FROM THE $L_{\text{IR}}$–$T$ RELATION TO THE LIMITED SIZES OF DUSTY STARBURSTING REGIONS AT HIGH REDSHIFTS

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ABSTRACT

Using the far-infrared (IR) data obtained by the Herschel Space Observatory, we study the relation between the IR luminosity ($L_{\text{IR}}$) and the dust temperature ($T$) of dusty starbursting galaxies at high redshifts (high-$z$). We focus on the total IR luminosity from the cold-dust component ($L_{\text{IR}}^{\text{cd}}$), whose emission can be described by a modified blackbody (MBB) of a single temperature ($T_{\text{mbb}}$). An object on the ($L_{\text{IR}}^{\text{cd}}, T_{\text{mbb}}$) plane can be explained by the equivalent of the Stefan–Boltzmann law for an MBB with an effective radius of $R_{\text{eff}}$. We show that $R_{\text{eff}}$ is a good measure of the combined size of the dusty starbursting regions (DSBRs) of the host galaxy. In at least one case where the individual DSBRs are well resolved through strong gravitational lensing, $R_{\text{eff}}$ is consistent with the direct size measurement. We show that the observed $L_{\text{IR}}$–$T$ relation is simply due to the limited $R_{\text{eff}}$ ($\lesssim2$ kpc). The small $R_{\text{eff}}$ values also agree with the compact sizes of the DSBRs seen in the local universe. However, previous interferometric observations to resolve high-$z$ dusty starbursting galaxies often quote much larger sizes. This inconsistency can be reconciled by the blending effect when considering that the current interferometry might still not be of sufficient resolution. From $R_{\text{eff}}$ we infer the lower limits to the volume densities of the star formation rate (minSFR3D) in the DSBRs, and find that the $L_{\text{IR}}$–$T$ relation outlines a boundary on the ($L_{\text{IR}}^{\text{cd}}, T_{\text{mbb}}$) plane, below which is the “zone of avoidance” in terms of minSFR3D.

Key words: galaxies: evolution – galaxies: high-redshift – galaxies: starburst – infrared: galaxies

1. INTRODUCTION

Dusty infrared (IR) galaxies are known to have a correlation between their IR luminosities and dust temperatures ($L_{\text{IR}}$–$T$ relation). Generally speaking, ultra-luminous IR galaxies (ULIRGs; $L_{\text{IR}} \sim 10^{12}$–$10^{13} L_{\odot}$) and hyper-luminous IR galaxies (HyLIRGs; $L_{\text{IR}} \gtrsim 10^{13} L_{\odot}$) have typical dust temperatures of $\sim40$–$60$ K, while luminous IR galaxies (LIRGs; $L_{\text{IR}} \sim 10^{11}$–$10^{12} L_{\odot}$) and others at lower luminosities have lower dust temperatures of $\sim20$–$30$ K. This trend was clearly revealed when submillimeter galaxies (SMGs), which are high-$z$ ULIRGs, were compared to ULIRGs and other IR galaxies in the local universe (e.g., Blain et al. 2003; Chapman et al. 2003). There have been a number of studies to understand the nature of this relation, such as its dependence on redshifts, different galaxy populations, etc. (e.g., Chapman et al. 2005; Kovács et al. 2006; Clements et al. 2010; Hwang et al. 2010; Magdis et al. 2010; Magnelli et al. 2010; Symeonidis et al. 2013; Magnelli et al. 2014).

In Ma & Yan (2015, hereafter MY15), we have studied the quasars from the Sloan Digital Sky Survey (SDSS) that have far-IR (FIR) counterparts in the wide-field survey data from the Herschel Space Observatory (Pilbratt et al. 2010). We have shown that the majority of them are ULIRGs and that their FIR emission originated from the cold-dust component is predominantly powered by starbursts rather than active galactic nuclei (AGNs). One of our conclusions is that they follow the same $L_{\text{IR}}$–$T$ relation. We have further shown that this relation is simply due to the limited maximum size of the combined dusty starbursting regions (DSBRs) in the host galaxies. The motivation of our current work is that this maximum size is only around $\sim2$ kpc, which seems to be significantly smaller than the claimed physical sizes of high-$z$ ULIRGs based on a number of direct measurements through submillimeter (submm) or radio interferometry. These observations have subarcsec resolutions, and typically result in rather extended sizes of $\sim4$–$8$ kpc or even larger (e.g., Chapman et al. 2004; Biggs & Ivison 2008; Younger et al. 2008, 2010; Simpson et al. 2015).

