Supermassive Black Hole Discovery and Measurement with Triaxial Schwarzschild Modelling

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Slides at emilyliepold.com/today

The Big Picture

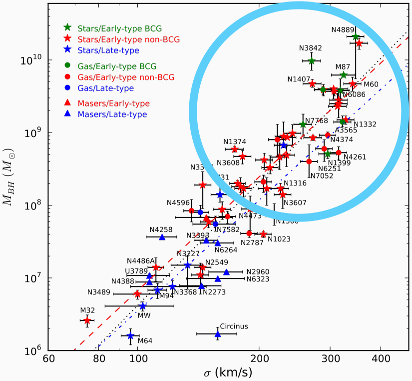
Triaxial Schwarzshild modelling!

First results! NGC1453 and NGC2693

M87

Motivation: What are we looking at?

The **MASSIVE** Survey targets **MASSIVE** galaxies
with **MASSIVE** black holes



(McConnell+Ma 2013)

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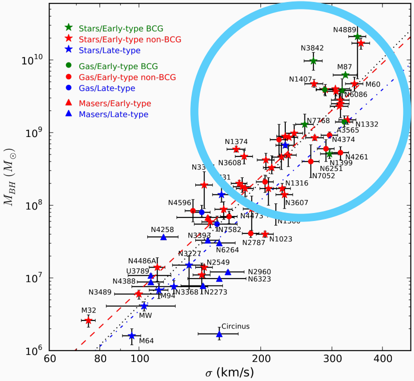
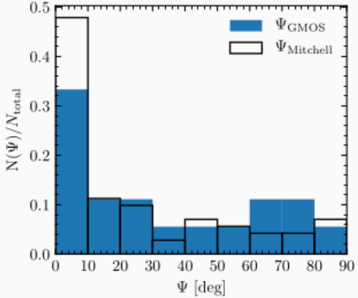


(McConnell+Ma 2013)

- These galaxies often have **kinematic misalignments**
- **Kinematic misalignments** strongly suggest a **triaxial** intrinsic shape (not axisymmetry!)



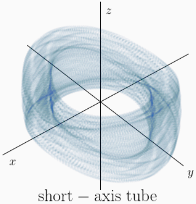
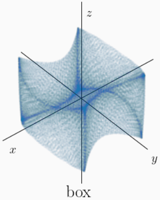
(Ene+20)

Motivation: Why do we care about the shape?

Shape of ρ $\rightarrow$ Shape of Φ $\rightarrow$ *Symmetries* of Φ $\rightarrow$ Conserved quantities and allowed orbits

Symmetry		Conserved Quantity	Orbits
Spherical	$\frac{d\Phi}{d\Omega} = 0$	$(E, \vec{L})$	Rosettes in fixed planes
Axisymmetry	$\frac{d\Phi}{d\phi} = 0$	(E, L_z, I_3)	Loops about symmetry axis
Triaxiality	Eh...	$(E, \mathbf{I}_2, \mathbf{I}_3)$	It's complicated...

Some orbits in triaxial potentials are strange!

Loop Orbits	**Box** Orbits
	
Appears in axisymmetric potentials	Not present in axisymmetry!

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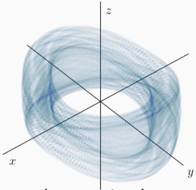
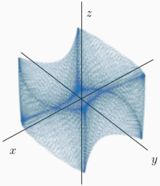
 short – axis tube	 box
Appears in axisymmetric potentials Persistent sense of rotation about either the **short** or **long** axis	Not present in axisymmetry! No persistent sense of rotation

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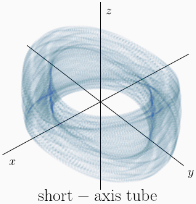	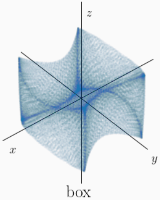
Appears in axisymmetric potentials Persistent sense of rotation about either the **short** or **long** axis **Centrophobic**	Not present in axisymmetry! No persistent sense of rotation Can be **Centrophilic**

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Schwarzschild Orbit Modelling

Strategy:

1. Propose a (triaxial) stellar density distribution
2. Integrate representative orbits that span the phase space
3. Superimpose those orbits such that (1) is reproduced

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5. Repeat (1-4) with a bunch of different mass models

The TriOS Triaxial Orbit Superposition Code (Liepold+20, Quenneville+21,22)

(Spawned from earlier code from van den Bosch+ 2008)
A `fortan`-based code for Schwarzschild orbit modelling in triaxial stellar potentials.

