High-resolution Observations of Molecular Gas Kinematics in Nearby Galaxies

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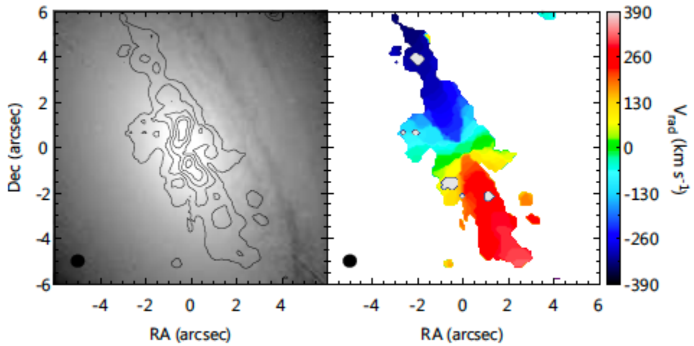
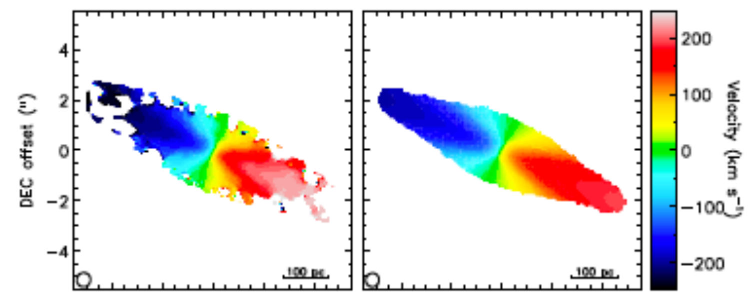
WISDOM Project – weigh SMBHs





I: NGC 3665 SMBH mass

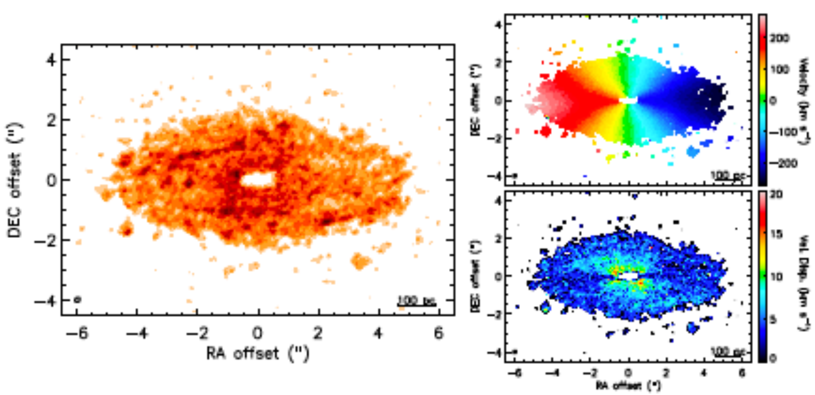
Onishi+17, MNRAS, 468, 4663

WISDOM

mm-Wave Interferometric Survey of Dark Object Masses

II: NGC 4697 SMBH mass

Davis+17a, MNRAS, 468, 4675



IV: NGC 5064 SMBH mass

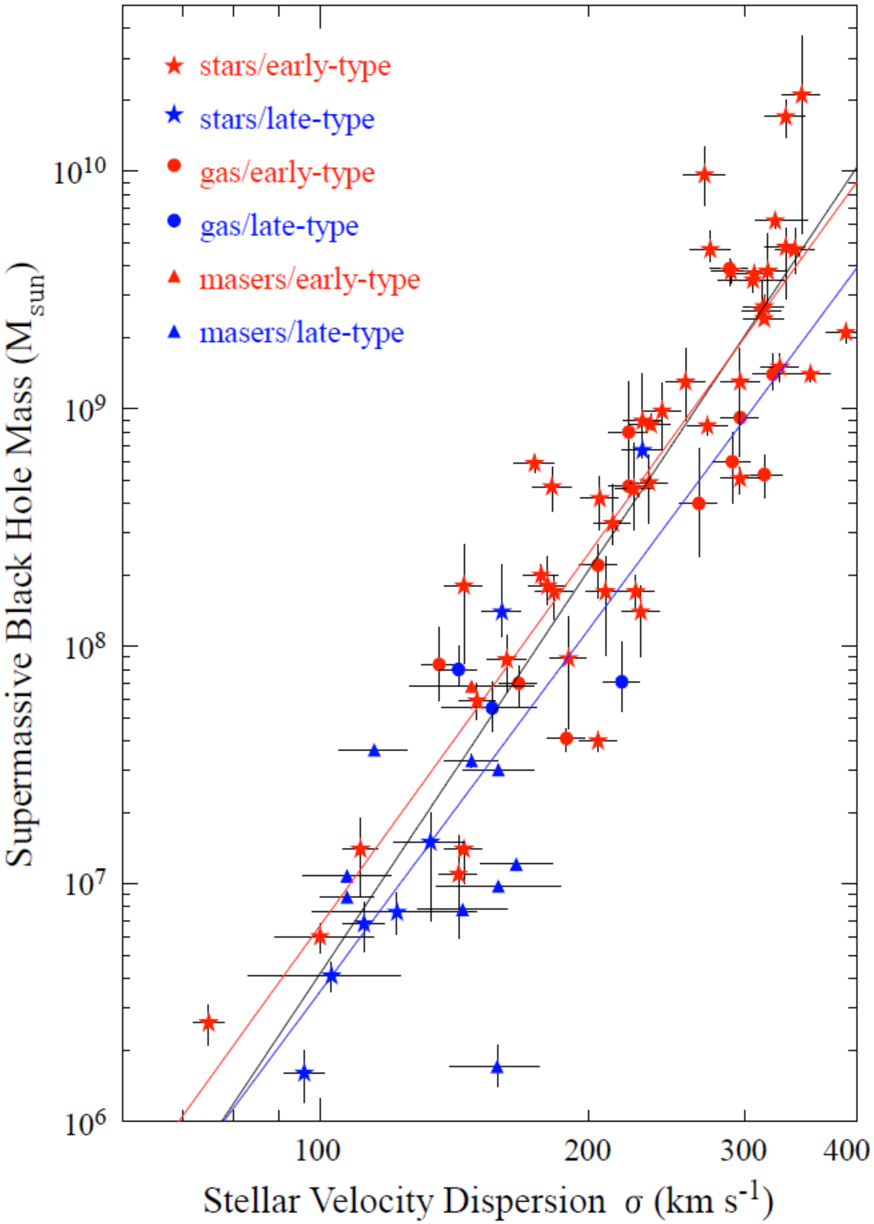
Onishi+ in prep.

… and more!

III: NGC 4429 SMBH mass

Davis+17b, MNRAS, in press

Supermassive black hole (SMBH) in galaxies



Larger galaxy, heavier BH

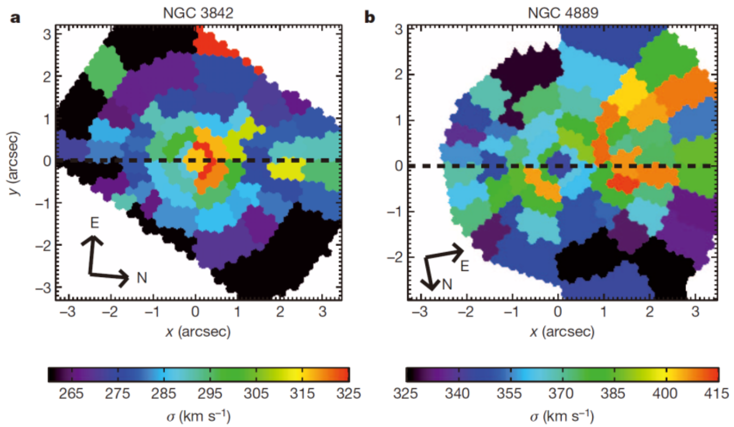
coevolution?

need larger sample

SMBH mass – velocity dispersion (M-sigma), galaxy luminosity, bulge mass, etc.

Ferrarese & Merrit 2000, McConnel & Ma 2013, Kormendy & Ho 2013, Läsker+ 2014, Savrognan+ 2015, etc.

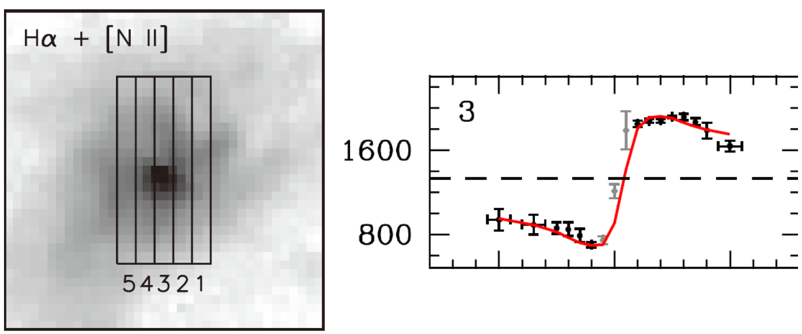
Why WISDOM weighs SMBHs?



