AGN Torus Detectability at Submillimeter Wavelengths: What to Expect from ALMA Continuum Data

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Abstract

Dust close (~few pc) to the accretion disk in active galactic nuclei (AGNs) is key to understanding many of their observational signatures, and it is key to tracing how the AGN is fed or even evolves along its duty cycle. With estimated sizes of less than 10 pc, as constrained by mid-IR (MIR) high angular resolution data, only the superb spatial resolution achieved by ALMA is able to actually image this dusty structure. However, the question regarding how the dust at submillimeter wavelengths (sub-mm, typical ALMA band) behaves in the AGN contest, arises. We study the detectability of the emission associated with the AGN dusty structure at submillimeter wavelengths using ALMA, in a theoretical and observational way. Theoretically, we use the Clumpy models from Nenkova et al., together with the MIR to X-ray and radio fundamental plane scaling relations. We find that it is more likely to detect bigger and denser dusty tori at the highest ALMA frequency (666 GHz/450 μm). We also find that with 1 hr at 353 GHz/850 μm and 10 hr at 666 GHz/450 μm we can detect, with a high detection limit, a 1 mJy torus (characteristic of bright AGNs). This means that an object for which the unresolved spectral energy distribution (SED) is at 12 μm has a flux of ~1 mJy. Observationally, we use four prototypical AGNs: NGC 1052 (low-luminosity AGN), NGC 1068 (type 2), NGC 3516 (type 1.5), and I Zw 1 (QSO), with radio, submillimeter, and MIR data available. All the MIR spectra are best fit with the smooth model reported by Fritz et al. A power law and a single, or a composition of, synchrotron component(s) reproduce the centimeter radio wavelengths. We combined and extrapolated both fits to compare the extrapolation of both torus and jet contributors at submillimeter wavelengths with data at these wavelengths. Our observational results are consistent with our theoretical results. The most promising candidate to detect the torus is the QSO I Zw 1 (therefore, highly accreting sources in general), although it cannot be resolved owing to the distance of this source. We suggest that to explore the detection of a torus at submillimeter wavelengths, it is necessary to perform an SED analysis including radio data, with particular attention to the angular resolution.

Key words: galaxies: active – galaxies: individual (NGC 1052, NGC 1068, NGC 3516, I Zw 1) – submillimeter: general

1. Introduction

Although the unification scheme (e.g., Antonucci 1993; Urry & Padovani 1995) of active galactic nuclei (AGNs) may not be universal, the most accepted description is that dust surrounding the central engine is key to explaining some observational differences between AGN classes. As a first approach, the point of view of the observer with respect to this dusty structure is able to explain the type 1/type 2 dichotomy (Pier & Krolik 1993; Granato & Danese 1994; Efstathiou & Rowan-Robinson 1995).

The morphology and properties of this dusty structure are far from being understood (see, e.g., Netzer 2015). The torus dust grains absorb ultraviolet photons from the central engine and reradiate them in the infrared (IR), peaking at mid-IR (MIR) wavelengths around 5–35 μm (e.g., Sanders et al. 1989; Sargsyan et al. 2011; Shi et al. 2014). Thus, from the observational point of view, many studies have been devoted to studying the spectral energy distribution (SED) of the dusty region at near-IR (NIR) and MIR wavelengths. Several model fittings aimed at extracting physical and geometrical properties from the unresolved SED, by using high angular resolution data (subarcseconds; e.g., Ramos Almeida et al. 2009, 2011; Alonso-Herrero et al. 2011; Martínez-Paredes et al. 2015; Fuller et al. 2016; Lopez-Rodriguez et al. 2016; García-Burillo et al. 2017; González-Martín et al. 2017; Martínez-Paredes et al. 2017) and, in some cases, milliarcsecond interferometric observations (e.g., Höning et al. 2010; Tristram & Schartmann 2011). They found that for Seyferts the dusty structure should be concentrated into the inner <5 pc, as derived from NIR and MIR wavelengths (Radomski et al. 2008; Ramos Almeida et al. 2009, 2011; Alonso-Herrero et al. 2011), which extend for the highest AGN luminosities (Martínez-Paredes et al. 2017), and it is even smaller than 1 pc for low-luminosity AGNs (LLAGNs; González-Martín et al. 2017).

Ramos Almeida et al. (2014) found that a minimal set of data (J+K+M-band photometry + N-band spectroscopy) is necessary to constrain the geometrical parameters of the dusty torus using clumpy models for Seyfert galaxies. However, to have a reliable estimate of the torus size at MIR, it is necessary to add the FIR emission to the SED in order to probe the coolest dust of the torus (Fuller et al. 2016; García-Burillo et al. 2016; Lopez-Rodriguez et al. 2018). This implies the need for FIR subarcsecond resolution data. Infrared interferometry constitutes one of the most precise ways of characterizing the dusty structure using observations by comparing them with torus models (Hönig et al. 2006; Tristram & Schartmann 2011). However, the signal-to-noise ratio required for, e.g., the Very Large Telescope Interferometer (ESO-VLTI) observations strongly restricts the number of observable sources.
This has changed with the new submillimeter capabilities of the Atacama Large Millimeter Array (ALMA) and the Large Millimeter Telescope (LMT). High-resolution submillimeter observations are important in probing the morphology, column density, and dynamics of obscuring matter in AGNs. ALMA is able to achieve 0\"0.0 resolution continuum images at >400 \micron. Very recently, some works attempted to detect and study the dusty torus, e.g., Izumi et al. (2018) studied the dusty central region of the Circinus galaxy by testing the multiphase dynamic torus model, and Combes et al. (2018) explored the close environment around seven Seyfert associated with the dusty torus.

However, two main issues need to be faced when using submillimeter telescopes to study the dust in AGNs: (1) Sensitivity issue: the peak of the dusty emission is below 30 \micron. The total flux expected above 400 \micron must be only a small fraction of what is observed at MIR wavelengths. Thus, although ALMA has a very good sensitivity limit, a proper study on the detectability of the dusty continuum at submillimeter wavelengths needs to be addressed. Aalto et al. (2017) were not able to detect the dusty structure in the radio-quiet NGC 1377 using a similar waveband compared to that used by García-Burillo et al. (2017). (2) Jet contribution: most of these AGNs show a strong synchrotron contribution coming from the radio jet. This contribution is expected to be dominant at radio frequencies, but a tail of this emission can contribute at other wavelengths, with non-negligible contribution to the submillimeter wavelengths. Izumi et al. (2017) studied the LLAGN NGC 1097 with less than 10 pc resolution at ~800 \micron. Indeed, they claimed that most of the submillimeter continuum emission is dominated by the jet thanks to the study of long-term variations at submillimeter wavelengths.

It is the aim of this paper to study the detectability of extended emission associated with AGN dusty structure at submillimeter wavelengths using ALMA. For this purpose we will consider the most used SED models for dusty AGN emission as the Clumpy models (Nenkova et al. 2008a, 2008b), together with known scaling relations between the accretion disk luminosity and the torus continuum (Gandhi et al. 2009; Asmus et al. 2015; Netzer 2015), and the accretion disk luminosity, jet contribution, and supermassive black hole (SMBH) mass (Bonchi et al. 2013; Saikia et al. 2015) (see Section 2). In Section 3, we study the sensitivity and contributors to the submillimeter wavelengths of four prototypical AGNs, covering a wide range of AGN classes: NGC 1052 (LLAGN), NGC 1068 (type 2 Seyfert), NGC 3516 (type 1.5 Seyfert), and I Zw 1 (QSO). Details on the target selection are given in Section 3.1. Using these targets, we will study the detectability of the submillimeter torus with available archival and/or literature data, combining together MIR, radio, and submillimeter continuum flux densities (see Section 3). Our findings are discussed in Section 4, and a short summary of our results is given in Section 5. We use the standard cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) throughout the text.

2. Torus Detection with ALMA through Theoretical Predictions

We compute the expected contributions to the submillimeter range as the ratio between the flux at submillimeter wavelengths and that at X-ray wavelengths. This allows us to scale the submillimeter flux density to the accretion disk flux density. We use the integrated luminosity in the 2–10 keV band (hereafter \( L_{2\text{–}10\text{ keV}}\)) for the X-ray luminosity and the monochromatic luminosities at 100 GHz (3000 \micron, ALMA band 3), 353 GHz (850 \micron, ALMA band 7), and 666 GHz (450 \micron, ALMA band 9) for the submillimeter wavelengths. Hereafter, we refer to the fluxes at these bands as \( F_{\nu}=3000 \text{ \micron} \), \( F_{\nu}=850 \text{ \micron} \), and \( F_{\nu}=450 \text{ \micron} \) respectively. We chose these bands because they cover the full waveband covered by ALMA. These three bands can achieve a spatial resolution of 0\"2, 0\"06, and 0\"03, respectively, considering the largest configuration (C43-7 available during cycle 6). The 666 GHz continuum emission (band 9) was chosen by García-Burillo et al. (2016); see also Imanishi et al. 2016b; Aalto et al. 2016c to identify the torus contribution to the continuum at submillimeter wavelengths for NGC 1068 and NGC 1377, respectively (see Section 1). In the same manner, Izumi et al. (2017) used 350 GHz (band 7) to try to recover the torus contribution to the submillimeter wavelengths for NGC 1097. We also test band 3 (100 GHz) because it provides slightly better sensitivity compared to the other bands.

Note that in this section we do not take into account the dilution, although it might be important if spatial resolution is moderate (see Section 3, e.g., for the case of NGC 1068). For instance, the MIR flux will change if the field of view of the observations changes (e.g., Prieto 2010; Tristram et al. 2014).

