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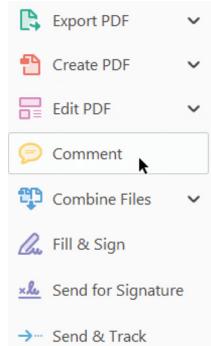
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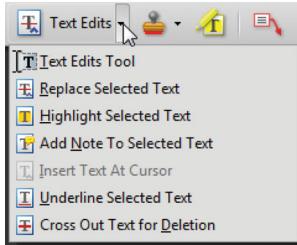


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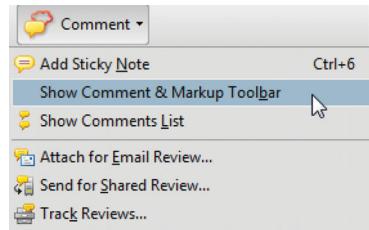
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# Herschel far-infrared photometry of the Swift Burst Alert Telescope active galactic nuclei sample of the local universe – III. Global star-forming properties and the lack of a connection to nuclear activity

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## ABSTRACT

We combine the *Herschel Space Observatory* PACS (Photoconductor Array Camera and Spectrometer) and SPIRE (Spectral and Photometric Imaging Receiver) photometry with archival *WISE* (Wide-field Infrared Survey Explorer) photometry to construct the spectral energy distributions (SEDs) for over 300 local ( $z < 0.05$ ), ultrahard X-ray (14–195 keV) selected active galactic nuclei (AGN) from the *Swift* Burst Alert Telescope (BAT) 58-month catalogue. Using a simple analytical model that combines an exponentially cutoff power law with a single temperature modified blackbody, we decompose the SEDs into a host galaxy and AGN component. We calculate dust masses, dust temperatures, and star formation rates (SFRs) for our entire sample and compare them to a stellar mass-matched sample of local non-AGN galaxies. We find AGN host galaxies have systematically higher dust masses, dust temperatures, and SFRs due to the higher prevalence of late-type galaxies to host an AGN, in agreement with previous studies of the *Swift*/BAT AGN. We provide a scaling to convert X-ray luminosities into 8–1000  $\mu\text{m}$  AGN luminosities, as well as determine the best mid-to-far IR colours for identifying AGN-dominated galaxies in the IR regime. We find that for nearly 30 per cent of our sample, the 70  $\mu\text{m}$  emission contains a significant contribution from the AGN (>0.5), especially at higher luminosities ( $L_{14-195\text{keV}} > 10^{42.5} \text{ erg s}^{-1}$ ). Finally, we measure the local SFR–AGN luminosity relationship, finding a slope of 0.18, large scatter (0.37 dex), and no evidence for an upturn at high AGN luminosity. We conclude with a discussion on the implications of our results within the context of galaxy evolution with and without AGN feedback.

**Key words:** galaxies: active – galaxies: evolution – galaxies: Seyfert – galaxies: star formation – infrared: galaxies.

## 1 INTRODUCTION

Ever since the discoveries that the large-scale properties of galaxies are related to the mass of the supermassive black holes (SMBHs) they host (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Marconi & Hunt 2003; Häring & Rix 2004;

Gültekin et al. 2009; Kormendy & Ho 2013; McConnell & Ma 2013), studies have intensely focused on finding the link between the evolution and growth of both the galaxy and SMBH. Theoretical arguments (e.g. Silk & Rees 1998), as well as cosmological simulations (e.g. Bower et al. 2006; Croton et al. 2006) support the idea that SMBHs, while accreting material in their active galactic nuclei (AGN) phase, can affect both their own growth and the growth of their host galaxy through a mechanism that shuts down accretion and star formation (i.e. negative feedback).

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Early evidence backing this theory seemed to be found in the observation that the star formation rate (SFR) density and accretion rate density of the [universe](#) evolve similarly with redshift (Boyle & Terlevich 1998; Franceschini et al. 1999; Silverman et al. 2008, 2009; Aird et al. 2010; Merloni & Heinz 2013). Further, AGN host galaxies were found to predominantly lie in the ‘green valley’ of the colour–magnitude diagram, in between the blue, star-forming galaxies and ‘red-and-dead’ quiescent ones (Martin et al. 2007; Nandra et al. 2007; Silverman et al. 2008; Schawinski et al. 2010; Koss et al. 2011), suggesting that nuclear activity plays a role in transitioning its host galaxy from star forming to quiescence.

While suggestive, optical colours can be strongly affected by extinction due to dust that might move a galaxy from ‘blue’ to ‘green’ (Cowie & Barger 2008; Cardamone et al. 2010). Other measures of the SFR including emission line, ultraviolet (UV), and mid-infrared (MIR) luminosities that are extensively used for normal, non-AGN galaxies suffer from varying degrees of contamination in the presence of an AGN, especially unabsorbed ( $N_{\mathrm{H}} < 10^{22} \text{ cm}^{-2}$ ) type I AGN.

This problem was solved with the advent of far-infrared (FIR;  $\lambda = 40\text{--}500 \mu\text{m}$ ) telescopes, including the *Infrared Astronomical Satellite (IRAS)*, the *Infrared Space Observatory (ISO)*, the *Spitzer Space Telescope*, and most recently the *Herschel Space Observatory* (Pilbratt et al. 2010). FIR emission remains the ideal waveband to study star formation in AGN host galaxies for two reasons: (1) the rapidly declining spectral energy distribution (SED) associated with AGN-heated dust in the FIR regime (Fritz, Franceschini & Hatziminaoglou 2006; Netzer et al. 2007; Mullaney et al. 2011; Shi et al. 2014) ensures little AGN contamination, and (2) thermal emission of large grains heated by the ionizing emission of recently formed massive stars (Lonsdale Persson & Helou 1987; Devereux & Young 1990) creates a strong FIR ‘bump’ and provides a reliable measure of the recent (10–100 Myr) SFR (Kennicutt 1998a).

Even though the FIR can provide a reliable SFR tracer, individual investigations into the connection between AGN activity and star formation have produced conflicting and even contradictory results. Some studies (Page et al. 2012; Barger et al. 2015) have reported lowered SFRs for the highest luminosity AGN, indicative of a suppression of star formation due to AGN feedback. Others have found weak or flat relationships (Diamond-Stanic & Rieke 2012; Mullaney et al. 2012; Rosario et al. 2012; Rovilos et al. 2012; Azadi et al. 2015; Stanley et al. 2015), especially at more moderate AGN luminosities. Finally, some find an overall positive correlation (Lutz et al. 2008; Netzer 2009; Rosario et al. 2012; Rovilos et al. 2012; Chen et al. 2013; Dai et al. 2015).

Many of the studies may however suffer from one or more problems that include small number statistics either due to a small area survey or low sensitivity (e.g. Harrison et al. 2012), an inaccurate scaling from monochromatic luminosities to a total SFR, and source confusion due to the relatively large beam size of *Herschel*, especially at longer wavelengths. Further, as Barger et al. (2015) pointed out, stacking and averaging analyses can overestimate the level of star formation taking place in the bulk of the X-ray sample because the true SFR distribution is unknown.

In this paper, we examine the AGN–star formation relationship in the low-redshift [universe](#). We have performed a *Herschel* survey of a sample of AGN from the *Swift* Burst Alert Telescope (BAT) 58-month catalogue, which selected sources over the entire sky in the 14–195 keV energy range. At this high energy, we are nearly unbiased with respect to any host galaxy properties including SFR, as well as obscuration below a hydrogen column density ( $N_{\mathrm{H}}$ ) of  $10^{24} \text{ cm}^{-2}$ . The *Swift*/BAT AGN sample has been extensively

studied ever since the release of the first catalogues. Most relevant to our work, Koss et al. (2011) performed an optical survey of over 100 *Swift*/BAT AGN using combined Sloan Digital Sky Survey (SDSS) and Kitt Peak National Observatory imaging to study their host galaxy properties. They found that the *Swift*/BAT AGN are dominated by massive ( $M_{\mathrm{star}} > 10^{9.5} M_{\odot}$ ) spirals with bluer colours than a mass-matched sample of non-AGN galaxies. Koss et al. (2011) further found that AGN showed enhanced FIR luminosities, using 90  $\mu\text{m}$  photometry from *Akari*.

With five-band imaging with *Herschel* along with archival photometry from the *Wide-field Infrared Survey Explorer (WISE)*, we have constructed MIR–FIR SEDs for over 300 AGNs, allowing us to accurately measure the SFR in a robust manner. Because of the low-redshift nature of our sources, every AGN is easily able to be identified, and there is no concern over source confusion. These SEDs allow us to not only calculate SFRs but also test varying SED decomposition methods and models, as well as measure other properties of the host galaxies, such as the dust mass and dust temperature, to compare with non-AGN samples. With a high detection rate (95, 83, 86, 72, and 46 per cent at 70, 160, 250, 350, and 500  $\mu\text{m}$ ), our measured properties from the SEDs are well constrained, removing much of the uncertainty due to censoring.

The paper is organized as follows. In Section 2, we briefly describe the *Herschel*-BAT AGN sample; in Section 3, we detail our *WISE* and *Herschel* data sets. Section 4 introduces our non-AGN comparison sample. Section 5 qualitatively examines the SEDs and determines the average SED as a function of AGN luminosity, while Section 6 outlines our fitting methods. Sections 7 and 8 then discuss our results, compare with other studies, and conclude the paper. Throughout, we use a cosmology with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$ , and  $\Omega_\Lambda = 0.7$  to calculate luminosity distances from redshifts.

## 2 *Herschel*-BAT SAMPLE

Because *Swift*/BAT continuously monitors the entire sky in the energy range 14–195 keV for gamma-ray bursts, it simultaneously provides an all-sky survey at ultrahigh X-ray energies. This allows for the creation of complete catalogues with increasing sensitivity the longer *Swift*/BAT remains in operation. Given the extreme environments necessary to produce strong 14–195 keV emission, the majority of sources in the *Swift*/BAT catalogues are AGN.

We chose 313 AGNs from the parent sample of  $\sim 720$  AGNs detected in the 58-month catalogue<sup>1</sup> after imposing a redshift cutoff of  $z < 0.05$  and excluding Blazars and BL Lac objects to form our *Herschel*-BAT AGN sample. With a mean redshift of  $\langle z \rangle = 0.025$ , our AGN sample provides a comprehensive view of the properties of AGN host galaxies in the local [universe](#). Our selection at ultrahigh X-ray energies further removes biases and selection effects due to host galaxy contamination and obscuration (Mushotzky 2004) that can influence samples at other wavelengths.

The demographics of our sample are nearly evenly split between type I (43 per cent) and type II (53 per cent) with the remaining 4 per cent (5 objects) either a Low-Ionization Nuclear Emission-line Region (LINER) or unclassified. The *Herschel*-BAT sample spans nearly four orders of magnitude in 14–195 keV luminosity ( $10^{41} < L_{14\text{--}195\text{ keV}} < 10^{45} \text{ erg s}^{-1}$ ) allowing for a robust determination of the connection between AGN strength and SFR. For a complete listing of our sample with names, luminosity distances,

<sup>1</sup> <https://swift.gsfc.nasa.gov/results/bs58mon>

**Table 1.** Best-fitting C12 model parameters, luminosities, and AGN fractions. *Column 1:* name of the source. *Column 2:* log of the dust mass in solar units. *Column 3:* dust temperature for the MBB component. ‘–’ indicates the dust temperature was fixed at 23 K. *Column 4:* slope of the power-law component. *Column 5:* turnover wavelength. *Column 6:* log of the total infrared luminosity from 8 to 1000  $\mu\text{m}$  in solar units. *Column 7:* log of the MBB component luminosity in solar units. *Column 8:* log of the power-law component luminosity in solar units. *Column 9:* fractional contribution of the AGN to the total infrared luminosity calculated using equations (4) and (5). The full version of this table is available online as Supporting Information.

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### 3 DATA

#### 3.1 Herschel photometry

293 of the *Herschel*-BAT AGNs were observed with *Herschel* as part of a Cycle 1 open time programme (OT1\_rmushotz\_1, PI: Richard Mushotzky). The remaining 20 sources were part of other programmes with public archival data. *Herschel* observed all 313 AGNs using both the Photoconductor Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) producing images in five wavebands: 70, 160, 250, 350, and 500  $\mu\text{m}$ .

Detailed descriptions of the data reduction process and photometric flux extraction can be found in Meléndez et al. (2014) for PACS and Shimizu et al. (2016) for SPIRE. The following is a short description of the flux extraction procedure. We measured fluxes at each waveband directly from the images using aperture photometry with a concentric annulus to define the local background. We applied aperture corrections for sources where we used a point source aperture as defined in the respective PACS and SPIRE data reduction guides. Fluxes for sources that were unresolved at all three wavebands in SPIRE were determined using the SPIRE timeline fitter within the *Herschel* Interactive Processing Environment. All fluxes have a signal-to-noise ratio of at least 5, otherwise we provided a  $5\sigma$  upper limit.

In Shimizu et al. (2016), using the SPIRE flux ratios, we found six radio-loud objects, which have a large contribution to their FIR emission from synchrotron radiation due to their jets. These sources are Pictor A, 3C 111.0, 3C 120, 2MASX J23272195+1524375, PKS 2331–240, and [HB89] 0241+622. For this work, we remove these sources from all analysis; however, we still provide figures of their SED fits in Appendix D and list their best-fitting parameters in Table 1.

Also in Shimizu et al. (2016), we flagged objects with a ‘D’ that likely had strong contamination due to a nearby source. For these sources, we treat the SPIRE fluxes as upper limits. For a small number of very nearby galaxies with large angular size (NGC 2655, NGC 3718, NGC 4939, NGC 4941, NGC 5033, and NGC 6300), we

<sup>2</sup> <http://irsa.ipac.caltech.edu/frontpage/>

<sup>3</sup> <http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/>

realized that the PACS FOV of our observations did not encompass the entirety of the galaxy leading to possible underestimations of the 70 and 160  $\mu\text{m}$  flux densities. Therefore, for this work, we chose to conservatively increase the uncertainty to 50 per cent.

#### 3.2 WISE photometry

To extend the SEDs into the MIR, we supplemented our *Herschel* data with archival WISE (Wright et al. 2010) photometry. WISE performed a broad-band all-sky survey at 3.4 (W1), 4.6 (W2), 12 (W3), and 22 (W4)  $\mu\text{m}$  with angular resolution comparable to *Herschel*/PACS at 70  $\mu\text{m}$  for W1, W2, and W3 and 160  $\mu\text{m}$  for W4. We queried the AllWISE catalogue through the NASA/IPAC Infrared Science Archive<sup>2</sup> to search for coincident sources within 6 arcsec. Counterparts were found for all but one AGN (Mrk 3) at every waveband. The catalogue contained only W1 and W2 fluxes for Mrk 3 due to differences in the depth of coverage for W1/W2 and W3/W4; therefore, Mrk 3 is not included as part of the sample in this work.

The AllWISE catalogue provides magnitudes determined using multiple extraction methods. We consider only the profile-fitting magnitudes ( $wN_{\text{N}pro}$  where N is 1, 2, 3, or 4) and the elliptical aperture magnitudes ( $wNg_{\text{mag}}$ ). Profile-fitting magnitudes were determined by fitting the position-dependent point spread function using deblending procedures when necessary to decompose overlapping sources. The  $wN_{\text{N}pro}$  magnitudes therefore are only relevant for unresolved sources.

If a WISE source is associated with a source in the Two Micron All Sky Survey (2MASS) Extended Source Catalog (XSC), then  $wNg_{\text{mag}}$  magnitudes were also measured using an elliptical aperture with the same shape from the XSC and sizes scaled given the larger WISE beam. Thus,  $wNg_{\text{mag}}$  magnitudes are more appropriate for extended sources. For details of all of the WISE magnitude measurements, we point the reader to the All-Sky Release Explanatory Supplement.<sup>3</sup>

Given the low-redshift nature of our sample, 294/313 galaxies are in the 2MASS XSC and using only the  $wN_{\text{N}pro}$  magnitudes would severely underestimate the flux for many of them. To decide

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which magnitude to include in the SED for each source, we used the reduced  $\chi^2$  value ( $wNrchi2$ ) from the profile fitting. If  $wNrchi2 < 3$ , then we chose the  $wNmpro$  magnitude, otherwise  $wNgmag$  was chosen. For 55/313 sources, we used the  $W1$  profile-fitting magnitudes; for 129/313 sources, we used the  $W2$  profile-fitting magnitudes; for 210/313 sources, we used the  $W3$  profile-fitting magnitudes; and for 267/313 sources, we used the  $W4$  profile-fitting magnitudes. The increasing numbers of sources for which we use the profile-fitting magnitudes is due to the increasing FWHM of the *WISE* point spread function that changes from 6 arcsec at  $W1$  to 12 arcsec at  $W4$ .

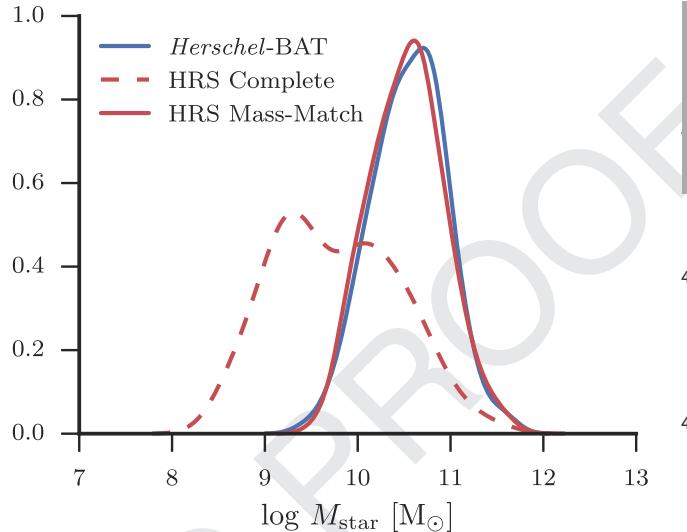
#### 4 COMPARISON SAMPLE

To test whether the AGN has any effect on the star-forming properties of their host galaxies, we need samples of galaxies that contain little evidence for nuclear activity. These samples also need to occupy the same redshift range to mitigate against evolutionary effects and have been observed with nearly the same instruments so the properties can be compared on an equal level. Three low-redshift samples exist that satisfy these constraints. They are the *Herschel Reference Survey* (HRS; Boselli et al. 2010), *Key Insights on Nearby Galaxies: a Far-Infrared Survey with Herschel* (KINGFISH; Kennicutt et al. 2011), and the *Herschel Stripe 82 Survey* (HerS; Viero et al. 2014). While the KINGFISH sample has been observed at all of the same wavelengths as the *Herschel*-BAT AGN, the sample was selected in a heterogeneous manner and only contains 61 galaxies, which does not allow for stellar mass matching. The HerS sample is numerous and covers a large range in mass, but was only observed with SPIRE. Further, the catalogue was built based on SPIRE detections, which imposes a selection effect associated with the SFR. We therefore chose the HRS as our comparison sample to the *Herschel*-BAT AGN.

The HRS was a guaranteed time key *Herschel* programme dedicated to studying the dust content of ‘normal’ galaxies. The 323 galaxy sample is volume limited ( $15 < D < 25$  Mpc) to avoid distance effects and  $K$ -band flux limited to avoid selection effects due to dust and provides a representative population of local galaxies. The size of the HRS and its local nature make it an ideal sample to compare to the *Herschel*-BAT galaxies.

The HRS galaxies also were imaged using both PACS and SPIRE, although the 100  $\mu\text{m}$  filter was used instead of the 70  $\mu\text{m}$  filter. Cortese et al. (2014) and Ciesla et al. (2012) measured the PACS and SPIRE flux densities, respectively, using similar techniques as the *Herschel*-BAT galaxies. *WISE* 12 and 22  $\mu\text{m}$  photometry for HRS were provided in Ciesla et al. (2014). The available data for the HRS SEDs are nearly identical to our sample.

The only issue in comparing the HRS galaxies to the *Herschel*-BAT AGN concerns the stellar mass ( $M_{\star}$ ) distribution. Because the near-infrared is most strongly affected by the mass of the older stellar population, the HRS  $K$ -band selection produces an  $M_{\star}$  distribution that is representative of the naturally occurring  $M_{\star}$  distribution. However, many recent studies have shown that AGN prefer high  $M_{\star}$  galaxies (e.g. Schawinski et al. 2010; Xue et al. 2010), a feature that is also found in the BAT AGN (Koss et al. 2011). Fig. 1 displays the  $M_{\star}$  distributions for the *Herschel*-BAT and HRS sample (dashed line) represented using a Kernel Density Estimate (KDE).<sup>4</sup> The *Herschel*-BAT galaxies have an average  $M_{\star}$  of



**Figure 1.** Kernel Density Estimates (KDEs) of the  $M_{\star}$  distribution for the BAT AGN (blue), full HRS sample (red), and mass-matched HRS sample (red dashed). The *Herschel*-BAT AGNs probe a higher  $M_{\star}$  galaxy population than the full samples; however, with mass-matching we can reproduce the stellar-mass distribution of the *Herschel*-BAT AGN with non-AGN.

10.6  $M_{\odot}$ , whereas the average  $M_{\star}$  for HRS is 9.8  $M_{\odot}$ , nearly a 10-fold difference.

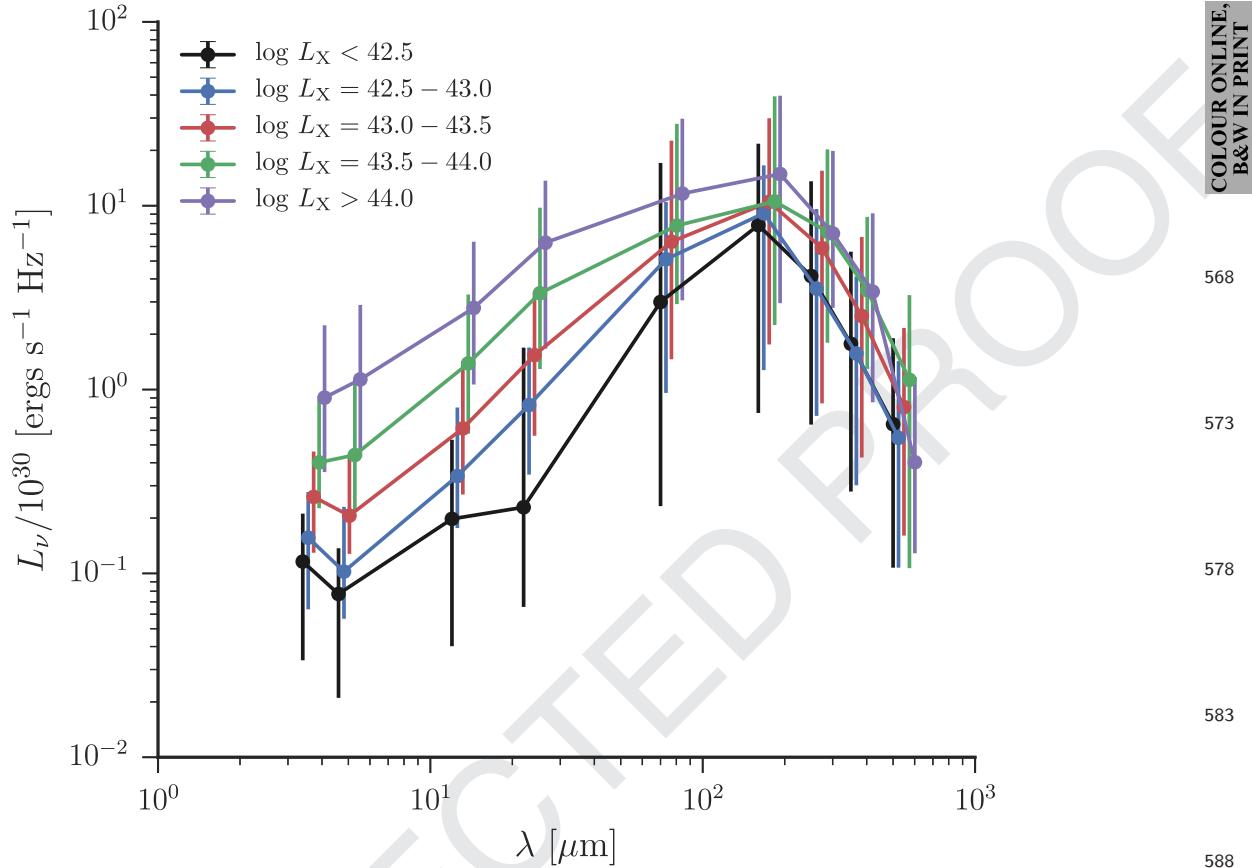
To account for possible stellar mass effects, we decided to produce a mass-matched HRS sample in the following way. Stellar masses for the *Herschel*-BAT AGNs were calculated based on the AGN-subtracted  $ugriz$  photometry from Koss et al. (2011) and the  $g - i$  calibrated stellar mass relation from Zibetti, Charlot & Rix (2009). This is the same method that stellar masses were calculated for the HRS sample, given in Cortese et al. (2012b). For each of the 122 *Herschel*-BAT AGNs that have stellar mass estimates, we chose all HRS galaxies that have a stellar mass within 0.15 dex of the *Herschel*-BAT mass. We then randomly selected an HRS galaxy from this pool. Because high-mass galaxies are relatively rare in the HRS sample, some matches are duplicated. We find that 97/122 of the matched HRS galaxies are unique, representing 80 per cent of the sample, so the duplicating effects should not be large. The red solid line in Fig. 1 now shows the mass-matched HRS sample, which overlaps with the *Herschel*-BAT mass distribution. Throughout the rest of this paper, we refer to the HRS mass-matched sample as simply the HRS sample unless otherwise noted.

