Title: Stellar Dynamical Measurements of the Black Hole in M87 and Friends

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Abstract: Stellar dynamical measurements of black hole masses have become the de facto standard method. I will give a brief review of how this measurement method works, along with arguments for its overall reliability and caveats. Then I will turn my attention to the case of the black hole in M87. The black hole is undeniably large â€“ billions of solar masses â€“ but has a stellar dynamical mass measurement in disagreement with gas dynamical mass measurements at about the 2 sigma level. I will discuss potential systematic uncertainties in both measurements and avenues to reconciling the discrepancy.

The stellar dynamical mass of the BH in M87 and friends

Kayhan Gültekin
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Karl Gebhardt, Joshua Adams, Douglas Richstone, Tod R. Lauer, S. M. Faber, Kayhan Gültekin, Jeremy Murphy, & Scott Tremaine (2011, ApJ, 729, 119; arXiv:1101.1954)

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The BH in M87 has $GM/c^2D = 3.6 \pm 0.2$ mircoarcsec

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And you should trust our mass estimate

- Understand how stellar dynamical method of measuring SMBH masses works.
- See how this method works for M87.
- Understand the differences between the results of this method and that of gas dynamical measurement. (Jonelle Walsh's talk tomorrow.)

Supermassive BH masses are important in and of themselves.

- Eddington limit (L_{Edd}) and accretion properties
- Spin angular momentum ($a = Jc/GM^2$)
- Innermost Stable Circular Orbit
    - $R_{\mathrm{ISCO}} = 6\ GM/c^2\ (a = 0)$
    - $R_{\mathrm{ISCO}} = GM/c^2\ (a = 1)$
    - $R_{\mathrm{Schw}} = 2\ GM/c^2$

There is more than one way to measure SMBH masses

- Sgr A*
- Stellar dynamical
- Megamasers
- Gas dynamical

} Primary

- Reverberation mapping

} Secondary*

- Single epoch

} Tertiary

How everyone measures black hole mass:

$$v^2 = \frac{GM}{r}$$

How everyone measures black hole mass:

$$M = \frac{v^2 r}{G}$$

Step 1: Image galaxy

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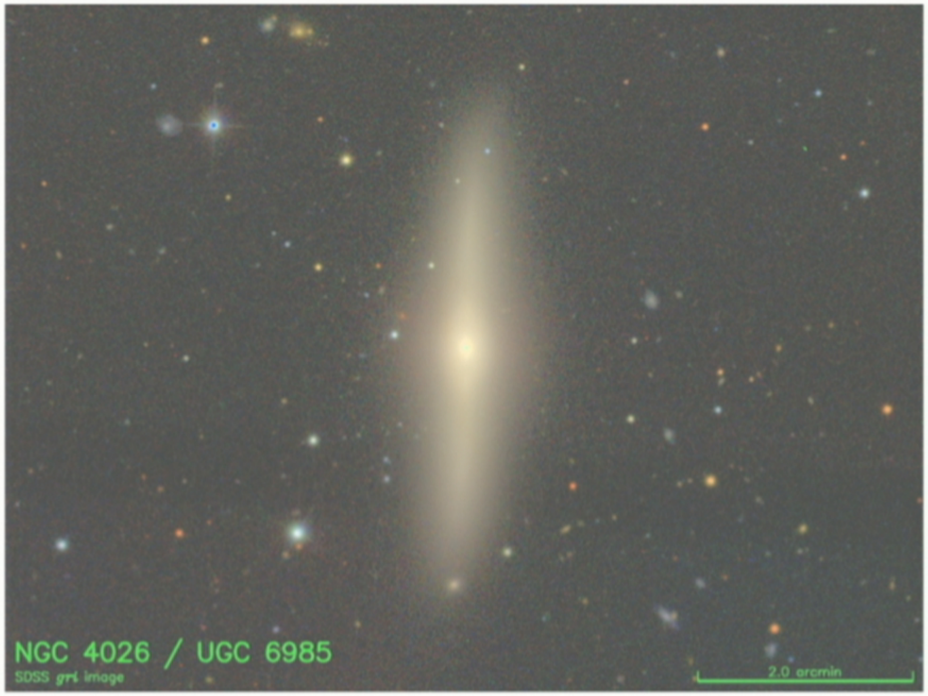

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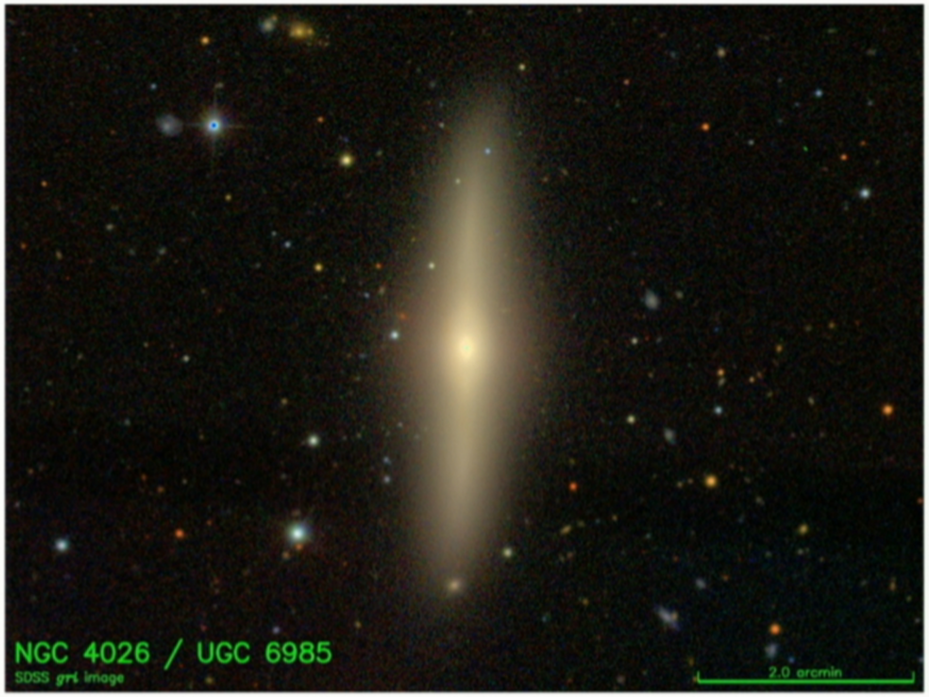

