# Big Galaxies & Big Black Holes & Nanohertz Gravitational Waves & Even Bigger Black Holes

**The high-mass local galaxy stellar mass function and progress in stellar dynamical measurements of (ultramassive) black holes**


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

Emily Liepold, postdoc @ UC Berkeley Astronomy
emilyliepold@berkeley.edu (slides at emilyliepold.com/today)

**refining** the **high-mass** local galaxy stellar mass function

**finding** and **measuring** supermassive black holes using stellar dynamics

**refining** the **high-mass** local galaxy stellar mass function

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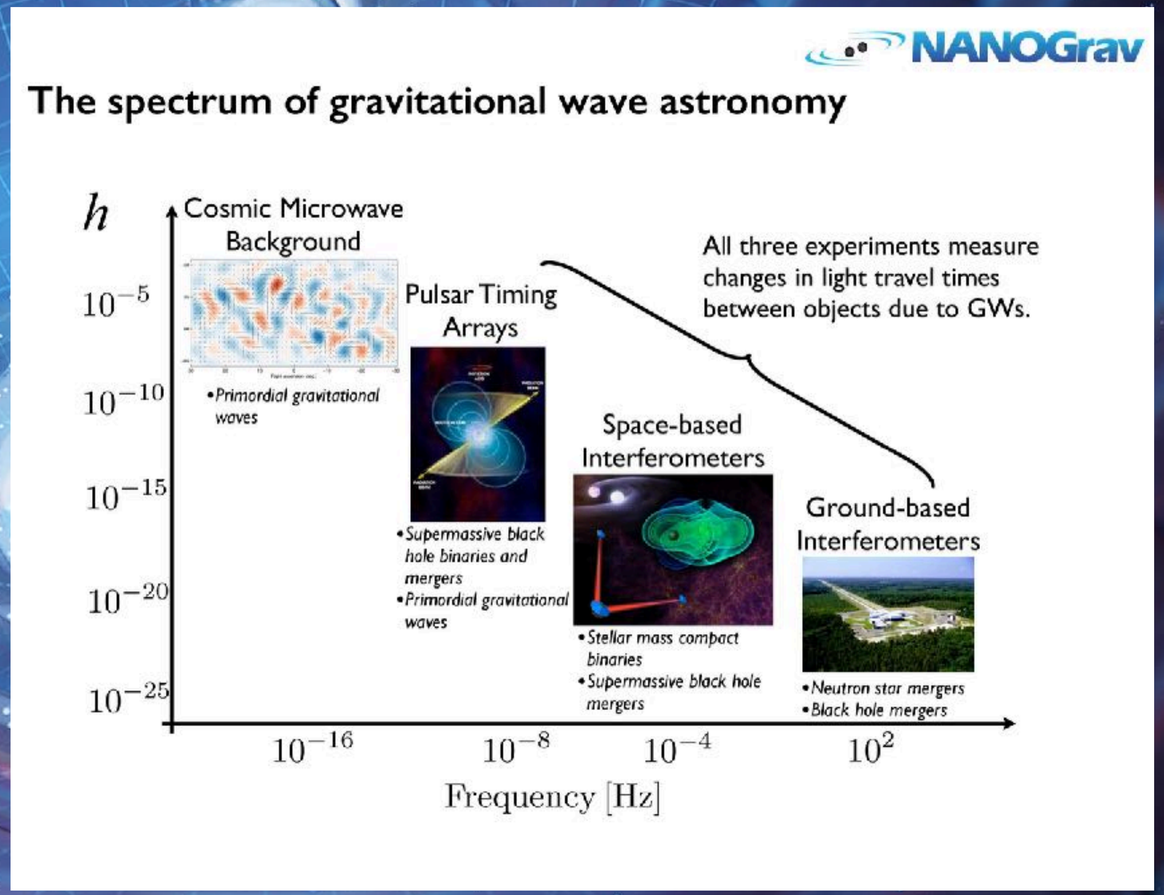
# A Puzzle: Is the local SMBH population consistent with measurements of the stochastic gravitational wave background?

- Pulsar Timing Arrays (PTAs) measure timing residuals from dozens of millisecond pulsars
- Earth-passing gravitational waves will induce correlations in these residuals
- PTA collaborations have found **evidence** for a stochastic nanohertz gravitational wave background
- The most plausible source for this background is supermassive black hole binary mergers