1. Stellar kinematics

~70% (thus ~50) of the whole sample target biased to early-types

McConnell et al. 2011: NGC 4889, NGC 3842

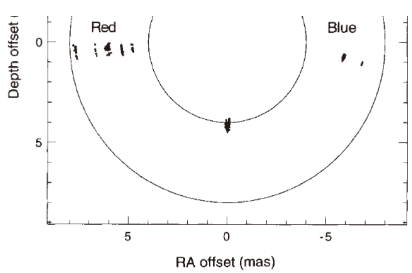


2. Ionized gas kinematics

Disturbed sometimes

Not many was successful

Walsh et al. 2013: M87

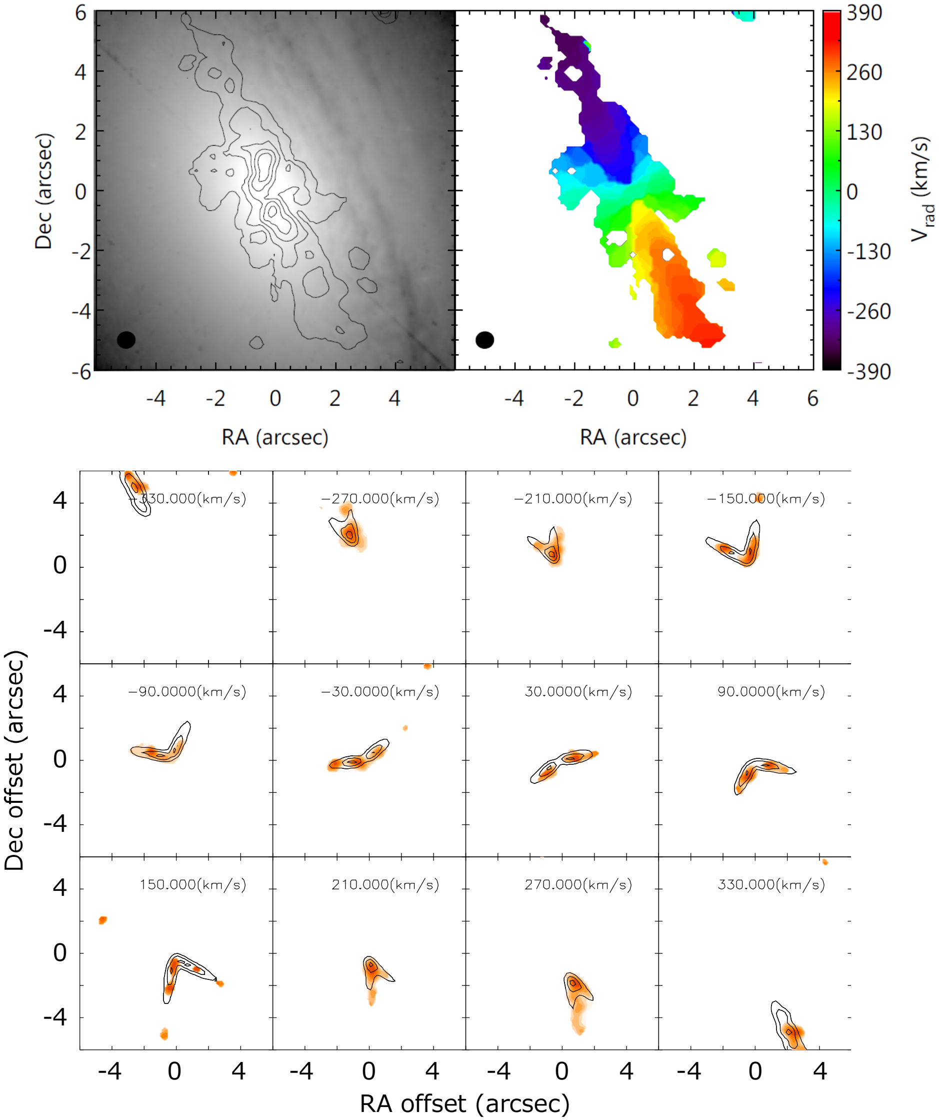


3. megamasers

Systems themselves are rare

Miyoshi et al. 1995: NGC 4258

Why WISDOM weighs SMBHs?

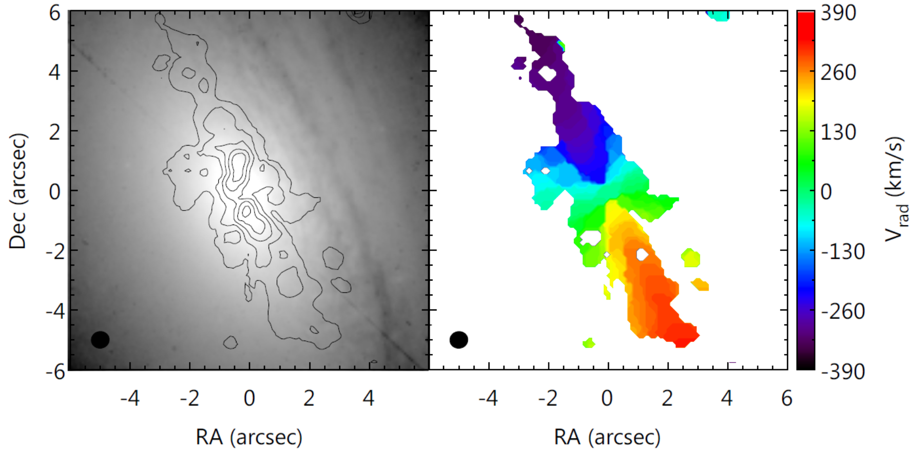


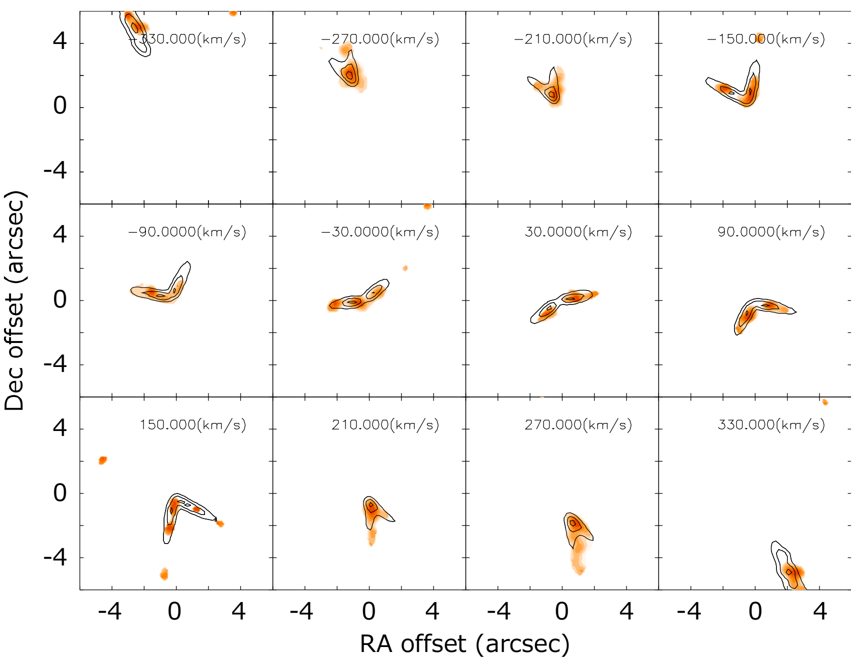
4. mol. gas kinematics

target any types of galaxies
dynamically cold
started recently (Davis+13)
potential targets in ubiquity

Onishi et al. 2017a:NGC 3665

How WISDOM weighs SMBHs?





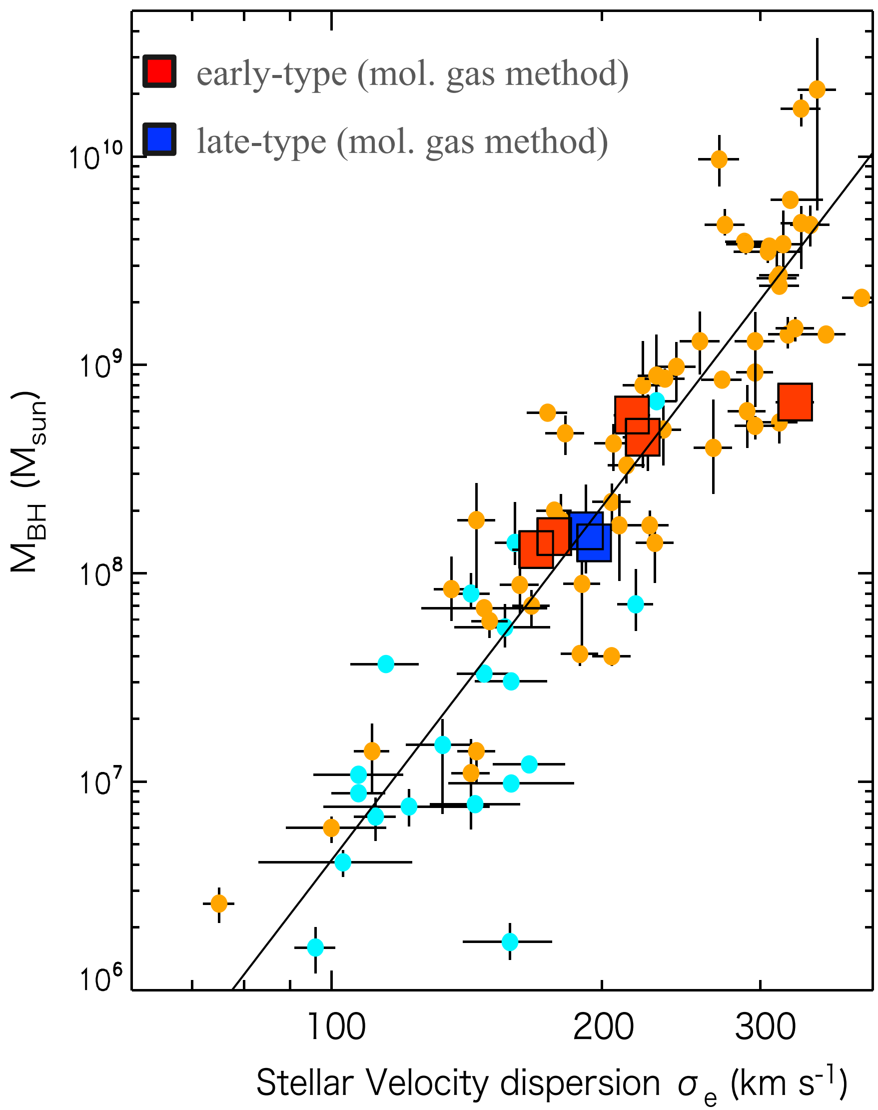
Observe the kinematics from an emission line
(normally CO)

Model a mass distribution
(stars+SMBH)

Set up parameters/assumptions
(inclination, disc thickness, etc.)

Fitting
(use rotation curve or data cube)

Weighing SMBHs with ALMA (and CARMA)



N4526; $4.5^{+1.5}_{-1.3}$ x10^8 (Davis+13)

N1097; 1.4±0.1 x10^8 (Onishi+15)

N1332; $6.64^{+0.65}_{-0.63}$ x10^8 (Barth+16)

N3665; 5.75±0.4 x10^8 (Onishi+17)

N4697; 1.3±0.2 x10^8 (Davis+17a)

N4429; 1.5±0.15 x10^8 (Davis+17b)

N5064; $1.6^{+1.0}_{-0.6}$x10^8 (Onishi+ in prep.)

Seems sensible, one agreement with other methods (one disagreement also found, others have not checked yet).

