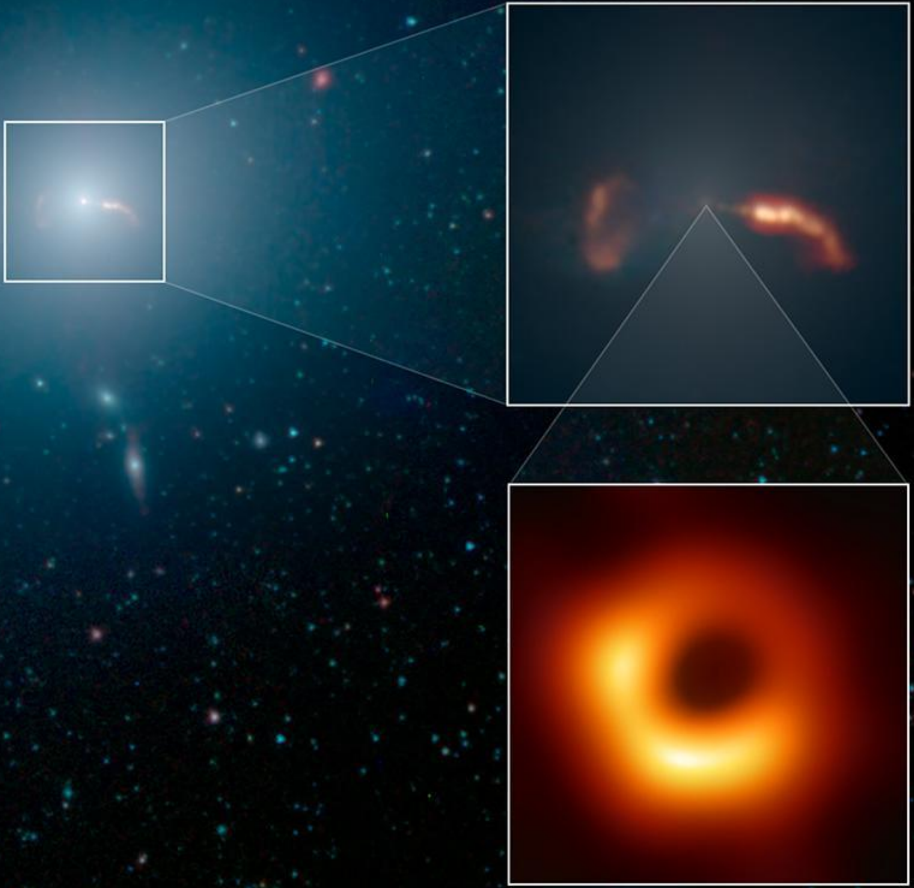
The Black Hole Mass of M87 with Stellar Kinematics



Sargent (1978) + Gebhardt (2011)

The Context:

- Schmidt+1963: Quasars + 3C273

1040 NATURE March 16, 1963 Vol. 197

3C 273 : A STAR-LIKE OBJECT WITH LARGE RED-SHIFT

By Dr. M. SCHMIDT

Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena

- Hoyle, Fowler, Zeldovich, Salpeter, etc. (1965-1975): Mass concentration is likely black hole with jets

ACCRETION OF INTERSTELLAR MATTER BY MASSIVE OBJECTS

Observations of quasi-stellar radio sources have indicated the existence in the Uni-
verse of extremely ma
the possible further gr
of interstellar gas ont
evidence for (and poss
inside ordinary galaxi
of mass $M > 10^6$ (mas
what like ours.

ON THE NATURE OF STRONG RADIO SOURCES

F. Hoyle and William A. Fowler

(Received 1962 August 27)

- Wolfe and Burbidge+1970: Velocity dispersions could mean a black hole

BLACK HOLES IN ELLIPTICAL GALAXIES

A. M. Wolfe* and G. R. Burbidge

Department of Physics, University of California, San Diego

Received 1970 January 26; revised 1970 April 7

ABSTRACT

- Sargent+1978: First evidence of SMBH

DYNAMICAL EVIDENCE FOR A CENTRAL MASS CONCENTRATION IN THE GALAXY M87

W. L. W. Sargent* and Peter J Young

Hale Observatories, California Institute of Technology, Carnegie Institution of Washington

A. Boksenberg*† and Keith Shortridge*

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C. R. Lynds

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and

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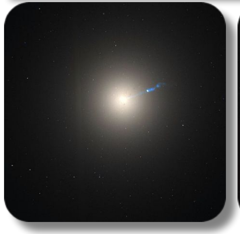
Department of Astronomy, University of Victoria

Received 1977 September 26; accepted 1977 November 1

Overview of Sargent+1978

New radial velocity **and** velocity dispersion measurements on UCL image photon counting system



M87 “remarkable behavior”

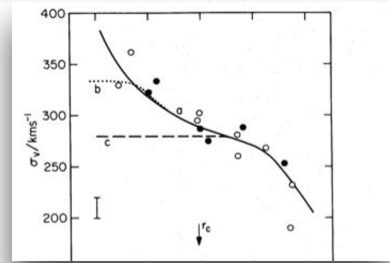
NGC 3379 “standard galaxy”

DYNAMICAL EVIDENCE FOR A CENTRAL MASS CONCENTRATION IN THE GALAXY M87

W. L. W. SARGENT* AND PETER J YOUNG
Hale Observatories, California Institute of Technology, Carnegie Institution of Washington
A. BOKSENBERG*† AND KEITH SHORTRIDGE*
Department of Physics and Astronomy, University College London
C. R. LYNDS
Kitt Peak National Observatory
AND
F. D. A. HARTWICK*
Department of Astronomy, University of Victoria
Received 1977 September 26; accepted 1977 November 1

Implement Fourier Quotient Method on spectra (Sargent+1977) to extract velocity dispersion, redshift, line strength

→



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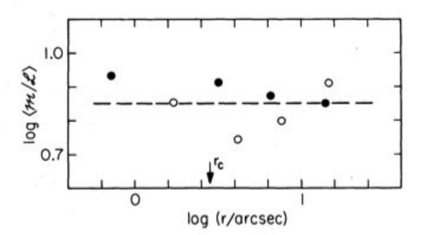
Fit Parameters to King+1966 model, allowing M/L calculations