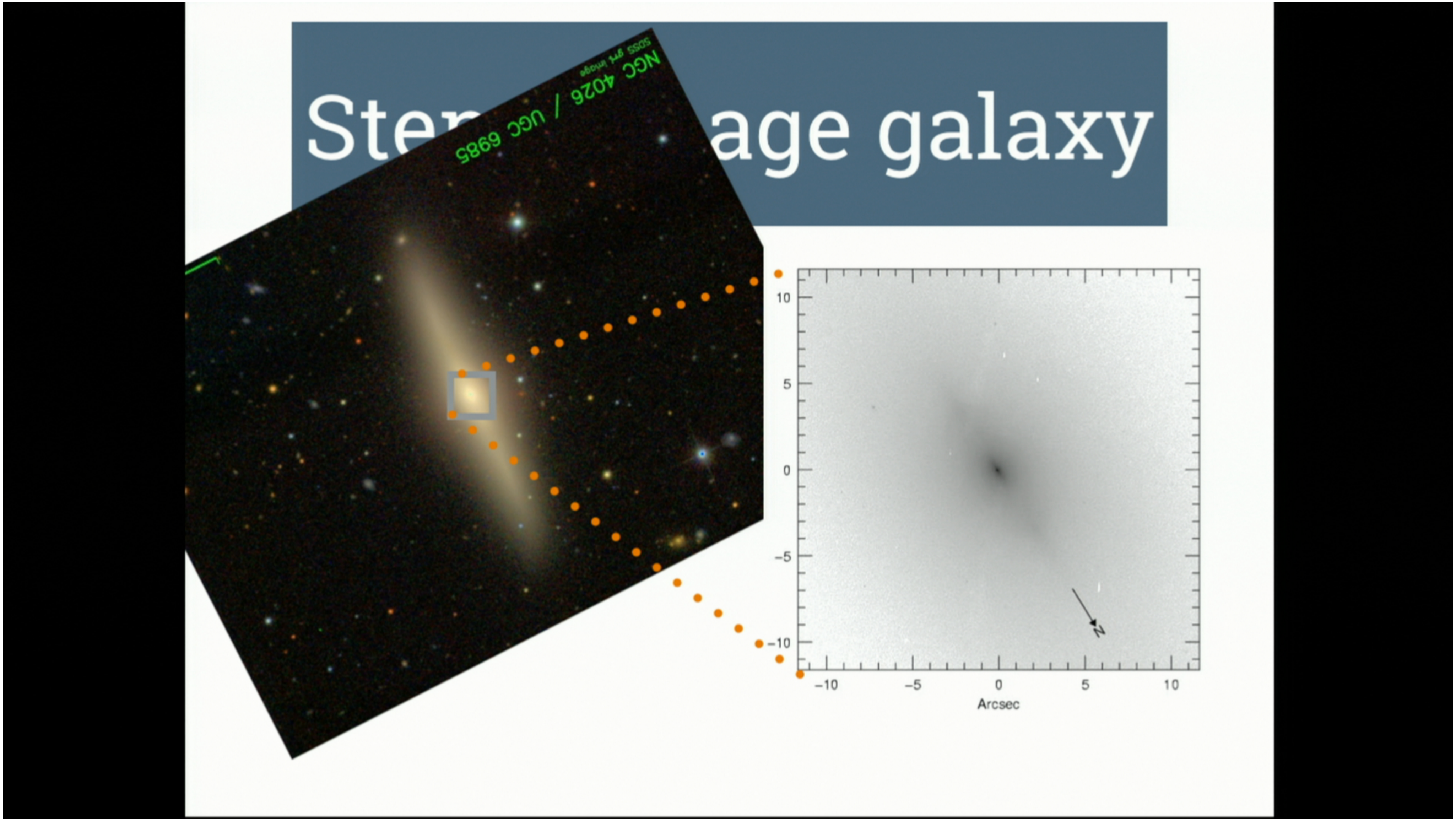
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age galaxy
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Step 2: Turn surface brightness into luminosity density

- Requires knowledge of geometry.
- Requires knowledge of viewing angle.

Step 2: Turn surface brightness into luminosity density

Assume axisymmetry

- Requires knowledge of geometry.
- Requires knowledge of viewing angle.

Parametrize inclination

Step 3: Turn luminosity density into stellar mass density

- Requires knowledge of M/L ratio.

Step 3: Turn luminosity density into stellar mass density

Parametrize value

Assume constant

- Requires knowledge of M/L ratio.

