A MEASUREMENT OF THE BLACK HOLE MASS IN NGC 1097 USING ALMA

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ABSTRACT

We present an estimate of the mass of the supermassive black hole (SMBH) in the nearby type-I Seyfert galaxy NGC 1097 using Atacama Large Millimeter/submillimeter Array (ALMA) observations of dense gas kinematics. Dense molecular gas dynamics are traced with HCN(J = 1 – 0) and HCO+(J = 1 – 0) emission lines. Assuming a host galaxy inclination of 46°, we derive an SMBH mass, $M_{\text{BH}} = 1.40^{+0.27}_{-0.18} \times 10^9 M_\odot$, and an l-band mass to light ratio to be $5.14^{+0.03}_{-0.04}$ using HCN(J = 1 – 0). The estimated parameters are consistent between the two emission lines. The measured SMBH mass is in good agreement with the SMBH mass and bulge velocity dispersion relationship. Our result showcases ALMA’s potential for deriving accurate SMBH masses, especially for nearby late-type galaxies. Larger samples and accurate SMBH masses will further elucidate the relationship between the black hole (BH) and host galaxy properties and constrain the coevolutionary growth of galaxies and BHs.

Key words: black hole physics – galaxies: individual (NGC 1097) – quasars: supermassive black holes

1. INTRODUCTION

Recent observations suggest that supermassive black holes (SMBHs) reside in the centers of most massive galaxies (e.g., Kormendy & Ho 2013 and references therein). In the nearby universe a variety of host galaxy properties are known to be correlated with the central SMBH mass. For instance there is a tight correlation between the SMBH mass and the bulge luminosity ($M_{\text{BH}}$ – L$\text{bulge}$ relation, e.g., Kormendy & Richstone 1995; Kormendy & Ho 2013; McConnell & Ma 2013), the bulge mass ($M_{\text{BH}}$ – M$\text{bulge}$ relation, e.g., Magorrian et al. 1998; Marconi & Hunt 2003; Belfiori et al. 2012; Kormendy & Ho 2013), and the central velocity dispersion ($M_{\text{BH}}$ – $\sigma$ relation, e.g., Ferrarese & Merritt 2000; Gültekin et al. 2009; Kormendy & Ho 2013; McConnell & Ma 2013). These empirical correlations suggest that black holes (BHs) may play a key role in the growth and evolution of galaxies.

Recent studies, however, reveal that the correlation between the SMBH mass and bulge/host galaxy properties are more complex than originally thought. For instance McConnell & Ma (2013) showed that the best-fit $M_{\text{BH}}$ – $\sigma$ relation differs between early- and late-type galaxies. The difference results in the SMBH mass to be two times larger at a given velocity dispersion for the early-type $M_{\text{BH}}$ – $\sigma$ relation than for the late-type systems. In contrast, there does not seem to be a correlation between galaxies hosting pseudo-bulges and their SMBH masses (Kormendy & Ho 2013). Much of the uncertainty comes from the scarce number of measurements of the SMBH masses especially in late-type galaxies, which is especially difficult with current methods for measuring the SMBH mass.

The most reliable way to estimate SMBH mass is to use dynamics/kinematics of gas or stars near the SMBH in a galaxy. So far, SMBH masses have been measured in the following ways: using proper motion of stars around the SMBH (e.g., Genzel et al. 2000; Ghez et al. 2008), using proper motion and dynamics of megamasers (e.g., Miyoshi et al. 1995; Kuo et al. 2011), stellar dynamics (usually only for elliptical or lenticular galaxies) (e.g., Dressler & Richstone 1988; McConnell et al. 2011; Onken et al. 2014), and ionized gas dynamics (e.g., Macchetto et al. 1997; de Francesco et al. 2008).

