Overdensities of SMGs around *WISE*-selected, ultra-luminous, high-redshift AGN

Suzy F. Jones,1⋆ Andrew W. Blain,2 Roberto J. Assef,3 Peter Eisenhardt,4 Carol Lonsdale,5 James Condon,5 Duncan Farrah,6 Chao-Wei Tsai,4,7 Carrie Bridge,4 Jingwen Wu,8 Edward L. Wright7 and Tom Jarrett9

1 Department of Space, Earth, and Environment, Chalmers University of Technology, Onsala Space Observatory, SE-43992, Onsala, Sweden
2 University of Leicester, XROA, Department of Physics & Astronomy, University Road, Leicester LE1 7RH, UK
3 Núcleo de Astronomía de la Facultad de Ingeniería, Universidad Diego Portales, Av. Ejército Libertador 441, Santiago, Chile
4 Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA
5 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903-2475 USA
6 Virginia Polytechnic Institute & State University, Department of Physics MC 0435, 850 West Campus Drive, Blacksburg, VA 24061, USA
7 Department of Physics and Astronomy, University of California, Los Angeles, 430 Portola Plaza, Los Angeles, CA, 90095-1547, USA
8 National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing, 100012, China
9 Astronomy Department, University of Cape Town, Rondebosch 7701, Republic of South Africa

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ABSTRACT

We investigate extremely luminous dusty galaxies in the environments around *WISE*-selected hot dust obscured galaxies (Hot DOGs) and *WISE*/radio-selected active galactic nuclei (AGNs) at average redshifts of $z = 2.7$ and $z = 1.7$, respectively. Previous observations have detected overdensities of companion submillimetre-selected sources around 10 Hot DOGs and 30 *WISE*/radio AGNs, with overdensities of $\sim 2 - 3$ and $\sim 5 - 6$, respectively. We find that the space densities in both samples to be over-dense compared to normal star-forming galaxies and submillimetre galaxies (SMGs) in the SCUBA-2 Cosmology Legacy Survey (S2CLS). Both samples of companion sources have consistent mid-IR colours and mid-IR to submm ratios as SMGs. The brighter population around *WISE*/radio AGNs could be responsible for the higher overdensity reported. We also find the star formation rate density (SFRDs) are higher than the field, but consistent with clusters of dusty galaxies. *WISE*-selected AGNs appear to be good signposts for protoclusters at high redshift on arcmin scales. The results reported here provide an upper limit to the strength of angular clustering using the two-point correlation function. Monte Carlo simulations show no angular correlation, which could indicate protoclusters on scales larger than the SCUBA-2 1.5 arcmin scale maps.

Key words: galaxies: active – galaxies: clusters: general – galaxies: high-redshift – galaxies: quasars: general – infrared: galaxies – submillimetre: galaxies

1 INTRODUCTION

Advances in infrared (IR) telescope technology like the NASA’s *Wide-Field Infrared Survey Explorer* (*WISE*; Wright et al. 2010) have enabled observations of luminous AGN that have been difficult to find with previous IR missions. *WISE* is able to find luminous, dusty, high-redshift, active galaxies because the hot dust heated by AGN and/or starburst activity can be traced using the *WISE* 12 µm (W3) and 22 µm (W4) bands. Eisenhardt et al. (2012), Bridge et al. (2013) and Lonsdale et al. (2013) have shown that *WISE* can find different classes of interesting, luminous, high-redshift, dust-obscured AGN.

⋆ E-mail: suzy.jones@chalmers.se
Eisenhardt et al. (2012) and Wu et al. (2012) observed galaxies with faint or undetectable flux densities in the 3.4 µm (W1) and 4.6 µm (W2) bands, and well detected fluxes in the W3 and/or W4 bands, with a radio blind selection, giving a “W1W2-dropout” selection yielding hot, dust obscured galaxies (Hot DOGs).

Another population of luminous, dusty, WISE-selected AGNs were found by Lonsdale et al. (2013), by combining WISE and National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS) (Condon et al. 1998) and/or Faint Images of the Radio Sky at Twenty-cm (FIRST) (Becker et al. 1995). They were selected in a similar method in the mid-IR, and are a similarly high luminosity, dust-obscured population and in this paper are known as WISE/radio AGNs. The strong compact radio emission from AGNs can be of high significance in 30 µm (W1) and 4.6 µm (W2) bands, and well detected submm fluxes in the W3 and/or W4 bands. Eighty-one companion sources were detected at 3σ or greater significance in 30 WISE/radio-selected AGN fields reported by Jones et al. (2015) with an average root mean square (RMS) noise of 1.8 mJy beam$^{-1}$, as shown in Table 1.

Follow-up Spitzer Infrared Array Camera (IRAC) imaging of a subset of Hot DOGs found an overdensity of galaxies within 1 arcmin above the number observed in random pointings (Assef et al. 2013). They also found that Hot DOG environments are as dense as the clusters found by the Clusters Around Radio-loud AGN (CARLA) surveys (Wylezalek et al. 2013, 2014).

Studying the environments of Hot DOGs and WISE/radio AGNs will help to understand the evolution of galaxies and the link with their host galaxy. This paper will explore the clustering and surface number density of the fields to study the environments surrounding the WISE-selected AGN. Also the properties of the companion sources around Hot DOGs and WISE/radio AGNs will be investigated to determine their nature.

In Section 2 the surface number density and space density of SMG sources in the fields around Hot DOGs and WISE/radio AGNs are compared. In Section 3 the angular two-point correlation function is used to characterise the clustering of the companion SMGs around the WISE/radio AGNs. In Section 4 the properties of the companion sources in the Hot DOG and WISE/radio AGN fields are compared using submm, SFR estimations, star formation rate density (SFRD) estimates, mid-infrared (mid-IR) and radio data with previous surveys of companion SMG sources in the Hot DOG and WISE/radio-selected AGN fields. The nature of the companion sources detected in the overdense regions of both Hot DOGs and WISE/radio AGNs. The nature and properties of the companion sources around Hot DOGs and WISE/radio AGNs are described in Section 5.

Throughout this paper we assume a ΛCDM cosmology with H$_0$ = 71 km s$^{-1}$ Mpc$^{-1}$, Ω$_m$ = 0.27 and Ω$_\Lambda$ = 0.73. WISE catalogue magnitudes are converted to flux densities using zero-point values on the Vega system of 306.7, 170.7, 29.04 and 8.284 Jy for WISE 3.4, 4.6, 12 and 22 µm wavelengths, respectively (Wright et al. 2010).

2 COMPANION SOURCE DENSITY

JCMT SCUBA-2 observations of Hot DOGs and WISE/radio AGN were in the “CV DAISY” mode that produces a uniformly deep coverage 3-arcmin diameter map (Holland et al. 2013). Seventeen companion sources were detected at 3σ significance or above in 10 JCMT SCUBA-2 fields of Hot DOGs reported by Jones et al. (2014) with an average root mean square (RMS) noise of 2.1 mJy beam$^{-1}$, as shown in Table 1.

Eighty-one companion sources were detected at 3σ or greater significance in 30 WISE/radio-selected AGN fields reported by Jones et al. (2015) with average RMS noise of 2.1 mJy beam$^{-1}$, see Table 2-5. They concluded that they have a higher density of SMGs when compared with Hot DOGs by an additional factor of 2.4 ± 0.9 (Jones et al. 2013). The WISE/radio AGNs have a lower redshift range, fewer of the WISE-selected AGNs are submm detected and lower total IR luminosities compared with Hot DOGs (Jones et al. 2014, 2015). The lower redshift range and higher overdensity of SMGs around WISE/radio AGNs can be seen in Figure 1. While the observed Hot DOGs have a typically higher redshift than the WISE/radio AGNs, the companion sources are matched in submm luminosity (see Tables 1-9) and they are consistent with having similar mid-IR to submm ratios. The K-correction at wavelengths longer than 500microns remains approx. constant with increasing redshift. Due to this K-correction effect the SCUBA-2 fraction of SMG detection should be independent of redshift.