Step 4: Add other sources of mass

Assume a form and *parametrize* the values

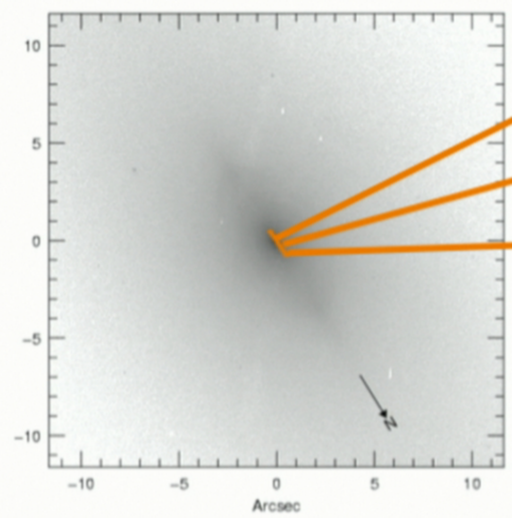
- Dark matter halo
- Black hole

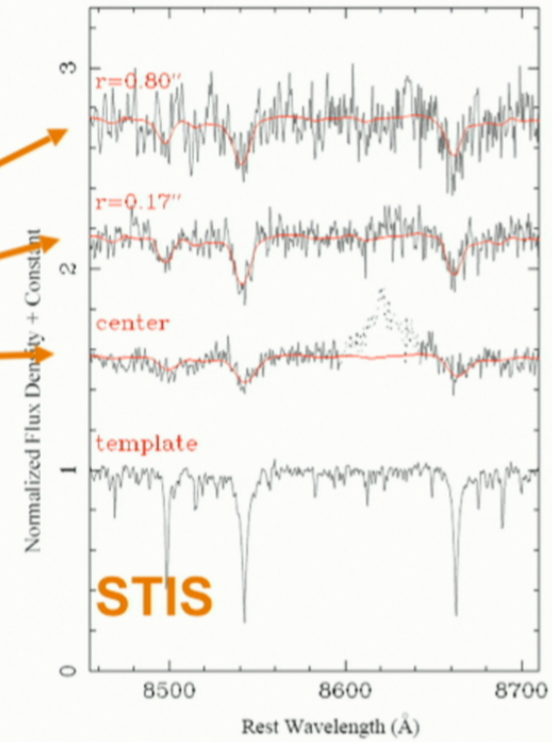
Parametrize value

Step 5: Solve Poisson's equation to get gravitational potential

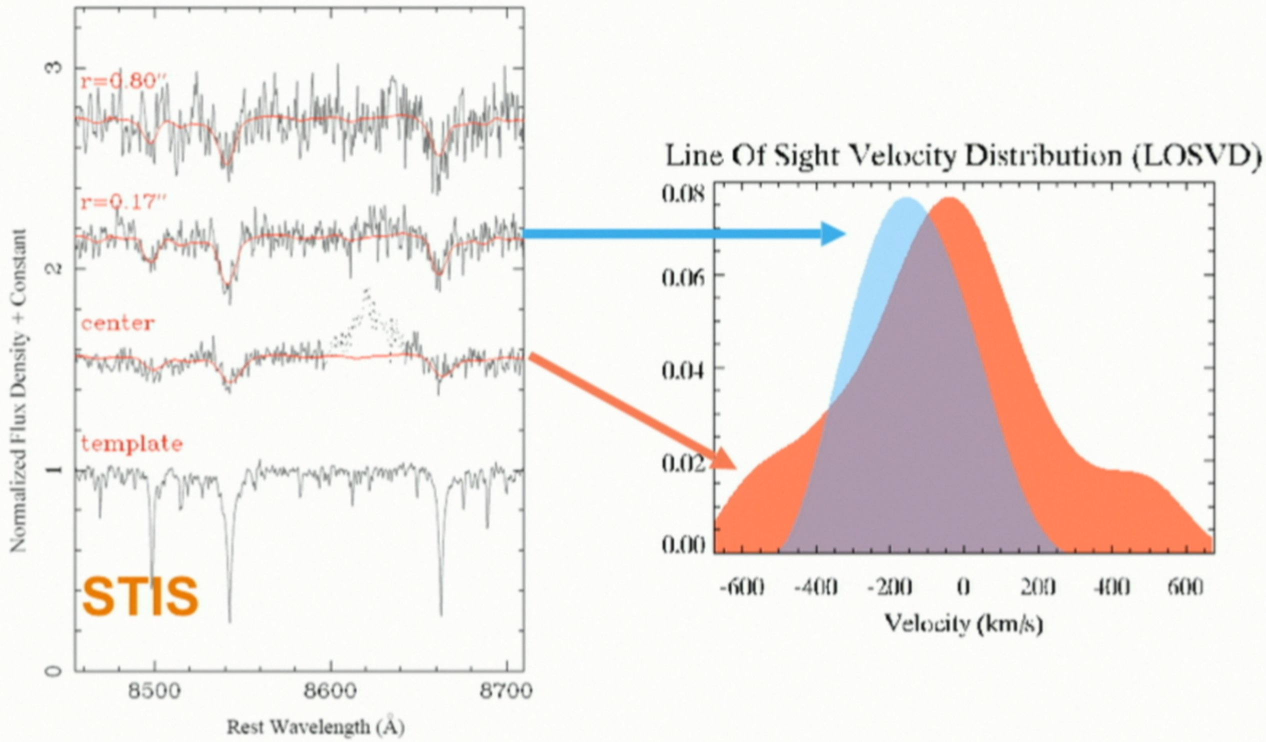
$$\nabla^2 \Phi = 4\pi G \rho$$

Step 6: Get spectra of the galaxy

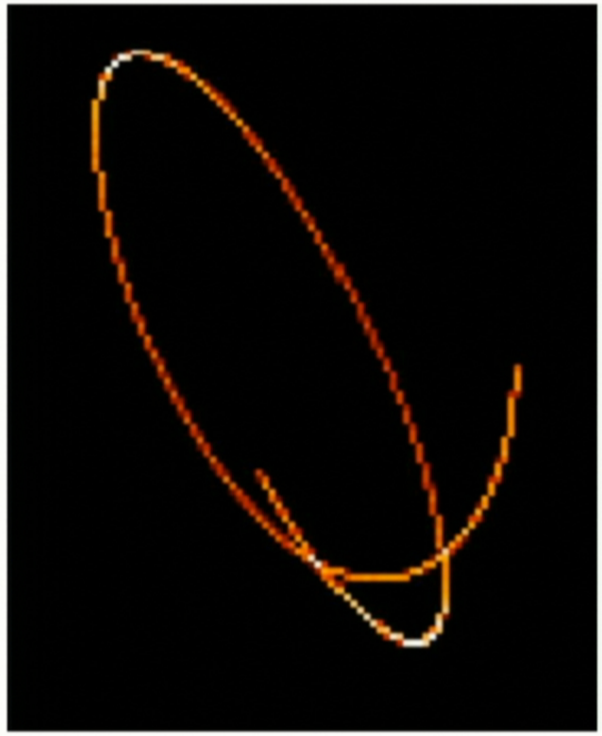




Step 7: Turn spectra into line-of-sight velocity distributions



Step 8: Integrate orbits of representative stars in the potential



van den Bosch+ 08

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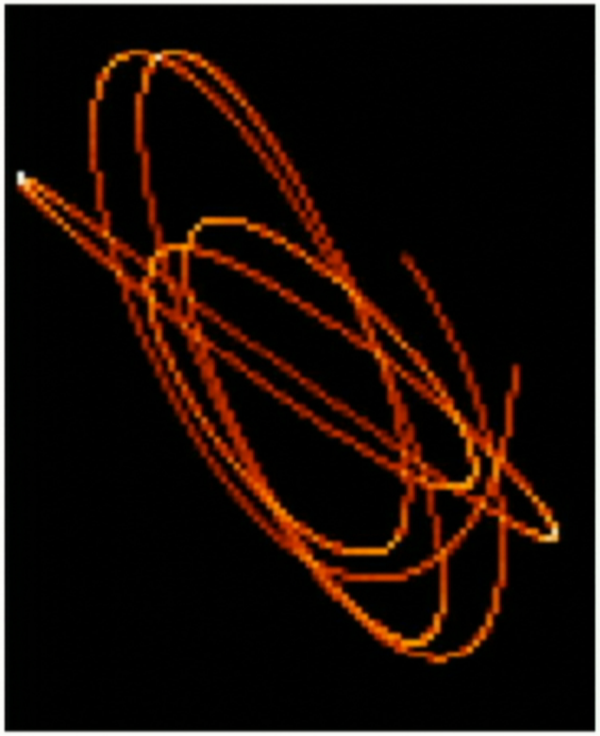

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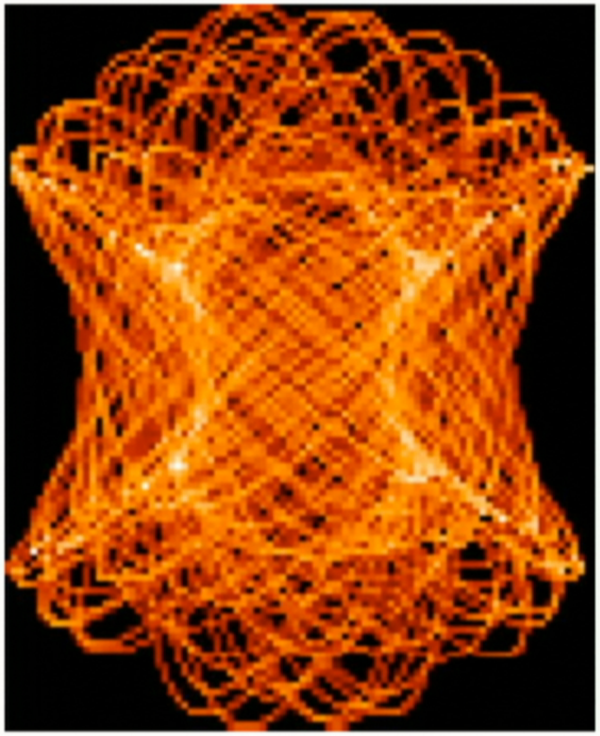

