

Realizing the Full Potential: Detecting and Measuring (Ultra)massive Black Holes in Triaxial Galaxies

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Berkeley Big BH Bunch:
Emily Liepold

Matthew Quenneville
Jacob Pilawa

Chung-Pei Ma
(Others)

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

How to **measure**
supermassive black holes
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Big BHs are intriguing

- Local Ultramassive BHs ($M_{\text{BH}} \gtrsim 10^9 M_{\odot}$) are
 - Pulsar Timing Array sources
 - Event Horizon Telescope sources?
 - Endpoint of mergers + evolution

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Big BHs are **booming**

27 from stellar or gas with

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

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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**

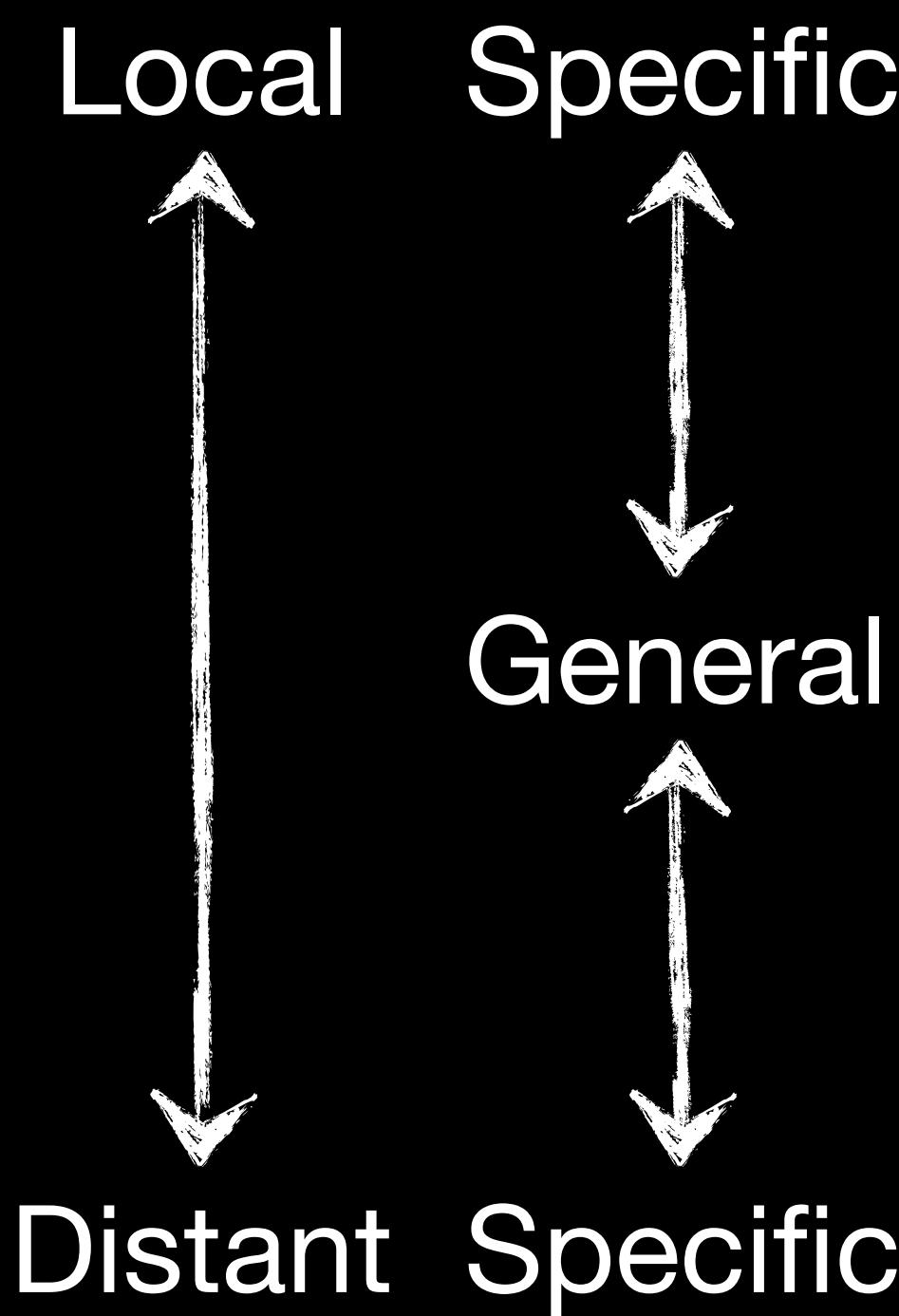
27 from stellar or gas with
 $M_{\text{BH}} \gtrsim 10^9 M_{\odot}$
4 with $M_{\text{BH}} \gtrsim 10^{10} M_{\odot}$



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

How to find SMBHs

Different methods for different galaxies

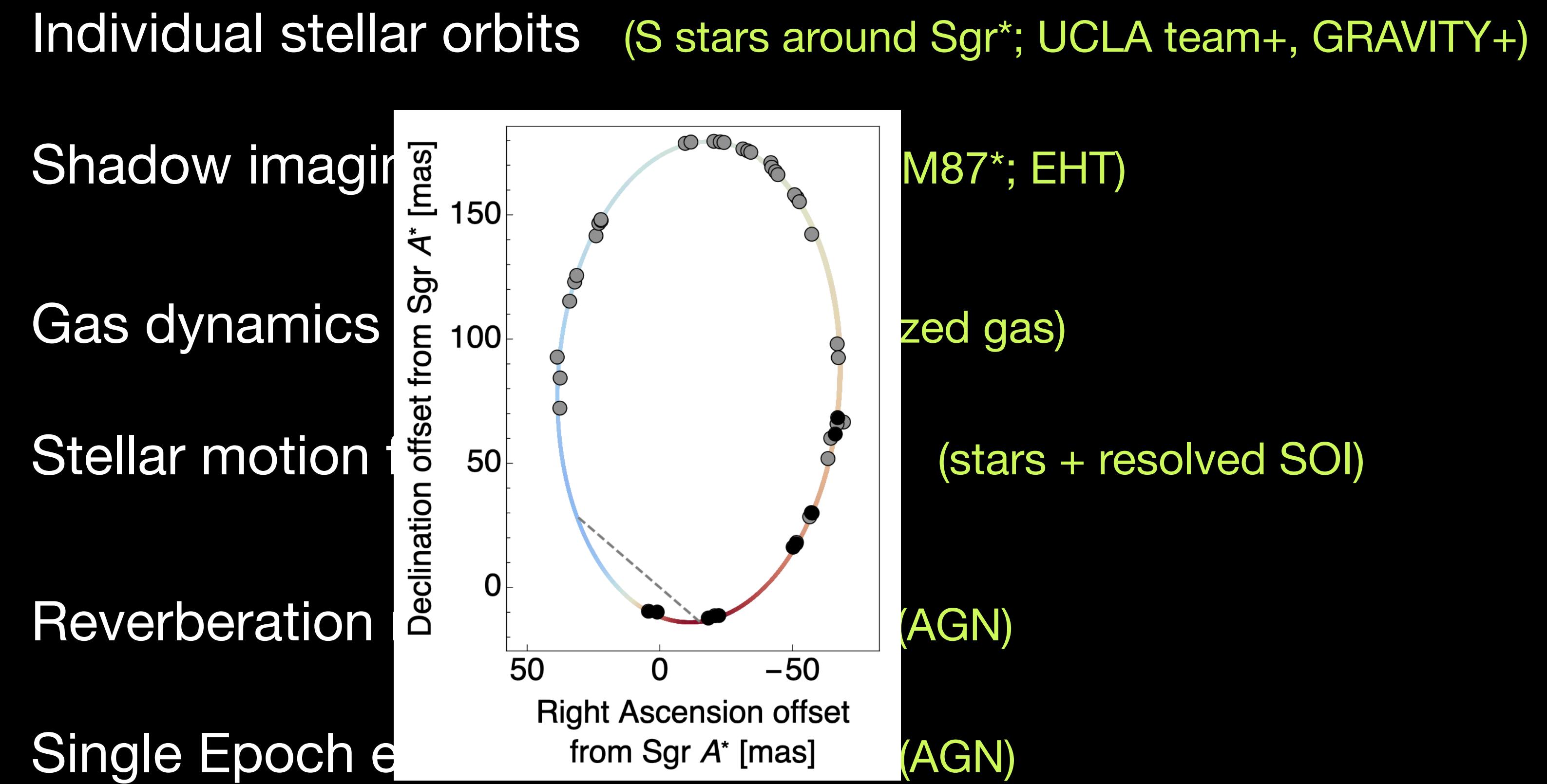
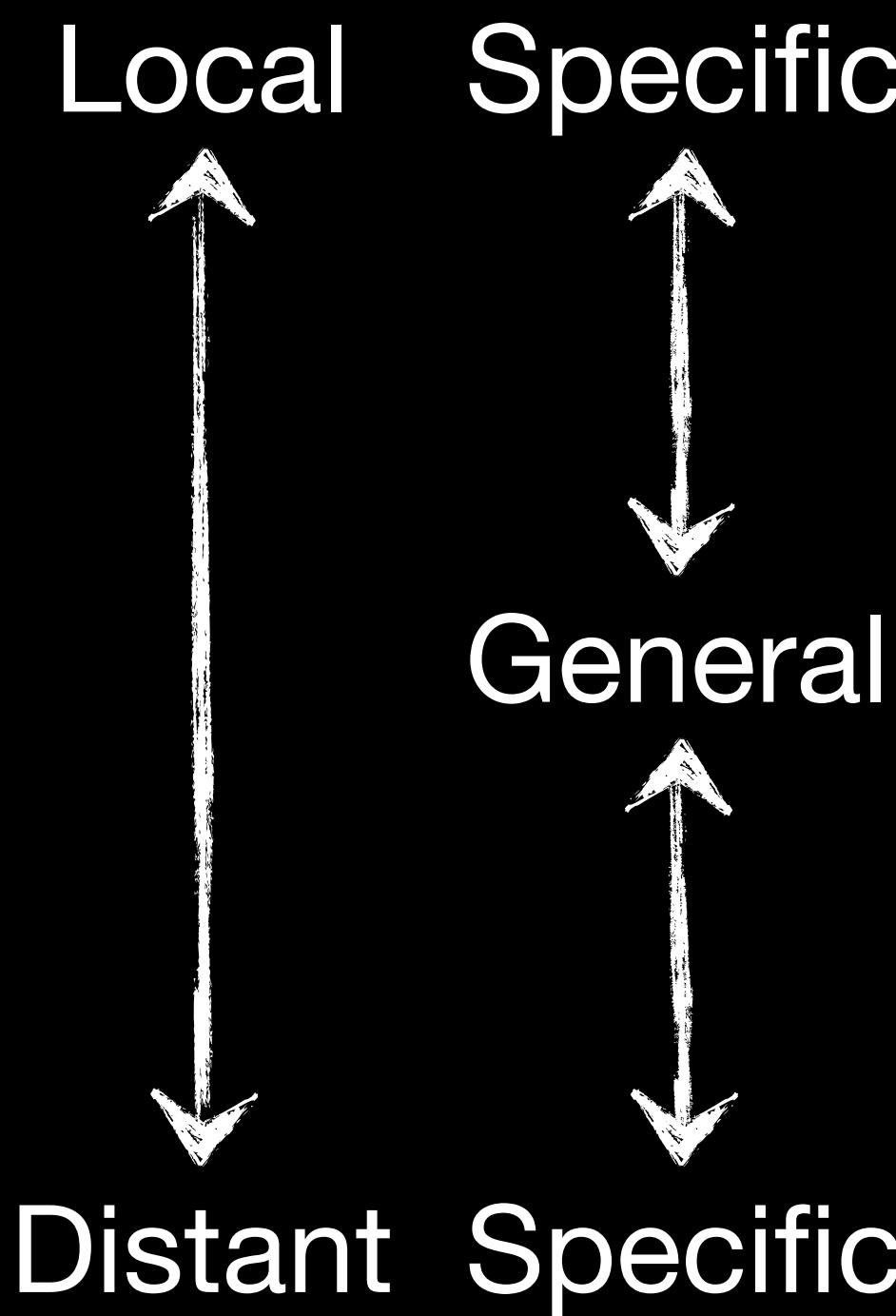


- | | |
|--------------------------------------|---|
| Individual stellar orbits | (S stars around Sgr*; UCLA team+, GRAVITY+) |
| Shadow imaging | (only Sgr* and M87*; EHT) |
| Gas dynamics | (CO or ionized gas) |
| Stellar motion from integrated light | (stars + resolved SOI) |
| Reverberation mapping | (AGN) |
| Single Epoch emission line width | (AGN) |

How to find SMBHs

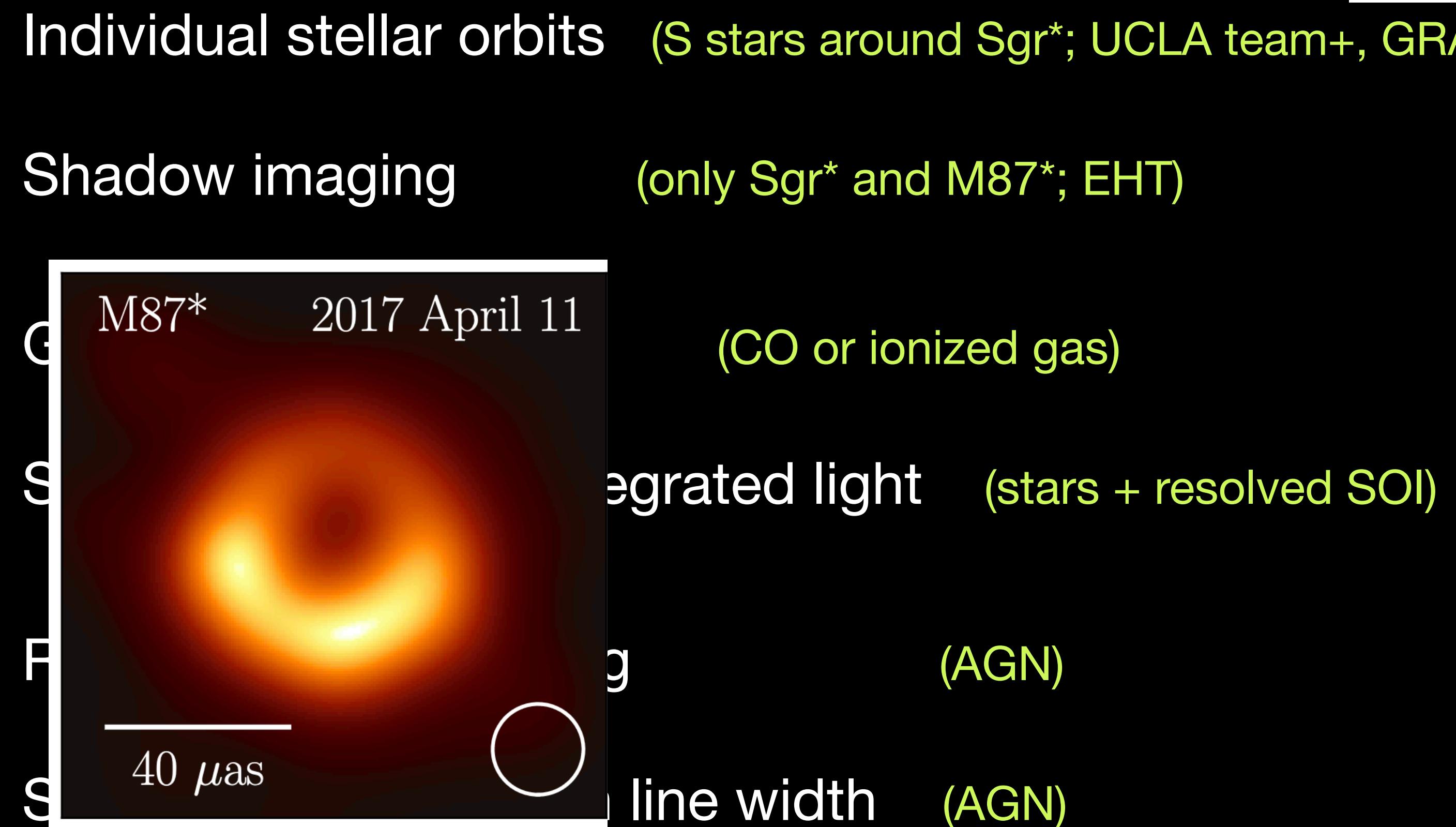
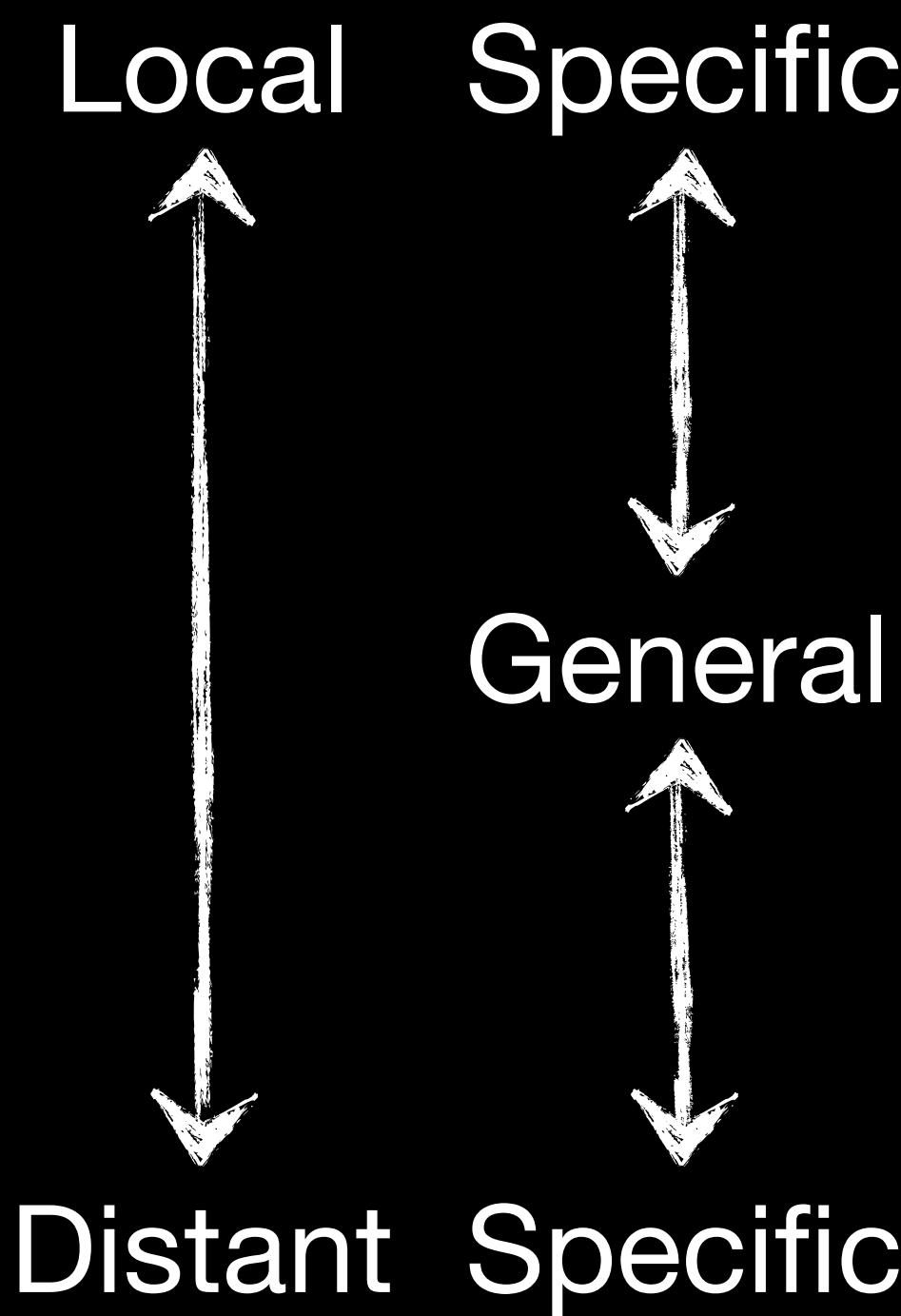
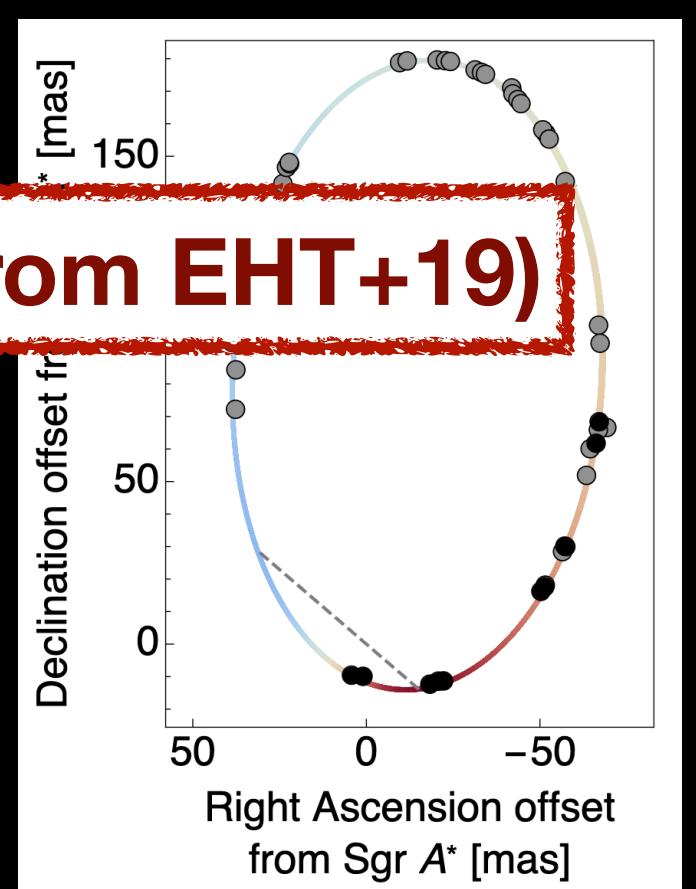
Different methods for different galaxies