The detection level was set at 3σ or greater in order to have completeness but reduce the chance of spurious false positive detections. However, there is controversy over whether 3σ are reliable (e.g. Copin et al. 2005, Casey et al. 2012). Figure 2 presents the signal-to-noise ratio (SNR) of the companion sources around Hot DOGs and WISE/radio AGN and for the two data sets combined. As expected the higher SNR the fewer sources detected and the less complete the sample. Jones et al. (2015) looked at the number of SMGs in the WISE/radio AGN fields detected at greater than 3σ and 4σ and compared to the LABOCA ECDFS Submm Survey (LESS) (Weiβ et al. 2009) and con-
cluded the overdensity of SMGs detected above $3\sigma$ is consistent with SMGs detected above $4\sigma$.

Comparing these number counts to “blank field submm” surveys shows them to be overdense. The blank field submm surveys used to compare were the LESS survey, Cosmological Evolution Survey (COSMOS) (Casey et al. 2013) and the SCUBA Half-Degree Extragalactic Survey (SHADES) (Coppin et al. 2006) fields. The Hot DOG fields have a SMG overdensity by factor of $\sim 2 - 3$ compared with previous blank field submm surveys, and the WISE/radio-selected AGN fields have an even greater overdensity, by a factor $\sim 5 - 6$ (Jones et al. 2015). However, LESS fields could be under dense by a factor of $\sim 2$ e.g. Swinbank et al. (2014), and the overdensity factor of the Hot DOG fields is less secure, but compared to COSMOS and SHADES there is still an overdensity factor between 2-3.

The surface number density of SMGs in the Hot DOG fields is $866\pm210\,\text{deg}^{-2}$, and $1375\pm152\,\text{deg}^{-2}$ in the WISE/radio AGN fields, to a depth of $1.8\,\text{mJy\,beam}^{-1}$ and $2.1\,\text{mJy\,beam}^{-1}$ (submm single dish), respectively. These are higher than previous observations of the surface number density of SMGs, as can be seen in Figure 3 where SMG surface number densities of different submm surveys are plotted against RMS. Toft et al. (2014) found at $z \gtrsim 3$ the surface density of bright SMGs is $60\pm10\,\text{deg}^{-2}$ to a depth of $1.3\,\text{mJy\,beam}^{-1}$ (submm interferometer), which was found to be $\sim30\%$ lower than $z \sim 2$ quiescent galaxies. SMGs from the LABOCA-COSMOS survey were found to have a surface density between $34\pm14\,\text{deg}^{-2}$ and $54\pm18\,\text{deg}^{-2}$ at a depth of $1.5\,\text{mJy\,beam}^{-1}$ (submm interferometer), which was higher than models predicted (Smolčič et al. 2013). In the GOODS-N field the surface density of SMGs was found to be $\gtrsim 87\,\text{deg}^{-2}$ (Pope et al. 2005) at depths ranging from 0.3 to 4.1 mJy beam$^{-1}$ (submm single dish). This was likely higher than previous observations due to the association with a protocluster at $z \sim 4.05$. Geach et al. (2017) found a tentative overdensity in the GOODS-N compared to the rest of the S2CLS, while combining all of the S2CLS fields, the number counts are consistent with previous studies. Figure 3 also visually highlights the difference in RMS between single dish and interferometer measurements.

The space density of SMGs in the Hot DOG fields on average is $3.7\,\text{Mpc}^{-3}$ (range $3.0\,\text{Mpc}^{-3}$ to $6.2\,\text{Mpc}^{-3}$) and in the WISE/radio AGN fields the average space density is $2.9\,\text{Mpc}^{-3}$ (range $0.7\,\text{Mpc}^{-3}$ to $15\,\text{Mpc}^{-3}$). These space densities are higher than normal star-forming galaxies ($\sim 2\times10^{-4}\,\text{Mpc}^{-3}$) and local luminous red galaxies ($\sim 10^{-4}\,\text{Mpc}^{-3}$) (Wake et al. 2008). Previous studies have found SMGs have low number densities of $\sim 1-2\times10^{-3}\,\text{Mpc}^{-3}$, and are consistent across all redshifts (Wilkinson et al. 2017). The S2CLS was found to have SMG number densities between $4\times10^{-5}\,\text{Mpc}^{-3}$ to $2\times10^{-4}\,\text{Mpc}^{-3}$. This confirms that the fields around Hot DOGs and WISE/radio AGNs are overdense compared to previous studies of SMGs and normal star-forming galaxies.

3 TWO-POINT CORRELATION FUNCTION

The angular two-point correlation function $\omega(\theta)$ is a statistical way to characterise the clustering of galaxies in 2-dimensional (2D) space (Connolly et al. 1998).

![Figure 1. The number of submm companion sources found in each of the 10 Hot DOG fields with known redshifts (Jones et al. 2014), and the 10 WISE/radio-selected AGN fields with known redshifts (Jones et al. 2015), are shown by black diamonds and red asterisks, respectively. From previous blank field submm surveys $\sim 1$ companion source is expected in each 1.5 arcmin radius SCUBA-2 field.

We detect galaxies on a 2D surface and hence we use the angular version of the 3D spatial correlation function (Peebles 1980). It is the excess probability of finding galaxies separated by $\theta$ as compared with a random distribution. Using the one of the popular estimators described by Landy & Szalay (1993):

$$\omega(\theta) = \left( \frac{\left| DD \right| - 2 \times | DR | + | RR |}{| RR |} \right) + \sigma^2$$

where $\omega(\theta)$ is the angular correlation function, $DD$ is the number of pairs of galaxies counted in the sample, $RR$ is the number of pairs of galaxies expected in a random distribution, $DR$ is the number of pairs of galaxies counted between the sample and a random distribution and $\sigma$ is the integral constraint (Groth & Peebles 1977). The counts have been normalised by dividing by the total number of pairs in each of the three samples; $DD$, $DR$, $RR$.

The angular correlation function was calculated for the 30 WISE/radio-selected AGN fields. It was not calculated for the Hot DOG fields because there were only 10 fields and not a large enough number of companion sources to be statistically significant: the errors would be greater than the large errors on the 30 WISE/radio AGNs. To calculate the angular correlation function, 100,000 random fake galaxies were used and compared with the blank-field survey from Weiβ et al. (2008), that investigated clustering of faint galaxies, see Figure 4. Weiβ et al. (2009) found significant clustering on scales less than 1 arcmin and a characteristic angular clustering scale $\theta_0 = 14'\pm 7''$ and a spatial correlation length of $r_0 = 13\pm 6\,\text{Mpc}$. We also compared to Wilkinson et al. (2017) that analysed the largest sample of SMGs (610) in a single field to date from the SCUBA-2 Cosmology Legacy Survey (S2CLS) in the redshift range $1 < z < 3$. 

$$\omega(\theta) = \left( \frac{\left| DD \right| - 2 \times | DR | + | RR |}{| RR |} \right) + \sigma^2$$

where $\omega(\theta)$ is the angular correlation function, $DD$ is the number of pairs of galaxies counted in the sample, $RR$ is the number of pairs of galaxies expected in a random distribution, $DR$ is the number of pairs of galaxies counted between the sample and a random distribution and $\sigma$ is the integral constraint (Groth & Peebles 1977). The counts have been normalised by dividing by the total number of pairs in each of the three samples; $DD$, $DR$, $RR$. 

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$$\omega(\theta) = \left( \frac{\left| DD \right| - 2 \times | DR | + | RR |}{| RR |} \right) + \sigma^2$$
3. They found a marginally weaker clustering signal than previous studies, but within 1σ uncertainty the results are consistent with [Blain et al. (2004); Adelberger et al. (2005); Hickox et al. (2012)]. They also concluded that radio-selected SMGs were slightly more strongly clustered.

It can be seen in Figure 4 the results in the WISE/radio AGN fields provide an upper limit to the strength of an angular clustering signal, and yields a clustering angle of $\theta_0 \geq 80^\prime$. The clustering signal appears to be inconsistent to previous clustering results of SMGs, however, further observations would provide more definite results. The results from [Jones et al. (2014, 2015)] found no evidence for angular clustering when looking at the cumulative fraction of the total number of companion sources in each field within different radii of the WISE target and when looking at typical separations compared to Monte Carlo simulations.

