# Dynamical black-hole mass measurements with 3D molecular gas interferometry

**Timothy A. Davis – ESO Fellow**
M. Bureau, M. Cappellari, M Sarzi, L. Blitz

3D2014

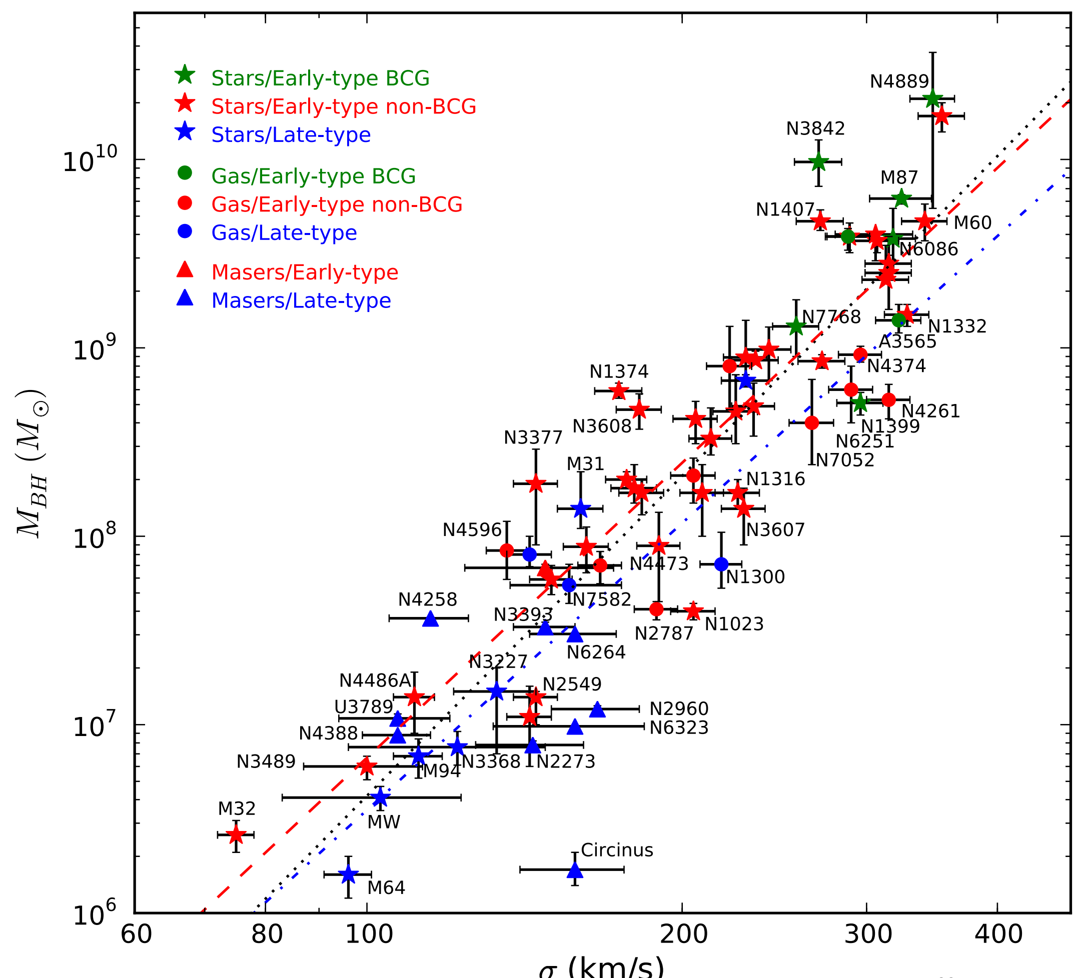
# Dynamical black-hole mass measurements with molecular gas

- **Black-hole masses are found to correlate with galaxy properties**

Also (to varying degrees with):

- Bulge Luminosity
- Bulge Mass
- Core deficit
- Galaxy mass
- Galaxy luminosity
- V_flat…

Big Question: **WHY**?!



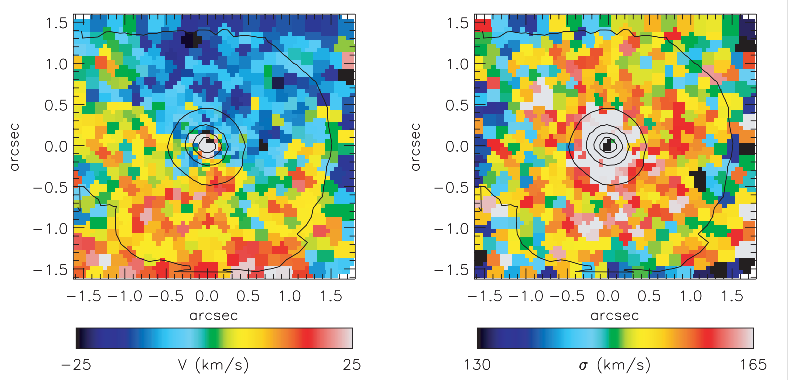

McConnell & Ma 2013

# Dynamical black-hole mass measurements with molecular gas

- In order to understand this problem we need a good understanding of the BH-galaxy correlations, and techniques for measuring them

**Stellar Kinematics**

- Observe stellar abs. features
- Make a model
- Rotation+Large vel. Disp
- Only usually possible in early-type galaxies
- Resolution limit set by HST/AO




Cappellari et al., 2009

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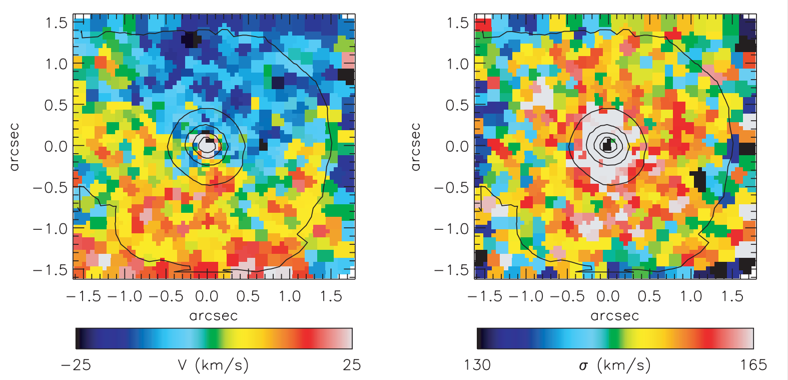
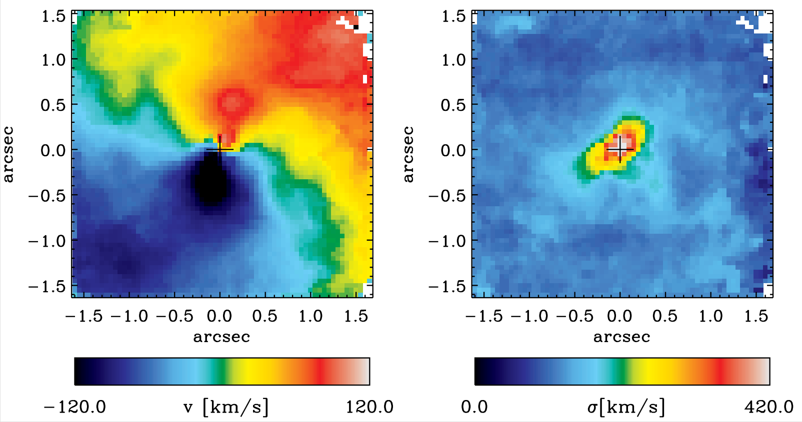



Cappellari et al., 2009

**Ionised gas**

- Observe emission line kinematics
- Make a model
- Rotation+smeller vel. Disp
- Larger range of galaxy types
- Resolution limit set by HST/AO




Neumayer et al., 2007

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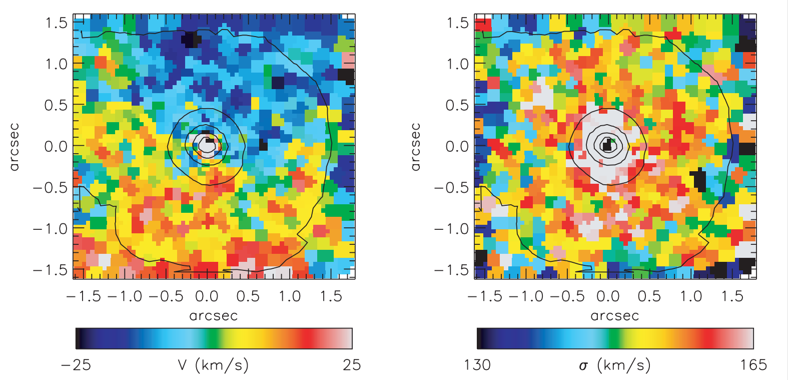
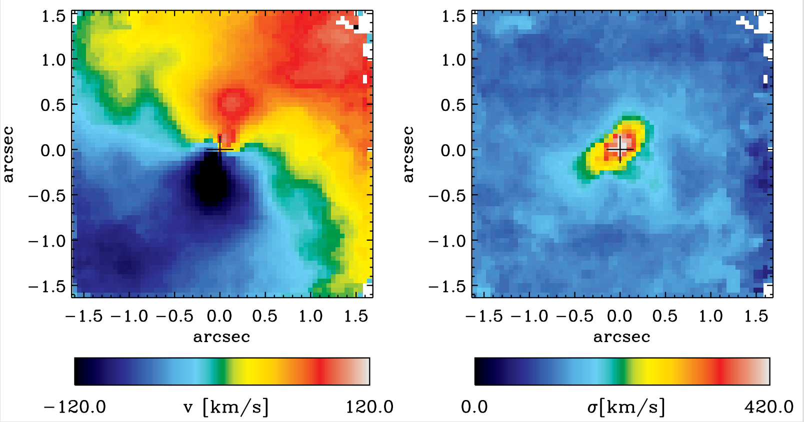



Cappellari et al., 2009

**Ionised gas**

- Observe emission line kinematics
- Make a model
- Rotation+smaller vel. Disp
- Larger range of galaxy types
- Resolution limit set by HST/AO




Neumayer et al., 2007

**Masers**

- Detect maser emission from accretion disk
- Great when present, but rare!

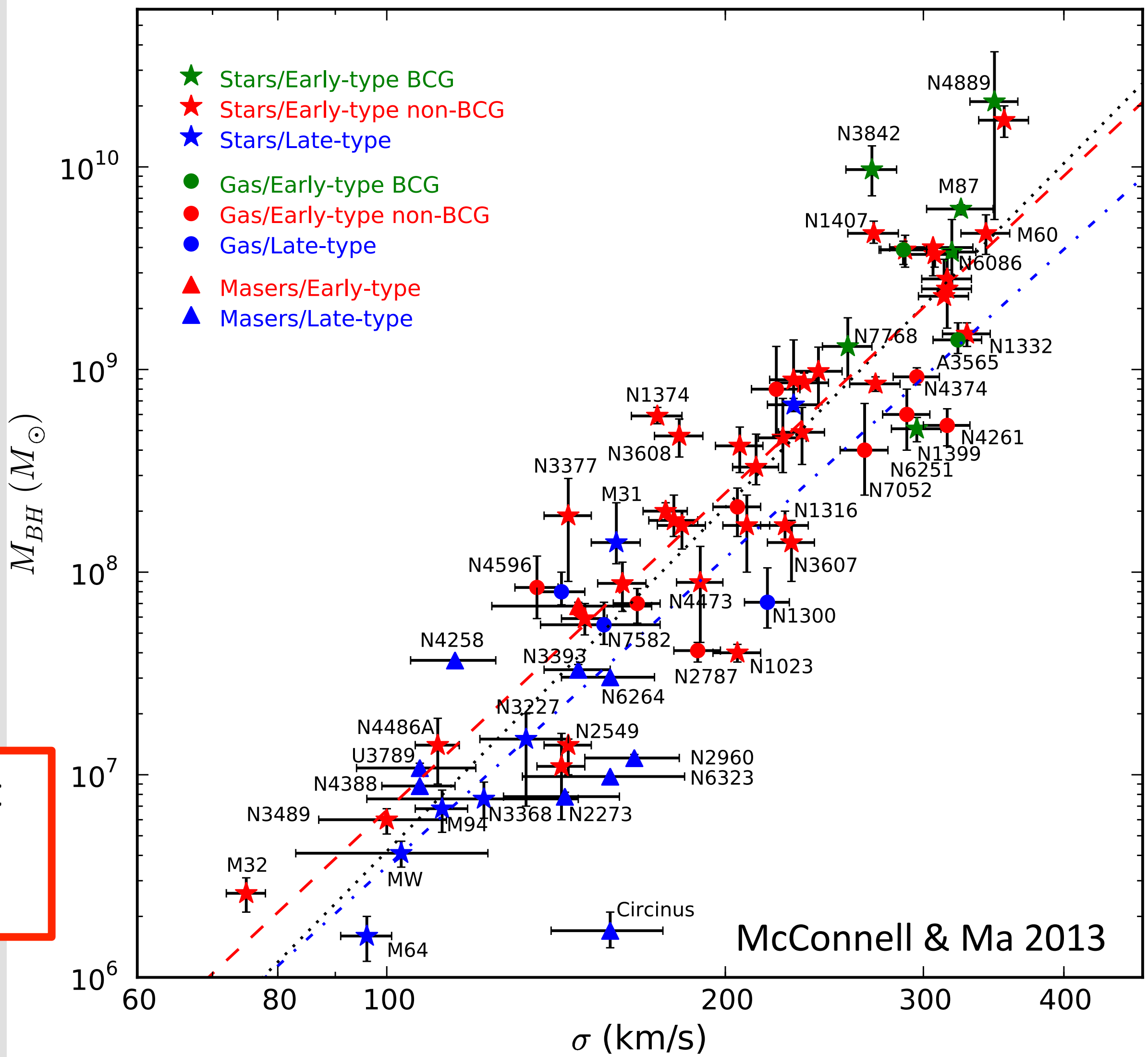
# Dynamical black-hole mass measurements with molecular gas

**Spiral and early-type galaxies**

In a hierarchical picture spirals (with smooth SF histories) may have different BH mass relations….