Here, we further investigate this problem, using an enlarged sample that incorporates different high-$z$ IR galaxy populations. Throughout this Letter, we adopt the following cosmological parameters: $\Omega_M = 0.27$, $\Omega_{\Lambda} = 0.73$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$.

2. DATA AND ANALYSIS

We followed MY15 in this current work. While there are a considerable number of IR galaxies from other sources that have existing IR luminosity and dust temperature estimates from the literature, these are based on various observations and methods, and thus are not ideal for our purpose because they are impacted by different systematic effects. We sought to base our analysis on a large sample that could be treated uniformly, and we only used the objects that have spectroscopic redshifts.

2.1. Input Samples

The largest addition to the MY15 sample is through the use of the 13th edition Véron Catalogue of Quasars and Active Nuclei (Véron-Cetty & Véron 2010), which contains 34,231 and 133,332 AGNs and quasars, respectively (V-AGNs and V-QSOs, respectively). The next is from Casey et al. (2012, hereafter C12), which contains 767 spectrally-galaxies. We also included the SMGs from Chapman et al. (2005, hereafter C05) and Ivison et al. (2005, hereafter I05), and a few sources of mixed selections from Magdis et al. (2011, hereafter M11) and Yan et al. (2014, hereafter Y14).

The FIR counterpart identification was based on the latest source catalogs from three major wide-field surveys by Herschel, namely, the Herschel Multi-tiered Extragalactic
Survey (HerMES, ~100 deg$^{-2}$; Oliver et al. 2012; the “xID” catalogs from Wang et al. 2014), the Herschel Stripe 82 Survey (HerS, ~80 deg$^{-2}$; Viero et al. 2014), and the Scientific Demonstration Phase data of the Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS SDP, ~19.3 deg$^{-2}$; Eales et al. 2010; Ibar et al. 2010; Pascale et al. 2011; Rigby et al. 2011). The FIR spectral energy distributions (SEDs) were constructed using the three-band photometry from the Spectral and Photometric Imaging REceiver (SPIRE; Griffin et al. 2010) at 250, 350, and 500 μm. As in MY15, we obtained the SPIRE photometry by matching the sources to the aforementioned Herschel catalogs, adopting the matching radius of 3″ to minimize the contaminated sources due to blending. We only considered the objects that are detected in all three of these bands.

We also incorporated a number of objects that are outside of the aforementioned Herschel survey fields but have reported SPIRE photometry. These include the high-z quasars from Leipski et al. (2013), hereafter L13, the radio galaxies from Drouart et al. (2014, hereafter D14), and the 3 C radio sources from Podgadchoksi et al. (2015, hereafter P15). While these objects certainly contain powerful AGNs, we are convinced (as these authors are also inclined to believe) that their FIR emissions should be dominated by starbursts as in the SDSS quasars presented in MY15.

Finally, we included a few high-z ULIRGs that are known to be amplified by strong gravitational lensing, which all have spectroscopic redshifts, reported SPIRE photometry, and adopted amplification factors ($\mu$). These include the most highly lensed SMGs from Swinbank et al. (2010) and Ivison et al. (2010, hereafter S10), the strong Planck source from Fu et al. (2012, hereafter F12), the South Pole Telescope’s lensed galaxies from Weiß et al. (2013) and Hezaveh et al. (2013 hereafter W&H13), and the lensed galaxies in the H-ATLAS SDP from Bussmann et al. (2013, hereafter B13; only the two sources with grade “A” lensing models and $\mu > 10$ were used).

2.2. SED Fitting and the Final Sample

As in MY15, we only studied the coldest-dust component, which dominates the FIR emission that is sampled by the SPIRE bands. While this will certainly underestimate (by ~0.1–0.2 dex) the total IR luminosity that consists of the contributions from other components of higher temperatures, the simplification has the advantages that the associated luminosity can be safely attributed to starbursts and that the dust temperature is uniquely defined. Following MY15, we analyzed their FIR SEDs by fitting a single-temperature, modified blackbody (MBB) spectrum. We briefly describe the procedure below.

