A Measurement of the Black Hole Mass in NGC 1097 using ALMA

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Galaxy Evolution and Supermassive Black Hole

Galaxy evolution seems to include myriad of processes.

Supermassive black holes lurk in centres of massive galaxies
(Kormendy&Ho 2013, etc.)

Coevolution of galaxy and black hole (BH)?

- (BH mass) - (host galaxy properties) relation
  (McConnell&Ma 2013, Kormendy&Ho 2013, Laesker et al. 2014, etc.)
- numerical studies suggest the coevolution process;
  AGN feedback process (Di Matteo et al. 2005, etc.)

BH mass is an important quantity to discuss on the galaxy evolution process.

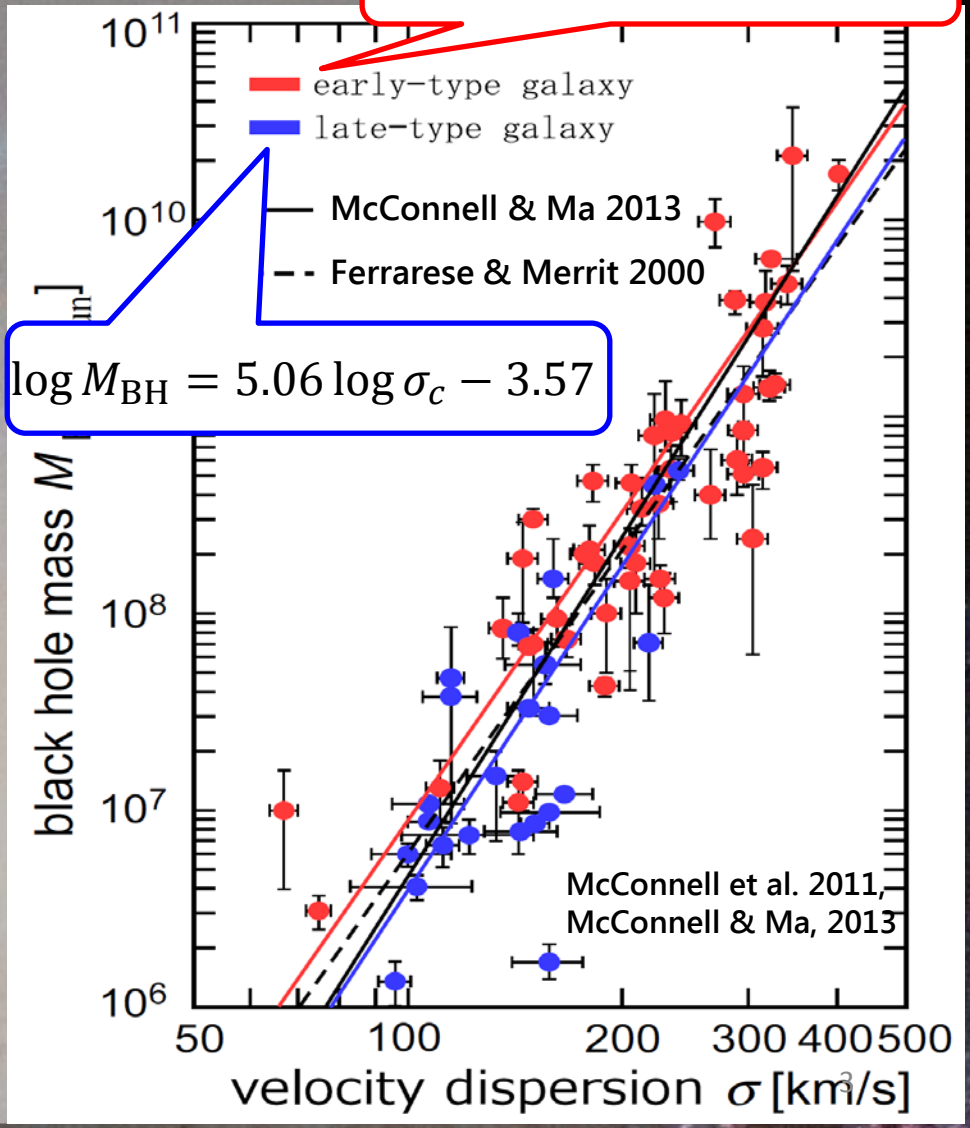
BH mass - bulge velocity dispersion (M_{BH}-σ relation)

- Early- vs. Late-type M-sigma
- ~80 samples
- smaller number of late-types
- classical vs. pseudo bulge

Larger number

Ubiquitous types

of samples are required

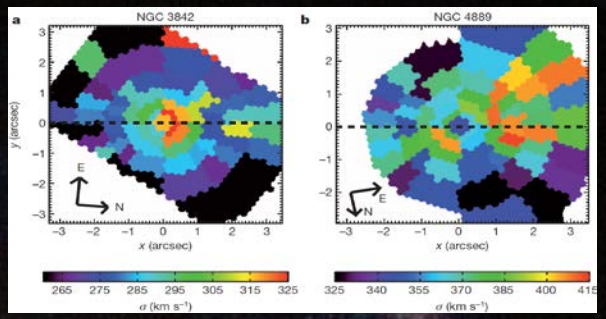


How do we estimate BH mass?