(Image from Do+19)



How to find SMBHs

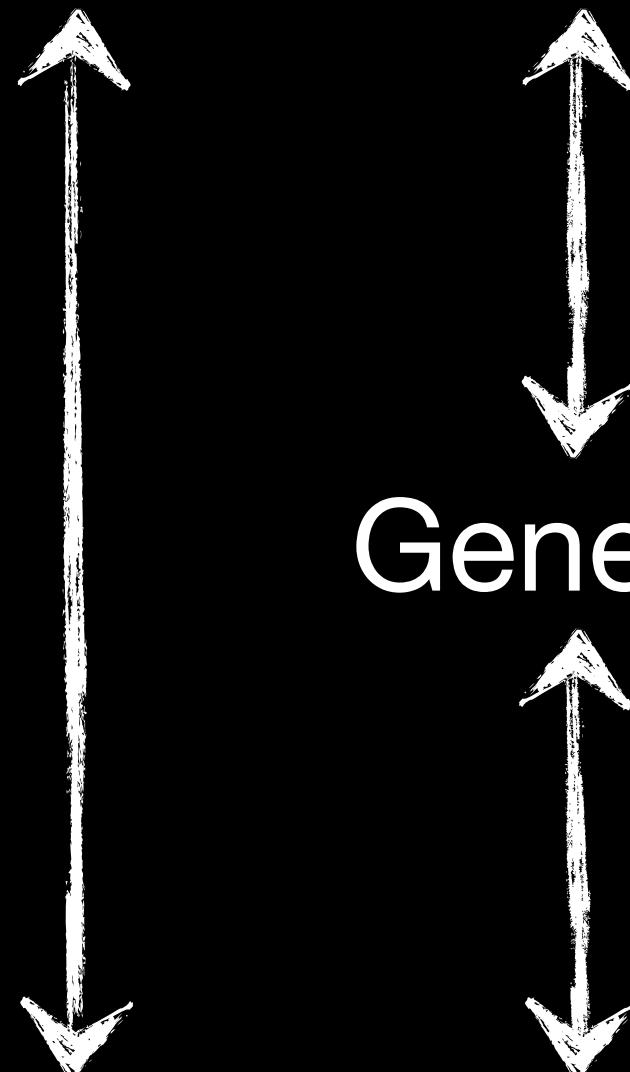
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How to find SMBHs

Different methods for SMBHs

Local Specific



Indi-

Shad-

Gas dynamics

Stellar motion from integrated light

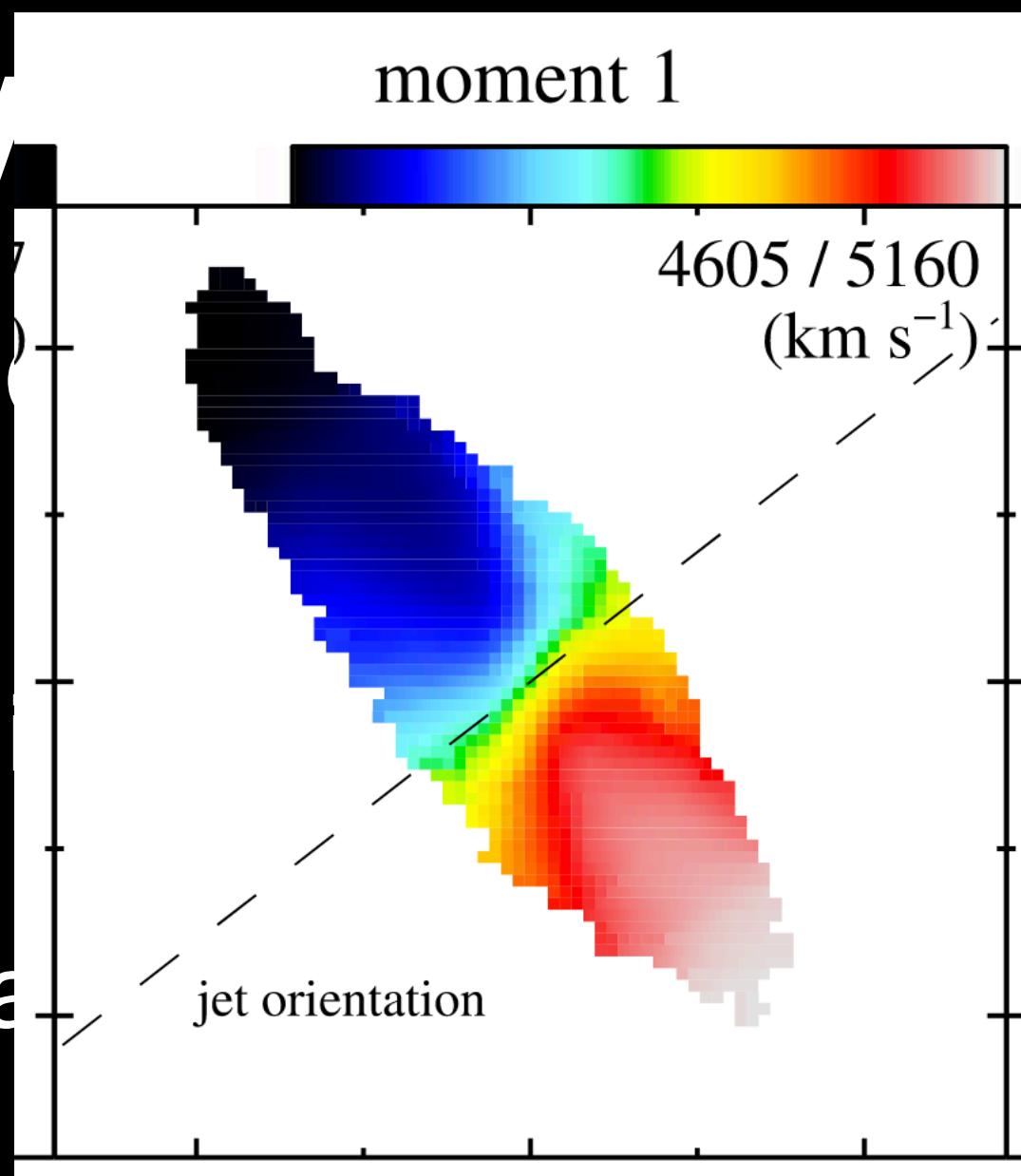
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Reverberation mapping

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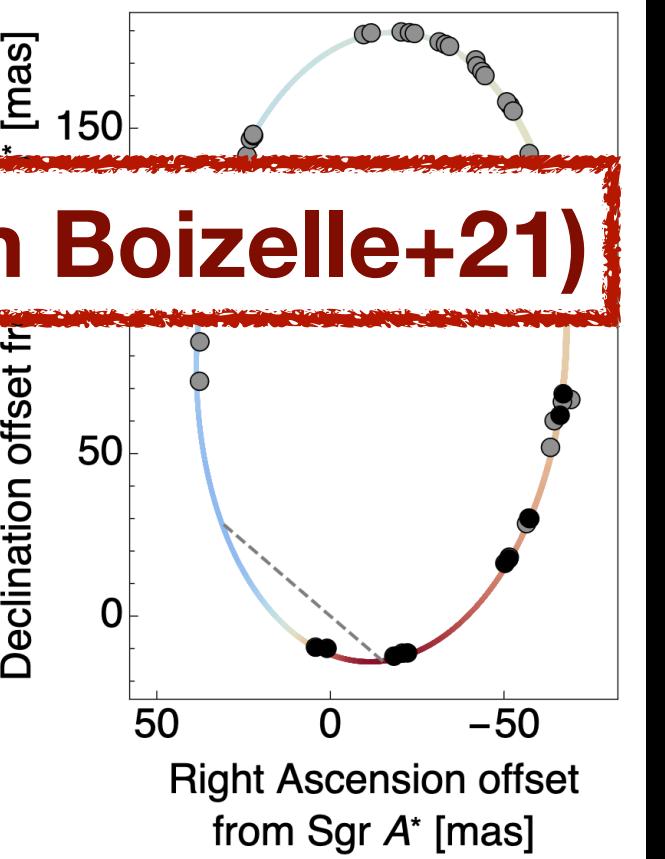
(AGN)



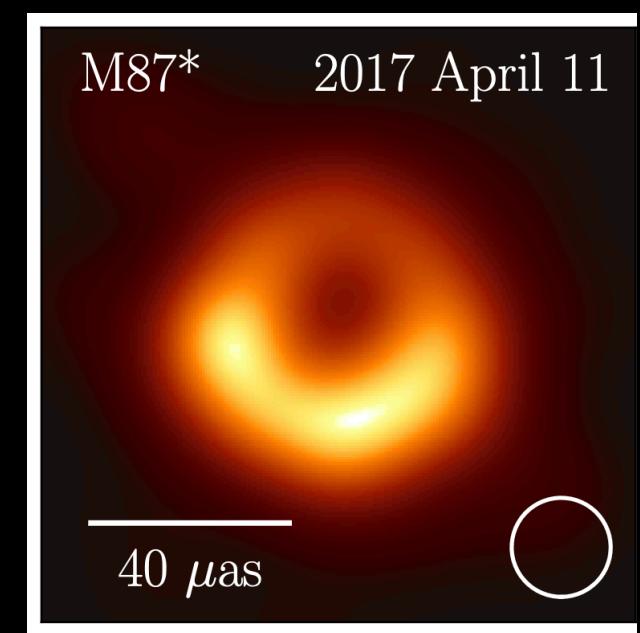
es

S stars around Sgr*

(only Sgr* and M87*; EHT)

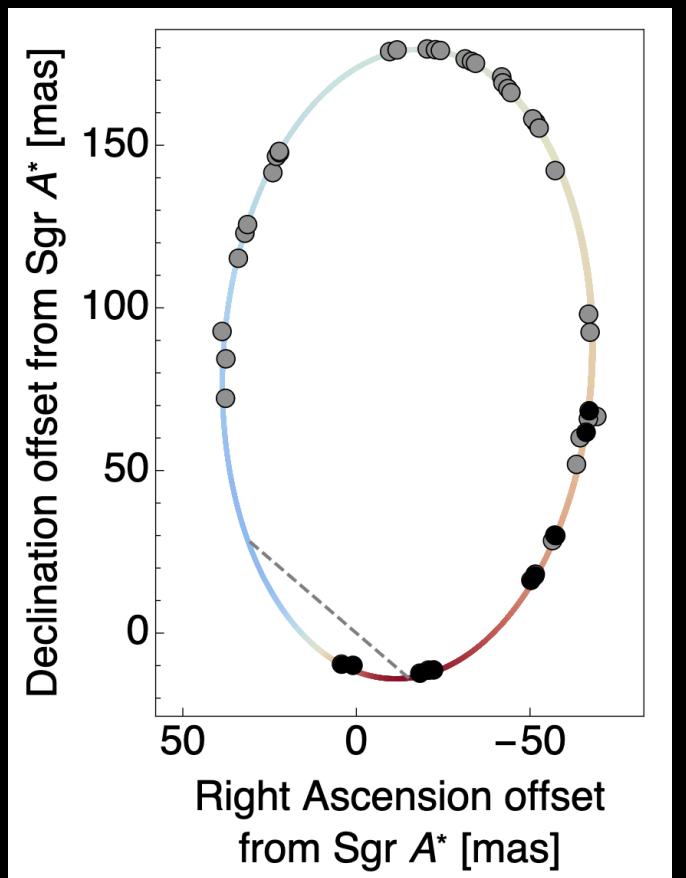
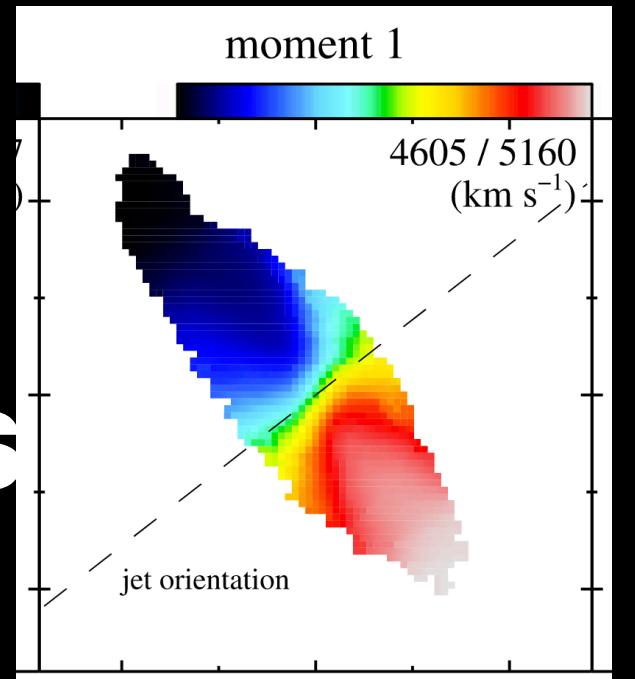
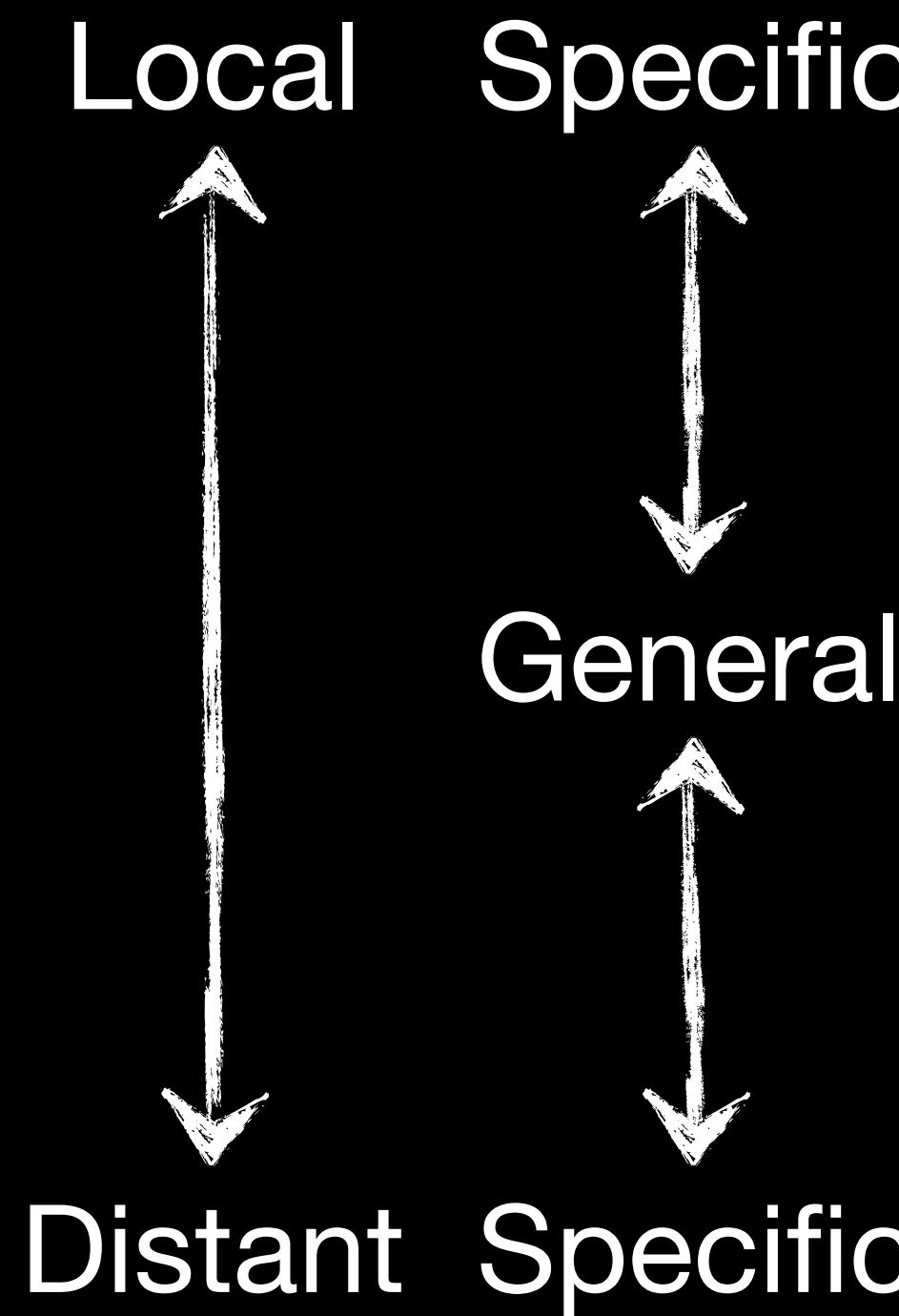


(Image from Boizelle+21)