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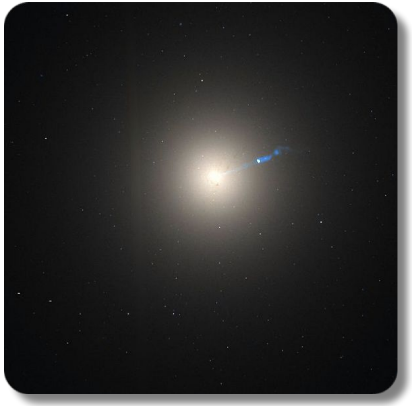
Model independent calculations of M/L for M87 center

$$M_{BH} \sim 5 \times 10^9 M_\odot$$

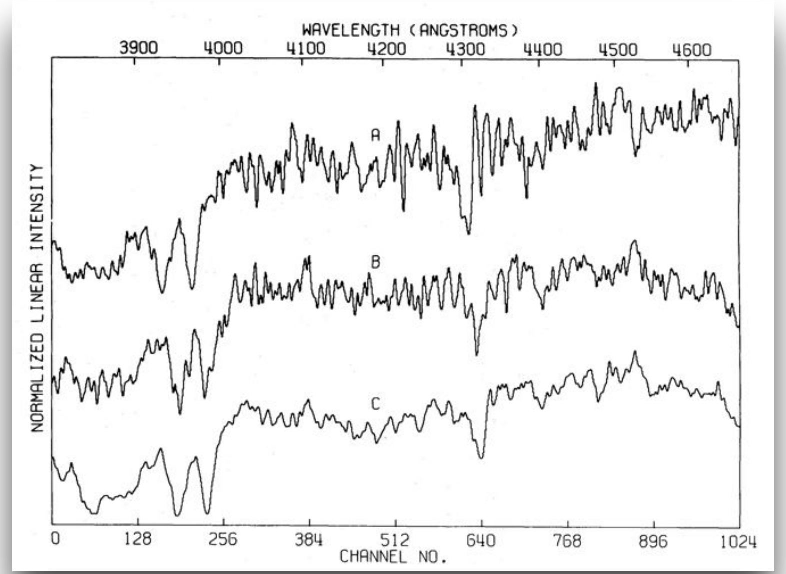
Observations



- Kitt Peak 4m telescope
- 20 simultaneous spectra
- 1000 channels covering 1060Å
- Particular care to avoid jet

- 5m Hale Telescope
- 17 simultaneous spectra
- 1000 channels over 310Å
- Spatial resolution of 2".4 along slit

Additional Spectra of 3 Comparison Stars



An aside…

Measuring Velocity Dispersion

VELOCITY DISPERSIONS FOR 13 GALAXIES

WALLACE L. W. SARGENT
Hale Observatories, California Institute of Technology, Carnegie Institution of Washington

PAUL L. SCHECHTER
Institute for Advanced Study

AND

A. BOKSENBERG AND KEITH SHORTRIDGE
Department of Physics and Astronomy, University College London

Received 1976 June 17

“Fourier Quotient Method”
(Sargent+1977)

Fourier Quotient Method (Sargent+1977)

- Method to extract velocity dispersion σ, radial velocity *cz*, and line ratio γ (between the galaxy and comparison star)
- **Assumption:** Each galaxy spectrum is the convolution of a mean stellar spectrum and a Doppler **broadening function** *B(k)*.
- Least squares solution for σ, *z*, and γ

$$G(k) = S(k) \circ B(k)$$

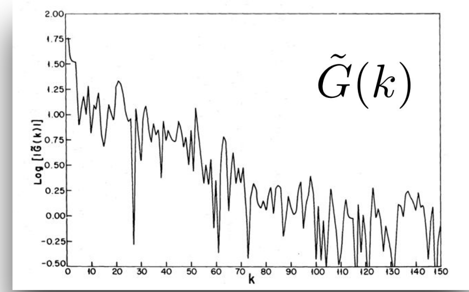
$$Q(k) = \underbrace{\tilde{G}(k)}_{\text{DFT of galaxy spectrum}} \; / \; \underbrace{\tilde{S}(k)}_{\text{DFT of mean stellar spectrum}}$$

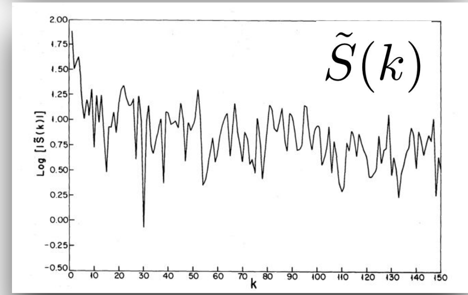
$$\tilde{B}(k) = \gamma \exp\left[-\frac{1}{2}\left(\frac{2\pi k\sigma_v}{nc\Delta\ln\lambda}\right)^2 + \frac{2\pi i k\ln(1+z)}{n\Delta\ln\lambda}\right]$$

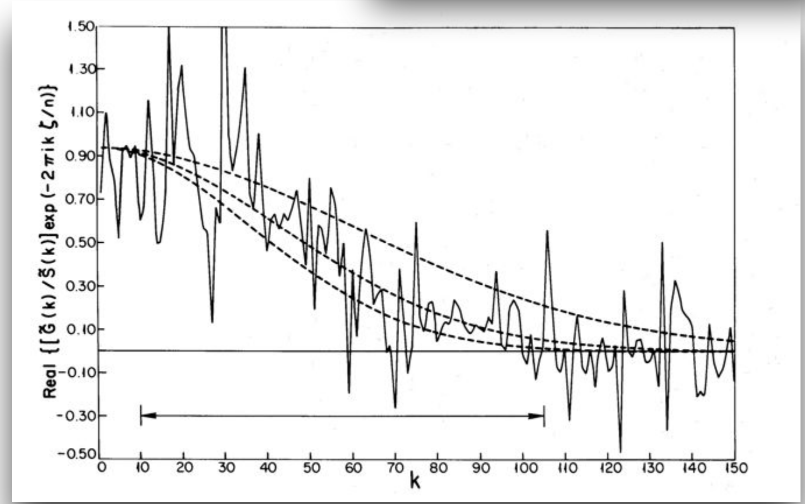
$$\tilde{B}(k) = Q(k) = \frac{\tilde{G}(k)}{\tilde{S}(k)}$$

Fourier Quotient Method (Sargent+1977)

$$\tilde{B}(k) = Q(k) = \frac{\tilde{G}(k)}{\tilde{S}(k)}$$







$$\chi^2 = \sum_{k=k_L}^{k_H} \left| \frac{Q(k) - B(k)}{\Delta Q(k)} \right|^2$$

$$\tilde{B}(k) = \gamma \exp\left[-\frac{1}{2} \left(\frac{2\pi k \sigma_v}{nc\Delta \ln \lambda} \right)^2 + \frac{2\pi i k \ln(1+z)}{n\Delta \ln \lambda} \right]$$

$$Q(k) = \underbrace{\tilde{G}(k)}_{\text{DFT of galaxy spectrum}} \; / \; \underbrace{\tilde{S}(k)}_{\text{DFT of mean stellar spectrum}}$$

- Dashed lines are the fits with estimates from minimization: *cz = 84 km/s, σ = 60, 84, 100 km/s*

Robustness of Fourier Quotient Method

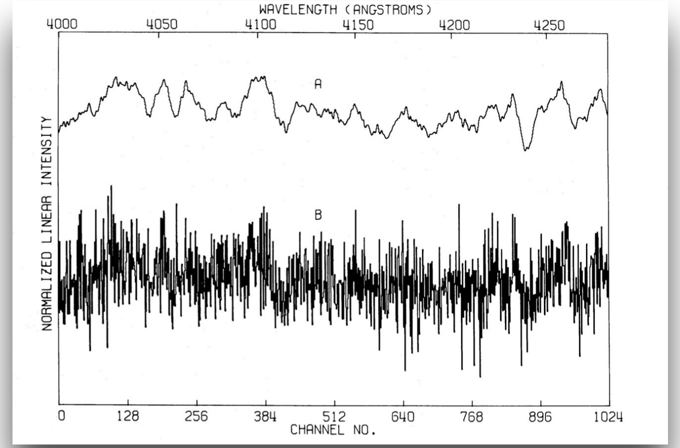
Previous Tests

- Agreement with visual methods
- Agreement across comparison stars
- Different spectral regions gave the same σ
- Differing regions of Fourier space gave the same results