Use dynamics of stars or interstellar gas (for nearby galaxies).

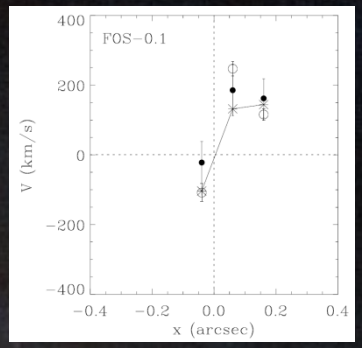
1. Stellar velocity dispersion
   McConnell et al. 2011: NGC 4889, NGC 3842

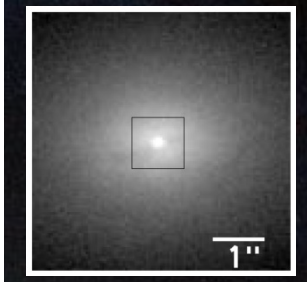
   64/80 galaxy samples
   The method is only for elliptical galaxies



2. radial velocity profile of ionized gas
   Verdoes et al. 2000: IC 1459

   3-5 slits are not always enough to trace velocity fields





3. Proper motion of stars around the BH
   Ghez et al. 2008 : Milky Way

4. megamaser dynamics
   Miyoshi et al. 1995: NGC 4258

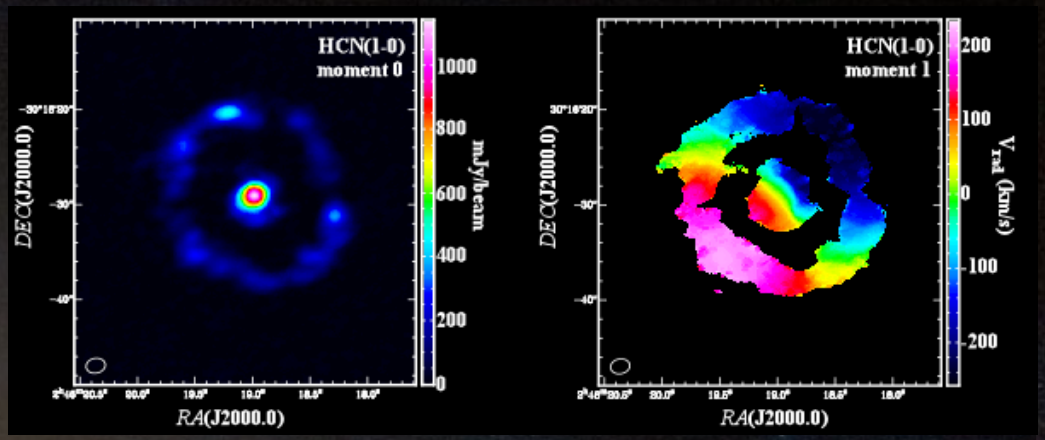
Increasing samples (late-type) is difficult..

How do we estimate BH mass?

Why not molecular gas?

K. Onishi, S. Iguchi, K. Sheth, and K. Kohno 2015, ApJ 806 39

5. Molecular gas dynamics
   - Davis et al. 2013: NGC 4526
   - Onishi et al. 2015: NGC 1097



Onishi et al. 2015, ApJ 806 39

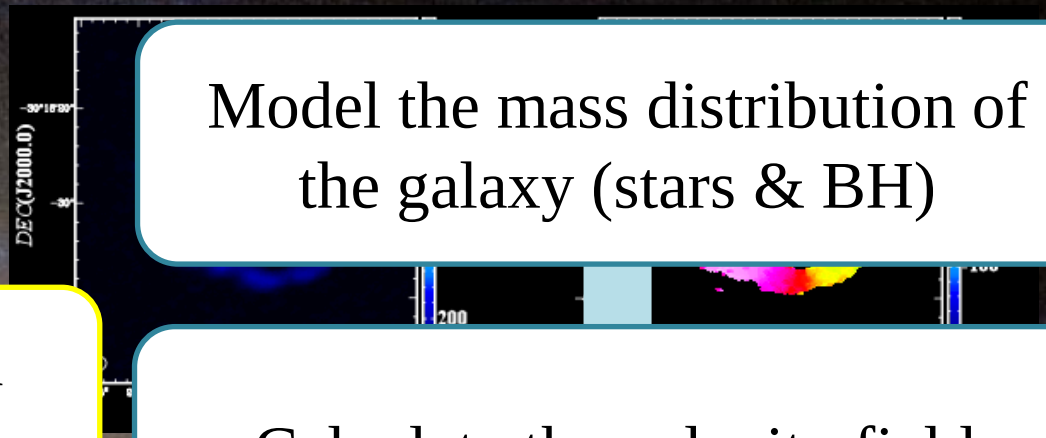
Not achieved till Davis+ 2013 using CARMA due to
- low angular resolution
- low sensitivity

ALMA realizes enough BOTH to estimate SMBH mass in some local galaxies.