4. PROPERTIES OF THE COMPANION SOURCES AROUND HOT DOGS AND WISE/RADIO AGNS

4.1 Counterparts of the companion Sources

A search radius of half SCUBA-2 850 μm beam size (~8 arcsec) was used to find counterparts of these companion SMGs in other catalogues ([Lilly et al. (1999); Ivison et al. (2002); Hainline et al. (2009)]. This search radius is determined from the probability of finding a source at a given distance from the SMG position ([Lilly et al. (1999); Ivison et al. (2002)]). This search radius is relatively large due to the difficulty of identifying SMGs at optical and near-IR wavelengths because of the large submm (SCUBA-2) beam, 15 arcsec at 850 μm ([Dempsey et al. (2013)]).

Multiple objects within the WISE AllWISE Source catalog had two potential counterparts within the 8 arcsec search radius. To reduce ambiguity in the result the clos-
est in WISE W1-W4 bands object is chosen while excluding objects that have WISE colours consistent with stars.

4.2 Mid-IR counterparts

The WISE colour-colour ([W2 - W3] vs [W1 - W2]) plots of the companion sources around Hot DOGs and WISE/radio AGNs are shown in Figure 5. These plots can separate different populations of galaxies because of the underlying mechanisms present in each, leading to different mid-IR emission. AGNs are dominated by power-law emission at mid-IR wavelengths. In contrast, normal and star-forming galaxies have a stellar Rayleigh-Jeans tail with additional strong PAH emission, and a continuum that peaks at 70-170 µm due to warm dust heated by young stars (Jarrett et al. 2011).

Both sets of companion sources have similar WISE colours. However, most have upper limits in the W3 band and so have limits to their red W2 - W3 colour. When comparing with the WISE colour-colour diagram of different galaxy populations in Figure 12 in Wright et al. (2010) and Figure 26 [Jarrett et al. 2011], the companion sources lie in both the starburst (star-forming) galaxy zone and AGN zone.

The Hot DOGs and WISE/radio AGNs are redder than the companion sources, see Figure 6. This is no surprise because they were selected to be red (Eisenhardt et al. 2005), and have SEDs dominated by cooler dust emission (20 - 50 K) (Hainline et al. 2009). Overdense environments around WISE-selected AGNs (Yajima et al. 2015). Observations at redshifts z > 1 found higher SFRs are associated with higher densities (Cooper et al. 2007). The mean SFR at the core of protoclusters have been found to be enhanced, up to a factor ~ 5.9 over the field (Alexander et al. 2016), and out-
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side of the central region the SFR is consistent with field galaxies. ALMA observations of the SSA22 protocluster at redshift $z = 3.09$ found enhanced SFR in the densest regions [Umehata et al. 2013]. Therefore, higher SFRs of the SMGs around WISE/radio AGNs than the SMGs around Hot DOGs is expected.

The star formation rate density (SFRD) represents the total star formation transpiring per unit time and volume at a given redshift, as seen in Figure 6. SFRDs allows direct comparison of the importance of IR-luminous galaxies to the build-up of stellar mass in the Universe. From previous work the SFRD in clusters increases with redshift from $z \sim 1$ to $z \sim 3$ [e.g. Hopkins et al. 2006; Bouwens et al. 2011; Magnelli et al. 2011; Clements et al. 2014]. e.g. [Dannerbauer et al. 2014] measured an SFRD of $\sim 900 M_\odot$ yr$^{-1}$ Mpc$^{-3}$ in the field around the spiderweb radio galaxy at redshift $z = 2.16$ in a region of 2 Mpc. However, there are observations of high-redshift clusters with a combination of quiescent and star-forming galaxies [Gobat et al. 2013; Strazzullo et al. 2013], and clusters dominated by quiescent galaxies [Tanaka et al. 2013]. Therefore, higher redshift SFRDs are needed to understand the history of galaxy clusters especially in the peak epoch of star formation at redshifts $1 < z < 3$, which includes this paper. The SFRDs were calculated for each cluster, which is the WISE-selected source and its surrounding SMGs, assuming the SMGs are at the same redshift as the source. We assumed that each cluster was spherical, and derived an angular radius from the SCUBA-2 map, 1.5 arcmin. The angular radius was converted to a proper distance at the redshift for each cluster, where the redshift is unknown the average redshift is assumed, $z = 1.7$ for WISE/radio AGNs. The volume for each cluster was calculated by assuming this proper distance is the radius of the cluster. The SFRDs are presented in Table 6, these are lower limits because faint SMGs could be missed due to the shallow depths of the SCUBA-2 maps.

The SFRDs range for Hot DOGs from $1523 \pm 30 M_\odot$ yr$^{-1}$ Mpc$^{-3}$ to $7949 \pm 159 M_\odot$ yr$^{-1}$ Mpc$^{-3}$, and average $3533 M_\odot$ yr$^{-1}$ Mpc$^{-3}$. These are lower than WISE/radio AGNs with a range from $1219 \pm 49 M_\odot$ yr$^{-1}$ Mpc$^{-3}$ to $18715 \pm 374 M_\odot$ yr$^{-1}$ Mpc$^{-3}$, and average $3929 M_\odot$ yr$^{-1}$ Mpc$^{-3}$. Our results can be compared to Figure 15 from [Clements et al. 2014] and the SFRDs calculated in this paper are higher than field galaxies from [Hopkins et al. 2006; Bouwens et al. 2011], with SFRDs of $\sim 900 M_\odot$ yr$^{-1}$ Mpc$^{-3}$ and $\sim 700 M_\odot$ yr$^{-1}$ Mpc$^{-3}$ at $z = 2$ respectively. Our values are similar to four Herschel Multitiered Extragalactic Survey (HerMES) clusters of dusty, star-forming galaxies at redshifts between $z = 0.76$ to $z = 2.26$, and other clusters with MIR/FIR measurements from the literature with SFRDs ranging from $\sim 200 M_\odot$ yr$^{-1}$ Mpc$^{-3}$ to $\sim 3000 M_\odot$ yr$^{-1}$ Mpc$^{-3}$. Simulations of massive galaxy clusters cannot account for the overdensity found by [Clements et al. 2014], which is thought to be due to insufficient peaks of star formation activity in the simulations at early epochs, and including strong starbursts in the simulations is required to explain the statistical properties of SMGs [Granato et al. 2013].

Dusty star forming galaxies (DSFG)-rich protoclusters at redshifts $2 < z < 3$ were shown to have slightly higher SFRDs compared to the field, due to their large occupying volumes [Casey 2016]. In contrast virialised clusters at redshifts $z < 1$ have a substantially higher SFRD. This is in agreement with the lower redshift WISE-selected AGNs W0342+3753, W1501+1324 and W2230–0720 that have a redshift of $z = 0.47$, $z = 0.505$ and $z = 0.444$, respectively and a significantly higher SFRD at $18715 \pm 374 M_\odot$ yr$^{-1}$ Mpc$^{-3}$, $6051 \pm 190 M_\odot$ yr$^{-1}$ Mpc$^{-3}$ and $12596 \pm 252 M_\odot$ yr$^{-1}$ Mpc$^{-3}$, respectively. This is due to a high overdensity of SMGs in each field; seven, four and four serendipitous SMG sources in each field respectively.

Completeness is the rate at which a source is expected to be detected in a map [Hatsukade et al. 2014]. It is computed by simulating the detection rate of 1,000 fake point sources per flux bin placed in the real cleaned signal map [Tamura et al. 2009]. Brighter SMGs where the flux density is $S_{1100\mu m} \geq 2.7$ mJy were found not to be significantly affected from incompleteness and false detections [Tamura et al. 2009]. They found that the completeness was $\sim 50\%$ at 2.7 mJy and 90% at 4.0 mJy. All the companion sources detected around Hot DOGs and WISE/radio AGNs have flux densities $S_{850\mu m} \geq 4.6$ mJy and $S_{850\mu m} \geq 5.5$ mJy, respectively see Tables 1–5. The completeness was found to range from 77% and 100% reported by [Hatsukade et al. 2014] from 15 SMGs observed. It was concluded that the correction for incompleteness and contamination has an effect on the low flux density bins ($S_{850\mu m} < 2.9$ mJy) and a minimal effect on the high flux density bins $S_{850\mu m} \geq 2.9$ mJy [Casey et al. 2013]. This is also confirmed by [Weiß et al. 2009] where the source extraction is complete (> 95%) for sources with flux densities $S_{870\mu m} \geq 6.5$ mJy and 50% complete at about 4.0 mJy. Therefore, the SMG completeness of the fields around Hot DOGs and WISE/radio AGNs should be between 50 and 100% complete. Hence the SFRDs could be higher than calculated here. This will also have an effect on the number count comparison with other submm surveys, where the overdensities in the WISE-selected Hot DOG and WISE/radio-selected AGN fields could have an even higher overdensity.
4.4 Radio Emission

None of the companion sources around Hot DOGs or WISE/radio AGNs were detected at radio wavelengths in FIRST and/or NVSS, where the typical 1.4 GHz detection limit was 1.0 mJy/beam, see Table 1-5. From previous observations ~ 65% of SMGs with submm flux densities $S_{\text{submm}} > 5$ mJy had detectable radio emission in much deeper observations with RMS ~ $10$ mJy (range 2.3 to 17.4 mJy) (Ivison et al. 1998, 2002, Chapman et al. 2003).