SMBH mass measurements – NGC 3665

Onishi et al. 2017

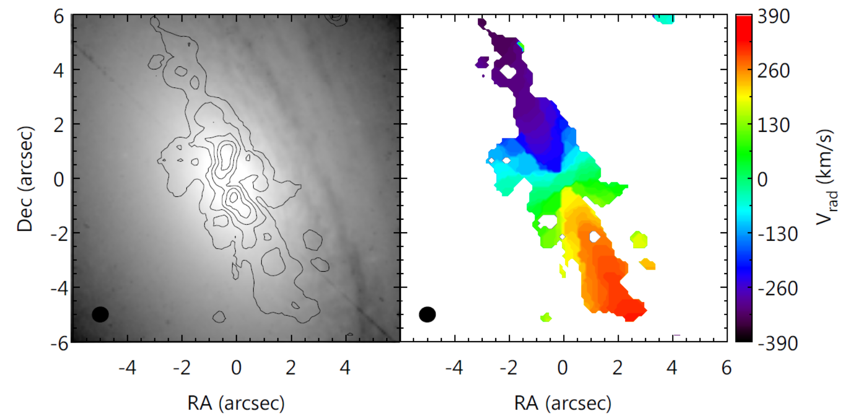
NGC 3665:

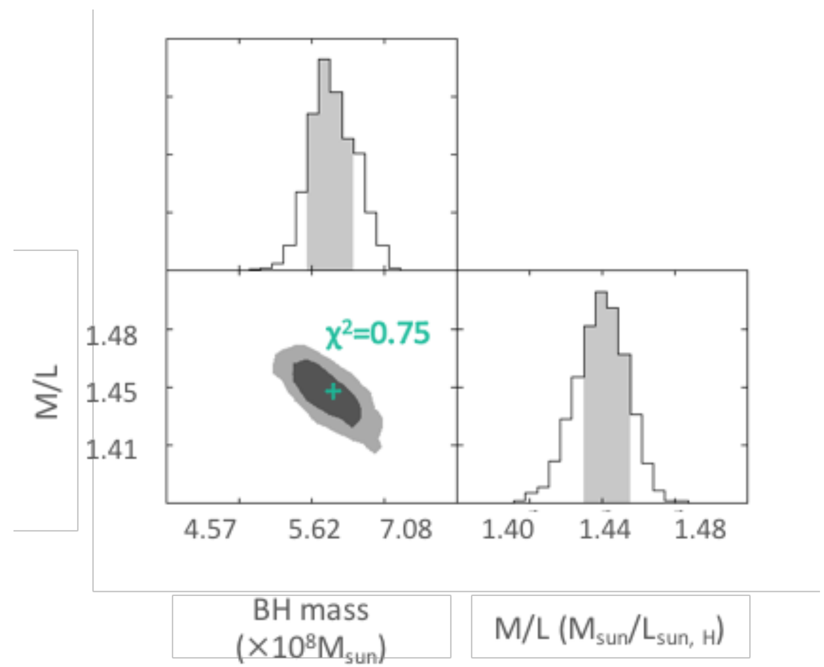
SA0 fast rotator, w/ radio jet (Parma+1986 etc.)

Observed CO(2-1) with CARMA (PI: M. Bureau) @ 0”.6 (100pc) beam

$M_{BH}=5.75^{+1.49}_{-1.18}\times10^{8}M_{sun}$

$M/L=1.45\pm0.04\ (M/L_{sun,\ H})$





SMBH mass measurements – NGC 4697

Davis et al. 2017a

NGC 4697:

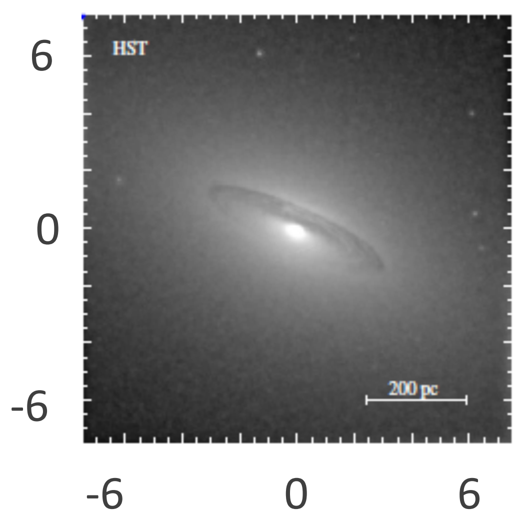
E6 fast rotator, CO (2-1) observed at 0”.5(~30pc) beam

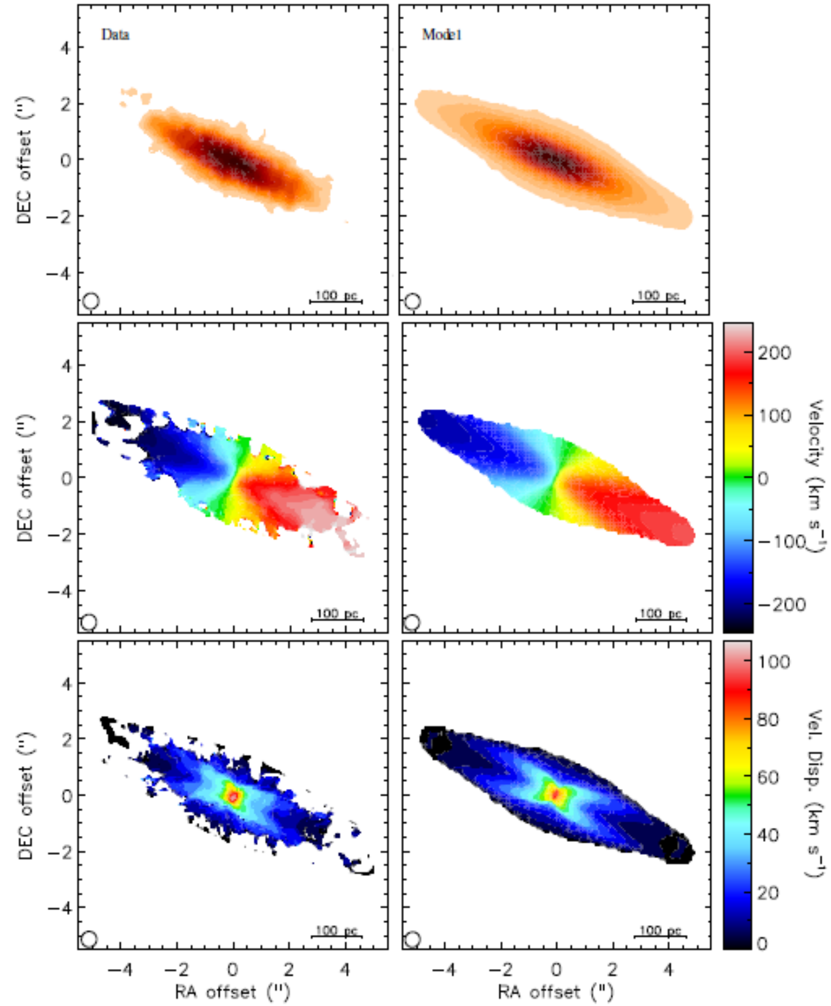
with ALMA Cycle 3 (PI: M. Bureau)

$M_{BH}=1.3^{+0.18}_{-0.17}\times10^{8}M_{sun}$

$M/L=2.14^{+0.04}_{-0.05}$ ($M/L_{sun,\ I}$)

consistent with stellar dynamics method ~$1.6\times10^{8}M_{sun}$ (Gebhardt+03)





SMBH mass measurements – NGC 4429

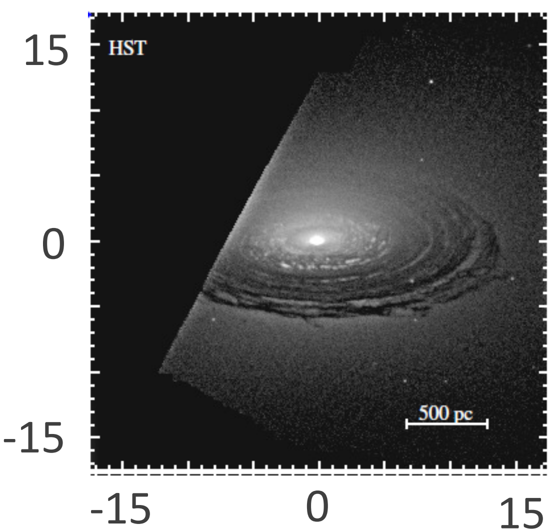
Davis et al. 2017b

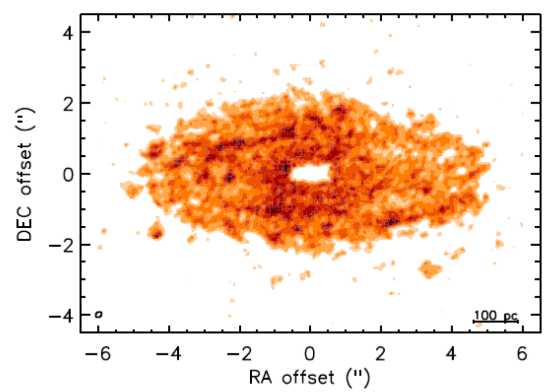
NGC 4429:

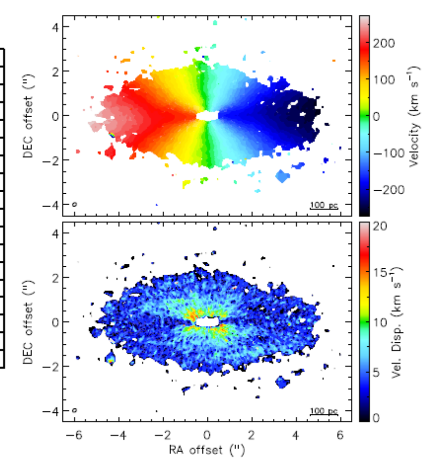
S0 fast rotator, CO (3-2) observed at 0”.18(~14pc) beam

with ALMA Cycle 2 (PI: M. Bureau)

$M_{BH}=1.5^{+0.1}_{-0.1}\times10^{8}M_{sun}$, $M/L=6.59\text{-}8.25$ ($M/L_{sun,\,r}$) with a power-law radial profile







SMBH mass measurements – NGC 5064

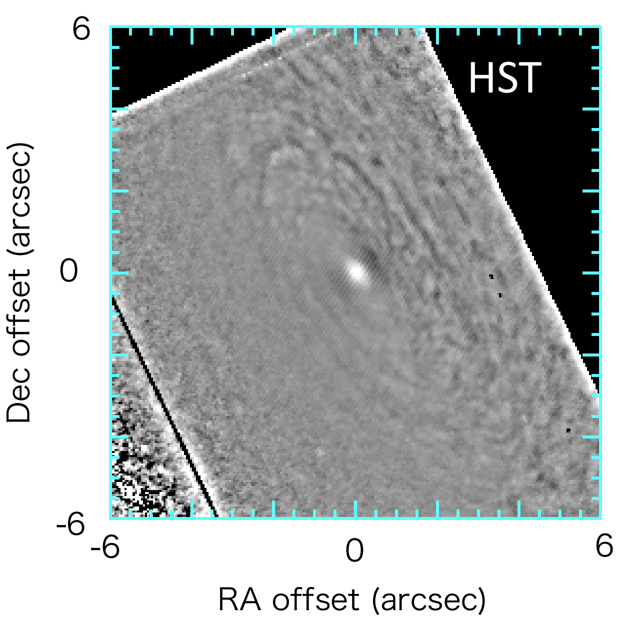
Onishi et al. in prep.