BH mass measurement using molecular gas kinematics

K. Onishi, S. Iguchi, K. Sheth, and K. Kohno 2015, ApJ 806 39

model



Model the mass distribution of the galaxy (stars & BH)

observation

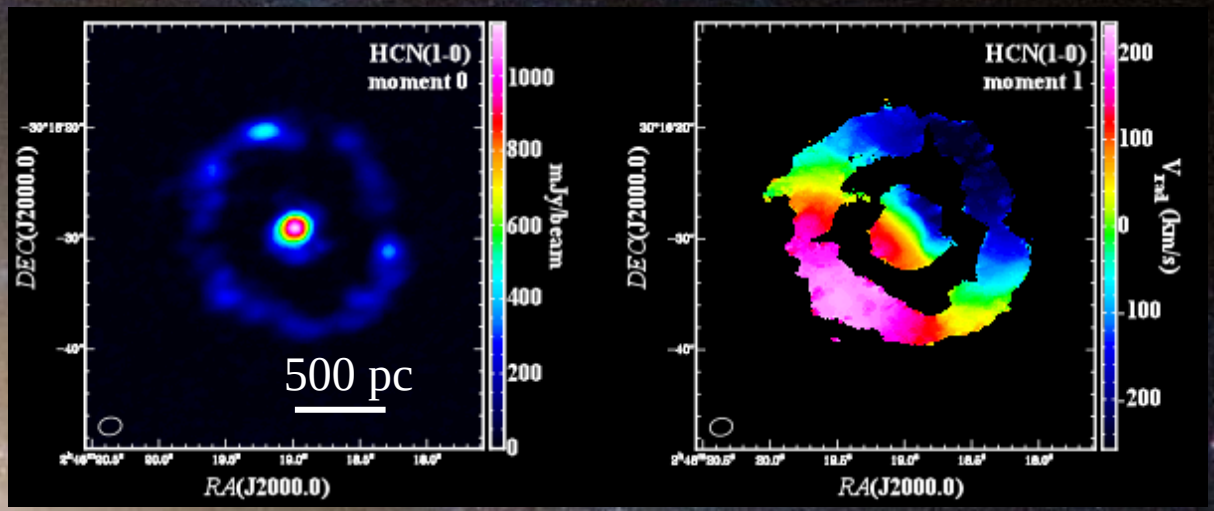
Observe velocity field using molecular gas

Calculate the velocity field

Fit the model by assuming the inclination and the position angle of a molecular gas disk

BH mass measurement for NGC 1097 (Onishi+2015)

K. Onishi, S. Iguchi, K. Sheth, and K. Kohno 2015, ApJ 806 39



NGC 1097
Seyfert-1

BH mass measurement for NGC 1097 (Onishi+2015)

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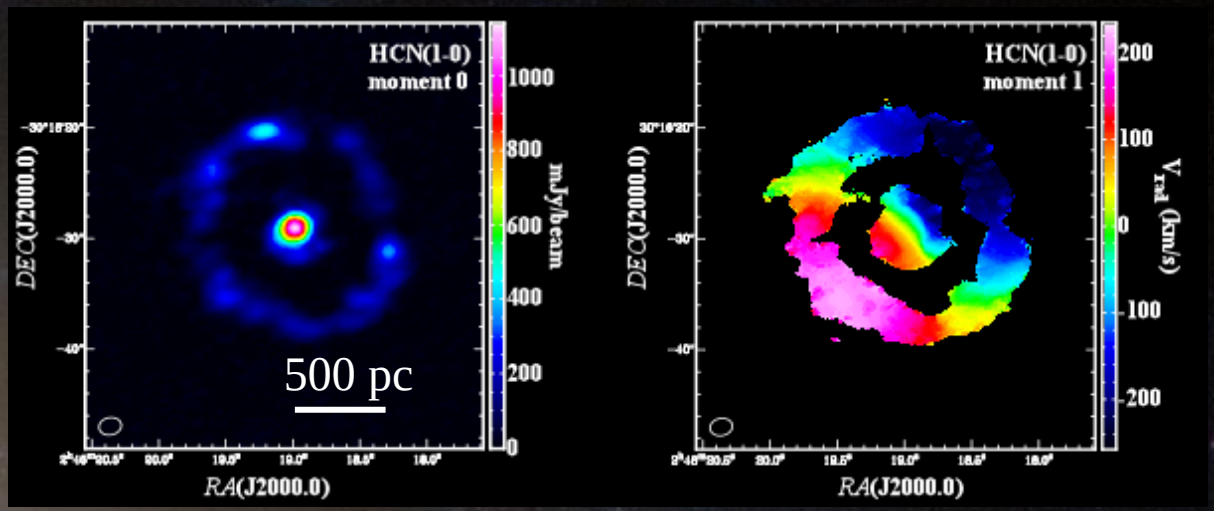


