Title: Gas Dynamical Black Hole Mass Measurements for M87

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Abstract: M87 is one of the most luminous nearby galaxies and hosts one of the most massive black holes known, making it a very important target for extragalactic studies. The supermassive black hole has been the subject of several stellar and gas dynamical mass measurements; however, the best current stellar dynamical black hole mass is larger than the gas dynamical determination by a factor of two, corresponding to a 2-sigma discrepancy. In this talk, I will review the gas dynamical black hole mass measurements that have been made over the years for M87, focusing in particular on the most recent measurement from multi-slit Space Telescope Imaging Spectrograph observations from the Hubble Space Telescope. I will also discuss the strengths and weaknesses generally associated with stellar and gas dynamical black hole mass measurement methods, and the current state of cross-checks between the two methods that have been carried out within the same galaxy.

Gas-dynamical Black Hole Mass Measurements for M87

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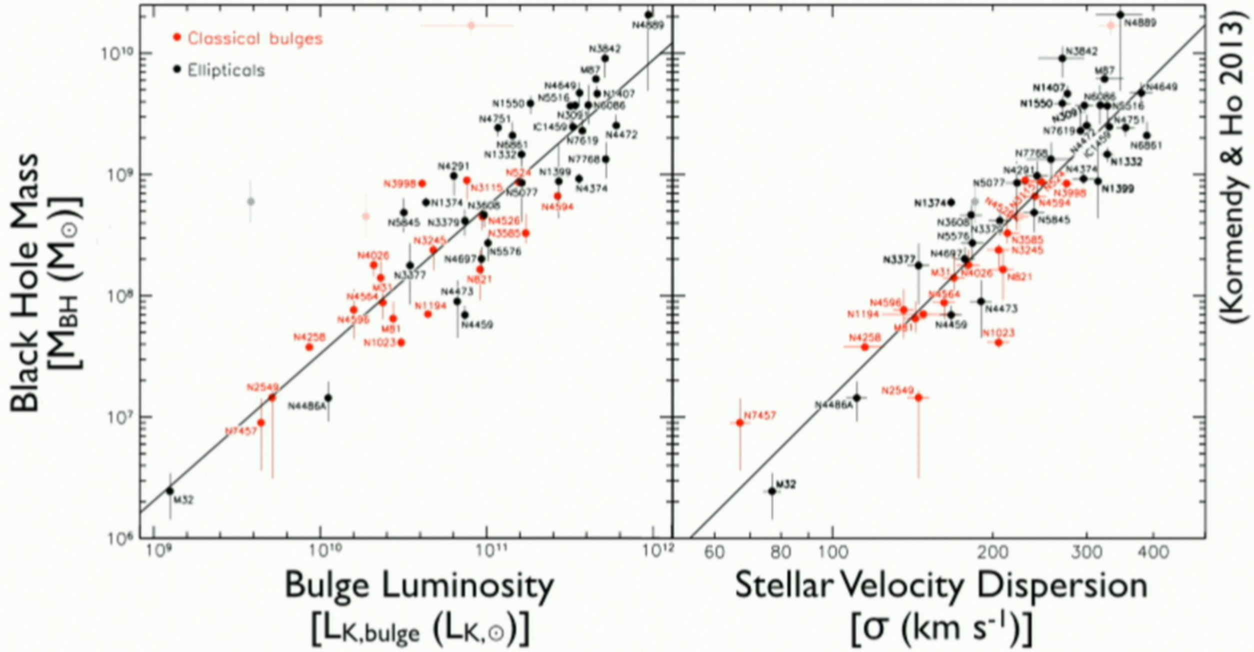
EHT 2014, Perimeter Institute

Introduction



- ✦ Interpretations of the M_{BH} - galaxy relations rests on reliable M_{BH} measurements.
- ✦ To date, ~80 M_{BH} measurements have been made, but there remain open questions.
- ✦ At the high-mass end of the correlations:
  - slope, intrinsic scatter, and possibly functional form are not well understood
  - M_{BH} - σ and M_{BH} - L disagree

Pro's and Con's of Each Method

GAS-DYNAMICAL MODELING vs. **STELLAR-DYNAMICAL MODELING**

Gas-dynamical modeling

- Conceptually simple, BUT...
- Assumption of circular rotation must be verified.
- Often the observed velocity dispersion is larger than that predicted from models.
  - what is the physical origin and what does that mean for M_{BH}?