#### 5 THE IR SEDs OF $z = 0$ AGN

Before fitting the SEDs and comparing to a non-AGN sample, we begin with a qualitative look at the SEDs of the 313 AGNs. Fig. D1 shows the 12–500  $\mu\text{m}$  SED for every source in the *Herschel*-BAT sample. Immediately noticeable is the varied SED shapes. Some of the SEDs (e.g. 2MASX J07595347+2323241, Cen A, ESO 005-G004, NGC 4051, NGC 4138, and NGC 6814) feature a very prominent FIR bump that is recognizable in nearly all star-forming galaxies and is indicative of thermally heated dust from

point in the sample by a specific kernel, which are then summed together. We use a Gaussian kernel with a width according to ‘Scott’s Rule’ (Scott 1992), width =  $N^{-1/5}$ , where  $N$  is the number of data points. The appearance of a histogram can change based on the number of bins, bin width, and bin centres whereas a KDE is only dependent on the kernel width.

<sup>4</sup> Instead of the standard histogram, we choose to visualize distributions in this work with KDEs. KDEs are constructed by first representing each data



**Figure 2.** Median IR SEDs in units of  $10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}$  for the *Herschel*-BAT AGNs binned by  $L_{14-195\text{keV}}$ . Each point in the SEDs is the median  $L_\nu$  for the sources in the bin including upper limits calculated using the Kaplan–Meier product-limit estimator. The error bars represent the 68 per cent confidence interval determined from the 16th and 84th percentiles. SEDs have been slightly offset by 0.02 dex in wavelength so that the error bars can be clearly shown.

recently formed massive stars, as well as cirrus emission heated by an older population. The general shape is usually well fitted by a blackbody modified by a frequency-dependent optical depth (e.g. Calzetti et al. 2000; Smith et al. 2012; Bianchi 2013; Symeonidis et al. 2013; Cortese et al. 2014).

These star formation dominated objects represent one extreme end of the shapes we observe. The other extreme are SEDs whose shapes seem to peak shortwards of 70  $\mu\text{m}$  and display rapidly falling emission with increasing wavelength. Examples include 2MASX J06561197–4919499, 2MASX J210900996–0940147, ESO 103–035, IC 4329A, MCG -05-23-016, and Mrk 335. Emission in the MIR dominates these SEDs and is likely associated with hotter dust heated by the AGN. MIR colours are commonly used to select AGN samples because they display strong red (i.e. increasing SED with increasing wavelength shortwards of 70  $\mu\text{m}$ ) colours compared to non-AGN galaxies (Lacy et al. 2004; Donley et al. 2012; Stern et al. 2012) due to the dust in the obscuring torus heated by the optical and UV emission from the accretion disc. Monochromatic MIR luminosities, especially for sources dominated by an unresolved central component, show near linear correlations with the X-ray luminosity (e.g. Lutz et al. 2004; Gandhi et al. 2009; Asmus et al. 2015) providing more evidence that much of the MIR in AGN host galaxies is associated with the AGN.

The remaining *Herschel*-BAT AGNs display SEDs somewhere in between MIR-dominated and FIR-dominated as a result of competing contributions between the AGN and star formation. The varied shapes of the SED emphasizes the need for SED decomposition,

especially at shorter wavelengths, to accurately determine the IR luminosity associated with either star formation or the AGN.

If star formation suppression occurs at high AGN luminosity, then we expect the IR SEDs for the most X-ray luminous sources to resemble the MIR-dominated SEDs, as Barger et al. (2015) observed. To test this, we binned the SEDs by logarithmic 14–195 keV luminosity. Five bins ( $\log L_{14-195\text{keV}} > 42.5$ ,  $\log L_{14-195\text{keV}} = 42.5 - 43.0$ ,  $43.0 - 43.5$ ,  $43.5 - 44.0$ , and  $\log L_{14-195\text{keV}} > 44.0$ ) were chosen with 0.5 dex widths to ensure enough sources occupied each one. The number of sources in each bin is 22, 39, 94, 116, and 35.

We then calculated the median luminosity density for each waveband in the SED within each X-ray luminosity bin. We used the **ASURV** (Feigelson & Nelson 1985) package, which applies the principles of survival analysis to astronomical data. Information contained in the upper limits can then be included in the measurement of statistical properties of samples without biasing results towards brighter sources that are more likely to be detected. Specifically, ASURV calculates the non-parametric Kaplan–Meier product-limit (KMPL) estimator for a sample distribution. The KMPL estimator is an estimate of the survival function, which is simply  $1 - \text{CDF}$  (cumulative distribution function). Using the KMPL, we calculate for each waveband the median luminosity density (50th percentile) and estimate the uncertainty using the 16th and 84th percentiles.

Fig. 2 shows the median IR SED for sources in each X-ray luminosity bin. From visual inspection, the median SED as a function of X-ray luminosity seems to be driven more by an increasing MIR hot dust component. There does not seem to be any indication that

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star formation is being suppressed at the highest luminosities. The wavebands that show the largest change with X-ray luminosity are the MIR bands. At wavelengths longer than 160  $\mu\text{m}$ , the SED shows no significant change, consistent with the correlations we measured in Meléndez et al. (2014) and Shimizu et al. (2016). If we make the assumption that the longer wavelengths are mainly associated with star formation, then the lack of change indicates that star formation, on time-scales of  $\sim 100$  Myr, is unrelated to X-ray luminosity within the range probed by our sample. However, to definitively test this, we need to decompose the SED into star-forming and AGN components to accurately calculate SFRs.

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## 6 SED FITTING

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Many models and templates exist in the literature to fit the broad-band SEDs of galaxies. We chose a model that allowed us to both decompose the SED into star-forming and AGN components, and provide estimates on the dust temperature and dust mass.

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### 6.1 Casey (2012) model

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One of the most widely used models for fitting the FIR SED of galaxies is a single modified blackbody (MBB). The simple model consists of a normal, single temperature blackbody that represents isotropic dust emission combined with a frequency-dependent opacity given that dust is not a perfect blackbody. In the optically thin limit, the opacity can be approximated as a power law (PL),  $\tau_\nu = (\nu/\nu_0)^\beta$ . The form of the single MBB for the flux density at each frequency is then

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$$S(\nu) \propto \nu^\beta B_\nu(T_d), \quad (1)$$

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where  $\beta$  is the spectral emissivity index and  $B_\nu(T_d)$  is the standard Planck blackbody function for an object with temperature  $T_d$ . This simple model has been shown to fit well the prominent FIR bumps for large samples of star-forming galaxies and provides estimates of the dust temperature, dust mass, and SFR (e.g. Calzetti et al. 2000; Bianchi 2013; Cortese et al. 2014).

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To calculate the dust mass, we must assume a particular dust absorption coefficient,  $\kappa_0$  at a particular frequency,  $\nu_0$ . For this work, we assume  $\kappa_0 = 0.192 \text{ m}^2 \text{ kg}^{-1}$  and  $\nu_0 = 857 \text{ GHz}$  (i.e. 350  $\mu\text{m}$ ) from Draine (2003). However, as Bianchi (2013) shows, by assuming a specific  $\kappa_0$ , we must also fix the spectral emissivity index to the value used to measure  $\kappa_0$ . In this work, we fix  $\beta = 2.0$  to match the spectral emissivity index used by Draine (2003).<sup>5</sup> The final full form of the single MBB model is then

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$$S_{\text{MBB}}(\nu) = \frac{M_d \kappa_0}{D_L^2} \left( \frac{\nu}{\nu_0} \right)^\beta \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT_d} - 1}, \quad (2)$$

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where  $M_d$  is the dust mass,  $D_L$  is the luminosity distance,  $c$  is the speed of light,  $h$  is the Planck constant, and  $k$  is the Boltzmann constant. The two free parameters then are  $M_d$  and  $T_d$ , the dust mass and dust temperature, respectively.

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The simple assumption that dust emission in the IR can be modelled with a single temperature blackbody works well for ‘normal’ star-forming galaxies. However, for galaxies with large amounts

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of hot dust either due to a compact starburst or central AGN, this assumption can quickly break down. To account for this hot dust, we also fit our sample using the model described in Casey (2012, hereafter C12), which is the combination of a single MBB and an exponentially cutoff PL. The C12 model takes the form

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$$S_{\text{C12}}(\nu) = N_{\text{pl}} \left( \frac{\nu}{\nu_c} \right)^{-\alpha} e^{-\nu_c/\nu} + S_{\text{MBB}}(\nu), \quad (3)$$

where  $\nu_c$  represents the turnover frequency and  $N_{\text{pl}}$  is a normalization constant. C12 illustrated using the Great Origins All-Sky LIRG Survey (GOALS) sample that this model provides better estimates of the cold dust temperature, dust mass, and IR luminosity compared to both a single temperature MBB and template libraries.

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The C12 model introduces three more free parameters ( $N_{\text{pl}}$ ,  $\alpha$ , and  $\nu_c$ ); however, within the implementation used by C12,  $N_{\text{pl}}$  and  $\nu_c$  are tied to the normalization of the MBB component and dust temperature to produce a smoothly varying SED and reduce the number of free parameters from five to three.

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But, after early tests using this initial setup, we found that fixing  $N_{\text{pl}}$  and  $\nu_c$  as a function of the other parameters produced unreliable fits. This is because AGN SEDs from the MIR to FIR are not as smooth as those seen in (U)LIRGS, likely due to the disconnect between star formation and AGN heating. Within starbursting galaxies both the hot and cold dust are related through the same heating process, i.e. star formation, while much of the MIR emission in AGN host galaxies originates from dust around the AGN with no strong connection to global star formation in the galaxy. Therefore, we chose to leave both  $N_{\text{pl}}$  and  $\nu_c$  as free parameters resulting in a total of five for the entire model.

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We describe in detail within Appendix A the exact fitting method used to estimate each parameter. In short, we use a Bayesian framework with a Markov chain Monte Carlo (MCMC) to probe the posterior probability distribution function (PDF). We marginalize the resulting posterior PDF for each parameter and use the median as our best-fitting value and the 16th and 84th percentiles to define our lower and upper uncertainties, respectively.

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For 35 sources in our sample, the SEDs contain less than four detected points. These sources are undetected for several reasons. Either they are (a) intrinsically faint, (b) at relatively large distances, or (c) located in a region with high foreground cirrus emission. This last reason causes problems because it produces high upper limits on the fluxes for the SPIRE wavebands, which give the appearance that a substantial amount of FIR emission could exist. Thus, we tested our modelling of these sources with three fixed dust temperatures: 15, 23, and 40 K. 15 and 40 K are the extreme low and high temperatures we find for the whole sample, while 23 K is the median dust temperature. We fit only the 70–500  $\mu\text{m}$  points/upper limits and let the dust mass increase until the model SED exceeded one of the points/upper limits.

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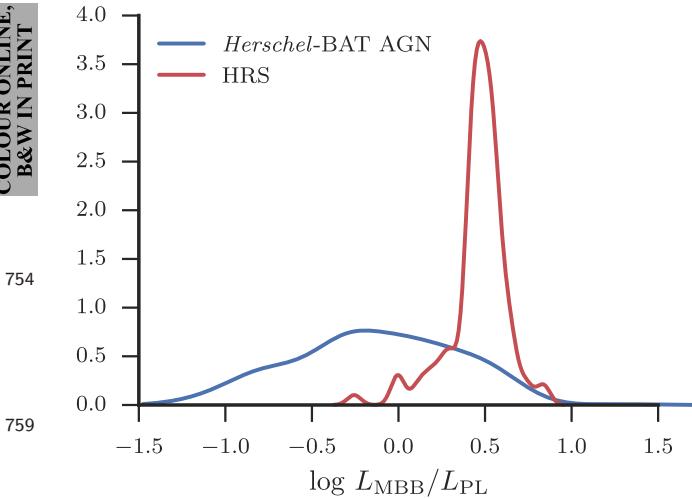
We find that using a dust temperature of either 23 or 40 K produces consistent MBB luminosities. Using a 15 K dust temperature results in MBB luminosities *lower* than the 23 K and 40 K ones. Thus, it is reasonable to assume that conservative upper limits on the MBB luminosity can be constrained with a higher dust temperature. The parameter most affected by the choice of temperature is the dust mass. Lower temperatures produce higher upper limits on the dust mass. In fact, moving from a 15 K temperature to a 40 K temperature changes the dust mass by two orders of magnitude. Given these tests, we chose to run our modelling of these 35 sources by fixing the dust temperature at 23 K, the median temperature of our whole sample. We acknowledge that for some of the undetected sources, we might be underestimating the upper limit on the dust mass. Since this

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<sup>5</sup> We have tested the effect of allowing  $\beta$  to be a free parameter by refitting sources, which were detected in all wavebands. We find a median  $\beta = 1.8 \pm 0.3$ , consistent with our choice to fix  $\beta = 2.0$ . Furthermore, we find that all of the derived parameters, especially the integrated luminosities, are consistent within measurement uncertainty with their values when  $\beta$  is fixed at 2.0.



**Figure 3.** KDEs of the  $L_{\text{MBB}}/L_{\text{PL}}$  distribution for the *Herschel*-BAT AGN (blue) and HRS (red) samples. The HRS galaxies have a narrowly distributed ratio, while the BAT AGNs span a wide range due to the AGN contribution.

subsample is only  $\sim 10$  per cent of the whole, we do not anticipate any large effect on the overall results.

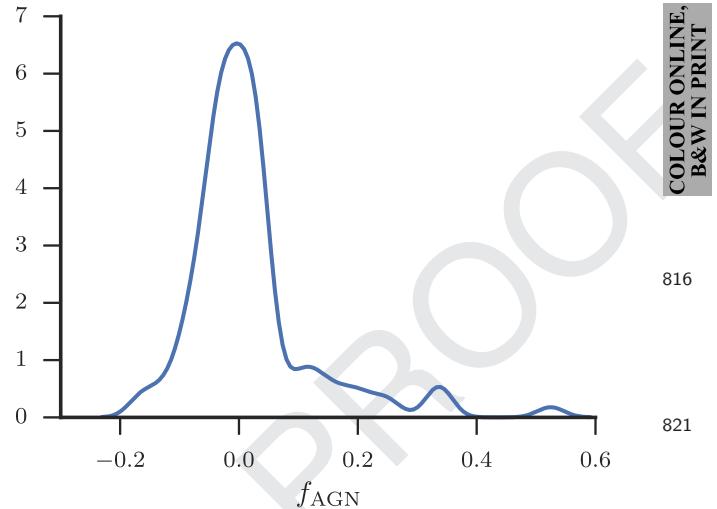
We fit all 313 of the *Herschel*-BAT AGNs using the modified C12 model and report the best-fitting parameters in Table 1. Best-fitting model SEDs are shown along with the observed SEDs in Fig. D1. We also fit HRS galaxies using the exact same model so that we can accurately compare the star-forming properties between non-AGN and AGN host galaxies. For the HRS sources with less than four detected points, we fix the dust temperature at 21 K, the median dust temperature for the whole HRS sample.

## 6.2 Luminosities and AGN fractions

In addition to the parameters associated with the model, we also calculated several luminosities and an AGN fraction. For this work, we define three luminosities: (1)  $L_{\text{IR}}$  will represent the total infrared luminosity determined by integrating the full SED from 8 to 1000  $\mu\text{m}$ , (2)  $L_{\text{SF}}$  will represent the 8–1000  $\mu\text{m}$  luminosity due to star formation in the host galaxy, and (3)  $L_{\text{AGN, IR}}$  will represent the 8–1000  $\mu\text{m}$  luminosity due to AGN-heated dust.

To determine  $L_{\text{SF}}$  and  $L_{\text{AGN, IR}}$ , we first start with  $L_{\text{PL}}$  and  $L_{\text{MBB}}$ , the 8–1000  $\mu\text{m}$  luminosities of the separate PL and MBB components from our SED decomposition. If we made the assumption that the PL component is completely dominated by the AGN in all sources, then we could simply represent  $L_{\text{PL}}$  as the  $L_{\text{AGN, IR}}$  and  $L_{\text{MBB}}$  as  $L_{\text{SF}}$ . However, we quickly recognized the well-known effect that the PL component for some AGN host galaxies can have a strong contribution from dust heated by stars. Thus, a correction factor must be applied to convert  $L_{\text{PL}}$  and  $L_{\text{MBB}}$  into  $L_{\text{AGN, IR}}$  and  $L_{\text{SF}}$ .

We make this correction using the results of the C12 modelling for the HRS sample. Since all of the galaxies in this sample have either no or low-luminosity AGN, the MIR emission is primarily the result of stochastically heated grains near star-forming regions. In Fig. 3, we show the distribution of  $L_{\text{MBB}}/L_{\text{PL}}$ , the ratio of the MBB component luminosity to the MIR PL component. The ratio for the HRS sample is narrowly distributed around a single value, indicating that for our lower mass non-AGN comparison sample the energy contained in the PL and MBB components are tightly connected. We find a median  $\log(L_{\text{MBB}}/L_{\text{PL}}) = 0.48 \pm 0.13$ , which transforms to  $L_{\text{PL,SF}} \approx \frac{1}{3}L_{\text{MBB}}$ , where we now indicate the contribution to the



**Figure 4.**  $f_{\text{AGN}}$  distribution for HRS. The standard deviation of this distribution quantifies the uncertainty on  $f_{\text{AGN}}$  associated with the correction factor used to calculate  $f_{\text{AGN}}$ .

PL component from star formation as  $L_{\text{PL,SF}}$ . We can calculate the AGN contribution for the *Herschel*-BAT AGN then by assuming that the star-forming emission follows the same ratio,

$$L_{\text{AGN, IR}} = L_{\text{PL}} - L_{\text{PL,SF}} = L_{\text{PL}} - \frac{1}{3}L_{\text{MBB}}, \quad (4)$$

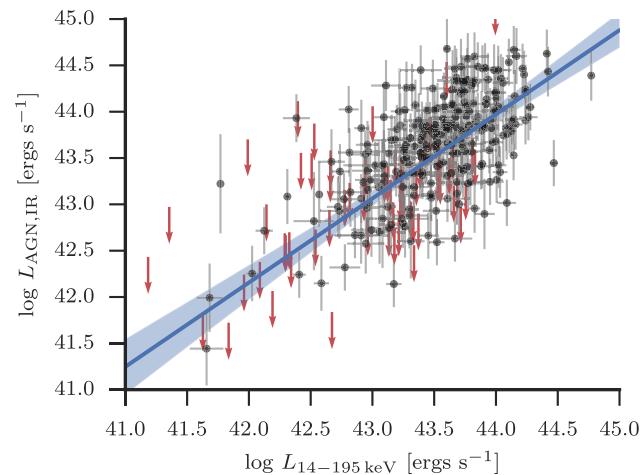
$$f_{\text{AGN}} = L_{\text{AGN, IR}}/L_{\text{IR}}, \quad (5)$$

$$L_{\text{SF}} = L_{\text{MBB}} + L_{\text{PL,SF}} = \frac{4}{3}L_{\text{MBB}}. \quad (6)$$

The uncertainty on the correction factor leads to an uncertainty on  $f_{\text{AGN}}$  using this method, which we estimate by measuring  $f_{\text{AGN}}$  for the HRS sample. Fig. 4 shows the distribution of ' $f_{\text{AGN}}$ ' for HRS. As expected the distribution is centred on 0. We estimate the spread of the distribution by calculating the standard deviation, finding an uncertainty of 0.1. Therefore, we add in quadrature an uncertainty of 0.1 to all of our  $f_{\text{AGN}}$  estimates. Any  $f_{\text{AGN}}$  below 0.1 are converted to upper limits with a value of 0.1.

In Appendix B, we detail our comparison between our chosen C12 model and two other template-based models that aim to decompose the IR SEDs of AGN host galaxies. We find broad agreement between all three models in the measurement of these three luminosities and the AGN fraction. These comparisons also provided additional systematic uncertainties on these parameters associated with model choice that we apply for the rest of this work. Further in Appendix C, we analyse the relationship between our measured  $L_{\text{SF}}$  and polycyclic aromatic hydrocarbon (PAH) luminosities from *Spitzer/HRS* spectra and compare the relationship with a star-forming galaxy sample. We determine that the relationship between our measured  $L_{\text{SF}}$  and PAH luminosities is consistent with that seen in a purely star-forming sample.

As explained in Appendix A, we used flat priors for all of the parameters in the C12 model except for  $\nu_c$ , the turnover frequency, for which we used a Gaussian prior centred at 45  $\mu\text{m}$  and a spread of 20  $\mu\text{m}$ . We imposed this prior due to how poorly  $\nu_c$  is constrained in individual sources. Therefore, if the ‘intrinsic’ AGN SED in reality extends to longer wavelengths than presumed, it is possible we are underestimating  $L_{\text{AGN, IR}}$  for our sources and overestimating  $L_{\text{SF}}$ . Symeonidis et al. (2016) recently showed for powerful AGN ( $L_X > 10^{43.5} \text{ erg s}^{-1}$ ), AGN-heated dust might contribute more than



**Figure 5.** Correlation between  $L_{\text{AGN, IR}}$  and  $L_{14-195 \text{ keV}}$  for the *Herschel*-BAT sample (black points). The solid blue line shows the result of Bayesian linear regression with the shaded region indicating the 95 per cent confidence interval. The strong correlation between the two luminosities provides evidence our SED decomposition performed well in measuring the IR luminosity associated with AGN-heated dust.

expected in the FIR. The Symeonidis et al. (2016) intrinsic AGN SED falls much more slowly with increasing wavelength than our model and other previous templates for the AGN SED (see their fig. 12).

We test the effect of the Symeonidis et al. (2016) SED by replacing the mean AGN SED used in our implementation of the DECOMPIR model with the Symeonidis et al. (2016) SED since we show in Appendix B that DECOMPIR and C12 broadly agree in the determination of the various luminosities. We only fit the sources with more than four detected points in the SED to ensure the SED is sampled well. We calculate a median difference of only 0.01 dex between the  $L_{\text{AGN, IR}}$  using the mean AGN SED from DECOMPIR and the  $L_{\text{AGN, IR}}$  using the Symeonidis et al. (2016). The standard deviation of the difference is 0.2 dex, consistent with the uncertainties we find in Appendix B. Therefore, we conclude that the uncertainties on our estimates of the luminosities and AGN fractions adequately encompass the possibility of the AGN SED extending farther into the FIR than expected.

## 7 RESULTS AND DISCUSSION

### 7.1 Correlation between $L_{\text{AGN, IR}}$ and $L_{14-195 \text{ keV}}$

In Fig. 5, we plot the relationship between the 14–195 keV luminosity and  $L_{\text{AGN, IR}}$ . As expected, we find a strong correlation between the two luminosities indicating we have measured  $L_{\text{AGN, IR}}$  accurately from the C12 model and our correction factor. To quantify the relationship, we performed linear regression using a PYTHON implementation of LINMIX\_ERR<sup>6</sup> (Kelly 2007), a Bayesian method for linear regression that incorporates errors in both independent and dependent variables, as well as non-detections. Kelly (2007) showed through simulations that LINMIX\_ERR outperforms other popular linear regression methods such as ordinary least squares and FITEXY. LINMIX\_ERR outputs marginalized posterior probability distributions for the slope, intercept, and intrinsic scatter between

the two variables, as well as the correlation coefficient,  $\rho$ . Our reported best-fitting parameters here and throughout the rest of the paper will be the median of the marginalized posterior probability distribution with an uncertainty equal to the standard deviation. The linear model assumed is of the form

$$Y = mX + b + \epsilon_{\text{int}}, \quad (7)$$

where  $Y$  and  $X$  are the dependent and independent variables,  $m$  is the slope,  $b$  is intercept, and  $\epsilon_{\text{int}}$  represents intrinsic scatter in the relationship beyond that related to measurement error.  $\epsilon_{\text{int}}$  is modelled as a Gaussian random variable with mean 0 and a variance of  $\sigma^2$ .