Olena Shmahalo for NANOGrav

# A Puzzle:

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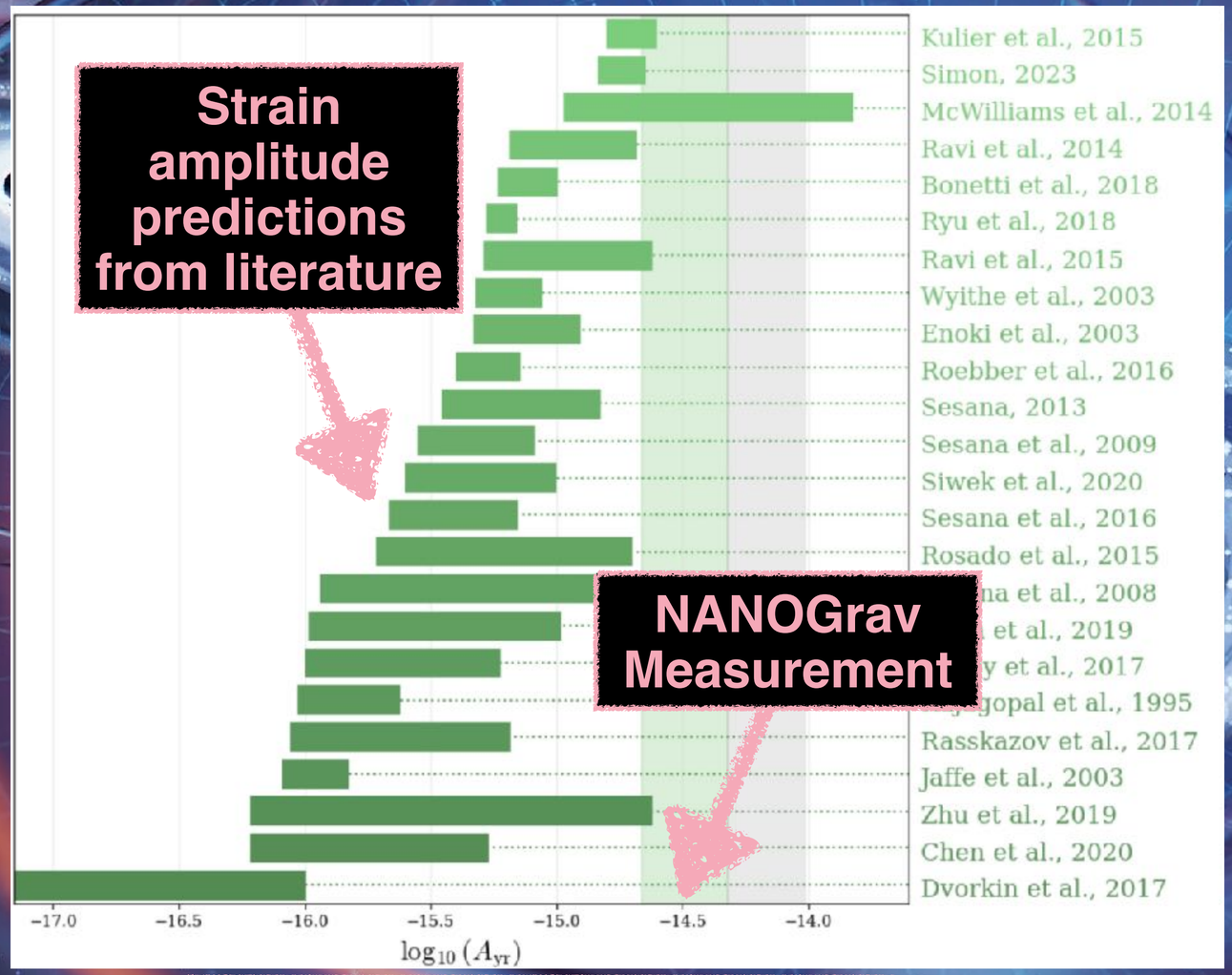



Agazie et al 2023, ApJL, 952:L37
arXiv:2306:16220

# A Puzzle:

## Is the local SMBH population consistent with measurements of the stochastic gravitational wave background?

### Where are NANOGrav's big black holes?

Gabriela Sato-Polito,[1,*] Matias Zaldarriaga,[1] and Eliot Quataert[2]

[1] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, United States*
[2] *Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA*

Multiple pulsar timing array (PTA) collaborations have recently reported the first detection of gravitational waves (GWs) of nanohertz frequencies. The signal is expected to be primarily sourced by inspiralling supermassive black hole binaries (SMBHBs) and these first results are broadly consistent with the expected GW spectrum from such a population. Curiously, the measured amplitude of the GW background in all announced results is a bit larger than theoretical predictions. In this work, we show that the amplitude of the stochastic gravitational wave background (SGWB) predicted from the present-day abundance of SMBHs derived from local scaling relations is significantly smaller than that measured by the PTAs. We demonstrate that this difference cannot be accounted for through changes in the merger history of SMBHs and that there is an upper limit to the boost to the characteristic strain from multiple merger events, due to the fact that they involve black holes of decreasing masses. If we require the current estimate of the black hole mass density — equal to the integrated quasar luminosity function through the classic Sołtan argument — to be preserved, then the currently measured PTA result would imply that the typical total mass of SMBHs contributing to the background should be at least $\sim 3\times10^{10}\,M_\odot$, a factor of $\sim 10$ larger than previously predicted. The required space density of such massive black holes corresponds to order 10 $3\times10^{10}\,M_\odot$ SMBHs within the volume accessible by stellar and gas dynamical SMBH measurements. By virtue of the GW signal being dominated by the massive end of the SMBH distribution, PTA measurements offer a unique window into such rare objects and complement existing electromagnetic observations.