Stellar-dynamical modeling

- Widely applicable, BUT...
- Models are complex.
- Models can be biased due to a number of systematic effects.
  - M_{BH} - M/L - DM degeneracies
  - intrinsic shape/orientation effects

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Black Hole Mass Consistency Tests

- There have been very few consistency checks between stellar and gas-dynamical BH mass measurement methods.

CONSISTENT

NGC 3227
(Davies et al. 2006, Hicks & Malkan 2008)

NGC 4151
(Onken et al. 2014, Hicks & Malkan 2008)

NGC 4258
(Siopis et al. 2009, Pastorini et al. 2007)

DISCREPANT

NGC 4335
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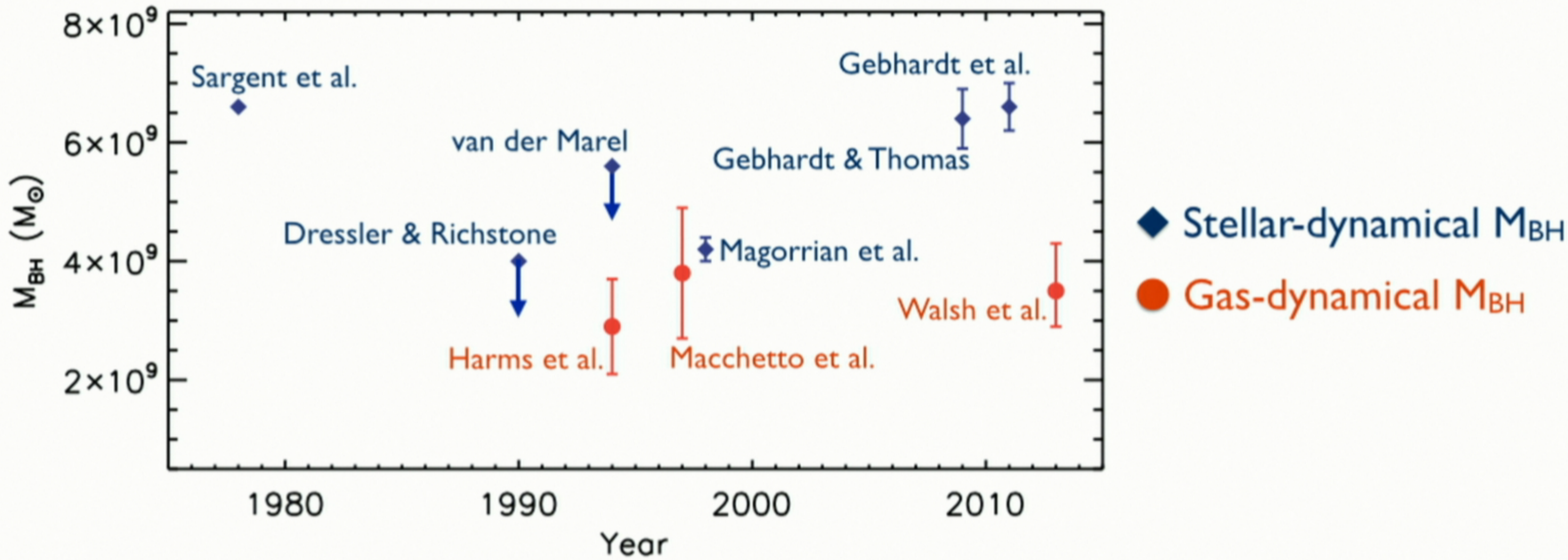
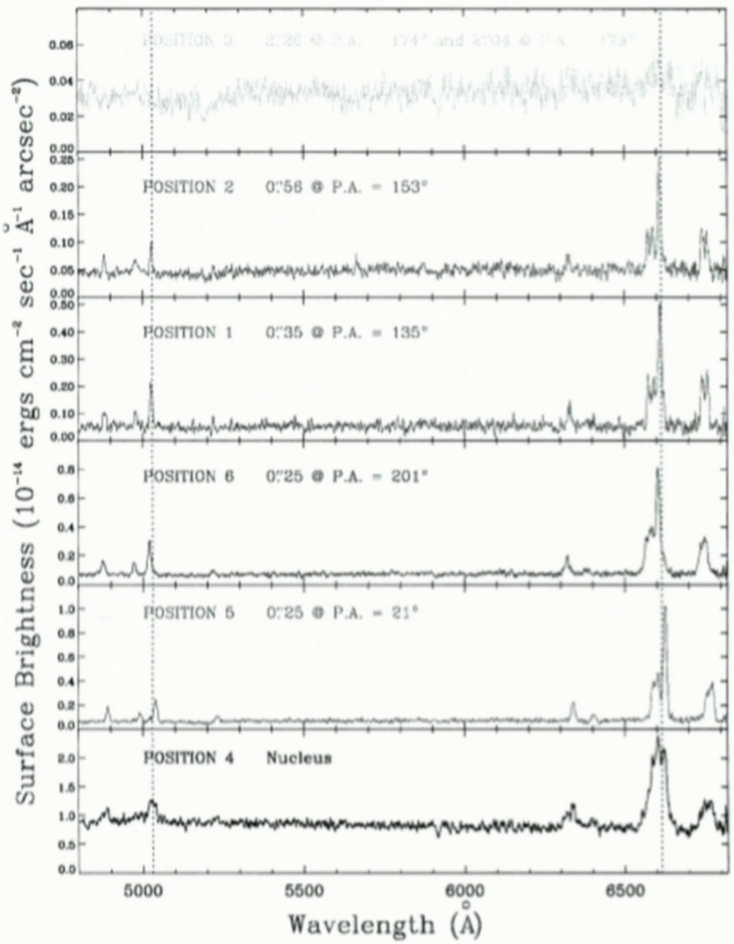
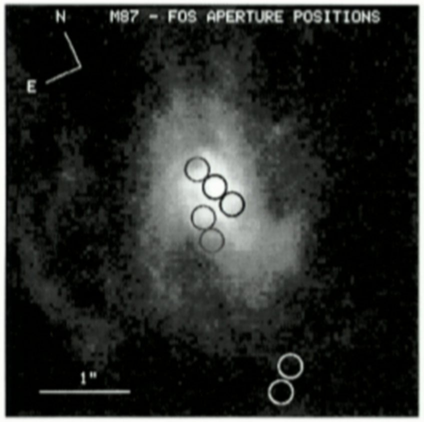
M87 BH Mass Measurements