2.1 Torus Contribution

In order to estimate the torus contribution to the submillimeter range, we estimate two ratios: (1) the 12 \micron/2–10 keV flux ratio (\( F_{12\text{ \micron}}/F_{2\text{–}10\text{ keV}} \)) and (2) the submillimeter/12 \micron flux ratio (\( F_{\nu}/F_{12\text{ \micron}} \)).

We use the well-established MIR-to-X-ray scaling relation for AGNs (Lutz et al. 2004; Gandhi et al. 2009) to estimate the \( F_{12\text{ \micron}}/F_{2\text{–}10\text{ keV}} \) ratio. The most updated version of this relation is presented by Asmus et al. (2015) using a sample of 152 nearby AGNs and can be written as

\[
\log \left( \frac{L_{\text{nuc},12\text{ \micron}}}{10^{43} \text{ erg s}^{-1}} \right) = (0.30 \pm 0.03) + (0.98 \pm 0.03) \log \left( \frac{L_{2\text{–}10\text{ keV}}}{10^{43} \text{ erg s}^{-1}} \right).
\]

We then compute the expected \( F_{\nu}/F_{12\text{ \micron}} \) using the SEDs of the clumpy torus model produced by Nenkova et al. (2008b). This clumpy torus model depends on six parameters: the observer inclination angle toward the torus \( i \), the half angular width of the torus \( \sigma \), the outer radius of the torus scaled to the inner radius \( R_{\text{out}}/R_{\text{in}} \), the number of clouds at the equatorial plane of the torus \( N_{\text{cl}} \), the steepness of the radial distribution of clouds \( q \), and the opacity of the individual clouds \( \tau_{\nu} \). Thus, our \( F_{\nu}/F_{12\text{ \micron}} \) ratio depends on these six parameters. Note that the SEDs of the clumpy torus model cover up to 1000 \micron. We linearly extrapolate the SEDs above 1000 \micron to estimate the expected flux at 3000 \micron (i.e., band 3 at 100 GHz).

The inner radius of the torus is set to the sublimation radius of the dust, which depends on the accretion disk bolometric luminosity.
The distribution of torus $F_{\nu}/F_{[2-10 \text{ keV}]}$ ratios is shown in the top panel of Figure 1. As expected, the highest torus contribution is obtained in 666 GHz (450 μm), with a submillimeter flux density $\sim 10^{-6}$ to $10^{-3}$ times the X-ray flux density.

We also show how the parameter space affects the torus contribution to the submillimeter wavelengths in Figure 2. Each panel shows the distribution of the $F_{\nu}/F_{[2-10 \text{ keV}]}$ ratio for the lowest (light gray) and highest (dark gray) values for each parameter. The highest values are obtained for a higher number of clouds in the equatorial plane ($N_0$), larger outer radius of the torus compared to the inner one ($Y$), larger half angular width of the torus ($\sigma$), flatter radial distribution of clouds ($q$), and larger values of the optical depth of individual clouds ($\tau_\nu$). No significant effect is produced by edge-on or face-on torus (the inclination angle $i$). Altogether this means that, as expected, bigger and denser dusty tori are more likely to be detected at submillimeter wavelengths. Finally, we also considered how the fraction of the sky obscured by dust, i.e., the covering factor, at the highest ALMA frequency can be incisive in the torus detectability, and the result is shown in Figure 3. Large covering factor values ($f_{\text{cov}} > 0.6$) are those for which the torus contribution could be important in the submillimeter window. However, because of the wide width of the distribution, it is worth noticing that a large covering factor is not a determinant condition.

Finally, we investigate how these results could be influenced by the torus model selected. Figure 4 shows the distribution of the clumpy torus model by Nenkova et al. (2008b), the smooth torus model by Fritz et al. (2006), and the disk+wind model by Höning & Kishimoto (2017), together with the jet contribution at the highest ALMA frequency considered (666 GHz/450 μm, for which the highest torus contribution is obtained). The contribution of the AGN dusty torus depends on the distribution of the dust grains. For the case of a polar dusty wind torus distribution, the model predicts a negligible contribution of torus emission in the submillimeter band, while for dust grains distributed in a smooth torus the model predicts a larger contribution. Even if the most optimistic model, i.e., the smooth model, is used, the torus seems to be difficult to detect at submillimeter wavelengths (see Section 3). The histogram is also telling us that an important contribution from
the synchrotron emission from the radio jet could contaminate the dust emission over the most commonly used clumpy torus. Moreover, we also considered an additional contribution from the hot graphite dust and the dusty narrow-line region (NLR) clouds as proposed in several works to describe the main emission components in the NIR and MIR spectra (e.g., Mor et al. 2009; Mor & Netzer 2012). The former contributes mainly at $\sim 3 \mu m$, and it decays very steeply, while the latter could contribute to the MIR spectrum. Indeed, it contributes above 10 $\mu m$ and could be as large as 40% of the total emission at 24 $\mu m$. Assuming that this percentage of contribution remains the same at submillimeter wavelengths, a shift of the torus models distributions in Figure 4 by a factor of only 0.2 toward the right, may occur. Thus, the NLR contribution does not have a large impact on the result presented above.

2.2. Jet Contribution

We extrapolate the contribution of the radio jet in the submillimeter range using the so-called fundamental plane relation (Merloni et al. 2003), for which radio luminosity ($L_R$) is correlated with both the (hard) X-ray luminosity $L_{2-10 \text{ keV}}$ (from a corona closely linked to the accretion disk emission) and the mass of the SMBH ($M_{\text{BH}}$). This implies that a correlation between jet and disk flux density is unavoidable.

Bonchi et al. (2013) measured a fundamental plane for the largest AGN-only sample for which radio, X-ray, and K-band luminosity information exists. Moreover, they added radio upper limits and considered a wide range of redshifts (up to $z \sim 5$). The fundamental plane relation obtained is the following:

$$\log L_R = 0.39 \log (L_{2-10 \text{ keV}}) + 0.68 \log (M_{\text{BH}}) + 16.61,$$

(2)

where $L_R$ is the 5 GHz nuclear luminosity in units of erg s$^{-1}$, with 1.4 GHz radio luminosities converted into 5 GHz luminosities assuming a radio spectral index $\alpha = -0.7$ (where $L_{\nu} \propto \nu^\alpha$). $L_{2-10 \text{ keV}}$ is the 2–10 keV nuclear X-ray luminosity in units of erg s$^{-1}$, and $M_{\text{BH}}$ is the SMBH mass in units of $M_\odot$ (Merloni et al. 2003). It is from Equation (2) that we extrapolate our expected submillimeter jet luminosity. Therefore, we derive our submillimeter fundamental plane as

$$\log (L_\nu) = 0.39 \log (L_{2-10 \text{ keV}}) + 0.68 \log (M_{\text{BH}}) + 16.61 - \alpha \log \left( \frac{S_{\text{GHz}}}{\nu} \right),$$

(3)

where $\alpha$ represents the spectral index, i.e., the slope, for an optically thin radio component emitting synchrotron radiation,
and $\nu$ are the three possible ALMA frequencies considered in this paper (i.e., 100, 353, and 666 GHz). Therefore, the $F^\lambda/\overline{F}_{[2-10 \text{ keV}]}$ ratio still depends on the X-ray luminosity $L_{[2-10 \text{ keV}]}$ as follows:

$$
\log \left( \frac{F^\lambda}{\overline{F}_{[2-10 \text{ keV}]}}, \nu \right) = C(\alpha, \nu) - 0.61 \log(L_{[2-10 \text{ keV}]}),
$$

where the constant $C(\alpha, \nu) = 16.61 - \alpha \log(5\text{GHz}/\nu)$.

For the purpose of our study we explore typical ranges for the parameters: spectral indices for local AGNs (Condon et al. 2002; Sadler et al. 2014) of $\alpha = [-0.5, -0.7]$, X-ray luminosity of $L_{[2-10 \text{ keV}]} = [10^{42}, 10^{46}]$ erg s$^{-1}$, and SMBH masses of $M_{\text{BH}} = [10^6, 10^9]$ M$_\odot$. The distribution of the submillimeter jet contribution peaks at around $\sim 10^{-6}$, irrespective of the chosen submillimeter frequency (see histogram in the bottom panel of Figure 1). Note that this value might be an overestimate of the jet contribution. Saijia et al. (2018) investigated whether or not 1.4 GHz fluxes can trace nuclear activity (using 10,149 AGNs taken from the Faint Images of the Radio Sky at Twenty cm [FIRST] survey; White et al. 1997). They concluded that the 1.4 GHz FIRST fluxes do not trace the pure “core” jet and instantaneous nuclear activity. Bonchi et al. (2013) mostly used data from the FIRST survey (with angular resolution of $5''$), and they considered sources in a wide range of redshifts, meaning that several synchrotron components could contribute within the radio beam. Therefore, the radio flux density could be contaminated by radio extended emission, e.g., from the radio lobe, which can overestimate the radio flux density. This can produce an upshift in the fundamental plane. In practice, this means that the pure core-jet component would have a lower flux density and the histograms shown in Figure 1 (bottom panel) would move toward lower values. To isolate as much as possible the central radio components, observations at high resolution (e.g., using the JVLA in its A configuration) and at high radio frequencies are needed.

