 ± 0.09	10.34 ± 0.22	2.74 ± 0.15	0.70 ± 0.07	27.4	46.66 ± 0.06	...	<45.05
AS2COS0362.1	149.69350	1.72286	3.79 ± 0.12	10.81 ± 0.09	2.50 ± 0.12	0.69 ± 0.07	31.6	46.57 ± 0.03	...	<44.89

region by Gillman et al. (2024). We assess the presence of distorted morphology, asymmetric structures, or tidal features by the color-composite images of the F115W, F150W, F277W, and F444W bands. Additionally, we check for the presence of possible companions in the F444W images. We classify sources with strongly disturbed morphology, tidal features, or potential bright companions (within a factor of four brightness of the target galaxy) as “major” merger candidates. Sources with less disturbed morphology or fainter companions are classified as “minor” merger candidates. The color-composite images of the 105 AS2COSMOS sources in the coverage of NIRCam are summarized in Figure 4.2. We identify 62/105 ($59^{+5}_{-6}\%$) as potential merger candidates, from which 33/105 ($31 \pm 5\%$) are classified as major mergers. These fractions are broadly consistent with the previous work by Gillman et al. (2024). Note that we find six systems where both of the merging galaxies are included in the AS2COSMOS sample (AS2COS0036.1/36.2, AS2COS0048.1/48.3, AS2COS0076.1/76.2, AS2COS0143.2/143.2, AS2COS0228.1/228.2, and AS2COS0239.1/239.2). If these systems are counted once, the merging fractions are 56/99 ($57^{+5}_{-6}\%$) and 28/99 ($28 \pm 5\%$) for all merger candidates and major mergers, respectively. We stress that the possible companions are not spectroscopically confirmed and some of them may be foreground or background galaxies.

We also study the F770W-band morphology of the 38/258 AS2COSMOS sources in the coverage of both NIRCam and MIRI imaging (Figure C.1 in Appendix C.1), which is considered to better trace obscured AGN activity. We find that AS2COS0019.1 and AS2COS0048.1 have point-like morphology in the MIRI/F770W band. These sources are confirmed to host AGNs by SED analysis, and their mid-infrared emission are expected to be dominated by the AGN component. Thus, the point-like morphology in the MIRI/F770W band is consistent with AGN emission, as predicted by the SED analysis.

4.4 Results and Discussion

In this section, we discuss the physical properties of the X-ray-detected and SED AGN SMGs including a comparison of their far-infrared and X-ray luminosities, their SED-derived host galaxy properties, X-ray absorption and X-ray versus bolometric luminosities of the AGNs and their SFRs (Sections 4.4.1–4.4.5), before ending on a discussion of the population statistics of AGN in SMGs and their connection to dynamical interactions as indicated by JWST imaging. The sample of the X-ray

and SED AGNs are summarized in Table 4.1. The complete table of the host galaxy properties including infrared luminosity, dust luminosity, dust mass, dust temperature, and color excess of dust attenuation for stellar emission is provided in Appendix C.8. The SEDs and the best-fit models of the SED AGNs are summarized in Appendix C.7. We also show the X-ray spectra and the line-of-sight hydrogen column densities of the 23 X-ray-detected SMGs in Appendix C.7.

4.4.1 Comparison of Far-infrared Luminosity and X-ray Luminosity

Figure 4.7 compares the rest-frame far-infrared (40–120 μm) luminosities and the X-ray luminosities for the X-ray-detected AS2COSMOS sources. We also plot the empirical relation for local quasars (Elvis et al., 1994), AGN-classified SMGs, and starburst-classified SMGs (Alexander et al., 2005). We confirm that the X-ray-detected AS2COSMOS sources have more than one dex higher X-ray luminosities than those expected from their star-formation activity ($L_X = 10^{-4}L_{\text{FIR}}$). This suggests that the X-ray emission is dominated by AGNs, which verifies the assumption that the X-ray-detected AS2COSMOS sources host AGNs. Thus, we regard these sources as “X-ray AGNs” in the following sections. Note that the X-ray to far-infrared luminosity correlation in galaxies without AGNs has also been studied by a recent CXO study in the Great Observatories All-Sky LIRG survey (Torres-Albà et al., 2018). According to their relation, even galaxies with $L_{\text{FIR}} = 10^{46} \text{ erg s}^{-1}$ ($\sim 10^{12.4} L_{\odot}$) cannot be brighter than $L_X = 10^{42} \text{ erg s}^{-1}$. Thus, we may conservatively say that the X-ray emission in our X-ray AGN sample is dominated by the AGN activities. The X-ray AGN sample exhibits about a median of 6 times higher X-ray luminosities than the empirical relation of AGN-classified SMGs ($L_X = 0.004L_{\text{FIR}}$), assuming Compton-thin absorption. This can be attributed to the selection using the relatively shallow X-ray observations in the COSMOS field, as compared with the deeper CXO observations employed in Alexander et al. (2005).

Regarding the X-ray stacking analysis, we plot in Figure 4.7 the median far-infrared luminosities and the stacked X-ray luminosities for the X-ray undetected SED AGNs. We find that the stacked values are consistent with the empirical relation of AGN-classified SMGs assuming Compton-thin absorption. This implies that the X-ray undetected SED AGNs are probably the same population as the AGN-classified SMGs reported in the previous studies using deeper X-ray observations (Alexander

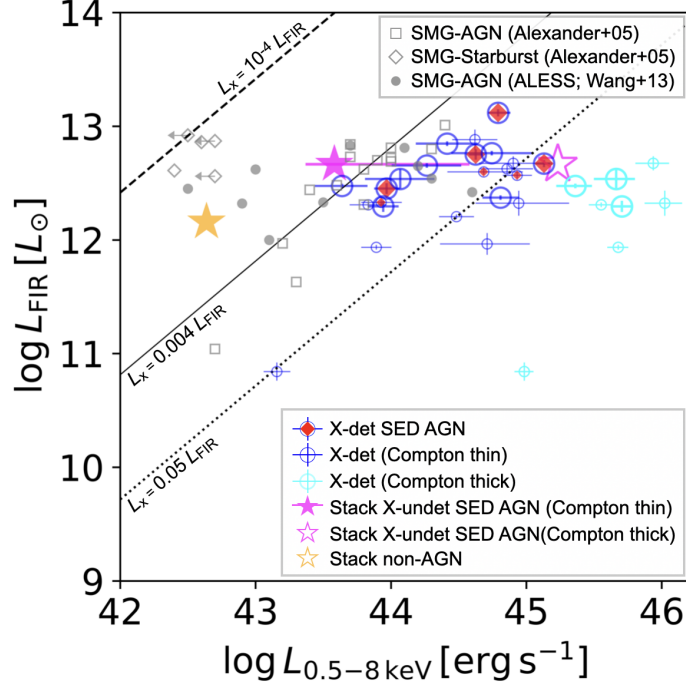


Figure 4.7: Comparison between far-infrared luminosity (rest-frame 40–120 μm) and X-ray (rest-frame 0.5–8 keV) luminosity for X-ray-detected (X-det) SMGs. For the AS2COSMOS sources, we apply a factor of 1/1.91 to convert total infrared luminosity to far-infrared luminosity (Magnelli et al., 2012). In addition, we convert the rest-frame 2–10 keV luminosity to rest-frame 0.5–8 keV luminosity assuming an intrinsic power-law spectrum with a photon index of 1.9. The stacked values of X-ray undetected (X-undet) SED AGNs and non-AGNs are also plotted. The solid and dashed lines show the empirical relations of AGN-classified SMGs and starburst-classified SMGs, respectively (Alexander et al., 2005). The dotted line shows the empirical relation of local quasars (Elvis et al., 1994). The large symbols show the spec- z sample, while the smaller ones show the photo- z sample. The redshift uncertainties are not considered in these plots. The X-ray-detected AS2COSMOS sources have more than one dex higher X-ray luminosities than those expected from the empirical relation of starburst-classified SMGs, suggesting that the X-ray emission is dominated by AGNs.

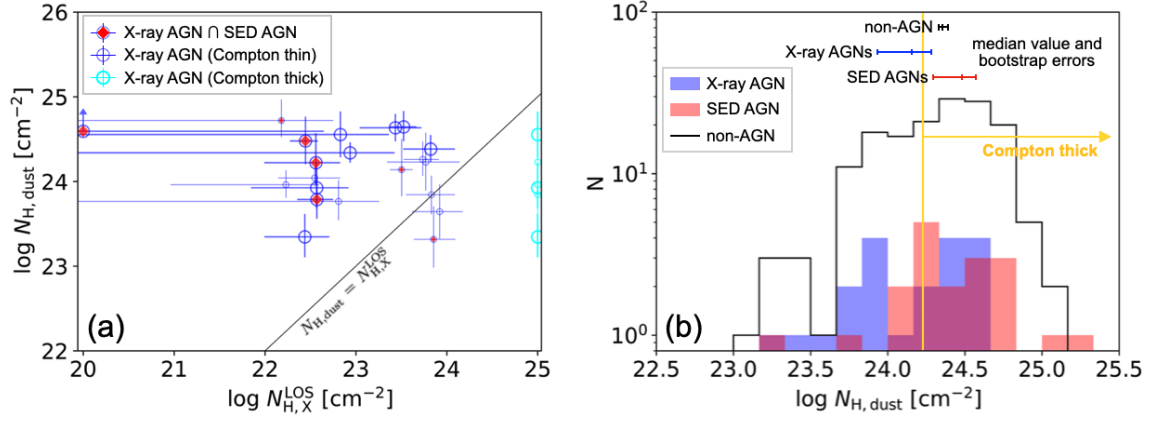


Figure 4.8: (a) Comparison of line-of-sight hydrogen column density measured by X-ray spectral analysis ($N_{H,X}^{\text{LOS}}$) with that estimated from the dust properties ($N_{H,\text{dust}}$). AS2COS0055.2 and AS2COS246.2 are not plotted in this panel because they are too faint to derive reliable sizes. The large symbols show the spec- z sample, while the smaller ones show the photo- z sample. (b) Histogram of the line-of-sight hydrogen column density calculated from the dust properties for the X-ray AGN, the SED AGNs, and the rest of the AS2COSMOS sources (non-AGNs). Only the sources whose sizes are well-constrained are included in these histograms. The vertical solid line shows the threshold of Compton-thick absorption ($N_H = 1.7 \times 10^{24} \text{ cm}^{-2}$). The redshift uncertainties are not considered when calculating the plotted values in these panels.

et al., 2005; Wang et al., 2013). On the other hand, if we consider the Compton-thick case, the stacked values align with the empirical relation of local quasars ($L_X = 0.05 L_{\text{FIR}}$). To distinguish between these two possibilities, deeper hard X-ray observations above rest-frame 10 keV are needed. Moreover, we plot the median far-infrared luminosities and the stacked X-ray luminosities of the non-AGNs. We find that the stacked X-ray luminosity is ~ 0.7 dex higher than that expected from their star-formation activity. This supports the prediction in Section 4.3.2.3 that there remain obscured AGNs that are not detected in X-ray nor identified as SED AGNs. Thus, we also calculate the upper bound of the AGN luminosity in the non-AGN sample from the integrated count rate derived from our stacking analysis, which is used in Section 4.4.5. Here we assume the same X-ray spectral model as in Section 4.3.2.2 placed at the median redshift of $z = 2.45$, and the line-of-sight hydrogen column density is fixed to $N_{H,X}^{\text{LOS}} \sim 10^{23.2} \text{ cm}^{-2}$ as predicted by the stacking analysis (Section 4.3.2.3).

4.4.2 X-ray Absorption by Host Galaxy Gas

If we make assumptions about the distribution of dust and gas-to-dust ratio, we can estimate the line-of-sight hydrogen column densities of the host-galaxy dust based on the dust masses and the sizes of the dust-emitting regions. We assume that the half mass of galaxy dust is uniformly distributed within a sphere with a half-light radius centered at the SMBH. The H_2 -to-dust mass ratio is fixed to 90 (Swinbank et al., 2014). Based on these assumptions across the whole sample, the median hydrogen column density in the molecular phase is estimated as $N_{\text{H,dust}}^{\text{mol}} = 8.7_{-0.3}^{+0.9} \times 10^{23} \text{ cm}^{-2}$, which is consistent with the previous study of the bright subsample of AS2UDS ($N_{\text{H,dust}}^{\text{mol}} = 9.8_{-0.7}^{+1.4} \times 10^{23} \text{ cm}^{-2}$; Simpson et al. 2017). Then, we convert the hydrogen column density in the molecular phase to total hydrogen column density by applying a factor of 2.5 following Andonie et al. (2024), which is based on theoretical models by Lagos et al. (2011) and Fu et al. (2012). Finally, we obtain the median hydrogen column density of $N_{\text{H,dust}} = 1.4_{-0.6}^{+0.5} \times 10^{24} \text{ cm}^{-2}$, $N_{\text{H,dust}} = 3.0_{-1.1}^{+0.7} \times 10^{24} \text{ cm}^{-2}$, and $N_{\text{H,dust}} = 2.2_{-0.1}^{+0.2} \times 10^{24} \text{ cm}^{-2}$ for the X-ray AGNs, SED AGNs, and the rest of the AS2COSMOS sources. These values are slightly higher than the previous report on the average ISM column density of 24 submillimeter-infrared quasars at $z \sim 1\text{--}3$ in the COSMOS field: $\langle N_{\text{H, ISM}} \rangle_{\text{submm-IRquasars}} = (0.8 \pm 0.1) \times 10^{24} \text{ cm}^{-2}$ (Andonie et al., 2024). Given the tight correlation between dust mass and 870- μm flux density (Dudzevičiūtė et al., 2020), this may be attributed the bright submillimeter selection of our sample.

Figure 4.8 (a) compares the line-of-sight hydrogen column density measured by X-ray spectral analysis ($N_{\text{H,X}}^{\text{LOS}}$) with that estimated by the dust properties ($N_{\text{H,dust}}^{\text{mol}}$). In the majority of cases (18/21), the line-of-sight hydrogen column density estimated from the dust properties is significantly larger than the X-ray measurements in the Compton-thin cases. This suggests that the host-galaxy clouds have non-spherical geometry and/or have complex (e.g., clumpy) distributions. We may also consider the possibility that the X-ray absorption of those sources is dominated by the opacity in the host galaxy rather than the torus. Moreover, this results might suggest that many of the X-ray AGNs are Compton thick and the line-of-sight hydrogen column densities are not properly constrained by the X-ray spectral analysis. Figure 4.8 (b) shows the histogram of the line-of-sight hydrogen column density estimated from the dust properties. We find that the SED AGNs have tentatively ~ 0.3 dex higher column densities than the X-ray AGNs. The median value of the SED AGNs is $N_{\text{H,dust}}^{\text{mol}} = 1.2_{-0.4}^{+0.3} \times 10^{24} \text{ cm}^{-2}$, which is broadly equivalent to the threshold of

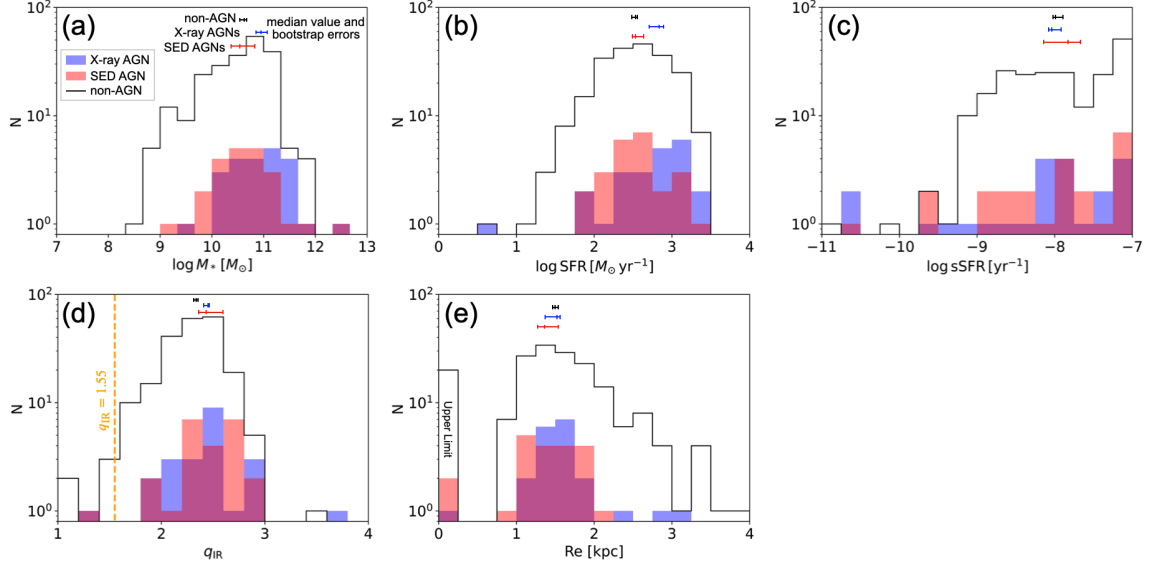


Figure 4.9: Histograms of (a) stellar masses, (b) SFRs, (c) specific SFRs, (d) radio-IR correlation factors (q_{IR}), and (e) the dust continuum sizes (R_e) for the X-ray AGNs, SED AGNs, and the rest of the AS2COSMOS sources (non-AGNs). In the histogram of R_e , the bins at $R_e = 0$ kpc show the number of sources whose dust sizes are only given as the upper confidence intervals. We confirm no significant difference between the samples, suggesting the similarity of their host galaxies, regardless of the presence of an X-ray or SED AGN.

Compton-thick absorption ($N_{\text{H}} = 1.7 \times 10^{24} \text{ cm}^{-2}$). Thus, this might suggest that in bright SMGs AGNs can be heavily obscured by the host galaxies, which makes them difficult to detect with X-ray observations.

4.4.3 Comparison of Physical Properties between Samples

Figure 4.9 compares the stellar masses, SFRs, specific SFRs, radio-IR correlation factors, and the sizes of dust-emitting regions of the X-ray AGNs, the SED AGNs, and the rest of the AS2COSMOS sources (non-AGNs). We find that the median SFR and stellar mass of the X-ray AGN sample ($\log \text{SFR}[M_{\odot} \text{ yr}^{-1}] = 2.84^{+0.05}_{-0.13}$ and $\log M_*[M_{\odot}] = 10.94^{+0.12}_{-0.09}$) are about two times higher than those of the non-AGN sample ($\log \text{SFR}[M_{\odot} \text{ yr}^{-1}] = 2.53^{+0.02}_{-0.06}$ and $\log M_*[M_{\odot}] = 10.62^{+0.04}_{-0.09}$), while the median SFR and stellar mass of the SED AGN sample ($\log \text{SFR}[M_{\odot} \text{ yr}^{-1}] = 2.53^{+0.10}_{-0.04}$ and $\log M_*[M_{\odot}] = 10.53^{+0.30}_{-0.16}$) agree with the non-AGNs. This might be attributed to the X-ray selection bias of these sources. Since the X-ray observations in the COSMOS field are relatively shallow, the X-ray AGNs are biased to bright AGNs, which likely host higher-mass SMBHs. Hence, if we assume the positive correlation

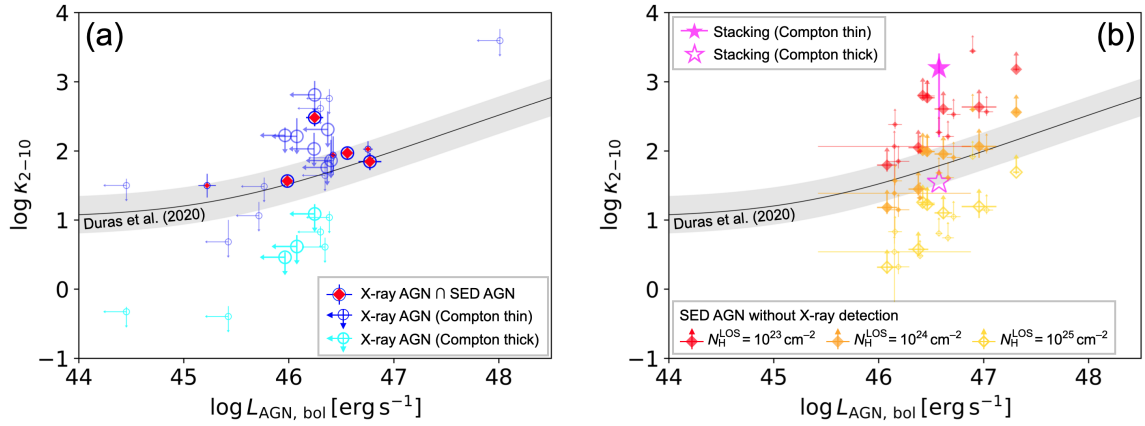


Figure 4.10: Comparison of X-ray to bolometric correction factor (κ_{2-10}) and bolometric AGN luminosity for (a) the X-ray AGNs and (b) the SED AGNs (the overlapped sources are plotted in panel (a)). The black solid line denotes the empirical relation at $z = 0-4$ (Duras et al., 2020). Symbols with arrows show the 3σ upper bound for each parameter. The redshift uncertainties are not considered when calculating the overall uncertainties of the plotted values. The large symbols show the spec- z sample, while the smaller ones show the photo- z sample. We find that the X-ray AGNs are predicted to be Compton-thin AGNs, while the majority of X-ray undetected SED AGNs are nearly Compton-thick AGNs, if the empirical relation holds.

between stellar mass and SMBH mass (Kormendy & Ho, 2013), the X-ray AGNs are expected to be hosted by massive galaxies, which may have high SFR according to the scaling relation of SFR and stellar mass. This argument is supported by the similarity in the distributions of the specific SFRs between the X-ray AGNs, SED AGNs, and non-AGNs (the median specific SFRs of the X-ray AGN, SED AGN, and non-AGN samples are $-8.04^{+0.12}_{-0.04} \text{ yr}^{-1}$, $-7.83^{+0.23}_{-0.31} \text{ yr}^{-1}$, and $-7.99^{+0.10}_{-0.03} \text{ yr}^{-1}$, respectively). We also find that the radio-IR correlation factors and the dust-continuum sizes do not significantly vary between the samples. This implies that the vast majority of the X-ray AGNs and the SED AGNs are radio quiet and the properties of their host galaxy are similar to those of the non-AGNs.

4.4.4 X-ray Luminosity versus Bolometric AGN Luminosity

Figure 4.10 compares the X-ray to bolometric correction factor ($\kappa_{2-10} = L_{\text{AGN, bol}}/L_{2-10 \text{ keV}}$) with the bolometric AGN luminosity for our AGN samples. We also plot the empirical relation of AGNs at $z < 3.5$ from Duras et al. (2020). We find that six out of the seven X-ray-detected SED AGNs show good agreement with the empirical relation, while one source has about one dex higher X-ray luminosity than the empirical

relation (AS2COS0048.1; $\kappa_{2-10} = 326$). We also find that all the X-ray AGNs are predicted to be Compton-thin AGNs, while the majority of the X-ray undetected SED AGNs (14/17) appear to be nearly Compton thick ($N_{\text{H,X}}^{\text{LOS}} \geq 10^{24} \text{ cm}^{-2}$), assuming the empirical relation holds. This is consistent with the recent observation that a significant fraction of AGNs in local U/LIRGs show Compton-thick absorption (16/35; Ricci et al. 2021). However, some studies have reported that AGNs in the local U/LIRGs are intrinsically X-ray weak ($\kappa_{2-10} = 100\text{--}1000$; Teng et al. 2014; Yamada et al. 2021). If this phenomenon is applicable to our samples, the X-ray undetected SED AGNs do not have to be Compton thick. Note that the X-ray AGNs are not predicted to be intrinsically X-ray weak, based on the upper limits of the X-ray to bolometric correction factors.

Regarding the X-ray stacking analysis, we plot the average X-ray to bolometric correction factors and the median bolometric AGN luminosities for the X-ray undetected SED AGNs. We find that assuming the Compton-thin case, the inferred average X-ray to bolometric corrections for the X-ray undetected SED AGNs is more than one dex higher than the empirical relation and higher than any X-ray-detected SED AGN in our sample. This may indicate that the X-ray undetected SED AGNs are either Compton thin and intrinsically X-ray weak or they are Compton thick.

4.4.5 SFR versus Bolometric AGN Luminosity

Figure 4.11 compares the SFR with the bolometric AGN luminosity for the X-ray AGNs and SED AGNs. Here we use the bolometric AGN luminosity derived from the SED modeling for the SED AGNs. For X-ray AGNs, excluding X-ray AGNs that are also identified as SED AGNs, the bolometric AGN luminosities are converted from the X-ray luminosities using the calibration by Duras et al. (2020). Note that we use the X-ray luminosities calculated with the Compton-thin assumption based on the discussion in Section 4.4.4. We also plot the median SFR and the upper bound of the bolometric AGN luminosity for the non-AGN sample calculated from the X-ray stacking (Section 4.4.1), where the calibration by Duras et al. (2020) is adopted to convert the X-ray luminosity upper bound to the bolometric AGN luminosity upper bound. For comparison, we plot the “simultaneous galaxy-SMBH evolution” line for the co-evolution of SMBHs and the host galaxies. Assuming that SMBHs and the host galaxies co-evolve simultaneously across cosmic time, the relative ratio of star

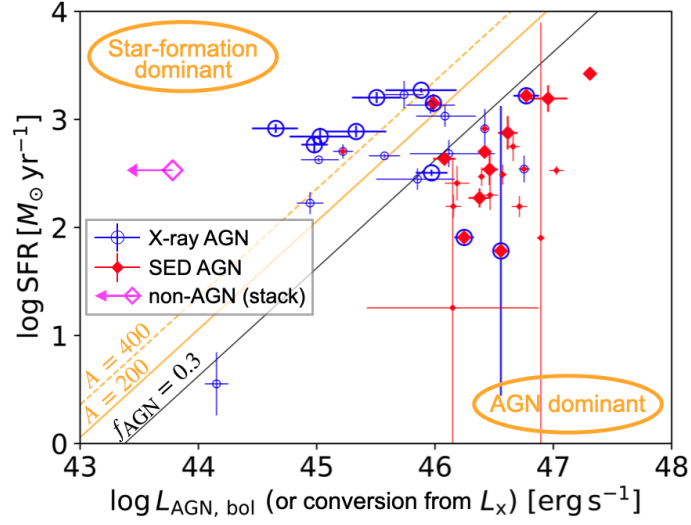


Figure 4.11: Comparison of SFR and bolometric AGN luminosity for the X-ray AGNs and the SED AGNs. The orange solid and dashed lines show the “simultaneous evolution” with $A = 200$ (bulge only) and $A = 400$ (bulge+disk), respectively. The black solid line shows the detection limit of the type-2 SED AGNs (see Section 4.3.1.5). The large symbols show the spec- z sample, while the smaller ones show the photo- z sample. We find that the SED AGNs are distributed in the AGN-dominant region, suggesting that in such a phase AGNs can be nearly Compton-thick and missed in X-ray.

formation and AGN activity is expected to track this relationship.

$$\begin{aligned}
 \text{SFR} \times (1 - R) &= A \times \dot{M}_{\text{BH}} \\
 &= L_{\text{AGN, bol}} \times (1 - \eta) / \eta c^2
 \end{aligned}
 \tag{4.5}$$

where R is the return function (the fraction of stellar masses that are ejected back to the interstellar medium), A is the mass ratio of stars to SMBHs, η is the accretion efficiency, and c is the speed of light. We assume $R = 0.41$ (Chabrier IMF) and $\eta = 0.05$. For A , we calculate in two settings: $A = 200$ and $A = 400$. The former value is the typical mass ratio of stars in bulge components to SMBHs in the local universe (Kormendy & Ho, 2013), while the latter value includes the disk components (see Section 4.4 in Ueda et al. 2018). We find that the SED AGNs are distributed in the AGN dominant phase, where SMBHs grow faster than the host galaxies, while the X-ray AGNs are almost distributed around the simultaneous evolution lines. The bias of SED AGNs to higher AGN luminosity can be explained by the selection effect discussed in Section 4.3.1.5. We can potentially interpret these results within the merger-driven evolutionary scenario: on the basis of this scenario, galaxy mergers first trigger star formation activity and later evoke AGN activity after the gas has had time to reach the nuclear region (e.g., via stellar winds, supernovae,

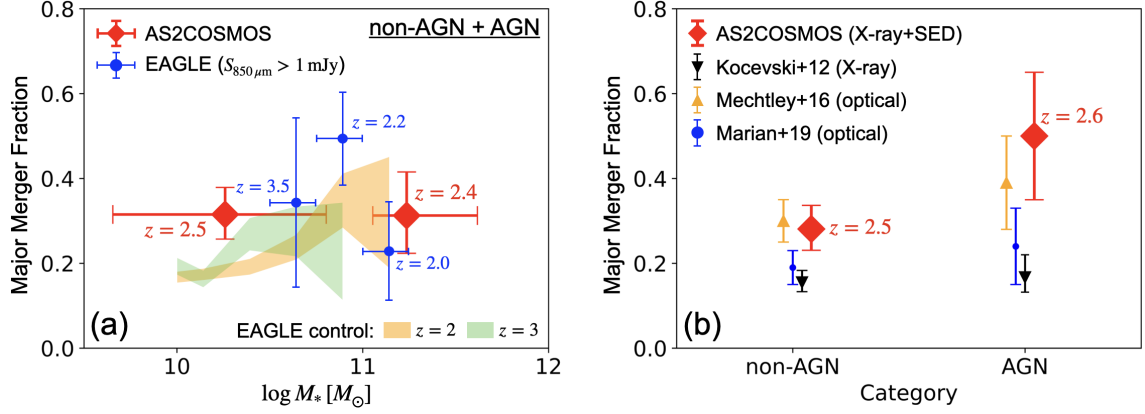


Figure 4.12: (a) Comparison of the major merger fraction in the AS2COSMOS sample with the theoretical prediction from EAGLE (McAlpine et al., 2019). The errors on M_* of AS2COSMOS sample indicate the 16–84% intervals of each stellar mass bin. (b) Dependencies of the major merger fraction as a function of AGN activity. The X-ray and optical selected AGNs at $z \sim 2$ are also plotted (Kocevski et al., 2012; Marian et al., 2019; Mechtley et al., 2016). Each data point is annotated with the median redshift of the galaxies in that bin. We find that major mergers may play a key role in triggering AGN activity in bright SMGs.

or through gravitational torques). Within this scenario, the SED AGNs would correspond to the transition phase, where merging has reached the nuclear regions and the AGN activity has been enhanced, but the star formation is not yet quenched. Hence, we might say that in such phases, AGNs are likely to be heavily obscured by dust or have unusually suppressed X-ray emissions, which makes them difficult to detect with X-ray observations. We note that the selection of the AGNs by SED modeling strongly depends on the quality of the multi-wavelength photometry and the assumptions of models. Thus, these results should be verified by other methods like future sensitive observations with Advanced Telescope for High Energy Astrophysics (Athena; Nandra et al. 2013).

4.4.6 Population Statistics

4.4.6.1 AGN Number Fraction

The depths of the X-ray observations in the COSMOS field are only moderate (~ 160 ks per pixel). Thus, the X-ray AGNs in the AS2COSMOS sample are not complete even for X-ray bright sources above luminosities of $L_X = 10^{43} \text{ erg s}^{-1} \text{ cm}^{-2}$. The SED AGNs are also incomplete due to the selection shown in Section 4.3.1.5. Hence, the AGN number fraction in our sample provides a lower limit for bright SMGs. In

this study, the AGN number fraction in the AS2COSMOS sample is estimated as 16_{-2}^{+3} per cent for all AGNs (SED AGNs and X-ray AGNs) and 9 ± 2 per cent for only X-ray AGNs. The number fraction of X-ray AGNs in our sample is therefore consistent with that in the AS2UDS sample (8 ± 2 per cent; Stach et al. 2019), where the depth of the X-ray observations used in that work are more comparable to those in the COSMOS field (X-UDS; 200–600 ks with CXO; Kocevski et al. 2018).

To identify trends in AGN fraction with the SMG population, we separate the sample into four bins based on the redshifts and 870- μm flux densities. Since our sample is only complete for SMGs brighter than $S_{870\mu\text{m}} = 6.2\text{ mJy}$, we separate the sample at $S_{870\mu\text{m}} = 6.2\text{ mJy}$. We also separate the sample at $z = 3$, because the selection of AGNs by SED modeling is more reliable at low redshift ($z < 3$; Section 4.3.1.3).