- ✦ M87 has been the subject of a number of M_{BH} measurements.
- ✦ Earliest measurements come from Young et al. & Sargent et al. 1978.
- ✦ Most recent stellar and gas-dynamical measurements disagree by a factor of ~2.

A Gas-dynamical BH Mass from FOS

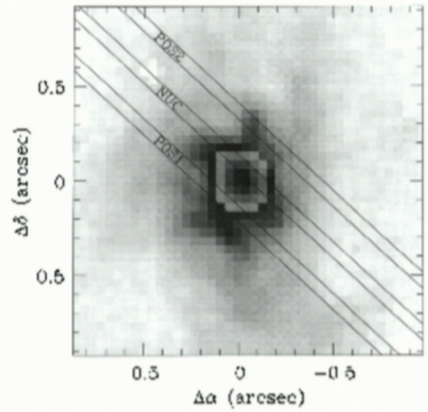




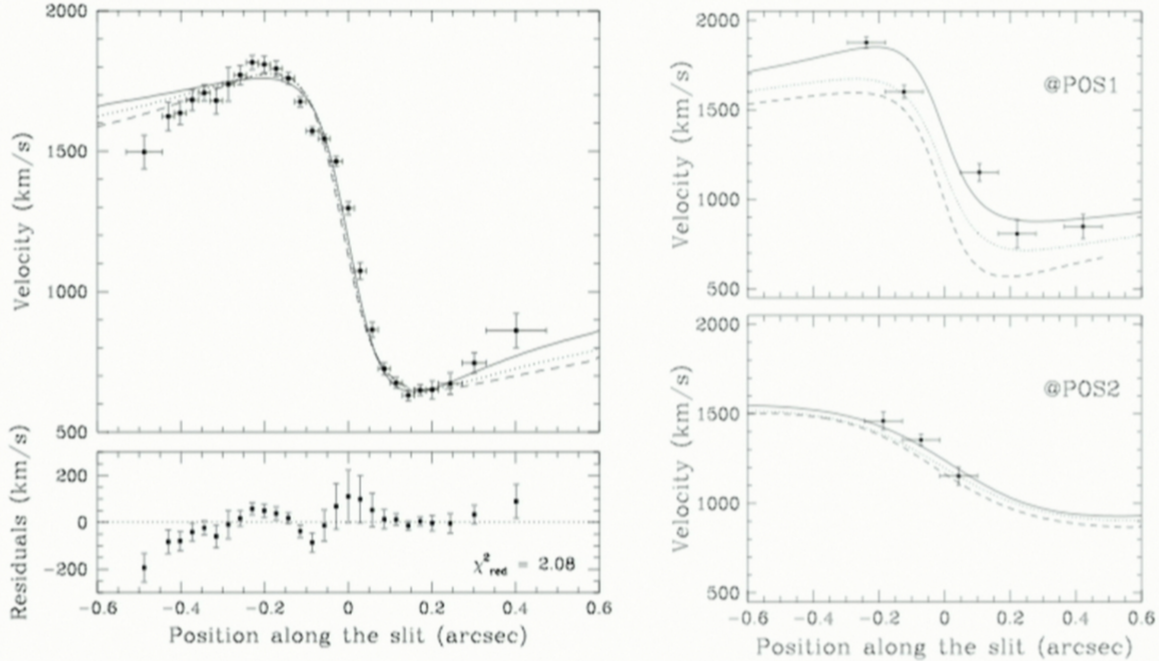
Harms et al. 1994

- Obtained spectra with HST/FOS at 6 aperture positions.
- Fit a rotating thin disk model to the velocity measurements.

A Gas-dynamical BH Mass from FOC



Macchetto et al. 1997



- ✦ Acquired spectra with HST/FOC at 3 parallel, non-contiguous slit positions.
- ✦ Used rotating thin disk models that, for the first time, incorporated the effects of the propagation of light through the telescope and spectrograph optics.

The Need to Revisit the M87 Gas-dynamical BH Mass