The method using the proper motion of stars around the central SMBH is the simplest of the four, but spatially resolving stars around a SMBH, besides the one in our Galaxy, is not currently possible. The SMBH mass measurements in galaxies using megamasers, which are rare and difficult to find, requires observations with very high angular resolution (~0.3 milliarcsecond, for example, in Miyoshi et al. 1995), accomplished with Very Long Baseline Interferometer. Stellar dynamics have been used to measure the largest number of SMBH masses at this point. An orbit superposition model (Schwarzschild 1979) is fit to spectroscopic observations and the method is primarily restricted to elliptical and lenticular systems. The errors in this method can be amplified when a mass profile is asymmetric. Ionized gas dynamics can be observed in larger samples (at least compared to the use of stellar or maser dynamics), by taking spectra of a galaxy using multiple slits or Integral Field Units (IFUs). The weak point of this method is that ionized gas is not necessarily settled into a pure rotating disk because it is more easily affected by non-circular motion from turbulence, shocks, radiation pressure, outflows, etc. Inferring the velocity field from slit observations is also problematic because such measurements may not always show non-circular motions which could be affecting the gas dynamics. Note that recent IFU observations can avoid this problem and are improving to be very useful to obtain velocity fields.

Deriving SMBH mass from molecular gas dynamics was not accomplished until Davis et al. (2013) because millimeter-wavelength interferometers did not have sufficient angular resolution and sensitivity to map out the precise kinematics of molecular gas around a BH. The SMBH mass in the central region of NGC 4526 was measured using the observed CO emission line from its circumnuclear, molecular-gas disk (Davis et al. 2013). This method was also proposed by Onishi.
Table 1
Properties of NGC 1097

| Parameter         | Value       | Reference |
|-------------------|-------------|-----------|
| Morphology        | SB(s)b      | 1         |
| Nuclear activity  | Type 1 Seyfert | 2        |
| Position of nucleus | 3          |           |
| R.A.(J2000.0)     | 02°46′18″96 | ...       |
| Decl.(J2000.0)    | −30°16′28″9 | ...       |
| Systemic velocity (km s$^{-1}$) | 125$^a$     | 4         |
| Position angle (°) | 130        | 1, 4      |
| Inclination angle (°) | 46 ± 5     | 5         |
| Distance (Mpc)    | 14.5        | 6         |
| Linear scale (pc arcsec$^{-1}$) | 70         | 6         |
| I-band luminosity (mag) | 8.09       | 7         |

Note.
$^a$ Systemic velocity here is a heliocentric velocity determined with molecular lines. Koribalski et al. (2004) shows the heliocentric velocity to be 1271 km s$^{-1}$ determined with HIPASS observation.

References. (1) de Vaucouleurs et al. (1991), (2) Storchi-Bergmann et al. (1993), (3) Hummel et al. (1987), (4) this work, (5) Ondrechen et al. (1989), (6) Tully (1988), (7) Springob et al. (2007).

Table 2
ALMA Observation Parameters

| Parameter          | Value       | Reference |
|--------------------|-------------|-----------|
| Date               | 2012 Jul 29, Oct 19 |          |
| On-source time     | 105.24 minutes |          |
| Configuration      | extended (Cycle 0) |          |
| Phase center       | R.A.(J2000.0) | 02°46′19″06 |
| Decl.(J2000.0)     | −30°16′29″7 |          |
| Primary beams      | 69″         |           |
| Frequency coverage (GHz) | 85.400–89.104 | 97.271–100.917 |
| Velocity resolution (km s$^{-1}$) | 1.7 | 1.5 |
| Central frequency of each spectral window (GHz) | 86.338, 88.166 | 98.209, 99.979 |

Note.
1. Molecular gas

1.1. NGC 1097

NGC 1097 is a nearby Type-1 Seyfert galaxy at a distance of 14.5 Mpc (Tully 1988) (~70 pc arcsec$^{-1}$). The position of the nucleus is determined by the peak position of the 6 cm continuum emission (Hummel et al. 1987): R.A. (J2000.0) = 02°46′18″96, decl. (J2000.0) = −30°16′28″9. The peak position of the 860 μm continuum emission coincides with the 6 cm peak (Izumi et al. 2013). Properties of NGC 1097 are summarized in Table 1.