We plot the best-fitting linear regression for the whole sample in Fig. 5 as a blue line with shading to indicate the 95 per cent confidence interval. The best-fitting line corresponds to the following relationship:

$$\log(L_{\text{AGN,IR}}) = (0.91 \pm 0.06) \log(L_{14-195 \text{ keV}}) - (4.03 \pm 2.6), \quad (8)$$

The correlation coefficient from LINMIX\_ERR is  $0.8 \pm 0.03$  and the intrinsic scatter is 0.15 dex. The probability of zero correlation is only  $10^{-77}$ . Our measured slope of 0.91 agrees perfectly with the measured slope of  $0.91 \pm 0.04$  in Asmus et al. (2015) using the nuclear 12  $\mu\text{m}$  emission from high angular resolution imaging. Given our very simple method for determining the AGN MIR luminosity from broad-band SED decomposition, a slope consistent with the more robust Asmus et al. (2015) relationship and high correlation coefficient provide confidence that the decomposition has performed reasonably well. Further, equation (8) will provide future studies with estimates of the full 8–1000  $\mu\text{m}$  AGN contribution and allow better estimates of IR-based SFRs for AGN, as long as X-ray data are available.

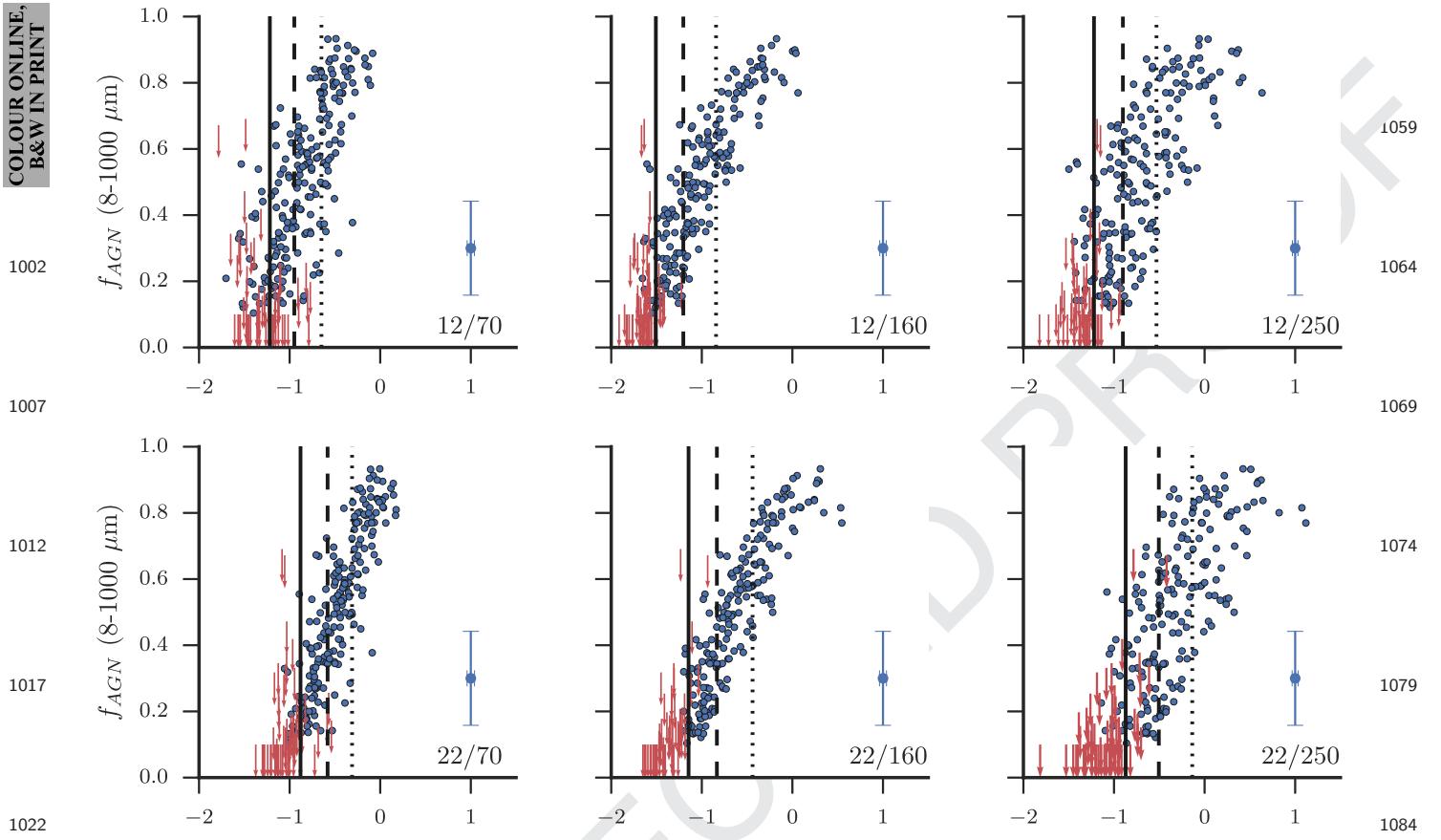
Because we are comparing luminosities and the *Swift*/BAT sample is flux-limited, the correlation we see could simply be due to a confounding variable, in this case distance. To investigate this possibility, we performed a partial correlation test with ASURV using distance as our third variable along with the 14–195 keV luminosity and AGN-related IR luminosity. The partial correlation test calculates Kendall's  $\tau$  rank correlation coefficient between all three variables, and then estimates the intrinsic correlation coefficient after removing the dependence on the third variable (i.e. distance).

We find  $\tau = 0.30 \pm 0.03$  and reject the null hypothesis of zero partial correlation at a significance level of  $10^{-23}$ . While the value of the correlation coefficient is less than the correlation coefficient from LINMIX\_ERR, the partial correlation test does not account for scatter due to measurement error.

To further show that our SED decomposition has accurately estimated the IR luminosity due to the AGN, we calculated the correlation between just the total 8–1000  $\mu\text{m}$  luminosity ( $L_{\text{IR}}$ ) and 14–195 keV luminosity using the same method. We find a slope of  $0.41 \pm 0.05$  and a correlation coefficient of only  $0.44 \pm .05$ . A  $z$  test between the  $L_{\text{AGN,IR}}$  correlation coefficient and the  $L_{\text{IR}}$  correlation coefficient indicates a zero probability that the  $L_{\text{IR}}-L_X$  correlation is stronger than the  $L_{\text{AGN,IR}}-L_X$  correlation.

14–195 keV luminosities are only available for our low-redshift sample; therefore, equation (8) is useless at higher redshifts. We can convert 14–195 keV luminosity to the more accessible 2–10 keV luminosity by making the simple assumption that the shape of the X-ray spectrum of AGN is a PL with a photon index of 1.8 (e.g.

<sup>6</sup> <https://github.com/jmeyers314/linmix>



**Figure 6.** Relationship between different IR colours and  $f_{\text{AGN}}$ , the fraction of the 8–1000  $\mu\text{m}$  luminosity attributed to AGN-heated dust. The IR colours ( $x$ -axis) are in logarithmic units. Upper limits on  $f_{\text{AGN}}$  are indicated as red arrows and are at 95 per cent confidence. We also display the 75th, 50th, and 25th percentile colours for the *Herschel*-BAT AGN as solid, dashed, and dotted vertical lines, respectively. Choosing a sample with colours *above* these would result in 75, 50, and 25 per cent completeness for the *Herschel*-BAT AGN.

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**Table 2.** Linear regression between flux ratios and  $f_{\text{AGN}}$ .

	$F_1/F_2$	$m$	$b$	$\sigma_{\text{int}}$	$\rho$	75th percentile (percentile for HRS)	50th percentile (percentile for HRS)	25th percentile (percentile for HRS)	
1032	12/70	$0.67 \pm 0.04$	$1.02 \pm 0.03$	$0.016 \pm 0.004$	$0.89 \pm 0.02$	-1.23 (90)	-0.97 (50)	-0.66 (21)	1094
	12/160	$0.58 \pm 0.02$	$1.05 \pm 0.03$	$0.002 \pm 0.002$	$0.99 \pm 0.01$	-1.51 (31)	-1.21 (5.2)	-0.85 (2.2)	
	12/250	$0.51 \pm 0.03$	$0.84 \pm 0.03$	$0.019 \pm 0.004$	$0.87 \pm 0.03$	-1.22 (28)	-0.91 (5.2)	-0.57 (1.5)	
	22/70	$0.79 \pm 0.03$	$0.86 \pm 0.02$	$0.001 \pm 0.001$	$0.99 \pm 0.01$	-0.89 (32)	-0.60 (16)	-0.32 (12)	
	22/160	$0.58 \pm 0.02$	$0.85 \pm 0.02$	$0.0004 \pm 0.0005$	$0.997 \pm 0.003$	-1.14 (5.6)	0.83 (1.2)	-0.45 (0)	
	22/250	$0.49 \pm 0.03$	$0.65 \pm 0.02$	$0.016 \pm 0.004$	$0.90 \pm 0.02$	0.87 (6.8)	-0.51 (0.02)	-0.18 (0)	1099

Vasudevan et al. 2013). The ratio of  $L_{14 - 195}/L_{2 - 10}$  is then  $\sim 2.7$ . Switching to  $L_{2-10}$  changes equation (8) to

$$\log(L_{\text{AGN,IR}}) = (0.91 \pm 0.06) \log(L_{2-10\text{keV}}) - (3.64 \pm 2.6). \quad (9)$$

$L_{2-10\text{keV}}$  assumes that the luminosity has been absorption-corrected. Differences in the assumed photon index only change the intercept by at most 0.3 dex.

1047

## 7.2 IR colours as a predictor of $f_{\text{AGN}}$ and selecting AGN

We utilize our broad coverage of the IR SED for AGN host galaxies to test the viability of different IR colours for predicting the AGN IR luminosity fraction (i.e.  $f_{\text{AGN}}$ ). For large surveys and/or high-redshift studies, coverage from 12 to 500  $\mu\text{m}$  might not be available or possible.

In Fig. 6, we plot six MIR/FIR flux ratios (12/70, 12/160, 12/250, 22/70, 22/160, 22/250) against the measured  $f_{\text{AGN}}$  for the *Herschel*-BAT AGN. The flux ratios are all in log units to better visualize the relationships. Upper limits on  $f_{\text{AGN}}$  are shown as downward-pointing arrows. In the lower-right corner of each subplot, we show representative error bars. We fit a linear model between each flux ratio and  $f_{\text{AGN}}$  with the following form:

$$f_{\text{AGN}} = m \log(F_1/F_2) + b + \epsilon_{\text{int}}, \quad (10)$$

where  $F_1/F_2$  represents each flux ratio. To calculate the best-fitting parameters, we again used LINMIX\_ERR.

Table 2 outlines the best-fitting parameters for each relationship. Each flux ratio is highly correlated with  $f_{\text{AGN}}$  (all  $\rho > 0.87$ ). Fig. 2 also reemphasizes this result as the MIR fluxes change more than the FIR ones as the X-ray luminosity changes. The worst indicators

1052

are the flux ratios involving the 250  $\mu\text{m}$  flux with  $\rho$  less than 0.9 and significant scatter as shown in Fig. 6. The 250  $\mu\text{m}$  flux is located on the Rayleigh–Jeans side of the blackbody and varies much more strongly as a function of the dust temperature due to the rapidly declining shape of the SED at long wavelengths compared to the 160  $\mu\text{m}$  flux, which is nearer to the peak of the MBB component. Thus, the 160  $\mu\text{m}$  flux is more tightly related to the total MBB luminosity and  $f_{\text{AGN}}$ .

Based on the slope of the linear regressions, the 22/70  $\mu\text{m}$ , with a slope of 0.8, overall seems to be the best flux ratio to use as an indicator of the AGN contribution to the IR SED. These two wavebands bracket the region where the intrinsic AGN SED is thought to turnover (e.g. Netzer et al. 2007; Mullaney et al. 2011) and seems to be the crucial transition region where the SED shifts from AGN-dominated to host galaxy dominated. The 22/70  $\mu\text{m}$  colour is also quite similar to the long used 25/60  $\mu\text{m}$  colour derived from the *IRAS* survey as an indicator of AGN activity (de Grijp et al. 1985; de Grijp, Lub & Miley 1987).

In Fig. 6, we also plot the 75th, 50th, and 25th percentile colours for the *Herschel*-BAT sample as black solid (25th), dashed (50th), and dotted (75th) vertical lines. In Table 2, the last three columns list the colours in logarithmic units for the 75th, 50th, and 25th percentiles. Thus, if these colours were used as a selection method, 75, 50, and 25 per cent of the *Herschel*-BAT sample would have been selected.

While these colours are useful for selecting AGN host galaxies, we also want to know what percentage of non-AGN galaxies would be selected with these colour cuts as contamination for a sample. Therefore, we also calculated the percentile of HRS galaxies that would be selected. For this analysis, we used the complete HRS sample since it represents the natural field galaxy population, and we do not want to restrict to only high-mass non-AGN galaxies. The HRS sample, unfortunately, was not observed at 70  $\mu\text{m}$ ; therefore, to calculate the 12/70, and 22/70 colours, we simply used the 70  $\mu\text{m}$  flux from the best-fitting model. The percentiles for HRS are given in parentheses next to the values of the colours in Table 2.

We find that the best colour to use in selecting an AGN-only sample would be the 22/160 colour. Using the 75th percentile colour ( $-1.14$ ), we would only select 5.6 per cent of the HRS sample. To get only around 1 per cent of the HRS sample, we would have to use the 50th percentile 22/160 or 22/250 colour. To select no HRS galaxies would require pushing to the 25th percentile colours and risk missing a large fraction of the *Herschel*-BAT AGN. We note that this analysis is quite simple and does not take into account other contributing factors such as the flux-limit of *Swift*/BAT and how representative HRS is of the non-AGN population. Rather, we only mean to briefly explore how well certain colours would select our AGN and our comparison non-AGN. In a forthcoming paper, we aim to evaluate these colours along with other MIR colour selection techniques (e.g. Donley et al. 2012; Stern et al. 2012) to determine the biases and selection effects with regards to the SFR of the galaxy and strength of the AGN.

### 1171 7.3 The AGN contribution to the 70 $\mu\text{m}$ emission

Many studies examining the relationship between nuclear activity and star formation rely on single monochromatic luminosities as an indicator of star formation (e.g. Netzer et al. 2007; Netzer 2009; Rosario et al. 2012). The most widely used indicator has been the 60  $\mu\text{m}$  luminosity given its availability from the all-sky *IRAS* survey.

With our *Herschel*-BAT sample and SED modelling, we can test how often and at what level AGN emission contributes to different wavelength bands. We test the AGN contribution to the 70  $\mu\text{m}$  emission. Based on visual inspection of all of the SED fits, we found that this waveband is the only *Herschel* band with a noticeable AGN contribution. All other longer wavelength bands were dominated by the MBB component. We restrict this analysis to only those sources with well-determined SEDs longwards of 70  $\mu\text{m}$ , excluding those objects with less than four detected SED points. We note that the majority of these objects are likely AGN dominated at 70  $\mu\text{m}$ ; however, the uncertainty in their FIR SED, especially their dust temperature, results in a largely unconstrained calculation.

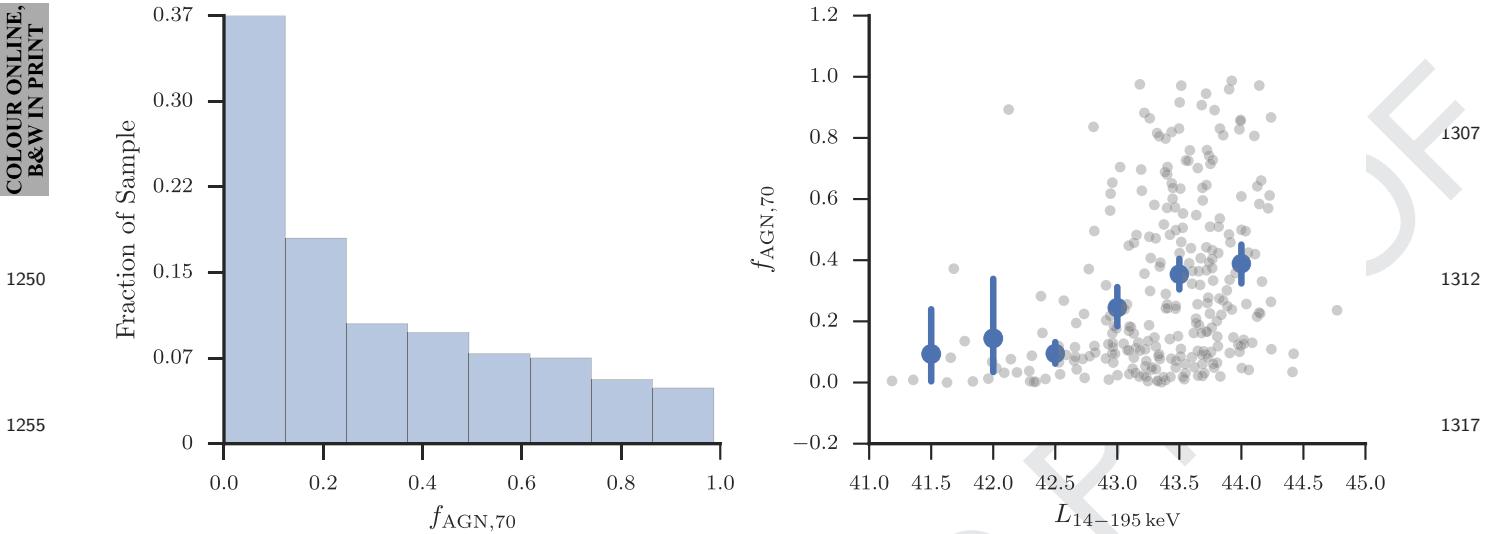
To determine the AGN contribution to the 70  $\mu\text{m}$  emission, we first estimated the PL component associated with star formation. We assumed the shape of the star-forming PL component followed the average PL slope ( $\alpha = 0.0$ ) and turnover wavelength ( $\lambda_c = 50 \mu\text{m}$ ) from the HRS sample. We then adjusted the PL normalization such that the integrated luminosity of the PL component would equal  $1/3L_{\text{MBB}}$ , which is the ratio found for non-AGN galaxies from the HRS sample (see Section 6.2). We combined the estimated star-forming PL component with the measured MBB component to form each of the *Herschel*-BAT AGN's total star-forming component. The 70  $\mu\text{m}$  AGN contribution was then calculated as the excess 70  $\mu\text{m}$  emission leftover after subtracting the star-forming contribution from the total 70  $\mu\text{m}$  emission from the best-fitting SED. We denote the fraction contributed by the AGN as  $f_{\text{AGN}, 70}$ .

The left-hand panel of Fig. 7 shows the distribution of  $f_{\text{AGN}, 70}$ . We find that for 48 per cent of the sample,  $f_{\text{AGN}, 70} < 0.2$  but for 24 per cent of the sample  $f_{\text{AGN}, 70} > 0.5$ . Using the 70  $\mu\text{m}$  luminosity as a single SFR indicator would overestimate values by at least a factor of 2 for almost one-third of an AGN sample.

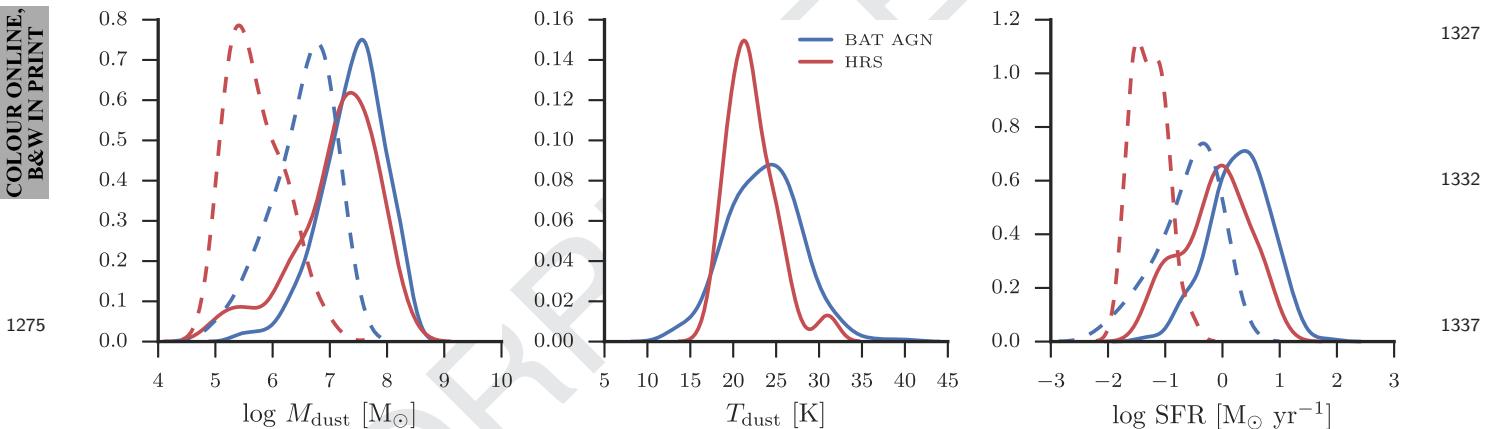
In the right-hand panel of Fig. 7, we show  $f_{\text{AGN}, 70}$  as a function of the 14–195 keV luminosity. The grey points indicate the individual points while the blue points with error bars are binned averages with a 68 per cent confidence interval determined through bootstrapping. It is clear that at  $\log L_{14-195 \text{ keV}} < 42.5$ ,  $f_{\text{AGN}, 70}$  is largely negligible with only two sources with  $f_{\text{AGN}, 70} > 0.2$ . These AGNs are NGC 1052 and NGC 4941. Both are quite pointlike, possibly unresolved at 70  $\mu\text{m}$ , while at long wavelengths show large-scale extended emission.

Above  $\log L_{14-195 \text{ keV}} = 42.5$ , the AGN contribution at 70  $\mu\text{m}$  varies nearly uniformly between 0 and 1. This indicates that the AGN contribution is not a simple function of high AGN luminosity, rather it is due to the competing interplay between AGN emission and star formation. This reinforces the need for SED decomposition to determine accurate SFRs when an AGN is present. We repeated this process at 160  $\mu\text{m}$ , finding no source with an AGN contribution above the 5 per cent level.

A possible complication relating to the calculation of the AGN contribution at 70  $\mu\text{m}$  is the effect of stochastically heated small grains. These grains are hotter than the relatively cooler large grains that produce the majority of the long wavelength FIR emission. In starburst galaxies, the small grains can provide a large amount emission at warmer dust temperatures, which results in enhanced emission in the 30–70  $\mu\text{m}$  region and a steep MIR PL slope. Indeed, C12 uses her model to fit the SEDs of local ULIRGs. However, none of the *Herschel*-BAT AGNs would be classified as a ULIRG and very few are LIRGs. Furthermore, we showed in Shimizu et al. (2015) that only a small percentage of our AGN are above the main sequence where starbursts are found. Therefore, we do not consider a strong starburst component to be affecting a large number of our sources and affecting our 70  $\mu\text{m}$  AGN contributions.



**Figure 7.** Left: histogram of the estimated 70  $\mu\text{m}$  contribution by AGN-heated dust. Each bar is a bin with a width of 0.1 and a height equal to the fraction of the total sample. Right: relationship between the 14–195 keV luminosity and 70  $\mu\text{m}$  AGN contribution. Grey dots represent each individual source while blue dots with error bars are averages within bins according to 14–195 keV luminosity. Error bars indicate the 68 per cent confidence interval determined using bootstrap analysis.



**Figure 8.** Comparison of  $M_{\text{dust}}$ ,  $T_{\text{dust}}$ , and SFR between the *Herschel*-BAT AGN (blue) and HRS mass-matched sample (red). The distributions with dashed lines indicate sources with only upper limits on these values.

#### 7.4 $M_{\text{dust}}$ , $T_{\text{dust}}$ , and SFR of local AGN host galaxies

Fig. 8 compares the distribution of  $M_{\text{dust}}$ ,  $T_{\text{dust}}$ , and SFR for our three samples of galaxies. We calculated SFRs using the conversion from 8 to 1000  $\mu\text{m}$  star-forming luminosity using the following equation from Murphy et al. (2011):

$$\text{SFR} = \frac{\text{L}_{\text{SF}}}{2.57 \times 10^{43}}. \quad (11)$$

The solid lines show the KDE for sources that have firm measurements, while the dashed lines show the KDE for the sources with only upper limits. Table 3 displays the medians for these three properties and each sample. The values inside parentheses indicate the 16th and 84th percentiles for each distribution. The median, 16th, and 84th percentiles were calculated using survival analysis and the KMPL as in Section 5 to account for upper limits.