Model includes BH, stars, and dark matter halo:

$$\Phi = \Phi_{BH} + \Phi_{*} + \Phi_{DM}$$

Stellar kinematics (LOSVDs) described by Gauss-Hermite expansion with $y = (v - V)/\sigma$:

$$f(v) = \frac{e^{-\frac{y^2}{2}}}{\sqrt{2\pi\sigma^2}} \left[1 + \sum_{m=3}^{n} h_m H_m(y) \right]$$

2D (projected) and 3D (intrinsic) mass distributions are constrained for self-consistency.

Efficient Sampling for Triaxial Modelling

(Quenneville+22, Pilawa+22, Liepold+23)

Each `TriOS` model gives a χ^2 value for a single point in the parameter-space

- We need to search over M_{BH}, M/L (1 or 2 parameters), shape (3 parameters), and halo (1 or 2 parameters) – at least **6-8 dimensions**. (Grid Searches are inefficient)

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- This is **expensive**. Each model evaluation takes 10-30 CPU hours. (Highly iterative searches are impractical)
- As data improves, confidence volumes **shrink** with $\sim (\mathrm{Number\,of\,Constraints})^{-\mathrm{D}/2}$

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Our Strategy (inspired by Bayesian Optimization and nested sampling):

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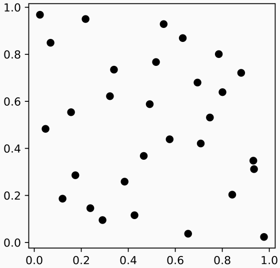

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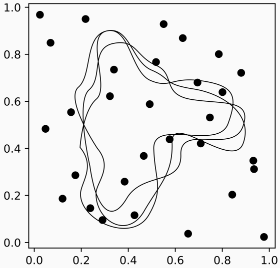

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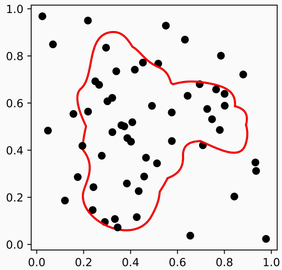

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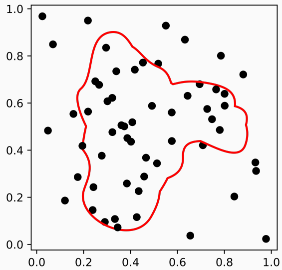

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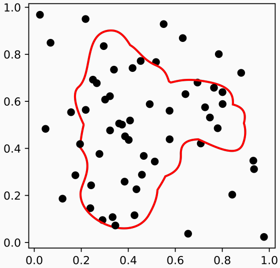

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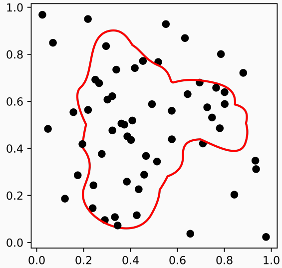
- For a reasonable-resolution grid search (10 pt per dimension), we'd need $\mathrm{O}(10^6)$ models – 20,000,000 CPU-hours!
- (We've been averaging 1.5M CPU-hours / year on Expanse at SDSC)



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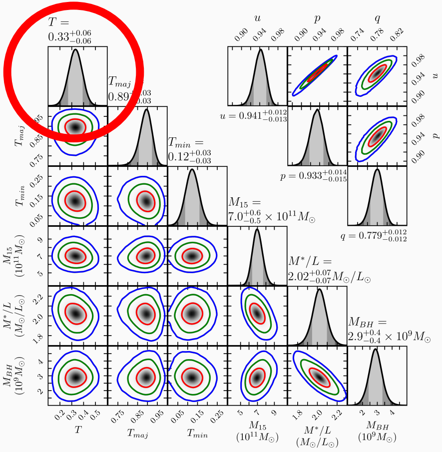
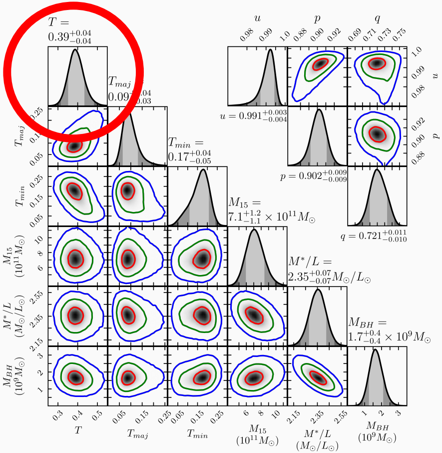