- Harms et al. 1994 and Macchetto et al. 1997 were milestones for HST and the field of BH detection, but:
  - Neither study was able to map out the full kinematic structure of disk.
  - Disk inclination angle was a source of uncertainty.
  - Is there velocity dispersion internal to the disk, and if dynamically significant, how does that affect M_{BH}?
- Walsh et al. 2013: Goal was to improve gas-dynamical measurement using new HST data and calculating more comprehensive models than had previously been used for M87.

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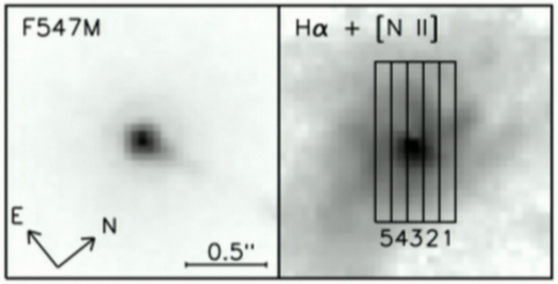
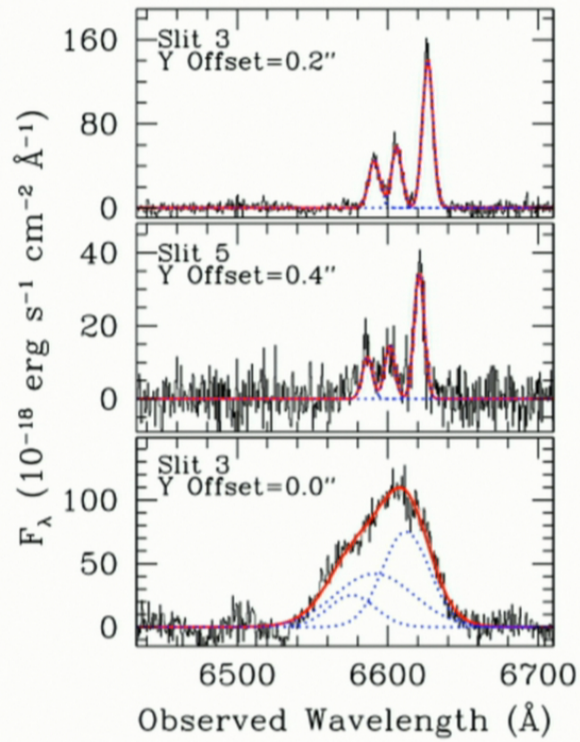
STIS Observations & Measurements

- ✦ Acquired new HST/STIS observations.
  - 0.1''-wide slit placed at 5 positions
  - spatial scale: 0.05''/pix
  - spectral coverage of Hα region