Assumptions

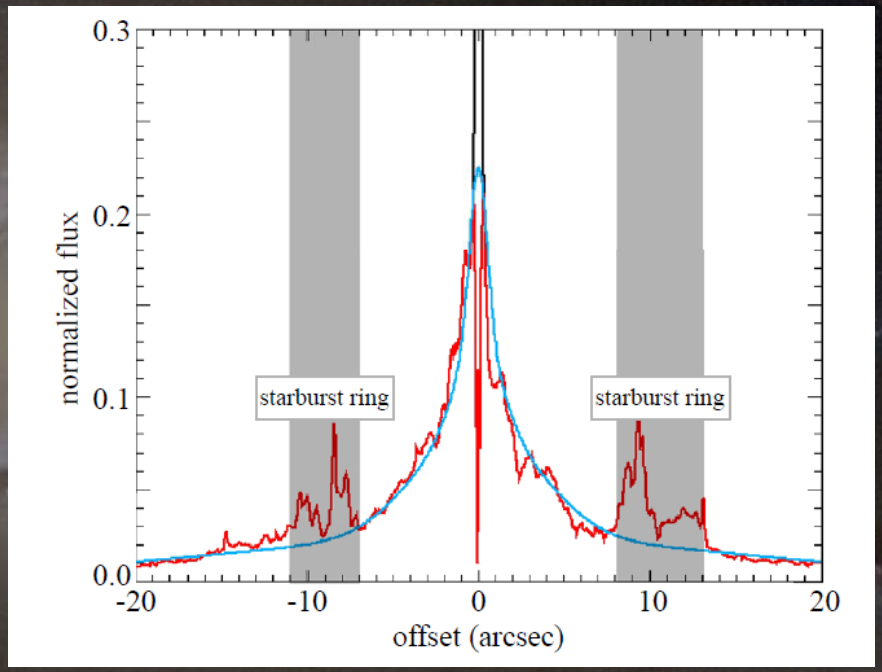
Inclination angle: 46 deg
molecular gas: HCN(1-0) (and HCO^+(1-0))
kinematical position angle: 130 deg
All mass sources are distributed axisymmetrically
(MGE, Emsellem et al. 1994)

BH mass measurement for NGC 1097 (Onishi+2015)

K. Onishi, S. Iguchi, K. Sheth, and K. Kohno 2015, ApJ 806 39

Mass model

(Stellar mass distribution) = (MGEd luminosity profile)×M/L



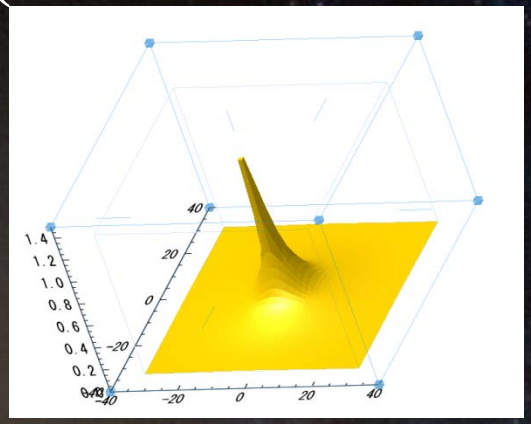
B: observed
R: without AGN
B: model

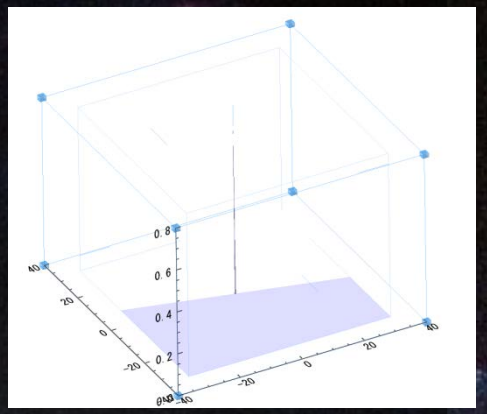
BH mass measurement for NGC 1097 (Onishi+2015)

K. Onishi, S. Iguchi, K. Sheth, and K. Kohno 2015, ApJ 806 39

Mass model

(total mass distribution)=(stellar mass distribution)+(BH mass)





- M/L
- BH mass

BH mass measurement for NGC 1097 (Onishi+2015)

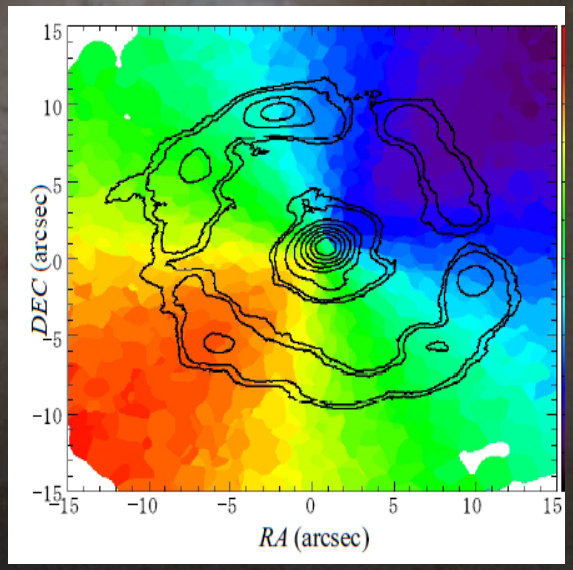
K. Onishi, S. Iguchi, K. Sheth, and K. Kohno 2015, ApJ 806 39

