Keck Integral-Field Spectroscopy of M87 Reveals an Intrinsically Triaxial Galaxy and a Revised Black Hole Mass

Emily Liepold, UC Berkeley
emilyliepold@berkeley.edu

Liepold, Ma, and Walsh, ApJL, 945 L35. (12 days old!)
Download the paper at **emilyliepold.com/M87**

Our Observations

Our Data

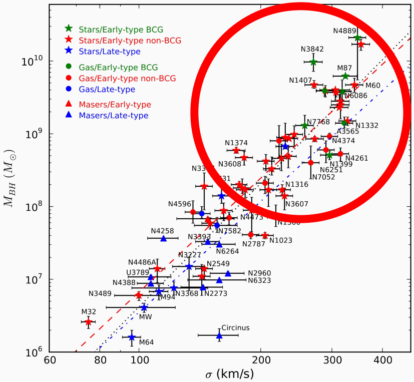
Triaxiality!

Triaxial Schwarzschild Modelling

Results!

Motivation: What are we looking at?

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



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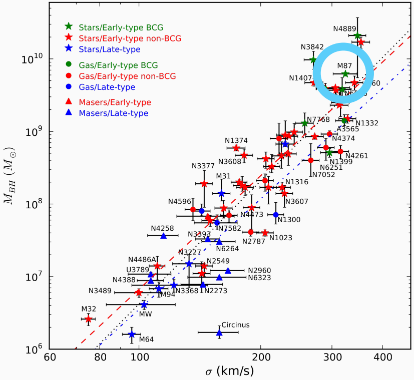
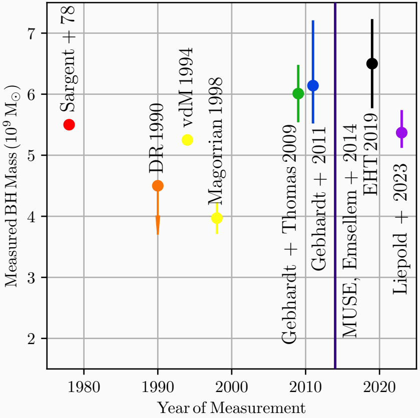
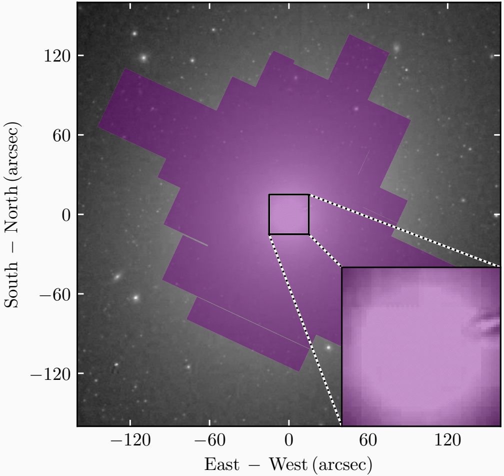




Our KCWI Observations

(Liepold+23)



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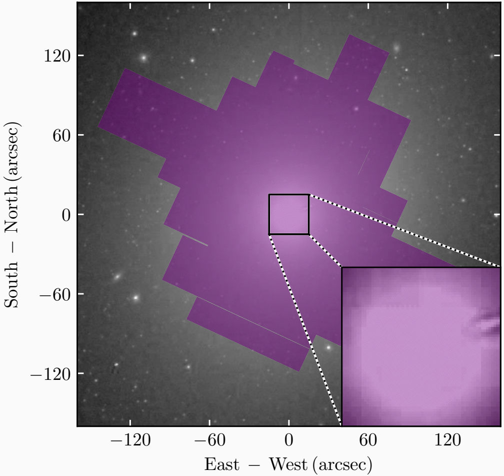