None of the 17 or 81 companion sources in the Hot DOG and WISE/radio AGN fields, respectively, are detected in NRAO snapshot follow-up VLA radio maps (priv. comm. with C. Lonsdale). The non-detections are consistent with SMG SEDs at relevant redshifts.

4.5 X-ray Emission

No counterparts to the companion sources from point sources were found in the third XMM-Newton companion Source Catalog, 3XMM-DR5 (Rosen et al. 2015). However, previous deeper X-ray observations of SMGs found only 16 with X-ray detections from sample size of 35 (45±8%) (Laird et al. 2009). These observations were from the 2-Ms Chandra survey with flux limits on the order of $10^{-17}$ erg cm$^{-2}$ s$^{-1}$ and a range 1.1 to $17.7 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$, and are deeper compared with 3XMM-DR5 of the order $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ for 3 sigma detections. Therefore, non-detections from point sources are expected.

5 DISCUSSION

5.1 Companion Source Clustering

Figure 4 provides an upper limit to the strength of an angular clustering signal in the WISE/radio AGN fields, and appears to be inconsistent with previous clustering studies of SMGs from Weiß et al. (2009); Hickox et al. (2012); Wilkinson et al. (2017). Weiß et al. (2009) found consistent correlation length values of SMGs with Blain et al. (2004); Farrah et al. (2006) but inconsistent with Scott et al. (2006), this could be explained by the small significance of the clustering signal in both studies. Hickox et al. (2012) reanalysed SMGs from the LABOCA survey in a novel method to cross-correlate SMGs in the LABOCA survey and galaxies from Spitzer IRAC. They found a lower correlation length, $r_0 = 7.7^{+1.3}_{-2.3}$ h$^{-1}$ Mpc at $z = 2$, than Weiß et al. (2009), but one that is consistent with measurements for optically-selected QSOs. The observed clustering could depend on the submm flux limit of the survey, presence of redshift spikes and uncertainties in redshift selection function (Williams et al. 2014, Adelberger et al. 2005), which could result in uncertainties in clustering estimates. Hickox et al. (2012) compared their autocorrelation length $r_0$ to previous SMG results with a range of 850 µm flux limit from 3 to 6 mJy, and found consistent angular clustering estimates. They concluded that SMGs are likely to represent a short-lived transition phase from cold, gas-rich, star-forming galaxies to passively evolving systems. Wilkinson et al. (2017) found when analysing the largest sample of SMGs in the S2CLS, SMGs are not as strongly clustered as previously thought. However, their measurements were in agreement with previous studies Blain et al. (2004); Hickox et al. (2012) within 1σ errors, and found a weaker clustering signal when comparing to Weiß et al. (2009). Accounting for blending could bring the previous studies into better agreement with Wilkinson et al. (2017). Alternatively, the SMG clustering could depend on redshift, large-scale environment and merger history. They found that the clustering of SMGs are consistent with star-forming population and lower than passive population at the same redshift, and tentative evidence of halo downsizing. Chapman et al. (2003) proposed that SMGs do not necessarily trace the most massive dark matter halos. Donoso et al. (2014) analysed the angular clustering properties of a sample of ~ 170,000 WISE-selected AGN with very red mid-IR colours. The whole sample were found to have a similar clustering strength to optically-selected quasars at comparable redshifts ($z = 1.1$) in the Sloan Digital Sky Survey (SDSS) (Porciani et al. 2004; Croom et al. 2009; Myers et al. 2007). They are found in denser environments when compared with all SDSS galaxies at that redshift. Redder AGN which are well detected at 4.6 µm (W2) have a stronger clustering bias (relationship between the distribution of dark matter and luminous matter) than blue AGN. WISE/SDSS obscured AGN are more strongly clustered and inhabit denser environments than unobscured AGN. DiPompeo et al. (2014) confirmed this but found a smaller difference in angular clustering amplitude between WISE-selected obscured quasars and unobscured quasars. However, Mendez et al. (2016) found no significant difference between obscured and unobscured AGN.

There is an overdensity of SMGs with ~ 2 or 3 SMGs per SCUBA-2 field compared with the expectation of 1 SMG from blank field submm surveys. The number of sources for the angular two-point correlation function of Hot DOGs and WISE/radio AGN fields were not numerous enough to see an angular clustering clustering signal. Monte Carlo simulations of the typical separation of the companion sources and the cumulative fraction of the total number of companion sources within different radii from the WISE target showed no angular clustering. This is agreement with Assef et al. (2013) who found no angular dependence of the IRAC overdensities around a subset of Hot DOGs.

From previous evidence there could be clustering on scales greater than the SCUBA-2 fields (Scoville et al. 2004; Blain et al. 2004; Greve et al. 2004; Farrah et al. 2006; Ivison et al. 2007; Weiß et al. 2009; Cooray et al. 2010; Scott et al. 2010; Hickox et al. 2012). Alternatively, the clustering peak could be off centre from the WISE source and not on the SCUBA-2 1.5 arcmin map scale. This agrees with Smail et al. (2014) where overdensities of the most active, ultraluminous star-forming galaxies were offset from the assumed protocluster centre and are situated in the lower-density environments. Dannerbauer et al. (2014) observed a density of SMGs up to four times greater than in blank field surveys that were not centred on the submm-bright radio galaxy.

Muldrew et al. (2014) explored the structures of protoclusters and their relationship with high-redshift galaxies using the Millennium Simulation. They found that protocluster structures are very extended at the redshifts ($z = 2$) we are probing with 90% of their mass is dispersed across ~
30 arcmin (≈ 35 h⁻¹ Mpc comoving). This would imply that many observations of protoclusters and high-redshift clusters are not imaging all of the cluster. Many protoclusters have no central or main halo that could be classified as a high-redshift cluster, only 10% were dominated by a single halo at redshift $z = 2$. This could explain why there is no evidence or only an upper limit of angular clustering in the Hot DOGs and WISE/radio AGNs fields on ≈ 1.5 arcmin scales from Monte Carlo simulations of typical separations. Alternatively, the cluster might be peaked substantially off-centre from the WISE target. Further observations of companion sources in the fields around WISE/radio AGN are needed to determine the angular two-point correlation function $\omega(\theta)$. Wide-field sub(mm) surveys are needed to cover the total (proto)cluster structure, and is in agreement with results from Casey (2016), Hung et al. (2016), where Casey (2016) found protoclusters subextend 10 arcsec to a half degree in the sky and at redshifts $z > 2$ their overdensity is difficult to detect due to their large occupied volumes. Hung et al. (2016) found large scale structure around a cluster to within 10 arcsec.

Viero et al. (2013) presented observations from Herschel and found a clustering signature from SMGs that could be decomposed into 2-halo (linear) power from galaxies in separate halos, and 1-halo (non-linear) power from multiple central and satellite galaxies occupying massive halos. It has been found that a fraction of luminous sources are found within these satellite halos for example González et al. (2011) predicts 38% SMGs and 24% SMGs with $S_{500\mu m} > 5$ mJy are satellites. Additionally, star-forming galaxies in groups and clusters were found in the outskirts of massive cluster-scale halos (Muldrew et al. 2013). The lack of clustering signal of SMGs in the Hot DOG and WISE/radio AGN fields could be because they are also in the outskirts of diffuse massive halo and not having enough sources.