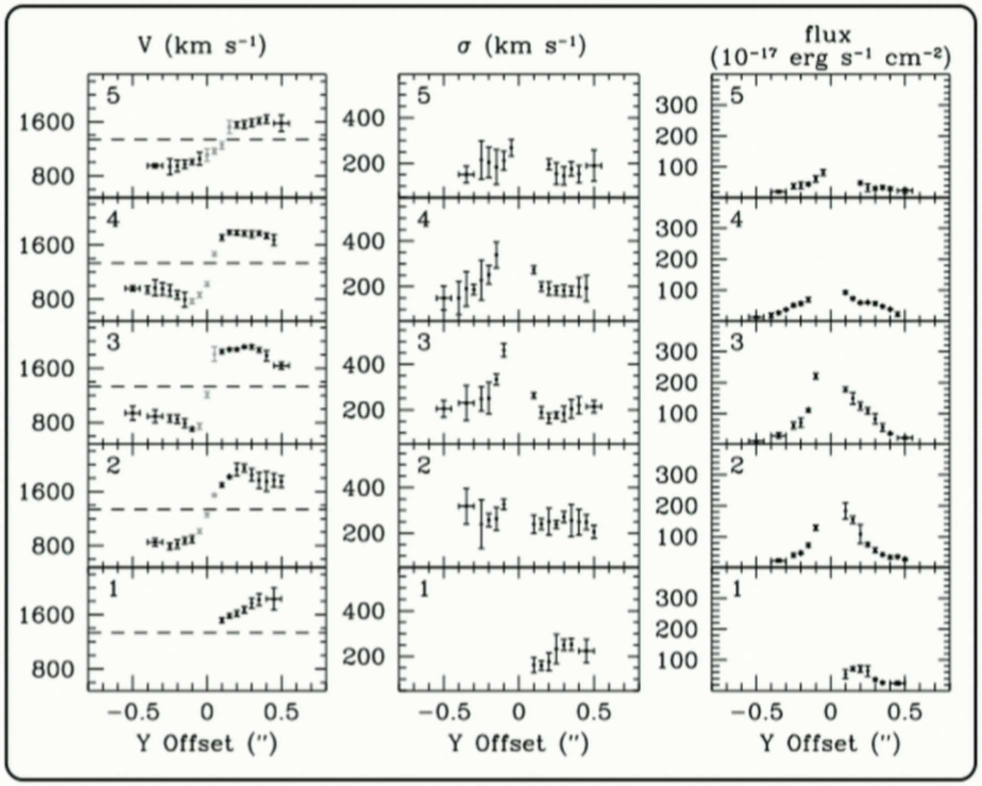


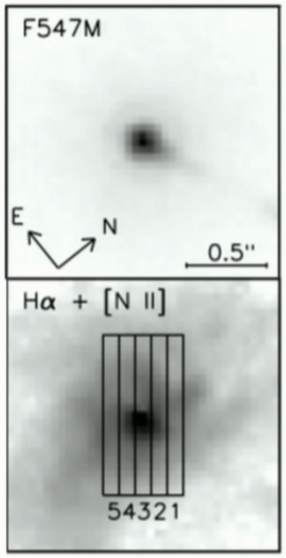
- ✦ Extracted spectra from individual rows of 2D STIS image.
- ✦ Simultaneously fit 3 Gaussians to Hα and [N II] emission lines.



Observed Velocity Fields

- Measured the velocity, velocity dispersion, and flux as a function of location along the slit.