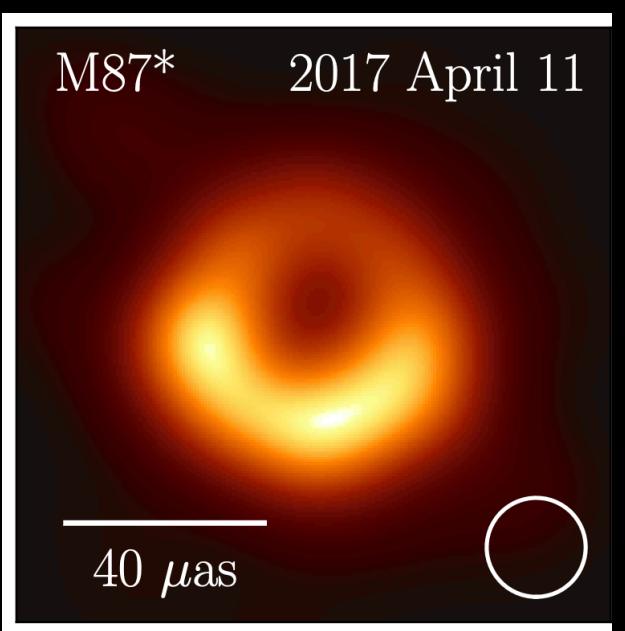


How to find SMBHs

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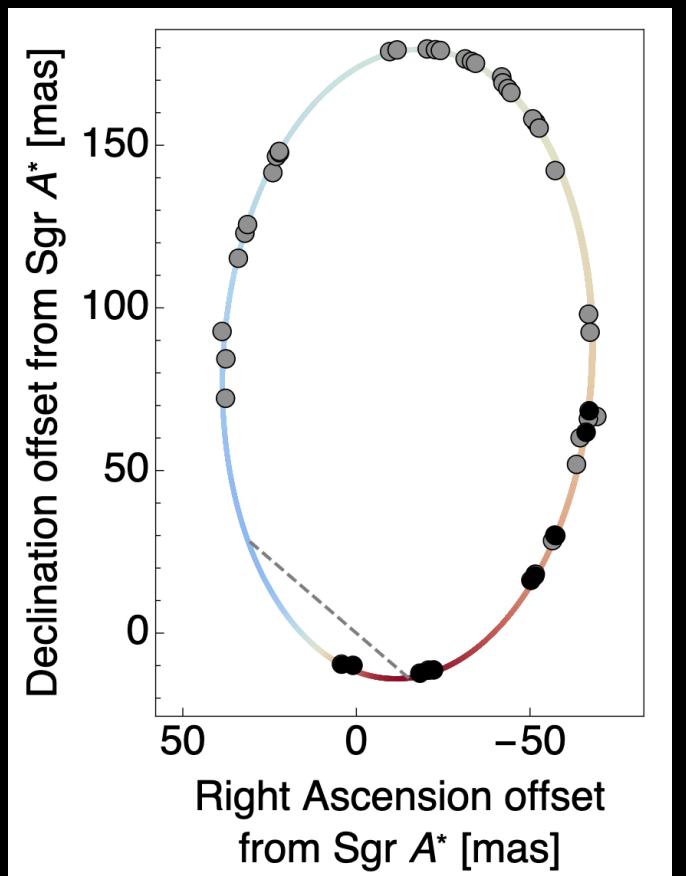
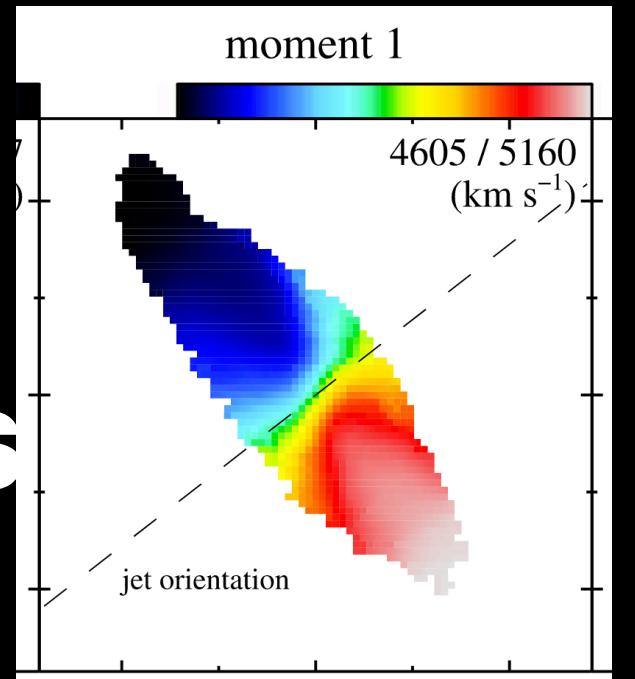
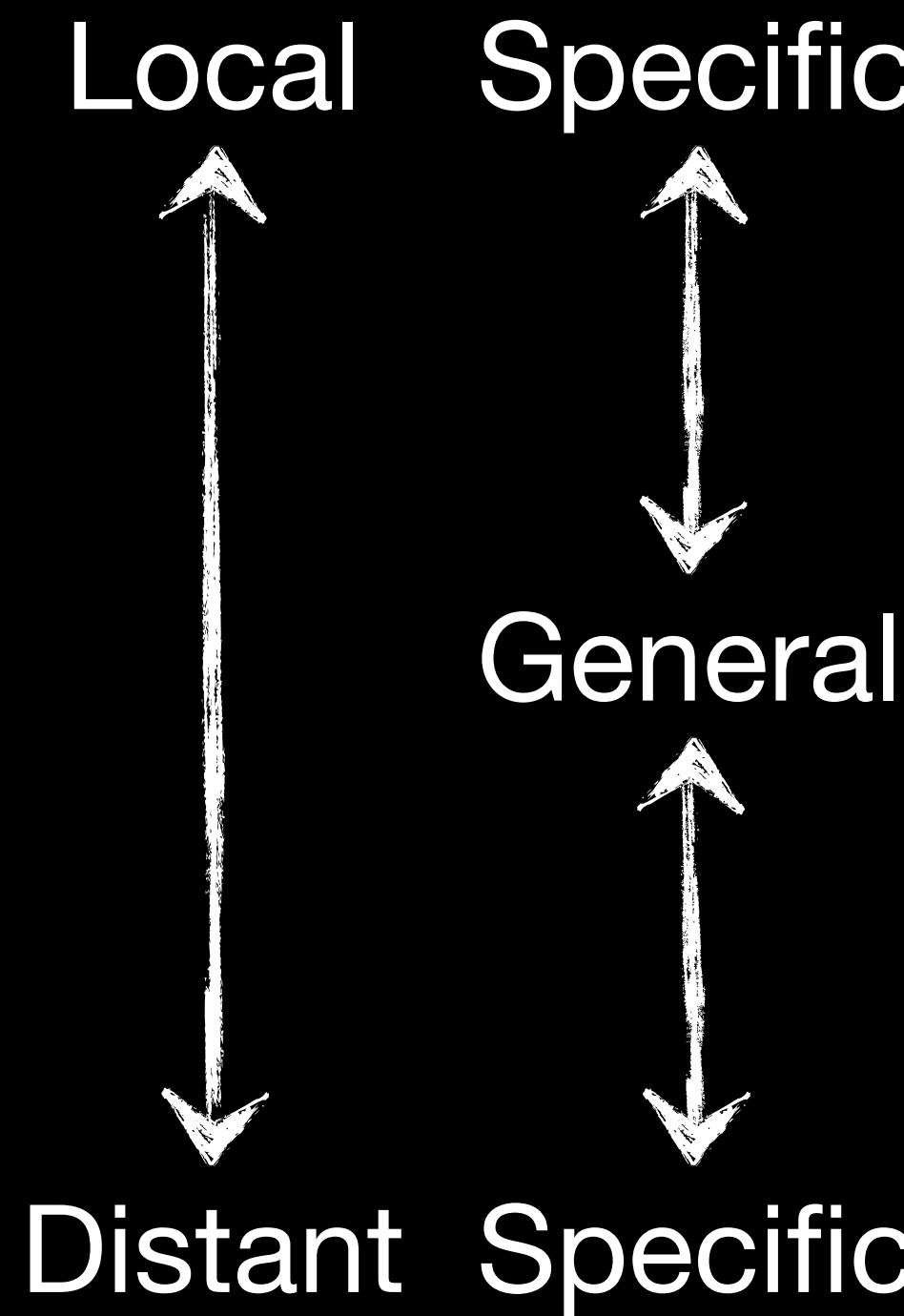
Stellar motion from integrated light (stars + resolved SOI)

Reverberation mapping (AGN)

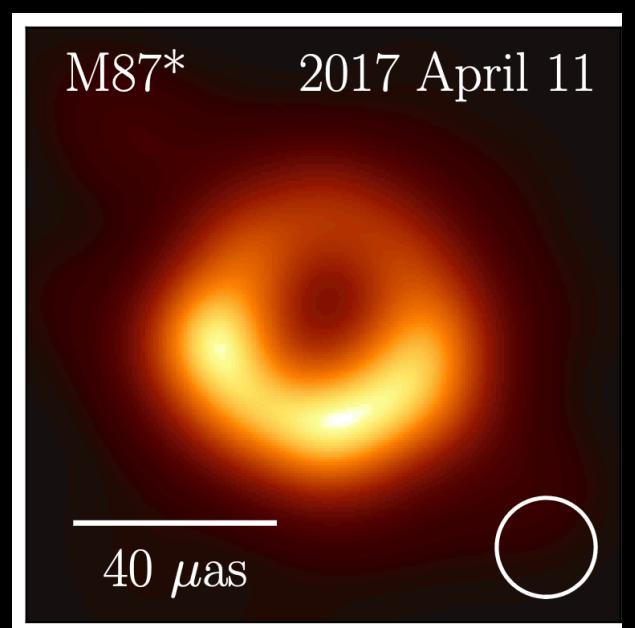
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Idea:

Relative velocities doppler-shift a star's spectrum.

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The motions of stars are related to the mass distribution of the galaxy

How to find SMBHs

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The motions of stars are related to the mass distribution of the galaxy

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

MASSIVE is a...

- Volume-limited ($D < 108 \text{ Mpc}$, $\delta > -6^\circ$)
- 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 $\sim 100 \text{ Mpc}$

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

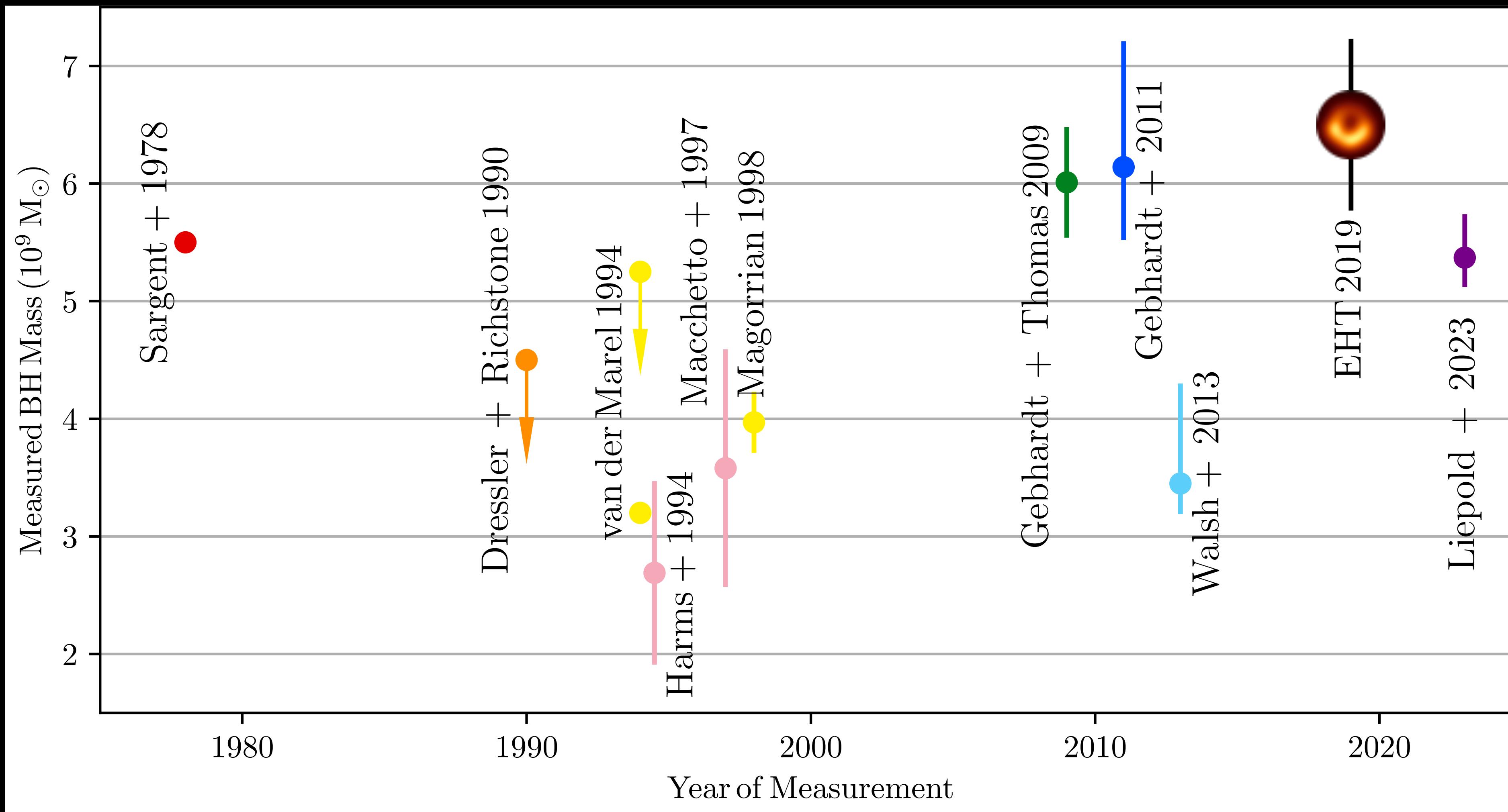
(And lots of people! Chung-Pei Ma, Jenny Greene, Jonelle Walsh, Nicholas McConnell, Jens Thomas, Melanie Veale, Irina Ene, Viraj Pandya, Charles Goullaud, Matthew Quenneville, Emily Liepold, Jacob Pilawa, Silvana Andrade Delgado and others)

An Example: M87

Liepold, Ma, Walsh 2023

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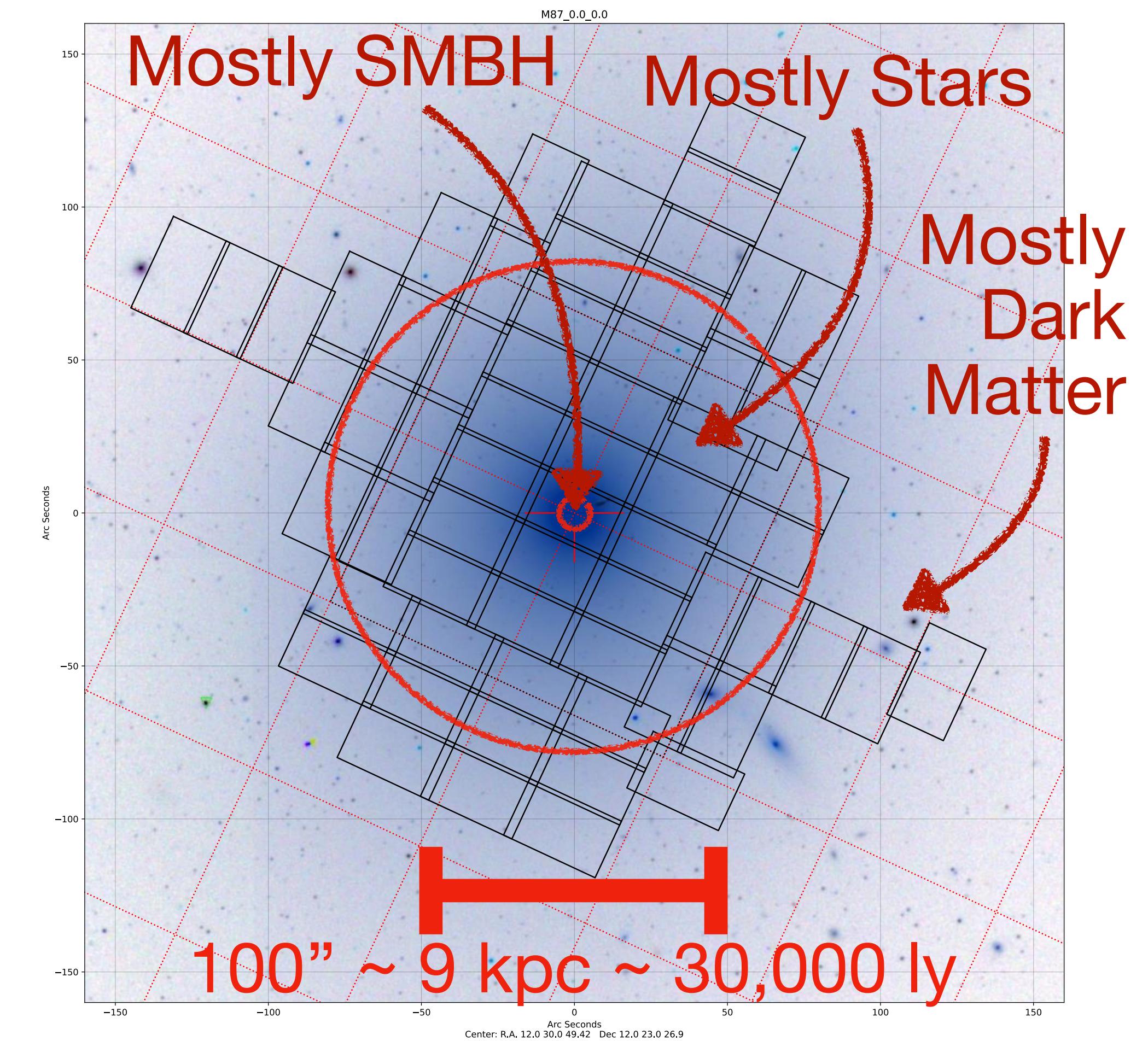
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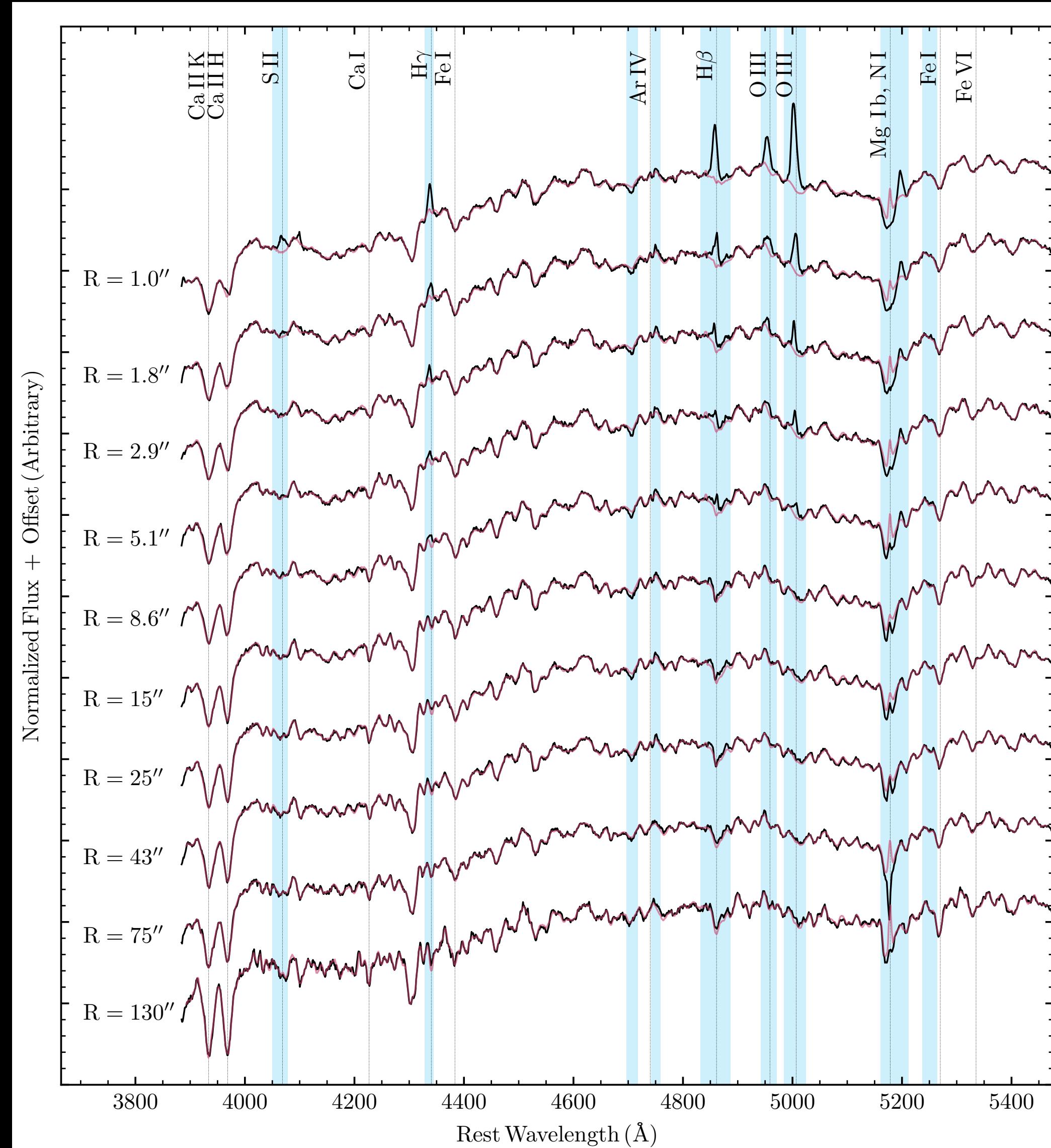
- We observed M87 with Keck Cosmic Web Imager (KCWI) during four observing runs from May 2020 - April 2022.
- 62 pointings were observed, each corresponding to a $20.4'' \times 33''$ FOV with $0.3'' \times 1.4''$ spatial pixels
- This is an integral field unit, yielding a distinct spectrum at each spatial 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!)