The SMBH mass in NGC 1097 is estimated to be (1.2 ± 0.2) × 10$^8$M$_\odot$ by Lewis & Eracleous (2006) using the empirical $M_{BH}−σ$ relation from Tremaine et al. (2002) with an observed $σ = 196 ± 5$ km s$^{-1}$. The uncertainty in this estimate is large, depending on the assumed $M_{BH}−σ$ relation. The latest $M_{BH}−σ$ relation [$\log_{10}(M_{BH}/M_\odot) = 8.32 + 5.64 \log_{10}(σ/200 \text{ km s}^{-1})$, McConnell & Ma (2013)] would yield SMBH mass of (1.9 ± 0.3) × 10$^8$M$_\odot$. Note that this relation is a fit to both late-type and early-type galaxies. When selecting only the late-type galaxies, the $M_{BH}−σ$ relation becomes [$\log_{10}(M_{BH}/M_\odot) = 8.07 + 5.06 \log_{10}(σ/200 \text{ km s}^{-1})$] (McConnell & Ma 2013) and the estimated SMBH mass becomes (1.1 ± 0.3) × 10$^8$M$_\odot$.

The enclosed mass in 40 pc radius has been studied by (Izumi et al. 2013) to be $2.8 \times 10^8$M$_\odot$, using the dynamics from HCN($J = 4 − 3$) emission line. In contrast, Fathi et al. (2013) report a dynamical mass in 40 pc radius as $8.0 \times 10^8$M$_\odot$ from the same data of Izumi et al. (2013). The difference occurs because Fathi et al. (2013) assume a thin disk and extracts the non-circular motions of the gas while Izumi et al. (2013) assume a simple Keplerian rotation. Note but the dynamical mass of Izumi et al. (2013) includes all the mass within that radius, not showing the intrinsic SMBH mass. A more detailed study of NGC 1097 is thus necessary to precisely measure the SMBH mass.

2. OBSERVATIONS AND DATA REDUCTION

NGC 1097 was observed with the band 3 receiver on ALMA using the two sideband dual-polarization setup as a cycle 0 observation (Project code = 2011.0.0108.S; PI = K. Kohno). The observations were conducted on 2012 Jul 29 and 2012 Oct 19 with an hour angle from −4 to 2 and a total on-source time of 105.24 minutes. The antennas were in the Cycle 0 extended configuration (400 m baselines) which resulted in a synthesized beam of $1′.60 \times 2′.20$ at a position angle $−81°2$ ($\sim112$ pc × 154 pc). The receivers were tuned to cover the frequency range from 87.275 to 100.917 GHz with two spectral windows each in the upper sideband (USB) and the lower sideband (LSB). Each spectral window had a bandwidth of 1.875 GHz with 3840 channels. The frequency resolution was 0.488 MHz per channel. Observational parameters are summarized in Table 2. The field of view (full width half maximum of the primary beam) at these frequencies was 69″. The data were reduced and imaged using Common Astronomy Software Applications 4.0 with a robustness parameter of 0.5. We binned the data by 2 channels to improve the signal to noise ratio and our final resolution is 0.976 MHz or $\sim3$ km s$^{-1}$. Molecular gas emission is detected over 560 km s$^{-1}$ (HCN($J = 1 − 0$)
emission is seen from 88.1524–88.3467 GHz and $JHCO^+(1-0)$ from 88.7139–88.9082 GHz. The integrated intensity moment zero and intensity weighted velocity maps were made using Karma (Gooch 1996). These are shown in Figure 1. The noise in the integrated intensity maps is 22 (mJy beam$^{-1}$ km s$^{-1}$) in HCN($J=1-0$) (upper panel), and 26 (mJy beam$^{-1}$ km s$^{-1}$) in HCO$^+(J=1-0)$ maps respectively. The peak flux is detected at 52$\sigma$ in the HCN($J=1-0$) map and at 29$\sigma$ in the HCO$^+(J=1-0)$ map respectively. The data clearly show the rotation dominated kinematics of the molecular gas around the SMBH.

