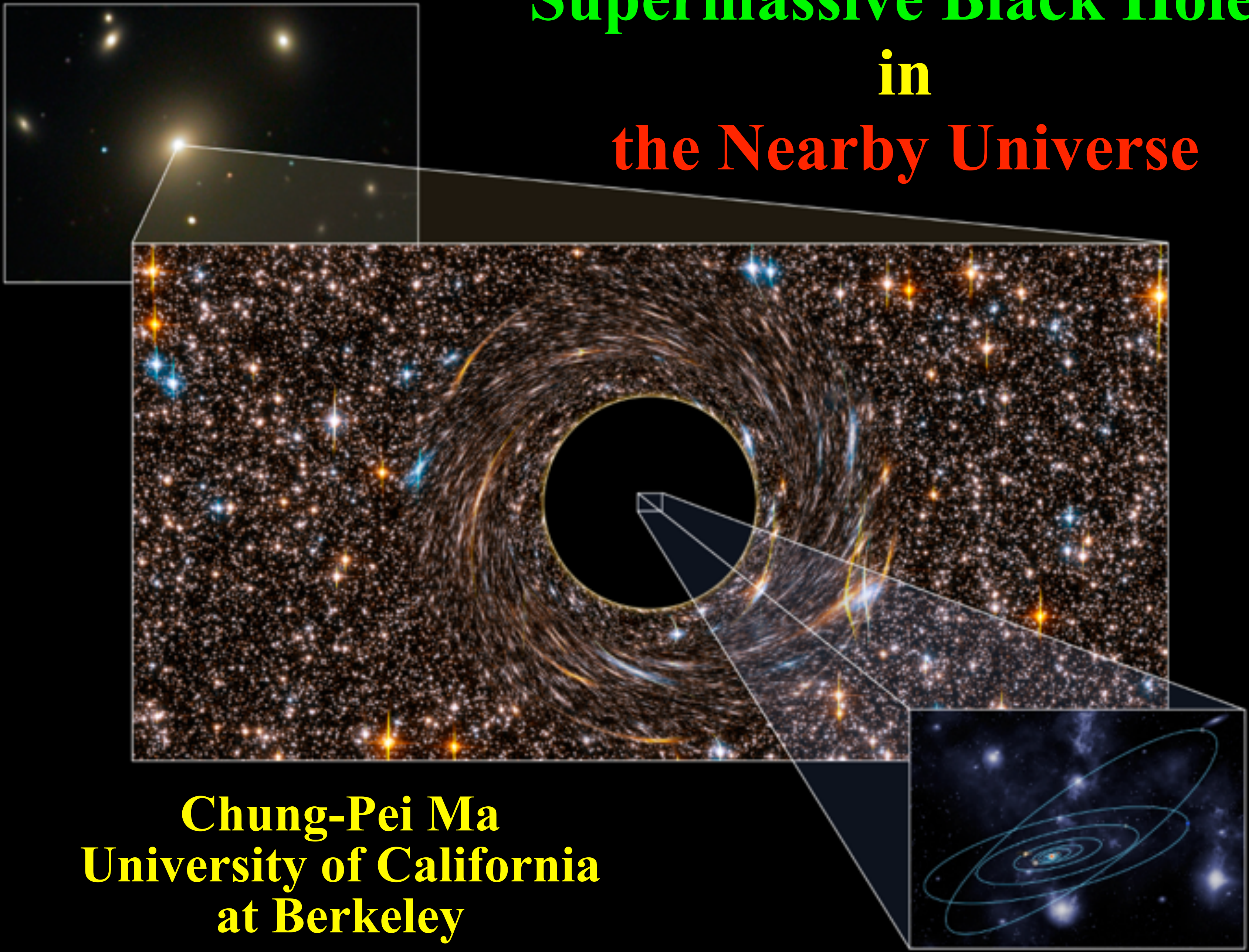
Supermassive Black Holes
in
the Nearby Universe



Chung-Pei Ma
University of California
at Berkeley

Talk Outline

1. Supermassive black hole demographics

2. Detect SMBHs via stellar dynamics

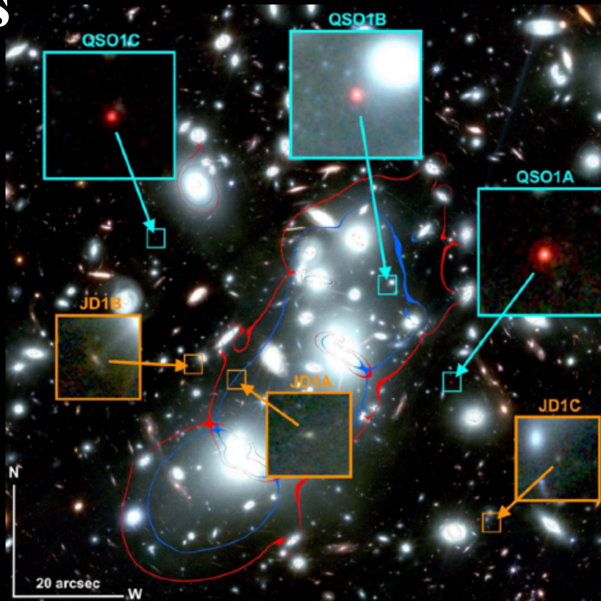
3. Revisit M87

4. Beyond M87

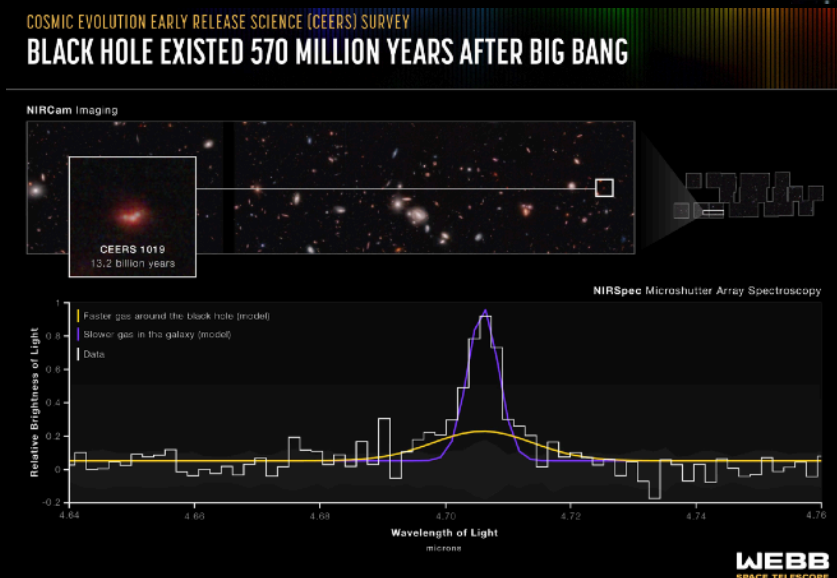
Supermassive Black Holes

Centers of Galaxies

Cygnus A
Blandford+ (2019)



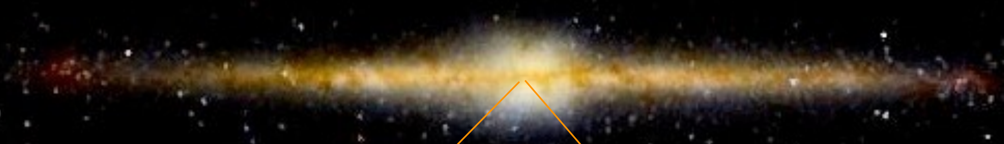
Lensed z=7.6 AGN?
Furtak+ (2023)



z=8.679 AGN M_{BH}~9e6 M_{sun}
Larson+ (2023)

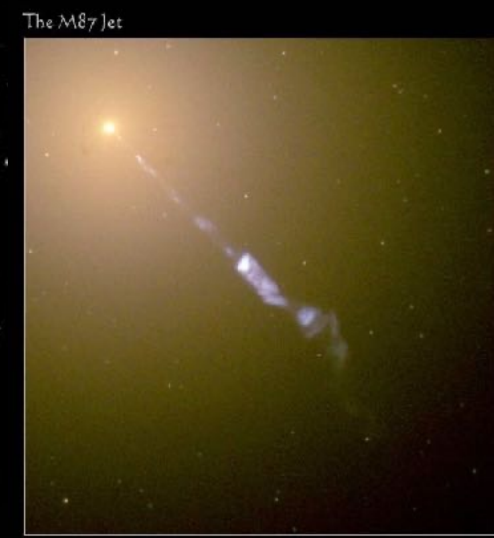
The Two Most-Studied Supermassive Black Holes