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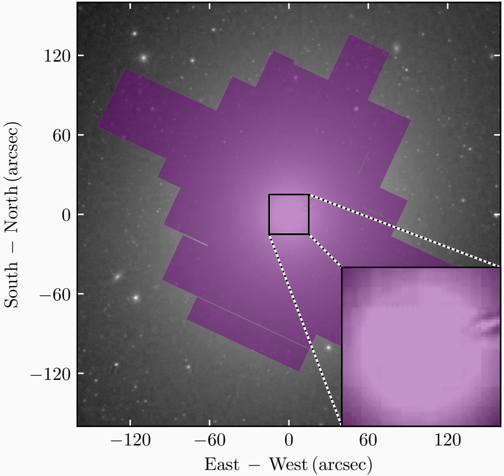

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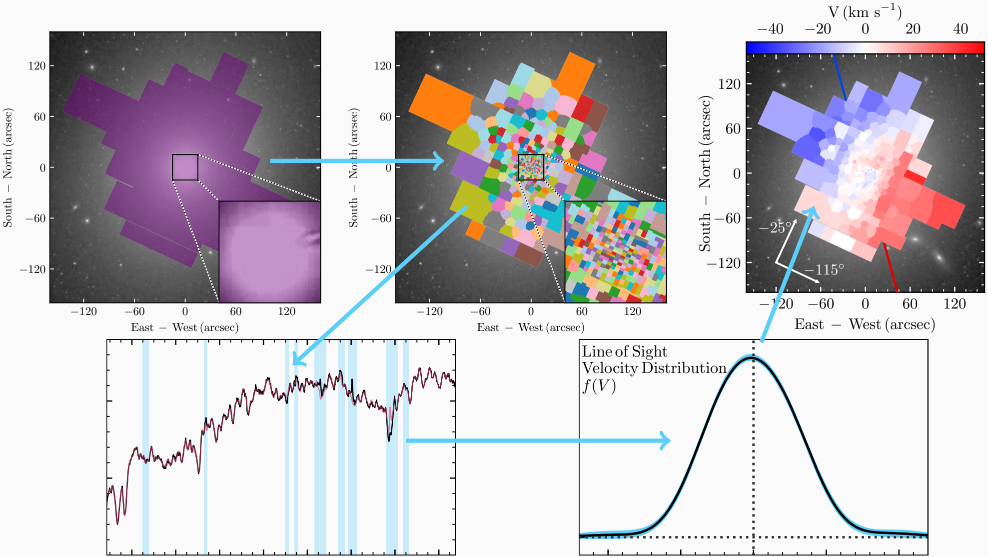
- The spectra are usable from 3500Å and 5600Å with $R \sim 900$

From Spectra to Stellar Velocities

(Liepold+23)



M87's Stellar Velocity Field

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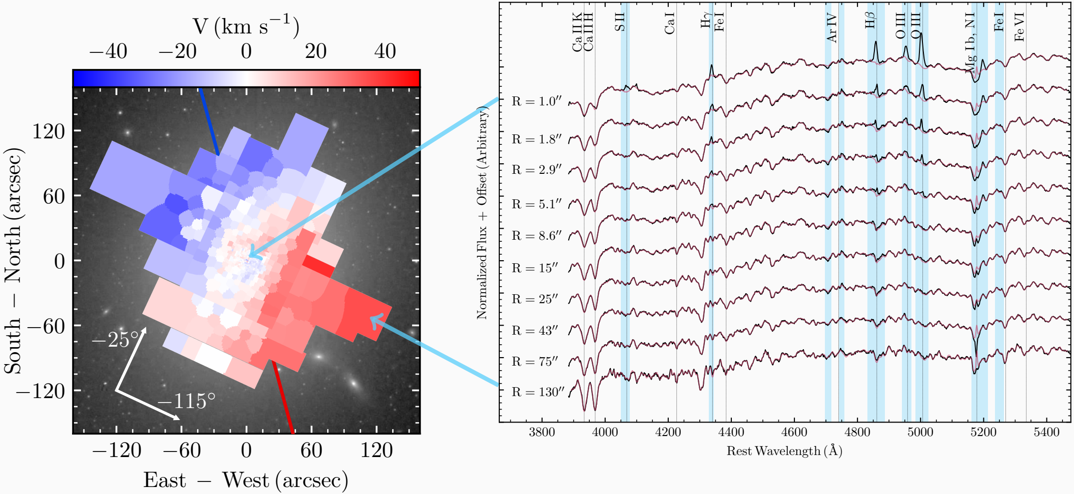