We also show how the X-ray luminosity $L_{[2-10 \text{ keV}]}$, the SMBH mass $M_{\text{BH}}$, the synchrotron spectral index $\alpha$, and the accretion rate $L_{\text{bol}}/L_{\text{Edd}}$ affect the jet contribution considering the highest-frequency band (666 GHz/450 $\mu$m) in Figure 5. The lowest jet contribution in this band is obtained considering high X-ray luminosity, low SMBH masses, and, therefore, high accretion rates. No significant effect is produced by the narrow range of $\alpha$. It is worth mentioning that a spectral indices of $-0.5$ and $-0.7$ are tracing a similar class of objects. Merloni et al. (2003) claimed that, using a wide range of $\alpha$ (i.e., flat radio source with $\alpha > -0.4$ and steep radio sources with $\alpha < -0.4$), the fundamental plane shows a considerable scatter. In order to reduce this scatter, they suggest to restrict to a specific class of object, as we did considering the narrow $\alpha$ range of $[-0.5, -0.7]$. Also note that we exclude from this plot the lowest values of the total distribution because they are obtained with $L_{\text{bol}}$ above the Eddington limit. Nevertheless, note that the radio jet contribution seems to be present for a wide range of cases in the submillimeter band, effectively showing $F_{[450 \mu m]}/\overline{F}_{[2-10 \text{ keV}]} \sim 10^{-8} - 10^{-4}$.

### 2.3. Detectability of the Torus Using ALMA

We discussed in previous subsections in which conditions the torus and jet have a maximum or minimum contribution to the submillimeter wavelengths. Here we study (1) the detectability of the torus compared to the jet contribution and (2) the detectability of the torus considering the sensitivity limits of ALMA at the studied frequencies.

We computed the mean and 10th and 90th percentiles of the torus and jet distributions at 100, 353, and 666 GHz compared to
the X-ray flux ($F_x/F_{2-10\,\text{keV}}$). These numbers are reported in Column (3) of Table 1 (10% and 90% recorded within brackets). We then computed the median percentage of contribution for both the torus and jet contribution. The minimum (maximum) percentage is computed using the minimum (maximum) ratio for one of the components and the maximum (minimum) ratio for the other. These percentages are reported in Column (4) of Table 1. The jet component fully dominates the 100 GHz/3000 μm band. The torus component could dominate over the jet component in the 353 GHz/850 μm band, although the median contribution is ~35%. As expected, the best chances to detect the torus over the jet contribution are obtained for the 666 GHz/450 μm frequency, with an average of ~96% of the torus component. However, even using this frequency, the contribution of torus can be as low as ~5%.

We then computed the expected flux density at submillimeter wavelengths for a typical AGN of $F_{12,\,\mu m} = 150$ mJy and $F_{12,\,\mu m} = 10$ Jy (reported in Columns (5) and (6) of Table 1). For that purpose we used the X-ray-to-MIR relation to convert MIR flux $F_{12,\,\mu m}$ to X-ray flux $F_{2-10\,\text{keV}}$. We then used the median, minimum, and maximum for $F_x/F_{2-10\,\text{keV}}$ to estimate the expected flux at the three submillimeter frequencies studied. The ALMA sensitivity limits, or the rms, according to the exposure time calculator, considering 1 hr (on-source) observing time using the most sensitive ALMA configuration and the full bandwidth (BW) receivers (~8 GHz BW), are ~12, ~85, and ~260 μJy at 100 GHz/3000 μm, 353 GHz/850 μm, and 666 GHz/450 μm, respectively. Comparing our results with these limits further constrains the plausible detectability of the torus. A torus at 100 GHz/3000 μm is not detectable, even with observations of 10 hr long. This integration time would give an rms of 4 μJy, but it is still not enough to detect, with a marginal detection limit (5σ), the flux density of the brightest torus (10 μJy at 100 GHz/3000 μm). Using the 350 GHz/850 μm band, it is possible to have a good detection (a 10σ detection) for a torus with flux density larger than 850 μJy (~1 mJy), selecting a sample of bright AGNs (with flux density as bright as ~10 Jy). Fainter tori are not detectable even with larger integration time. A 10 hr, integration time observation at this frequency band can reach an rms of 30 μJy. However, this is still not enough to detect a 4 μJy torus or the tori of those AGNs with hundreds of mJy flux density. Therefore, although a large fraction of torus could be detected at the 353 GHz/850 μm band (see Column (4) of Table 1), its median values would never be detected for an AGN with 150 mJy at 12 μm and for an AGN as bright as 10 Jy.

A larger flux density is expected for the torus contribution at the 666 GHz/450 μm band. At this frequency it is possible to have good detection (a 10σ detection) for tori brighter than ~2.6 mJy, therefore selecting bright tori of bright AGNs (with flux density as bright as ~10 Jy). Using a longer integration time, e.g., 10 hr, the rms can go down to ~80 μJy, giving the chance to detect tori brighter than 800 μJy. However, in this scenario it is still difficult to detect the flux density of the brightest torus for a 150 mJy AGN (it would be detected at the ~3σ detection limit). Overall, the result is that, even if on average the torus dominates at this frequency (see Column (4) of Table 1)
of Table 1), it will not be detected considering the median of the distribution.

Knowing the ALMA rms estimate of 1 hr or 10 hr integration time, the median value of the radio jet is, in principle, not detected in the submillimeter range. However, bright radio jets for bright AGNs (with flux density as bright as ~10 Jy) can contaminate the submillimeter continuum flux density at all three frequency/wavelength bands considered.

Thus, only the brightest, largest, thickest tori with the largest number of clouds (see Section 2.1) will produce enough flux to be detected at either the 353 GHz/850 μm or 666 GHz/450 μm submillimeter frequencies. To give a general estimate of the ALMA detectability of the torus and to summarize the above paragraph, we can say that 1 mJy torus (characteristic of bright AGNs, with flux density at 12 μm S ~10 Jy) can be detected with a 10σ detection limit, observing 1 hr at 353 GHz/850 μm and 10 hr at 666 GHz/450 μm. However, the observer has to be aware of the possible contamination (and in some cases with very high percentage) by the radio jet at these submillimeter bands. In fact, Table 1 shows that the median value of the jet contributor is not detected at any of the three ALMA frequencies and considering 1 hr or the longer 10 hr integration time. However, the bright radio jet for bright AGNs might dominate at these frequencies.

3. Torus Detection with ALMA through Observations
3.1. Cases of Study

With no attempt to define a complete sample, we select four AGNs to confront our predictions on the detectability of the torus at submillimeter wavelengths with actual data. As we showed in Section 2, the detectability is sensitive to the brightness at X-ray/MIR wavelengths, the accretion rate, and the BH mass. It also depends on the torus parameters, but we cannot know these parameters ahead of the analysis.

We select targets with available radio data to trace the jet contribution, with MIR data to trace the torus contribution, and with continuum submillimeter observations. Additionally, we selected our targets by probing different optical classes. These targets are the LLAGN NGC 1052, the type 2 Seyfert NGC 1068, the type 1 Seyfert NGC 3516, and the QSO 1 Zw 1. Our four AGNs cover a wide range of X-ray luminosity with more than 2 orders of magnitude, a factor of 10 in BH masses, and a wide range of 12 μm fluxes from 150 mJy to 35 Jy. General information about our selected targets is shown in Table 2.

NGC 1052 is a nearby (z = 0.005; we used the average distance independent of redshift reported in NED) elliptical galaxy that hosts an LLAGN in its center (with luminosity between 1 and 100 GHz: $L_{1-100\ GHz} = 4.4 \times 10^{40}$ erg s$^{-1}$; Wrobel 1984). It shows a twin-jet system in the east–west direction at radio kiloparsec and parsec scales, oriented close to the plane of the sky (Vermeulen et al. 2003; Cooper et al. 2007), which is contained within the optical galaxy. Its optical spectrum is characterized by strong forbidden lines from low-ionization states. For this reason this source is considered a prototypical LINER (low-ionization nuclear emission-line region; Heckman 1980) galaxy. The X-ray images of NGC 1052 show a point-like X-ray source, and its X-ray spectrum is extremely flat, most likely explained by the advection-dominated accretion flow (ADAF) mechanism (Guainazzi et al. 2000b). To model the AGN X-ray spectrum, large absorbing column densities have been discussed, supporting the idea of a highly dense obscuring torus (e.g., Risaliti et al. 2002). Evidence of an obscuring torus has also been suggested from very long baseline interferometry (VLBI) observations in the radio regime; a prominent emission gap has been detected in the twin-jet system (e.g., Kadler et al. 2003). Although NGC 1052 has been part of large samples to study the torus component in LLAGNs (Mason et al. 2012; González-Martín et al. 2015, 2017), its torus has never been modeled individually.

NGC 1068 (z = 0.002; redshift independence reported in NED) is the prototype Seyfert 2 galaxy, where the central engine is supposed to be blocked by the dusty torus. It has been studied at a large number of wavelengths: e.g., in the radio band (at 5 and 8.4 GHz) using the VLBI technique (Muxlow et al. 1996; Gallimore et al. 2004), in millimeter band (Krips et al. 2006), in NIR and MIR bands (Marco & Alloin 2000; Galliano & Alloin 2002; Jaffe et al. 2004; Galliano et al. 2005), and at high-energy X-rays (Guainazzi et al. 2000b). The relativistic jet is prominent and extends for several kiloparsecs in both directions. It changes the direction about 0°2 from the nuclear region. This change is presumed to be the result of an interaction with a molecular cloud (Gallimore et al. 2004).