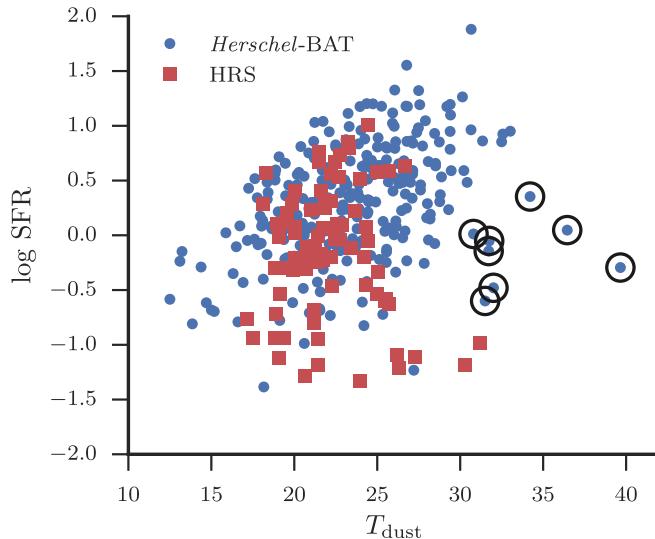
We find that the *Herschel*-BAT AGNs have higher dust masses than the HRS sample, slightly higher dust temperatures, and higher SFRs. Because we have mass-matched the HRS sample to the

**Table 3.** Mean  $M_{\text{dust}}$ ,  $T_{\text{dust}}$ , and SFR including non-detections.

Sample	$\log M_{\text{dust}}$ ( $\text{M}_\odot$ )	$T_{\text{dust}}$ (K)	$\log \text{SFR}$ ( $\text{M}_\odot \text{ yr}^{-1}$ )
<i>Herschel</i> -BAT	7.36 (6.56–7.90)	23.8 (19.4–27.5)	0.23 (−0.57–0.81)
HRS	7.08 (5.12–7.70)	21.5 (19.4–24.6)	−0.23 (−1.57–0.36)

*Herschel*-BAT sample, there should be no effects due to stellar mass. To confirm that the distributions are statistically different, we run the Peto–Prentice two-sample test. The Peto–Prentice two sample test is comparable to the Kolmogorov–Smirnov test, which calculates the probability that two separate samples were drawn from the same parent population. The Peto–Prentice test, however, allows for the inclusion of censored data.

For the comparison of dust masses, we find the probability that the *Herschel*-BAT AGNs and HRS galaxies are drawn from the same parent distribution is  $1.8 \times 10^{-5}$ . The probability for the dust temperatures is  $4 \times 10^{-4}$ , while the probability for the SFRs



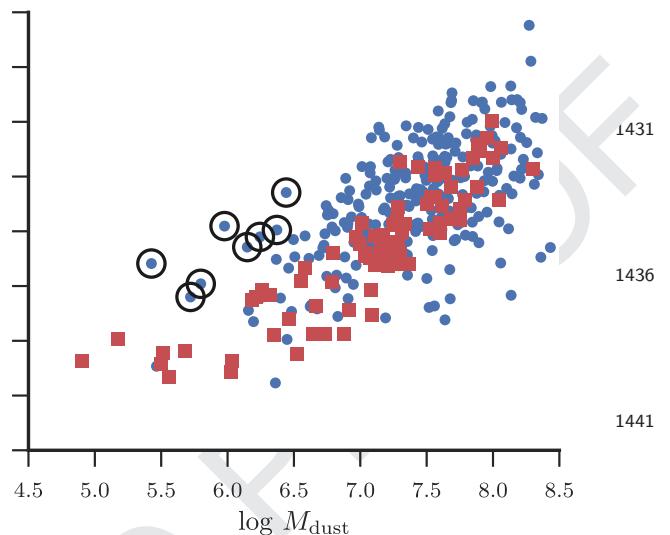
**Figure 9.** Left: correlation between dust temperature and SFR for the *Herschel*-BAT AGNs (blue points) and HRS galaxies (red squares). Circled blue points indicate possible sources that are dominated by AGN-heated dust. Right: correlation between dust mass and SFR for *Herschel*-BAT AGNs and HRS galaxies. The circled points are again the sources that could be dominated by AGN-heated dust.

is  $8.4 \times 10^{-11}$ . All three probabilities are less than 0.05, and the standard cutoff for declaring two samples are inconsistent with being drawn from the same parent population.

The increased SFRs for the *Herschel*-BAT sample compared to the mass-selected HRS sample are consistent with the results of Koss et al. (2011). Koss et al. (2011), using optical colours, found that the *Swift*/BAT AGNs displayed bluer colours compared to a mass-matched sample of SDSS galaxies, indicative of increased levels of star formation.

These results may seem contradictory with our previous work in Shimizu et al. (2015) where, using the SFRs calculated here, we showed that AGN host galaxies are experiencing decreased levels of star formation given their stellar mass. However, the discrepancy lies in the comparison being done. In Shimizu et al. (2015), we compare the *Herschel*-BAT AGNs to the so-called star-forming ‘main sequence,’ a tight nearly linear correlation between SFR and  $M_{\text{star}}$  (Brinchmann et al. 2004; Noeske et al. 2007; Salim et al. 2007), finding that the AGNs are falling off and transitioning towards quiescence. In this work, as well as in Koss et al. (2011), simple mass-matching is used to form comparison samples, which leads to selecting only high stellar mass non-AGN galaxies due to the high stellar masses of the BAT AGNs. Based on previous studies of the colour-magnitude relation, however, selection of high-mass galaxies will result in a large quiescence fraction especially at low redshifts (Kauffmann et al. 2003; Wuyts et al. 2011; Bell et al. 2012). Therefore, since the *Herschel*-BAT AGNs show both intermediate optical colours and SFRs, it makes sense that a mass-selected non-AGN sample will indicate bluer colours and higher SFRs for AGN host galaxies given quiescent galaxies are largely red with low SFRs.

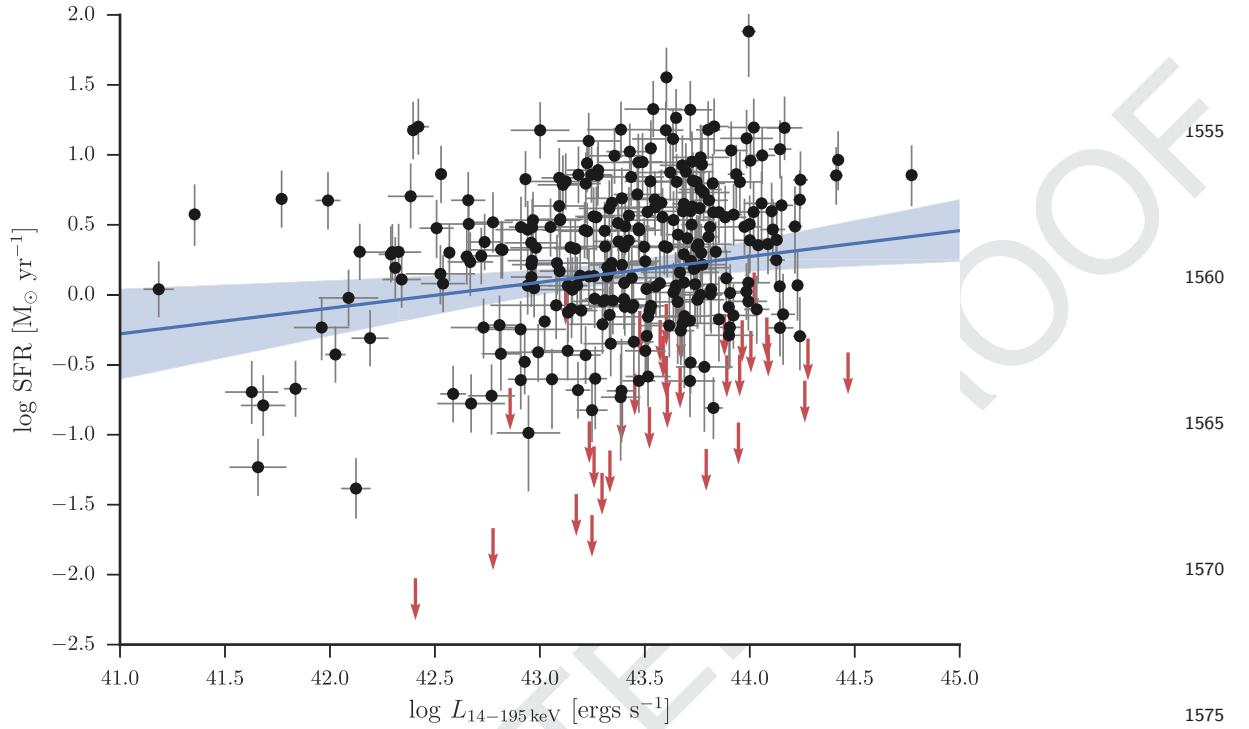
Further, looking into the details of our mass-selected HRS sample, we find that 47/122 (50 per cent) are morphologically classified as early type (E/S0), the dominant morphology for quiescent galaxies (Wuyts et al. 2011; Bell et al. 2012). The *Herschel*-BAT AGNs, though, are largely late-type spirals (Koss et al. 2011), and even the few ellipticals in our sample show higher SFRs than expected for quiescent galaxies (Shimizu et al. 2015). Thus, we can reconcile the results of Koss et al. (2011), Shimizu et al. (2015), and this



work by understanding that mass-matching preferentially selects low star-forming, red galaxies in contrast to the intermediate star-forming, blue AGNs. All of this agrees with previous work comparing X-ray-selected AGNs with mass-matched non-AGN galaxies such as Santini et al. (2012) who found enhanced SFRs in AGN host galaxies. This enhancement, however, disappeared after removing quenched galaxies from the comparison non-AGN sample.

The increased dust temperatures observed in the *Herschel*-BAT AGNs could be explained by the increased SFRs. Dust temperatures are known to increase with both infrared luminosity and specific SFR (e.g. Chapman et al. 2003; Symeonidis et al. 2013; Cortese et al. 2014; Magnelli et al. 2014), although these studies did not extend to the low luminosities and specific SFR we observe in our samples. Because we know that our sample contains an AGN, it is possible that at least some of the increased dust temperatures could be due to AGN heating. Recently, García-González et al. (2016) spatially decomposed the FIR images of a small sample of nearby Seyfert galaxies and found that nuclear emission shows markedly higher dust temperatures than the host galaxy (as probed through the 70/160  $\mu\text{m}$  colour). Sources that are dominated by AGN-related nuclear emission should then show higher temperatures that do not match with the overall correlation between SFR and  $T_{\text{dust}}$ .

In the left-hand panel of Fig. 9, we show the relationship between SFR and  $T_{\text{dust}}$  for the *Herschel*-BAT AGNs and HRS galaxies. The bulk of both samples follow in general a broad positive correlation. There exists a group of HRS galaxies at low SFR ( $\log \text{SFR} < -1.0$ ) that show a flat relationship with  $T_{\text{dust}}$ . All but one of these galaxies are early type, which are known to show dust temperatures up to 30 K (Temi, Brighenti & Mathews 2007). The encircled *Herschel*-BAT AGNs at  $T_{\text{dust}} > 30$  K and  $\log \text{SFR} < 0.5$  seem to represent distinct outliers from both samples. These sources are 2MASX J09235371–3141305, 2MASXJ 15462424+6929102, ESO 103–035, ESO 417–G006, MCG –05-23-016, MCG –06-30-015, Mrk 841, and NGC 3516. Except for 2MASX J09235371–3141305, these sources also all have  $f_{\text{AGN}} > 0.5$ , indicating that the MIR PL component is quite



**Figure 10.** Correlation between AGN luminosity as probed by  $L_{14-195 \text{ keV}}$  and SFR. Error bars on  $L_{14-195 \text{ keV}}$  correspond to the 90 percentile confidence interval from the 58-month BAT catalogue. Error bars on the SFR correspond to the 68 percentile confidence interval from our SED fitting. Downward-pointing arrows plot 95 per cent confidence upper limits on the SFR. The solid blue line with shading plots the best-fitting line and 95 percentile confidence interval for our AGN–SFR relationship from LIMIX\_ERR. No strong relationship exists between the AGN strength and global star formation.

dominant. ESO 103–035, MCG –05-23-016, and Mrk 841 show SEDs that peak around  $20 \mu\text{m}$ , highly indicative of an SED dominated by IR emission from the AGN. For these seven AGNs, then, it is possible that the large dust temperatures are due to AGN heating, rather than star formation.

Besides the seven sources listed, though, the bulk of the *Herschel*-BAT AGNs seem to show  $T_{\text{dust}}$  largely consistent with star formation heated dust.

The higher SFRs could also explain the slightly larger dust masses observed for the *Herschel*-BAT AGNs.<sup>7</sup> The *Herschel*-BAT AGNs have a median  $\log M_{\text{dust}}$  of  $7.38 M_{\odot}$  versus  $7.0 M_{\odot}$  for the HRS. The 16th percentiles also extend to much lower dust masses for the HRS. Cortese et al. (2012a) showed using the full HRS sample that the dust-to-stellar mass ratio is anticorrelated with  $\text{NUV} - r$  colour, a proxy for specific SFR and decreases strongly when moving from late-type to early-type galaxies. da Cunha et al. (2010) also showed, using over 3000 galaxies from SDSS, a strong correlation between the cold dust mass of galaxies and their SFRs, likely a manifestation of the well-known Schmidt–Kennicutt law (Schmidt 1959; Kennicutt 1998b), which links the SFR surface density with the surface density of gas.

In the right-hand panel of Fig. 9, we show the correlation between SFR and  $M_{\text{dust}}$  for both samples with the same colours and symbols as before. While both samples follow the same overall correlation, the HRS galaxies display a much tighter relationship between SFR

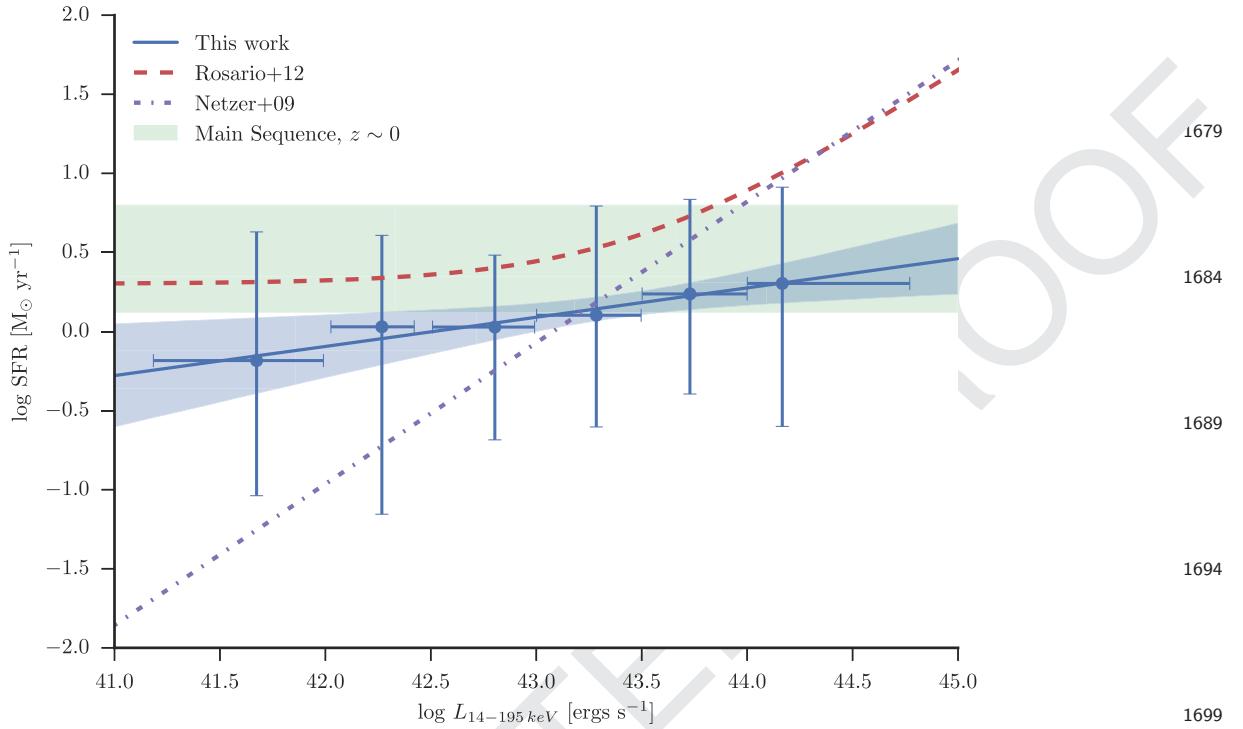
and  $M_{\text{dust}}$  than the *Herschel*-BAT sample. The *Herschel*-BAT AGNs seem to scatter more above the HRS galaxies such that for a fixed  $M_{\text{dust}}$ , the *Herschel*-BAT AGNs have higher SFRs. If we assume that  $M_{\text{dust}}$  follows  $M_{\text{gas}}$ , then on average the *Herschel*-BAT AGNs would have higher  $\text{SFR}/M_{\text{gas}}$ , a proxy for the star formation efficiency (SFE). This was tentatively seen in Maiolino et al. (1997) and more recently in Saintonge et al. (2012) with the COLDGASS sample where AGNs showed decreased gas depletion times ( $t_{\text{dep}} = \text{SFE}^{-1}$ ). Our result is also tentative given we are using the dust mass as a tracer of the gas mass; therefore, CO observations of the *Herschel*-BAT AGNs would be an intriguing study to test the results seen here and in Saintonge et al. (2012). Because of the tentative nature of this finding, we refrain from overinterpreting and simply note that the increased dust masses seen in Fig. 8 can be explained by the increased SFRs of the *Herschel*-BAT AGNs given the strong correlation between the two properties.

## 7.5 The correlation between SFR and AGN luminosity

Our main goal in this paper is to robustly assess the observational evidence for a connection between the AGN and star formation in its host galaxy in the local universe. To accomplish this, we analyse the correlation between the AGN strength and SFR. We assume that the  $14-195 \text{ keV}$  luminosity ( $L_{14-195 \text{ keV}}$ ) linearly probes the bolometric AGN luminosity, as shown by Winter et al. (2012).  $L_{\text{SF}}$  measures the SFR using equation (11).

Fig. 10 plots the correlation between the SFR and  $L_{14-195 \text{ keV}}$  for the *Herschel*-BAT AGNs. Black points with error bars indicate all of our detected sources, while red arrows show 95 per cent confidence

<sup>7</sup> Excluding the objects with only upper limits on the dust mass, which are dependent on the assumed fixed dust temperature we used in the modelling (see Section 6), produces the same overall trend of higher dust masses in the *Herschel*-BAT AGN sample.



**Figure 11.** Comparison between the measured SFR– $L_{14\text{--}195\text{ keV}}$  from the *Herschel*-BAT sample (blue line with shaded region) and previous relationships from Netzer (2009, dotted line) and Rosario et al. (2012, red dashed line). The points with error bars are the median SFRs binned by  $L_{14\text{--}195\text{ keV}}$  from the *Herschel*-BAT sample. Error bars represent the 68 per cent confidence interval. The green shaded region represents the expected SFR for a main-sequence galaxy in the local universe at a stellar mass of  $10^{10.5} \text{ M}_\odot$ .

upper limits for objects with less than four SED points. We determine parameters for the following linear model:

$$\log \text{SFR} = m \log L_{14\text{--}195\text{ keV}} + b + \epsilon_{\text{int}}, \quad (12)$$

using LINMIX\_ERR as before. The blue line and shaded region in Fig. 10 represents the best-fitting line and 95 per cent confidence interval, respectively. We find a best-fitting  $m = 0.18 \pm 0.07$ ,  $b = -7.85 \pm 2.93$ , and  $\sigma^2 = 0.37 \pm .04$  with a correlation coefficient of only  $0.17 \pm .06$ . Due to our large sample size, though, the probability for a null correlation is small with only a 0.25 per cent chance of measuring this correlation randomly.

The scatter in the relationship is high, covering nearly two orders of magnitude in SFR for a given AGN luminosity. In Fig. 11, we compare our correlation with previous measured relationships at low redshift from Rosario et al. (2012, red dashed line) and Netzer (2009, black dotted line). The blue points show the median log SFR in bins of 14–195 keV luminosity with error bars indicating the 16th and 84th percentiles. We further display as the green shaded region the expected SFR for main-sequence galaxies with a stellar mass of  $10^{10.5} \text{ M}_\odot$ , equal to the average stellar mass of the *Herschel*-BAT sample. The shaded region spans the range of SFRs using different estimates of the main sequence from the literature including Shimizu et al. (2015), Schreiber et al. (2015), and Speagle et al. (2014). This reiterates our result from Shimizu et al. (2015) that X-ray-selected AGN largely reside in main sequence and below main-sequence galaxies.

Our correlation does not match with either the Rosario et al. (2012)  $z = 0$  relationship (which is the same relationship presented in Lutz et al. (2010) and Shao et al. (2010)) or the Netzer (2009) relationship. Compared to Rosario et al. (2012), our correlation

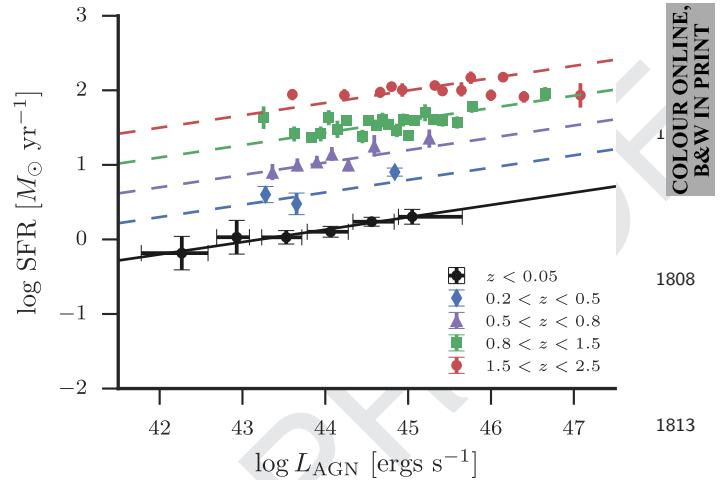
has a lower normalization and no evidence for an upturn at high luminosities. Compared to Netzer (2009), our correlation has a flatter slope. The slope of the Netzer (2009) relationship is 0.8, which also coincides with the slope of the Rosario et al. (2012) relationship at high luminosities.

As Rosario et al. (2012) point out, the discrepancy between Netzer (2009) and studies, which find a flatter slope, including this one, is the focus in Netzer (2009) on AGN-dominated galaxies. This selection criterion could have produced two effects: (1) selecting against highly star-forming, low-luminosity AGN host galaxies and (2) an unaccounted for contribution from the AGN to the SFR estimate. Netzer (2009) specifically uses the 60  $\mu\text{m}$  luminosity as their proxy for the SFR, which we have shown in this work can be largely affected by AGN-heated dust.

The differences between our relationship and the  $z = 0$  relationship from Rosario et al. (2012) is interesting given both are based on the sample parent sample of AGN from the *Swift*/BAT catalogue. While we use individual *Herschel* detections and SED fitting to determine the SFR, Rosario et al. (2012) relied on the 60  $\mu\text{m}$  luminosity derived from the *IRAS* survey (Faint Source Catalogue or SCANPI). Our sample as well imposed a redshift cutoff of  $z < 0.05$ , while Rosario et al. (2012) used all AGN with  $z < 0.3$ .

Due to the use of a single 60  $\mu\text{m}$  luminosity to estimate the SFR, our lower normalization of the relationship could be related to the subtraction of the AGN component in our SED fitting. This could also explain the upturn seen in Rosario et al. (2012). At higher AGN luminosities, the AGN component will dominate the host galaxy and contribute more to the monochromatic 60  $\mu\text{m}$  luminosity.

However, it is still possible that our sample did not extend to high enough AGN luminosity to reveal the upturn seen in Rosario et al. (2012). The upper error bars on our binned points do extend to the



**Figure 12.** Evolution of the SFR– $L_{\text{AGN}}$  relationship combining the results of this work (black points) and those of Stanley et al. (2015, coloured points) for  $z > 0.2$ . The *Herschel*-BAT points were converted to  $L_{\text{AGN}}$  from  $L_{14-195\text{ keV}}$  using the calibration from Winter et al. (2012). Error bars on each point represent the standard error on the mean rather than the 68 per cent confidence interval as in Fig. 11. The black solid line shows our measured  $z < 0.05$  SFR– $L_{\text{AGN}}$  relationship. Each subsequent coloured, dashed line is a simple scaling from  $z < 0.05$  to higher redshifts by increasing the SFR by 0.5, 0.9, 1.3, and 1.7 dex.

