M87 and Beyond:

Recent Progress in Stellar Dynamical Measurements of (ultramassive) Black Hole Masses

Berkeley Big BH Bunch:
Emily Liepold
Matthew Quenneville
Jacob Pilawa
Chung-Pei Ma

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How to **find**
supermassive black holes
using stellar dynamics

How to **measure**
supermassive black holes
using stellar dynamics

How to find supermassive black holes

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How to measure supermassive black holes

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Big BHs are intriguing

- Ultramassive BHs are
  - PTA sources?
  - EHT sources?
  - Endpoint of mergers + evolution?

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Big BHs are booming

27 from stellar or gas with
$M_{\rm BH} \gtrsim 10^9 M_\odot$
4 with $M_{\rm BH} \gtrsim 10^{10} M_\odot$

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  - EHT sources?
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Boizelle+21: NGC 315
Quenneville+22: NGC 1453
Pilawa+22: NGC 2693
Liepold+23: M87
De Nicola+24: NGC 708
Dominiak+24: NGC 997, and 1684
Mehrgan+24: NGCs 1407, 4751, 5328, 5516, 7619
Pilawa+soon, NGC 57
Liepold+soon, Holmberg 15A

Big BHs are booming

27 from stellar or gas with $M_{\rm BH} \gtrsim 10^9 M_\odot$

4 with $M_{\rm BH} \gtrsim 10^{10} M_\odot$

12 from past 3 years!
8 this year!
(Plus more in the pipeline)

Big BHs are uncommon

Problem:

The biggest BHs live in the biggest galaxies

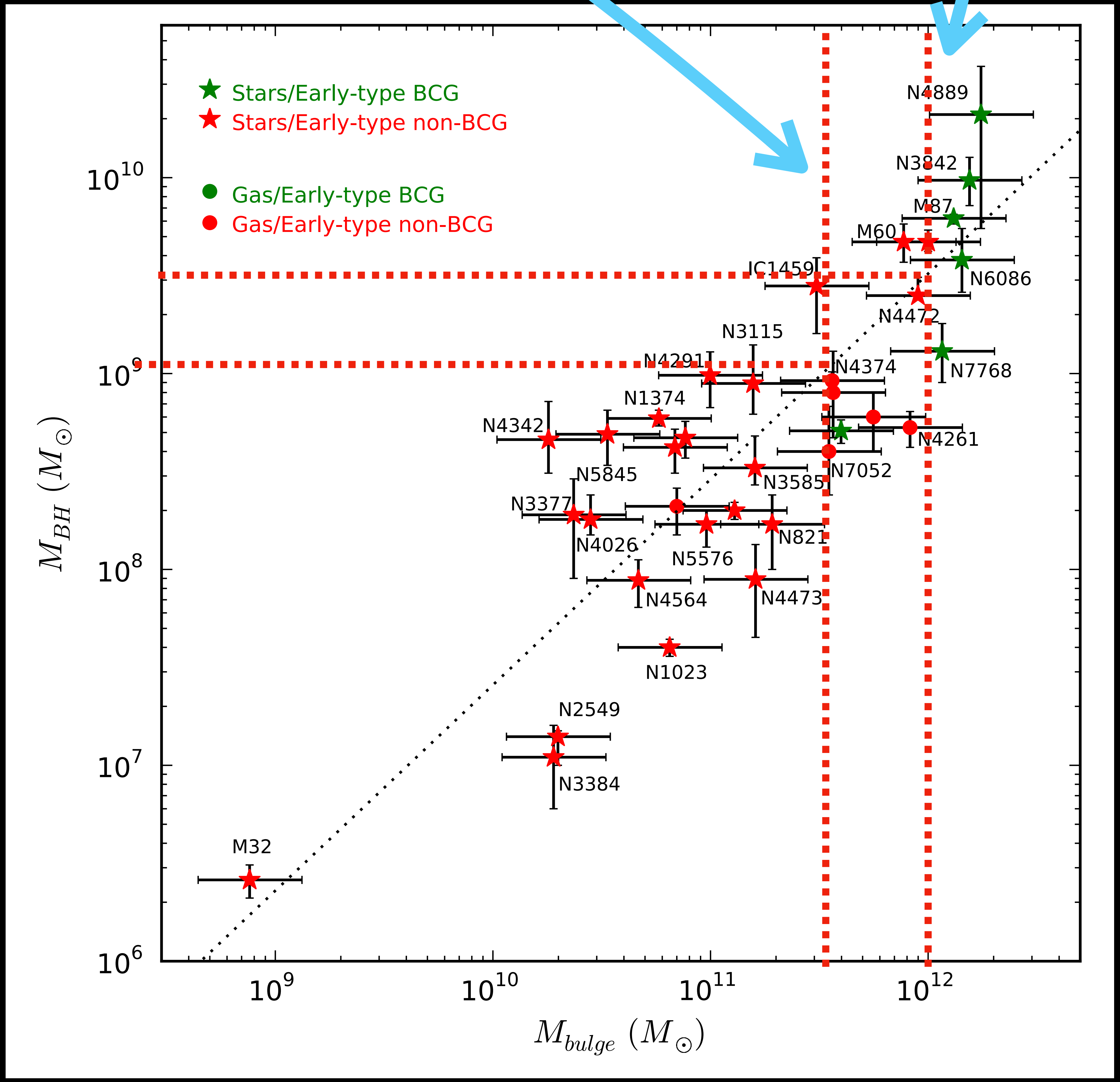
Big Galaxies are rare

~200 galaxies within 100 Mpc with $M_* \gtrsim 10^{11.5} M_\odot \rightarrow M_{\rm BH} \gtrsim 10^9 M_\odot$

~20 galaxies within 100 Mpc with $M_* \gtrsim 10^{12} M_\odot \rightarrow M_{\rm BH} \gtrsim 3 \times 10^9 M_\odot$

~ 20 within 100 Mpc

~ 200 within 100 Mpc



How to find SMBHs

Different methods for different galaxies

Local Specific

General

Distant Specific

Individual stellar orbits (S2, etc around Sga*; UCLA team+, GRAVITY+)

Shadow imaging (Sga* and M87; EHT)

Gas dynamics (CO or ionized gas; e.g. Walsh+, Boizelle+, Barth+, WISDOM team, numerous others)

Integrated stellar motion (Galaxies with stars + resolved SOI)

Reverberation mapping (AGN; e.g., Bentz+)

Single Epoch emission line width (AGN; e.g., Greene + Ho 2005)

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Specific — General — Specific

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Relative velocities ***doppler-shift*** a star's spectrum.

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What do we need?

- Spectra! (To observe the doppler shifts)
- High S/N (To measure the velocity distributions precisely)
- High spatial resolution (To probe the area dominated by the SMBH)
- Large spatial coverage (To probe the area dominated by dark matter)
- And a bunch of modelling!

The **MASSIVE** Survey

Ma+2014

MASSIVE is a…

- Volume-limited (D < 108 Mpc, $\delta > -6^\circ$)
- Mass-limited (M_K < -25.3; $M_* \gtrsim 10^{11.5} M_\odot$)

Photometric and ***Spectroscopic*** Survey of **~100** of the most massive galaxies within **~100 Mpc**

19 primary MASSIVE papers so far — Stellar populations, Molecular Gas kinematics, Stellar kinematics, Ionized gas kinematics, HST + CFHT photometry, **SMBH mass measurements**…

(And lots of people! Chung-Pei Ma, Jenny Greene, Jonelle Walsh, Nicholas McConnell, Jens Thomas, Melanie Veale, Irina Ene, Viraj Pandya, Charles Goullaud, Matthew Quenneville, Emily Liepold, Jacob Pilawa, Silvana Andrade Delgado and others)

The MASSIVE Survey

Ma+2014

MASSIVE is a…

- Volu
- Mas

There are lots of other folks also looking at massive BHs w/ stellar dynamics!:
See University of Vienna team (van de van+), Leiden team (Thomas+), and Michigan team (Valluri+)

Photom … of the most massive galaxies within **~100 Mpc**

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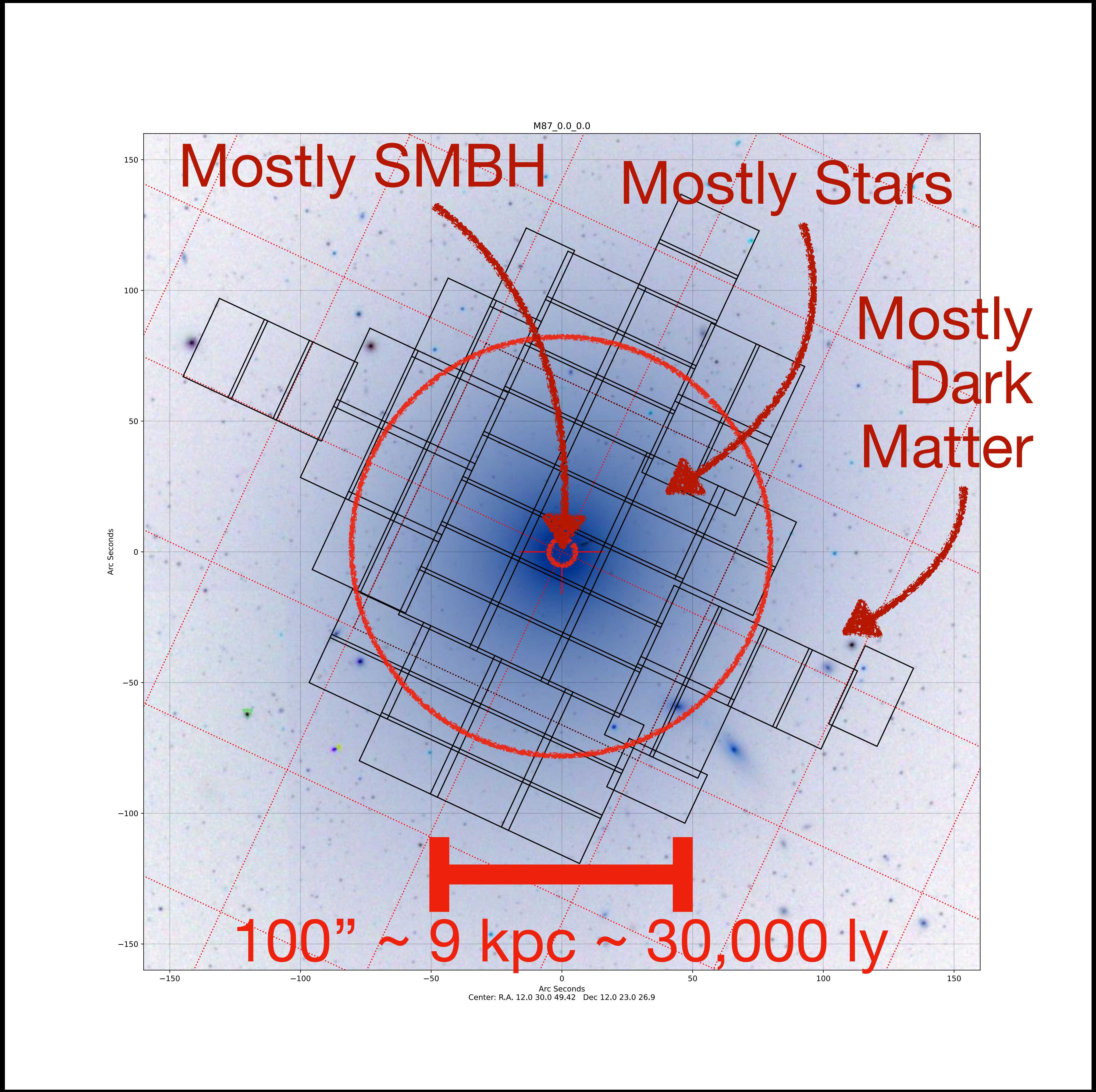
An Example: M87

Liepold, Ma, Walsh 2023

- We observed M87 with Keck Cosmic Web Imager (KCWI) during four observing runs from May 2020 - April 2022.
- 62 pointings were observed, each corresponding to a $20.4'' \times 33''$ FOV with $0.3'' \times 1.4''$ spatial pixels
- This is an integral field unit, yielding a distinct spectrum at each spatial pixel.
- The full FOV spans about 23 kpc along the photometric major axis and 28 kpc along the minor (11.6 square arcmin in total!)