Sato-Polito et al 2023
arXiv:2312.06756

# The MASSIVE Galaxy Survey

Ma+2014

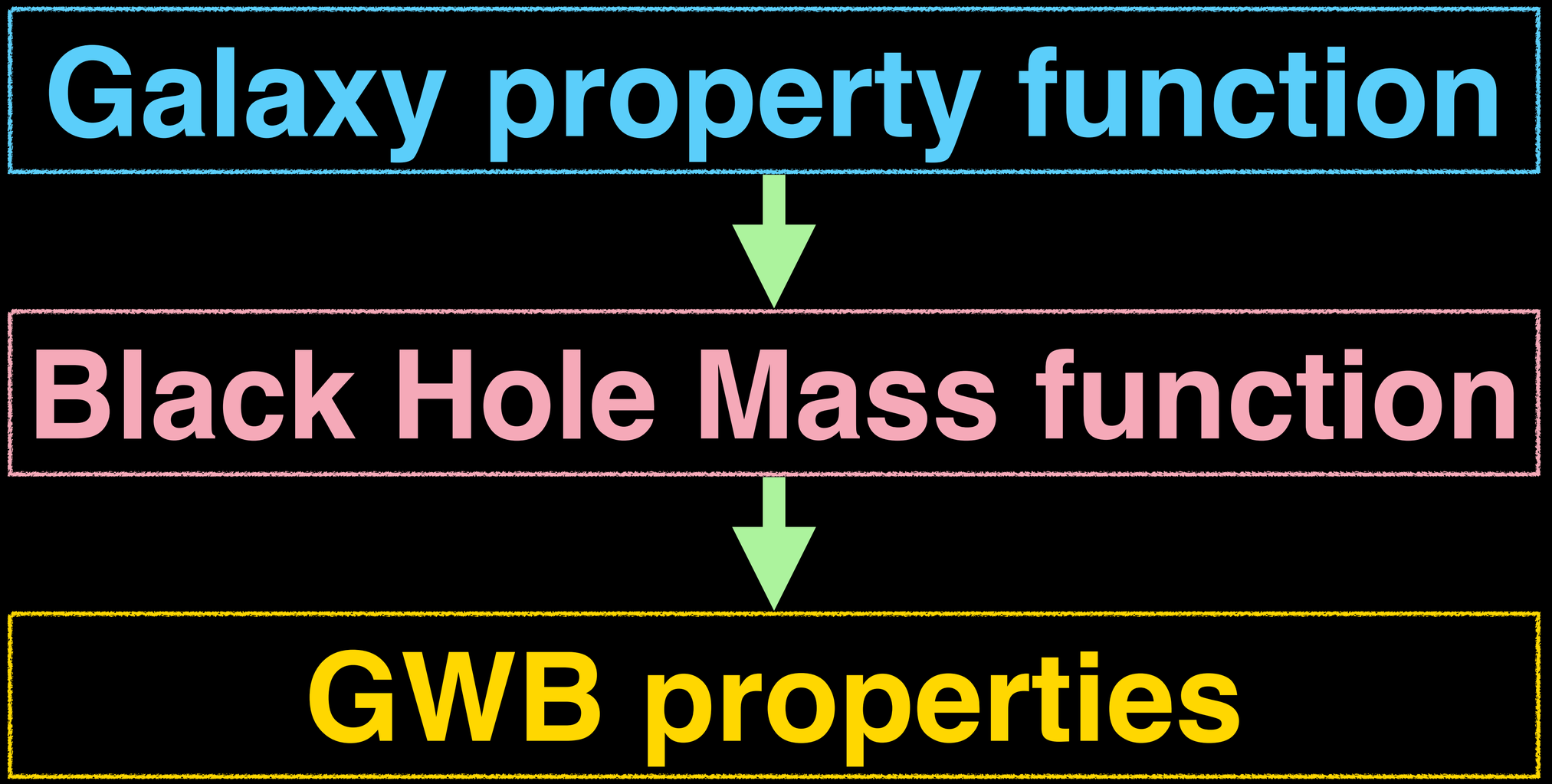
**MASSIVE** is a…

- 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**

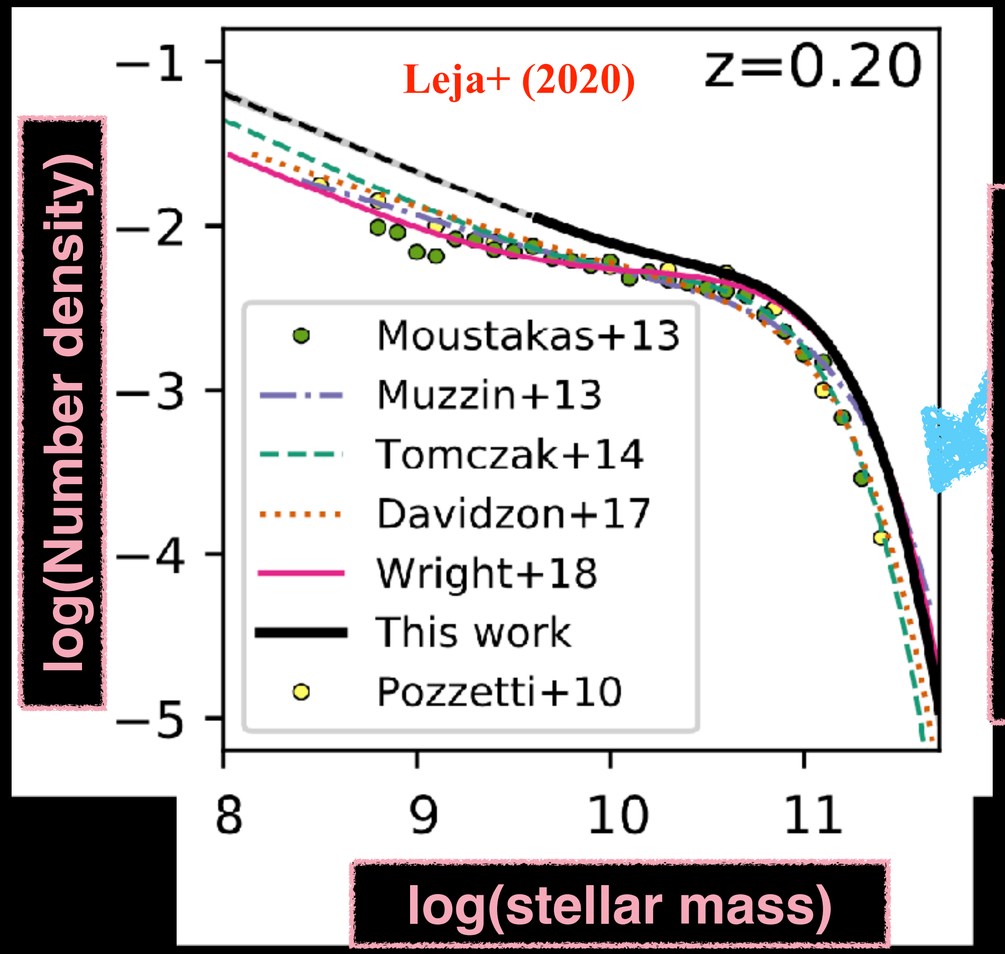
20 primary MASSIVE papers so far — **Stellar populations**, Stellar kinematics, Molecular and Ionized Gas kinematics, **HST + CFHT photometry**, **SMBH mass measurements**…