Significant NIR and MIR emission is associated with the inner radio jet (Marco & Alloin 2000; Jaffe et al. 2004; Galliano et al. 2005), which is presumed to be the result of shock heating of the dust in the interstellar medium (ISM) by the passage of
Table 2
General Information of Our Selected Case of Study

| Obj. Name | Coordinates (J2000) | Distance (Mpc) | \( \log(M_{\text{BH}}) \) (\( M_\odot \)) | \( L_{2-10\text{keV}} \) (erg s\(^{-1}\)) | \( F_{12\mu\text{m}} \) (mJy) | Class. | Observations |
|-----------|---------------------|----------------|---------------------------------|---------------------------------|----------------|--------|--------------|
| NGC 1052  | 02:41:04.798–08:15:20.75 | 20.6 | 8.1 ± 0.3\(^{(1)}\) | 4.60 \times 10^{41} \(^{(a)}\) | 150 | LINER | IRS(LR)/Spitzer, JVLA, ALMA |
| NGC 1068  | 02:42:40.711–00:00:47.81 | 10.6 | 6.9 ± 0.1\(^{(2)}\) | 1.0 \times 10^{41} \(^{(b)}\) | 17 \times 10^{3} | Seyfert 2 | T-ReCS/Gemini, JVLA, ALMA |
| NGC 3516  | 11:06:47.490+72:34:06.88 | 51.5 | 7.0 ± 0.3\(^{(3)}\) | 2.51 \times 10^{43} \(^{(c)}\) | 300 | Seyfert 1.5 | IRS(HR)/Spitzer, JVLA, CARMA |
| I Zw 1    | 00:53:34.940+12:41:36.20 | 240.7 | 7.13\(^{(4)}\) | 7.1 \times 10^{43} \(^{(d)}\) | 430 | QSO | IRS(LR)/Spitzer, JVLA, ALMA, JCMT |

Note. Observational details of our selected objects. Column (1): object name. Column (2): coordinates in J2000. Column (3): distance measured in Mpc. Column (4): SMBH mass in logarithmic scale. Column (5): 2–10 keV X-ray luminosity measured in erg s\(^{-1}\). Column (6): observed 12 \( \mu \text{m} \) flux. Column (7): AGN classification. References for BH masses: (1) BH mass determined using the correlation between stellar velocity dispersion (from HyperLeda) and BH mass; (1) Hernández-García et al. 2014; (2) Lodato & Bertin 2003; (3) Onken et al. 2003; (4) Crummy et al. 2006. References for X-ray luminosities: (a) Brenneman et al. 2009; (b) Cappi et al. 2006; (c) Edelson & Nandra 1999; (d) Zhou & Zhang 2010. Note that no error was reported by Crummy et al. (2006) for the BH mass of I Zw 1.
Figure 6. MIR spectral fit to the smooth dusty model described by Fritz et al. (2006) for NGC 1052 (top left), NGC 1068 (top right), NGC 3516 (bottom left), and I Zw 1 (bottom right). For each object we show the best fit to the data in the top panel and the ratio between model and data in the bottom panel. The blue shaded area shows the error on the measurement. The red long-dashed line shows the dusty model best fit, and the black solid line shows the total fit, i.e., toroidal model + emission lines (see text).

Table 3

| Par. | NGC 1052 | NGC 1068 | NGC 3516 | I Zw 1 |
|------|----------|----------|----------|--------|
| i    | 61 ± 5   | 60 ± 9   | 19 ± 11  | <11    |
| σ    | >20.0    | 20 ± 8   | 58.5 ± 3 | >58    |
| γ    | 0.14°    | 0.01°    | <6.0     | 3.2 ± 0.4 |
| β    | -0.03 ± 0.02 | -0.99     | <0.01    | -0.95 ± 0.04 |
| Y    | 10.7 ± 0.3 | 142 ± 19 | 11.5 ± 0.1 | 19.2 ± 1 |
| τ    | 4.0 ± 0.4 | 1.81 ± 0.2 | 3.81 ± 0.07 | 1.37 ± 0.12 |
| R_out | ~0.4     | ~2.3     | ~2.9     | ~8.1    |
| χ²/dof | 1217.72/993 | 70.98/262 | 9575.07/1471 | 721.05/992 |

Note. i: viewing angle toward the torus; σ: angular width of the torus; β: inversely related to the amount of absorption; γ: exponent of the logarithmic azimuthal density distribution; Y: ratio between the outer and the inner radius of the torus; τ: silicate dust contribution. The asterisks represent frozen parameters, which could not be constrained. The first and second rows in NGC 1068 show the two values reported for γ and τ parameters for the N and Q bands, respectively (see text).

The radio jet. Lopez-Rodriguez et al. (2018) used SOFIA, infrared, and submillimeter observations in order to characterize the emission and distribution of the dust in NGC 1068. They fitted the nuclear SED of NGC 1068 using clumpy and smooth torus models, finding for the clumpy torus an angular width σ = 43 ± 12°, a radial thickness Y = 18 ± 1, a number of equatorial clouds N_0 = 4 ± 1, a radial distribution q = 0.08 ± 0.06, an optical depth τ_V = 70 ± 14, a viewing angle i = 75 ± 8°, an inner radius r_{in} = 0.28 ± 0.01 pc, and an outer radius r_{out} = 5.1 ± 0.4 pc, and for the smooth torus an opening angle θ_A = 37 ± 8°, a radial thickness Y = 20 ± 3, a fixed radial distribution q = 1, an optical depth τ_V = 250 ± 20, a viewing angle i = 79 ± 7°, an inner radius r_{in} = 0.41 ± 0.05 pc, and an outer radius r_{out} = 8.5 ± 0.7 pc. Moreover, Fritz et al. (2006) fitted the SED of NGC 1068 using their smooth model, and their parameters were an opening angle θ_A = 160°, a radial thickness Y = 20, a radial density distribution β = -1, an altitude density distribution γ = 6, an optical depth τ_V = 8, and a viewing angle i = 70°. They obtained a minimum radius r_{min} = 0.82 pc and a maximum radius r_{max} = 16.4 pc. Note that with both models, clumpy and smooth, a similar torus size is obtained, given by the Y parameter.
NGC 3516 is a bright type 1.5 Seyfert galaxy. It has a redshift of $z = 0.012$ (using redshift-independent measurement reported in NED). Its SMBH is estimated to have a mass of $M_{\text{BH}} = 1 \times 10^7 M_\odot$ (Onken et al. 2003). NGC 3516 has been extensively observed and studied at UV and X-rays. This source has strong UV absorption lines, specifically NV, C IV, and Si IV, to have been detected with the International Ultraviolet Explorer (IUE; Ulrich & Boisson 1983). In several works it has been found that these lines vary on timescales as short as weeks (Voit et al. 1987; Walter et al. 1990; Kolman et al. 1993). Kraemer et al. (2002) found optical absorption features associated with eight distinctive kinematic components. This complex outflowing feature can also be seen at X-rays (Netzer et al. 2002; Turner et al. 2005; Huerta et al. 2014). D. Esparza-Arredondo et al. (2019, in preparation) studied the MIR and X-ray observations of NGC 3516 to explore the torus parameters. They fitted the SED using the MIR (smooth torus model by Fritz et al. 2006) and X-ray (Borus model, Baloković et al. 2018) models simultaneously and found that the torus parameters for these sources are as follows: viewing angle $i = 10^\circ$, torus angular width $\sigma_{\text{torus}} = 60^\circ$, dust density radial profile $\gamma = 5.9$, $\beta = 10^{-2}$, a radial extent $Y = 11.9$, and an optical depth $\tau = 3.5$. No direct observations of its radio jet have been performed so far.

I Zw 1 is a prototypical narrow-line Seyfert 1 (Osterbrock & Pogge 1985) with narrow permitted lines, weak [O III] emission, strong [Fe II] emission, a steep soft X-ray spectrum, and strong X-ray variability (Sargent & Searle 1968; Phillips 1976; Oke & Lauer 1979; Boller et al. 1996; Gallo et al. 2004; Véron-Cetty et al. 2004). It is also classified as an infrared-excess Palomar Green QSO and a possible candidate for an ongoing minor merger (Schmidt & Green 1983). Its redshift is $z = 0.059$ (Ho & Kim 2009); therefore, I Zw 1 is considered one of the closest QSOs. Martínez-Paredes et al. (2017) studied the NIR and MIR continuum emission of I Zw 1, fitting the SED to Clumpy models using BayesClumpy (Asensio Ramos & Ramos Almeida 2009). The parameters found were as follows: a viewing angle $i = 79^\circ \pm 3^\circ$, a torus...
angular width $\theta_{\text{torus}} < 17^\circ$, a radial extent $Y = 67^{+15}_{-12}$, a number of equatorial clouds $N_0 < 4$, a radial distribution $q = 1.5^{+0.04}_{-0.03}$, and an optical depth $\tau_{\nu} = 54 \pm 4$. No direct observations of its radio jet have been performed so far.

### 3.2. The Data

#### 3.2.1. MIR Data

The sources NGC 1052, NGC 3516, and I Zw 1 are point-like sources at several wavelengths (e.g., Schmidt & Green 1983; Capetti & Balmaverde 2005; Burtscher et al. 2013), and their MIR emission is mostly dominated by the AGN itself (González-Martín et al. 2017; Martínez-Paredes et al. 2017; D. Esparza-Arredondo et al. 2019, in preparation). For this reason we used the high- and low-resolution Spitzer/IRS spectral data from the CASSIS\(^5\) catalog (the Cornell Atlas of Spitzer/IRS Sources; Lebouteiller et al. 2011). The resolution of Spitzer/IRS is $R \sim 60 - 130$. CASSIS provides flux-calibrated nuclear spectra associated with each observation. The source NGC 1068 is characterized by well-known MIR extended emission that dominates the Spitzer spectrum (see Lopez-Rodriguez et al. 2018); therefore, high angular resolution data are mandatory to decontaminate the MIR emission from the contribution of the host galaxy. For this reason, we used the $N$- and $Q$-band data from the Thermal-Region Camera Spectrograph (T-ReCS; Telesco et al. 1998, De Buizer & Fisher 2005) located in the 8.1 m Gemini-South Telescope. These data better isolate ($\sim 0^\circ.3 - 0^\circ.4$ point-spread function) the torus component from other dust contributors. T-ReCS data were processed using the pipeline RedCan (González-Martín et al. 2013) and have also been previously used by Ramos Almeida et al. (2014).