In the brighter SMG samples, the AGN number fraction (SED AGN and X-ray AGN) is about two times higher at high redshift ($24_{-6}^{+8}\%$) than at low redshift ($13_{-4}^{+5}\%$), which is also confirmed for X-ray AGNs ($10_{-4}^{+6}\%$ and $6_{-2}^{+4}\%$, respectively). This might suggest that the SMBH growth is more intense in high-redshift SMGs. However, we stress that the evidence for high-redshift SED AGNs ($z > 3$) is fairly limited and care should be taken with this issue. For low-redshift samples, the SED AGN number fraction is higher in the brighter SMGs ($7_{-3}^{+4}\%$) than in the fainter SMGs ($1_{-1}^{+2}\%$), while the X-ray AGN number fractions are consistent within their confidence intervals ($6_{-2}^{+4}\%$ and $8_{-3}^{+4}\%$, respectively). This might suggest that, in bright SMGs, AGNs tend to be heavily obscured or have unusually weak X-ray emission. As the 870- μm flux density is tightly correlated with the dust mass of a galaxy Dudzevičiūtė et al. (2020), this trend might be attributed to the dust obscuration by the host galaxies (Section 4.4.2). Nevertheless, we need to be cautious about the selection bias due to the quality of multi-wavelength photometry. Brighter SMGs are more likely have higher S/N in the mid- to far-infrared photometry, which can highlight the imperfection of the host-galaxy models and cause the misidentification of SED AGNs. On the other hand, in fainter SMGs, the S/N in the mid- to far-infrared photometry is expected to be lower, which can miss the presence of SED AGNs.

4.4.6.2 Merger Fraction

The connection between galaxy mergers and AGN/host-galaxy properties is an important, but still unresolved issue. In the low-redshift universe ($z \leq 1$), several observational studies have shown that galaxies in mergers are more likely to host

AGNs than isolated galaxies (e.g., Gao et al. 2020; Goulding et al. 2018). While theoretical investigations predict that the fraction of merger-induced starburst in SMGs increases with submillimeter flux density (Hayward et al., 2013), although other theoretical work investigating the dependence of merger fraction on the stellar mass and found that the merger fraction in SMGs is similar to the general galaxy population, suggesting that mergers are not the sole driver of the enhanced star formation in SMGs (McAlpine et al., 2019). To address this issue in our study we examine the merger fraction of the AS2COSMOS sources as functions of stellar masses ($M_* > 10^{11} M_\odot$ or $M_* < 10^{11} M_\odot$) and AGN activity (AGN or non-AGN).

Figure 4.12 (a) shows the dependence of major merger fractions on stellar masses. We also plot the theoretical prediction using the EAGLE simulation by McAlpine et al. (2019). We find no significant difference between the massive and less massive subsets of SMGs ($31^{+10}_{-9}\%$ and $32 \pm 6\%$, respectively) and the major merger fractions of the two subsets are consistent with the EAGLE simulation. Figure 4.12 (b) shows the dependence of major merger fractions on AGN activity. For comparison, we plot the major merger fractions in X-ray selected AGNs (Kocevski et al., 2012) and optical selected AGNs (Mechtley et al. 2016 and Marian et al. 2019) at $z \sim 2$ (see also Villforth 2023 for the summary of these studies). Notably the major merger fraction in the AS2COSMOS non-AGN sample ($28^{+6}_{-5}\%$) is consistent with those of the general population at $z \sim 2$. However, we find that the major merger fraction in the AS2COSMOS AGN sample ($50 \pm 15\%$) is potentially twice as high as that in the non-AGN sample, which is more significant than the enhancement reported for the general AGN samples at $z \sim 2$, although the uncertainties are large. These results suggest that major mergers are not necessarily required for the enhanced star formation in SMGs as predicted by the EAGLE simulation, but may play a key role in triggering AGN activity in bright SMGs. We caution that there still remain large statistical uncertainties and further studies with large samples are needed. For example, dependency of major merger fraction on AGN luminosity cannot be confirmed in this study, but should be investigated in future studies with larger samples. In addition, the selection of AGNs by SED analysis strongly depends on the model assumptions. If we adopt the Donley et al. (2012) criteria for the selection of SED AGN, the major merger fraction in the AGN sample is $43^{+13}_{-12}\%$, which is still almost consistent with the major merger fraction in our AGN sample. The slight difference might originate from the galaxy contamination in the Donley et al. (2012) selection. We also note that the stellar masses of most of the companions are not measured in this study, but it may not affect the main conclusion of this study.

4.5 Summary

We performed multi-component SED modeling and X-ray spectral analysis for the sample of bright SMGs from the AS2COSMOS survey. The sample consists of 260 SMGs with $S_{870\mu\text{m}} = 0.7\text{--}19.2\text{ mJy}$, which is effectively complete for SMGs with $850\text{-}\mu\text{m}$ flux densities $S_{850\mu\text{m}} \geq 6.2\text{ mJy}$ in the S2COSMOS catalog. Our main results are listed below:

- Using an SED fitting methodology, we identified 24 AGN candidates (SED AGNs). Supplemented by 23 X-ray-detected AGNs (X-ray AGNs), we construct a sample of 40 AGN candidates, of which seven sources overlap between the two subsets.
- The X-ray AGNs have a median of 6 times higher X-ray luminosities than the empirical relation between the X-ray luminosity and far-infrared luminosity for AGN-classified SMGs, assuming Compton-thin absorption. This can be attributed to the selection from the relatively shallow X-ray observations in the COSMOS field. An X-ray stacking analysis shows that the stacked luminosities of X-ray undetected SED AGNs show good agreement with the empirical relation of the AGN-classified SMGs with the assumption of Compton-thin absorption. This indicates that the X-ray undetected SED AGNs are likely to be the same population as the AGN-classified SMGs detected in deeper X-ray studies.
- From the dust masses and the sizes of the dust emitting region, the median hydrogen column densities are calculated as $N_{\text{H,dust}} = 1.4^{+0.5}_{-0.6} \times 10^{24}\text{ cm}^{-2}$, $N_{\text{H,dust}} = 3.0^{+0.7}_{-1.1} \times 10^{24}\text{ cm}^{-2}$, and $N_{\text{H,dust}} = 2.2^{+0.2}_{-0.1} \times 10^{24}\text{ cm}^{-2}$ for the X-ray AGNs, SED AGNs, and the rest of AS2COSMOS sources. The SED AGNs have about two times higher column densities than the X-ray AGNs. This may suggest that the SED AGNs are heavily obscured by the host galaxy dust, which makes them difficult to detect with X-ray observations.
- Among the seven X-ray-detected SED AGNs, six are consistent with the empirical relation of X-ray luminosity and bolometric luminosity of AGNs at $z < 3.5$, while one source has about one dex higher X-ray luminosity than the empirical relation. Assuming the empirical relation, the X-ray AGNs are predicted to be Compton-thin AGNs, while the majority of X-ray undetected SED AGNs are nearly Compton-thick AGNs. However, if we consider the X-ray weak cases, the SED AGNs can be Compton-thin AGNs.

- In the SFR versus AGN luminosity plane, the SED AGNs are distributed in the AGN-dominant phase, while X-ray AGNs are distributed around the simultaneous evolution lines. Assuming a merger-driven evolutionary scenario, our AGN sample may correspond to the transition phase, where merging has finished, but the star formation is not yet quenched. Thus our results suggest that in such phases, AGNs are likely to be heavily obscured by dust or have anomalously suppressed X-ray emissions, which makes them difficult to detect with X-ray observations.
- The AGN number fraction in the AS2COSMOS sample is 16^{+3}_{-2} per cent for total (SED AGNs and X-ray AGNs) and 9 ± 2 per cent for only X-ray AGNs. These values are lower than the previous estimate with deeper X-ray observation, which can be attributed to the relatively shallow X-ray observations in the COSMOS field and also the selection bias of the SED AGNs.
- Using visual classification, we identify $47^{+16}_{-15}\%$ and $25^{+6}_{-5}\%$ of the AGN hosts and galaxies without AGNs as major merger candidates, respectively. The major merger fraction in the AS2COSMOS non-AGN sample is almost consistent with the general population at $z \sim 2$. This suggests that major mergers are not necessarily required for the enhanced star formation in SMGs. On the other hand, the major merger fraction in the AS2COSMOS AGN sample is potentially twice as high as that in the AS2COSMOS non-AGN sample. This suggests that major mergers may play a key role in triggering AGN activity in bright SMGs.

CHAPTER 5

Concluding Remarks

5.1 Summary

SMGs and AGNs are key populations to understand the coevolution of galaxies and SMBHs in the high-redshift universe, as they are the rapidly growing phases of galaxies and SMBHs, respectively. In this thesis, I focused on two SMG samples constructed by recent ALMA observations: ALCS and AS2COSMOS. ALCS is one of the deepest surveys with ALMA, utilizing the lensing effect of galaxy clusters. On the other hand, AS2COSMOS is a follow-up of the brightest SMGs detected in the SCUBA-2 COSMOS survey.

In Chapter 2, we studied the evolutionary phase of the X-ray-detected AGNs in the ALCS sample. The main results are summarized as follows:

1. Utilizing the archival data of CXO, we identified three AGNs out of the 180 millimeter galaxies securely detected in the ALCS. These AGNs are found in the fields of Abell370, MACSJ0416.1–2403, and MACS0329.7–021 at spectroscopic redshifts of 1.06 and 2.09, and photometric redshift of 2.84, respectively.
2. From the X-ray spectral analysis, we find that two AGNs so not show significant

absorption ($\log N_{\text{H}}/\text{cm}^{-2} < 23$), while one shows signs of moderate absorption ($\log N_{\text{H}}/\text{cm}^{-2} \sim 23.5$).

3. We performed SED modelling of the X-ray to millimeter photometry with the CIGALE code. We find that the three X-ray AGNs have both high mass-accretion rates (intrinsic 0.5–8 keV X-ray luminosities of $\sim 10^{44-45}$ erg s $^{-1}$) and star-formation rates ($\gtrsim 100 M_{\odot}$ yr $^{-1}$).
4. ALCS-XAGNs show higher mass-accretion rates than other ALMA selected X-ray AGN samples. They also show higher SFRs than a purely X-ray-selected AGN sample. This can be explained by the selection bias, showing that a wide and deep survey with ALMA, combined with medium-depth X-ray data, can efficiently detect intense growth stage of both galaxies and SMBHs in high-redshift universe.

In Chapter 3, we studied the overall properties of the ALCS sample. The main results are summarized as follows:

1. We performed UV to millimeter SED modeling of the whole ALCS sample (except for the cluster members and the ALCS-XAGNs), utilizing the photometric data obtained with HST, Spitzer, Herschel, and ALMA.
2. We confirm that the majority of the ALCS sources lie on the star-forming main sequence, while a smaller fraction shows intense starburst activities. This trend is the same as for other ALMA-detected SMG samples, e.g., ALESS, AS2UDS, and ASAGAO, although the ALCS sample contains galaxies with even lower SFRs and stellar masses thanks to the lensing effect.
3. We find two extremely dust-obscured galaxies (A2744-ID7 [$z = 2.41$] and R0600-ID111 [$z=1.56$]). These galaxies have steeper attenuation slopes than the average, which may result in more UV absorption and hence higher IRX.
4. We confirm that the ALCS sample exhibits a wider range in dust temperatures than the conventional SMG samples (ALESS, and AS2UDS) in the same redshift range. We also confirm that the ALCS sample shows a large scatter in a lower dust mass range than the conventional SMG samples after lensing correction.
5. We identify six AGN candidates that are not detected in the archival CXO data. The X-ray upper bounds indicate that these AGNs are heavily obscured

or Compton-thick AGNs. This suggests that a significant fraction of AGNs in SMGs are heavily obscured by gas and dust and might be missed in the previous X-ray observations.

In Chapter 4, we studied the AGN properties of the AS2COSMOS sample. The main results are summarized as follows:

- Using an SED fitting methodology, we identified 24 AGN candidates (SED AGNs). Supplemented by 23 X-ray-detected AGNs (X-ray AGNs), we construct a sample of 40 AGN candidates, of which seven sources overlap between the two subsets.
- The X-ray AGNs have a median of 6 times higher X-ray luminosities than the empirical relation between the X-ray luminosity and far-infrared luminosity for AGN-classified SMGs, assuming Compton-thin absorption. This can be attributed to the selection from the relatively shallow X-ray observations in the COSMOS field. An X-ray stacking analysis shows that the stacked luminosities of X-ray undetected SED AGNs show good agreement with the empirical relation of the AGN-classified SMGs with the assumption of Compton-thin absorption. This indicates that the X-ray undetected SED AGNs are likely to be the same population as the AGN-classified SMGs detected in deeper X-ray studies.
- From the dust masses and the sizes of the dust emitting region, the median hydrogen column densities are calculated as $N_{\text{H,dust}} = 1.4^{+0.5}_{-0.6} \times 10^{24} \text{ cm}^{-2}$, $N_{\text{H,dust}} = 3.0^{+0.7}_{-1.1} \times 10^{24} \text{ cm}^{-2}$, and $N_{\text{H,dust}} = 2.2^{+0.2}_{-0.1} \times 10^{24} \text{ cm}^{-2}$ for the X-ray AGNs, SED AGNs, and the rest of AS2COSMOS sources. The SED AGNs have about two times higher column densities than the X-ray AGNs. This may suggest that the SED AGNs are heavily obscured by the host galaxy dust, which makes them difficult to detect with X-ray observations.
- Among the seven X-ray-detected SED AGNs, six are consistent with the empirical relation of X-ray luminosity and bolometric luminosity of AGNs at $z < 3.5$, while one source has about one dex higher X-ray luminosity than the empirical relation. Assuming the empirical relation, the X-ray AGNs are predicted to be Compton-thin AGNs, while the majority of X-ray undetected SED AGNs are nearly Compton-thick AGNs. However, if we consider the X-ray weak cases, the SED AGNs can be Compton-thin AGNs.

- In the SFR versus AGN luminosity plane, the SED AGNs are distributed in the AGN-dominant phase, while X-ray AGNs are distributed around the simultaneous evolution lines. Assuming a merger-driven evolutionary scenario, our AGN sample may correspond to the transition phase, where merging has finished, but the star formation is not yet quenched. Thus, our results suggest that in such phases, AGNs are likely to be heavily obscured by dust or have anomalously suppressed X-ray emissions, which makes them difficult to detect with X-ray observations.
- The AGN number fraction in the AS2COSMOS sample is 16^{+3}_{-2} per cent for total (SED AGNs and X-ray AGNs) and 9 ± 2 per cent for only X-ray AGNs. These values are lower than the previous estimate with deeper X-ray observation, which can be attributed to the relatively shallow X-ray observations in the COSMOS field and also the selection bias of the SED AGNs.
- Using visual classification, we identify $47^{+16}_{-15}\%$ and $25^{+6}_{-5}\%$ of the AGN hosts and galaxies without AGNs as major merger candidates, respectively. The major merger fraction in the AS2COSMOS non-AGN sample is almost consistent with the general population at $z \sim 2$. This suggests that major mergers are not necessarily required for the enhanced star formation in SMGs. On the other hand, the major merger fraction in the AS2COSMOS AGN sample is potentially twice as high as that in the AS2COSMOS non-AGN sample. This suggests that major mergers may play a key role in triggering AGN activity in bright SMGs.

In conclusion, this work provides two key insights into the co-evolution of galaxies and SMBHs in the high-redshift universe. First, we identify a substantial population of AGNs in SMGs that are heavily obscured or have unusually weak X-ray emissions, making them challenging to detect with conventional X-ray observations below 10 keV. These AGNs lie in the AGN-dominant region in the SFR versus AGN luminosity plane, indicating that the SMBHs are more rapidly growing than the host galaxies. This finding suggests that, during the rapid growth phase of SMBHs in SMGs, AGNs tend to be heavily obscured or exhibit anomalously suppressed X-ray emissions. Second, we find that the fraction of major mergers in bright SMGs is consistent with the general population at $z \sim 2$, while a slight enhancement is seen in the AGN hosts. This suggests that major mergers are not the principal driver of enhanced star formation in bright SMGs, but might play a key role in triggering AGN activity in those systems. This finding indicates that the galaxy-SMBH co-evolution at high

redshift has not been driven solely by the merger-driven evolutionary scenario.

5.2 Future Prospects

The next step is to increase the sample size. Currently, the number of secure SMG samples observed with JWST is limited, which leaves considerable statistical uncertainties in the morphological analyses presented in this thesis. Ongoing and future extensive surveys with JWST will be essential to establishing a more statistically sound picture of how major mergers influence AGN activity in the high-redshift universe. In addition, spectroscopic surveys with Euclid (Euclid Collaboration et al., 2024) and the Nancy Grace Roman Space Telescope will also open windows for the study of high-redshift AGNs. They may provide the estimates of black hole masses, and enable us to compare the properties of AGNs at different evolutionary stages. Moreover, future sensitive X-ray observations with upcoming observatories like Athena or/and the high energy X-ray probe (HEX-P) will be critical for confirming the hidden AGN populations inferred in this work.

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APPENDIX A

Appendices of Chapter 2

A.1 Parameters used in the SED analysis

Table A.1 summarize the free parameters used in the SED modelling. Each SED module is explained in Section 2.3.2.

Table A.1: Parameter Ranges Used in the SED Modelling with CIGALE. Note that we adopt the well-studied “ $\alpha_{\text{ox}}-L_{2500\text{\AA}}$ ” relation for the X-ray module, where α_{ox} is defined as $\alpha_{\text{ox}} \equiv -0.3838 \times \log(L_{2500\text{\AA}}/L_{2\text{keV}})$ and the empirical relation is written as $\alpha_{\text{ox}} = -0.137 \log(L_{2500\text{\AA}}) + 2.638$ (Just et al., 2007).

Parameter	Symbol	Value
SFH (Delayed SFH)		
e-folding time of the main stellar population	τ_{main} [Myr]	300, 600, 1000, 3000, 5000, 7000, 9000
Age of the main stellar population	age _{main} [Myr]	300, 600, 1000, 2000, 3000, 4000, 5000
IMF of the stellar model	SSP (bc03; Bruzual & Charlot 2003)	
Metallicity of the stellar model	Chabrier (2003)	
	0.02	
Dust Attenuation (dustatt_modified_starburst; Calzetti et al. 2000)		
The colour excess of the nebular lines.	$E(B - V)_{\text{lines}}$	0.05, 0.1, 0.15, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4
Reduction factor to apply $E(B - V)_{\text{lines}}$ to calculate the stellar continuum attenuation	$E(B - V)_{\text{factor}}$	0.44
Power-law index to modify the attenuation curve	δ	-0.6, -0.3, 0.0
AGN emission (skirtor2016; Stalevski et al. 2012, 2016)		
Average edge-on optical depth at 9.7 micron	$\tau_{9.7}$	3, 7, 11
Radial gradient of dust density	p	1.0
Dust density gradient with polar angle	q	1.0
Half-opening angle of the dust-free cone	Δ [°]	40
Ratio of outer to inner radius	R	20
Inclination	θ [°]	30, 60
Fraction of AGN IR luminosity to total IR luminosity	f_{AGN}	0.1, 0.3, 0.5, 0.7, 0.9
Extinction in polar direction	$E(B - V)_{\text{pol}}$	0.0, 0.1, 0.8
Temperature of the polar dust	T_{pol} [K]	100, 200
Dust emission (Themis; Jones et al. 2017)		
Mass fraction of small hydrocarbon solids	q_{PAH}	2.5
Minimum radiation field	U_{min}	1, 5, 10, 25, 50
Power-law index of the starlight intensity distribution	α	2.0, 2.5
Fraction of dust illuminated from U_{min} to U_{max}	γ	0.01, 0.05, 0.1
X-ray emission		
Photon index	Γ	1.9
Maximum deviation of α_{ox} from the empirical relation		0.2

APPENDIX B

Appendices of Chapter 3

B.1 Detailed Description of X-ray Analysis

The X-ray spectrum of an AGN mainly consists of three components: (1) a direct component from the nucleus, (2) reflection components from the torus and/or the accretion disk, and (3) a scattered component and emission from photoionized plasma. Since the emission from photoionized plasma is not dominant above rest-frame 2 keV, we exclude this component from our model. We disregard the reflection component from the accretion disk, whose interpretation is under debate (see e.g., Ogawa et al. 2019). Furthermore, we do not consider the X-ray emission from star-formation activity, which is much fainter than the AGN component above rest-frame 2 keV. Hence, in this study, we only consider a direct component, a reflection component from a torus, and a scattered component. This model is described as follows in the XSPEC terminology:

$$\text{model 1} = \text{phabs} * (\text{zphabs} * \text{cabs} * \text{zcutoffpl} + \text{const} * \text{zcutoffpl}) \quad (\text{B.1.1})$$

$$+ \text{atable}\{\text{xclumpy_v01_RC.fits}\} \quad (\text{B.1.2})$$

$$+ \text{atable}\{\text{xclumpy_v01_RL.fits}\})$$

1. The first term (**phabs**) represents the photo-electric absorption by our Galaxy, which is fixed at the value estimated from the source position using the method of Willingale et al. (2013).
2. The first term in the parentheses represents the direct component. The **zphabs** and **cabs** represent photo-electric absorption and Compton scattering by torus matter. The line-of-sight hydrogen column density is tested at $\log N_{\text{H}}^{\text{LOS}} = 21, 23, 24.5$. The photon index and cutoff energy are fixed at $\Gamma = 1.9$ and $E_{\text{cut}} = 370 \text{ keV}$, respectively, as typical values of local AGNs (Ricci et al., 2017b).
3. The second term in the parentheses represents the unabsorbed scattered component. The parameters of **zcutoffpl** are linked to those of the direct component. We fix the scattered fraction (**const**) to 0.01 as a typical value (Gupta et al., 2021; Ricci et al., 2017b).
4. The third and fourth terms in the parentheses represent the reflection continuum and fluorescence lines from the torus. We model these components with the XCLUMPY model (Tanimoto et al., 2019). The photon index, cutoff energy, and normalization are linked to those of the direct component. We fixed the torus angular width at $\sigma = 20^\circ$. The inclination angle is fixed at $i = 30^\circ$ when $\log N_{\text{H}}^{\text{LOS}}/\text{cm}^{-2} = 21$, and $i = 70^\circ$ when $\log N_{\text{H}}^{\text{LOS}}/\text{cm}^{-2} = 23$ and 24.5 . The equatorial hydrogen column density ($N_{\text{H}}^{\text{Equ}}$) is set to be consistent with the line-of-sight hydrogen column density and the torus geometry (see Equation 3 in Tanimoto et al. 2019).

X-ray spectra of distant AGNs are often analyzed with simpler models, such as an absorbed power law model. Accordingly, we also estimate the X-ray luminosity upper bounds with a simple model described as follows in the XSPEC terminology:

$$\text{model 2} = \text{phabs} * \text{zphabs} * \text{cabs} * \text{zcutoffpl} \quad (\text{B.1.3})$$

The meanings of each symbol in model 2 are the same as those in the direct component of model 1. The line-of-sight hydrogen column density, photon index, and cutoff energy are fixed to $\log N_{\text{H}}^{\text{LOS}}/\text{cm}^{-2} = 22$, $\Gamma = 1.9$, and $E_{\text{cut}} = 370 \text{ keV}$, respectively.

B.2 Detailed description of SED modeling

First, the ALCS tier-1/2/5/6 samples were analyzed with a basic parameter set, which is summarized in Table B.1. This adequately reproduces all the SEDs ($\chi^2/\text{dof} < 5$) except for A2744-ID227. The left panel of Figure B.1 shows the SED and the best-fit models of A2744-ID227 analyzed with the basic parameter set. We noticed a significant excess in the mid-infrared band, suggesting the existence of a type-2 AGN. Hence, we reanalyzed the SED with an extended parameter set of the AGN module, which is given in Table B.2. The right panel of Figure B.1 shows the SED and the best-fit models of A2744-ID227 analyzed with the extended parameter set. This operation greatly improved the goodness of the fit for this object ($\chi^2/\text{dof} = 10.6 \rightarrow 4.1$). Second, the ALCS tier-3/4 sources were analyzed with a limited parameter set for the dust emission model to avoid unreasonable fitting results. This parameter set is summarized in Table B.3. This adequately reproduces all the SEDs in the tier-3/4 samples ($\chi^2/\text{dof} < 5$).

The observed SEDs and best-fit models of all the objects are shown in Figure B.2. We note that the best-fit SEDs of A383-ID50 and M0416-ID156 look inconsistent with the observed ALMA fluxes ($\log F_{\text{obs}[1.2\text{ mm}]} / F_{\text{model}} > 1$). This may be caused by the oversimplification of the dust SED model. We also note that the best-fit SED of ACT0102-ID50 looks inconsistent with the photometric data of Herschel ($\log F_{\text{obs}[250\text{ }\mu\text{m}]} / F_{\text{model}} > 1$). This might be caused by the blending effect from nearby sources or additional star-formation activities that are deeply embedded in dust and not detected in optical to near-infrared bands.

B.3 Validity of photometric redshift and Impact of redshift uncertainty on physical properties

In this section, we discuss the validity of photometric redshifts and the impact of redshift uncertainty on physical properties. The photometric redshifts of the ALCS sources are estimated by several methods. For example, most of the photometric redshifts of tier-1/2/5/6 sources are estimated by optical to near-infrared SED analysis with EAZY (Kokorev et al., 2022), whereas those of five objects (A2537-ID24, A2537-ID66, M0035-ID33, R0032-ID63, R0032-ID81) are taken from the literature and those of two objects (ACT0102-ID223, ACT0102-ID294) are estimated by the

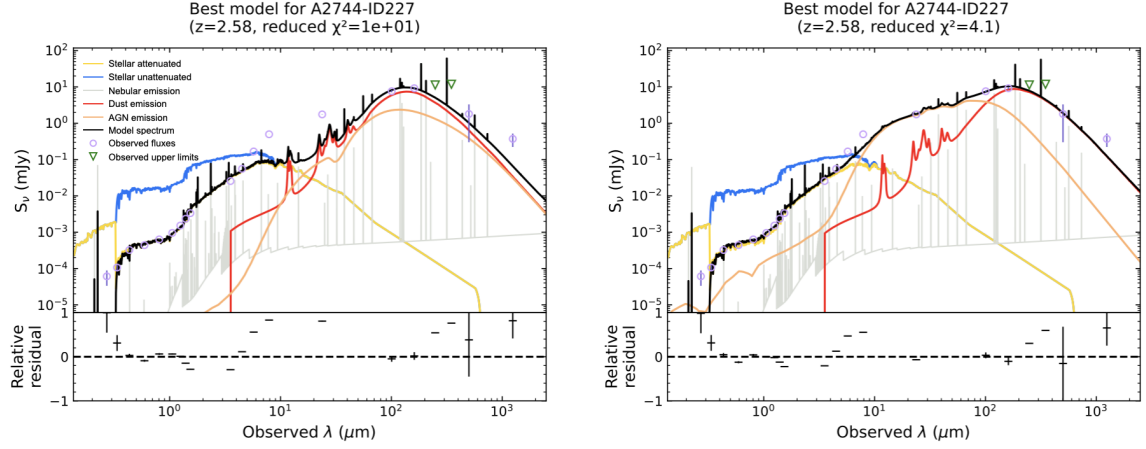


Figure B.1: The SED and the best-fit model of A2744-ID227 analyzed with the basic parameter set (left panel) and those with the extended parameter set (right panel). The SEDs are NOT corrected for lensing magnification. The colors and the symbols are the same as those in Figure 3.4.

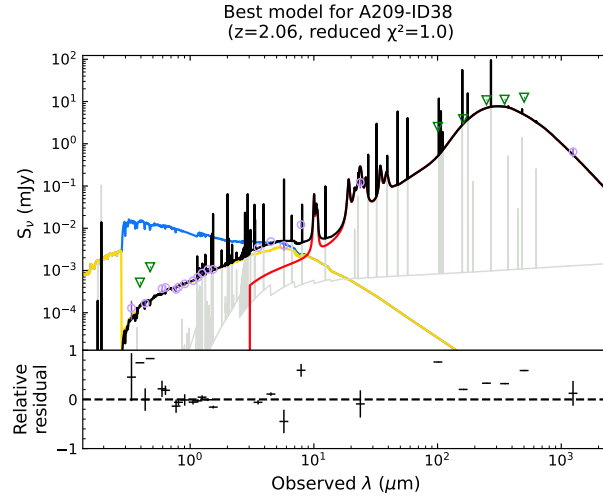


Figure B.2: Example of the SED and the best-fit model of the ALCS sample. The complete figure set (160 images) is available in the online journal.

Table B.1: Basic parameter set used for the SED modeling

Parameter	Symbol	Value
	SFH (sfhdelayed)	
e-folding time of the main stellar population	τ_{main} [Myr]	100, 316, 1000, 3162, 10000
Age of the main stellar population	age_{main} [Myr]	100, 158, 251, 398, 631, 1000, 1585, 2512, 3981, 6310
e-folding time of the late burst population	τ_{burst} [Myr]	100
Age of the late burst population	$\text{age}_{\text{burst}}$ [Myr]	5, 10, 50, 100
Mass fraction of the late burst population	f_{burst}	0, 0.05, 0.1, 0.3
	SSP (bc03; Bruzual & Charlot 2003)	
IMF of the stellar model		Chabrier (2003)
Metallicity of the stellar model		0.02
	Dust Attenuation (dustatt_modified_starburst; Calzetti et al. 2000)	
The color excess of the nebular lines.	$E(B - V)_{\text{lines}}$	0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4
Reduction factor to apply $E(B - V)_{\text{lines}}$ to calculate the stellar continuum attenuation	$E(B - V)_{\text{factor}}$	0.44
UV bump amplitude		0, 3 (MW)
Power-law index to modify the attenuation curve	δ	-1.6, -1.2, -0.8, -0.4, 0.0, 0.4
	Dust emission (EThemis)	
Mass fraction of the small hydrocarbon solids	q_{hac}	0.01, 0.02, 0.06
Minimum radiation field	$\log U_{\text{min}}$	-1.0, -0.2, 0.4, 0.8, 1.2, 1.6, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 3.6, 3.8
Power-law index of the starlight intensity distribution	α	2.5
Mass fraction of dust illuminated with $U = U_{\text{min}}$	$1 - \gamma$	0.95, 0.99
	AGN emission (skirtor2016; Stalevski et al. 2012, 2016)	
Average edge-on optical depth at 9.7 micron	$\tau_{9.7}$	11
Radial gradient of dust density	p	1.0
Dust density gradient with polar angle	q	1.0
Half-opening angle of the dust-free cone	Δ [°]	40
Ratio of outer to inner radius	R	20
Inclination	θ [°]	30, 70
Fraction of AGN IR luminosity to total IR luminosity	f_{AGN}	0.0, 0.1, 0.3, 0.5, 0.7, 0.9 (0.0 for the SECONDARY sample)
Extinction in polar direction	$E(B - V)$	0.3
Temperature of the polar dust	T_{pol} [K]	150

Table B.2: Parameter set of AGN component used for A2744-ID227

Parameter	Symbol	Value
AGN emission (skirtor2016; Stalevski et al. 2012, 2016)		
Average edge-on optical depth at 9.7 micron	$\tau_{9.7}$	3, 11
Radial gradient of dust density	p	1.0
Dust density gradient with polar angle	q	1.0
Half-opening angle of the dust-free cone	Δ [°]	40
Ratio of outer to inner radius	R	20
Inclination	θ [°]	70
Fraction of AGN IR luminosity to total IR luminosity	f_{AGN}	0.0, 0.1, 0.3, 0.5, 0.7, 0.9
Extinction in polar direction	$E(B - V)$	0.0, 0.3
Temperature of the polar dust	T_{pol} [K]	150

Table B.3: Parameter set of dust emission component used for tier-3/4 samples

Parameter	Symbol	Value
	Dust emission (EThemis)	
Mass fraction of the small hydrocarbon solids	q_{hac}	0.01
Minimum radiation field	$\log U_{\text{min}}$	-1.0, -0.2, 0.4, 0.8, 1.2, 1.6, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 3.6, 3.8
Power-law index of the starlight intensity distribution	α	2.5
Mass fraction of dust illuminated with $U = U_{\text{min}}$	$1 - \gamma$	0.99

sky positions and the lens model. The photometric redshifts of the tier-3/4/7/8 sources are estimated by near-infrared to millimeter SED analysis with a composite SED model obtained from AS2UDS sample (Dudzevičiūtė et al., 2020). To simplify the discussion, here we only discuss the photometric redshifts estimated by EAZY.