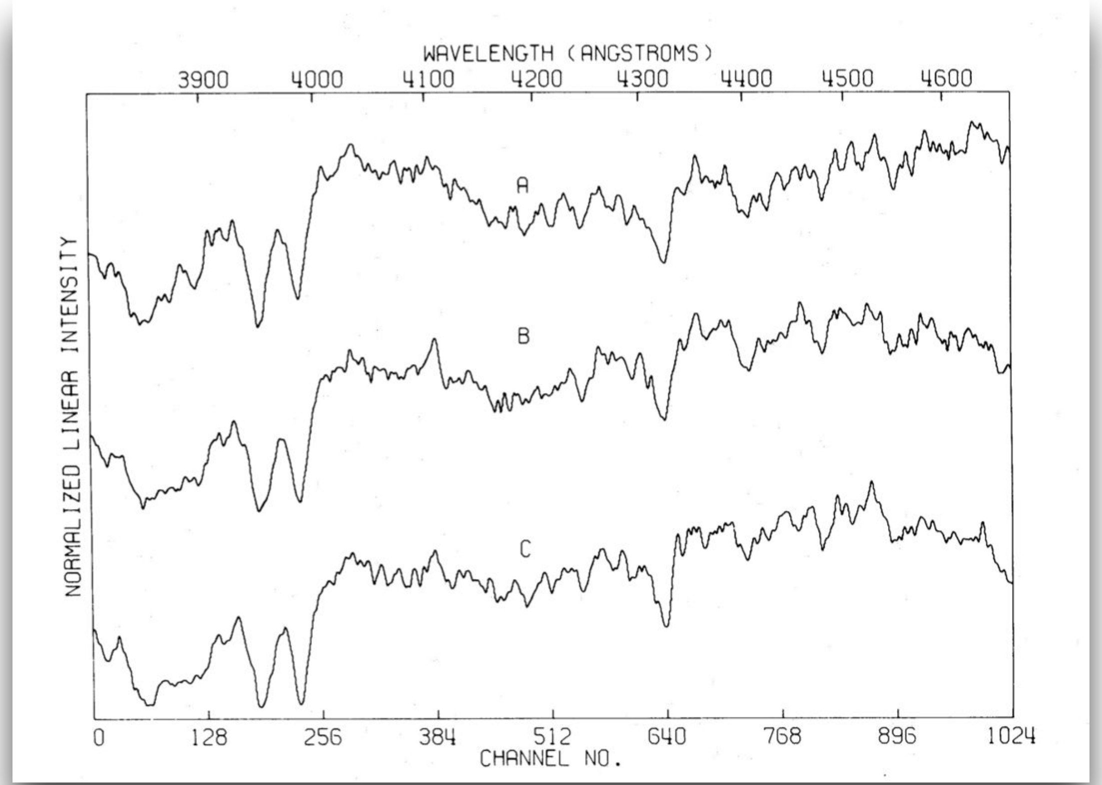
does it work with faint outer parts of galaxies?

New Tests

- Exclusion of Ca II H and K lines so that metallicity doesn't bias σ
- Simulating a central blue continuum source which did not affect velocity dispersion
- Random noise in galaxy and star spectra leads to $\Delta\sigma$ = 2 km/s.



Fourier Quotient Method for M87



9” West of Center σ = 300 km/s

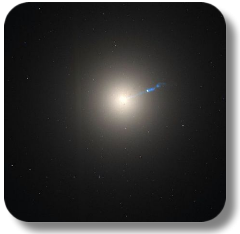
2” West of Center σ = 350 km/s

- Slightly broader lines

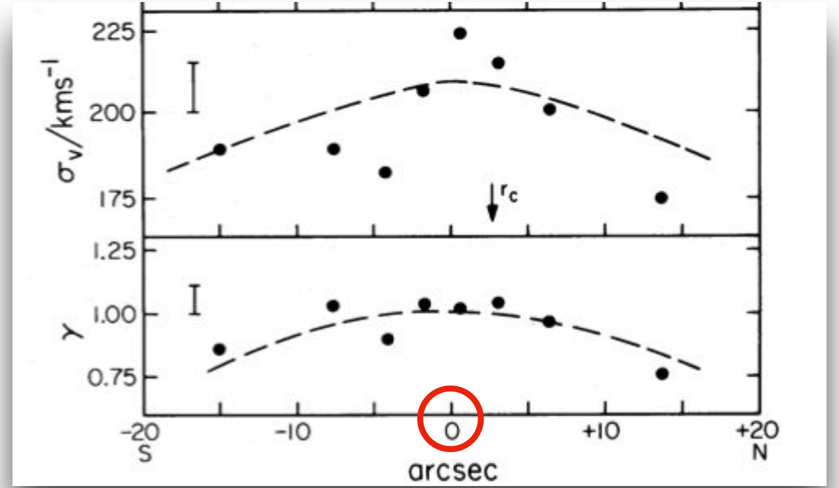
3” East of Center σ = 325 km/s

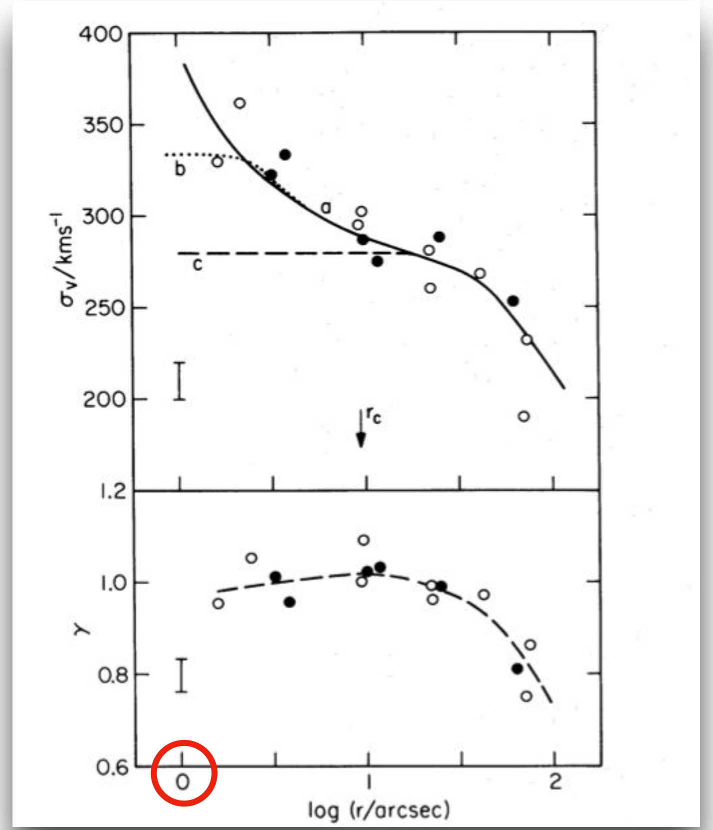
Results of FQM in Sargent+1978…

NGC 3379



M87





King Models (BT, page 307)

$$f_K(\mathcal{E}) = \begin{cases} \rho_1 (2\pi\sigma^2)^{-3/2} \left(e^{\mathcal{E}/\sigma^2} - 1\right) & \mathcal{E} > 0 \\ 0 & \mathcal{E} \le 0 \end{cases}$$