Liepold, Ma, Walsh 2023

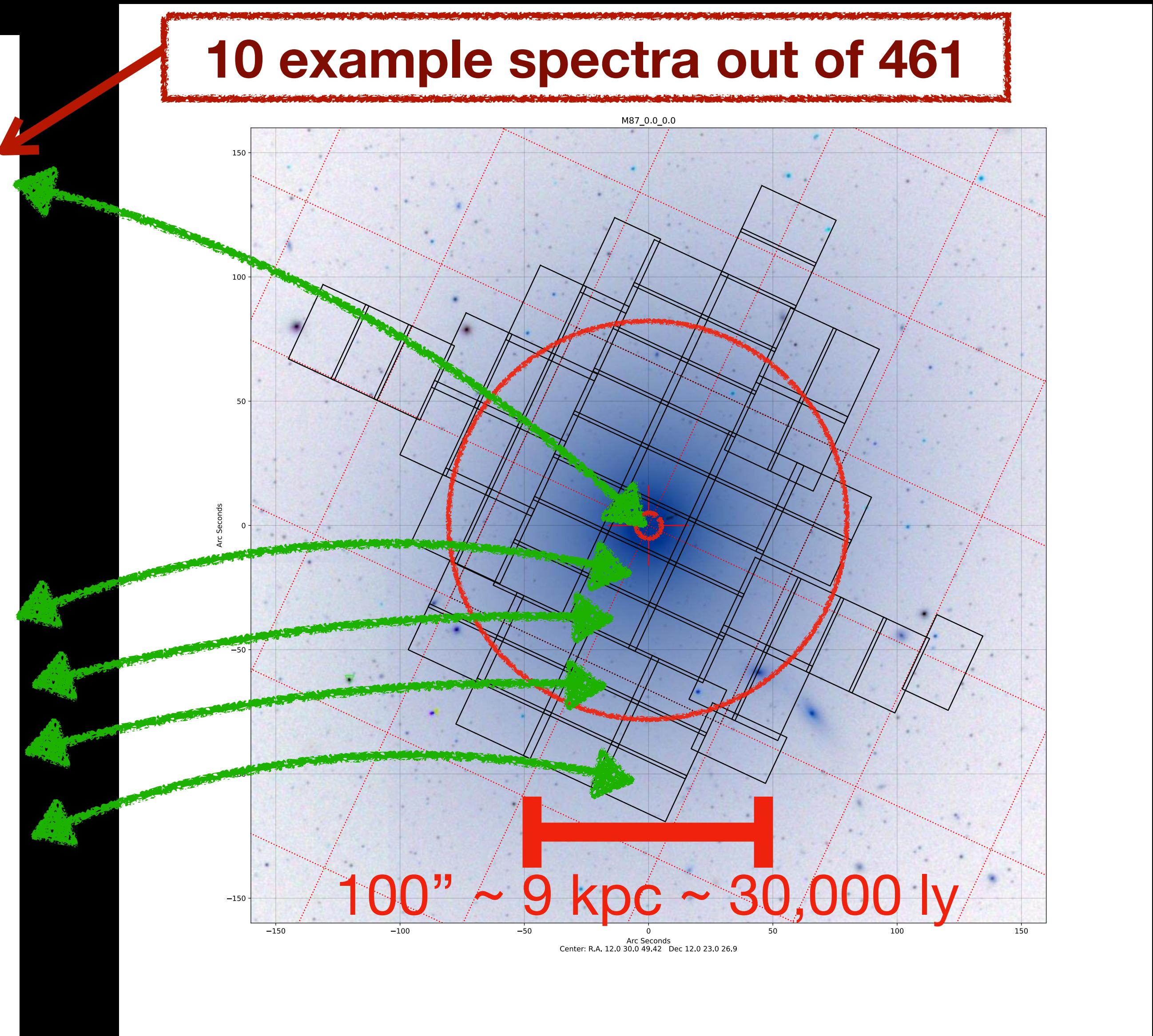


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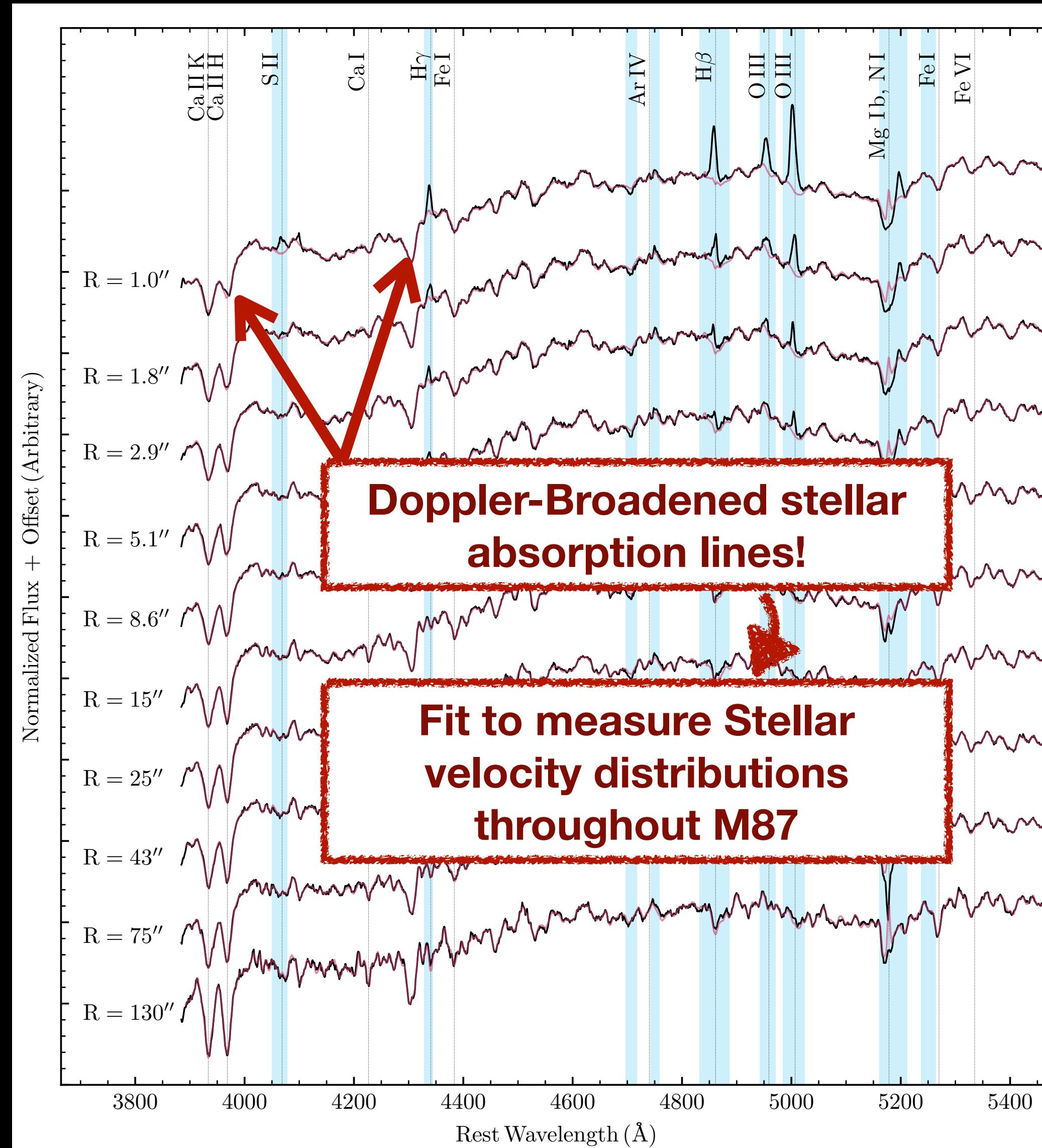


10 example spectra out of 461

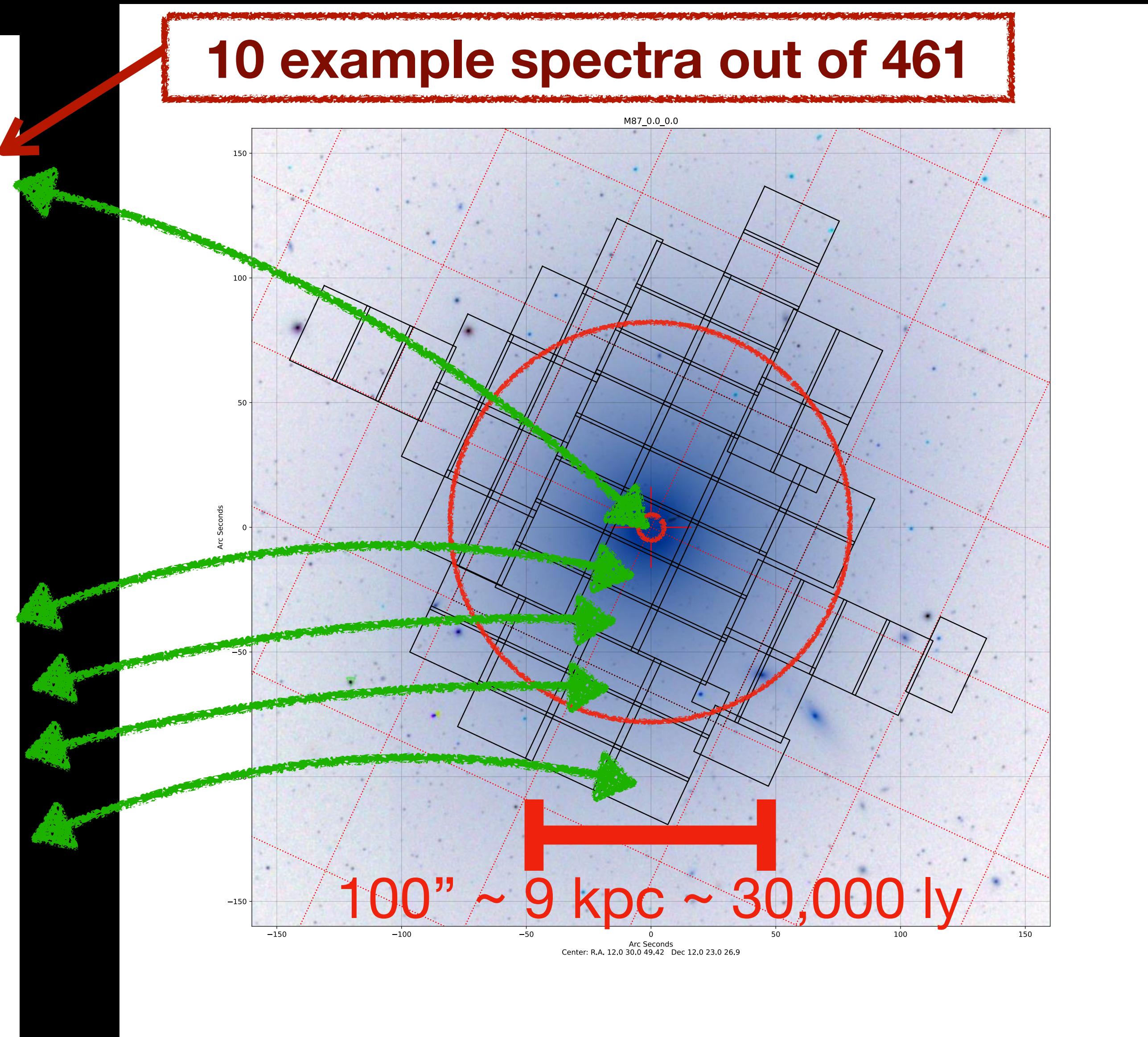


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Liepold, Ma, Walsh 2023

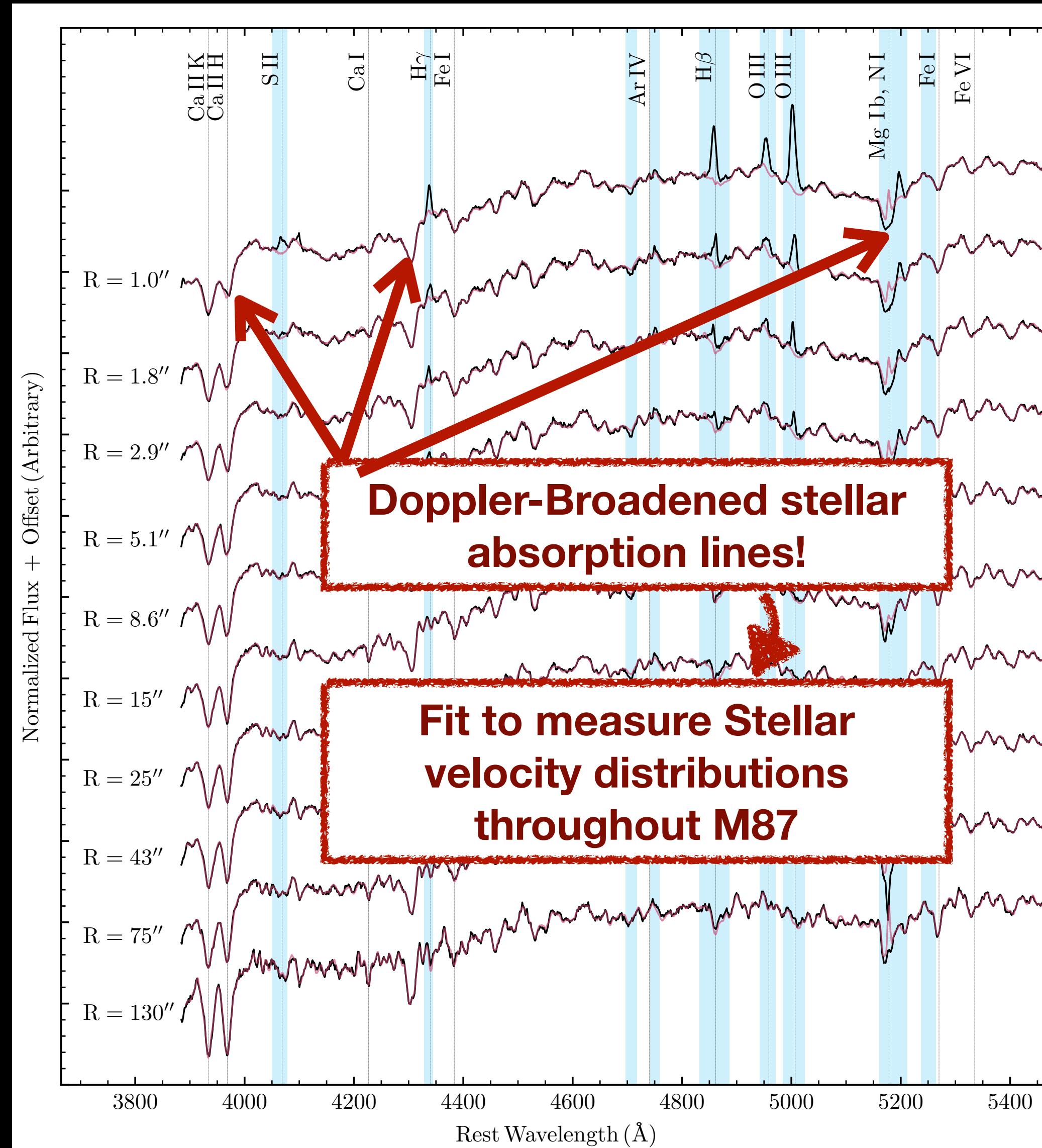


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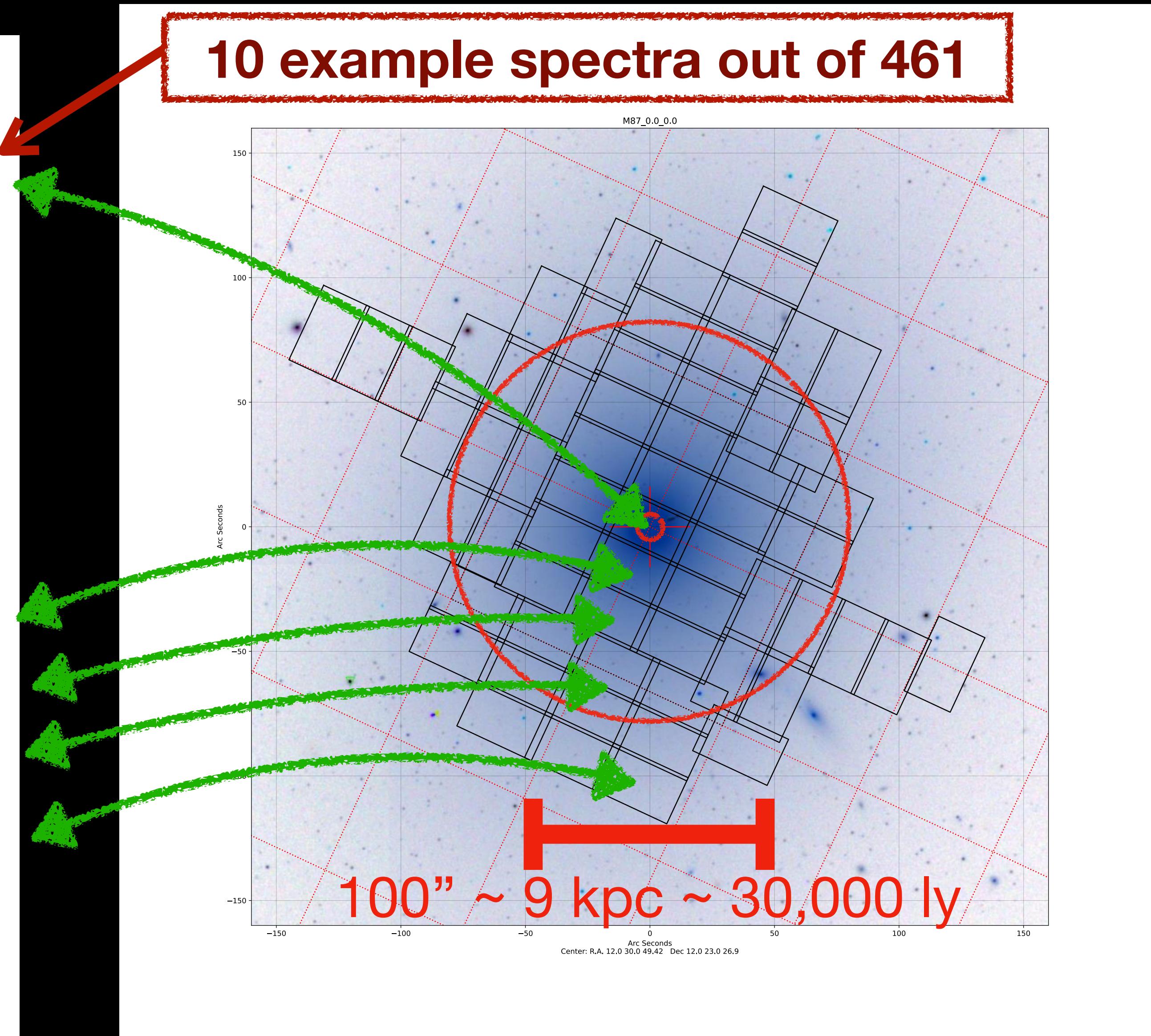