First, we calculate the photometric redshifts of tier-1/2/5/6 sources by optical to millimeter SED analysis with MAGPHYS PHOTO-Z EXTENSION (Battisti et al., 2019). Since the current version of MAGPHYS cannot treat an AGN component, the ALCS-XAGNs and ALCS-nonXAGNs are not analyzed in this section. Figure B.3 shows the results. The left panel plots photometric redshifts estimated by MAGPHYS PHOTO-Z EXTENSION versus spectroscopic ones. We confirm good agreement in those values, where 34/44 (77%) sources meet $|z_{\text{spec}} - z_{\text{photo}}|/(1 + z_{\text{spec}}) < 0.2$. The right panel plots photometric redshifts derived by MAGPHYS versus ones obtained by EAZY. We again confirm good agreement in those values, where 59/72 (82%) sources meet $|z_{\text{MAGPHYS}} - z_{\text{EAZY}}|/(1 + z_{\text{EAZY}}) < 0.2$.

Second, in order to evaluate the impact of redshift uncertainty on the derived physical properties, we independently estimate the physical parameters by optical to millimeter SED analysis with MAGPHYS HIGH-Z EXTENSION (v2) (Battisti et al., 2020; da Cunha et al., 2015), where the redshifts are fixed at the photometric ones derived by EAZY. Figure B.4 plots the physical properties estimated with variable redshifts versus those estimated at fixed redshifts. The standard deviations from the identity relations are 0.54 dex, 0.29 dex, 0.47 dex, 0.42 dex, and 6.1 K for SFR, stellar mass, dust luminosity, dust mass, and dust temperature, respectively. This indicates that the uncertainties in redshift measurement can cause at least these levels of uncertainties in each of the parameters.

B.4 Comparison between cigale and magphys

In this section, we check possible systematic differences in the estimation of physical properties between CIGALE and MAGPHYS. See also Hunt et al. (2019) and Pacifici et al. (2023) for comprehensive studies among some popular SED analysis codes. For a conservative discussion, we only discuss the tier-1 samples, where the physical properties are more reliably constrained than the other samples. In addition, since the current version of MAGPHYS cannot treat an AGN component, ALCS-XAGNs and ALCS-nonXAGNs are excluded. Figure B.5 compares the major physical properties

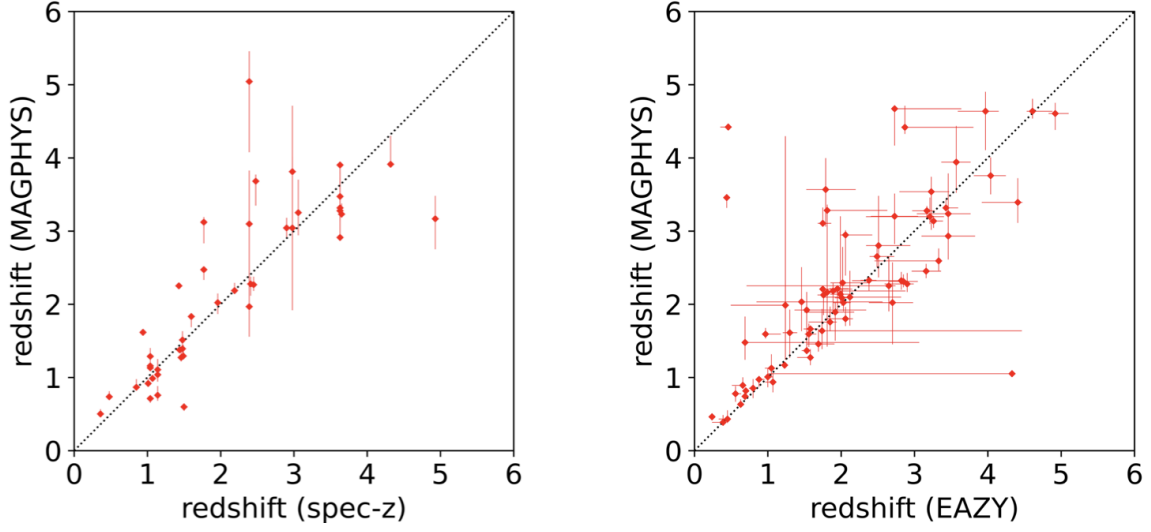


Figure B.3: (Left) Comparison between spectroscopic redshift and photometric redshift estimated by MAGPHYS. (Right) Comparison between photometric redshift estimated by EAZY and that estimated by MAGPHYS. The black dotted lines show the identity relations.

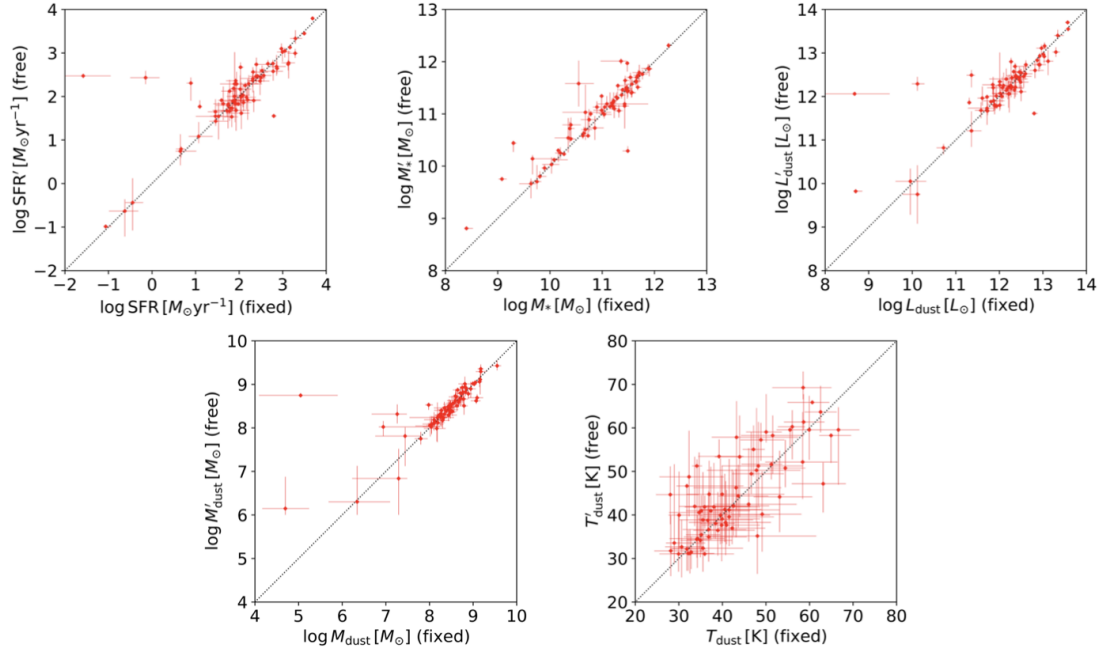


Figure B.4: Comparison of the physical properties estimated with redshifts left as a free parameter (vertical axis) versus those estimated at fixed redshifts (horizontal axis). The black dotted lines show the identity relations. The lensing magnification is not corrected for the SFR, stellar mass, dust luminosity, and dust mass.

estimated with CIGALE with those with MAGPHYS. We perform Passing-Bablok regression analysis for each parameter, where the conversion relation is shown at the bottom of each panel. We find good agreement for SFR, dust luminosity, and dust mass, while a large discrepancy is found for dust temperature (~ 7 K at 30 K) and stellar mass (~ 0.37 dex at $\log M_*/M_\odot = 10.5$). These differences can be explained as follows:

1. The systematic difference in dust temperature can be attributed to its definition. In the EThemis model (used in CIGALE), dust temperature is defined as the intrinsic temperature of cold interstellar dust illuminated by a radiation field of $U = U_{\text{min}}$. By contrast, in MAGPHYS, dust temperature is defined as the luminosity-weighted average of warm birth clouds and cold interstellar dust. Since dust temperature derived by MAGPHYS is also affected by the warm dust components, this value tends to be larger than that derived by CIGALE.
2. The systematic difference in stellar mass can be attributed to the difference in dust attenuation models. In this study, we use the modified Calzetti law in CIGALE, whereas the Charlot & Fall (2000) model is used in MAGPHYS. The modified Calzetti law assumes a single dust component (interstellar dust) with flexible attenuation curves. By contrast, the Charlot & Fall (2000) model assumes two dust components with fixed power-law attenuation slopes (interstellar dust and birth cloud). In the model of Charlot & Fall (2000), even near-infrared emission from young stars can be heavily attenuated by thick birth clouds. This may cause overestimation of intrinsic near-infrared luminosities, and hence stellar masses in MAGPHYS.* In CIGALE, we can also choose the Charlot & Fall (2000) model for the dust attenuation model. In this case, we confirm good agreement between stellar mass estimated with CIGALE and that with MAGPHYS (Figure B.6).

Moreover, we confirm that the standard deviations around the regression lines are 0.59 dex, 0.40 dex, 0.17 dex, 0.33 dex, and 7.8 K for SFR, stellar mass, dust luminosity, dust mass, and dust temperature, respectively. These values are significantly larger than the median statistical errors estimated with CIGALE and MAGPHYS. This indicates that the reported errors in the physical properties are fairly underestimated, considering the uncertainties in the SED models.

*By contrast, stellar masses can be underestimated with CIGALE because of the simplified dust component, which may underestimate the near-infrared emission from young stars.

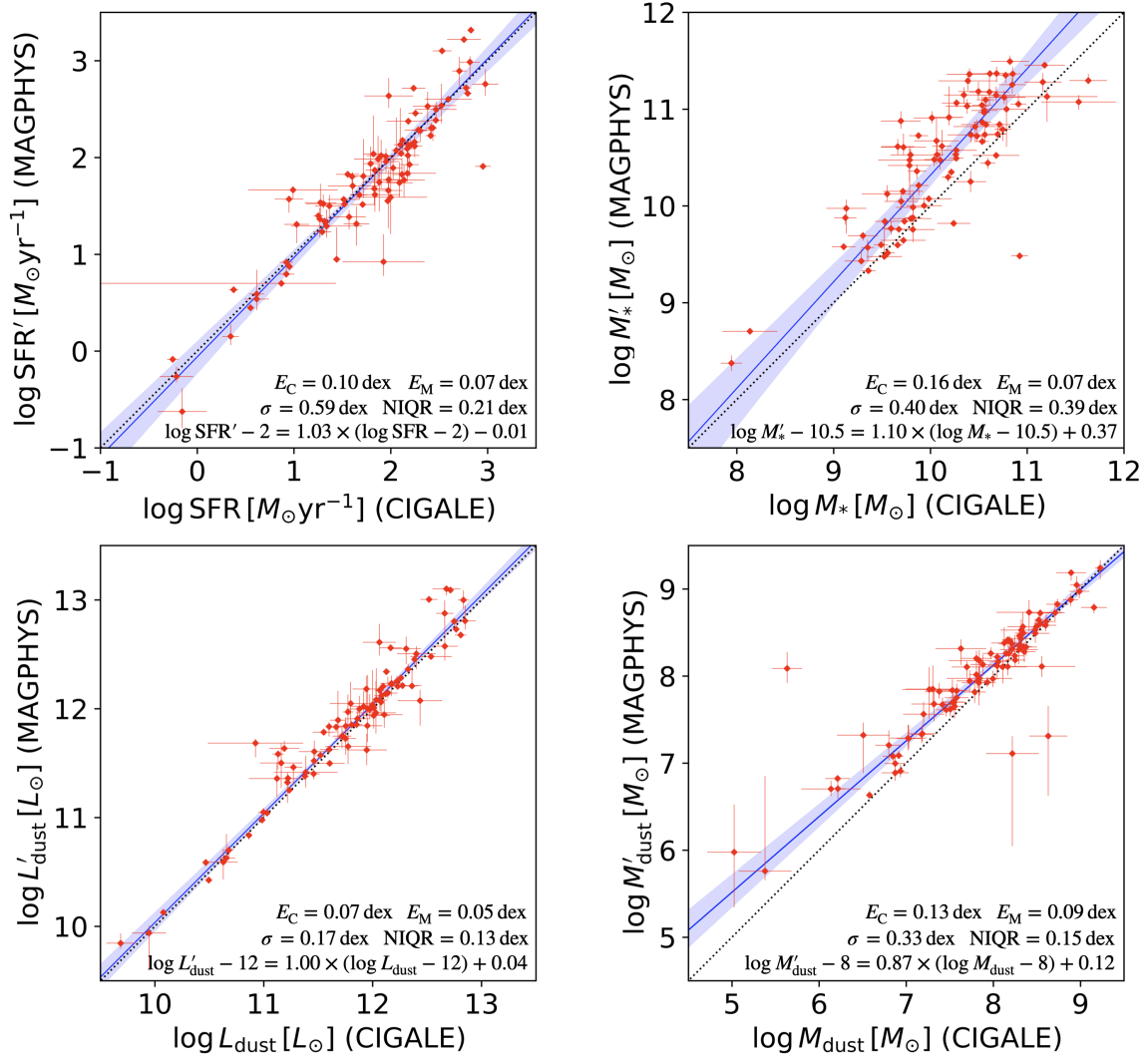


Figure B.5: Comparison of SFR, stellar mass, dust luminosity, dust mass, and dust temperature measured by CIGALE and MAGPHYS. The blue solid lines show the regression lines, which are shown in the bottom equations in each panel. The semi-transparent blue bands show the 95% confidence regions of each correlation. The standard deviations (σ) and normalized interquartile ranges (NIQR) around the regression lines measured in the vertical axes are shown at the bottom of each panel. We also show the median value of the statistical errors estimated with CIGALE (E_C) and MAGPHYS (E_M) for comparison. The black dotted lines show the identity relations. For a conservative discussion, only the tier-1 samples are plotted for the ALCS sample. The multiply-imaged sources are plotted individually. The lensing magnification is corrected for the SFR, stellar mass, dust luminosity, and dust mass.

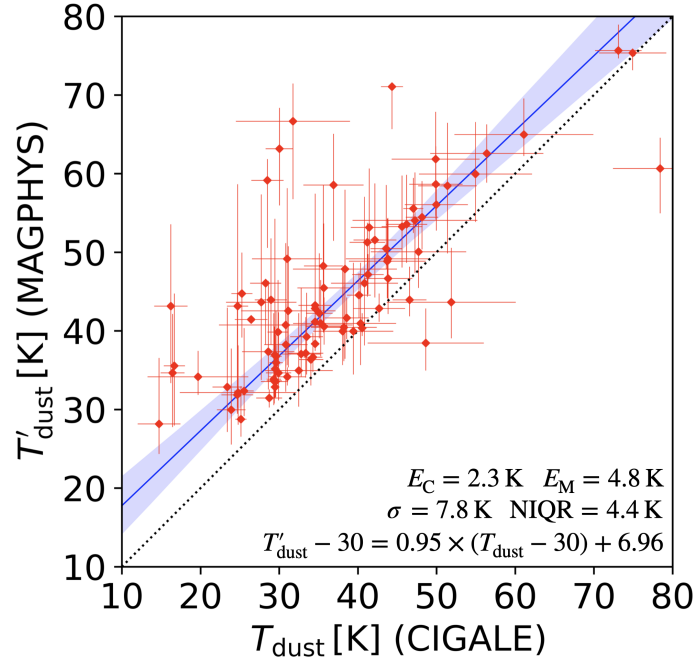


Figure B.5 (continued)

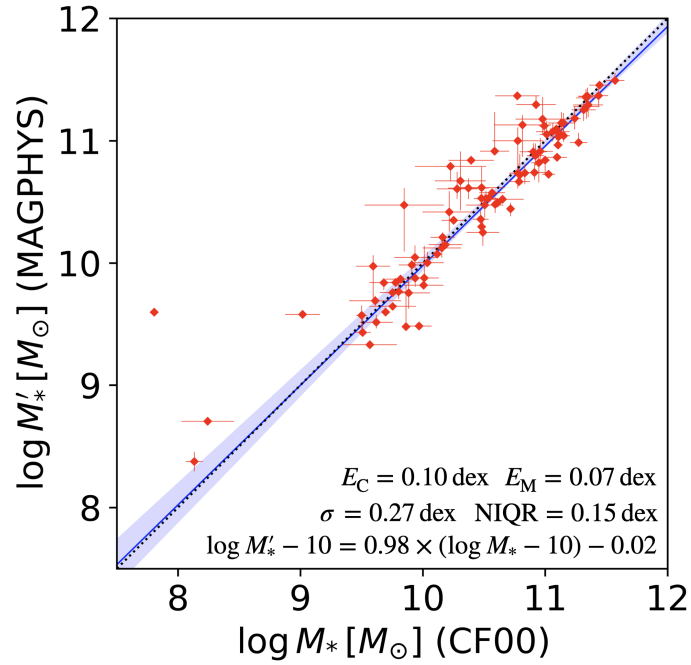


Figure B.6: Comparison of stellar mass estimated with CIGALE using the Charlot & Fall (2000) model with that estimated with MAGPHYS. The symbols are the same as those in Figure B.5. The lensing magnification is corrected for the stellar masses.

B.5 Conversion method of dust temperature

In this section, we summarize the conversion method of dust temperature among different definitions. First, for the ALESS sample, da Cunha et al. (2021) adopted a single optically-thin graybody with various emissivity indices. In this case, characteristic dust temperature is calculated as:

$$T_{\text{dust}}^{\text{peak}} = [W(-(\beta + 3)e^{-\beta-3}) + \beta + 3] / 2.821 \times T_{\text{dust}} \quad (\text{B.5.4})$$

where W is the Lambert W function (principal branch) and β is the emissivity index. Second, for the AS2UDS sample, Dudzevičiūtė et al. (2020) estimated the dust temperatures by adopting a single optically-thin graybody with an emissivity index of 1.8. This value is converted to the characteristic temperature by applying Equation B.5.4 assuming $\beta = 1.8$, which is described as:

$$T_{\text{dust}}^{\text{peak}} \simeq 1.7 \times T_{\text{dust}} \quad (\text{B.5.5})$$

Third, in the case of the ALCS sample, as shown in Nersesian et al. (2019), the far-infrared emission from the EThemis model can be approximated by a graybody with an emissivity index of 1.79. Therefore, we convert the value by applying Equation B.5.5. Finally, for the ASPECS sample, Aravena et al. (2020) used MAGPHYS to estimate the dust temperature. Since MAGPHYS uses a complex dust emission model, it is difficult to obtain the conversion relation from the model itself. Hence, we utilize the conversion law between MAGPHYS and CIGALE denoted in Figure B.5, and yield the conversion relation using Equation B.5.5, which is described as:

$$\begin{aligned} T_{\text{dust}}^{\text{peak}} &\simeq 1.7 * T_{\text{dust}}[\text{CIGALE}] \\ &\simeq 1.7 * (T_{\text{dust}}[\text{MAGPHYS}] - 8.3) / 0.95 \end{aligned} \quad (\text{B.5.6})$$

APPENDIX C

Appendices of Chapter 4

C.1 MIRI Images of AS2COSMOS Sources

Figure C.1 shows the color-composite images of the 40 sources in the coverage of both NIRCam and MIRI. AS2COS0019.1 and AS2COS0048.1 have point-like morphology in the MIRI/F770W band, which is consistent with the results of the SED modeling.

C.2 Astrometry Check for X-ray Sources

Figure C.2 (a) shows the positional offset between the X-ray source positions and the optical source positions used for the astrometry correction. After the correction, 95% of the X-ray sources have their optical counterparts within 0.74 arcsec, which is 18% smaller than the value before the correction (0.90 arcsec). Then, to check the astrometric accuracy, we cross-match the X-ray source positions derived in Section 4.2.6.2 to the COSMOS2020 catalog. Figure C.2 (b) shows the histogram of the separation. For comparison, we plot the separation between the X-ray source positions in Civano et al. (2016) and the optical to near-infrared source positions in the COSMOS2020 catalog. We find that the median separation is about two

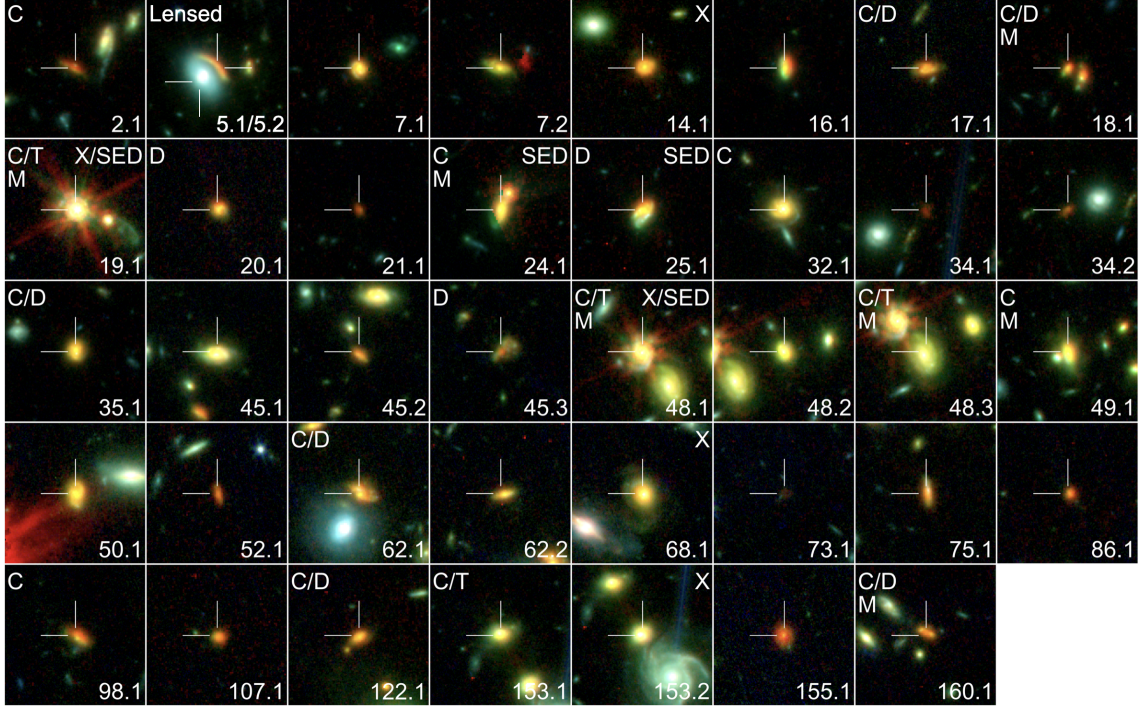


Figure C.1: 8 arcsec $\times$ 8 arcsec JWST images of the 40 AS2COSMOS sources in the coverage of both NIRCam and MIRI imaging. The blue, green, and red colors correspond to the F115W+F150W, F277W+F444W, and F770W filters, respectively. We label the merger candidates, which have tidal features (T), disturbed morphology (D) or possible companions (C) (see Section 4.3.3). The major merger candidates are indicated by “M”. The X-ray AGNs and the SED AGNs are indicated by “X” and “SED” (see Section 4.3.1.3 and Section 4.4.1). Note that F150W is not used in the composite image of AS2COS0107.1, because this object is outside the coverage of F150W. For the same reason, F444W is not used in the composite image of AS2COS155.1.

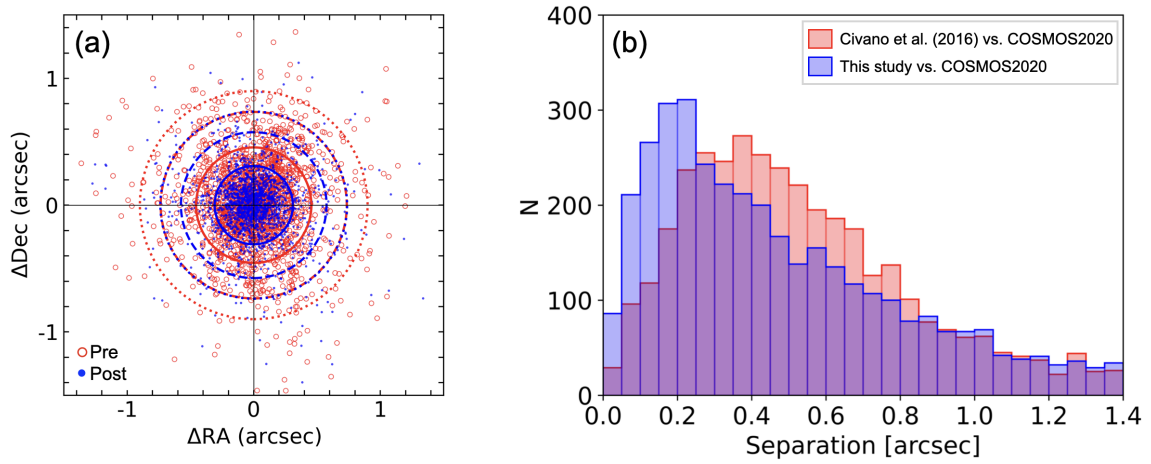


Figure C.2: (a) Positional offsets between optical sources and X-ray sources used for the astrometry correction. The solid, dotted, and dashed circles encompass 68%, 90%, and 95% of the sources before (red) and after (blue) the correction, respectively. (b) Histogram of the separation between the X-ray source positions and the optical to near-infrared source positions in the COSMOS2020 catalog. The red area shows the separation between Civano et al. (2016) and the COSMOS2020 catalog, while the blue area denotes the separation between our X-ray source catalog (Section 4.2.6.2) and the COSMOS2020 catalog.

times smaller in our catalog than Civano et al. (2016). This suggests that the X-ray source positions in our catalog are better aligned with the COSMOS2020 catalog than Civano et al. (2016), which is likely because our source positions are calibrated by the COSMOS2020 catalog whereas the CFHT MegaCam catalog (McCracken et al., 2012) was used as a reference in Civano et al. (2016).

Figure C.3 shows the positions of the X-ray-detected sources near AS2COS0353.1 and AS2COS0353.2 plotted over the Ultravista K_s -band image.* The red points show the X-ray source positions listed in the catalog by Civano et al. (2016), whereas the blue points show the positions derived in our analysis. We notice a systematic offset of about 1 arcsec between the source positions of the two catalogs. As noticeable in boxes (b) and (e) in Figure C.3, the X-ray source positions in our catalog look better aligned with the Ultravista K_s -band image than those in Civano et al. (2016). The X-ray source in the (c) box is first identified as the X-ray counterpart of AS2COS0353.2. However, the corresponding X-ray source in our image looks likely associated with AS2COS0353.1. Therefore, we consider that the X-ray source in the (c) box is associated with AS2COS0353.1.

*The K_s -band image of the COSMOS field is provided on the COSMOS website (<https://cosmos.astro.caltech.edu/page/optical>).

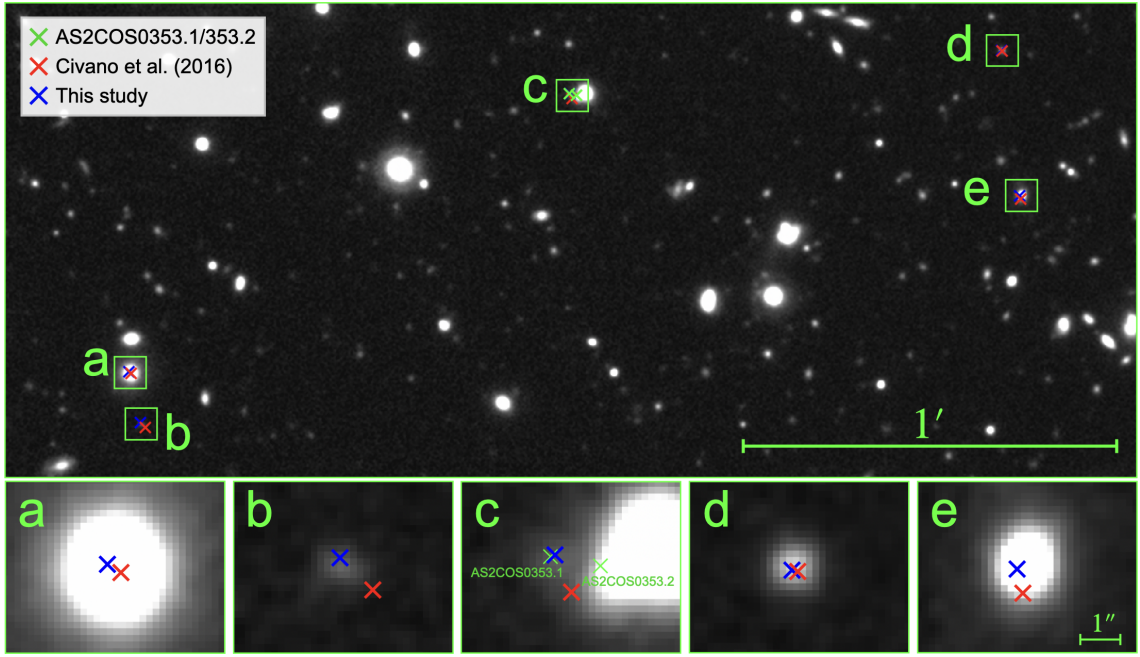


Figure C.3: Positions of the X-ray-detected sources near AS2COS0353.1 and AS2COS0353.2 plotted over the Ultravista K_s -band image. The red points show the X-ray source positions listed in the catalog by Civano et al. (2016), whereas the blue points show the positions derived in our analysis (Section 4.2.6.2). The green points show the positions of AS2COS0353.1 and AS2COS0353.2. The bottom panels show the zoomed-in images of the X-ray sources.

C.3 Details of Iteration of the SED Modeling

In this section, we describe the details of the second run in SED modeling. For comparison purposes, we summarize the “basic” parameter set used in the first run in Table C.1. After the first run, we notice some issues in the photometry and the parameter settings. Therefore, we add the following operations and re-perform SED modeling. We confirm that these operations significantly improve the best-fit statistic.

C.3.1 Photometry Optimization

In the first run, we notice some inconsistencies between the photometry within individual sources. This can be attributed to the remaining blending effect or a failure in extracting the photometry. For these reasons, we check the images and decide to treat the following photometry as upper limits: AS2COS0001.1 (Spitzer 3.6 μm), AS2COS0043.1 (Ultravista $YJHK_s$), AS2COS0065.2 (Ultravista $YJHK_s$), and AS2COS0228.1 (Ultravista $YJHK_s$). We also treat the Ultravista $YJHK_s$ photometry of AS2COS123.1 as upper limits because we confirm no significant detection in those images. Moreover, we notice systematic offsets between the HSC *grizY* and Ultravista $YJHK_s$ photometry of AS2COS0019.1, AS2COS0086.1, AS2COS0175.1, and AS2COS0203.1. This might be caused by calibration issues. Hence, we replace these photometry with the ones extracted from the COSMOS2020 catalog.

In addition to these operations, we optimize the photometry of some sources by referring to the HSC-SSP DR3 catalog. We replace the optical photometry of AS2COS0063.1, AS2COS0123.1, and AS2COS0228.1 with the ones extracted from the HSC-SSP DR3 catalog (Aihara et al., 2022). We also update the Ultravista $YJHK_s$ photometry of AS2COS0063.1 with the ones extracted from the Ultravista DR4 catalog, which appear to be less affected by a bright contaminating source. Furthermore, we exclude the Spitzer 4.5 μm , 5.8 μm , and 8.0 μm photometry of AS2COS0228.1 because of the significant contamination by AS2COS0228.2.

Table C.1: Basic parameter sets used for the SED modeling. The overall size of the parameter grid is 3,594,240,000.