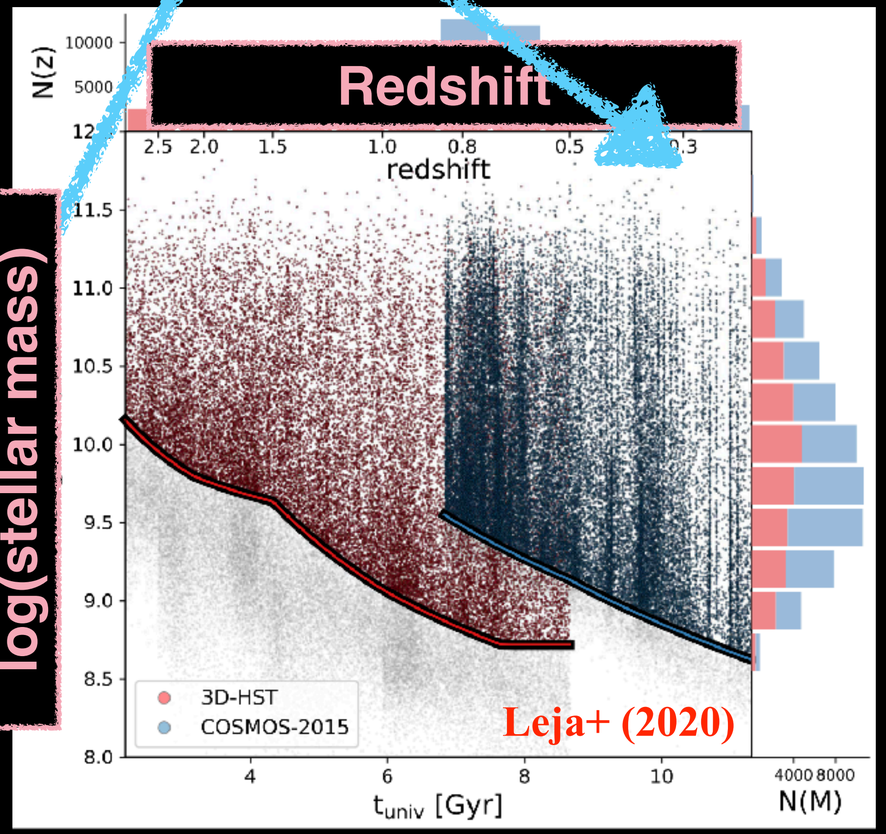
(And lots of people! Chung-Pei Ma, Jenny Greene, Jonelle Walsh, Nicholas McConnell, Jens Thomas, Melanie Veale, Irina Ene, Viraj Pandya, Charles Goullaud, Matthew Quenneville, Emily Liepold, Jacob Pilawa, Silvana Andrade Delgado and others)