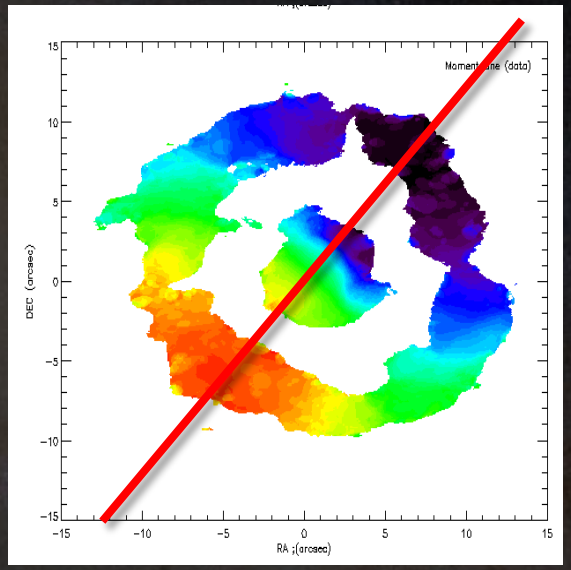
Mass model

(total mass distribution)=(stellar mass distribution)+(BH mass)

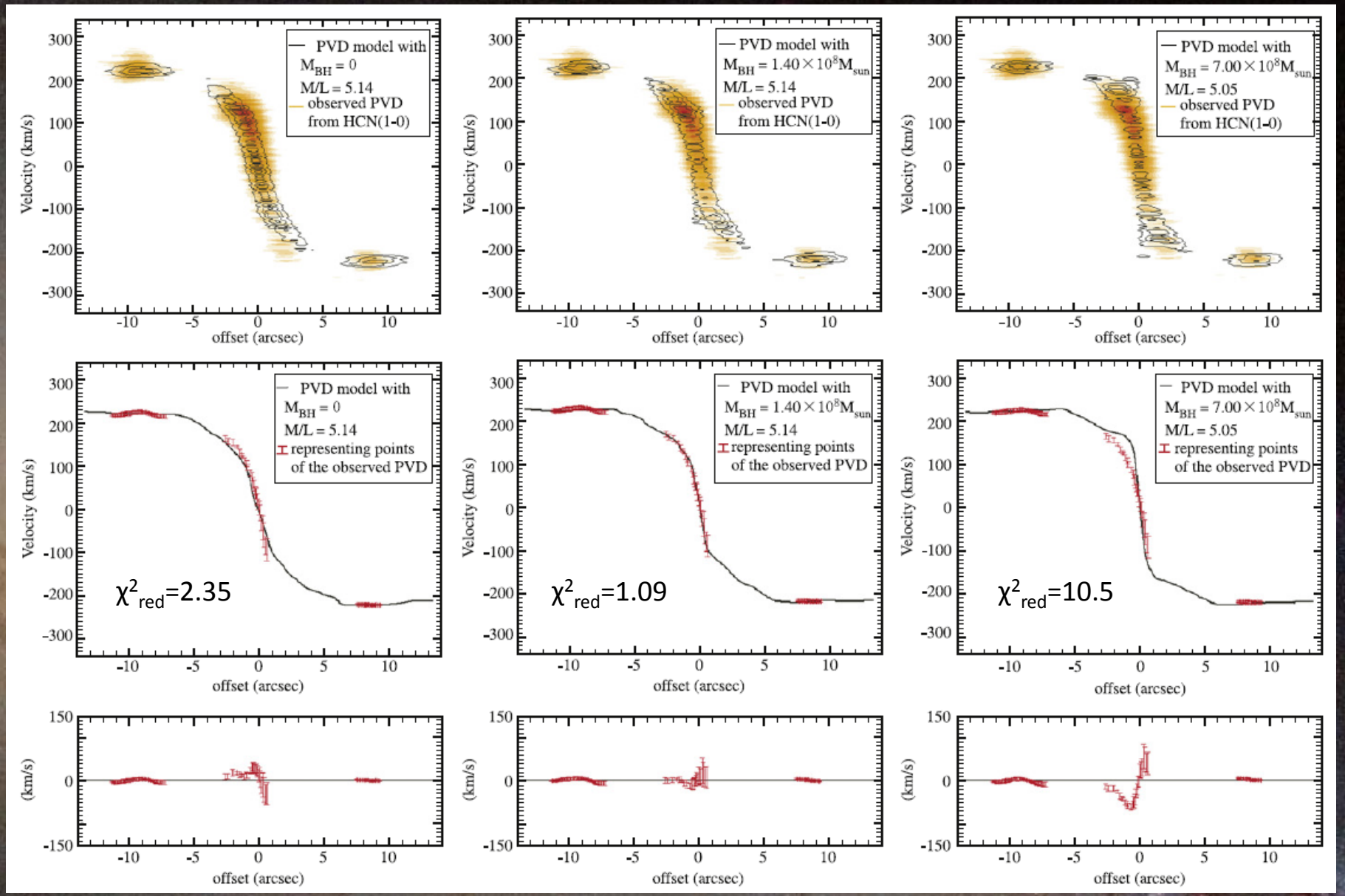
Velocity model

calculated with assumed M/L and BH mass





BH mass measurement for NGC 1097 (Onishi+2015)



BH mass measurement for NGC 1097 (Onishi+2015)

K. Onishi, S. Iguchi, K. Sheth, and K. Kohno 2015, ApJ 806 39

Grid simulation:

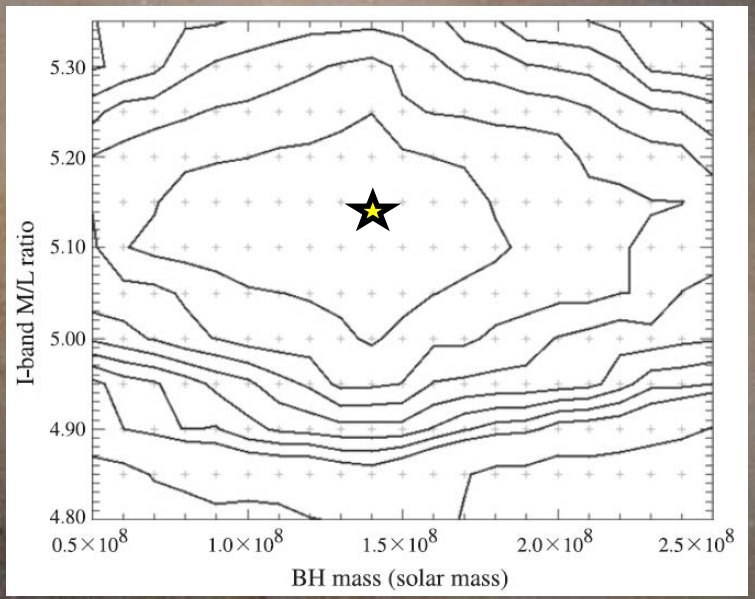
M/L=5.14

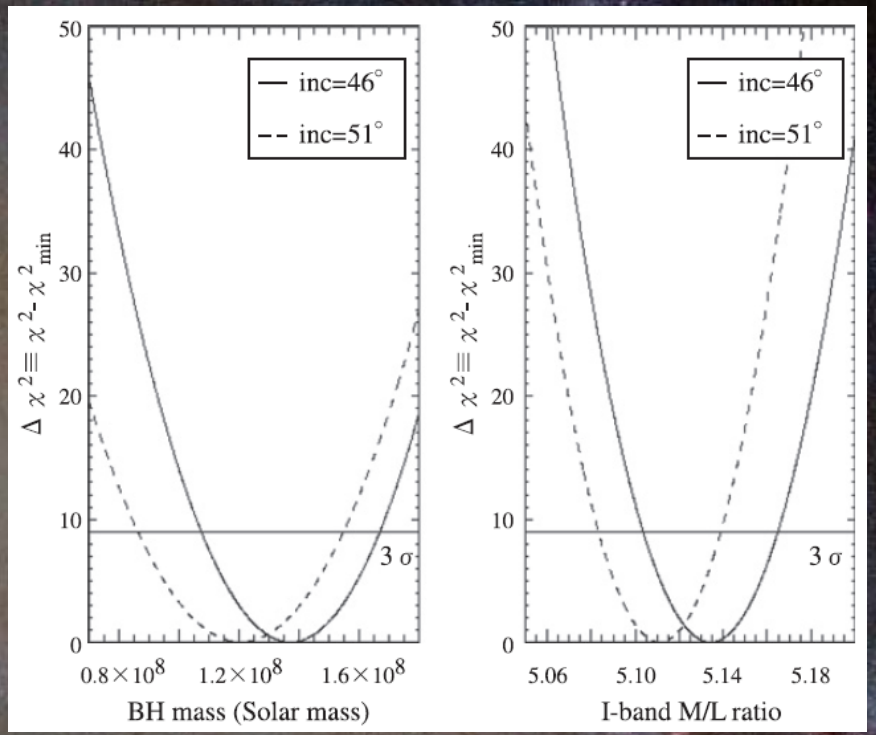
M_{BH}=1.40 × $10^8 M_{SUN}$

Error budget determination:

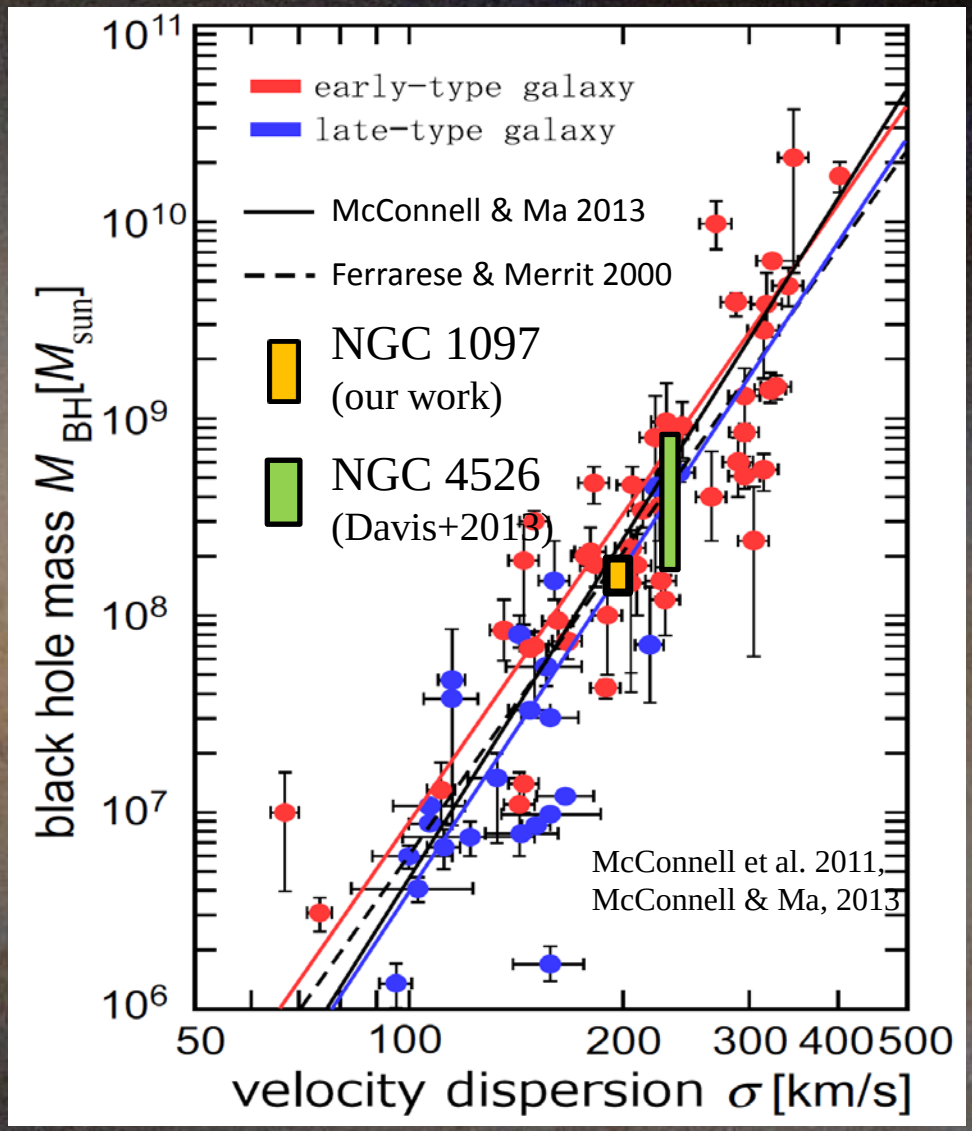
$M/L = 5.14^{+0.03}_{-0.04}$

$M_{BH} = (1.40^{+0.27}_{-0.32}) \times 10^8 M_{SUN}$





The molecular gas method gives the result consistent with M_{BH}-σ relation



For NGC 1097 (Onishi+2015)

$M_{BH} = (1.40\ ^{+0.27}_{-0.32}) \times 10^8 M_{SUN}$

σ=196 ±5 km/s (Lewis+ 2006)

For NGC 4526 (Davis+ 2013)

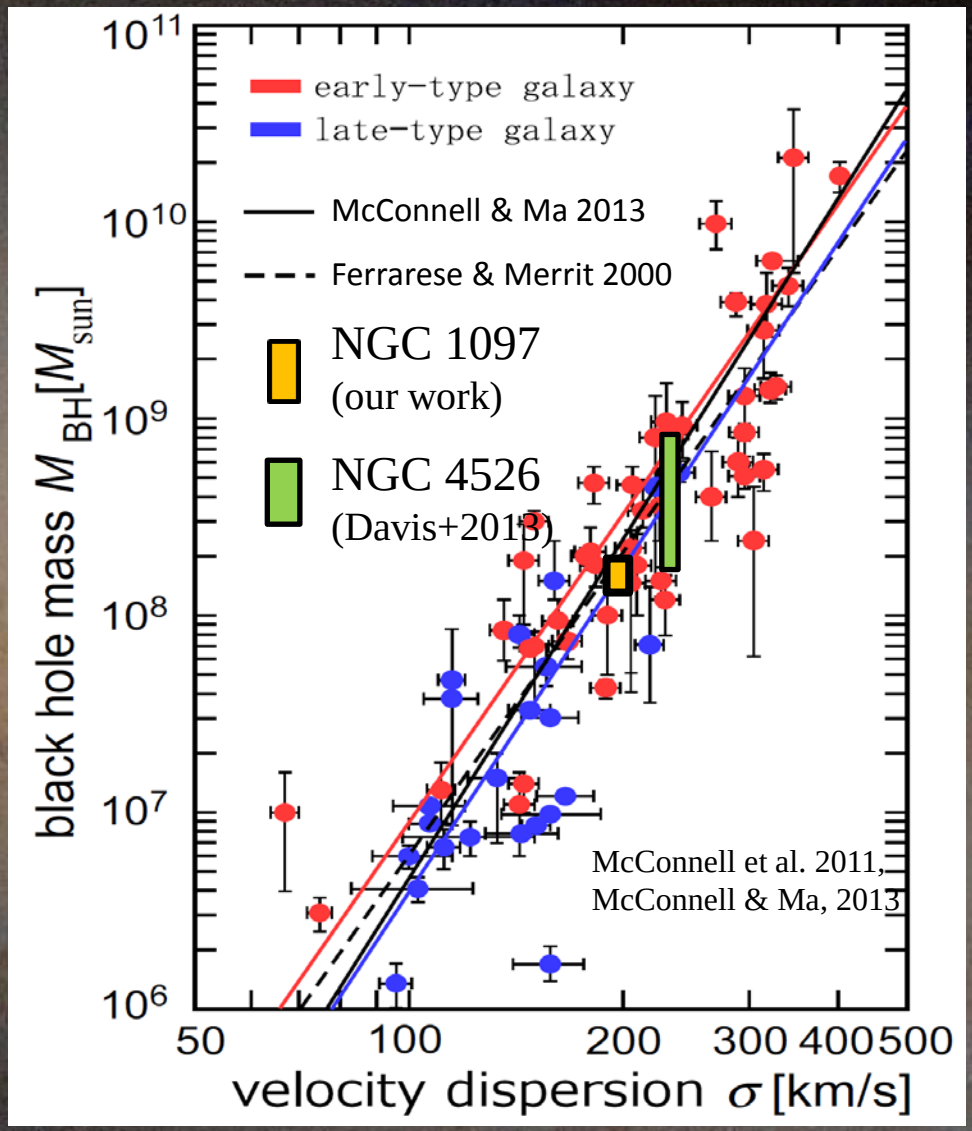
$M_{BH} = (4.5\ ^{+4.2}_{-3.1}) \times 10^8 M_{SUN}$