Parameter	Symbol	Value
SFH (sfhdelayedbg)		
E-folding time of the main stellar population	τ_{main} [Myr]	100, 316, 1000, 3162, 10000
Age of the main stellar population	age_{main} [Myr]	100, 158, 251, 398, 631, 1000, 1585, 2512, 3981, 6310
Age of the late burst/quench population	age_{bg} [Myr]	10
Ratio of the SFR after/before age_{bg}	r_{SFR}	1, 10, 100, 1000
SSP (bc03; Bruzual & Charlot 2003)		
IMF of the stellar model		Chabrier (2003)
Metallicity of the stellar model		0.02
Dust attenuation (dustatt_modified_starburst; Calzetti et al. 2000; Leitherer et al. 2002)		
Colour excess of the nebular lines.	$E(B - V)_{\text{lines}}$	0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.4, 2.8, 3.2
Reduction factor to apply $E(B - V)_{\text{lines}}$ to calculate the stellar continuum attenuation	$E(B - V)_{\text{factor}}$	0.44
UV bump amplitude		0 (no bump)
Power-law index to modify the attenuation curve	δ	-0.4, 0.0, 0.4
Dust emission (EThemis; Uematsu et al. 2024)		
Mass fraction of the small hydrocarbon solids	q_{hac}	0.01, 0.02, 0.06, 0.10
Minimum radiation field	U_{min}	0.0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4, 3.0
Power-law index of the starlight intensity distribution	α	2.5, 3.0
Mass fraction of dust illuminated with $U = U_{\text{min}}$	$1 - \gamma$	0.9
AGN emission (skirtor2016; Stalevski et al. 2012, 2016)		
Average edge-on optical depth at 9.7 micron	$\tau_{9.7}$	3, 7
Radial gradient of dust density	p	1.0
Dust density gradient with polar angle	q	1.0
Half-opening angle of the dust-free cone	Δ [°]	40
Ratio of outer to inner radius	R	20
Inclination	θ [°]	30, 60, 80
Fraction of AGN IR luminosity to total IR luminosity	f_{AGN}	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
Extinction in polar direction	$E(B - V)$	0.0, 0.1
Temperature of polar dust	T_{pol} [K]	100
Redshifting		
Redshift	z	0.1-6.0 (step size: 0.1) or fixed at spectroscopic redshifts

Table C.2: Extended parameter set of the AGN module used for AS2COS175.1.

Parameter	AGN emission (skirtor2016; Stalevski et al. 2012, 2016)	Symbol	Value
Average edge-on optical depth at 9.7 micron		$\tau_{9.7}$	3, 5, 7, 9
Radial gradient of dust density		p	1.0
Dust density gradient with polar angle		q	1.0
Half-opening angle of the dust-free cone		$\Delta [^\circ]$	40
Ratio of outer to inner radius		R	20
Inclination		$\theta [^\circ]$	30, 40, 50, 60, 70, 80
Fraction of AGN IR luminosity to total IR luminosity		f_{AGN}	0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
Extinction in polar direction		$E(B - V)$	0.0, 0.05, 0.1
Temperature of the polar dust		$T_{\text{pol}} [\text{K}]$	100

C.3.2 Misidentified Source

The potential optical counterpart of AS2COS0072.1 was detected in the DEIMOS 10K spectroscopic survey. They spectroscopically confirmed that the source is at $z = 0.802$ with a quality flag of $Q_f = 4$ (highest quality). However, the submillimeter line scan performed by Liao et al. (2024) showed that AS2COS0072.1 is at $z = 3.798$. This inconsistency can be attributed to the misidentification of the counterpart. We thus regard the source at $z = 0.802$ as the foreground of AS2COS0072.1 and treat the optical to mid-infrared photometry as upper limits.

We also conclude that the optical to near-infrared counterpart of AS2COS0159.1 in HSC and Ultravista is misidentified. The high-resolution imaging by JWST revealed that there were two sources near the $870\text{-}\mu\text{m}$ source position. One was identified as a galaxy at $z = 0.033$ from the optical spectroscopy by PRIMUS. This source was initially identified as an optical counterpart of AS2COS0159.1, however, we notice that the peak wavelength of the far-infrared SED of AS2COS0159.1 is too long for a galaxy at $z = 0.033$.^{*} Therefore, we consider that the source at $z = 0.033$ is foreground of AS2COS00159.1. We confirm that the foreground source was only dominant below the F277W band. We thus decide to treat the optical to near-infrared photometry as upper limits.

C.3.3 SED Fitting Parameter Optimization

With the basic parameter set used in the first run, the mid- to far-infrared SED AS2COS175.1 is not well reproduced. This can be attributed to the oversimplification of the AGN component. Hence, we extend the parameter grids and recalculate the SED of these sources. The extended parameter set is summarized in Table C.2.

C.3.4 Overall Quality of the Final Fits

Following the procedures described above, we finally obtain reasonable fits for all the sources. Figure C.4 shows the histogram of the reduced χ^2 for the final fits. The

^{*}The peak of the far-infrared emission of AS2COS0159.1 is $\sim 350\text{ }\mu\text{m}$ in the observed frame. This corresponds to 9 K assuming an optically-thin graybody with an emissivity index of 1.8 at $z = 0.033$.

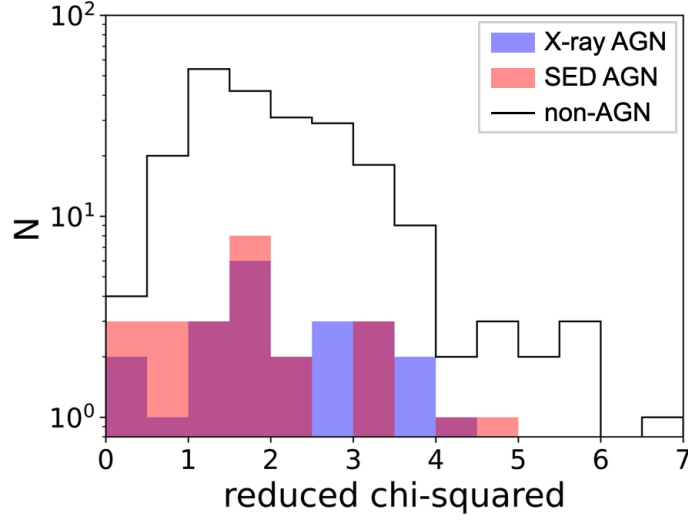


Figure C.4: Histogram of the reduced χ^2 for the final fits. The median and the maximum reduced χ^2 are 1.8 and 6.5, respectively.

median and the maximum reduced χ^2 are 1.8 and 6.5, which indicates that the SEDs are well reproduced.

C.4 Consistency Check of SED Modeling

Figure C.5 compares some observational properties with the physical properties derived by the SED modeling that they are expected to most strongly correlate with. We confirm positive correlations in these plots, supporting the validity of our SED analysis.

C.5 Mock Analysis

Figure C.6 compares the stellar masses and SFRs derived by CIGALE with those derived from the mock catalog. We confirm that most of the sources align well, but AS2COS0285.2 shows a large discrepancy in stellar mass, and AS2COS0175.1 shows large discrepancies in both stellar mass and SFR. AS2COS0285.2 is a galaxy without an AGN. This source is not detected in the optical band and has no spectroscopic redshift, which may make it difficult to constrain the stellar component. AS2COS0175.1 is a type-1 SED AGN. According to the SED fitting result, the optical to near-infrared SED of this source is dominated by the AGN emission, which may

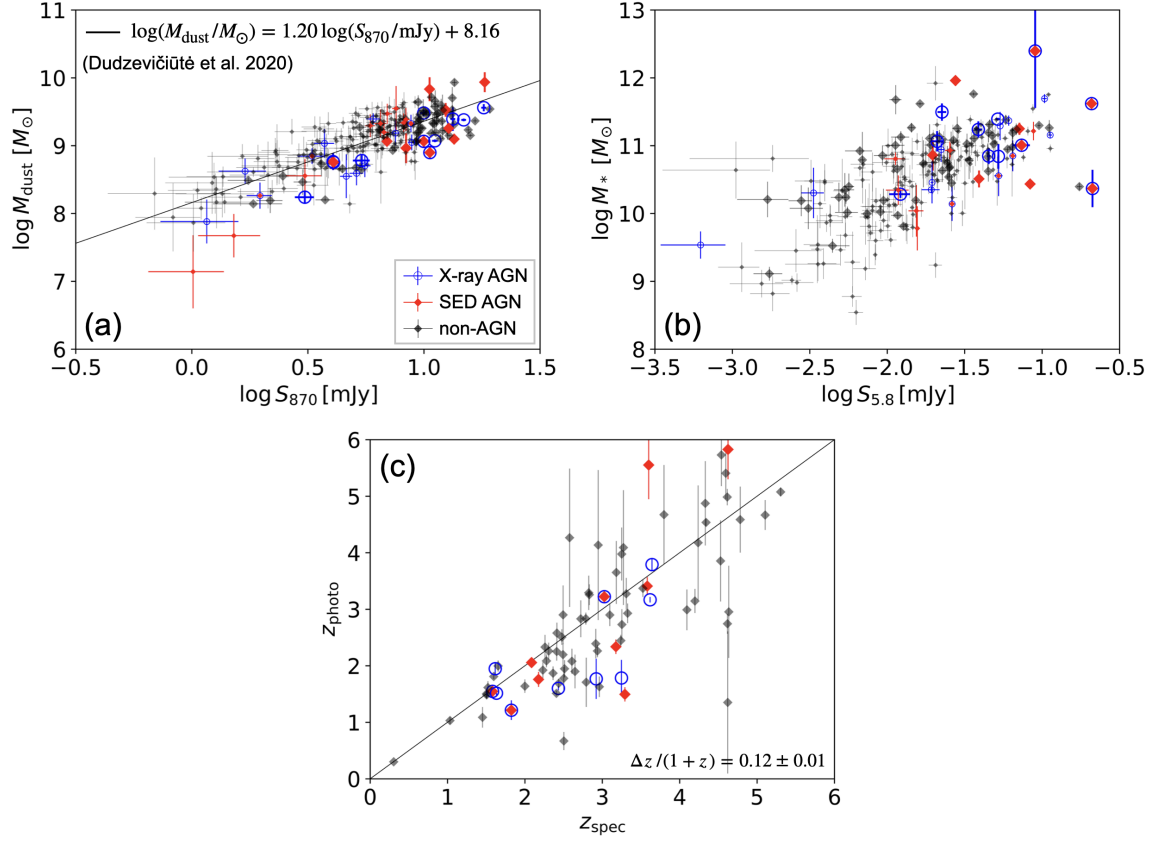


Figure C.5: Comparison of the physical properties derived by the SED template fitting and the observational properties for the X-ray-detected AS2COSMOS sources (X-ray AGN; see Section 4.4.1), SED AGNs, and the rest of the AS2COSMOS sources (non-AGNs). In panel (a) and (b), the large symbols show the spec- z sample, while the smaller ones show the photo- z sample. In panel (b), the sample is limited to the sources that are detected in Spitzer 5.8 μm . In panel (c), only the spec- z sample is plotted.

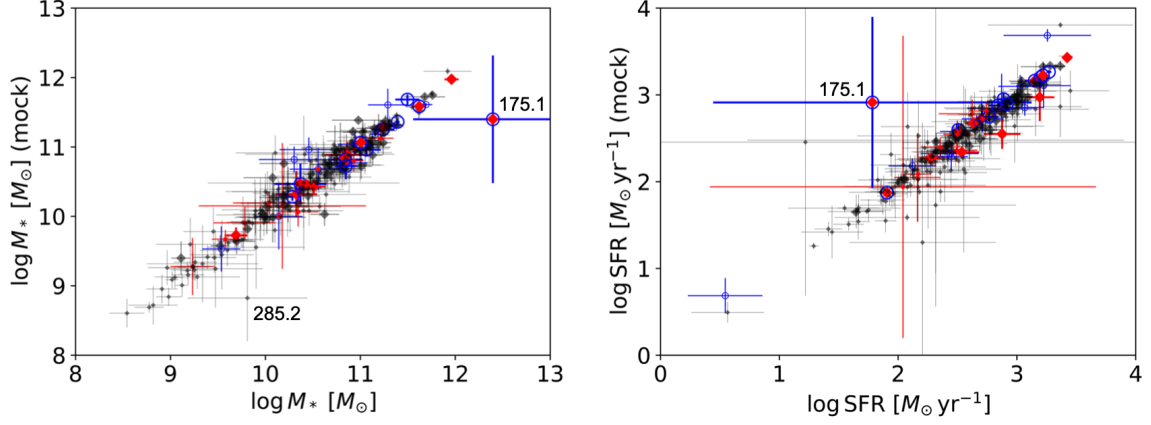


Figure C.6: Comparison of the stellar mass and SFR derived by the SED analysis with those derived from the mock catalog. We confirm that most of the sources align well, but AS2COS0285.2 shows a large discrepancy in stellar mass, and AS2COS0175.1 shows large discrepancies in both stellar mass and SFR. The large symbols show the spec- z sample, while the smaller ones show the photo- z sample.

make the estimations unreliable. We generated probability distribution functions (PDFs) of SFRs and stellar masses for several sources, including the problematic sources mentioned above. We confirmed that most of the PDFs have single-horn shapes, showing that the parameters are well constrained. However, the PDFs of AS2COS0175.1 have multi-horn structures. This indicates that the SFR and stellar mass of AS2COS0175.1 are unreliable.

C.6 Background Modeling for CXO ACIS-I

Table C.3 summarizes the best-fit parameters of the CXO ACIS-I background modeling (Section 4.3.2.1).

C.7 Figures of Individual Sources

Figure C.7 shows the X-ray spectra and best-fit models of the X-ray AGNs. Figure C.8 summarizes the plots of the goodness of fit as a function of the line-of-sight hydrogen column densities. Figure C.9 shows the SEDs and the best-fit models of the SED AGNs. Figure C.10 shows the SEDs and the best-fit models of the non-AGNs.

Table C.3: Summary of the background modeling for CXO ACIS-S (VFAINT mode).

Model	Parameter	Value	Unit
gaussian	E	1.487	keV
	σ	1	eV
	norm	$5.3^{+3.9}_{-3.7}$	10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$
gaussian	E	1.557	keV
	σ	1	eV
	norm	$7.7^{+3.9}_{-3.7}$	10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$
gaussian	E	2.123	keV
	σ	1	eV
	norm	$25.5^{+4.7}_{-4.5}$	10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$
gaussian	E	2.205	keV
	σ	1	eV
	norm	$11.0^{+4.4}_{-4.2}$	10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$
gaussian	E	2.410	keV
	σ	1	eV
	norm	$4.9^{+3.2}_{-3.1}$	10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$
gaussian	E	2.7	keV
	σ	61^{+39}_{-45}	eV
	norm	$8.2^{+4.3}_{-3.7}$	10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$
gaussian	E	7.478	keV
	σ	1	eV
	norm	$64.3^{+5.5}_{-5.3}$	10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$
gaussian	E	9.713	keV
	σ	1	eV
	norm	$139.8^{+6.8}_{-6.6}$	10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$
gaussian	E	9.628	keV
	σ	1	eV
	norm	linked	$1/9 \times \text{norm of Au } L\alpha_1$
gaussian	E	8.265	keV
	σ	1	eV
	norm	$14.5^{+4.2}_{-4.0}$	10^{-6} photons $\text{cm}^{-2} \text{s}^{-1}$
powerlaw	Γ	$0.143^{+0.026}_{-0.026}$	
	norm	$163.2^{+7.4}_{-7.4}$	10^{-6}
gabs	E	0.25	keV
	σ	153.5	eV
expdec	Strength	$0.99^{+2.39}_{-0.66}$	10^4
	α	$1.58^{+0.88}_{-0.49}$	
	norm	$3.1^{+5.6}_{-0.8}$	10^{-4}

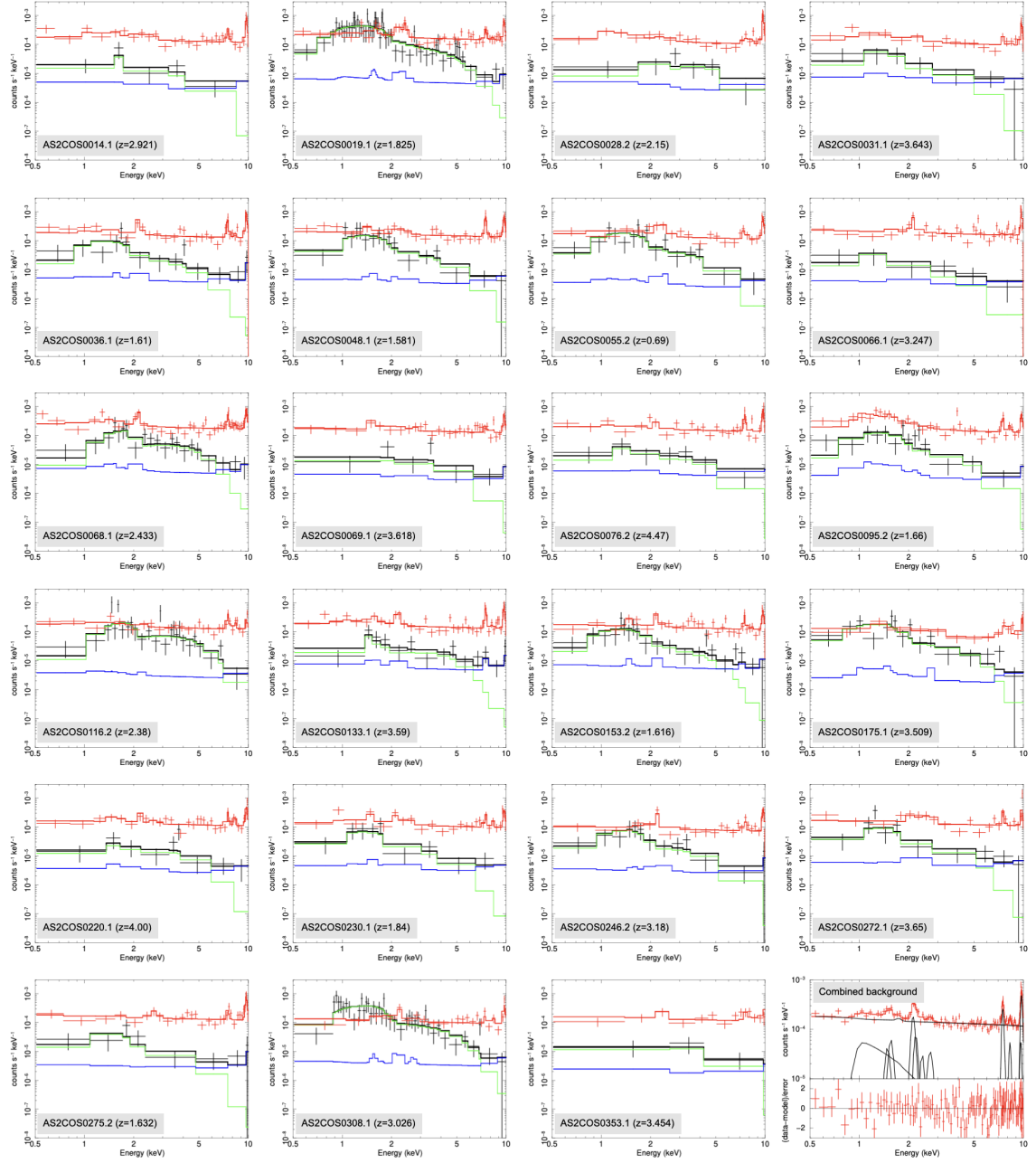


Figure C.7: (*AS2COS0014.1–AS2COS0353.1*) The 0.5–10 keV spectra of the 23 X-ray AGNs. The black points and the black solid lines show the observed spectra and the best-fit models. The red points and the red solid lines show the background spectra and the best-fit models. The blue solid lines show the scaled background spectra. The green solid lines show the background-subtracted source spectra. To improve visibility, the source and the background spectra are binned to have at least 1.5σ and 3σ in each bin, respectively. (*Combined background*) The combined background spectrum. The red points and the red solid line show the background spectra and the best-fit model. The black solid lines show the components of the model. The lower panel shows the residuals. To improve visibility, the combined background spectrum is binned to have at least 7σ in each bin. Note that the spectrum binning only affects the presentation of the data and does not affect the spectral analysis results.

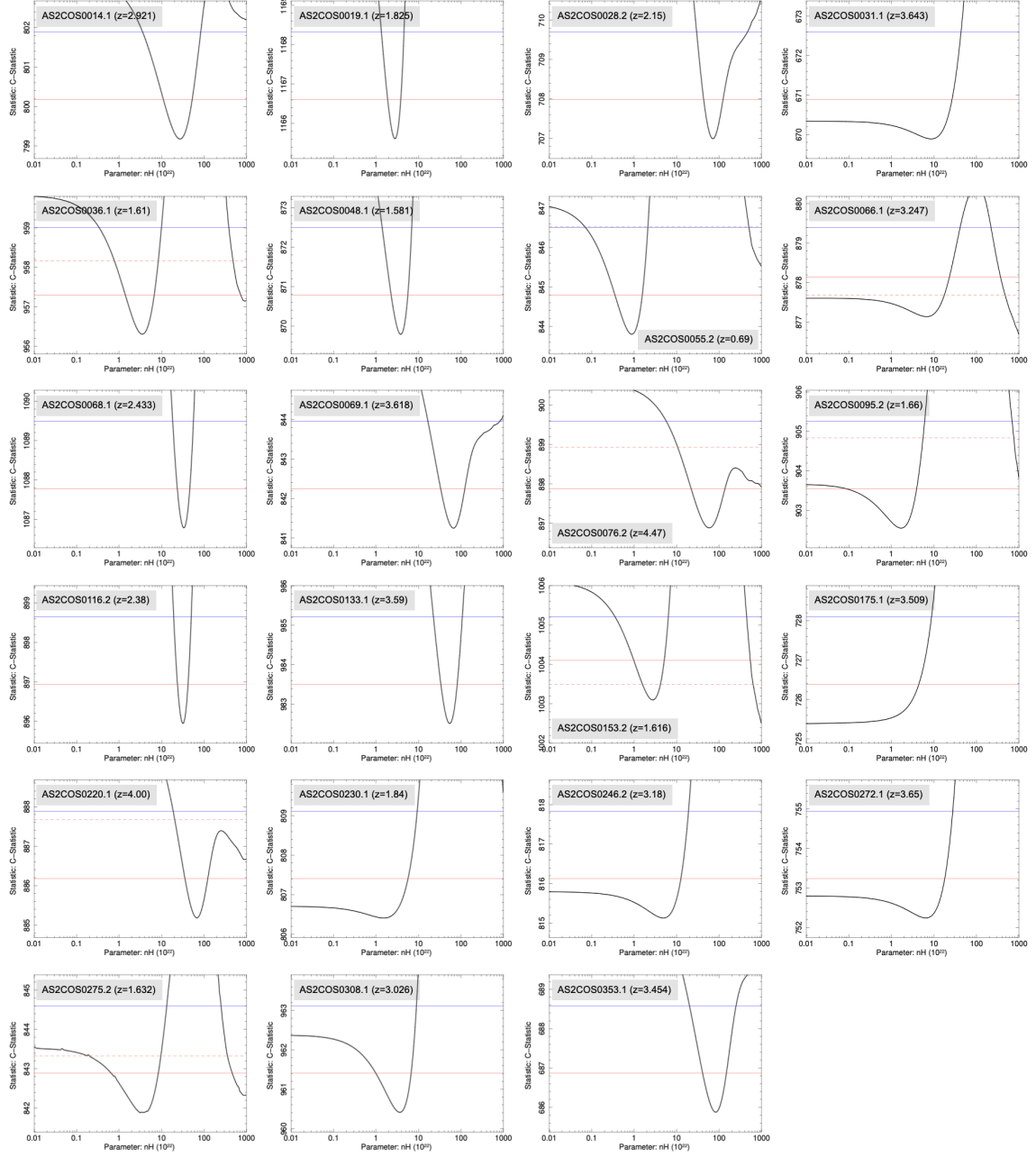


Figure C.8: Plots of the goodness of fit as a function of the line-of-sight hydrogen column densities. The vertical axes show the statistical values of the C-statistic. The horizontal axes show the line-of-sight hydrogen column densities in units of 10^{22} cm^{-2} . The blue lines show the 90 per cent confidence levels compared with the best-fit values. The red solid lines show the 68.27 per cent confidence levels (1σ) compared with the Compton-thin solutions. The red dashed lines show the 68.27 per cent confidence levels (1σ) compared with the Compton-thick solutions, if exist.

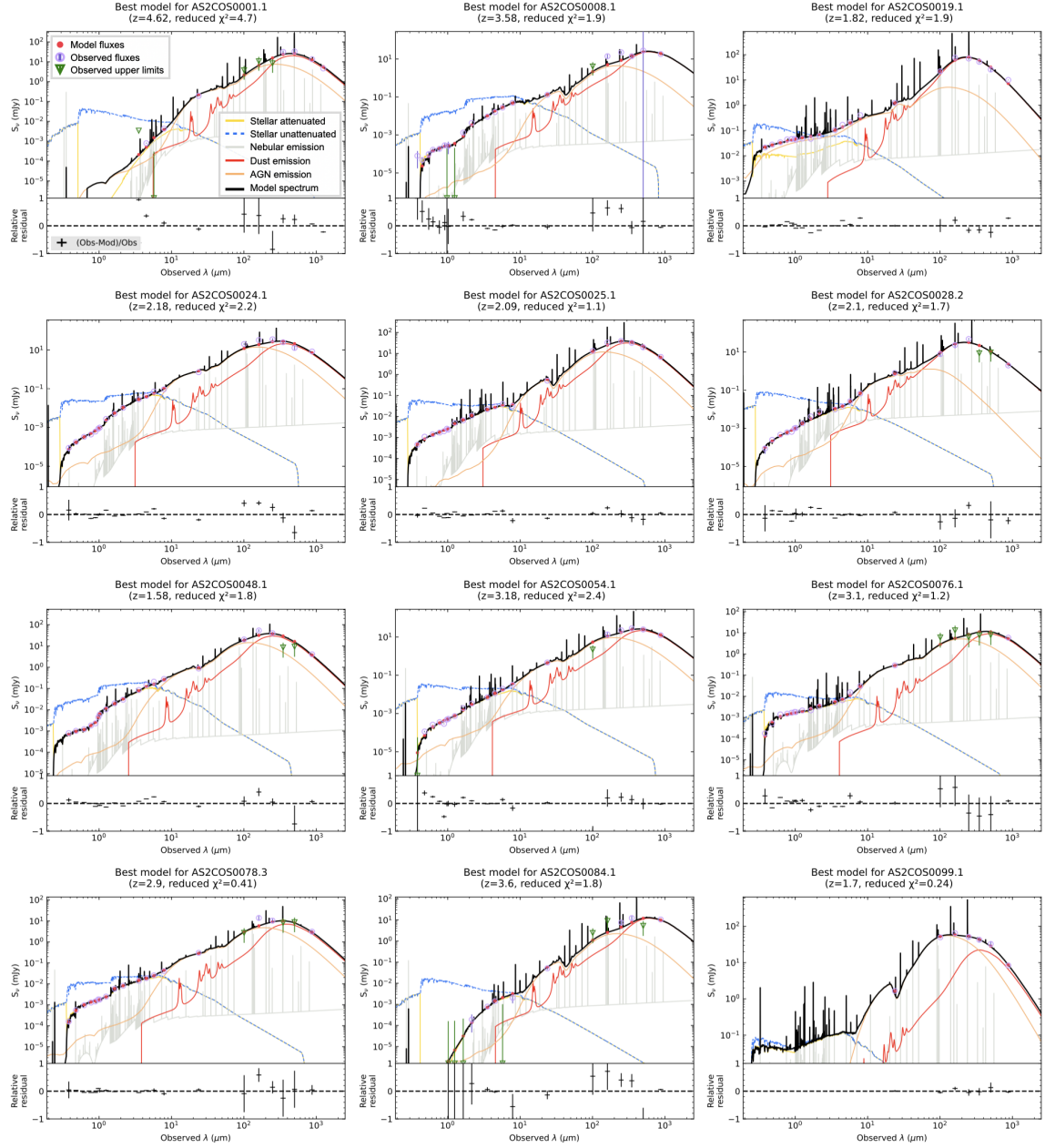


Figure C.9: The SEDs and best-fit models of the SED AGNs. The black solid line represents the composite spectrum. The yellow solid line illustrates the stellar emission attenuated by interstellar dust. The blue dashed line depicts the unattenuated stellar emission for a reference purpose. The orange line corresponds to the emission from an AGN. The red line shows the infrared emission from interstellar dust. The gray line denotes the nebulae emission. The observed data points are represented by purple circles, accompanied by 1σ error bars. The bottom panel displays the relative residuals.

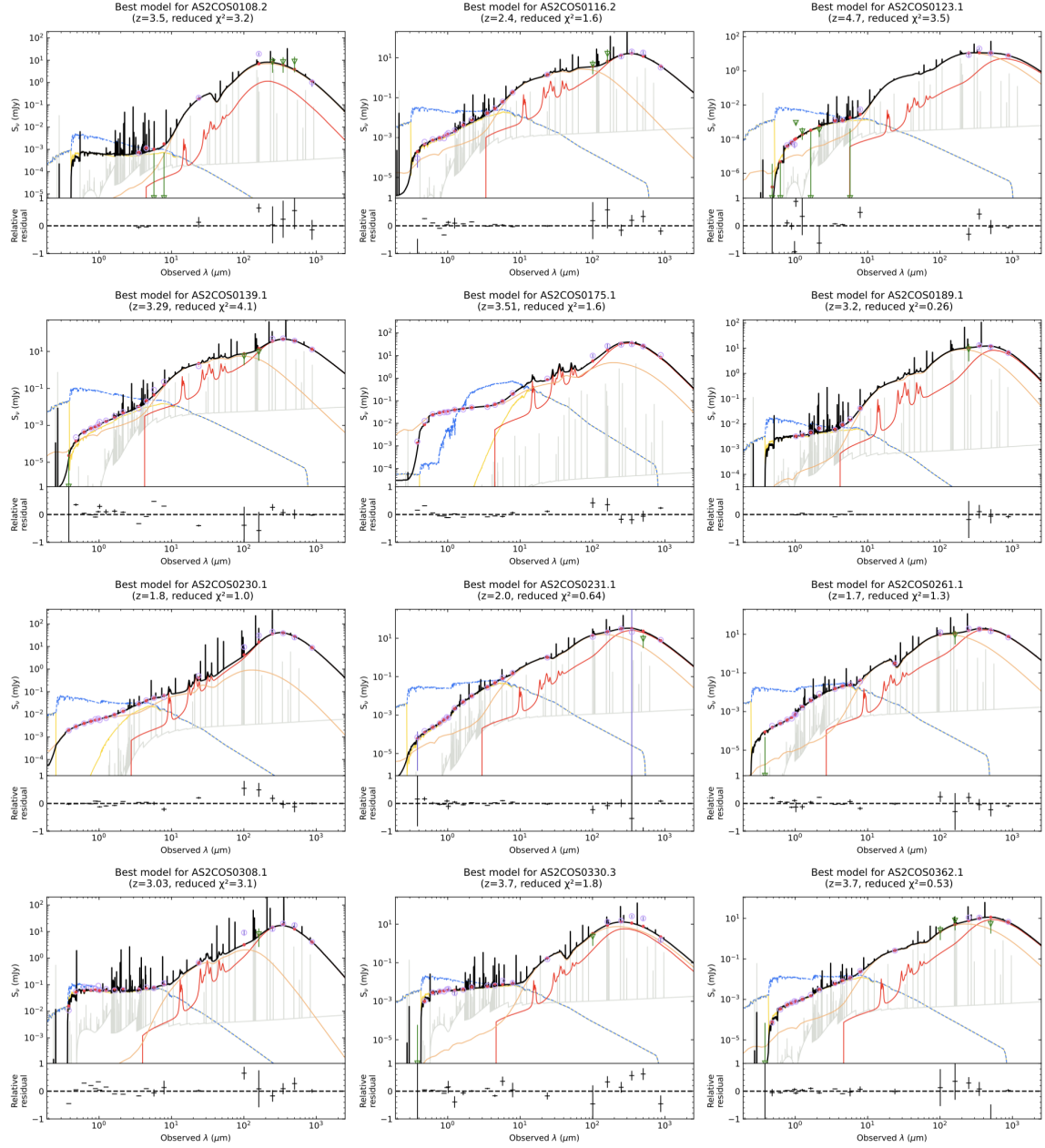


Figure C.9 (continued)

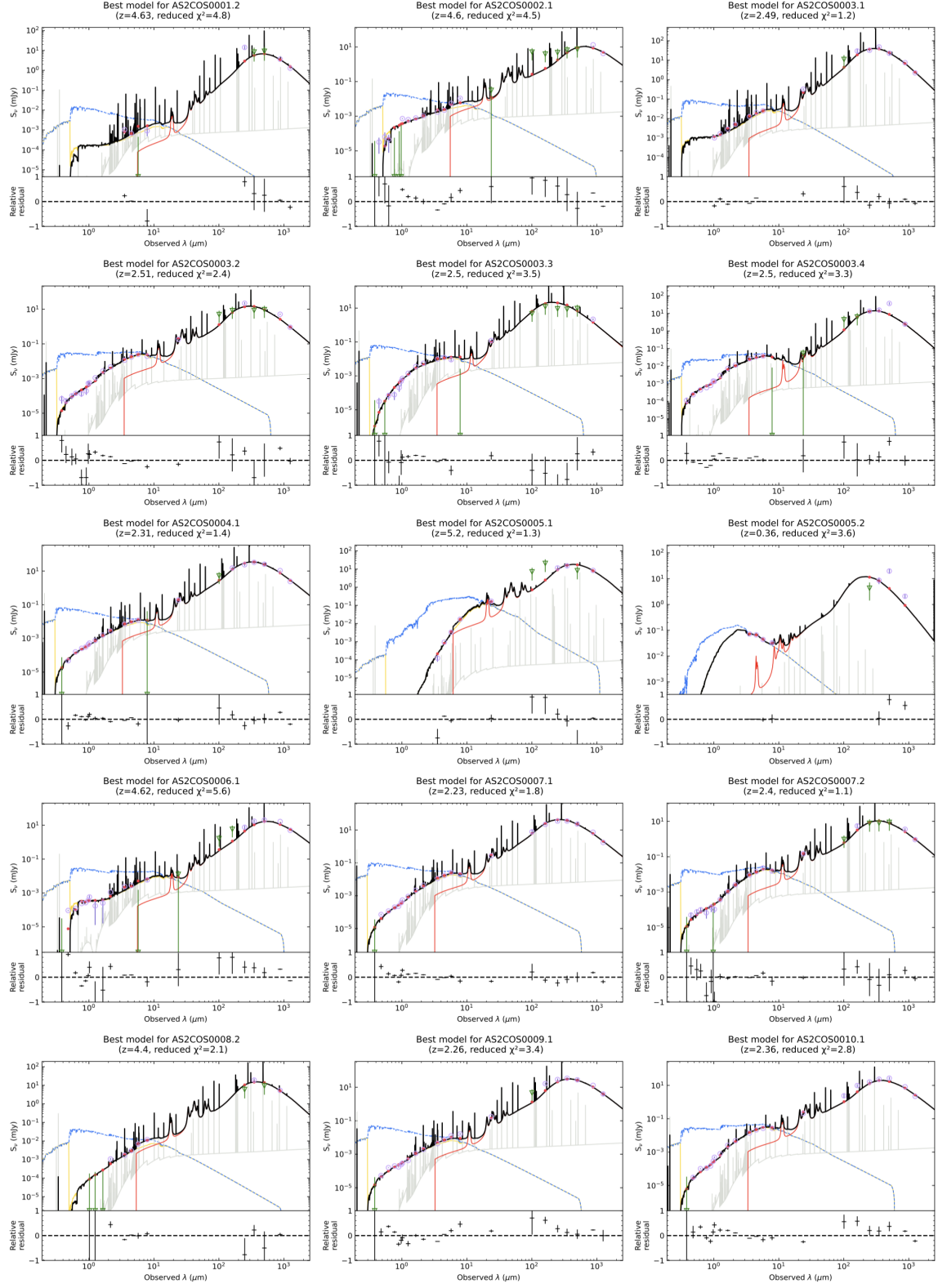


Figure C.10: Same as Figure C.9, but for the non-AGNs.