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Liepold, Ma, Walsh 2023

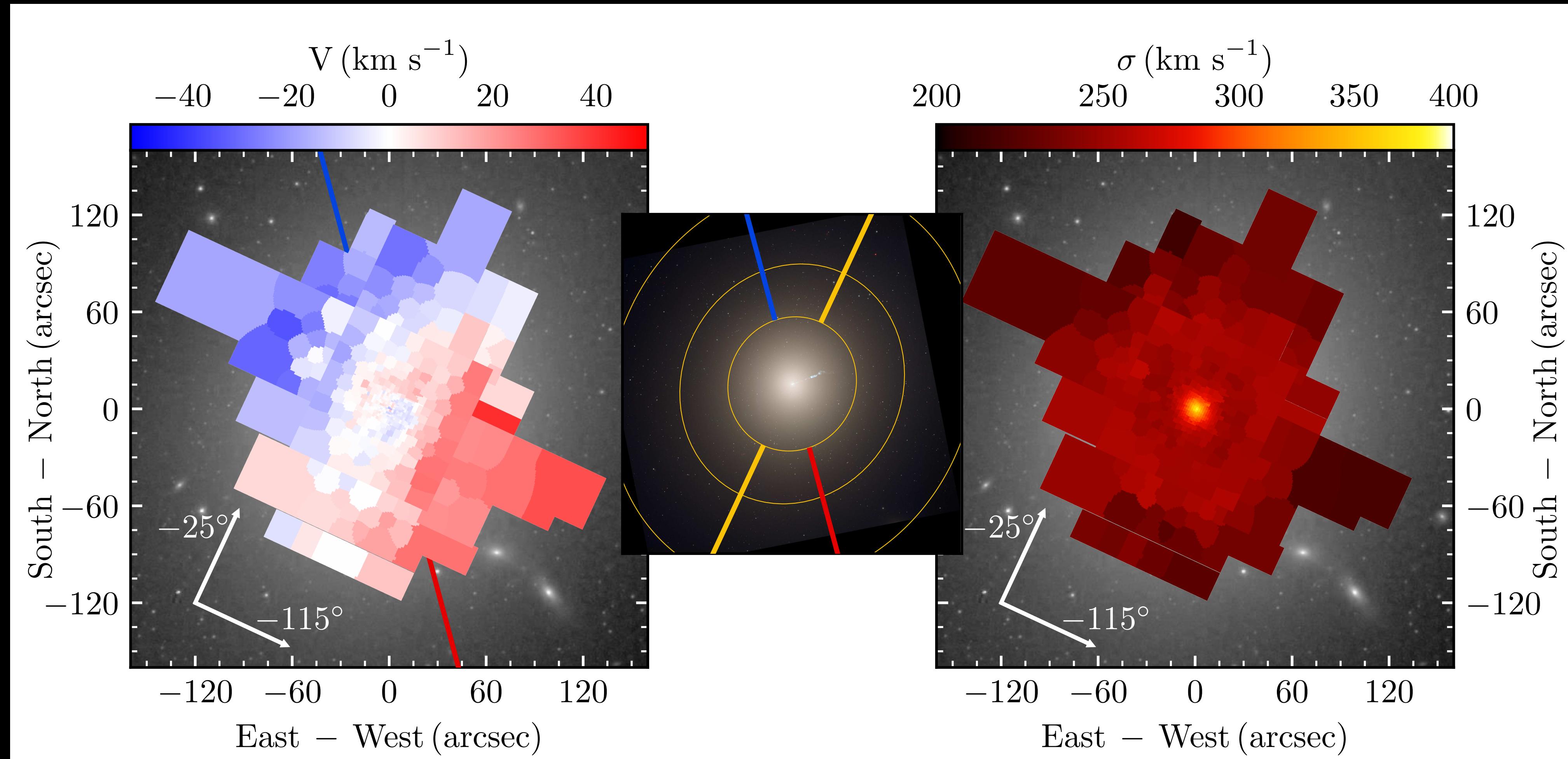


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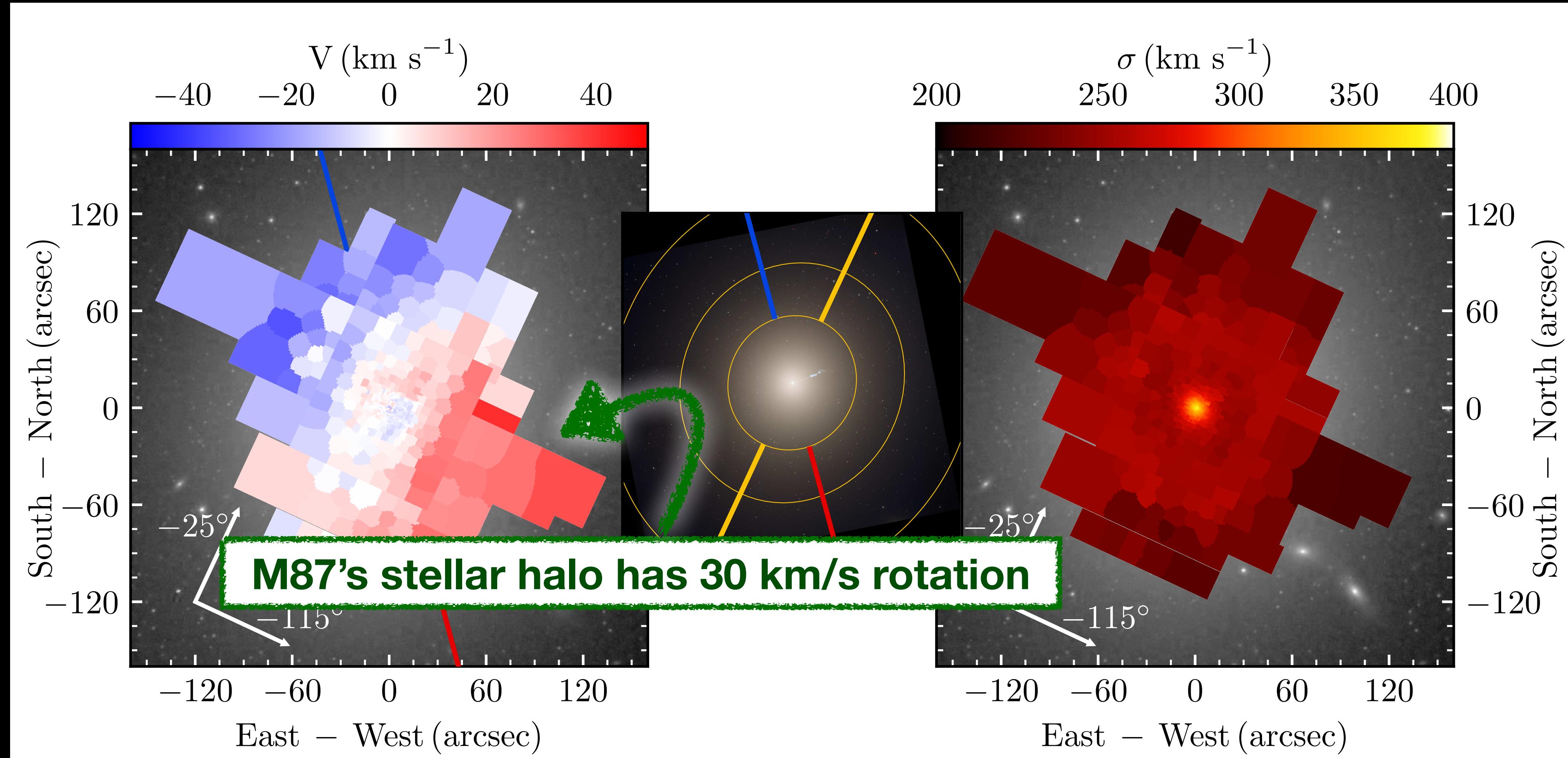
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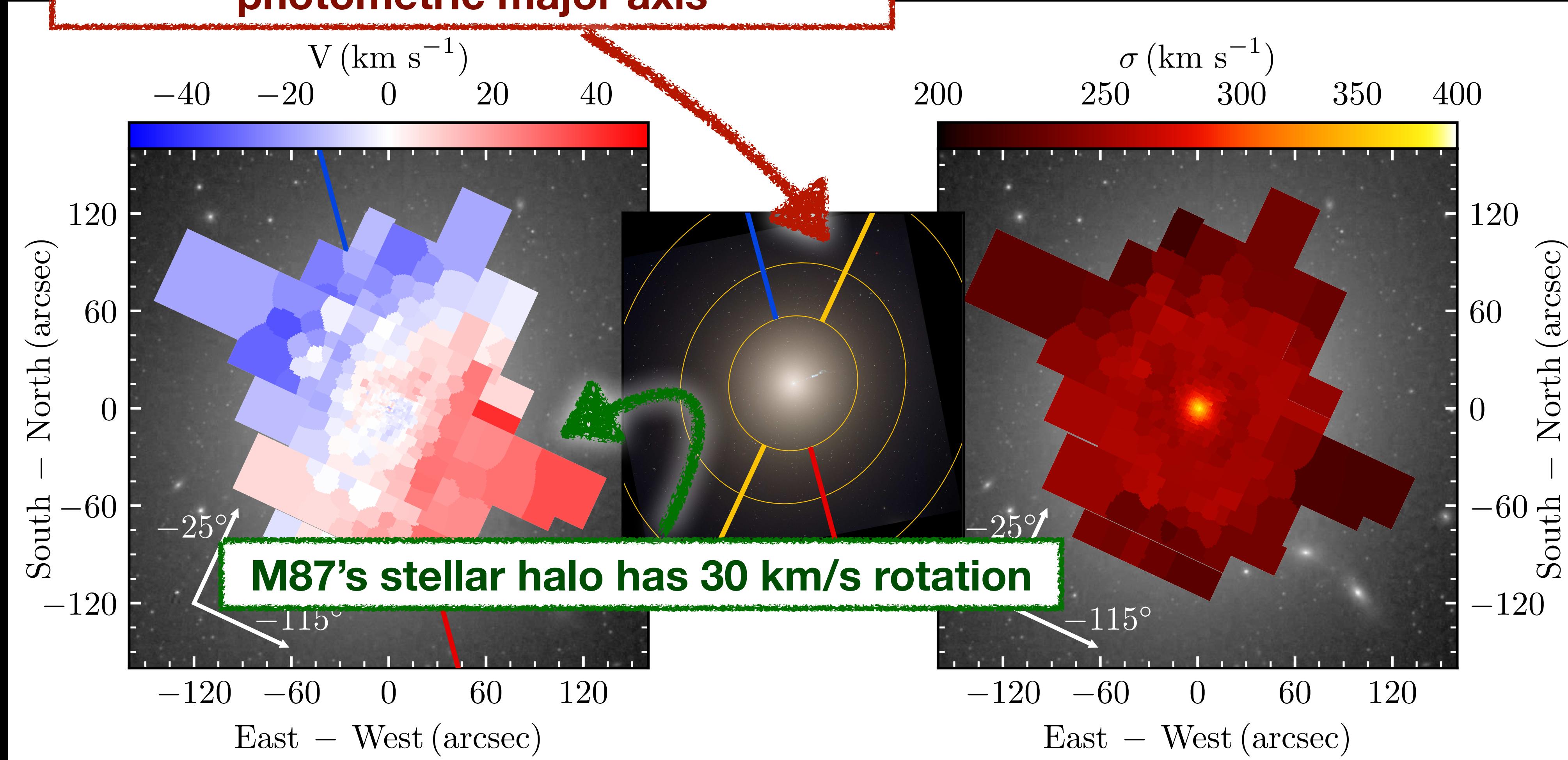
Liepold, Ma, Walsh 2023



An Example: M87

Liepold, Ma, Walsh 2023

The rotation is *misaligned* with the photometric major axis

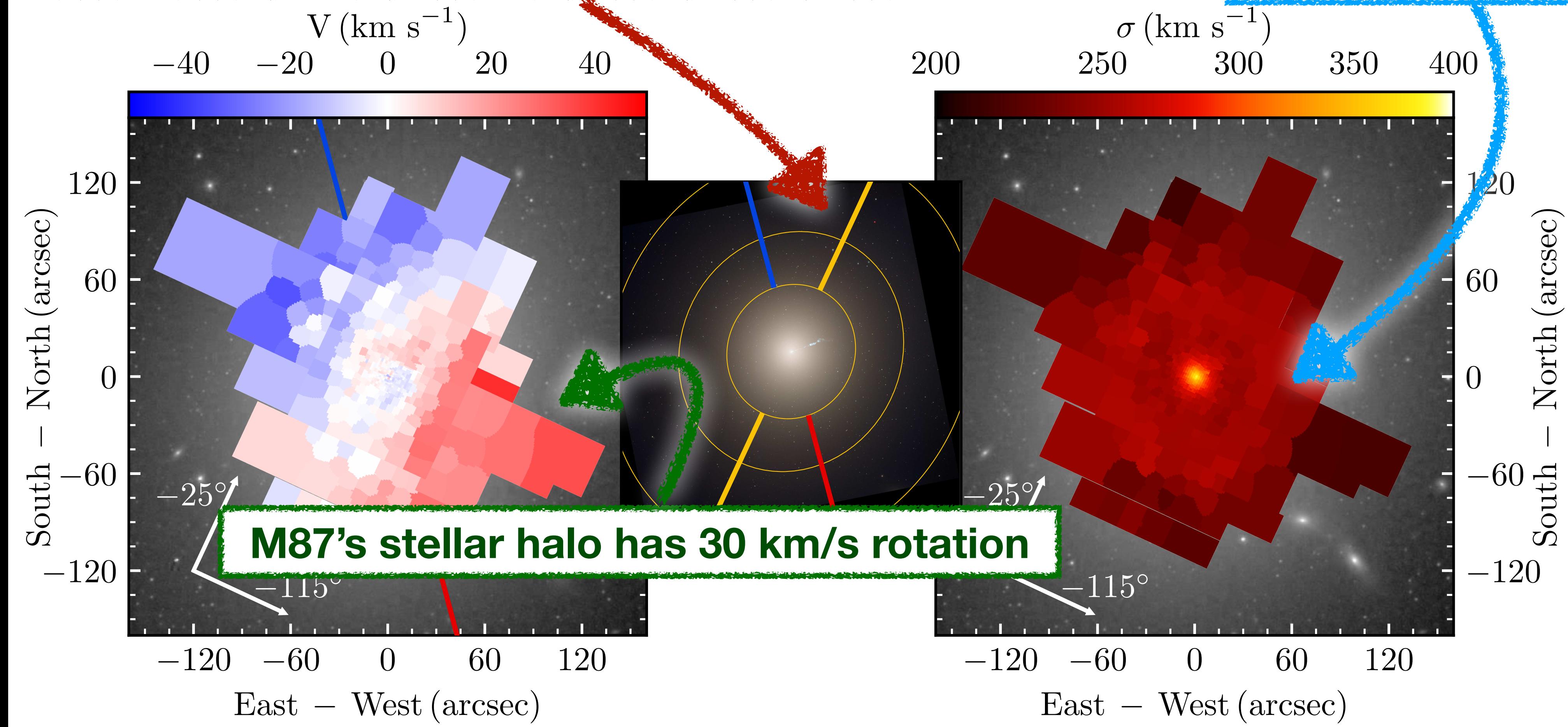


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The rotation is *misaligned* with the photometric major axis

The velocity dispersion rises *quickly* towards the center!

We found a black hole!



An Example: M87

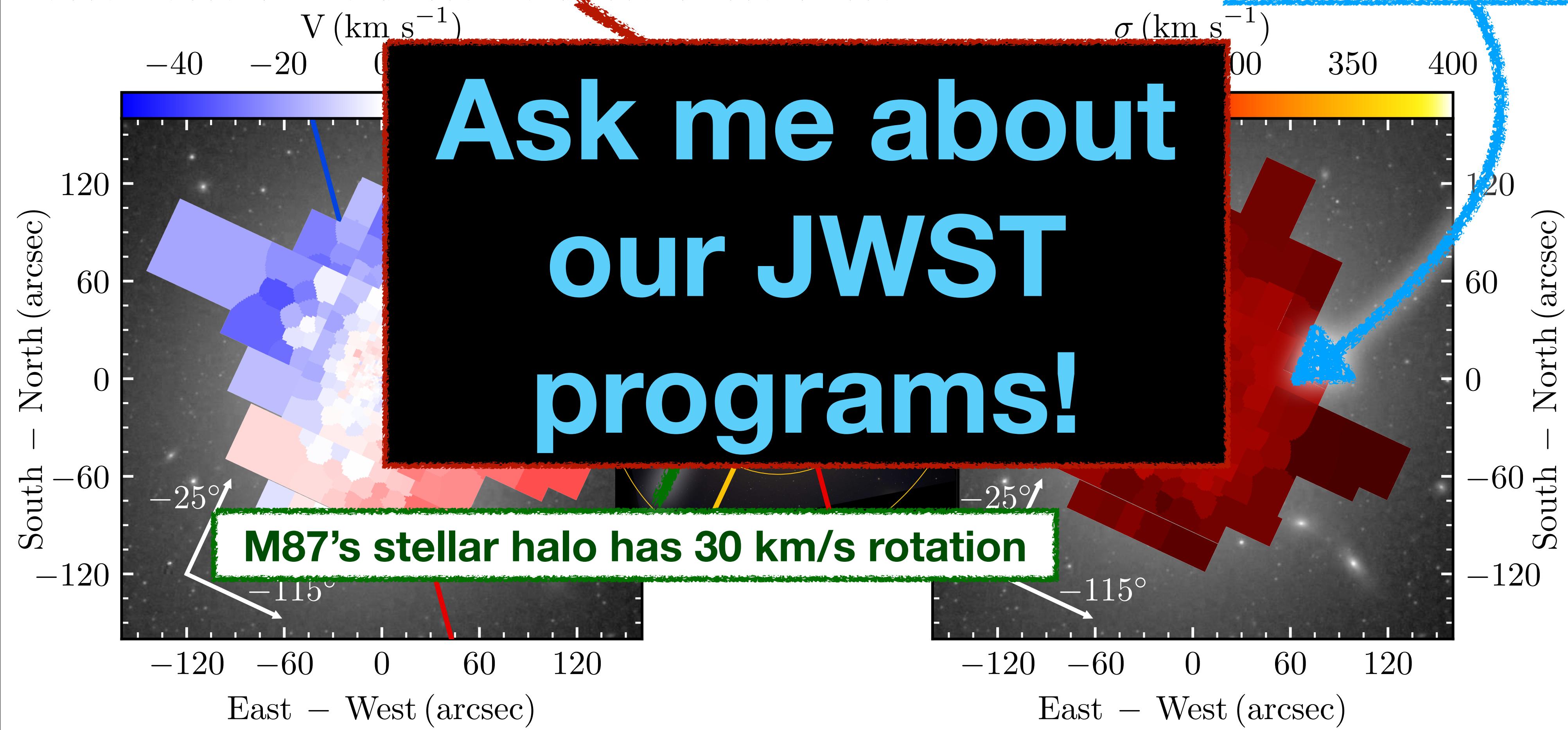
Liepold, Ma, Walsh 2023

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Ask me about
our JWST
programs!

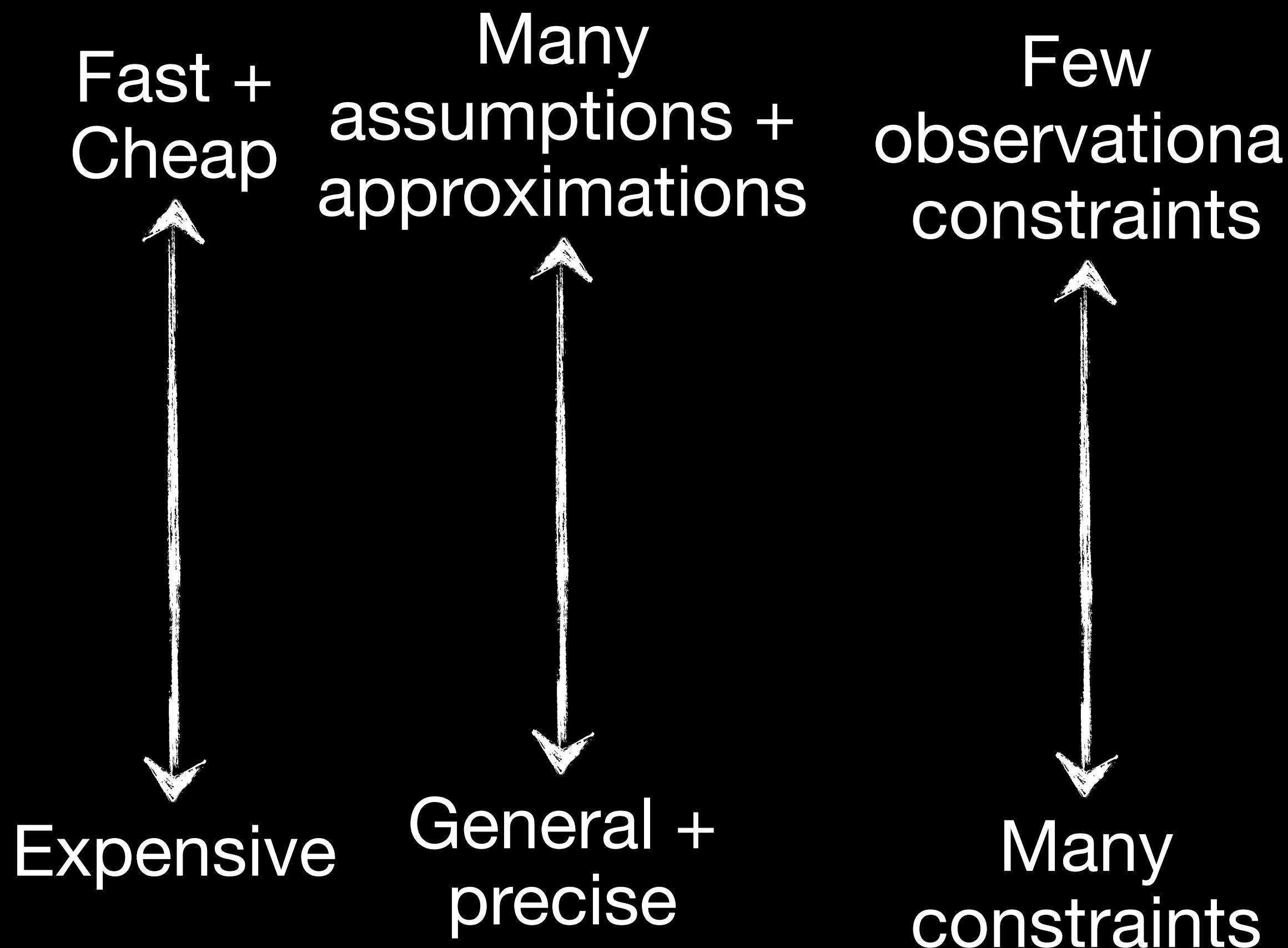


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How to measure SMBHs

Stellar dynamical *modelling*



- Virial – estimate enclosed using stellar dispersion + Virial Theorem
- Jeans – estimate SMBH using Jeans Equation
- 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

How to measure SMBHs

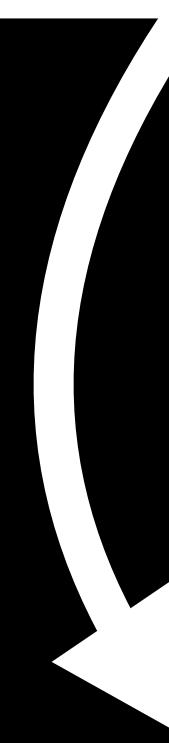
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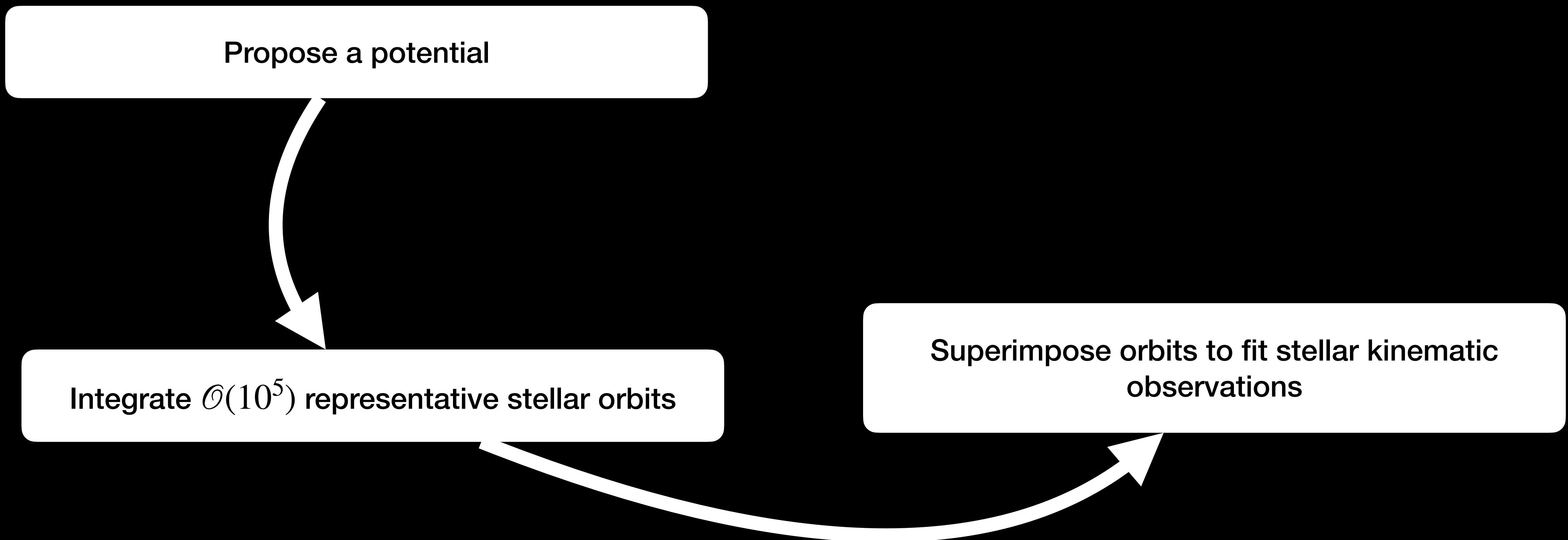


