THE COMPLETE INFRARED VIEW OF ACTIVE GALACTIC NUCLEI FROM THE 70MONTH SWIFT/BAT CATALOG

KOHEI ICHIKAWA1,2,3, CLAUDIO RICCI4,5, YOSHIHIRO UEDA6, KENTA MATSUOKA6, YOSHIKI TOBA7, TAIKI KAWAMURO6, BENNY TRAKHTENBRODT8, AND MICHAEL J. Koss3

1 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan; k.ichikawa@astro.columbia.edu
2 Department of Physics and Astronomy, University of Texas at San Antonio, One UTSA Circle, San Antonio, TX 78249, USA
3 Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027, USA
4 Institute of Astrophysics, Pontificia Universidad Catolica de Chile, Avenida Vicuna Mackenna 4860, 7820436, Chile
5 Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China
6 Department of Astronomy, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan
7 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 10617, Taiwan
8 Institute for Astronomy, Department of Physics, ETH Zurich, Wolfgang-Pauli-Strasse 27, CH-8093 Zurich, Switzerland

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ABSTRACT

We systematically investigate the near- to far-infrared (FIR) photometric properties of a nearly complete sample of local active galactic nuclei (AGNs) detected in the Swift/Burst Alert Telescope (BAT) all-sky ultra-hard X-ray (14–195 keV) survey. Out of 606 non-blazar AGNs in the Swift/BAT 70 month catalog at high galactic latitudes of |b| > 10°, we obtain IR photometric data of 604 objects by cross-matching the AGN positions with catalogs from the WISE, AKARI, IRAS, and Herschel infrared observatories. We find a good correlation between the ultra-hard X-ray and mid-IR luminosities over five orders of magnitude (41 < logL<sub>14–195</sub> < 46). Informed by previous measurements of the intrinsic spectral energy distribution of AGNs, we find FIR pure-AGN candidates whose FIR emission is thought to be AGN-dominated with low star-formation activity. We demonstrate that the dust covering factor decreases with the bolometric AGN luminosity, confirming the luminosity-dependent unified scheme. We also show that the completeness of the WISE color–color cut in selecting Swift/BAT AGNs increases strongly with 14–195 keV luminosity.

Key words: galaxies: active – galaxies: nuclei – infrared: galaxies – X-rays: galaxies

Supporting material: machine-readable table

1. INTRODUCTION

Understanding the cosmic evolution of supermassive black holes (SMBHs) in galactic centers and their connections with the evolution of their host galaxies is one of the main goals in modern astronomy. Active galactic nuclei (AGNs) are the fundamental laboratories for these studies because they are in the stage where the surrounding gas is accreting onto the SMBHs by releasing their gravitational energy as radiation. It is known that the central engines of AGNs are surrounded by a dusty “torus” (Krolik & Begelman 1986). Since optical and ultraviolet emission are easily absorbed by the torus, a complete survey of AGNs including obscured populations is crucial to elucidate the growth history of SMBHs.

The ultra-hard X-ray (E > 10 keV) band is extremely useful for detecting the entire population of AGNs because they have (1) stronger penetrating power than optical/UV and even hard (E < 10 keV) X-ray radiation and (2) very little contamination from the starburst emission. Ultra-hard X-ray detectors such as the Swift/Burst Alert Telescope (BAT; Barthelmy et al. 2005), IBIS/ISGRI on board INTEGRAL (Winkler et al. 2003), and FPMA/FPMB on board NuSTAR (Harrison et al. 2013) are therefore well suited for these studies. Among them, Swift/BAT provides the most sensitive ultra-hard X-ray survey of the whole sky in the 14–195 keV range.

Since most of the Swift/BAT sources are local objects, they have been observed by a large number of multi-wavelength facilities, which allow us to study their properties. Follow-up studies below 10 keV have shown that the fraction of obscured (N<sub>H</sub> > 10<sup>22</sup> cm<sup>-2</sup>) AGNs highly depends on the intrinsic X-ray luminosities (e.g., Beckmann et al. 2009; Burlon et al. 2011; Ricci et al. 2014; Kawamuro et al. 2016b) and also proved to be an effective tool in identifying the previously missed classes of AGNs with small opening-angle tori (e.g., Ueda et al. 2007; Eguchi et al. 2009, 2011; Winter et al. 2009; Ricci et al. 2011) and Compton-thick AGNs (Gandhi et al. 2015; Ricci et al. 2015; Tanimoto et al. 2016). Studies carried out by optical spectroscopy enable us to investigate the properties of extended (>100 pc) narrow-line regions (NLRs; e.g., Hainline et al. 2013, 2014b) through analysis of the [O III]λ5007 emission line (Winter et al. 2009; Ueda et al. 2015) and also offer the opportunity to estimate black hole masses through broad-line region or velocity dispersion measurements. The Swift/BAT AGN Spectroscopic Survey is in progress to complete the first large (>500) sample of BAT-detected AGNs with optical spectroscopy, which enables us to constrain the nature of the NLR (Berney et al. 2015; Koss et al. 2016; Oh et al. 2016).

Cross-matching the Swift/BAT AGNs with all-sky mid-infrared (MIR<sup>9</sup>) catalogs can provide information on the dust surrounding the central engine. While the MIR sometimes suffers contamination from the star formation, for luminous AGNs the MIR is dominated by the torus dust re-emission with 14–195 keV luminosity. Since the completeness of the Swift/BAT AGNs increases strongly with 14–195 keV luminosity, we obtain IR photometric data of 604 objects by cross-matching the AGN positions with catalogs from the WISE, AKARI, IRAS, and Herschel infrared observatories.

<sup>9</sup> Here we define near-IR (NIR) as λ < 5 μm and MIR as 5 μm < λ < 25 μm since all of the all-sky IR surveys used here cover IR bands in 5 μm < λ < 25 μm, whereas only the WISE survey covers IR bands at λ < 5 μm.
and it has shown that clumpy torus models (e.g., Nenkova et al. 2002, 2008a, 2008b; Höning et al. 2006; Schartmann et al. 2008; Höning & Kishimoto 2010; Kawaguchi & Mori 2010, 2011; Stalevski et al. 2012; Siebenmorgen et al. 2015) are favored to explain why the MIR emission of AGNs is almost isotropic (Mullaney et al. 2011; Ichikawa et al. 2012a; Asmus et al. 2015; García-Bernete et al. 2016), rather than the smooth torus models (Pier & Krolik 1992, 1993; Efstathiou & Rowan-Robinson 1995).

Near-IR (NIR) observations (λ < 5 μm) are useful for identifying luminous obscured AGNs because the NIR colors trace well the hot dust emission, which cannot be reproduced by starburst galaxies (Lacy et al. 2004; Stern et al. 2005; Hickox et al. 2007; Imanishi et al. 2010; Donley et al. 2012; Mateos et al. 2012; Stern et al. 2012; Assef et al. 2013; Castro et al. 2014; Ichikawa et al. 2014). However, the color–color plots often miss the known X-ray-selected obscured/Compton-thick AGNs due to the strong contamination from the host galaxies in the NIR bands (e.g., Gandhi et al. 2014, 2015), especially at the low luminosity end (Kawamuro et al. 2016a).

Thus, we are motivated to evaluate the NIR two-color selection efficiency as a function of AGN luminosity, using a complete sample including Compton-thick and low luminosity AGNs.

On the other hand, far-IR (FIR; λ > 60 μm) data shed light on the starburst emission in the host galaxies of AGNs. Using Infrared Astronomical Satellite (IRAS) FIR bands, Rodríguez Espinosa et al. (1987) found that the FIR 60–100 μm colors of nearby AGN and starburst galaxies are indistinguishable, suggesting that most of the FIR emission of nearby AGNs must originate from star-formation processes (see also Netzer et al. 2007; Mullaney et al. 2011). Using the clumpy torus model, Ichikawa et al. (2015) demonstrated that torus model emission is one order of magnitude smaller than the observed Herschel 70 μm data points, suggesting starburst emission is necessary in order to reproduce them. Utilizing the Herschel/ Photodetector Array Camera and Spectrometer (PACS) 70/160 μm bands, Meléndez et al. (2014) and Mushotzky et al. (2014) found that the FIR emission of most AGNs is dominated by the nuclear starburst within the ∼2 kpc scale, although there are exceptions where the emission is dominated by the AGN torus (e.g., Matsuoka & Woo 2015; García-González et al. 2016). Hatziminaoglou et al. (2010) also found that the Spitzer/MIPS and Herschel/SPIRE two-color plots (f250/f70 and f100/f250) can separate AGN and starburst galaxies because the 24 μm flux is dominated by the torus emission. However, the SPIRE colors alone do not differ from those of non-AGN galaxies. Thus, combining the MIR and FIR as well as the hard X-ray band enables us to investigate the properties of torus, host galaxies, and accretion processes in AGNs, all of which are the key components to understand SMBH/host galaxy connection.

We report here the NIR to FIR (3–500 μm) properties of ultra-hard X-ray-selected AGNs from the Swift/BAT 70 month catalog (Baumgartner et al. 2013), by cross-matching the AGN positions with the WISE, 2MASS, and IRAS all-sky surveys as well as the Herschel archived data. The main advantage of the BAT 70 month survey compared to previous Swift/BAT surveys includes better sensitivity resulting from a complete reprocessing of the data with an improved data reduction pipeline and more exposure time. Throughout the paper, we adopt H0 = 70.0 km s⁻¹ Mpc⁻¹, ΩM = 0.3, and ΩΛ = 0.7.