#### 3.2.2. Radio Centimeter and Submillimeter Data

For the purpose of our project, we collected radio continuum data observed with the Karl G. Jansky Very Large Array (JVLA) of the National Radioastronomy Observatory (NRAO)\(^6\) in its A configuration to be able to isolate the radio emission of the the

\(^5\)http://cassis.sirtf.com/atlas/

\(^6\)The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
central engine as much as possible. We obtained the A configuration radio data from the JVLA data archive or literature. For the sources I Zw 1 and NGC 3516, in order to obtain a better radio SED fit, we also added data from literature obtained at different JVLA configurations. These data points continue to well represent the central engine flux density. Also for the source NGC 1052, two data points obtained with radio instruments different from the JVLA have been used to better constrain the radio SED. Information about the JVLA project ID, the JVLA A configuration clean beam, its position angle (PA), and literature references are reported in Table 5 in the Appendix.

In the submillimeter window, we collected data from the ALMA archive. When ALMA data were not available, submillimeter flux densities obtained using other submillimeter instruments and already published have been used. In particular, we used the Combined Array for Research in Millimeter-wave Astronomy (CARMA) data published by Behar et al. (2018) for the source NGC 3516 and the James Clerk Maxwell Telescope (JCMT) data published by Hughes et al. (1993) for the source I Zw 1. Table 6, in the Appendix, summarizes the submillimeter information at our disposal.

JVLA archival data have been calibrated using the data-reduction package CASA (Common Astronomy Software Applications; version 5.1.2). Standard procedures for flux density, using the standard calibrators 3C 286 and 3C 48, and phase calibration have been applied. Moreover, for the more recent wide-band projects (IDs: 16B-289 and 16B-343) also channel flagging procedures and standard bandpass and delay calibration have been performed. From the calibrated data, Stokes I images were made for all the targets at each band running the CASA clean task. In order to isolate as much as possible the central radio component, we performed the cleaning using robust 0 or uniform weighting. Because the majority of the data sets come from the old JVLA correlator (consisting of two intermediate frequencies [IFs] of 50 MHz bandwidth each), the nterm parameter has been set equal to 1 (i.e., the change in the spectral index within that small bandwidth is neglected). On the cleaned maps, a Gaussian fit has been performed on the point-like central radio component. Because of the complex morphology of the source NGC 1068, an additional process has been performed to the radio images at X and Ku bands (8.4 and 15.0 GHz). We convolved the uniform weighted maps to the L-band resolution (1.4 GHz with ~1" angular resolution) in order to perform a proper Gaussian fit to the elongated structure resulting from the cleaning. All the compact radio components that are present in the central position of this AGN are well resolved only when reaching subarcsecond angular resolution (therefore, at Q band, 43 GHz, for our case). In order to match spatial resolutions during the fitting procedure, we sum the flux densities of the four 43 GHz radio components (NE, C, S1, and S2) that are clearly resolved and studied by Gallimore et al. (1996) and Cotton et al. (2008).

ALMA continuum flux densities have been collected analyzing the products of continuum Stokes I maps available for each project at the ALMA archive web page.8 On the continuum Stokes I maps, a Gaussian fit on the central submillimeter component has been performed to obtain the submillimeter flux density value. The flux densities for each target at each frequency are listed in Table 7 in the Appendix.

### 3.3. Fitting Procedure and Results

#### 3.3.1. Mid-infrared Spectral Fit to Dusty Models

Our purpose is to extrapolate the MIR spectral fit to submillimeter wavelengths to establish the detectability of the torus component at those wavelengths. For that purpose we fit the MIR data to dusty models. Note that we are not interested in well sampling the NIR to MIR SEDs; therefore, we will not focus on the finding of a very detailed derivation of the model parameters. Instead, we will test our theoretical predictions from model extrapolations.

The dusty models can be grouped into four classes: smooth (Fritz et al. 2006; Feltre et al. 2012), clumpy (Nenkova et al. 2008a, 2008b; Hönig et al. 2010; Hönig & Kishimoto 2010), smooth + clumpy (Stalevski et al. 2012), and windy (Siebenmorgen et al. 2015; Hönig & Kishimoto 2017). Among them, the most extensively used to fit data at MIR wavelengths is the clumpy model by Nenkova et al. (2008b), due to their large number of SEDs and probed ability to explain the spectra of low-luminosity (González-Martín et al. 2017), intermediate-luminosity (Ramos Almeida et al. 2009; Alonso-Herrero et al. 2011), and high-luminosity (Nikutta et al. 2009; Martínez-Paredes et al. 2017) AGNs. However, smooth models have been proposed to explain some peculiar anomalies of the spectra of high-luminosity AGNs (Martínez-Paredes et al. 2017). Furthermore, windy models are based on a more realistic configuration of dust according to dynamical arguments (Elitzur 2006; Elitzur & Ho 2009, and references therein). We have tested in this work all the models that have

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7 https://science.nrao.edu/facilities/vla/data-processing

8 https://almascience.eso.org/almadata/archive
public access to an SED library: (1) Smooth model by Fritz et al. (2006); (2) Clumpy model by Nenkova et al. (2008b); (3) Clumpy model by Hönig & Kishimoto (2010); (4) Windy model by Siebenmorgen et al. (2015); and (5) Windy model by Hönig & Kishimoto (2017). We are currently working on a paper that fully examines the similarities and differences between these five models (González-Martín et al. 2019a, in preparation) and which of these models better describe current MIR spectra of AGNs (González-Martín et al. 2019b, in preparation).

We converted these SED libraries to multiparametric models within the spectral-fitting tool XSPEC. XSPEC is a command-driven, interactive, spectral-fitting program within the HEASOFT software. XSPEC provides a wide range of tools to perform spectral fitting to data, being able to process in parallel in order to speed them up. To use these capabilities, we need to convert our SEDs into XSPEC format in order to upload our models within XSPEC as additive tables. The basic concept of a table model is that the file contains an $N$-dimensional grid of model spectra with each point on the grid having been calculated for particular values of the $N$ parameters in the model. XSPEC is able to interpolate on the grid. We have created an additive table for each torus model. For further models provide a reasonable fit to the data. However, the smooth dusty model described by Fritz et al. (2006) is the only one that does not need an additional component to provide a good fit to the data. For the others, a stellar component is needed to account for the short wavelengths (below 10 $\mu$m).

Thus, we used the smooth dusty model reported by Fritz et al. (2006) hereafter since, providing an equally good fit ($\Delta \chi^2$/dof < 0.1), it is the simplest baseline model that satisfactorily describes the data. The main difference between the resulting fits occurs at short wavelengths, so long wavelengths are quite insensitive to the model used. Therefore, we do not expect large discrepancies on the expected contribution of dust at submillimeter wavelengths owing to the selection of models.

In the case of NGC 1068 we consider initial inclination angles valid for type 2 Seyferts and toroidal sizes according to those found in the literature (see García-Burillo et al. 2016; Lopez-Rodriguez et al. 2018) using MIR high angular resolution data. However, we were not able to fit both $N$- and $Q$-bands of NGC 1068 with the same values for the parameters of the torus model. We try different fits; first, we link the parameters in both bands, without getting a good fit. We also tried adding the constant multiplicative model available in XSPEC to mimic a possible different resolution (or perhaps flux slit losses) between the bands, but they failed to reproduce both bands at the same time. Essentially, the shapes of the $N$- and $Q$-band spectra cannot be fitted with the same SED. Then, we unlink some parameters individually between both bands. We tested several combinations of unlinked parameters (e.g., $Y$ and $\tau$). The best result is obtained unlinking $\gamma$, $\beta$, and $\tau$ parameters (i.e., the coefficients within the density function and the optical depth). Note that although we use the model by Fritz et al. (2006) for our fit, we obtain different values of the parameters, since they add to their fit an IR template of a starburst galaxy to reproduce the colder component of the emission of dust. NGC 1068 has a well-reported complex dust distribution (Lopez-Rodriguez et al. 2018, and references therein). Indeed, the Spitzer spectrum shows a continuum flux more than 10 times brighter than the ground-based T-ReCS spectra, indicating external dust contributors at radii larger than a few hundreds of parsecs. We interpret that this

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9 https://heasarc.gsfc.nasa.gov

10 Engineering unit describing the integrated charge per pixel from an event recorded in a detector.

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Figure 10. SED fit for NGC 3516 to the MIR spectra (black spectrum) with the torus model (long-dashed line) and to the centimeter wavelengths (blue points) with synchrotron emission (dotted line). Pink plus signs are submillimeter data.
behavior of the $N$ and $Q$ bands reflects a complex structure of the dust within the inner $\sim 100$ pc that cannot be easily reproduced with a simple dusty model.

