# Understanding the mass growth of supermassive black holes in the universe

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**Abstract**

We propose ngVLA high-angular-resolution ($\sim$1 mas) dense molecular line observations at $\sim$3 mm ($\sim$85 GHz) of nearby active galactic nuclei (AGNs) which are believed to contain actively mass-accreting supermassive black holes (SMBHs). We aim to scrutinize the morphological and dynamical properties of the surrounding $<$10-pc-scale material, the so-called dusty molecular *torus*, with $\lesssim$1 pc spatial resolution. Our scientific goals are to unravel the nature of this mass reservoir just outside the central mass-accreting SMBHs and to understand how to fuel the central SMBHs by removing angular momentum and achieve SMBH mass growth in the universe.

**Key words:** quasars: supermassive black holes — galaxies: nuclei — galaxies: Seyfert

## 1. Introduction : Role of "Torus" in Active Galactic Nuclei

Active galactic nuclei (AGNs) are galaxy nuclei that shine very brightly from compact regions. The bright compact emission is believed to originate in an actively mass-accreting supermassive black hole (SMBH) with mass of $>10^6 M_\odot$. Optical spectroscopy of AGNs has found that some display broad ($\gtrsim$2000 km s$^{-1}$) emission lines (classified as type-1), while others show only narrow ($\lesssim$1000 km s$^{-1}$) emission lines (type-2). It is now widely believed that the presence of type-1 and -2 AGNs can naturally be explained by the presence of $\lesssim$10 parsec (pc)-scale toroidally distributed dust and gas, the so-called dusty molecular "torus", which surrounds a UV-optical-continuum-emitting accretion disk around an SMBH and the sub-pc-scale broad-line-emitting regions photo-ionized by the continuum emission (Antonucci 1993; Honig 2019) (see Figure 1).

The torus is a structure where a large amount of dense material is present in a concentrated form just outside the mass-accreting SMBH, and so is believed to be an important mass reservoir to fuel the central SMBH. However, according to the classical torus picture, the torus is thought to be less massive than the central SMBH and rotate with almost Keplerian motion, largely affected by the gravity of the central mass-dominating SMBH, because molecular viscosity in the torus is too small to significantly extract the angular momentum in a short timescale (Wada et al. 2009; Wada et al. 2016). In this case, mass in the torus will not be efficiently transported inward and no significant mass-accretion onto the SMBH will happen. This means that the SMBH will not be ignited and no luminous AGN will be observed in the universe. However, there are many luminous AGNs found in the universe. There must be still unknown physical mechanisms that realize mass fueling from the torus to the central SMBH by removing angular momentum. It is of crucial importance to observationally unravel the secret mechanisms if we are to fully understand how luminous AGNs appear and how SMBHs grow in mass in our universe.

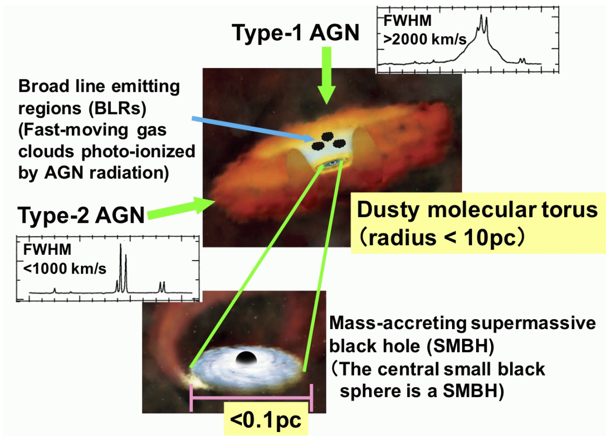


**Fig. 1.** The widely accepted unified model of AGNs. The mass-accreting SMBH consists of a central SMBH and an accretion disk ($<$0.1 pc scale), both of which are thought to be surrounded by toroidally distributed dust and dense molecular gas, the so-called "torus" with $\lesssim$10 pc scale. Fast-moving gas clouds in the vicinity of the central SMBH, dominated by the strong SMBH's gravity, are photo-ionized by UV-optical radiation from the accretion disk, forming the so-called broad line emitting regions (BLRs). When we see the BLRs directly, from the face-on direction of the torus, the AGN is observed as type-1 which displays broad (FWHM $>$ 2000 km s$^{-1}$) optical emission lines. When we see the torus from an edge-on direction and optical emission from the BLRs is blocked by the torus, the AGN is observed as type-2 which does not show broad optical emission lines.