2. SAMPLE

2.1. Swift/BAT Hard X-Ray Catalog

Our initial sample contains the 834 AGNs reported in the 70 month Swift/BAT catalog (Baumgartner et al. 2013; Ricci et al. 2016b), 105 of which are blazars. Blazars were identified based on the Rome BZCAT (Massaro et al. 2015) and on recent literature (Ricci et al. 2016b). Of the remaining 729 sources, 697 sources have secure redshift information as presented in Ricci et al. (2016b). Next, we removed galaxy pairs or interacting galaxies not resolved in the BAT survey because the BAT catalog in Baumgartner et al. (2013) only provides the counterpart name of the Galaxy pair, not the Galaxy itself, which makes obtaining the IR counterpart very difficult for those sources. Out of 697 sources, 684 fulfilled this criterion. Further, the 606 sources located at higher galactic latitudes with |b| > 10° were selected to reduce the contamination in the crowded region through IR catalog matching. In the following, we refer only to these 606 non-blazar AGNs as the parent sample. The sample is local, with an average redshift of (z) = 0.055 as shown in Figure 1 (black solid lines).10 Ricci et al. (2016b) collected the X-ray spectra below 10 keV, including the ∼60 unknown objects in the Swift/BAT 70 month catalog, then derived the best estimated line of sight column density (NHI) and absorption-corrected BAT 14–195 keV luminosity (L14–195). Even in the energy band of the Swift/BAT survey, the observed flux is affected by obscuring material if the column density of the target exceeds NHI > 10²¹ cm⁻² (e.g., see Figure 1 of Ricci et al. 2015). Thus, we use the absorption-corrected 14–195 keV luminosity (L14–195) in this study, and all the values of L14–195 and NHI will be tabulated in Ricci et al. (2016b).

2.2. IR Catalogs

The available NIR to FIR data were obtained as follows.

2.2.1. ALLWISE Catalog

The WISE mission mapped the entire sky in 3.4 (W1), 4.6 (W2), 12 (W3), and 22 μm (W4) bands. In this study, we obtained the data from the latest ALLWISE catalog (Cutri et al. 2013), which achieved better sensitivity than the WISE all-sky data release (Wright et al. 2010) thanks to an improved data processing pipeline. The catalog tabulates the pipeline-measured magnitudes based on the profile fitting on ∼6 arcsec scale. In this study, we use this instrumental profile-fit photometry magnitude. The 5σ sensitivity achieved by ALLWISE 3.4, 4.6, 12, and 22 μm is 0.054, 0.071, 1, and 6 mJy, respectively. The positional accuracy based on cross-matching with the 2MASS catalog is ∼2 arcsec at the 3σ level. We only use sources with flux quality ph_qual = A, with a signal-to-noise ratio larger than 10. We also check sources of contamination and/or biased flux, due to proximity to an image artifact (e.g., diffraction spikes, scattered-light halos, and/or optical ghosts), using the flag name ccflag. A source that is unaffected by known artifacts is flagged as ccflag = 0. We thus only use sources with ccflag = 0 for each band.

10 M81 is not shown in the figures due to its low redshift (z < 10⁻³).
2.2.2. AKARI Point Source Catalogs

To further obtain the IR properties of the Swift/BAT AGNs, we use the AKARI All-Sky Survey Point Source Catalogs (AKARI-PSC). AKARI carries two instruments, the infrared camera (IRC; Onaka et al. 2007) operating in the 2–26 μm band (centered at 9 and 18 μm) and the Far-Infrared Surveyor (FIS; Kawada et al. 2007) operating in the 50–200 μm band (centered at 65, 90, 140, and 160 μm). The AKARI catalogs cover the brightest sources (>1 Jy at 12 μm band) whose fluxes ALLWISE could not trace properly due to saturation. The AKARI-PSC achieved the flux sensitivities of 0.05, 0.09, 2.4, 0.55, 1.4, and 6.3 Jy with position accuracies of 6 arcsec at the 9, 18, 65, 90, 140, and 160 μm bands, respectively. In our study, we only utilize sources with the quality flag of fqual = 3, whose flux measurements are reliable.11

2.2.3. IRAS Catalogs

The IRAS mission performed an unbiased all-sky survey in the 12, 25, 60, and 100 μm bands. The typical position accuracy at 12 and 25 μm is 7 and 35 arcsec in the scan and cross-scan direction, respectively (Beichman et al. 1988). In this paper we use the two largest catalogs, the IRAS Point Source Catalog (IRAS-PSC) and the IRAS Faint Source Catalog (IRAS-FSC). IRAS achieved 10σ point source sensitivities better than 0.7 Jy over the whole sky. The IRAS-FSC contains even fainter sources with fluxes of >0.2 Jy in the 12 and 25 μm bands. We use only IRAS sources with fqual = 3 (the highest quality).12

2.2.4. Herschel/BAT AGN Catalog

The Swift/BAT AGNs were also observed with Herschel/PACS (Poglitsch et al. 2010) and the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010). Meléndez et al. (2014) compiled a catalog of 313 nearby (z < 0.05) sources observed with Herschel/PACS. The PACS covers the two bands at the center wavelength of 70 μm (60–85 μm) and 160 μm (130–210 μm) simultaneously. The PSF is 1.4 and 2.85 arcsec at 70 μm and 160 μm, respectively. Considering the median redshift (z ~ 0.025) of the catalog, the PACS 70 μm PSF covers ~2.8 kpc, which contains most of the host galaxy component. Shimizu et al. (2016) reported that 293 nearby (z < 0.05) sources were observed with Herschel/SPIRE as part of a cycle-1 open time program. In addition, 20 other sources from other separate programs were included to complete the sample. The PSF is 18, 24, and 36 arcsec for 250, 350, and 500 μm, respectively.

2.3. Cross-matching of BAT AGNs with the IR Catalogs

We first compile the IR counterparts by cross-matching the BAT AGN positions with the IR catalogs. In this study, the IR luminosity L_X,μm represents the observed frame luminosity \( L_X (X \, \mu m) \) (erg s\(^{-1}\)), where 3.4 ≤ X ≤ 500.

11 See the release note of the AKARI/FIS catalog for the details of fqual. It is not recommended to use the flux data when fqual < 2 to ensure reliable scientific analysis. http://iras.ipac.caltech.edu/data/AKARI/documentation/AKARI-FIS_BSC_V1_RN.pdf.

12 See Beichman et al. (1988) for the definition of fqual in the IRAS catalogs. False detections may be included when fqual ≤ 2.
2.3.1. NIR Bands

We determine the NIR (3.4 and 4.6 μm) counterparts of the Swift/BAT AGNs through positional matching with WISE. We applied a cross-matching radius of 2 arcsec, informed by the cross-matches with the 2MASS catalog as described in Section 2.2.1. Using ALLWISE, we found 591 NIR counterparts out of 606 sources within the 2 arcsec radius. Considering the superb sensitivity of ALLWISE over that of the BAT survey (see the Appendix), all of them should essentially be detected. Therefore, we checked again the ALLWISE counterparts of the remaining 15 non-detected sources by expanding the matching radius. As a result, 13 sources were found within a 5 arcsec radius, and we confirmed that the detections are real based on visual inspection of DSS optical and ALLWISE images. One of the remaining two sources not detected, the counterpart of NGC 3516, was classified as one of the ALLWISE reject table sources. Another source (3C 59) was not detected even by expanding the search radius up to 15 arcsec. After checking the visual inspection between the DSS optical and XMM/PN X-ray images, we found that the coordinate of 3C 59 in the BAT catalog traces the jet lobe component, not the central object. We used the coordinate of the central object obtained from Simbad (R.A., decl.) = (31.7592, 29.512775) for this target and we successfully found the WISE counterpart. In total, 605 counterparts were identified in the ALLWISE catalog.

Out of the 605 sources, 602 and 603 sources fulfill ph_qual = A at 3.4 and 4.6 μm. After selecting the sources that fulfill ccf_flag = 0, the number of IR counterparts at 3.4 and 4.6 μm turns out to be 549 (~90.6%) and 548 (~90.4%) sources, respectively. The number of IR counterparts in the NIR band (either 3.4 or 4.6 μm) is 560 (~92.4%) sources.

2.3.2. MIR Bands

We determine the MIR (9–25 μm) counterparts of the Swift/BAT AGNs by cross-matching the ALLWISE, AKARI, and IRAS catalogs in this order. Our primary goal is to obtain photometric data in the IR band as completely as possible for the Swift/BAT-selected AGNs. We give the highest priority to the ALLWISE catalog because of its 50 times better sensitivity than AKARI, which allows us to search for fainter sources in the MIR all-sky view. Then we cross-match the sources undetected by ALLWISE with AKARI. AKARI covers the brighter sources, which are saturated due to the high sensitivity of ALLWISE, and have the advantage of a 2–4 times higher sensitivity than the IRAS survey. While all the IRAS sources should be detected with AKARI, the flux quality flags of AKARI for very nearby (z < 0.005) objects turn out to be bad, due to their extended morphology when fitted with a single Gaussian. In such cases, we refer to the IRAS data with good flux quality, which have ~11 times worse angular resolution than AKARI, since we aim to measure the total MIR flux from both nucleus and host galaxy in a uniform way for the entire AGN sample.

The positional matching of the optical counterparts of the Swift/BAT AGNs with IR survey catalogs was already discussed in Section 2.3.1 for ALLWISE and in Ichikawa et al. (2012a) for AKARI and IRAS, and we follow the same approach here. For the MIR bands, the number of detections is compiled at the second column in Table 2. Here the detection at 12 μm represents the detection either at AKARI 9 μm, WISE 12 μm, or IRAS 12 μm; 22 μm represents detection at either AKARI 18 μm, WISE 22 μm, or IRAS 25 μm; the MIR band represents detection either at the 12 μm or 22 μm band defined above. Finally, we obtained 601 (~99.2%) counterparts in at least one MIR band. Thus, the identification in the MIR bands is almost as complete as in the NIR bands. The redshift distribution of the IR counterparts at each wavelength is shown in Figure 1.