Rosario et al. (2012) relationship making the difference between our relationship and Rosario et al. (2012) only  $\sim 1\sigma$  although the 95 per cent confidence interval on our relationship does not overlap with Rosario et al. (2012). Nevertheless, perhaps with more sources at higher AGN luminosity, an upturn could be revealed. The highest AGN luminosities are where we expect the AGNs to have the greatest influence and the strongest link to current star formation as seen in merger simulations (e.g. Di Matteo, Springel & Hernquist 2005). Treister et al. (2012) further showed that major mergers trigger only the most luminous AGNs while moderate luminosity AGNs seem to be fuelled by secular processes such as disc instabilities. Therefore, perhaps the moderate luminosity AGNs that comprise our sample are simply not probing the stage in an AGN host galaxy’s lifetime where global star formation and nuclear activity are linked.

At moderate luminosities, two different explanations have been proposed to explain the lack of a relationship seen between the strength of the AGN and SFR. Recently, Diamond-Stanic & Rieke (2012) suggested that the AGN only influences star formation in the nuclear regions of galaxies and find that when restricting their measurements to only the inner 1 kpc, a stronger relationship appears. Esquej et al. (2014), probing even smaller scales ( $r < 100$  pc) using MIR interferometry, also found a nearly linear relationship between the nuclear SFR and SMBH accretion rate, and LaMassa et al. (2013), utilizing the fixed aperture of the SDSS fibre, found that only within 1.7 kpc a positive relationship between the SFR and accretion rate occurs. These are all in agreement with hydrodynamical simulations (Hopkins & Quataert 2010; Thacker et al. 2014) that predict an increasingly linear relationship as the star formation size scale decreases. Work is currently ongoing to spatially map the SFRs of the *Herschel*-BAT sample to determine whether the relationship strengthens near the nucleus.

The second explanation involves the varying time-scales associated with star formation and accretion on to the SMBH. Measuring the SFR from the IR luminosity results in an average SFR over nearly 100 Myr (Kennicutt & Evans 2012), while the X-ray luminosity is more aligned with the instantaneous AGN luminosity especially given the observation that the X-ray emission likely originates very near to the SMBH (e.g. Chen et al. 2011). Therefore, if the AGN luminosity can vary over 100 Myr, while the SFR is relatively stable, this will cause any intrinsic relationship between the two to weaken. Hickox et al. (2014) explored this using a simple toy model for the Eddington ratio distribution for an AGN and a linear relationship between the AGN luminosity and SFR, finding that variability can largely explain the observed correlations between SFR and AGN luminosity. This model also successfully reproduced the upturns seen in Rosario et al. (2012).

Recently, Stanley et al. (2015) measured the SFR–AGN luminosity relationship for over 2000 X-ray-detected AGNs across a range of redshifts and compared their results to the predictions of toy models. They found that at all redshifts, the relationship is quite flat, which matches the model predictions that describe AGN host galaxies having a highly variable AGN luminosity and living in relatively normal star-forming galaxies.

We add their data (from their table 2) to our SFR–AGN luminosity plot to see if the local universe is broadly following the higher redshift universe that Stanley et al. (2015) explored. Our results are directly comparable since they similarly used *Herschel* data and SED fitting with an AGN component to calculate SFRs in X-ray-detected AGNs. They further also used survival analysis to include galaxies with only upper limits in their averages and analysis.

Fig. 12 shows the combined results from this work and Stanley et al. (2015). We converted our  $L_{14-195\text{ keV}}$  values to  $L_{\text{AGN}}$  using the

calibration from Winter et al. (2012) to properly compare the data sets. We also use the error on the mean rather than the 68 per cent confidence interval for the error bars on the SFR to follow Stanley et al. (2015). The addition of our  $z < 0.05$  points follow the same trends seen at higher redshifts. The average SFR of X-ray-detected AGN host galaxies decreases from high to low redshift and within each redshift range the global SFR is only weakly related to  $L_{\text{AGN}}$ . We show this in Fig. 12 where the black solid line represents our measured relationship and each dashed line is our relationship but with 0.5, 0.9, 1.3, and 1.7 dex higher SFRs for the  $0.2 < z < 0.5$ ,  $0.5 < z < 0.8$ ,  $0.8 < z < 1.5$ , and  $1.5 < z < 2.5$  redshift bins, respectively. No formal fitting of the data was done only a shift by eye to test whether there is broad agreement up to  $z \sim 2.5$ . Indeed, it seems that at least up to  $z \sim 1.5$ , the same relationship as that found in the local universe can describe the connection between SFR and AGN luminosity. Only in the highest redshift bin and at the highest AGN luminosities does the local relationship appear to break down where SFRs are lower than expected.

The broad agreement between our results and those of Stanley et al. (2015) indicates that the same properties and processes are leading to a weak or flat relationship between the global SFR and AGN strength. Stanley et al. (2015) were able to fit their SFR– $L_{\text{AGN}}$  relationships with an updated version of the Hickox et al. (2014) variability model. They found that to reproduce the flatness, the faint-end slope of the assumed Eddington ratio distribution needed to be steepened. This removed the strong upturns at high AGN luminosity, which we also do not observe. Therefore, it is likely that the same model can accurately describe our local relationship.

If there is an intrinsically positive correlation between the SFR and AGN luminosity, whether on small spatial scales or long timescales, it can simply be explained by the availability of their common fuel, namely cold gas without invoking any AGN feedback. Large amounts of cold gas will spur both high accretion rates and high SFRs. Certainly, observations that a significant fraction of X-ray-detected AGNs lie below the star-forming main sequence (Matsuoka

et al. 2015; Mullaney et al. 2015; Shimizu et al. 2015) are suggestive that the AGN is connected to quenching. AGN-driven outflows that are likely suppressing star formation have been observed in some samples (Veilleux et al. 2013; Cicone et al. 2014; Genzel et al. 2014; Tombesi et al. 2015); but in a recent study of 50 nearby *Swift*/BAT AGNs, Stone et al. (2016) found only four objects with evidence for a molecular outflow, strengthening the argument that AGNs only contribute to driving gas out of the galaxy at high luminosity ( $L_{\text{AGN}} > 10^{45} \text{ erg s}^{-1}$ ). Indeed, many of the sources where AGN-driven outflows have been detected occur in powerful AGNs (e.g. Cano-Díaz et al. 2012; Brusa et al. 2015; Cresci et al. 2015; Perna et al. 2015).

Instead, it is equally possible that at least some of our galaxies are going through passive quenching, whereby gas is simply being slowly depleted through star formation and star-formation-driven outflows after accretion on to the galaxy has slowed or been shut off (Peng, Maiolino & Cochrane 2015). This scenario agrees with the so-called bathtub model for galaxy evolution proposed in Lilly et al. (2013). The fact that we observe a large fraction of AGN host galaxies in transition would be a consequence that AGN activity is more likely in galaxies with ongoing star formation, but there is a delay between the peak of star formation and accretion on to the SMBH (Davies et al. 2007; Sani et al. 2012; Schawinski et al. 2014) due to the longer time-scales necessary for gas to reach the central SMBH.

It is clear then that the situation involving the connection between an AGN and star formation in its host galaxy is quite complicated. Using our well-constrained IR luminosities and ultrahard X-ray luminosities, we find a lack of a relationship between the SFR and AGN strength. Because our sample is not extending to quasar luminosities, though, we might be missing the phase of an AGN's lifetime where the strongest link between star formation and AGN luminosity is thought to exist. Further, the AGN influence might only work over small physical scales and AGN variability might be smearing any intrinsic relationship. Future work will involve remedying two of these problems by combining our sample with low-redshift quasar samples such as the Palomar–Green quasar sample and utilizing the relatively high spatial resolution of the *Herschel* images to look for a connection at smaller scales.

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## 8 CONCLUSIONS

Using our high-quality *Herschel* photometry from Meléndez et al. (2014) and Shimizu et al. (2016) combined with archival *WISE* 12 and 22  $\mu\text{m}$  photometry, we have constructed and modelled the SEDs for over 300 AGNs. Our sample is unique given its nearly unbiased selection based on ultrahard X-ray detection, as well as its local nature that eliminates possible biases and source confusion. The following is a summary of our results and conclusions.

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(i) After correcting for host galaxy contribution, we find a nearly linear correlation between the estimated 8–1000  $\mu\text{m}$  luminosity due to the AGN and the 14–195 keV luminosity, signifying our decompositions are accurate.

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(ii) We determined relationships between various MIR and FIR colours as a proxy for the AGN contribution to the total 8–1000  $\mu\text{m}$  luminosity ( $f_{\text{AGN}}$ ), finding that the 22/70 and 22/160 colours follow the best relationship with  $f_{\text{AGN}}$ .

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(iii) We investigated the AGN contribution to the 70  $\mu\text{m}$  emission of a galaxy and showed that for nearly 30 per cent of our sample, more than half of the 70  $\mu\text{m}$  flux is likely due to AGN heating.

(iv) We calculated a median dust mass of  $10^{7.36} \text{ M}_\odot$ , dust temperature of  $\sim 24 \text{ K}$ , and SFR of  $1.7 \text{ M}_\odot \text{ yr}^{-1}$  for AGN host galaxies. In a comparison with a mass-matched sample of non-AGNs, we find that all three properties are systematically higher by a factor 2 for the dust mass, 2 K in dust temperature, and a factor of 3 in SFR. This can be explained as a consequence of high-mass non-AGN samples largely being composed of quiescent early-type galaxies.

(v) Confident in our measures of the SFR, we find a nearly flat (slope =  $0.18 \pm 0.07$ ) relationship between the SFR and AGN luminosity. Our flat relationship is in contrast to previous low-redshift studies that find either a nearly linear relationship or an upturn at high luminosities but in agreement with recent studies at higher redshift. If nuclear activity is related to global star formation, it is only on long time-scales; however, another possible explanation is that the relationship strengthens only as the physical scales probed decrease.

We are working to determine whether spatial decomposition combined with our SED decomposition can illuminate the exact nature of the relationship between the AGN and nuclear star formation. This will also further test our simple decomposition methods and help expand our knowledge of the intrinsic AGN infrared SED into the FIR regime. Finally, we are also in the process of comparing the star-forming properties for type 1 and type 2 objects to test if the obscuration of the AGN makes any significant difference.

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## SUPPORTING INFORMATION

Supplementary data are available at [MNRAS](#) online.

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**Table 1.** Best-fitting C12 model parameters, luminosities, and AGN fractions.

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To find the best-fitting parameters in our SED modelling, instead of standard least-squares analysis, we used a Bayesian framework along with MCMC to probe the posterior PDFs for each parameter. The Bayesian framework allows for robust estimates of the uncertainty and for explicit statements about prior knowledge of the parameters. It also makes it relatively easy to include information contained in the undetected photometry of the SED.

The likelihood defines the probability of observing a set of data given a specific model. In SED fitting, this translates to the combined probability of measuring all the photometric data points in the observed SED given a model for the SED (whether based on templates or analytic models). The total likelihood can then be expressed as the product of the probabilities of observing each single photometric point:

$$\mathcal{L}(F|M) = \prod_i P(F_i|M), \quad (A1)$$

where  $F$  is the set of photometric fluxes  $F_i$  and  $M$  is the model. For our analysis, we assume that the probability of our observations follows a Gaussian distribution with mean equal to  $M$  and standard deviations equal to the measurement errors  $\sigma_i$ :

$$P(F_i|M) = \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(\frac{-(F_i - M)^2}{2\sigma_i^2}\right), \quad (A2)$$

Equation (A2) defines only the probability for detected fluxes. To use the information contained in the undetected photometry  $U_i$ , we define a different probability under the assumption that all of the upper limits are  $5\sigma$ :

$$\begin{aligned} P(U_i|M) &= \int_{-\infty}^{U_i} \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(\frac{-(x - M)^2}{2\sigma_i^2}\right) dx, \\ &= \frac{1}{2} \left(1 + \text{erf}\left[\frac{U_i - M}{\sigma_i \sqrt{2}}\right]\right), \end{aligned} \quad (A3)$$

where  $\sigma_i = \frac{U_i}{5}$  and erf is the standard error function. For numerical accuracy and simplicity, it is customary to minimize the negative log-likelihood. Supposing we have  $N$  total SED points with  $D$  detections and  $D - N$  non-detections, then the total negative log-likelihood combining equations (A1), (A2), and (A3) is

$$\begin{aligned} -\log \mathcal{L} &= \frac{1}{2} \sum_{i=0}^D \left[ \log(2\pi\sigma_i^2) - \left(\frac{F_i - M}{\sigma_i}\right)^2 \right] \\ &\quad + \sum_{j=0}^{D-N} \log \left[ 1 + \text{erf}\left(\frac{U_j - M}{\sigma_j \sqrt{2}}\right) \right]. \end{aligned} \quad (A4)$$

It is important to recognize here how  $M$  is calculated, no matter whether it represents a template or analytic model. Each data point in an SED is the observer-frame flux density measured over a defined wavelength range. Therefore, to determine the model flux densities, we first redshifted the full rest-frame model SED into the observer frame using the known redshifts of all of our sources. This observer-frame SED was then convolved with each instrument filter transmission curve to produce model flux densities that can be accurately compared to the observed ones.

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## A2 Bayesian MCMC analysis

Within the Bayesian framework, the important probability is the probability of the model given the data at hand, i.e. the most probable SED model given the observed fluxes. This probability can be determined using Bayes theorem:

$$P(M|F) = \frac{P(F|M)P(M)}{P(F)}, \quad (A5)$$

and is known as the posterior probability distribution.  $P(F|M)$  is proportional to the likelihood (equation A1),  $P(M)$  codifies our prior knowledge about the model, and  $P(F)$  is the model

evidence and can be disregarded as a simple normalization term.

The reader may notice that assuming a flat prior,  $P(M) \propto 1$ , reduces equation (A5) to  $P(M|F) \propto \mathcal{L}$ , verifying our use of maximum likelihood in determining the best template models.

For the C12 model, we used flat priors for the dust temperature and dust mass. We placed conservative limits on both the dust temperature and  $\log M_{\text{dust}}$  to be between 1 and 100 K and 1 and  $10 M_{\odot}$ , respectively. Within the PL component for the C12 model, we also used flat priors for the PL slope between -5 and 5 and the log of the normalization between -10 and 10. Based on previous work attempting to measure the intrinsic AGN SED and modelling the dusty torus, we expect the SED to turnover anywhere in the range between 20 and 70  $\mu\text{m}$ . Thus, we imposed a Gaussian prior centred at 45  $\mu\text{m}$  with a standard deviation of 20  $\mu\text{m}$ . We found that using this prior resulted in better and more realistic fits to the SEDs compared to a flat prior.

We used the PYTHON package EMCEE (Foreman-Mackey et al. 2013) to perform MCMC and sample the posterior PDF (equation A5). EMCEE runs an implementation of the Affine-Invariant MCMC sampler from Goodman & Weare (2010). Instead of one single MCMC chain, it samples the posterior PDF with multiple ‘walkers’, each with their own chain. For our analysis, we used 50 walkers that each produced a 1000-step chain. To allow for each chain to stabilize and move away from the initial guesses for the parameters, we imposed a 200-step ‘burn-in’. In total, this resulted in 40 000 steps to define the full posterior PDF.

To determine the best-fitting parameters, we first marginalized the posterior PDF over all other parameters and then calculated the median. All quoted uncertainties represent the 68 per cent confidence interval determined from the 16th and 84th percentile of the marginalized posterior PDF.

For sources with less than four detections in their SED, we fixed the dust temperature to 25 K since the peak of the FIR bump is no longer constrained. In these cases, we only obtained upper limits on the dust mass by calculating the upper 95th percentile of the marginalized PDF.

## APPENDIX B: COMPARISON BETWEEN DIFFERENT MODELS

In this section, we compare the results for the total luminosity, IR AGN luminosity, and star-forming luminosity between the C12 model and two other models to decompose the SED. We exclude

from this analysis objects that were only detected by *Herschel* in less than one waveband given the strong uncertainties associated with their properties. We also exclude as before the six radio-loud objects and Mrk 3 (for lack of WISE data).

### B1 DECOMPIR model

Besides analytic models, another popular method is the use of template SEDs. Templates are constructed based on well-sampled SEDs of large samples of galaxies and usually parametrized according to a known property such as infrared luminosity.

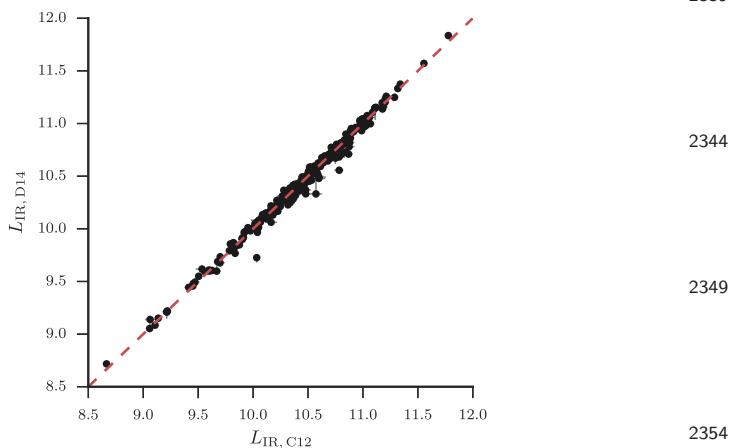
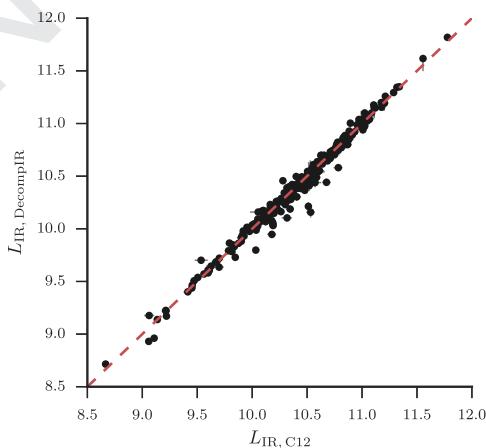
For galaxies known to host an AGN, recent studies have turned to the DECOMPIR (Mullaney et al. 2011) templates. DECOMPIR consists of five host galaxy templates that span the IR colour and luminosity range of the original Brandl et al. (2006) starburst galaxy templates. Mullaney et al. (2011) constructed the AGN templates based on a subsample of the *Swift/BAT* AGN, which had AGN-dominated *Spitzer/IRS* spectra determined by the equivalent width of the 11.3  $\mu\text{m}$  feature being  $<0.03 \mu\text{m}$ . The *Spitzer/IRS* spectra were combined with *IRAS* photometry at 60 and 100  $\mu\text{m}$  to define the ‘intrinsic’ AGN SED from 6 to 100  $\mu\text{m}$ .

Mullaney et al. (2011) created three different AGN templates: one based only on high AGN luminosity objects, low AGN luminosity objects, and a median of the entire sample. For this work, we only consider the median AGN template given our SEDs only contain two points in the MIR where AGN-related emission is expected to dominate.

### B2 Dale et al. (2014) model

The third model we chose to test on our sample is the semi-empirical templates from Dale et al. (2014, hereafter D14). These templates also contain two components, one for dust emission in the host galaxy and one for the AGN. The host galaxy components were built from an updated version of the Dale & Helou (2002) model. Each component represents an SED produced using a different value of  $\alpha_{\text{SF}}$ , which is the PL slope of the intensity distribution for the interstellar radiation field that is heating the dust. These SEDs contain a mixture of emission from PAHs, small stochastically heated grains, and thermally radiating large grains.

For the AGN component, D14 chose the median SED of the Palomar-Green quasars from Shi et al. (2013) citing the care with which any star-forming component was removed and the prominence of several AGN-related MIR features such as the [O IV] fine



**Figure B1.** Correlations of total  $L_{\text{IR}}$  between the C12 model and DECOMPIR and D14. The red dashed line indicates a one-to-one correspondence.

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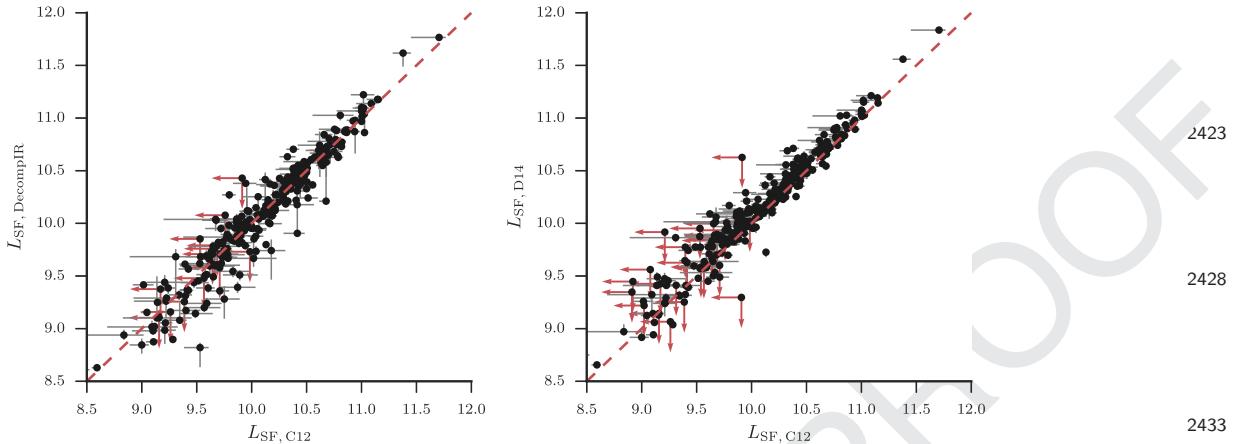
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**Figure B2.** Same as Fig. B1 but for  $L_{SF}$ .

structure line and the broad 10 and 18  $\mu\text{m}$  silicate emission bumps. At long wavelengths, the AGN template falls as a blackbody.

Instead of two separate templates for the AGN and host galaxy, D14 provided a single set of templates based on different combinations of  $\alpha_{SF}$  and  $f_{AGN}$ , the fractional contribution of the AGN to the 5–20  $\mu\text{m}$  emission. In total, there are 1365 templates that range in  $\alpha_{SF} = 0.0625$ –4.0 in 0.0625 intervals and  $f_{AGN} = 0$ –1 in 0.05 intervals.

### B3 SED fitting for the template models

For each template in a model set, equation (A4) was minimized to determine the best-fitting normalization. We then chose the normalized template with the lowest  $-\log \mathcal{L}$  as the best-fitting model for a source. For the DECOMPIR set, this meant first simultaneously optimizing over a normalization for the AGN component and each host galaxy component, then choosing the combined template that resulted in the minimum  $-\log \mathcal{L}$ . For D14, this meant calculating  $-\log \mathcal{L}$  over the entire set of  $\alpha$  and  $f_{AGN}$  templates.

Uncertainties using the maximum likelihood method were determined by generating 1000 simulated SEDs for each source. These data points in the simulated SEDs were calculated by assuming that each detected point followed a Gaussian distribution with mean equal to the observed flux density and a standard deviation equal to the measured error. Each of the simulated SEDs were refitted using the same method. The standard deviation on the set of best-fitting parameters from the simulated SEDs then was used as the uncertainty. In this way, both statistical and systematic errors can be taken into account in assessing the reliability of our best-fitting parameters.

### B4 $L_{IR}$ comparison

The measured property that should be most model independent is the total infrared luminosity,  $L_{IR}$ . Assuming that each model was able to fit well the broad-band SEDs and reproduce the observed photometry,  $L_{IR}$  is simply the total integrated energy underneath the SED, regardless of how the SED is decomposed. In Fig. B1, we plot the correlations between the C12 model and DECOMPIR and D14 models for  $L_{IR}$ .

The median  $\log L_{IR}$  for the C12, DECOMPIR, and D14 models are all  $10.39 L_{\odot}$  with a spread of 0.5 dex. Clearly, based on Fig. B1, each model well fits the broad-band SED of our sample with a small scatter around the one-to-one correspondence line. The average

difference in the luminosities from each model is only  $\sim 0.01$  dex with a standard deviation between 0.05 and 0.08 dex, slightly higher than the median statistical uncertainty for the C12 model of 0.03 dex.

### B5 $L_{SF}, L_{AGN, IR}$ , and $f_{AGN}$ comparison

Where the models begin to disagree more, is in the actual decomposition of the SED. In particular, we compare  $L_{SF}$ ,  $L_{AGN, IR}$ , and  $f_{AGN}$ . Calculating these parameters for the template models is relatively easy compared to the corrections we had to make for the C12 model. For the DECOMPIR template set,  $L_{IR}$ ,  $L_{SF}$ , and  $L_{AGN, IR}$  were simply calculated from the best-fitting total, host galaxy, and AGN SEDs. For the D14 model set,  $L_{IR}$  was measured from the best-fitting template, and  $L_{SF}$  and  $L_{AGN, IR}$  were calculated based on the best-fitting  $f_{AGN}$ .<sup>8</sup> Uncertainties on all of these luminosities were determined with the same Monte Carlo method used to determine the uncertainties on the best-fitting parameters.