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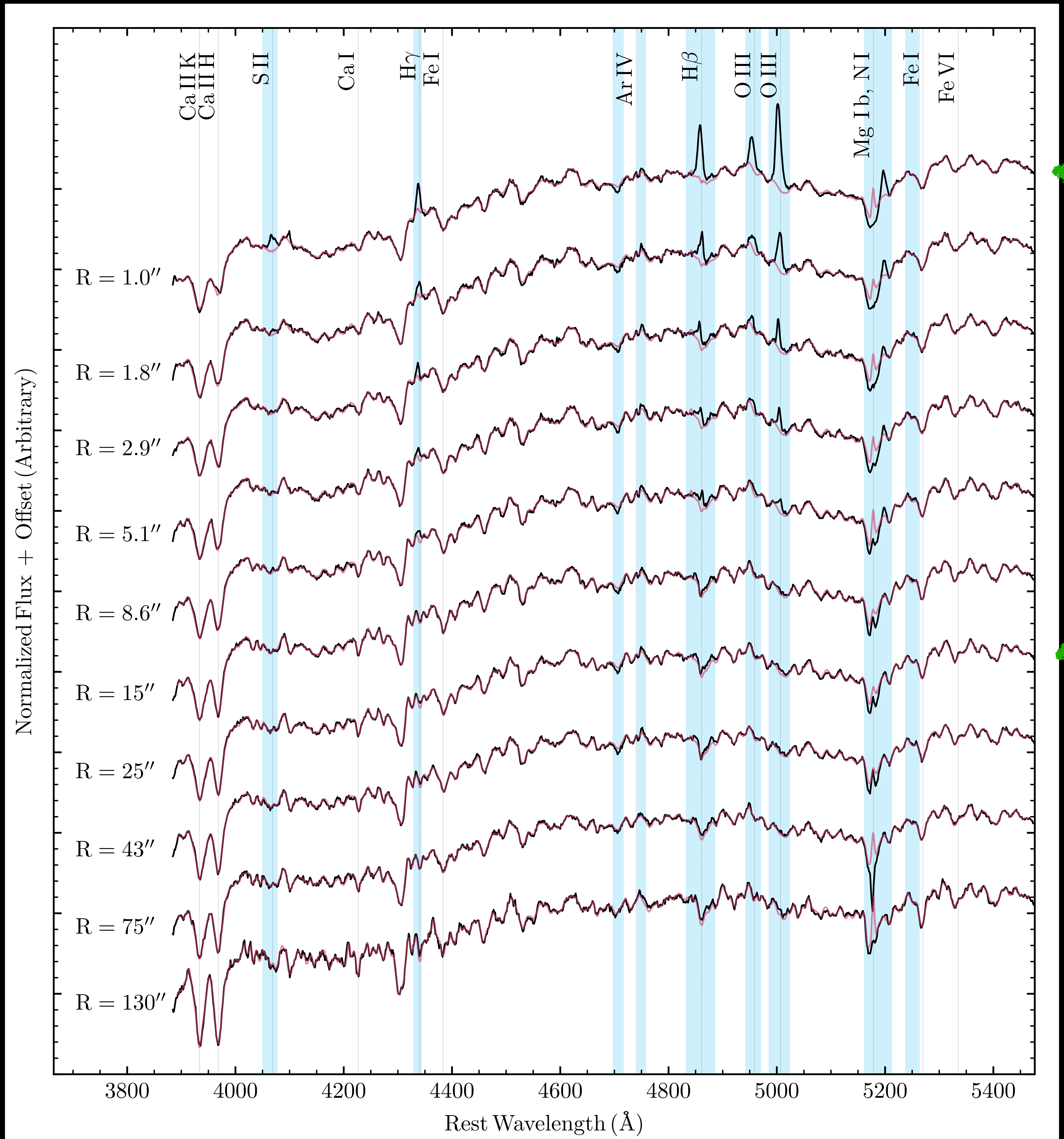

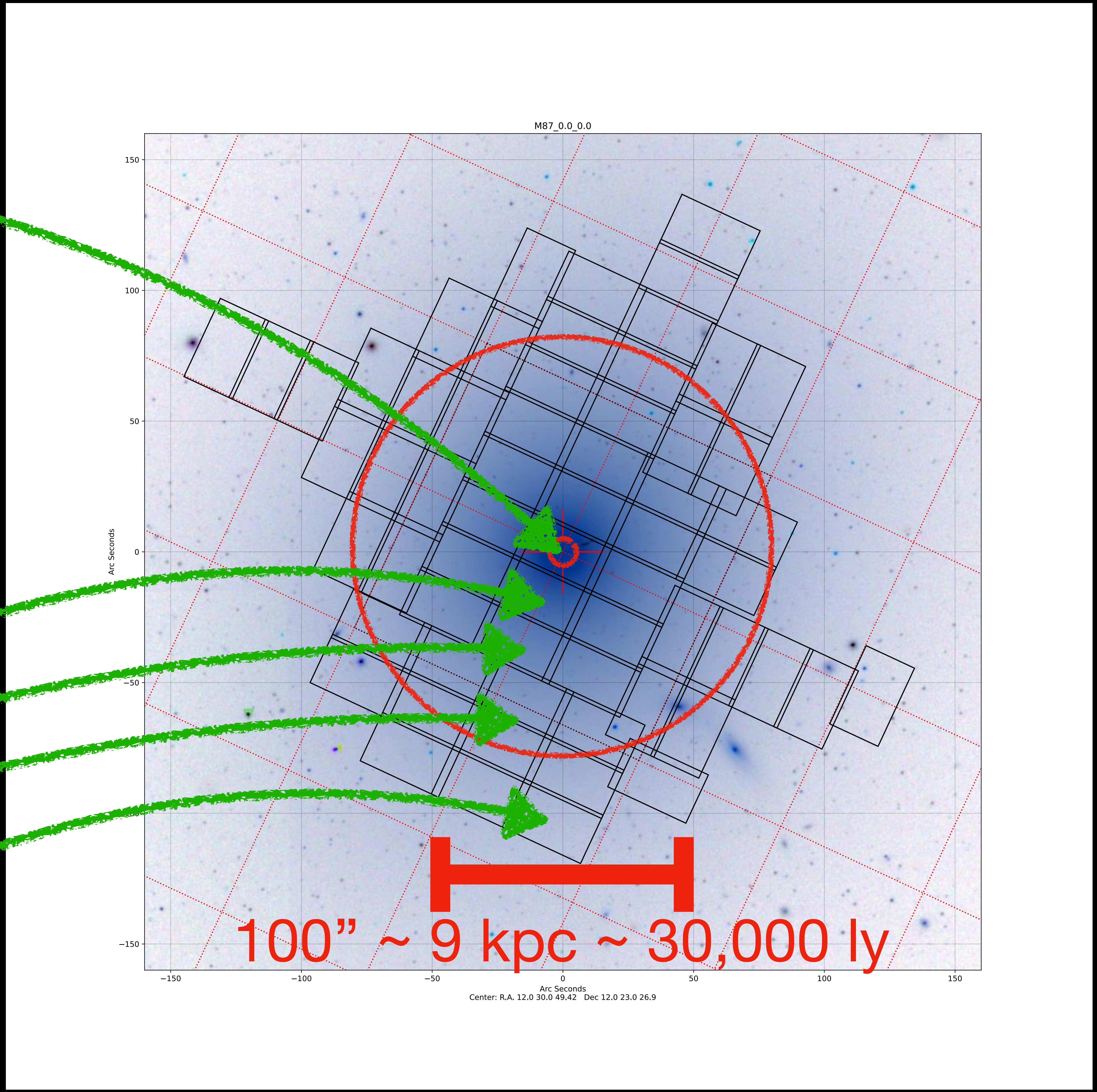

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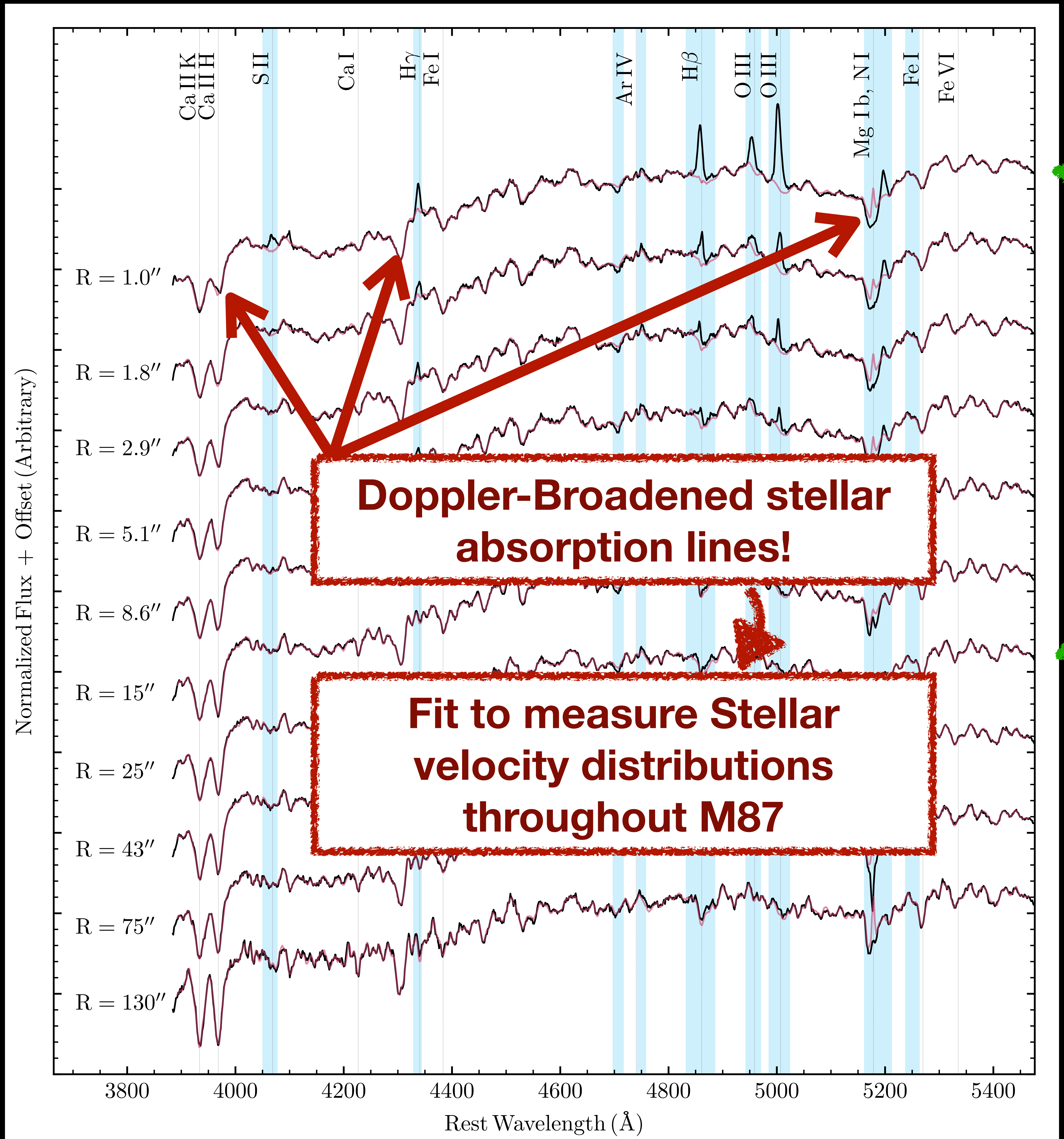