2.3.3. FIR Bands

The FIR counterparts of the Swift/BAT AGNs at 60 ≤ λ ≤ 160 μm were gathered by cross-matching the AKARI, IRAS, and Herschel catalogs in this order. Our goal is to obtain photometric data for the full host galaxy emission in the FIR band. We gave AKARI counterparts the highest priority because of the better sensitivity with respect to IRAS surveys. Then we matched the photon of the sources undetected by AKARI with IRAS. Considering the better sensitivity of AKARI/FIS, one might expect that IRAS would not cover many sources. However, AKARI often misses emission from sources with extended morphology due to its better angular resolution. In such cases, IRAS gives the best quality estimate of flux by measuring the whole FIR flux from the host galaxies. Finally, the remaining distant sources or faint sources, which neither AKARI nor IRAS detected, were cross-matched with the Herschel/PACS catalog of Meléndez et al. (2014). We cross-matched the sources by referring to the counterpart source names reported by Meléndez et al. (2014) and the Swift/BAT catalog.

For the FIR counterpart at 250 ≤ λ ≤ 500 μm, only the Herschel/SPIRE catalog can access those wavelengths. We also cross-matched the sources by referring to the counterpart source names written in Shimizu et al. (2016) and the Swift/BAT catalog.

For the FIR bands, 388 (~64.2%), 241 (~39.9%), 89 (~14.7%), 229 (~37.9%), 213 (~35.3%), 170 (~28.1%), and 107 (~17.7%) sources were compiled at 70 (either at IRAS 60 μm, AKARI 65 μm, or Herschel 70 μm), 90 (either at AKARI/90 μm or IRAS 100 μm), 140 (at AKARI/140 μm), 160 μm at (Herschel 160 μm or AKARI 160 μm), 250 μm (at Herschel/SPIRE 250 μm), 350 μm (at Herschel/SPIRE 350 μm), and 500 μm (at Herschel/SPIRE 500 μm), respectively. Those numbers are also compiled in the second column of Table 2. Finally, 402 (~66.3%) IR counterparts are obtained in at least one FIR band. Thus, the identification in the FIR bands is not yet complete, but a statistically significant sample has been compiled for this analysis.

2.4. Luminosity Correlation Among IR Catalogs

Since the four IR catalogs have slightly different central wavelengths and aperture sizes, we investigate the correlation between the AKARI/IRAS/WISE/Herschel luminosities, using only the sources detected in two separate observations. For the MIR bands, we choose AKARI 9 μm and IRAS 12 μm for WISE 12 μm, and AKARI 18 μm and IRAS 25 μm for WISE 22 μm, respectively, because of the proximity of the central wavelengths. For the FIR bands, AKARI 65 μm and IRAS 60 μm were chosen for Herschel/PACS 70 μm, IRAS 100 μm for AKARI 90 μm, and AKARI 160 μm for Herschel/PACS 160 μm. Figure 2 displays the flux correlations between the two bands, showing that the flux correlations...
Table 1
IR and 14–195 keV X-Ray Properties of the Swift/BAT 70 Month AGN Catalog

| No. | Name                  | $z$ | $f_{3.4}$ | $f_{4.6}$ | $f_{12}$ | $f_{22}$ | $f_{70}$ | $f_{90}$ | $f_{140}$ | $f_{160}$ | $f_{250}$ | $f_{350}$ | $f_{500}$ IR Catalog | $L_{3.4}$ | $L_{4.6}$ | $L_{12}$ | $L_{22}$ | $L_{70}$ | $L_{90}$ | $L_{140}$ | $L_{160}$ | $L_{250}$ | $L_{350}$ | $L_{500}$ | $C_{12}$ | $C_{12}$ |
|-----|-----------------------|-----|----------|----------|----------|---------|---------|---------|----------|----------|----------|----------|-------------|----------|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--------|--------|
| 2   | Farall 1203           | 0.058400 | ...       | ...       | ...       | ...     | ...     | ...     | ...       | ...       | ...     | ...     | ...       | ...       | ...       | ...     | ...       | ...       | ...       | ...       | ...       | ...       | ...       | 43.87  | ...       |
| 3   | NGC 7811              | 0.025500 | 0.015     | 0.015    | 0.052    | 0.103   | 0.456   | ...     | ...       | ...       | ...     | ...     | ...       | ...       | ...       | ...     | ...       | ...       | ...       | ...       | ...       | ...       | ...       | 0.404  | 0.418    |
| 4   | Mrk 335               | 0.025800 | 0.072     | 0.099    | 0.163    | 0.312   | 0.309   | ...     | 1.150     | 0.068    | ...     | ...     | ...       | ...       | ...       | ...     | ...       | ...       | ...       | ...       | ...       | 43.68  | 43.99    |
| 5   | [HB89] 0026+129       | 0.14200  | 0.013     | 0.017    | 0.028    | 0.048   | ...     | ...     | ...       | ...       | ...     | ...     | ...       | ...       | ...       | ...     | ...       | ...       | ...       | ...       | ...       | 44.78  | 44.78    |
| 6   | [ESO12+6]             | 0.029000 | 0.010     | 0.007    | 0.025    | 0.049   | 1.019   | 1.183   | ...       | ...       | ...     | ...     | ...       | ...       | ...       | ...     | ...       | ...       | ...       | ...       | ...       | 44.19  | 44.45    |
| 7   | 2MASX J00091156-0036551 | 0.073300 | 0.005     | 0.008    | ...       | ...     | ...     | ...     | ...       | ...       | ...     | ...     | ...       | ...       | ...       | ...     | ...       | ...       | ...       | ...       | ...       | ...       | 0.219  | 0.226    |

Note. Infrared to X-ray properties of Swift/BAT 70 month AGNs located at $|b| > 10^\circ$. (1) Source No. in Baumgartner et al. (2013); (2) object name; (3) redshift; (4)-(14) IR flux density ($f_{\nu}$) at 3.4, 4.6, 12, 22, 70, 90, 140, 160, 250, 350, and 500 $\mu$m in units of Jy; (15) IR reference catalogs for 12, 22, 70, 90, and 160 $\mu$m: A = AKARI-PSC, H = Herschel/PACS, If = IRAS Faint Source Catalog, Ip = IRAS Point Source Catalog, W = WISE, X = Non Detection; (16)-(26) logarithmic IR luminosities ($L_{\nu}$) at 3.4, 4.6, 12, 22, 70, 90, 140, 160, 250, 350, and 500 $\mu$m in units of erg s$^{-1}$; (27)-(28) covering factor based on the correction of Stalevski et al. (2016) using the MIR information at 12 and 22 $\mu$m, respectively. (This table is available in its entirety in machine-readable form.)
between the different IR catalogs are tight and significant. The standard deviation of the flux-ratio distribution between these two bands are given in the caption of Figure 2.

Figure 2 also shows that the flux relations are independent of the redshift. Although within the scatter, the flux relations between WISE 12, 22 μm and IRAS 12, 25 μm show systematic z dependence, where the flux ratio of $f_{\text{IRAS}}/f_{\text{WISE}}$ is anti-correlated to z. This could be due to the much larger aperture of IRAS than that of WISE; therefore, the MIR emission from the host galaxy slightly contaminates the IRAS fluxes of low-z sources.

Based on the flux correlation, we derive the empirical formula to convert the flux of each band into the WISE 12 μm, 22 μm, Herschel/PACS 70 μm, 160 μm, and AKARI 90 μm bands as follows:

\[
\frac{f_{\text{WISE} 12 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} = \frac{f_{\text{AKARI} 9 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} - 0.074
\]

\[
\frac{f_{\text{WISE} 12 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} = \frac{f_{\text{IRAS} 12 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} - 0.167
\]

\[
\frac{f_{\text{WISE} 22 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} = \frac{f_{\text{AKARI} 18 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} + 0.017
\]

\[
\frac{f_{\text{WISE} 22 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} = \frac{f_{\text{IRAS} 25 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} - 0.045
\]

\[
\frac{f_{\text{PACS} 70 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} = \frac{f_{\text{AKARI} 65 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} + 0.091
\]

\[
\frac{f_{\text{PACS} 70 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} = \frac{f_{\text{IRAS} 60 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} - 0.053
\]

\[
\frac{f_{\text{AKARI} 90 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} = \frac{f_{\text{IRAS} 100 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} - 0.204
\]

\[
\frac{f_{\text{PACS} 160 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} = \frac{f_{\text{AKARI} 160 \mu m}}{\text{erg s}^{-1} \text{cm}^{-2}} + 0.092.
\]

Assuming that AGNs that are not detected in the highest priority bands (WISE 12 μm, 22 μm, Herschel/PACS 70 μm, 160 μm, and AKARI 90 μm) but in the second or third priority bands should follow the same correlations examined here, we apply the conversion factors reported above to derive the 12, 22, 70, 90, and 160 μm luminosities. In doing so, we can discuss the luminosity correlation with the 14–195 keV band in a uniform way regardless of the matched catalogs. All the IR properties of the parent sample of AGNs are summarized in Table 1.

### 2.5. AGN Type

To examine the IR properties of different AGN populations, we divide the sample into two types based on the column density ($N_{H}$) obtained from the X-ray spectral fitting by Ricci et al. (2016b). The AGNs with $N_{H} < 10^{22}$ cm$^{-2}$ are called “X-ray type-1” (hereafter type-1), and the AGNs with $N_{H} \geq 10^{22}$ cm$^{-2}$ are called “X-ray type-2” (hereafter type-2). The sample is divided into 311 type-1 AGNs and 293 type-2 AGNs. The AGN type of each source will be tabulated in Ricci et al. (2016b).