Figs B2, B3, and B4 display the relationship between each model's  $L_{SF}$ ,  $L_{AGN, IR}$ , and  $f_{AGN}$ . Out of the three parameters,  $L_{SF}$  is most consistent between the three models. The C12, DECOMPIR, and D14 models have a median  $L_{SF}$  of  $10.12$ ,  $10.12$ , and  $10.19 L_{\odot}$ , respectively. The average difference between C12 and DECOMPIR is only 0.006 dex with a standard deviation of 0.16 dex while the average difference between C12 and D14 is  $-0.07$  dex with a standard deviation of 0.11 dex. The DECOMPIR and D14 are measuring slightly higher star-forming luminosities. Based on these differences, we assign a conservative uncertainty of 0.2 dex for  $L_{SF}$  to account for model dependence.

The comparison for  $L_{AGN, IR}$  shows increased scatter compared to the two previous luminosities. The median  $L_{AGN, IR}$  for the three models is  $10.04$ ,  $9.9$ , and  $9.85 L_{\odot}$  for the C12, DECOMPIR, and D14 models, respectively. The average difference between C12 and DECOMPIR is 0.10 dex with a standard deviation of 0.20 dex while the average difference between C12 and D14 is 0.14 dex with a standard deviation of 0.20 dex. Since the DECOMPIR and D14 were measuring higher  $L_{SF}$ , it makes sense that they are measuring lower  $L_{AGN, IR}$  given that the total infrared luminosities between the three models was identical. It is likely that the more flexible C12 model,

<sup>8</sup> D14 only provide  $f_{AGN}$  calculated between 5 and 15  $\mu\text{m}$ ; however, D. Dale graciously provided the authors with  $f_{AGN}$  calculated between 8 and 1000  $\mu\text{m}$  through private communication in 2015 August.

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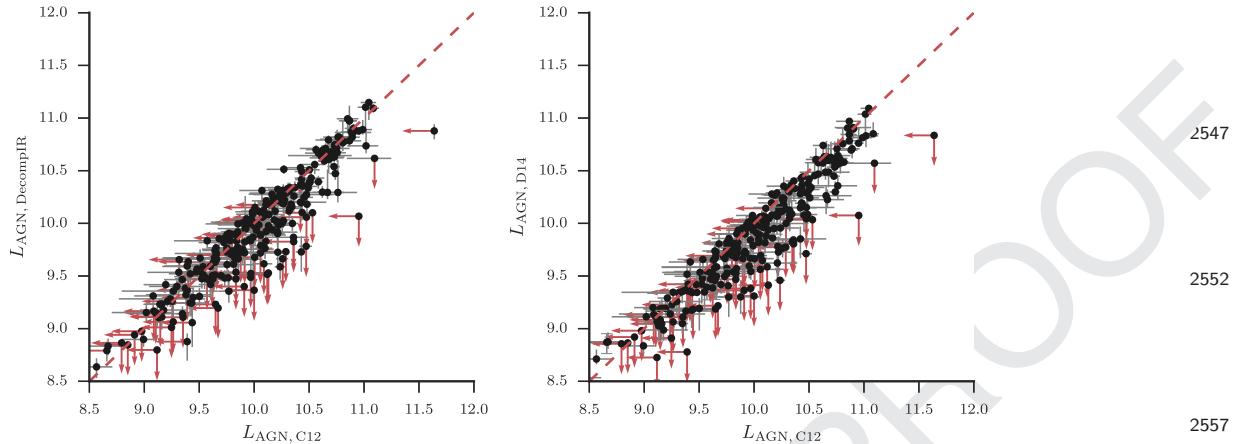
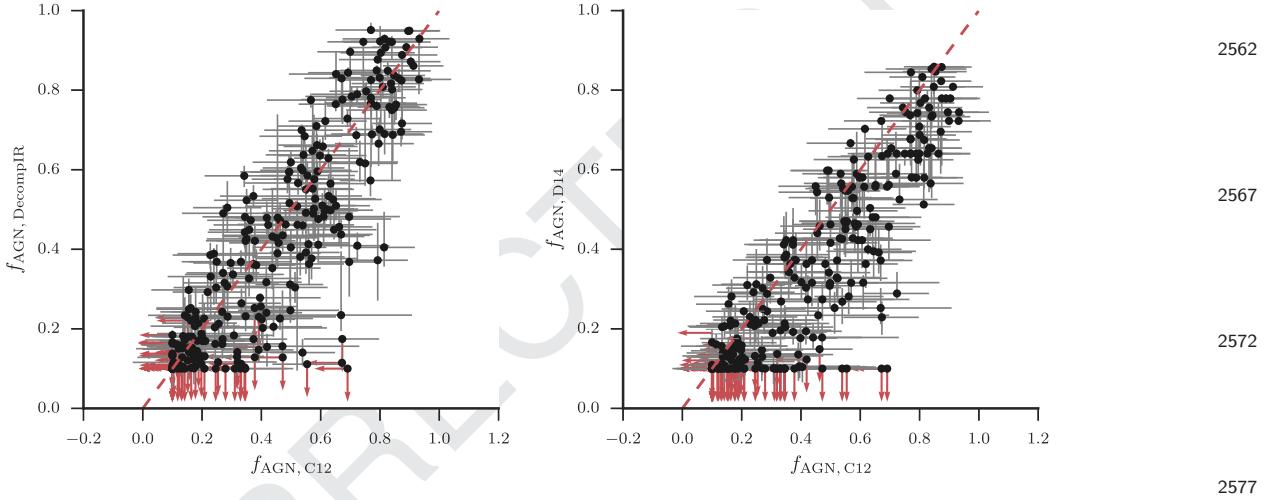
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Figure B3. Same as Fig. B1 but for  $L_{\text{AGN, IR}}$ .Figure B4. Correlations of  $f_{\text{AGN}}$  from the three SED models. Error bars represent the 68 per cent confidence interval. Upper limits are indicated as red downward-pointing arrows. The red dashed line indicates a one-to-one correspondence.

which allows the PL component to extend to longer wavelengths, creates the discrepancy between it and the template based models. Our implementation of DECOMPIR and D14 adheres to a strict single template for the intrinsic AGN SED. Adding the offset and spread in the differences in quadrature indicates an uncertainty of 0.25 dex in the determination of  $L_{\text{AGN, IR}}$ .

The relatively large uncertainty in  $L_{\text{AGN, IR}}$  then leads to a large scatter in  $f_{\text{AGN}}$  as shown in Fig. B4. The average difference between C12 and DECOMPIR is only 0.02; however, the standard deviation is 0.13. The average difference between C12 and D14 is 0.1 with a standard deviation of 0.11. Given that the spread in  $f_{\text{AGN}}$  is comparable to the average statistical uncertainty (0.14) from our C12 modelling, we do not add any more uncertainty on to our estimates.

The 15 per cent uncertainty between the three models represents our general lack of knowledge about the details of decomposing broad-band SEDs of AGN host galaxies. The estimated  $f_{\text{AGN}}$  is highly dependent on the assumed models of both the host galaxy and AGN, and currently at best we can only constrain to within 15 per cent. This influences then the calculations of both the SFR (based on  $L_{\text{SF}}$ ) and the IR portion of AGN luminosity ( $L_{\text{AGN, IR}}$ ). Studies relying on calculating the SFRs of AGN host

galaxies using the infrared need to take these discrepancies into account or else risk overinterpreting results based on broad SED decomposition. This also highlights the need for high angular resolution studies of AGN, to determine the true shape of the AGN IR SED.

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#### APPENDIX C: COMPARISON OF $L_{\text{SF}}$ WITH PAH MEASUREMENTS

To test our estimates of the star-forming luminosity ( $L_{\text{SF}}$ ), we compare them with estimates of the star-forming luminosity calculated from the PAH 11.3 and 7.7  $\mu\text{m}$  luminosity. PAH features are thought to be caused by the vibrations of complex hydrocarbons (Draine & Lee 1984; Puget & Leger 1989) and have been shown to be reliable tracers of the SFR (Roussel et al. 2001; Sargsyan & Weedman 2009; Treyer et al. 2010; Shipley et al. 2016) even for AGN (Diamond-Stanic & Rieke 2010). Thus, comparing our  $L_{\text{SF}}$  with the 11.3 and 7.7  $\mu\text{m}$  PAH luminosity provides a further check on our SED decomposition.

To measure the 7.7 and 11.3  $\mu\text{m}$  luminosities, we first searched the Cornell Atlas of Spitzer IRS Sources (CASSIS; Lebouteiller et al. 2011) for low-resolution *Spitzer*/IRS spectra of the *Herschel*

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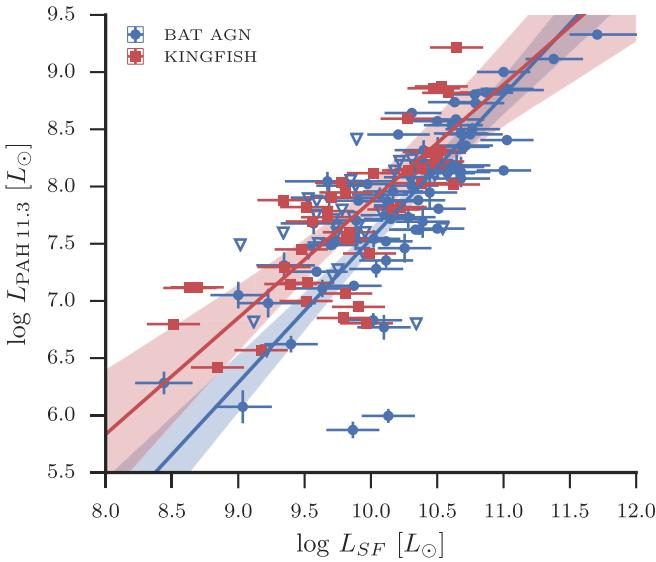
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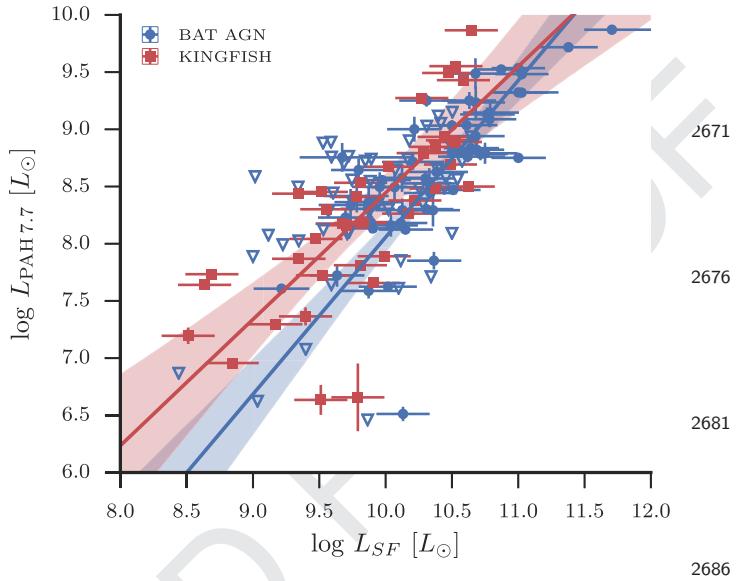


**Figure C1.** Correlation between  $L_{SF}$  and the 11.3 (left) and 7.7  $\mu\text{m}$  (right) luminosity. Blue points correspond to the *Herschel*-BAT AGN and red squares correspond to the KINGFISH galaxies. Sources with upper limits on  $L_{PAH}$  are shown as open triangles. Measured correlations between  $L_{SF}$  and the 11.3 and 7.7  $\mu\text{m}$  luminosity are shown as solid blue and red lines for the *Herschel*-BAT AGN and KINGFISH samples, respectively. The shaded region around the median correlations indicate the 95 per cent confidence interval. The broad consistency of the correlation for both the KINGFISH and *Herschel*-BAT samples shows that SFRs determined from  $L_{SF}$  will be comparable without any systematic bias.

-BAT AGNs. We found 120/313 AGNs on CASSIS and downloaded their reduced spectra using the default extraction method. Due to the different sizes of the short-low (SL) slit and the long-low (LL) slit, the continuum of each can be offset mainly from extended emission not captured by the SL slit. Therefore, spectral orders were stitched together by fitting a line to the ends of each order and scaling to match the overlapping regions. SL2 and LL2 were first matched and scaled to SL1 and LL1, respectively. Then, the combined SL1/LL2 spectra were matched to the combined LL1/LL2 spectra to produce the final full *Spitzer*/IRS low-resolution spectra.

We fitted each spectra using small spectral windows centred on 7.7 and 11.3  $\mu\text{m}$ . Following Smith et al. (2007) and the popular spectral fitting software package, PAHFIT, we modelled the PAH features using a Drude profile and any emission lines contained in the spectral windows as narrow Gaussians. The full width at half-maximum (FWHM) and central wavelength of the emission lines were kept fixed at the values in table 2 of Smith et al. (2007). The 7.7 and 11.3  $\mu\text{m}$  features are actually complexes with multiple sub-features. PAHFIT models these with multiple Drude profiles chosen to reproduce the observed features, and we follow this method using the values for the fractional contribution and FWHM as given in table 3 of Smith et al. (2007). We model the continuum as a simple third-order polynomial. This allows the continuum to take on many shapes that are more necessary for AGN spectra, which can show broad silicate absorption and emission and varying continuum slopes (Spoon et al. 2007; Wu et al. 2009; Baum et al. 2010). While silicate absorption is included within PAHFIT, silicate emission is absent prompting the need for our own modelling. Finally, to determine the best-fitting model, we again use the Bayesian methodology and MCMC described in Appendix A. This allows us to treat the continuum and other nearby features as nuisance parameters and robustly determine uncertainties on the 7.7 and 11.3  $\mu\text{m}$  luminosities.

Fig. C1 shows the correlation between  $L_{SF}$  and  $L_{PAH}$  for both the 7.7 (right) and 11.3  $\mu\text{m}$  (left) complexes. We chose



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to use the KINGFISH galaxies (red squares) as a comparison here rather than HRS given the readily available PAH measurements.  $L_{SF}$  was determined using the C12 model in the same way as the HRS sample and  $L_{PAH}$  is from Smith et al. (2007). The  $L_{PAH}$  for KINGFISH were measured using PAHFIT, but given the large similarity with our method, we do not expect large differences.

Based on Fig. C1, both the KINGFISH and *Herschel*-BAT samples seem to follow broadly the same correlation indicating that we are neither over- nor underestimating  $L_{SF}$  from our SED decomposition for the *Herschel*-BAT AGNs. Using LINMIX, we measured the relationship for both samples and both PAH luminosities. The median correlations with 95 per cent confidence intervals are shown in Fig. C1 with the blue and red solid lines and shaded regions corresponding to the *Herschel*-BAT AGN and KINGFISH samples, respectively. For the *Herschel*-BAT AGNs, we find slopes of  $1.26 \pm 0.1$  (11.3  $\mu\text{m}$ ) and  $1.32 \pm 0.11$  (7.7  $\mu\text{m}$ ) with correlation coefficients of 0.92 and 0.93 while for the KINGFISH galaxies we find slopes of  $1.02 \pm 0.15$  and  $1.11 \pm 0.16$  with correlation coefficients of 0.82 for both. In all four cases, the probability of a null correlation is extremely small with the largest probability being  $10^{-10}$ . The *Herschel*-BAT AGNs show a slightly steeper relationship than the KINGFISH galaxies; however, they are still within  $\sim 1.5\sigma$  of each other. The steepness of the correlation for the *Herschel*-BAT AGNs could be driven by the large number of upper limits for the PAH luminosities. Indeed, when excluding these from the analysis, we find slopes of  $1.13 \pm 0.09$  and  $1.15 \pm 0.12$ , much closer to the KINGFISH galaxies.

For the purposes of this work, Fig. C1 indicates that our SED decomposition of the *Herschel*-BAT AGN has produced reliable estimates of the star-forming luminosity consistent with measurements of the PAH 11.3 and 7.7  $\mu\text{m}$  luminosity. A more detailed analysis on the exact correlation between broad-band IR luminosity and PAH emission for AGN is beyond the scope of this paper and has no bearing on our results.

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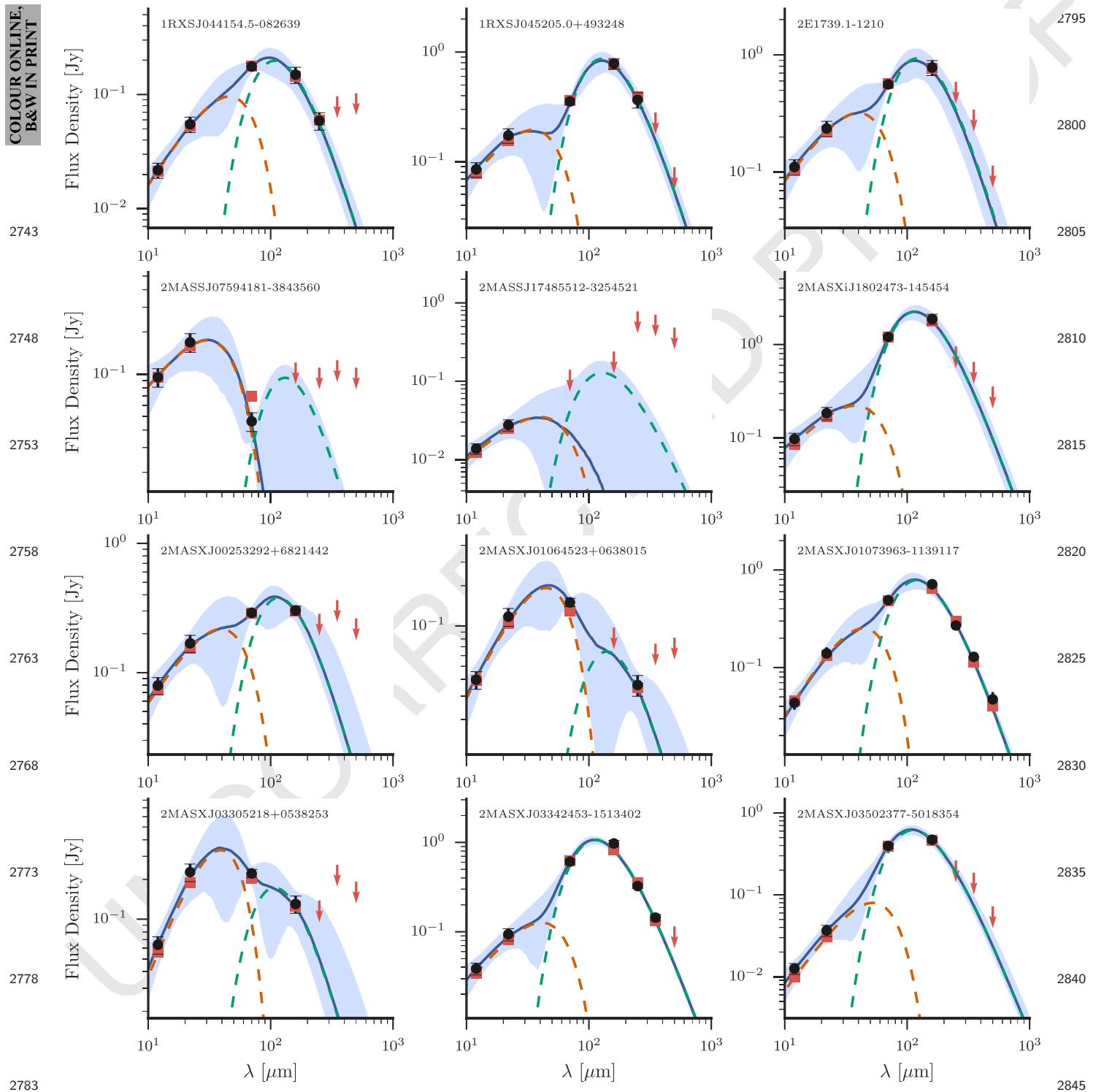
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## APPENDIX D: SED FIGURES

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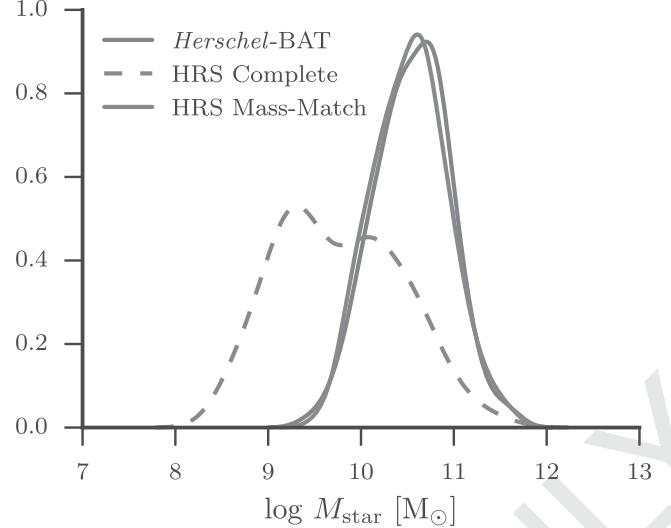
**Figure D1.** Observed frame 12–500  $\mu\text{m}$  SEDs for all of the *Herschel*-BAT sample. Black points plot the observed flux densities with downward-pointing red arrows indicating  $5\sigma$  upper limits. The solid blue line and shaded region shows the best-fitting C12 model with a 95 per cent confidence interval. The red squares are the model flux densities after convolving the best-fitting model SED with each instrument's transmission curve. The orange and green dashed lines show the best-fitting PL and MBB components, respectively.



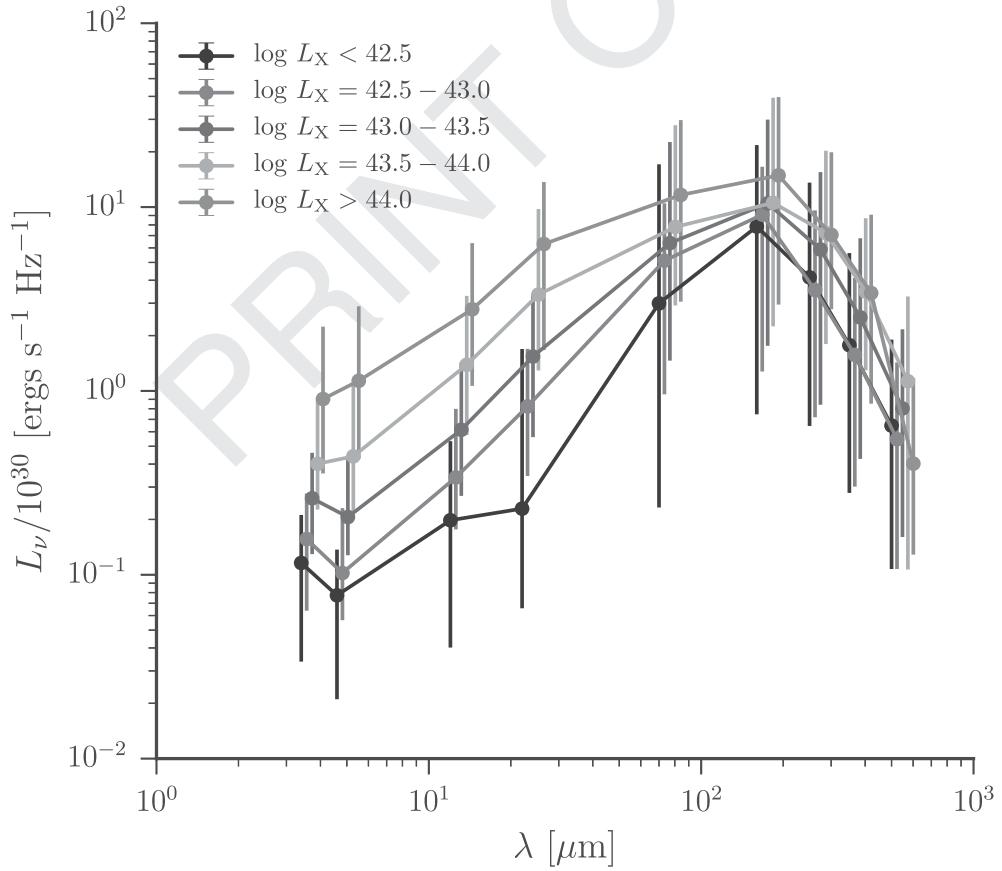
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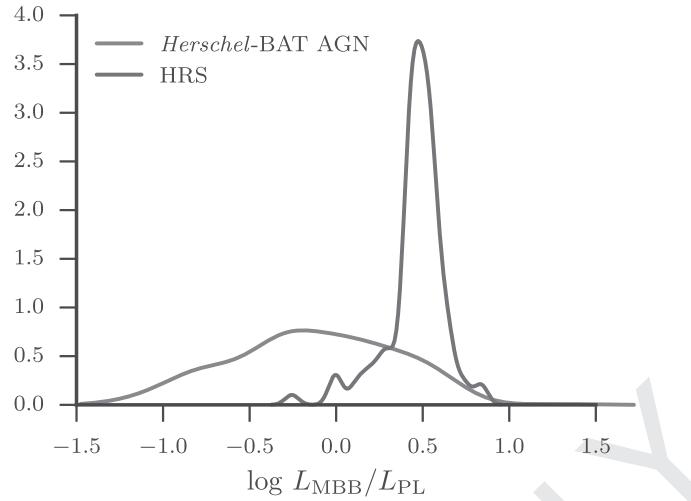
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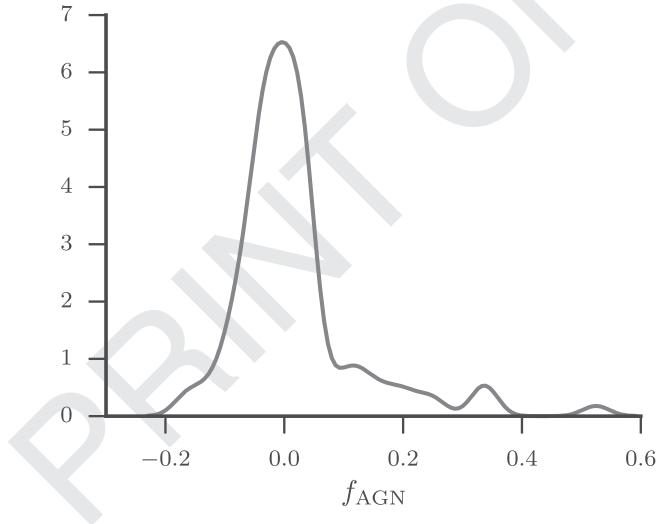
**Figure 1.** Kernel Density Estimates (KDEs) of the  $M_{\text{star}}$  distribution for the BAT AGN (blue), full HRS sample (red), and mass-matched HRS sample (red dashed). The *Herschel*-BAT AGNs probe a higher  $M_{\text{star}}$  galaxy population than the full samples; however, with mass-matching we can reproduce the stellar-mass distribution of the *Herschel*-BAT AGN with non-AGN.