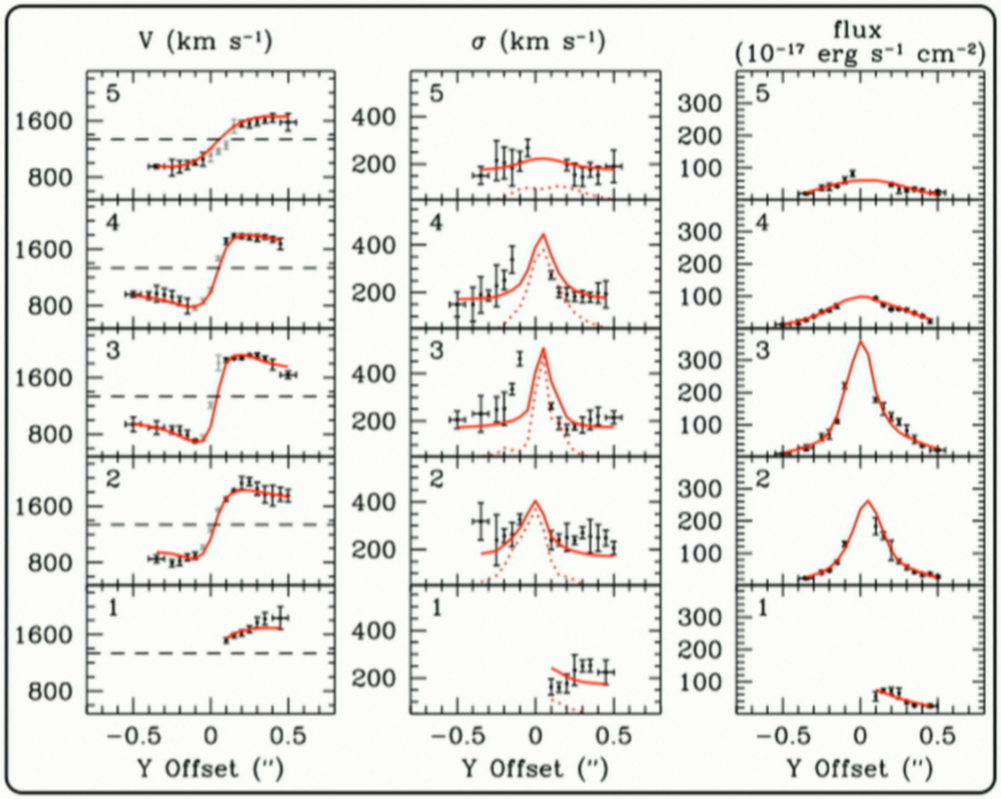




Gas-dynamical Models

- Assume a thin disk of gas in circular rotation. Determine v_c based on enclosed mass.
- Project onto the plane of the sky given *i*.
- Intrinsic line-of-sight velocity profiles assumed Gaussian before passing through the telescope optics.
- Model velocity field "observed" in a manner that matches the STIS observations.
- Extract a 1D spectrum from each row of the model 2D spectral image and fit a Gaussian to the emission line.
- Determine best-fit parameters (M_{BH}, M/L, i, θ, v_{sys}, x_{offset}, y_{offset}) that produce a model velocity field that most closely matches the observations.

Modeling Results



- $M_{BH} = (3.5^{+0.8}_{-0.6}) \times 10^9\ M_\odot$
- M/L = 4 (V-band solar)
- $i = 42°$
- v_{sys} = 1335 km/s
- θ = 6°
- x_{offset} = -0.02"
- y_{offset} = 0.03

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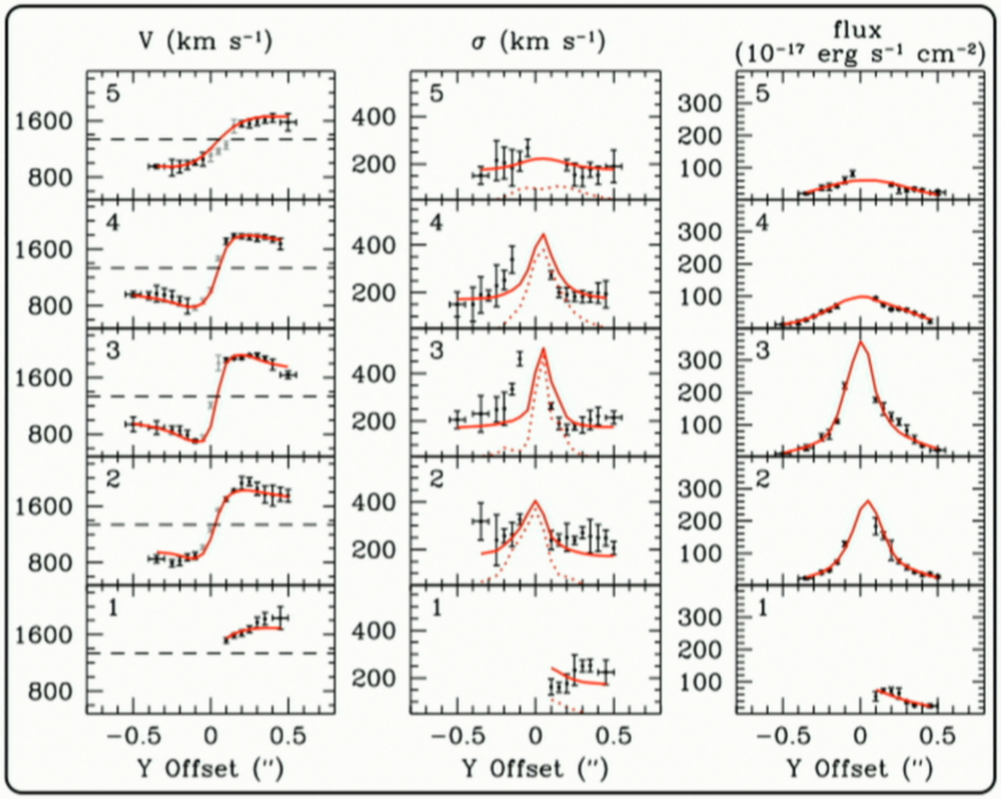