### 3. RESULTS AND DISCUSSION

#### 3.1. Correlation Between the MIR and Ultra-hard X-Ray Luminosities

Figure 3 shows the luminosity correlations between the MIR (12 and 22 μm) luminosities ($L_{12 \mu m}, L_{22 \mu m}$) and $L_{14-195}$ in the luminosity range of $10^{40} < L_{14-195} < 10^{43}$ erg s$^{-1}$. Blue and red crosses represent type-1 and type-2 AGNs, respectively. The error bars are not shown in Figures 3 and 4 since the uncertainties of both infrared luminosities and 14–195 keV luminosity are vanishingly small (<10%) in the log-log plot.

Since our motivation is to determine the slope of the luminosity relation between $L_{\text{MIR}}$ and $L_{14-195}$ as two independent variables, we apply ordinary least-squares Bisector fits, which minimizes perpendicular distance from the slope line to data points (Isobe et al. 1990). The ordinal least-squares Bisector fits (with the form of $[\log(L_{\text{MIR}}/10^{43} \text{erg s}^{-1}) = (a \pm \Delta a) + (b \pm \Delta b)\log(L_{14-195}/10^{43} \text{erg s}^{-1})]$), where $\Delta a$ and $\Delta b$ is the standard deviation of $a$ and $b$.

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Note. Correlation properties between 14 and 195 keV X-ray luminosity and infrared luminosities. (1) IR band in units of μm; (2) number of sample; (3) the Spearman’s rank coefficient for luminosity correlations ($\rho_{L}$); (4) the Spearman’s rank coefficient for flux–flux correlations ($\rho_{F}$); (5) the standard Student t-test null significance level for luminosity correlations ($P_{t}$). ✓ represents $P_{t} < 0.01$; (6) the standard Student t-test null significance level for flux–flux correlations ($P_{f}$). ✓ represents $P_{f} < 0.01$; (7) regression intercept (a) and its 1σ uncertainty; (8) slope value (b) and its 1σ uncertainty. Equation is represented as $Y = a + bX$.
Figure 2. Flux–flux relations of AGNs between two IR bands. The red filled circle represents a source detected in both bands. The size of the circle is proportional to the redshift of the source. The solid line represents the best-fit line and the red shaded area represents the 1σ dispersion of each linear scaling relation. The number of sources for the fitting and 1σ error is also written in the bottom right corner at each panel. (Left) From top to bottom, AKARI 9 μm vs. WISE 12 μm, AKARI 18 μm vs. WISE 22 μm, AKARI 65 μm vs. Herschel/PACS 70 μm, IRAS 100 μm vs. AKARI 90 μm, (right) from top to bottom, IRAS 12 μm vs. WISE 12 μm, IRAS 25 μm vs. WISE 22 μm, IRAS 60 μm vs. Herschel/PACS 70 μm, AKARI 160 μm vs. Herschel/PACS 160 μm.
Table 3
Equations of the Luminosity Correlation Between the MIR and X-Ray Band

| (1) MIR Band | (2) X-ray Band | (3) Equation | (4) z Range | (5) \(L_X\) Range | (6) Selection | (7) AGN Type | (8) Reference |
|--------------|----------------|--------------|-------------|----------------|--------------|--------------|--------------|
| 12 \(\mu\)m | 14–195 keV     | \(\log \frac{L_{12\mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.10 \pm 0.02) + (0.96 \pm 0.02) \log \frac{L_{4-195}}{10^{44} \text{ erg s}^{-1}}\) | \(z < 0.3\) | \(41 < \log L_{4-195} < 46\) | X-ray | both | this study |
| 22 \(\mu\)m | 14–195 keV     | \(\log \frac{L_{22\mu m}}{10^{43} \text{ erg s}^{-1}} = (0.02 \pm 0.02) + (0.98 \pm 0.02) \log \frac{L_{4-195}}{10^{44} \text{ erg s}^{-1}}\) | \(z < 0.3\) | \(41 < \log L_{4-195} < 46\) | X-ray | both | this study |
| 12 \(\mu\)m | 14–195 keV     | \(\log \frac{L_{12\mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.21 \pm 0.03) + (1.05 \pm 0.03) \log \frac{L_{4-195}}{10^{44} \text{ erg s}^{-1}}\) | \(z < 0.3\) | \(43 < \log L_{4-195} < 46\) | X-ray | both | this study |
| 22 \(\mu\)m | 14–195 keV     | \(\log \frac{L_{22\mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.09 \pm 0.03) + (1.07 \pm 0.03) \log \frac{L_{4-195}}{10^{44} \text{ erg s}^{-1}}\) | \(z < 0.3\) | \(43 < \log L_{4-195} < 46\) | X-ray | both | this study |
| 6 \(\mu\)m  | 2–10 keV       | \(\log \frac{L_{6\mu m}}{10^{43} \text{ erg s}^{-1}} \approx 2.1 \times 10^{-2} \left( 512 - \sqrt{2.2 \times 10^6 - 4.7 \times 10^4 \log \frac{L_{2-10}}{10^{40} \text{ erg s}^{-1}}} \right)\) | \(1.5 < z < 4.7\) | \(45 < \log L_{2-10} < 46.2\) | optical | type-1 | Stern (2015) |
| 6 \(\mu\)m  | 2–10 keV       | \(\log \frac{L_{6\mu m}}{10^{43} \text{ erg s}^{-1}} = 0.40 + 1.39 \log \frac{L_{2-10}}{10^{40} \text{ erg s}^{-1}}\) | \(0.2 < z < 4\) | \(42 < \log L_{2-10} < 46\) | X-ray | type-1 | Fiore et al. (2009) |
| 12 \(\mu\)m | 2–10 keV       | \(\log \frac{L_{12\mu m}}{10^{43} \text{ erg s}^{-1}} = (0.19 \pm 0.05) + (1.11 \pm 0.07) \log \frac{L_{2-10}}{10^{40} \text{ erg s}^{-1}}\) | \(z < 0.1\) | \(41 < \log L_{2-10} < 45\) | X-ray | both | Gandhi et al. (2009) |
| 12 \(\mu\)m | 2–10 keV       | \(\log \frac{L_{12\mu m}}{10^{43} \text{ erg s}^{-1}} = 0.30 + 0.99 \log \frac{L_{2-10}}{10^{40} \text{ erg s}^{-1}}\) | \(0.05 < z < 2.8\) | \(42 < \log L_{2-10} < 46\) | X-ray | both | Mateos et al. (2015) |
| 12 \(\mu\)m | 2–10 keV       | \(\log \frac{L_{12\mu m}}{10^{43} \text{ erg s}^{-1}} = (0.33 \pm 0.04) + (0.97 \pm 0.03) \log \frac{L_{2-10}}{10^{40} \text{ erg s}^{-1}}\) | \(z < 0.3\) | \(40 < \log L_{2-10} < 46\) | X-ray | both | Asmus et al. (2015) |

Note. Correlation properties between the X-ray luminosity and MIR luminosities. (1) MIR band in units of \(\mu\)m; (2) X-ray band in units of keV; (3) equation of the luminosity correlation between MIR and X-ray; (4) \(z\) range of the sample for each study; (5) X-ray luminosity range of the sample for each study; (6) the energy band used to select the parent AGN sample; (7) the main AGN type in the sample. “Type-1” means type-1 AGNs, and “both” means both type-1 and type-2 AGNs; (8) reference.
the slope in our study using only high luminosity sources with $\log L_{14-195} > 43$. The other dashed lines represent the slope in the study of Fiore et al. (2009, orange), Stern (2015, gray), Gandhi et al. (2009, purple), Mateos et al. (2015, green), Asmus et al. (2015, cyan), respectively. The studies with local sample (mostly $z < 0.1$ and main luminosity range of $41 < L_X < 46$) are our study, Gandhi et al. (2009), and Asmus et al. (2015). The studies with high-$z$ sample (mostly $0.1 < z < 5$ and $42 < L_X < 46$) are Fiore et al. (2009), Mateos et al. (2015), and Stern (2015). The studies with type-1 AGNs are Fiore et al. (2009) and Stern (2015), and with both type-1 and type-2 AGNs are Gandhi et al. (2009), Mateos et al. (2015), Asmus et al. (2015), and our study. See Table 2 for more details.

Figure 3. Luminosity correlations between the luminosities at 12 \(\mu\)m (right) ($L_{12,\mu m}$, $L_{22,\mu m}$) and 14–195 keV ($L_{14-195}$). Blue/red crosses represent type-1/2, respectively. The black solid line represents the slope of Equation (1) in our study, left panel, and of Equation (2), right panel. The black dashed line represents the slope in our study using only high luminosity sources with $\log L_{14-195} > 43$. The other dashed lines represent the slope in the study of Fiore et al. (2009, orange), Stern (2015, gray), Gandhi et al. (2009, purple), Mateos et al. (2015, green), Asmus et al. (2015, cyan), respectively. The studies with local sample (mostly $z < 0.1$ and main luminosity range of $41 < L_X < 46$) are our study, Gandhi et al. (2009), and Asmus et al. (2015). The studies with high-$z$ sample (mostly $0.1 < z < 5$ and $42 < L_X < 46$) are Fiore et al. (2009), Mateos et al. (2015), and Stern (2015). The studies with type-1 AGNs are Fiore et al. (2009) and Stern (2015), and with both type-1 and type-2 AGNs are Gandhi et al. (2009), Mateos et al. (2015), Asmus et al. (2015), and our study. See Table 2 for more details.