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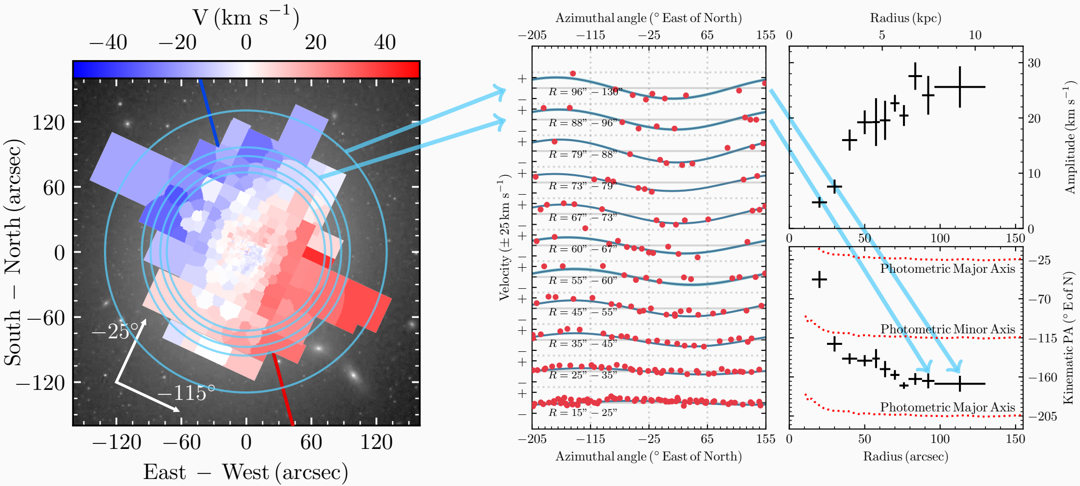
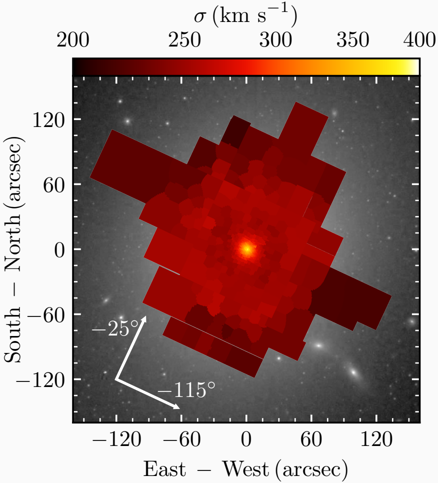
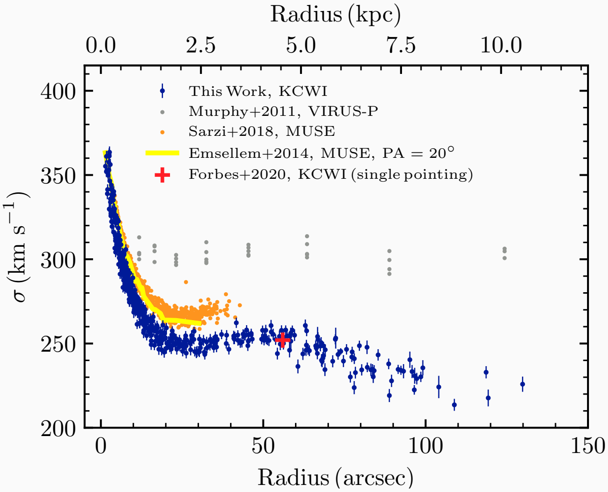


M87’s Stellar Velocity Dispersion

(Liepold+23)



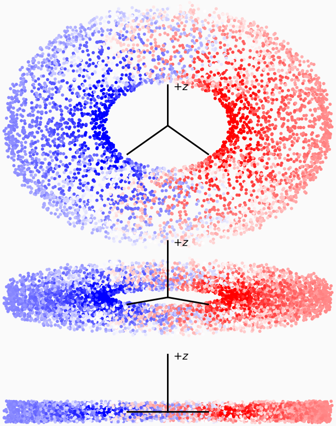


Motivation: Why do we care about the shape?