Galaxy property function
Black Hole Mass function
GWB properties

# A Related Puzzle: Where are the high-mass local galaxies?

Few z~0 galaxies at $M^* > 10^{11.3}\ M_{sun}$




Leja et al 2020, ApJ, 893, 111

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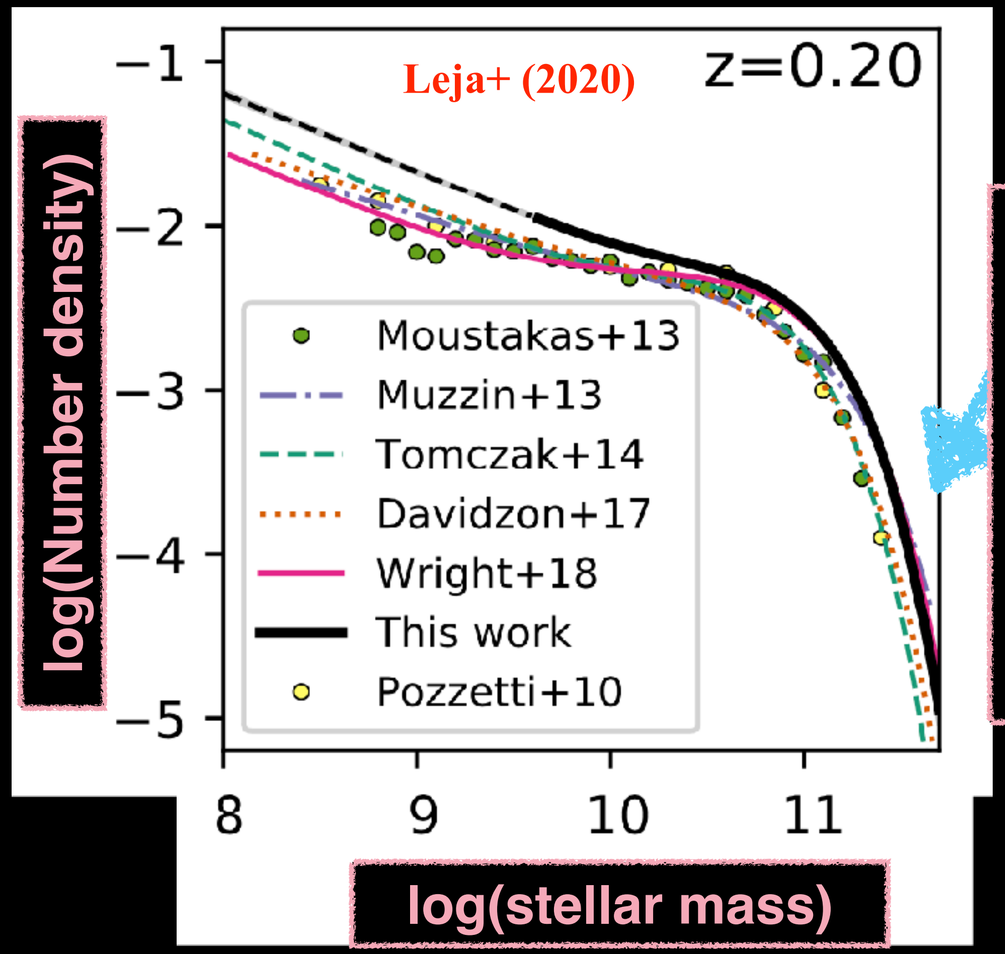