$b$, respectively) gives the correlations of

$$\log \frac{L_{12,\mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.10 \pm 0.02) + (0.96 \pm 0.02) \times \log \frac{L_{14-195}}{10^{43} \text{ erg s}^{-1}},$$

(1)

$$\log \frac{L_{22,\mu m}}{10^{43} \text{ erg s}^{-1}} = (0.02 \pm 0.02) + (0.98 \pm 0.02) \times \log \frac{L_{14-195}}{10^{43} \text{ erg s}^{-1}},$$

(2)

The significance of the correlations between the two bands’ luminosities (and fluxes) can be obtained by performing Spearman’s test. The results are summarized in Table 2. We find that both luminosity–luminosity and flux–flux correlations between the NIR and MIR bands and the 14–195 keV bands are highly significant.

In the Seyfert galaxy class with $L_{14-195} < 10^{44}$ erg s$^{-1}$, the correlation between MIR and X-ray was first reported using ground telescopes with low spatial resolutions (Elvis et al. 1978; Krabbe et al. 2001) and then by several authors thanks to the new windows opened by the ISO satellite (Lutz et al. 2004; Ramos Almeida et al. 2007) and Spitzer (Sazonov et al. 2012). Studies based on ground-based high spatial resolution MIR photometry were first compiled by Horst et al. (2006), then expanded independently by Levenson et al. (2009) and Gandhi et al. (2009), and finally by Asmus et al. (2015). The correlation parameters of Gandhi et al. (2009) and Asmus et al. (2015) are the most widely used because they include Compton-thick AGNs. Gandhi et al. (2009) show steeper results than us, with $b = 1.11 \pm 0.04$, but Asmus et al. (2015) report results consistent with our studies within the uncertainties, with $b = 0.97 \pm 0.03$. Both slopes are overplotted in Figure 3 and also compiled in Table 3. Since both studies used $2–10$ keV luminosity as the X-ray luminosity, we apply the conversion factor of $L_{14-195}/L_{2-10} = 1.9$ under the assumption of $\Gamma = 1.9$ for the overplot in Figure 3. Hereafter, we always apply this conversion factor for estimating $L_{14-195}$ from $L_{2-10}$.

The host galaxy contamination in the MIR emission, especially in the low luminosity end, could affect the slope values of $b = 0.96–0.98$ in our study. If we use only the sources with $L_{14-195} > 10^{43}$ erg s$^{-1}$, the luminosity relations become

$$\log \frac{L_{12,\mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.21 \pm 0.03) + (1.05 \pm 0.03) \times \log \frac{L_{14-195}}{10^{43} \text{ erg s}^{-1}},$$

(3)

$$\log \frac{L_{22,\mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.09 \pm 0.03) + (1.07 \pm 0.03) \times \log \frac{L_{14-195}}{10^{43} \text{ erg s}^{-1}},$$

(4)

which is slightly steeper, but within 2\(\sigma\) uncertainty of Asmus et al. (2015). The slope obtained by Gandhi et al. (2009) depends on the choice of algorithm, and the value becomes $b = 1.00 \pm 0.08$ when using the same method as Asmus et al. (2015). Therefore, our results are generally fully consistent with the high spatial resolution results in the high luminosity end with $L_{14-195} > 10^{43}$ erg s$^{-1}$. Although our results with poorer spatial resolution suffer from contamination from the host galaxies in the lower luminosity end, our study has the advantage of completeness ($\sim 98\%$) in the MIR bands of the ultra-hard-X-ray flux-limited Swift/BAT 70 month catalog, which is the least biased against absorption up to $N_H \simeq 10^{24}$ cm$^{-2}$.

Comparison to higher luminosity (and also high-$z$) studies with $L_{14-195} \geq 10^{44}$ erg s$^{-1}$ in the literature can also provide
important information. We compile the luminosity correlations of those studies in Table 3. Fiore et al. (2009) derived the observed rest-frame 6 μm and 2–10 keV luminosities of ~80 X-ray-selected type-1 AGNs in the COSMOS and CDF-S fields obtained from the Chandra and Spitzer satellites. The slope is quite steep, with $b = 1.39$ for $\log L_{6 \mu m} \gtrsim 43$. Although the detailed fitting algorithm was not mentioned in their studies, there is a trend of increasing MIR–X-ray ratio at the high luminosity end with $\log L_{6 \mu m} \gtrsim 44$. Further evidence of this trend is obtained by Stern (2015); plotted as the gray dotted line in Figure 3) using SDSS DR5, mainly tracing high-$z$ QSOs at $2 < z < 4$. They used a quadratic function to reproduce the X-ray–MIR luminosity relations.

If the trends above are true, the steeper slope suggests that X-ray emission is inefficient in the high luminosity end. This is reported in several observations: the SED shape of AGNs change with luminosity and Eddington ratio (Vasudevan & Fabian 2007). The existence of X-ray-weak sources at high bolometric luminosities has recently been confirmed by Ricci et al. (2016a), who found that Hot Dust Obscured Galaxies (hot DOGs; Wu et al. 2012) seem to have X-ray luminosities one or two orders of magnitude below the value expected from the local X-ray–MIR correlation. Since our sample is ultra-hard X-ray selected, our studies might miss those X-ray-saturated sources in the high luminosity end. Those sources could be located in the faint end of the 14–195 keV flux, but not in MIR fluxes. Since the BAT 14–195 keV flux limit is over one order of magnitude shallower than that of MIR fluxes, a deeper survey is necessary to assess the luminosity relation between the MIR and 14–195 keV luminosity at the high luminosity end (see also Figure 12). Another suggestion from this trend is that AGNs might have a large obscuring fraction in the high luminosity regime and/or in the high-$z$ universe (Buchner et al. 2015). This might be true, considering the X-ray studies where the fraction of Compton-thick AGNs increases with redshift from $z = 0$ to $z = 2$ (Brightman & Ueda 2012). We do not attempt to solve this question at high luminosities here, but it is valuable to mention other reasons for the slope differences among those studies at the high luminosity end. One reason why the slope is steeper could be because of the 6 μm bands instead of 12 μm. Asmus et al. (2015) pointed out that the hot dust component rather than the typical torus warm component, which peaks around 20–30 μm (e.g., Mullaney et al. 2011), could dominate around 6 μm (Mor & Netzer 2012). The contamination from the host galaxies at 6 μm is also a possibility. Mateos et al. (2015) revised the $L_{6\mu m}$–$L_{2-10}$ luminosity relations using a complete and flux-limited sample of >200 AGNs from the bright ultra-hard XMM-Newton Survey and WISE. They obtained absorption-corrected X-ray luminosities and also derived the 6 μm AGN luminosity by spectral decomposition of the torus and host galaxies. They applied the Bayesian approach to linear regression with errors in both X and Y axes using the IDL command linmix_err with the X-ray luminosity as an independent variable, which is the same method used by Asmus et al. (2015). They report a slope of $b = 0.99 \pm 0.03$ (overplotted as the green dotted line in Figure 3) up to luminosities of $L_{2-10} \sim 10^{46} \text{erg s}^{-1}$. This agrees well with the results of Asmus et al. (2015) and ours ($b = 0.96 \pm 0.02$). Note that the study by Mateos et al. (2015) might also have missed very luminous sources, due to the limited survey volume in X-ray, which is possibly making the slope shallower.

Equations (1) and (2) also show that the intercept $b$ of $L_{22, \mu m}$ is higher than that of $L_{12, \mu m}$. This tendency can be explained by two possibilities: (1) the torus emission peaks in $\nu F_{\nu}$ units at 20–40 μm rather than at ~10 μm, which is suggested by both observations (Weedman et al. 2005; Buchanan et al. 2006; Asmus et al. 2011, 2014; Mullaney et al. 2011; Ichikawa et al. 2015; Fuller et al. 2016) and clumpy torus models (Nenkova et al. 2008a; Höing & Kishimoto 2010; Schartmann et al. 2008), and (2) the star-formation component contaminates more at longer wavelengths (e.g., Netzer et al. 2007; Mullaney et al. 2011). The former contributes more strongly at the high luminosity end ($L_{14,195} > 10^{44} \text{erg s}^{-1}$) because the relative star-formation contamination could be smaller considering that the slope of $L_{\text{FIR}}$–$L_{14,195}$ is shallower ($b < 0.94$). On the other hand, the latter contributes strongly to lower luminosity sources.

Figure 4. Luminosity correlations between the luminosities at 70 and 90 μm ($L_{70, \mu m}$, $L_{90, \mu m}$) and bolometric luminosity ($L_{\text{bol}}$) estimated from Equation (5). Blue/red color represents type-1/-2, respectively. The black solid line represents the slope of Equations (6) and (7), respectively. The black dashed line represents the slope of Equations (8) and (9), respectively. The dotted–dashed line (navy) represents the slope obtained by Netzer (2009). The gray solid line represents the pure-AGN sequence reported in Equations (11) and (12), respectively.
(L_{14-195} < 10^{44} \text{ erg s}^{-1}). This will be discussed again in Section 3.6.