**Hard to study!**
**Different tracers→ different biases**

Need to find a relation that could work in all galaxy types, at all masses

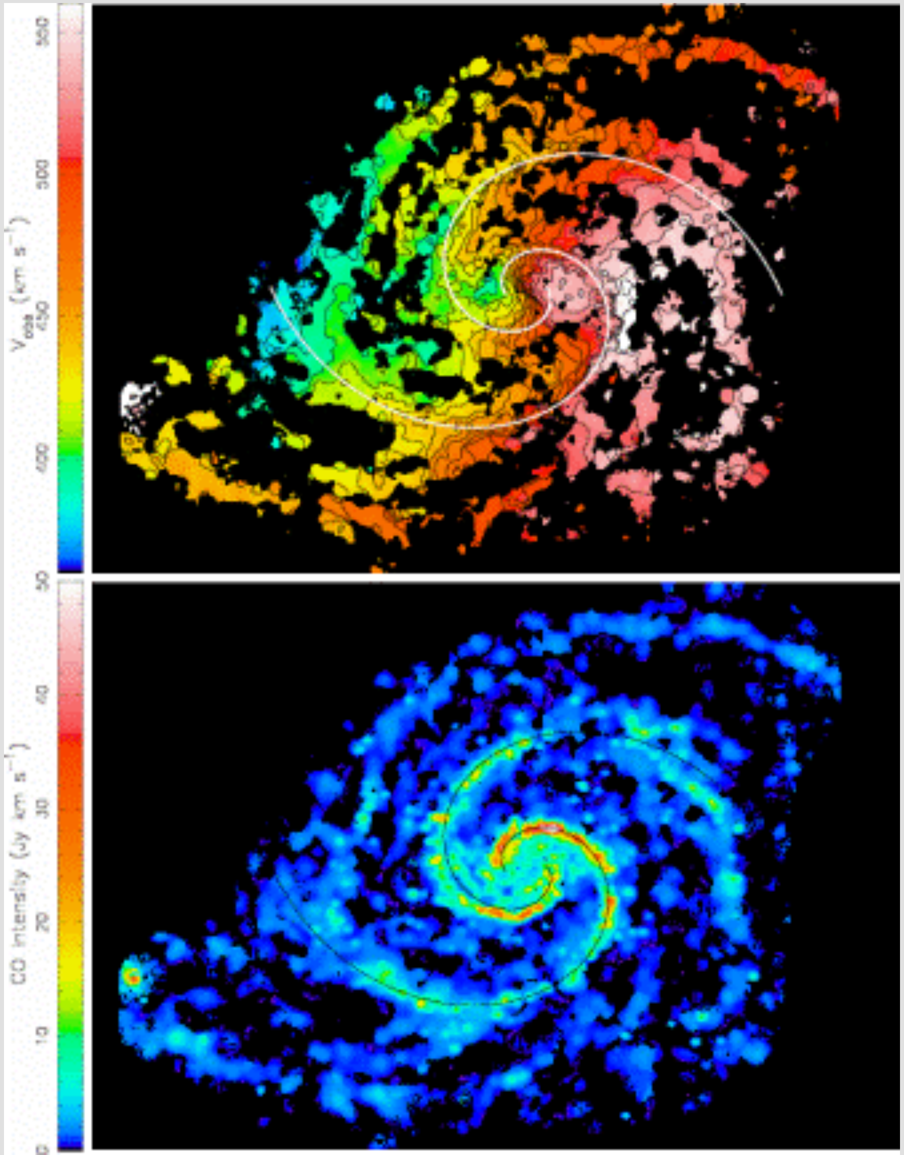


# Dynamical black-hole mass measurements with molecular gas

- **Could molecular gas help?**
- Present in 22% of Early type galaxies (Young et al., 2011) and almost all spirals
- Generally low velocity dispersion (<10 km/s)

**Requirements:**

- An ideal tracer would be dynamically cold in all galaxy types
- Present to the very centre
- Observable at high angular resolution



# Dynamical black-hole mass measurements with molecular gas

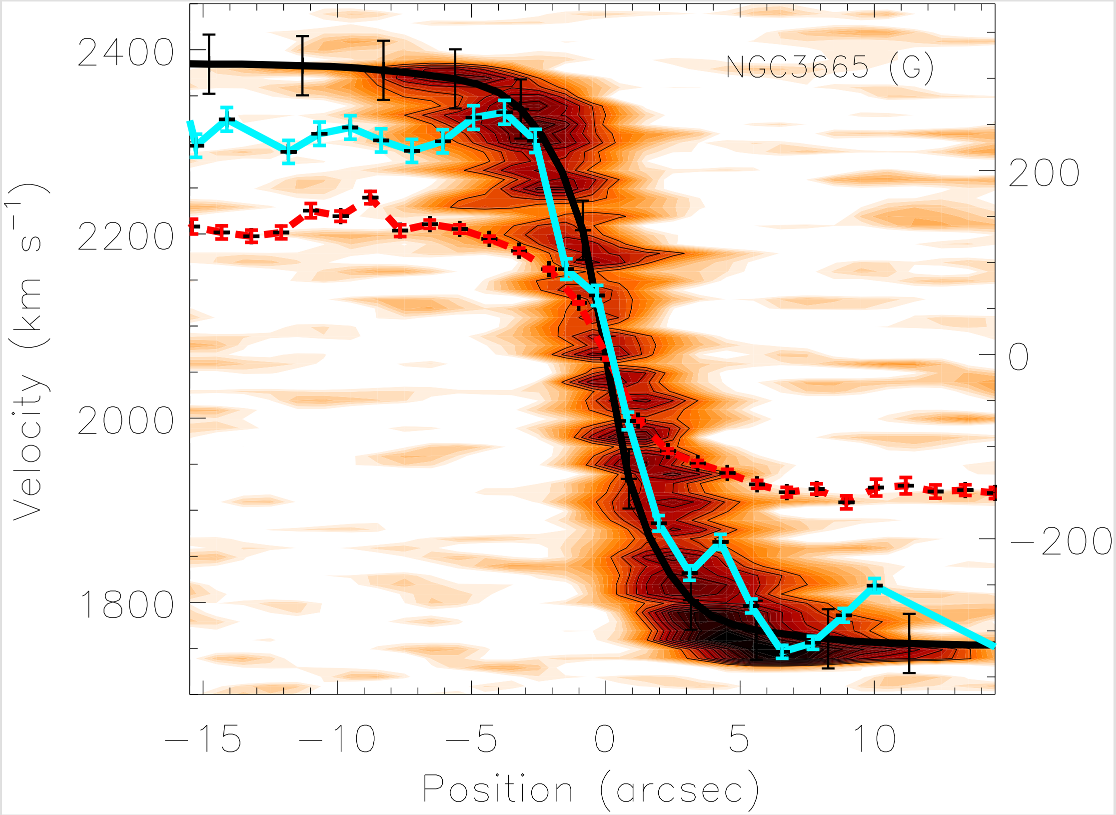
Is CO a good tracer of the circular velocity in dispersion dominated galaxies?

Use the sample of 40 mapped ETGs from ATLAS$^{3D}$

4.5” resolution

Compare CO with JAM $V_{circ}$ (jeans models)

Want to compare and see if observations fit the predicted circular velocity




Davis et al., 2013a (Paper XIV)

→ Need to account for observational effects (beam smearing, projection, finite channel width…)

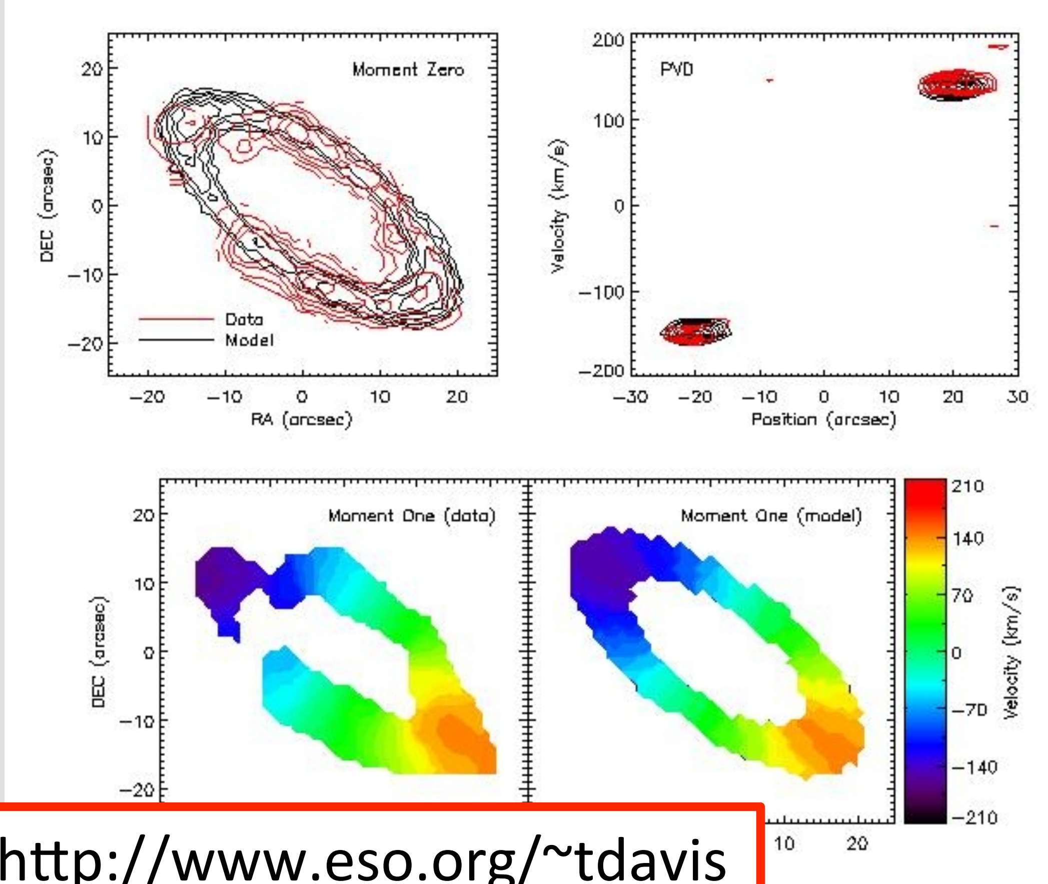
# Dynamical black-hole mass measurements with molecular gas

## KINetic Molecular Simulation tool

- An IDL tool for simulating cold gas distributions

- Inputs: (all in either 1D or 3D)
    - Surface brightness
    - Velocity curve
    - Velocity dispersion
    - Scale Height
- Outputs a simulation data cube