How do we measure the mass in order to calculate a mass to light ratio?

$$\mathcal{E} = \Psi - \frac{1}{2}v^2 \text{ where } \Psi \equiv \Phi_0 - \Phi$$

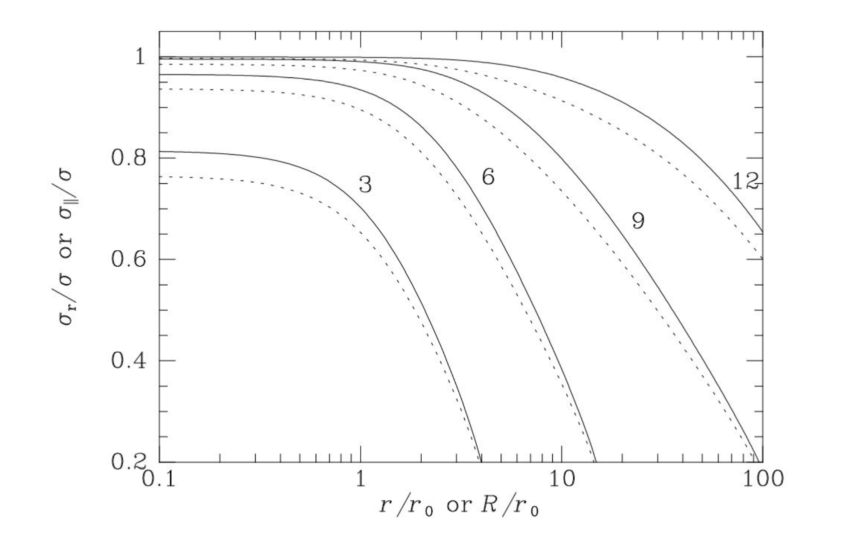
We want a family of models that is like an isothermal sphere at small radii and less dense at large radii.

We typically choose phi0 so that F(E<=0)=0.

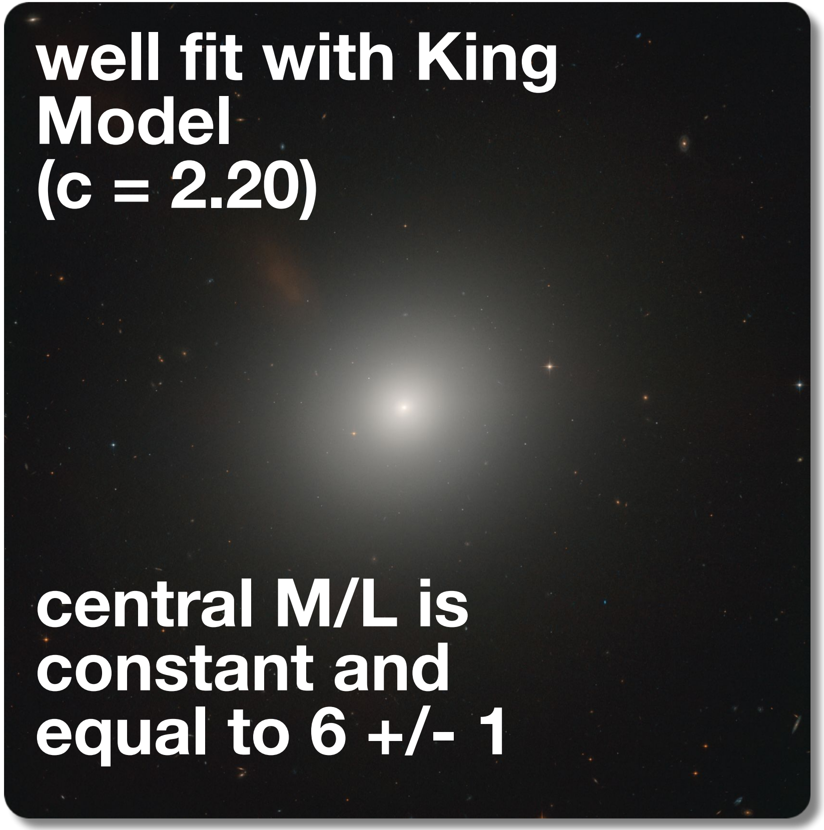
They are characterized by either the concentration *c* or the quantity $\Psi(0)/\sigma^2$

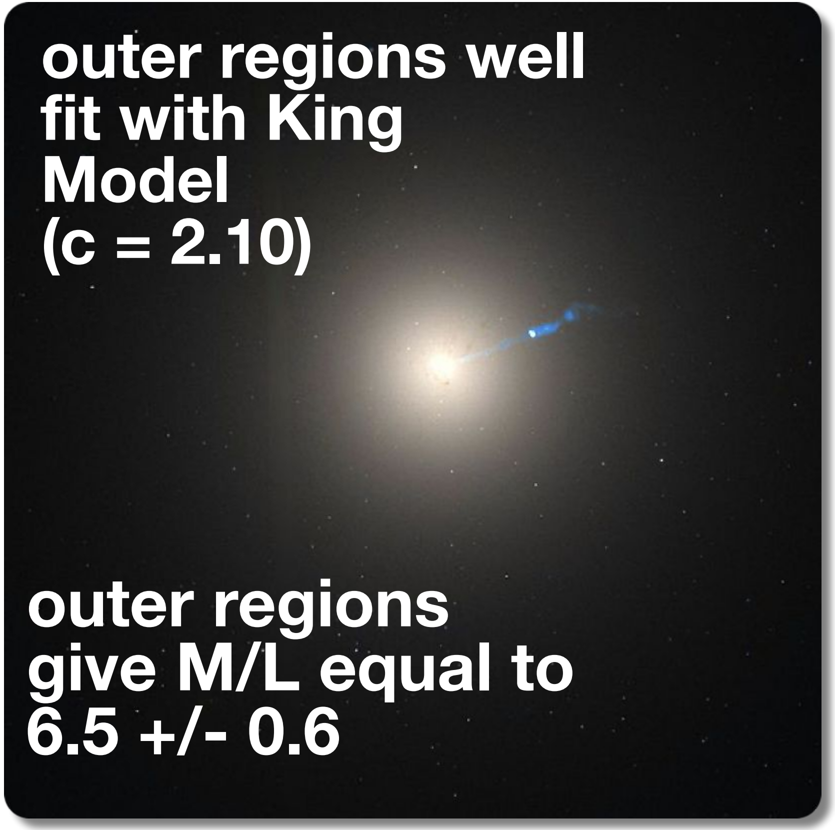
$$\rho_K(\Psi) = \rho_1 \left[e^{\Psi/\sigma^2} \text{erf}\left(\frac{\sqrt{\Psi}}{\sigma}\right) - \sqrt{\frac{4\Psi}{\pi\sigma^2}} \left(1 + \frac{2\Psi}{3\sigma^2}\right) \right]$$

$$\tilde{\rho} \equiv \frac{\rho}{\rho_0} \quad \text{and} \quad \tilde{r} \equiv \frac{r}{r_0}, \quad \text{where} \quad r_0 \equiv \sqrt{\frac{9\sigma^2}{4\pi G \rho_0}}.$$