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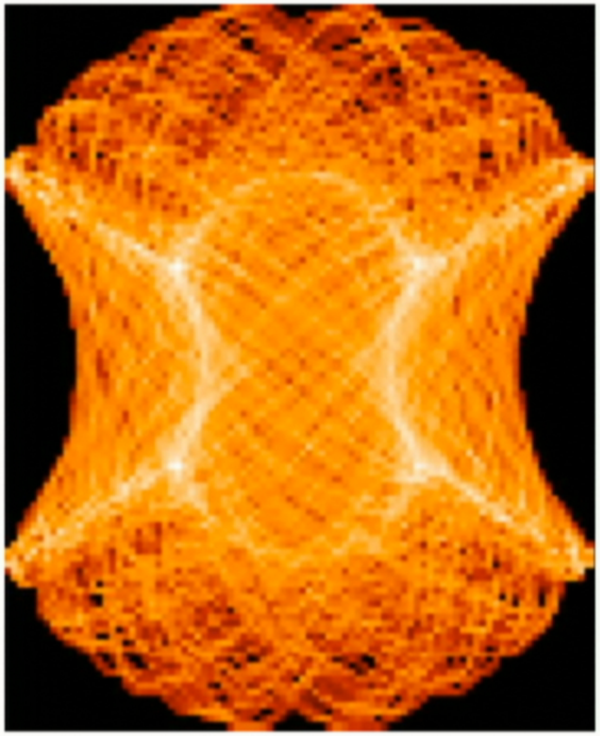
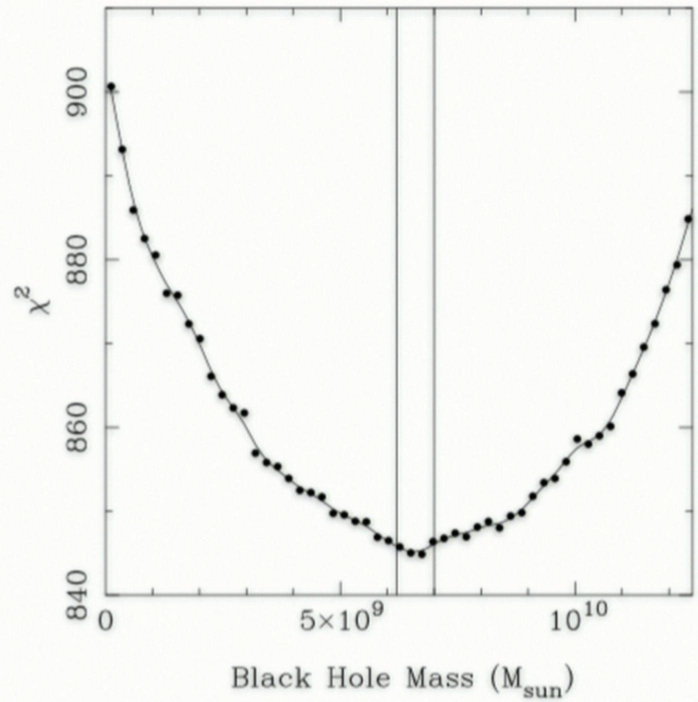


van den Bosch+ 08

Step 9: Having kept track of how much light and line-of-sight velocity each orbit contributes in each spatial bin, find the set of non-negative weights that most closely matches the observed LOSVD, subject to the condition that it reproduces the observed surface brightness.

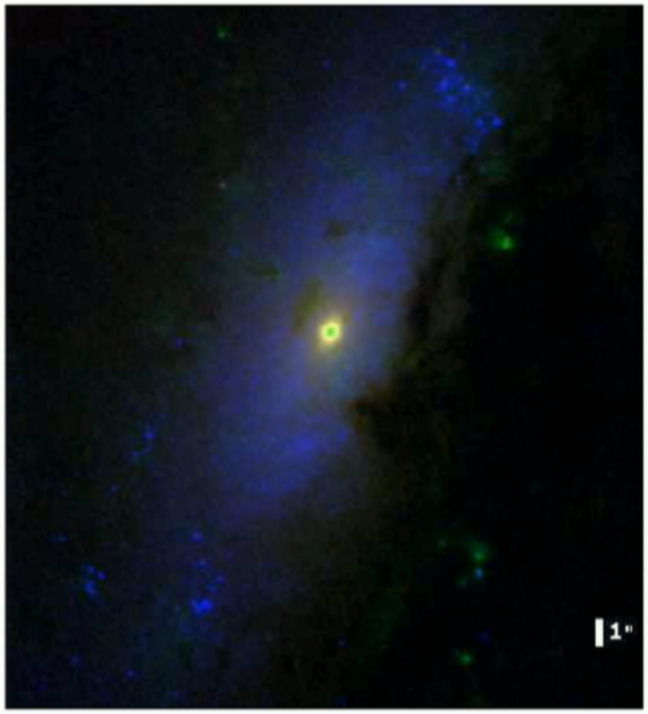
- The Schwarzschild orbit library method.
- Want lots of orbits.
- Self-consistent.

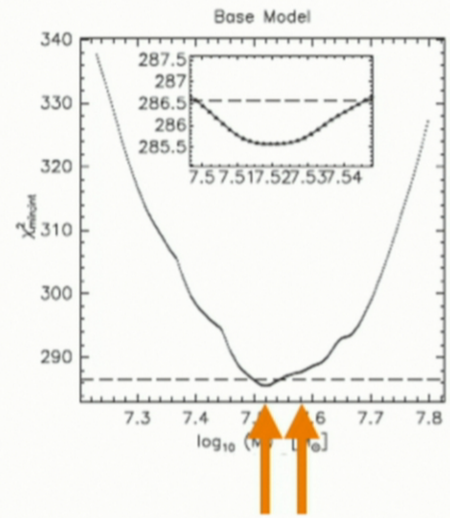
Step 10: Repeat until you cover parameter space.



Gebhardt+ 2011

We know this method is reliable because we have tested it against the maser mass in NGC 4258.