σ=222 km/s (Cappellari+ 2006)

possibility to increase samples a lot in the near future!

K. Onishi, et al. 2015, ApJ 806 39

The molecular gas method gives the result consistent with M_{BH}-σ relation



possibility to …

- ✓ **increase samples**
- ✓ **more variety (morphology)**
- ✓ **ubiquitous study over the M-sigma plane**
- ✓ **BH mass estimation in ~1hr observation!**

K. Onishi, et al. 2015, ApJ 806 39

Summary

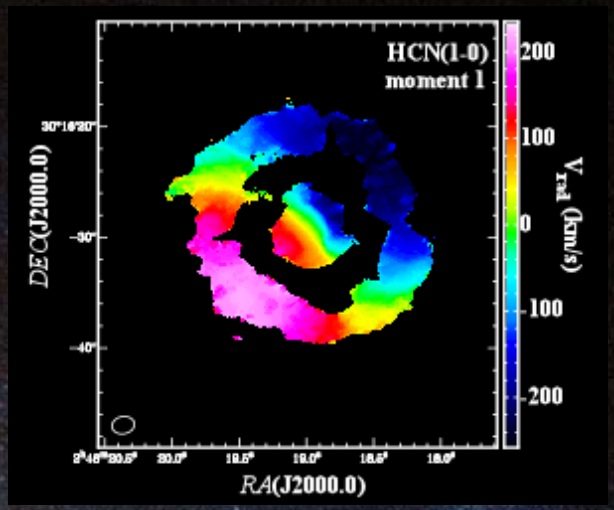
・Our aim is to constrain the M_{BH}-σ relation, which suggests the coevolution process, by estimating more BH mass.

・Measuring the BH mass in nearby galaxies using molecular gas dynamics is possible and will play an important role to increase the number, ubiquiteness, and availability of kinematically measured BH mass. (Davis+2013 for NGC 4526, Onishi+ 2015a for NGC 1097, Onishi+2015b in prep)

・For NGC 1097 case, we have made some assumptions (inclination angle, kinematical position angle, fitting in position-velocity diagram, etc.) , which will be discussed and explored in our next work.

Discussable points for the method

- skewed velocity field (nuclear spiral motion)
  Fathi et al. (2013)
  → build up a model?
- dynamics is traced with dense gas tracers (HCN, HCO^+)
  → use the Cycle2 data (CO)?



Onishi+ 2015

- different inclination angle reported
  - 46±5° VLA H_I observation @3kpc scale
  - 34° Hα broad line profile study
  - 42° CO observation @~500pc scale
  - 40-46° HST Iband morph. @~1kpc scale

  → warped or misaligned disk?

Discussable points for the method

- No more PVD fitting!

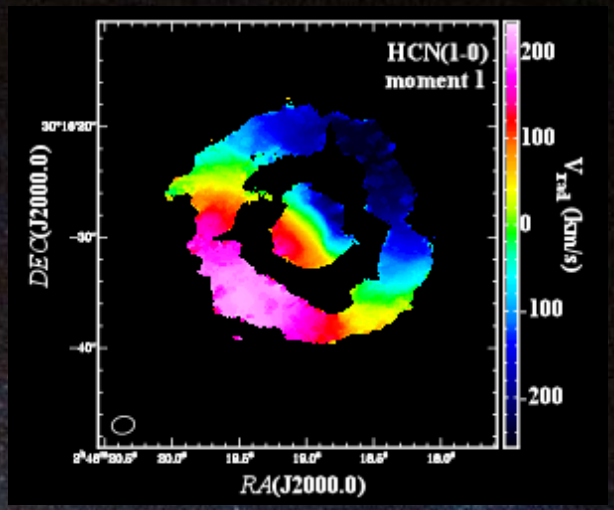
  → fit the cube itself

- put some more parameters to fit (disk property, inclination, position angle, etc.)

  → adding a bit more, using MCMC

- (possibly) add inflow/outflow motion?

  → need to build up the model



Onishi+ 2015