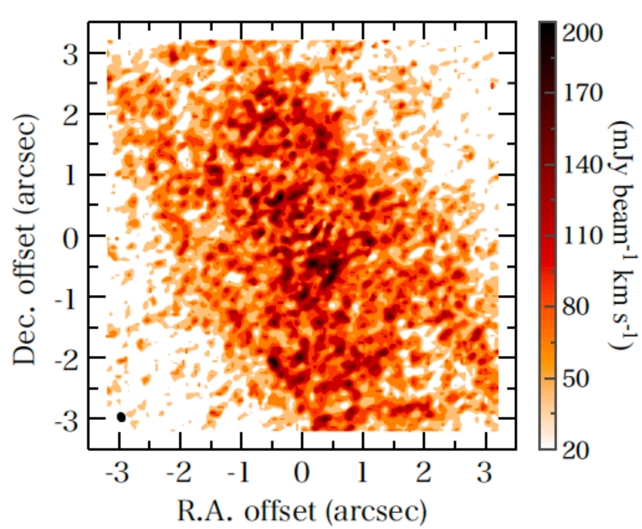
NGC 5064:

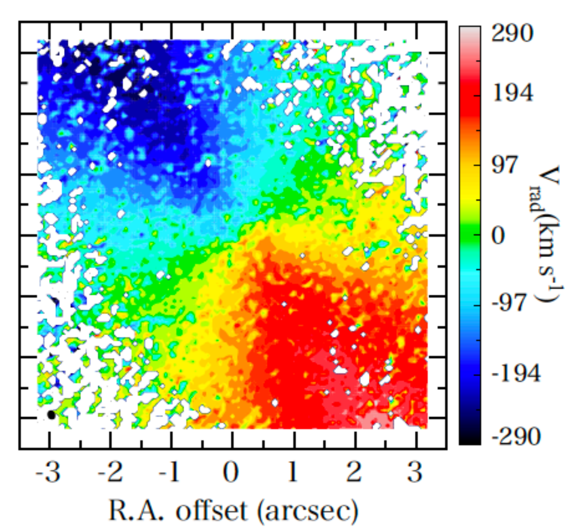
SA, CO (2-1) observed at 0".14(~28pc) beam

with ALMA Cycle 3 (PI: K. Onishi)

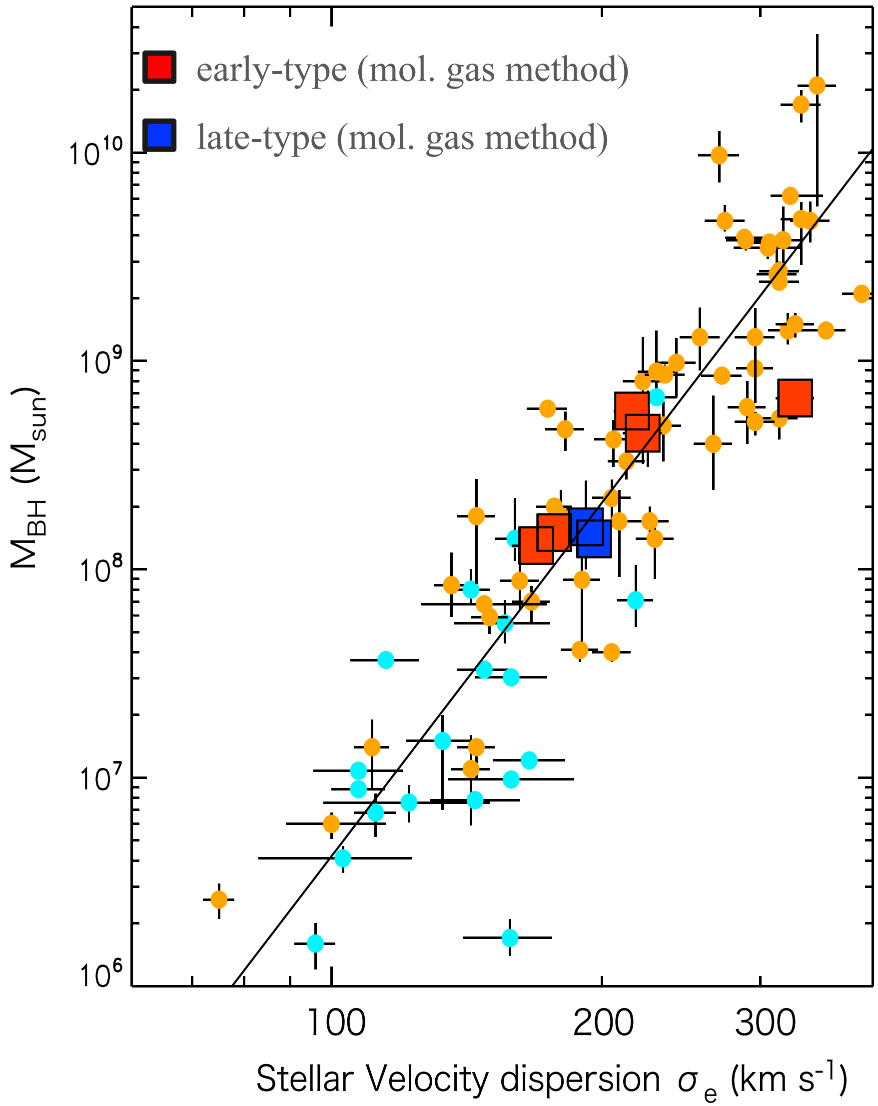
$M_{BH}=1.61^{+1.06}_{-0.64}\times10^{8}M_{sun}$, $M/L=0.390\pm0.005$ ($M/L_{sun, H}$)







Weighing SMBHs with ALMA (and CARMA)



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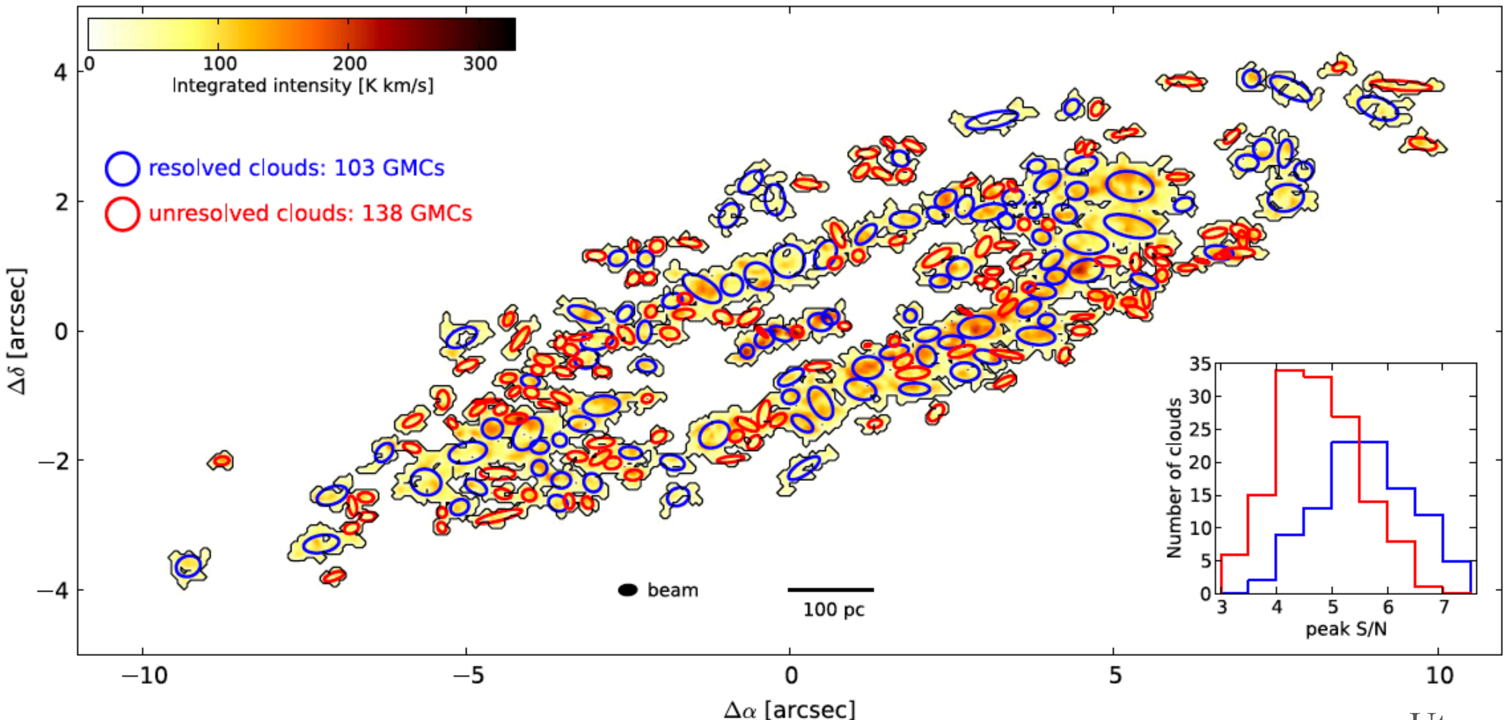
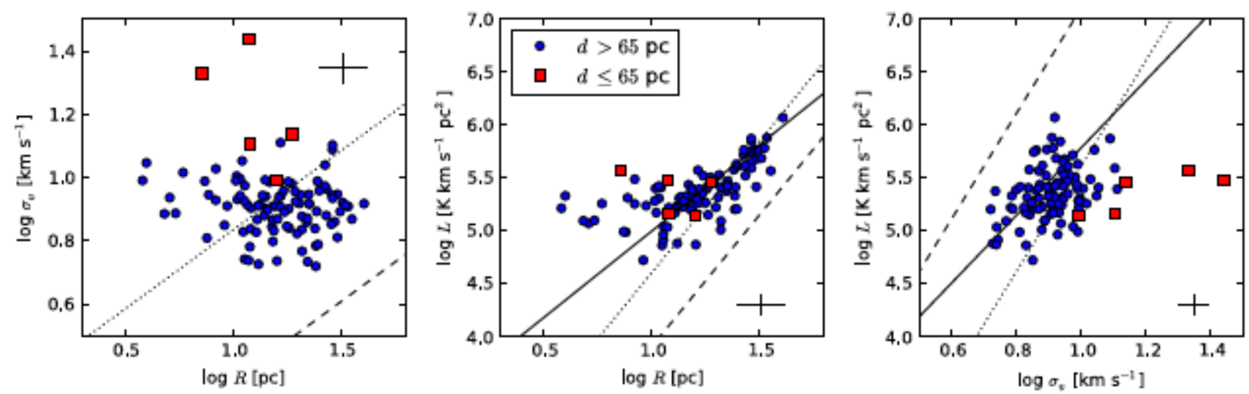
Seems sensible, one agreement with other methods (one disagreement also found, others have not checked yet).