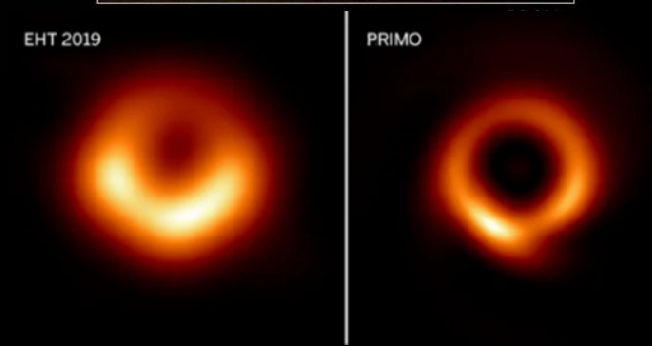
The Milky Way



UCLA team
GRAVITY team

Giant elliptical galaxy M87



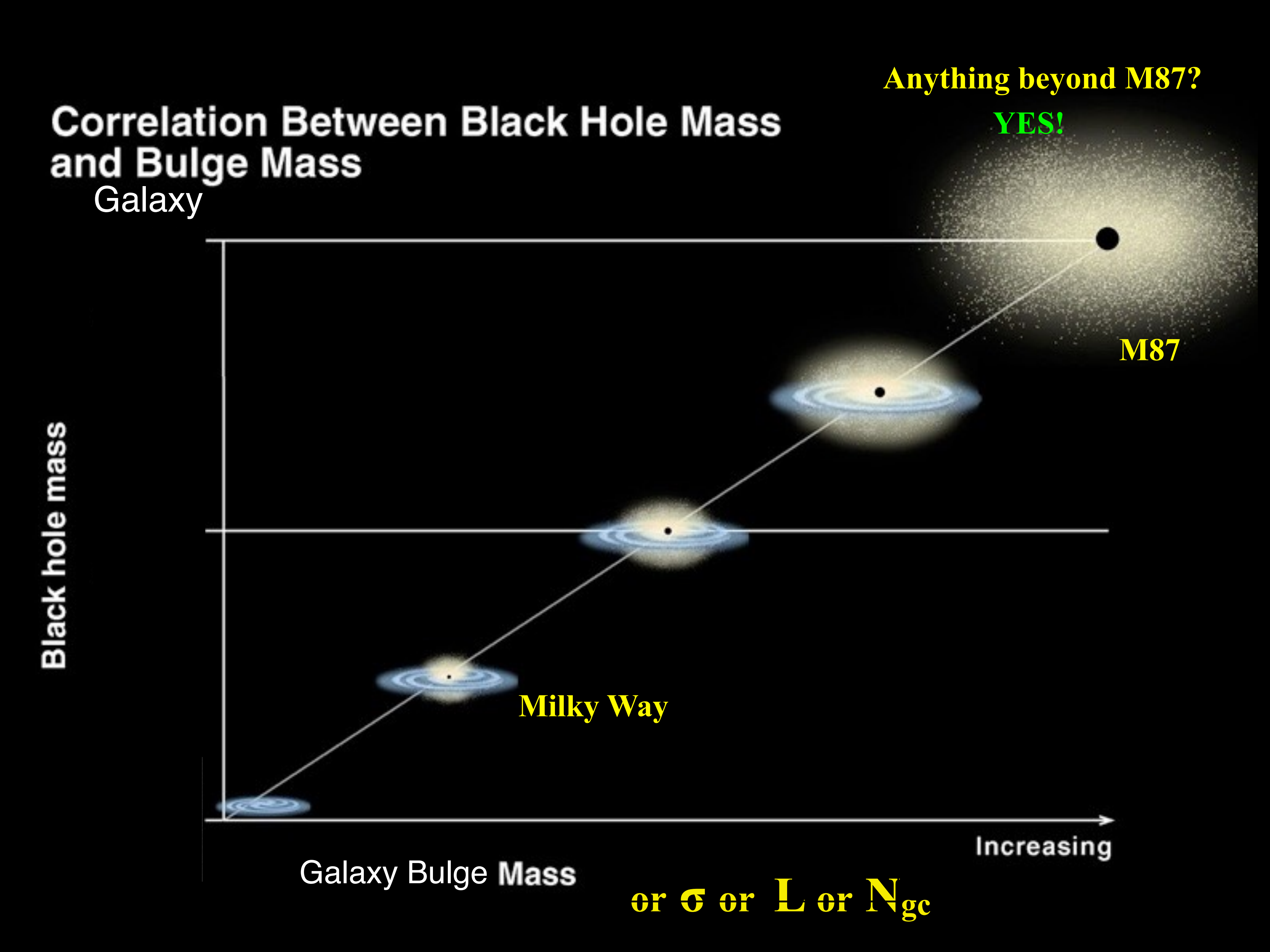


EHT (2019)

Medeiros+ (2023)

Supermassive Black Holes via Direct Dynamics

- 100+ nearby galaxies have direct dynamical BH masses
- 4 types of mass tracers: stars, ionized gas, masers, CO
- Individual stellar orbits (Sgr A*) vs integrated stellar light (all others)
- Few systems have independent masses from multiple tracers
- Among these, some agree (e.g. NGC 4258), some differ (e.g. M87)
- Almost all prior stellar dynamical studies assumed axisymmetry



Anything beyond M87?
YES!
Correlation Between Black Hole Mass
and Bulge Mass
Galaxy
M87
Black hole mass
Milky Way
Increasing
Galaxy Bulge Mass
or σ or L or Ngc

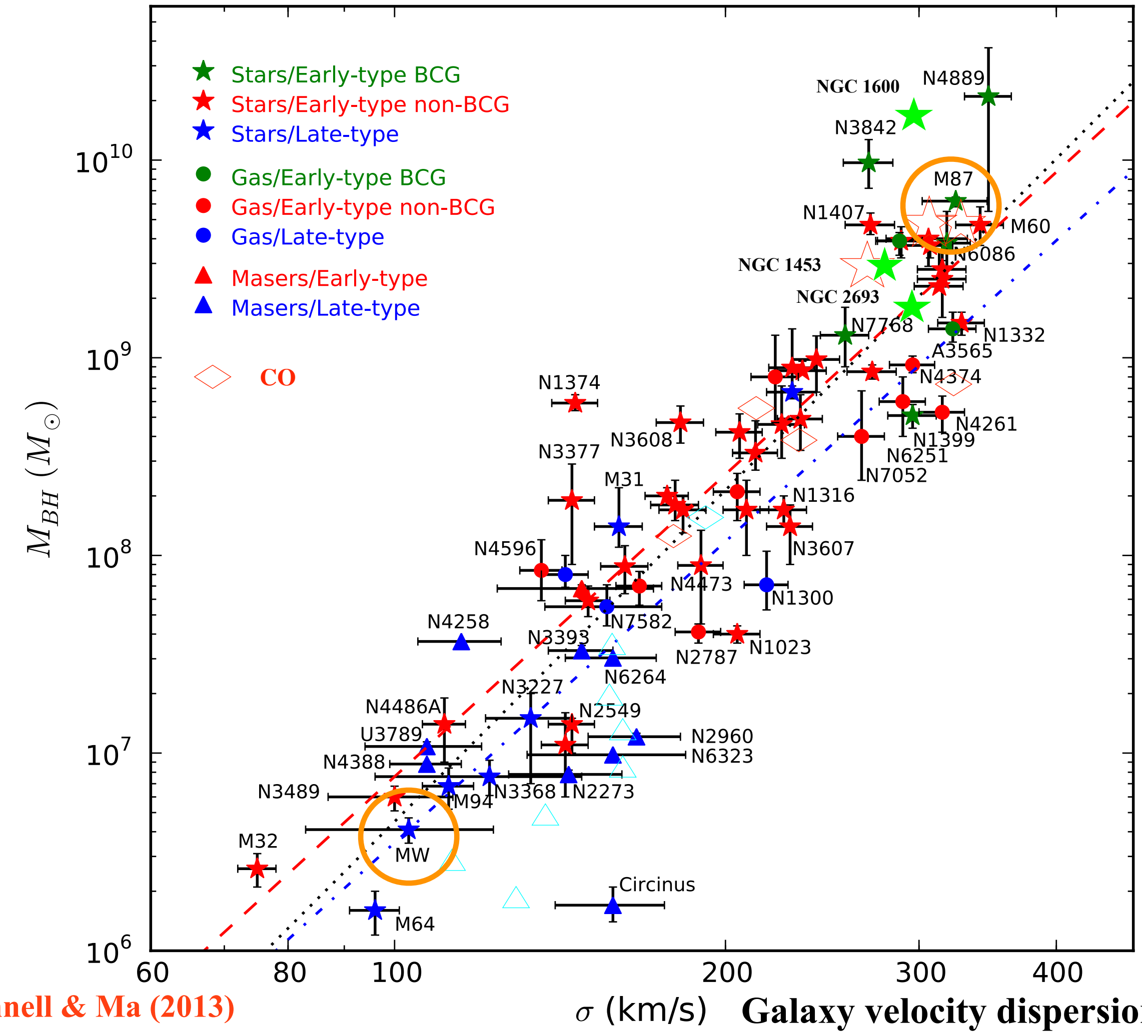
The Local M_{BH} - σ Relation

100+ local galaxies have direct dynamical BH masses
4 types of tracers: stars, ionized gas, masers, CO