3.2. Correlation between the FIR and AGN Bolometric Luminosities

The correlation between FIR and AGN bolometric luminosity (L_{bol}) could shed light on the link between the star-formation activity of the AGN host galaxies and the accretion rate of AGNs. Since the accretion disk emission cannot be directly obtained for all sources in our sample, the bolometric correction should be applied to L_{14-195} to estimate the bolometric luminosity. Marconi et al. (2004) account for variations in AGN SEDs by using the well-known anticorrelation between the optical-to-X-ray spectral index (\alpha_{OX}). Then, they renormalize the template SED to a particular \alpha_{OX} to obtain the bolometric correlation with AGN luminosity. Therefore, they assume a varying relation between optical/UV and X-ray luminosity, not a constant value (e.g., Elvis et al. 1994). A similar approach is followed by Hopkins et al. (2007) who, however, used a template SED generated from the averages of real SEDs in different wavebands. There is a systematic difference in that the L_{bol} of Hopkins et al. (2007) is roughly a factor of \sim 1.5 larger than that of Marconi et al. (2004). This is because Hopkins et al. (2007) define L_{bol} as the integral of the observed template SED including the reprocessed emission in the MIR from the accretion disk, whereas Marconi et al. (2004) only integrate the emission of the optical-UV and X-ray radiated by the accretion disk itself and the hot corona, respectively. Since the accretion rate is better related to the total luminosity directly produced by the accretion process, the L_{bol} defined by Marconi et al. (2004) is better suited for our study. Hence, we apply the bolometric correction of Marconi et al. (2004):

\[
\log L_{bol} = 0.0378(\log L_{14-195})^2 - 2.03 \log L_{14-195} + 61.6. \tag{5}
\]

Figure 4 shows the FIR luminosities (L_{70 \mu m}, L_{90 \mu m}) plotted against L_{bol}. The least-squares bisector fits to the FIR versus bolometric AGN luminosity with a power law give the correlations of

\[
\log \frac{L_{70 \mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.49 \pm 0.05) + (0.79 \pm 0.03) \times \log \frac{L_{bol}}{10^{43} \text{ erg s}^{-1}}, \tag{6}
\]

\[
\log \frac{L_{90 \mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.29 \pm 0.05) + (0.76 \pm 0.03) \times \log \frac{L_{bol}}{10^{43} \text{ erg s}^{-1}}. \tag{7}
\]

Since our relations are obtained based on the FIR-detected sample, which is not complete (65% for the 70 \mu m band and 45% for the 90 \mu m band) as shown in Figure 1, we check the dependence of the completeness by restricting the redshift down to z < 0.076 for the 70 \mu m band and z < 0.022 for the 90 \mu m band to achieve 80% completeness of the IR counterparts, respectively. The relation at each band is given as

\[
\log \frac{L_{70 \mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.53 \pm 0.06) + (0.83 \pm 0.04) \times \log \frac{L_{bol}}{10^{43} \text{ erg s}^{-1}}, \tag{8}
\]

\[
\log \frac{L_{90 \mu m}}{10^{43} \text{ erg s}^{-1}} = (-0.19 \pm 0.08) + (0.82 \pm 0.05) \times \log \frac{L_{bol}}{10^{43} \text{ erg s}^{-1}}. \tag{9}
\]

The slope here is slightly steeper than those reported in Equations (6) and (7), but the slopes are consistent within the 1\sigma uncertainties (see also Figure 4). Therefore, we conclude that dependence of the completeness is weak.

In addition, we also estimate the effective luminosity range based on the limited volume of the Swift/BAT AGN sample. This is because AGNs with the highest luminosity are rare and so might be found in the limited Swift/BAT survey volume. Likewise, faint AGNs will be missing from the sample because of the Swift/BAT ultra-hard X-ray flux limits. First, based on the flux limit of the Swift/BAT survey of f_{14-195} = 1.34 \times 10^{-11} \text{ erg s}^{-1} \text{ cm}^{-2} (Baugartner et al. 2013), and the conversion factor of f_{2-10} = 2.1 \times f_{14-195}, we estimate the survey volume as a function of the flux-limited luminosity V(L_{2-10}) = (4/3)\pi D_{14-195}^2 \text{ Mpc}^3. Next, we calculate the expected number of AGN detections as a function of L_{2-10} using the 2-10 keV luminosity function from Ueda et al. (2014) with a z dependence of \propto (1+z)^{\beta}. Then, we define the effective luminosity range in which the expected number of detected AGNs per dex in L_{2-10} is greater than 10, which is sufficient to measure the luminosity relation. The result is 40.8 < \log L_{2-10} < 45.5, which is equivalent to 41.1 < \log L_{14-195} < 45.8 and 41.8 < \log L_{bol} < 47.7. Therefore, a deeper and/or wider survey is needed to measure the relations between the FIR and AGN luminosity both at log L_{bol} < 41.8 and log L_{bol} > 47.7.

In Figure 4, we also show the relation from Netzer (2009; navy dashed line). Our local sample reproduces well the relation of Netzer (2009) using local optical type-2 AGNs (z \leq 0.2). The difference between our study and that of Netzer (2009) is that while we used L_{FR} as a proxy for star formation, Netzer (2009) used the break at 4000 Å (D4000) to estimate L_{FR}. Matsuoka & Woo (2015) reported that while D4000-based SFR is not well determined at lower SFR since the calibration was based on starburst galaxies, the systematic difference between D4000-based SF luminosity and L_{FR} is small enough compared to the broad distribution between SF luminosity and L_{AGN}. Even with the L_{FR}, we find a result consistent with Matsuoka & Woo (2015) using a sample of SDSS DR7 local AGNs at z < 0.2.

Recent studies have reported that the “mean” or “binned” L_{FR}–L_{bol} shows a flatter (or even horizontal) pattern in each redshift bin (e.g., Shao et al. 2010; Rosario et al. 2012; Stanley et al. 2015) for 0 < z < 2.5. However, such a flatter pattern is not detected in our sample when we use individual luminosity measurements instead of the mean luminosities. To check this, the binned analysis is also applied to our 70 \mu m or 90 \mu m detected sources, and the results are shown in Figure 5. The plotted bin is the median value in each luminosity bin with error bars showing the interpercentage range containing 80% of the sample. Green points represent the mean measurements of the 70 and 90 \mu m luminosity averaged.
in bins of bolometric luminosity, while black points represent the mean bolometric luminosity averaged in bins of 70 and 90 μm luminosity, respectively. The dashed line represents the estimated relation based on the least-squares bisector fits. As shown in the figure, the slope \((b = 0.54 \pm 0.08 \text{ for } 70 \mu \text{m} \text{ and } b = 0.56 \pm 0.07 \text{ for } 90 \mu \text{m})\) of the green dashed line (binned with \(L_{\text{bol}}\)) is significantly shallower than that of the black dashed line (binned with \(L_{\text{FIR}}\); \(b = 0.88 \pm 0.05 \text{ for } 70 \mu \text{m} \text{ and } b = 0.82 \pm 0.06 \text{ for } 90 \mu \text{m}\)). To further model the trend of green points, we apply the curve fit used in Rosario et al. (2012). The function is written as

\[
\log L_{\text{FIR}} = \log (10^b \log L_{\text{bol}} + \log L_0 - b \log L_c + 10 \log L_0)
\]  

with three free parameters \(b, \log L_0, \log L_c\) but we fix the slope \(b = 0.78\) following Rosario et al. (2012). \(L_0\) is a constant value mainly determined by the constant \(L_{\text{FIR}}\) value where \(L_{\text{AGN}}\) is small. \(L_c\) represents the value of \(L_{\text{AGN}}\) where the function becomes equal to \(L_0\). We fit the green points using a non-linear least-squares fitting procedure (curve_fit in Python).

The result is shown with the green solid line in Figure 5. The model nicely reproduces the flattened relation, but has a systematically smaller value (\(\log L_0 = 42.79 \pm 0.02 \text{ for } 70 \mu \text{m} \text{ and } \log L_0 = 42.64 \pm 0.03 \text{ for } 90 \mu \text{m}\)) than the line of local AGNs (\(\log L_0 = 43.57 \pm 0.08\)) in Rosario et al. (2012). Rosario et al. (2012) within the broad scatter range.

Overall, whereas the IR averaging (in bins of bolometric luminosity, shown by the green points) nicely reproduces the flattened trend as reported in the literature (Shao et al. 2010; Rosario et al. 2012), the black solid bin still shows a rising trend that is almost the same as the relation obtained from the individual objects. This could have originated from the different timescales of SF and AGN activity. Hickox et al. (2014) calculated the mean \(L_{\text{FIR}} / L_{\text{bol}}\) in two ways. Hickox et al. (2014) constructed a simple model population of SF galaxies in which SF and the BH growth are correlated in galaxies in the range \(0.25 < z < 1.25\), with a \(z\)-dependent distribution in SFR from the FIR luminosity function derived by Gruppioni et al. (2013). They assigned an observed average SFR to BH accretion rate of 3000 (e.g., Rafferty et al. 2011; Mullaney et al. 2012; Chen et al. 2013), and also assumed that the instantaneous accretion rate relative to the average is distributed from the given fiducial luminosity distribution. They first derived the average \(L_{\text{bol}}\) for galaxies in each \(L_{\text{FIR}}\) bin and compared the results obtained by Symeonidis et al. (2011) and Chen et al. (2013) for the range \(0.25 < z < 1.25\). This reproduces well the rising relation as shown in our study. They next computed the average \(L_{\text{bol}}\) as a function of \(L_{\text{bol}}\). This then reproduces well the flattened relation. This result strongly suggests a picture in which SF and BH accretion are closely connected over long timescales, but this correlation is sometimes hidden at low to moderate \(L_{\text{bol}}\) due to short-term AGN variability. Note that there are clear differences in the sample used in the aforementioned studies and ours. They included all FIR-detected galaxies whereas we focused only on AGN host galaxies with detections in both FIR and X-rays. Further studies using the spectral decomposition of IR SEDs will be discussed in a forthcoming paper (K. Ichikawa et al. 2016, in preparation).