Integrate $\mathcal{O}(10^5)$ representative stellar orbits

How to measure SMBHs

Schwarzschild modelling

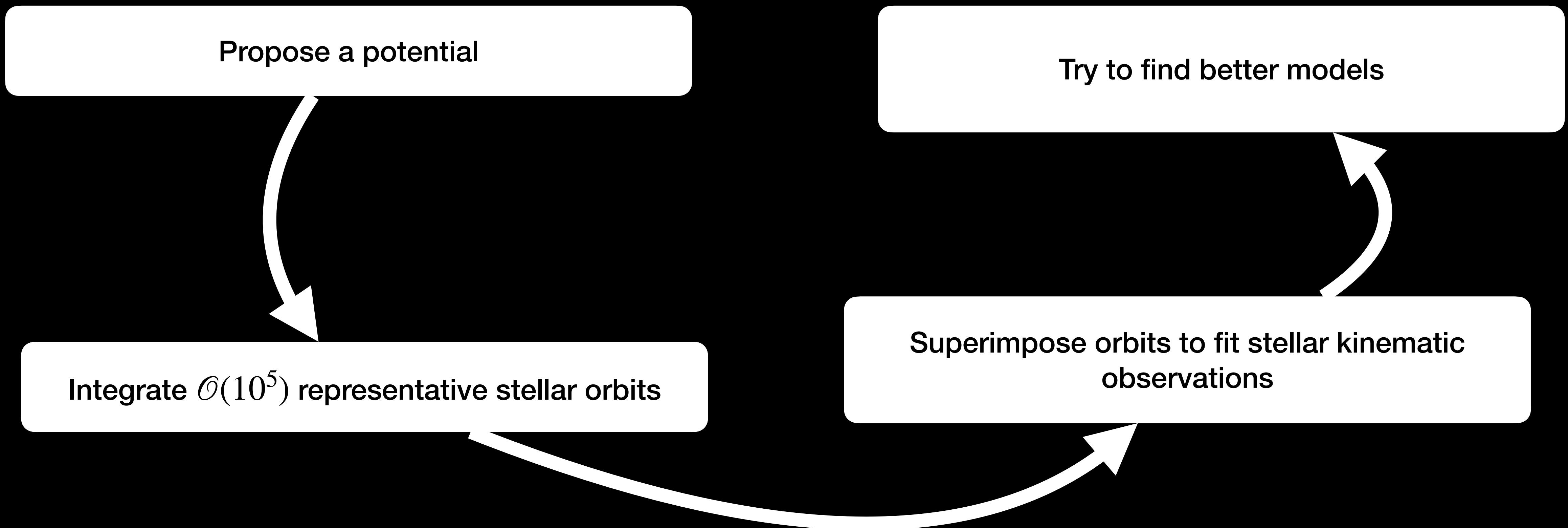
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How to measure SMBHs

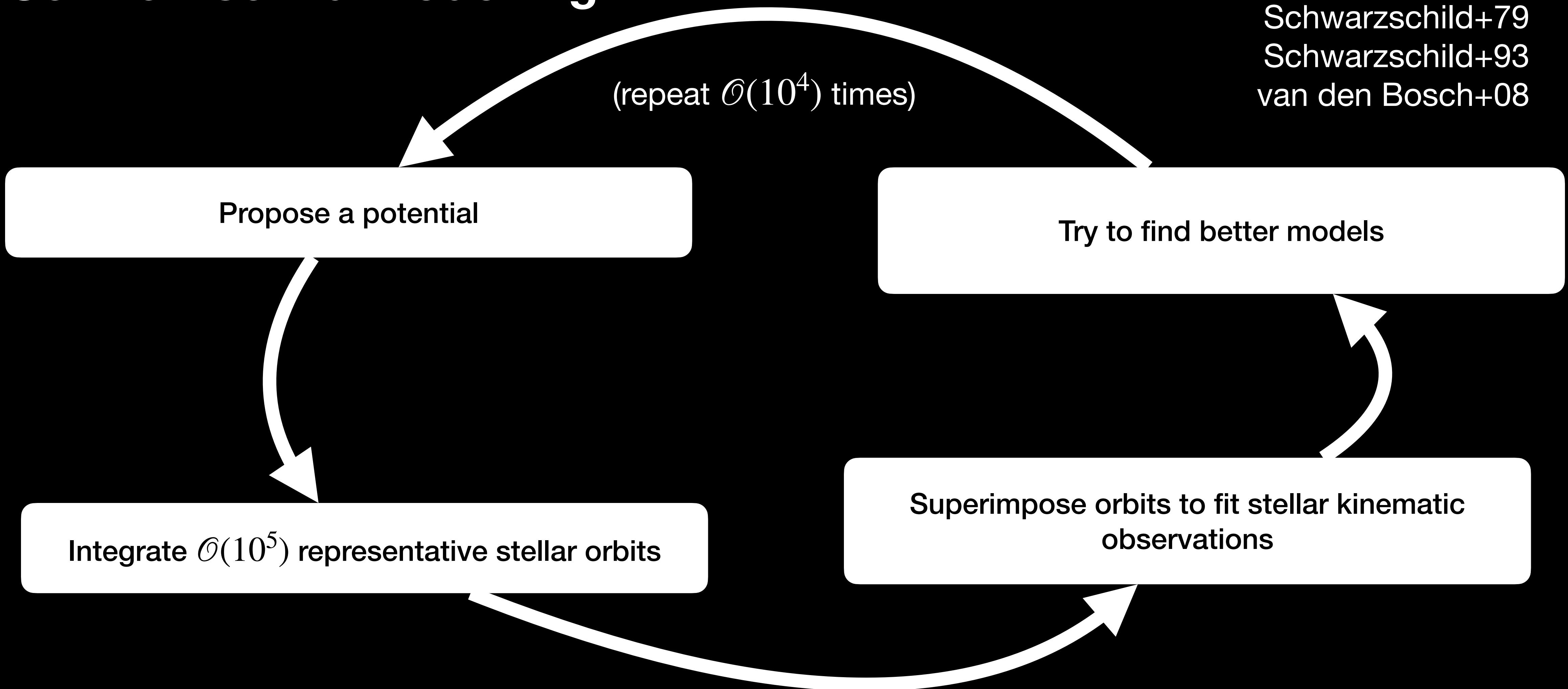
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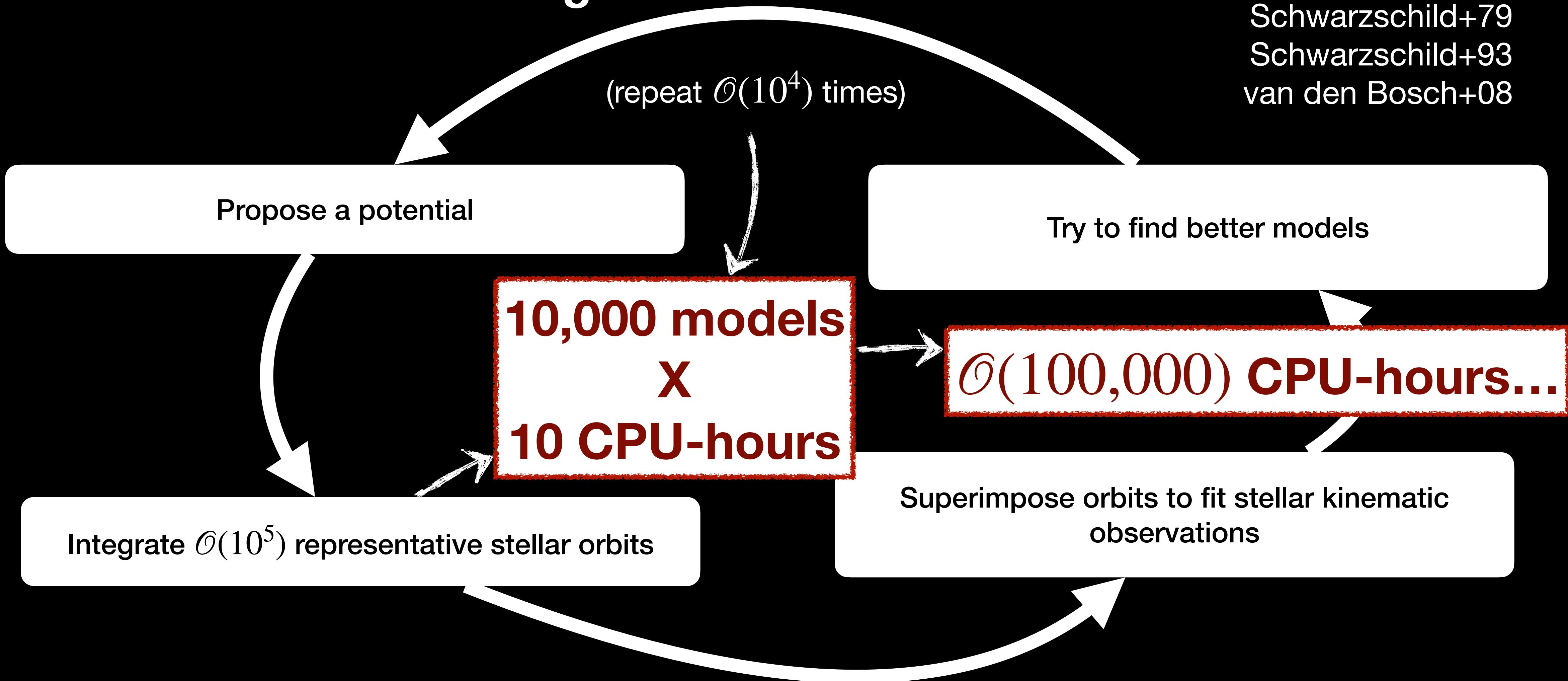
How to measure SMBHs

Schwarzschild modelling



How to measure SMBHs

Schwarzschild modelling



How to (really) measure SMBHs

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

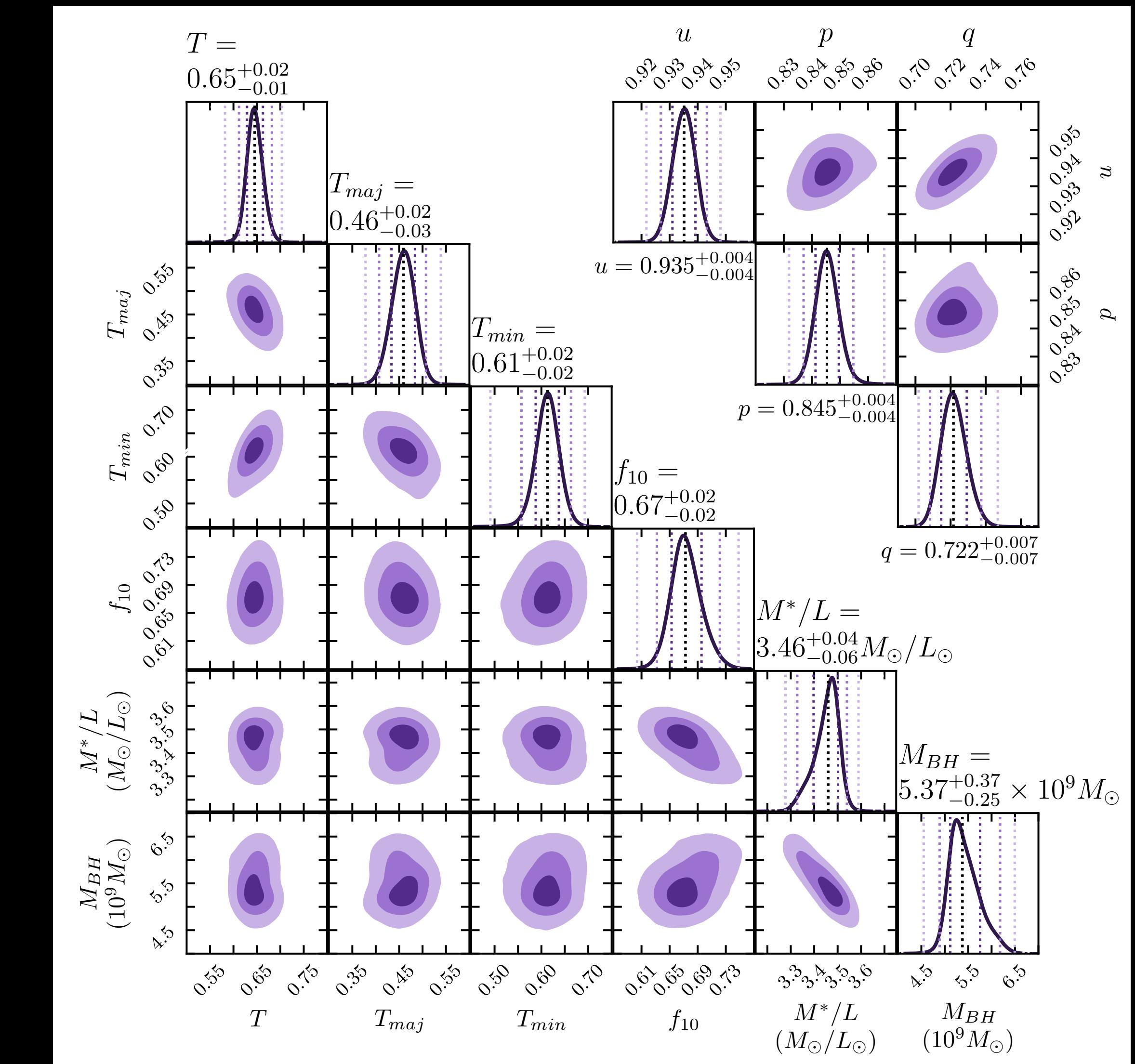
- Accurate orbit composition + symmetry in axisymmetric and triaxial galaxies
- Code efficiency improvements (~order of magnitude speedups!)

We've also made methodology improvements!

- Model sampling + parameter inference improvements!
(~couple order of magnitude speedups)
- Robustness tests with mock galaxy data!
(Liepold+20,23; Quenneville+21,22; Pilawa+22,24)

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Liepold, Ma, Walsh 2023

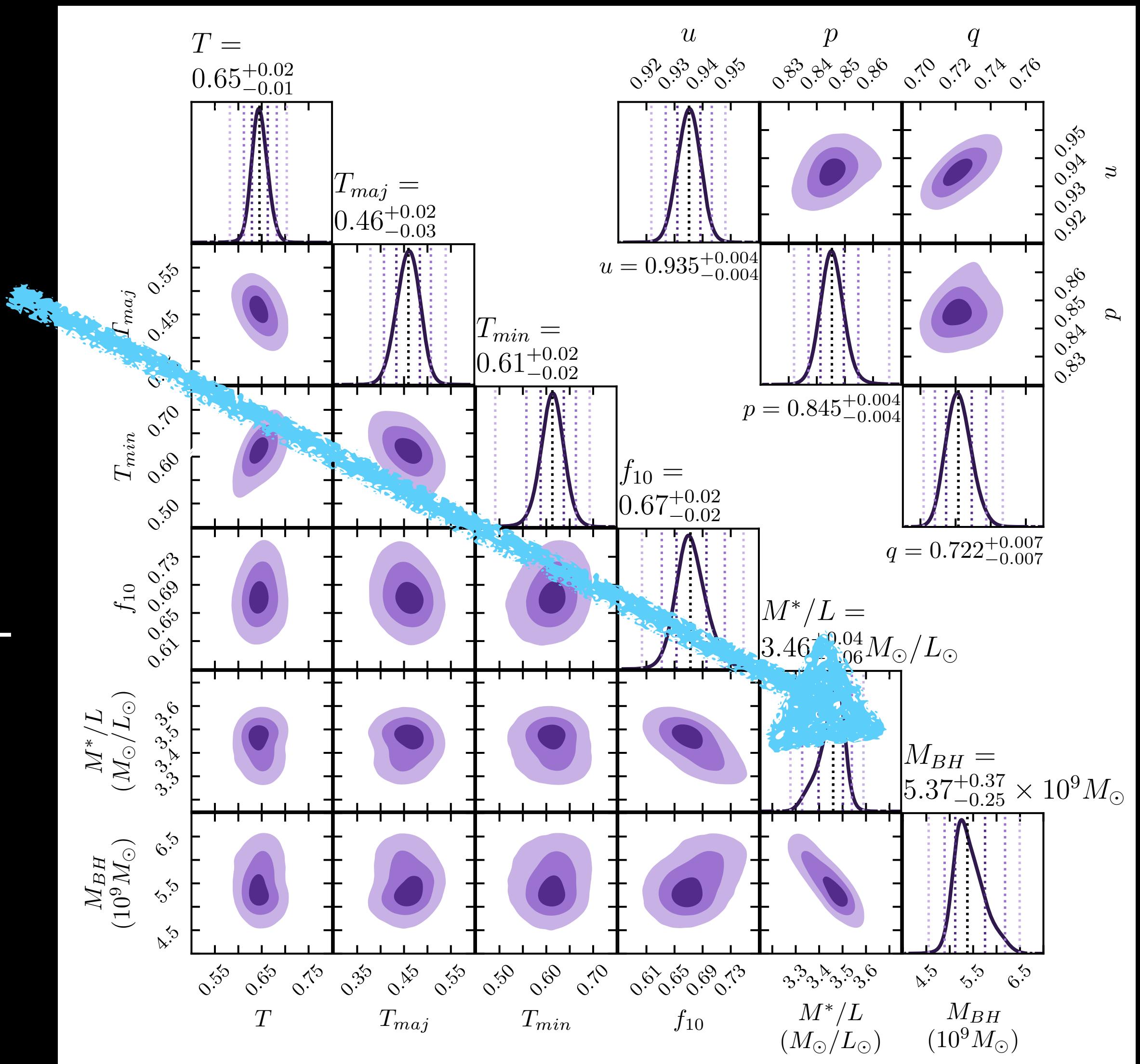


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Black Hole Mass

$5.37 \times 10^9 M_{\odot}$

Liepold, Ma, Walsh 2023



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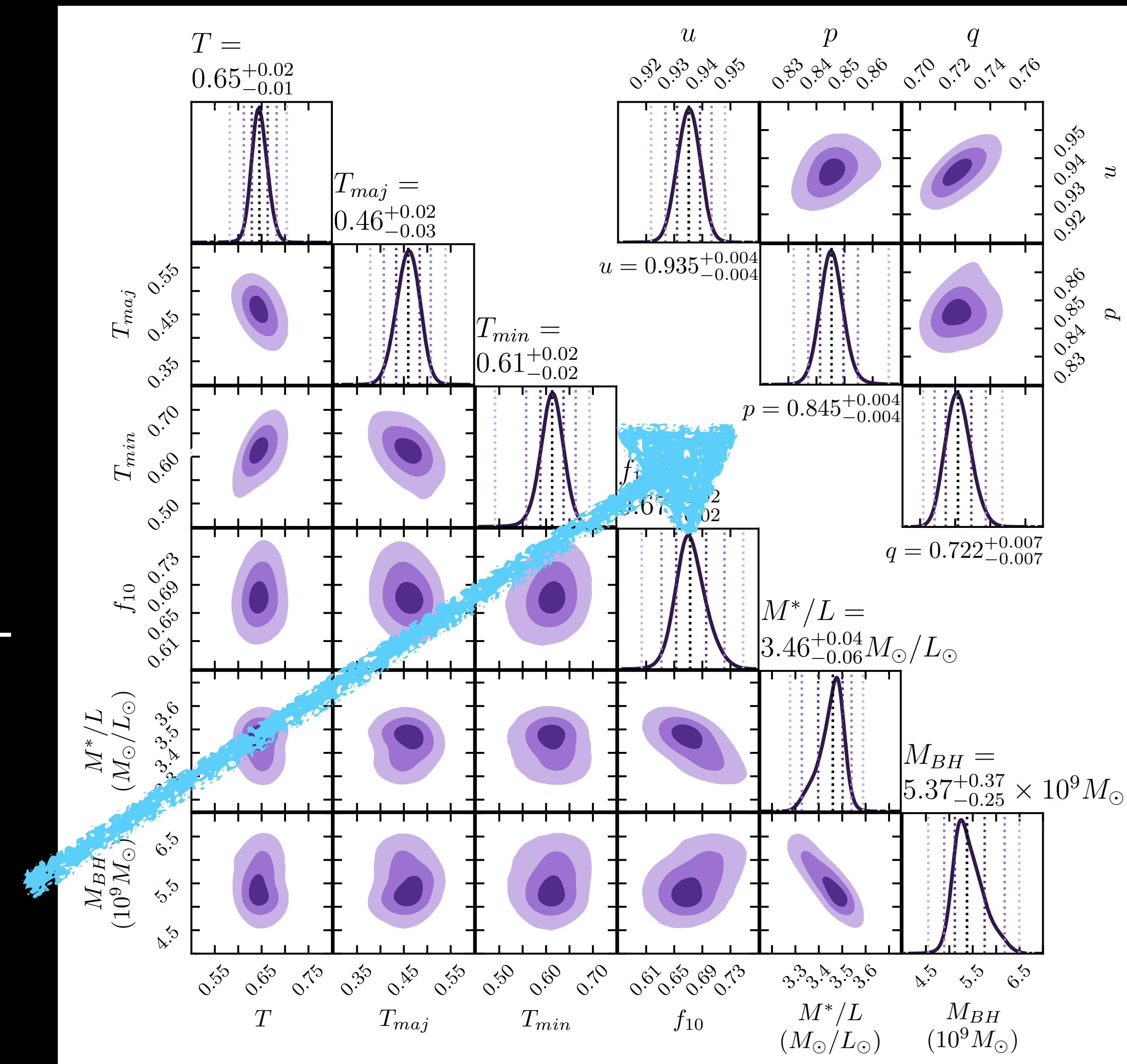
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Long :
intermediate :
short axis
lengths

