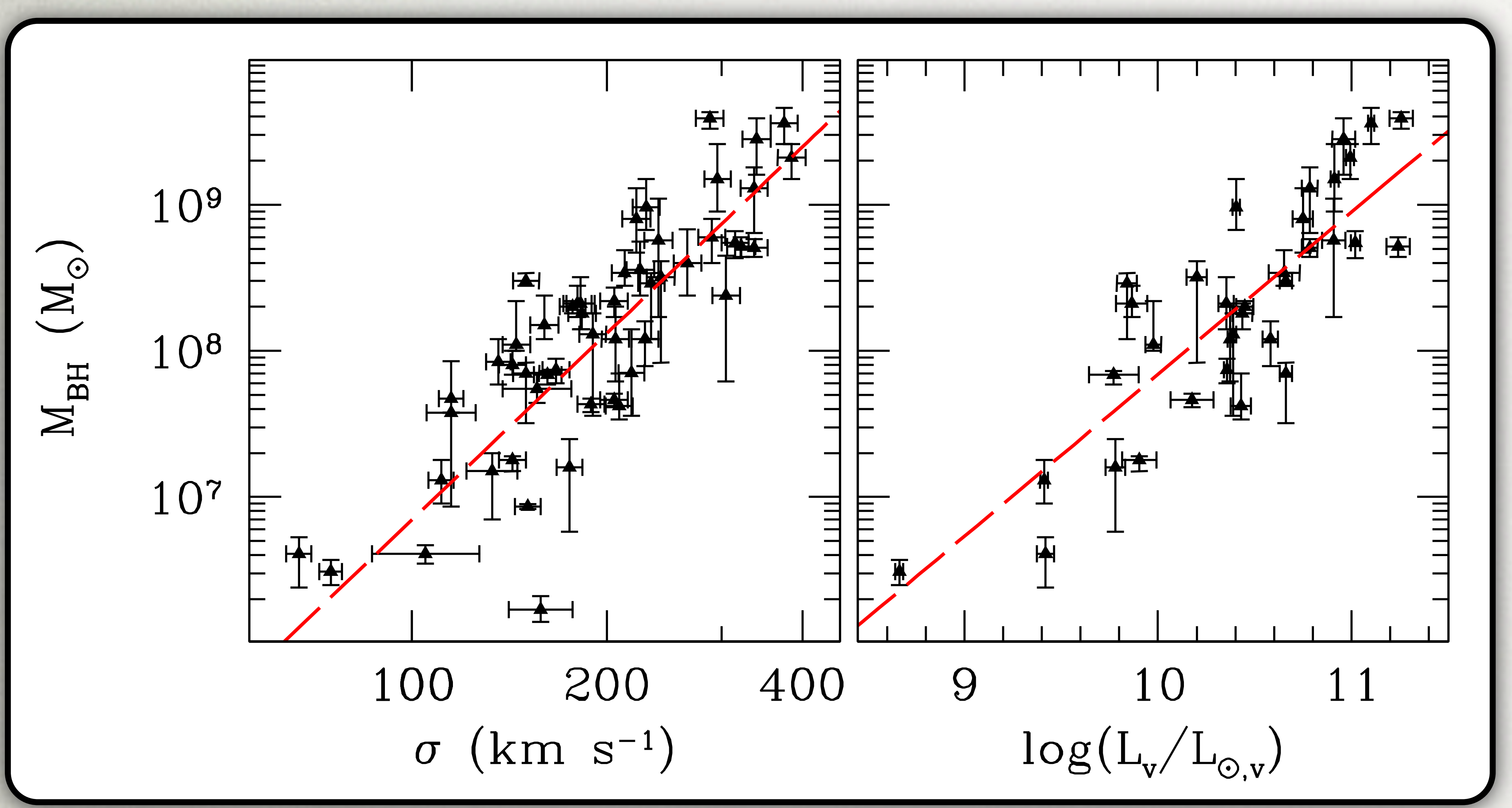
Gas and Stellar Dynamical Black Hole Mass Measurements:

Revisiting M84 and a Consistency Test with NGC 3998

Jonelle Walsh (UC Irvine/UT Austin)
Aaron Barth (UC Irvine)
Remco van den Bosch (MPIA)
Marc Sarzi (Univ. of Hertfordshire)

Introduction

Gültekin et al. (2009)



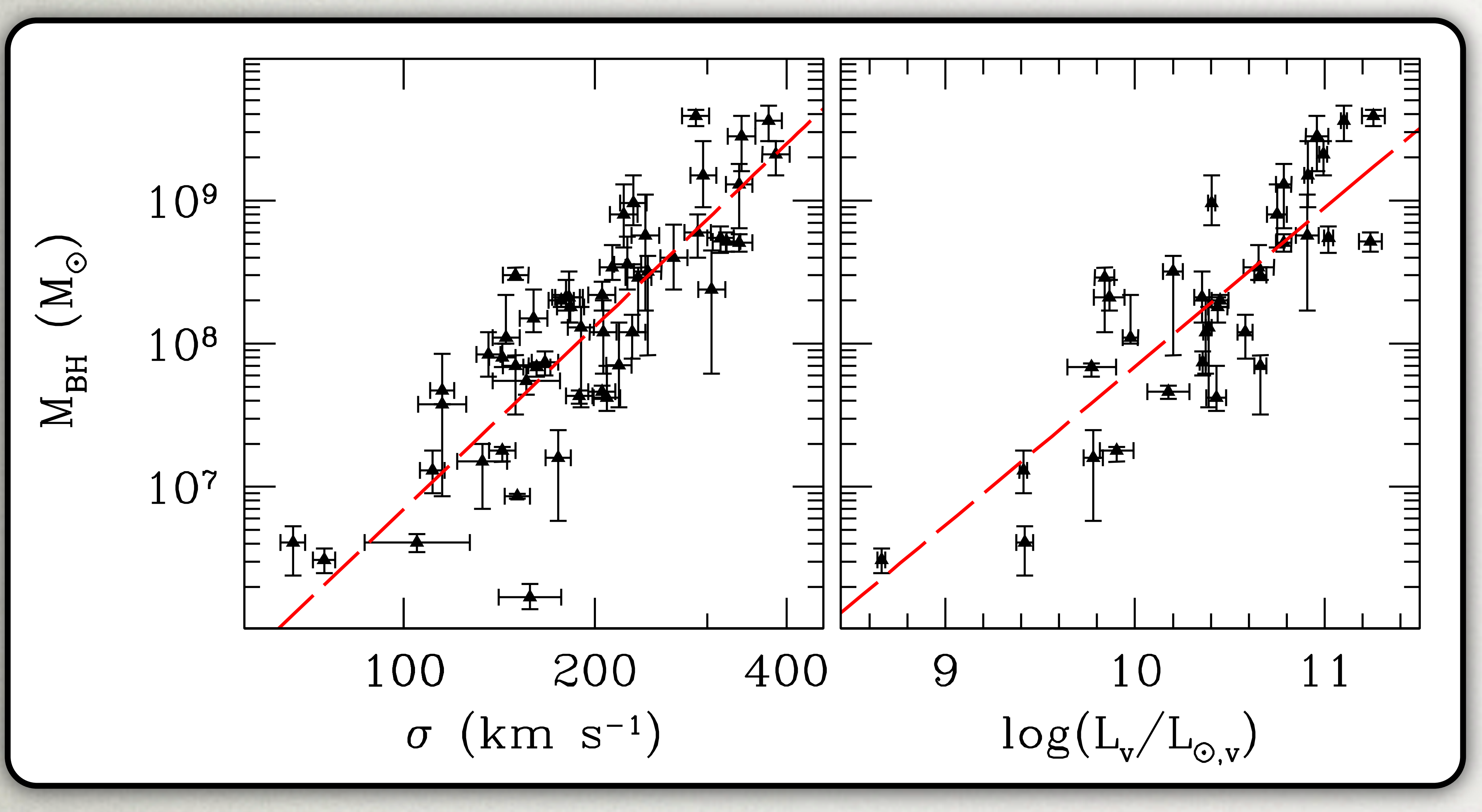
- Our interpretation of the M_{BH}-σ and M_{BH}-L relationships rests on reliable M_{BH} measurements.
- About 70 M_{BH} measurements have been made to date, often through the dynamical modeling of gas disks or stars.

GAS DYNAMICAL MODELING

- 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.

Introduction

Gültekin et al. (2009)



- Our interpretation of the M_{BH}-σ and M_{BH}-L relationships rests on reliable M_{BH} measurements.
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STELLAR DYNAMICAL MODELING

- Widely applicable, BUT...
- Orbit-based models are complex.
- Models can be biased due to M_{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).

Introduction

- 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.

