Gas and Stellar Dynamical Black Hole Mass Measurements: Revisiting M84 and a Consistency Test with NGC 3998

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Introduction

❖ Conceptually simple, BUT...
❖ Assumption of circular rotation must be verified.
❖ Often the observed velocity dispersion is larger than that expected from rotational broadening. The physical origin of this intrinsic velocity dispersion is unknown.

❖ Our interpretation of the $M_{BH}-\sigma$ and $M_{BH}-L$ relationships rests on reliable $M_{BH}$ measurements.

About 70 $M_{BH}$ measurements have been made to date, often through the dynamical modeling of gas disks or stars.

Gültekin et al. (2009)
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Widely applicable, BUT...

Orbit-based models are complex.

Models can be biased due to $M_{\text{BH}}$-$M/L$-dark matter degeneracies, the use of incomplete orbital libraries, and inaccurate assumptions about galaxy shape.
Introduction

❖ Recent work has shown that some previous stellar dynamical $M_{BH}$ measurements have been underestimated:

❖ **Including dark matter:** Gebhardt & Thomas 2009 (M87), Schulze & Gebhardt 2011

❖ **More complete orbital libraries:** Shen & Gebhardt 2010 (M60), Schulze & Gebhardt 2011

❖ **Triaxial models:** van den Bosch & de Zeeuw 2010 (NGC 3379)

❖ These studies suggest that some previous measurements may need to be re-evaluated, and there is a renewed motivation to pursue gas dynamical measurements.

❖ **First part of talk:** re-examining the black hole in M84 with gas dynamical modeling (Walsh, Barth, & Sarzi 2010, ApJ, 721, 762).
Carrying out consistency tests between gas and stellar dynamical modeling within the object is crucial, but such checks have only been attempted on a few galaxies with limited results.

- **IC 1459** (Verdoes Kleijn et al. 2000; Cappellari, 2002)
- **NGC 3379** (Shapiro et al. 2006)

  - Gas kinematics turned out to be disturbed.

- **M87** (e.g., Macchetto et al. 1997; Gebhardt & Thomas 2009)

  - Stellar dynamical $M_{BH}$ about a factor of 2 larger than gas measurement.

- **Cen A** (e.g., Neumayer et al. 2007; Cappellari et al. 2009)

  - Gas and stellar dynamical $M_{BH}$ measurements in excellent agreement.

**Second part of talk:** testing the consistency of gas and stellar dynamical $M_{BH}$ measurements with NGC 3998.
M84 is an elliptical galaxy containing a type 2 AGN.

With $\sigma = 296$ km s$^{-1}$, M84 sits at the upper-end of the $M_{\text{BH}} - \sigma$ galaxy relations.

Bower et al. (1998) measured $M_{\text{BH}} = (1.5^{+1.1}_{-0.6}) \times 10^9$ M$_{\odot}$ from HST/STIS observations.

From same STIS data, Maciejewski & Binney (2001) estimated $M_{\text{BH}} = 4.0 \times 10^8$ M$_{\odot}$.

We aim to resolve the uncertainty in the M84 black hole mass.
M84 observed under GO-7124 (Bower et al. 1998).
- STIS 52x0.2 aperture at 3 positions.
- Spatial scale: 0.05”/pix.
- Coverage of Hα region.

Extracted spectra from individual rows of 2D STIS image.
- Simultaneously fit 5 Gaussians to all emission lines.
- Could not adequately fit central 3 rows - not using these measurements in the gas dynamical model.
From the Gaussian fit to the [N II] $\lambda 6583$ Å line, we 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 $v_c$ relative to $v_{sys}$ based on enclosed mass, which depends on $M_{BH}$, the stellar mass profile, and $\Upsilon$.

- Project onto the plane of the sky given $i$.

- Intrinsic LOS velocity profiles assumed Gaussian before passing through telescope optics.

- Model velocity field “observed” in a manner that matches the STIS observations.

- Left with model 2D spectrum similar to STIS data. Extract spectrum from each row of model 2D image and fit a Gaussian to the emission line.

- Determine best-fit parameters ($M_{BH}$, $\Upsilon$, $\theta$, $i$, $v_{sys}$, $x_{offset}$, $y_{offset}$) that produce a model velocity field that most closely matches the observed velocity field.
Modeling Results

\[ M_{\text{BH}} = (4.3^{+0.8}_{-0.7}) \times 10^8 \, M_\odot \]
\[ \gamma = 4 \text{ (V-band solar)} \]
\[ i = 67^\circ \]
\[ v_{\text{sys}} = 1060 \text{ km/s} \]
\[ \theta = 27^\circ \]
\[ x_{\text{offset}} = 0.02'' \]
\[ y_{\text{offset}} = -0.04'' \]

\[ M_{\text{BH}} = (8.5^{+0.9}_{-0.8}) \times 10^8 \, M_\odot \]
\[ \gamma = 4 \text{ (V-band solar)} \]
\[ i = 72^\circ \]
\[ v_{\text{sys}} = 1060 \text{ km/s} \]
\[ \theta = 28^\circ \]
\[ x_{\text{offset}} = 0.01'' \]
\[ y_{\text{offset}} = -0.05'' \]
Conclusions

✴ Re-analyzed multi-slit archival STIS observations of the M84 nucleus.