- Perfect for direct modeling, or for inputting into another simulation tool (e.g. *simdata* in CASA)
- Described in Davis et al., 2013a




Available to download: http://www.eso.org/~tdavis

# Dynamical black-hole mass measurements with molecular gas

## CARMA survey- Kinematics

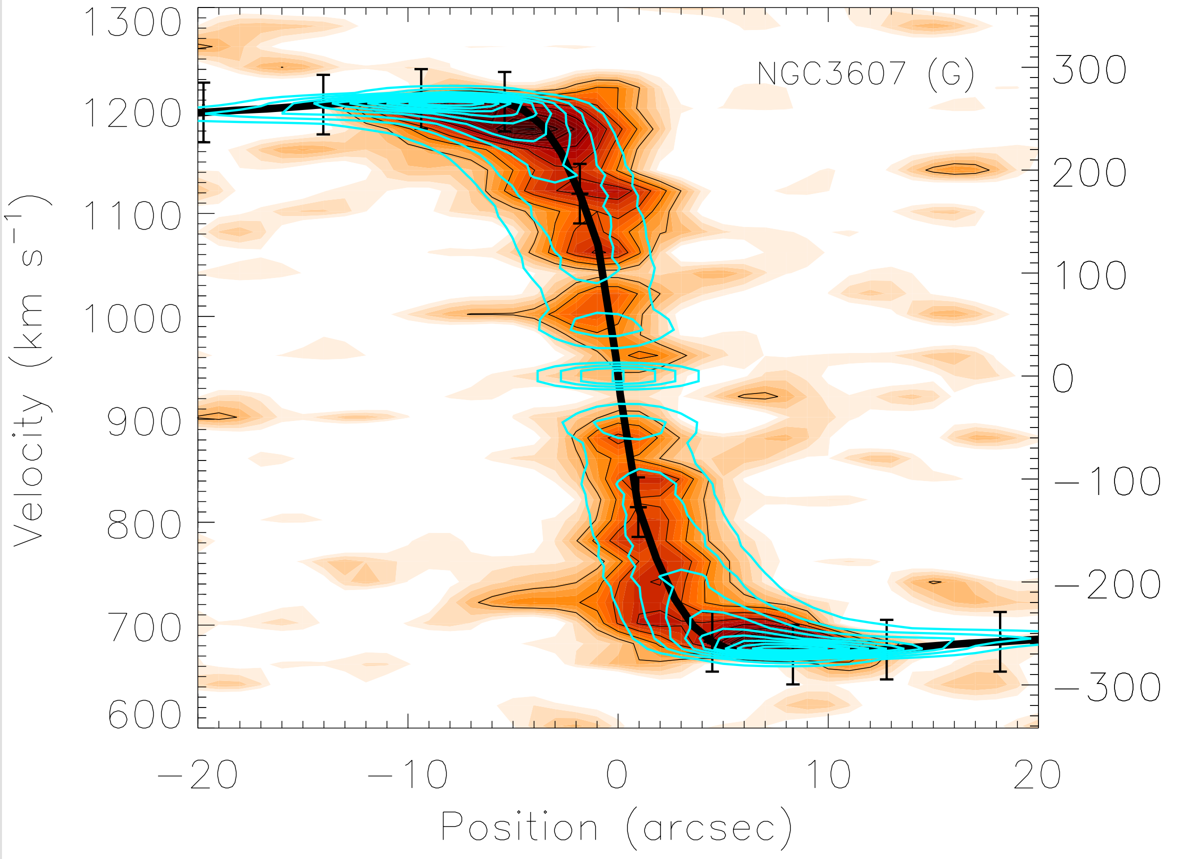
Is CO a good tracer of the circular velocity in these dispersion dominated galaxies?

Used KinMS to Compare CO with JAM $V_{circ}$

Only "Disturbed" galaxies don't follow $|V_{circ}|$

→CO is a great tracer to use!

Example:
The CO Tully Fisher Relation
Paper V: Davis et al., 2011a




Davis et al., 2013a (Paper XIV)