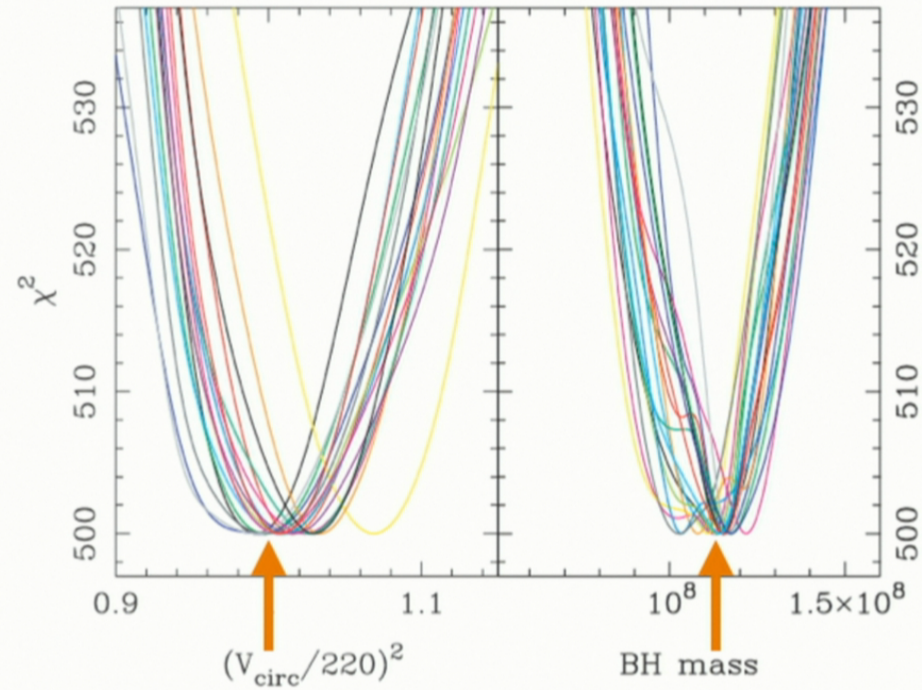




Siopis+2009 stellar dynamical

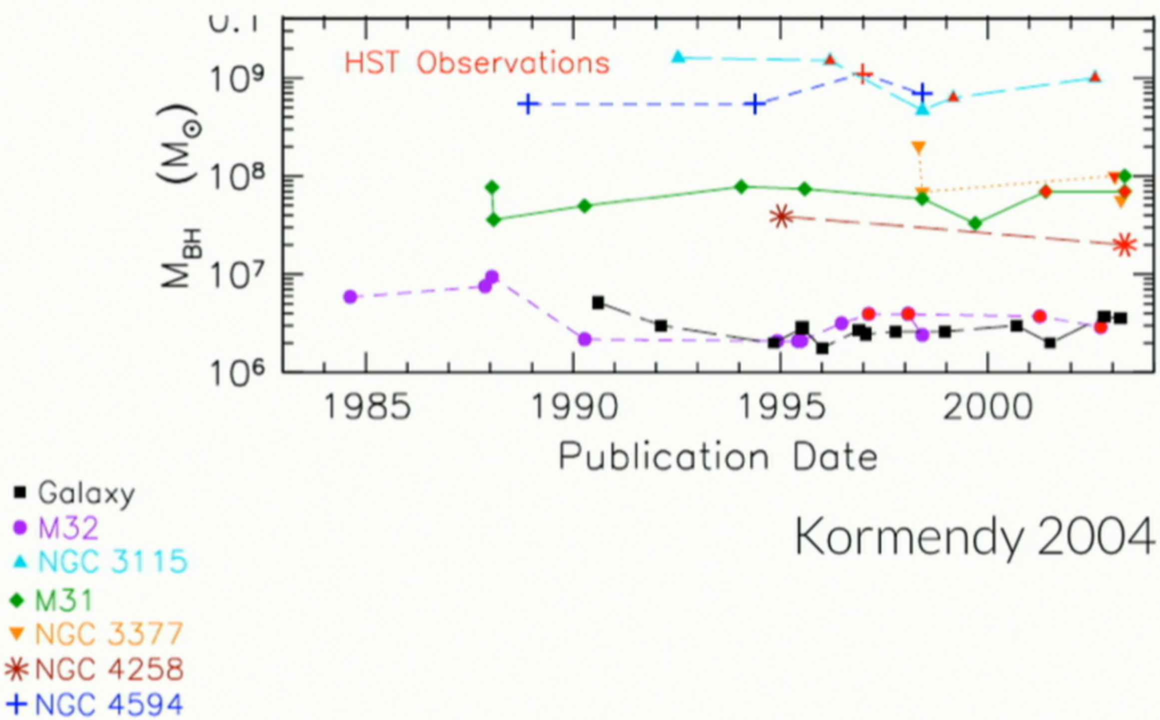
Herrnstein+ 2005 maser dynamical

We know it's reliable because we've tested it against simulated data sets.



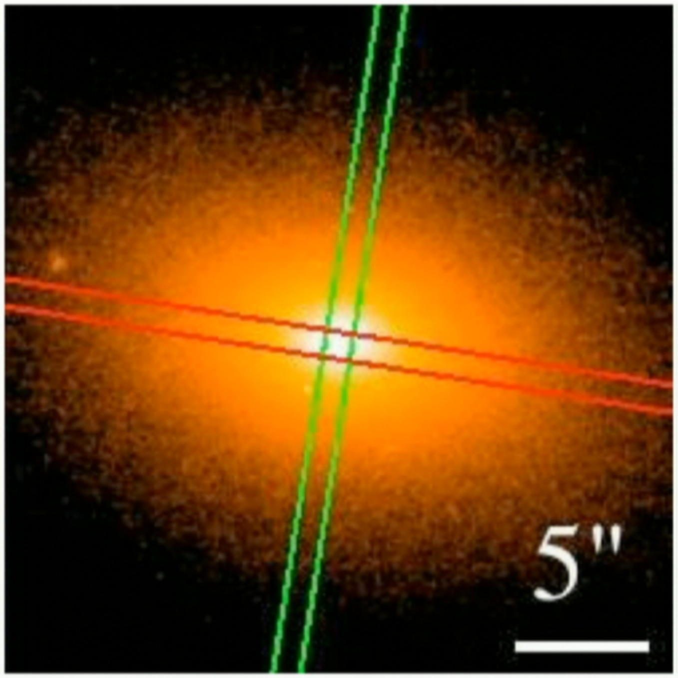
Siopis+2009

We know it's reliable because it can be repeated on different data sets of the same galaxy using different codes and get consistent results.