1 : 0.85 : 0.72



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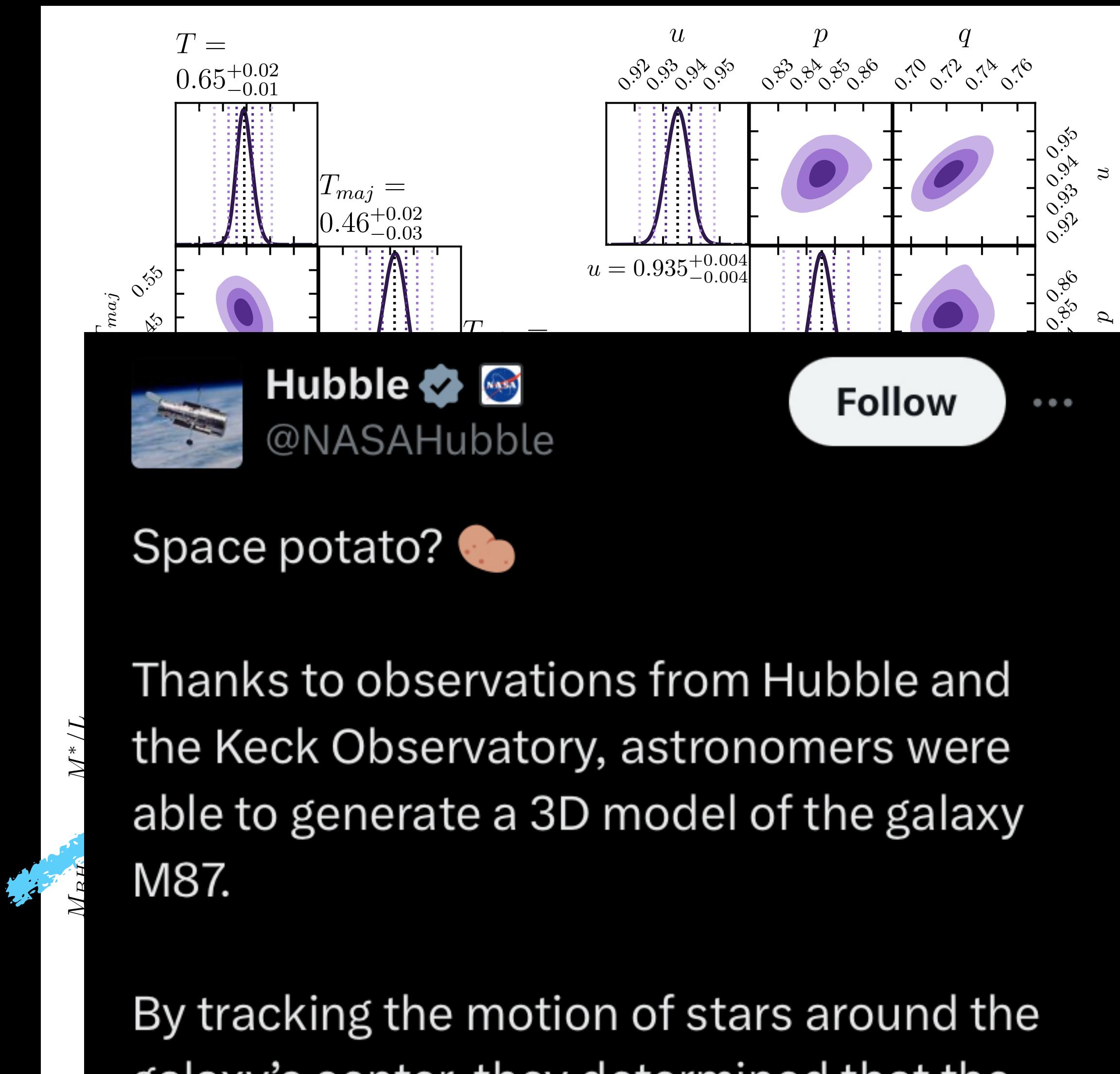
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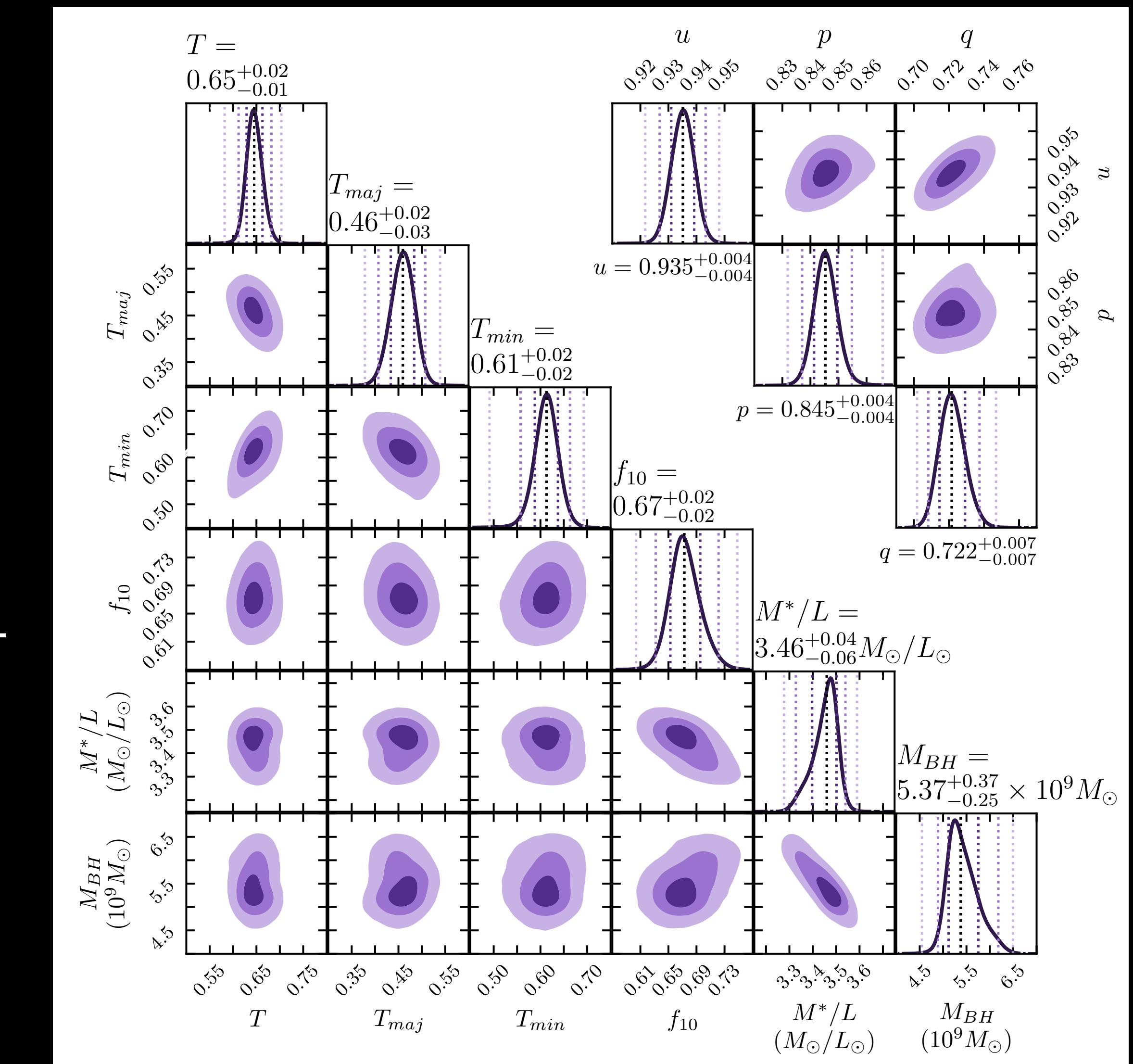
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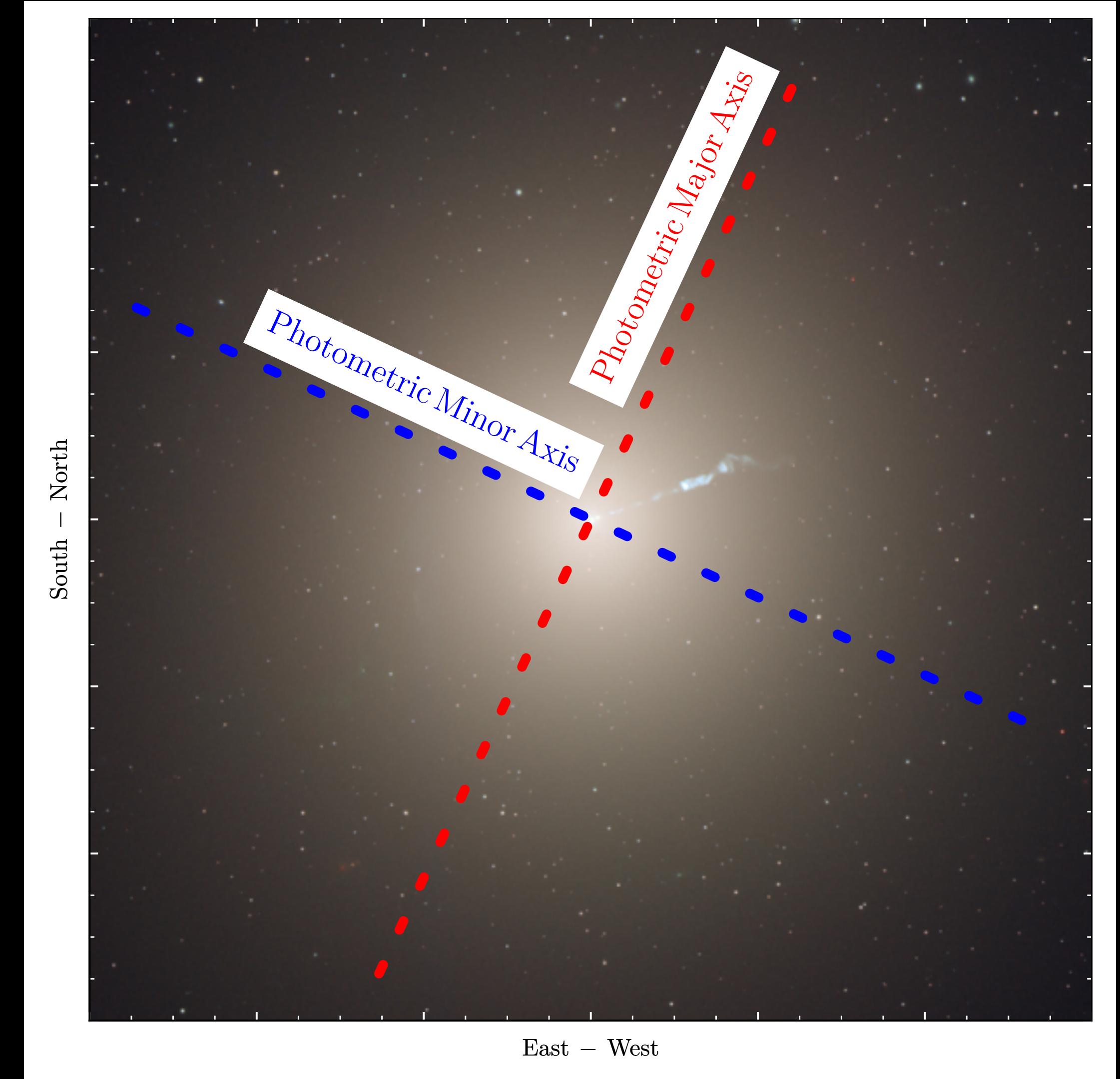
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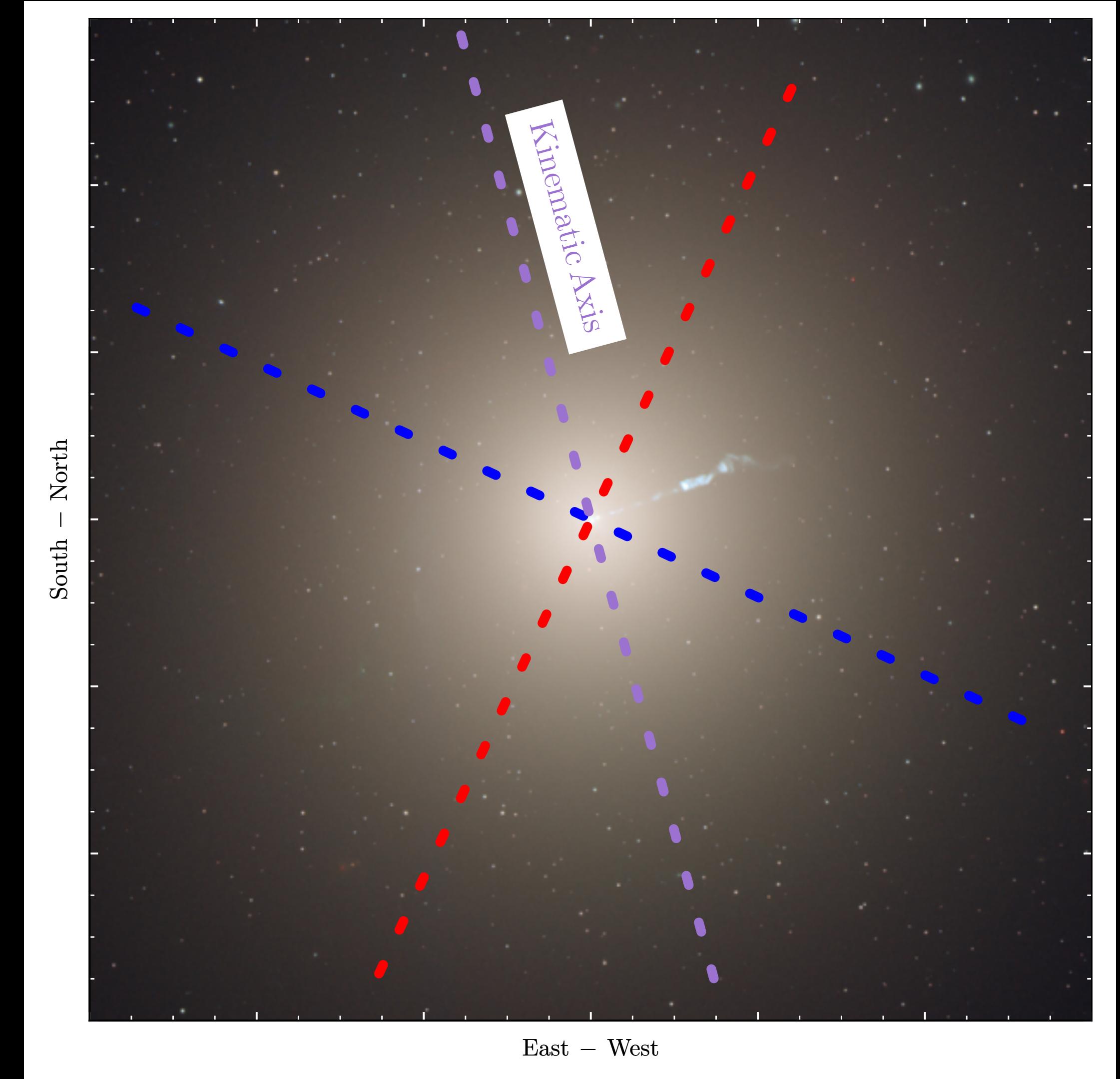
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- The **kinematic axis** is misaligned from the **photometric axes**

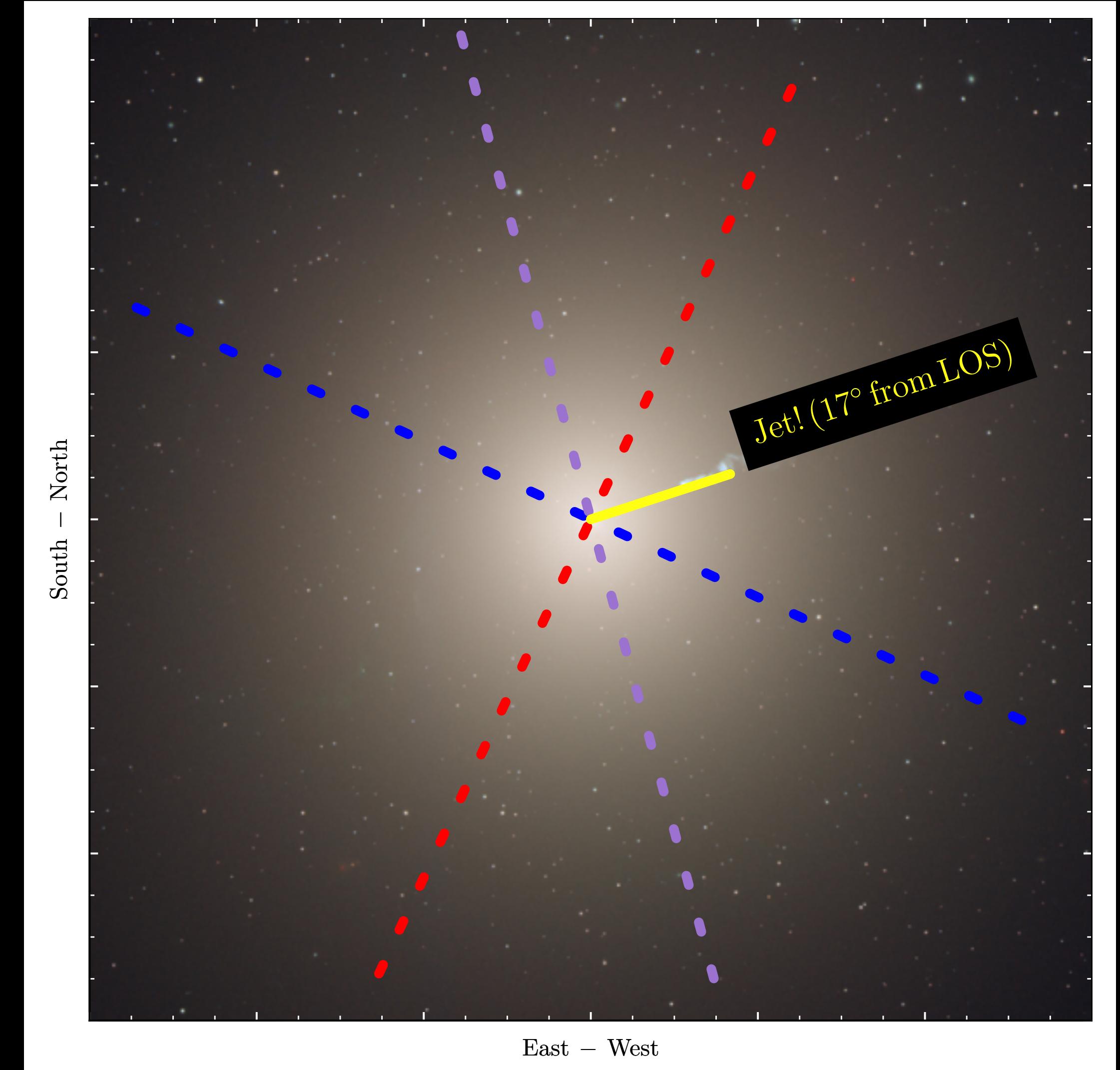
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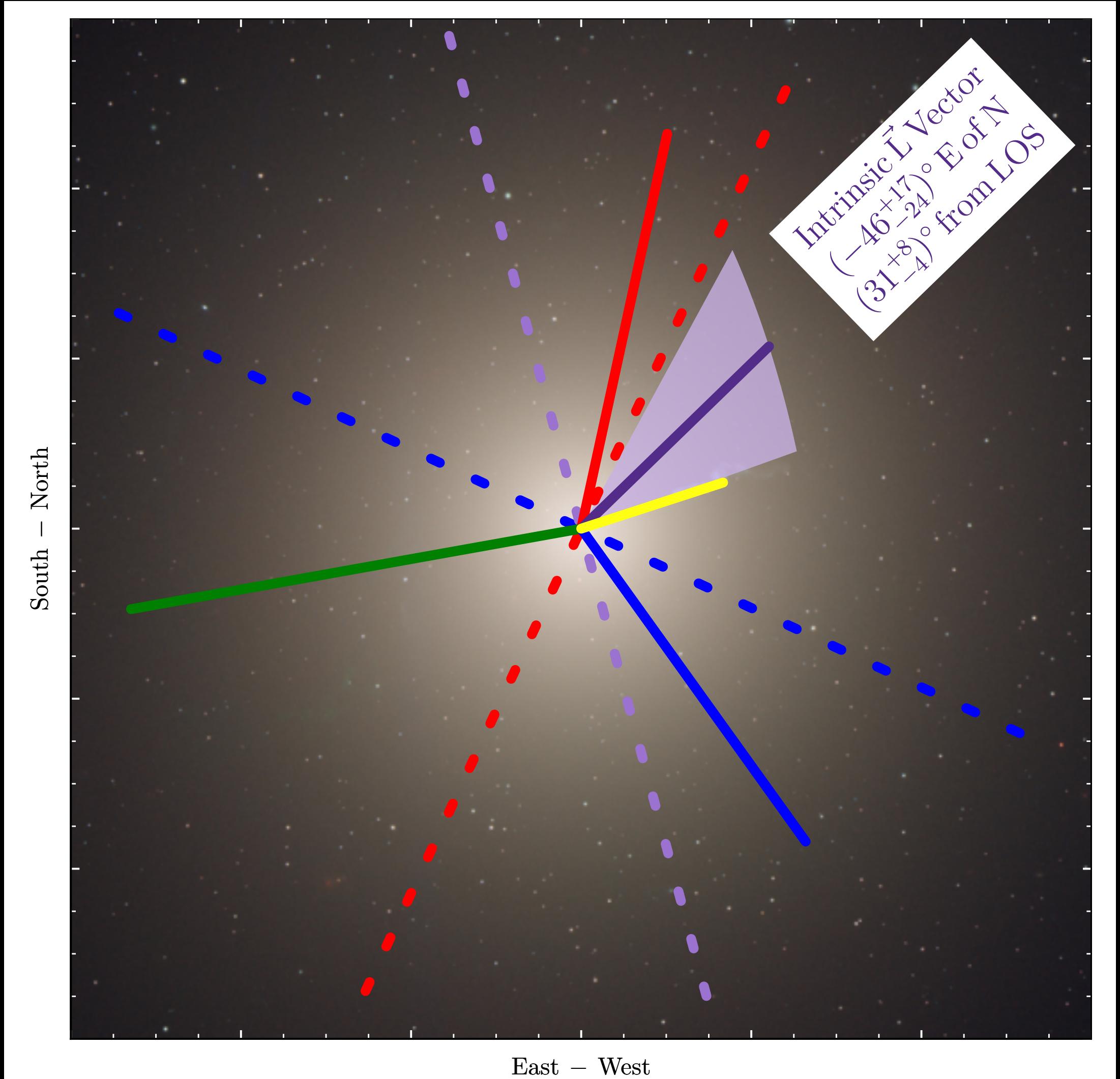
- The **kinematic axis** is **misaligned** from the **photometric axes**
- The **jet** is almost perpendicular to the kinematic axis on the sky