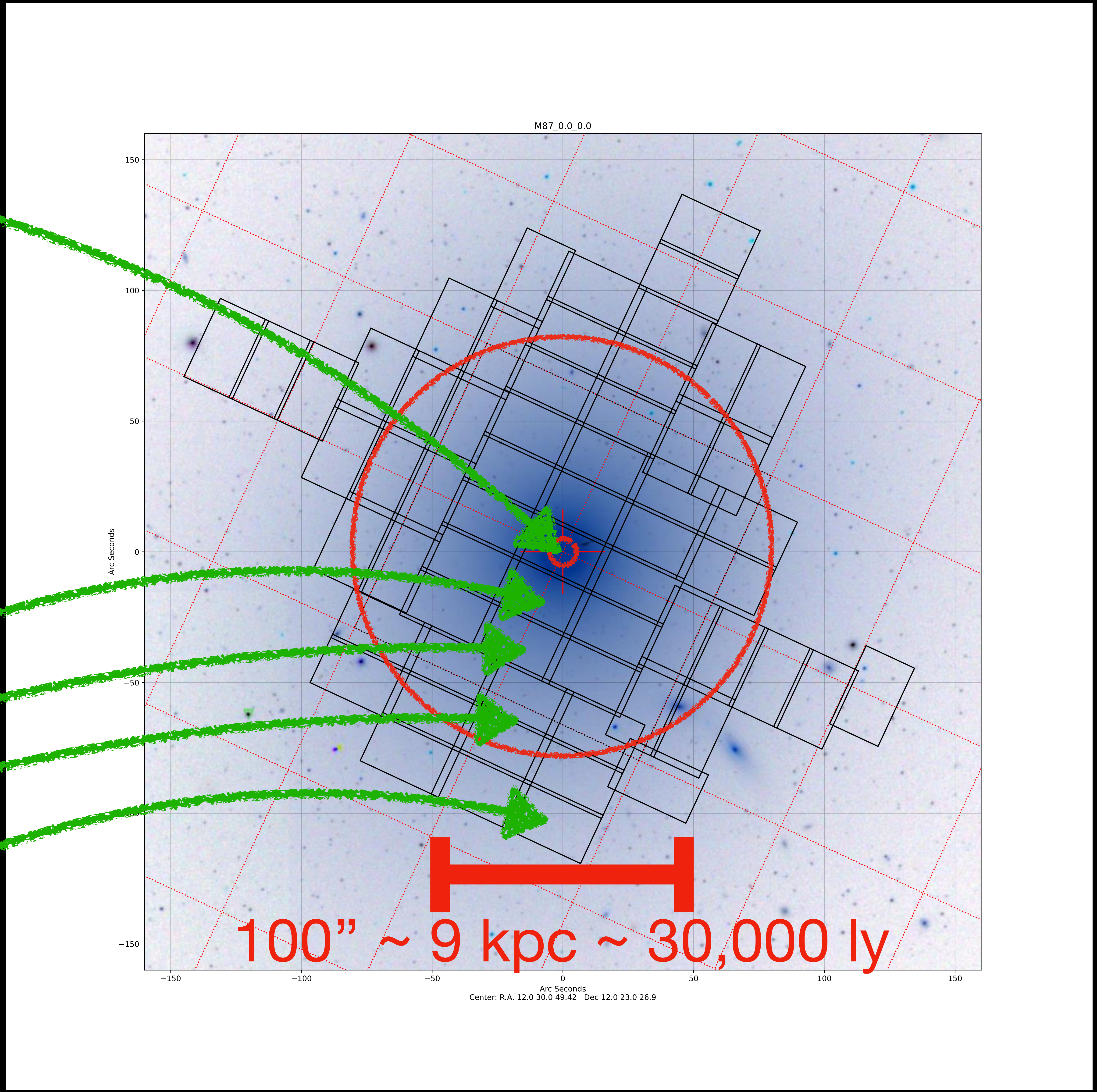

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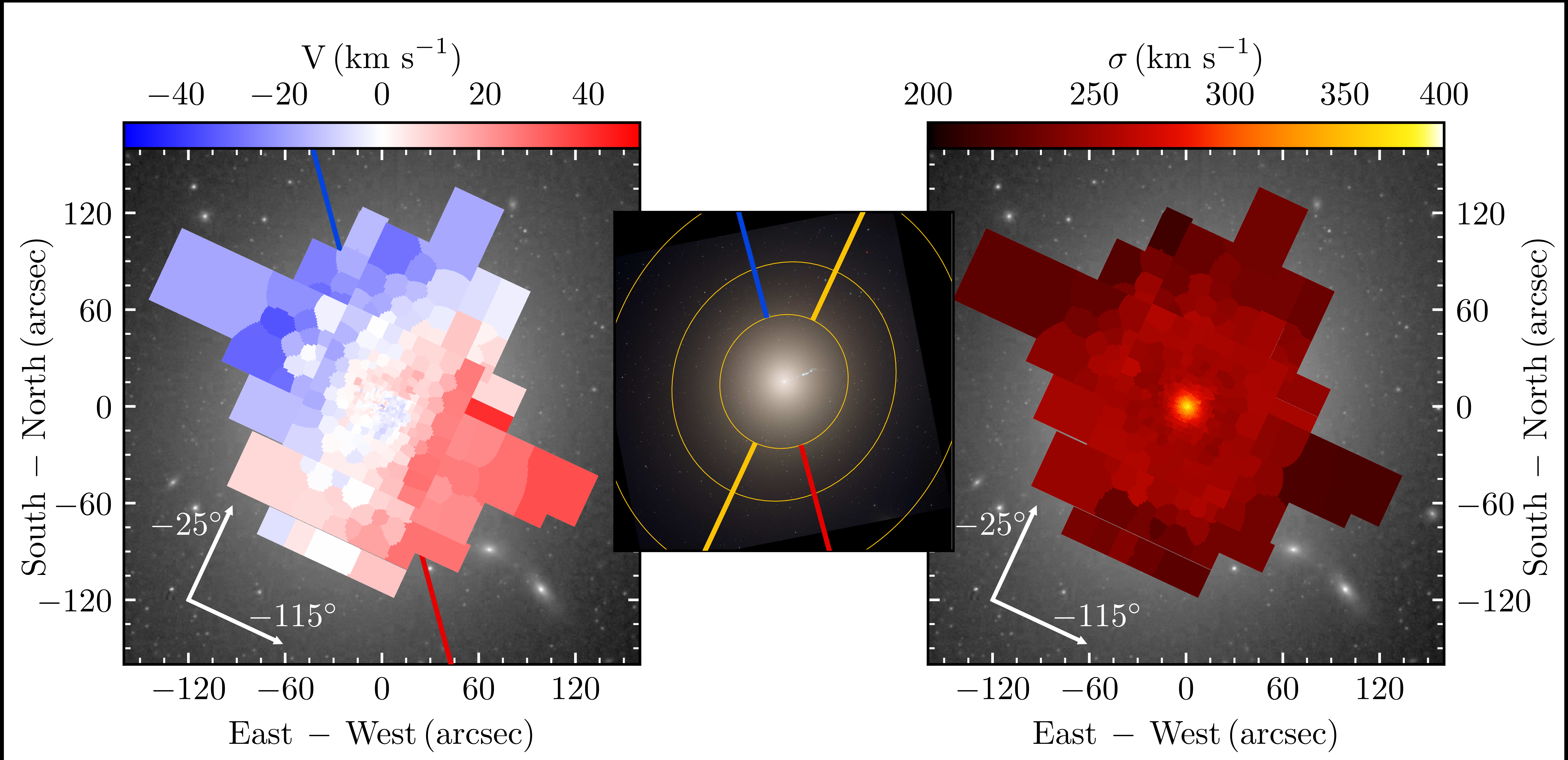

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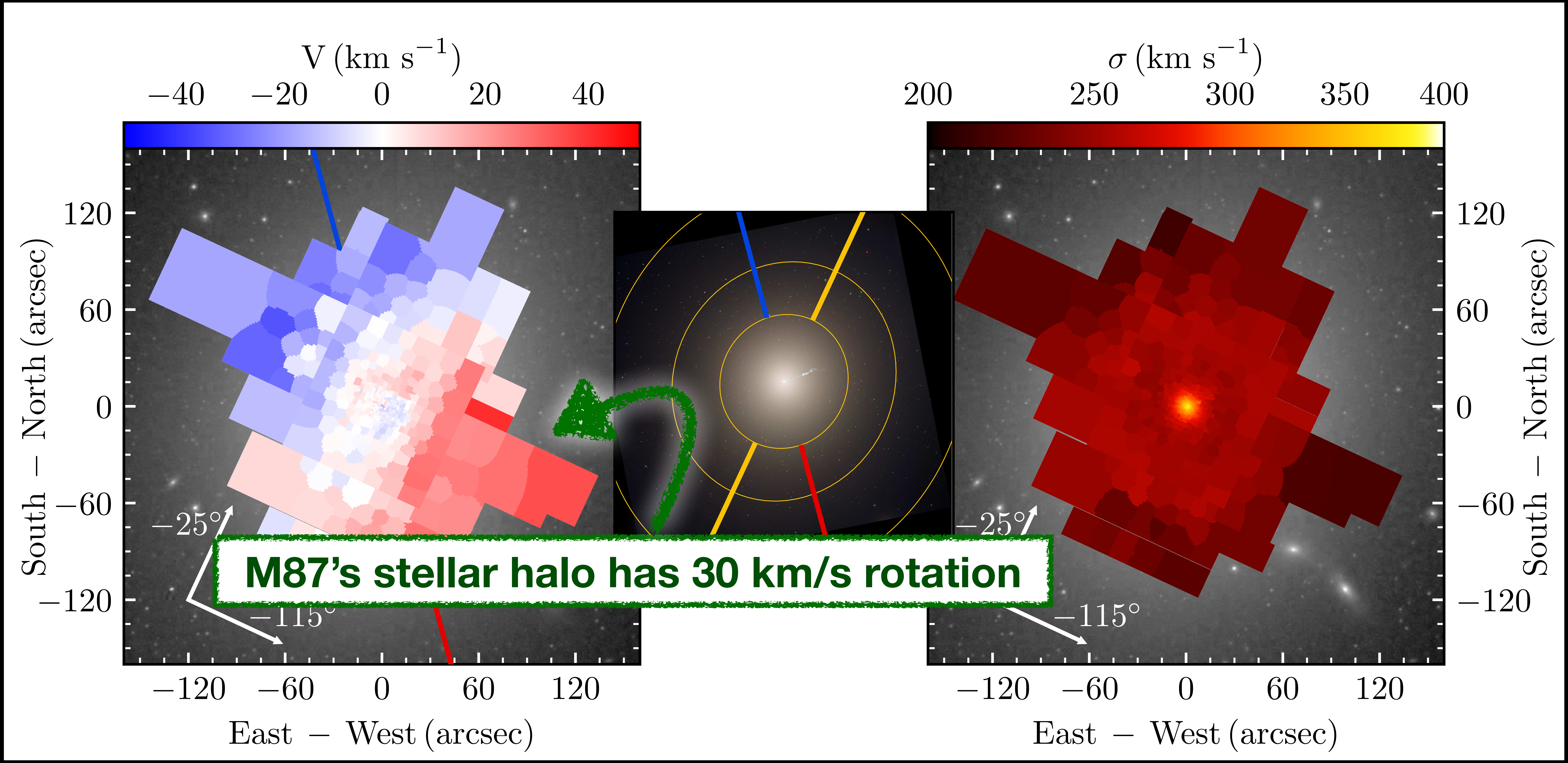

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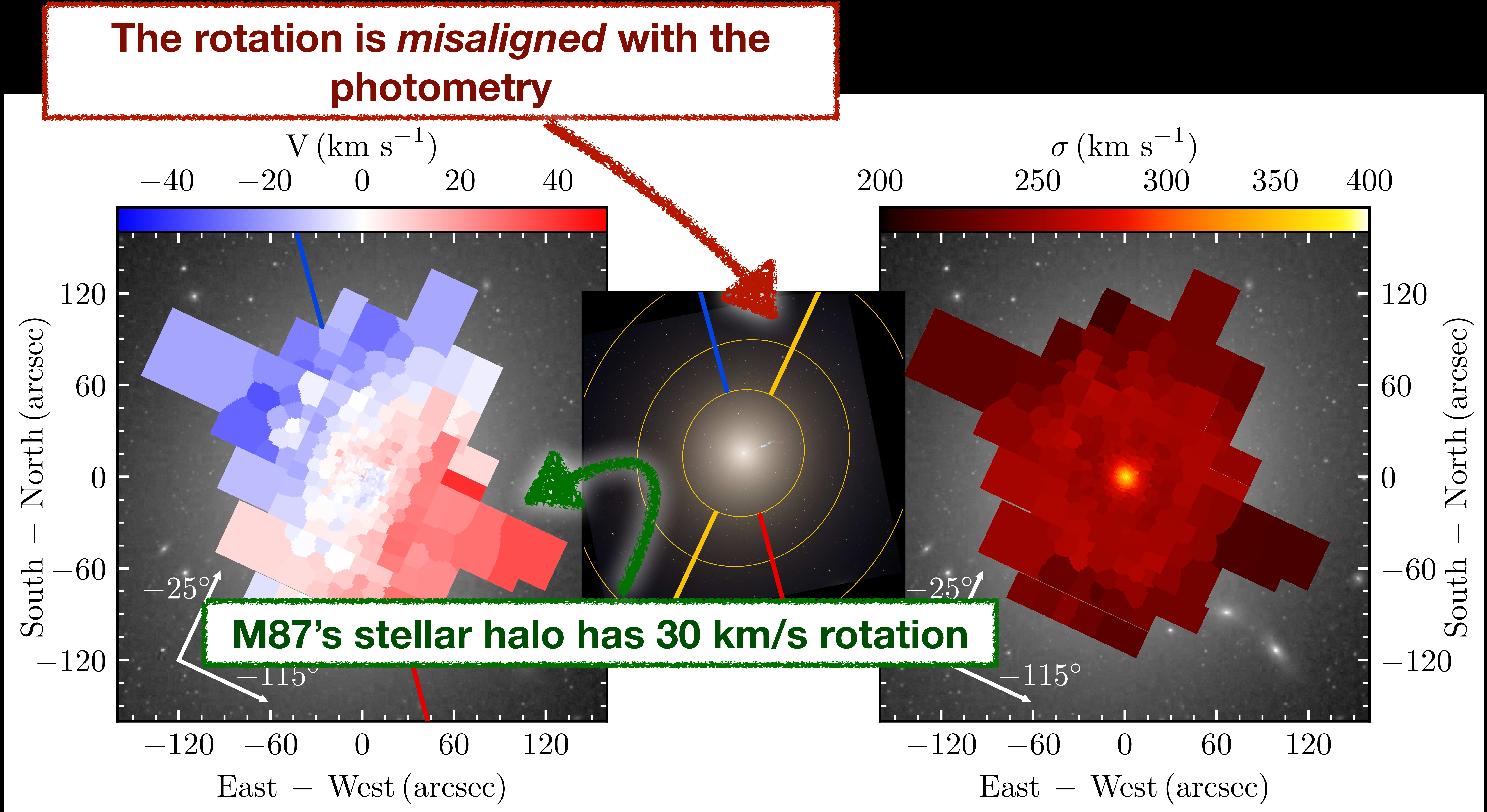