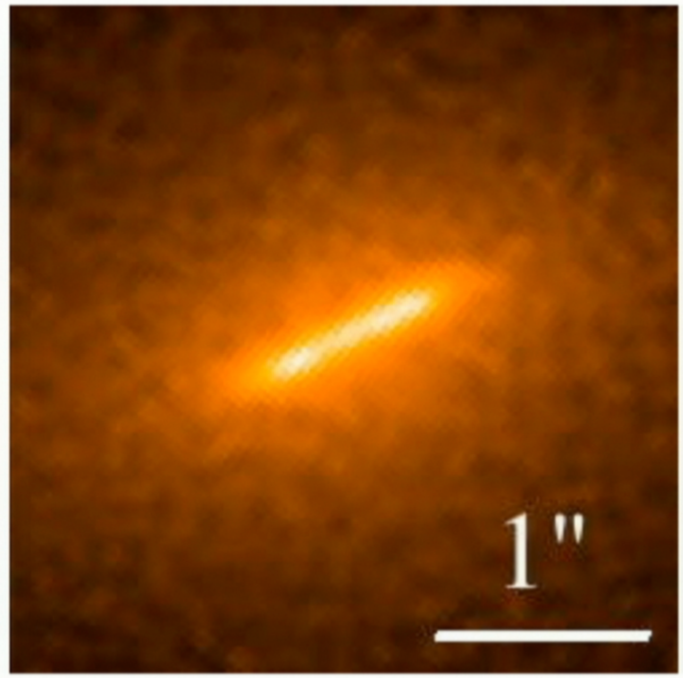


Kormendy 2004

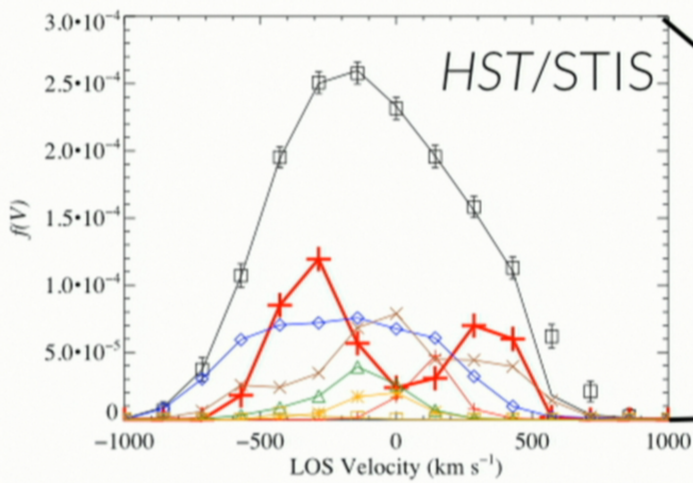
NGC 3706

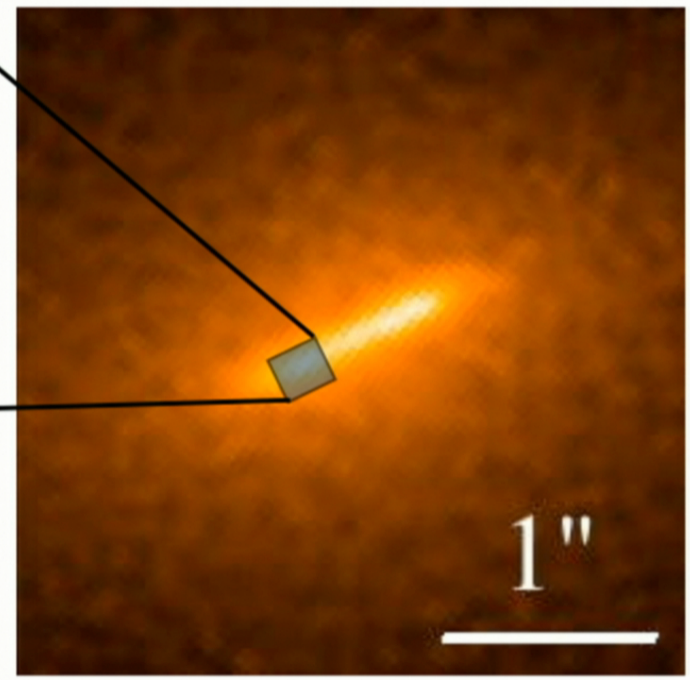


KG+ (2014)



N3706 has a stellar ring that rotates in both directions





Velocity

KG+ (2014)

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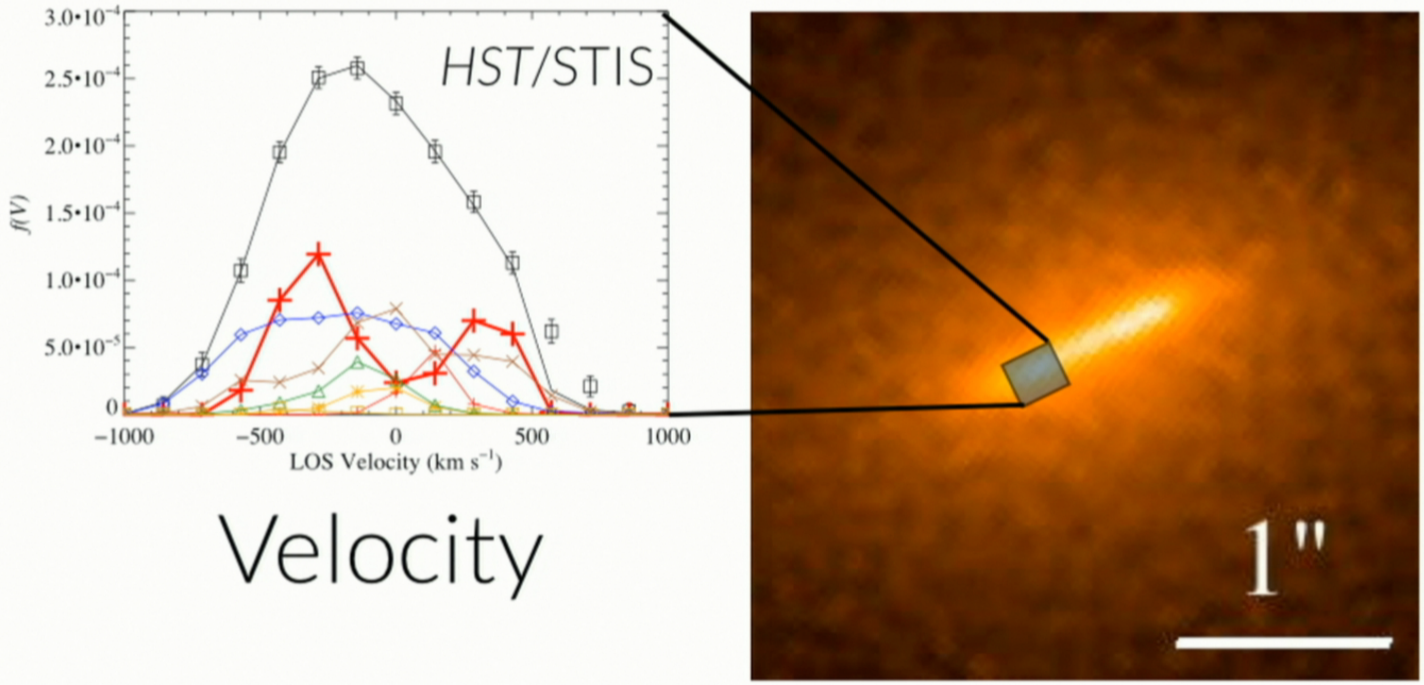
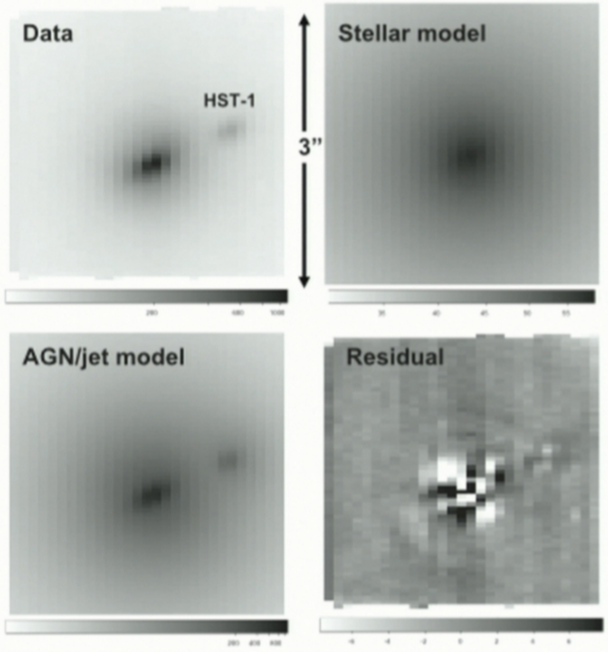


Velocity

KG+ (2014)

M87 Data

- Imaging:
  - Gemini AO + *HST* (Lauer +92) + ground (Kormendy+09)
- Spectroscopy:
  - Gemini NIFS AO
  - SAURON (Emsellem+ 2004), VIRUS-P (Murphy+ 2011)