NGC2693



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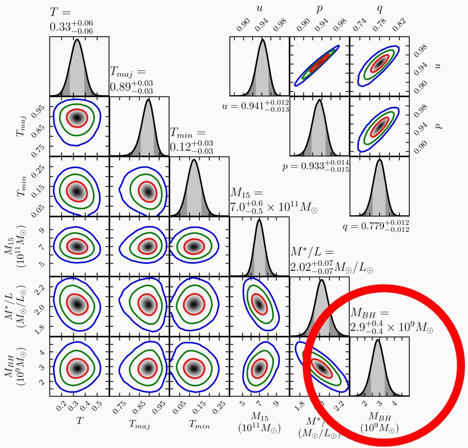

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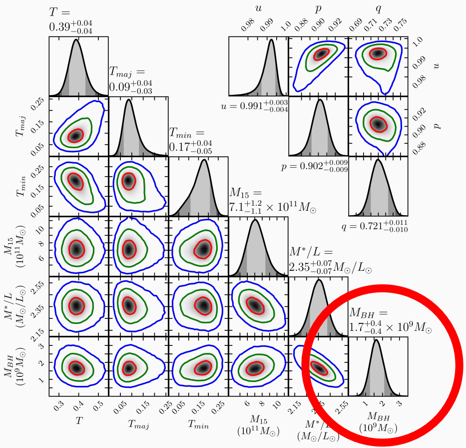

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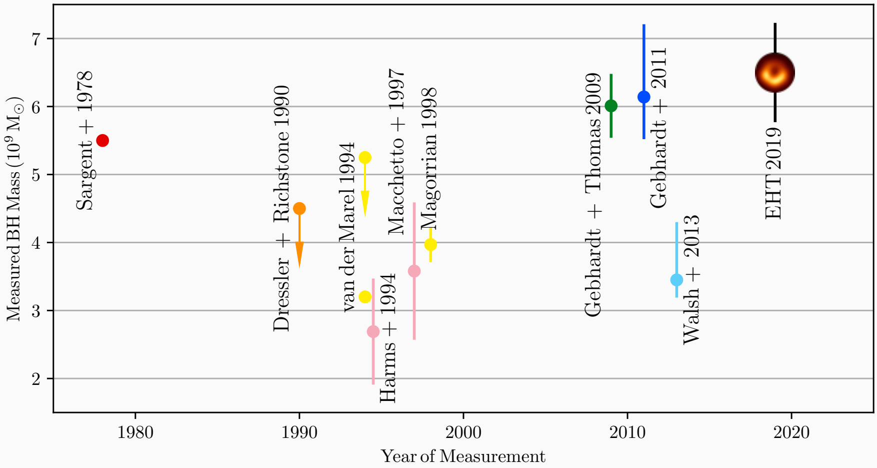
M87* has a *long* history



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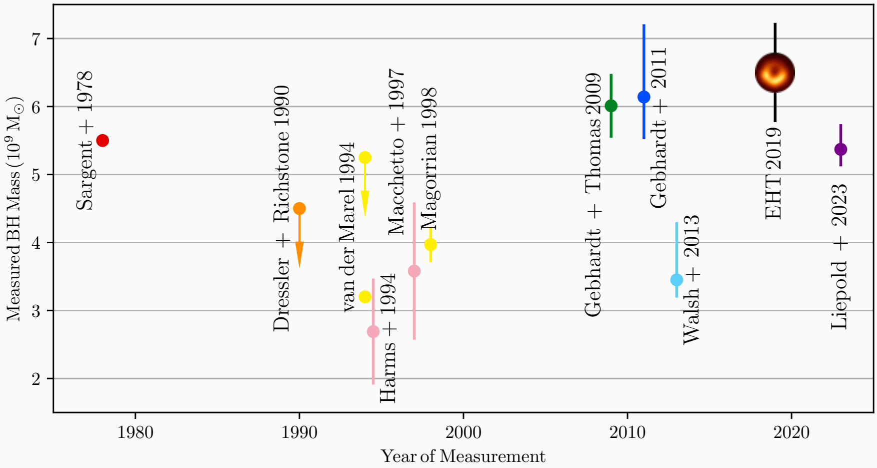
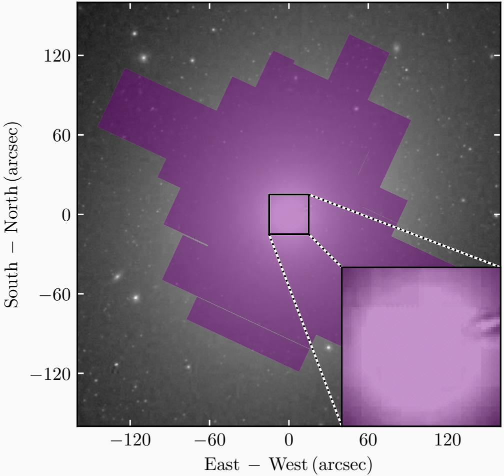
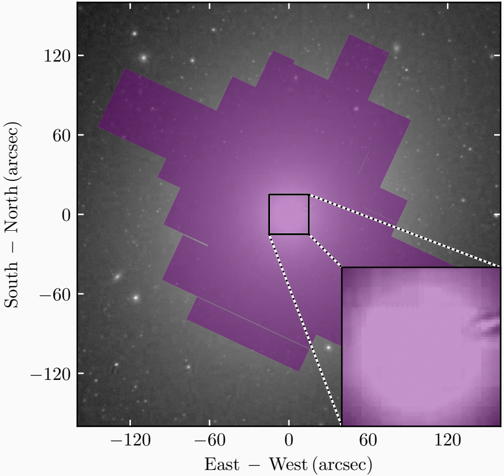