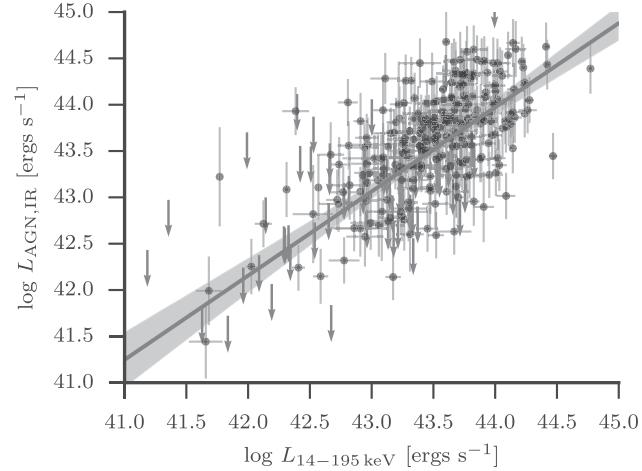
**Figure 2.** Median IR SEDs in units of  $10^{30} \text{ erg s}^{-1} \text{ Hz}^{-1}$  for the *Herschel*-BAT AGNs binned by  $L_{14-195\text{keV}}$ . Each point in the SEDs is the median  $L_{\nu}$  for the sources in the bin including upper limits calculated using the Kaplan–Meier product-limit estimator. The error bars represent the 68 per cent confidence interval determined from the 16th and 84th percentiles. SEDs have been slightly offset by 0.02 dex in wavelength so that the error bars can be clearly shown.



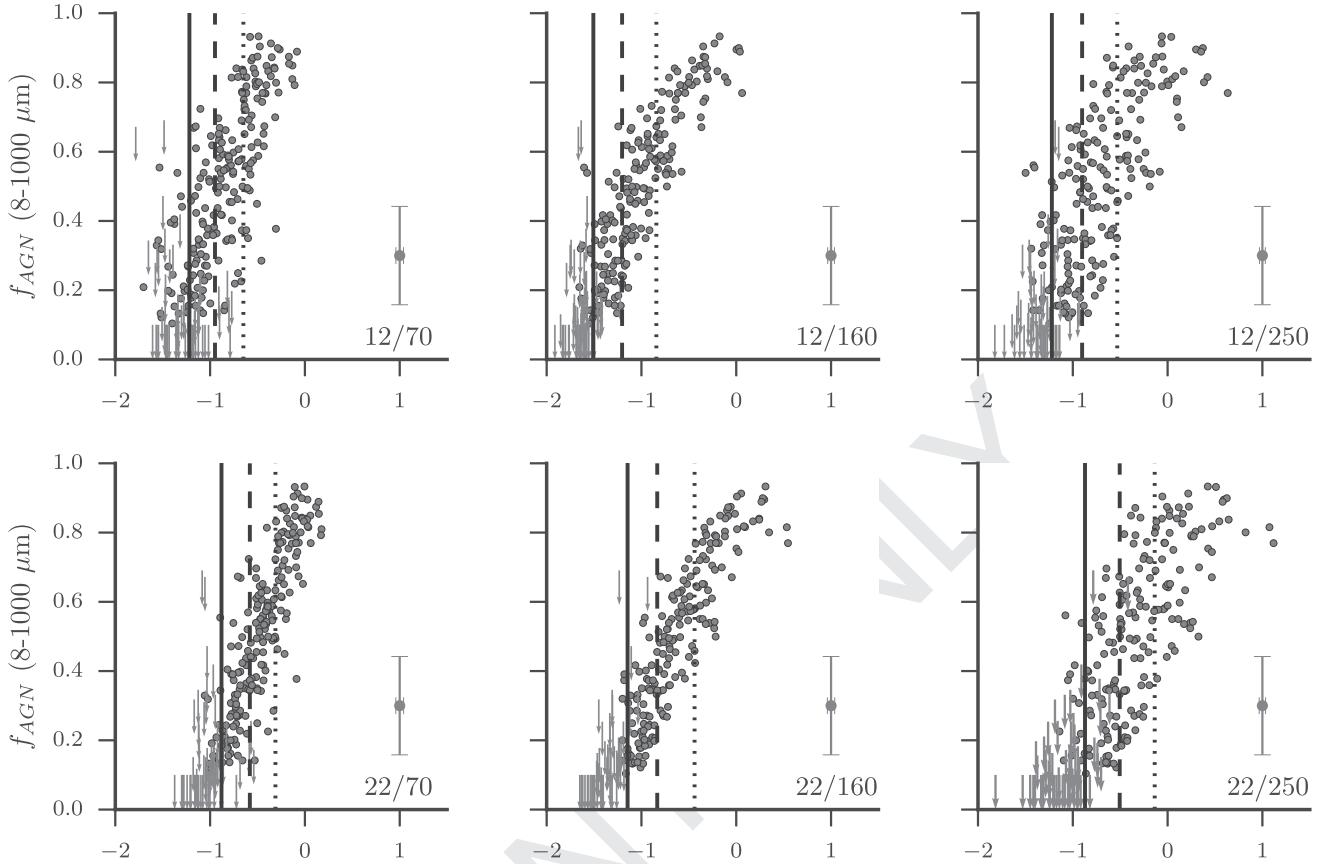
**Figure 3.** KDEs of the  $L_{\text{MBB}}/L_{\text{PL}}$  distribution for the *Herschel*-BAT AGN (blue) and HRS (red) samples. The HRS galaxies have a narrowly distributed ratio, while the BAT AGNs span a wide range due to the AGN contribution.



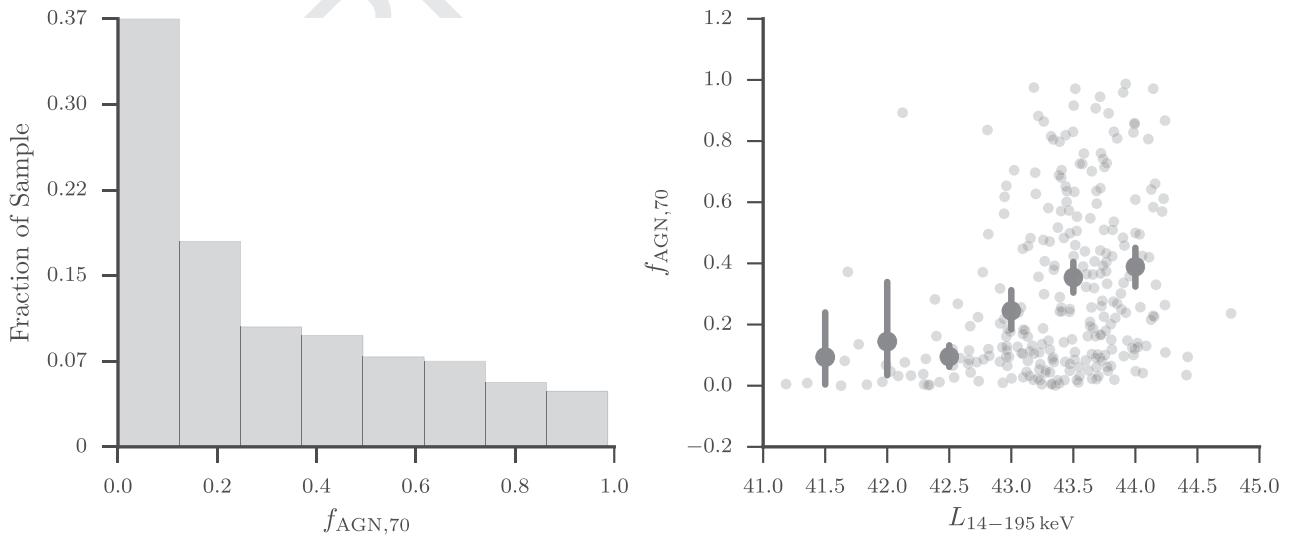
**Figure 4.**  $f_{\text{AGN}}$  distribution for HRS. The standard deviation of this distribution quantifies the uncertainty on  $f_{\text{AGN}}$  associated with the correction factor used to calculate  $f_{\text{AGN}}$ .



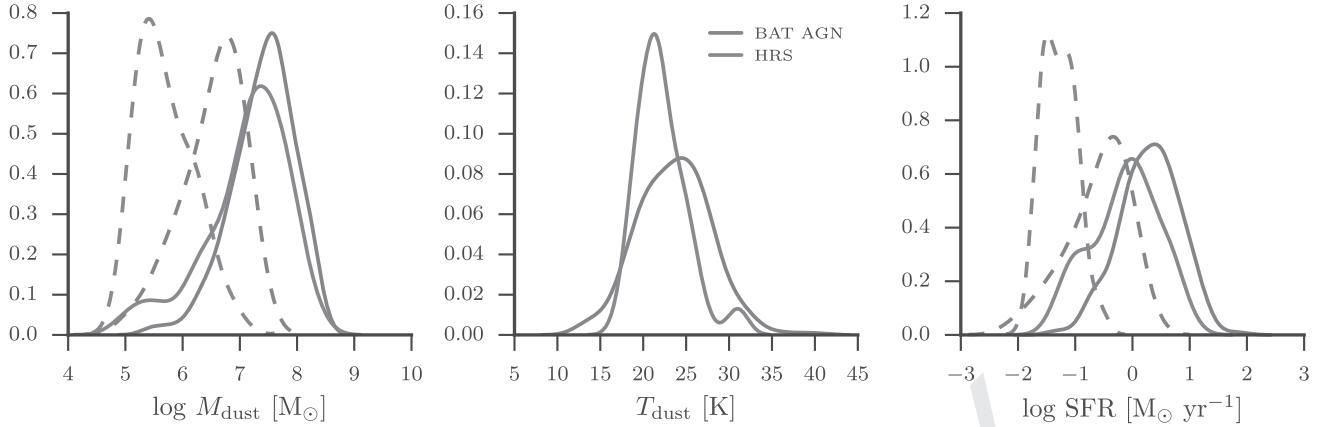
**Figure 5.** Correlation between  $L_{\text{AGN, IR}}$  and  $L_{14-195 \text{ keV}}$  for the *Herschel*-BAT sample (black points). The solid blue line shows the result of Bayesian linear regression with the shaded region indicating the 95 per cent confidence interval. The strong correlation between the two luminosities provides evidence our SED decomposition performed well in measuring the IR luminosity associated with AGN-heated dust.



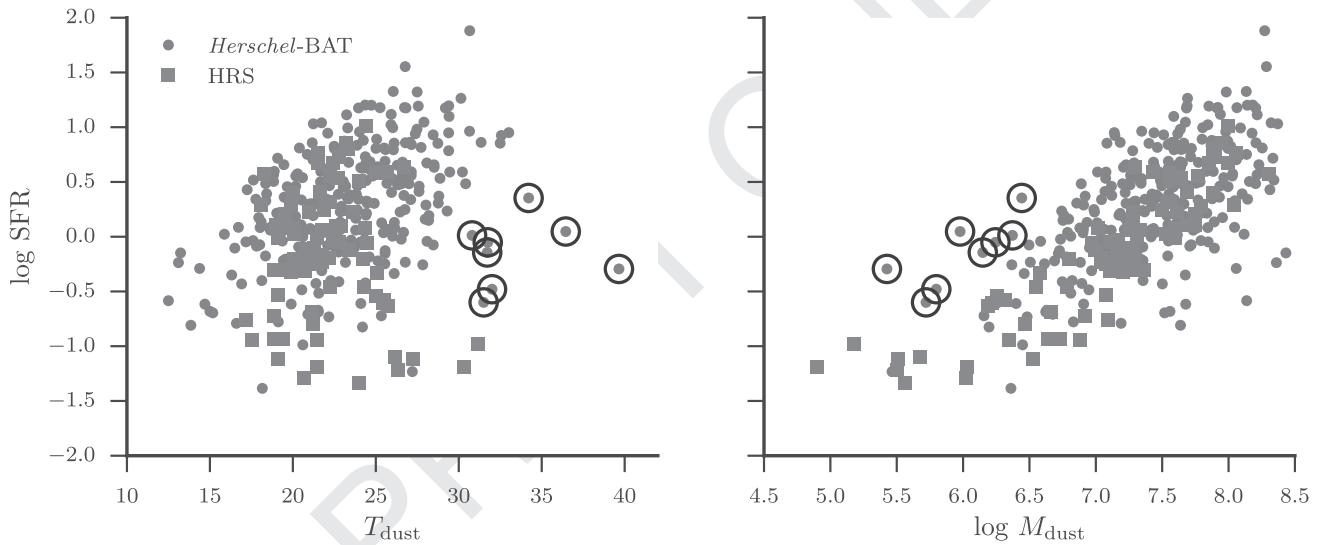
**Figure 6.** Relationship between different IR colours and  $f_{AGN}$ , the fraction of the 8–1000  $\mu\text{m}$  luminosity attributed to AGN-heated dust. The IR colours (x-axis) are in logarithmic units. Upper limits on  $f_{AGN}$  are indicated as red arrows and are at 95 per cent confidence. We also display the 75th, 50th, and 25th percentile colours for the *Herschel*-BAT AGN as solid, dashed, and dotted vertical lines, respectively. Choosing a sample with colours *above* these would result in 75, 50, and 25 per cent completeness for the *Herschel*-BAT AGN.



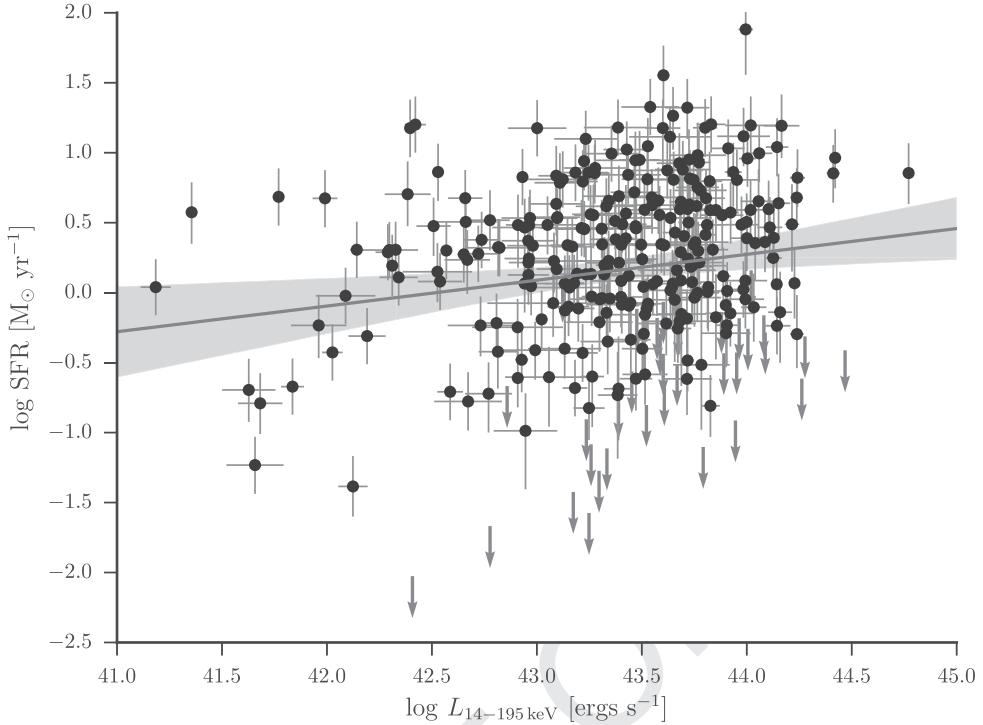
**Figure 7.** Left: histogram of the estimated 70  $\mu\text{m}$  contribution by AGN-heated dust. Each bar is a bin with a width of 0.1 and a height equal to the fraction of the total sample. Right: relationship between the 14–195 keV luminosity and 70  $\mu\text{m}$  AGN contribution. Grey dots represent each individual source while the blue dots with error bars are averages within bins according to 14–195 keV luminosity. Error bars indicate the 68 per cent confidence interval determined using bootstrap analysis.



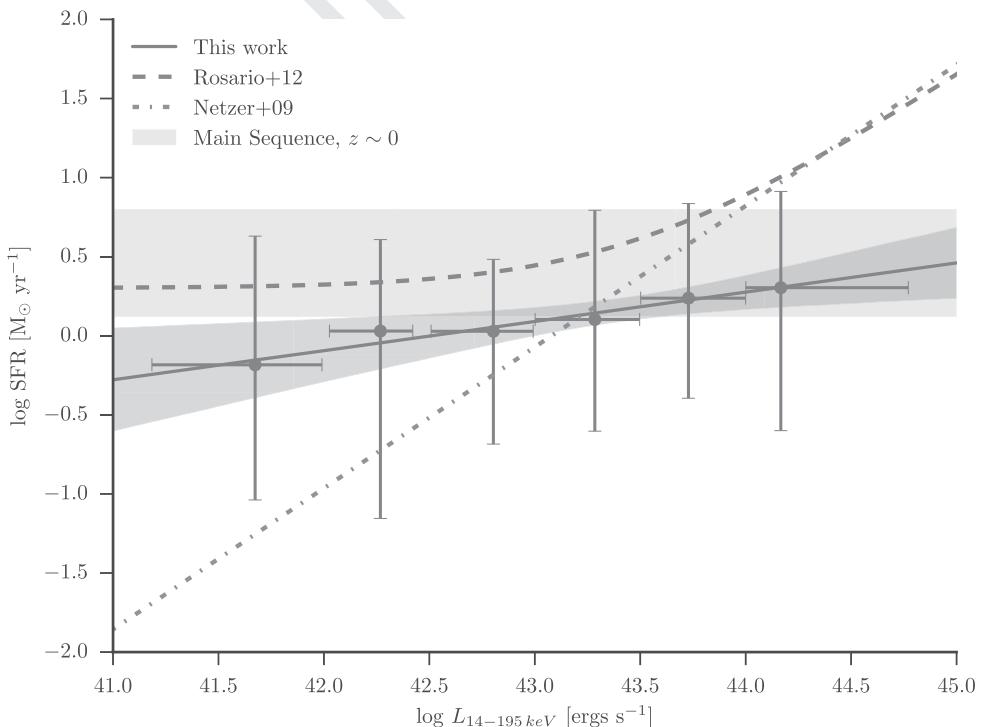
**Figure 8.** Comparison of  $M_{\text{dust}}$ ,  $T_{\text{dust}}$ , and SFR between the *Herschel*-BAT AGN (blue) and HRS mass-matched sample (red). The distributions with dashed lines indicate sources with only upper limits on these values.



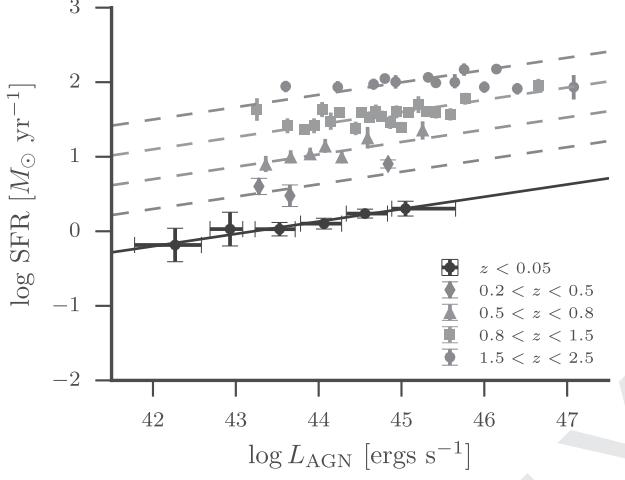
**Figure 9.** Left: correlation between dust temperature and SFR for the *Herschel*-BAT AGNs (blue points) and HRS galaxies (red squares). Circled blue points indicate possible sources that are dominated by AGN-heated dust. Right: correlation between dust mass and SFR for *Herschel*-BAT AGNs and HRS galaxies. The circled points are again the sources that could be dominated by AGN-heated dust.



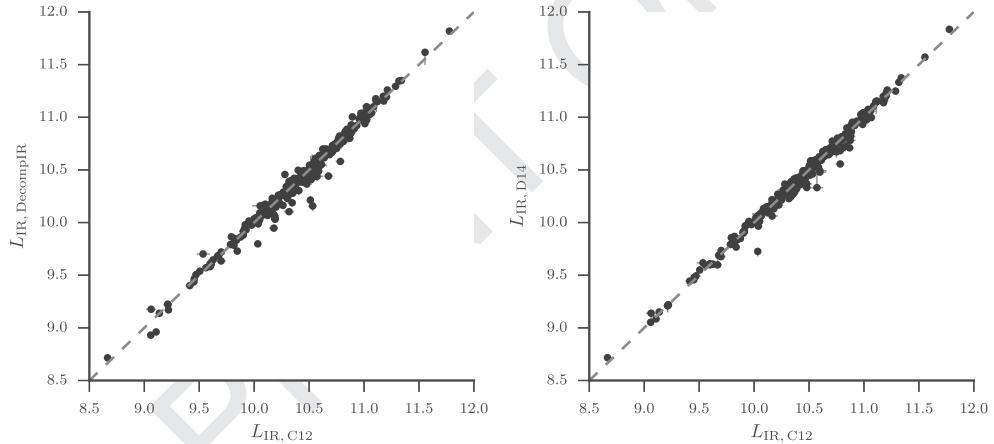
**Figure 10.** Correlation between AGN luminosity as probed by  $L_{14-195 \text{ keV}}$  and SFR. Error bars on  $L_{14-195 \text{ keV}}$  correspond to the 90 percentile confidence interval from the 58-month BAT catalogue. Error bars on the SFR correspond to the 68 percentile confidence interval from our SED fitting. Downward-pointing arrows plot 95 per cent confidence upper limits on the SFR. The solid blue line with shading plots the best-fitting line and 95 percentile confidence interval for our AGN–SFR relationship from LINMIX\_ERR. No strong relationship exists between the AGN strength and global star formation.