✴ Modeled the velocity fields as a cold, thin disk in circular rotation, but found that an intrinsic velocity dispersion was needed to match the observed line widths.

✴ Calculated a second disk model in which the intrinsic velocity dispersion is dynamically significant. We favor this model, giving $M_{\text{BH}} = (8.5^{+0.9}_{-0.8}) \times 10^8 \, M_\odot$.

✴ Our new $M_{\text{BH}}$ is $\sim 2\times$ smaller than the Bower et al. measurement.

✴ $M_{\text{BH}}$ now lies closer to the expected mass from the $M_{\text{BH}}-\sigma$ and $M_{\text{BH}}-L$ relationships.
NGC 3998 is a nearby, S0 galaxy with a LINER nucleus.

NGC 3998 has a large stellar velocity dispersion of $\sigma = 305$ km s$^{-1}$.

Gas kinematics has been shown to be well fit with a circularly rotating thin disk model by de Francesco et al. (2006).

$r_{\text{sphere}}$ can be resolved with AO-assisted IFUs on large ground-based telescopes, and nucleus can be used as a TT reference.

Our goal is to measure $M_{\text{BH}}$ using orbit-based stellar dynamical models and to compare to the existing gas dynamical measurement.
Observations

- Obtained LGS AO OSIRIS observations.
  - Kbb filter
  - 0.05" spatial scale
  - used nucleus as TT star
  - 3.8 hours on source

- Acquired LRIS observations.
  - red-side grating: 831/8200 Å
  - placed 1"-wide slit along 4 PAs

- Used images to measure the surface brightness distribution.
  - HST WFPC2/PC F791W image
  - CFHT WIRCam K-band image
Measured stellar kinematics ($V$, $\sigma$, $h_3$, $h_4$) in each bin with pPXF (Cappellari & Emsellem 2004).
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Stellar Dynamical Models

- Constructed triaxial Schwarzschild models (van den Bosch et al. 2008).
- Potential consists of contributions from the stars, black hole, and dark matter.
- A representative orbital library is generated and the orbits are integrated in the potential.
- Weights for each orbit are found such that the superposition reproduces the observed kinematics and surface brightness.
- Process is repeated for different combinations of parameters until the lowest $\chi^2$ is found.
Preliminary Results

- Initially fixed $M_{\text{BH}}$, and explored the shape of NGC 3998.

- Varied $M_{\text{BH}}$ and $M/L$ while sampling 8 shapes, which ranged from oblate to triaxial.

\[ M_{\text{BH}} = (9.2^{+3.3}_{-2.4}) \times 10^8 \, M_\odot \]

\[ M/L \text{ (I-band, solar)} = 5.0^{+0.2}_{-0.4} \]

\[ p = b/a; \quad q = c/a \]

\[ T = (1 - p^2)/(1 - q^2) \]

![Graph showing axis ratio vs. radius](image1)

![Map showing $M_{\text{BH}}$ vs. $M/L$](image2)
Preliminary Results

\[ M_{\text{BH}} = (9.2 \pm 3.3 - 2.4) \times 10^8 M_\odot \]

\[ M/L (I\text{-band, solar}) = 5.0^{+0.2}_{-0.4} \]

\[ p = b/a; q = c/a \]

\[ T = \frac{1 - p^2}{1 - q^2} \]

Initially fixed \( M_{\text{BH}} \), and explored the shape of NGC 3998.

Varied \( M_{\text{BH}} \) and \( M/L \) while sampling 8 shapes, which ranged from oblate to triaxial.
We have measured the stellar kinematics on scales within $r_{\text{sphere}}$ and on large scales out to $\sim 1 \, R_e$.

We have constructed three-integral, orbit-based, triaxial stellar dynamical models, finding a (preliminary) $M_{\text{BH}}$ of $(9.2^{+3.3}_{-2.4}) \times 10^8 \, M_\odot$.

Our preliminary stellar dynamical $M_{\text{BH}}$ is about a factor of about 4 larger than the de Francesco et al. gas measurement [ $(2.1^{+1.9}_{-1.6}) \times 10^8 \, M_\odot$ ]

With $\sigma = 305 \, \text{km s}^{-1}$, $M_{\text{BH}}-\sigma$ predicts: $M_{\text{BH}} = 7.9 \times 10^8 \, M_\odot$

With $L_v = 7.2 \times 10^9 \, L_\odot$, $M_{\text{BH}}-L$ predicts: $M_{\text{BH}} = 4.8 \times 10^7 \, M_\odot$

Further work will include running additional model grids to assess the robustness of our $M_{\text{BH}}$ measurement.
Open Questions

- How much of the scatter in the $M_{BH}$-$\sigma$ and $M_{BH}$-$L$ relationships is the result of inconsistencies between the main mass measurement techniques?

- Is there a systematic difference between the masses derived from gas and stellar dynamical methods? If so, how does this affect the slope of the $M_{BH}$-host galaxy relations?

- What causes the intrinsic velocity dispersion that is observed in some nuclear gas disks?

- By how much have previous stellar dynamical $M_{BH}$ measurements been biased by assumptions of the galaxy shape, neglecting the contribution of dark matter, and using incomplete orbital libraries?