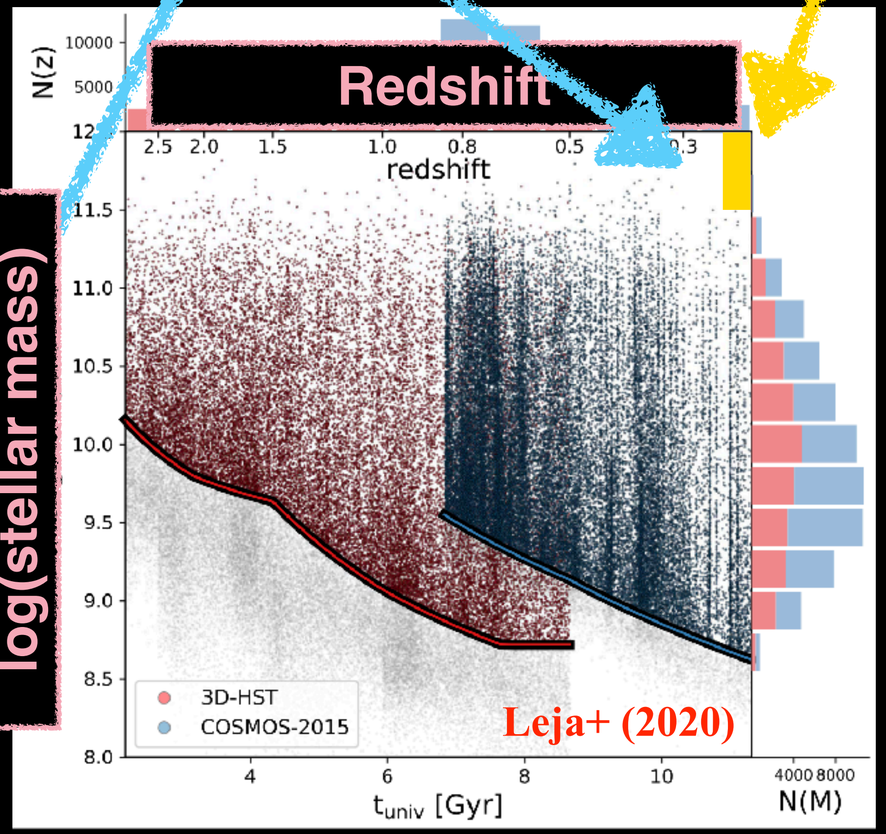


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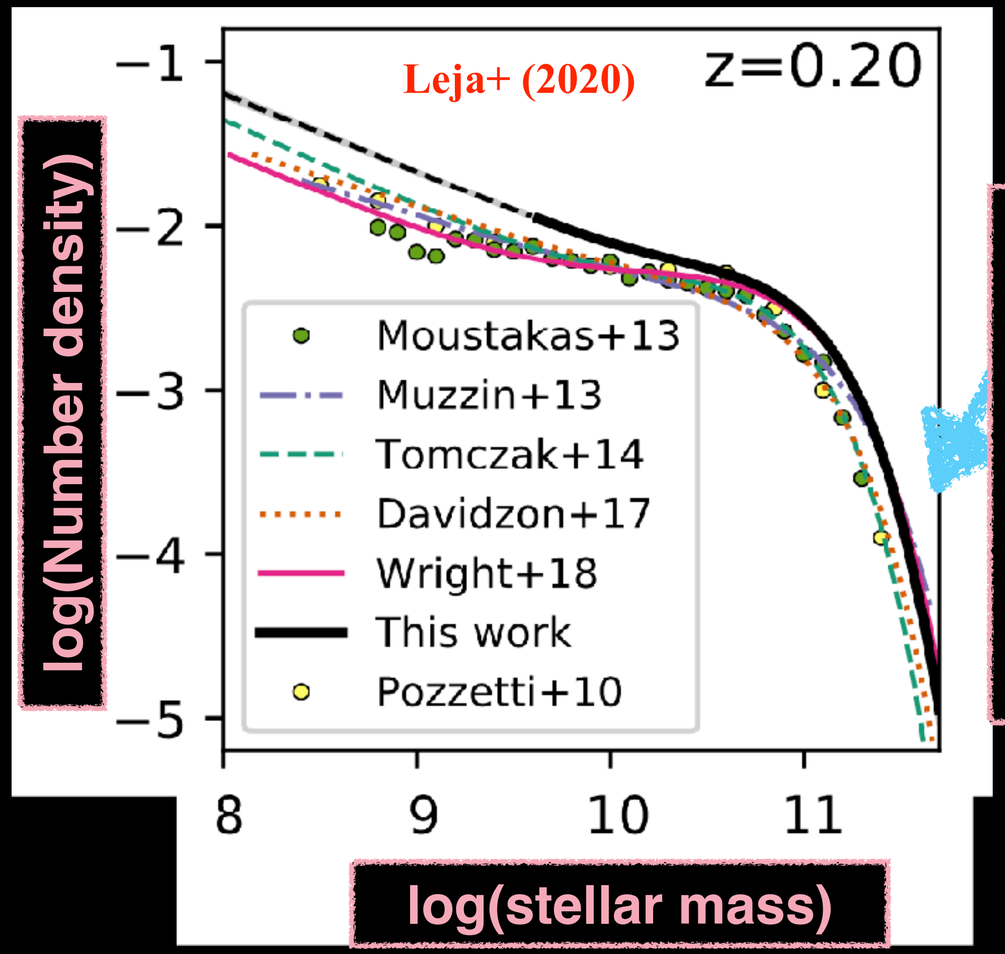
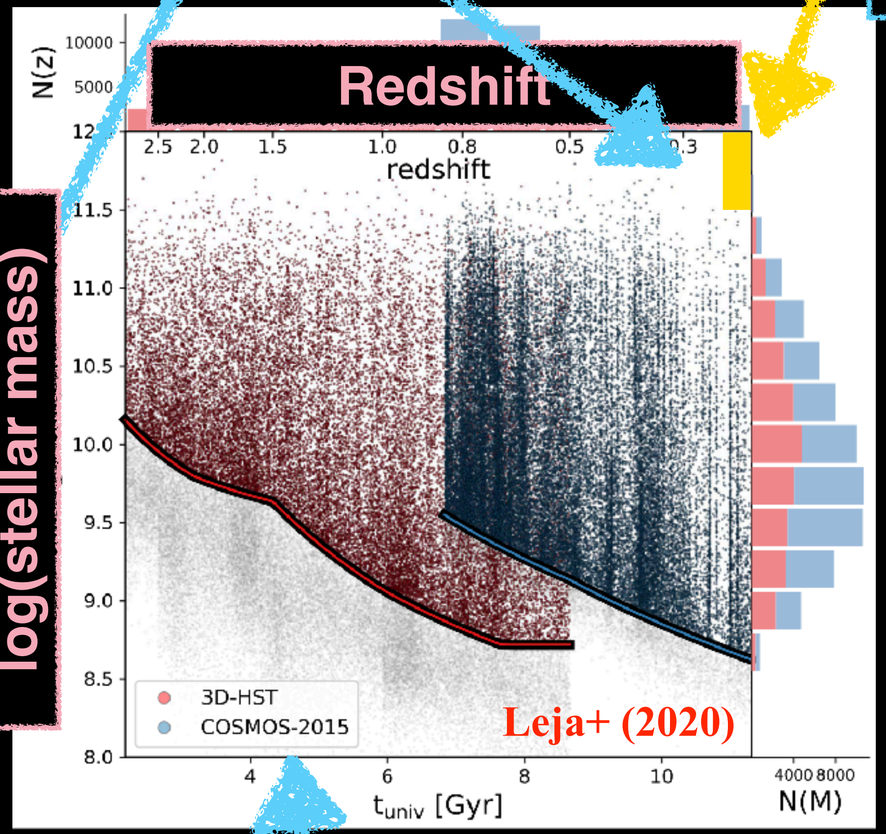
MASSIVE