### 5.2 Companion Source Properties

Only a fraction of the SCUBA-2 companion sources are detected in WISE. The WISE colours of the companion sources are consistent with star-forming galaxies and AGN, while their mid-IR to submm ratios are not consistent with AGN dominated sources (Jones et al. 2013). The companion sources hence appear to be consistent with SMGs. The SMG SFRs were estimated using their submm flux densities and are consistent with SMGs; the average SFR is ≈ 1240 M$\odot$ yr⁻¹ for SMGs around WISE/radio AGNs, slightly lower than the SFR ≈ 1460 M$\odot$ yr⁻¹ for SMGs around Hot DOGs. The SMGs around WISE/radio AGNs have slightly higher SFRs than around Hot DOGs by ≈ 18%, which is expected that SFRs are enhanced in denser regions.

When comparing the companion SMG sources radio properties to previous SMGs, around 65 - 70% of bright SMGs ($S_{500\mu m} > 7$ mJy) have been detected at S$_{1.4$GHz$}$ (Ivison et al. 2002, Borys et al. 2004). It has been suggested that the radio-undetected SMGs may have colder dust or lie at $z > 3$ (Ivison et al. 2002, Eales et al. 2003, Swinbank et al. 2008). No companion sources have radio detections in shallow NVSS or FIRST images, and the radio data are not deep enough to assess their dust temperatures.

The SFRDs of the WISE-selected AGNs are higher than the field but consistent with measurements of dusty galaxies from HerMES and DSFGs or luminous AGN. Conclusions from observations of $z > 2$ protoclusters suggest that the universe’s largest galaxy clusters are thought to be built by massive $> 10^{14}$ M$\odot$ galaxies in short-lived bursts of activity. The challenge has been to observe these structures when they have such large volumes, subextending ≈ 0.5 degrees on the sky (Casey 2016). However, the WISE-selected AGNs have high SFRDs with consistent values to these previous observations of clusters of dusty star-forming galaxies, but are on smaller volumes, with a SCUBA-2 map radius of 1.5 arcmin. Therefore, WISE-selected AGNs could be used to study protoclusters at high redshift on small volumes (arcmin scales) of the sky.

### 6 SUMMARY

Previously Hot DOGs and WISE-selected AGNs were found to be extremely obscured, hyperluminous AGN at redshifts between $0.4 < z < 4.6$. Their environments were found to be overdense in SMGs and these overdensities have been investigated here.

- The space densities of SMGs around the WISE-selected AGNs were found to be overdense compared to normal star-forming galaxies and SMGs in the S2CLS.
- The SMGs around WISE/radio AGNs $\sim 18$% higher SFRs than SMGs around Hot DOGs.
- The SFRDs of the WISE-selected AGNs are higher than field galaxies, and consistent with values for known clusters of dusty galaxies.
- The results impose an upper limit to the strength of angular clustering of the companion SMG sources in Hot DOGs and WISE/radio AGNs on SCUBA-2 1.5 arcmin scales. The typical separations when compared to Monte Carlo simulations showed no angular clustering. This is an agreement with the cumulative fraction of companion sources in different radii from the WISE target. This could be because they are satellite galaxies in the massive halo or that the protocluster is on bigger scales (up to $\sim 30$ arcmin) and we are not fully probing the protocluster.
- Hot DOGs and WISE/radio AGNs appear to be signposts of overdense environments.

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Table 1. Coordinates and photometry of the 17 companion SMG sources found around 10 Hot DOGs, with 3.4 µm, 4.6 µm, 12 µm and 22 µm magnitudes from the AllWISE Source Catalog and 850 µm flux densities from SCUBA-2. The targets with WISE upper limits have SNR < 2 and therefore in the AllWISE Source Catalog the magnitudes quoted are 2σ upper limits. The top six WISE-selected HotDOGs are detected at 850 µm, while the bottom four Hot DOGs have upper limits at 850 µm. No Herschel, NVSS, FIRST data and no objects found in SIMBAD for all the 17 companion SMG sources. FIRST detection limit for each source position is given in mJy/beam, “undetected” represents that there is no FIRST coverage or NVSS detection. A search radius of 8 arcsec was used, which is a typical search radius of SMG counterparts (Hainline et al. 2009). a Subset of these Hot DOGs have been reported by Tsai et al. (2015). b Subset of these Hot DOGs have been reported by Eisenhardt et al. (2012).

| Source Name | R.A. (J2000) | Dec. (J2000) | Distance To WISE Target (arcsec) | WISE Name | 3.4 µm (mag) | 4.6 µm (mag) | 12 µm (mag) | 22 µm (mag) | 850 µm SNR | FIRST/NVSS Detection Limit (mJy/beam) |
|-------------|-------------|-------------|---------------------------------|-----------|-------------|-------------|-------------|-------------|-----------|------------------------------------|
| W0831+0140-1 | 08:31:49.565 | 01:41:10.80 | 78 ± 8 | WISE undetected | N/A | N/A | N/A | N/A | 6.4 ± 2.1 | 3.0 | 1.00 |
| W0831+0140-2 | 08:31:48.498 | 01:40:30.80 | 73 ± 7 | WISE undetected | N/A | N/A | N/A | N/A | 7.7 ± 2.1 | 3.7 | 0.99 |
| W0831+0140-3 | 08:31:50.899 | 01:39:58.80 | 32 ± 3 | WISE undetected | N/A | N/A | N/A | N/A | 6.9 ± 2.1 | 3.3 | 0.99 |
| W1136+4236-1 | 11:36:32.866 | 42:35:14.42 | 40 ± 5 | WISE undetected | N/A | N/A | N/A | N/A | 5.4 ± 1.7 | 3.0 | 0.96 |
| W1136+4236-1 | 16:03:59.222 | 27:47:05.48 | 70 ± 7 | WISE undetected | N/A | N/A | N/A | N/A | 6.8 ± 1.8 | 3.8 | 0.93 |
| W1835+4355-1 | 18:35:28.518 | 43:54:52.36 | 77 ± 8 | WISE undetected | N/A | N/A | N/A | N/A | 4.6 ± 1.5 | 3.1 | Undetected |
| W2216+0723-1 | 22:16:21.520 | 07:24:06.50 | 30 ± 3 | WISE undetected | N/A | N/A | N/A | N/A | 4.9 ± 1.6 | 3.1 | Undetected |
| W2216+0723-2 | 22:16:16.142 | 07:24:34.83 | 33 ± 3 | WISE undetected | N/A | N/A | N/A | N/A | 5.3 ± 1.6 | 3.3 | Undetected |
| W2246−0526-1 | 22:46:02.433 | −05:26:35.43 | 84 ± 8 | WISE undetected | N/A | N/A | N/A | N/A | 6.3 ± 2.1 | 3.0 | Undetected |
| W2357+0328-1 | 23:57:08.930 | 03:27:11.40 | 48 ± 5 | J235708.59+032712.1 | 17.574 ± 0.212 | 16.679 ± 0.375 | < 12.031 | < 8.677 | 5.3 ± 1.9 | 3.1 | Undetected |
| W2357+0328-2 | 23:57:05.457 | 03:27:11.40 | 84 ± 8 | J235705.39+032710.3 | 16.536 ± 0.084 | 16.177 ± 0.240 | < 11.869 | < 8.856 | 6.7 ± 1.9 | 3.5 | Undetected |
Table 2. Coordinates and photometry of the 81 companion SMG sources found around 30 WISE/radio AGNs, with 3.4 μm, 4.6 μm, 12 μm and 22 μm magnitudes from the AllWISE Source Catalog and 850 μm flux densities from SCUBA-2. The targets with WISE upper limits have SNR < 2 and therefore in the AllWISE Source Catalog the magnitudes quoted are 2σ upper limits. No Herschel, NVSS, FIRST data and no objects found in SIMBAD for all the 81 companion SMG sources. FIRST detection limit for each source position is given in mJy/beam, "undetected" represents that there is no FIRST coverage or NVSS detection. A search radius of 8 arcsec was used, which is a typical search radius of SMG counterparts (Hainline et al. 2009).