We used the cmcirsed code of Casey (2012) to perform the MBB fitting. The MBB spectrum can be written as

$$S_\lambda(\lambda) = N \cdot I_{mbb}(\lambda)$$

$$= N \frac{1 - e^{-\frac{(\lambda/\lambda_0)^\beta}{\mu}}}{1 - e^{-1}} \left(\frac{2\pi c^3}{\lambda^5}\right),$$

where $T_{mbb}$ is the characteristic temperature of the MBB, $N$ is the scaling factor that is related to the intrinsic luminosity, $\beta$ is the emissivity (when $\beta = 0$, Equation (1) reduces to the form of a blackbody), and $\lambda_0$ is the reference wavelength where the opacity is unity. We adopted $\beta = 1.5$ and $\lambda_0 = 100 \mu m$. The total IR luminosity of the cold-dust component, $L_{IR}^{cd}$, can be obtained as

$$L_{IR}^{cd} = L_{IR}^{mbb} \equiv \int_{8 \mu m}^{1000 \mu m} S_\lambda(\lambda) d\lambda$$

by integrating the best-fit MBB model $S_\lambda(\lambda)$ from 8 to 1000 μm.

Our further analysis is based on $L_{IR}^{cd}$ and $T_{mbb}$, thus obtained. We only retained the objects that have reasonable SED fitting quality ($\chi^2 < 10$) and reliable $T_{mbb}$ measurements ($T_{mbb}/\Delta T_{mbb} > 3$), which sum up to 400 objects in total. As examples, Figure 1 shows the SED fitting results for a few objects from our final sample. Figure 2 shows the $L_{IR}^{cd}$–$T_{mbb}$ relation from the entire sample, where the number of contributing objects from each initial sample is also labeled. The distributions of redshifts, $L_{IR}^{cd}$, and $T_{mbb}$ are shown in the top panel of Figure 3.

3. INTERPRETATIONS

Depending on the samples, the photometry, or the analyzing methods (e.g., fitting model and parameters), the $L_{IR}^{cd}$–$T_{mbb}$ relations discussed in the literature could be different in their details as compared to that revealed in Figure 2. However, the general trend is the same, namely, there are few objects with high IR luminosities and low dust temperatures. As addressed in MY15, such a trend is not due to selection effects but is governed by the equivalent of the Stefan–Boltzmann law in the case of MBB. Here, we fully develop this idea.
3.1. Effective Radius of DSBRs

The location of an object on the \((L_{IR}^{(cd)}, T_{mbb})\) plane is determined by the intensity of the MBB as expressed in Equation (1). To obtain the total power radiated from the cold-dust component of the object, i.e., its total luminosity, one should integrate the MBB function \(I_{mbb}(\lambda)\) over wavelength and over the solid angle (\(\Omega\)) that its surface area \((A)\) subtends as seen from the source, and multiply by this surface area:

\[
L = A \cdot \int_0^\infty I_{mbb}(\lambda) \, d\lambda \int d\Omega \quad \text{(3)}
\]

where we make the substitution of \(u = \frac{hc}{\lambda K}\), set \(\tau = \frac{\lambda K T}{hc}\), and also write \(T_{mbb}\) as \(T\) for convenience. If there were no the modified term \((1 - e^{-\tau u})^\beta\) to the Planck’s blackbody function, the integral above would be \(\pi^2/15\) and Equation (3) would reduce to the Stefan–Boltzmann law, i.e., \(L = A\sigma T^4\), where \(\sigma = \frac{2\pi^2k^4}{15h^2c^2}\) is the Stefan–Boltzmann constant. For simplicity, we introduce

\[
\bar{\sigma}(T, \beta, \lambda_0) = \frac{2\pi^2 k^4}{h^2c^2} \int_0^\infty \frac{1 - e^{-(\tau u)^\beta}}{1 - e^{-1}} \frac{u^3}{e^u - 1} \, du,
\]

which is the equivalent of the Stefan–Boltzmann constant in the MBB case. Note that \(\bar{\sigma}\) is dependent on \(T\) because \(\tau \equiv \frac{\lambda_0 k T}{hc}\) is involved.

We approximate the integral in Equation (3) to be only over the conventional total IR regime from 8 to 1000 \(\mu m\) (as in Equation (2)) such that \(L \approx L_{IR}^{(cd)}\), i.e., we have \(L_{IR}^{(cd)} = A\bar{\sigma}T_{mbb}^4\), which we refer to as the MBB S-B equivalent.