Shape of $\rho \rightarrow$ Shape of $\Phi \rightarrow$ *Symmetries* of $\Phi \rightarrow$ 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...

More Motivation: Kinematic fingerprints of non-axisymmetry



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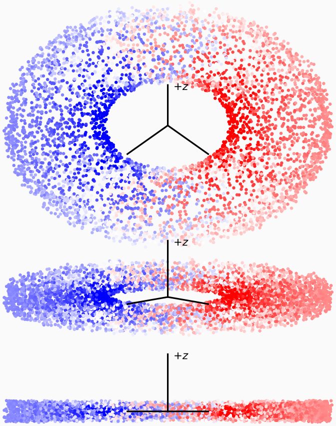

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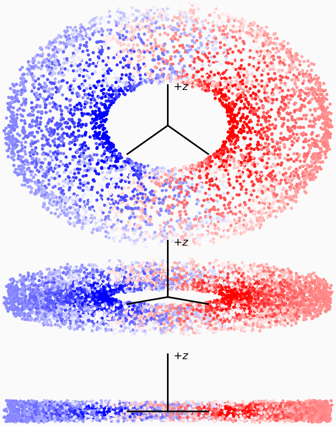

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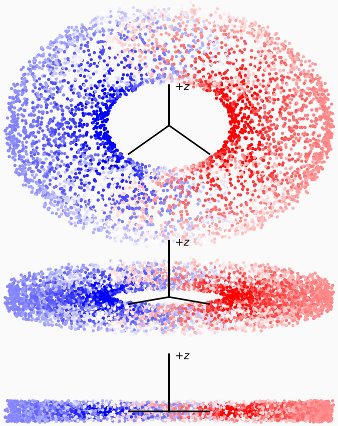

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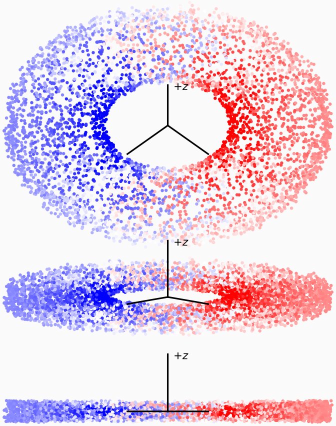

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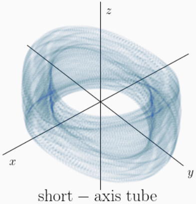
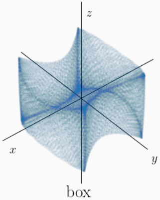
- **(That's M87!)**

Orbits in triaxial potentials

Loop Orbits	Box Orbits





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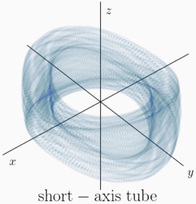	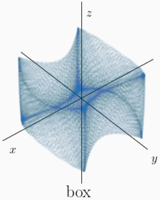
Appears in axisymmetric potentials	Not present in axisymmetry!

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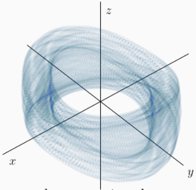
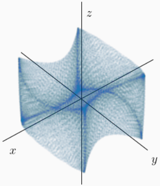
 short – axis tube	 box
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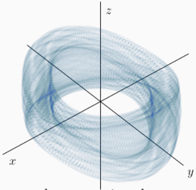
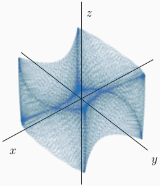
 short – axis tube	 box
Appears in axisymmetric potentials Persistent sense of rotation about either the **short** or **long** axis **Centrophobic**	Not present in axisymmetry! No persistent sense of rotation Can be **Centrophilic**

Schwarzschild Orbit Modelling

Schwarzschild 1979: Can triaxial stellar systems in dynamical equilibrium be self-consistent?