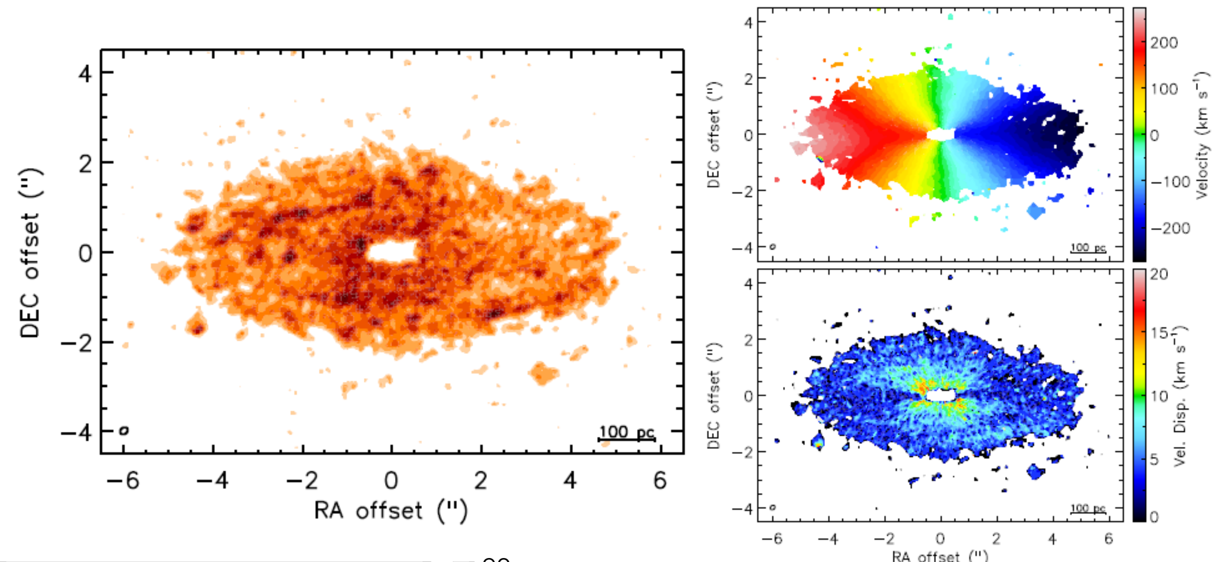
Not only SMBH mass but also GMC statistics



Utomo et al. 2015

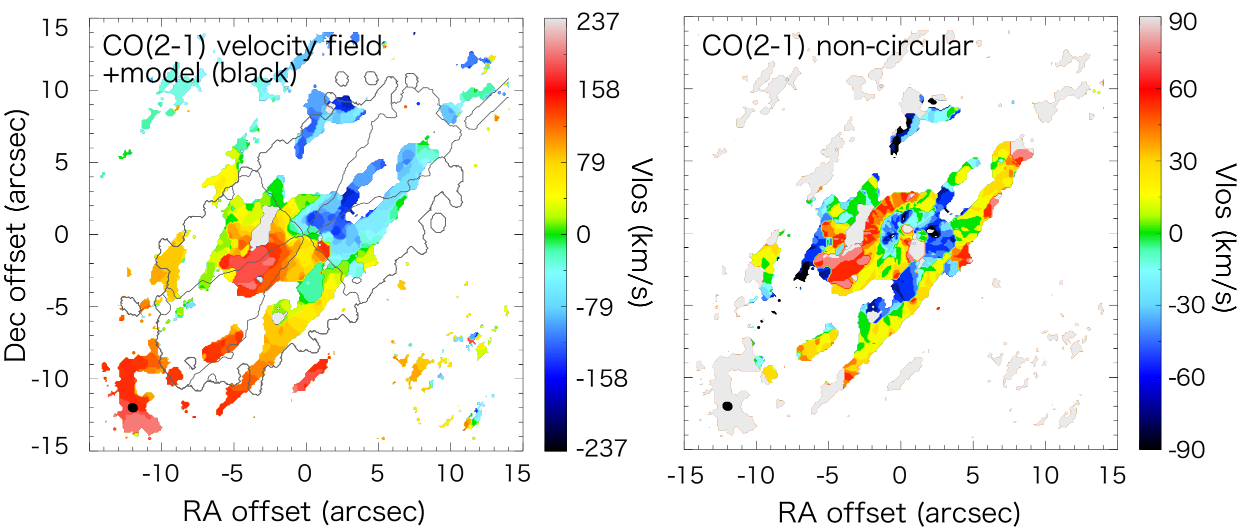


Not only SMBH mass but also molecular holes/ non-circular motions



Davis et al. 2017b

Onishi et al. in prep.



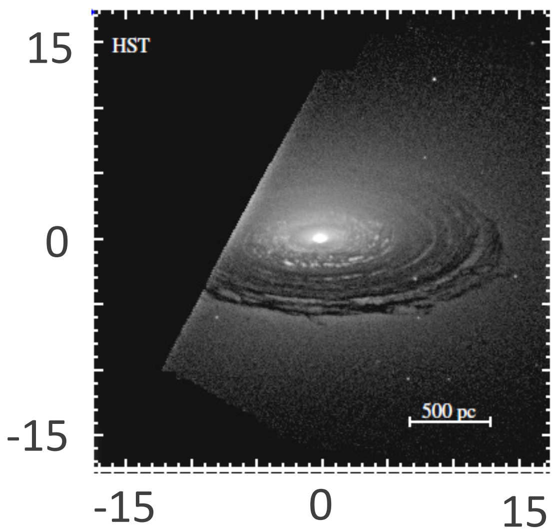
Molecular hole in NGC 4429

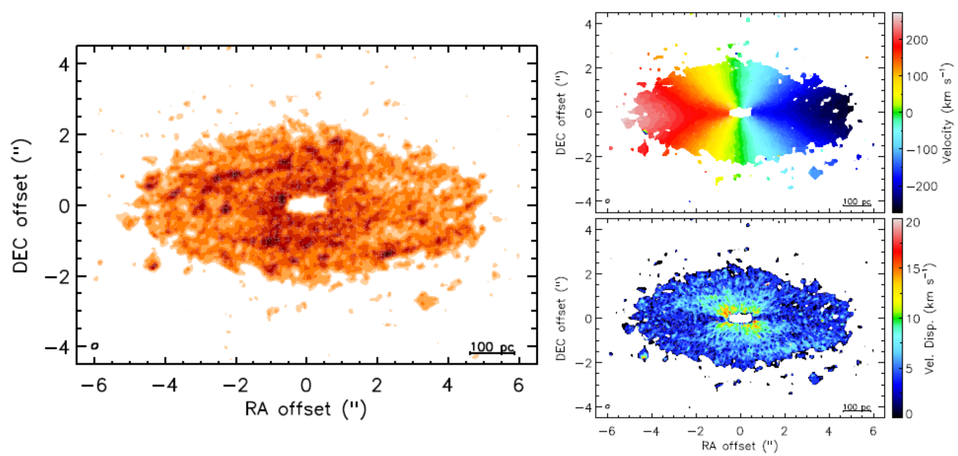
Davis et al. 2017b

~48 pc radius hole

Outer truncation radius ~650 pc, both seen w/ CO(3-2).

- Resonances?
- Stability?
- Tidal force?





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Davis et al. 2017b

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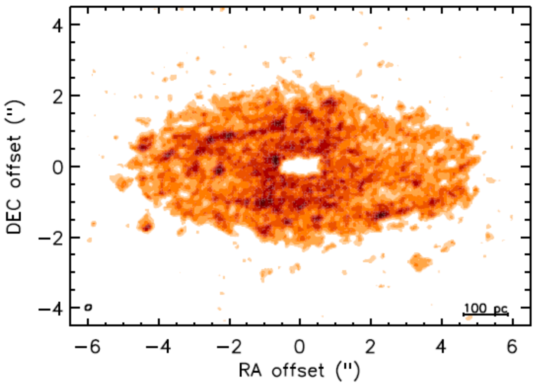
- Resonances?... Unlikely. 680 km/s kpc^{-1} pattern speed required.
- Stability?
- Tidal force?



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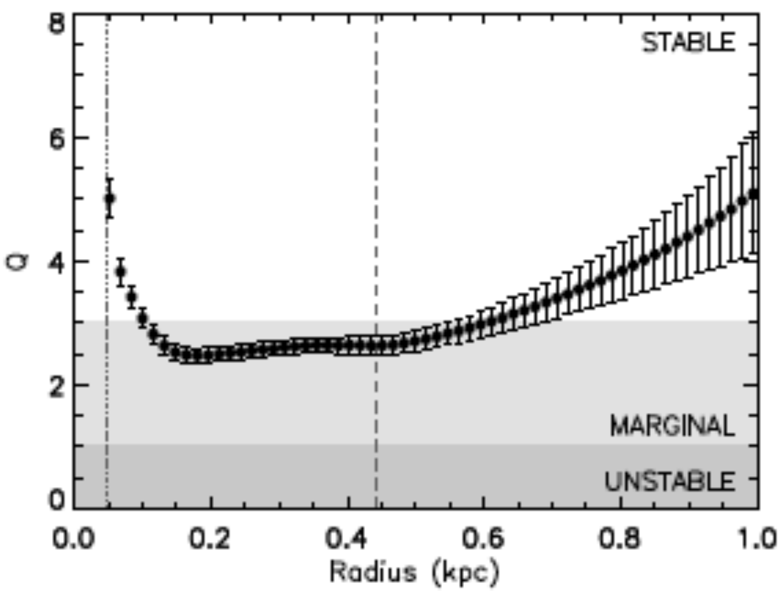
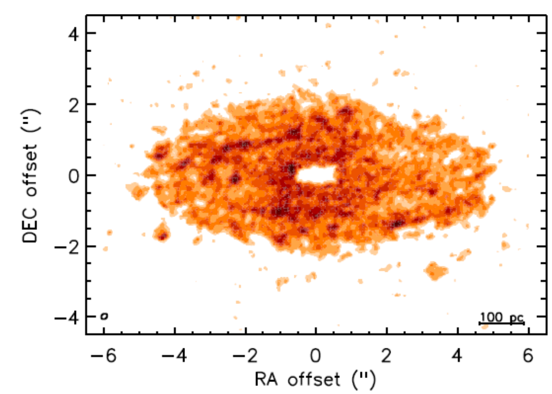
- Stability?... Q parameter higher at inner/outer radii. Not perfect.