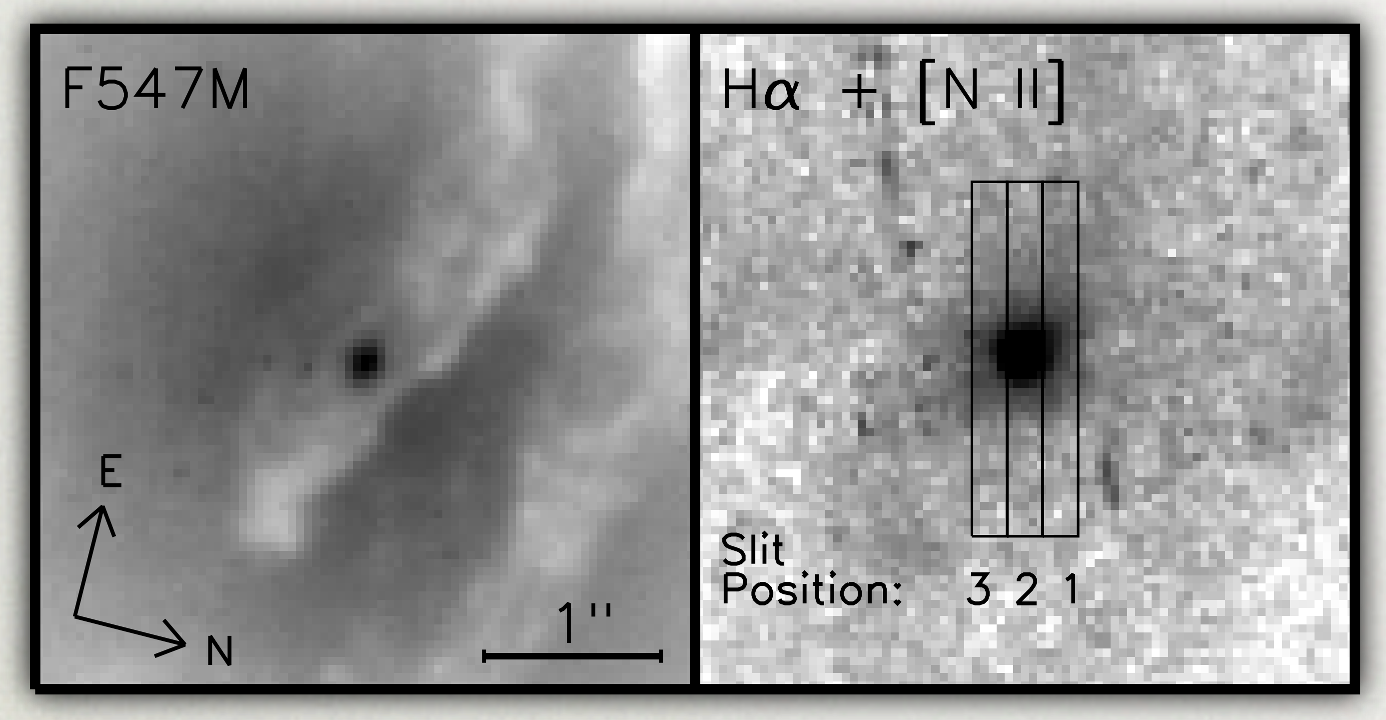
The Supermassive Black Hole in M84 Revisited

- M84 is an elliptical galaxy containing a type 2 AGN.
- With σ = 296 km s^{-1}, M84 sits at the upper-end of the M_{BH} - σ galaxy relations.
- Bower et al. (1998) measured $M_{BH} = (1.5^{+1.1}_{-0.6}) \times 10^9\ M_\odot$ from HST/STIS observations.
- From same STIS data, Maciejewski & Binney (2001) estimated $M_{BH} = 4.0 \times 10^8\ M_\odot$.
- **We aim to resolve the uncertainty in the M84 black hole mass.**

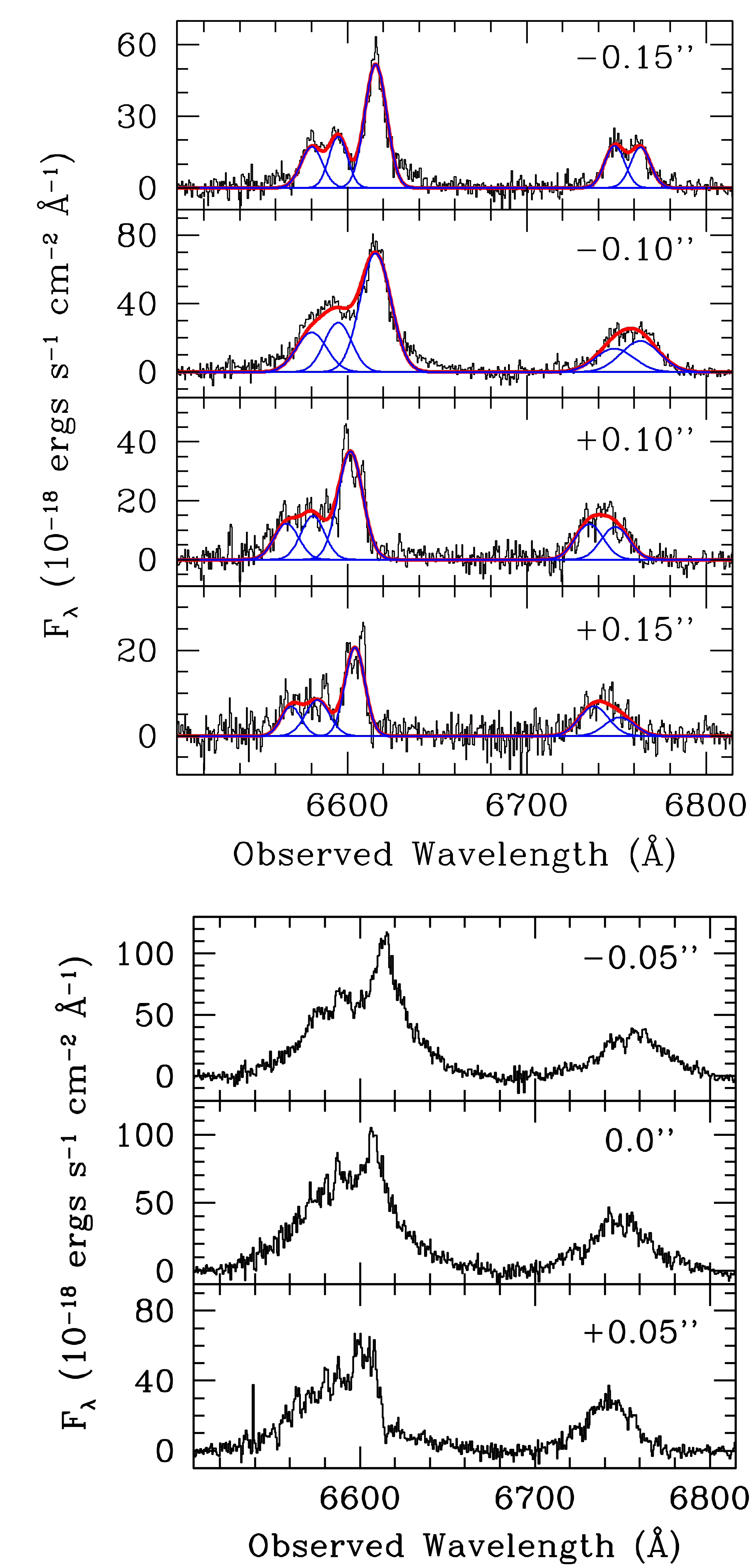
SDSS image of M84

Observations & Measurements

- 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.