# Dynamical black-hole mass measurements with molecular gas

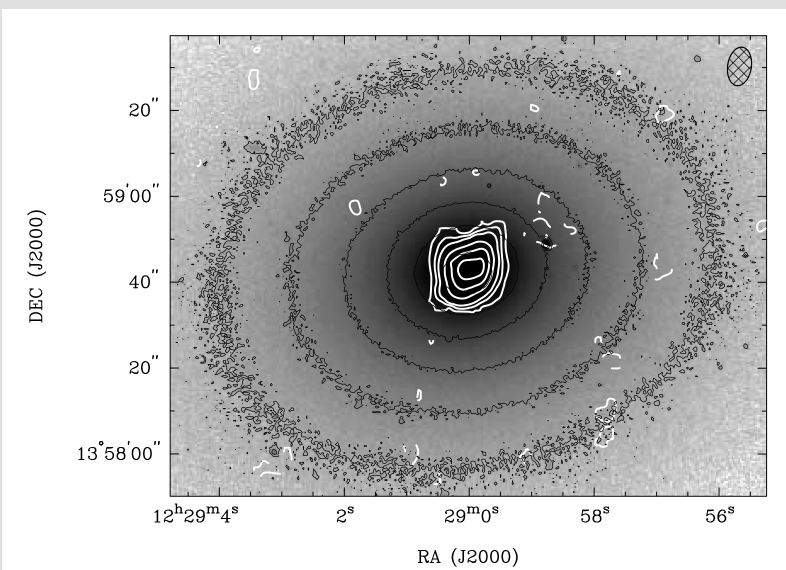
## 2) High resolution

Current (pre-ALMA) instrument can already get reasonable resolution

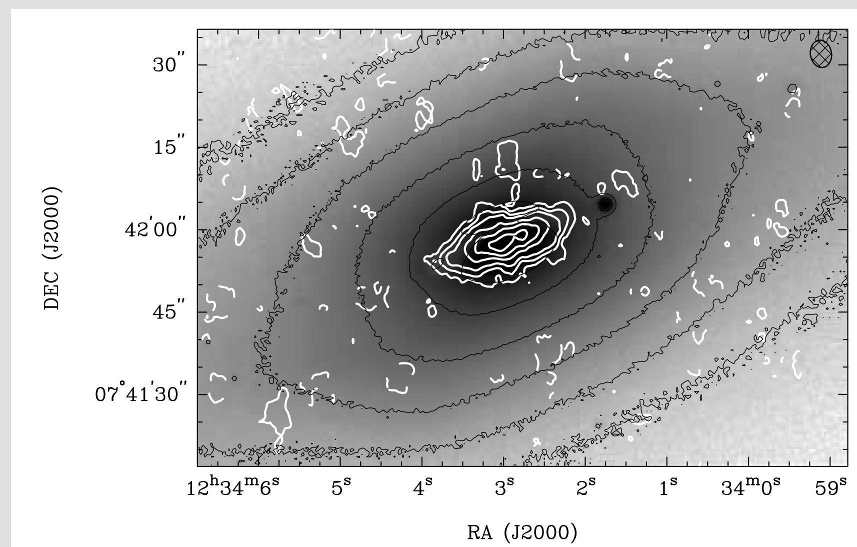
- 0.15” with CARMA
- 0.25” with PdBI

**Examples:**

NGC4459



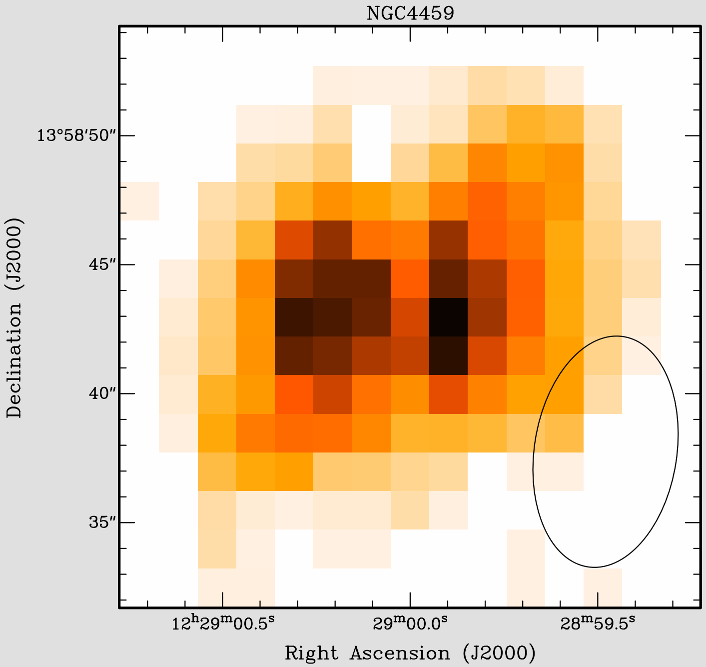

NGC4526




Both Young et al., 2008

# Dynamical black-hole mass measurements with molecular gas

## NGC4459:

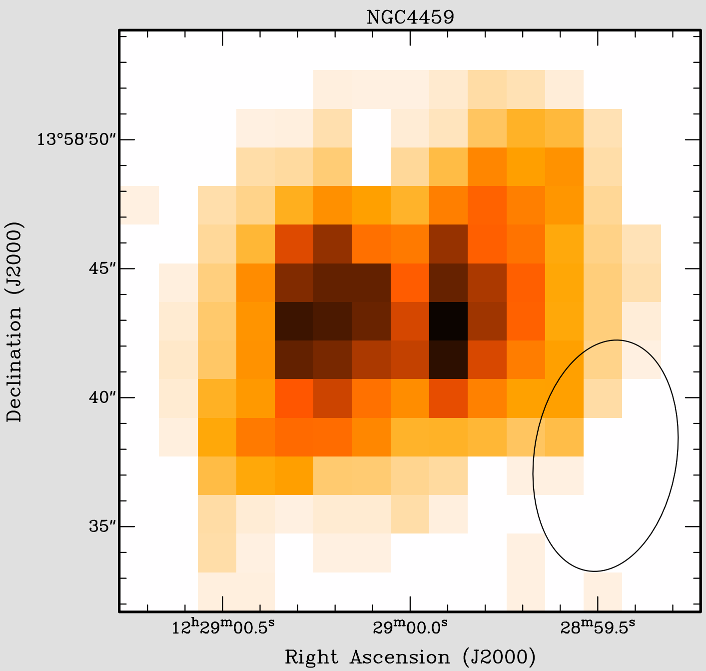



BIMA observations of Young et al., 2008

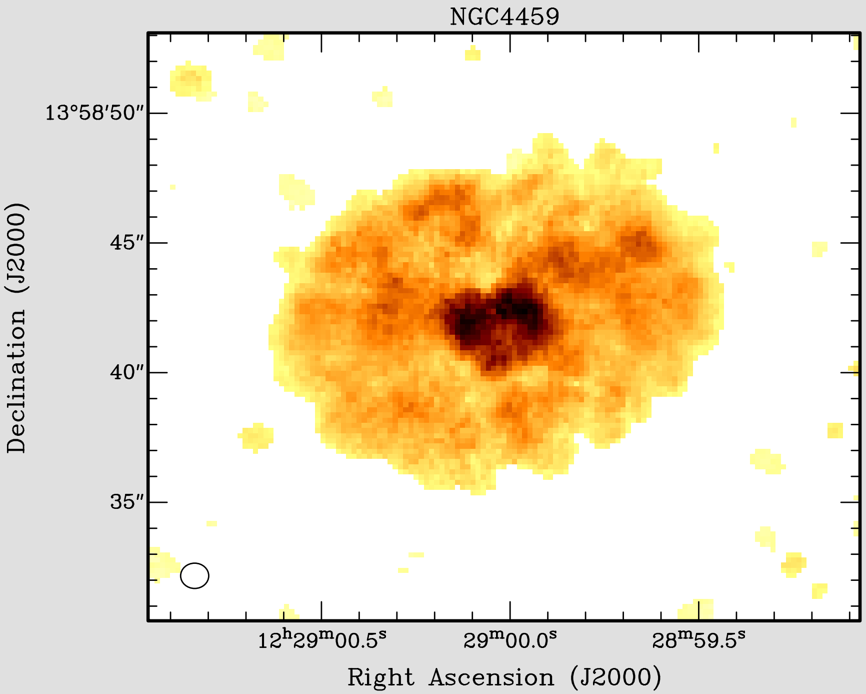
Resolution: 9.0 x 5.5 arcseconds

# Dynamical black-hole mass measurements with molecular gas

## NGC4459:




→



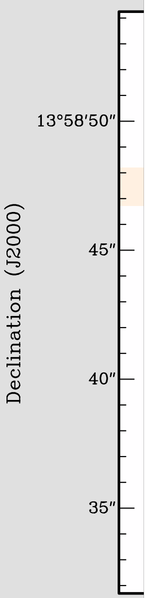

BIMA observations of Young et al., 2008

Resolution: 9.0 x 5.5 arcseconds

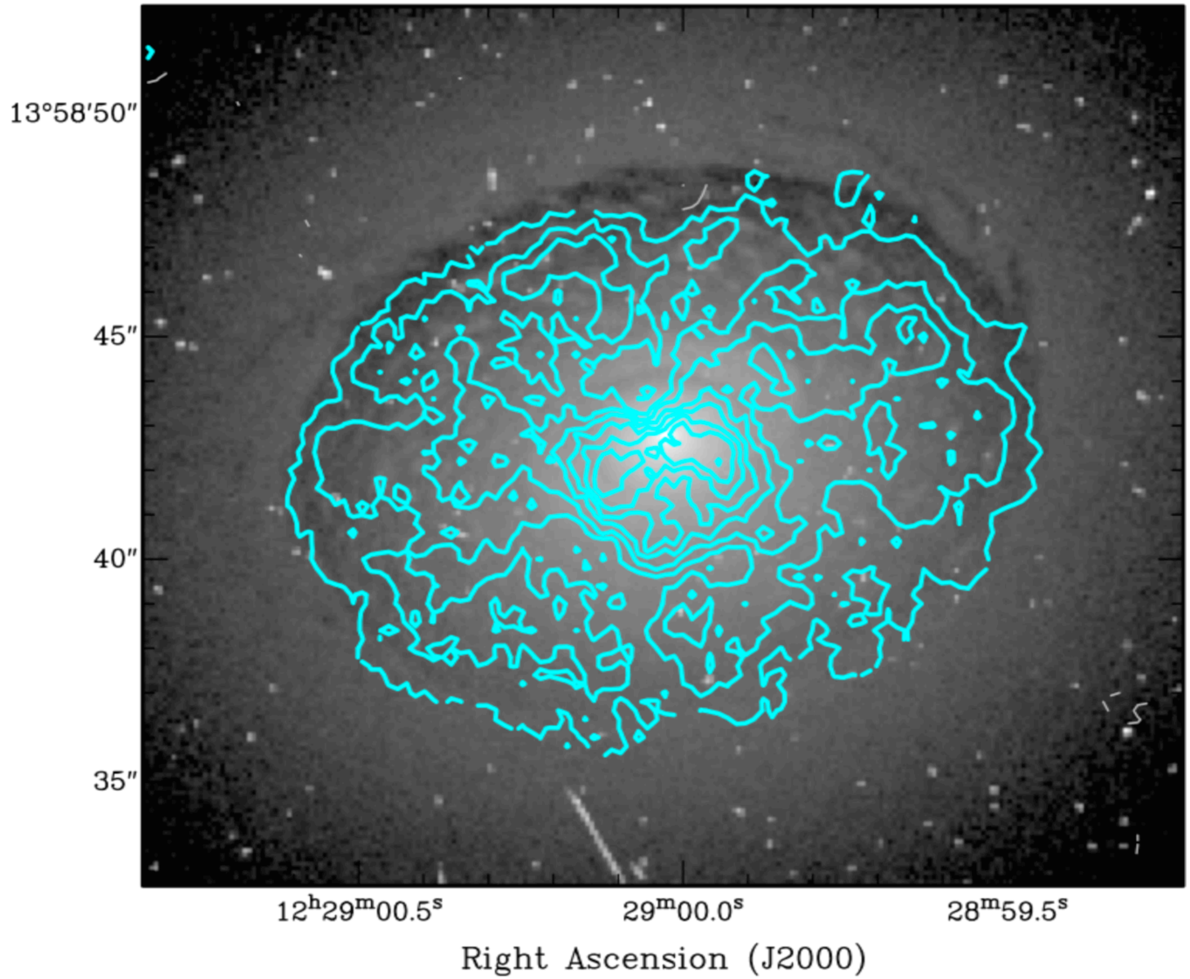
CARMA observations of Davis et al., in prep
Resolution: 1x1 arcseconds

→ Resolve inner ring
→ Outer disk is flocculent

## NGC445




Correlates well with dust structures visible in HST images

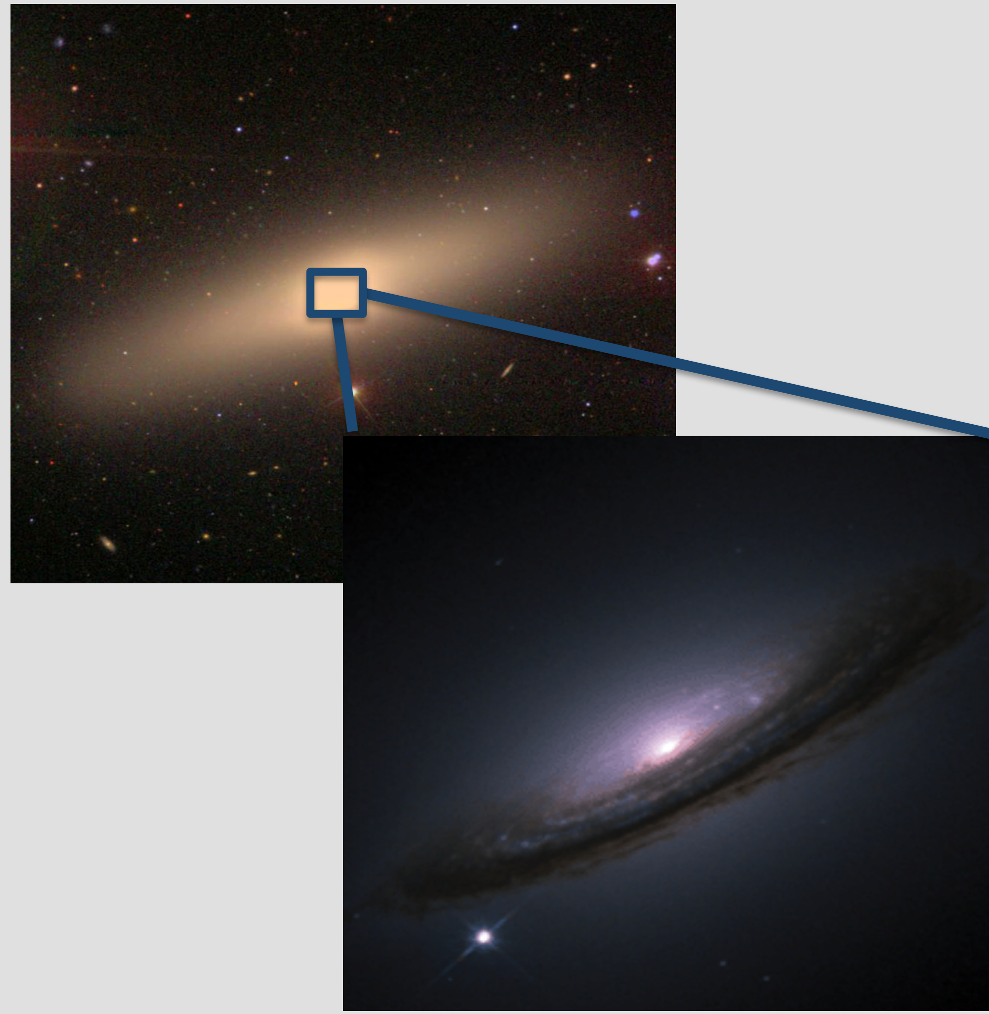



BIMA c ... rep

Resolu

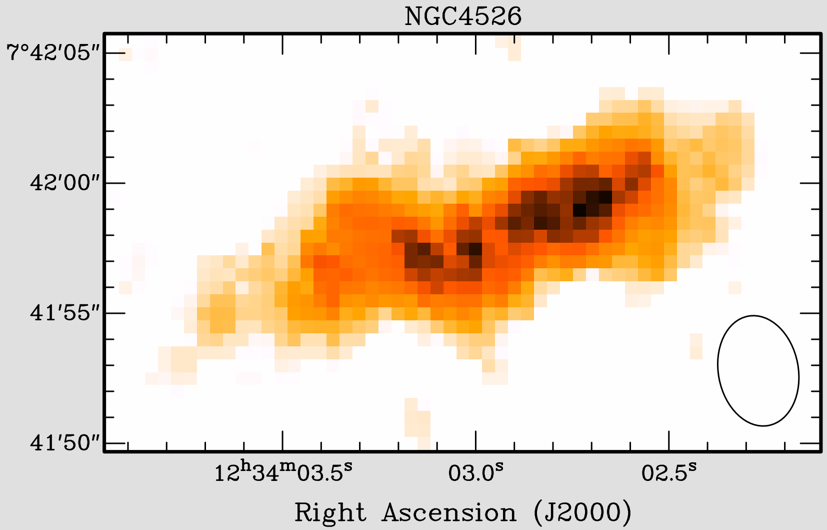
## NGC4526: A BH mass measurement candidate

- An S0 galaxy in the Virgo cluster
- D= 16.4 Mpc
  → 80 pc/arcsecond
- σ = 216 km/s
  → Predicted BH mass: $2x10^8$ Msun
- BH SOI= 20pc = 0.25 arcseconds
- Nice smooth dust lanes visible right to centre
  → Good selection criteria (see Ho et al., 2002)



# Dynamical black-hole mass measurements with molecular gas

## NGC4526: Our BH mass measurement candidate




BIMA observations of Young et al., 2008

Resolution: 5.0 x 3.8 arcseconds

Davis et al., 2013, Nature, 494, 328-330

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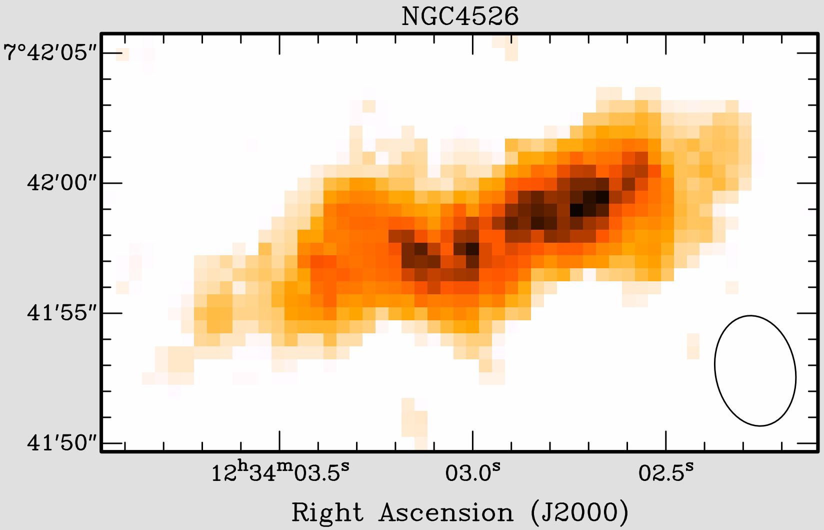
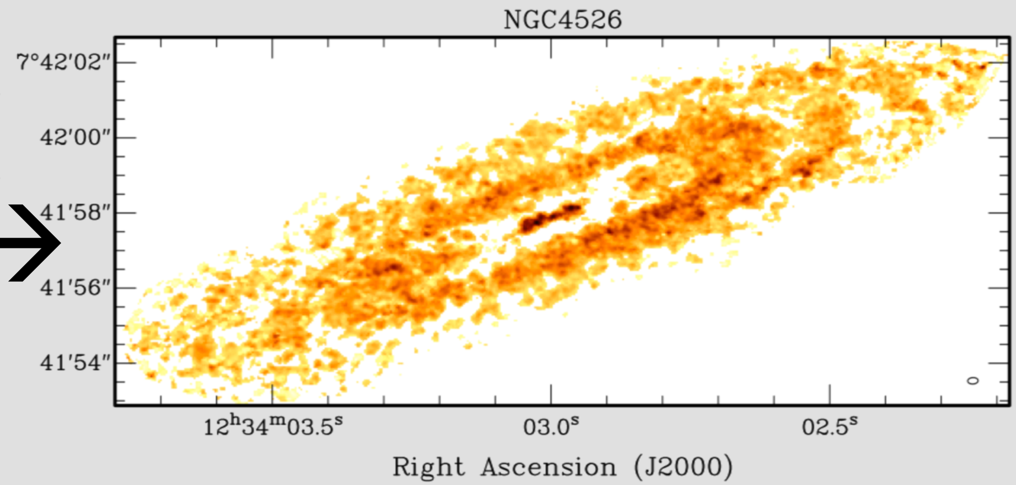