Figure 6 shows the best fit for the targets using the smooth dusty model by Fritz et al. (2006). The resulting parameters of the MIR fitting parameters are reported in Table 3 for completeness purposes, and the errors were calculated using the error tool$^{12}$ in XSPEC with a 99% confidence. It is out of the scope of this work to properly characterize the torus properties of our sample. For that purpose, NIR (Ramos Almeida et al. 2014) and/or X-ray (D. Esparza-Arredondo et al. 2019, in preparation) data are needed. From our fitting we find that the viewing angle for the type 1 AGNs (i.e., I Zw 1 and NGC 3516) is consistent with a direct view of the central engine, while that of the type 2 AGNs (i.e., NGC 1068) is consistent with the interception of the dusty torus in the line of sight, as previously found using well-sampled NIR to MIR unresolved SEDs (e.g., González-Martín et al. 2017; Martínez-Paredes et al. 2017; D. Esparza-Arredondo et al. 2019, in preparation; Lopez-Rodriguez et al. 2018).

3.3.2. Radio Spectral Fit to the Synchrotron Emission

The total intensity radio spectra of the targets have been fitted using a power law ($S_{\nu}^{\text{PL}}$), representing the optically thin part of a radio synchrotron spectrum and a single or a combination of two synchrotron emitting components ($S_{\nu}^{\text{SSA}}$ and $S_{\nu}^{\text{SSA2}}$), considering homogeneous, self-absorbed sources. Each synchrotron-emitting component is modeled with power-law electron energy distributions with spectral index in the optically thick and thin parts of the spectrum $\alpha_{\text{thick}} = 2.5$ and $\alpha_{\text{thin}}$, respectively. The equations used for the radio spectra fitting are the following:

1. A power law (optically thin synchrotron spectrum) with a slope $\alpha_{\text{thin}}$ (left to vary):

   \[ S_{\nu}^{\text{PL}} \propto \nu^{\alpha_{\text{thin}}}. \]  

2. A single synchrotron self-absorption component ($S_{\nu}^{\text{SSA}}$):

   \[ S_{\nu}^{\text{SSA}} \propto \nu^{2.5} \left( 1 - \exp \left( -\left( \frac{\nu}{\nu_0} \right)^{\alpha_{\text{thin}} - 2.5} \right) \right), \]  

   where $\nu_0$ is the frequency where the emission changes from optically thick, with a spectral index of 2.5, to optically thin with a spectral index $\alpha_{\text{thin}}$ (left to vary).

3. A combination of two synchrotron components ($S_{\nu}^{\text{SSA2}}$) with fixed $\alpha_{\text{thin}} = -0.7$ in order to reduce the number of free parameters.

To fit the above functions to the data, we used the python task curvefit on the centimeter wavelength data (i.e., JLVA data and centimeter wavelength from literature) only. For this radio-fitting procedure we considered the errors of the data points as absolute. This allows us to provide the variance of the estimated fit parameters as the square root of the diagonal of

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12 This tool determines the error ranges by sorting the Monte Carlo chain values and taking a central percentage of the values corresponding to the confidence level as indicated by the delta fit statistic.
the covariance matrix. For each source, we selected the best model according to the lowest statistical reduced chi-squared test ($\chi^2$/dof) value.

The resulting parameters of the radio fitting are reported in Table 4. Figure 7 shows the results of the radio fitting of the targets using a single power law for the sources I Zw 1 and NGC 1068, one synchrotron component for the source NGC 3516, and two synchrotron components for the source NGC 1052. Submillimeter data points (ALMA and CARMA or JCMT) are also shown in the plots (as green squares and magenta crosses, respectively). We marked with a black arrow those ALMA data for which the angular resolution is larger than 0\".3 (which correspond to a spatial resolution of $\sim$340, $\sim$140, and $\sim$800 pc for NGC 1052, NGC 1068, and NGC 3516, respectively, and $\sim$4 kpc for I Zw 1). These data, together with submillimeter data obtained from other sub-millimeter telescopes (i.e., magenta cross), could overestimate the flux density at that frequency owing to the large beam size. We will discuss this issue in Section 4. The radio spectra fitting works very well for the sources I Zw 1 and NGC 3516, while the fit shows large $\chi^2$/dof values for the sources NGC 1068 and NGC 1052. The fit cannot represent the JVLA high-frequency data point (at 43.4 GHz) for NGC 1068 without adding a second synchrotron component in the submillimeter window (see the discussion section). NGC 1052 shows a complex behavior, which cannot be accounted for with our fit, due to its variability at intermediate and high radio frequencies (for $\nu > 5$ GHz); multifrequency instantaneous radio observations could resolve this issue.

The fundamental plane prediction (green dashed line and gray band) shown in each plot gives an idea of the order of magnitude of the flux density of the radio jet. The fundamental plane, considering its uncertainties, follows the trend of the radio emission described by the jet in all cases except for NGC 3516, where the fundamental plane is an order of magnitude above the radio emission. Moreover, it does not account for the complexity of the radio emission. For example, in the case of NGC 1052 it is clear that the AGN needs two synchrotron components in order to represent the high radio frequency part of the spectrum (for frequencies larger than $\sim$10 GHz or wavelength smaller than $\sim$3 $\times$ 10$^4$; see Table 4); instead, the fundamental plane prediction goes below the high-frequency JVLA data. For NGC 1068 and NGC 1052, for which we have many more submillimeter values at our disposal, the submillimeter flux densities increase toward larger wavelengths, opposite to what is expected if this emission is associated with dust. Despite the possible inaccuracies described above, it is worth noticing that the fundamental plane seems to include, in all the cases of study, a non-negligible jet contribution to the submillimeter band.

These fits probe that the submillimeter part of the spectra is still (partially) contaminated by synchrotron emission (perhaps dominating for NGC 1052 and NGC 1068). However, a better analysis on this aspect is given in Section 4, where the MIR fit and the radio fit are combined together, giving a broad view on the contributors to the SED of these four AGNs.

### 4. Discussion

There is no doubt that the dust around AGNs plays an important role in obscuring the central engine and eventually fueling the accretion disk (Netzer 2015, and references therein). Therefore, the distribution and composition of the dust in AGNs and how they might evolve at different stages of the AGN evolution are of great importance (Elitzur 2006; Elitzur et al. 2014; Elitzur & Netzer 2016). This is why the torus properties in AGNs have been largely discussed in the literature, mainly through unresolved SED fitting (e.g., Ramos Almeida et al. 2009, 2011; Alonso-Herrero et al. 2011; González-Martín et al. 2015; Martínez-Paredes et al. 2015, 2017; Fuller et al. 2016; González-Martín et al. 2017), and also with MIR interferometric measurements (Tristram et al. 2009, 2014; Tristram & Schartmann 2011), since its size ($< 10$ pc) cannot be resolved with arcsecond-resolution images. The only facility able to achieve subarcsecond angular resolution at submillimeter, and therefore to actually image (at least some of) the AGN tori, is ALMA. This submillimeter interferometer provides a unique opportunity to directly measure the size of the torus. However, this wavelength band can be contaminated by the contribution of synchrotron emission by the jet and/or dust heated by star formation (Alonso-Herrero et al. 2014; Esquej et al. 2014; Esparza-Arredondo et al. 2018; Martínez-Paredes et al. 2018). The latter might be decontaminated thanks to the superspatial resolution of ALMA data. In this work we use two main assumptions to compute the percentage of torus contribution at submillimeter wavelengths: (1) the continuum of dust at MIR wavelengths follows a well-reported relation with the X-ray luminosity (Lutz et al. 2004; Gandhi et al. 2009; Asmus et al. 2015), and (2) the 5 GHz luminosity is also linked to the X-ray luminosity, known as the BH mass of the system (known as the radio fundamental plane; Bonchi et al. 2013). We used the dusty torus models of Nenkova et al. (2008b) for MIR wavelengths and a power-law distribution for centimeter wavelengths to extrapolate these predictions to the submillimeter wavelengths. In this way we showed that the chances to detect the torus are low. These chances slightly increase when using the lowest ALMA wavelengths (or the highest ALMA frequencies; see Figure 1) and high-accretion sources (mainly low BH mass and high luminous sources; see Figure 5). Among all of these assumptions, the riskiest one is the radio fundamental plane. It actually traces radio-core emission; however, a compact new radio jet component (therefore dominating at higher radio frequency) could contribute to the radio band and, in particular, substantially to the submillimeter band. Indeed, in the previous section we show that the fundamental plane is a rough estimator of the submillimeter contribution of the jet (see Figure 7). However, it cannot describe a possible complex behavior in the radio band, as clearly seen at least in NGC 1052 (and perhaps in NGC 1068; see below). Furthermore, in the particular case of NGC 3516, the fundamental plane overpredicts the jet contribution compared to the detailed analysis of the SED.

In order to make a clear picture on the contributors to submillimeter wavelengths, we show the full SED fitting when combining together the MIR and the radio data for NGC 1052, NGC 1068, NGC 3516, and I Zw 1 in Figures 8–11, respectively. We kept the same symbols and colors to describe the MIR and radio data as those used during the separated fitting procedure. The ALMA data with angular resolution larger than 0\".3 are marked with black arrows. These data points, together with JCMT and CARMA data, could be overestimating the flux density at that frequency/wavelength due to external contributors, because of the relatively large beam size. Both fits have been extrapolated in the
submillimeter window, and the sum of the two components is shown as a black straight line.

For the LLAGN NGC 1052 the radio jet contribution expands toward the submillimeter window while the torus contribution falls down very quickly at ~100 μm (Figure 8). This is consistent with our theoretical predictions, which show that the low-accretion AGNs (with high BH mass and low X-ray luminosity) tend to be highly dominated by the jet at submillimeter wavelengths (see Section 2.2). It is also in agreement with previous analysis of ALMA data for the LLAGNs NGC 1097 (Izumi et al. 2017) and NGC 1377 (Aalto et al. 2017), where they report strong contributions of a variable component associated with the jet.