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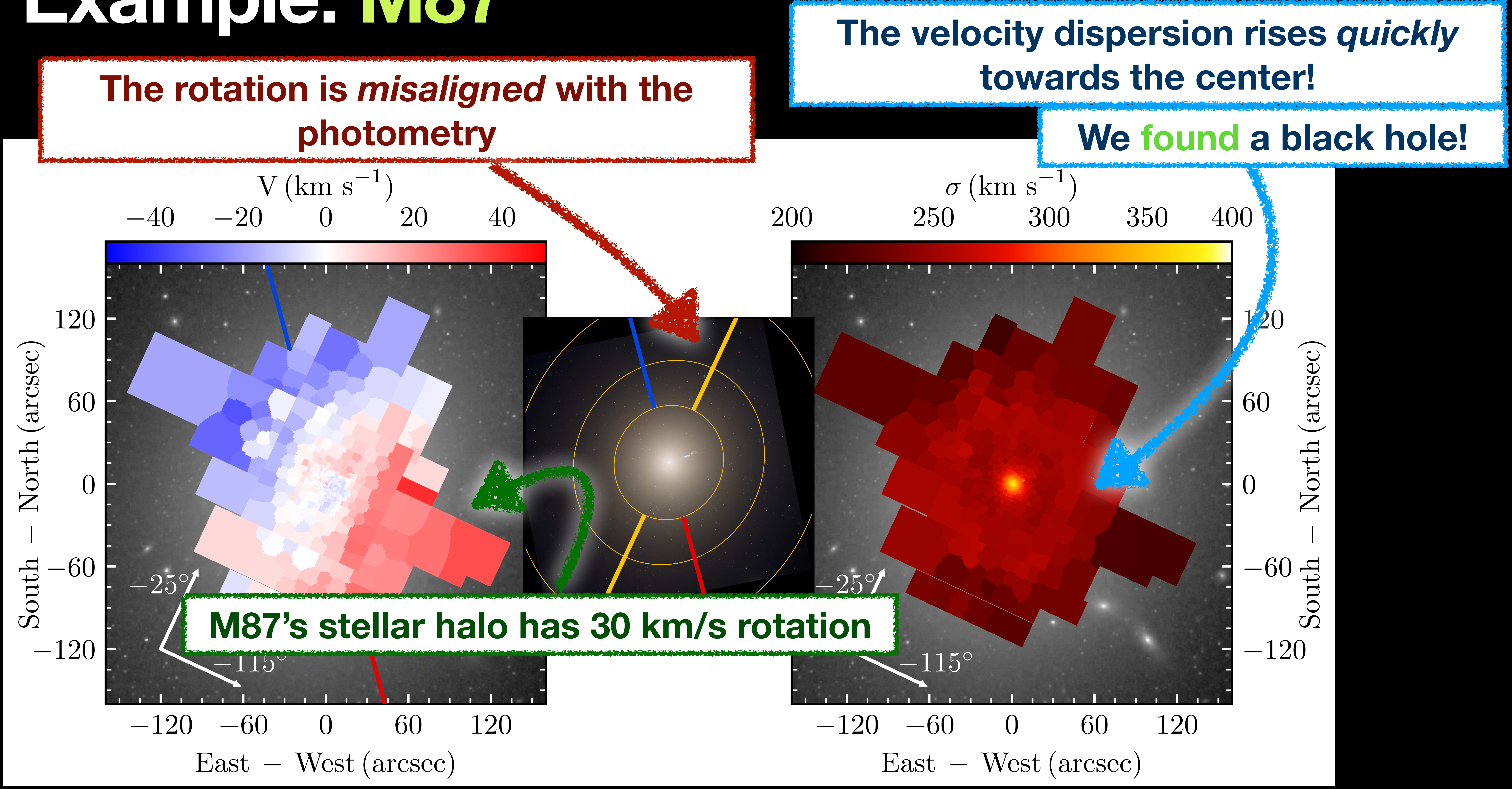
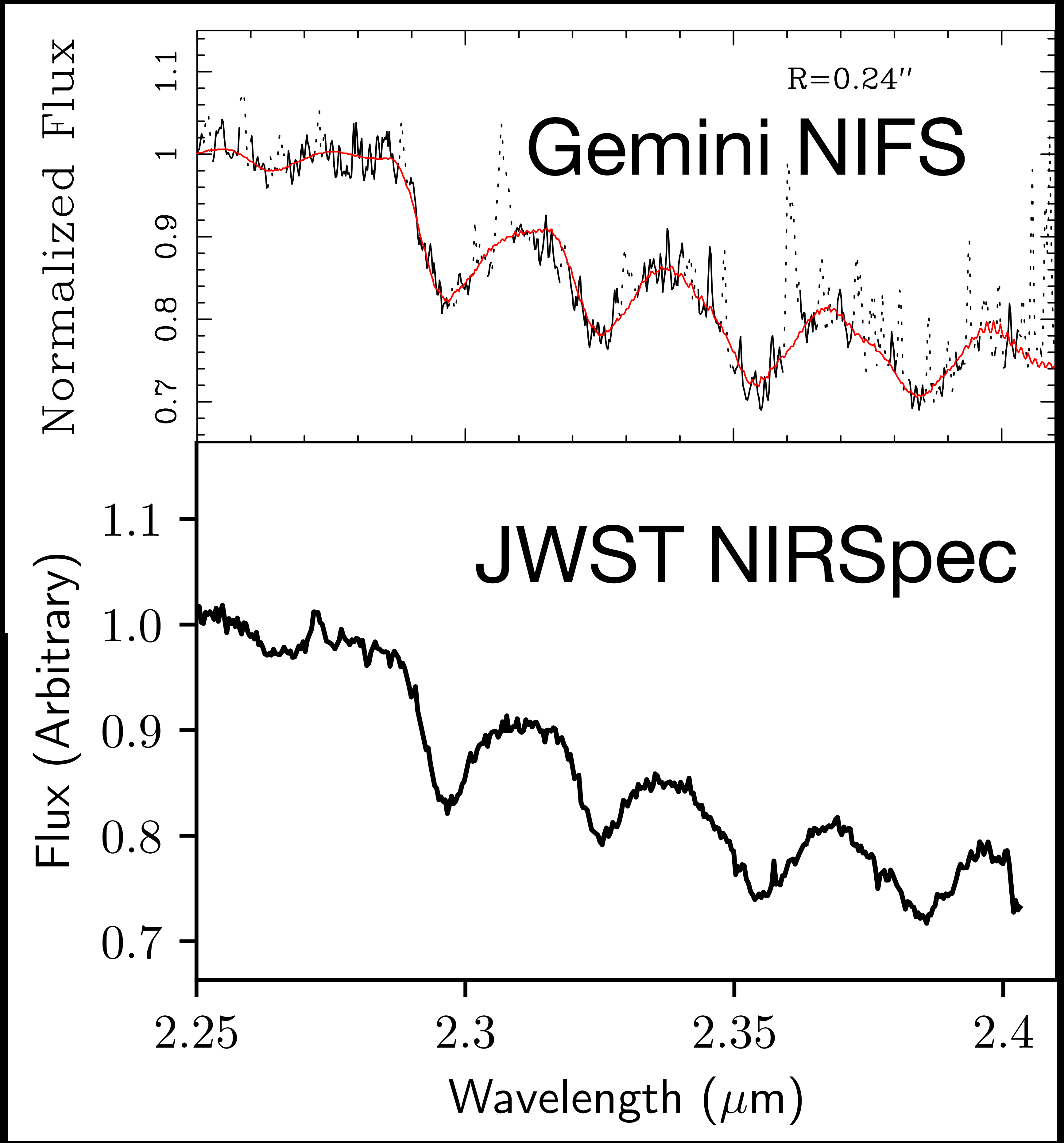


JWST observations
(a sneak peak)

Cycle 1 GO 2228: PI Jonelle Walsh,
Co-I's Greene, Liepold, Ma

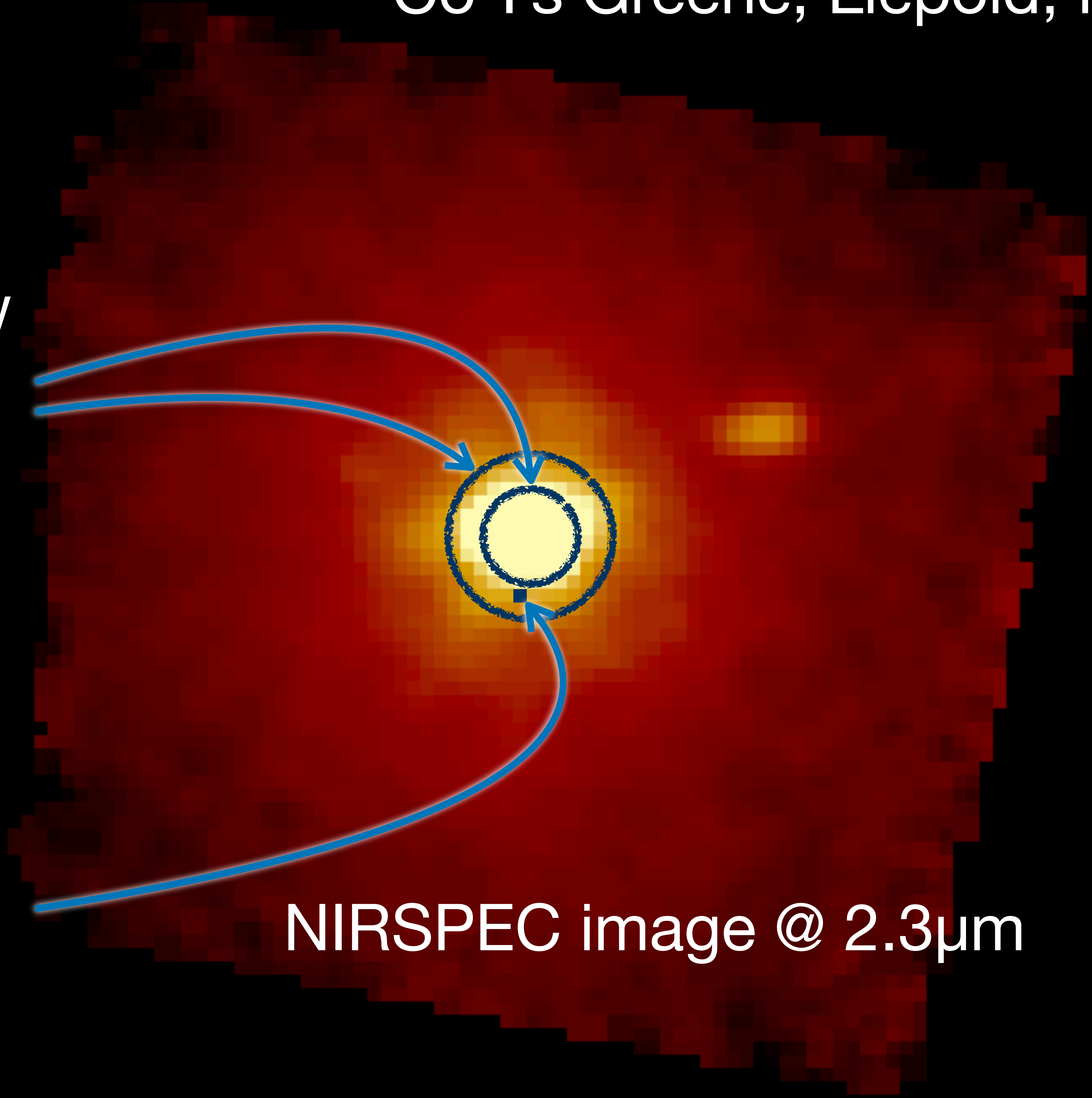


All pixels btw 0.185" and 0.315" in Gebhardt+11

(17-29 pc)

One 0.05" x 0.05" spaxel with JWST

(4.5pc)



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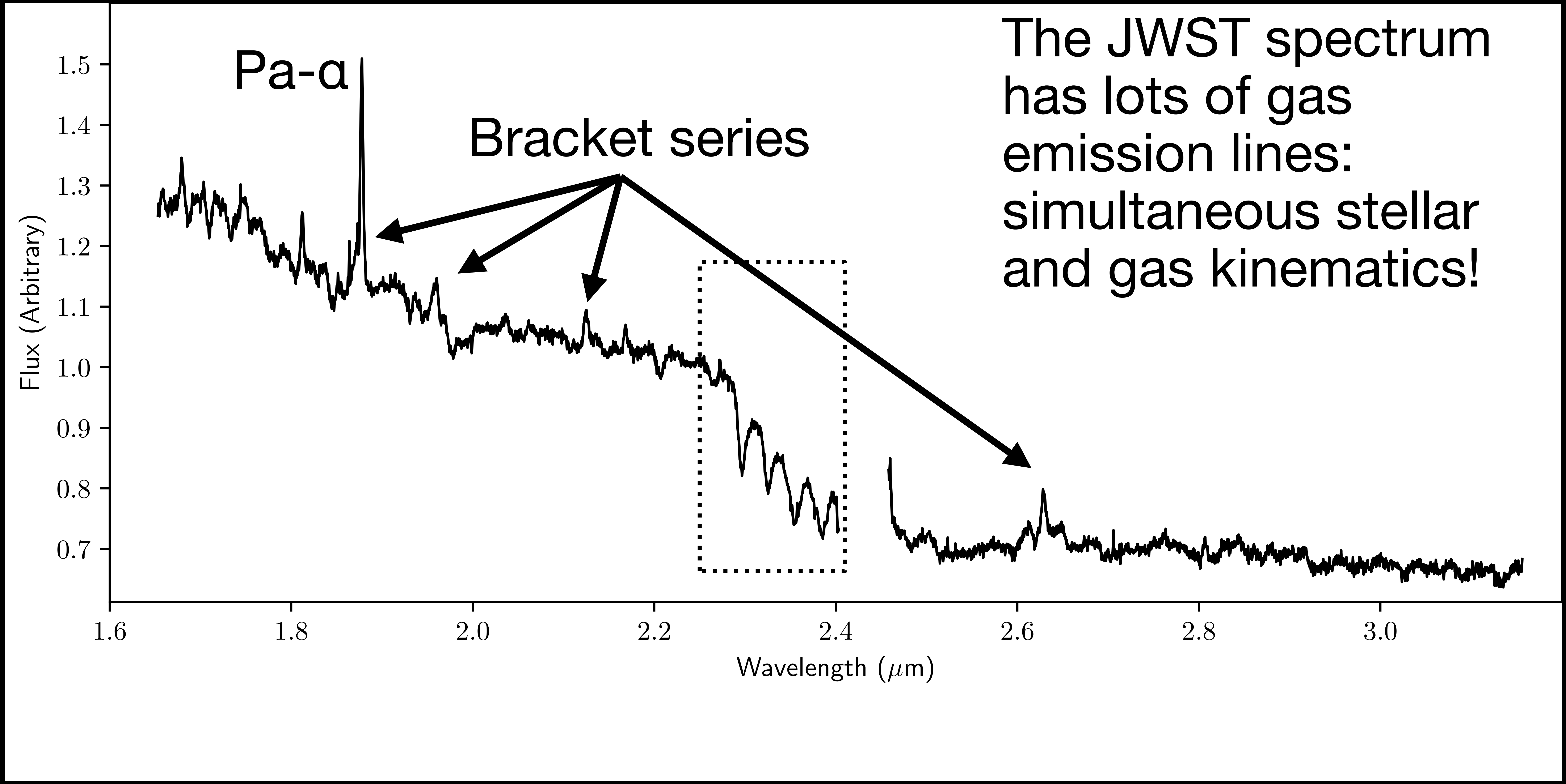