3. SMBH MASS ESTIMATION

The measurement procedure for the SMBH mass and its result are described in this section. We model a mass distribution of the galaxy with multiple Gaussians to express the combination of stellar mass profile and the SMBH mass. The gravitational potential is derived by following the equations described in Cappellari et al. (2002), which uses a Multi Gaussian Expansion (MGE) method. Circular velocity is calculated from the gravitational potential field by using MGE _ circular _ velocity code, which is in the JAM modeling package$^6$ of Cappellari (2008). The SMBH mass is estimated from the total mass profile, which gives a velocity field best matched to the observed result. When comparing the derived velocity profile with the observational results, we use the Kinematic Molecular Simulation (KinMS, Davis et al. 2013) in order to consider disk properties (e.g., disk thickness, position angle, and inclination) and the observational effect of beam-smearing. We show the details of each procedure in the following sections.

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6 http://purl.org/cappellari/idl
3.1. The Mass Model

We express the mass distribution as a summation of the SMBH mass and the stellar mass profile, expressed as the stellar luminosity distribution multiplied by a constant I-band mass-to-light ratio (M/L). Assuming that the galaxy is axisymmetric, the stellar luminosity distribution along the galaxy major axis is modeled as a superposition of Gaussian components, using the idea of MGE (Emsellem et al. 1994). The major axis defined here is at a position angle of 130° from de Vaucouleurs et al. (1991). We use an I-band image observed with the Advanced Camera for Surveys Wide Field Channel F814W filter on Hubble Space Telescope (HST) to obtain the luminosity distribution along the major axis (black line in Figure 2). We subtract the contribution from the Active Galactic Nucleus (AGN) and flatten the starburst dominated region (both are shaded in Figure 2) in order to estimate the underlying stellar luminosity profile. The AGN profile is calculated by the convolution of a delta function with the Point Spread Function (PSF), measured to be 0.2″ (full width half maximum, FWHM) from five unresolved stars in the same image. The PSF is also checked by using “Tiny Tim” package (version 6.3) developed by Krist et al. (2011). The luminosity value of the delta function is determined to obtain the residual luminosity distribution larger than 0 at any radius. Note that the AGN subtraction does not greatly affect the SMBH mass estimation. Even the peak before subtraction gives a mass of less than 6.00 × 10^6 M⊙ for a M/L ratio 5.14, and it is at least one digit smaller than the SMBH mass we put in the model. The starburst ring region is determined to be in the range of radii from −11″ to −7″ and from 8″ to 13″ along the major axis. The ring includes younger stars than inside or outside of the ring, and is bluer in color. We model the stellar luminosity profile by calculating the least-square value with the luminosity distribution without the ring and the AGN. The model (blue line in Figure 2), therefore, consists mainly of old stars, but does not include younger stars on the ring. See also Table 3 for MGE parameters we give for the data. The mass profile is simply modeled by multiplying the constant I-band M/L ratio to the modeled stellar luminosity profile and adding the assumed SMBH point mass in the center. Note again that we model older stars, by which means we are assuming that the radial difference of the M/L ratio is negligible.

3.2. Velocity Field Calculation

With a given mass profile from Section 3.1, we calculate the velocity field from a gravitational potential field derived with equations from Cappellari et al. (2002). We use MGE_circular_velocity code, which is in the JAM modeling package of Cappellari (2008). The inclination angle is set to be 46° (Ondrechen et al. 1989). See Section 4.2 for more details regarding the inclination angle.