Molecular hole in NGC 4429

Davis et al. 2017b

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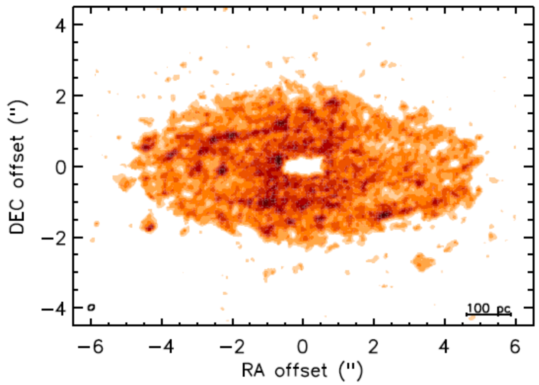
- Resonances?... Unlikely. 680 km/s kpc^{-1} pattern speed required.
- Stability?... Q parameter higher at inner/outer radii. Not perfect.
- Tidal force?... needs $>9x10^4 cm^{-3}$ to survive within the inner radius.

  possible, but do not truncate at the outer radius.



Molecular hole in NGC 4429

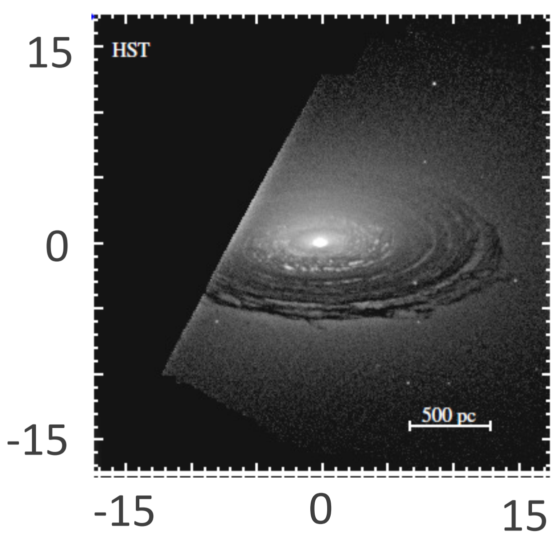
Davis et al. 2017b

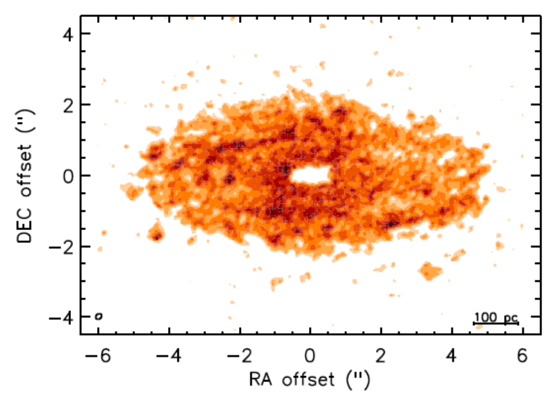
~48 pc radius hole

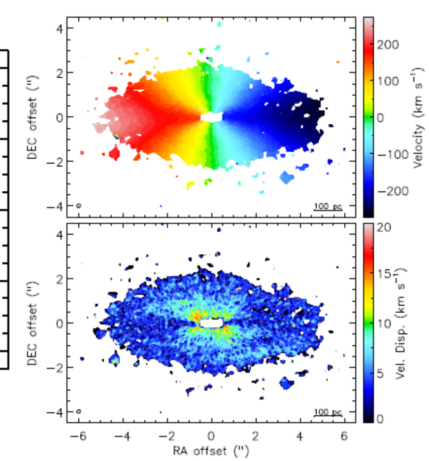
Outer truncation radius ~650 pc, both seen w/ CO(3-2).

- Likely occurred from the combination of stability and tidal force.

Should also account for AGN radiation (though LLAGN; Nyland+16).







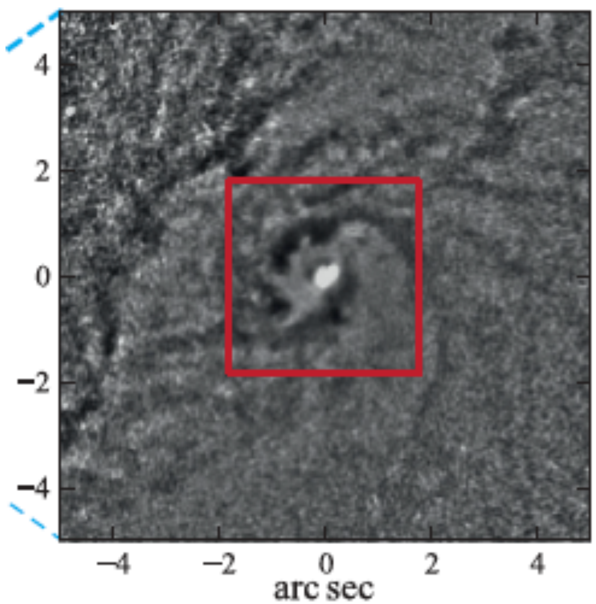
Non-circular motions– NGC 4501

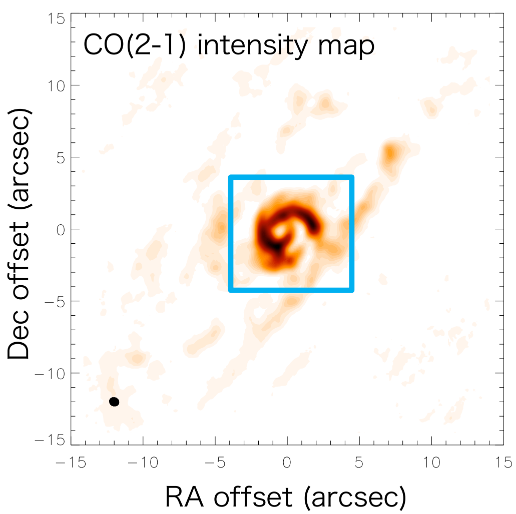
Preliminary; Onishi+ in prep.

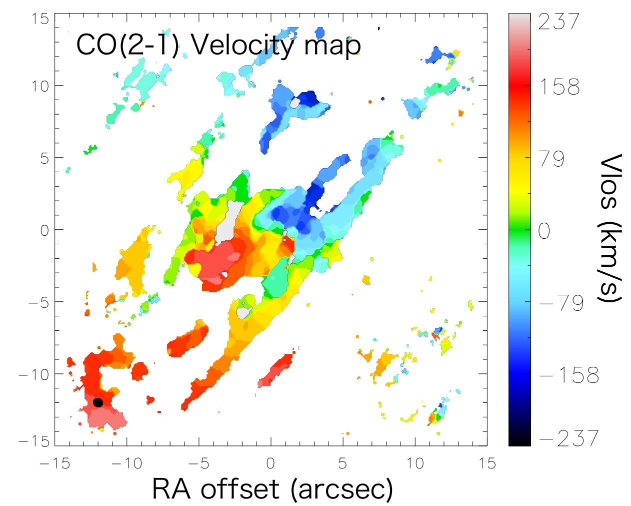
NGC 4501:

SA, Sy2, CO (2-1) observed at 0".63(~50pc) beam

with ALMA Cycle 3 (PI: K. Onishi)







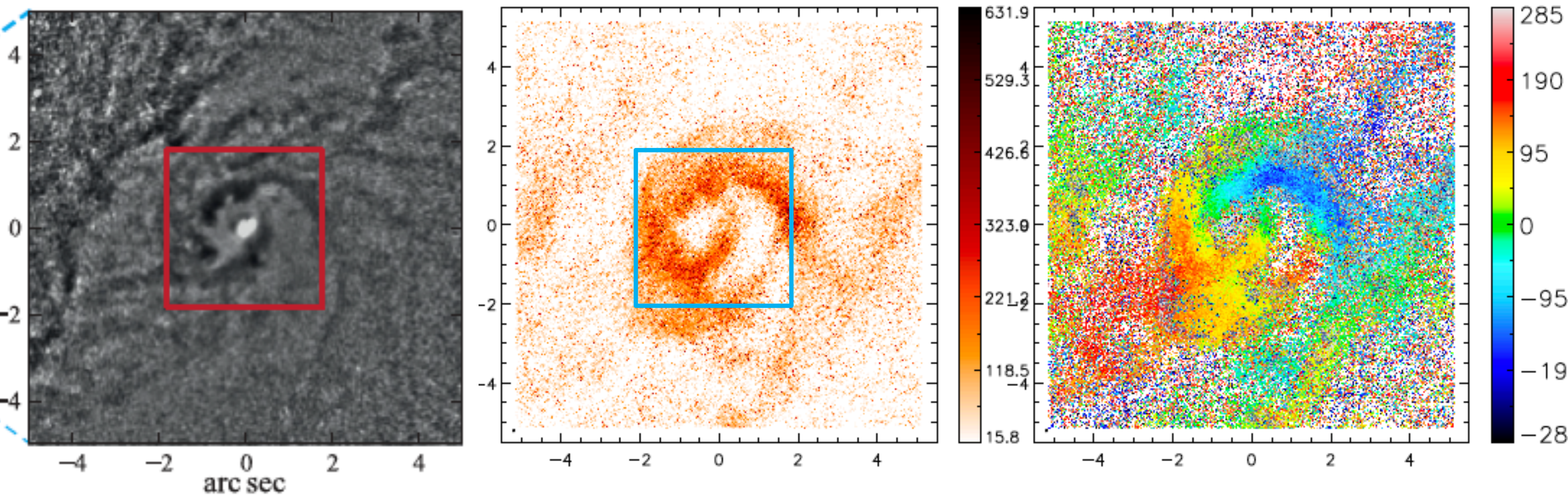
Non-circular motions– NGC 4501

Preliminary; Onishi+ in prep.