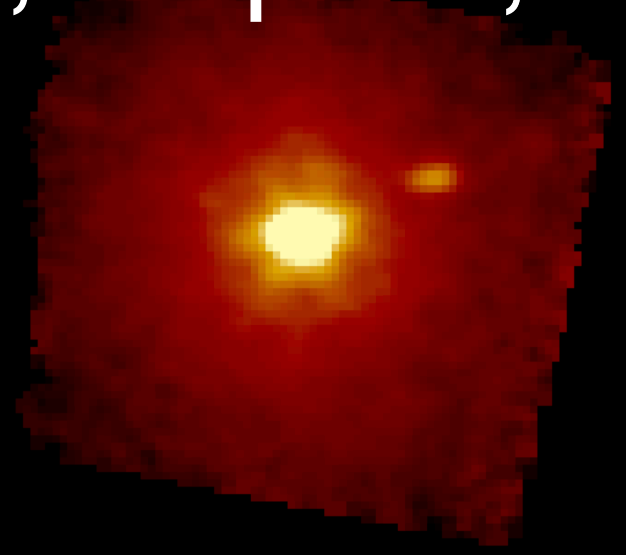

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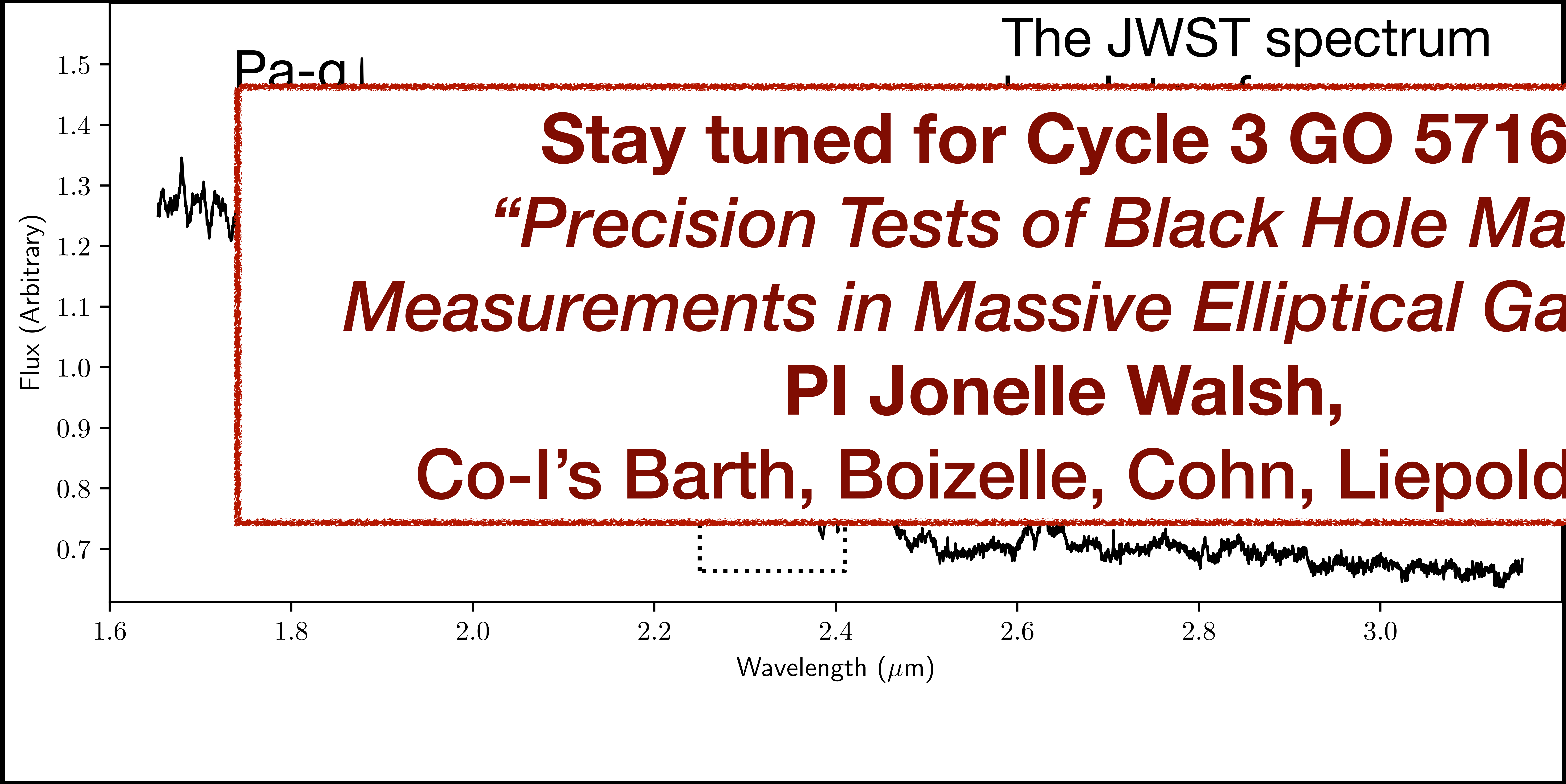

Stay tuned for Cycle 3 GO 5716!

“Precision Tests of Black Hole Mass Measurements in Massive Elliptical Galaxies”

PI Jonelle Walsh,

Co-I’s Barth, Boizelle, Cohn, Liepold, Ma

How to **find** supermassive black holes using stellar dynamics

How to **measure** supermassive black holes using stellar dynamics

How to measure SMBHs

Stellar dynamical *modelling*

Fast + Cheap

Expensive

Lots of assumptions + approximations

General + precise

- Virial — estimate SMBH using stellar dispersion + Virial Theorem
  (E.g., Cappellari+2006)
- Jeans — estimate SMBH using Jeans Equation
  (implemented in JAM; Cappellari+2020)
- Orbit / Schwarzschild — estimate SMBH by integrating and superimposing orbits

How to measure SMBHs
Schwarzschild modelling

Schwarzschild+79
Schwarzschild+93
van den Bosch+08

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Propose a potential

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Schwarzschild modelling

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Propose a potential

Integrate $\mathcal{O}(10^5)$ representative stellar orbits

How to measure SMBHs

Schwarzschild modelling

Schwarzschild+79
Schwarzschild+93
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Propose a potential

Integrate $\mathcal{O}(10^5)$ representative stellar orbits

Superimpose orbits to fit observations

How to measure SMBHs

Schwarzschild modelling

Schwarzschild+79
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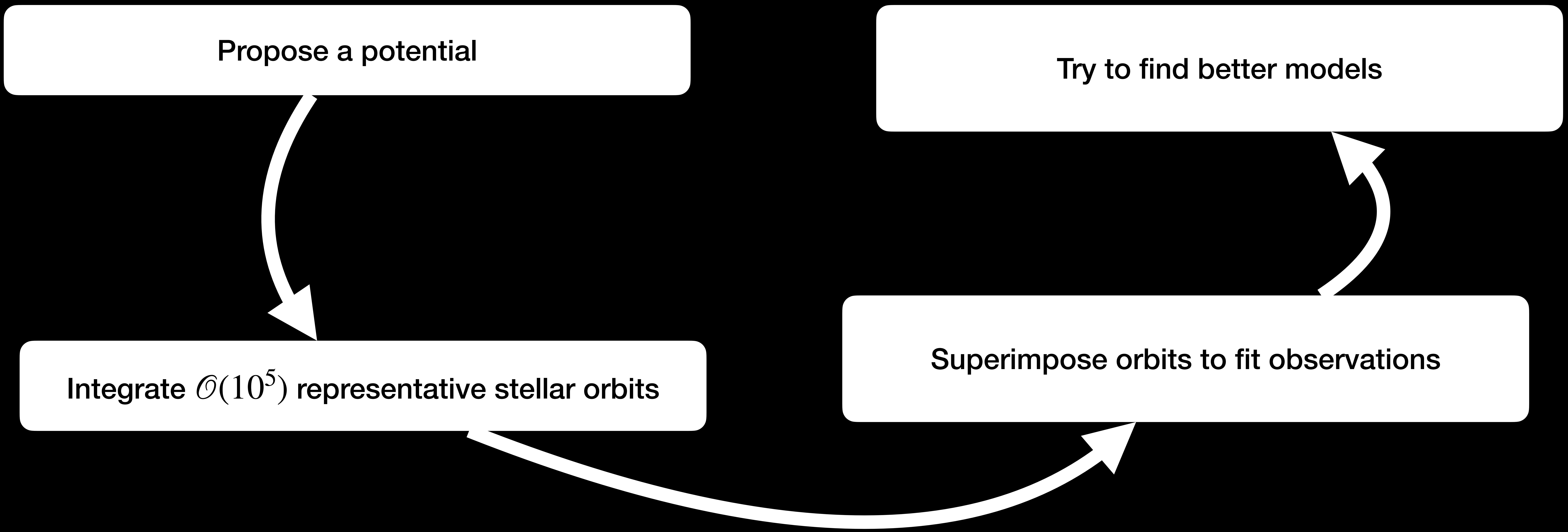


How to measure SMBHs

Schwarzschild modelling

Schwarzschild+79
Schwarzschild+93
van den Bosch+08

(repeat $\mathcal{O}(10^4)$ times)

Propose a potential

Integrate $\mathcal{O}(10^5)$ representative stellar orbits

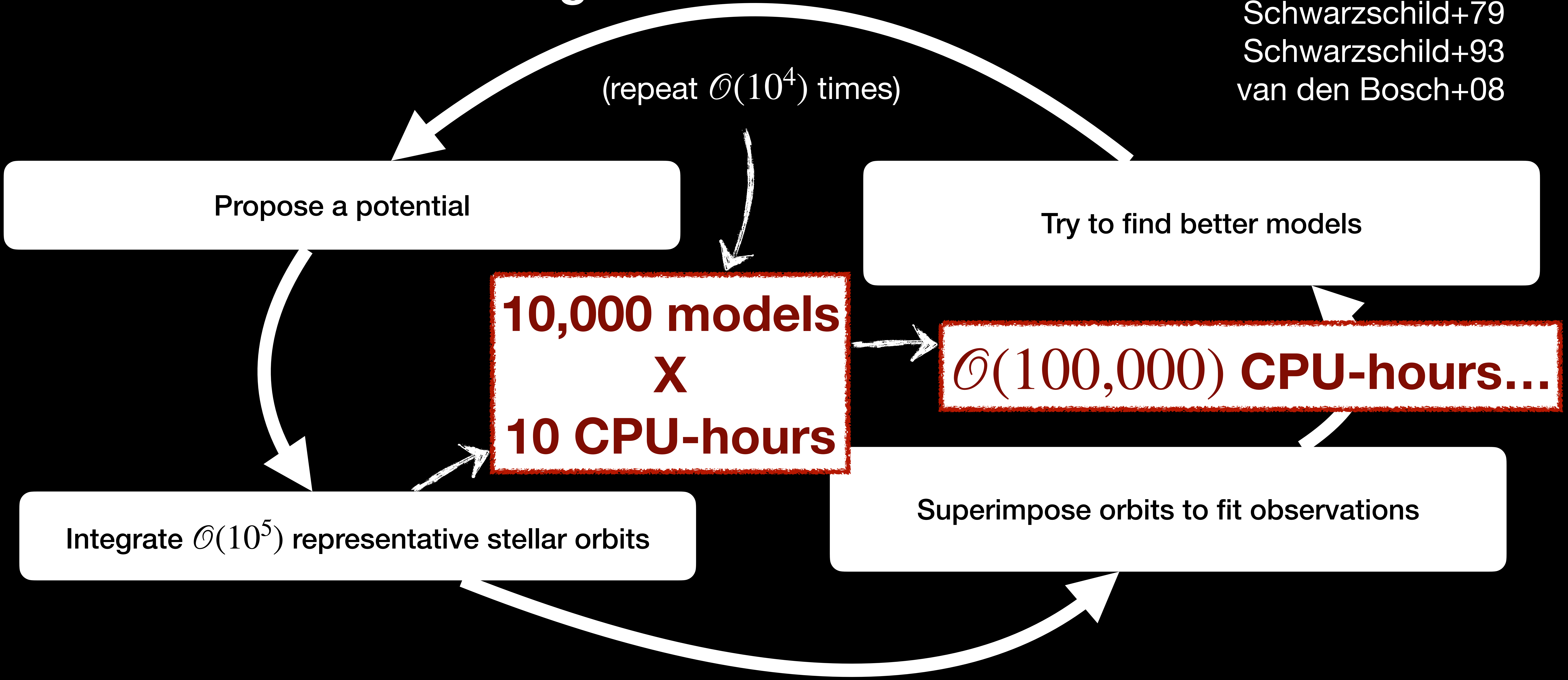
Superimpose orbits to fit observations

Try to find better models

How to measure SMBHs

Schwarzschild modelling

Schwarzschild+79
Schwarzschild+93
van den Bosch+08



How to (really) measure SMBHs

We've substantially modified the *triaxial orbit* code of van den Bosch+08
(Now we call it **TriOS**)

1. Accurate orbit composition + symmetry in axisymmetric and triaxial galaxies

   (Liepold+20, Quenneville+21, Quenneville+22)

2. Code efficiency improvements (~order of magnitude speedups!)

   (Quenneville+21, Quenneville+22)

3. Model sampling + parameter inference improvements!

   (~couple order of magnitude speedups)

   (Quenneville+22, Pilawa+22, Liepold+23, Pilawa+24)

4. Robustness tests with mock galaxy data!

   (Pilawa+24)

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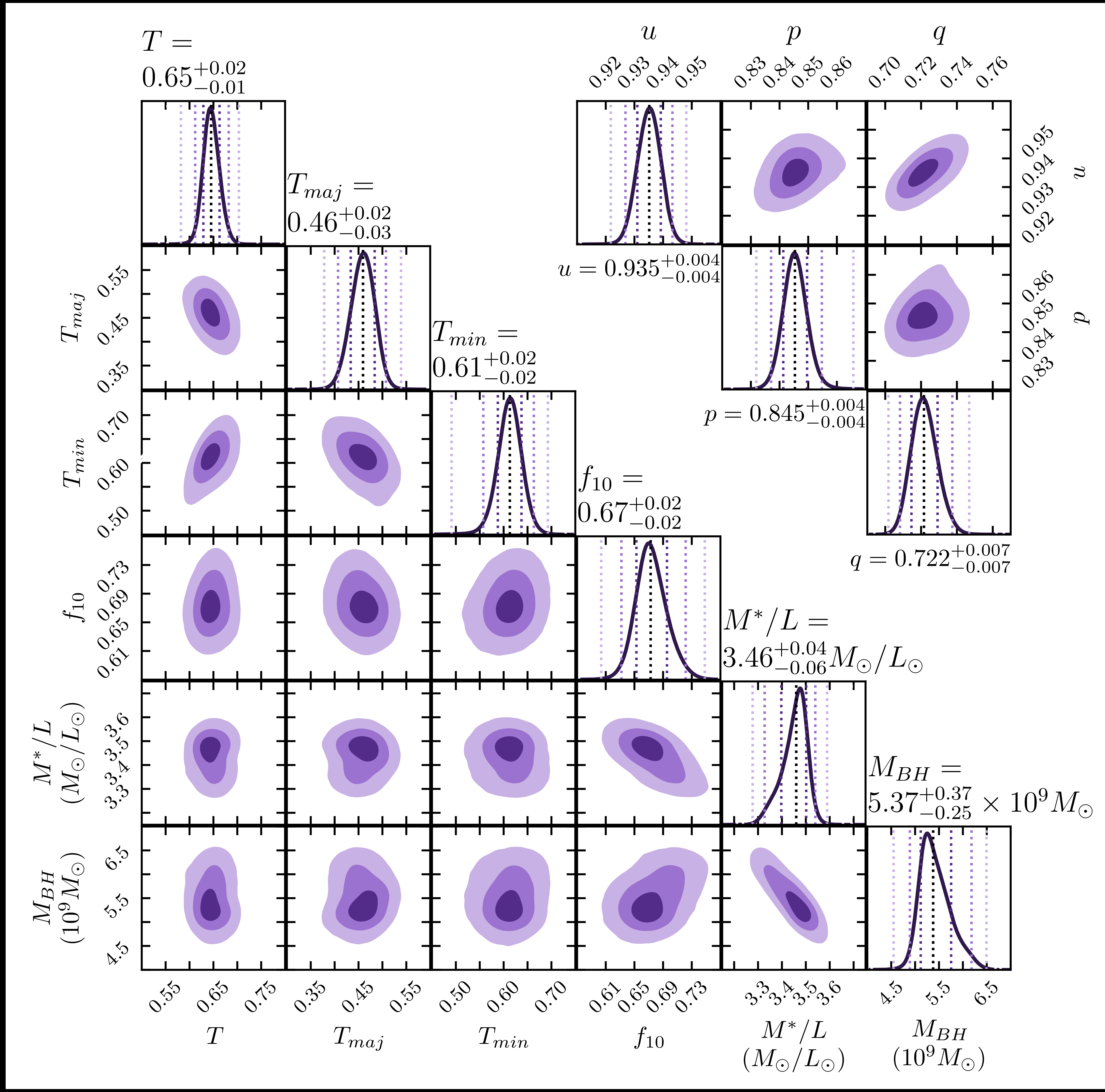
Liepold, Ma, Walsh 2023