BIMA observations of Young et al., 2008

Resolution: 5.0 x 3.8 arcseconds

CARMA observations of Davis et al., 2012

Resolution: 0.27 x 0.17 arcseconds

→ At least 2 molecular rings!
→ Spiral spurs between these rings

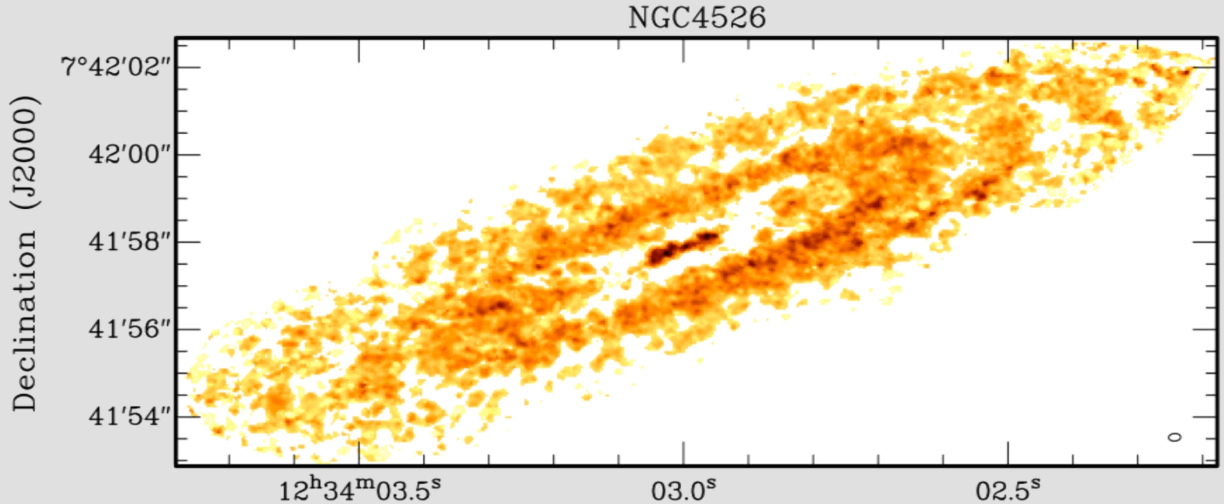
Davis et al., 2013, Nature, 494, 328-330

**Higher resolution image of gas in an ETG ever!**

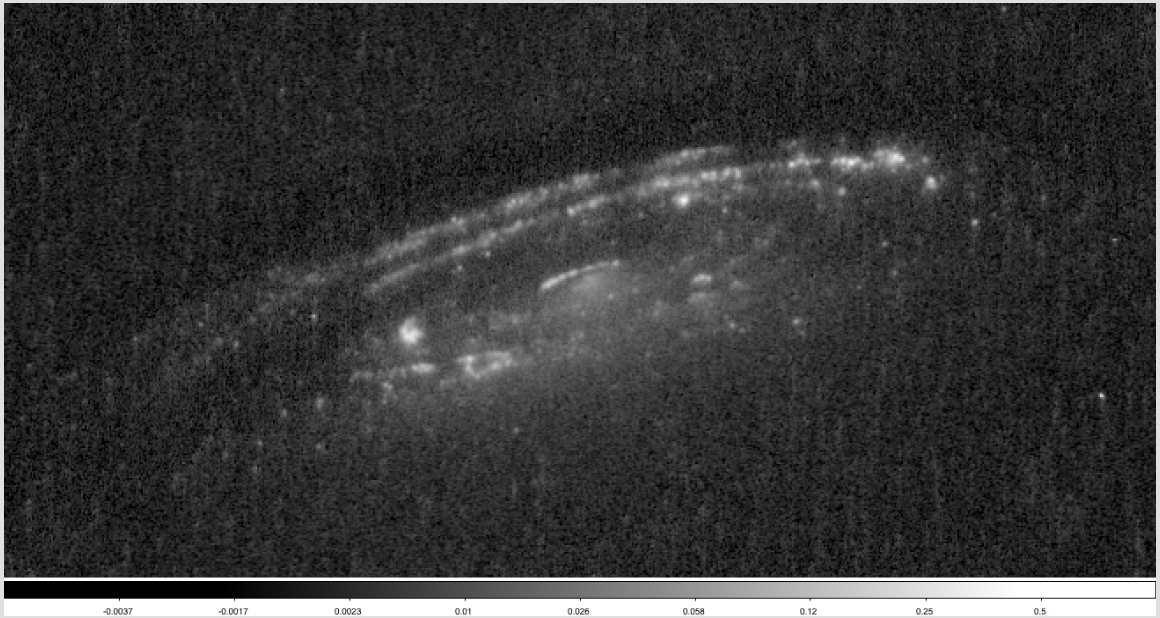
# Dynamical black-hole mass measurements with molecular gas

CARMA Data →
0.25 arcsecond resolution
= ~20 pc @ 16.4 Mpc

- Resolve individual molecular clouds




HST WFPC3 NUV data→
0.04 arcsecond resolution



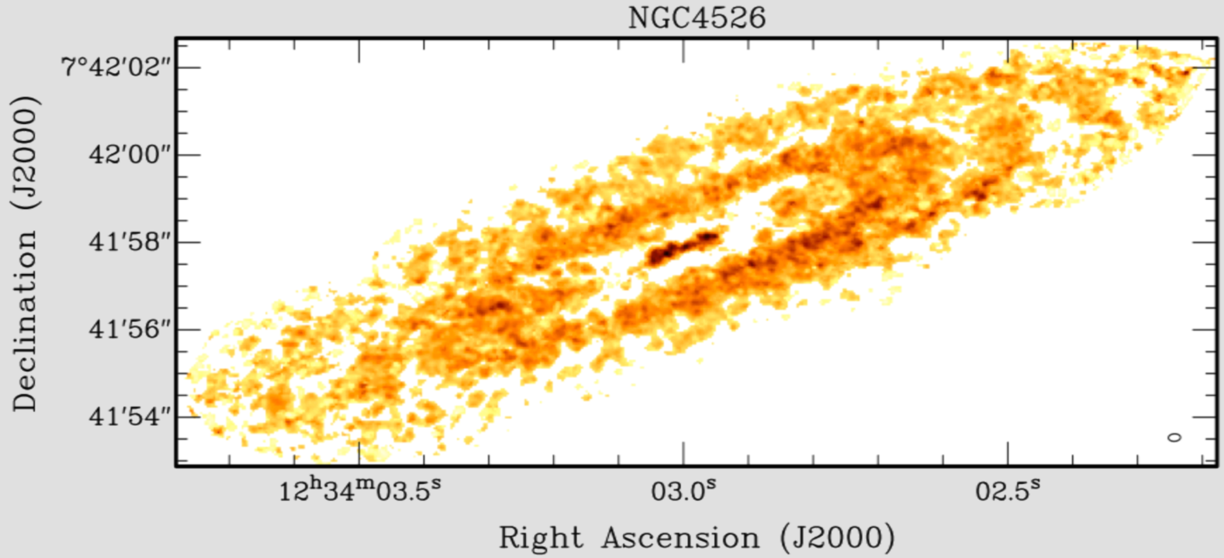
Great correspondence!
Coming soon:
(very) resolved SF laws in NGC4526!

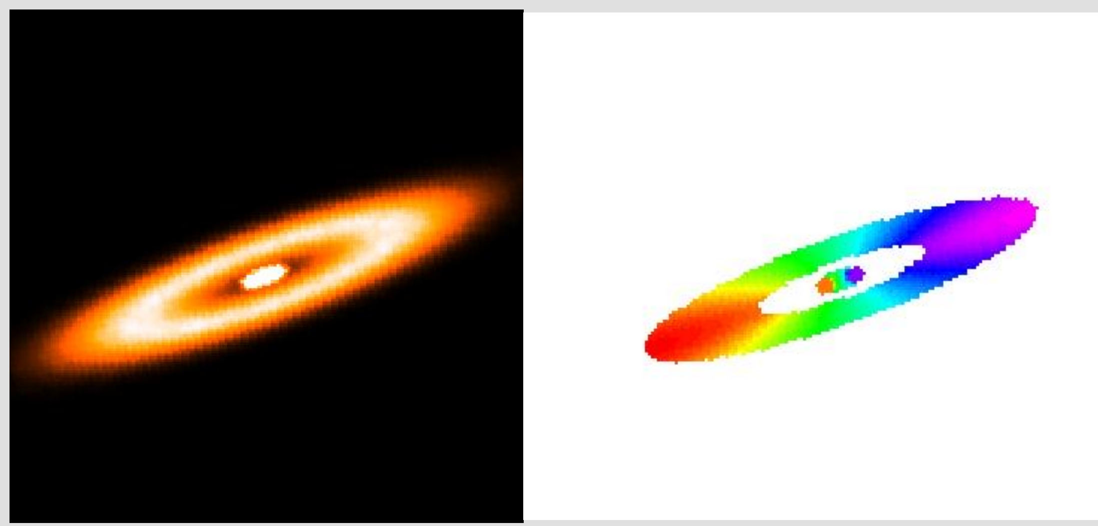
Davis et al., 2013, Nature, 494, 328-330

# Dynamical black-hole mass measurements with molecular gas

**Gas model**

- Need to model the effect of the interferometer well to get good constraints
- Include inner and first ring
- Model gas distribution expect with and without BHs
- Couple the KinMS tool to a Baysian MCMC fitter