Strategy:

1. Propose a (triaxial) stellar density distribution
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This turns out to easy for reasonable proposed models. We can also try to fit kinematic observables to compare different proposed potentials.

The TriOS Triaxial Orbit Superposition Code

(Liepold+20, Quenneville+21,22)

van den Bosch+ 2008: Development of 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. The code was un-named. We call our improved version 'TriOS' (**Tri**axial **O**rbit **S**uperposition)

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 $\sim (\mathrm{Number\,of\,Constraints})^{-\mathrm{D}/2}$

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

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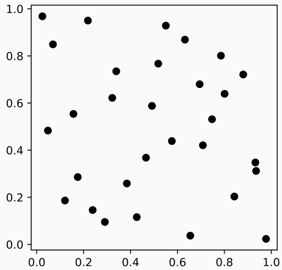

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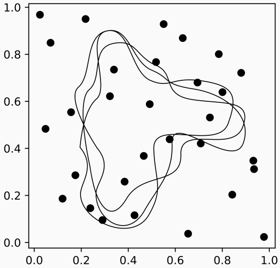

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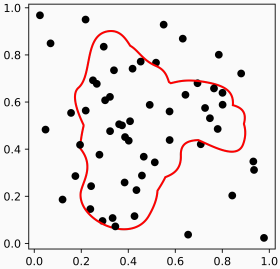

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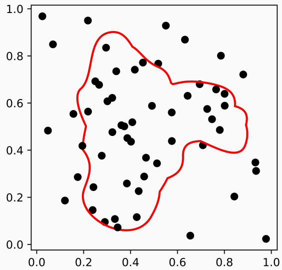

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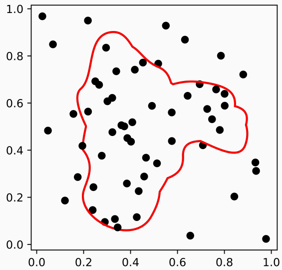
For a reasonable-resolution grid search (10 pt per dimension), we'd need $\mathrm{O}(10^6)$ models – 20,000,000 CPU-hours!



Efficient Sampling of the Shape

(Quenneville+22)

- The 3D shape is determined through **deprojection** of the 2D surface brightness profile (we use MGEs)
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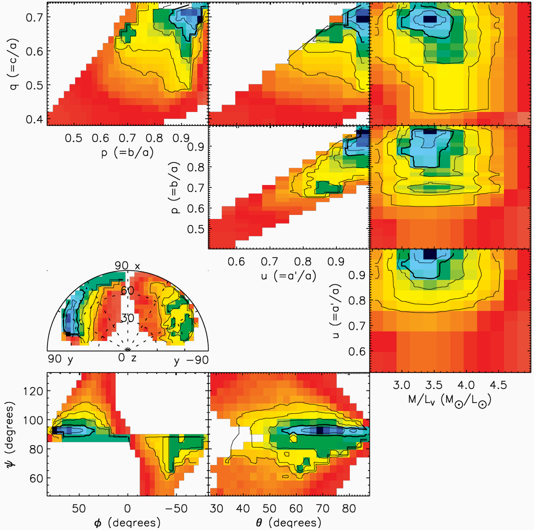

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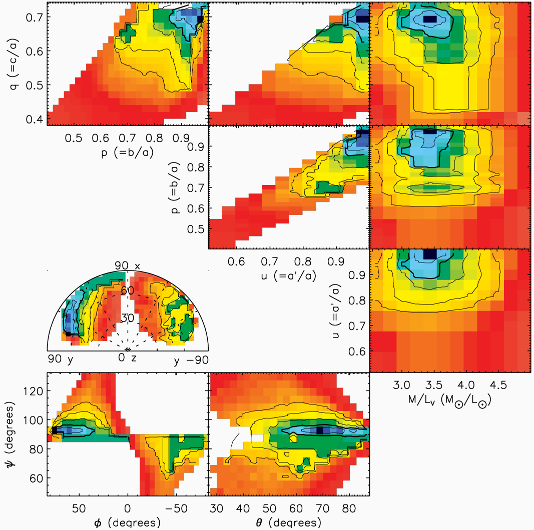
- We've found an additional set of parameters which map the deprojectible shape space to a unit cube with minimal covariances