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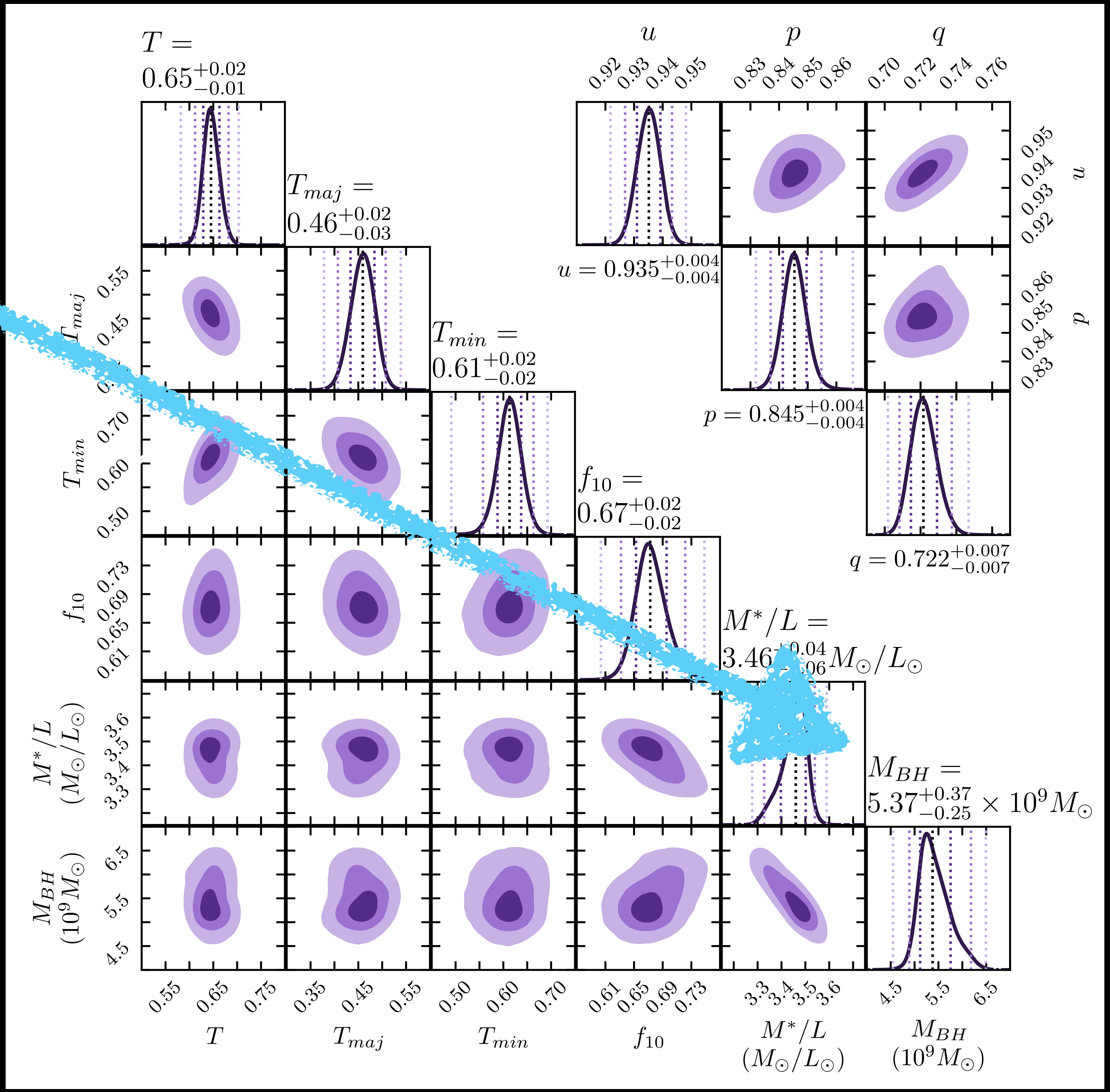
Liepold, Ma, Walsh 2023

Black Hole Mass 5.37 x 10^9 $M_\odot$



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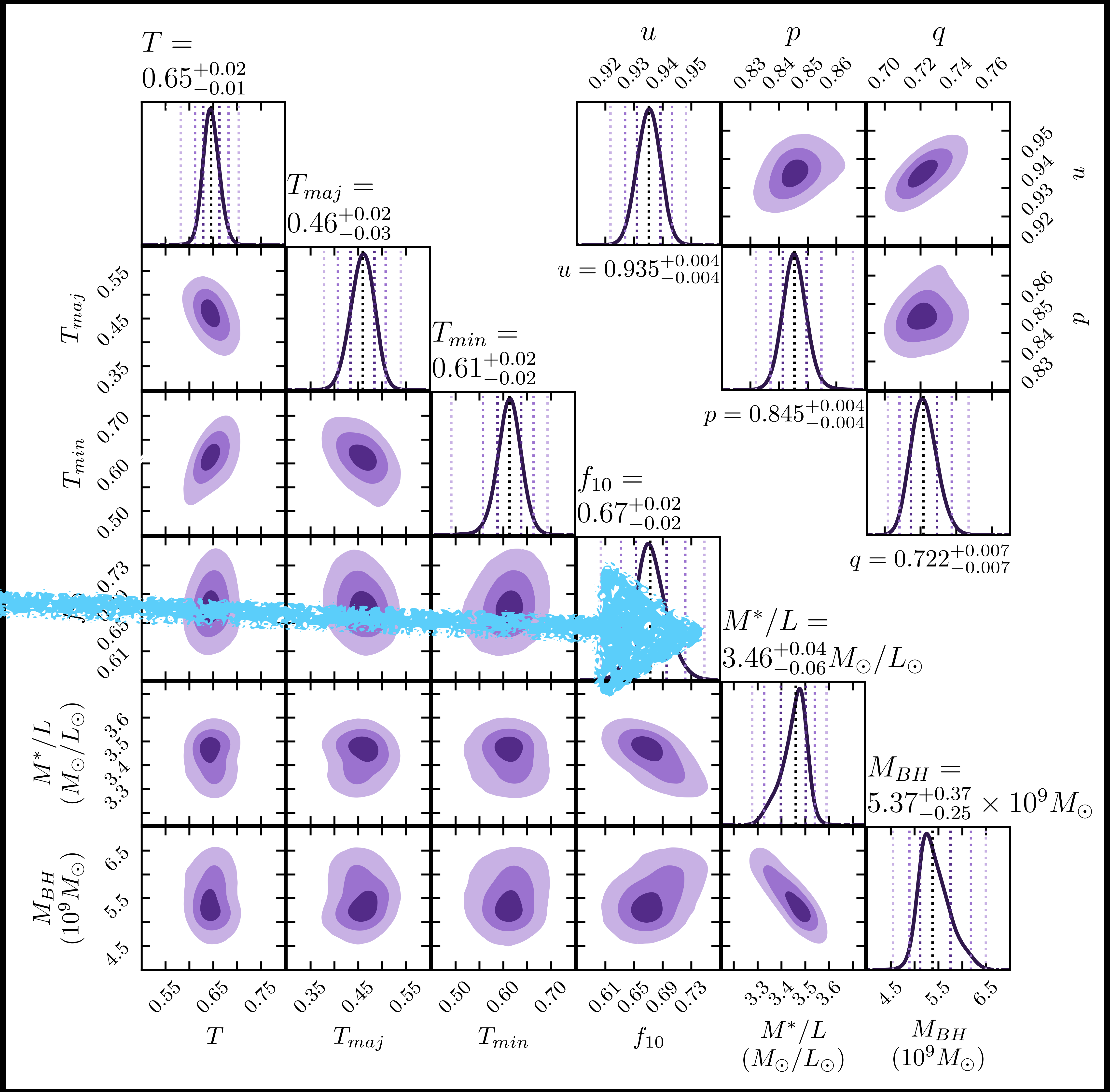
Liepold, Ma, Walsh 2023

Black Hole Mass	**5.37 x 10^9 $M_\odot$**
Inner Stellar Mass-to-light	**8.65 $M_\odot$ / $L_{\odot,V}$** (With M/L gradient!)



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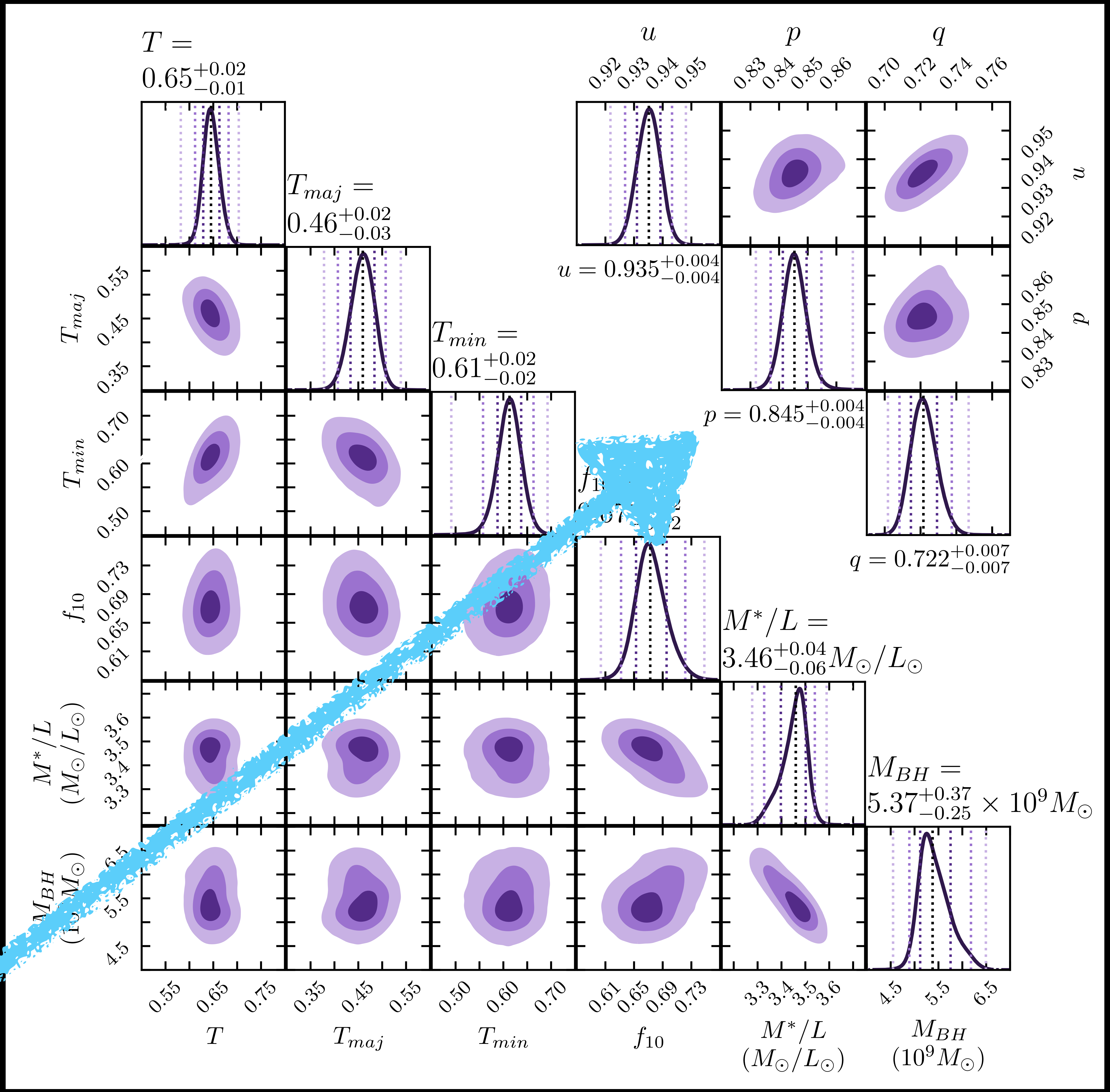
Black Hole Mass	**5.37 x 10⁹ M⊙**
Inner Stellar Mass-to-light	**8.65 M⊙ / L⊙,V** (With M/L gradient!)
Average axis ratios	1 : 0.85 : 0.72



Liepold, Ma, Walsh 2023

M87

Hubble @NASAHubble · Follow

Space potato? 🥔

Thanks to observations from Hubble and the Keck Observatory, astronomers were able to generate a 3D model of the galaxy M87.