Indeed, the jet of NGC 1052 dominates the vast majority of the emission in the 5–10^6 μm range, with the overall peak of the emission at radio frequencies. This is not the case for the remaining three sources, where the overall peak of the emission is below 50 μm. In any of these cases, neither the torus nor the jet can explain solely or as a combined effect the submillimeter emission with a ratio between data and model of ~3, 8, and even 100 for NGC 1068, NGC 3516, and I Zw 1, respectively.

The situation for NGC 1068 is very complex. We could not fit the N- and Q-band MIR spectra to a single model. On the contrary, we needed to allow three parameters (γ, β, and τ; see Table 3)\(^{13}\) to behave differently while the rest of the parameters are set to the same value. In this way we obtained two extrapolations of the torus component to the submillimeter wavelengths. We highlight to the reader that the fit reported here is far from realistic but is a clear indication of the complex configuration of dust, which cannot be fitted to a simple torus model (see Section 3.3.1), which is well documented in the literature (see Lopez-Rodriguez et al. 2016, and references therein).

Note that the SOFIA data reported by Lopez-Rodriguez et al. (2018) at the 20–50 μm range show the peak of the MIR emission in the 30–40 μm range, consistent with the Q-band rather than with the N-band spectral fit. After SED fitting to MIR and ALMA data at ~450 μm (i.e., 666 GHz), they reported a torus outer radius of ~5 pc. This outer radius is larger than the one reported here (~2 pc; see Table 3). However, they argue that the use of SOFIA and ALMA data yields a larger estimate on the outer radius of the torus. This was also shown by García-Burillo et al. (2016), Gallimore et al. (2016), and Imanishi et al. (2018). The question we would like to answer is whether the submillimeter ALMA data are actually tracing the dust in the torus. Indeed, the MIR Q-band spectral fit can easily account for the ~450 μm density flux (Figure 9). Moreover, the MIR N-band fit could even predict the ALMA upper limits at ~3000 μm. However, the entire SED at submillimeter wavelengths (with flux densities increasing with wavelength) is tough to explain with any complex scenario of dust. When considering NGC 1068 radio centimeter and submillimeter data points altogether for the radio fitting, the result is a combination of two synchrotron components with two different spectral indices representing the optically thin parts (see Figure 12). The first synchrotron component peaks at 2.24 (±0.09) [GHz] with flux density 3088 (±301) [mJy] and has a spectral index value of \(\alpha_{\text{el}} \sim -2.0 \pm 0.1\); the second component peaks at 60 (±2) [GHz] with a flux density of 50 (±2) [mJy] and a spectral index value of \(\alpha_{\text{el}} \sim -0.75 \pm 0.03\). The \(\chi^2/\text{dof}\) value of the fit is 0.8. The former value represents an “aged” distribution of synchrotron electrons, while the latter is flatter. This increases the jet contribution in the submillimeter window, placing further the possibility to detect the emission from the dusty torus at this wavelength band.

Also puzzling is the case of NGC 3516. The submillimeter data point (CARMA data) does not lie on its predicted value if it is the sum of the jet and the torus contributors (large angular resolution). Thus, either the parameters of the torus obtained from the MIR wavelengths are wrong, or there is another component contributing to the submillimeter wavelength. This extra component could be (1) dust heated by star formation (considering the lower spatial resolution of the submillimeter data point) or (2) a younger knot component of the jet as seen in NGC 1052 or NGC 1068.

In the case of I Zw 1 the submillimeter data points are well above the prediction, most likely because of the large angular resolution. This object is clearly extended at MIR on scales of a few hundred parsecs (Martínez-Paredes et al. 2017), but it is still not clear whether the extended emission is related to the possible presence of a circumnuclear ring (~1.7 kpc of diameter) detected by Schinnerer et al. (1998) using ¹²CO (2–1) and ¹³CO (1–0) molecular lines. A fraction of this emission could also be attributed to a silicate-emitting dust component that extends until the inner part of the NLR (Schweitzer et al. 2008). On the other hand, Hughes et al. (1993) argued that a fraction of the emission at submillimeter wavelength could be attributed to dust heated by an extended (>1 kpc) starburst region. Therefore, the JCMT data (i.e., the magenta crosses) could be simply explained by an additional dust contributor from star formation, peaking around ~100–200 μm. Uncertain are the ALMA data at 1000 μm. Although this point could be overestimating the flux density at this wavelength, it lies where the contribution of the flux density changes from the torus to the jet contributor. Dust heat by star formation (as an extrapolation of the JCMT data) could also explain the ALMA detected flux. However, even with all the caveats in mind, this is the most promising case of the torus being the dominant contributor to submillimeter wavelength because at least a large fraction of emission is expected to come from the dusty torus. This result is consistent with our theoretical predictions because I Zw 1 is the highest accreting source among our sample (with relatively low BH mass and high X-ray luminosity; see Table 2). Finally, the estimated outer radius of the torus for this source is ~8 pc, which at the distance of I Zw 1 (240.7 Mpc) implies that the torus has an angular size on the sky of ~0″007. The ALMA image in fact shows a point-like morphology with a beam size of ~0″6 (Imanishi et al. 2016b). Thus, even if the torus is dominating in this high-accretion source, it might be difficult to resolve it with current interferometric observations.

As a final caveat, we would like to stress that our findings on the SED fitting are biased toward the use of the library of SED models. Although we tested up to the five most used dusty models (see Section 3.3.1), we decided to use in all the cases the smooth torus model described by Fritz et al. (2006). The rest of the models need an extra stellar component to account for the short MIR wavelengths. Although we do not expect large discrepancies using any of the other models to extrapolate the torus to the submillimeter wavelengths, all of them are (perhaps not very realistic) simplifications of the configuration.
of dust in AGNs. This is clearly shown in the case of NGC 1068, where a complex fit was needed to account for the spectral fit of both $N$ and $Q$ bands together. Therefore, a much more complex scenario could yield to a different contribution of the dusty torus at submillimeter wavelengths. Indeed, as already mentioned in Section 2.1, we also considered the contributions from the hot graphite dust and the dusty NLR clouds (Mor et al. 2009; Mor & Netzer 2012). The contribution by the former is insignificant when extrapolated to the submillimeter window, and the contribution of the latter, although it could be as large as 40% of the total emission at $24 \mu\text{m}$, is not enough to describe the behavior in the submillimeter band.

The message to take away is that unfortunately there are very few chances to detect the torus over the jet at submillimeter wavelengths. This has been claimed to be the case for NGC 1068 (García-Burillo et al. 2016). They claimed the detection of the dusty torus based on a fitting of the $u-v$ visibilities within a radius of $0'' 2$. From this result the torus would be within $0'' 1$. However, looking at the resolution of their continuum image, the source is resolved by only 2–3 telescope beam size; therefore, it is marginally resolved. Moreover, although they do mention that 18% of the total flux within that region could come from other mechanisms different from thermal dust, from our theoretical calculation we do estimate that the contribution from the synchrotron emission from the radio jet could be as high as $\sim 94\%$ at this high frequency. Indeed, from our SED analysis, these observations might be contaminated by the jet components. The most promising case among our targets is I Zw 1. However, even in this case the chances to spatially resolve it are low. We also explored the SED of the type Seyfert 2, the Circinus galaxy. However, this is a complex source, as shown in the recent work by Izumi et al. (2018), with a large ISM contamination in the MIR $Spitzer$ spectrum. Therefore, due to the large contamination of warm dust from star formation, we could not extrapolate this contribution to the submillimeter range. Moreover, Elmouttie et al. (1998) revealed a very flat radio source at the position of the nuclear region at frequency larger that 8 GHz. Therefore, also in this case, it is plausible that there is still synchrotron emission contamination in the submillimeter band, due to high-frequency radio components from the radio jet. We strongly suggest to perform SED analysis, including radio data, with particular attention to the angular resolution used, before drawing any conclusion on the detection of a torus at submillimeter wavelengths. Another possibility already exploited by other authors (e.g., Izumi et al. 2017) is to study the variability pattern of the submillimeter wavelengths because we do not expect the torus to vary in a year-period basis, while the jet would show such variations.

5. Summary

This work aims to study the detectability of the torus in the submillimeter window. Specifically, we wanted to analyze this aspect considering the ALMA capabilities. Indeed, this submillimeter interferometer is the only facility able to achieve subarcsecond angular resolution and very good sensitivity (tens of $\mu$Jy) to actually image the AGN tori. We hack this issue using two approaches: the first is a theoretical approach, and the second is an observational one.

For the former, we considered the most used SED models for dusty AGN emission as the Clumpy models (Nenkova et al. 2008a, 2008b), together with known scaling relations between the accretion disk luminosity and the torus continuum (Gandhi et al. 2009; Asmus et al. 2015; Netzer 2015), and the accretion disk luminosity, jet contribution, and SMBH mass (Bonchi et al. 2013; Saikia et al. 2015). We extrapolated the scaling relations to the submillimeter wavelengths and estimated in which conditions the torus could prevail on the radio jet. The main result is that we are more likely to detect bigger and denser dusty tori at the highest ALMA frequency ($666 \text{ GHz} / 450 \mu\text{m})$. A 1 mJy torus (characteristic of bright AGNs, with flux density $S \sim 10 \text{ Jy}$) can be detected with a high detection limit, observing 1 hr at 353 GHz/$850 \mu\text{m}$ and 10 hr at 666 GHz/$450 \mu\text{m}$, being aware of the possible contamination by the radio jet.