$$T = \frac{1-p^2}{1-q^2} \qquad T_{\mathrm{maj}} = \frac{1-u^2}{1-p^2} \qquad T_{\mathrm{min}} = \frac{(uq')^2-q^2}{p^2-q^2}$$

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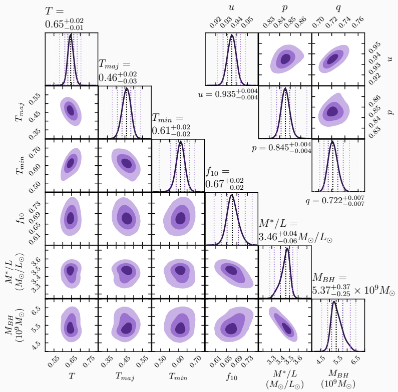
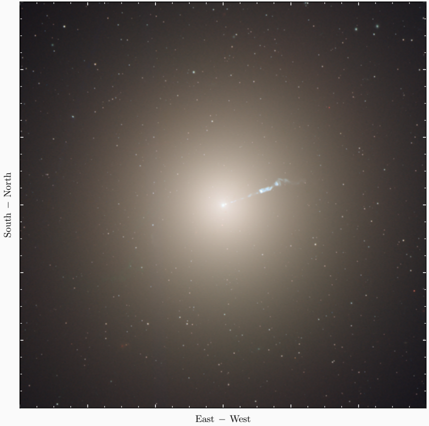


M87 Property (units)	Inferred value
Black hole mass $M_{\rm BH}$ (10^9 $M_\odot$)	$5.37^{+0.37}_{-0.25} \pm 0.22$
Inner M^*/L (V-band; $M_\odot/L_\odot$)	$8.65^{+0.10}_{-0.15} \pm 0.38$
Dark matter fraction at 10 kpc f_{10}	0.67 ± 0.02
Shape parameter T	0.65 ± 0.02
Average middle-to-long axis ratio p	0.845 ± 0.004
Average short-to-long axis ratio q	0.722 ± 0.007

M87's Intrinsic Angular Momentum Axis

(Liepold+23)



	PA on Sky (° E of N)	Angle from Line of Sight

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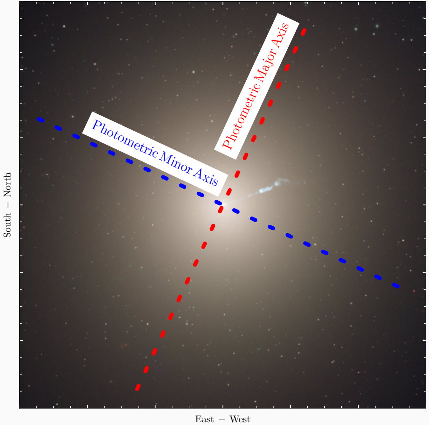

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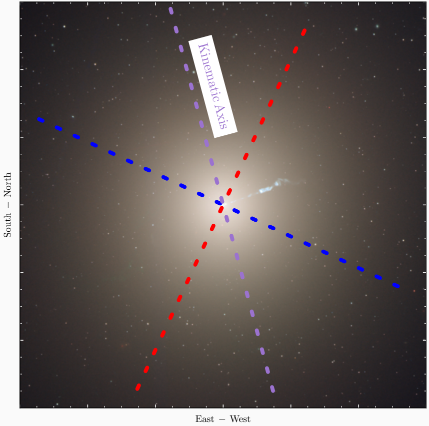