We can define an effective radius, \(R_{eff}\), such that \(A = 4\pi R_{eff}^2\). This is to imagine that all the star-forming regions within the galaxy are combined into an effective sphere of radius \(R_{eff}\) We thus have

\[
L_{IR}^{(cd)} = 4\pi R_{eff}^2 \bar{\sigma}T_{mbb}^4. \quad \text{(4)}
\]

For \(T_{mbb}\) within the range of interest (~10–100 K), the deviation of \(\bar{\sigma}\) from \(\sigma\) is within a factor of two and can be well approximated as

\[
\bar{\sigma}(T) / \sigma = 10^{-3}(-3.03T^{1.5} + 45.55T - 127.53), \quad \text{(5)}
\]

for our choice of \(\lambda_0 = 100 \mu m\) and \(\beta = 1.5\) (see the right panel of Figure 2).

Thus, the data points on the \((L_{IR}^{(cd)}, T_{mbb})\) plane can be explained by a family of MBB S-B equivalent curves of different \(R_{eff}\) which are shown in Figure 2. MY15 uses the same argument and shows that (1) in the low-luminosity regime, the increasing of \(L_{IR}^{(cd)}\) is due to the increasing of \(R_{eff}\); while in the high-luminosity regime, the increase of \(L_{IR}^{(cd)}\) has to be attributed to the increased heating intensity, and (2) \(R_{eff}\) cannot be increased arbitrarily and has a limit of \(\lesssim 2\) kpc. MY15 takes a less rigorous approach and approximates the temperature-dependent \(\sigma\) by \(\sigma T^{\alpha}\) and obtains \(L_{IR} = 4\pi R_{eff}^2 \sigma T^{4.32}\). The derivation of Equation (4) here is more appropriate, which results in a more accurate determination of \(R_{eff}\).

The distribution \(R_{eff}\) is shown in Figure 3 for all the objects in our sample. The vast majority of them (98.3%) have

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**Figure 2.** \(L_{IR} - T\) relation as revealed by our final sample. The individual objects from different input samples and the total numbers are shown with symbols of different colors as in the legend. The dashed curves are a family of MBB S-B equivalent to different \(R_{eff}\), whose values are marked next to the curves (see Section 3.1). The right panel shows \(\bar{\sigma}(T) / \sigma\) (red dashed curve) and the fit (gray solid curve).
$R_{\text{eff}} \leq 2 \text{ kpc}$, and this limit is the reason for the observed $L_{\text{IR}}-T$ relation. The error in $R_{\text{eff}}$ for each object can be estimated through error propagation using Equation (4), which we have also independently verified through simulations. In general, $\Delta R_{\text{eff}}/R_{\text{eff}} \sim 20\%-30\%$.

### 3.2. SFR Surface and Volume Densities

While $R_{\text{eff}}$ as introduced above is a mathematical representation, it can also be a physical scale indicator and thus can have important implications.

As an example, we can use $R_{\text{eff}}$ to derive the SFR surface densities ($\Sigma_{\text{SFR}}$, or $\Sigma_{\text{SFR}2D}$) that are often used in the literature. Following Kennicutt (1998), to convert the IR luminosity to the SFR and assuming the initial mass function of Chabrier (2003), we get $\text{SFR} \sim 10^{10} L_{\text{IR}}(\text{cd})/L_{\odot} \text{ yr}^{-1}$. The surface area going into the SFR2D calculation is the area of the DSBRs projected on the sky. Assuming spherical symmetry, the total surface area of the $i$th DSBR is $4\pi R_i^2$, where $R_i$ is its radius. We further assume that all the DSBRs in a given galaxy have the same dust temperature. The definition of $R_{\text{eff}}$ thus implies that $4\pi R_{\text{eff}}^2 = \sum_i 4\pi R_i^2$, where the summation over $i$ goes through all the DSBRs. The projected surface area of the $i$th DSBR on the sky is $\pi R_i^2$, and hence $\Sigma_{\text{SFR}} = \text{SFR}/\sum_i \pi R_i^2 = \text{SFR}/\pi R_{\text{eff}}^2$. Considering Equation (4) and that $\sigma = 1.411 \times 10^5 L_\odot \text{ kpc}^{-2} \text{ K}^{-4}$, we have $\Sigma_{\text{SFR}} = 5.644 \times 10^{-3} (\sigma/\sigma) T_{\text{mbb}}^4$, which means that $\Sigma_{\text{SFR}}$ is constant for a fixed $T_{\text{mbb}}$. Of course, this conclusion hinges upon the approximation that the DSBRs have the same $T_{\text{mbb}}$ and, to a lesser degree, also the spherical symmetry of the DSBRs. In the future, examining the observed $\Sigma_{\text{SFR}}$ as a function of $T_{\text{mbb}}$ for a large sample can test how well such approximations hold.