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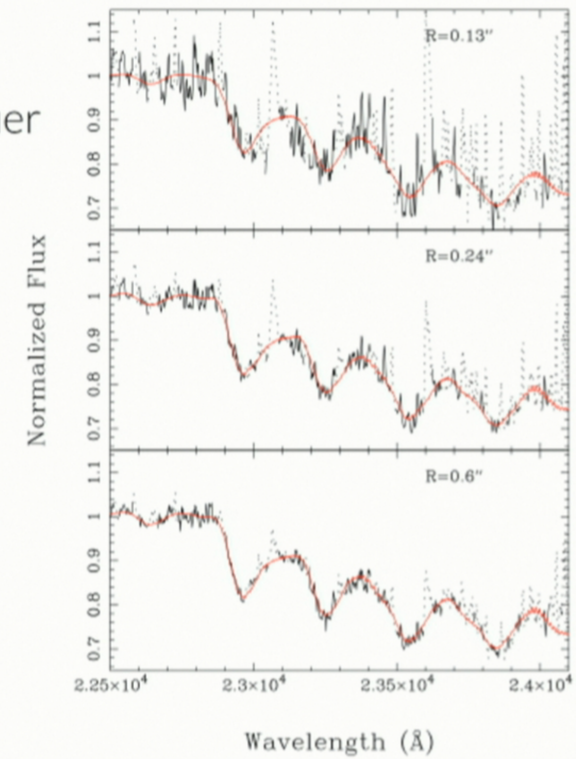
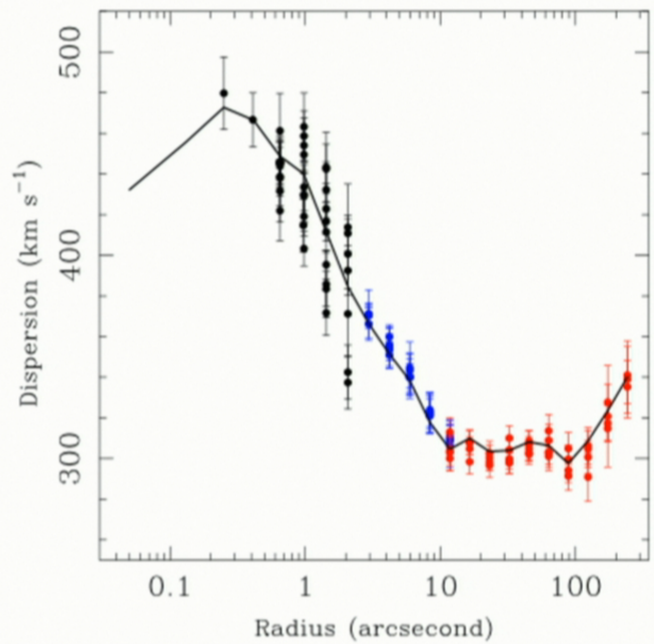
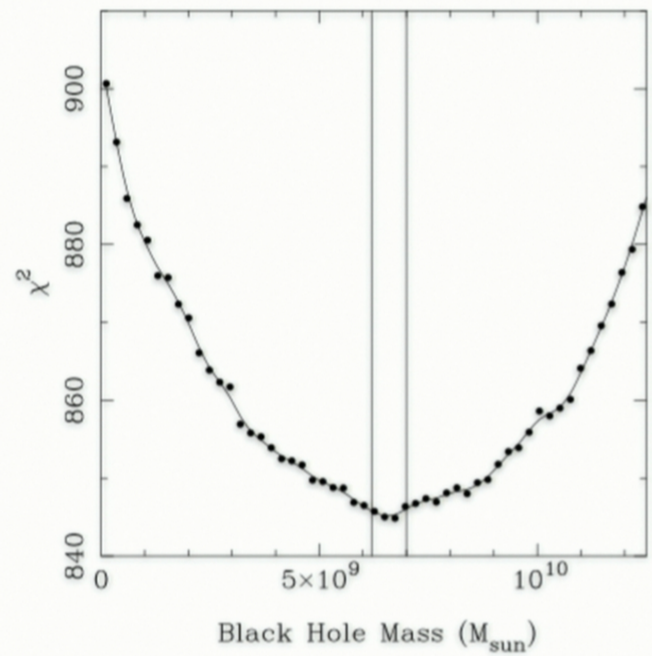


M87 results



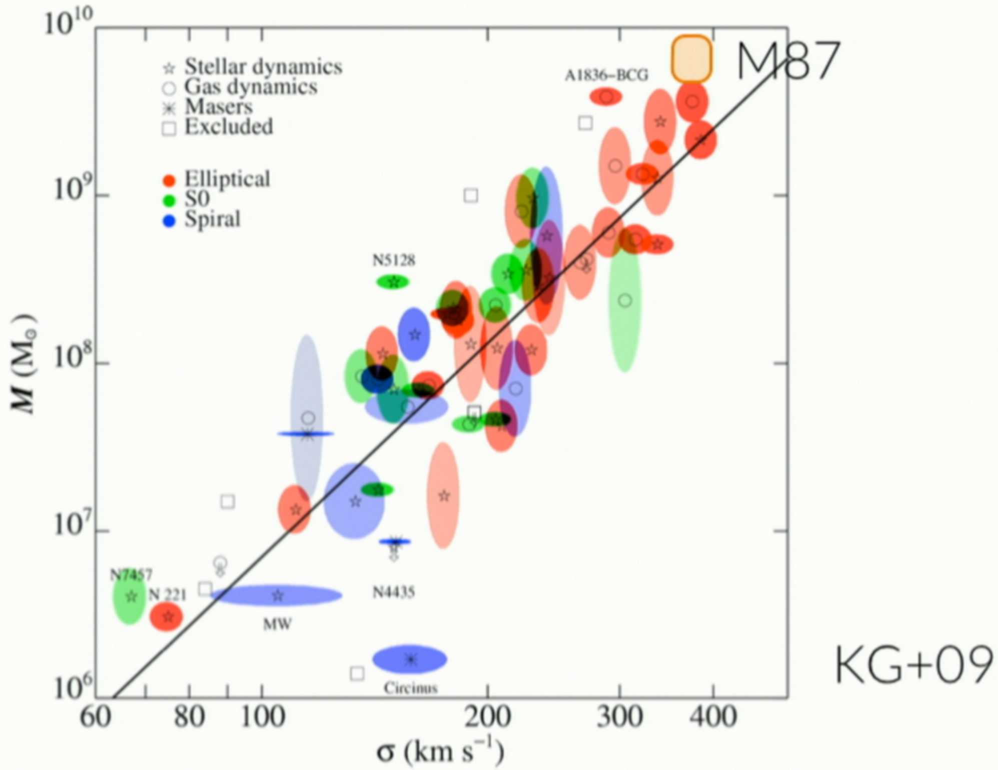


Gebhardt+ 2011

M87 is not strongly dependent on the assumptions made

- Sphere of influence ($r = GM/\sigma^2$) is so well resolved, that M/L doesn't really matter.
- Inclination was varied and doesn't make much difference.
- Axisymmetry (or close enough) at center is likely.

Is M87 an outlier?



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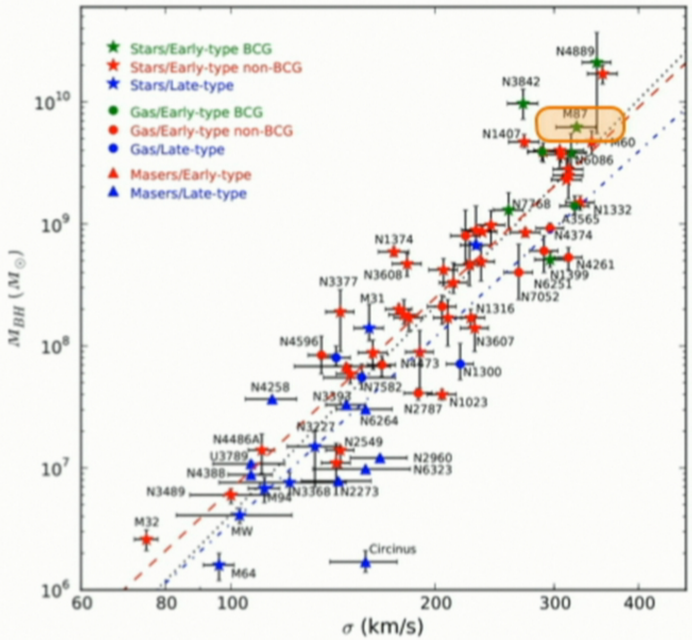
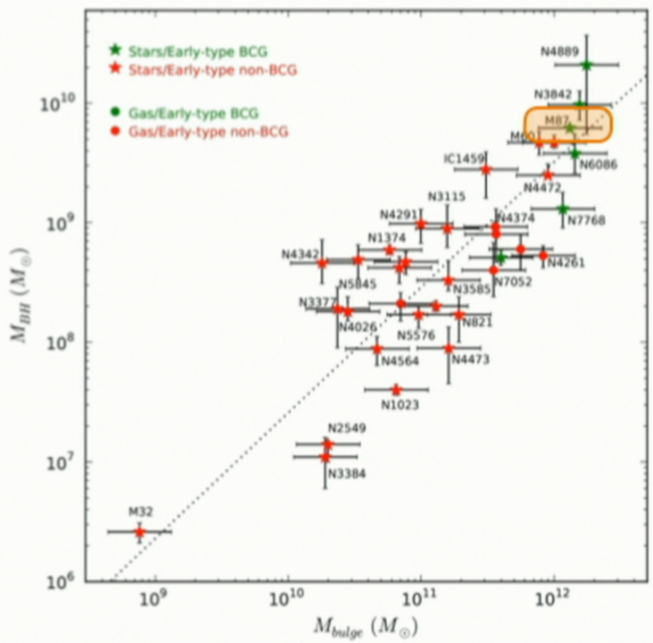