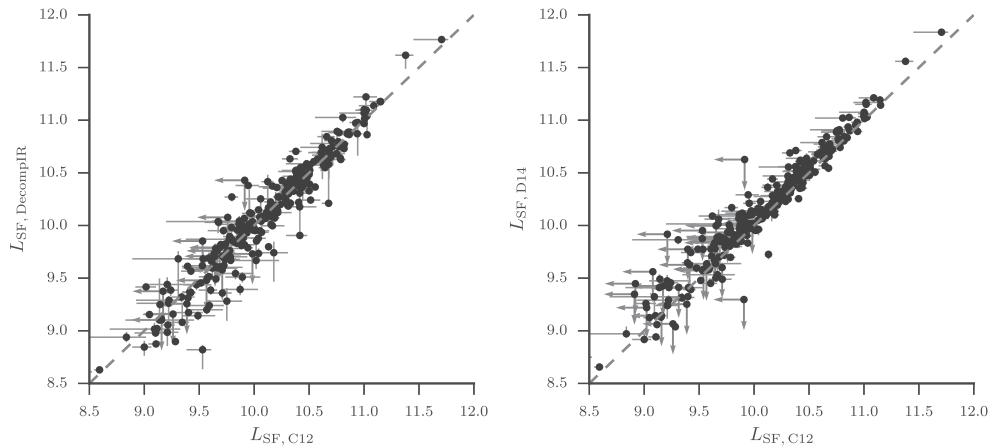
**Figure 11.** Comparison between the measured SFR– $L_{14-195 \text{ keV}}$  from the *Herschel*–BAT sample (blue line with shaded region) and previous relationships from Netzer (2009, dotted line) and Rosario et al. (2012, red dashed line). The points with error bars are the median SFRs binned by  $L_{14-195 \text{ keV}}$  from the *Herschel*–BAT sample. Error bars represent the 68 per cent confidence interval. The green shaded region represents the expected SFR for a main-sequence galaxy in the local universe at a stellar mass of  $10^{10.5} M_{\odot}$ .



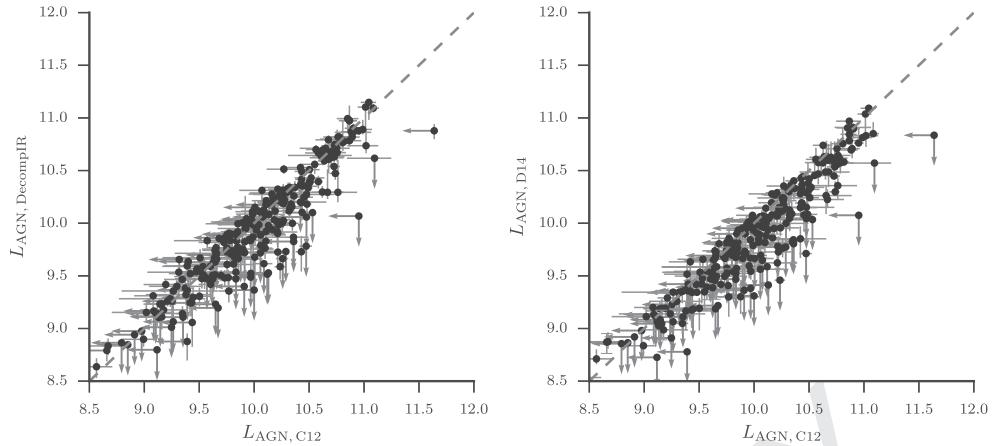
**Figure 12.** Evolution of the SFR–LAGN relationship combining the results of this work (black points) and those of Stanley et al. (2015, coloured points) for  $z > 0.2$ . The *Herschel*-BAT points were converted to  $L_{\text{AGN}}$  from  $L_{14-195\text{keV}}$  using the calibration from Winter et al. (2012). Error bars on each point represent the standard error on the mean rather than the 68 per cent confidence interval as in Fig. 11. The black solid line shows our measured  $z < 0.05$  SFR– $L_{\text{AGN}}$  relationship. Each subsequent coloured, dashed line is a simple scaling from  $z < 0.05$  to higher redshifts by increasing the SFR by 0.5, 0.9, 1.3, and 1.7 dex.



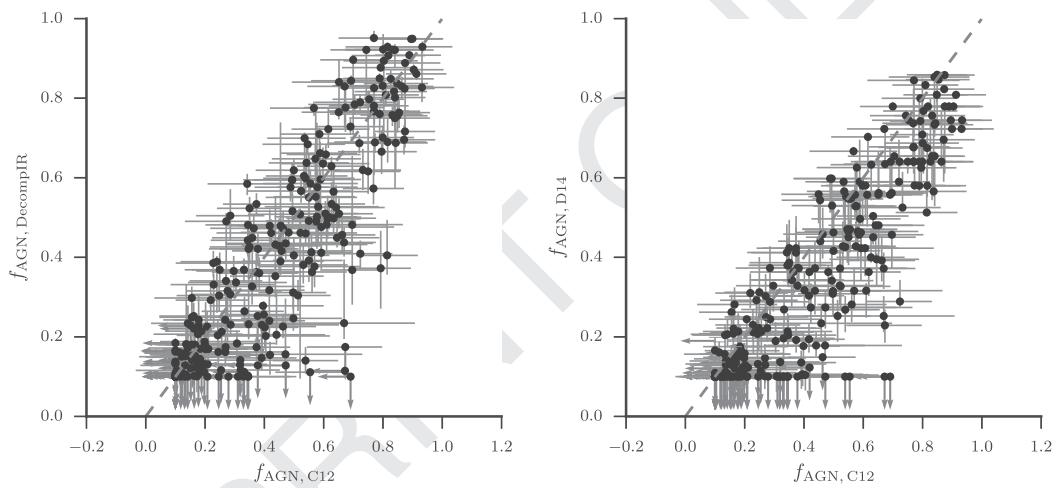
**Figure B1.** Correlations of total  $L_{\text{IR}}$  between the C12 model and DECOMPIR and D14. The red dashed line indicates a one-to-one correspondence.



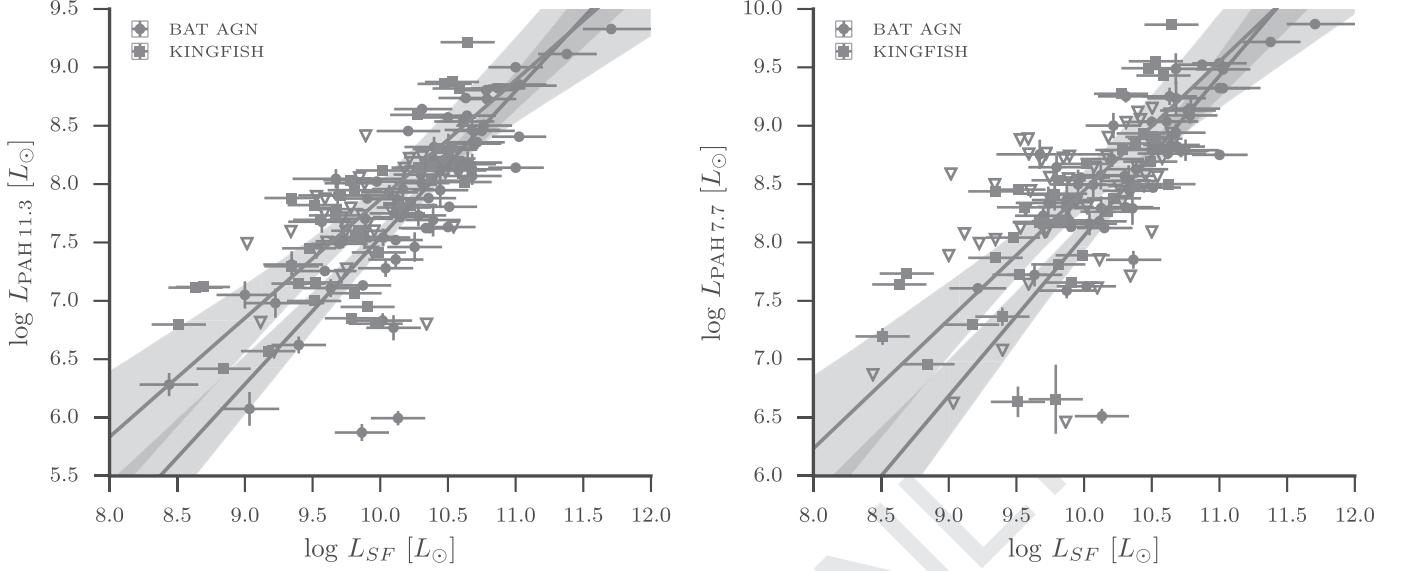
**Figure B2.** Same as Fig. B1 but for  $L_{\text{SF}}$ .



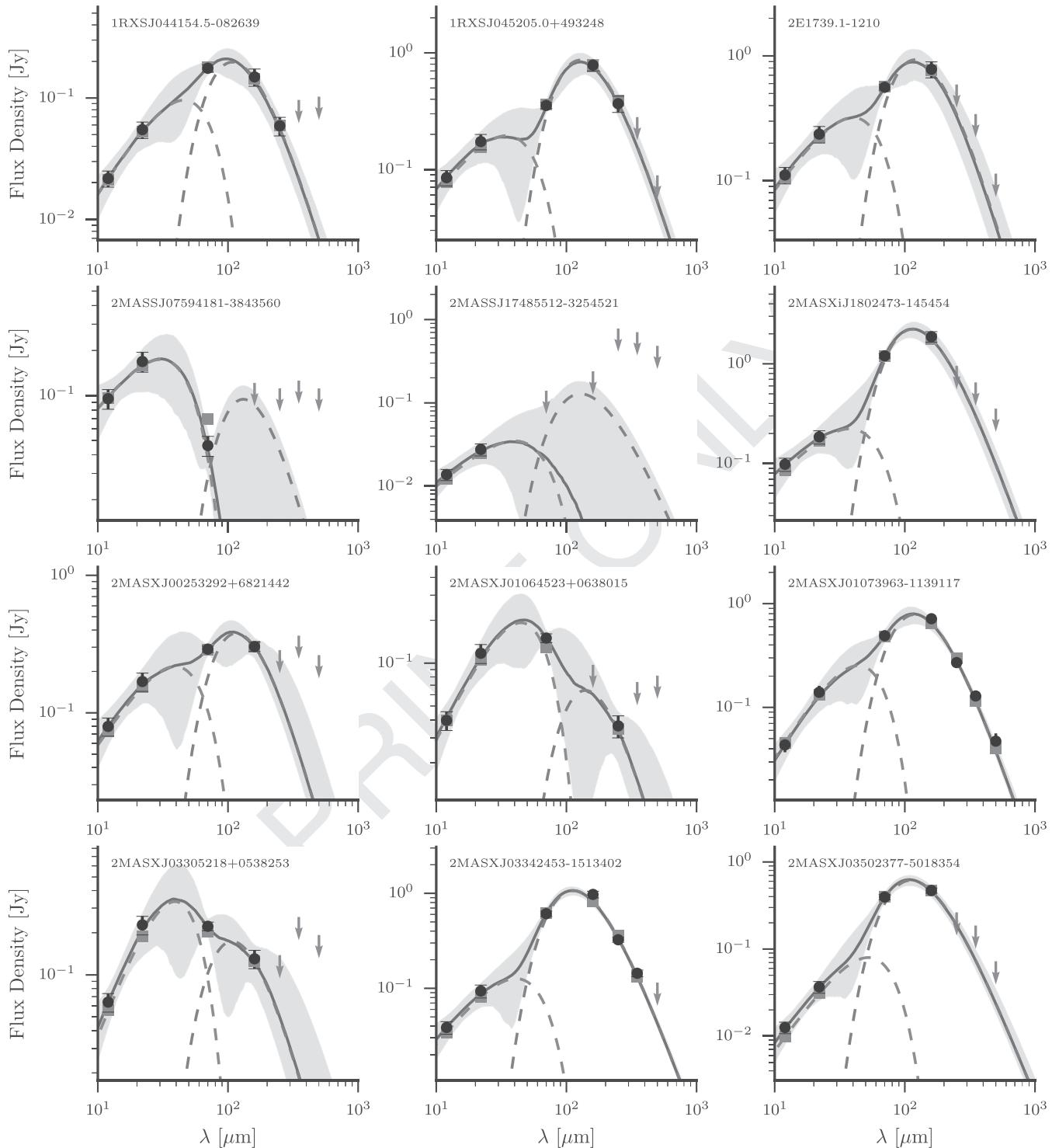
**Figure B3.** Same as Fig. B1 but for  $L_{\text{AGN, IR}}$ .



**Figure B4.** Correlations of  $f_{\text{AGN}}$  from the three SED models. Error bars represent the 68 per cent confidence interval. Upper limits are indicated as red downward-pointing arrows. The red dashed line indicates a one-to-one correspondence.



**Figure C1.** Correlation between  $L_{SF}$  and the 11.3 (left) and 7.7  $\mu\text{m}$  (right) luminosity. Blue points correspond to the *Herschel*-BAT AGN and red squares correspond to the KINGFISH galaxies. Sources with upper limits on  $L_{PAH}$  are shown as open triangles. Measured correlations between  $L_{SF}$  and the 11.3 and 7.7  $\mu\text{m}$  luminosity are shown as solid blue and red lines for the *Herschel*-BAT AGN and KINGFISH samples, respectively. The shaded region around the median correlations indicate the 95 per cent confidence interval. The broad consistency of the correlation for both the KINGFISH and *Herschel*-BAT samples shows that SFRs determined from  $L_{SF}$  will be comparable without any systematic bias.



**Figure D1.** Observed frame 12–500  $\mu\text{m}$  SEDs for all of the *Herschel*-BAT sample. Black points plot the observed flux densities with downward-pointing red arrows indicating  $5\sigma$  upper limits. The solid blue line and shaded region shows the best-fitting C12 model with a 95 per cent confidence interval. The red squares are the model flux densities after convolving the best-fitting model SED with each instrument’s transmission curve. The orange and green dashed lines show the best-fitting PL and MBB components, respectively.

# List of astronomical key words

## (updated 2013 July)

This list is common to *Monthly Notices of the Royal Astronomical Society*, *Astronomy and Astrophysics*, and *The Astrophysical Journal*. In order to ease the search, the key words are subdivided into broad categories. No more than six subcategories altogether should be listed for a paper.

The subcategories in boldface containing the word ‘individual’ are intended for use with specific astronomical objects; these should never be used alone, but always in combination with the most common names for the astronomical objects in question. Note that each object counts as one subcategory within the allowed limit of six.

The parts of the key words in italics are for reference only and should be omitted when the key words are entered on the manuscript.

### General

editorials, notices  
errata, addenda  
extraterrestrial intelligence  
history and philosophy of astronomy  
miscellaneous  
obituaries, biographies  
publications, bibliography  
sociology of astronomy  
standards

### Physical data and processes

acceleration of particles  
accretion, accretion discs  
asteroseismology  
astrobiology  
astrochemistry  
astroparticle physics  
atomic data  
atomic processes  
black hole physics  
chaos  
conduction  
convection  
dense matter  
diffusion  
dynamo  
elementary particles  
equation of state  
gravitation  
gravitational lensing: strong  
gravitational lensing: weak  
gravitational lensing: micro  
gravitational waves  
hydrodynamics  
instabilities  
line: formation  
line: identification  
line: profiles  
magnetic fields

magnetic reconnection  
(*magnetohydrodynamics*) MHD  
masers  
molecular data  
molecular processes  
neutrinos  
nuclear reactions, nucleosynthesis, abundances  
opacity  
plasmas  
polarization  
radiation: dynamics  
radiation mechanisms: general  
radiation mechanisms: non-thermal  
radiation mechanisms: thermal  
radiative transfer  
relativistic processes  
scattering  
shock waves  
solid state: refractory  
solid state: volatile  
turbulence  
waves

### Astronomical instrumentation, methods and techniques

atmospheric effects  
balloons  
instrumentation: adaptive optics  
instrumentation: detectors  
instrumentation: high angular resolution  
instrumentation: interferometers  
instrumentation: miscellaneous  
instrumentation: photometers  
instrumentation: polarimeters  
instrumentation: spectrographs  
light pollution  
methods: analytical  
methods: data analysis  
methods: laboratory: atomic  
methods: laboratory: molecular  
methods: laboratory: solid state  
methods: miscellaneous  
methods: numerical  
methods: observational  
methods: statistical  
site testing  
space vehicles  
space vehicles: instruments  
techniques: high angular resolution  
techniques: image processing  
techniques: imaging spectroscopy  
techniques: interferometric  
techniques: miscellaneous  
techniques: photometric  
techniques: polarimetric  
techniques: radar astronomy  
techniques: radial velocities

techniques: spectroscopic  
telescopes

### Astronomical data bases

astronomical data bases: miscellaneous  
atlases  
catalogues  
surveys  
virtual observatory tools

### Astrometry and celestial mechanics

astrometry  
celestial mechanics  
eclipses  
ephemerides  
occultations  
parallaxes  
proper motions  
reference systems  
time

### The Sun

Sun: abundances  
Sun: activity  
Sun: atmosphere  
Sun: chromosphere  
Sun: corona  
Sun: coronal mass ejections (CMEs)  
Sun: evolution  
Sun: faculae, plages  
Sun: filaments, prominences  
Sun: flares  
Sun: fundamental parameters  
Sun: general  
Sun: granulation  
Sun: helioseismology  
Sun: heliosphere  
Sun: infrared  
Sun: interior  
Sun: magnetic fields  
Sun: oscillations  
Sun: particle emission  
Sun: photosphere  
Sun: radio radiation  
Sun: rotation  
(*Sun:*) solar-terrestrial relations  
(*Sun:*) solar wind  
(*Sun:*) sunspots  
Sun: transition region  
Sun: UV radiation  
Sun: X-rays, gamma-rays

### Planetary systems

comets: general  
**comets: individual: ...**

Earth  
interplanetary medium  
Kuiper belt: general  
**Kuiper belt objects: individual: ...**

meteorites, meteors, meteoroids  
minor planets, asteroids: general  
**minor planets, asteroids: individual: ...**

Moon  
Oort Cloud  
planets and satellites: atmospheres  
planets and satellites: aurorae  
planets and satellites: composition  
planets and satellites: detection  
planets and satellites: dynamical evolution and stability  
planets and satellites: formation  
planets and satellites: fundamental parameters  
planets and satellites: gaseous planets  
planets and satellites: general  
**planets and satellites: individual: ...**  
planets and satellites: interiors  
planets and satellites: magnetic fields  
planets and satellites: oceans  
planets and satellites: physical evolution  
planets and satellites: rings  
planets and satellites: surfaces  
planets and satellites: tectonics  
planets and satellites: terrestrial planets  
planet–disc interactions  
planet–star interactions  
protoplanetary discs  
zodiacal dust

### Stars

stars: abundances  
stars: activity  
stars: AGB and post-AGB  
stars: atmospheres  
(stars:) binaries (*including multiple*): close  
(stars:) binaries: eclipsing  
(stars:) binaries: general  
(stars:) binaries: spectroscopic  
(stars:) binaries: symbiotic  
(stars:) binaries: visual  
stars: black holes  
(stars:) blue stragglers  
(stars:) brown dwarfs  
stars: carbon  
stars: chemically peculiar  
stars: chromospheres  
(stars:) circumstellar matter  
stars: coronae  
stars: distances  
stars: dwarf novae  
stars: early-type  
stars: emission-line, Be  
stars: evolution  
stars: flare  
stars: formation  
stars: fundamental parameters  
(stars:) gamma-ray burst: general  
(stars:) **gamma-ray burst: individual: ...**  
stars: general  
(stars:) Hertzsprung–Russell and colour–magnitude diagrams  
stars: horizontal branch  
stars: imaging  
**stars: individual: ...**

stars: interiors  
stars: jets  
stars: kinematics and dynamics  
stars: late-type  
stars: low-mass  
stars: luminosity function, mass function  
stars: magnetars  
stars: magnetic field  
stars: massive  
stars: mass-loss  
stars: neutron  
(*stars:*) novae, cataclysmic variables  
stars: oscillations (*including pulsations*)  
stars: peculiar (*except chemically peculiar*)  
(*stars:*) planetary systems  
stars: Population II  
stars: Population III  
stars: pre-main-sequence  
stars: protostars  
(*stars:*) pulsars: general  
**(*stars:*) pulsars: individual: ...**  
stars: rotation  
stars: solar-type  
(*stars:*) starspots  
stars: statistics  
(*stars:*) subdwarfs  
(*stars:*) supergiants  
(*stars:*) supernovae: general  
**(*stars:*) supernovae: individual: ...**  
stars: variables: Cepheids  
stars: variables: δ Scuti  
stars: variables: general  
stars: variables: RR Lyrae  
stars: variables: S Doradus  
stars: variables: T Tauri, Herbig Ae/Be  
(*stars:*) white dwarfs  
stars: winds, outflows  
stars: Wolf-Rayet

#### **Interstellar medium (ISM), nebulae**

ISM: abundances  
ISM: atoms  
ISM: bubbles  
ISM: clouds  
(*ISM:*) cosmic rays  
(*ISM:*) dust, extinction  
ISM: evolution  
ISM: general  
(*ISM:*) H II regions  
(*ISM:*) Herbig-Haro objects  
**ISM: individual objects: ...**  
(*except planetary nebulae*)  
ISM: jets and outflows  
ISM: kinematics and dynamics  
ISM: lines and bands  
ISM: magnetic fields  
ISM: molecules  
(*ISM:*) planetary nebulae: general  
**(*ISM:*) planetary nebulae: individual: ...**  
(*ISM:*) photodissociation region (PDR)  
ISM: structure  
ISM: supernova remnants

#### **The Galaxy**

Galaxy: abundances  
Galaxy: bulge  
Galaxy: centre  
Galaxy: disc  
Galaxy: evolution  
Galaxy: formation  
Galaxy: fundamental parameters  
Galaxy: general  
(*Galaxy:*) globular clusters: general  
**(*Galaxy:*) globular clusters: individual: ...**  
Galaxy: halo  
Galaxy: kinematics and dynamics  
(*Galaxy:*) local interstellar matter  
Galaxy: nucleus  
(*Galaxy:*) open clusters and associations: general  
**(*Galaxy:*) open clusters and associations: individual: ...**  
(*Galaxy:*) solar neighbourhood  
Galaxy: stellar content  
Galaxy: structure

#### **Galaxies**

galaxies: abundances  
galaxies: active  
(*galaxies:*) BL Lacertae objects: general  
**(*galaxies:*) BL Lacertae objects: individual: ...**  
galaxies: bulges  
galaxies: clusters: general  
**galaxies: clusters: individual: ...**  
galaxies: clusters: intracluster medium  
galaxies: distances and redshifts  
galaxies: dwarf  
galaxies: elliptical and lenticular, cD  
galaxies: evolution  
galaxies: formation  
galaxies: fundamental parameters  
galaxies: general  
galaxies: groups: general  
**galaxies: groups: individual: ...**  
galaxies: haloes  
galaxies: high-redshift  
**galaxies: individual: ...**  
galaxies: interactions  
(*galaxies:*) intergalactic medium  
galaxies: irregular  
galaxies: ISM  
galaxies: jets  
galaxies: kinematics and dynamics  
(*galaxies:*) Local Group  
galaxies: luminosity function, mass function  
(*galaxies:*) Magellanic Clouds  
galaxies: magnetic fields  
galaxies: nuclei  
galaxies: peculiar  
galaxies: photometry  
(*galaxies:*) quasars: absorption lines  
(*galaxies:*) quasars: emission lines  
(*galaxies:*) quasars: general  
**(*galaxies:*) quasars: individual: ...**  
(*galaxies:*) quasars: supermassive black holes  
galaxies: Seyfert

galaxies: spiral  
galaxies: starburst  
galaxies: star clusters: general  
**galaxies: star clusters: individual: ...**  
galaxies: star formation  
galaxies: statistics  
galaxies: stellar content  
galaxies: structure

infrared: galaxies  
infrared: general  
infrared: ISM  
infrared: planetary systems  
infrared: stars  
radio continuum: galaxies  
radio continuum: general  
radio continuum: ISM  
radio continuum: planetary systems  
radio continuum: stars  
radio lines: galaxies  
radio lines: general  
radio lines: ISM  
radio lines: planetary systems  
radio lines: stars  
submillimetre: diffuse background  
submillimetre: galaxies  
submillimetre: general  
submillimetre: ISM  
submillimetre: planetary systems  
submillimetre: stars  
ultraviolet: galaxies  
ultraviolet: general  
ultraviolet: ISM  
ultraviolet: planetary systems  
ultraviolet: stars  
X-rays: binaries  
X-rays: bursts  
X-rays: diffuse background  
X-rays: galaxies  
X-rays: galaxies: clusters  
X-rays: general  
**X-rays: individual: ...**  
X-rays: ISM  
X-rays: stars

## Cosmology

(cosmology:) cosmic background radiation  
(cosmology:) cosmological parameters  
cosmology: miscellaneous  
cosmology: observations  
cosmology: theory  
(cosmology:) dark ages, reionization, first stars  
(cosmology:) dark energy  
(cosmology:) dark matter  
(cosmology:) diffuse radiation  
(cosmology:) distance scale  
(cosmology:) early Universe  
(cosmology:) inflation  
(cosmology:) large-scale structure of Universe  
(cosmology:) primordial nucleosynthesis

## Resolved and unresolved sources as a function of wavelength

gamma-rays: diffuse background  
gamma-rays: galaxies  
gamma-rays: galaxies: clusters  
gamma-rays: general  
gamma-rays: ISM  
gamma-rays: stars  
infrared: diffuse background