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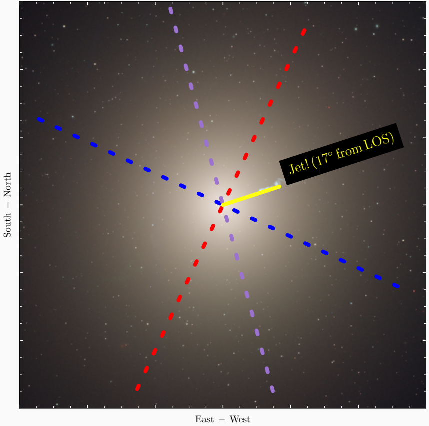

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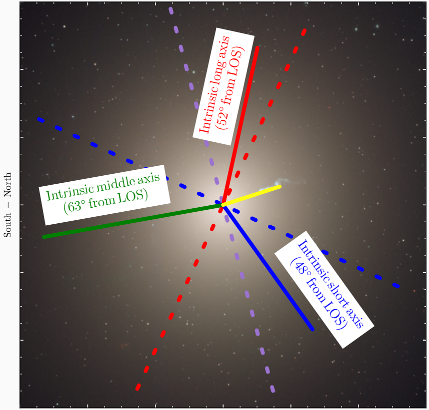

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Intrinsic Long Axis	−12°	52°
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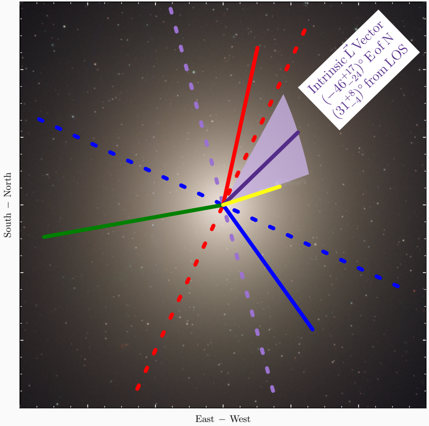

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Intrinsic $\vec{L}$ Vector (between 80" and 150")	$(-46^{+17}_{-24})^\circ$	$(31^{+7}_{-4})^\circ$

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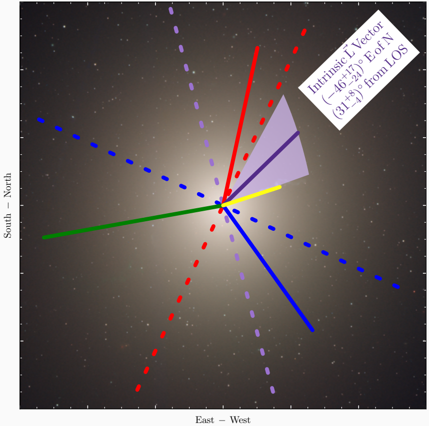

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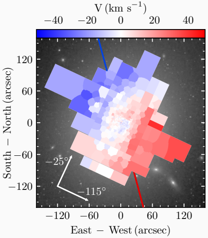
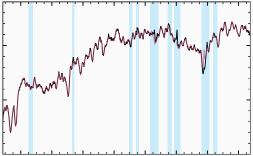
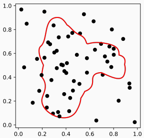
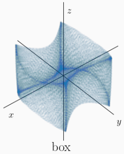
The intrinsic angular momentum axis of M87's stellar component is only $(17^{+11}_{-7})^\circ$ from the jet!

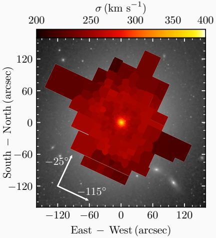
Thank you! (Questions?)

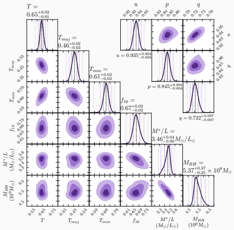












$M_{\rm BH}$ ($10^9\ M_\odot$)	$5.37^{+0.37}_{-0.25} \pm 0.22$
Shape parameter T	0.65 ± 0.02
Axis ratio p	0.845 ± 0.004
Axis ratio q	0.722 ± 0.007