σ is not a good M_{BH} proxy for massive ellipticals

4.5 dex

BH mass

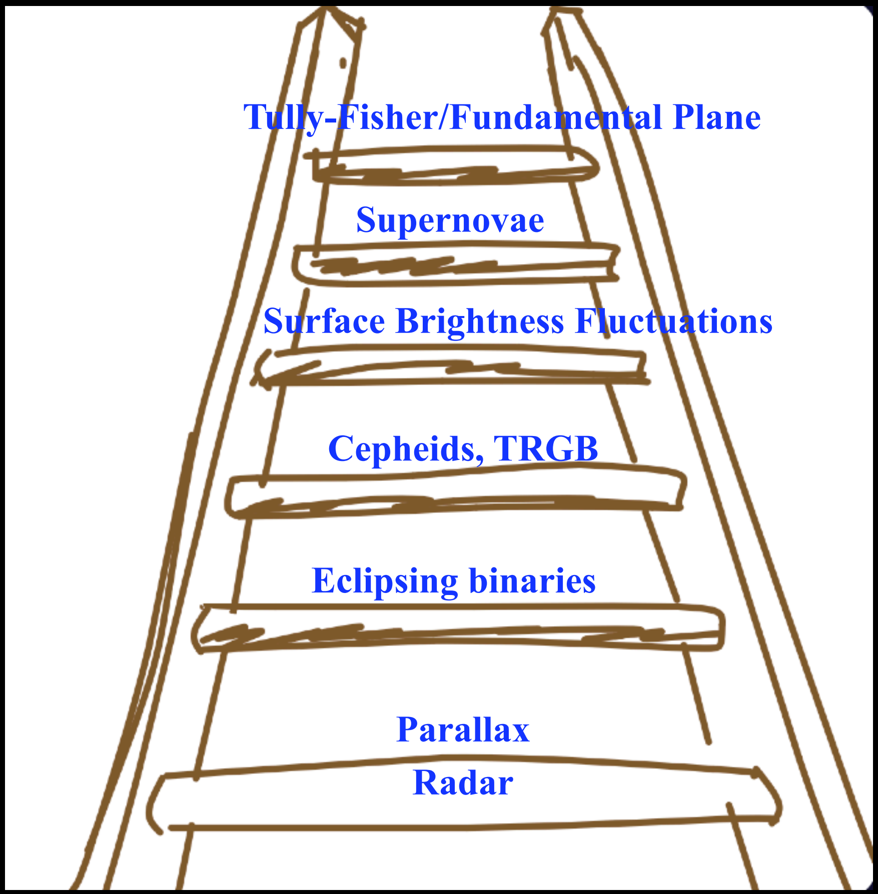


Galaxy velocity dispersion

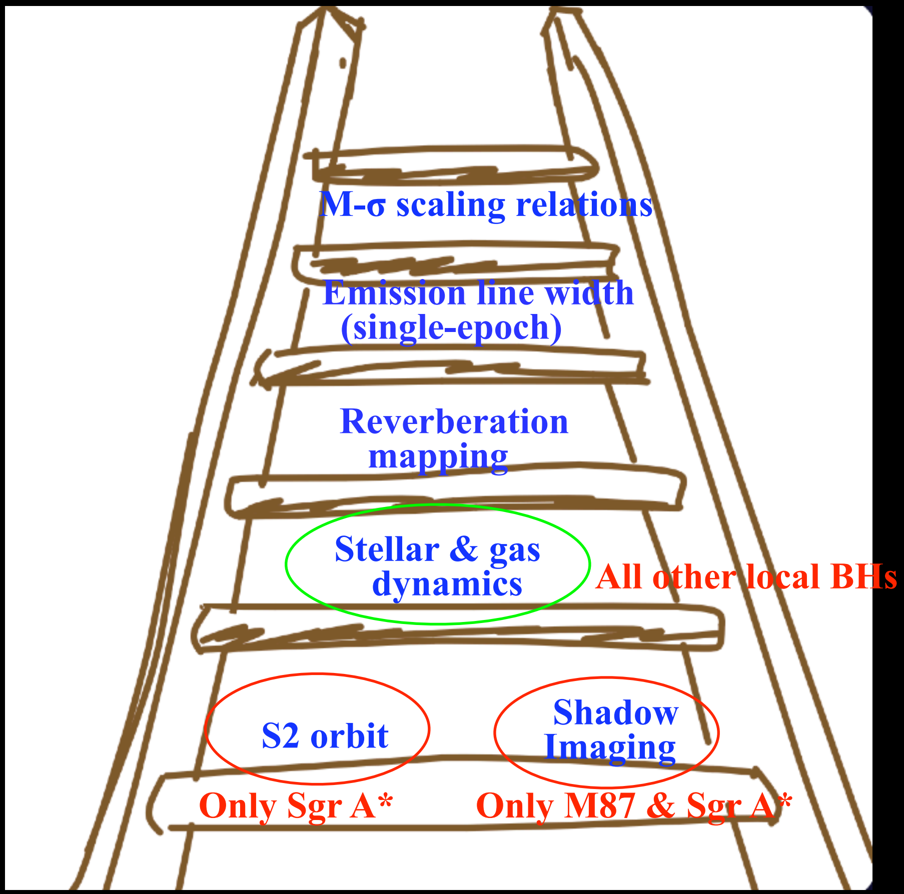
McConnell & Ma (2013)
+ some updates

Local black hole mass measurements are critical for higher-redshift studies

Distance Ladder



Black Hole Mass Ladder



Some Big Questions

How massive can black holes get?

How did they form and how were they fed?

Where do they live?

What is the mass function of black holes locally? At higher z?

What is their spin distribution?

How symbiotic is their relation with host galaxies?

How do binary SMBHs evolve? Where are they?

What are the gravitational-wave signatures from binary mergers?

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3. Revisit M87

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Spectroscopic Requirements for SMBH Detection via Stellar Dynamics

1. **Spatially-resolved IFU spectra** to map out stellar motions in many spatial bins

2. **High S/N** (>~100) absorption features to determine full line-of-sight stellar velocity distributions (LOSVDs) beyond V and σ

3. **Large dynamic range** to resolve SMBH sphere of influence and cover large field of view

Modeling Requirements for SMBH Detection via Stellar Dynamics

Schwarzschild Stellar Orbit Modeling

Advantages

- Stellar distribution function can depend on 3 integrals of motion
- Galaxy models can be triaxial
- No assumptions on velocity anisotropy
- All available (IFU) stellar kinematic data can be used as constraints
- Mass-anisotropy degeneracy can be broken

Challenges $$$

- Each galaxy model requires > 10^4 orbits
- A triaxial galaxy has at least 6 model parameters
- Conventional grid search doesn't work

e.g. Schwarzschild (1979) Rix+ (1997) Cretton+ (1999) Gebhardt+ (2000) Thomas+ (2004) Valluri+ (2004) Cappellari+ (2006) van den Bosch+ (2008) Vasiliev+ (2020) Liepold+ (2020) Quenneville+ (2021, 2022)

Schwarzschild Stellar Orbit Modeling

Our recent progress

1. Axisymmetry → Triaxial models

Most earlier stellar dynamical results assumed spherical or axisymmetric gravitational potential

But few (if any) galaxy obeys exact axisymmetry

Need to compute new stellar orbit libraries ("boxed" orbits) allowed by triaxial gravitational potentials

We've been working on the TriOS code (Triaxial Orbit Superposition)

Liepold + (2020, 2023) Quenneville + (2021, 2022) Pilawa + (2022)

Schwarzschild Stellar Orbit Modeling

Our recent progress

2. **New search strategy for high-dimensional parameter space**

Galaxy model parameters: M_{BH}, $M*/L$ (include gradient), dark matter halo parameters, triaxial shape parameters

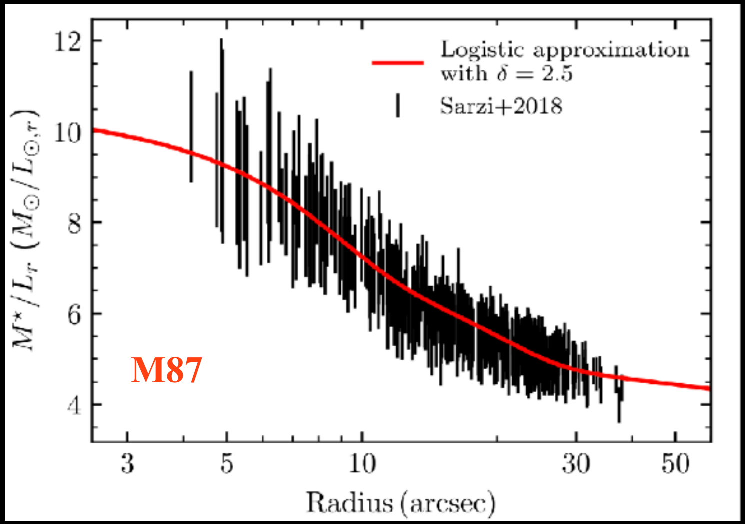
- **Triaxial shape: use unit-cube shape parameters (T, T_{min}, T_{maj}) instead of (p, q, u)**
- **Sampling: grid-free Latin hypercube; convex hull**
- **Gaussian process regression (GPR)**
- **Bayesian inference & nested sampling (Dynesty)**

Schwarzschild Stellar Orbit Modeling
Our recent progress

3. Better characterization of stellar velocity distributions (LOSVDs)

Prior work truncated at Gauss-Hermite moment h_4
We advocate constraining higher moments