3.3. Modeling a Position–Velocity Diagram (PVD)

We calculate a PVD model along the galaxy major axis by assuming that the observed molecular gas follows the velocity field obtained by our calculation. The observational effects are taken into account by utilizing KinMS (Davis et al. 2013). We convolve the model cloud distribution with our beamsize (1.60 × 2.20) to express the beam-smearing, and assume the molecular gas disk to be an axisymmetric thin disk. The position angle of the galaxy major axis is set to be 130° (de Vaucouleurs et al. 1991), which is consistent with the kinematical position angle estimated from our observational data. The position angle is also consistent with the one calculated by Spitzer Survey of Stellar Structure in Galaxies (S4G, Sheth et al. 2010), −52°, and global properties calculated via their pipeline 3 by Muñoz-Mateos et al. (2015). Note that we can mostly avoid the region with non-circular motion pointed out by Fathi et al. (2013) by using a PVD along the galaxy major axis. We assume that the streaming motion remaining in the PVD is negligible. We can also comment that when considering the error propagation for a simple equation of v^2/2 = GM/r, 10 percent error in the velocity could result in 20 percent error for the SMBH mass, which is consistent the error bar we derive from Figure 5.

3.4. Fitting the PVD Model to the Observational Result

The observed PVD of HCN(J = 1 − 0) is shown in the upper panel of Figure 3 with color filled contours. We set the kinematical position angle to be 130° ± 5°. The center of the galaxy is assumed to be the peak of 6 cm observation (Hummel et al. 1987), 860 μm, and HCN(J = 4 − 3) observation (Izumi et al. 2013). We fit the observed PVD with PVD models calculated with 2 free parameters, the I-band M/L ratio and the SMBH mass. We find the two parameters to be around M/L ~ 5.0 and M_BH ~ 1.0 × 10^8 M⊙ by initial robust-grid calculation. Then the finer grid of model parameters is set to be from...
\[ M/L = 4.80 \text{ to } 5.35 \text{ in steps of } 0.01 \text{ and } M_{BH} = 0.5 \times 10^8 M_\odot \text{ to } 2.5 \times 10^8 M_\odot \text{ in steps of } 0.1 \times 10^8 M_\odot \]. We calculate an optimal rotation curve from the observed PVD above \( 3\sigma \sim 8 \text{ mJy} \) as follows: we make two cuts—one in the horizontal and one in the vertical direction. A cut in the vertical direction gives us an intensity profile at each position. Peak positions for both are determined with the Gaussian fit. We use the points when the two are consistent, but abandon them when they do not match. In the latter case the spectrum is not well characterized by a Gaussian because the asymmetric distribution of the molecular gas and the beam smearing effect is skewing the profile. 106 points are extracted from the observed PVD (see Figure 3). The error bar along the velocity axis for each representative point of the PVD is defined to be a sum in quadrature of the channel width \( (3.284 \text{ km s}^{-1}) \) and the error from Gaussian fitting. After fitting a Gaussian, to the spectrum at each position, we determine the error budget to be the range of all the channels which has an observed value within the difference of half of the noise level from the maximum value of the fitted Gaussian. 

Chi-square values are calculated for each model for the 106 points in the observed PVD. Note that the degree of freedom becomes 104, because we have two free parameters, the SMBH mass and the I-band \( M/L \) ratio. Figure 4 shows the chi-square value distribution in the parameter space. The contour level is defined to be \( (0, 3, 4, 5, 6, 8, 12) \times \chi^2_{\text{min}} \). The smallest chi-square value of 113 (reduced chi-square value is 1.09 when divided with the degree of freedom) is realized with parameters of \( M_{BH} = 1.40 \times 10^8 M_\odot \) and the I-band \( M/L \) ratio = 5.14. See Figure 3 to compare three PVD models in black contours and lines calculated with different values of parameters \( M_{BH} = 0, M/L = 5.14 \text{ (left)}, M_{BH} = 7.00 \times 10^8 M_\odot, M/L = 5.05 \text{ (right)}. \) We also put the reduced chi-square value, which is a chi-square value divided with the degree of freedom of 104, as \( \chi^2_{\text{red}} \). (Lower panels) Residual between the black line and plots in the above panels of each.
4. DISCUSSION

While we determine the SMBH mass and the I-band $M/L$ ratio from the molecular gas dynamics, there are some uncertainties coming from the assumption we made when calculating the model. We discuss the effect of the observing band we use to model the stellar luminosity distribution in Section 4.1, how the inclination angle affects the result (Section 4.2), and what if we use a different emission line to observe the molecular gas dynamics (Section 4.3).