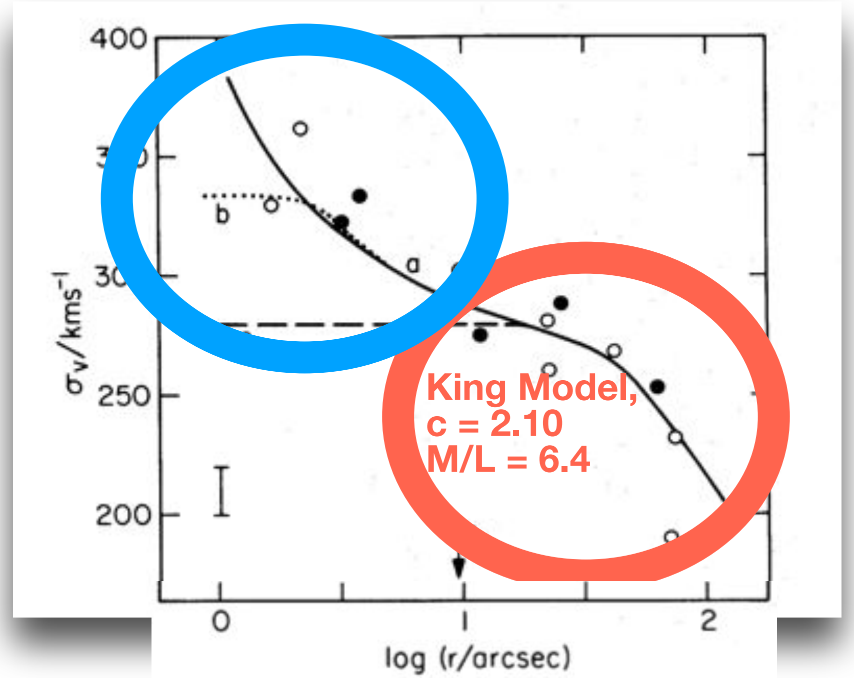


King Models and Photometric Data for NGC 3379 and M87





Central Mass Calculation



$$M(r < 1.5'') = (6.5 \pm 1.5) \times 10^9 M_\odot$$

$$\langle M/L \rangle = 58 \pm 16 \text{ solar units}$$

what about [M/L](r)?

$$\frac{d}{dr}\left[\rho_*(r)\sigma_v^2(r)\right] = -\frac{GM(r)}{r^2}\rho_*(r)$$

first moment of collisionless BE

$$M(1.''5) = 4 \times 10^9 \left[-\frac{d\ln L_*}{d\ln r} - \frac{d\ln(M/L)}{d\ln r} - \frac{d\ln\sigma_v^2}{d\ln r}\right] M_\odot$$

curve fits

Young+1978 b

Gebhardt+2011:

The Black-Hole Mass in M87 from Gemini/NIFS Adaptive Optics Observations

THE BLACK-HOLE MASS IN M87 FROM GEMINI/NIFS ADAPTIVE OPTICS OBSERVATIONS

KARL GEBHARDT[1], JOSHUA ADAMS[1], DOUGLAS RICHSTONE[2], TOD R. LAUER[3], S. M. FABER[4], KAYHAN GÜLTEKIN[2], JEREMY MURPHY[1], SCOTT TREMAINE[5]

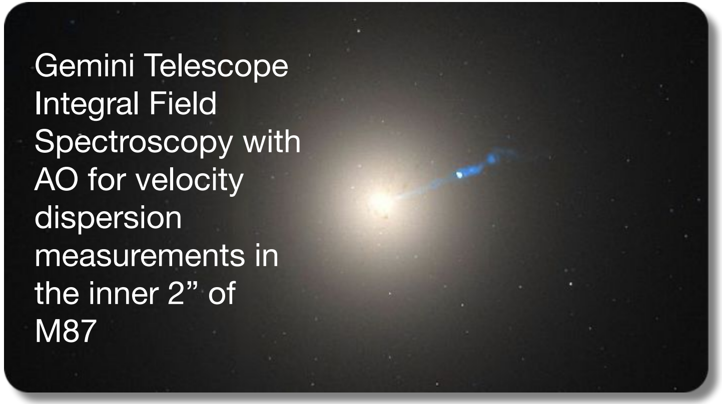
Draft version September 17, 2018

ABSTRACT

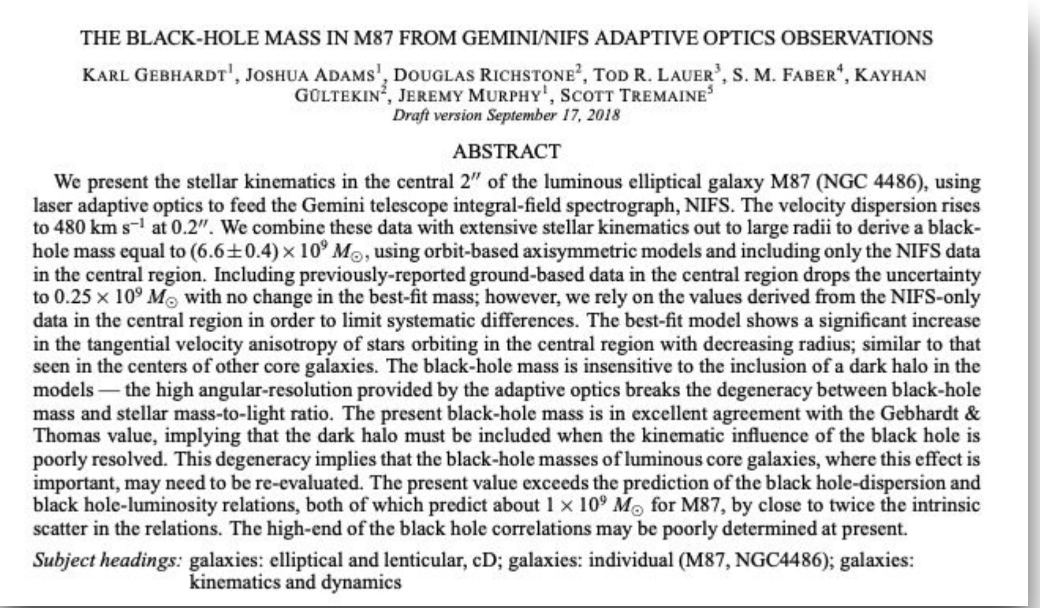
We present the stellar kinematics in the central 2″ of the luminous elliptical galaxy M87 (NGC 4486), using laser adaptive optics to feed the Gemini telescope integral-field spectrograph, NIFS. The velocity dispersion rises to 480 km s^{-1} at 0.2″. We combine these data with extensive stellar kinematics out to large radii to derive a black-hole mass equal to $(6.6 \pm 0.4) \times 10^9\ M_\odot$, using orbit-based axisymmetric models and including only the NIFS data in the central region. Including previously-reported ground-based data in the central region drops the uncertainty to $0.25 \times 10^9\ M_\odot$ with no change in the best-fit mass; however, we rely on the values derived from the NIFS-only data in the central region in order to limit systematic differences. The best-fit model shows a significant increase in the tangential velocity anisotropy of stars orbiting in the central region with decreasing radius; similar to that seen in the centers of other core galaxies. The black-hole mass is insensitive to the inclusion of a dark halo in the models — the high angular-resolution provided by the adaptive optics breaks the degeneracy between black-hole mass and stellar mass-to-light ratio. The present black-hole mass is in excellent agreement with the Gebhardt & Thomas value, implying that the dark halo must be included when the kinematic influence of the black hole is poorly resolved. This degeneracy implies that the black-hole masses of luminous core galaxies, where this effect is important, may need to be re-evaluated. The present value exceeds the prediction of the black hole-dispersion and black hole-luminosity relations, both of which predict about $1 \times 10^9\ M_\odot$ for M87, by close to twice the intrinsic scatter in the relations. The high-end of the black hole correlations may be poorly determined at present.