~17,280 deg²




~0.25 deg²

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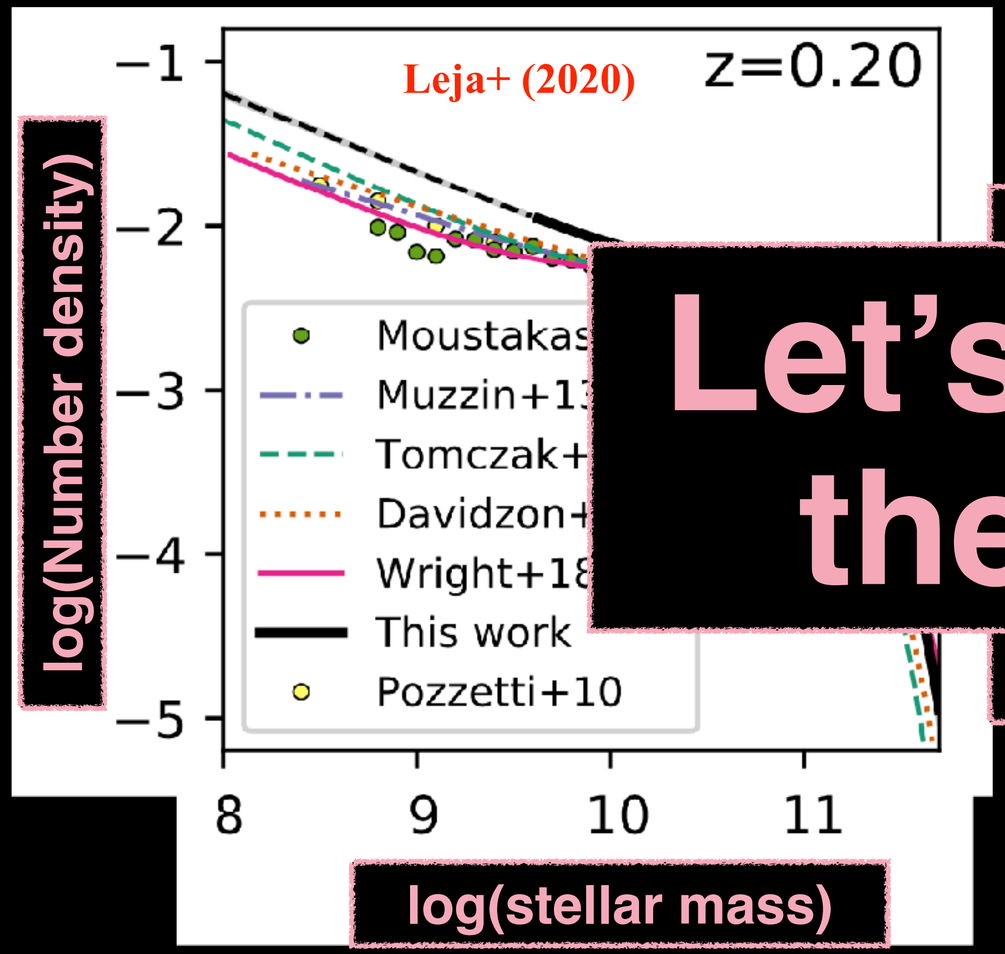
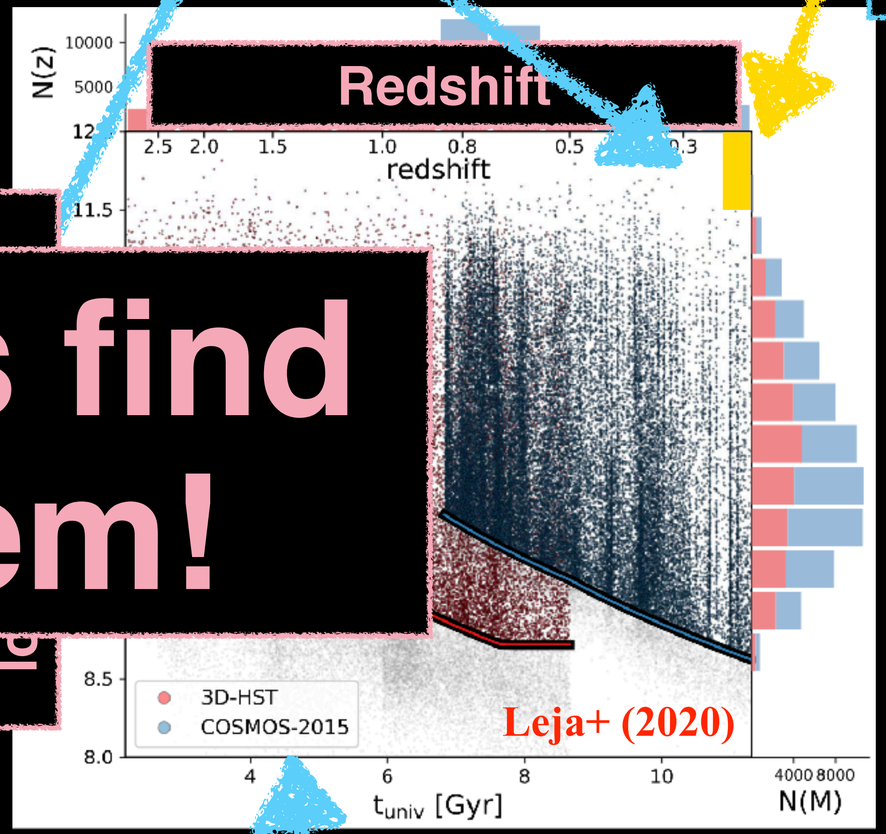



Let's find them!