### 3.3. FIR Pure-AGN Candidates

If there are luminous AGNs hosted by low-SF galaxies, we may find those “FIR pure-AGN” candidates at the bottom right in Figure 4. Matsuoka & Woo (2015) investigated the FIR pure-AGN sequence between \(L_{\text{FIR}}\) and \(L_{\text{bol}}\) by adopting the typical AGN SED template of Mullaney et al. (2011). The FIR pure-AGN sequences are given by

\[
\log \frac{L_{70 \mu \text{m}}}{\text{erg s}^{-1}} = (7.45 \pm 0.26) + 0.80 \log \frac{L_{\text{bol}}}{\text{erg s}^{-1}},
\]

\[
\log \frac{L_{90 \mu \text{m}}}{\text{erg s}^{-1}} = (7.17 \pm 0.26) + 0.80 \log \frac{L_{\text{bol}}}{\text{erg s}^{-1}}.
\]
AGNs and the average luminosity is high with \(\langle \log (L_{14-195}/\mathrm{erg\ s}^{-1})\rangle = 44.1\). Although the pure-AGN population is quite small at \(\sim 2\%\) (4 out of 274), it is a good sample to construct pure-AGN IR SEDs including the FIR end and to examine whether the extrapolation to FIR luminosities from the intrinsic-AGN SED is correct. They also could be in the stage where SF is suppressed because AGN feedback is in action (e.g., Woo et al. 2016). The future X-ray satellite e-ROSITA (Merloni et al. 2012) will discover over 3 million AGNs and cross-matching those with the FIR catalogs would reveal pure-AGN in large numbers.

### 3.4. Distribution of \(r_{12,22}\)

Figure 6 shows the histograms of the ratio defined as \(r_{12,22} = \log(L_{12\,\mu m,22\,\mu m}/L_{12\,\mu m,22\,\mu m}^{\text{slope}})\), where \(L_{12\,\mu m,22\,\mu m}^{\text{slope}}\) represents the expected MIR luminosities obtained from \(L_{14-195}\) using the slopes between \(L_{\text{MIR}}\) and \(L_{14-195}\). The standard deviation for each sample is compiled in Table 4. The standard deviation for the full sample is \(\sigma = 0.39\) at 12 \(\mu m\) and \(\sigma = 0.42\) at 22 \(\mu m\). This value is slightly larger than that of Asmus et al. (2015) with \(\sigma = 0.32\). In the 12 \(\mu m\) band, we obtain \(\sigma = 0.37 \pm 0.03\) for type-1 and \(\sigma = 0.41 \pm 0.04\) for

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**Figure 6.** Histograms of \(r_{12,22} = \log(L_{12\,\mu m,22\,\mu m}/L_{12\,\mu m,22\,\mu m}^{\text{slope}})\) (top and bottom panel, respectively). The solid black/shaded blue/shaded red lines represent the total, type-1, and type-2 samples, respectively.

**Table 4**

| Sample          | \(N\) | \(\sigma\) |
|-----------------|-------|------------|
| 3.4 \(\mu m\) all | 540   | 0.3773 \(\pm 0.0204\) |
| type-1          | 270   | 0.3260 \(\pm 0.0276\) |
| type-2          | 270   | 0.3333 \(\pm 0.0287\) |
| 4.6 \(\mu m\) all | 540   | 0.3544 \(\pm 0.0214\) |
| type-1          | 280   | 0.3339 \(\pm 0.0282\) |
| type-2          | 270   | 0.3617 \(\pm 0.0314\) |
| 12 \(\mu m\) all | 540   | 0.3937 \(\pm 0.0228\) |
| type-1          | 300   | 0.3702 \(\pm 0.0299\) |
| type-2          | 280   | 0.4176 \(\pm 0.0348\) |
| 22 \(\mu m\) all | 592   | 0.4266 \(\pm 0.0248\) |
| type-1          | 302   | 0.3941 \(\pm 0.0321\) |
| type-2          | 290   | 0.4572 \(\pm 0.0380\) |
| 70 \(\mu m\) all | 388   | 0.5496 \(\pm 0.0395\) |
| type-1          | 173   | 0.5173 \(\pm 0.0558\) |
| type-2          | 215   | 0.5659 \(\pm 0.0547\) |
| 90 \(\mu m\) all | 241   | 0.4665 \(\pm 0.0426\) |
| type-1          | 87    | 0.4566 \(\pm 0.0696\) |
| type-2          | 154   | 0.4727 \(\pm 0.0540\) |
| 140 \(\mu m\) all | 89    | 0.4291 \(\pm 0.0647\) |
| type-1          | 30    | 0.4593 \(\pm 0.1206\) |
| type-2          | 59    | 0.4161 \(\pm 0.0773\) |
| 160 \(\mu m\) all | 229   | 0.5860 \(\pm 0.0549\) |
| type-1          | 100   | 0.5816 \(\pm 0.0827\) |
| type-2          | 129   | 0.5906 \(\pm 0.0738\) |
| 250 \(\mu m\) all | 213   | 0.6155 \(\pm 0.0598\) |
| type-1          | 101   | 0.5973 \(\pm 0.0845\) |
| type-2          | 112   | 0.6270 \(\pm 0.0842\) |
| 350 \(\mu m\) all | 170   | 0.5316 \(\pm 0.0578\) |
| type-1          | 75    | 0.5245 \(\pm 0.0862\) |
| type-2          | 95    | 0.5362 \(\pm 0.0782\) |
| 500 \(\mu m\) all | 107   | 0.4487 \(\pm 0.0616\) |
| type-1          | 40    | 0.4589 \(\pm 0.1039\) |
| type-2          | 67    | 0.4458 \(\pm 0.0776\) |

**Note.** (1) IR band in units \(\mu m\); (2) number of sample; (3) standard deviation \((\sigma)\) from the expected value \(L_{12\,\mu m}^{\text{slope}}\) given the slope in \(L_{12\,\mu m}\) and \(L_{14-195}\).
type-2 AGNs. The scatter is consistent between type-1 and type-2 AGNs in our sample, within the statistical uncertainties, so we find no evidence of a difference in the scatter of the MIR to 14–195 keV X-ray ratio between AGN types. This result might support recent observations that most of the MIR emission comes from the polar extended region with \( \lesssim 10 \) pc scale (e.g., Höning et al. 2012, 2013; López-Gonzaga et al. 2016) or from even larger regions with \( \approx 100 \) pc scales (Asmus et al. 2016), since an extended dust geometry more easily produces isotropic MIR emission compared to traditional torus models.

### 3.5. Luminosity Dependence of the Covering Factor

We investigate the relation between the AGN and its surrounding dusty torus. Since MIR emission originates from the re-radiation from the dusty torus, one can naturally expect that the ratio of the MIR to AGN luminosity corresponds to the solid angle of the sky covered by the dust (i.e., covering factor; \( C_T \) and \( \log L_{\text{bol}}/L_{\text{bol}} \)). Figure 7 shows the luminosity dependence of the MIR/Lbol. The black solid and dashed line in Figure 7 represents the estimated line converted from the \( L_{\text{bol}}-L_{\text{L}14-195} \) luminosity relations of Equations (1) and (2) for the full sample, and Equations (3) and (4) for the high luminosity sample, respectively. We use Equation (5) for the bolometric correction. Figure 7 shows that \( L_{\text{bol}}/L_{\text{bol}} \) is declining when \( L_{\text{bol}} \) is increasing, which is consistent with the trend in so-called “luminosity-dependent unified models.” This model can describe the decrease of the covering factor through the receding of the sublimation radius with AGN luminosity (Lawrence & Elvis 1982).

However, Lusso et al. (2013) found that corrections for the anisotropy of the dust emission are necessary when using \( L_{\text{bol}}/L_{\text{bol}} \) as a proxy for the covering factors. In addition, using a 3D Monte Carlo radiation code, Stalevski et al. (2016) reported that the tori of type-1 (viewed face-on) AGNs make \( L_{\text{bol}}/L_{\text{bol}} \) underestimate low covering factors and overestimate high covering factors. Type-2 (viewed edge-on) AGNs always underestimate covering factors. They also provide the correction functions to account for anisotropy and obtain corrected covering factors. Thus, we derive the corrected covering factor using the combination of the ratio \( L_{12 \mu m}/L_{\text{bol}} \) and the correction function by Stalevski et al. (2016). We use the correction function of

\[
C_T = \begin{cases} 
-0.178R^4 + 0.875R^3 - 1.487R^2 + 1.408R + 0.192 \text{ (type1)} \\
2.039R^3 - 3.976R^2 + 2.765R + 0.205 \text{ (type2)} 
\end{cases}
\]

where \( R = L_{\text{MIR}}/L_{\text{bol}} \) and the estimated optical thickness of the torus at \( 9.7 \mu m \) is \( \tau_{9.7} = 3.0 \) (see Table 1 of Stalevski et al. 2016 for more details). Figure 8 shows the corrected \( C_T \) derived from the slopes tabulated in Table 2 as a function of \( L_{\text{bol}} \) (black solid area). It still holds that \( C_T \) is a declining function of \( L_{\text{bol}} \), confirming the trend of “luminosity-dependent unified models.”

It is in principle possible that the luminosity-dependent trend may be due largely to host galaxy contamination, since the emission from the host galaxy contributes significantly to MIR emission in the low luminosity end as discussed in Section 3.1. To check this effect, in Figures 7 and 8 we also show the \( L_{\text{MIR}}/L_{\text{bol}} \) and the corrected \( C_T \) using the slope from the high luminosity sample with \( L_{L14-195} > 43 \), then extrapolating them to the lower luminosity end. The luminosity dependence of the \( C_T \) mitigates, but still holds, the relations. This idea has been gaining observational evidence from radio (Grimes et al. 2004), IR (Maiolino et al. 2007; Treister et al. 2008; Mor et al. 2009; Alonso-Herrero et al. 2011; Ichikawa et al. 2012b; Toba et al. 2013, 2014), optical (Simpson 2005), and X-ray (Ueda et al. 2003, 2011, 2014; Beckmann et al. 2009; Lusso et al. 2013; Ricci et al. 2013) studies of AGNs. On the other hand, in the high-z universe with \( z = 2-3.5 \), Netzer et al. (2015) infer covering factors consistent with no evolution with AGN luminosity within the uncertainties for the bolometric correction factor reported in their sample.