## 2. Case for NGC 1068 - the Nearby Archetypal AGN

The torus-based AGN unification paradigm was originally proposed from observations of the nearby type-2 AGN, NGC 1068 ($z \sim$ 0.0038, distance $\sim$ 14 Mpc, 1 arcsec is $\sim$70 pc) (Antonucci & Miller 1985). Observationally scrutinizing the properties of the putative dusty molecular torus in NGC 1068 is an important first step toward understanding what the torus is and what its role is in AGNs. However, the apparent size of the putative $\lesssim$10 pc-scale torus is small (e.g., 10 pc is $0''.15$ at the distance of NGC 1068), so high-spatial-resolution observations are indispensable to spatially resolving it clearly. The use of ALMA has started to bring about significant advances in our understanding of the compact dusty molecular torus, because high-angular-resolution ($\lesssim$0.″1) and high sensitivity data can now routinely be obtained at the (sub)millimeter wavelength, where rotational (J) transition lines of many abundant molecules exist.

In the case of NGC 1068, radio jet emission and $\gtrsim$10 pc-scale optical [OIII] line emission photo-ionized by the AGN radiation extend to the north-south direction in the vicinity of the mass-accreting SMBH (Evans et al. 1991; Das et al. 2006; Gallimore et al. 2004). Since such emission can easily escape along a direction almost perpendicular to the putative dusty molecular torus, the rotating torus in NGC 1068 is presumed to be located roughly along the east-west direction of the SMBH. Imanishi et al. (2018) conducted ALMA $\sim$0.″04–0.″07 (2.8 pc $\times$ 4.9 pc)-resolution observations of the NGC 1068 nucleus using dense molecular tracers, HCN and HCO$^+$ J=3–2 lines, and revealed almost east-west-oriented dense molecular emission both morphologically and dynamically (Figure 2). This observational result conformed to what people had expected for the torus in NGC 1068. The dense molecular mass in the NGC 1068 torus was estimated to be $M_{torus} \sim 10^{5-6} M_\odot$ (Imanishi et al. 2016; Garcia-Burillo et al. 2016; Garcia-Burillo et al. 2019), which is much smaller than the central SMBH mass with $M_{SMBH} \sim 1\times10^7 M_\odot$ (Greenhill et al. 1996).

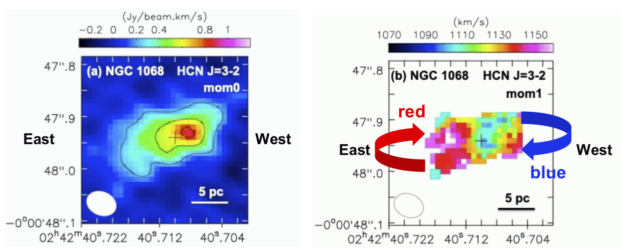


**Fig. 2.** *(Left)* Integrated intensity (moment 0) map and *(Right)* intensity-weighted mean velocity (moment 1) map of the HCN J=3–2 emission line (= a dense molecular gas tracer) from the putative torus of NGC 1068. The emission is elongated along the almost east-west direction as expected *(Left)*. The blueshifted and redshifted motions are also aligned to the same east-west direction *(Right)*. Adopted from Imanishi et al. (2018).

However, it was also found that (1) unlike the prediction of the classical torus model, the velocity difference between the blueshifted and redshifted components at the probed physical scale ($\sim$3 pc) is much smaller than that expected from Keplerian rotation dominated by the central SMBH, and (2) the dense molecular emission is *blueshifted (redshifted)* at the *western (eastern)* part of the torus, while both (a) innermost ($\lesssim$1 pc) $\sim$22 GHz $H_2O$ maser emission and (b) dense molecular emission in the host galaxy (50–150 pc scale) outside the torus, along the torus direction, show *redshifted (blueshifted)* components at the *western (eastern)* part (Greenhill et al. 1996; Gallimore et al. 2004; Imanishi et al. 2018). Namely, dense molecular gas in the putative torus looks to be counter-rotating with respect to the innermost ($\lesssim$1 pc) $H_2O$ maser emission and outer (50–150 pc) host galaxy dense molecular gas. Figure 3 illustrates the observed complex dynamics of dense molecular gas at the NGC 1068 nucleus. Very surprising torus properties were revealed in NGC 1068.