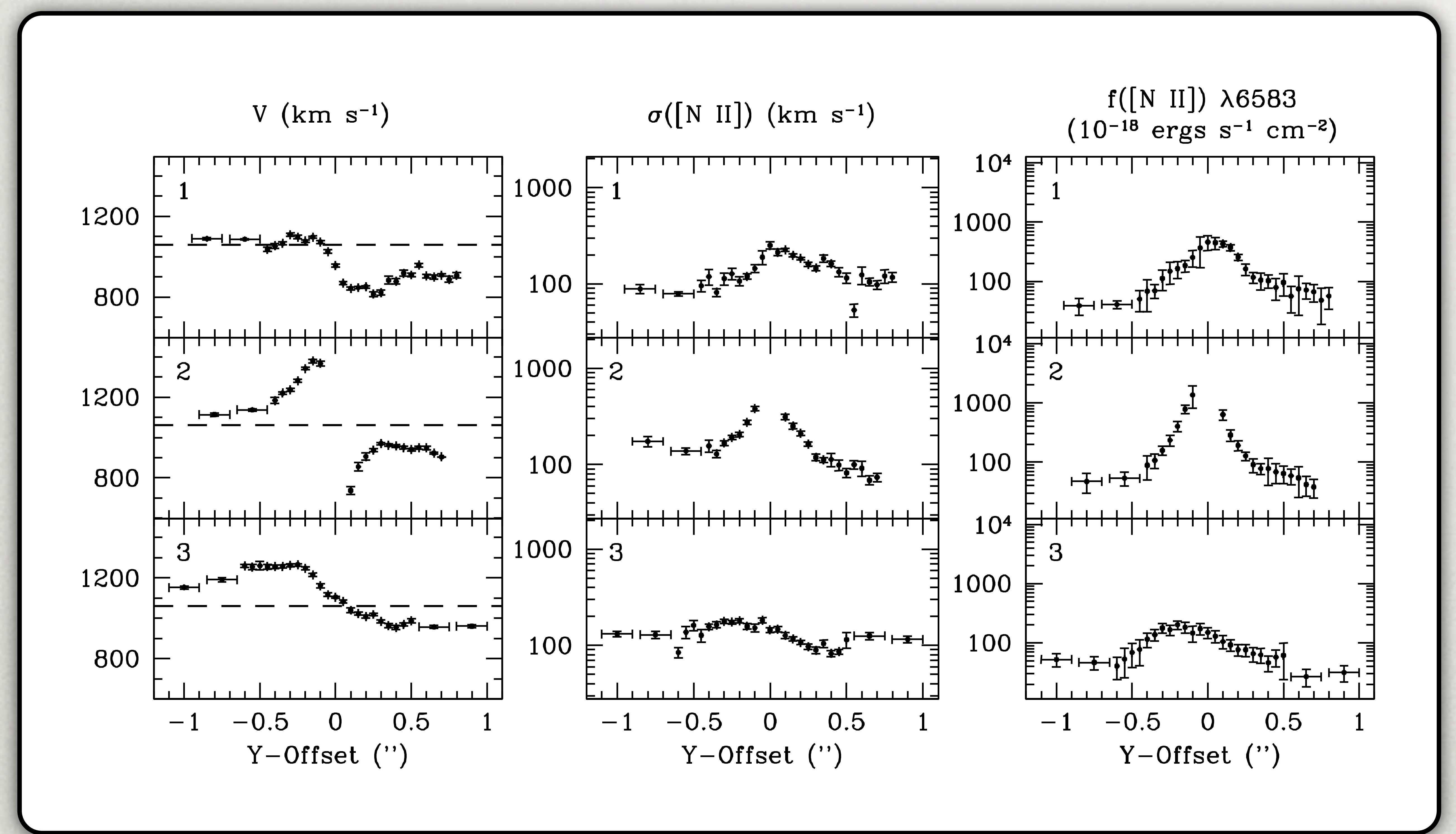


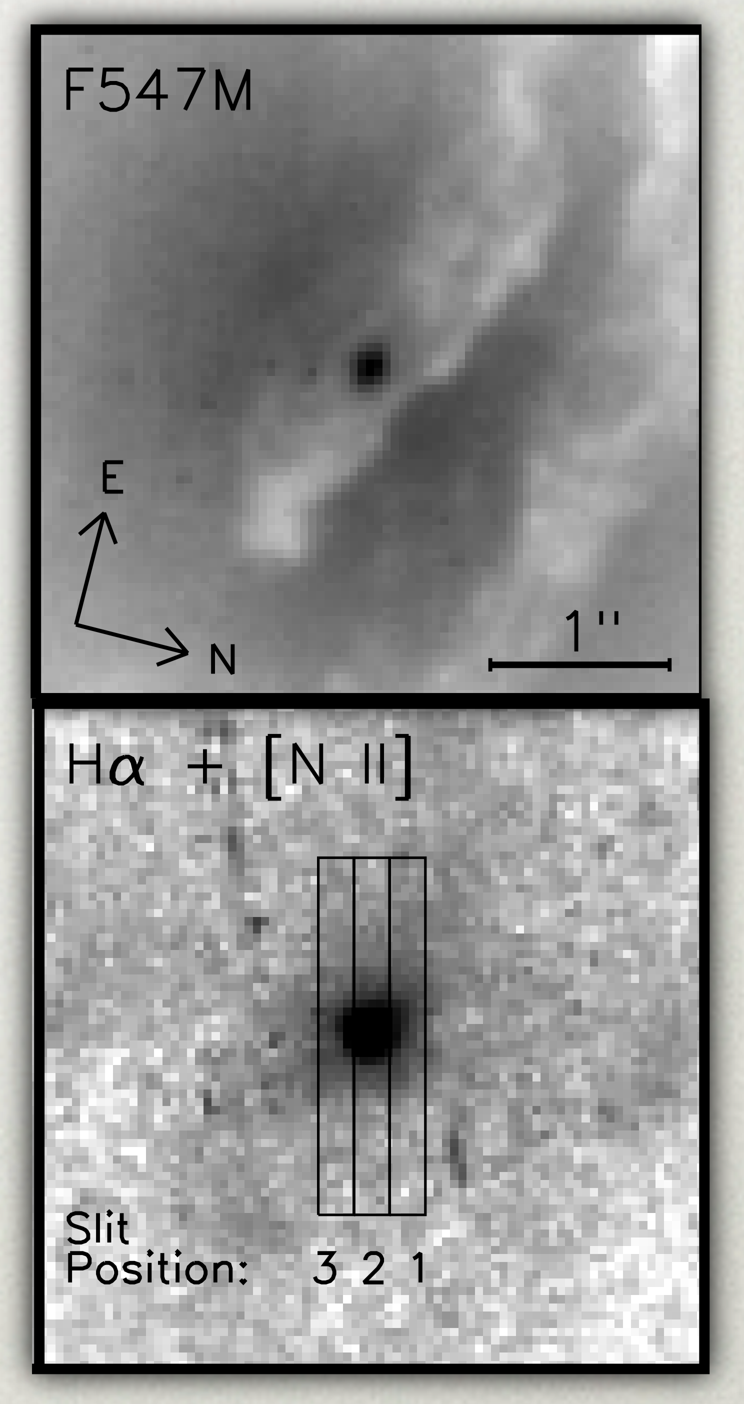
- Extracted spectra from individual rows of 2D STIS image.
- Simultaneously fit 5 Gaussians to all emission lines.
- Could not adequately fit central 3 rows - not using these measurements in the gas dynamical model.



Observed Velocity Fields

- From the Gaussian fit to the [N II] λ6583 Å line, we measured the velocity, velocity dispersion, and flux as a function of location along the slit.