Subject headings: galaxies: elliptical and lenticular, cD; galaxies: individual (M87, NGC4486); galaxies: kinematics and dynamics

Overview:



Gemini Telescope Integral Field Spectroscopy with AO for velocity dispersion measurements in the inner 2” of M87



THE BLACK-HOLE MASS IN M87 FROM GEMINI/NIFS ADAPTIVE OPTICS OBSERVATIONS

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Determination of PSF and removal of non-stellar features from the spectra

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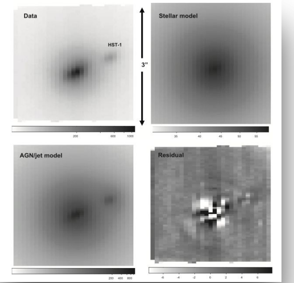

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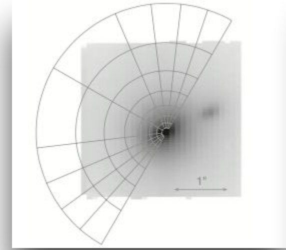
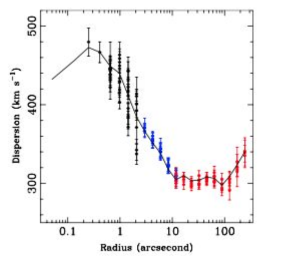
Kinematic and Dynamical Modeling for Velocity Dispersions and BH Mass





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Black Holes Mass and Consequences of BH-Galaxy Property Relations

$$M_{\rm BH} = (6.6 \pm 0.4) \times 10^9 M_\odot$$

“Why did we read this paper, too?”

Neglected, systematic effects that are addressed:

Dark Halo — Black hole’s kinematics are poorly resolved.

Incomplete Orbit Library — Orbital structure near the BH is dominated by tangential orbits. Older models are too radial.

Triaxiality — Factor of 2 increase versus axisymmetric models.

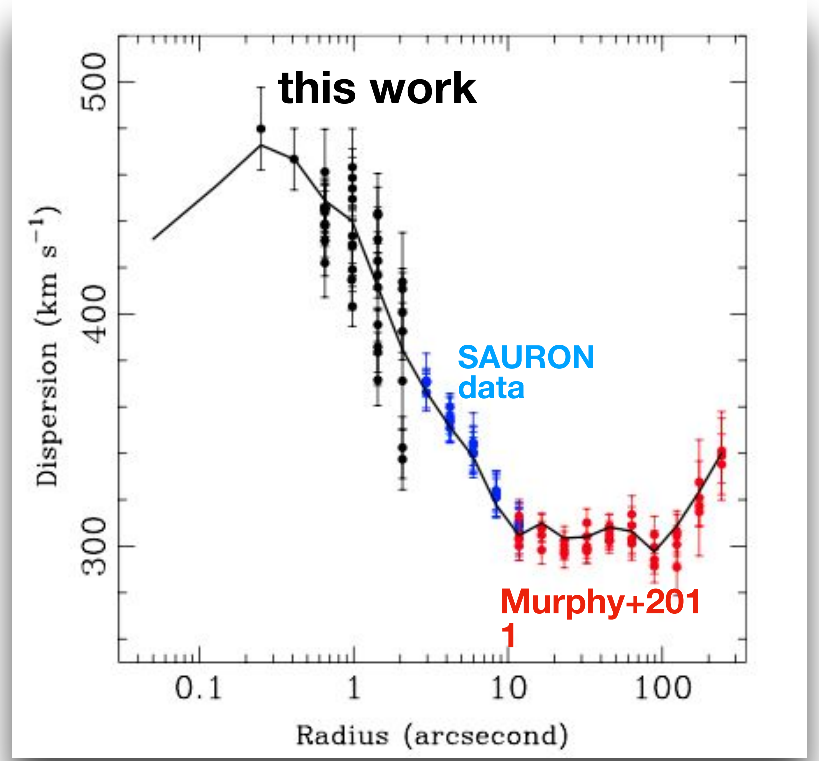
These effects predict higher masses.

Observations, Archival Data,
and the Power of AO

Spectra to the innermost ~0".2 of the nucleus of M87.

Archival data is so abundant that, "we rely on data that provide the highest spatial resolution, most complete coverage, and highest S/N."

Results use only present work's innermost data, so as to have independent results.



Obtaining similar kinematics, similar resolution, and similar S/N would require 90 hours on Hubble (compared to 10 hours with AO).

PSF and Stellar Components

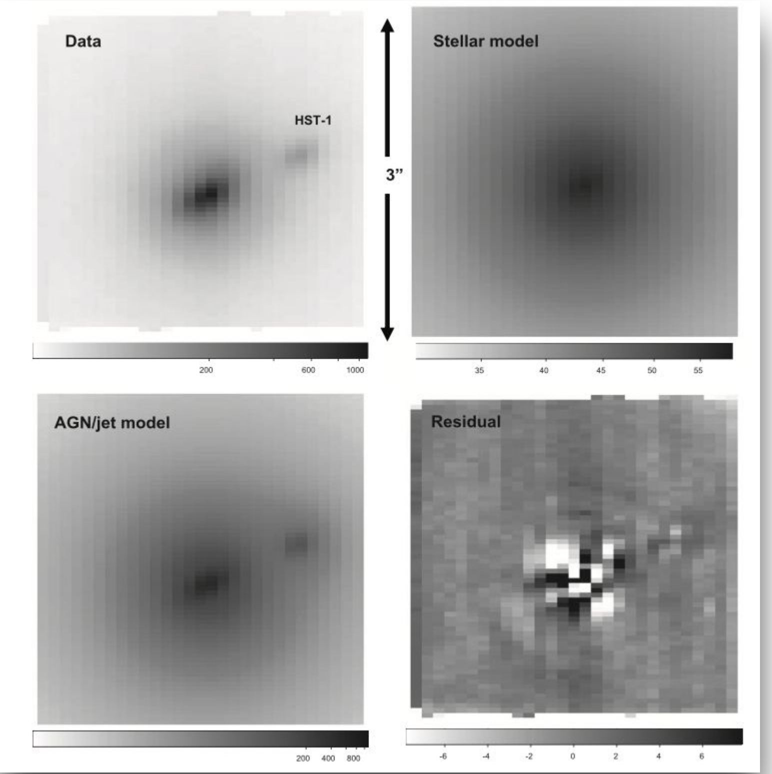
Measuring stellar kinematics.