4.1. The Proper Stellar Luminosity Profile without the Dust Effect

We estimate the expected stellar mass profile by excluding the bright AGN profile and luminosity enhancement by the starburst ring (Section 3.1), but we could not avoid the dust extinction effects, which could be important for this starburst galaxy with its prominent dust lane around the starburst ring. One way to mitigate the dust extinction effects is to observe at longer wavelengths such as the near infrared. NICMOS on HST has a narrow band filter F190N which observes at 1.9 microns. We calculate a velocity field from the assumed SMBH mass and the stellar mass profile derived from the luminosity profile of 1.9 microns, and obtain a PVD by following the method described in Section 3.3. We then compare the two PVDs calculated from the F190N luminosity profile and the F814W luminosity profile. Both luminosity profiles need to have the same PSF for a proper comparison. For the NICMOS data, which have a small field of view and no feasible stars available for a measurement of the PSF, we refer “Tiny Tim” package (version 6.3 Krist et al. 2011) and assume the shape as a Gaussian with its FWHM of 0.4. We convolve the I-band luminosity distribution with this PSF. Figure 6 shows the luminosity distribution of the PSF-convolved I-band and 1.9 microns normalized by each maximum value (upper panel) and the difference of two profiles (lower panel). This comparison already shows that the difference between the two luminosity profiles is negligible. We also examine the S4G data at 3.6 microns to compare the stellar profile with the HST data but the Spitzer Infrared Array Camera PSF is too large (~1.8) to do any detailed comparison.

We normalize the peak luminosity at 1.9 microns to the I-band peak, and then subtract the luminosity enhancement of the AGN, as described in Section 3.1. We also ignore the starburst region and use the same $M/L$ ratio to calculate the velocity field for the two stellar mass profiles. We find that a $M_{\text{BH}} = 1.40 \times 10^8 M_\odot$ and $M/L = 5.14$ gives the best-fit value for an inclination of 46°. The PVDs calculated as such are shown in Figure 7. Black and gray contours in Figure 7 are the PVD calculated from two stellar mass profile models—these do not differ much between the two luminosity profiles. We therefore conclude that the dust extinction effect with the F814W filter is not too serious for the measurement of the SMBH mass.

4.2. Effect from the Inclination Angle

We discuss briefly on the difference coming from how we set the inclination angle. The accuracy of the inclination angle is critical for calculating the velocity and therefore crucial for the SMBH mass estimation. It is however not straightforward to determine the inclination angle when comparing observations at different field of view. Previous studies of NGC 1097...
Hsieh et al. (2011) reported that the inclination angle of NGC 1097 is $41.7 \pm 0.6$ using the kinematic parameters of $^{12}$CO($J = 2 - 1$) observed with Submillimeter Array. They argue that the circumnuclear ring is nearly circular for the inclination of $\sim 42^\circ$, by which means the ring has an intrinsic elliptical shape in the galactic plane, of which case is not symmetric to the axis. Though the suggested asymmetry is interesting to note, we would like to leave it as a further discussion, since in this work we assume an axisymmetric distribution for stars and molecular gas when calculating the circular velocity field. This time we assume the galaxy inclination angle to be $46 - 51^\circ$ by referring to Ondrechen et al. (1989) and the axis ratio of the HST I-band observation. We evaluate the SMBH mass to be $1.40 \pm 0.32 \times 10^8 M_\odot$ and the the I-band $M/L$ ratio to be $5.14 \pm 0.03$ at the inclination angle of $46^\circ$, with the chi-square value of 113 (1.09 when divided with the degree of freedom 104). We also follow the same process in Section 3 with the inclination angle of $51^\circ$ and evaluate the SMBH mass to be $1.20 \pm 0.35 \times 10^8 M_\odot$ and the I-band $M/L$ ratio to be $5.11 \pm 0.03$ with the chi-square value of 117 (1.13 when reduced with the degree of freedom). See also dashed curves in Figure 5 for the chi-square distribution, used to determine the error bar for each parameter.