Our KCWI Observations

(Liepold+23)



- We observed M87 with Keck Cosmic Web Imager (KCWI) during four observing runs from May 2020 - April 2022.
- This is an integral field unit, yielding a distinct spectrum at each spatial pixel.



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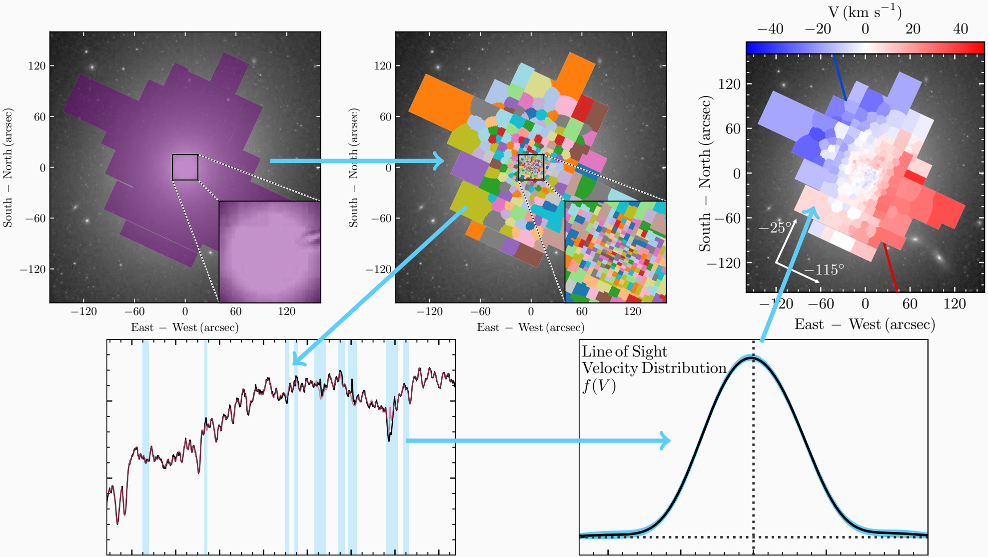
- This is an integral field unit, yielding a distinct spectrum at each spatial pixel.
- 62 pointings were observed, each corresponding to a $20.4'' \times 33''$ FOV with $0.3'' \times 1.4''$ spatial pixels
- The full FOV spans about 250” along the photometric major axis and 300” along the minor (11.6 square arcmin in total!)

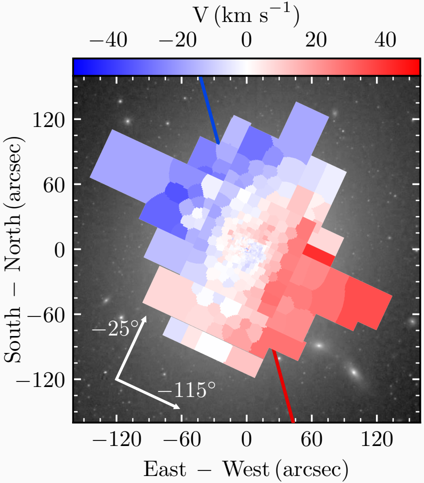
From Spectra to Stellar Velocities

(Liepold+23)