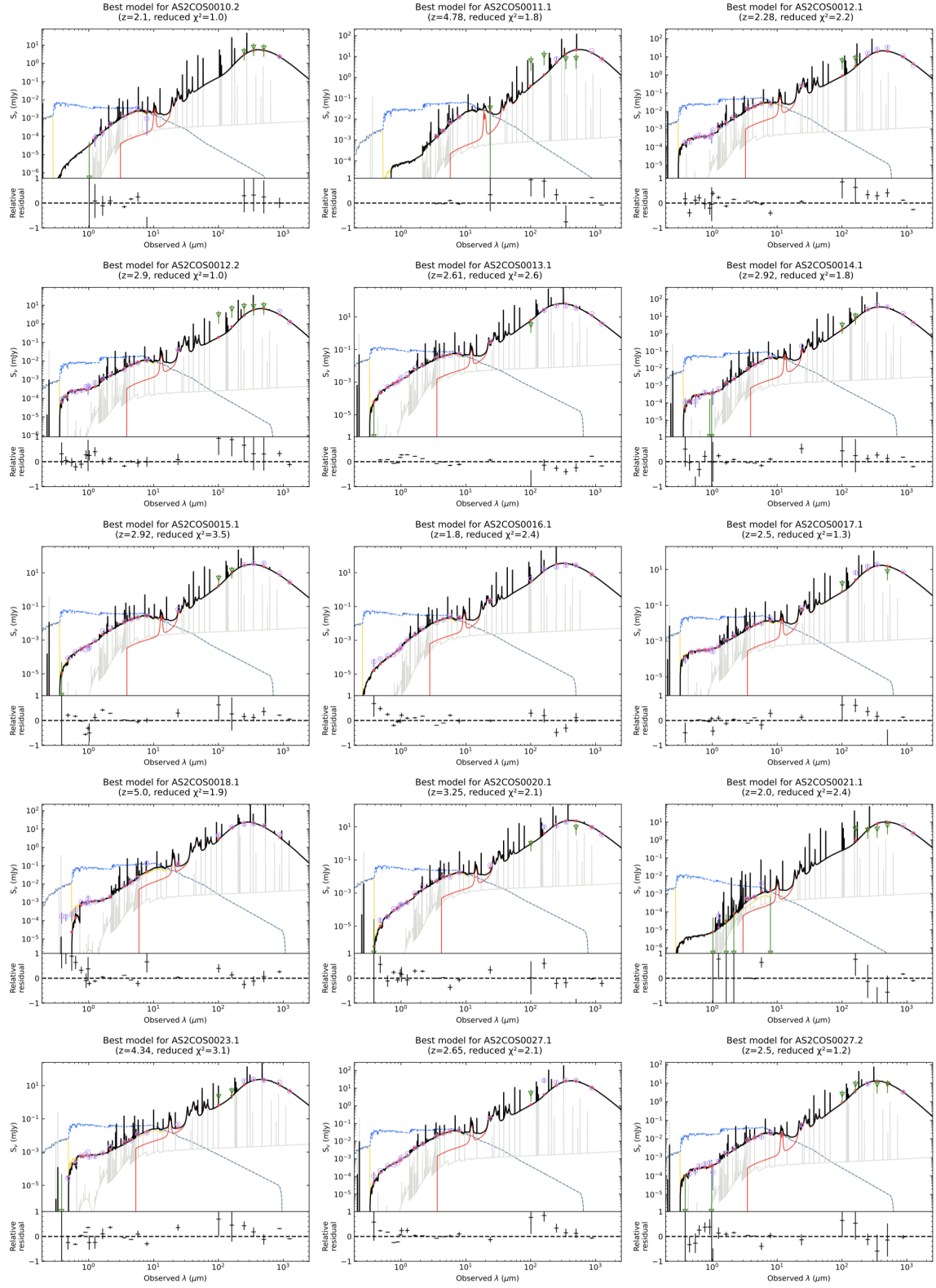


Figure C.10 (continued)

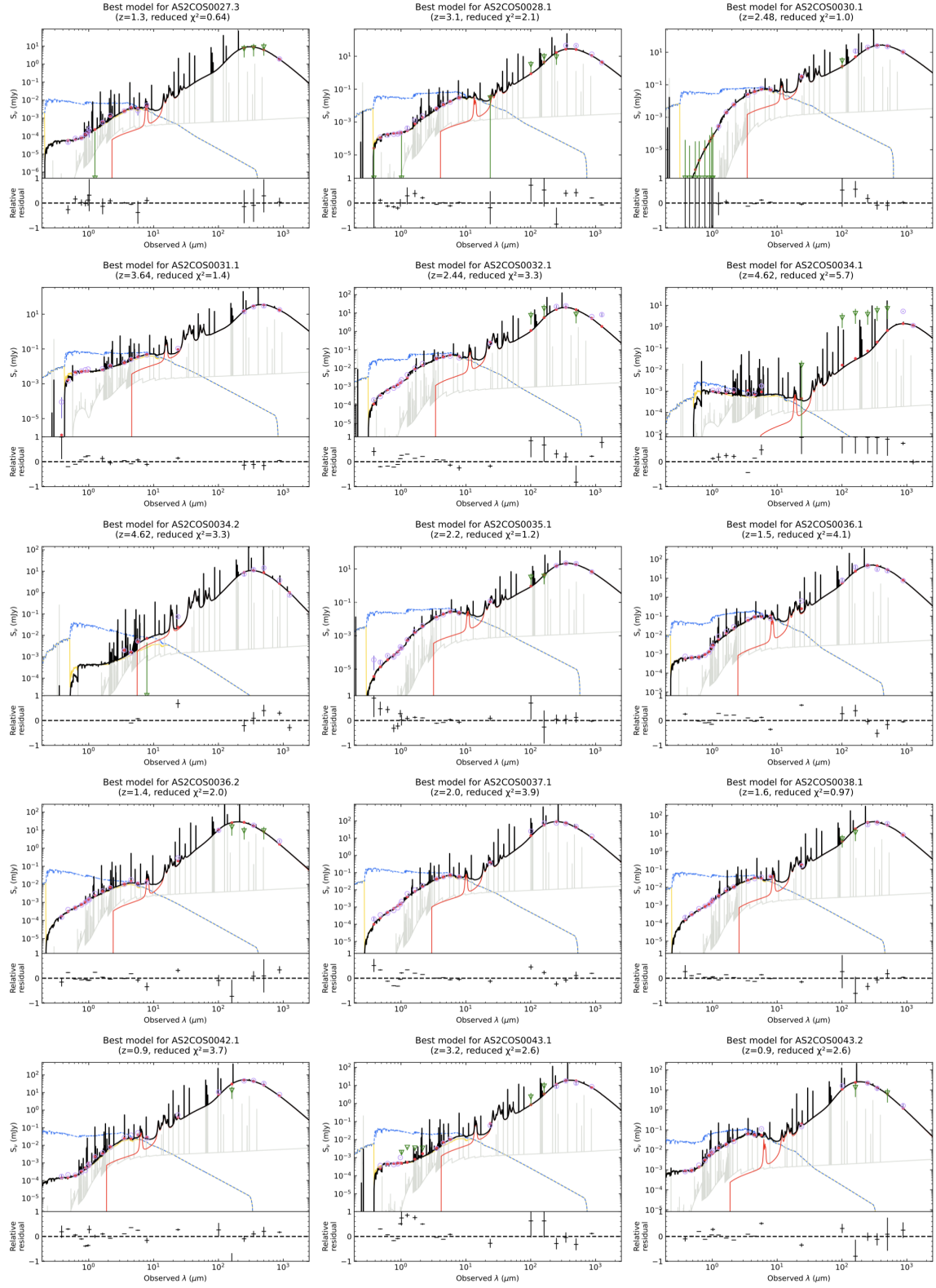


Figure C.10 (continued)

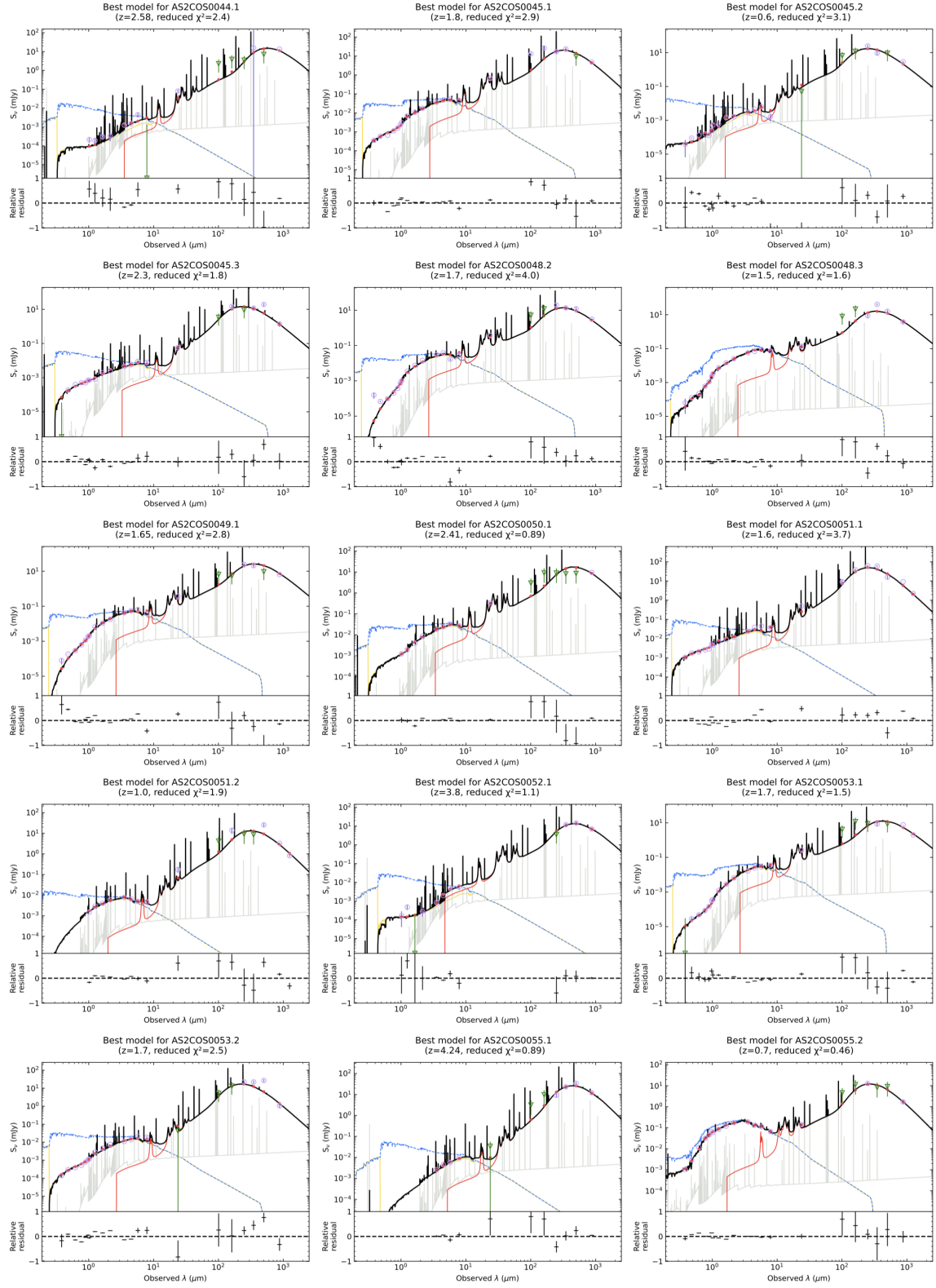


Figure C.10 (continued)

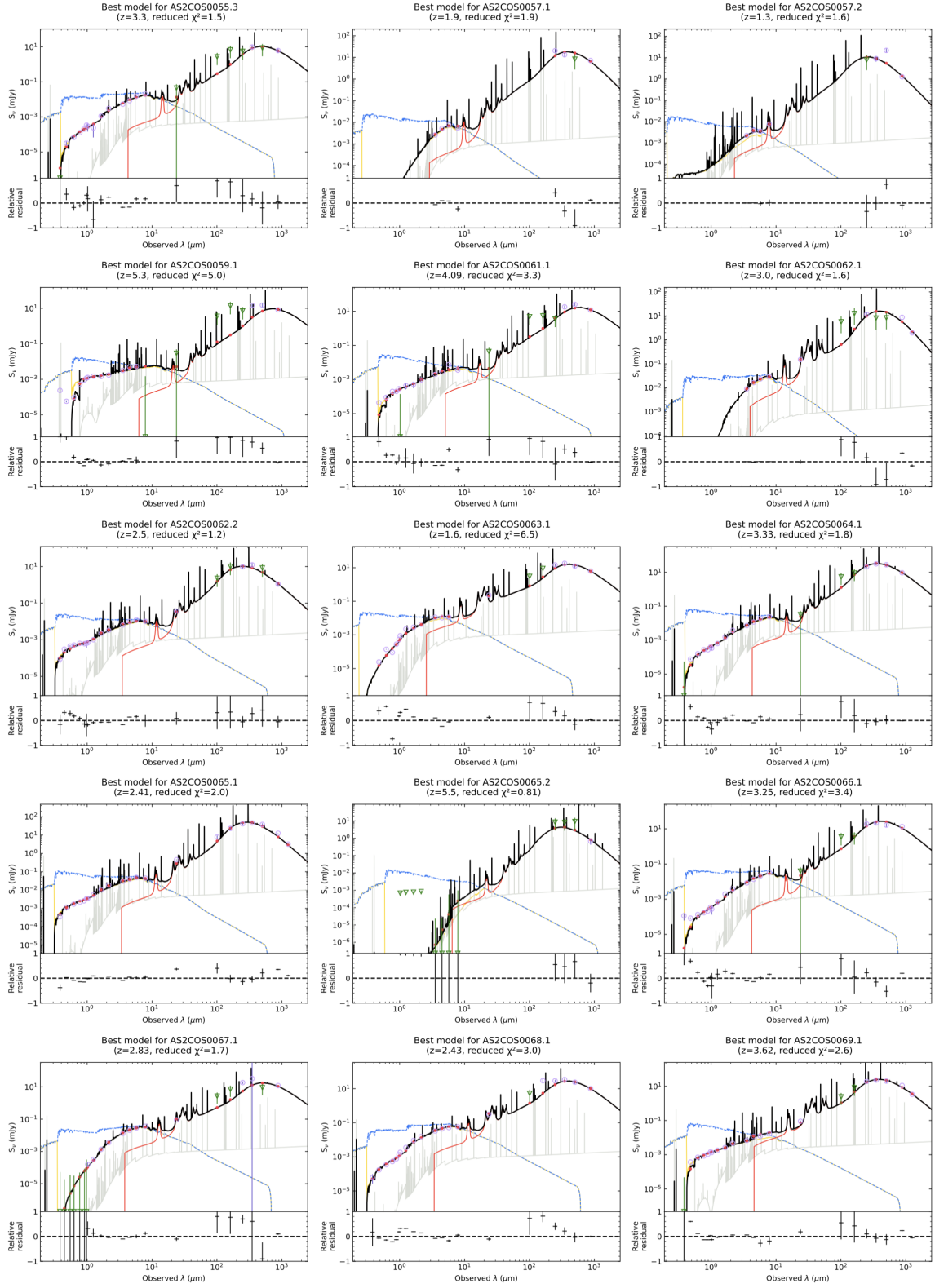


Figure C.10 (continued)

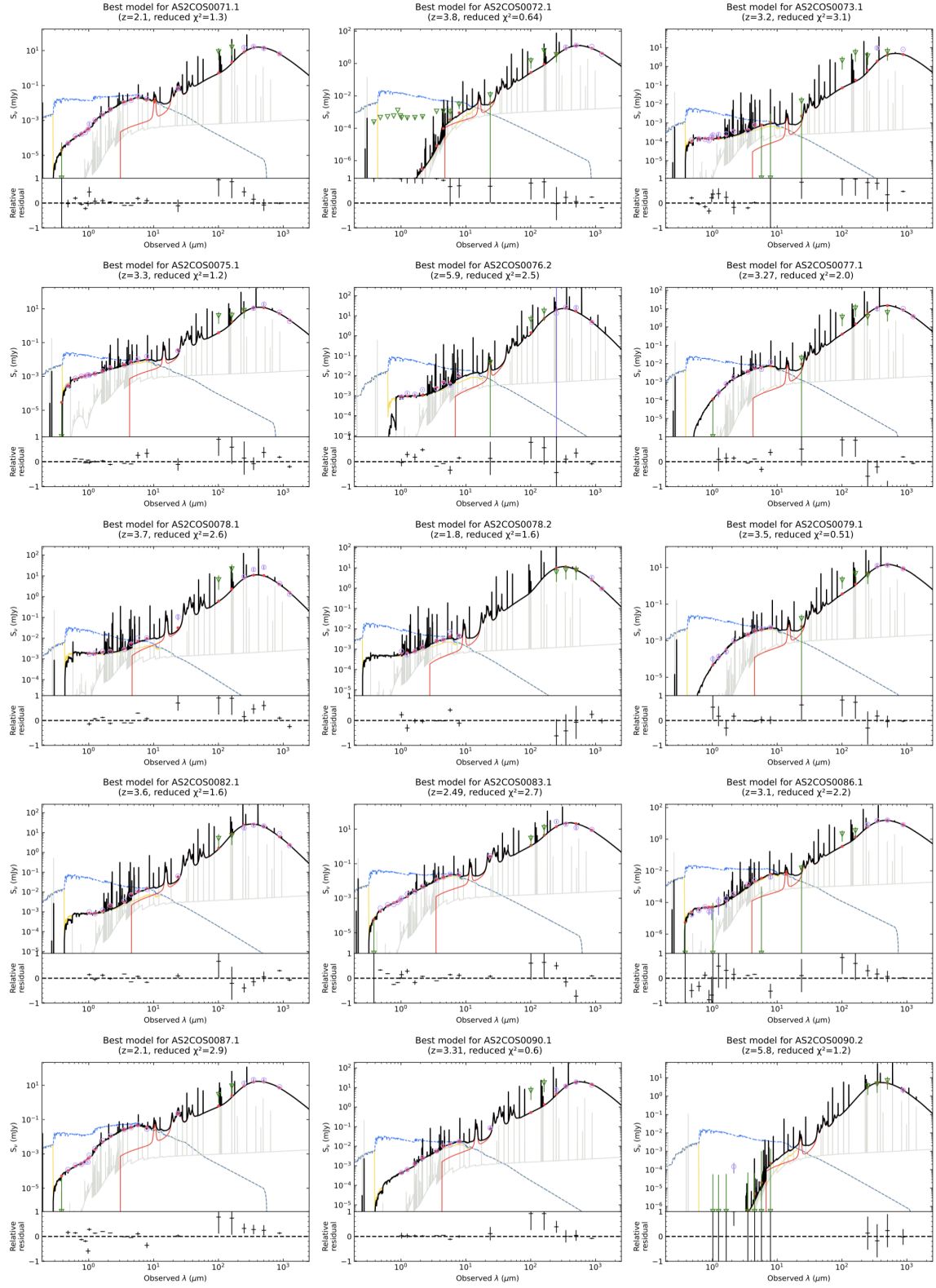


Figure C.10 (continued)

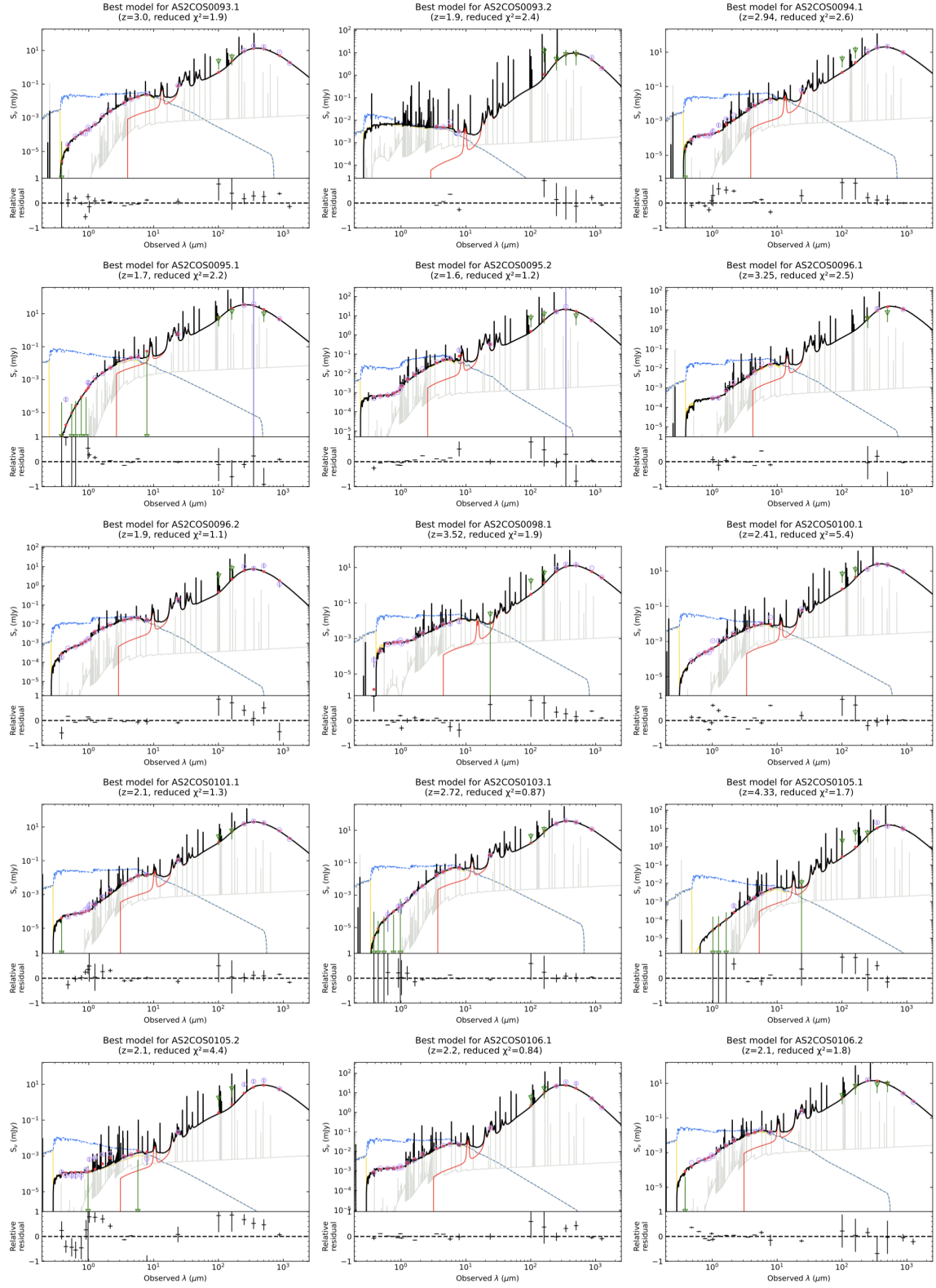


Figure C.10 (continued)

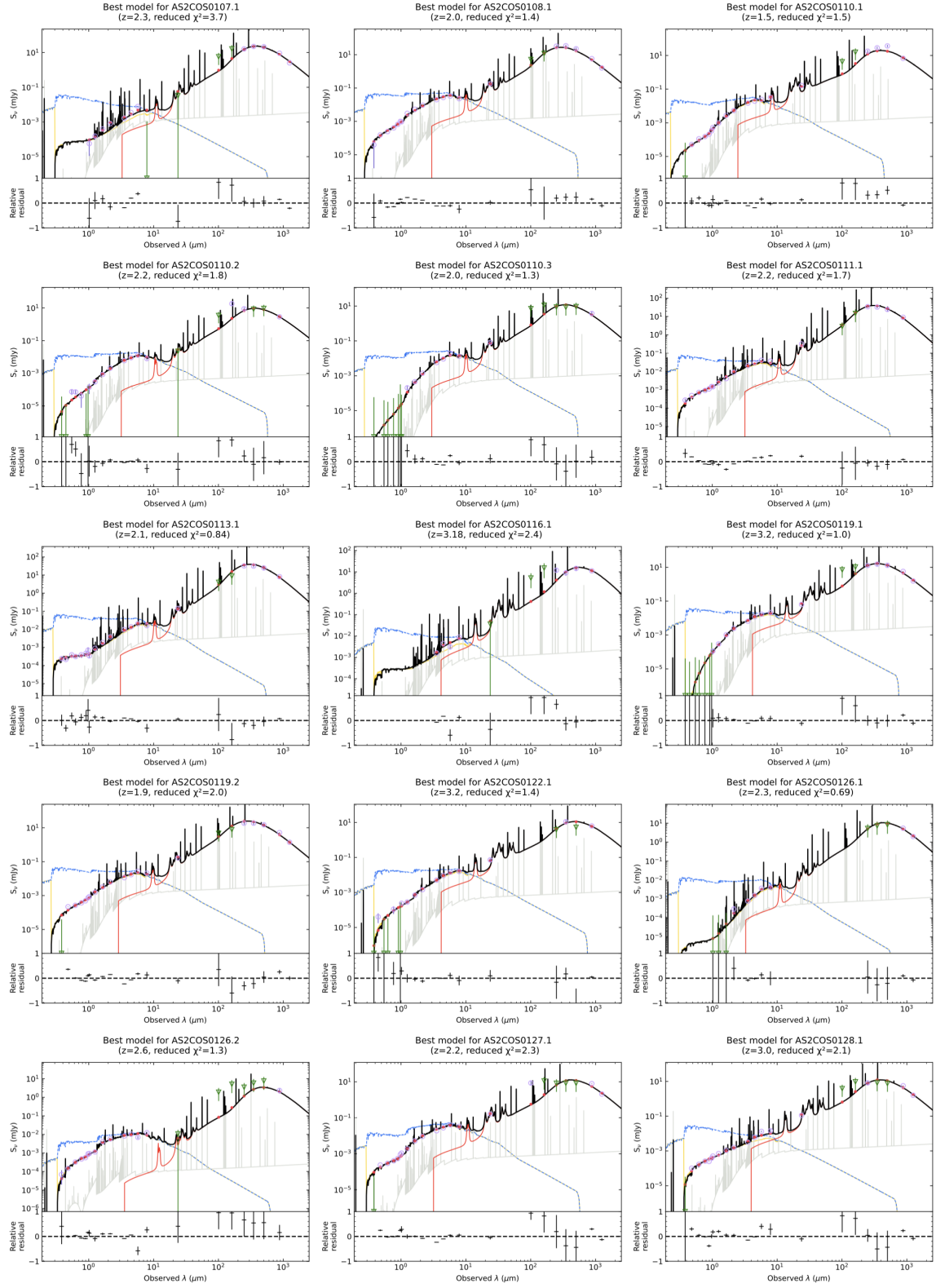


Figure C.10 (continued)

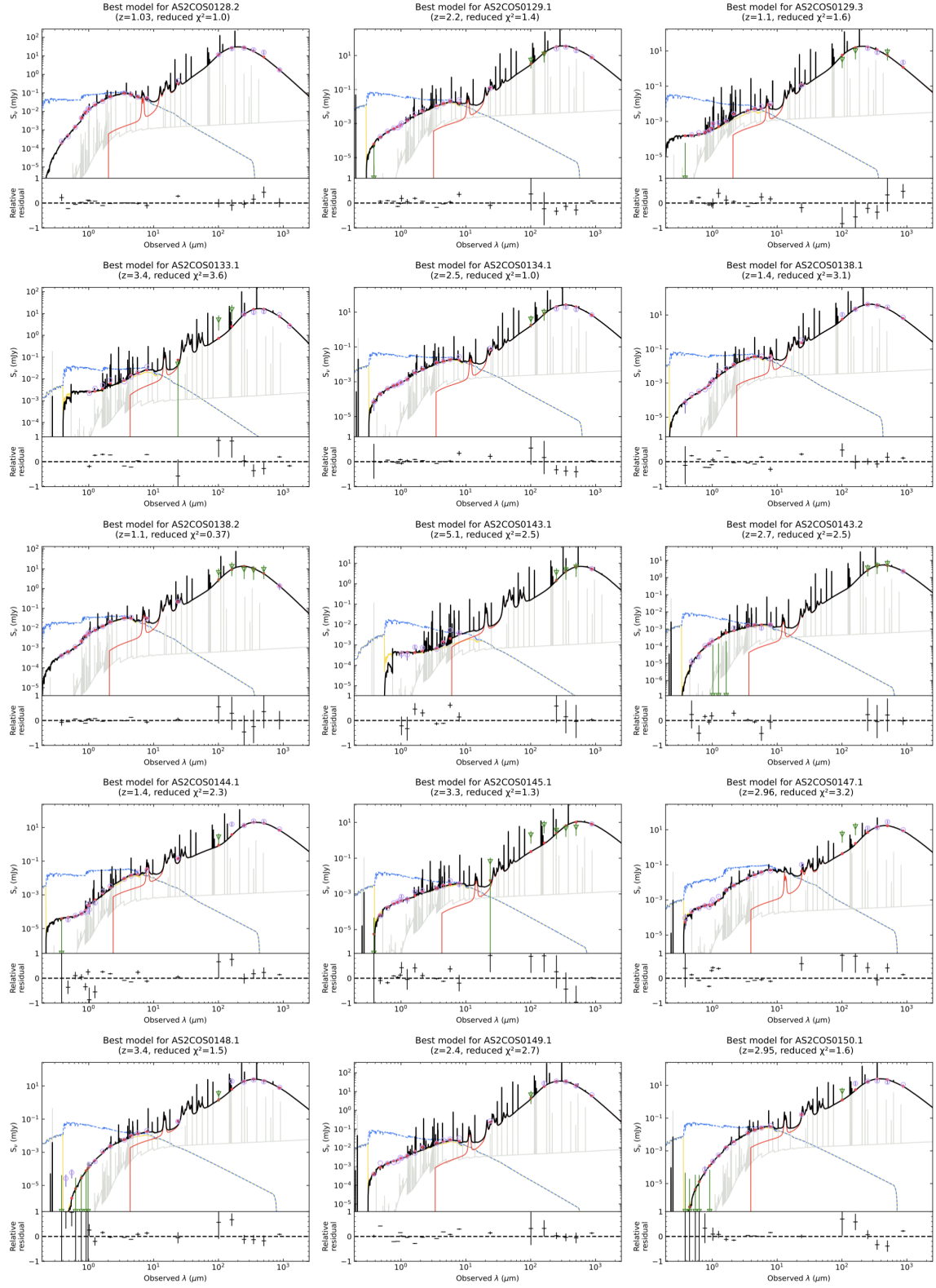


Figure C.10 (continued)