We can also consider the case of the inclination angle is $34 - 41^\circ$ by multiplying a factor of $\sin(i_{\text{intrinsic}})/\sin(46^\circ) \sim 0.78 - 0.91$ to the velocity where we write $i_{\text{intrinsic}}$ as an inclination angle of the observed component. Under the simplified assumption that the SMBH mass is proportional to the square of the velocity, we can estimate the change of the SMBH mass to be smaller than $0.31 \times 10^8 M_\odot$, which is mostly included in the error bar of our result $1.40 \pm 0.32 \times 10^8 M_\odot$. We therefore consider that it is not crucial to count this error into our error budget. Note that, however, this galaxy could have a warped or a misaligned structure, which could be interesting to investigate but requires a calculation for an asymmetric potential field.

### 4.3. SMBH Mass Estimation from Other Molecular Species

Our main result is obtained using the HCN line because it had the highest signal-to-noise ratio. It is important to measure the SMBH mass from other molecular species as well for consistency. We therefore repeat our method using the HCO$^+$(J = 1 − 0) emission line.

We apply the fitting procedure described in Section 3.4 to the PVD for HCO$^+$(J = 1 − 0), and estimate the SMBH mass to be $(1.40 \pm 0.30) \times 10^8 M_\odot$ and the I-band $M/L$ ratio to be $5.15 \pm 0.03$ with a galaxy inclination of $46^\circ$. These derived values are consistent with the measurement using HCN(J = 1 − 0). From Figure 8, we see that the observed PVDs of two molecular gases are in good agreement, indicating that the fitting parameters will be consistent between the two.

Reaching the velocity structure from multiple molecular species is one of the particular benefit of the SMBH mass measurement with millimeter/submillimeter wavelength observation, which enable one to observe more than two molecular species at the same frequency band.

### 5. CONCLUSION

We derive the SMBH mass in NGC 1097 to be $1.40^{+0.32}_{-0.33} \times 10^8 M_\odot$ by using dense molecular gas dynamics traced with HCN(J = 1 − 0) and HCO$^+$(J = 1 − 0) observed...
with ALMA. The value of SMBH mass is measured with two emission lines in good agreement, indicating the applicability of this method to any nearby galaxy with detectable molecular gas. Furthermore, the mass is consistent with $M_{\text{BH}}-\sigma$ relation (McConnell & Ma 2013) from the velocity dispersion observed by Lewis & Eracleous (2006). We can comment that the derived mass does not coincide with the $M_{\text{BH}}-\sigma$ relation for early-type galaxies, but for mixed samples and for late-type galaxies. This time we consider that the dust extinction effect is not very crucial to model the luminosity distribution of the galaxy, but the inclination angle could affect the SMBH mass derived mass does not coincide with the relation will lead us to higher accuracy of the correlation, which suggests the coevolution process of galaxies and BHs.

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Figure 8. Observed PVD of HCN($J = 1 - 0$). (upper panel) and HCO*($J = 1 - 0$) (lower panel) is respectively shown with black contours. The contour level of both is from $1\sigma$ to $4\sigma$ where $1\sigma = 4.6$ mJy for HCN($J = 1 - 0$) and $1\sigma = 3.2$ mJy for HCO*($J = 1 - 0$). The velocity structure of these two PVDs are in good agreement.

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