Liepold, Ma, Walsh 2023



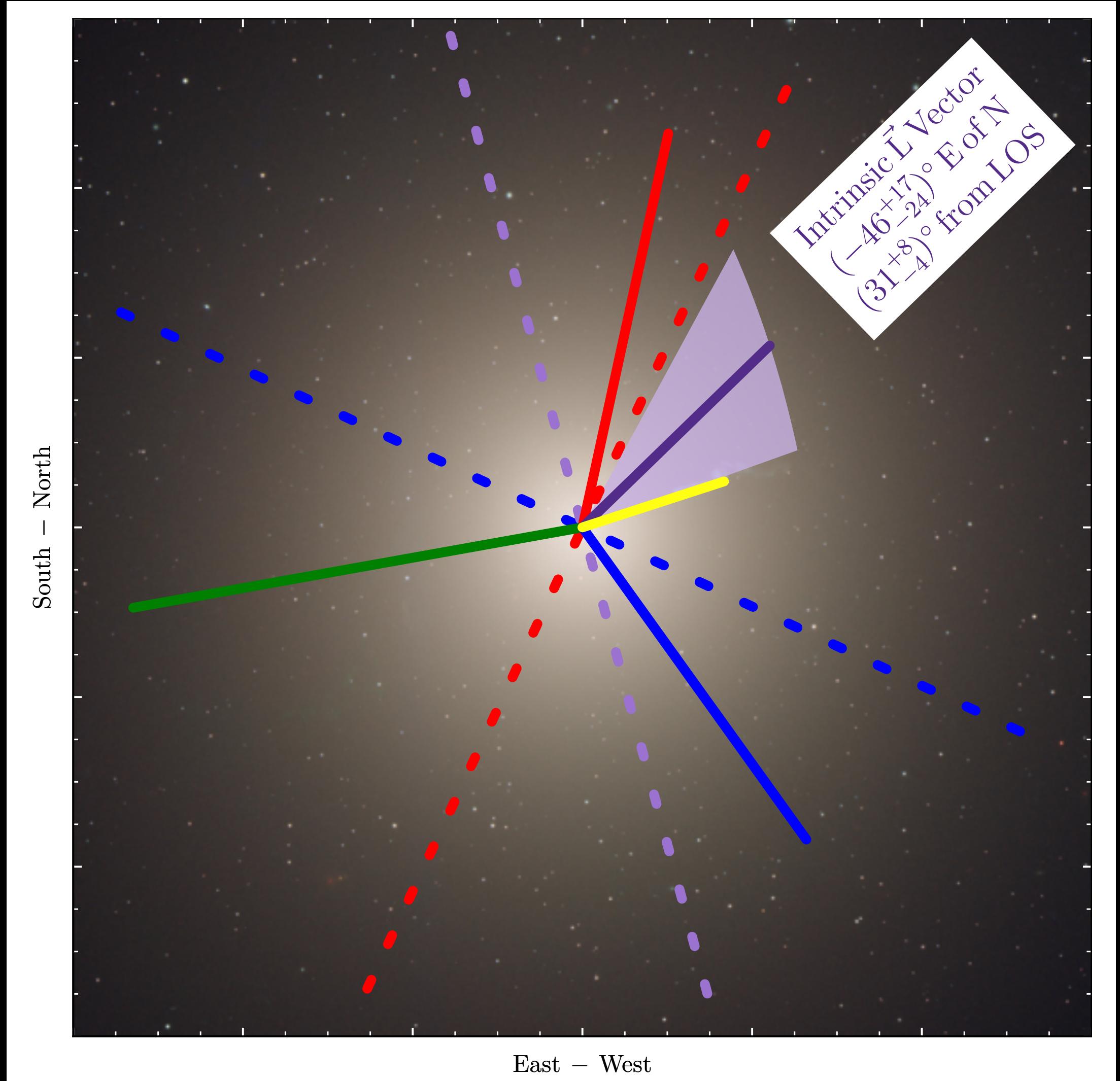
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- The mean stellar L vector from $80''$ to $150''$ is $(19 \pm 9)^\circ$ from the jet! (In 3D)



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



We now have

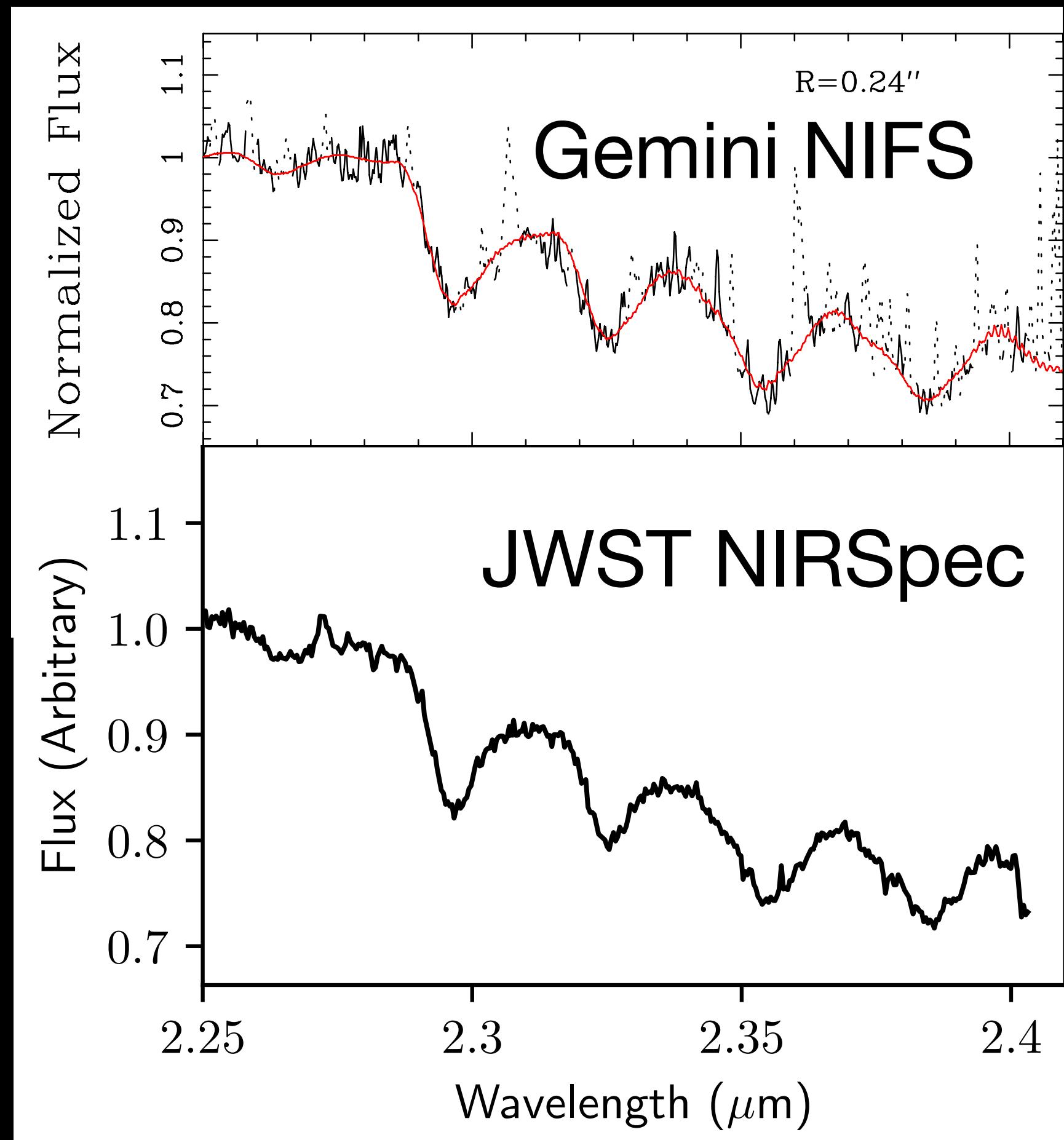
- Robust, efficient triaxial Schwarzschild modelling
- Lots of high S/N, high spatial resolution IFU observations of ~100 very massive local galaxies

Ongoing Efforts

- **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?**
Also check out Liepold+24a (out shortly!) — connecting the MASSIVE stellar mass distribution and NANOGrav's observed GW strain

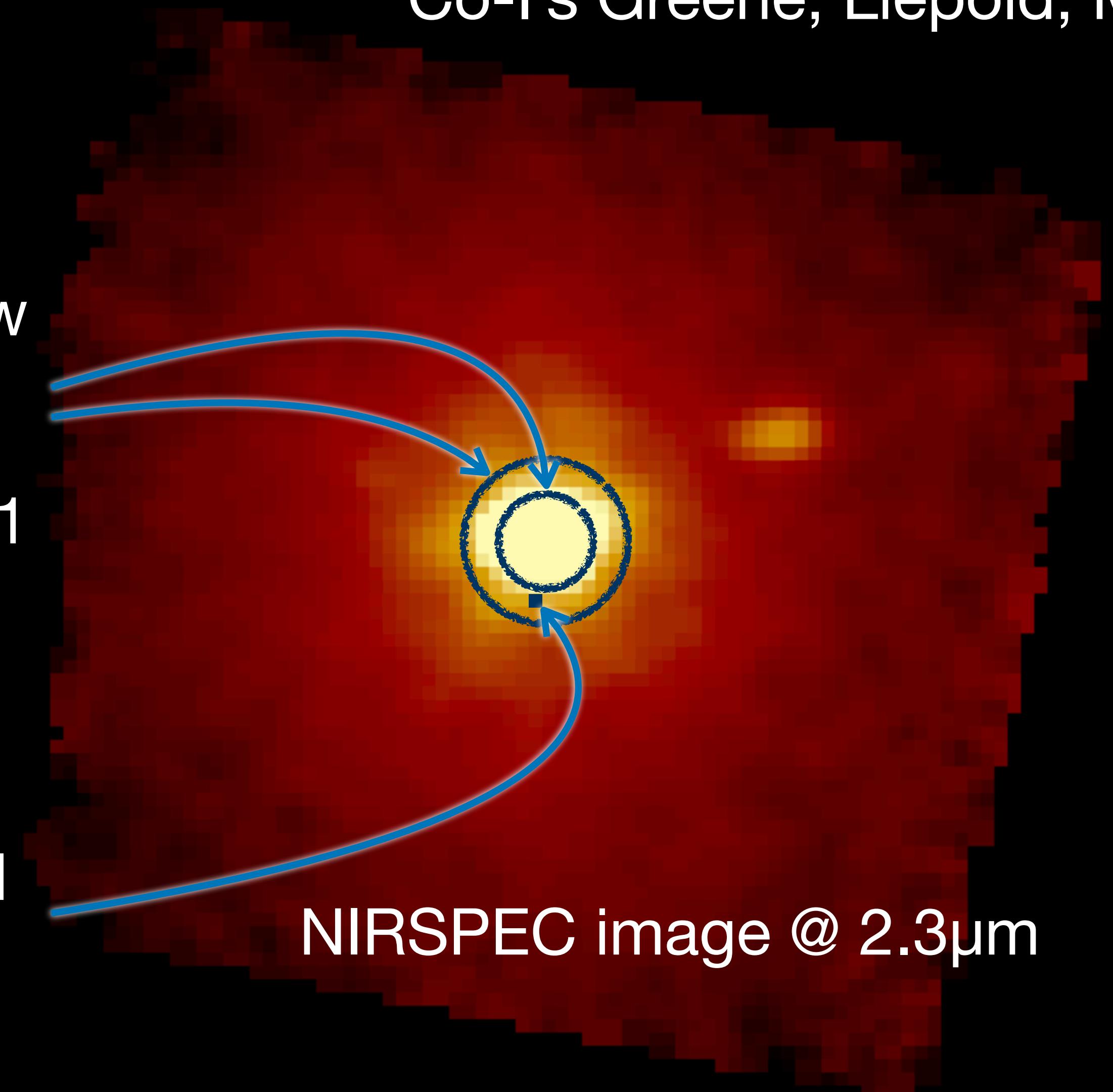
JWST observations (a sneak peak)

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



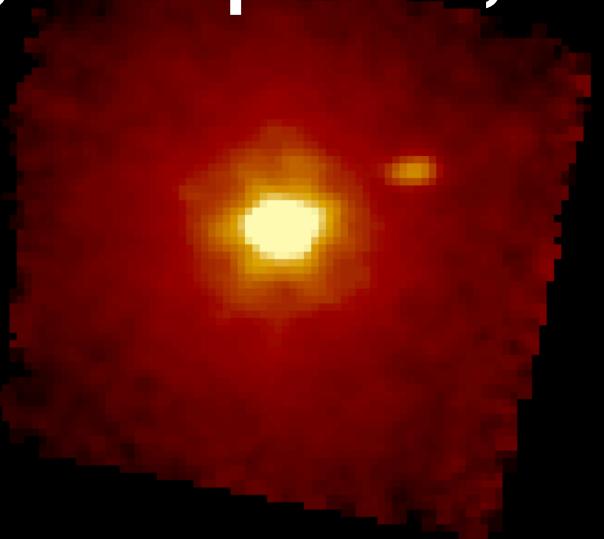
All pixels btw
0.185'' and
0.315'' in
Gebhardt+11
(17-29 pc)

One 0.05'' x
0.05'' spaxel
with JWST
(4.5pc)



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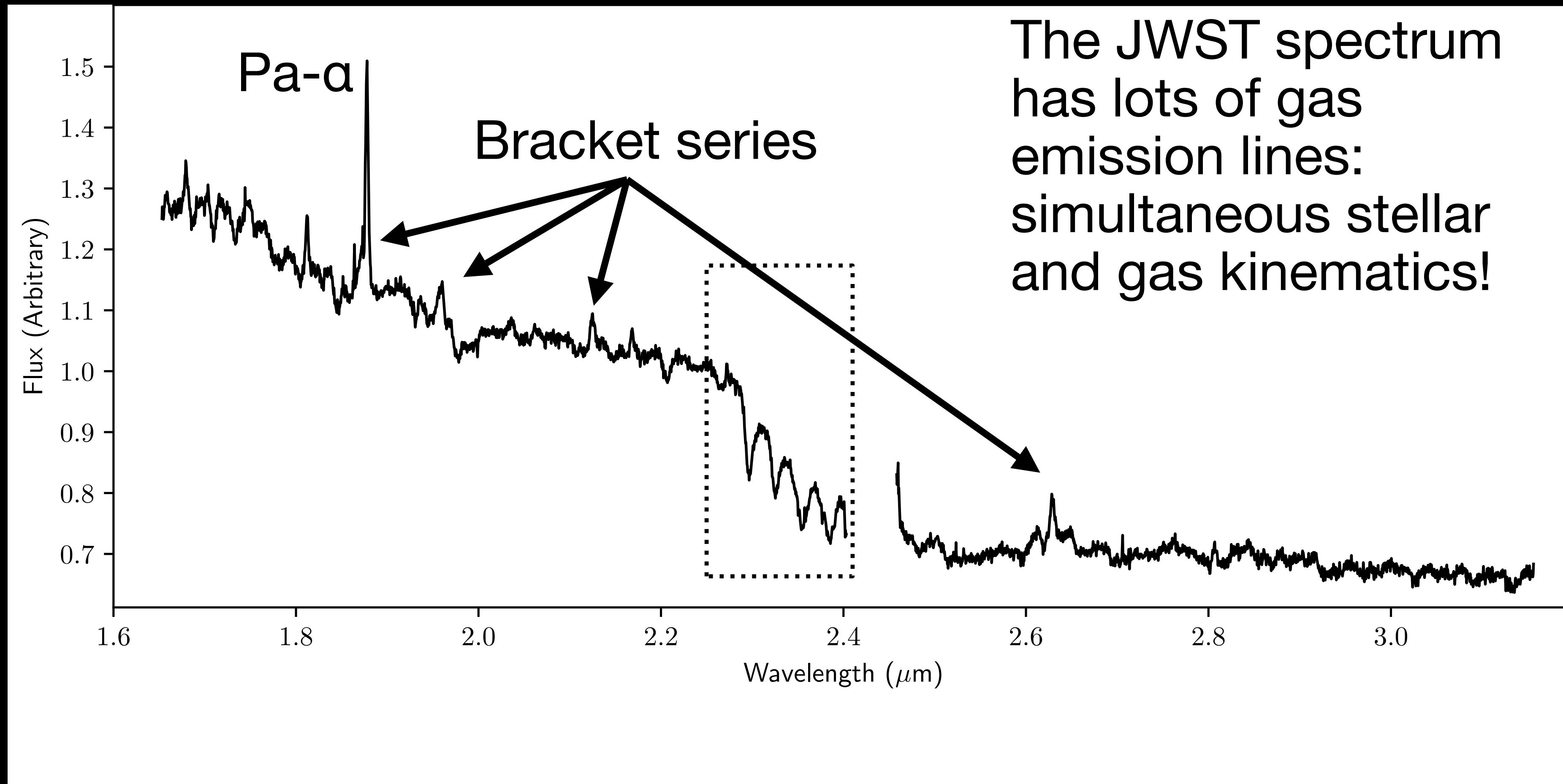
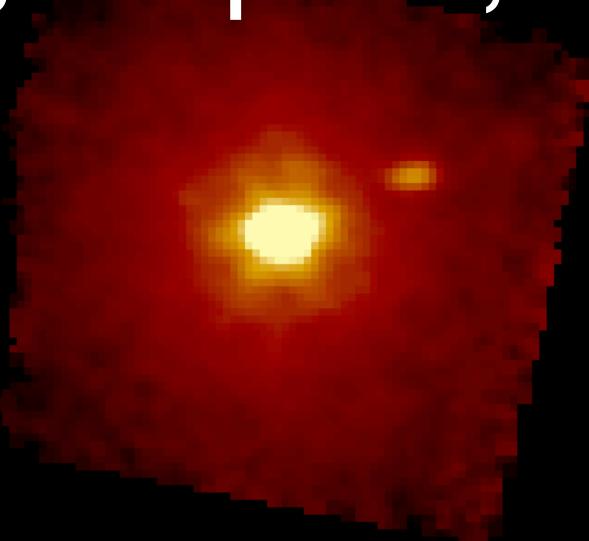


One $0.05'' \times 0.05''$ spaxel
with JWST

$(4.5pc)$

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



One $0.05'' \times 0.05''$ spaxel with JWST
(4.5pc)

JWST observations (a sneak peak)

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