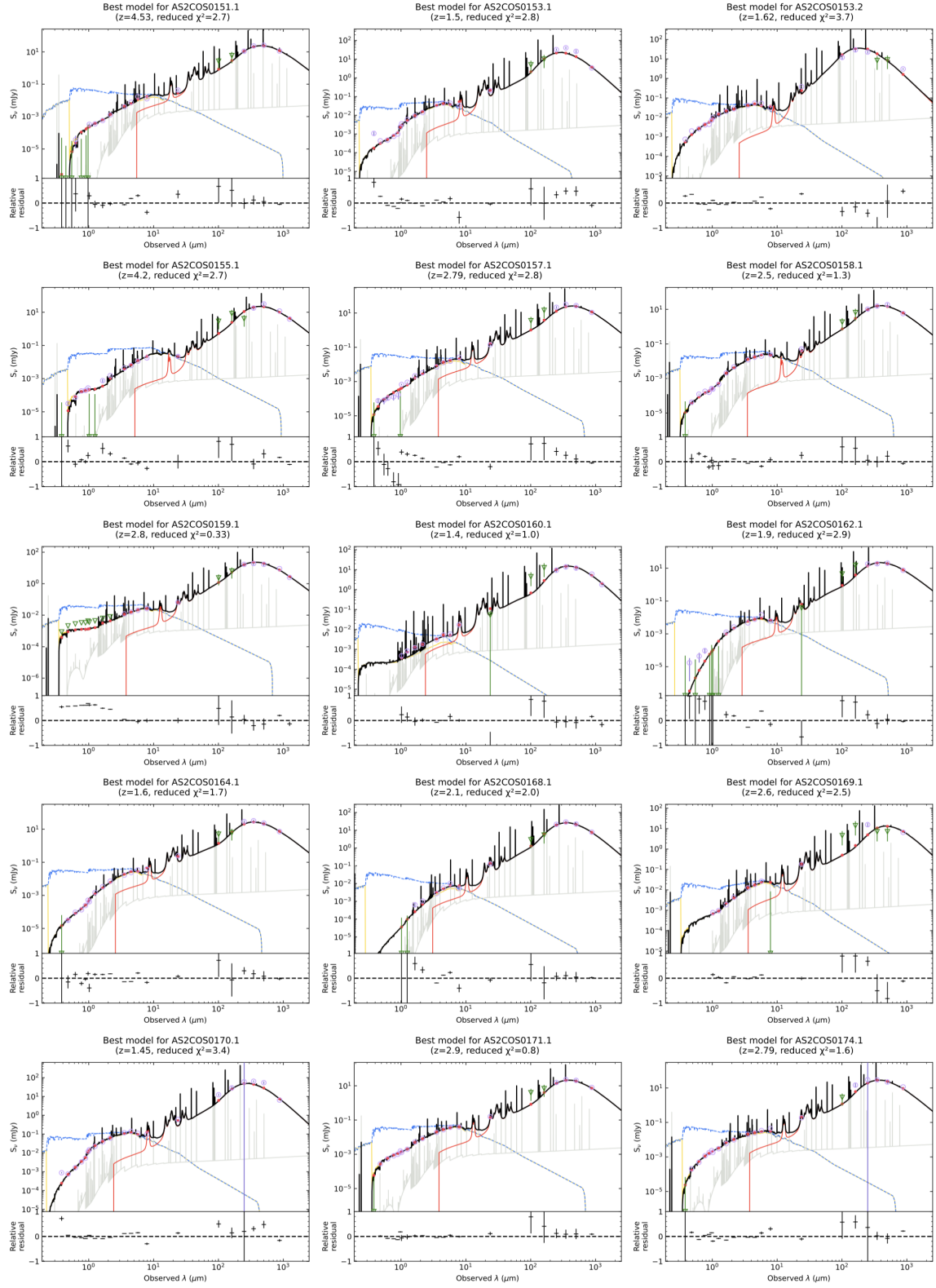


Figure C.10 (continued)

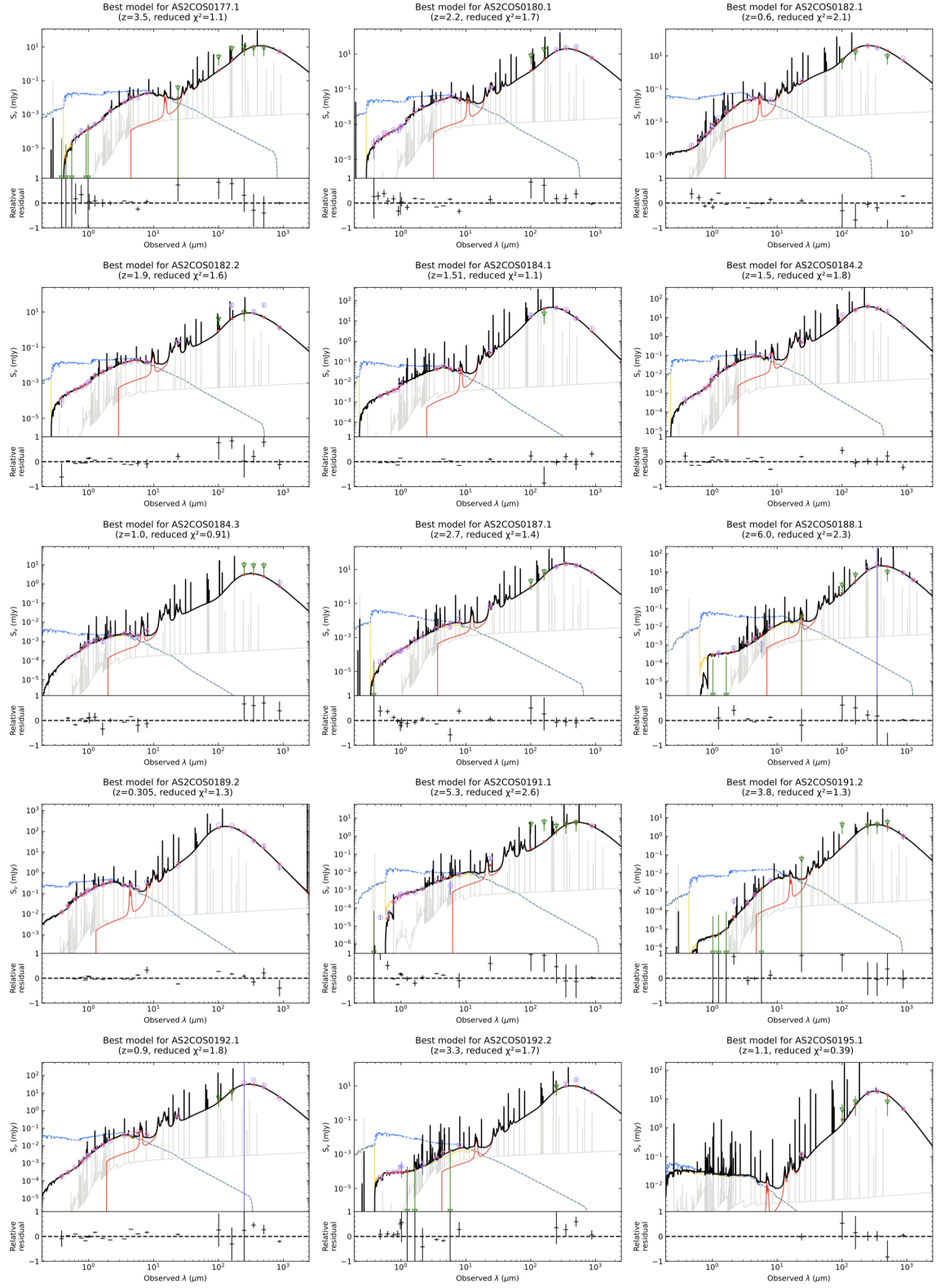


Figure C.10 (continued)

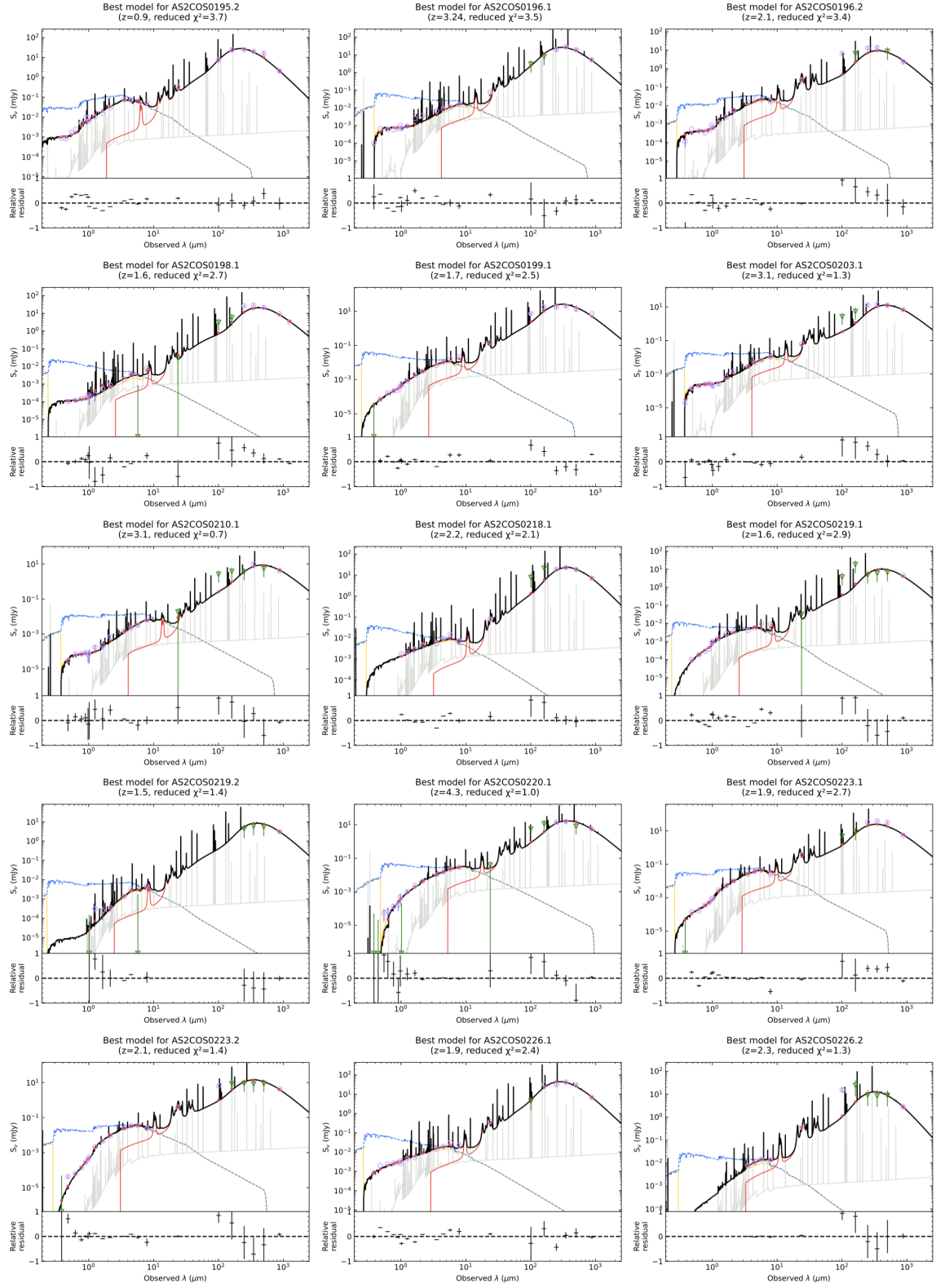


Figure C.10 (continued)

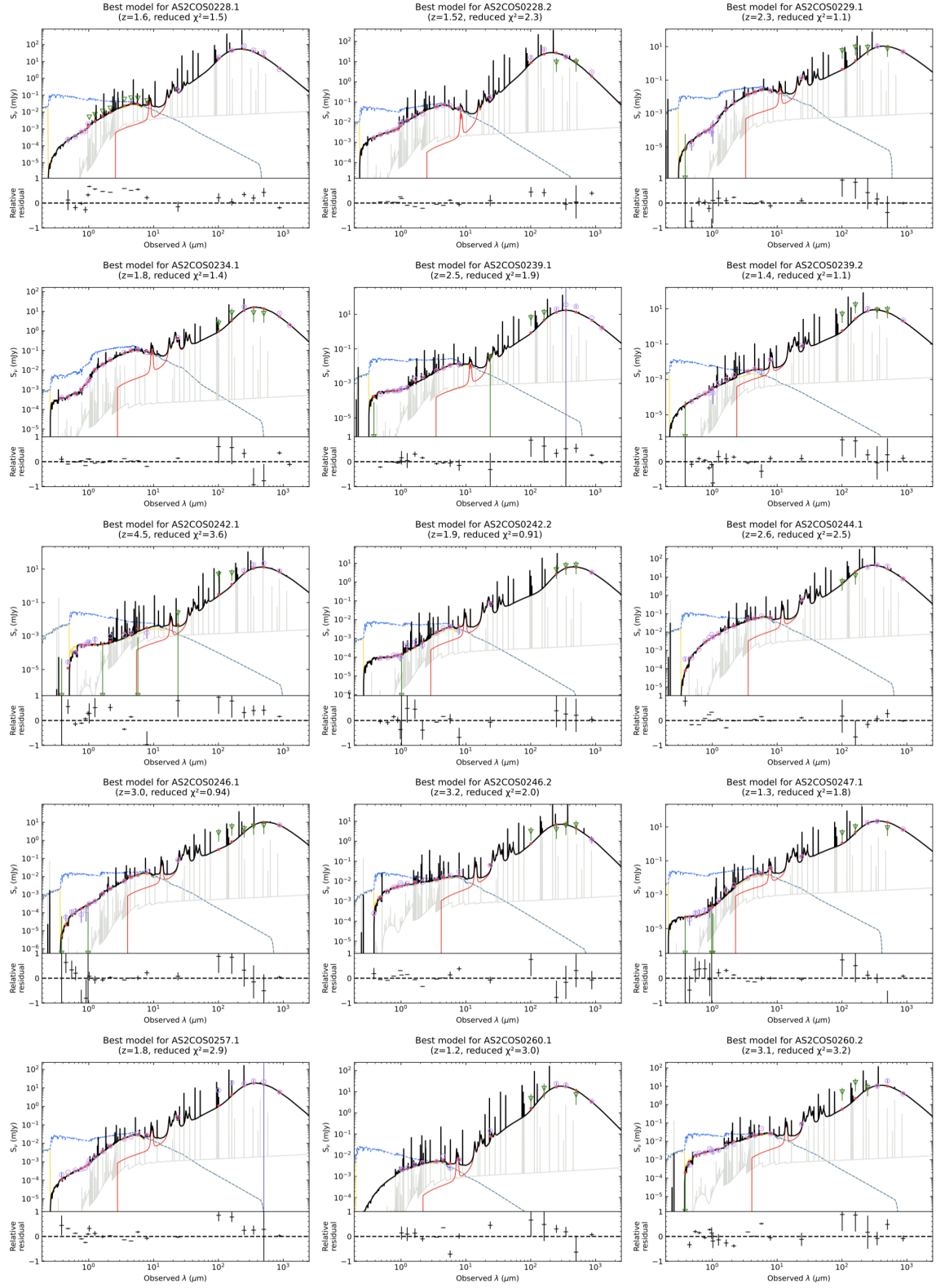


Figure C.10 (continued)

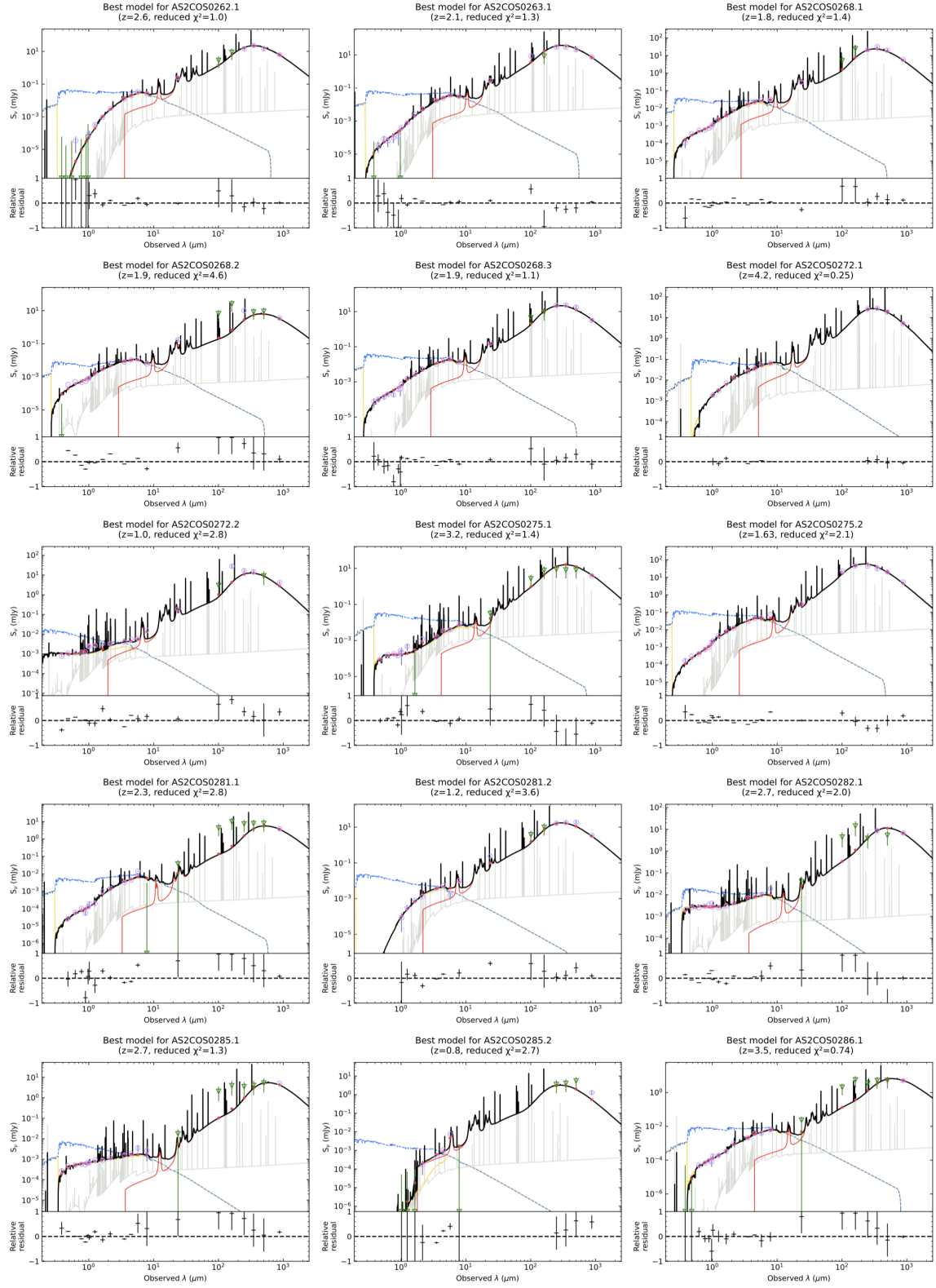


Figure C.10 (continued)

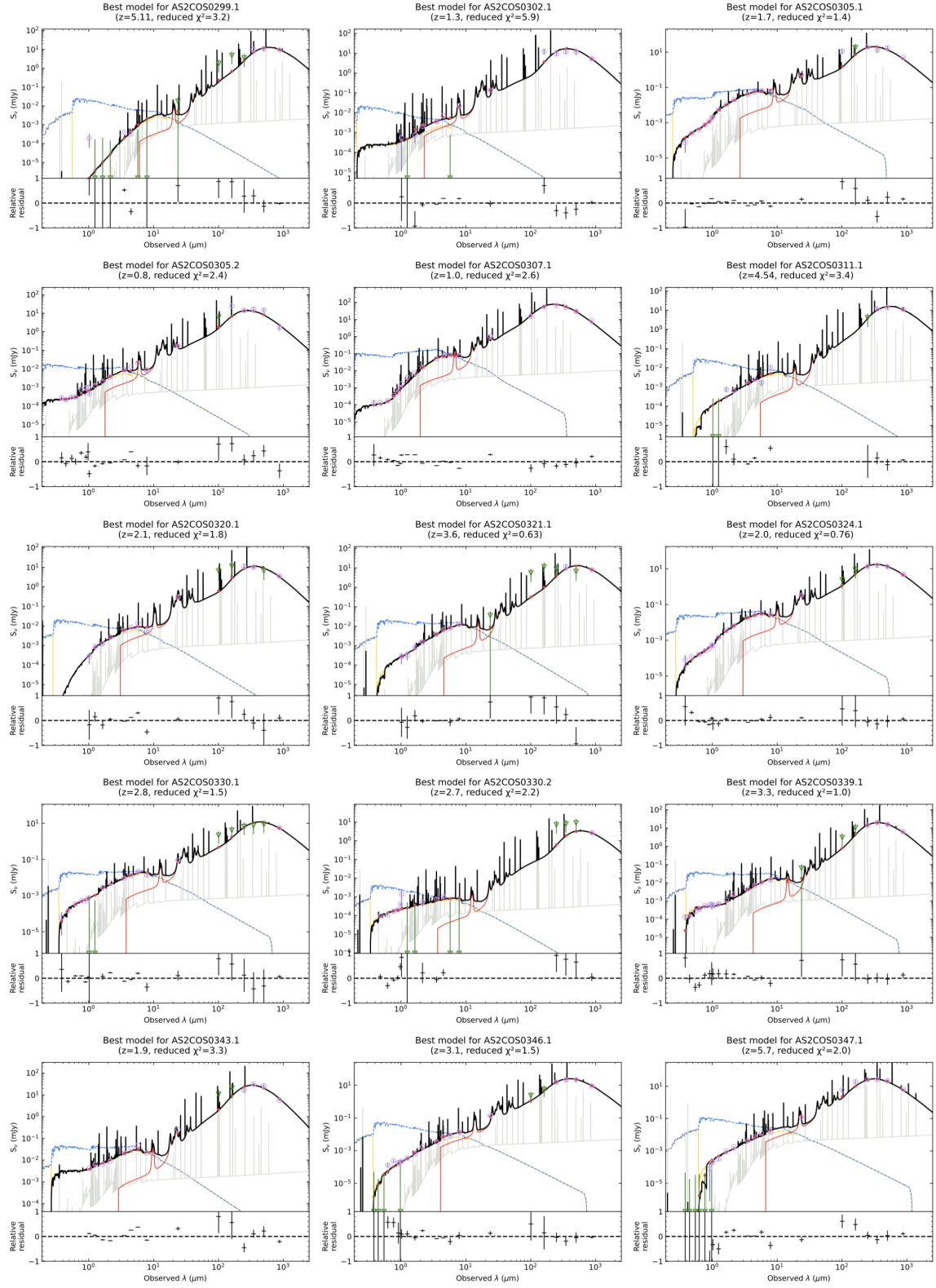


Figure C.10 (continued)

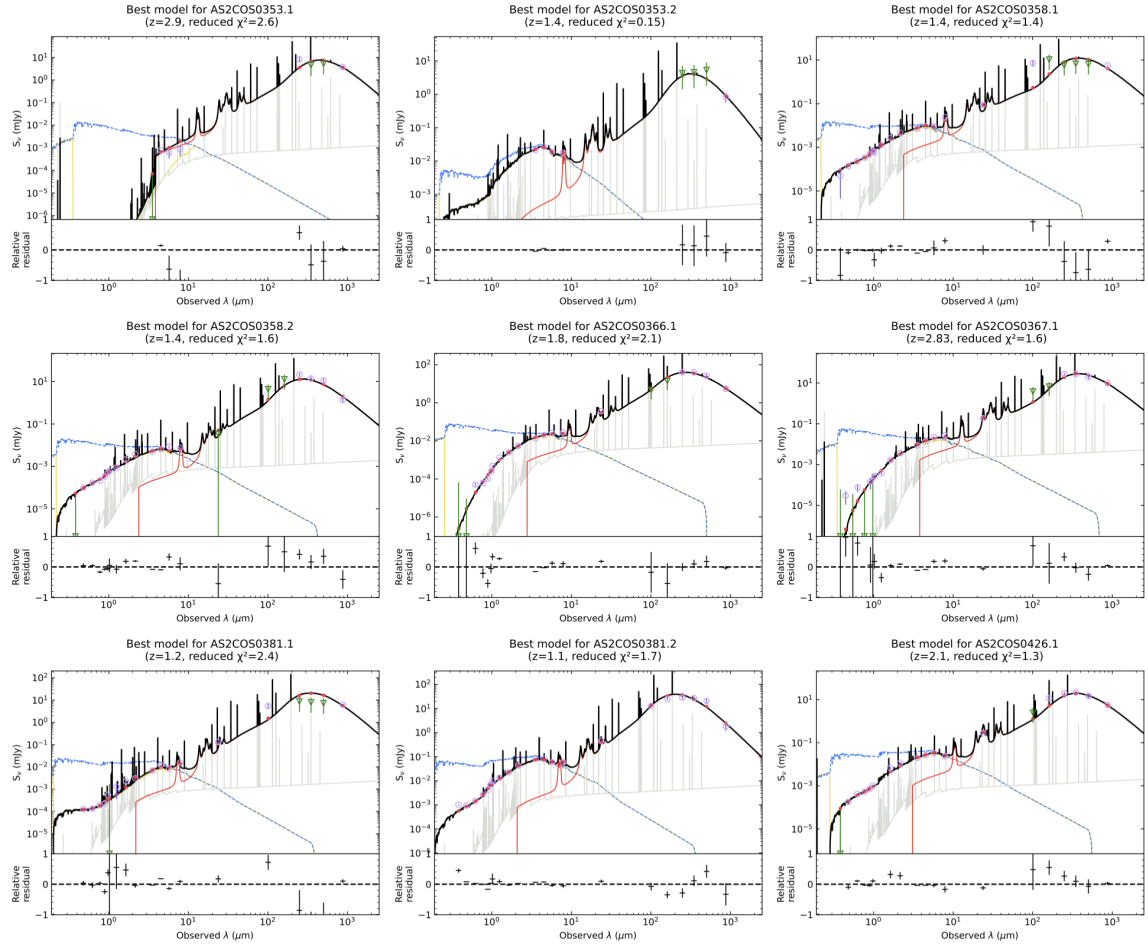


Figure C.10 (continued)

C.8 Physical Properties of non-AGNs

Table C.4 summarizes the host galaxy properties of the AS2COSMOS sources.

Table C.4: Physical properties of non-AGNs. (1), (2), (3), &(4) ALMA source ID, position, and 870- μ m flux density (same as Simpson et al. 2020); (5) redshift (three decimal digits are for spectroscopic redshifts and two are for photometric redshifts); (6) stellar mass; (7) star-formation rate; (8) dust luminosity^a; (9) dust mass^a; (10) dust temperature; (11) change in BIC by the addition of an AGN component in the SED modeling.

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu\text{m}}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_\odot$]	$\text{Log}_{10} \text{SFR}$ [$M_\odot \text{yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_\odot$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_\odot$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0001.1	150.03350	2.43675	13.49 ± 0.26	4.625	10.33 ± 0.22	3.19 ± 0.12	13.00 ± 0.10	9.10 ± 0.07	34.10 ± 1.72	57.2
AS2COS0001.2	150.03268	2.43701	3.62 ± 0.17	4.635	9.70 ± 0.20	2.65 ± 0.18	12.43 ± 0.20	8.73 ± 0.18	31.67 ± 4.52	15.3
AS2COS0002.1	150.06505	2.26362	13.24 ± 0.25	4.596	10.01 ± 0.09	2.96 ± 0.05	12.74 ± 0.05	9.53 ± 0.07	25.51 ± 1.20	-10.8
AS2COS0003.1	150.23728	2.33815	7.49 ± 0.30	2.494	10.67 ± 0.21	3.04 ± 0.09	12.93 ± 0.02	8.97 ± 0.02	34.58 ± 0.31	-4.7
AS2COS0003.2	150.23986	2.33645	5.09 ± 0.40	2.513	10.75 ± 0.25	2.51 ± 0.15	12.48 ± 0.11	8.68 ± 0.13	32.59 ± 2.90	-1.7
AS2COS0003.3	150.23863	2.33684	2.18 ± 0.28	2.504	10.02 ± 0.09	2.98 ± 0.06	12.76 ± 0.05	8.19 ± 0.18	44.45 ± 3.64	-8.1
AS2COS0003.4	150.23692	2.33577	2.47 ± 0.50	2.503	11.22 ± 0.06	2.32 ± 0.02	12.45 ± 0.02	8.55 ± 0.12	34.09 ± 1.66	-12.2
AS2COS0004.1	150.08228	2.53449	10.75 ± 0.54	2.308	9.97 ± 0.05	2.96 ± 0.02	12.74 ± 0.02	9.18 ± 0.02	29.49 ± 0.01	-12.4
AS2COS0006.1	149.98871	2.45850	16.61 ± 0.39	4.618	11.10 ± 0.17	3.09 ± 0.09	12.93 ± 0.07	9.36 ± 0.03	29.78 ± 1.18	-11.9
AS2COS0007.1	150.13895	2.43378	7.34 ± 0.31	2.232	10.45 ± 0.13	3.08 ± 0.02	12.89 ± 0.02	8.93 ± 0.02	34.58 ± 0.07	-10.9
AS2COS0007.2	150.13912	2.43195	3.58 ± 0.56	2.30 $\pm$ 0.23	11.05 ± 0.16	2.25 ± 0.22	12.23 ± 0.14	8.76 ± 0.11	28.54 ± 2.66	-9.6
AS2COS0008.1	150.70497	2.54874	18.27 ± 0.41	3.581	11.96 ± 0.07	2.27 ± 0.09	12.76 ± 0.02	9.94 ± 0.15	22.14 ± 1.48	15.8
AS2COS0008.2	150.70600	2.54899	5.31 ± 0.34	4.39 $\pm$ 0.56	10.49 ± 0.35	3.16 ± 0.21	12.99 ± 0.17	8.71 ± 0.18	39.41 ± 5.13	-3.3
AS2COS0009.1	150.11967	2.53433	13.09 ± 0.32	2.260	9.81 ± 0.05	2.80 ± 0.02	12.59 ± 0.02	9.45 ± 0.04	25.12 ± 0.35	9.5
AS2COS0010.1	150.09857	2.36537	8.22 ± 0.32	2.364	11.08 ± 0.04	2.44 ± 0.04	12.49 ± 0.03	9.30 ± 0.06	25.34 ± 0.87	1.2
AS2COS0010.2	150.09597	2.36526	2.33 ± 0.48	2.77 $\pm$ 0.89	9.54 ± 0.33	2.17 ± 0.37	11.99 ± 0.32	8.76 ± 0.32	26.73 ± 6.70	-9.9
AS2COS0011.1	150.42398	2.45358	19.24 ± 0.41	4.783	10.79 ± 0.41	3.23 ± 0.14	13.09 ± 0.06	9.54 ± 0.06	29.21 ± 1.10	-9.9
AS2COS0012.1	149.65819	2.23566	11.14 ± 0.36	2.279	10.92 ± 0.28	2.46 ± 0.19	12.46 ± 0.04	9.58 ± 0.13	22.50 ± 1.67	-8.6
AS2COS0012.2	149.65724	2.23406	4.66 ± 0.54	2.41 $\pm$ 0.57	10.10 ± 0.42	2.24 ± 0.32	12.15 ± 0.27	8.96 ± 0.18	25.84 ± 4.45	-6.8
AS2COS0013.1	150.14707	2.73144	15.51 ± 0.37	2.608	11.19 ± 0.14	3.22 ± 0.19	13.11 ± 0.12	9.23 ± 0.05	33.57 ± 2.03	-0.3
AS2COS0014.1	150.42100	2.06802	14.83 ± 0.35	2.921	11.50 ± 0.13	2.89 ± 0.05	12.94 ± 0.02	9.38 ± 0.02	29.50 ± 0.14	-3.6
AS2COS0015.1	150.34567	2.33497	9.27 ± 0.26	2.916	11.13 ± 0.10	3.00 ± 0.12	12.88 ± 0.05	9.06 ± 0.12	33.10 ± 2.37	-11.9
AS2COS0015.2	150.34656	2.33489	4.69 ± 0.28	2.48 $\pm$ 0.28	11.31 ± 0.09	1.75 ± 0.19	12.11 ± 0.07	8.94 ± 0.07	25.44 ± 1.31	-12.4

^a Here, the terms “dust luminosity” and “dust mass” only describe those of interstellar dust (i.e., not including those in the AGN torus).