By tracking the motion of stars around the galaxy's center, they determined that the galaxy is potato-shaped: go.nasa.gov/3MFV16L

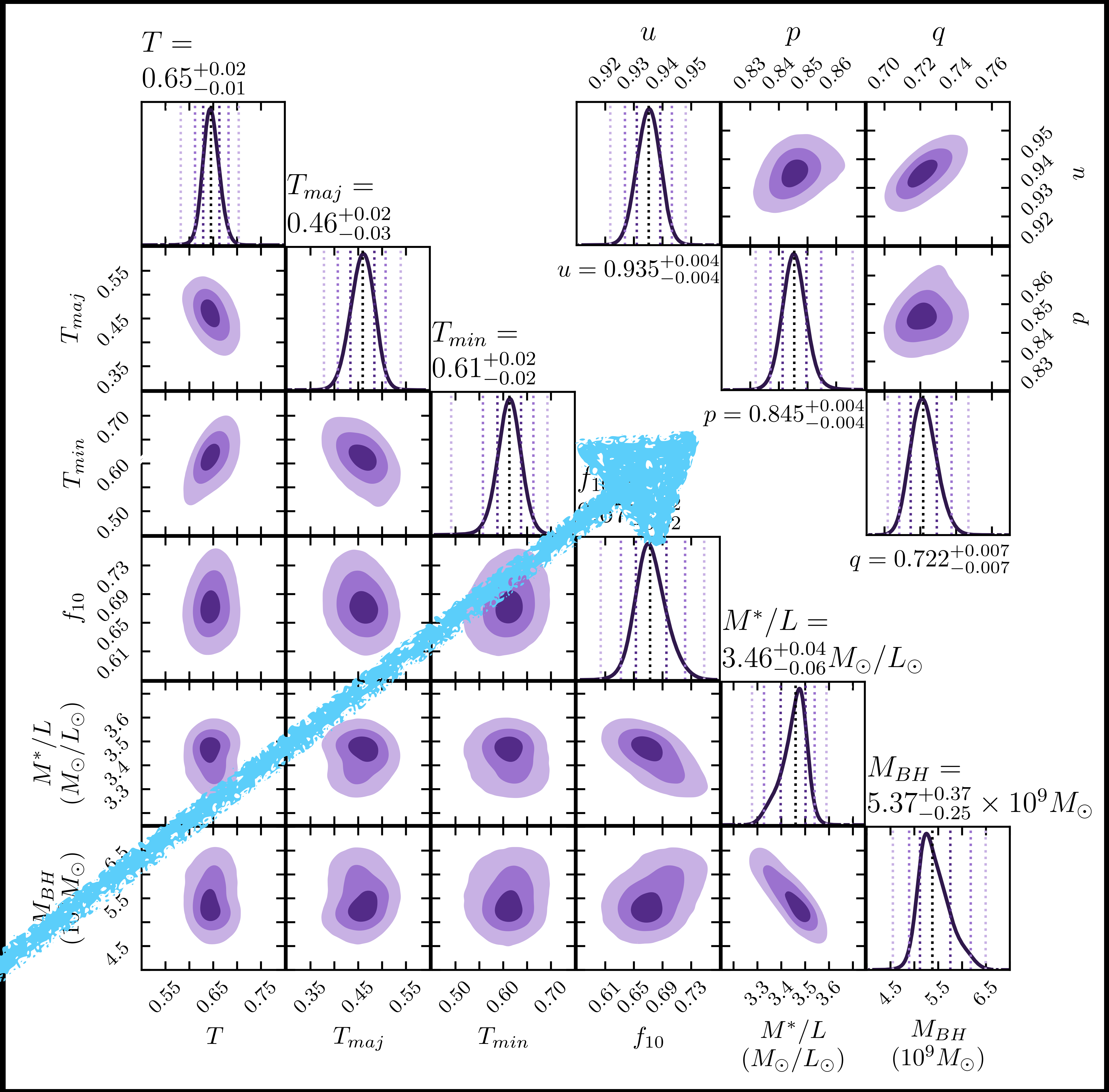
x 10^9 $M_\odot$

$M_\odot$ / $L_{\odot,V}$

l/L gradient!)

Average axis ratios

1 : 0.85 : 0.72



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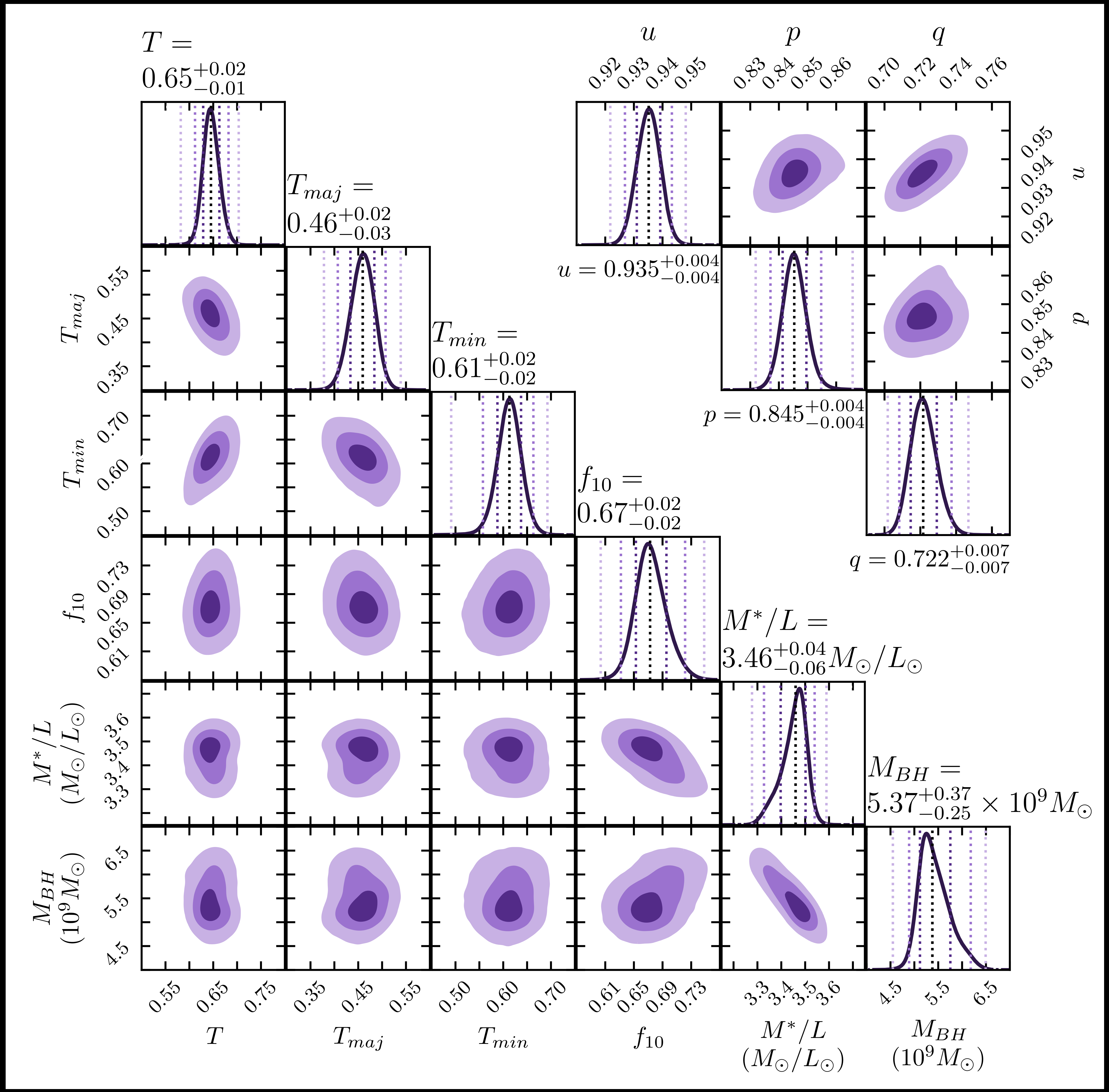

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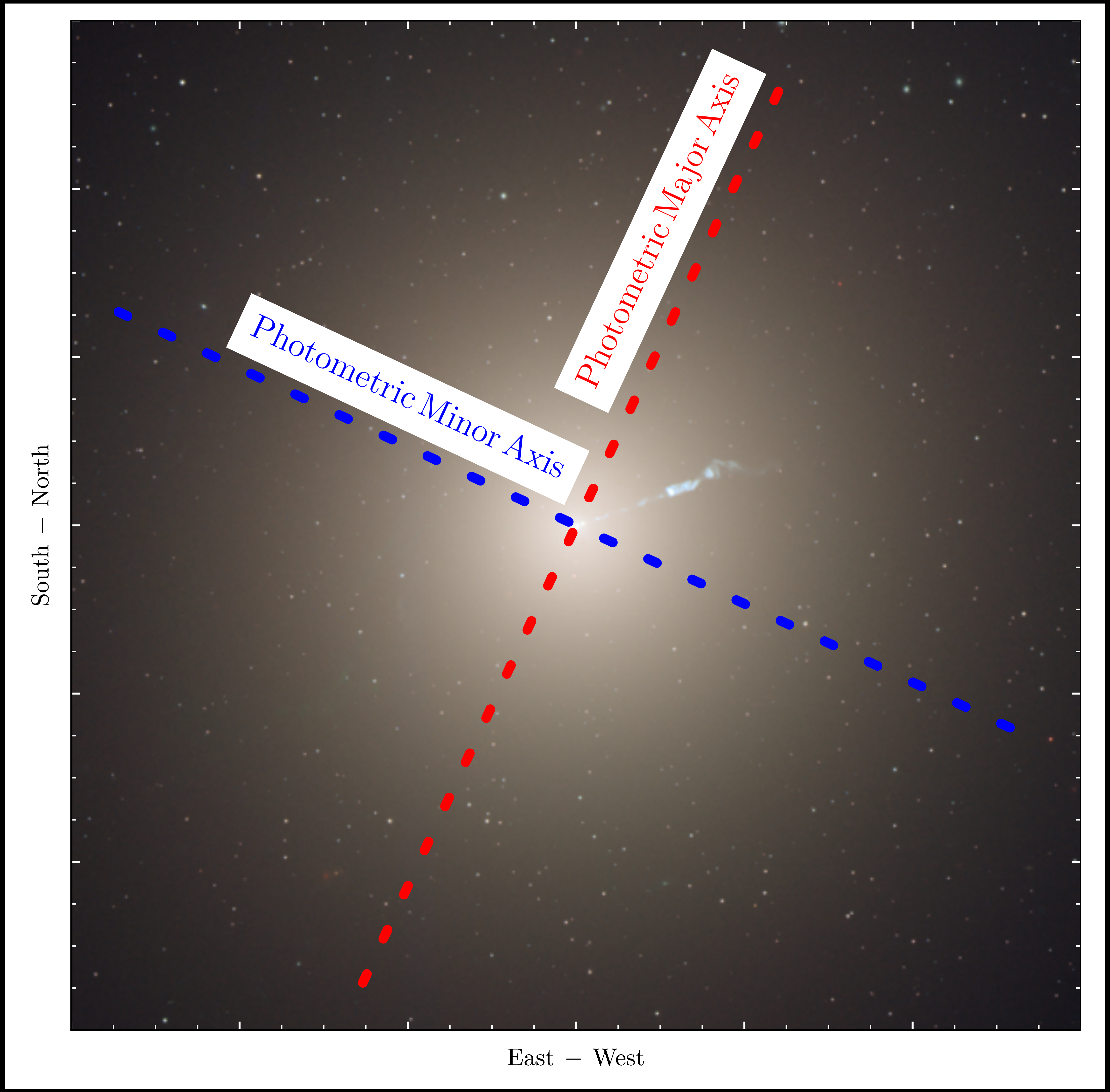
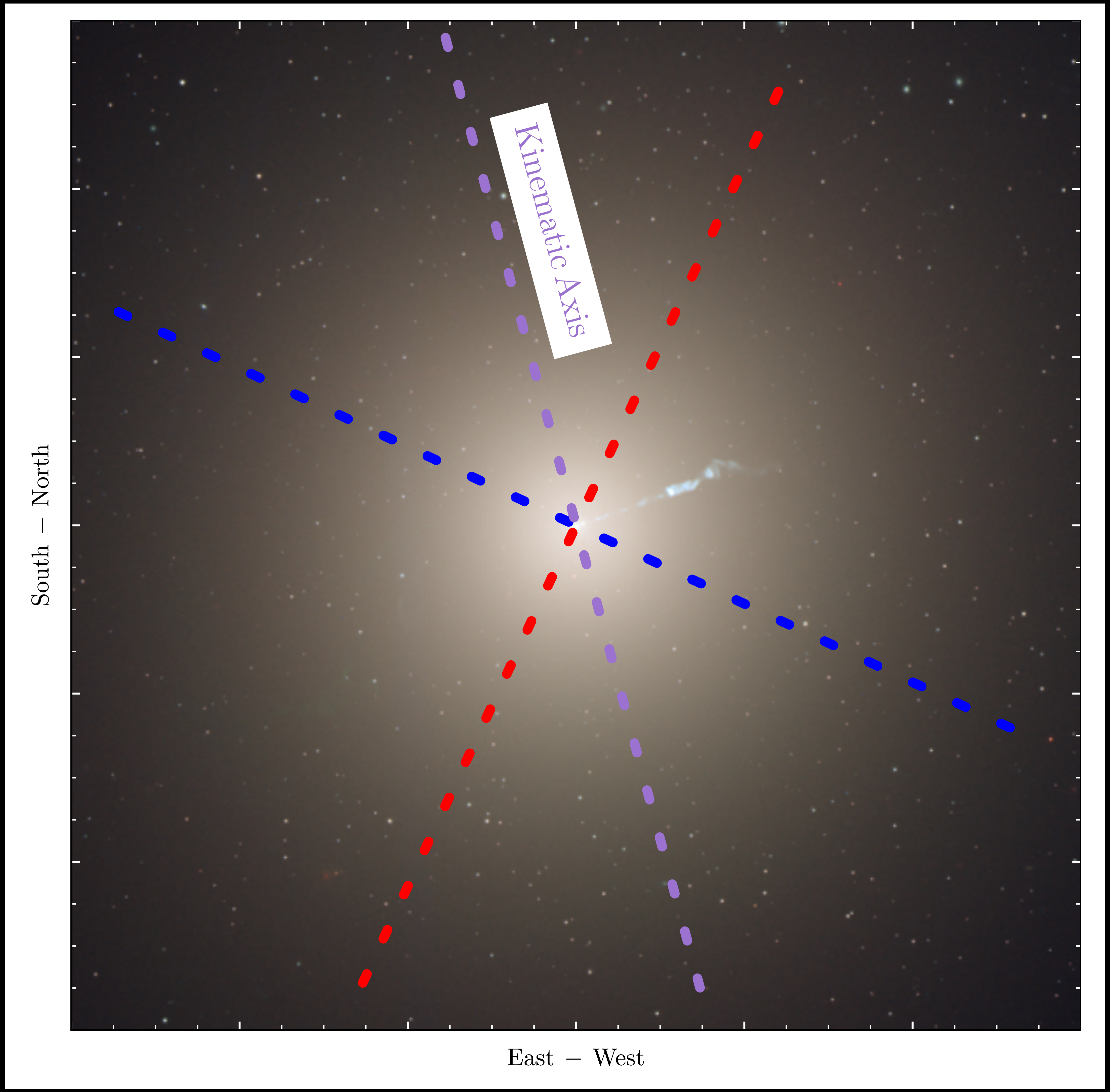