Similarly, we can calculate the SFR volume density (hereafter SFR3D, or $\rho_{\text{SFR}}$). Under the same assumptions as above, we define a different effective sphere with the radius of $r_{\text{eff}}$ whose volume is equal to the sum of the volumes of the individual DSBRs in a galaxy, i.e., $\frac{4}{3} \pi r_{\text{eff}}^3 = \sum_i \frac{4}{3} \pi R_i^3$. It is obvious that $r_{\text{eff}} \geq R_{\text{eff}}$, and generally there is no easy way to infer $r_{\text{eff}}$ from $R_{\text{eff}}$. However, in the limiting case that there is only one DSBR in the galaxy under question, we should have $R_{\text{eff}} = r_{\text{eff}}$. Therefore, we can calculate the minimum SFR volume density (hereafter minSFR3D, or $\rho_{\text{SFR}}^{\text{min}}$) as $\rho_{\text{SFR}}^{\text{min}} = \text{SFR}/\left(\frac{4}{3} \pi R_{\text{eff}}^3\right)$.

The histograms of SFR2D and minSFR3D of our sample are shown in Figure 3.

### 3.3. Nature of the $L_{\text{IR}}-T$ Relation

The $L_{\text{IR}}-T$ relation now has a new meaning. As a pair of $(L_{\text{IR}}, T_{\text{mbb}})$ corresponds to one $R_{\text{eff}}$ value, and hence one

![Figure 3. Statistics of the objects from our sample.](image-url)
minSFR3D value, the $L_{\text{IR}}^{(\text{cd})}-T$ plane can be converted into a minSFR3D surface, which is shown in Figure 4, where the average trend based on the data points in Figure 2 is also displayed. It is immediately clear that our objects form the minSFR3D surface, displayed. It is immediately clear that our objects form the observed $L_{\text{IR}}-T$ relation because they outline a region that has a narrow spread in minSFR3D.

We emphasize again that, as shown in the simulation of MY15 (see also Section 2), the lack of objects in the area below this relation cannot be due to selection bias. From Figure 4, it is clear that this high-$L_{\text{IR}}^{(\text{cd})}$, low $T_{\text{mbb}}$ area corresponds to low minSFR3D. We therefore suggest that this area is a zone of avoidance in terms of minSFR3D. In other words, very cold ULIRGs or HyLIRGs should be very rare because they would require very large $R_{\text{eff}}$ (and hence very low minSFRD) in order to achieve a high IR luminosity at a low dust temperature. On the other hand, the lack of objects in the area above the current $L_{\text{IR}}-T$ relation outlined by our objects could be due to the possible selection bias intrinsic to the SPIRE bands (see Section 4.1 and Figure 12 in MY15).

### 3.4. Consistency with the Direct Measurements

If $R_{\text{eff}}$ is a physical scale indicator, its small value ($\lesssim 2$ kpc) is consistent with that seen in the local ULIRGs (see also Lutz et al. 2015) but seems to contradict the claimed extended sizes of high-$z$ SMGs (see Section 1). However, these can be reconciled when considering that even the subarcsec submm interferometry still cannot resolve individual DSBRs at high-$z$ (0.3 0.8 kpc at $z \approx 1-4$) if they are too close to each other; the very extended submm morphologies could simply be due to the blending of a number of discrete DSBRs that are widely separated but still not resolved by the interferometry.

Currently, the only way to resolve the individual DSBRs at high-$z$ is through strong gravitational lensing, where proper modeling of the lens could reconstruct the intrinsic morphology of the highly amplified background source to great details. However, the accuracy of the reconstruction depends highly on how strong the amplification is and how well the lens is modeled.