| Source Name      | R.A. (J2000) | Dec. (J2000) | Distance To WISE Target (arcsec) | WISE Name | 3.4 μm (mag) | 4.6 μm (mag) | 12 μm (mag) | 22 μm (mag) | 850 μm (mJy) | SNR /NVSS Detection Limit (mJy/beam) |
|------------------|--------------|--------------|---------------------------------|-----------|--------------|--------------|-------------|-------------|--------------|-------------------------------------|
| W0010+1643-1     | 00:10:41.983 | 16:43:44.70  | 32±3                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 6.0 ± 1.9    | 3.2 Undetected                      |
| W0010+1643-2     | 00:10:42.284 | 16:43:28.70  | 36±4                            | J001042.69+164333.2 | 16.349 ± 0.071 | 16.116 ± 0.183 | < 11.970 | < 9.008 | 5.9 ± 1.9 | 3.1 Undetected |
| W0010+1643-3     | 00:10:40.614 | 16:42:52.37  | 34±4                            | J001040.14+164253.2 | 16.876 ± 0.108 | 16.268 ± 0.228 | < 11.943 | < 8.720 | 5.7 ± 1.9 | 3.0 Undetected |
| W0010+1643-4     | 00:10:36.461 | 16:42:16.37  | 23±3                            | J001036.63+164217.1 | 17.564 ± 0.187 | 16.550 ± 0.295 | < 12.102 | < 8.791 | 6.5 ± 1.9 | 3.4 Undetected |
| W0244+1123-1     | 02:44:23.184 | 11:24:58.40  | 58±6                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 7.9 ± 2.1   | 3.8 Undetected                      |
| W0244+1123-2     | 02:44:20.191 | 11:24:58.40  | 76±7                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 6.6 ± 2.1   | 3.1 Undetected                      |
| W0244+1123-3     | 02:44:19.421 | 11:24:10.40  | 68±7                            | J244419.14+112416.0 | 14.860 ± 0.032 | 14.546 ± 0.051 | < 12.121 | < 9.261 | 6.4 ± 2.1 | 3.0 Undetected |
| W0332+3205-2     | 03:32:28.489 | 32:05:28.67  | 21±3                            | J033228.76+320525.3 | 16.032 ± 0.061 | 16.060 ± 0.190 | < 12.561 | < 8.833 | 10.4 ± 2.0 | 5.2 Undetected |
| W0332+3205-2     | 03:32:34.155 | 32:05:48.99  | 69±7                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 6.5 ± 2.0   | 3.3 Undetected                      |
| W0342+3753-1     | 03:42:23.576 | 37:54:37.60  | 60±6                            | J034223.35+375442.8 | 14.520 ± 0.030 | 14.523 ± 0.055 | < 11.797 | < 8.743 | 8.8 ± 2.1 | 4.2 Undetected |
| W0342+3753-2     | 03:42:22.562 | 37:54:22.93  | 32±4                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 6.6 ± 2.1   | 3.1 Undetected                      |
| W0342+3753-3     | 03:42:20.872 | 37:54:26.27  | 52±5                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 7.0 ± 2.1   | 3.3 Undetected                      |
| W0342+3753-4     | 03:42:16.170 | 37:53:45.92  | 78±8                            | J034216.58+375348.5 | 17.429 ± 0.167 | < 16.701 | < 12.640 | < 8.999 | 6.9 ± 2.1 | 3.3 Undetected |
| W0342+3753-5     | 03:42:28.278 | 37:53:08.26  | 58±6                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 8.6 ± 2.1   | 4.1 Undetected                      |
| W0342+3753-6     | 03:42:28.644 | 37:53:26.27  | 57±6                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 7.6 ± 2.1   | 3.6 Undetected                      |
| W0342+3753-7     | 03:42:20.872 | 37:53:58.27  | 34±4                            | J034221.24+375401.9 | 15.910 ± 0.056 | 16.036 ± 0.167 | < 11.844 | < 8.938 | 7.4 ± 2.1 | 3.5 Undetected |
| W0352+1947-1     | 03:52:09.368 | 19:47:08.86  | 54±5                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 6.0 ± 1.9   | 3.2 Undetected                      |
| W0404+0712-1     | 04:04:41.751 | 07:12:59.20  | 40±4                            | J040441.89+071258.0 | 17.185 ± 0.145 | < 17.301 | < 12.608 | < 9.134 | 6.2 ± 1.9 | 3.3 Undetected |
| W0404+0712-2     | 04:04:43.566 | 07:12:30.20  | 35±4                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 6.2 ± 1.9   | 3.2 Undetected                      |
| W0443+0643-1     | 04:43:32.581 | 06:43:50.10  | 32±4                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 13.5 ± 3.7  | 3.6 Undetected                      |
| W0443+0643-2     | 04:43:34.230 | 06:42:09.81  | 68±7                            | J044334.58+064219.9 | 15.757 ± 0.049 | 15.578 ± 0.140 | < 12.240 | < 8.843 | 12.0 ± 3.7 | 3.2 Undetected |
| W0443+0643-3     | 04:43:35.534 | 06:42:18.67  | 70±7                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 6.0 ± 1.9   | 3.2 Undetected                      |
| W0815+3053-1     | 08:19:02.961 | 30:32:33.00  | 62±6                            | WISE undetected | N/A          | N/A          | N/A         | N/A         | 7.7 ± 2.4   | 3.2 0.93 |

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Table 3. Continue table of coordinates and photometry of the 81 companion SMG sources found around 30 WISE/radio AGNs, with 3.4 μm, 4.6 μm, 12 μm and 22 μm magnitudes from the AllWISE Source Catalog and 850 μm flux densities from SCUBA-2. The targets with WISE upper limits have SNR < 2 and therefore in the AllWISE Source Catalog the magnitudes quoted are 2σ upper limits. No Herschel, NVSS, FIRST data and no objects found in SIMBAD for all the 81 companion SMG sources. FIRST detection limit for each source position is given in mJy/beam, "undetected" represents that there is no FIRST coverage or NVSS detection. A search radius of 8 arcsec was used, which is a typical search radius of SMG counterparts [Hainline et al. 2009].