An Example: M87

Liepold, Ma, Walsh 2023

- The kinematic axis is **misaligned** from the photometric axes



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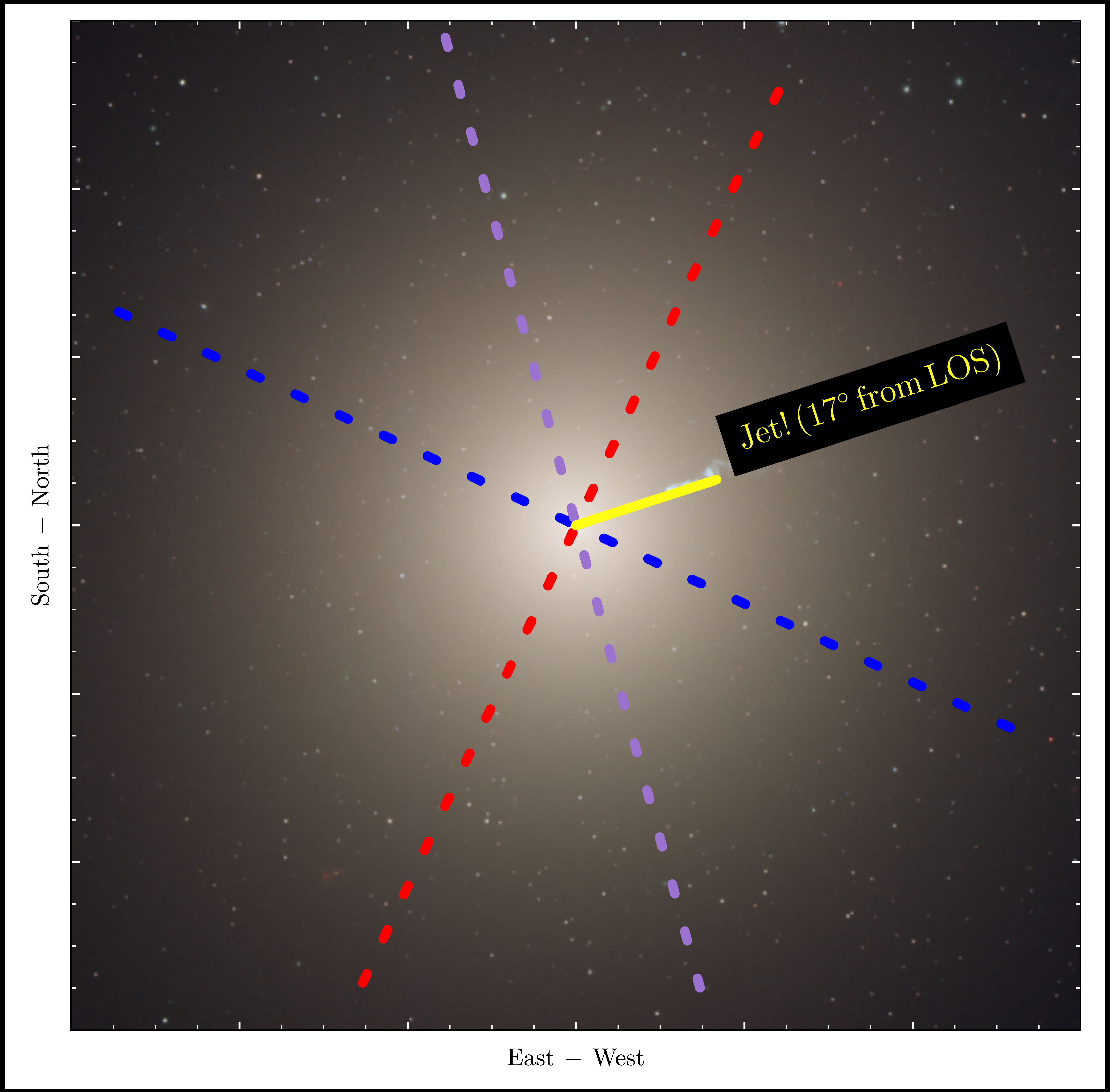
- The **jet** is almost perpendicular to the kinematic axis on the sky



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Liepold, Ma, Walsh 2023

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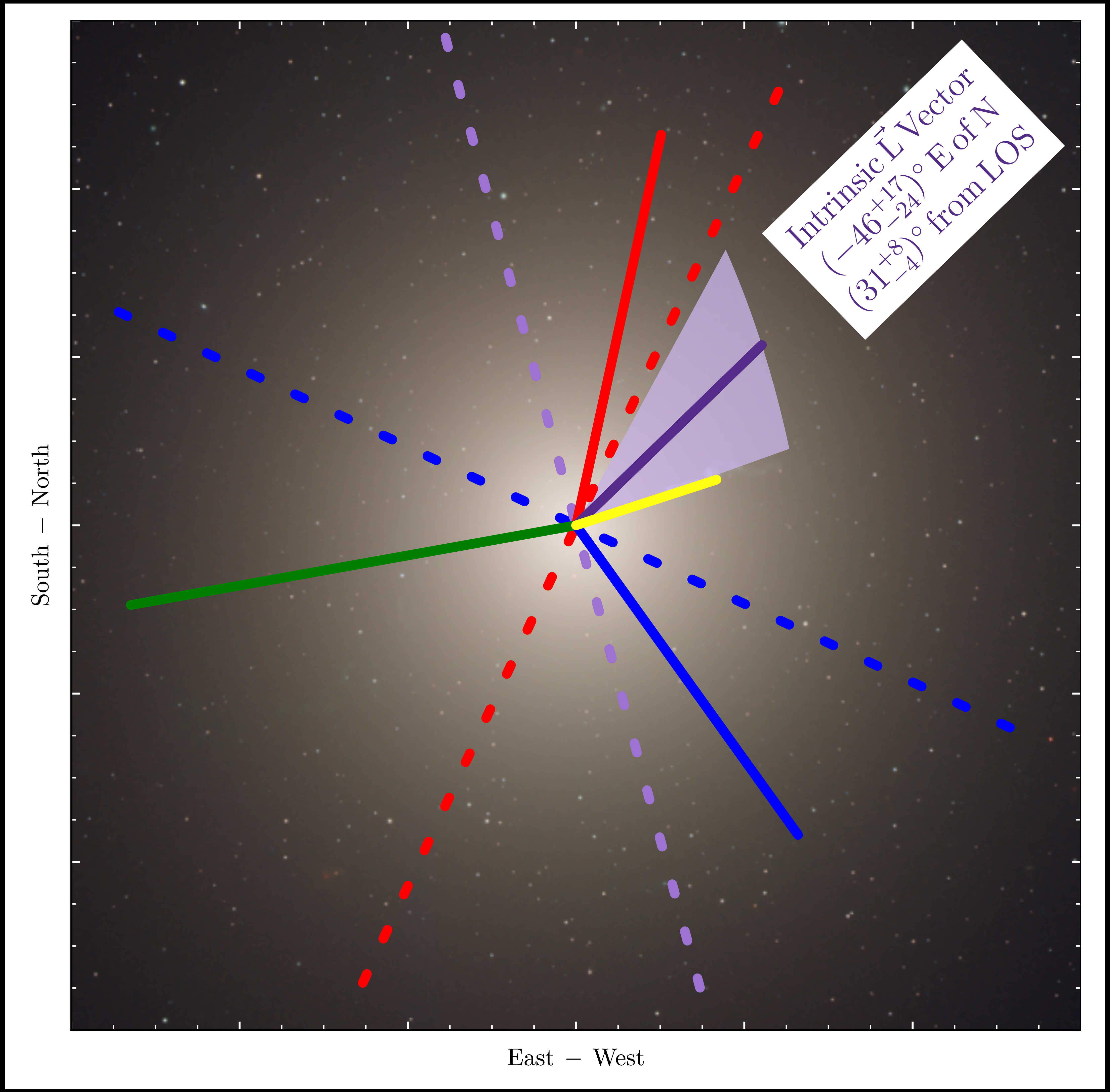
- The mean stellar L vector from 80” to 150” is $(19 \pm 9)^{\circ}$ from the jet! (In 3D)



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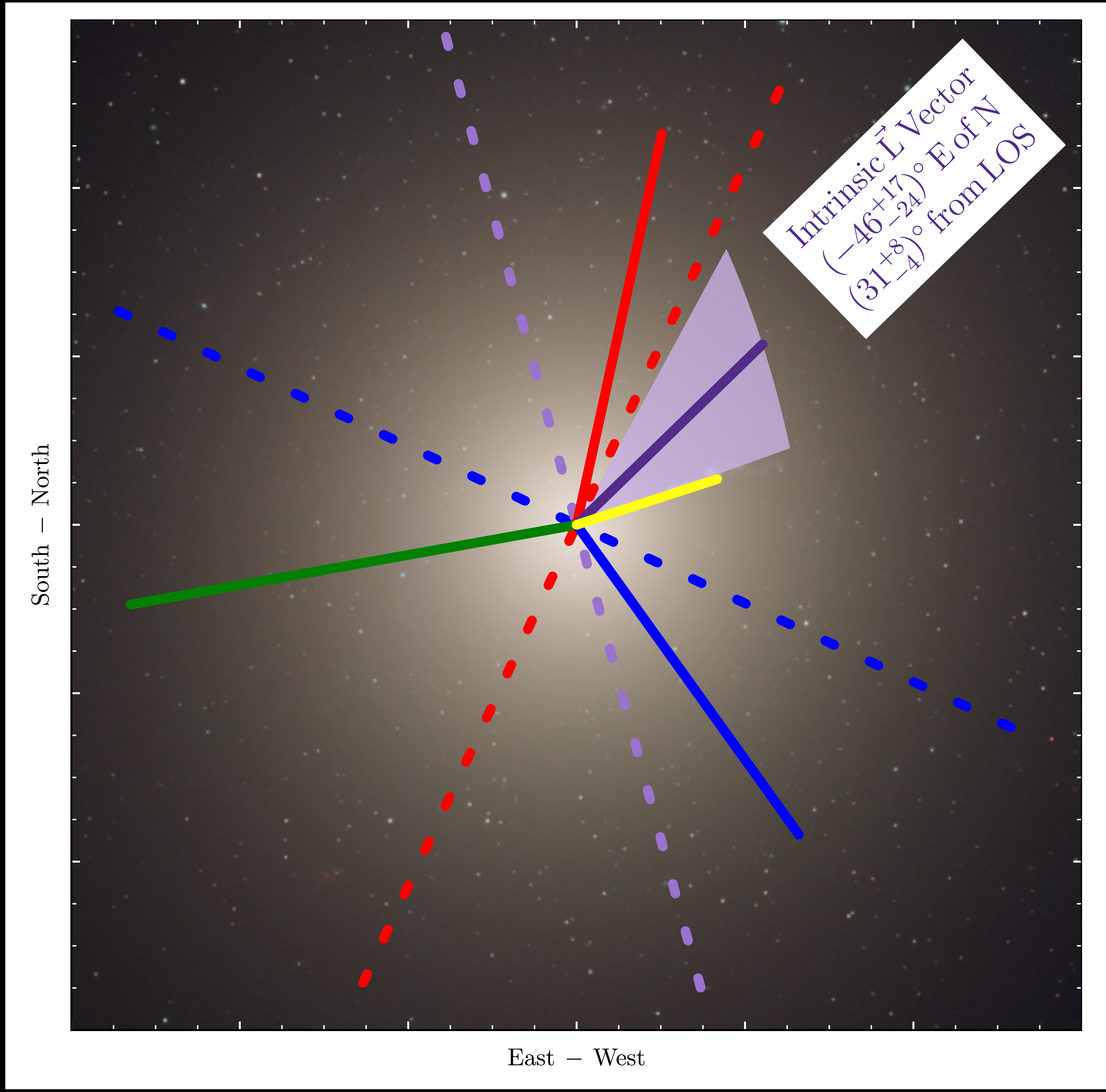
- The **jet** is almost perpendicular to the kinematic axis on the sky
- The mean stellar L vector from 80” to 150” is $(19 \pm 9)^{\circ}$ from the jet! (In 3D)
- Apparent alignment between, BH Spin, Jet axis, Stellar angular momentum, Virgo’s long axis

Liepold, Ma, Walsh 2023



Ongoing Efforts + Connections

- **Many MASSIVE galaxies still to model** (with Triaxial Schwarzschild method)

  Keep an eye out for NGC57 (Pilawa+24b) and NGC315 (Pilawa+24c)

- **Ultra-MASSIVE galaxies with KCWI**

  Keep an eye out for Holmberg 15A (upcoming Liepold+24b)

- **PTA sources? — implications for identifying continuous signals**

  Also check out Liepold+24a — MASSIVE stellar mass distribution is consistent with NANOGrav GW strain

- **Massive nearby SMBH are EHT targets**