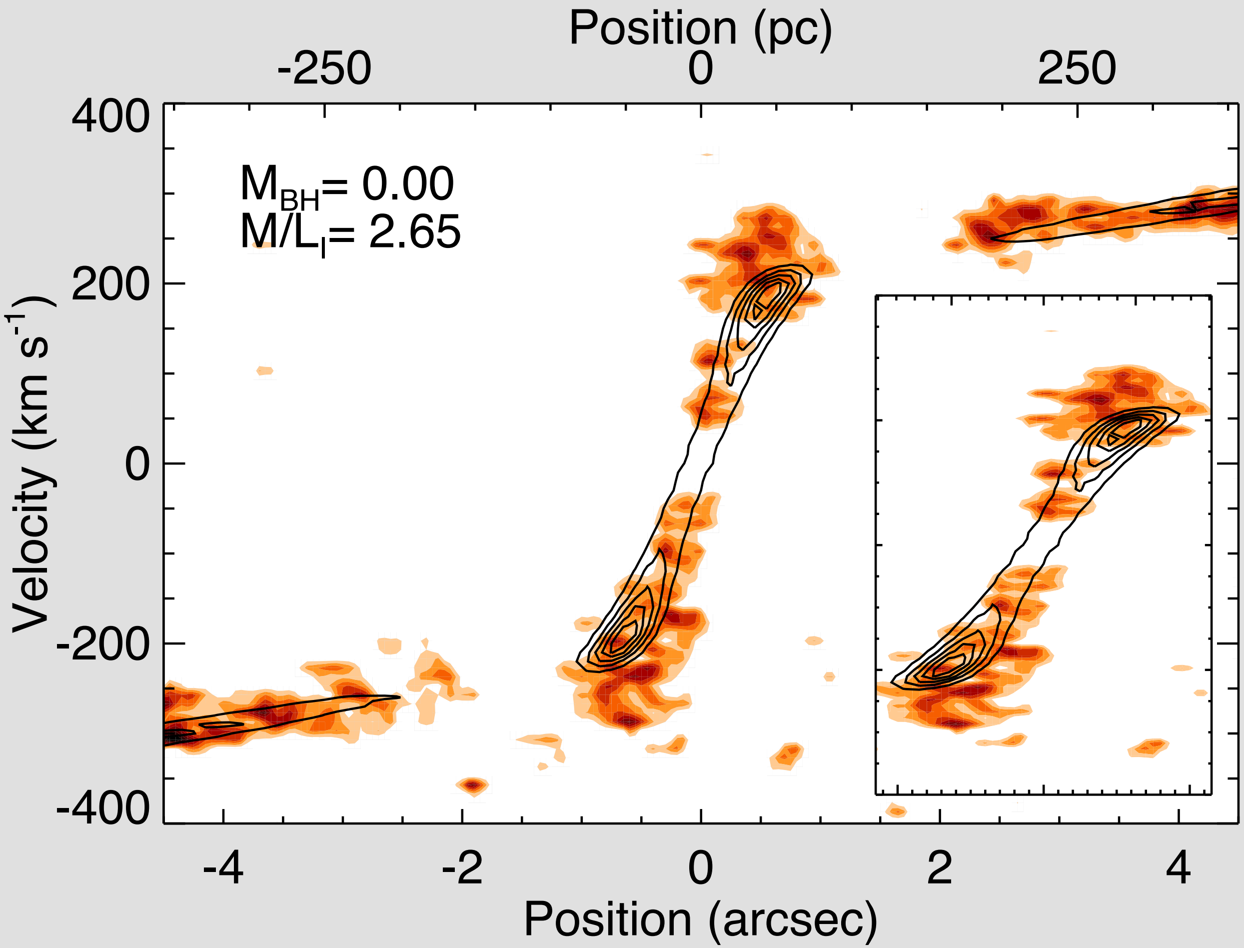


Davis et al., 2013, Nature, 494, 328-330

# Dynamical black-hole mass measurements with molecular gas

**No Black Hole (too cold!)**

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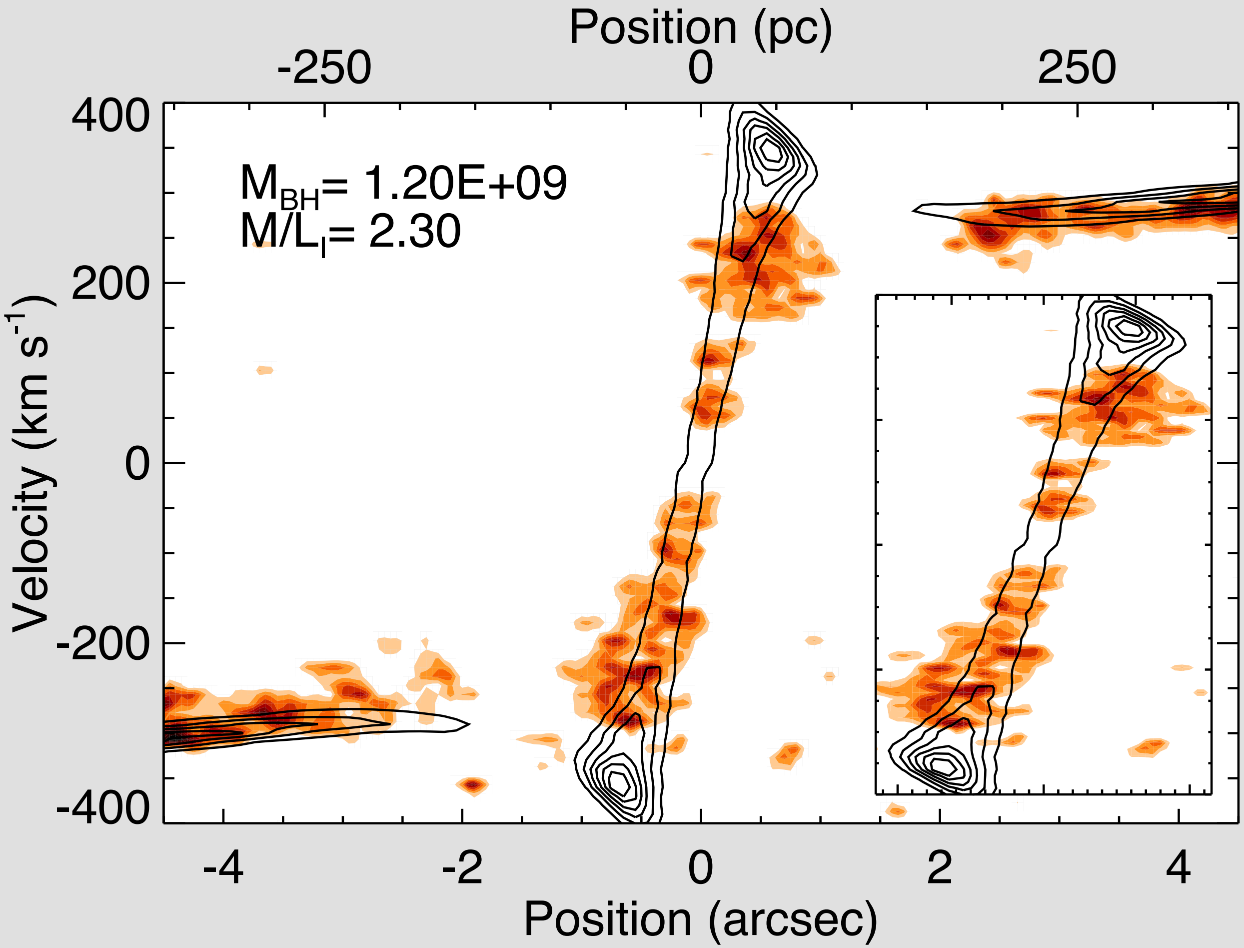
# Dynamical black-hole mass measurements with molecular gas

**Massive Black Hole (too hot!)**

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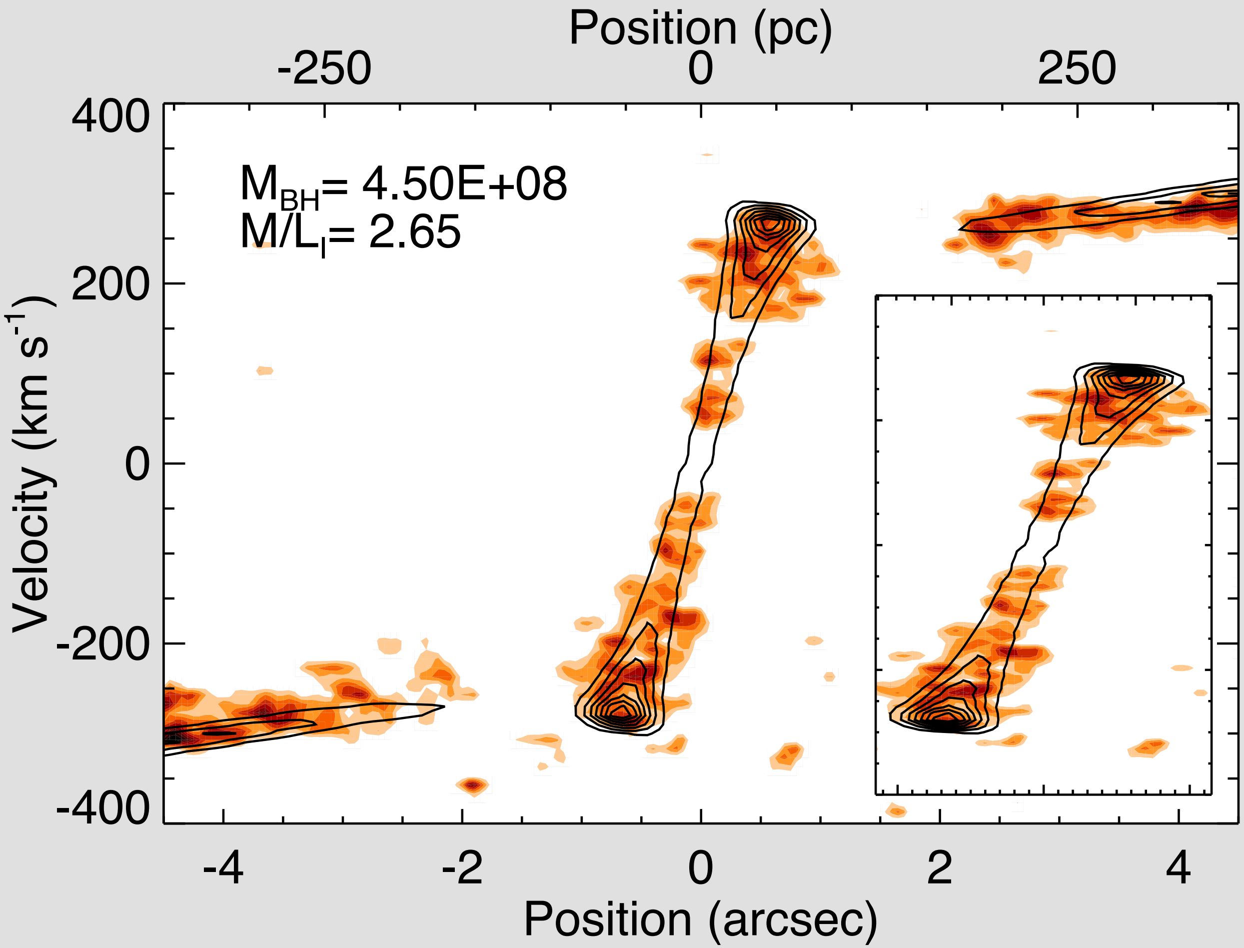
# Dynamical black-hole mass measurements with molecular gas

**Best fit Black Hole (just right!)**

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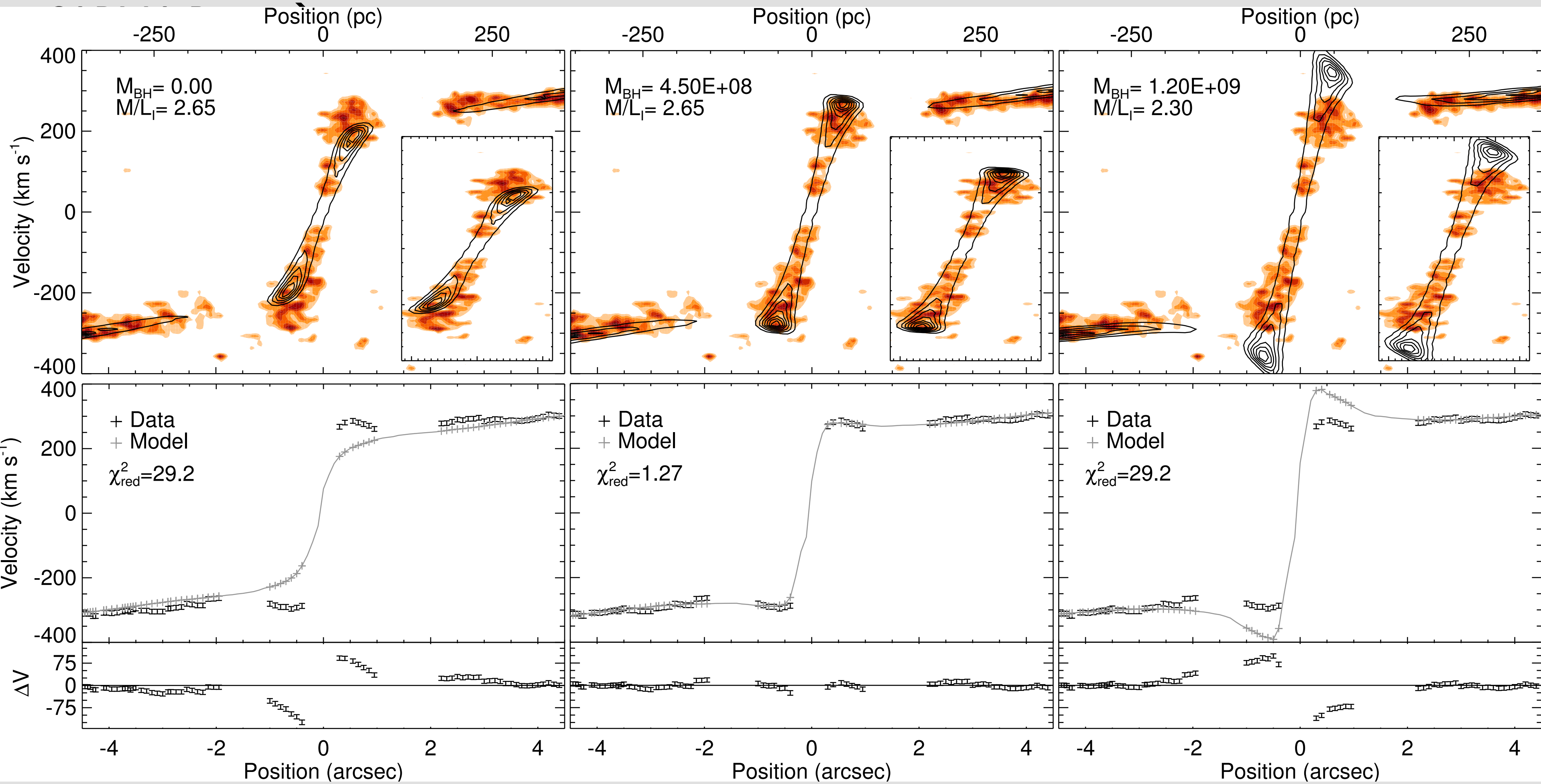