McConnell & Ma13

Is M87 an outlier?



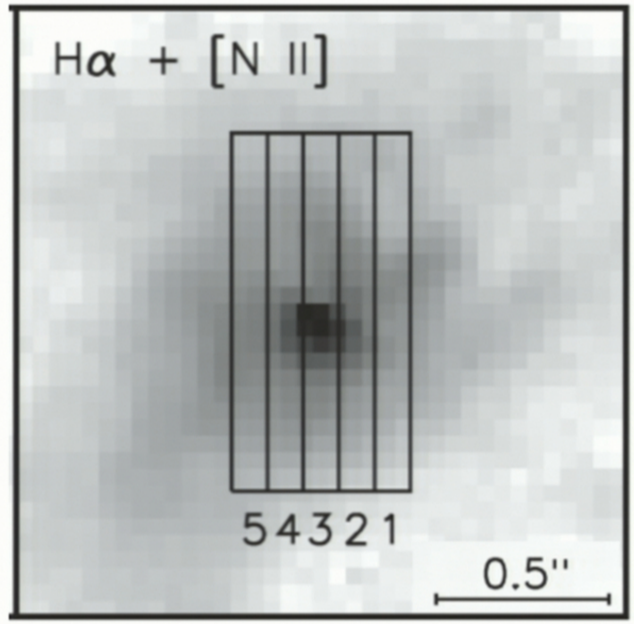
McConnell & Ma13

The stellar dynamical mass is 2 × the gas dynamical

- If we take the stellar dynamical mass as correct, what could have gone wrong with the gas dynamical mass?
- My guess is inclination is wrong, possibly due to spiral structure in the gas disk.
- Change inclination to 30° (instead of 42°) and the answers agree*. Jet is at 14°, but that is probably a non-sequitur.

My reservations about the gas dynamical mass

- Need undisturbed, well-ordered gas disk.
- Need to know inclination.



Walsh+ 2013

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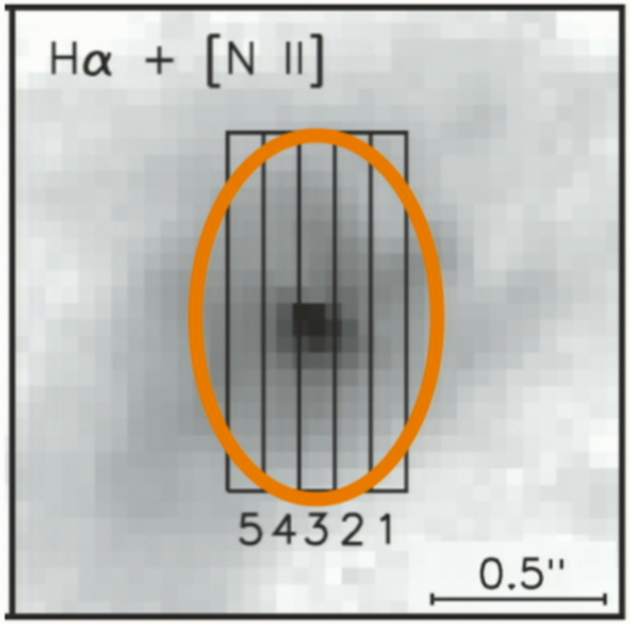

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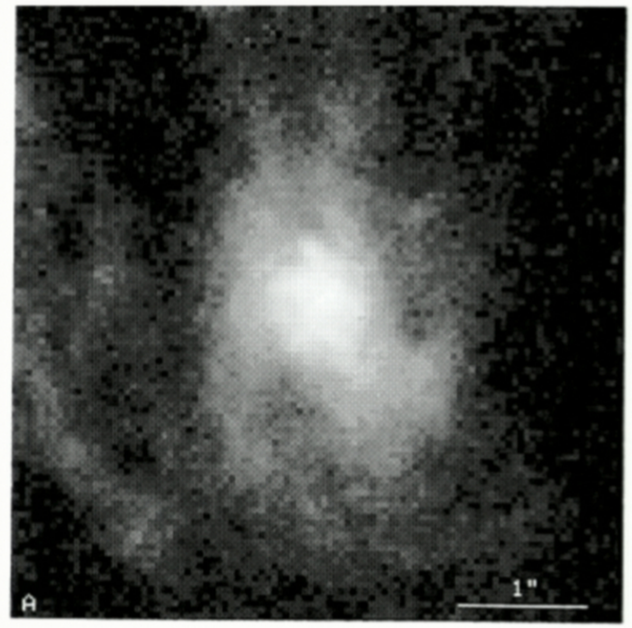

Ford+ 1994

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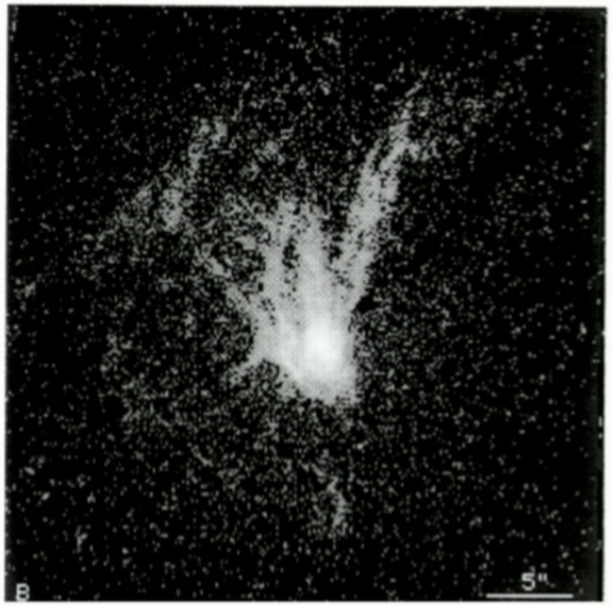

Ford+ 1994

The stellar dynamical mass of the BH in M87 is $(6.6 \pm 0.4) \times 10^9\ M_\odot$

- Based on reliable, tested method.
- Robust to assumptions made.
- Not an outlier when compared to similar galaxies.
- May be able to explain discrepancy with more face-on gas disk.