| Source Name | R.A. (J2000) | Dec. (J2000) | Distance To Target (arcsec) | WISE Name | 3.4 μm (mag) | 4.6 μm (mag) | 12 μm (mag) | 22 μm (mag) | 850 μm (mJy) | SNR /FIRST /NVSS Detection Limit (mJy/beam) |
|-------------|-------------|-------------|----------------------------|-----------|-------------|-------------|-------------|-------------|-------------|------------------------------------------|
| W0849+3033-2 | 08:49:05:438 | 30:32:12:33 | 76±8 | WISE undetected | N/A | N/A | N/A | N/A | 7.5 ± 2.4 | 3.1 |
| W0849+3033-3 | 08:49:07:270 | 30:32:12:33 | 83±8 | WISE undetected | N/A | N/A | N/A | N/A | 7.9 ± 2.4 | 3.3 |
| W1025+6128-1 | 10:25:02:081 | 61:28:49:02 | 54±5 | WISE undetected | N/A | N/A | N/A | N/A | 6.3 ± 2.0 | 3.2 |
| W1025+6128-2 | 10:25:12:691 | 61:27:40:36 | 58±6 | WISE undetected | N/A | N/A | N/A | N/A | 6.0 ± 2.0 | 3.0 |
| W1025+6128-3 | 10:25:14:969 | 61:27:21:36 | 78±8 | WISE undetected | N/A | N/A | N/A | N/A | 6.1 ± 2.0 | 3.1 |
| W1046-0250-1 | 10:46:31:465 | -02:50:06.70 | 30±4 | J104631.08+025001.8 | 17.645 ± 0.216 | 16.490 ± 0.283 | < 12.532 | < 8.979 | 6.7 ± 2.1 | 3.2 |
| W1046-0250-2 | 10:46:30:931 | -02:49:11.70 | 75±8 | WISE undetected | N/A | N/A | N/A | N/A | 7.2 ± 2.1 | 3.4 |
| W1046-0250-3 | 10:46:37:272 | -02:50:32.70 | 59±6 | WISE undetected | N/A | N/A | N/A | N/A | 6.2 ± 2.1 | 3.0 |
| W1107+3421-1 | 11:07:32:012 | 34:20:55.03 | 34±4 | WISE undetected | N/A | N/A | N/A | N/A | 7.0 ± 2.0 | 3.0 |
| W1107+3421-2 | 11:07:30:425 | 34:19:51.36 | 88±8 | WISE undetected | N/A | N/A | N/A | N/A | 6.4 ± 2.0 | 3.2 |
| W1107+3421-3 | 11:07:30:748 | 47:50:51.20 | 49±5 | J121031.00+475052.0 | 17.411 ± 0.141 | 16.638 ± 0.254 | < 12.681 | < 8.527 | 8.2 ± 2.3 | 3.6 |
| W1210+4750-1 | 12:10:30:748 | 47:50:50.51 | 88±8 | WISE undetected | N/A | N/A | N/A | N/A | 7.0 ± 2.3 | 3.0 |
| W1210+4750-2 | 12:10:30:748 | 47:50:50.51 | 88±8 | WISE undetected | N/A | N/A | N/A | N/A | 7.0 ± 2.3 | 3.0 |
| W1210+4750-3 | 12:10:30:515 | 47:49:50.86 | 28±3 | J121205.53+474556.7 | 16.952 ± 0.009 | 16.452 ± 0.203 | < 12.641 | < 9.017 | 7.6 ± 2.3 | 3.3 |
| W1210+4750-4 | 12:10:26:676 | 47:48:38.87 | 85±8 | J121207.36+474837.9 | 17.364 ± 0.129 | 17.296 ± 0.408 | < 12.331 | < 8.909 | 10.7 ± 2.3 | 4.7 |
| W1210+4750-5 | 12:10:21:181 | 47:49:27.85 | 75±8 | J121201.04+474927.4 | 17.210 ± 0.124 | 16.402 ± 0.207 | < 12.546 | < 8.992 | 7.7 ± 2.3 | 3.3 |
| W1212+4659-1 | 12:12:08:419 | 47:00:07.23 | 36±4 | J121208.25+470004.4 | 16.950 ± 0.103 | 16.375 ± 0.211 | < 12.261 | < 8.896 | 7.9 ± 2.5 | 3.2 |
| W1212+4659-2 | 12:12:10:015 | 46:59:34.56 | 48±5 | WISE undetected | N/A | N/A | N/A | N/A | 6.0 ± 1.9 | 3.2 |
| W1212+4659-3 | 12:12:11:970 | 46:59:42.22 | 63±6 | WISE undetected | N/A | N/A | N/A | N/A | 7.8 ± 2.5 | 3.1 |
| W1409+1732-1 | 14:09:22:400 | 17:32:20.03 | 82 | WISE undetected | N/A | N/A | N/A | N/A | 6.4 ± 2.0 | 3.2 |
| W1409+1732-2 | 14:09:26:832 | 17:31:44.35 | 30±4 | J140927.37+173142.7 | 17.603 ± 0.174 | < 16.764 | 12.961 ± 0.526 | < 8.759 | 6.4 ± 2.0 | 3.2 |
| W1409+1732-3 | 14:09:27:950 | 17:31:07.73 | 59±6 | J140928.23+173108.2 | 17.956 ± 0.211 | 16.908 ± 0.311 | < 12.657 | < 9.339 | 7.9 ± 2.0 | 4.0 |
| W1428+1113-1 | 14:29:00:256 | 17:12:11.25 | 68±7 | WISE undetected | N/A | N/A | N/A | N/A | 6.0 ± 1.9 | 3.7 |
| W1501+1324-1 | 15:01:41.713 | 13:24:57.90 | 44±4 | J150141.93+132450.8 | 18.011 ± 0.214 | < 17.207 | < 12.892 | < 9.321 | 7.1 ± 2.2 | 3.2 |
| W1501+1324-2 | 15:01:42.192 | 13:23:57.23 | 63±6 | J150142.45+132358.6 | 17.196 ± 0.106 | 16.988 ± 0.330 | < 12.984 | < 9.239 | 7.2 ± 2.2 | 3.3 |
Table 4. Continue table of coordinates and photometry of the 81 companion SMG sources found around 30 WISE/radio AGNs, with 3.4 µm, 4.6 µm, 12 µm and 22 µm magnitudes from the AllWISE Source Catalog and 850 µm flux densities from SCUBA-2. The targets with WISE upper limits have SNR < 2 and therefore in the AllWISE Source Catalog the magnitudes quoted are 2σ upper limits. No Herschel, NVSS, FIRST data and no objects found in SIMBAD for all the 81 companion SMG sources. FIRST detection limit for each source position is given in mJy/beam, “undetected” represents that there is no FIRST coverage or NVSS detection. A search radius of 8 arcsec was used, which is a typical search radius of SMG counterparts (Hainline et al. 2009).

| Source Name | R.A. (J2000) | Dec. (J2000) | Distance To Source (arcsec) | WISE Name | 3.4 µm (mag) | 4.6 µm (mag) | 12 µm (mag) | 22 µm (mag) | 850 µm (mJy) | SNR | FIRST/NVSS Detection Limit (mJy/beam) |
|-------------|--------------|-------------|----------------------------|-----------|--------------|--------------|--------------|-------------|----------------|-----|-------------------------------------|
| W1501+1324-3 | 15:01:40.022 | 13:23:33.90 | 76±7 | WISE undetected | N/A | N/A | N/A | N/A | 7.3 ± 2.2 | 3.3 | 0.94 |
| W1501+1324-4 | 15:01:38.423 | 13:24:33.57 | 20±3 | WISE undetected | N/A | N/A | N/A | N/A | 6.8 ± 2.2 | 3.1 | 0.94 |
| W1517+3523-1 | 15:17:59.282 | 35:24:29.97 | 32±3 | WISE undetected | N/A | N/A | N/A | N/A | 5.8 ± 1.9 | 3.1 | 0.94 |
| W1517+3523-2 | 15:17:56.992 | 35:23:49.97 | 24±3 | WISE undetected | N/A | N/A | N/A | N/A | 5.7 ± 1.9 | 3.0 | 0.99 |
| W1517+3523-3 | 15:17:51.703 | 35:23:33.95 | 88±8 | J151751.39+352327.9 | 17.874 ± 0.158 | < 17.702 | < 12.762 | < 9.464 | 5.7 ± 1.9 | 3.0 | 0.99 |
| W1517+3523-4 | 15:17:54.348 | 35:23:02.30 | 72±7 | J151754.19+352302.8 | 16.418 ± 0.052 | 15.611 ± 0.084 | 12.607 ± 0.319 | < 9.495 | 5.7 ± 1.9 | 3.0 | 0.99 |
| W1517+3523-5 | 15:17:56.065 | 35:22:35.30 | 74±7 | WISE undetected | N/A | N/A | N/A | N/A | 5.8 ± 1.9 | 3.1 | 0.99 |
| W1630+5126-1 | 16:30:41.014 | 51:26:52.03 | 56±6 | WISE undetected | N/A | N/A | N/A | N/A | 5.8 ± 1.9 | 3.1 | 0.96 |
| W1630+5126-2 | 16:30:30.174 | 51:27:04.36 | 73±7 | WISE undetected | N/A | N/A | N/A | N/A | 5.8 ± 1.9 | 3.1 | 0.97 |
| W1703+2615-1 | 17:03:35.673 | 26:16:19.28 | 70±7 | WISE undetected | N/A | N/A | N/A | N/A | 6.8 ± 2.0 | 3.4 | 0.98 |
| W1717+5313-1 | 17:17:00.517 | 53:13:51.29 | 49±5 | WISE undetected | N/A | N/A | N/A | N/A | 7.5 ± 2.5 | 3.0 | 0.95 |
| W1717+5313-2 | 17:17:00.592 | 53:13:15.63 | 53±5 | J171700.48+531319.7 | 15.618 ± 0.341 | 15.988 ± 0.195 | < 10.482 | < 8.604 | 11.7 ± 2.5 | 4.7 | 0.95 |
| W1717+5313-3 | 17:17:08.461 | 53:13:15.96 | 40±4 | WISE undetected | N/A | N/A | N/A | N/A | 7.5 ± 2.5 | 3.0 | 0.96 |
| W2126−0103-1 | 21:26:17.587 | −01:04:18.48 | 50±5 | WISE undetected | N/A | N/A | N/A | N/A | 7.8 ± 2.0 | 3.9 | 1.0 |
| W2133−1419-1 | 21:33:53.760 | −14:19:46.42 | 58±6 | J213353.65−141946.5 | 15.902 ± 0.037 | 14.929 ± 0.080 | < 12.506 | < 8.595 | 5.5 ± 1.8 | 3.1 | Undetected |
| W2212+3326-1 | 22:12:54.092 | 33:26:36.35 | 63±6 | WISE undetected | N/A | N/A | N/A | N/A | 8.9 ± 2.0 | 4.5 | Undetected |
| W2212+3326-2 | 22:12:50.943 | 33:27:24.72 | 86±6 | WISE undetected | N/A | N/A | N/A | N/A | 8.2 ± 2.0 | 3.6 | Undetected |
| W2212−1253-1 | 22:12:00.655 | −12:53:38.03 | 59±6 | WISE undetected | N/A | N/A | N/A | N/A | 8.0 ± 2.1 | 3.8 | Undetected |
| W2212−1253-2 | 22:12:09.226 | −12:54:07.70 | 59±6 | WISE undetected | N/A | N/A | N/A | N/A | 7.5 ± 2.1 | 3.6 | Undetected |
| W2222+0951-1 | 22:22:44.211 | 09:51:18.11 | 58±6 | WISE undetected | N/A | N/A | N/A | N/A | 7.3 ± 2.0 | 3.7 | 0.86 |
| W2222+0951-2 | 22:22:46.971 | 09:50:09.38 | 78±7 | J222247.42+095008.1 | 17.476 ± 0.180 | < 17.290 | < 12.598 | < 8.629 | 9.3 ± 2.0 | 4.7 | 0.85 |
| W2222+0951-3 | 22:22:50.953 | 09:50:29.02 | 62±6 | WISE undetected | N/A | N/A | N/A | N/A | 8.6 ± 2.0 | 4.3 | 0.86 |
| W2226+0025-1 | 22:26:20.255 | 00:24:35.57 | 69±7 | WISE undetected | N/A | N/A | N/A | N/A | 8.4 ± 1.9 | 4.4 | 0.77 |
| W2226+0025-2 | 22:26:21.855 | 00:24:04.23 | 74±7 | WISE undetected | N/A | N/A | N/A | N/A | 6.9 ± 1.9 | 3.7 | 0.77 |
Table 5. Continuum table of coordinates and photometry of the 81 companion SMG sources found around 30 WISE/radio AGNs, with 3.4 μm, 4.6 μm, 12 μm and 22 μm magnitudes from the AllWISE Source Catalog and 850 μm flux densities from SCUBA-2. The targets with WISE upper limits have SNR < 2 and therefore in the AllWISE Source Catalog the magnitudes quoted are 2σ upper limits. No Herschel, NVSS, FIRST data and no objects found in SIMBAD for all the 81 companion SMG sources. FIRST detection limit for each source position is given in mJy/beam, "undetected" represents that there is no FIRST coverage or NVSS detection. A search radius of 8 arcsec was used, which is a typical search radius of SMG counterparts (Hainline et al. 2009).