Unfortunately, there are still not many such measurements publicly available for us to compare to, especially when we require spectroscopic redshifts and the SPIRE photometry. The best example to date is the SMG SMJ2135-0102 from S&I10, which has $\mu \sim 32.5$. Its FIR emission is dominated by four individual DSBRs, each being mirrored into two images. By averaging the results from the reconstructions based on the two sets of mirrored images, the intrinsic radii of these four DSBRs are $390.0 \pm 64.0$, $290.5 \pm 59.9$, $192.5 \pm 36.9$, and $94.0 \pm 34.4$ pc, respectively. As these radii are the FWHM sizes, and hence only enclose $\sim 76\%$ of the total light from each DSBR, they should be multiplied by $\sqrt{1/0.76}=1.146$ to the full sizes. Following Section 3.2, we get $R_{\text{eff}}^{2}=609.0 \pm 67.6$ pc. In Section 3.1, we obtained $L_{\text{IR}}^{(\text{cd})}=1.76^{+0.33}_{-0.31} \times 10^{12}L_{\odot}$, $T_{\text{mbb}}=39.0 \pm 0.4 \, \deg{K}$, and $R_{\text{eff}}=675 \pm 57$ pc. This size agrees with the above to $\sim 11\%$. Considering that these four DSBRs, while being the dominant sources, might not contribute 100% of the total $L_{\text{IR}}^{(\text{cd})}$, the actual agreement could be even better.

For comparison, here we also discuss the case of Arp 220, the representative of the classic (low-$z$) ULIRGs. Arp 220 has two nuclei, which have recently been directly resolved in submm by Scoville et al. (2015) using the Atacama Large Millimeter/submillimeter Array (ALMA). These authors derive the FWHM sizes of the two nuclei as...
130 ± 2 × 87 ± 4 and 137 ± 2 × 116 ± 2 pc, respectively. Using spheres for approximation, we obtain the equivalent radii of 106 ± 2.6 and 126 ± 1.4 pc, respectively. They also suggest that these two nuclei account for ~71%–76% of the total FIR continuum, and hence we adopt the middle value of 74%. Similar to the calculation above, we correct the measured FWHM sizes by a factor of \( \sqrt{1/(0.761 \times 0.74)} = 1.333 \) to the full sizes and obtain \( \sum R_i^2 = 219.5 \pm 2.6 \) pc. Using the photometry at >40 \( \mu m \) retrieved from the NASA/IPAC Extragalactic Database and adopting 77 Mpc as its luminosity distance, we obtain \( L_{\text{IR}}^{(cd)} = 1.26^{+0.11}_{-0.10} \times 10^{12} L_\odot \), \( T_{\text{mbb}} = 50.4 \pm 2.1 \) K, and \( R_{\text{eff}} = 286.8 \pm 14.2 \) pc. Considering the various uncertainties, especially the fractional contribution from the two nuclei to the total FIR emission, the agreement is quite reasonable.

4. DISCUSSION

The exact value of \( R_{\text{eff}} \) depends on the MBB model parameters. For example, while \( L_{\text{IR}}^{(cd)} \) is insensitive to \( \lambda_0 \), our choice of a small \( \lambda_0 \) tends to result in a low \( T_{\text{mbb}} \) (see Appendix D of MY15 for details), and hence \( R_{\text{eff}} \) derived here tends to be larger than that would be obtained using a larger \( \lambda_0 \). Nevertheless, our main conclusions still hold regardless of such limitations.

First of all, \( R_{\text{eff}} \) cannot be increased arbitrarily. Even in the HyLIRG regime, it is still mostly confined to \( \lesssim 2 \) kpc. While in the low-luminosity regime, the increasing of \( L_{\text{IR}} \) can be achieved by increasing \( R_{\text{eff}} \) (e.g., increasing the number of DSBRs); in the high-luminosity regime, this can only be achieved by increasing the strength of the starburst (i.e., reflected in the rapid increase of \( T_{\text{mbb}} \)). MY15 has already reached this conclusion, and here we reinforce it with an enlarged sample that consists of objects from different initial selections, such as SMGs, high-\( z \) radio galaxies, etc.

Second, the \( L_{\text{IR}}-T \) relation reflects the MBB S-B equivalent and the aforementioned limit to \( R_{\text{eff}} \). Thus, this relation outlines the boundary of minSFR3D, which provides new clues in understanding dusty starbursting environment. The value of minSFR3D should be quite close to the actual SFR volume density, although strictly speaking it is only the lower limit. In the simplest case where the DSBRs are all spheres of the same radius and dust temperature, \( \rho_{\text{SFR}} = \sqrt{N \rho_{\text{SFR}}^{\text{min}}} \), where \( N \) is the total number of DSBRs in the galaxy.

Third, the small \( R_{\text{eff}} \) values suggest that the DSBRs in high-\( z \) ULIRGs are as physically compact as their counterparts in the local universe. While a small \( R_{\text{eff}} \) could still be the result of an extended DSBR with a low filling factor, our test cases in Section 3.4 strongly supports the scenario that DSBRs are universally compact (see also Ikarashi et al. 2015).

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