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- Assigning a dynamical origin to the intrinsic velocity dispersion causes M_{BH} to increase by 6%.

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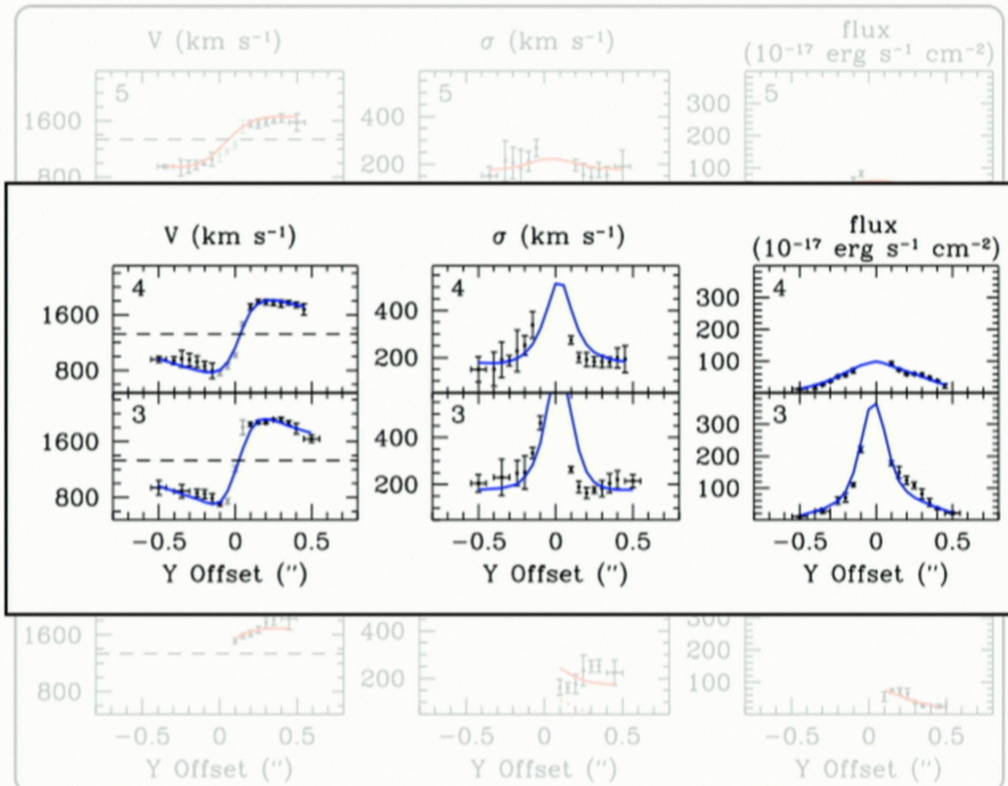

- $M_{BH} = (3.5^{+0.8}_{-0.6}) \times 10^9\ M_\odot$
- M/L = 4 (V-band solar)

- M_{BH} increases by 20% to $4.2 \times 10^9\ M_\odot$.