(1) Assume stellar population (color and spectral slope) do not vary near the center.

(2) Treat the AGN and jet as a set of point sources with flat continuum.

$$\mathrm{PSF}(x,y) = \underbrace{N(x,y)}_{\text{anistropic Gaussian inner PSF}} + \underbrace{M(x,y)}_{\text{power law outer PSF}}$$

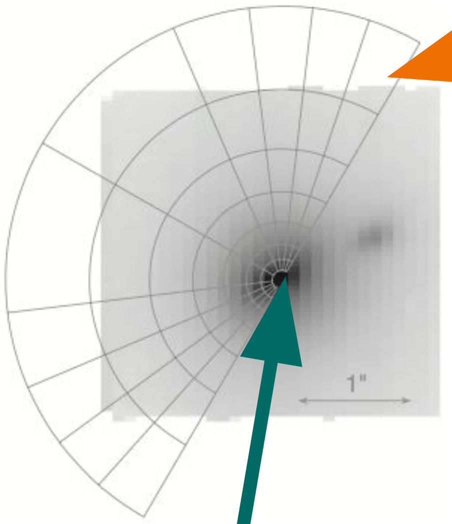
Tease out AGN/jet with the CO equivalent width at each pixel.



An aside: The AGN/jet is not offset from center like others (Batcheldor+2010) previously thought.

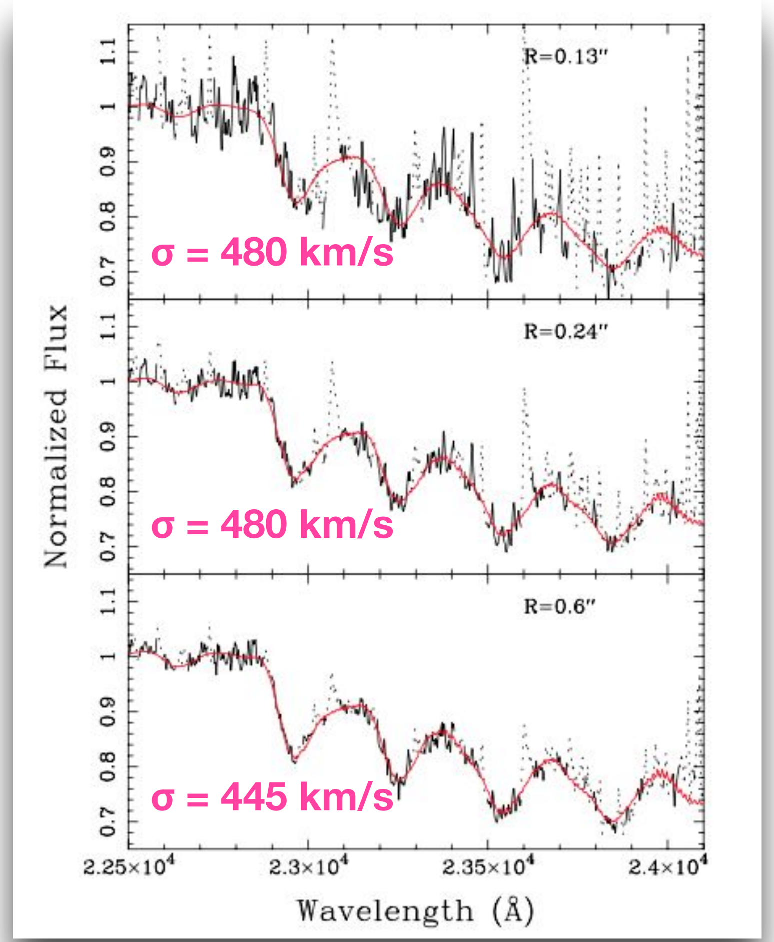
Kinematic Fits

Outer two bins combined for higher SNR.

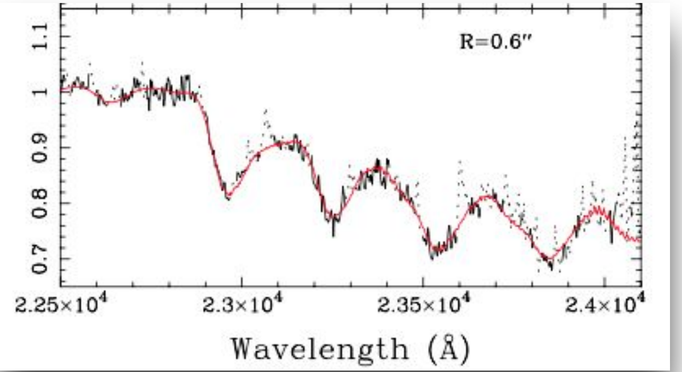


40 spectra used for dynamical modeling, with each radius being summed over.

Inner bins discarded due to AGN contamination.



But how do we actually get σ from these spectra?



= **Velocity Profile** * **Representative Template Spectra**

Goal: Find the best velocity dispersion given some representative spectra.

Task: Adjust stellar spectral weights and LOSVD until we fit the galaxy spectrum.

LOSVDs are not always Gaussian, so we parametrize in terms of the Gauss-Hermite polynomials.

$$f(y) = I_0 \exp\left(-\frac{y^2}{2}\right)\left[1 + h_3 H_3(y) + h_4 H_4(y)\right]$$

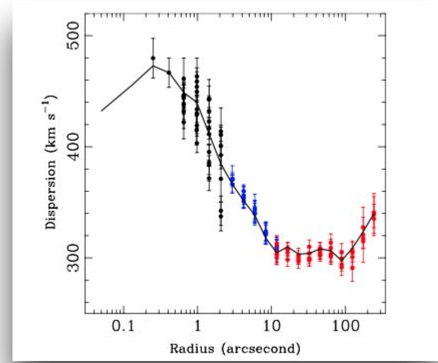
$$y \equiv \frac{v - v_{\rm fit}}{\sigma_{\rm fit}}$$

h_3: skewness

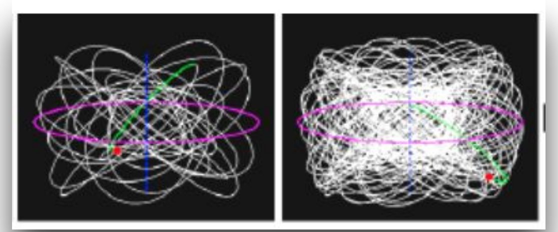
h_4: kurtosis

LOSVD Fitting (Pinkney+2003)