| Source Name | R.A. (J2000) | Dec. (J2000) | Distance To WISE Target (arcsec) | WISE Name | 3.4 μm (mag) | 4.6 μm (mag) | 12 μm (mag) | 22 μm (mag) | 850 μm (mJy) | SNR | FIRST/NVSS Detection Limit (mJy/beam) |
|-------------|--------------|-------------|----------------------------------|-----------|--------------|--------------|-------------|-------------|--------------|-----|--------------------------------------|
| W2230−0720-1 | 22:30:06.5993 | −07:19:51.90 | 70±7 | WISE undetected | N/A | N/A | N/A | N/A | 5.8 ± 1.8 | 3.2 | 0.93 |
| W2230−0720-2 | 22:30:09.189 | −07:19:59.90 | 57±6 | WISE undetected | N/A | N/A | N/A | N/A | 6.0 ± 1.8 | 3.3 | 0.93 |
| W2230−0720-3 | 22:30:12.080 | −07:20:47.90 | 59±6 | WISE undetected | N/A | N/A | N/A | N/A | 5.5 ± 1.8 | 3.1 | 0.93 |
| W2230−0720-4 | 22:30:08.607 | −07:22:24.23 | 80±8 | J223008.35−072220.9 | 17.423 ± 0.174 | 16.992 ± 0.438 | < 12.065 | < 8.834 | 5.7 ± 1.8 | 3.2 | 0.92 |
| W2325−0429-1 | 23:25:06.972 | −04:28:44.43 | 66±7 | WISE undetected | N/A | N/A | N/A | N/A | 7.1 ± 2.1 | 3.4 | 2.27 |
| W2325−0429-2 | 23:25:01.088 | −04:30:43.77 | 76±7 | WISE undetected | N/A | N/A | N/A | N/A | 9.8 ± 2.1 | 4.7 | 2.20 |
| W2331−1411-1 | 23:31:05.148 | −14:11:08.87 | 48±5 | J233104.89−141108.4 | 16.393 ± 0.074 | 16.900 ± 0.423 | < 12.543 | < 8.351 | 6.9 ± 2.2 | 3.1 | Undetected |
| W2345+3120-1 | 23:45:44.634 | 31:19:41.80 | 56±6 | J234544.45+311941.9 | 17.217 ± 0.124 | 15.988 ± 0.157 | < 12.585 | < 8.841 | 11.3 ± 2.0 | 5.7 | Undetected |
| W2345+3120-2 | 23:45:34.358 | 31:20:02.12 | 84±8 | WISE undetected | N/A | N/A | N/A | N/A | 6.3 ± 2.0 | 3.2 | Undetected |
Table 6. SFRDs of Hot DOGs (top 10) and WISE/radio AGNs (bottom 30) and their surrounding SMGs, assuming they are at the same redshift. The angular radius is estimated to be the size of the SCUBA-2 map, 1.5 arcmin. The spectroscopically known redshifts of the WISE-selected targets are shown. The unknown redshifts of the WISE/radio AGNs are assumed to the average of WISE/radio AGNs, $z = 1.7$.

| Source          | SFRD $\text{M}_\odot \text{yr}^{-1} \text{Mpc}^{-3}$ | Redshift |
|-----------------|-----------------------------------------------------|----------|
| W0831+0140      | 7949±159                                            | 3.91     |
| W1136+4236      | 2064±41                                             | 2.39     |
| W1603+2747      | 2989±60                                             | 2.63     |
| W1814+3412      | 1523±30                                             | 2.45     |
| W1835+4355      | 2406±48                                             | 2.3      |
| W2026+0716      | 2835±57                                             | 2.54     |
| W2054+0207      | 4304±86                                             | 2.52     |
| W2216+0723      | 2917±58                                             | 1.68     |
| W2246−0526      | 5808±116                                            | 4.59     |
| W2357+0338      | 2538±51                                             | 2.12     |
| W0010+1643      | 5311±106                                            | 2.855    |
| W0244+1123      | 4035±162                                            | Unknown  |
| W0332+3205      | 1799±72                                             | Unknown  |
| W0342+3753      | 18715±374                                           | 0.47     |
| W0352+1947      | 1045±42                                             | Unknown  |
| W0404+0712      | 2133±85                                             | Unknown  |
| W0443+0643      | 3686±147                                            | Unknown  |
| W0849+3033      | 4005±160                                            | Unknown  |
| W1025+0712      | 3091±124                                            | Unknown  |
| W1046−0250      | 2699±108                                            | Unknown  |
| W1107+3421      | 2119±42                                             | Unknown  |
| W1210+4750      | 4992±100                                            | Unknown  |
| W1212+4659      | 3178±64                                             | Unknown  |
| W1409+1732      | 3454±138                                            | Unknown  |
| W1428+1113      | 1219±49                                             | 1.6      |
| W1501+1324      | 9501±190                                            | 0.505    |
| W1517+3523      | 4499±90                                             | 1.515    |
| W1630+5126      | 2046±82                                             | Unknown  |
| W1703+2615      | 1364±55                                             | Unknown  |
| W1717+5313      | 3935±157                                            | 2.717    |
| W2126−0103      | 2247±89                                             | 0.607    |
| W2133−1419      | 1132±45                                             | Unknown  |
| W2212−1253      | 2931±117                                            | Unknown  |
| W2212+3326      | 1799±72                                             | Unknown  |
| W2222+0951      | 3149±63                                             | Unknown  |
| W2226+0025      | 4025±80                                             | 0.607    |
| W2230−0720      | 12596±252                                           | 0.444    |
| W2235−0429      | 2220±88                                             | 1.737    |
| W2231−1411      | 2177±87                                             | Unknown  |
| W2345+3120      | 2772±111                                            | Unknown  |