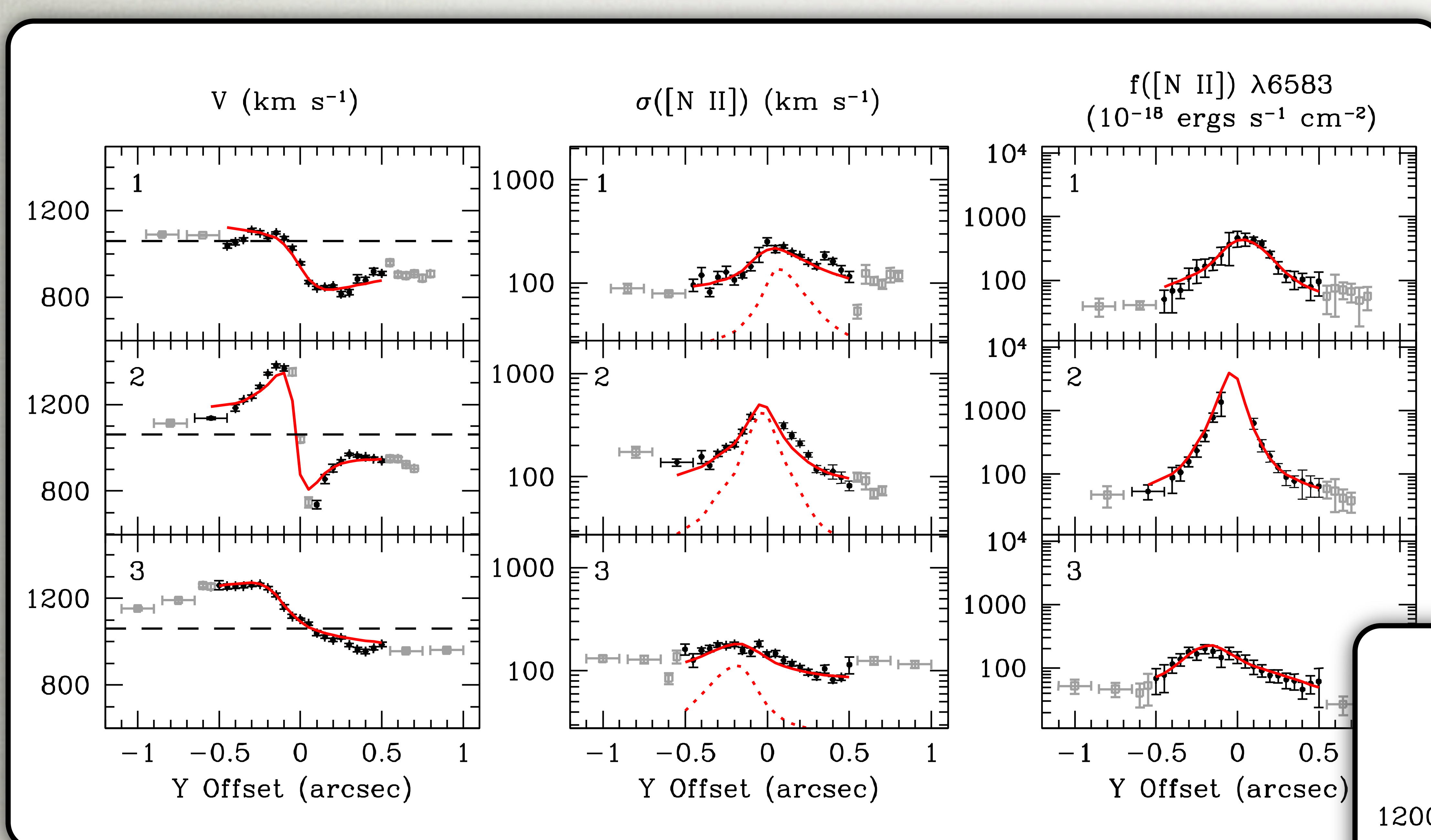




Gas Dynamical Models

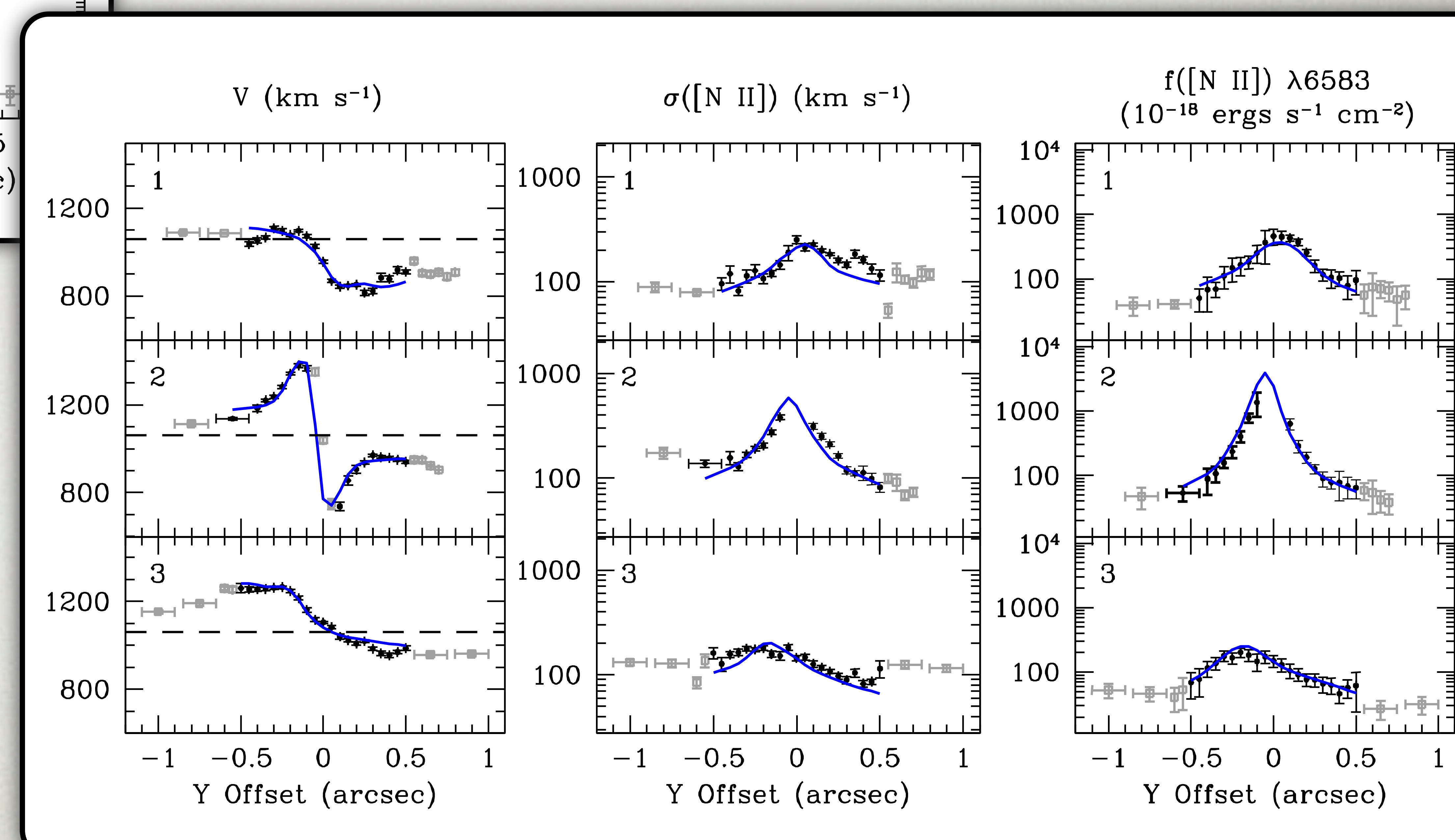
- Assume a thin disk of gas in circular rotation.
- Determine v_c relative to v_{sys} based on enclosed mass, which depends on M_{BH}, the stellar mass profile, and Υ.
- Project onto the plane of the sky given i.
- Intrinsic LOS velocity profiles assumed Gaussian before passing through telescope optics.
- 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}, Υ, θ, i, v_{sys}, x_{offset}, y_{offset}) that produce a model velocity field that most closely matches the observed velocity field.

Modeling Results



- ✴ M_{BH} = $(8.5^{+0.9}_{-0.8}) \times 10^8$ $M_\odot$
- ✴ Υ = 4 (V-band solar)
- ✴ i = 72°
- ✴ v_{sys} = 1060 km/s
- ✴ θ = 28°
- ✴ x_{offset} = 0.01″
- ✴ y_{offset} = -0.05″

- ✴ M_{BH} = $(4.3^{+0.8}_{-0.7}) \times 10^8$ $M_\odot$
- ✴ Υ = 4 (V-band solar)
- ✴ i = 67°
- ✴ v_{sys} = 1060 km/s
- ✴ θ = 27°
- ✴ x_{offset} = 0.02″
- ✴ y_{offset} = -0.04″



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 **$M_{BH} = (8.5^{+0.9}_{-0.8}) \times 10^8\ M_\odot$**.
- Our new M_{BH} is ~2x smaller than the Bower et al. measurement.
- M_{BH} now lies closer to the expected mass from the M_{BH}-σ and M_{BH}-L relationships.

Stars vs. Gas: Testing the Consistency of M_{BH} Measurements with NGC 3998

SDSS image of NGC 3998

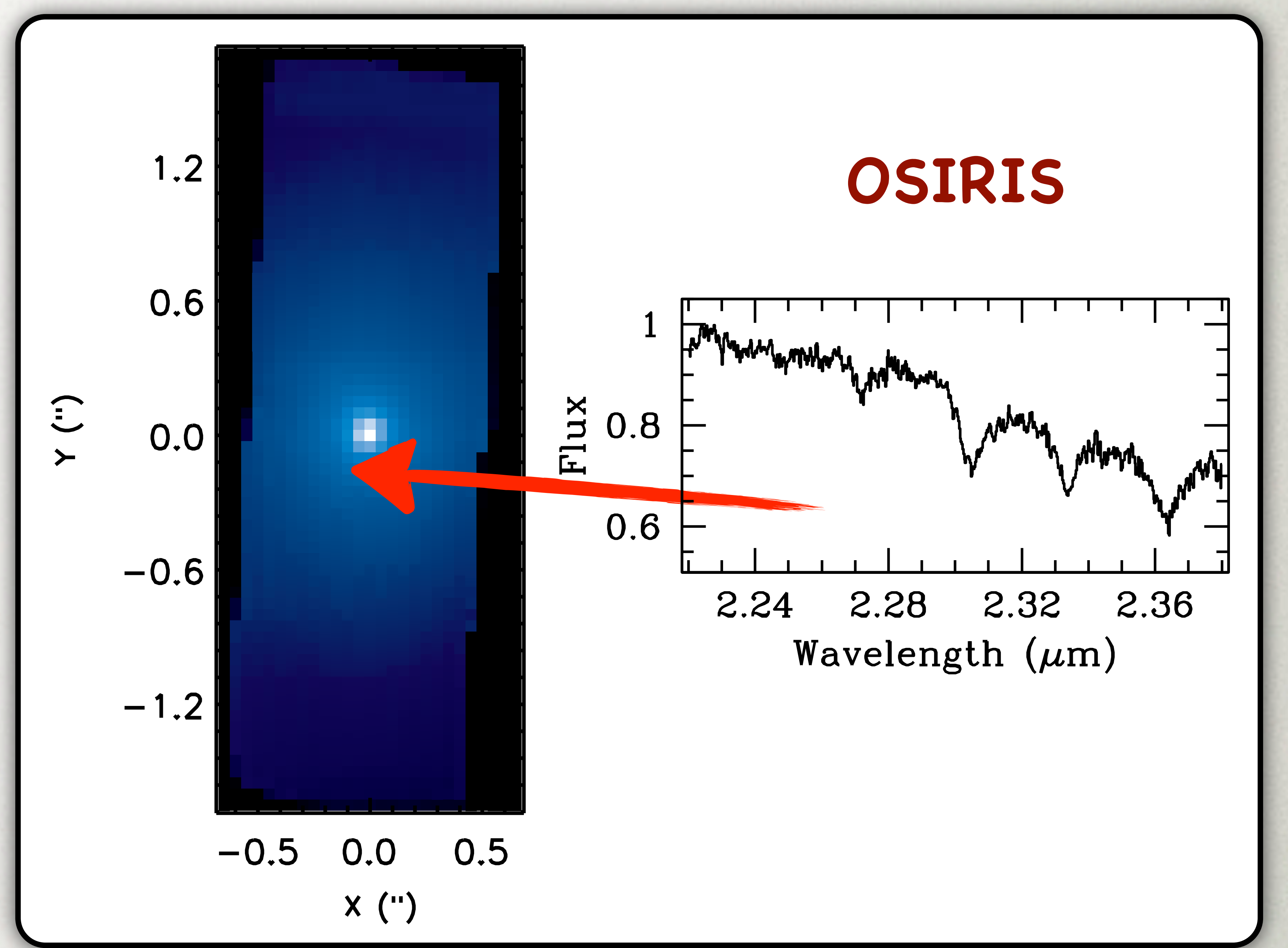
- NGC 3998 is a nearby, S0 galaxy with a LINER nucleus.
- NGC 3998 has a large stellar velocity dispersion of σ = 305 km s^{-1}.
- Gas kinematics has been shown to be well fit with a circularly rotating thin disk model by de Francesco et al. (2006).
- r_{sphere} can be resolved with AO-assisted IFUs on large ground-based telescopes, and nucleus can be used as a TT reference.
- **Our goal is to measure M_{BH} using orbit-based stellar dynamical models and to compare to the existing gas dynamical measurement.**