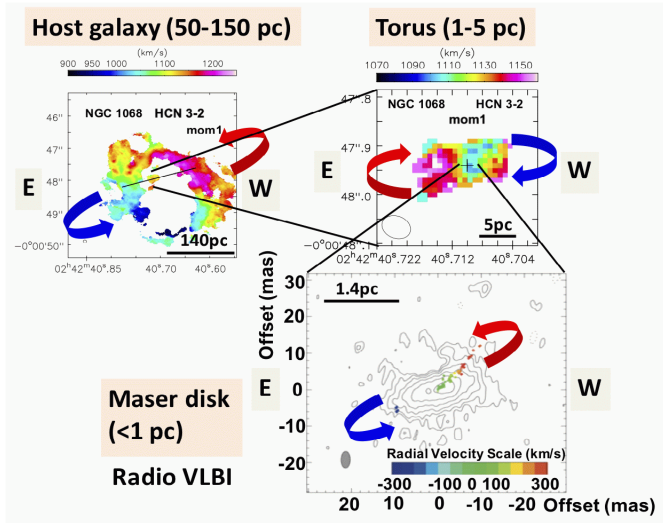


**Fig. 3.** Observed dynamical properties of dense molecular and $H_2O$ maser emission at the inner part of NGC 1068. *(Top Left)*: Intensity-weighted mean velocity (moment 1) map of HCN J=3–2 emission line in the host galaxy (50–150 pc) scale (Imanishi et al. 2018). The thin solid line crossing the torus at the center indicates the torus axis (PA $\sim$ 105°). *(Top Right)*: Moment 1 map of HCN J=3–2 in the torus (1–5 pc) scale (Imanishi et al. 2018). *(Bottom)*: $H_2O$ maser emission dynamics at the innermost ($\lesssim$1 pc) part. Modified from Gallimore et al. (2004). Velocity relative to their adopted systemic velocity is color coded. The coordinates are offset (in mas) from the VLBA 5 GHz continuum shown as contours. North is up and east is to the left in all plots. The length of the thick horizontal bar corresponds to 140 pc, 5 pc, 1.4 pc in the top-left, top-right, bottom panel, respectively. Thick curved blue and red arrows indicate blueshifted and redshifted motion relative to the systemic velocity of NGC 1068, respectively. The western side is *redshifted* for maser emission at $\lesssim$1 pc *(bottom)* and dense molecular emission in the host galaxy at 50–150 pc scale *(top left)*, but is *blueshifted* for the torus dense molecular emission at 1–5 pc scale *(top right)*.

Later, ALMA $\sim$0.″02 ($\sim$1.4 pc)-resolution HCN J=3–2 line data of the NGC 1068 torus unveiled the presence of inner ($\lesssim$2 pc) and outer ($\gtrsim$2 pc) dynamically decoupled dense molecular gas components, which are counter-rotating to each other (Figure 4) (Impellizzeri et al. 2019; Imanishi et al. 2020). Such counter-rotating molecular gas can easily remove the angular momentum of the torus, transport torus material inward, and naturally explain the observational fact that NGC 1068 is observed as a luminous AGN ($L_{AGN} > 4 \times 10^{44}$ erg s$^{-1}$) by accreting a sufficient amount of mass onto the central SMBH. We hypothesize that a compact massive gas clump fell into the pre-existing torus and altered the rotation of the outer torus (Figure 5).

In this way, our ALMA dense molecular line observational results have clearly demonstrated the power of high-spatial-resolution ($\sim$1 pc) to unravel the interesting dynamic nature of the compact ($\lesssim$10 pc) torus in this particular nearby archetypal AGN, NGC 1068. We have obtained an important clue to understand how to fuel the central SMBH by transporting torus material inward and ignite AGN activity.