Table C.4: (continued)

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu\text{m}}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_\odot$]	$\text{Log}_{10} \text{SFR}$ [$M_\odot \text{ yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_\odot$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_\odot$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0015.3	150.34321	2.33408	6.32 ± 0.80	2.98 ± 0.10	11.38 ± 0.07	2.32 ± 0.05	12.40 ± 0.07	8.92 ± 0.13	28.62 ± 1.92	-10.9
AS2COS0016.1	150.10540	2.31282	7.79 ± 0.30	1.76 ± 0.13	10.63 ± 0.14	2.63 ± 0.07	12.46 ± 0.06	9.29 ± 0.05	25.28 ± 0.86	0.4
AS2COS0017.1	150.20803	2.38314	7.54 ± 0.29	2.49 ± 0.13	10.75 ± 0.13	2.38 ± 0.07	12.40 ± 0.06	9.30 ± 0.11	24.72 ± 1.39	-5.7
AS2COS0018.1	150.14323	2.35602	4.79 ± 0.30	4.79 ± 0.36	11.92 ± 0.25	3.41 ± 0.06	13.44 ± 0.08	8.14 ± 0.14	58.37 ± 4.62	1.8
AS2COS0019.1	150.15840	2.13955	9.98 ± 0.30	1.825	10.37 ± 0.28	3.15 ± 0.08	12.92 ± 0.07	9.06 ± 0.10	33.48 ± 2.09	74.9
AS2COS0020.1	150.04228	2.22635	9.48 ± 0.31	3.254	10.85 ± 0.15	3.00 ± 0.13	12.85 ± 0.09	9.20 ± 0.16	30.80 ± 2.85	-7.6
AS2COS0021.1	150.10064	2.33483	6.59 ± 0.25	2.47 ± 0.63	9.26 ± 0.23	2.19 ± 0.17	11.98 ± 0.17	9.51 ± 0.14	19.40 ± 2.83	-10.6
AS2COS0023.1	149.92857	2.49394	15.84 ± 0.35	4.341	11.13 ± 0.09	3.14 ± 0.03	13.11 ± 0.02	9.15 ± 0.02	34.58 ± 0.08	-0.6
AS2COS0024.1	150.13265	2.21184	8.37 ± 0.28	2.176	11.25 ± 0.09	2.54 ± 0.14	12.59 ± 0.11	8.96 ± 0.22	30.65 ± 3.77	37.9
AS2COS0025.1	150.16352	2.37252	6.93 ± 0.30	2.086	10.51 ± 0.12	2.70 ± 0.05	12.62 ± 0.02	9.06 ± 0.05	29.60 ± 0.73	13.3
AS2COS0027.1	150.75042	2.41294	10.13 ± 0.35	2.648	11.11 ± 0.07	2.68 ± 0.02	12.69 ± 0.02	9.51 ± 0.07	25.32 ± 0.84	-6.5
AS2COS0027.2	150.75112	2.41246	3.33 ± 0.29	2.71 ± 0.33	10.90 ± 0.25	2.38 ± 0.19	12.39 ± 0.14	8.78 ± 0.15	30.32 ± 3.23	-8.5
AS2COS0027.3	150.75214	2.41403	1.93 ± 0.34	1.30 ± 0.30	9.45 ± 0.32	1.65 ± 0.24	11.53 ± 0.18	8.81 ± 0.20	21.43 ± 3.03	-11.3
AS2COS0028.1	149.99721	2.57805	13.51 ± 0.32	3.097	11.62 ± 0.02	2.90 ± 0.03	12.84 ± 0.02	9.31 ± 0.02	29.49 ± 0.05	-12.4
AS2COS0028.2	149.99795	2.57821	1.97 ± 0.24	2.15 ± 0.10	10.14 ± 0.25	2.87 ± 0.29	12.69 ± 0.21	8.26 ± 0.19	41.92 ± 3.70	19.0
AS2COS0030.1	150.01994	2.51259	10.47 ± 0.63	2.477	11.38 ± 0.07	2.64 ± 0.07	12.67 ± 0.02	9.49 ± 0.06	25.28 ± 0.73	-10.4
AS2COS0031.1	149.84586	2.86042	18.09 ± 0.45	3.643	11.24 ± 0.12	3.20 ± 0.05	13.13 ± 0.02	9.56 ± 0.05	29.39 ± 0.66	-3.0
AS2COS0032.1	150.05243	2.24559	6.42 ± 0.25	2.438	11.31 ± 0.07	2.43 ± 0.07	12.51 ± 0.09	9.23 ± 0.19	26.47 ± 2.70	-3.1
AS2COS0034.1	150.10446	2.43537	5.29 ± 0.36	4.615	9.11 ± 0.10	2.05 ± 0.03	11.62 ± 0.04	9.27 ± 0.05	18.37 ± 0.54	4.4
AS2COS0034.2	150.10572	2.43481	3.75 ± 0.34	4.621	10.24 ± 0.10	3.20 ± 0.02	12.98 ± 0.02	8.20 ± 0.02	47.53 ± 0.24	2.1
AS2COS0035.1	150.04823	2.25145	6.66 ± 0.28	2.07 ± 0.13	11.01 ± 0.07	2.33 ± 0.07	12.34 ± 0.09	9.32 ± 0.11	24.01 ± 1.73	-11.0
AS2COS0036.1	150.10616	2.01437	7.53 ± 0.31	1.61 ± 0.11	11.69 ± 0.07	2.43 ± 0.24	12.50 ± 0.09	9.18 ± 0.18	26.88 ± 2.76	-0.7
AS2COS0036.2	150.10630	2.01382	2.49 ± 0.37	1.40 ± 0.03	9.61 ± 0.10	2.54 ± 0.03	12.33 ± 0.03	8.37 ± 0.07	34.62 ± 1.08	-12.2
AS2COS0037.1	150.07522	2.80845	12.82 ± 0.31	2.000	11.24 ± 0.08	3.25 ± 0.02	13.09 ± 0.02	9.15 ± 0.02	34.58 ± 0.03	-12.2
AS2COS0038.1	150.43837	1.85613	8.45 ± 0.26	1.71 ± 0.25	10.47 ± 0.24	2.57 ± 0.11	12.51 ± 0.11	9.34 ± 0.09	25.43 ± 1.79	-6.9
AS2COS0042.1	149.98899	2.05313	7.65 ± 0.31	0.90 ± 0.05	10.47 ± 0.36	2.13 ± 0.07	12.04 ± 0.08	9.33 ± 0.09	21.11 ± 1.06	-12.2
AS2COS0043.1	150.14034	2.14715	8.53 ± 0.31	3.20 ± 0.18	10.62 ± 0.19	2.89 ± 0.14	12.77 ± 0.12	9.24 ± 0.08	29.18 ± 1.77	-8.6
AS2COS0043.2	150.13930	2.14951	1.62 ± 0.51	1.07 ± 0.19	10.96 ± 0.06	1.87 ± 0.19	11.94 ± 0.17	8.24 ± 0.13	31.65 ± 3.08	-12.0
AS2COS0044.1	149.79306	2.81548	13.52 ± 0.32	2.578	9.52 ± 0.10	2.48 ± 0.04	12.27 ± 0.05	9.93 ± 0.05	18.31 ± 0.14	-2.2

Table C.4: (continued)

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu m}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_{\odot}$]	$\text{Log}_{10} \text{SFR}$ [$M_{\odot} \text{yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_{\odot}$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_{\odot}$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0045.1	150.24689	2.28867	4.81 ± 0.34	1.86 ± 0.07	11.16 ± 0.06	2.40 ± 0.11	12.35 ± 0.05	9.13 ± 0.10	25.55 ± 1.38	5.9
AS2COS0045.2	150.24719	2.28775	2.87 ± 0.31	0.60 ± 0.04	8.54 ± 0.18	1.29 ± 0.04	11.10 ± 0.03	8.76 ± 0.04	18.31 ± 0.25	-12.2
AS2COS0045.3	150.24698	2.28626	1.39 ± 0.45	2.39 ± 0.16	9.75 ± 0.13	2.71 ± 0.07	12.49 ± 0.07	8.17 ± 0.16	40.33 ± 3.12	-10.6
AS2COS0048.1	150.28853	2.38193	4.06 ± 0.24	1.581	11.62 ± 0.06	1.91 ± 0.06	12.37 ± 0.02	8.77 ± 0.12	30.15 ± 1.72	11.0
AS2COS0048.2	150.28733	2.38185	3.12 ± 0.30	1.62 ± 0.34	10.86 ± 0.27	2.08 ± 0.31	12.02 ± 0.28	8.94 ± 0.12	24.36 ± 2.13	-6.0
AS2COS0048.3	150.28807	2.38143	3.72 ± 0.75	1.50 ± 0.02	11.54 ± 0.07	0.57 ± 0.31	11.94 ± 0.04	9.21 ± 0.10	21.23 ± 1.01	-11.2
AS2COS0049.1	150.03669	2.21791	6.46 ± 0.29	1.654	11.19 ± 0.09	2.36 ± 0.12	12.27 ± 0.06	9.31 ± 0.16	23.31 ± 1.94	-9.4
AS2COS0050.1	149.98786	2.19346	9.45 ± 0.35	2.411	11.02 ± 0.15	2.40 ± 0.07	12.39 ± 0.04	9.64 ± 0.10	21.22 ± 1.01	-6.9
AS2COS0051.1	150.03727	2.66970	9.23 ± 0.23	1.598	10.62 ± 0.15	2.81 ± 0.04	12.59 ± 0.04	9.06 ± 0.04	29.48 ± 0.20	-3.2
AS2COS0051.2	150.03708	2.66929	3.31 ± 0.19	0.97 ± 0.08	9.46 ± 0.23	1.58 ± 0.13	11.43 ± 0.10	9.02 ± 0.08	18.81 ± 1.22	-11.1
AS2COS0052.1	150.30096	2.14808	6.94 ± 0.29	4.11 ± 0.74	10.33 ± 0.47	2.91 ± 0.22	12.75 ± 0.20	9.13 ± 0.22	30.60 ± 5.13	-9.9
AS2COS0053.1	150.17991	2.08864	7.70 ± 0.29	1.71 ± 0.05	11.05 ± 0.07	1.94 ± 0.09	11.94 ± 0.03	9.55 ± 0.03	18.34 ± 0.38	-6.2
AS2COS0053.2	150.17930	2.08801	1.06 ± 0.27	1.65 ± 0.16	10.50 ± 0.12	2.30 ± 0.17	12.15 ± 0.14	8.34 ± 0.13	33.07 ± 3.15	-12.2
AS2COS0054.1	149.69140	2.72481	12.40 ± 0.40	3.176	10.86 ± 0.23	2.88 ± 0.15	12.73 ± 0.10	9.53 ± 0.10	25.71 ± 1.87	24.3
AS2COS0055.1	150.32177	1.71349	12.05 ± 0.32	4.239	10.40 ± 0.19	3.28 ± 0.06	13.07 ± 0.05	9.22 ± 0.12	33.45 ± 2.11	-9.6
AS2COS0055.2	150.32147	1.71421	1.70 ± 0.39	0.69 ± 0.03	11.16 ± 0.05	0.54 ± 0.31	11.13 ± 0.09	8.62 ± 0.19	19.51 ± 2.03	-12.2
AS2COS0055.3	150.32450	1.71422	6.22 ± 1.75	3.49 ± 0.27	11.06 ± 0.12	2.51 ± 0.14	12.54 ± 0.12	9.01 ± 0.38	29.63 ± 5.66	-9.7
AS2COS0057.1	150.16337	2.68131	7.15 ± 0.32	2.46 ± 0.80	9.94 ± 0.28	2.57 ± 0.28	12.39 ± 0.25	9.29 ± 0.23	25.12 ± 5.48	-8.3
AS2COS0057.2	150.16315	2.68219	1.26 ± 0.21	2.16 ± 1.31	9.47 ± 0.50	2.25 ± 0.49	12.05 ± 0.47	8.30 ± 0.30	33.54 ± 10.92	-8.3
AS2COS0059.1	150.08624	2.58900	8.29 ± 0.29	5.305	10.35 ± 0.25	2.94 ± 0.06	12.70 ± 0.05	9.40 ± 0.20	26.91 ± 2.54	-2.0
AS2COS0061.1	149.54490	2.10319	11.86 ± 0.41	4.094	9.99 ± 0.08	2.99 ± 0.06	12.77 ± 0.06	9.60 ± 0.10	25.47 ± 1.48	-10.8
AS2COS0062.1	150.05219	2.02340	8.70 ± 0.43	2.89 ± 0.33	11.09 ± 0.21	2.59 ± 0.20	12.62 ± 0.15	9.09 ± 0.11	29.13 ± 2.87	-8.5
AS2COS0062.2	150.05298	2.02448	1.10 ± 0.25	2.52 ± 0.21	10.46 ± 0.36	2.45 ± 0.15	12.33 ± 0.10	8.08 ± 0.16	39.24 ± 3.54	-10.5
AS2COS0063.1	150.26629	2.41352	6.32 ± 0.31	1.57 ± 0.08	10.12 ± 0.09	2.13 ± 0.06	11.97 ± 0.06	9.56 ± 0.07	18.49 ± 0.74	-2.5
AS2COS0064.1	150.05612	1.61796	9.33 ± 0.31	3.328	11.01 ± 0.12	3.20 ± 0.03	13.02 ± 0.02	9.08 ± 0.02	34.58 ± 0.10	-12.2
AS2COS0065.1	149.66786	2.08741	12.62 ± 0.30	2.414	11.02 ± 0.21	3.04 ± 0.11	12.92 ± 0.04	9.23 ± 0.14	31.29 ± 2.43	9.3
AS2COS0065.2	149.66865	2.08864	0.69 ± 0.26	5.09 ± 0.65	9.34 ± 0.59	1.98 ± 0.43	11.83 ± 0.41	8.29 ± 0.53	31.34 ± 12.27	-9.9
AS2COS0066.1	149.94410	1.95418	13.31 ± 0.32	3.247	11.07 ± 0.15	2.84 ± 0.08	12.82 ± 0.09	9.39 ± 0.18	28.26 ± 2.59	-10.6
AS2COS0067.1	150.54021	2.60905	12.02 ± 0.40	2.825	11.25 ± 0.17	2.69 ± 0.15	12.67 ± 0.17	9.52 ± 0.23	25.34 ± 4.00	-7.7

Table C.4: (continued)

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu\text{m}}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_\odot$]	$\text{Log}_{10} \text{SFR}$ [$M_\odot \text{ yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_\odot$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_\odot$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0068.1	150.14291	2.05061	9.97 $\pm$ 0.32	2.433	11.39 $\pm$ 0.02	2.51 $\pm$ 0.03	12.65 $\pm$ 0.02	9.48 $\pm$ 0.05	25.22 $\pm$ 0.72	-1.1
AS2COS0069.1	149.77102	2.36576	11.14 $\pm$ 0.31	3.618	10.28 $\pm$ 0.05	3.27 $\pm$ 0.02	13.05 $\pm$ 0.02	9.07 $\pm$ 0.02	34.58 $\pm$ 0.002	-2.0
AS2COS0071.1	149.88933	2.39638	6.50 $\pm$ 0.27	2.11 $\pm$ 0.19	10.79 $\pm$ 0.16	2.20 $\pm$ 0.10	12.22 $\pm$ 0.10	9.37 $\pm$ 0.12	22.51 $\pm$ 1.82	-10.2
AS2COS0072.1	150.02704	2.64379	11.32 $\pm$ 0.33	3.798	10.08 $\pm$ 0.35	2.83 $\pm$ 0.11	12.65 $\pm$ 0.08	9.37 $\pm$ 0.10	26.58 $\pm$ 2.05	-12.4
AS2COS0073.1	150.08900	2.01143	8.07 $\pm$ 0.30	3.27 $\pm$ 0.09	9.18 $\pm$ 0.07	2.16 $\pm$ 0.03	11.94 $\pm$ 0.03	9.60 $\pm$ 0.03	18.31 $\pm$ 0.13	-11.2
AS2COS0075.1	150.03142	2.19638	6.22 $\pm$ 0.31	3.35 $\pm$ 0.06	10.13 $\pm$ 0.20	2.81 $\pm$ 0.03	12.59 $\pm$ 0.03	9.02 $\pm$ 0.03	29.51 $\pm$ 0.32	-12.1
AS2COS0076.1	150.38388	2.07448	5.87 $\pm$ 0.28	3.08 $\pm$ 0.30	10.04 $\pm$ 0.38	2.49 $\pm$ 0.17	12.30 $\pm$ 0.11	9.29 $\pm$ 0.17	23.80 $\pm$ 2.33	31.3
AS2COS0076.2	150.38353	2.07446	4.63 $\pm$ 0.27	4.47 $\pm$ 1.20	10.30 $\pm$ 0.37	3.26 $\pm$ 0.37	13.04 $\pm$ 0.37	8.55 $\pm$ 0.32	44.53 $\pm$ 12.39	-4.1
AS2COS0077.1	150.34094	2.52487	10.24 $\pm$ 0.33	3.274	10.24 $\pm$ 0.22	2.70 $\pm$ 0.11	12.52 $\pm$ 0.08	9.46 $\pm$ 0.09	24.36 $\pm$ 1.53	-10.8
AS2COS0078.1	150.44706	2.41373	4.32 $\pm$ 0.27	3.92 $\pm$ 0.54	10.12 $\pm$ 0.23	3.04 $\pm$ 0.18	12.80 $\pm$ 0.19	8.65 $\pm$ 0.24	37.66 $\pm$ 7.88	-2.9
AS2COS0078.2	150.44785	2.41531	3.36 $\pm$ 0.52	3.82 $\pm$ 1.16	9.95 $\pm$ 0.41	2.77 $\pm$ 0.36	12.56 $\pm$ 0.36	8.42 $\pm$ 0.30	38.54 $\pm$ 8.97	-10.1
AS2COS0078.3	150.44575	2.41303	3.07 $\pm$ 0.53	2.75 $\pm$ 0.18	10.93 $\pm$ 0.13	2.35 $\pm$ 0.16	12.35 $\pm$ 0.15	8.56 $\pm$ 0.25	32.67 $\pm$ 4.45	13.8
AS2COS0079.1	150.08060	1.68515	8.47 $\pm$ 0.34	3.90 $\pm$ 0.55	9.97 $\pm$ 0.17	2.89 $\pm$ 0.14	12.67 $\pm$ 0.13	9.32 $\pm$ 0.17	27.50 $\pm$ 3.29	-10.8
AS2COS0082.1	149.83930	2.37779	8.82 $\pm$ 0.34	3.65 $\pm$ 0.14	10.36 $\pm$ 0.09	3.33 $\pm$ 0.06	13.11 $\pm$ 0.06	8.77 $\pm$ 0.06	40.17 $\pm$ 1.63	-7.8
AS2COS0083.1	149.91574	1.78681	9.62 $\pm$ 0.34	2.493	10.54 $\pm$ 0.20	2.70 $\pm$ 0.07	12.61 $\pm$ 0.02	9.38 $\pm$ 0.12	25.74 $\pm$ 1.48	-5.4
AS2COS0084.1	149.58108	2.25228	10.57 $\pm$ 0.27	3.600	9.69 $\pm$ 0.12	2.64 $\pm$ 0.06	12.43 $\pm$ 0.06	9.83 $\pm$ 0.18	20.27 $\pm$ 1.85	21.6
AS2COS0086.1	150.34490	2.01271	8.22 $\pm$ 0.29	2.91 $\pm$ 0.27	10.00 $\pm$ 0.35	2.73 $\pm$ 0.15	12.54 $\pm$ 0.14	9.40 $\pm$ 0.15	25.29 $\pm$ 2.67	-12.2
AS2COS0087.1	149.80084	2.16573	8.09 $\pm$ 0.35	2.08 $\pm$ 0.06	11.38 $\pm$ 0.04	2.29 $\pm$ 0.04	12.22 $\pm$ 0.04	9.56 $\pm$ 0.13	20.69 $\pm$ 1.36	-7.8
AS2COS0090.1	150.51175	1.74794	13.25 $\pm$ 0.37	3.310	10.65 $\pm$ 0.24	2.88 $\pm$ 0.10	12.73 $\pm$ 0.04	9.70 $\pm$ 0.16	23.81 $\pm$ 1.78	-8.9
AS2COS0090.2	150.51034	1.74590	2.13 $\pm$ 0.67	5.09 $\pm$ 0.65	9.90 $\pm$ 0.51	2.55 $\pm$ 0.32	12.40 $\pm$ 0.30	8.57 $\pm$ 0.49	34.51 $\pm$ 10.21	-9.9
AS2COS0093.1	150.05390	2.57638	7.94 $\pm$ 0.47	2.79 $\pm$ 0.23	10.89 $\pm$ 0.18	2.54 $\pm$ 0.09	12.55 $\pm$ 0.07	9.04 $\pm$ 0.07	29.00 $\pm$ 1.42	-5.0
AS2COS0093.2	150.05639	2.57325	6.23 $\pm$ 0.70	2.05 $\pm$ 0.14	9.39 $\pm$ 0.15	2.28 $\pm$ 0.07	11.90 $\pm$ 0.10	9.44 $\pm$ 0.09	19.18 $\pm$ 1.42	-9.2
AS2COS0094.1	150.26567	2.70349	9.63 $\pm$ 0.35	2.938	11.26 $\pm$ 0.07	2.53 $\pm$ 0.08	12.61 $\pm$ 0.02	9.46 $\pm$ 0.03	25.17 $\pm$ 0.32	-9.3
AS2COS0095.1	150.12660	2.69607	4.97 $\pm$ 0.28	1.88 $\pm$ 0.45	10.00 $\pm$ 0.26	2.82 $\pm$ 0.23	12.61 $\pm$ 0.22	8.96 $\pm$ 0.15	30.73 $\pm$ 4.79	-7.1
AS2COS0095.2	150.12596	2.69636	6.05 $\pm$ 0.42	1.66 $\pm$ 0.12	11.37 $\pm$ 0.07	2.12 $\pm$ 0.20	12.19 $\pm$ 0.05	9.39 $\pm$ 0.08	21.62 $\pm$ 1.12	-6.2
AS2COS0096.1	149.68595	2.40798	10.78 $\pm$ 0.42	3.251	11.11 $\pm$ 0.21	2.51 $\pm$ 0.11	12.56 $\pm$ 0.05	9.71 $\pm$ 0.15	22.21 $\pm$ 1.67	-9.9
AS2COS0096.2	149.68815	2.40780	1.25 $\pm$ 0.45	1.96 $\pm$ 0.12	10.75 $\pm$ 0.10	1.91 $\pm$ 0.15	11.96 $\pm$ 0.09	8.54 $\pm$ 0.21	28.03 $\pm$ 3.00	-6.8
AS2COS0098.1	150.40343	2.18615	9.34 $\pm$ 0.33	3.525	10.92 $\pm$ 0.06	2.57 $\pm$ 0.04	12.58 $\pm$ 0.02	9.19 $\pm$ 0.16	27.87 $\pm$ 2.13	-10.9
AS2COS0099.1	149.92558	1.77732	8.37 $\pm$ 0.32	1.60 $\pm$ 0.20	10.18 $\pm$ 0.88	2.04 $\pm$ 1.62	12.19 $\pm$ 0.13	9.39 $\pm$ 0.17	22.03 $\pm$ 2.90	27.2

Table C.4: (continued)

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu m}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_{\odot}$]	$\text{Log}_{10} \text{SFR}$ [$M_{\odot} \text{yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_{\odot}$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_{\odot}$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0100.1	150.58857	2.31911	9.43 ± 0.30	2.408	10.19 ± 0.17	2.74 ± 0.02	12.55 ± 0.02	9.41 ± 0.02	25.15 ± 0.09	5.2
AS2COS0101.1	149.88868	2.14242	6.71 ± 0.26	2.26 ± 0.63	10.50 ± 0.34	2.48 ± 0.38	12.43 ± 0.33	9.12 ± 0.19	27.30 ± 5.36	-5.7
AS2COS0103.1	150.71931	2.69979	11.92 ± 0.46	2.723	11.15 ± 0.19	2.91 ± 0.05	12.92 ± 0.02	9.36 ± 0.03	29.46 ± 0.38	-12.4
AS2COS0105.1	150.66849	1.76227	9.63 ± 0.31	4.331	10.19 ± 0.23	3.05 ± 0.08	12.85 ± 0.06	9.26 ± 0.13	30.03 ± 2.18	-10.8
AS2COS0105.2	150.66638	1.76289	5.69 ± 0.44	2.16 ± 0.08	9.12 ± 0.07	2.11 ± 0.04	11.89 ± 0.04	9.54 ± 0.06	18.36 ± 0.41	-12.4
AS2COS0106.1	149.70530	2.21713	4.88 ± 0.30	2.17 ± 0.07	10.77 ± 0.09	2.57 ± 0.05	12.55 ± 0.04	9.00 ± 0.04	29.56 ± 0.65	-12.4
AS2COS0106.2	149.70532	2.21534	2.60 ± 0.38	2.16 ± 0.14	10.82 ± 0.24	2.39 ± 0.15	12.26 ± 0.15	8.68 ± 0.15	29.86 ± 3.38	-7.7
AS2COS0107.1	149.81393	2.12983	9.18 ± 0.30	2.28 ± 0.06	9.71 ± 0.10	2.67 ± 0.04	12.46 ± 0.04	9.33 ± 0.03	25.07 ± 0.59	-11.1
AS2COS0108.1	150.09508	1.86125	5.75 ± 0.27	1.78 ± 0.23	10.80 ± 0.10	2.48 ± 0.12	12.44 ± 0.11	9.03 ± 0.09	27.97 ± 2.08	-11.0
AS2COS0108.2	150.09505	1.86019	1.01 ± 0.36	3.85 ± 0.80	9.23 ± 0.23	2.16 ± 0.19	11.91 ± 0.20	7.14 ± 0.54	49.05 ± 9.85	14.9
AS2COS0110.1	150.60020	2.53422	6.72 ± 0.38	1.78 ± 0.25	10.73 ± 0.23	2.35 ± 0.15	12.30 ± 0.19	9.36 ± 0.17	23.38 ± 3.05	-3.3
AS2COS0110.2	150.60001	2.53367	2.89 ± 0.31	2.16 ± 0.33	10.54 ± 0.21	2.08 ± 0.23	12.08 ± 0.19	8.86 ± 0.18	26.20 ± 3.75	-12.4
AS2COS0110.3	150.59883	2.53353	3.75 ± 1.08	2.15 ± 0.47	10.58 ± 0.30	2.17 ± 0.52	12.19 ± 0.35	8.66 ± 0.46	30.29 ± 8.27	-11.3
AS2COS0111.1	150.26479	1.80297	8.99 ± 0.33	2.19 ± 0.19	10.99 ± 0.36	2.81 ± 0.19	12.66 ± 0.18	9.31 ± 0.16	27.42 ± 3.45	-0.0
AS2COS0113.1	150.11027	2.75152	8.16 ± 0.30	2.10 ± 0.12	10.75 ± 0.19	2.76 ± 0.12	12.68 ± 0.07	9.18 ± 0.07	29.04 ± 1.38	-12.4
AS2COS0116.1	150.49172	1.74632	11.19 ± 0.40	3.181	10.08 ± 0.31	2.77 ± 0.09	12.59 ± 0.06	9.65 ± 0.16	23.04 ± 1.91	-9.6
AS2COS0116.2	150.49037	1.74637	3.30 ± 0.44	2.38 ± 0.17	10.85 ± 0.23	2.49 ± 0.14	12.42 ± 0.10	8.85 ± 0.11	29.72 ± 2.12	100.3
AS2COS0119.1	149.72370	2.28132	5.70 ± 0.34	3.47 ± 0.34	10.72 ± 0.20	3.01 ± 0.18	12.86 ± 0.14	8.72 ± 0.12	37.06 ± 3.79	-12.4
AS2COS0119.2	149.72580	2.27943	5.16 ± 0.42	2.01 ± 0.20	10.57 ± 0.22	2.55 ± 0.17	12.45 ± 0.12	8.91 ± 0.11	29.46 ± 2.63	-1.7
AS2COS0122.1	150.43602	2.23096	6.36 ± 0.29	3.68 ± 1.02	10.88 ± 0.23	2.60 ± 0.32	12.59 ± 0.27	9.20 ± 0.28	28.10 ± 6.59	-11.0
AS2COS0123.1	149.59827	2.20781	7.58 ± 0.29	4.84 ± 0.25	9.58 ± 0.14	2.53 ± 0.08	12.30 ± 0.08	9.55 ± 0.33	21.72 ± 3.45	16.4
AS2COS0126.1	150.37975	1.90237	5.44 ± 0.35	4.00 ± 0.94	10.14 ± 0.36	2.77 ± 0.35	12.61 ± 0.30	8.92 ± 0.27	31.76 ± 6.80	-10.3
AS2COS0126.2	150.38027	1.89993	2.33 ± 0.72	2.62 ± 0.12	10.72 ± 0.06	1.66 ± 0.10	11.69 ± 0.08	8.87 ± 0.45	22.55 ± 4.92	-12.2
AS2COS0127.1	150.29820	2.47807	7.87 ± 0.36	2.21 ± 0.08	11.31 ± 0.08	2.10 ± 0.16	12.17 ± 0.05	9.39 ± 0.05	21.56 ± 0.69	-2.7
AS2COS0128.1	150.10627	2.05350	5.61 ± 0.34	2.86 ± 0.40	9.83 ± 0.24	2.71 ± 0.20	12.50 ± 0.20	9.01 ± 0.12	28.65 ± 2.88	3.6
AS2COS0128.2	150.10668	2.05449	1.75 ± 0.32	1.032	10.95 ± 0.04	2.01 ± 0.09	12.04 ± 0.03	8.49 ± 0.04	29.45 ± 0.48	-12.2
AS2COS0129.1	150.63374	2.57831	8.16 ± 0.28	2.06 ± 0.28	10.48 ± 0.19	2.76 ± 0.19	12.58 ± 0.18	9.26 ± 0.15	27.11 ± 3.22	-6.1
AS2COS0129.3	150.63539	2.57635	2.22 ± 0.64	1.11 ± 0.07	9.19 ± 0.17	2.03 ± 0.09	11.83 ± 0.08	8.32 ± 0.17	29.14 ± 2.42	-9.5
AS2COS0133.1	149.99979	2.10924	8.86 ± 0.32	3.59 ± 0.23	10.46 ± 0.31	3.07 ± 0.16	12.88 ± 0.09	9.05 ± 0.12	32.72 ± 2.58	6.1