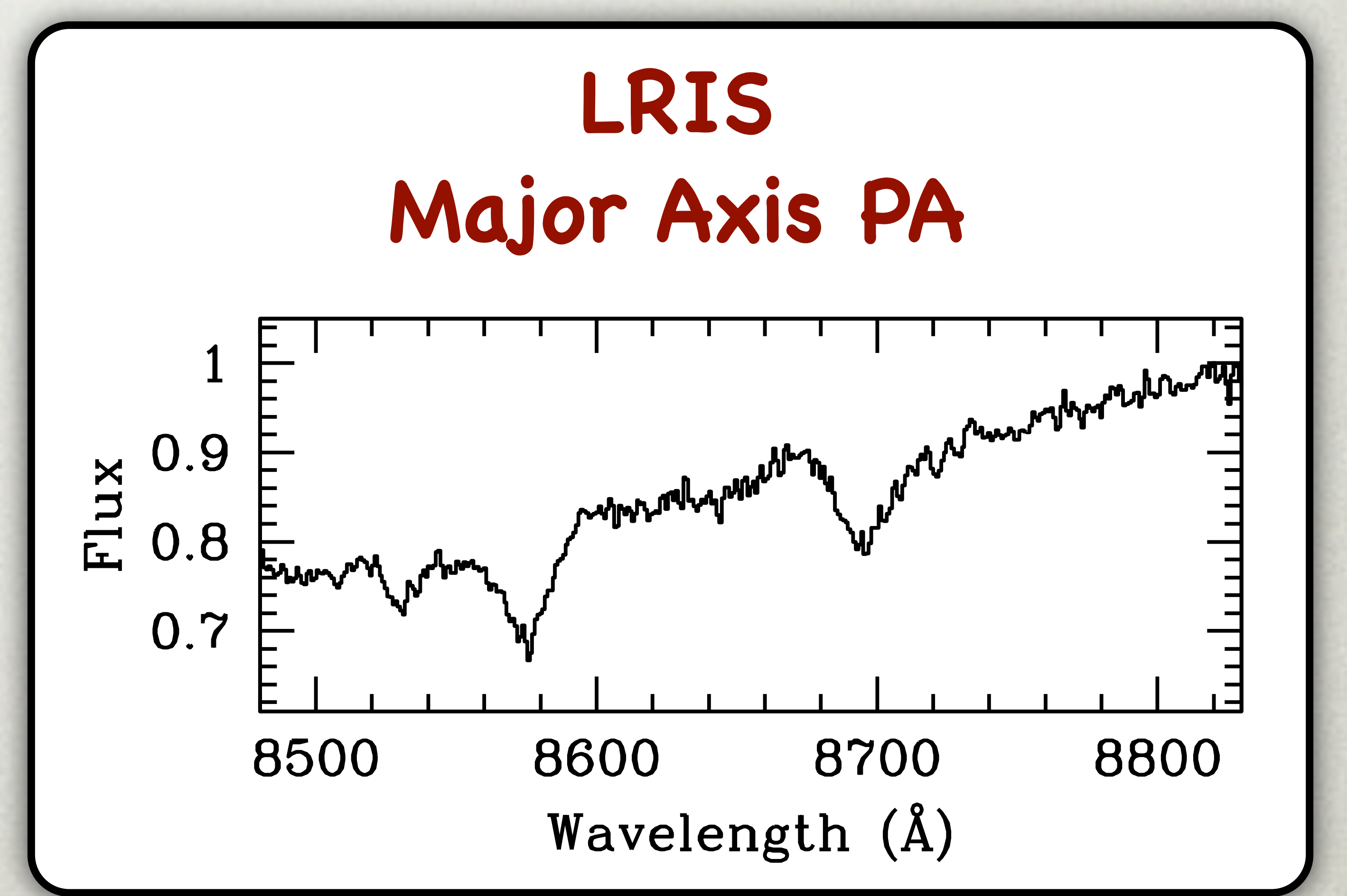
Observations

- 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

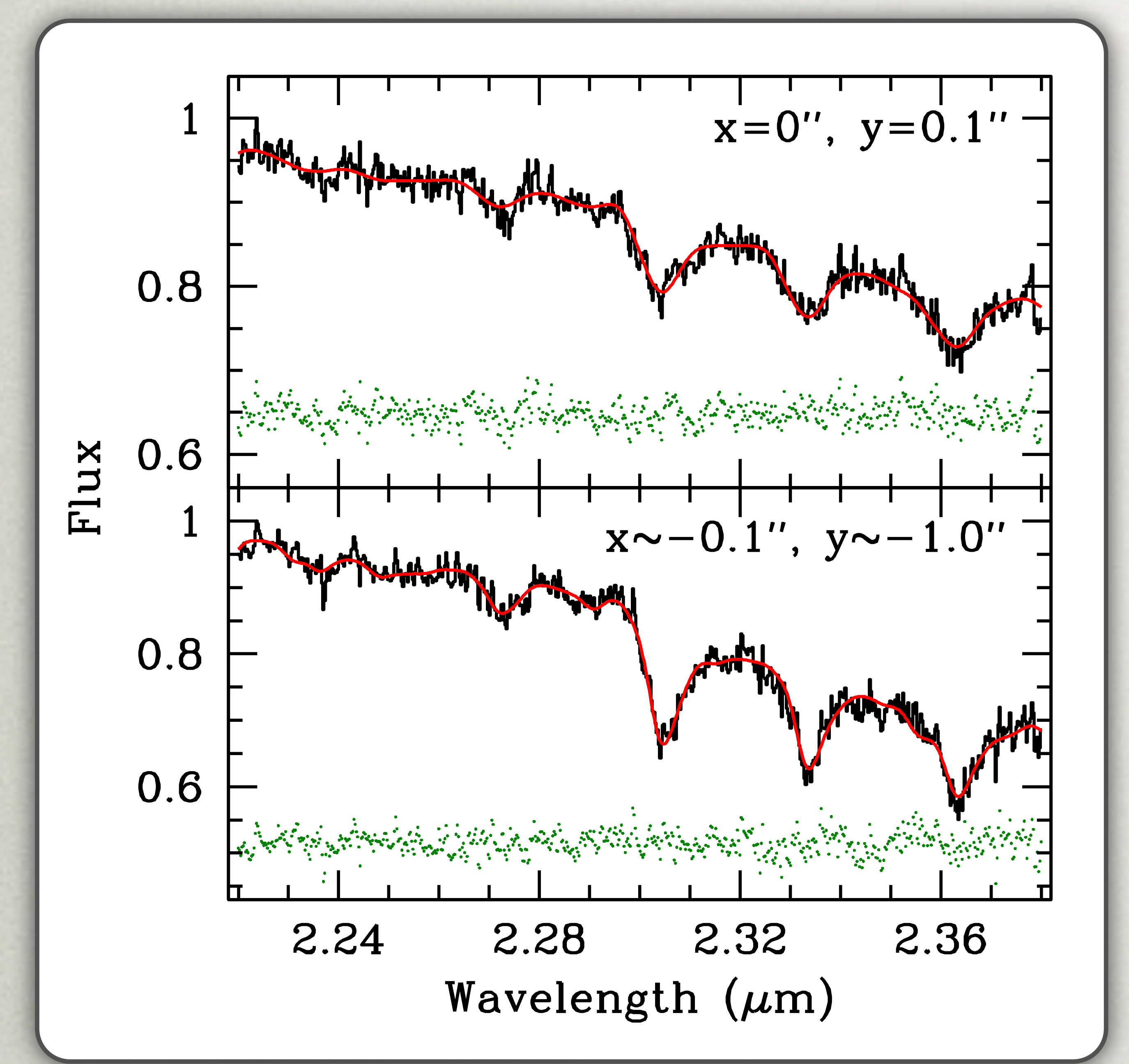


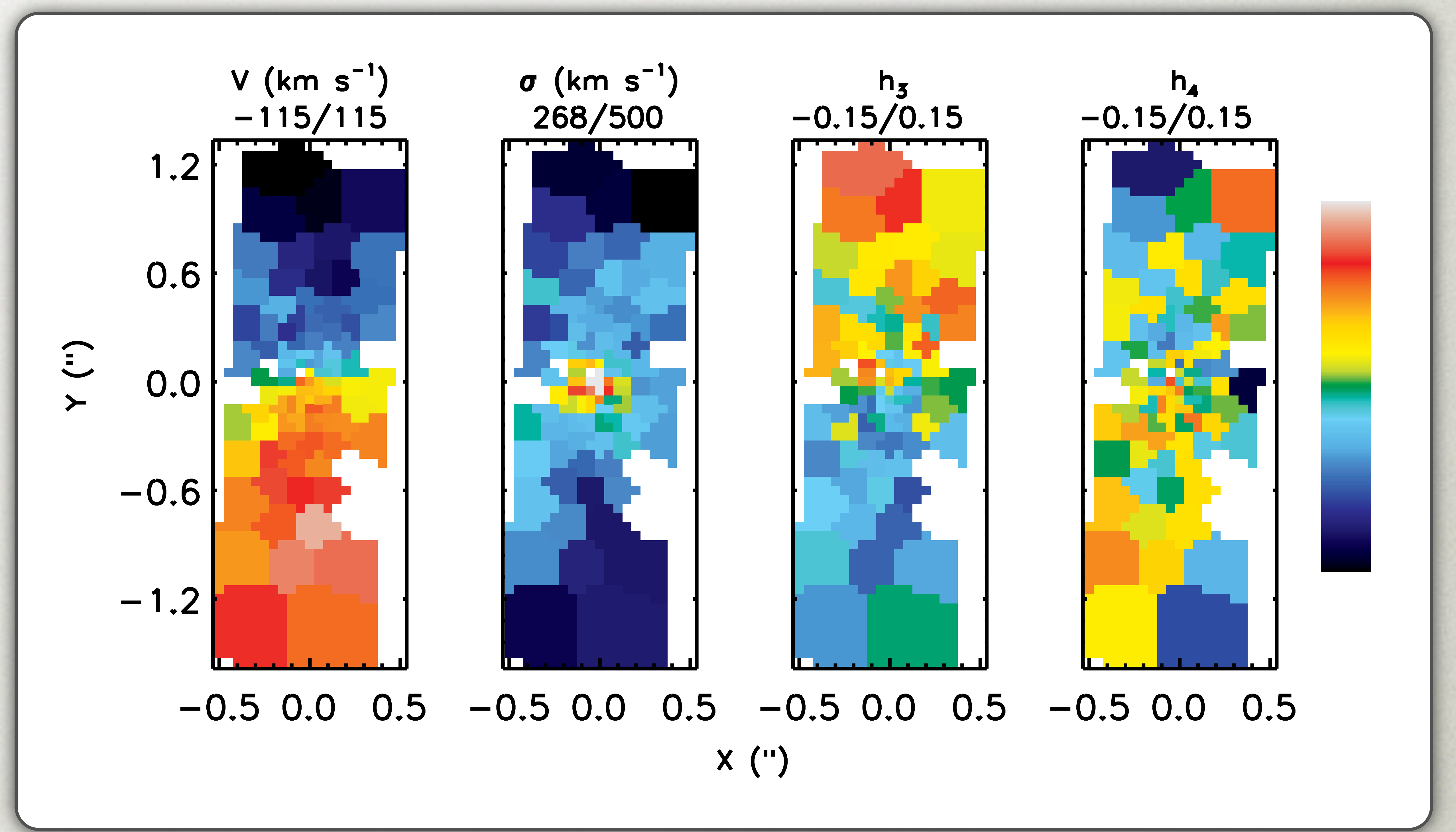


Kinematics