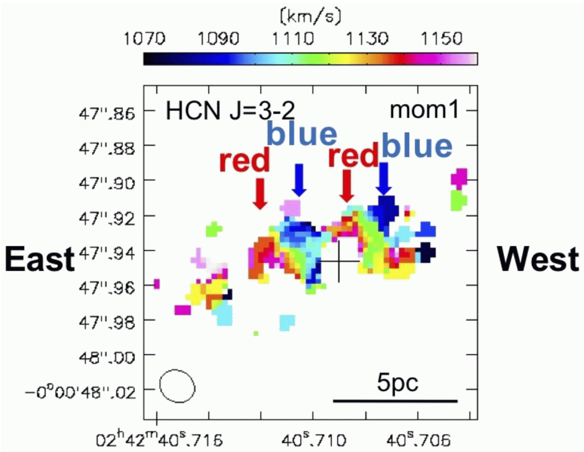


**Fig. 4.** Moment 1 map of the HCN J=3–2 emission of the torus in NGC 1068, revealed from ALMA very high-angular-resolution ($\sim$0.″02 or $\sim$1.4 pc) data (Imanishi et al. 2020). The inner dense molecular gas displays *redshifted (blueshifted)* motion at the *western (eastern)* part in a similar way to the innermost ($\lesssim$1 pc) $H_2O$ maser emission (Greenhill et al. 1996; Gallimore et al. 2004), while the outer one shows *blueshifted (redshifted)* motion at the *western (eastern)* side, as previously observed in $\sim$0.″04–0.″07-resolution HCN and $HCO^+$ J=3–2 line data (Imanishi et al. 2020).

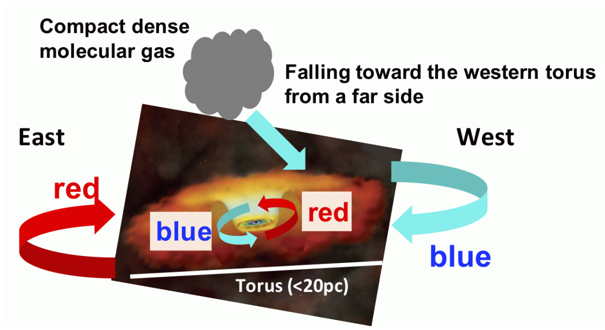


**Fig. 5.** Proposed scenario for the NGC 1068 torus: a massive compact gas clump collided with the western torus (right side) from a far side and altered the rotation there from redshifted to blueshifted motion, except for the innermost almost-Keplerian rotating molecular gas component whose dynamics is strongly governed by the central SMBH's gravity. Blueshifted and redshifted motions are shown with blue and red arrows, respectively. This scenario can naturally explain all observational results presented by Imanishi et al. (2020), including larger turbulence in the western torus and rotation of outer torus which is much slower than Keplerian.

## 3. Prospect for ngVLA

Although this is still only one example for NGC 1068, it is natural to propose the grand-unified picture for the origin of AGN phenomena in the universe. (1) Luminous AGNs are the population where the angular momentum of torus dense molecular gas is largely removed. (2) Non-AGNs do not have dense molecular torus to be fueled to the central SMBHs, or do have dense molecular torus which is dynamically rotation-dominated and angular momentum is not sufficiently removed.

The ngVLA will realize $\sim$1 mas angular resolution in the 3mm wavelength range, where bright dense molecular lines (e.g., HCN and $HCO^+$ J=1–0) exist. Using ngVLA, we can achieve nearly an order of higher angular resolution for dense molecular line observations than ALMA. The collecting area of ngVLA is also about an order of magnitude larger than ALMA at $\sim$3 mm ($\sim$85 GHz). Both the high-angular-resolution and high sensitivity of ngVLA will enable us to reveal the detailed dynamical properties of torus dense molecular gas with $\lesssim$0.1 pc physical scale in very nearby ($\sim$15 Mpc) AGNs, such as NGC 1068. The physical origin of the angular momentum removal in torus dense molecular gas will be better understood. For example, (1) do instability and/or shocks happen at the border of the counter-rotating dense molecular gas in the NGC 1068 torus, which dramatically extract angular momentum there? (2) Do star-formation happen in the torus which also helps significantly remove angular momentum and enhance mass-accretion inward (Wada & Norman 2002)? Observations of bright shock tracer lines (e.g., SiO, $CH_3OH$, SO, $SO_2$) and/or star-formation indicators (e.g., hydrogen recombination lines such as H40$\alpha$ or H42$\alpha$; Bendo et al. (2015)) in the 3mm band using ngVLA will provide invaluable information for these kinds of activity in the torus in a completely dust-extinction-free manner.

Most importantly, by utilizing an order of magnitude better angular resolution and high sensitivity of ngVLA, we can extend the interesting case study of NGC 1068 to other luminous AGNs and non-AGNs at further distance (>15 Mpc). This is crucial to test the proposed grand-unified picture, by observing a statistically significant number of luminous AGNs and non-AGNs at $\lesssim$1 pc spatial resolution. Using ngVLA, we aim to answer the fundamental questions of "How does AGN activity happen?" and "How do SMBHs in the universe grow in mass?".

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