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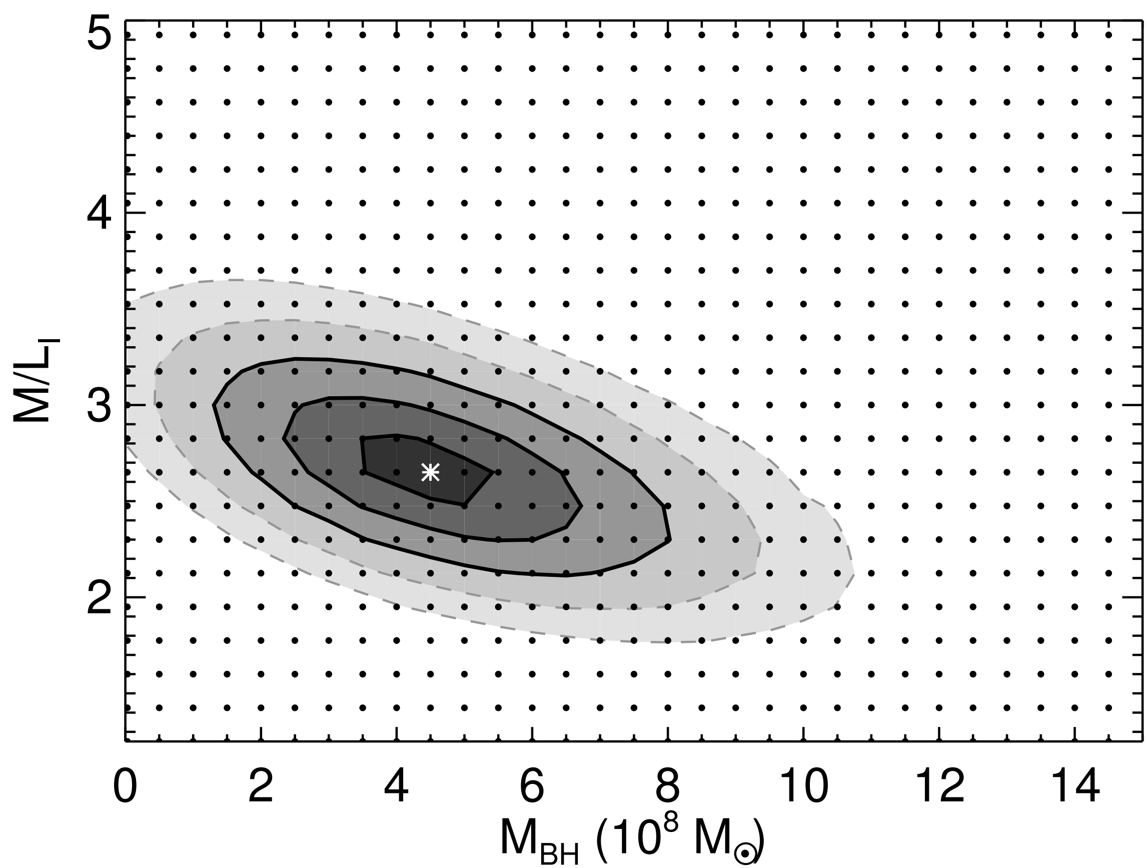



**Best fit BH (w/ 3 sigma errors):**

$M_{BH}$= $4.5^{+4.20}_{-3.09}\times10^8$ $M_{sun}$

**Agrees with M-σ relation**

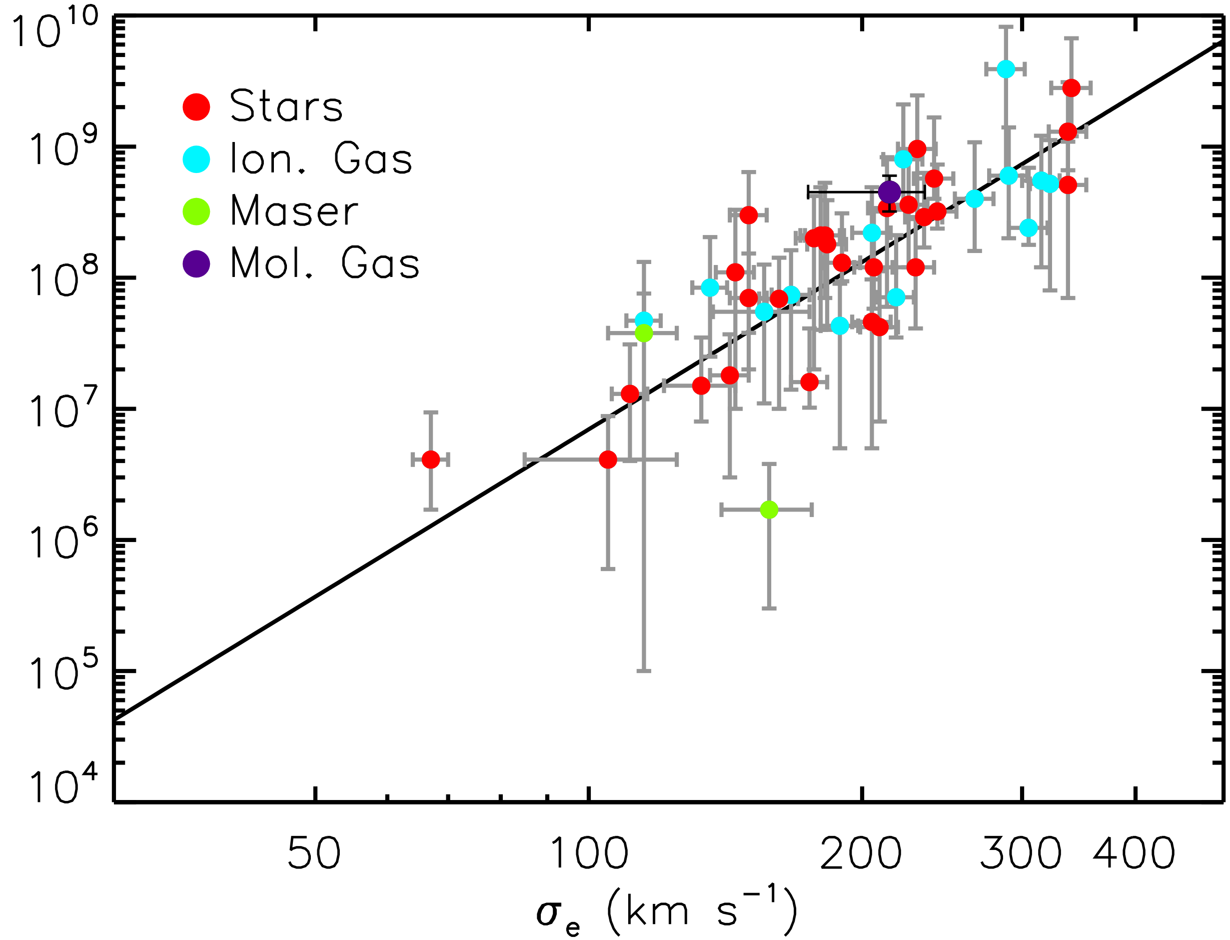
**Best fit M/L:**

$M/L_I$= 2.6±0.55 $M_{sun}/L_{sun}$

**Fits with M/L estimate from stellar pops of 2.6$M_{sun}/L_{sun}$**

Davis et al., 2013, Nature, 494, 328-330

# Dynamical black-hole mass measurements with molecular gas




Davis et al., 2013, Nature, 494, 328-330

**Errors smaller than average of any other technique!** **(e,g, Gould et al., 2013).**
**However- need to be careful with systematics**

# Dynamical black-hole mass measurements with molecular gas

## This technique will be very useful in the ALMA era:

- With full ALMA resolving the SOI of NGC4526 will be possible to 1000 Mpc (z=0.35!)
- A Milky-Way mass black-hole will be resolved out to 50 Mpc!
  - → Thousands of galaxies accessible!
  - → … over the whole range of the **M-σ relation**
  - → … with the same technique (reducing systematic uncertainties)
- Short integration times (CARMA=50 hours → ALMA=20 minutes…)

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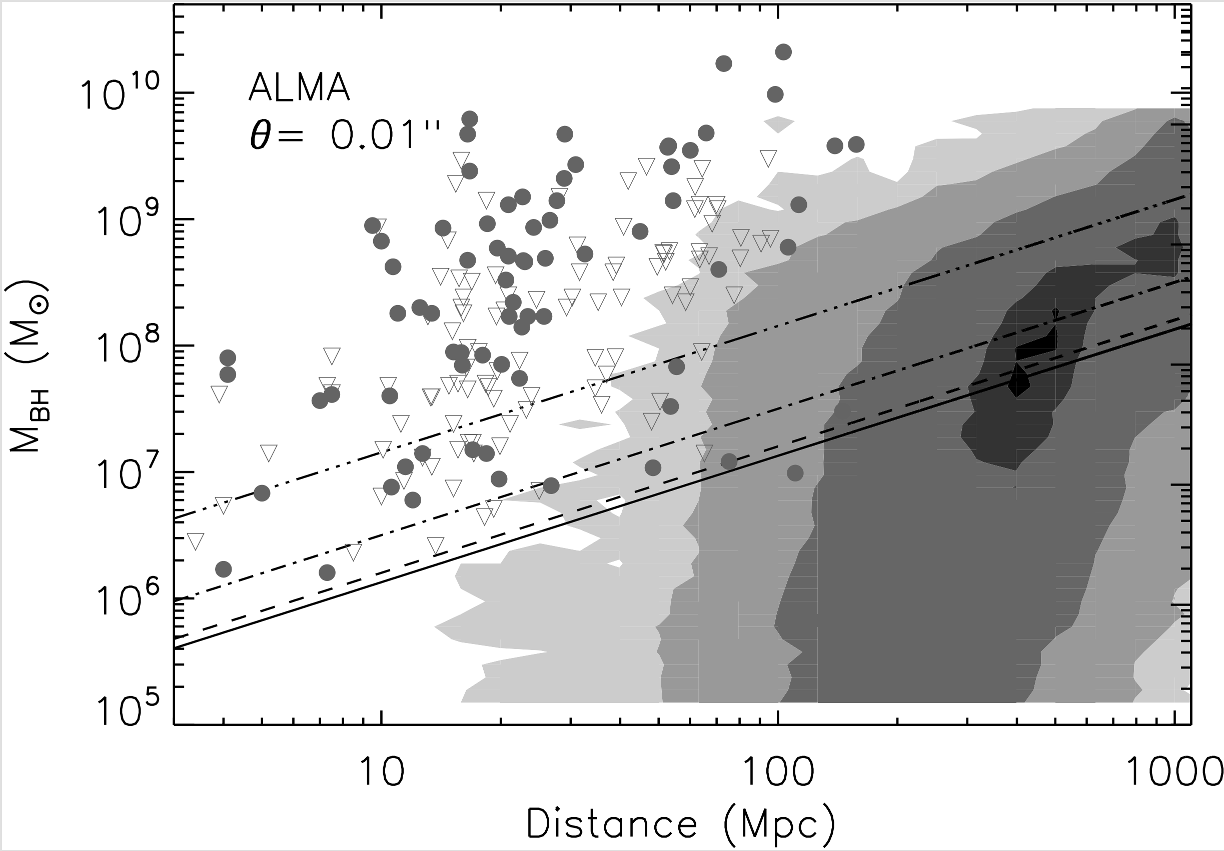
# Dynamical black-hole mass measurements with molecular gas

**How many galaxies are accessible?**

- Invert M-Sigma relation using SDSS velocity dispersion catalogue and redshifts
- Assuming ALMA resolution
- Also shown are the known black hole masses and upper limits - essentially all re-measurable → error checking