4. Allow for spatial gradients in M*/L



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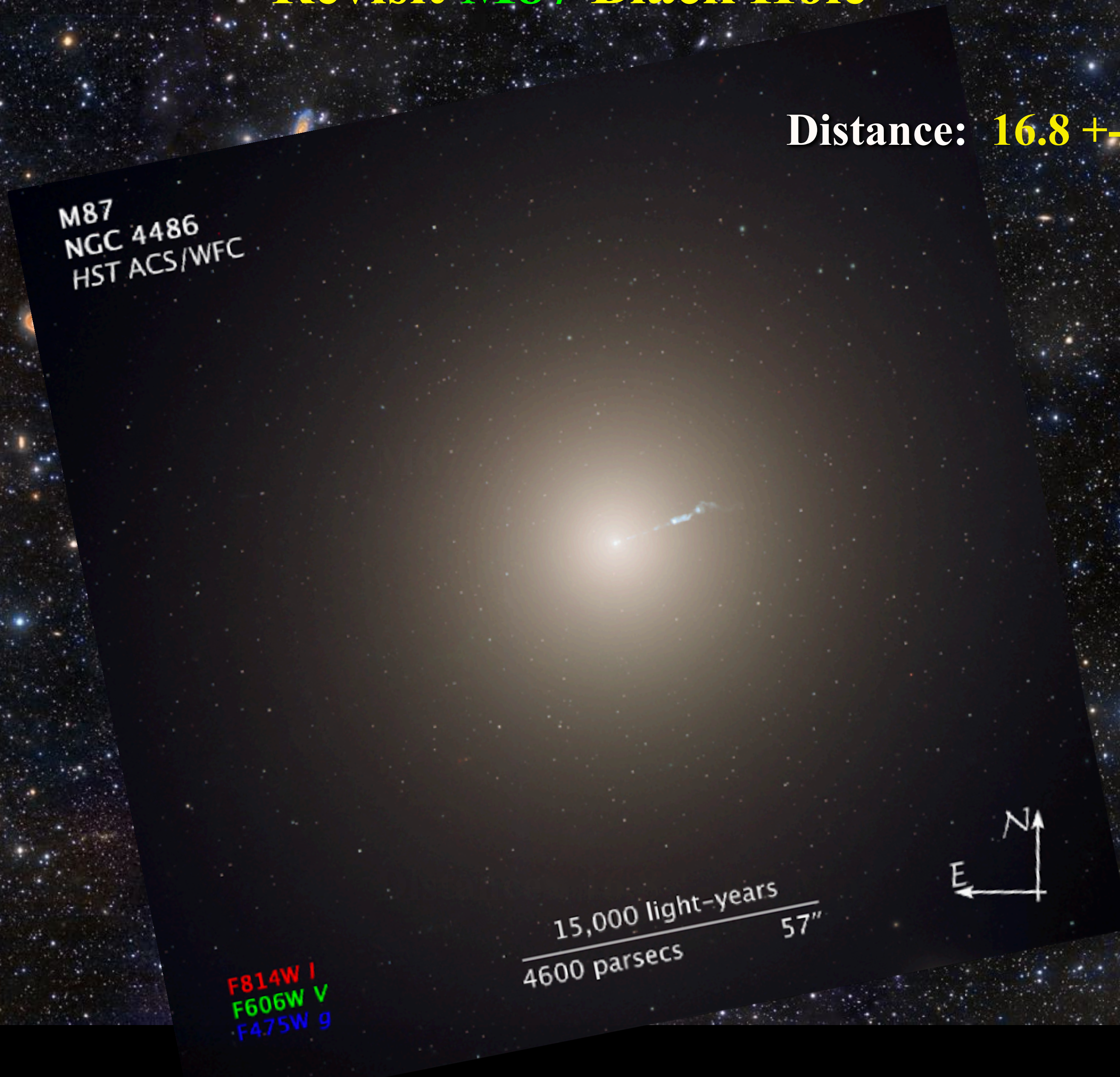
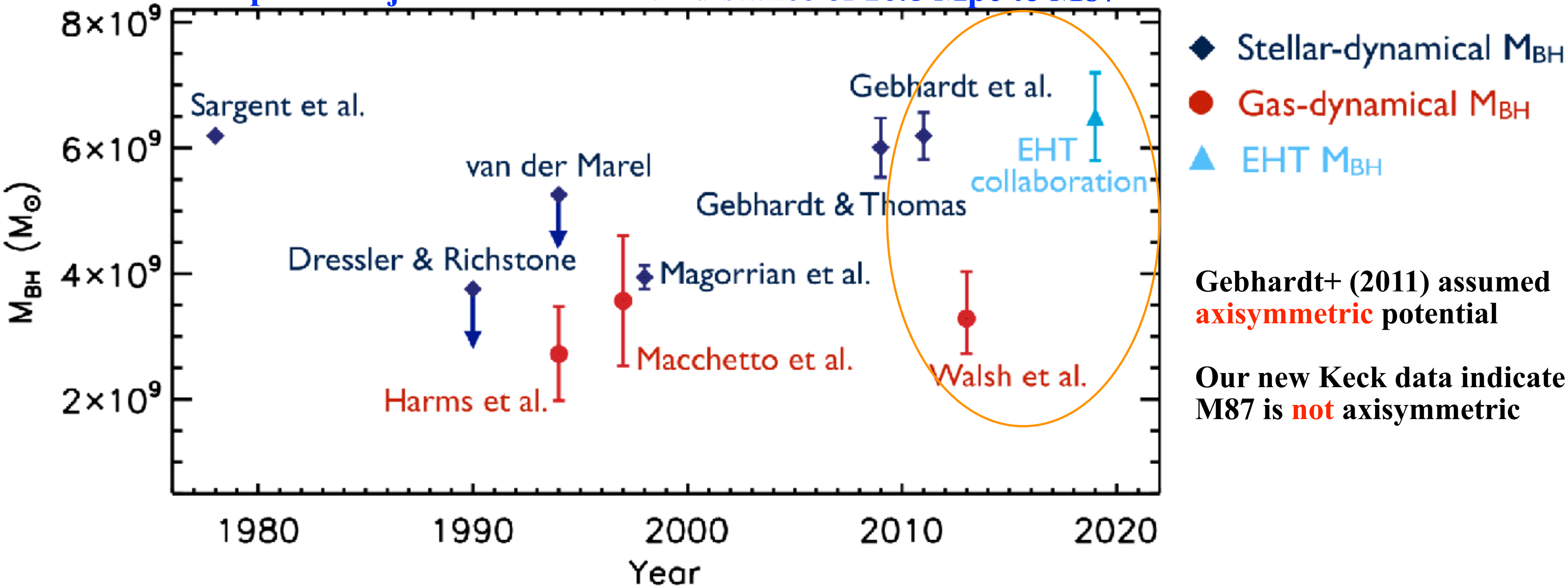
Revisit M87 Black Hole

Distance: 16.8 +- 0.7 Mpc



Revisit M87 Black Hole
45 Years of History

All points adjusted to a common distance of 16.8 Mpc to M87



Gebhardt+ (2011) assumed axisymmetric potential

Our new Keck data indicate M87 is not axisymmetric

Revisit M87 Black Hole

Our approach: integral field spectrographs on 8-10m ground-based telescopes

Liepold, Ma & Walsh (2023)

New Keck integral-field spectroscopy

62 pointings with Keck KCWI (2020-2022)

13 hr science exposures + 3 hr sky

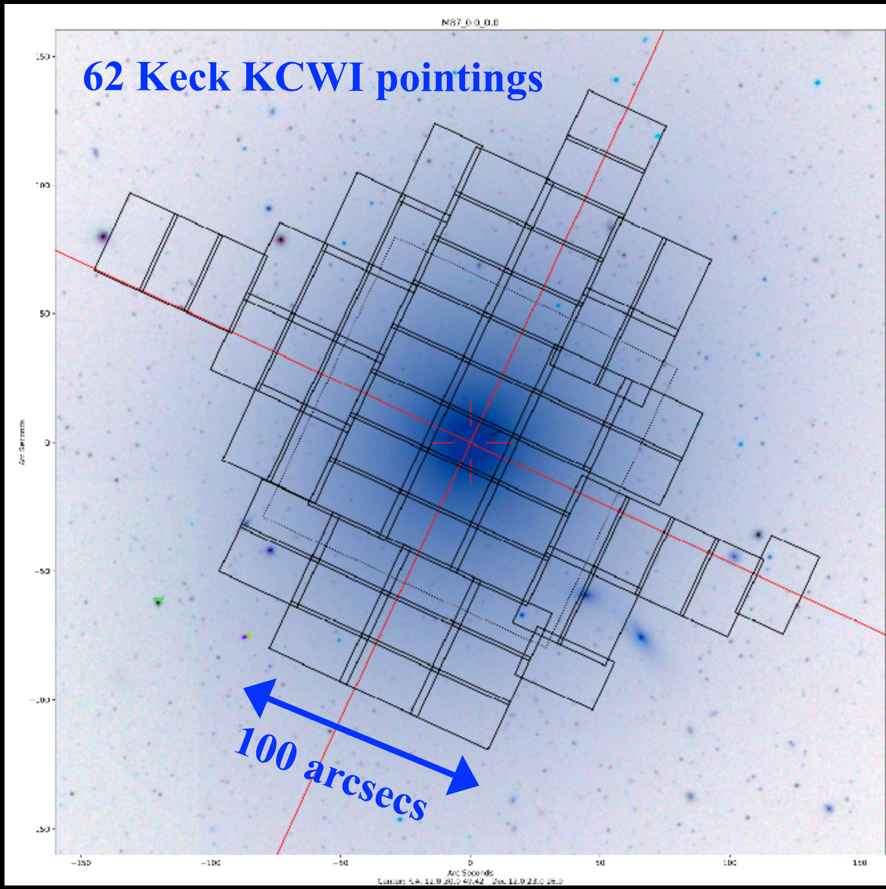
Cover 250” x 300” (20 kpc x 24 kpc) field of view