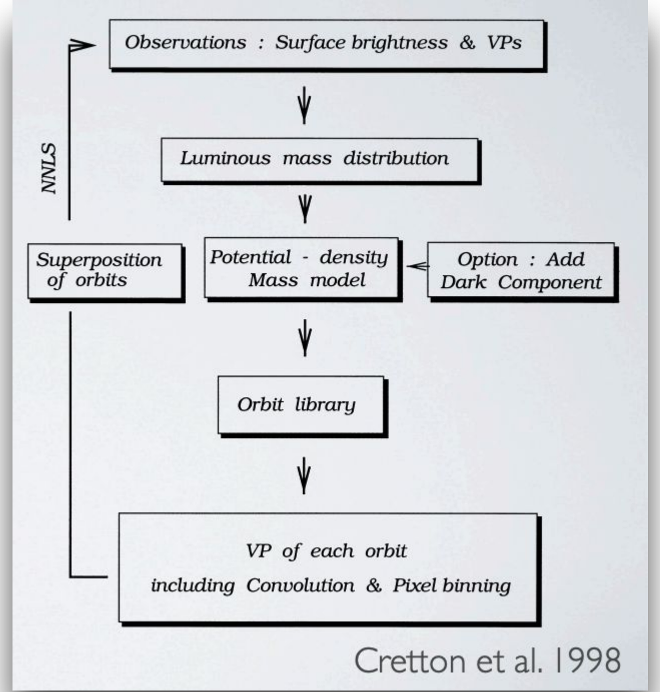
Dynamical Modeling of the SMBH (Schwarzschild Method)

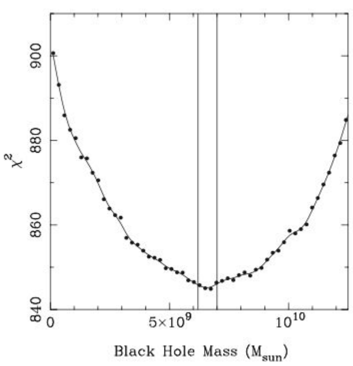


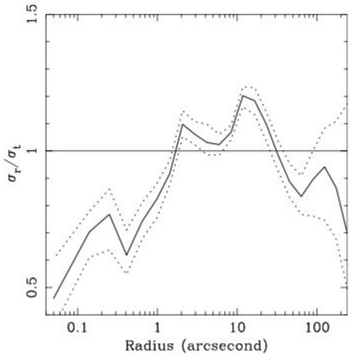
Observables



Orbit Library with Different Mass Distributions (40,000/model)







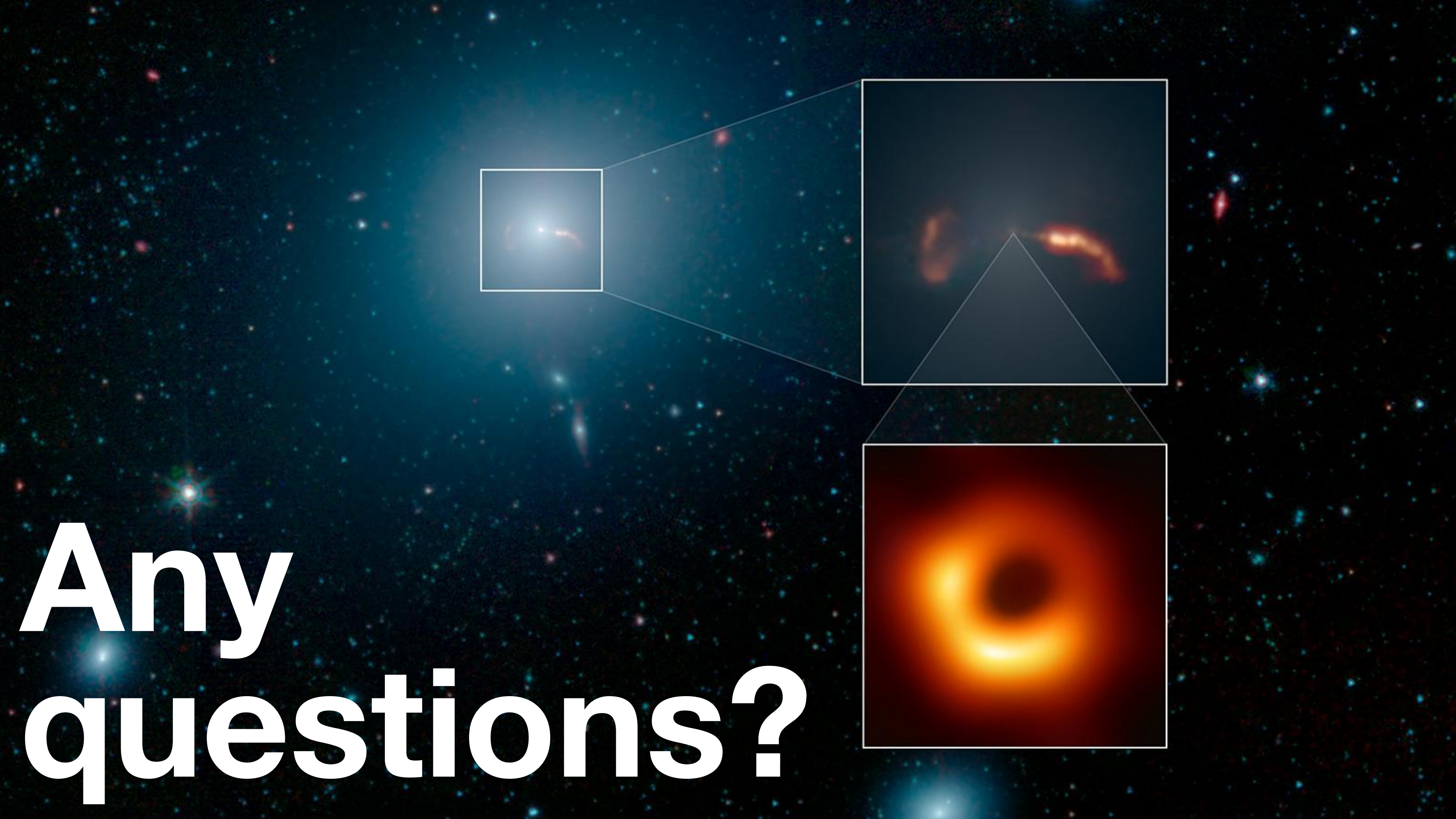
$$M_{\rm BH} = (6.6 \pm 0.4) \times 10^9 M_\odot$$

Consequences for the Past and Future

M-σ and M-L Relations → New measurements differ by 0.82 dex. Re-examined with new measurements and definitions of velocity dispersion.

Gas Kinematic Measurements → Still disagree at the 2σ level. Disk inclination is the reason?

Future Mass Measurements → High SNR, data at large radii break the degeneracy of the BH mass, DM halo, and M/L profile.


Any questions?