- Measured stellar kinematics (V, σ, h_3, h_4) in each bin with pPXF (Cappellari & Emsellem 2004).

OSIRIS





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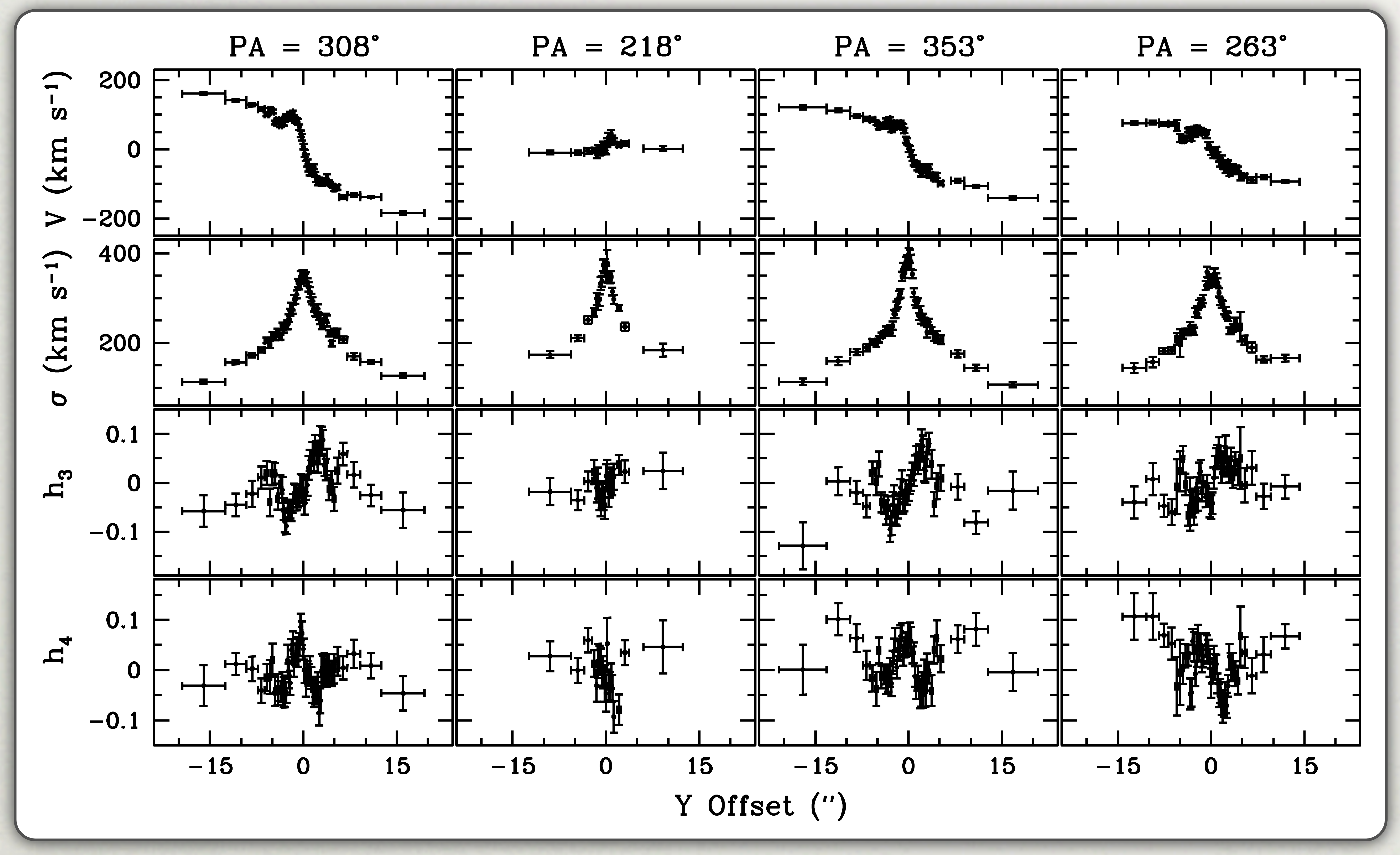
LRIS