High S/N (~100-200) spectra for 461 spatial bins

Spectral range: 3500-5600 A

Stellar kinematics: 50 pc to 12 kpc from nucleus

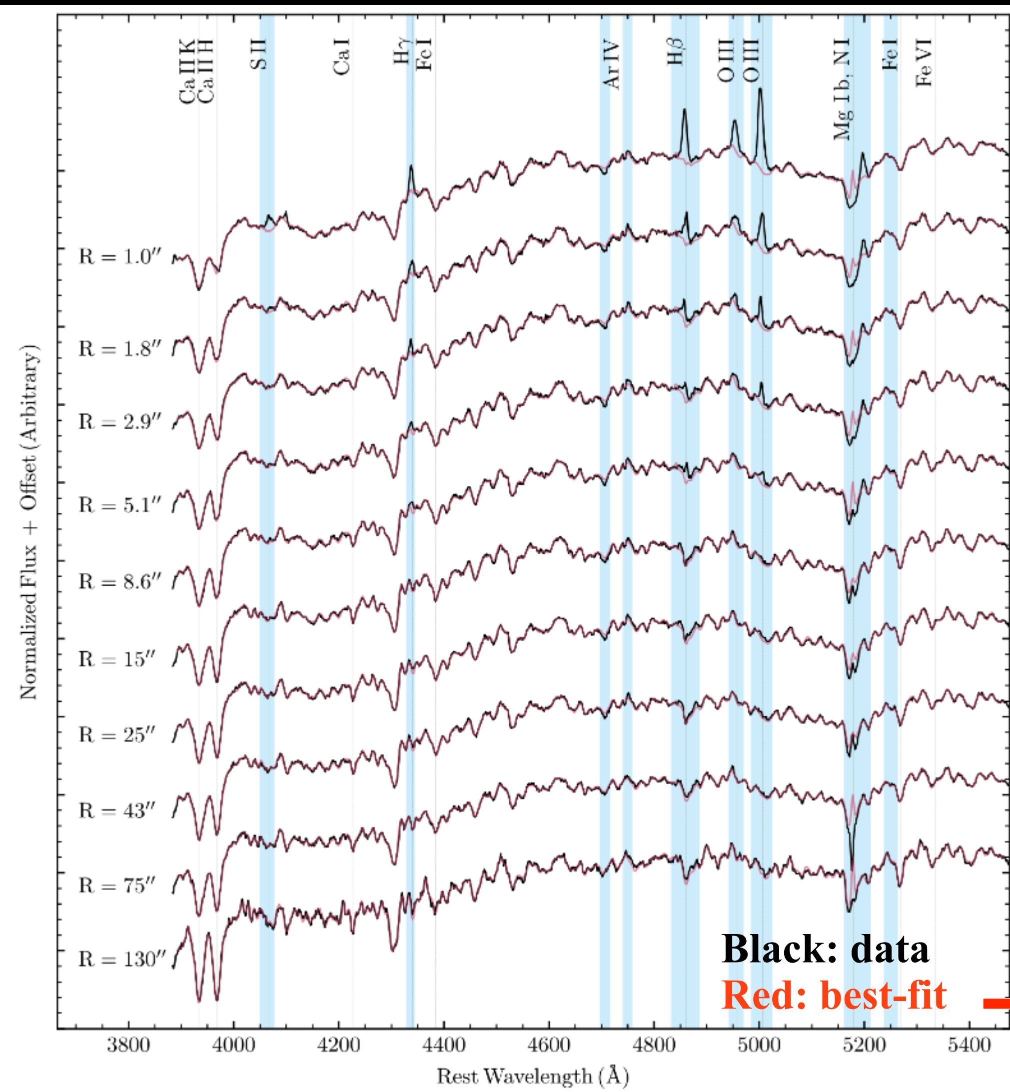
A total of ~4000 observational constraints



Revisit M87 Black Hole

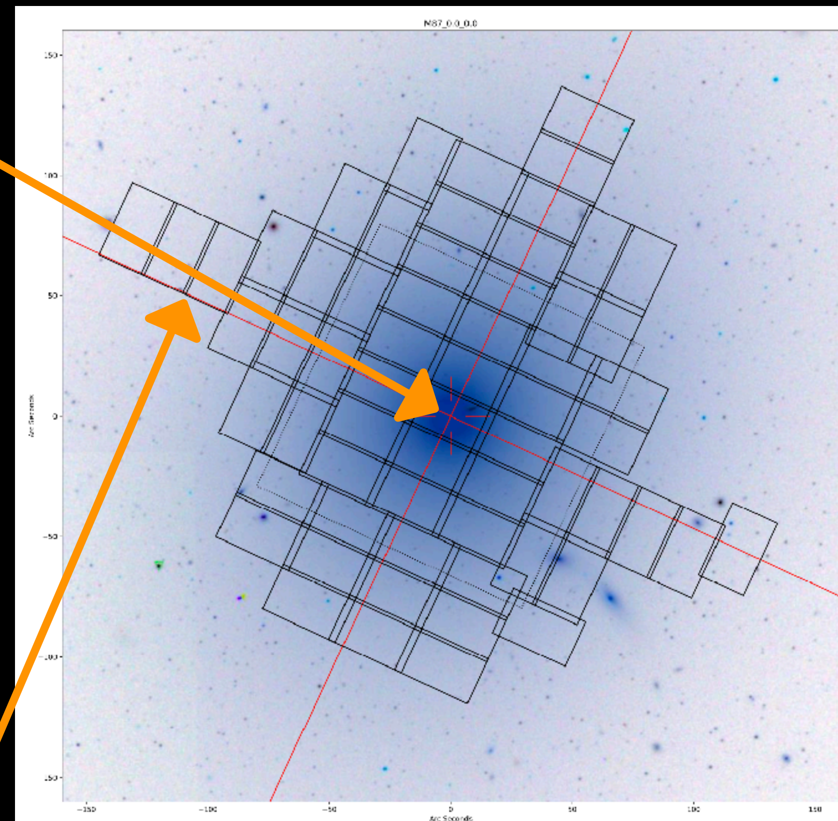
10 examples of 461 Keck spectra

Liepold, Ma & Walsh (2023)