M87's Stellar Velocity Field

(Liepold+23)



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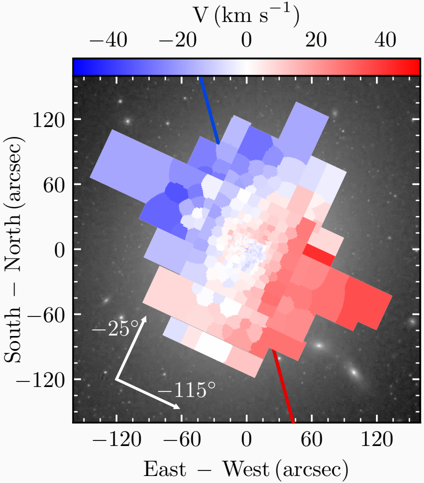
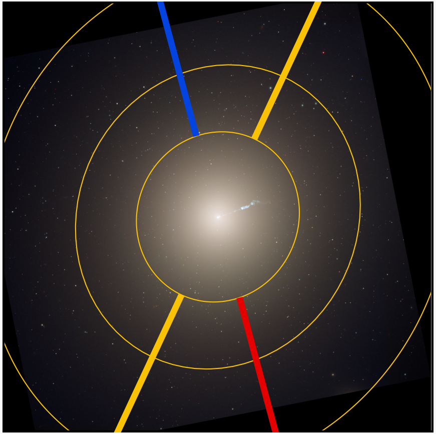
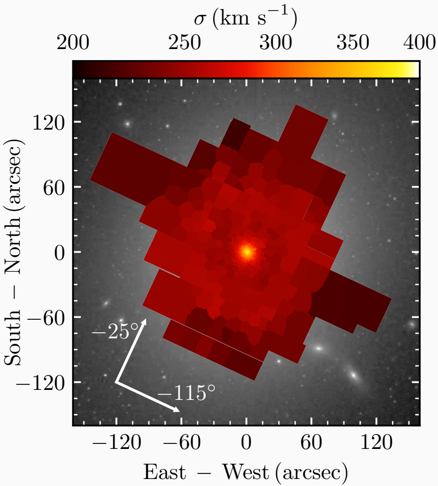
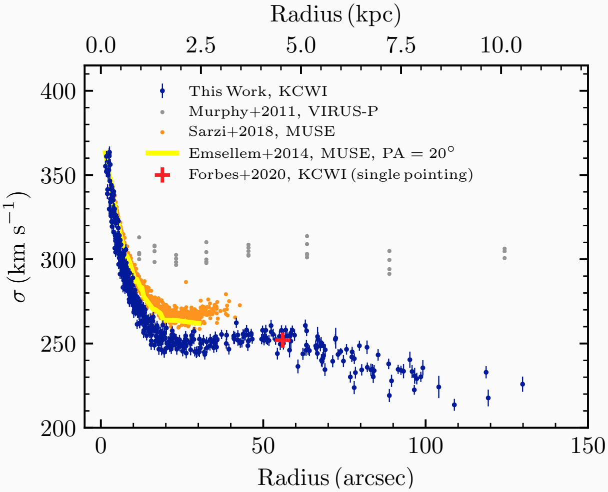




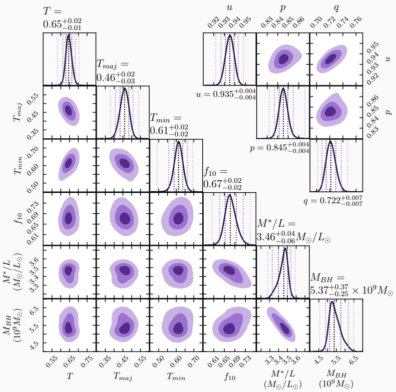
M87’s Stellar Velocity Dispersion

(Liepold+23)





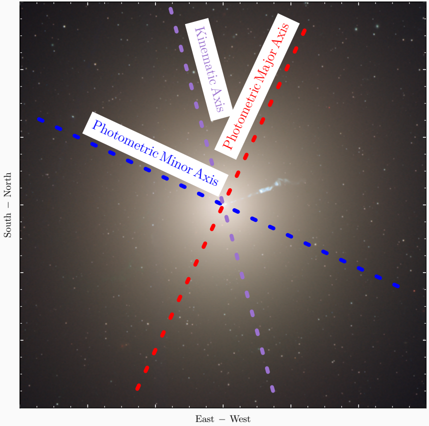
M87* is a little bit smaller than previously measured! (Liepold+23)