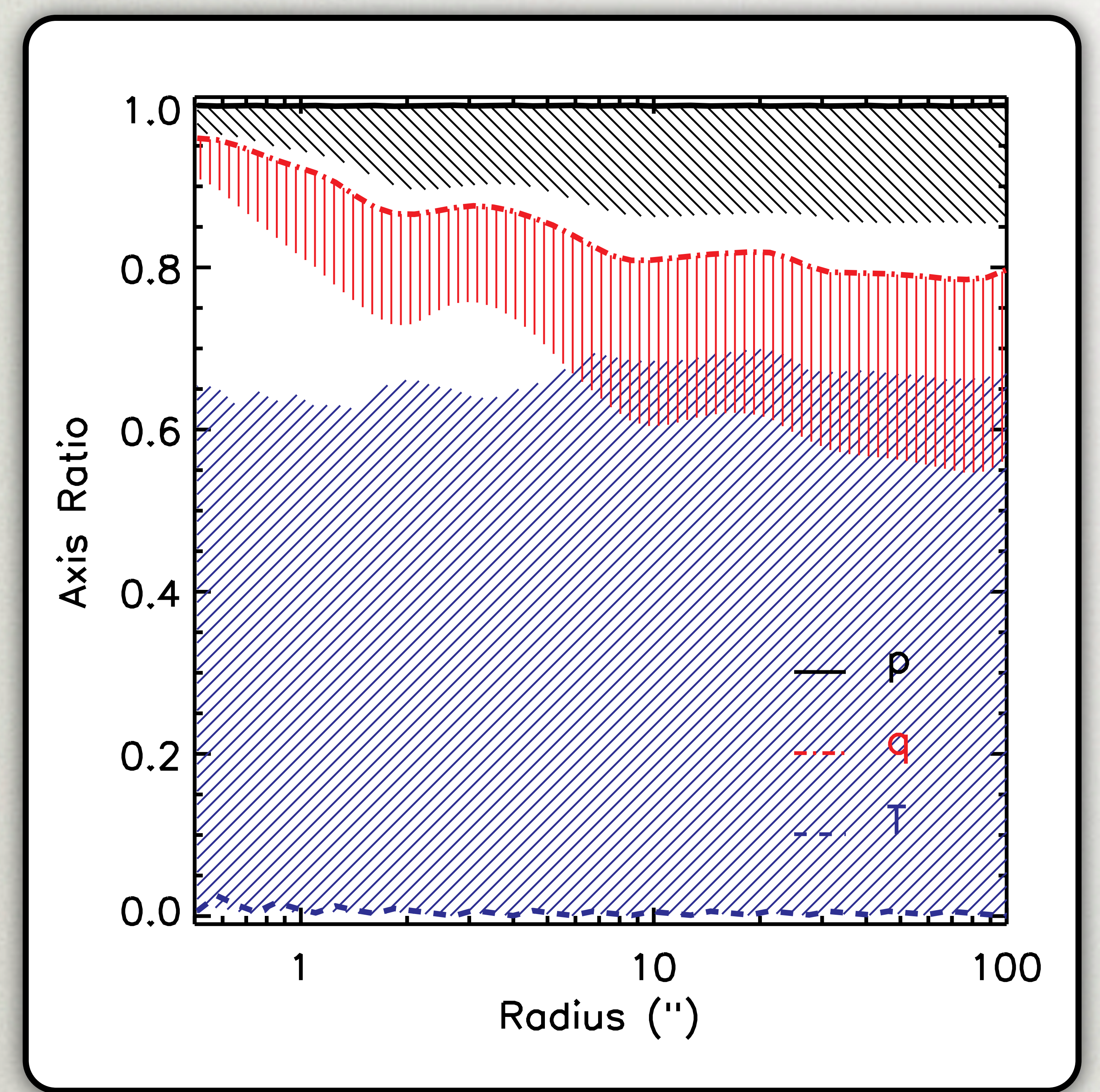


Stellar Dynamical Models

- 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 χ^2 is found.

Preliminary Results

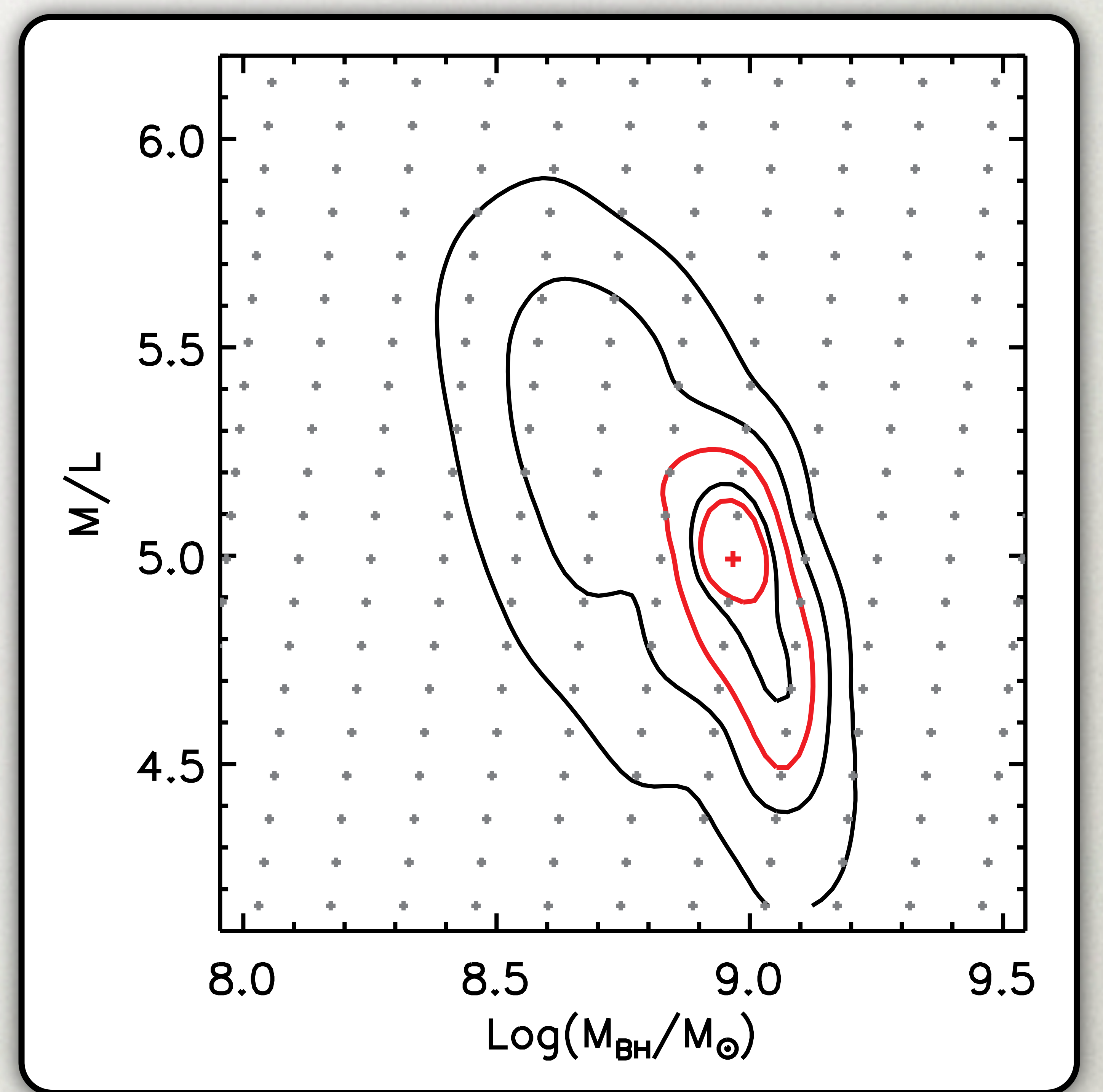
- Initially fixed M_{BH}, and explored the shape of NGC 3998.



$p = b/a$; $q = c/a$

$T = (1 - p^2)/(1 - q^2)$

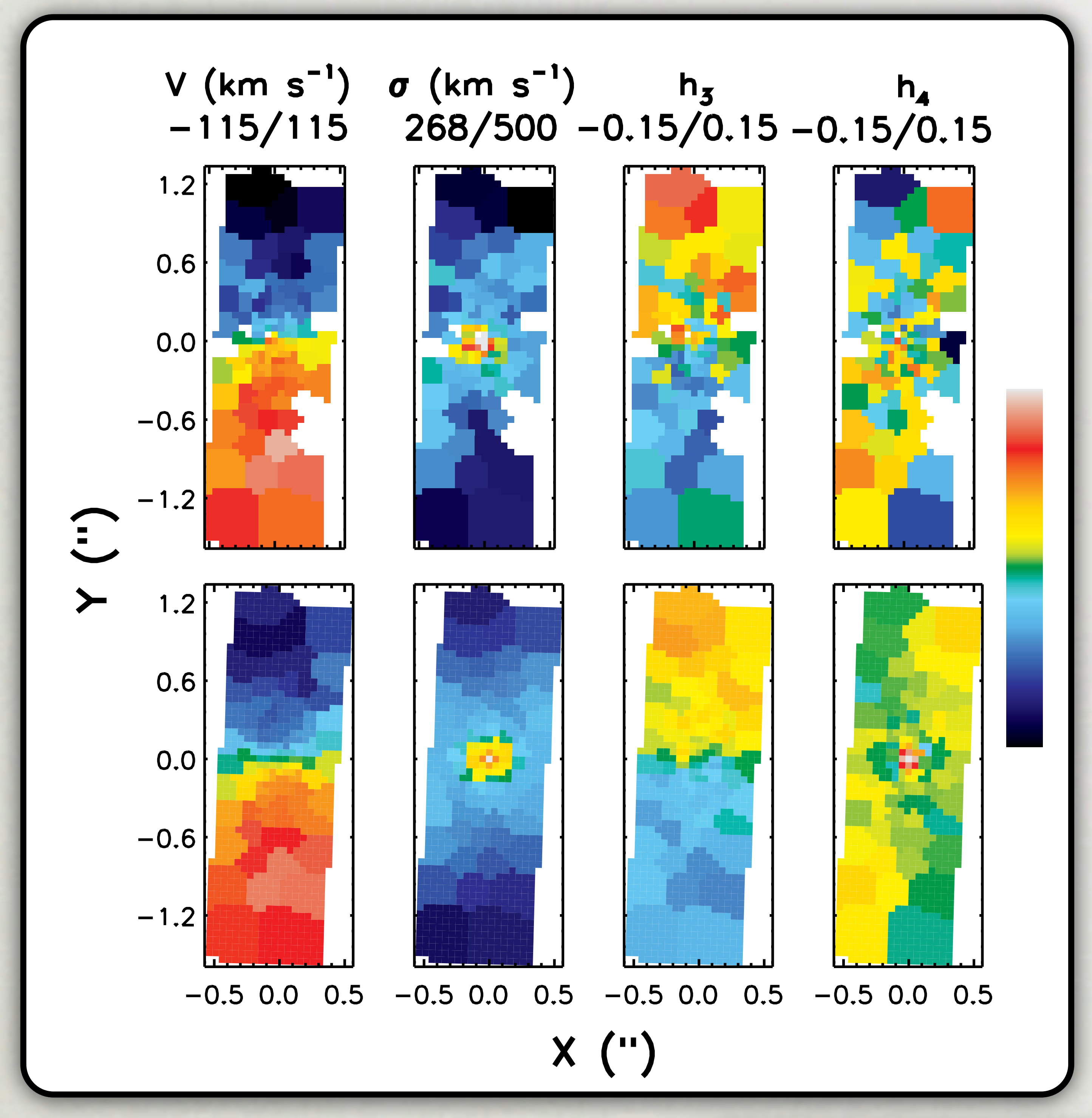
- Varied M_{BH} and M/L while sampling 8 shapes, which ranged from oblate to triaxial.