Black: data

Red: best-fit

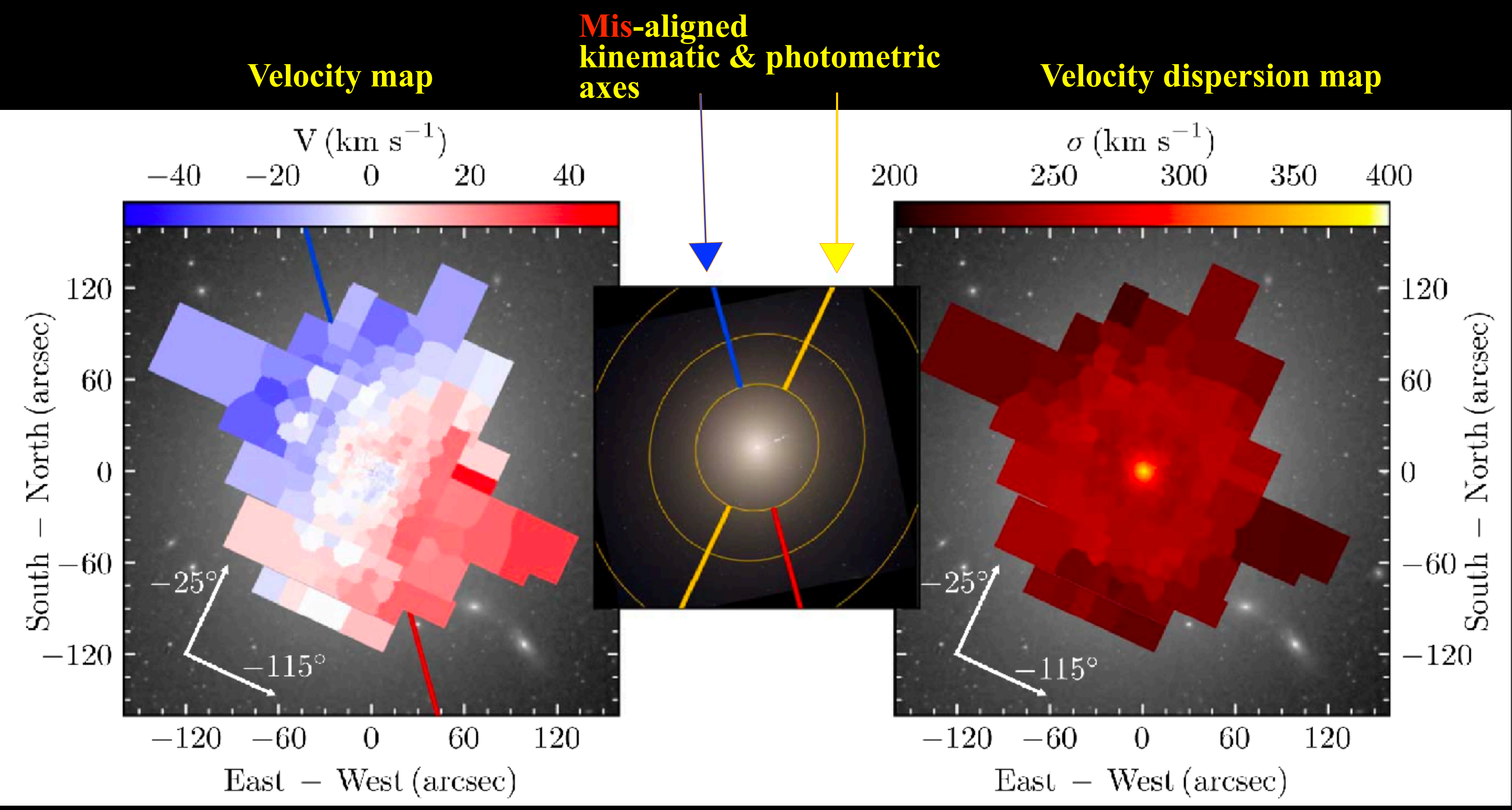


Measure stellar velocity distributions from broadened absorption features

$$L(v) = \frac{\exp\left(-\frac{(v-V)^2}{2\sigma^2}\right)}{\sqrt{2\pi\sigma^2}}\left(1+\sum_{m=3}^{n} h_m H_m\left(\frac{v-V}{\sigma}\right)\right)$$

Revisit M87 Black Hole

Liepold, Ma & Walsh (2023)



Kinematic misalignment → M87 is triaxial

Revisit M87 Black Hole

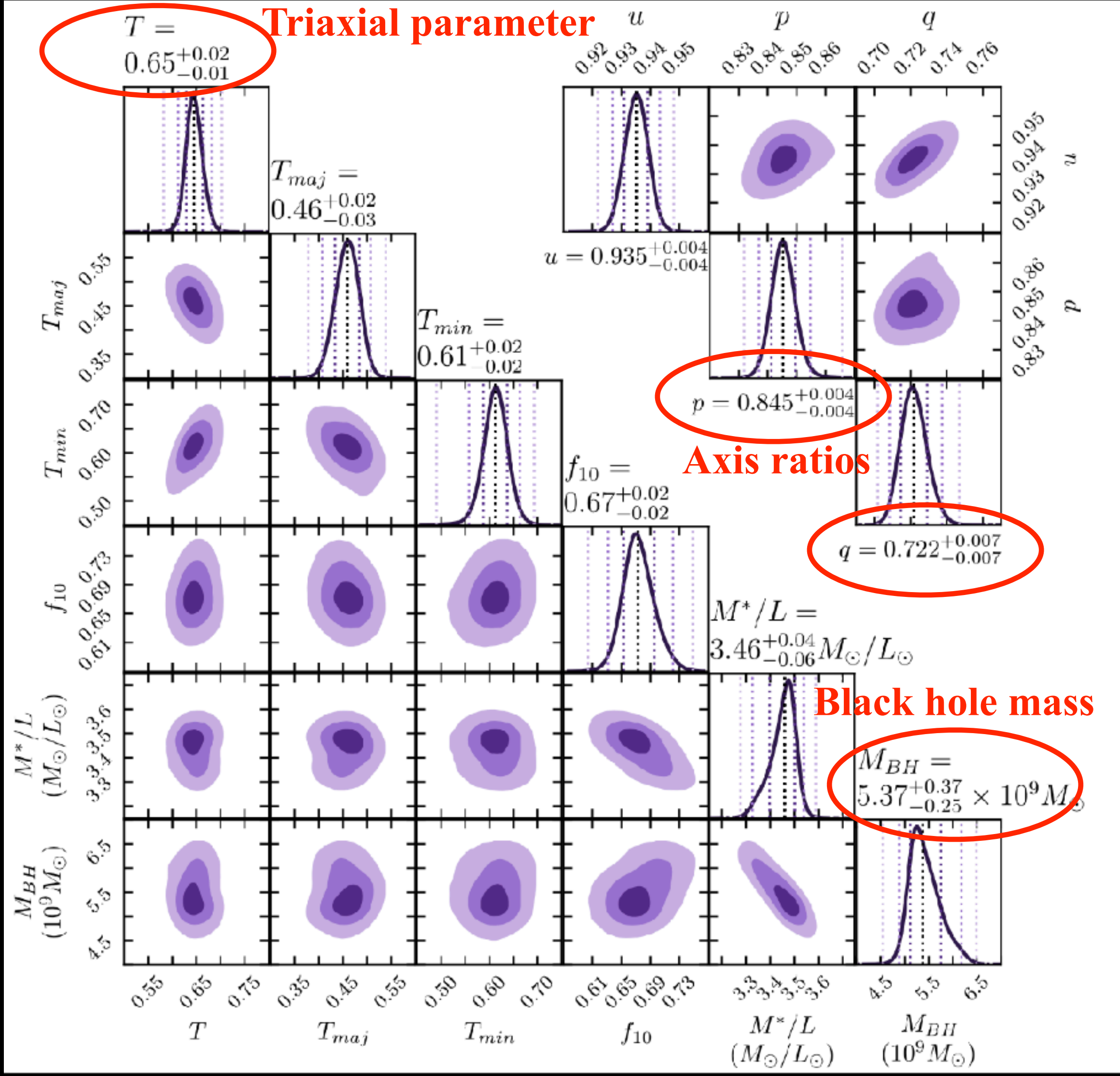
Liepold, Ma & Walsh (2023)

Triaxial orbit modeling with the TriOS code

Sampled ~20,000 galaxy models

Calculated ~500,000 orbits per model

→ First measurement of M87's intrinsic 3D shape



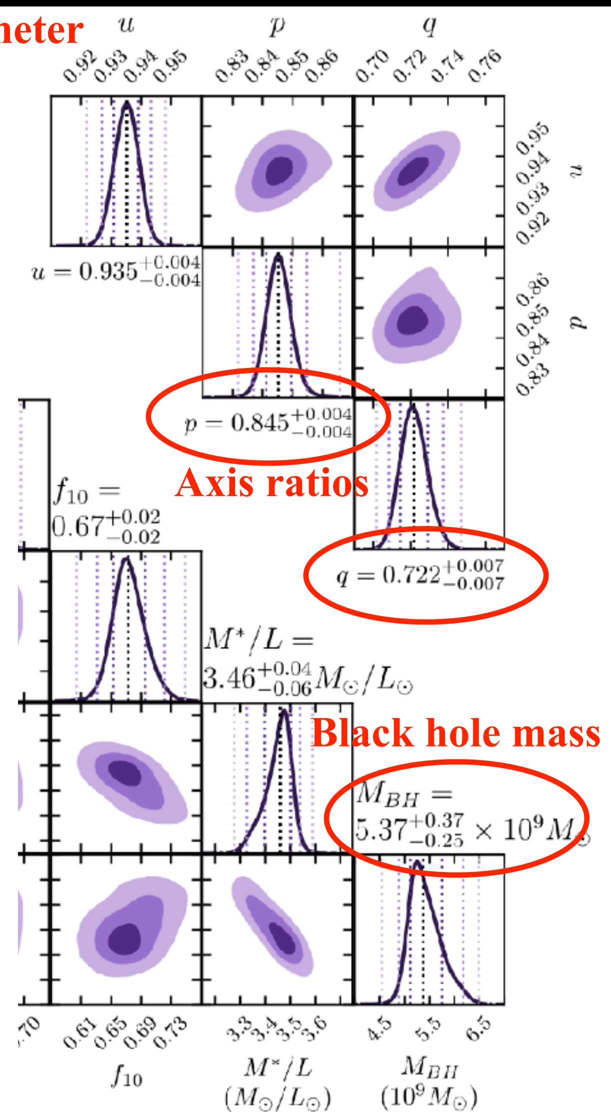
Revisit M87 Black Hole

Liepold, Ma & Walsh (2023)