Again, results from previous studies are also overplotted in Figures 7 and 8 using the bolometric correction of Marconi

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**Figure 7.** MIR luminosity to bolometric luminosity ratio as a function of bolometric luminosity. \( L_{\text{bol}} \) is estimated from Equation (5) for our sample, while it is estimated from Equation (14) for the other studies from the literature. (Left) \( \log L_{12\mu m}/L_{\text{bol}} \) vs. \( \log L_{\text{bol}} \). (Right) \( \log L_{22\mu m}/L_{\text{bol}} \) vs. \( \log L_{\text{bol}} \). Blue cross/red X-shape shows type-1/type-2 AGNs, respectively. The red crosses are shifted to the right by 0.1 dex for clarity. The main AGN type used in Fiore et al. (2009) and Stern (2015) is type-1, and that in Gandhi et al. (2009), Mateos et al. (2015), Asmus et al. (2015), and our study is both type-1 and type-2.
et al. (2004),

$$\log L_{\text{bol}} = 0.0378 (\log L_{14-195})^2 - 2.00 \log L_{14-195} + 60.5$$  \hspace{1cm} (14)

for 2–10 keV luminosity ($L_{2-10}$). As shown in Figures 7 and 8, studies in the local universe (Gandhi et al. 2009; Asmus et al. 2015) found a decrease of the covering factor with the AGN luminosity. Even in the high luminosity sample of Mateos et al. (2015) in the high-$z$ universe, the same trend can be observed. On the other hand, the studies by Fiore et al. (2009) and Stern (2015) carried out using high-$L$ (and high-$z$) sources strongly contradict the luminosity-dependent unified models. Considering the rare population of high luminosity AGNs in the local universe as discussed in Section 3.2, further investigation with deep survey is necessary to solve this controversy at the high luminosity end.

3.6. WISE Color–Color Distribution of Hard X-Ray-selected AGNs

IR color–color selection is useful in identifying obscured AGN candidates and is also efficient compared to other time-consuming methods such as spectroscopical methods. Figure 9 shows the distribution of AGNs on the WISE color–color plane. Increasing levels of AGN contribution to MIR emission have been shown in Figure 10 to move sources upwards in the plane with the color cut $W1 - W2 = 0.8$ (Stern et al. 2012) and also within the AGN wedge (Mateos et al. 2012). It is clear that our objects are not always located within the criteria above. As discussed in Section 3.1, lower luminosity sources could have non-negligible levels of contamination in the NIR and MIR bands from the host galaxies. To check it quantitatively, we divide the sample into subgroups of luminosities, then calculate the detection rate. Figure 11 shows the detection rate of AGNs using the thresholds of Stern et al. (2012, top) and Mateos et al. (2012, bottom). The detection rate increases dramatically at $L_{14-195} > 10^{43}$ erg s$^{-1}$ and most (>$80\%$) sources can be selected using the IR color–color methods at $L_{14-195} > 10^{44}$ erg s$^{-1}$. Thus, while the IR color–color methods are highly effective at high luminosities ($L_{14-195} > 10^{44}$ erg s$^{-1}$), searching for faint AGNs with $L_{14-195} < 10^{44}$ erg s$^{-1}$ with near-IR color–color methods should be complemented with other AGN identification methods such as hard ($E > 2$ keV) X-rays (e.g., LaMassa et al. 2015).

Figure 11 shows that type-1 and type-2 AGNs do not have any significant difference. It indicates that the detection rate does not originate from the different AGN populations, such as the effects of the suppressions of NIR SEDs on type-2 AGNs due to heavier obscuration by the torus clumps (Ramos Almeida et al. 2011), but more likely by the dilution from the host galaxy stellar direct emission, which causes blue $W1 - W2$ colors (e.g., Stern et al. 2005; Risaliti et al. 2006; Sani et al. 2008; Imanishi et al. 2010; Ichikawa et al. 2014). The same trend is also reported in Toba et al.
(2014), who used the WISE-matched SDSS AGNs selected using the BPT diagram (Baldwin et al. 1981). They showed that the WISE color-method efficiency increases with $L_{22 \mu m}$. Kawamuro et al. (2016a) also reported that hard X-ray-selected low luminosity AGNs cannot be found using the IR color selections above. These results are consistent with what is shown in Figure 11 by considering that most sources are at $L_{14-195} < 10^{44} \text{erg s}^{-1}$. The same trend is also reported from the X-ray studies of Compton-thick AGNs (Gandhi et al. 2015; Tanimoto et al. 2016). They reported that secure Compton-thick AGNs in the local universe do not preferentially locate within the AGN cut or wedge at $L_{14-195} < 10^{43} \text{erg s}^{-1}$. However, even for luminous AGNs, if they are heavily obscured AGNs such as buried AGNs, NIR and even MIR absorption may play a role to locate them outside the AGN cut or wedge (e.g., Hainline et al. 2014a; Imanishi et al. 2016). In addition, some authors (e.g., Satyapal et al. 2014; Secrest et al. 2015) find that the fraction of AGNs by WISE color selection is highest at lower stellar masses and drops dramatically in higher mass galaxies, suggesting that stellar mass (or Eddington ratio) is another key parameter affecting the success rate of the IR color selections as well as the X-ray luminosity discussed above.

### 4. CONCLUSIONS

We have compiled the IR (3–500 $\mu$m) counterparts of 604 nearby complete flux-limited AGN sources detected in the 70 month integration of the Swift/BAT all-sky survey in the 14–195 keV band. Utilizing the IR catalogs obtained from WISE, AKARI, IRAS, and Herschel, we identified 604, 560, 601, and 402 counterparts in the any-IR, NIR, MIR, and FIR bands, respectively. For our discussion, the detected sources were divided into two AGN types based on $N_H$ with a boundary of $N_H = 10^{22} \text{cm}^{-2}$. Our results are summarized as follows:

1. We find good luminosity correlation between the MIR and ultra-hard X-ray band over five orders of magnitude ($41 < \log(L_{3-45}/\text{erg s}^{-1}) < 46$). Using the linear relation of $\log(L_{\text{MIR}}/10^{43} \text{erg s}^{-1}) = a + b \log(L_{14-195}/10^{43} \text{erg s}^{-1})$, the slope $b = 0.96–0.98$ is obtained for the

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**Figure 10.** W1–W2 vs. W2–W3 two-color diagram in units of Vega magnitude with different 14–195 keV luminosity populations, denoted in blue (type-1) and red (type-2), overplotted with the total sample in gray.
whole sample and $b = 1.05–1.07$ for the high luminosity sample ($L_{14-195} > 10^{43}$ erg s$^{-1}$). This value is consistent with those obtained by high spatial resolution MIR image observations of X-ray-selected catalogs, whereas the slope is shallower than that obtained from the sample of high-$z$ optically selected luminous AGNs. This indicates that X-ray emission could be more saturated than MIR ones in the high luminosity end.

2. We find a rising trend between bolometric AGN power and FIR over five orders of magnitude in individual plots. The slope is consistent with that obtained by Netzer (2009) as well as Matsuoaka & Woo (2015). The binned analysis also shows that mean $L_{\text{bol}}$ as a function of $L_{\text{FIR}}$ shows the rising trend, which is consistent with the individual plot analysis. However, the mean $L_{\text{FIR}}$ as a function of $L_{\text{bol}}$ shows a flattened trend. This seemingly contradicting result could have originated from the difference in the dominant timescale between SF and AGN activity that SF and BH accretion is closely connected over long timescales, but this relation can be hidden at lower $L_{\text{bol}}$ due to short-term AGN variability.

3. We find a small number of FIR pure-AGN candidates that have strong AGN luminosity with very weak SF contribution from their host galaxies. These objects represent a good sample to construct the pure-AGN IR SED including the FIR end. They could be good candidates to study AGN feedback since they might be in the stage where SF activity is suppressed due to energy output from the AGN.

4. Using the correction to the covering factor from the MIR-to-bolometric luminosity ratio by Stalevski et al. (2016), we find that the covering factor decreases with bolometric luminosities, confirming the luminosity-dependent unified model.

5. We find that the efficiency of the WISE color–color cuts proposed by Stern et al. (2012) and Mateos et al. (2012) is highly AGN-luminosity dependent. These methods cannot completely pick up local X-ray-selected low luminosity AGNs with $L_{14-195} < 10^{44}$ erg s$^{-1}$, while the color–color cut methods efficiently pick up most of the AGNs with $L_{14-195} > 10^{44}$ erg s$^{-1}$.

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APPENDIX

FLUX CORRELATION BETWEEN The MIR And 14–195 keV BANDS

Figure 12 shows the flux correlations between the MIR (12 and 22 μm) and 14–195 keV bands. This shows that there is a clear correlation between the two bands even in the flux–flux plots with the slope of $b = 1.42$ for the 12 μm band and $b = 1.47$ for the 22 μm band, respectively. The figure also clearly shows that our sample is X-ray-flux limited. There is a clear sharp decline of the number of AGNs in the sample at faint 14–195 keV fluxes, especially at $f_{14-195} < 10^{-11}$ erg s$^{-1}$ cm$^{-2}$. The MIR detection limits for these sources are typically $2.5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the 12 μm band and $8.1 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the 22 μm band, which are below the detected fluxes from the sources. Therefore, the
Sample is effectively complete in the MIR and the selection is dominated by the X-ray-flux limits as discussed in Section 3.1.

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