NGC 4501:

SA, Sy2, CO (2-1) observed at 0”.05x0”.03 (~5pc!) beam

with ALMA Cycle 3 (PI: K. Onishi) & ACA (PI: L. Liu)

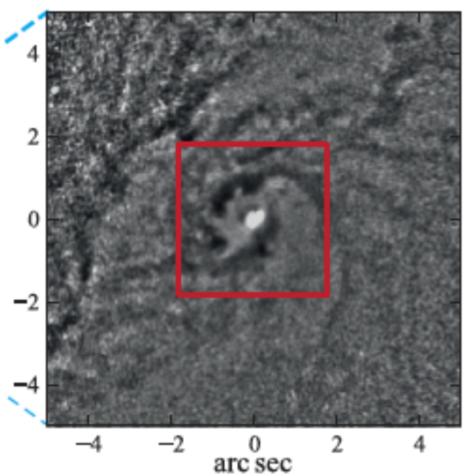


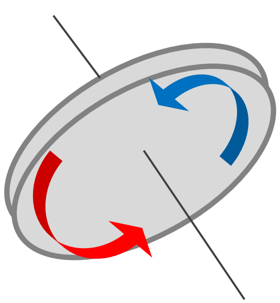
Non-circular motions– NGC 4501

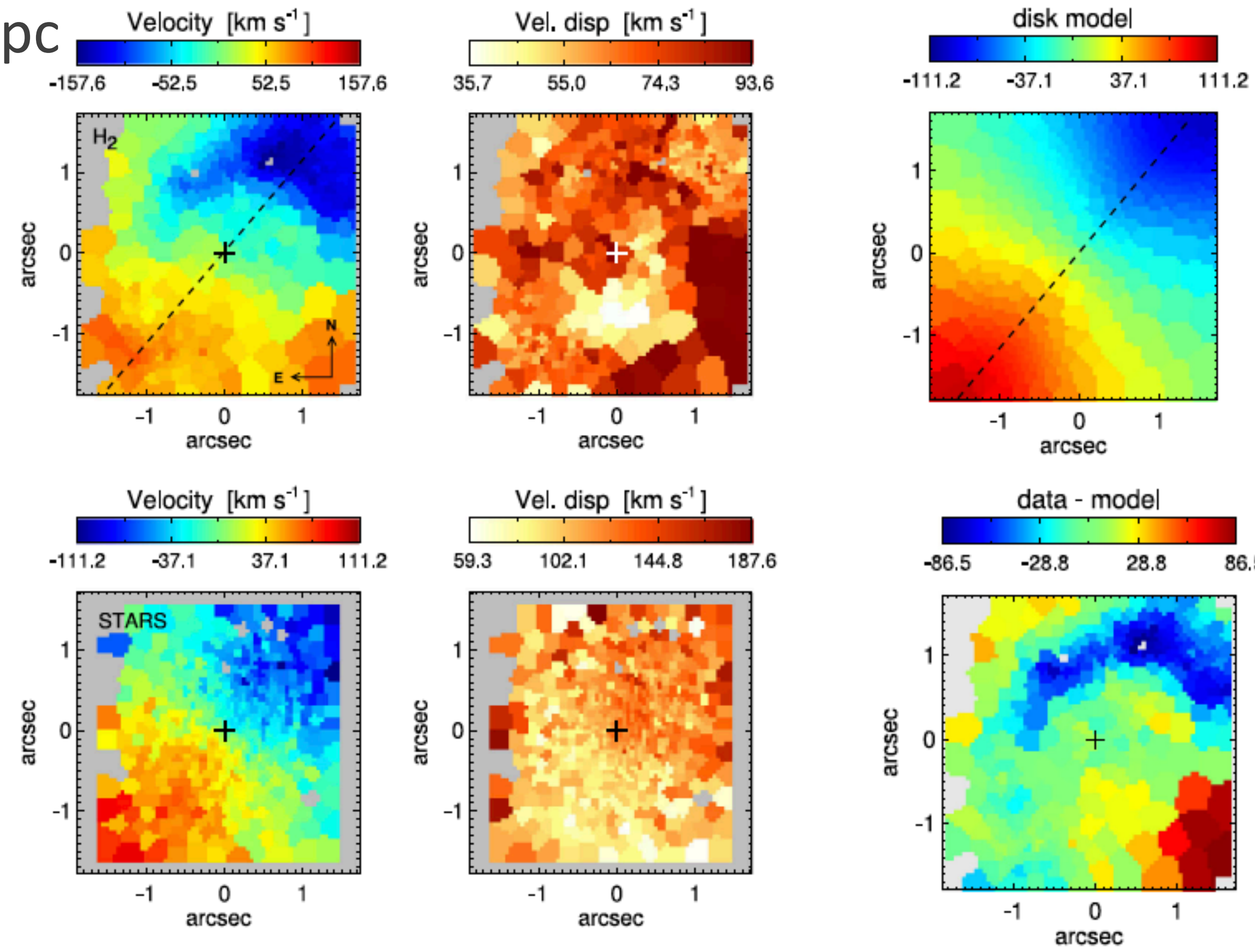
H_2, stars (Mazzalay+14 w/ SINFONI) kinematics

Observed @ 0”.2~16pc

HST F547M unsharp-masked







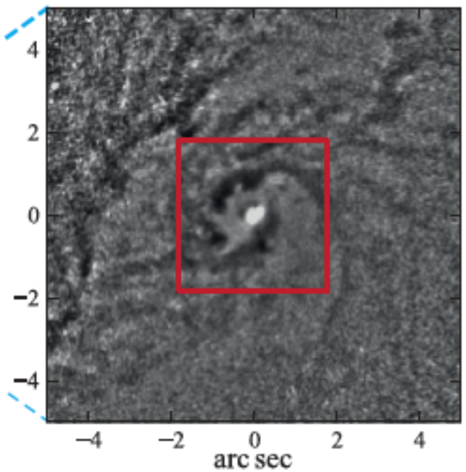
Mazzalay+14

Non-circular motions– NGC 4501

[N II], Hα(Reppetto+17 w/ GMOS) kinematics

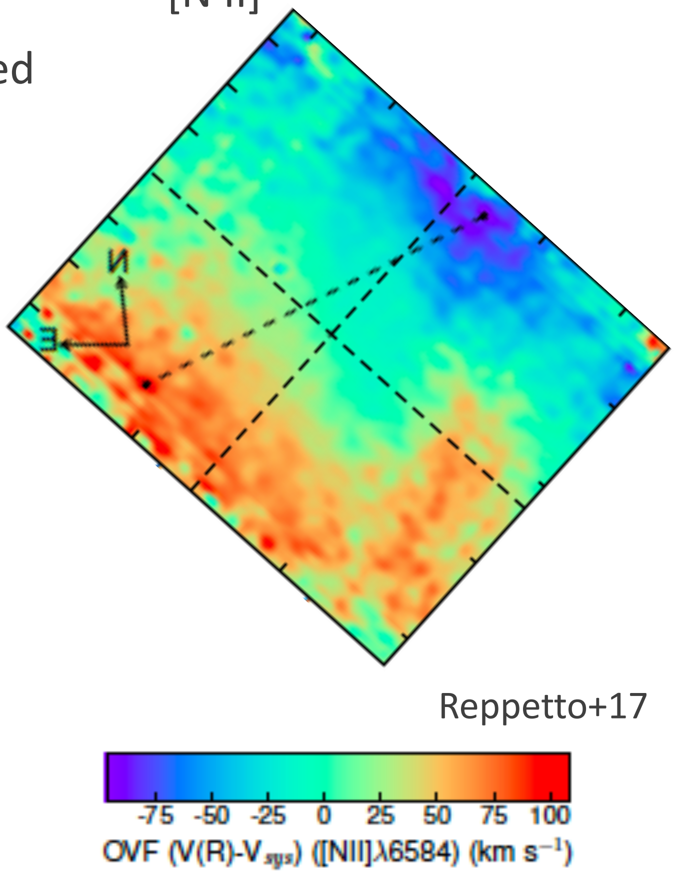
observed @0”.77~60 pc

HST F547M unsharp-masked



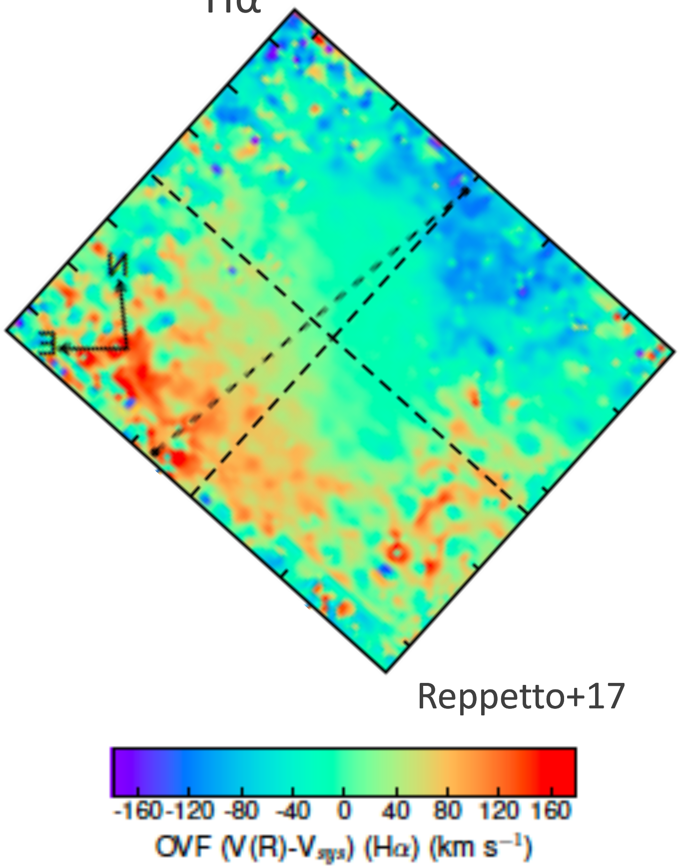
Mazzalay+14

[N II]