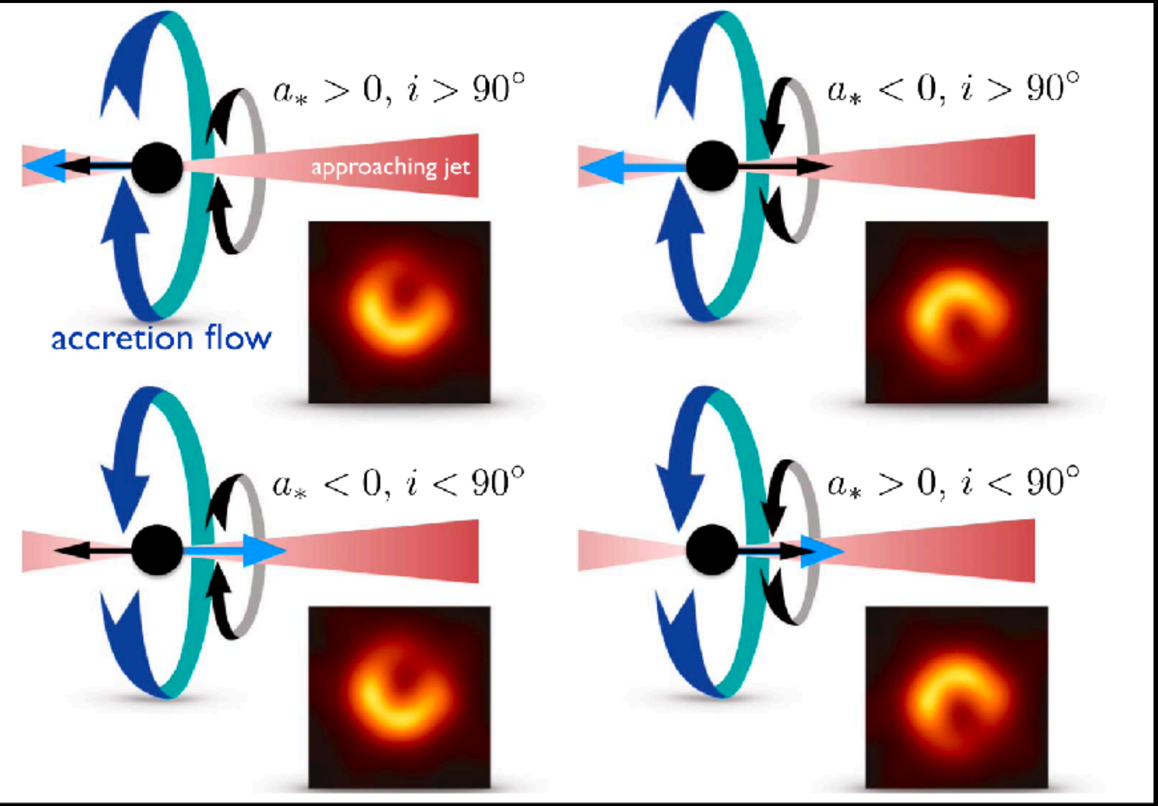
The Astrophysical Journal Letters, 945:L35 (11pp), 2023 March 10

Table 1
Mass and Shape Properties of M87

M87 Property (units)	Inferred Value
Black hole mass $M_{\rm BH}$ ($10^9\ M_\odot$)	$5.37^{+0.37}_{-0.25} \pm 0.22$
Outer M^*/L (V-band; $M_\odot/L_\odot$)	$3.46^{+0.04}_{-0.06} \pm 0.15$
Inner M^*/L (V-band; $M_\odot/L_\odot$)	$8.65^{+0.10}_{-0.15} \pm 0.38$
Dark matter fraction at 10 kpc f_{10}	0.67 ± 0.02
Total mass within 10 kpc ($10^{11} M_\odot$)	5.77 ± 0.12
Shape parameter T	0.65 ± 0.02
Shape parameter $T_{\rm maj}$	$0.46^{+0.03}_{-0.02}$
Shape parameter $T_{\rm min}$	0.61 ± 0.02
Average middle-to-long axis ratio p	0.845 ± 0.004
Average short-to-long axis ratio q	0.722 ± 0.007
Average apparent-to-intrinsic long axis ratio u	0.935 ± 0.004
Line-of-sight direction θ, ϕ (°)	$48.9^{+1.1}_{-1.0}$, $37.5^{+1.4}_{-1.3}$
Rotation about line of sight ψ (°)	$-61.3^{+1.4}_{-1.7}$



Revisit M87 Black Hole



Net angular momentum of stars

Our best-fit galaxy model

→ **Net stellar L is nearly aligned with jet !**

BH spin pointing away

BH spin pointing towards us

EHT Paper 5 (2019)

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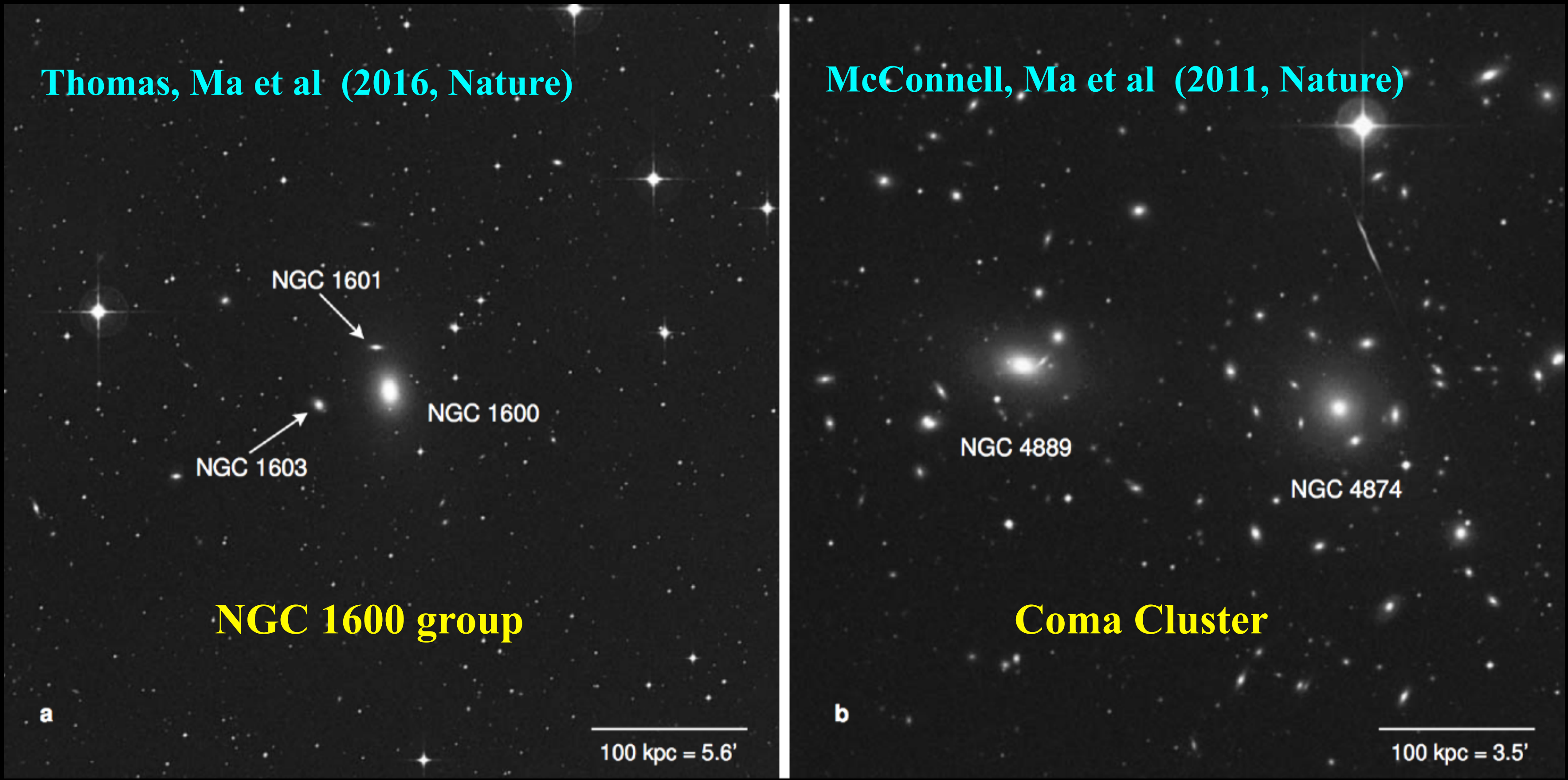
Biggest local black holes (17-20 billion M_{sun}) live in different environments



$M_{vir} \sim 1.5 \times 10^{14}\ M_{sun}$

$L_x \sim 1000$x lower

Rank 2 galaxy ~3x fainter (fossil-group)

D = 64 Mpc

$M_{vir} = (1.4\text{-}2.7) \times 10^{15}\ M_{sun}$

$L_x = 4 \times 10^{44}\ L_{sun}$

Rank 2 galaxy similar in L

D = 102 Mpc

The MASSIVE Survey

An **integral field spectroscopic** & **photometric** survey
of the ~100 most massive galaxies within ~100 Mpc

Volume-limited: target all early-type galaxies (northern sky)
with $M^* > 10^{11.5}$ M_{sun}

Multi-wavelength study of all mass components:
stars, cold/warm/hot gas, dark matter halos, black holes