For the observational approach, we used four prototypical AGNs: NGC 1052 (LLAGN), NGC 1068 (type 2 Seyfert), NGC 3516 (type 1.5 Seyfert), and I Zw 1 (QSO). These targets have been selected to have available radio data (to trace the jet contribution), MIR data (to trace the torus contribution), and continuum submillimeter observations. After performing individual MIR (using the smooth dusty model described by Fritz et al. 2006) and centimeter radio (using a power law and a single, or a composition of, synchrotron component(s)) fits to the spectra, we combined them together to compare the extrapolation of both torus and jet contributors at submillimeter wavelengths with data at those wavelengths. The radio jet of NGC 1052 dominates over the torus in the submillimeter range. In all the other cases, neither the torus nor the jet can explain the submillimeter emission. This result is consistent with the theoretical predictions for which low-accretion AGNs are highly dominated by the jet, while high-accretion sources (like I Zw 1) might be good candidates to detect emission from the torus at submillimeter wavelengths.

We therefore suggest to perform SED analysis including radio data in order to isolate the torus contribution from jet or dust heat by the AGN.

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Appendix

Radio Centimeter and Submillimeter Information

Here we report the radio centimeter and submillimeter information, such as the used radio centimeter and submillimeter telescope band and frequency, the archival project ID, literature references, and technical information (in Tables 5 and 6). Moreover, the radio centimeter and submillimeter flux densities are reported in Table 7.

### Table 5

| Source Name | Band | $\nu$ (GHz) | Project ID | Clean Beam (arcsec) | PA (deg) | Reference |
|-------------|------|-------------|------------|---------------------|----------|-----------|
| NGC 1052    |      | 0.08        |            |                     |          | Slee (1977)$^a$ |
|             | L    | 1.4         | 16B-289    | 2.8 x 1.0           | −47      |           |
|             | C    | 4.4         |            |                     |          | Perley (1982)$^b$ |
|             | C    | 6.2         | 16B-343    | 0.4 x 0.3           | −30      |           |
|             | X    | 8.4         | AW278      | 0.3 x 0.2           | −24      |           |
|             | Ku   | 14.9        | AF339      | 0.1 x 0.09          | −30      |           |
|             | K    | 22.1        | BC0066     | 0.09 x 0.07         | 4        |           |
|             |      | 31.4        |            |                     |          | Geldzahler & Witzel (1981)$^a$ |
| NGC 1068    | L    | 1.4         | AU079      | 1.5 x 1.3           | −24      |           |
|             | X    | 8.4         | AC467      | 0.2 x 0.2           | 4        |           |
|             | Ku   | 14.9        | AC467      | 0.1 x 0.1           | −75      |           |
|             | Q    | 43.0        | AC0565     | ...                 | ...      | Cotton et al. (2008)$^b$ |
| NGC 3516    | L    | 1.4         |            |                     |          | Ulvestad & Wilson (1984)$^b$ |
|             | C    | 4.8         |            |                     |          | Ulvestad & Wilson (1984)$^b$ |
|             | X    | 8.4         | AF360      | ...                 | ...      | Mundell et al. (2009)$^b$ |
|             | Ku   | 15.0        | AW0126     | ...                 | ...      | Ulvestad & Wilson (1989)$^c$ |
| I Zw 1      | L    | 1.4         | AK406      | 1.3 x 1.2           | 3        | ...       |
|             | C    | 4.8         | AK406      | 0.4 x 0.3           | −2       |           |
|             | X    | 8.4         | AB0670     | 0.2 x 0.2           | −9       |           |
|             | Ku   | 15.0        | AA0048     | ...                 | ...      | Barvainis & Antonucci (1989)$^d$ |

Notes.

$^a$ Two low angular resolution data points. These values are needed at the time of fitting the radio SED: the 80 MHz data point (from radioheliograph Culgoora-3) helps to search for the low/intermediate radio frequency synchrotron component. The 31 GHz observation (from the single-dish NRAO 11 m telescope at Kitt Peak) helps to find a good turnover point at high radio frequency.

$^b$ Data obtained using JVLA at A configuration.

$^c$ Observation using JVLA at B configuration; angular resolution at this frequency 0.4.

$^d$ This flux density has been obtained from VLA observation at C configuration, for which the angular resolution is 1.4. In this work, the continuum flux densities at L band (6.22 ± 0.35) and C band (2.21 ± 0.11) are also reported. These values are in agreement with higher angular resolution L band (4.91 ± 0.12) and C band (2.41 ± 0.12) from the project AK406. Therefore, we can assume that the Ku-band flux density obtained using C configuration well represents the core flux density at this frequency.

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Table 6
Submillimeter Information

| Source Name | $\nu$ (GHz) | Project ID | Clean Beam (arcsec) | PA (deg) | References |
|-------------|-------------|------------|---------------------|----------|------------|
| NGC 1052    | 108         | 2015.1.00591.S | $0.7 \times 0.6$ | $-65$ | ...        |
|              | 113         | 2015.1.00999.S | $1.4 \times 1.3$ | $-20$ | ...        |
|              | 214         | 2013.1.01225.S | $0.3 \times 0.2$ | $54$   | ...        |
|              | 230         | 2013.1.01225.S | $0.3 \times 0.2$ | $54$   | ...        |
|              | 340         | 2013.1.01225.S | $0.20 \times 0.15$ | $57$   | ...        |
|              | 350         | 2013.1.01225.S | $0.20 \times 0.15$ | $57$   | ...        |
| NGC 1068    | 93          | 2013.1.00055.S | $0.7 \times 0.5$ | $74$   | ...        |
|              | 103         | 2013.1.01151.S | $4.6 \times 2.1$ | $67$   | ...        |
|              | 223         | 2016.1.00232.S | $0.3 \times 0.3$ | $80$   | ...        |
|              | 251         | 2013.1.00221.S | $0.5 \times 0.5$ | $60$   | ...        |
|              | 350         | 2016.1.00232.S | $0.2 \times 0.2$ | $77$   | ...        |
|              | 694         | 2013.1.00055.S | $0.07 \times 0.05$ | $60$   | García-Burillo et al. (2016) |
| NGC 3516    | 100         | ... | ... | ... | Behar et al. (2018) |
| I Zw 1      | 252         | 2012.1.00034.S | $0.7 \times 0.6$ | $60$   | Imanishi et al. (2016a) |
|              | 374         | ... | ... | ... | Hughes et al. (1993) |
|              | 666         | ... | ... | ... | Hughes et al. (1993) |

Notes.

- a Data using CARMA telescope at C configuration, providing an angular resolution of $\sim 1''$.
- b Data using JCMT, providing an angular resolution at 374 GHz and at 666 GHz of 13'' and 9'', respectively.

Table 7
Radio and Submillimeter Flux Densities of the Targets

| Source Name | $\nu$ (GHz) | $S$ (mJy) | err$S$ | Note |
|-------------|-------------|------------|--------|------|
| multirow144emNGC 1052 | 0.08 | 4000 | 400 | (1) |
|              | 1.4         | 663.3      | 2.0    |      |
|              | 4.8         | 1130.0     | 113.0  |      |
|              | 6.2         | 1295.0     | 1.2    |      |
|              | 8.4         | 2910.0     | 30     |      |
|              | 14.9        | 1020.0     | 100.0  |      |
|              | 22.1        | 2460.0     | 20.0   |      |
|              | 31.4        | 1070.0     | 120.0  |      |
|              | 108.0       | 750.0      | 7.4    |      |
|              | 113.7       | 773.0      | 3.0    |      |
|              | 214.1       | 495.1      | 3.4    |      |
|              | 229.4       | 456.6      | 4.0    |      |
|              | 340.8       | 299.3      | 1.3    |      |
|              | 352.8       | 283.1      | 1.1    |      |
| NGC 1068    | 1.4         | 1585.0     | 51.0   |      |
|              | 8.4         | 361.0      | 12.0   |      |
|              | 14.9        | 97.0       | 6.0    | (4)  |
|              | 43.0        | 44.0       | 1.0    |      |
|              | 93.1        | 46.0       | 2.0    |      |
|              | 103.0       | 54.0       | 2.0    |      |
|              | 223.6       | 26.0       | 4.0    |      |
|              | 252.0       | 28.0       | 2.0    |      |
|              | 351.0       | 19.2       | 1.0    |      |
|              | 694.0       | 13.8       | 1.0    | (8)  |
| NGC 3516    | 1.4         | 5.0        | 1.0    | (5)  |
|              | 4.0         | 4.30       | 0.50   | (5)  |
|              | 8.0         | 2.50       | 0.20   | (6)  |
|              | 15.0        | 1.30       | 0.93   | (7)  |
|              | 100         | 1.34       | 0.29   | (8)  |
| I Zw 1      | 1.4         | 4.91       | 0.12   |      |
|              | 4.8         | 2.41       | 0.12   |      |
|              | 8.4         | 1.15       | 0.17   |      |
|              | 15.0        | 1.06       | 0.31   | (9)  |
|              | 252.0       | 1.20       | 0.06   | (10) |

Note. (1) From Slee (1977); (2) from Perley (1982); (3) from Geldzahler & Wittel (1981); (4) from Cotton et al. (2008); (5) from Ulvestad & Wilson (1984); (6) from Mundell et al. (2009); (7) from Ulvestad & Wilson (1989); (8) from Behar et al. (2018); (9) from Barvainis & Antonucci (1989); (10) from Imanishi et al. (2016a); (11) from Hughes et al. (1993); (*) flux density from García-Burillo et al. (2016): at the resolution $0''07 \times 0''05$ this value corresponds to the flux density of the claimed NGC 1068 core S1 component Gallimore et al. (2004).

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