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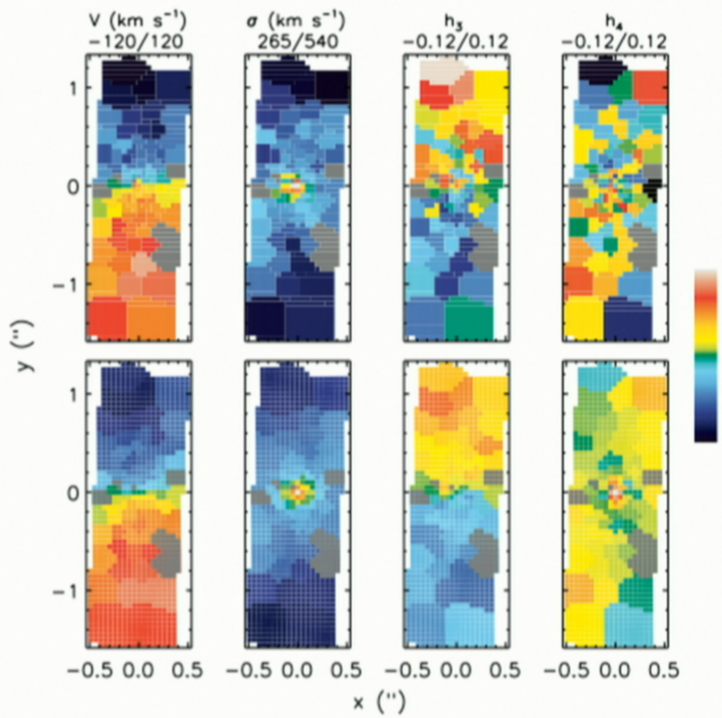
- ✦ An even larger discrepancy between the gas and stellar-dynamical BH measurements exists for NGC 3998.

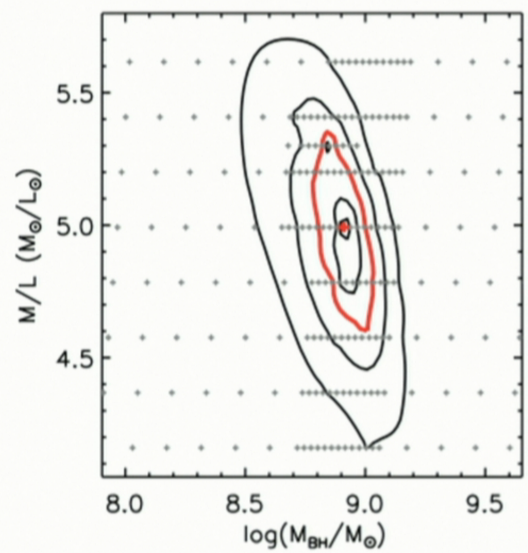
The Stellar-dynamical BH Mass for NGC 3998

- Obtained Keck/OSIRIS+AO observations and long-slit Keck/LRIS observations at 4 position angles to measure the stellar kinematics in NGC 3998.
- Constructed orbit-based models that sampled over possible intrinsic galaxy shapes and tested incorporating the contribution from dark matter.



$M_{BH} = (8.1^{+2.0}_{-1.9}) \times 10^8\ M_\odot$

(Walsh et al. 2012)



Comparison to the NGC 3998 Gas-dynamical BH Mass

- Gas kinematics from HST/STIS data were fit with a circularly rotating thin disk, suggesting $M_{BH} = (2.2^{+1.9}_{-1.6}) \times 10^8\ M_\odot$ (de Francesco et al. 2006).
- Observed and model line widths from gas-dynamical analysis do not fully match, but unclear how much M_{BH} would increase if an intrinsic velocity dispersion was included in the model and assigned a dynamical origin.
  - The effect could be small, as seen in M87, or quite large, as seen in M84 where M_{BH} increased by a factor of 2 (Walsh et al. 2010).

Conclusions

- Gas-dynamical models of STIS data for M87 suggest: $M_{BH} = (3.5^{+0.8}_{-0.6}) \times 10^9\ M_\odot$.

- Unlike past gas-dynamical studies of M87, we have:
  - mapped out the full kinematic structure of the disk, constraining *i*
  - found that there is a small amount of velocity dispersion internal to the disk
  - allowed for the intrinsic velocity dispersion to be dynamically significant

- Previous M_{BH} measurements: $(2.9 \pm 0.8) \times 10^9\ M_\odot$ (gas; Harms et al. 1994)
  $(3.8 \pm 1.1) \times 10^9\ M_\odot$ (gas; Macchetto et al. 1997)
  $(6.6 \pm 0.4) \times 10^9\ M_\odot$ (stars; Gebhardt et al. 2011)

- M87 and NGC 3998 highlight the need for carrying out more cross-checks between the two methods in the same galaxy.