Table C.4: (continued)

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu\text{m}}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_\odot$]	$\text{Log}_{10} \text{SFR}$ [$M_\odot \text{ yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_\odot$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_\odot$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0134.1	150.09691	2.68192	6.95 $\pm$ 0.28	2.56 $\pm$ 0.22	10.70 $\pm$ 0.21	2.64 $\pm$ 0.13	12.58 $\pm$ 0.08	9.16 $\pm$ 0.13	27.98 $\pm$ 2.26	-4.7
AS2COS0138.1	150.59179	2.41370	7.18 $\pm$ 0.42	1.46 $\pm$ 0.15	10.86 $\pm$ 0.08	2.59 $\pm$ 0.16	12.43 $\pm$ 0.16	9.22 $\pm$ 0.10	25.84 $\pm$ 2.26	-6.2
AS2COS0138.2	150.59117	2.41212	1.35 $\pm$ 0.50	1.10 $\pm$ 0.07	10.54 $\pm$ 0.12	1.67 $\pm$ 0.17	11.69 $\pm$ 0.12	8.29 $\pm$ 0.35	28.03 $\pm$ 4.79	-12.0
AS2COS0139.1	149.58247	2.60280	12.79 $\pm$ 0.31	3.292	10.43 $\pm$ 0.05	3.42 $\pm$ 0.02	13.21 $\pm$ 0.02	9.25 $\pm$ 0.02	34.58 $\pm$ 0.14	131.2
AS2COS0143.1	149.95809	1.92050	5.50 $\pm$ 0.33	4.86 $\pm$ 0.60	9.95 $\pm$ 0.26	2.85 $\pm$ 0.21	12.63 $\pm$ 0.21	9.13 $\pm$ 0.27	29.14 $\pm$ 4.98	-8.5
AS2COS0143.2	149.95878	1.92069	2.29 $\pm$ 0.36	2.71 $\pm$ 0.88	9.21 $\pm$ 0.36	2.05 $\pm$ 0.28	11.83 $\pm$ 0.27	8.90 $\pm$ 0.21	23.33 $\pm$ 3.74	-9.5
AS2COS0144.1	149.66525	2.35488	7.89 $\pm$ 0.30	2.19 $\pm$ 0.63	10.86 $\pm$ 0.16	2.36 $\pm$ 0.28	12.34 $\pm$ 0.32	9.44 $\pm$ 0.15	23.05 $\pm$ 3.99	-2.2
AS2COS0145.1	149.64582	2.19784	8.20 $\pm$ 0.32	3.35 $\pm$ 0.30	9.68 $\pm$ 0.19	2.58 $\pm$ 0.15	12.36 $\pm$ 0.15	9.63 $\pm$ 0.15	21.36 $\pm$ 2.28	-10.9
AS2COS0147.1	149.49402	2.54437	9.94 $\pm$ 0.42	2.963	11.76 $\pm$ 0.02	2.05 $\pm$ 0.03	12.53 $\pm$ 0.02	9.51 $\pm$ 0.17	23.92 $\pm$ 1.75	-3.7
AS2COS0148.1	149.71510	2.06426	8.34 $\pm$ 0.30	4.09 $\pm$ 0.77	10.40 $\pm$ 0.19	3.37 $\pm$ 0.18	13.15 $\pm$ 0.18	8.90 $\pm$ 0.19	39.08 $\pm$ 5.80	-12.4
AS2COS0149.1	149.65878	2.07194	6.63 $\pm$ 0.26	2.35 $\pm$ 0.11	10.79 $\pm$ 0.21	3.00 $\pm$ 0.13	12.81 $\pm$ 0.08	8.96 $\pm$ 0.10	33.38 $\pm$ 2.17	0.5
AS2COS0150.1	150.40056	1.86154	11.08 $\pm$ 0.43	2.947	10.69 $\pm$ 0.15	2.86 $\pm$ 0.08	12.79 $\pm$ 0.05	9.32 $\pm$ 0.13	28.43 $\pm$ 1.88	-8.3
AS2COS0151.1	149.45371	1.97824	11.26 $\pm$ 0.34	4.529	10.73 $\pm$ 0.35	3.37 $\pm$ 0.04	13.17 $\pm$ 0.02	9.19 $\pm$ 0.03	34.61 $\pm$ 0.43	-3.1
AS2COS0153.1	149.88204	2.31899	3.40 $\pm$ 0.29	1.50 $\pm$ 0.03	10.89 $\pm$ 0.12	2.27 $\pm$ 0.14	12.26 $\pm$ 0.12	8.93 $\pm$ 0.10	27.08 $\pm$ 2.30	-8.6
AS2COS0153.2	149.88157	2.31819	3.07 $\pm$ 0.29	1.616	10.84 $\pm$ 0.18	2.77 $\pm$ 0.08	12.58 $\pm$ 0.05	8.24 $\pm$ 0.08	40.20 $\pm$ 1.76	-5.1
AS2COS0155.1	149.88205	2.51222	11.77 $\pm$ 0.35	4.198	11.68 $\pm$ 0.21	2.89 $\pm$ 0.11	13.01 $\pm$ 0.05	9.10 $\pm$ 0.06	34.19 $\pm$ 1.36	-12.4
AS2COS0157.1	150.42576	1.67655	10.91 $\pm$ 0.38	2.793	10.19 $\pm$ 0.26	3.01 $\pm$ 0.07	12.81 $\pm$ 0.05	9.33 $\pm$ 0.13	28.62 $\pm$ 2.00	8.4
AS2COS0158.1	150.17315	2.69175	5.74 $\pm$ 0.31	2.49 $\pm$ 0.11	11.16 $\pm$ 0.07	2.43 $\pm$ 0.07	12.39 $\pm$ 0.05	9.21 $\pm$ 0.09	25.53 $\pm$ 1.27	-10.2
AS2COS0159.1	149.95946	1.89341	9.09 $\pm$ 0.31	3.88 $\pm$ 1.14	10.81 $\pm$ 0.27	3.16 $\pm$ 0.45	13.01 $\pm$ 0.35	8.90 $\pm$ 0.28	37.70 $\pm$ 8.59	-12.0
AS2COS0160.1	149.89734	2.32221	5.98 $\pm$ 0.34	1.83 $\pm$ 1.20	9.28 $\pm$ 0.45	2.17 $\pm$ 0.41	11.96 $\pm$ 0.41	9.34 $\pm$ 0.30	21.25 $\pm$ 8.49	-7.2
AS2COS0162.1	150.27353	2.54398	7.49 $\pm$ 0.29	2.09 $\pm$ 0.18	9.98 $\pm$ 0.20	2.58 $\pm$ 0.12	12.39 $\pm$ 0.11	9.37 $\pm$ 0.12	23.94 $\pm$ 2.02	-12.4
AS2COS0164.1	150.50721	1.67926	7.24 $\pm$ 0.38	1.72 $\pm$ 0.23	10.73 $\pm$ 0.13	2.31 $\pm$ 0.18	12.33 $\pm$ 0.16	9.39 $\pm$ 0.11	23.20 $\pm$ 2.70	-1.2
AS2COS0168.1	150.35411	1.86309	7.80 $\pm$ 0.30	2.15 $\pm$ 0.12	9.82 $\pm$ 0.18	2.70 $\pm$ 0.06	12.50 $\pm$ 0.06	9.35 $\pm$ 0.07	25.22 $\pm$ 1.11	-10.8
AS2COS0169.1	149.71906	2.15407	6.61 $\pm$ 0.34	2.64 $\pm$ 0.33	11.05 $\pm$ 0.26	2.57 $\pm$ 0.17	12.49 $\pm$ 0.20	9.24 $\pm$ 0.19	26.17 $\pm$ 3.72	-5.0
AS2COS0170.1	150.33935	2.74474	6.51 $\pm$ 0.34	1.453	11.26 $\pm$ 0.11	2.60 $\pm$ 0.09	12.56 $\pm$ 0.09	9.23 $\pm$ 0.11	26.90 $\pm$ 2.13	-4.2
AS2COS0171.1	149.97209	1.71414	7.98 $\pm$ 0.29	2.92 $\pm$ 0.11	11.25 $\pm$ 0.06	2.70 $\pm$ 0.06	12.72 $\pm$ 0.06	9.21 $\pm$ 0.09	28.96 $\pm$ 1.43	-8.8
AS2COS0174.1	150.41751	2.76322	11.49 $\pm$ 0.34	2.787	10.78 $\pm$ 0.28	2.91 $\pm$ 0.09	12.77 $\pm$ 0.03	9.48 $\pm$ 0.15	26.47 $\pm$ 1.99	-1.5
AS2COS0175.1	150.73578	2.19958	10.60 $\pm$ 0.43	3.509	12.40 $\pm$ 0.84	1.78 $\pm$ 1.34	13.24 $\pm$ 0.05	8.90 $\pm$ 0.08	40.01 $\pm$ 1.77	151.3
AS2COS0177.1	150.17184	1.66015	5.32 $\pm$ 0.32	3.83 $\pm$ 0.60	11.00 $\pm$ 0.25	2.64 $\pm$ 0.26	12.63 $\pm$ 0.20	8.98 $\pm$ 0.24	31.09 $\pm$ 5.38	-12.3

Table C.4: (continued)

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu m}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_{\odot}$]	$\text{Log}_{10} \text{SFR}$ [$M_{\odot} \text{yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_{\odot}$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_{\odot}$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0180.1	150.34798	2.76107	5.87 ± 0.30	2.13 ± 0.13	11.13 ± 0.10	2.42 ± 0.07	12.37 ± 0.07	9.24 ± 0.08	25.08 ± 1.29	-10.9
AS2COS0182.1	149.76385	1.91841	7.16 ± 0.28	1.37 ± 0.77	10.45 ± 0.38	2.08 ± 0.61	12.02 ± 0.55	9.17 ± 0.10	22.82 ± 4.91	-4.8
AS2COS0182.2	149.76339	1.91791	1.28 ± 0.27	1.86 ± 0.18	10.57 ± 0.15	2.14 ± 0.25	12.11 ± 0.18	8.36 ± 0.18	32.15 ± 4.40	-8.8
AS2COS0184.1	149.87882	2.57945	4.46 ± 0.52	1.506	10.83 ± 0.20	2.76 ± 0.07	12.60 ± 0.02	8.66 ± 0.06	34.43 ± 0.87	-11.1
AS2COS0184.2	149.87775	2.57646	3.33 ± 0.40	1.505	11.30 ± 0.03	2.53 ± 0.09	12.49 ± 0.02	8.87 ± 0.11	30.00 ± 1.52	-8.0
AS2COS0184.3	149.87991	2.57821	1.22 ± 0.45	1.15 ± 0.15	8.82 ± 0.26	1.44 ± 0.26	11.25 ± 0.22	8.45 ± 0.46	22.23 ± 4.78	-10.1
AS2COS0187.1	149.78955	2.08239	7.39 ± 0.28	2.70 ± 0.23	9.86 ± 0.14	2.84 ± 0.13	12.63 ± 0.12	9.16 ± 0.12	28.64 ± 2.26	-5.4
AS2COS0188.1	149.99497	2.58271	9.17 ± 0.35	5.46 ± 1.16	10.64 ± 0.42	3.45 ± 0.33	13.26 ± 0.33	8.76 ± 0.27	43.95 ± 7.74	-11.0
AS2COS0189.1	149.49363	2.28020	6.50 ± 0.37	2.79 ± 0.61	9.78 ± 0.33	2.62 ± 0.28	12.36 ± 0.26	9.33 ± 0.21	24.30 ± 4.32	30.1
AS2COS0189.2	149.49489	2.28063	1.84 ± 0.61	0.305	10.40 ± 0.05	1.65 ± 0.04	11.67 ± 0.02	8.14 ± 0.02	29.49 ± 0.01	-12.2
AS2COS0191.1	150.49063	2.61334	3.81 ± 0.27	5.03 ± 0.26	10.81 ± 0.20	2.62 ± 0.22	12.55 ± 0.17	8.85 ± 0.32	31.61 ± 5.42	0.5
AS2COS0191.2	150.49061	2.61404	1.02 ± 0.38	3.89 ± 1.12	10.23 ± 0.65	2.32 ± 0.68	12.29 ± 0.43	7.86 ± 0.42	43.36 ± 11.71	-8.6
AS2COS0192.1	150.01609	2.79236	4.98 ± 0.27	1.33 ± 0.56	10.81 ± 0.14	2.18 ± 0.35	12.07 ± 0.40	9.26 ± 0.17	22.45 ± 5.29	-8.0
AS2COS0192.2	150.01735	2.78974	4.45 ± 0.85	3.56 ± 0.22	9.76 ± 0.12	2.72 ± 0.10	12.51 ± 0.10	8.96 ± 0.19	29.70 ± 2.96	-4.0
AS2COS0195.1	149.49434	2.25671	4.74 ± 0.37	2.50 ± 1.44	10.40 ± 1.01	2.32 ± 1.59	12.41 ± 0.57	8.92 ± 0.37	30.85 ± 12.66	-6.9
AS2COS0195.2	149.49406	2.25438	2.05 ± 0.50	0.84 ± 0.38	10.72 ± 0.47	1.55 ± 0.47	11.63 ± 0.42	8.68 ± 0.10	23.62 ± 5.10	3.2
AS2COS0196.1	150.27020	2.48321	5.37 ± 0.31	3.240	11.00 ± 0.13	3.18 ± 0.03	13.00 ± 0.02	8.64 ± 0.03	40.52 ± 0.44	-2.7
AS2COS0196.2	150.26856	2.47994	2.38 ± 0.74	2.11 ± 0.10	11.05 ± 0.06	2.00 ± 0.11	12.12 ± 0.09	8.70 ± 0.27	27.98 ± 3.86	-4.6
AS2COS0198.1	150.38142	2.42112	9.15 ± 0.33	1.64 ± 0.29	9.24 ± 0.16	2.23 ± 0.14	12.02 ± 0.14	9.64 ± 0.09	18.71 ± 2.00	-12.2
AS2COS0199.1	150.42726	2.00408	6.99 ± 0.27	1.71 ± 0.13	10.16 ± 0.21	2.49 ± 0.09	12.29 ± 0.08	9.17 ± 0.10	24.89 ± 1.62	4.0
AS2COS0203.1	149.77696	2.40996	6.94 ± 0.27	3.11 ± 0.05	10.67 ± 0.12	2.57 ± 0.19	12.53 ± 0.12	9.27 ± 0.15	26.33 ± 3.12	-1.9
AS2COS0210.1	149.68098	2.75504	4.20 ± 0.30	3.06 ± 0.33	10.48 ± 0.31	2.27 ± 0.17	12.26 ± 0.15	9.07 ± 0.19	25.85 ± 3.23	-12.0
AS2COS0218.1	149.86927	2.13037	7.08 ± 0.35	2.18 ± 0.13	9.79 ± 0.14	2.68 ± 0.09	12.46 ± 0.08	9.29 ± 0.10	25.50 ± 1.72	-10.2
AS2COS0219.1	149.88538	1.83902	4.49 ± 0.30	1.62 ± 0.19	9.90 ± 0.17	1.88 ± 0.09	11.70 ± 0.09	9.34 ± 0.08	18.39 ± 0.57	1.5
AS2COS0219.2	149.88621	1.83974	3.04 ± 0.32	3.11 ± 0.90	10.94 ± 0.41	2.39 ± 0.35	12.24 ± 0.30	8.87 ± 0.26	27.97 ± 6.23	-9.8
AS2COS0220.1	150.00780	1.68614	5.56 ± 0.32	4.00 ± 0.57	10.94 ± 0.18	3.03 ± 0.18	12.96 ± 0.16	8.70 ± 0.17	39.25 ± 4.85	-12.4
AS2COS0223.1	149.74949	1.85186	5.36 ± 0.36	1.53 ± 0.50	10.95 ± 0.19	2.24 ± 0.26	12.22 ± 0.30	9.17 ± 0.08	24.41 ± 3.21	-12.2
AS2COS0223.2	149.75084	1.85217	4.40 ± 0.30	2.02 ± 0.09	11.00 ± 0.09	2.22 ± 0.13	12.23 ± 0.08	9.13 ± 0.13	24.44 ± 1.87	-5.6
AS2COS0226.1	149.52814	2.41321	6.68 ± 0.39	1.94 ± 0.24	10.00 ± 0.19	2.93 ± 0.10	12.71 ± 0.10	9.12 ± 0.07	29.93 ± 2.26	-8.4

Table C.4: (continued)

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu\text{m}}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_\odot$]	$\text{Log}_{10} \text{SFR}$ [$M_\odot \text{ yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_\odot$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_\odot$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0226.2	149.52903	2.41370	2.84 ± 0.29	2.22 ± 0.20	10.09 ± 0.28	2.61 ± 0.20	12.43 ± 0.16	8.66 ± 0.17	32.05 ± 3.90	-4.5
AS2COS0228.1	150.61665	2.16794	3.38 ± 0.21	1.86 ± 0.66	10.26 ± 0.39	3.01 ± 0.33	12.81 ± 0.32	8.65 ± 0.19	38.59 ± 8.87	-12.0
AS2COS0228.2	150.61636	2.16796	3.01 ± 0.26	1.523	10.98 ± 0.28	2.47 ± 0.14	12.41 ± 0.12	8.46 ± 0.19	34.84 ± 4.15	-9.4
AS2COS0229.1	150.32392	2.75163	4.92 ± 0.26	2.19 ± 0.18	11.21 ± 0.10	2.07 ± 0.18	12.08 ± 0.09	9.35 ± 0.12	21.21 ± 1.60	-9.8
AS2COS0230.1	149.61511	1.78955	8.80 ± 0.30	1.84 ± 0.23	10.56 ± 0.30	2.71 ± 0.17	12.57 ± 0.17	9.33 ± 0.13	26.18 ± 2.68	14.8
AS2COS0231.1	149.78372	2.81792	8.18 ± 0.39	1.97 ± 0.14	11.21 ± 0.14	2.31 ± 0.14	12.36 ± 0.12	9.34 ± 0.14	24.05 ± 2.25	44.8
AS2COS0234.1	149.92743	1.91710	7.96 ± 0.56	1.81 ± 0.03	11.75 ± 0.02	1.66 ± 0.02	12.16 ± 0.02	9.38 ± 0.03	21.46 ± 0.16	-10.6
AS2COS0239.1	150.31058	2.45154	6.14 ± 0.30	2.44 ± 0.24	10.70 ± 0.18	2.42 ± 0.15	12.43 ± 0.13	9.02 ± 0.12	28.15 ± 2.66	-12.4
AS2COS0239.2	150.31164	2.45101	2.30 ± 0.31	1.46 ± 0.07	8.98 ± 0.13	1.90 ± 0.07	11.68 ± 0.07	8.93 ± 0.11	21.43 ± 1.14	-8.2
AS2COS0242.1	150.28844	1.68255	7.80 ± 0.32	4.44 ± 0.15	10.02 ± 0.15	2.99 ± 0.14	12.78 ± 0.14	9.15 ± 0.25	30.79 ± 4.03	-7.6
AS2COS0242.2	150.28774	1.68316	3.39 ± 0.42	2.11 ± 0.25	9.89 ± 0.22	1.83 ± 0.17	11.80 ± 0.14	9.28 ± 0.16	19.61 ± 2.26	-11.6
AS2COS0244.1	150.70246	2.75411	7.98 ± 0.32	2.64 ± 0.07	10.83 ± 0.06	3.15 ± 0.05	13.05 ± 0.04	9.07 ± 0.04	34.65 ± 0.75	-12.1
AS2COS0246.1	150.50533	2.72621	7.10 ± 0.41	2.99 ± 0.17	10.80 ± 0.12	2.33 ± 0.11	12.34 ± 0.10	9.57 ± 0.15	21.49 ± 1.92	-7.9
AS2COS0246.2	150.50454	2.72503	1.16 ± 0.43	3.18 ± 0.06	10.35 ± 0.04	2.66 ± 0.03	12.49 ± 0.03	7.88 ± 0.32	44.76 ± 6.22	3.2
AS2COS0247.1	150.40264	2.61084	7.46 ± 0.51	1.55 ± 0.59	10.75 ± 0.23	2.17 ± 0.33	12.05 ± 0.31	9.50 ± 0.19	20.21 ± 5.09	-7.2
AS2COS0257.1	149.55848	2.00308	6.02 ± 0.36	1.77 ± 0.19	11.03 ± 0.17	2.22 ± 0.19	12.21 ± 0.12	9.34 ± 0.14	22.41 ± 2.20	6.2
AS2COS0260.1	149.48585	2.52023	3.55 ± 0.27	1.22 ± 0.06	9.02 ± 0.06	2.00 ± 0.04	11.78 ± 0.04	9.05 ± 0.06	21.34 ± 0.62	-10.8
AS2COS0260.2	149.48576	2.51969	3.88 ± 0.46	3.31 ± 0.24	11.05 ± 0.28	2.74 ± 0.14	12.69 ± 0.14	8.73 ± 0.22	34.70 ± 4.88	-4.2
AS2COS0261.1	149.64308	1.91751	6.95 ± 0.33	1.83 ± 0.16	10.93 ± 0.10	2.17 ± 0.11	12.08 ± 0.10	9.47 ± 0.15	20.44 ± 1.88	12.6
AS2COS0262.1	149.68030	1.70089	6.27 ± 0.36	2.44 ± 0.24	10.81 ± 0.18	2.56 ± 0.18	12.56 ± 0.15	9.15 ± 0.13	27.79 ± 2.80	-11.1
AS2COS0263.1	150.48797	1.73200	7.50 ± 0.38	2.60 ± 0.37	10.90 ± 0.20	2.98 ± 0.25	12.86 ± 0.18	9.03 ± 0.13	32.94 ± 3.55	-2.4
AS2COS0268.1	150.50471	1.84232	5.99 ± 0.39	1.95 ± 0.22	10.84 ± 0.15	2.54 ± 0.13	12.41 ± 0.13	9.20 ± 0.13	25.76 ± 2.44	-3.7
AS2COS0268.2	150.50512	1.84222	3.57 ± 0.53	2.03 ± 0.11	10.69 ± 0.13	1.93 ± 0.11	11.76 ± 0.11	9.25 ± 0.18	19.59 ± 2.11	-12.2
AS2COS0268.3	150.50642	1.84499	3.15 ± 0.63	1.94 ± 0.19	10.56 ± 0.17	2.55 ± 0.16	12.41 ± 0.13	8.83 ± 0.14	29.99 ± 2.56	-12.4
AS2COS0272.1	150.31664	1.60374	5.13 ± 0.35	3.65 ± 0.67	11.29 ± 0.21	3.22 ± 0.23	13.17 ± 0.19	8.59 ± 0.18	44.55 ± 6.46	-9.0
AS2COS0272.2	150.31896	1.60504	4.16 ± 0.61	1.06 ± 0.16	8.78 ± 0.15	1.74 ± 0.14	11.50 ± 0.14	9.10 ± 0.09	18.60 ± 1.05	4.6
AS2COS0275.1	149.95458	1.74377	3.84 ± 0.30	3.29 ± 0.09	10.45 ± 0.27	2.78 ± 0.28	12.63 ± 0.22	8.69 ± 0.27	35.09 ± 5.99	-12.0
AS2COS0275.2	149.95169	1.74405	5.39 ± 0.45	1.632	10.85 ± 0.12	2.92 ± 0.04	12.76 ± 0.02	8.78 ± 0.09	34.98 ± 1.49	-1.3
AS2COS0281.1	150.44598	1.65138	3.87 ± 0.31	2.46 ± 0.21	10.47 ± 0.25	1.85 ± 0.26	11.86 ± 0.15	9.33 ± 0.17	19.88 ± 2.48	-11.9

Table C.4: (continued)

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu m}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_{\odot}$]	$\text{Log}_{10} \text{SFR}$ [$M_{\odot} \text{yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_{\odot}$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_{\odot}$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0281.2	150.44660	1.65171	3.47 ± 0.32	1.19 ± 0.16	8.96 ± 0.20	1.95 ± 0.20	11.74 ± 0.20	9.08 ± 0.15	20.78 ± 1.38	-2.2
AS2COS0282.1	149.58540	1.80628	6.74 ± 0.56	2.71 ± 0.05	10.21 ± 0.15	2.41 ± 0.05	12.26 ± 0.02	9.48 ± 0.10	21.70 ± 0.98	0.5
AS2COS0285.1	150.58115	2.73314	5.09 ± 0.34	2.67 ± 0.32	9.25 ± 0.25	2.12 ± 0.11	11.88 ± 0.11	9.48 ± 0.09	18.76 ± 1.12	-10.1
AS2COS0285.2	150.58403	2.73346	1.28 ± 0.34	3.38 ± 1.13	9.81 ± 0.63	2.21 ± 0.61	12.09 ± 0.53	8.17 ± 0.39	35.55 ± 10.31	-7.5
AS2COS0286.1	149.68789	2.56845	5.09 ± 0.32	3.58 ± 0.24	10.48 ± 0.16	2.31 ± 0.20	12.27 ± 0.14	9.34 ± 0.23	23.26 ± 3.39	-11.7
AS2COS0299.1	149.59079	1.99385	9.46 ± 0.41	5.105	10.09 ± 0.15	3.04 ± 0.09	12.83 ± 0.09	9.36 ± 0.21	28.86 ± 2.99	-10.0
AS2COS0302.1	150.79212	1.87206	5.22 ± 0.38	1.37 ± 0.09	9.05 ± 0.09	2.02 ± 0.06	11.81 ± 0.06	9.45 ± 0.06	18.31 ± 0.15	-10.0
AS2COS0305.1	149.87457	2.66099	4.92 ± 0.31	1.71 ± 0.03	11.23 ± 0.02	2.14 ± 0.03	12.26 ± 0.02	9.09 ± 0.05	25.12 ± 0.43	-6.4
AS2COS0305.2	149.87553	2.65996	1.65 ± 0.48	0.84 ± 0.10	9.24 ± 0.19	1.41 ± 0.12	11.36 ± 0.11	8.84 ± 0.18	19.55 ± 2.15	-12.4
AS2COS0307.1	149.87311	1.89377	8.57 ± 0.50	1.00 ± 0.02	11.21 ± 0.06	2.45 ± 0.03	12.35 ± 0.02	9.20 ± 0.02	25.16 ± 0.13	-12.2
AS2COS0308.1	150.60879	2.76970	4.08 ± 0.28	3.026	11.01 ± 0.06	3.22 ± 0.02	12.72 ± 0.02	8.75 ± 0.04	34.63 ± 0.54	33.3
AS2COS0311.1	150.70736	1.72378	11.36 ± 0.44	4.539	10.21 ± 0.26	3.03 ± 0.09	12.83 ± 0.07	9.46 ± 0.17	27.61 ± 2.41	4.4
AS2COS0320.1	149.58456	2.67974	3.59 ± 0.50	2.14 ± 0.10	9.77 ± 0.22	2.46 ± 0.10	12.26 ± 0.09	8.88 ± 0.18	27.46 ± 2.78	-10.8
AS2COS0321.1	149.55510	1.83066	8.13 ± 0.40	3.93 ± 0.72	10.61 ± 0.29	2.78 ± 0.27	12.69 ± 0.21	9.29 ± 0.24	28.07 ± 4.89	-10.7
AS2COS0324.1	149.62441	1.95237	4.81 ± 0.34	2.02 ± 0.14	10.99 ± 0.11	2.29 ± 0.10	12.31 ± 0.09	9.13 ± 0.12	25.29 ± 2.00	-9.8
AS2COS0330.1	150.76831	1.73410	5.75 ± 0.38	2.69 ± 0.20	10.79 ± 0.13	2.32 ± 0.13	12.33 ± 0.11	9.30 ± 0.15	23.94 ± 2.23	-8.8
AS2COS0330.2	150.76815	1.73499	2.70 ± 0.42	2.70 ± 0.37	8.91 ± 0.16	1.86 ± 0.14	11.63 ± 0.14	9.21 ± 0.19	18.89 ± 1.35	-11.3
AS2COS0330.3	150.76551	1.73478	1.52 ± 0.45	3.74 ± 0.09	10.34 ± 0.22	2.74 ± 0.15	12.46 ± 0.14	7.67 ± 0.32	48.71 ± 6.54	27.4
AS2COS0339.1	150.62828	1.99782	6.59 ± 0.68	3.24 ± 0.18	10.87 ± 0.24	2.79 ± 0.08	12.77 ± 0.07	8.96 ± 0.15	32.89 ± 2.57	-10.5
AS2COS0343.1	149.52806	2.67051	5.47 ± 0.39	1.90 ± 0.05	10.64 ± 0.15	2.50 ± 0.09	12.45 ± 0.07	9.13 ± 0.15	26.92 ± 2.25	-9.6
AS2COS0346.1	149.83987	1.79379	9.02 ± 0.46	3.08 ± 0.13	10.05 ± 0.09	3.01 ± 0.06	12.80 ± 0.06	9.29 ± 0.10	28.89 ± 1.61	-0.3
AS2COS0347.1	150.51495	2.61761	6.53 ± 0.40	4.27 ± 1.88	10.42 ± 0.63	3.37 ± 0.61	13.16 ± 0.61	8.61 ± 0.46	47.22 ± 16.64	4.6
AS2COS0353.1	149.51390	2.04452	3.73 ± 0.37	3.13 ± 0.26	9.54 ± 0.20	2.45 ± 0.14	12.25 ± 0.14	9.03 ± 0.21	25.90 ± 3.57	-8.3
AS2COS0353.2	149.51358	2.04446	0.83 ± 0.26	2.48 ± 1.67	10.62 ± 0.33	1.22 ± 3.20	11.82 ± 0.72	7.94 ± 0.50	37.03 ± 16.42	-8.3
AS2COS0358.1	150.72967	2.07030	5.69 ± 0.41	1.50 ± 0.08	10.10 ± 0.19	1.90 ± 0.09	11.78 ± 0.06	9.42 ± 0.06	18.31 ± 0.16	-4.2
AS2COS0358.2	150.72979	2.07118	1.36 ± 0.41	1.47 ± 0.25	9.60 ± 0.29	2.21 ± 0.21	12.01 ± 0.20	8.54 ± 0.15	28.93 ± 3.96	-12.2
AS2COS0362.1	149.69350	1.72286	6.73 ± 0.34	3.79 ± 0.12	10.81 ± 0.09	2.50 ± 0.12	12.47 ± 0.09	9.20 ± 0.18	26.45 ± 2.59	31.6
AS2COS0366.1	149.80840	2.72038	5.49 ± 0.35	1.91 ± 0.11	10.23 ± 0.18	2.91 ± 0.12	12.71 ± 0.11	8.99 ± 0.10	31.75 ± 2.53	-6.7
AS2COS0367.1	150.59997	2.63999	9.81 ± 0.38	2.832	10.63 ± 0.17	3.01 ± 0.03	12.81 ± 0.02	9.26 ± 0.03	29.47 ± 0.32	-6.9

Table C.4: (continued)

ID	R.A. [degrees]	Dec. [degrees]	$S_{870\mu\text{m}}$ [mJy]	z	$\text{Log}_{10} M_*$ [$M_\odot$]	$\text{Log}_{10} \text{SFR}$ [$M_\odot \text{yr}^{-1}$]	$\text{Log}_{10} L_{\text{dust}}$ [$L_\odot$]	$\text{Log}_{10} M_{\text{dust}}$ [$M_\odot$]	T_{dust} [K]	ΔBIC
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
AS2COS0381.1	150.74617	1.64993	6.24 ± 0.40	1.38 ± 0.13	10.18 ± 0.20	1.97 ± 0.11	11.87 ± 0.07	9.43 ± 0.13	18.95 ± 1.29	-5.6
AS2COS0381.2	150.74664	1.65046	1.84 ± 0.68	1.07 ± 0.05	11.11 ± 0.06	2.29 ± 0.08	12.16 ± 0.07	8.61 ± 0.07	29.41 ± 0.88	-12.2
AS2COS0426.1	149.55924	1.57232	5.68 ± 0.32	2.17 ± 0.18	10.92 ± 0.07	2.41 ± 0.12	12.44 ± 0.11	9.13 ± 0.12	26.74 ± 2.27	-7.4