Reppetto+17

Hα

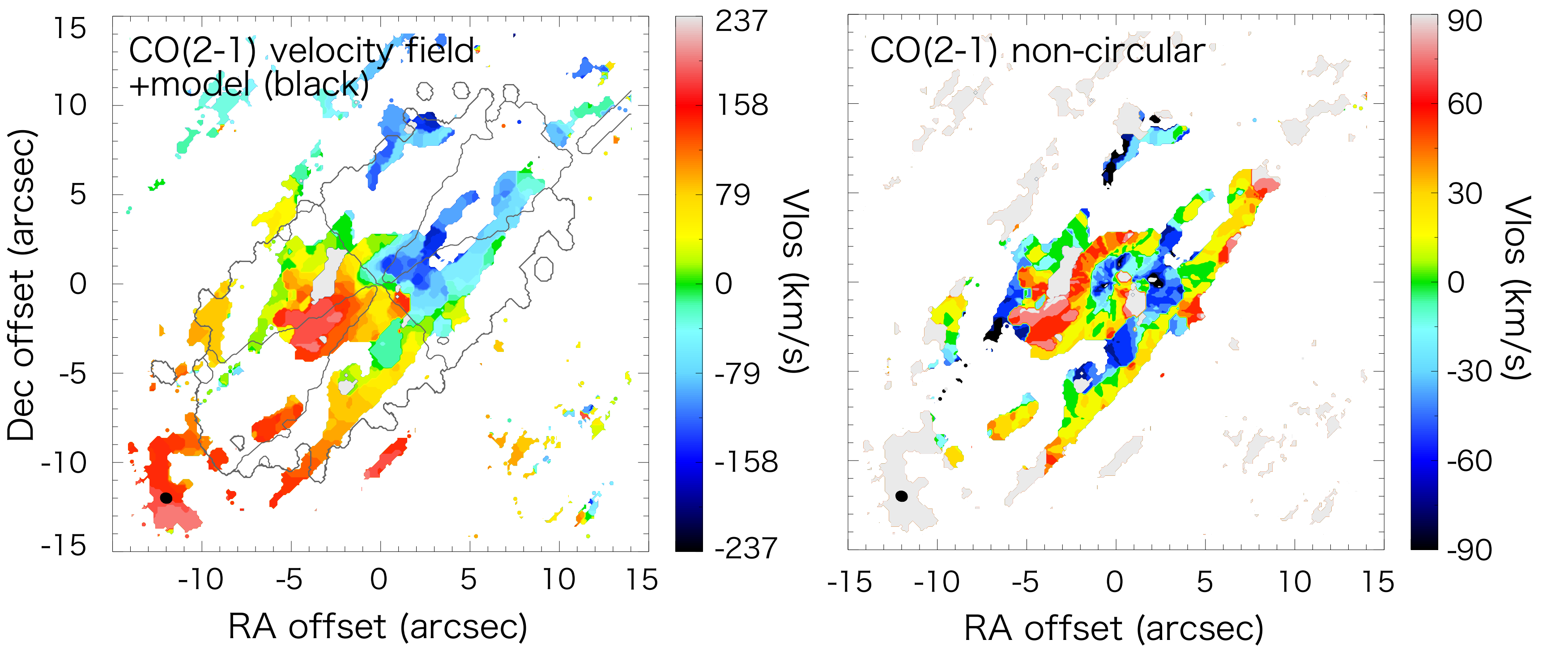


Reppetto+17

Non-circular motions– NGC 4501

CO ~50pc resolution non-circular motions detected.

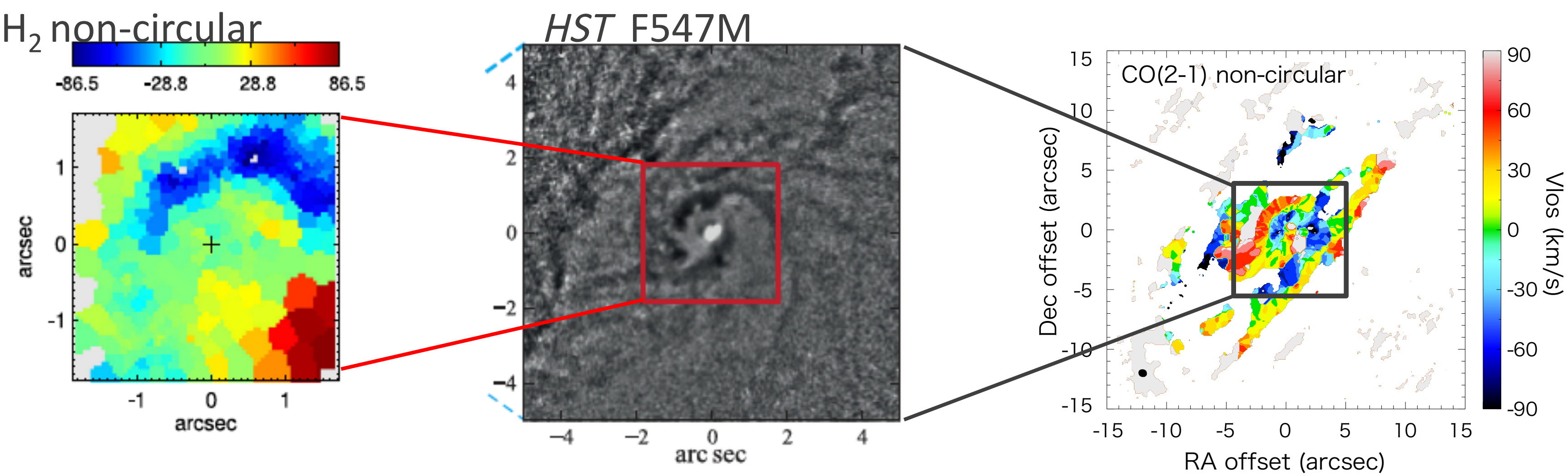
Trying the same for high-res (~5pc) but too much noise..



Non-circular motions– NGC 4501

Subtracted a preliminary velocity field from the observation to obtain non-circular motions.

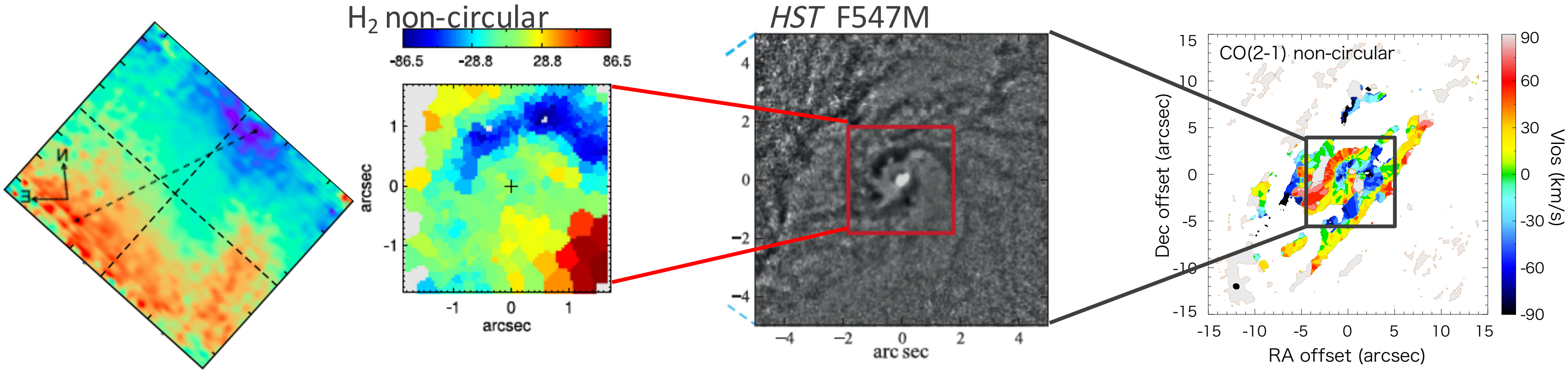
*CO being comparable to warm molecular, but not to ionized gas!



Non-circular motions– NGC 4501

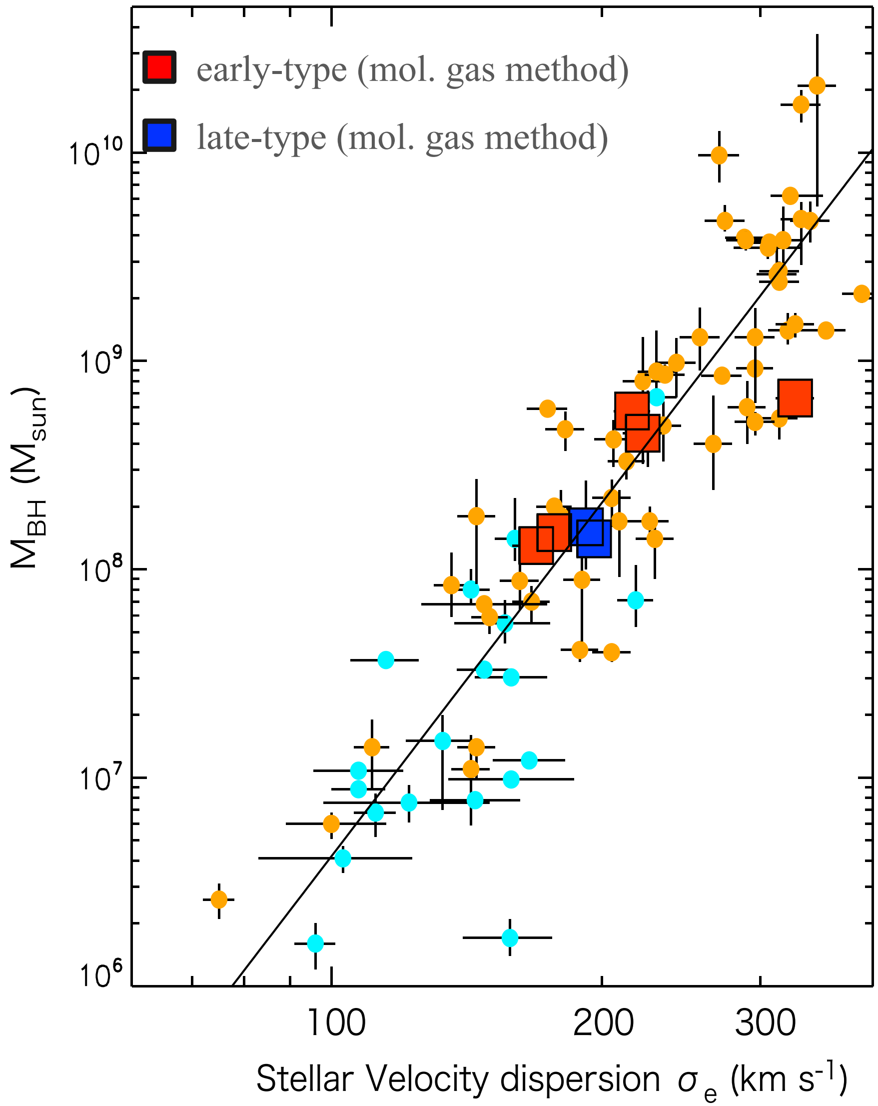
Seyfert 2 galaxy with an outflow of cold (and warm) molecular gas.

Ionized gas is not very perturbed (though we need a higher S/N).



Our high-res ALMA data possibly leads to an AGN feeding process.

Summary and conclusions –1. SMBH mass measurements



Molecular gas method seems to produce decent results.
(will be more powerful with more observations!)

The next step for the M-σ relation is ..

- origin of the scatter?
- systematic error among different methods?

Summary and conclusions –2. GMC/molecular gas properties and non-circular motions

- High-res observations of CO at nearby galaxies (typically @<30pc) can also be used for several topics:
  - GMC properties (Utomo+15)
  - Gas disc properties (Davis+17b)
  - Non-circular motions (e.g., Combes+14)

- These could lead to detailed studies of both star formation and SMBH growth → again, coevolution!