M87 Property (units)	Inferred value
Black hole mass $M_{\rm BH}$ ($10^9\ M_\odot$)	$5.37^{+0.37}_{-0.25} \pm 0.22$
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
Shape parameter T	0.65 ± 0.02
Average middle-to-long axis ratio p	0.845 ± 0.004
Average short-to-long axis ratio q	0.722 ± 0.007

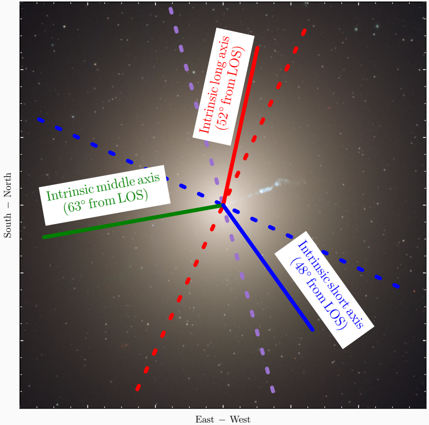
M87's Intrinsic Angular Momentum Axis

(Liepold+23, ongoing)



	PA on Sky (° E of N)	Angle from Line of Sight
Photometric Major Axis	$-25°$	—
Photometric Minor Axis	$+65°$	—
Kinematic Axis	$-165°$	—

(Liepold+23, ongoing)



	PA on Sky (° E of N)	Angle from Line of Sight
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Kinematic Axis	−165°	—
Intrinsic Long Axis	−12°	52°
Intrinsic Middle Axis	+100°	63°
Intrinsic Short Axis	−144°	48°

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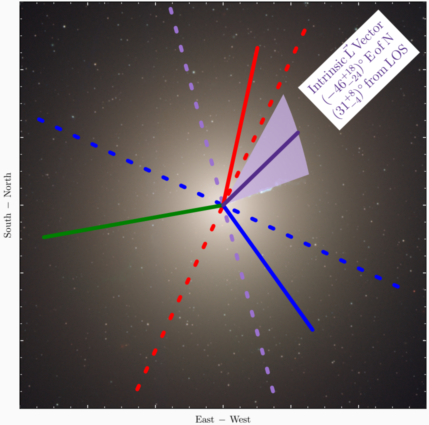

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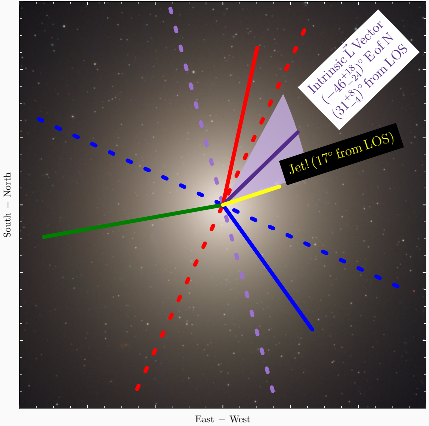
Intrinsic $\vec{L}$ Vector (between 80" and 150")	$(-46^{+17}_{-24})°$	$(31^{+7}_{-4})°$

M87's Intrinsic Angular Momentum Axis

(Liepold+23, ongoing)



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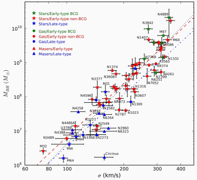
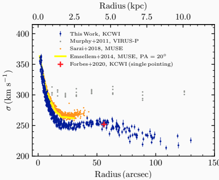
Intrinsic $\vec{L}$ Vector (between 80" and 150")	$(-46^{+17}_{-24})^\circ$	$(31^{+7}_{-4})^\circ$
Jet!	-72°	17°

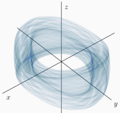
The intrinsic angular momentum axis of M87's stellar component is only $(17^{+11}_{-7})^\circ$ from the jet!

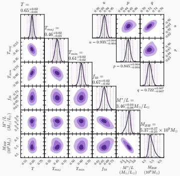
Thank you! (Questions?)

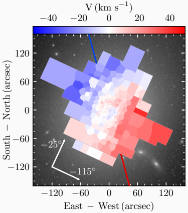
Looking Backward

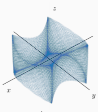












Looking Forward

- SUPER-MASSIVE galaxies with huge central cores
- JWST M87 data in 30 ± 27 days
- TriOS 2.0!