Chung-Pei Ma, Jenny Greene, Jonelle Walsh, Nicholas McConnell, Jens Thomas

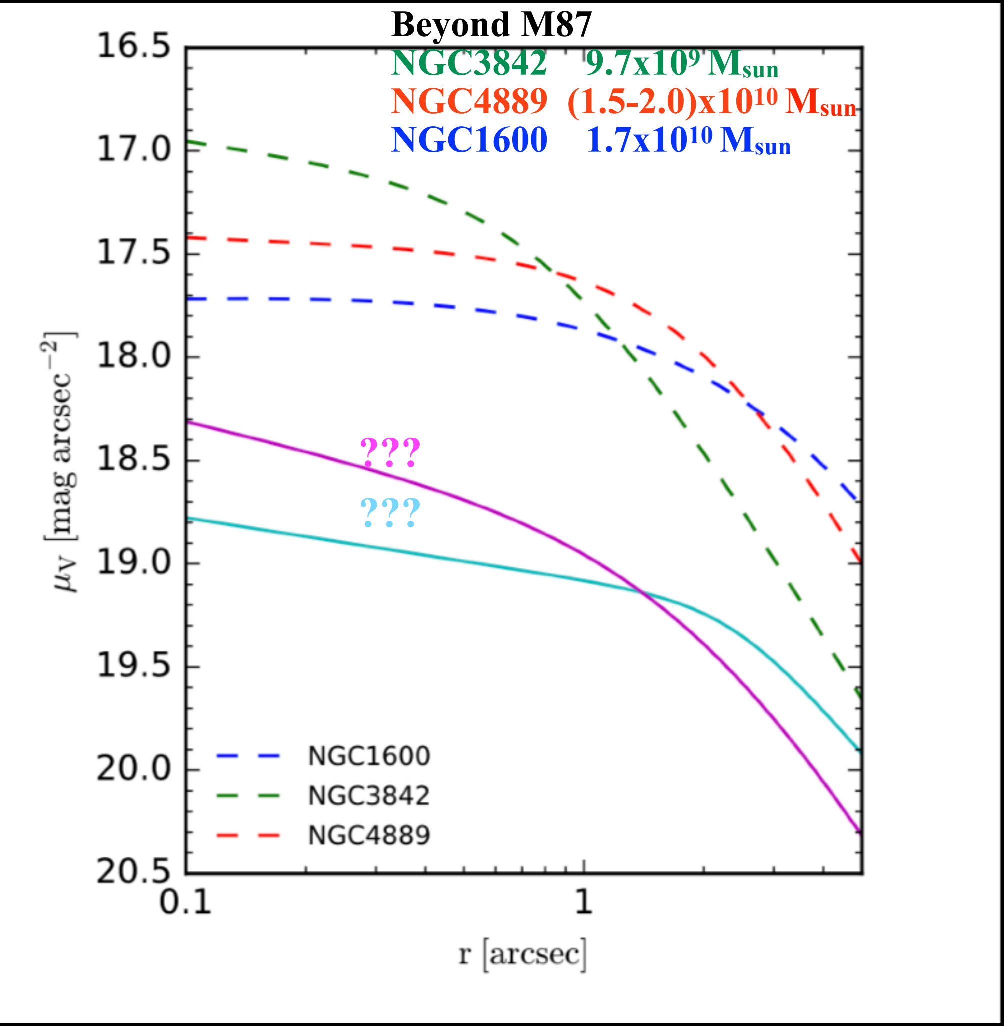
Graduate students: Melanie Veale, Irina Ene, Viraj Pandya, Charles Goullaud,
Emily Liepold, Matthew Quenneville, Jacob Pilawa, Silvana Andrade
Undergrads + High school students

MASSIVE-HST: John Blakeslee, Joe Jensen
MASSIVE-CFHT: John Blakeslee
MASSIVE-CO: Tim Davis
MASSIVE-Xray: Andy Goulding
MASSIVE-IMF: Meng Gu, Drew Newman

Sample of MASSIVE Survey Related Papers

I	Survey paper	Ma +	(2014) ApJ
II	Stellar pop gradient	Greene +	(2015) ApJ
III	Molecular gas #1	Davis +	(2016) MNRAS
IV	X-ray properties	Goulding +	(2016) ApJ
	NGC1600 black hole	Thomas +	(2016) Nature
V	Stellar kinematics	Veale +	(2017) MNRAS
VI	Ionized gas	Pandya +	(2017) ApJ
VII	λ & environment	Veale +	(2017) MNRAS
VIII	σ radial profile	Veale +	(2018) MNRAS
IX	WFC3 photometry	Goullaud +	(2018) ApJ
X	Kinematic alignment	Ene +	(2018) MNRAS
XI	Molecular gas #2	Davis +	(2019) MNRAS
XII	Stellar pop vs env	Greene +	(2019) ApJ
XIII	Core kinematics #1	Ene +	(2019) ApJ
XIV	Core kinematics #2	Ene +	(2020) ApJ
XV	NGC1453 black hole	Liepold +	(2020) ApJ
	SBF distances	Jensen +	(2021) ApJ
	SBF H_0	Blakeslee +	(2021) ApJ
	Axisymmetric orbit code	Quenneville +	(2021) ApJS
	Triaxial orbit code	Quenneville +	(2022) ApJ
XVI	Stellar pop & IMF	Gu +	(2022) ApJ
XVII	NGC2693 black hole	Pilawa+	(2022) ApJ
XVIII	CFHT imaging	Quenneville +	(2023) MNRAS
	Globular clusters	Hartmann +	(2023) ApJ
	M87 black hole	Liepold +	(2023) ApJ Letters
XIV	ALMA CO M_{BH}	Dominiak+	(2023) submitted
XX	IMF gradients	Gu +	(2023) In prep

eMASSIVE (beyond 100 Mpc)
Faint cores of massive elliptical galaxies with Keck KCWI



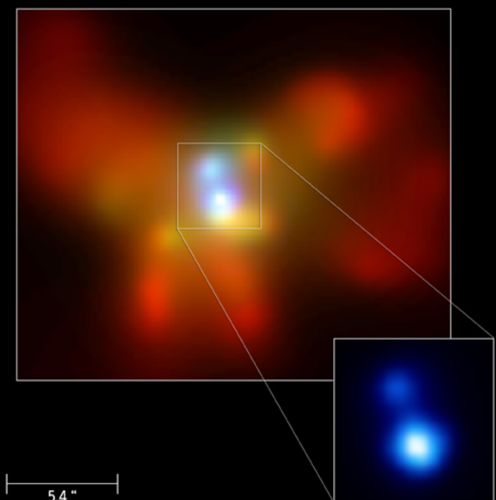
Currently only a handful black holes have larger dynamical mass than M87

Black hole mass is well correlated with stellar core size (Thomas+ 2016)

Target extreme faint, large cores of giant elliptical galaxies with Keck KCWI

Supermassive Black Hole Binaries?

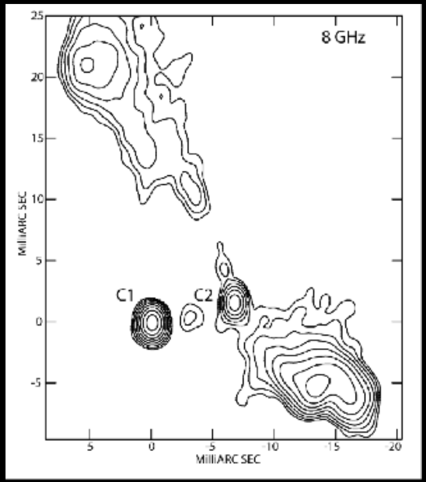
NGC 6240



z=0.024 LIRG
Luminous hard X-ray from two cores
Separation 1.4 kpc

Komossa+ (2003)

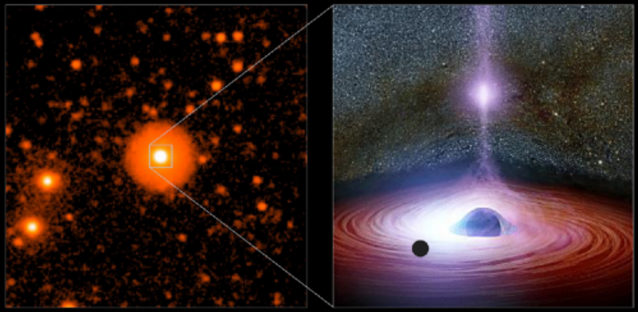
0402+379



z=0.06 radio galaxy
Two compact radio cores, flat spectrum
Separation 7.3 pc

Rodriguez+ (2006)

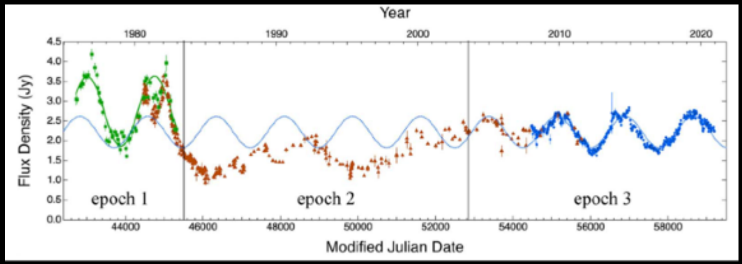
OJ 287



z=0.306 Blazar
Separation ~0.1 pc

Komossa+ (2023)
Gupta+ (2023)

PKS 2131-021



z=1.285 Blazar
Sinusoidal light curve
Separation ~0.001-0.01 pc

O'Neill+ (2022)

Stellar Dynamical Studies of SMBH: Looking Ahead

- Direct stellar dynamical M_{bh} measurements are difficult
  but essential for uncovering new black holes
  All galaxies have stars, but few have masers, CO, mm emission….

- 1990s HST slits (e.g. Nuker team)
  2010+ IFU/AO on large ground-based telescopes

- Urgent need for triaxial Schwarzschild orbit modeling (TriOS code)
  Systematic survey of massive galaxies (MASSIVE)
  New window into massive galaxies with faint cores (eMASSIVE)

- 2020+ Exciting synergy with EHT/ngEHT, PTAs, gravitational lensing
  M87 spin & accretion flow
  New population of local massive SMBHs are potential
  hot spots for low-frequency gravitational waves and ngEHT/EHE

Supermassive Black Holes: Looking Ahead

Next talks by Nick Stone, Steve Taylor, Kejia Lee