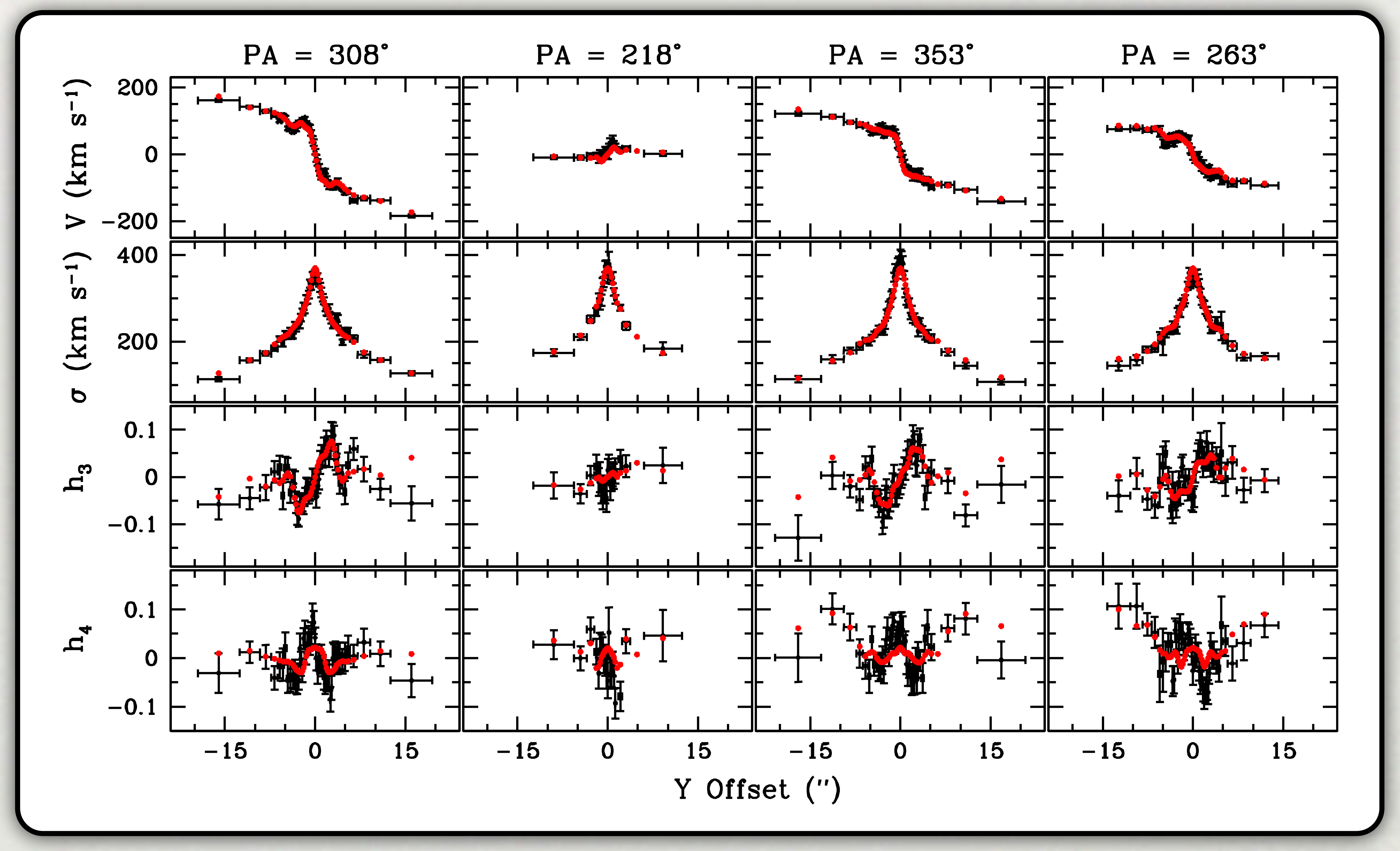


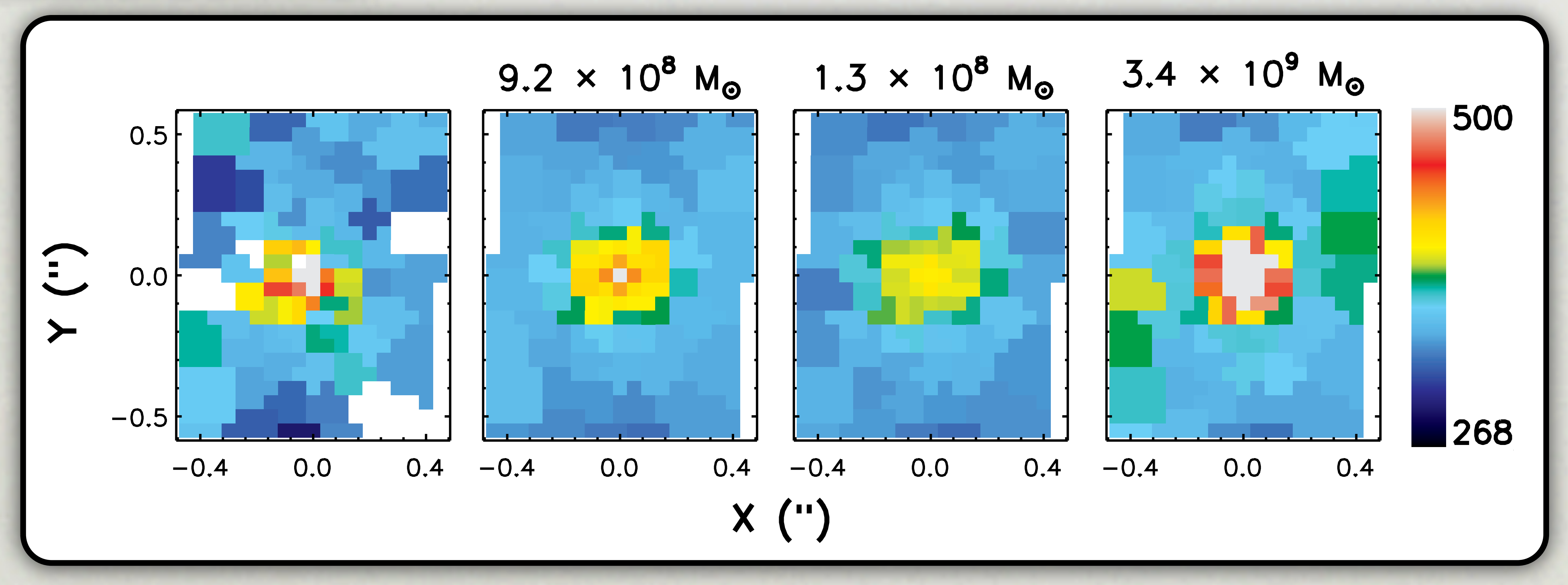
$M_{BH} = (9.2^{+3.3}_{-2.4}) \times 10^8\ M_\odot$

M/L (I-band, solar) = $5.0^{+0.2}_{-0.4}$

Preliminary Results







Initial Conclusions/Further Work

- We have measured the stellar kinematics on scales within r_{sphere} and on large scales out to ~ 1 R_e.

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

- Our preliminary stellar dynamical M_{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 σ = 305 km s^{-1}, M_{BH}-σ predicts: $M_{BH} = 7.9 \times 10^8\ M_\odot$
  With $L_V = 7.2 \times 10^9\ L_\odot$, M_{BH}-L predicts: $M_{BH} = 4.8 \times 10^7\ M_\odot$

- Further work will include running additional model grids to assess the robustness of our M_{BH} measurement.

Open Questions

- How much of the scatter in the M_{BH}-σ 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?