**~35,000 galaxies accessible! → revolutionary!**

# Dynamical black-hole mass measurements with molecular gas

## Whats next?

We need **WISDOM!!**

**mm-Wave Interferometric Survey of Dark Object Masses**

Aims:

- Estimate BH masses in accessible targets
- Calibrate techniques
- Identify targets for ALMA follow-up

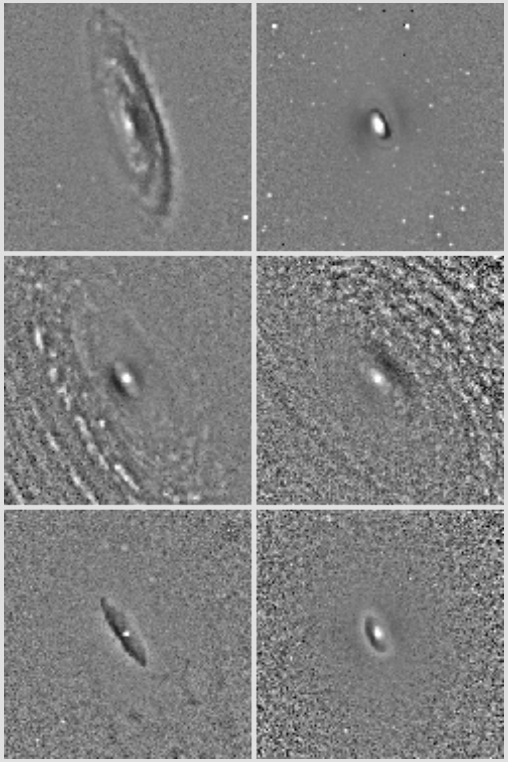
Data already requested/obtained

**Target Selection:**

- IRAM-30m fluxes – 30 objects **(proposal accepted)**
- APEX fluxes – 20 objects **(time allocated)**
- CARMA mapping **(50 hours of time allocated this semester)**

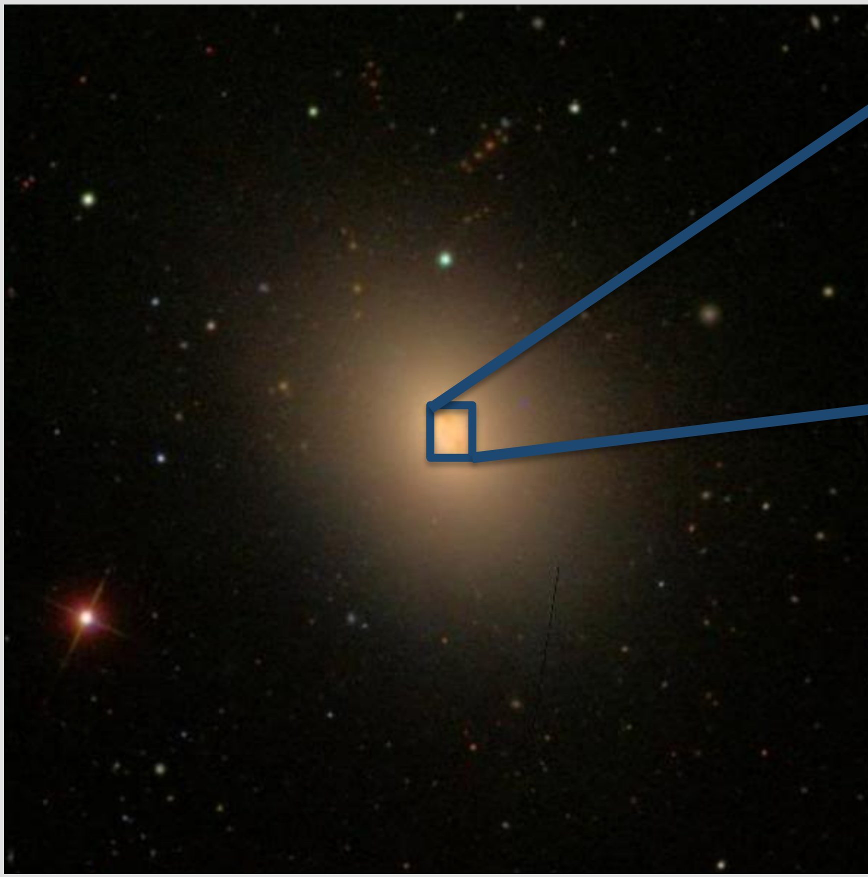
**Mass measurements:**

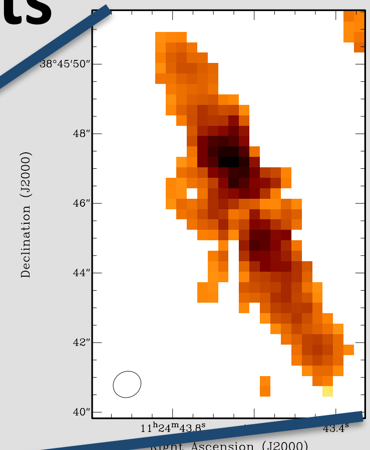
- IRAM PdBI – one object **(time allocated)**
- CARMA – two objects **(time allocated)**
- ALMA – three objects (proposal submitted)



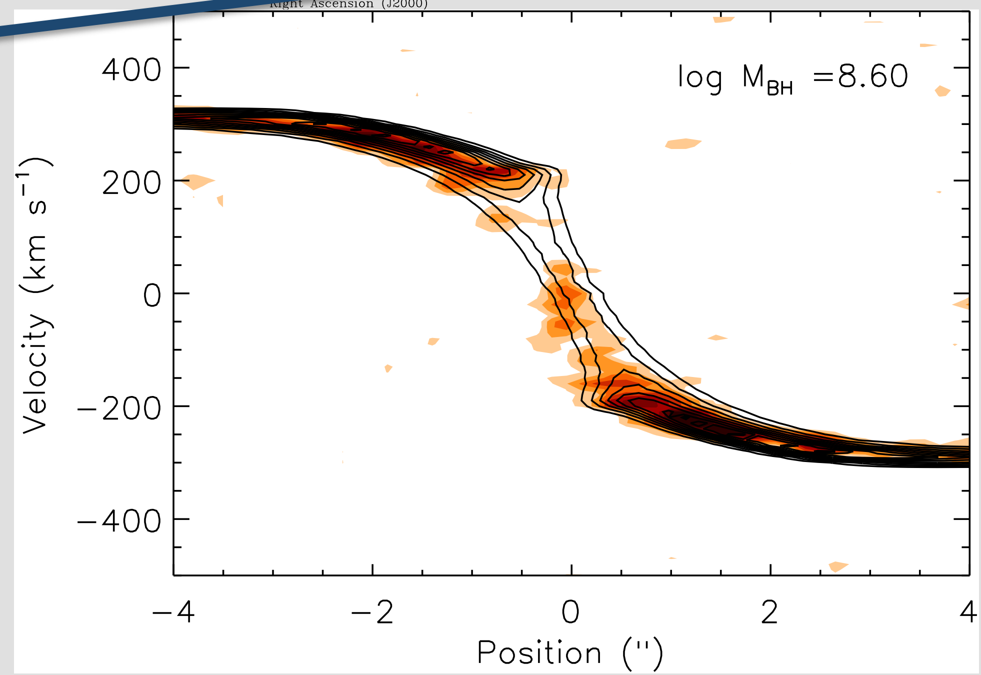
# Dynamical black-hole mass measurements with molecular gas

## Sneak Peak: first WISDOM results






**CARMA observations reveal a ~4x10$^8$ Msun SMBH!**




Field (fast-rotating) elliptical

Preliminary- watch this space!

# Dynamical black-hole mass measurements with molecular gas

## Conclusions:

- Molecular gas is a good kinematic tracer (in spirals+ETGs)

- You can estimate BH masses with molecular gas if you have enough resolution
- Errors are pretty low

- It is possible to resolve the SOI in some nearby galaxies with current instruments

**The Future:**

- **ALMA!! Many hundreds of BH masses potentially measurable in short observations!**
  - → Thousands of galaxies accessible!
  - → … over the whole range of the **M-σ relation**
  - → … with the same technique (reducing systematic uncertainties)

Use the **KinMS** tool for your research! http://www.eso.org/~tdavis

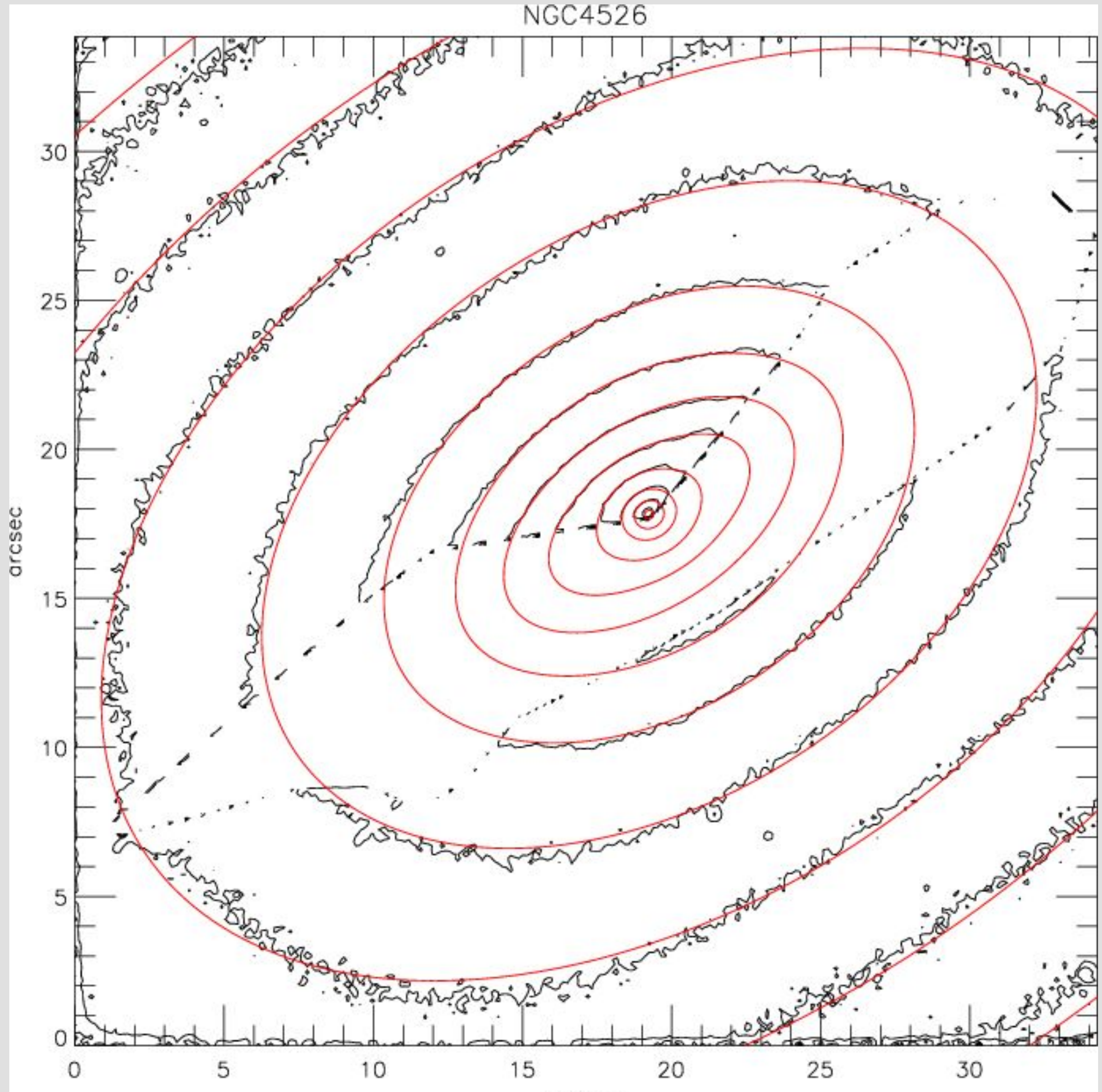

Thanks for Listening!
Any questions?
CARMA in winter: mmarray.org

# Dynamical black-hole mass measurements with molecular gas

**Dust disk in NGC4526**

- Dust contamination present
- Simple disk morphology
- Easily masked
- MGE fit ignoring these sectors is good

→ Should give a good mass model

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