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Leja et al 2020, ApJ, 893, 111

# Two ways to measure galaxy stellar masses

## Stellar Populations

1. Use spectra to infer stellar population
2. Infer M/L from stellar population

## Dynamical Measurements

1. Use spectra to infer stellar kinematics
2. Use kinematics to infer mass distribution

(second half of this talk!)

# But this is *expensive....*

**Our strategy:**

1. **Use direct measurements when available**
2. **Correlate $M_{\rm K}$ and $M_*$**
3. **Use high-precision $M_{\rm K}$ to infer $M_*$ for remaining targets**

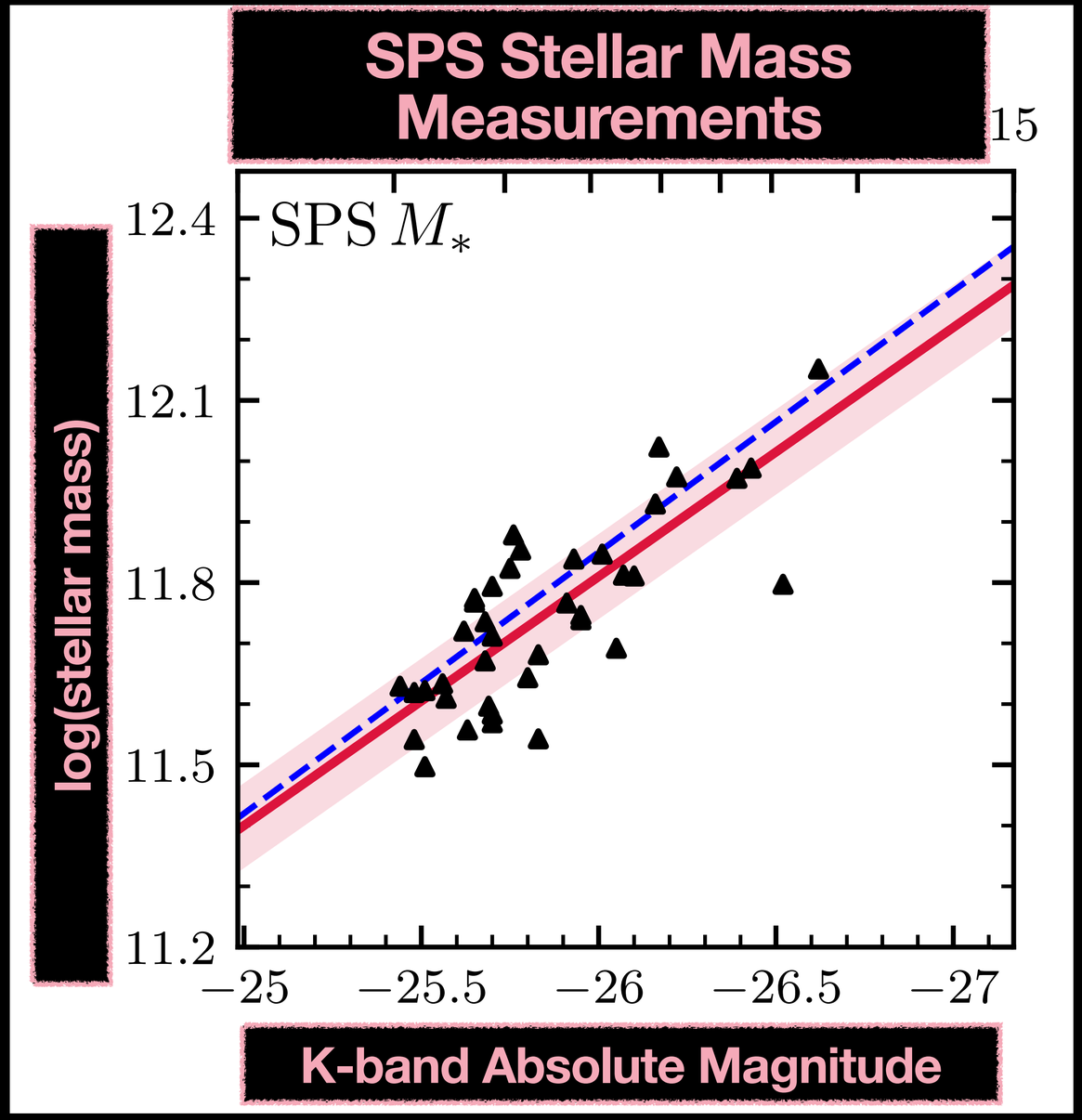
# Two ways to measure galaxy stellar masses

Liepold+Ma 2024
ApJL 971 L29

## Stellar Populations

Gu+22: **Stellar population synthesis** models of 41 MASSIVE galaxies

- Requires high-resolution, high-S/N slit spectroscopy
- These SPS models fit for the IMF, finding steeper-than-Kroupa IMF with $\langle \alpha \rangle = 1.8$
- (Among other things) These models measure stellar M/L for each galaxy
- Combine with Luminosities from Quenneville+24 to infer stellar mass





Gu et al 2022, ApJ, 932, 103
Quenneville et al 2024, MNRAS, 527, 249

# Two ways to measure galaxy stellar masses

Liepold+Ma 2024
ApJL 971 L29

## Dynamical Measurements

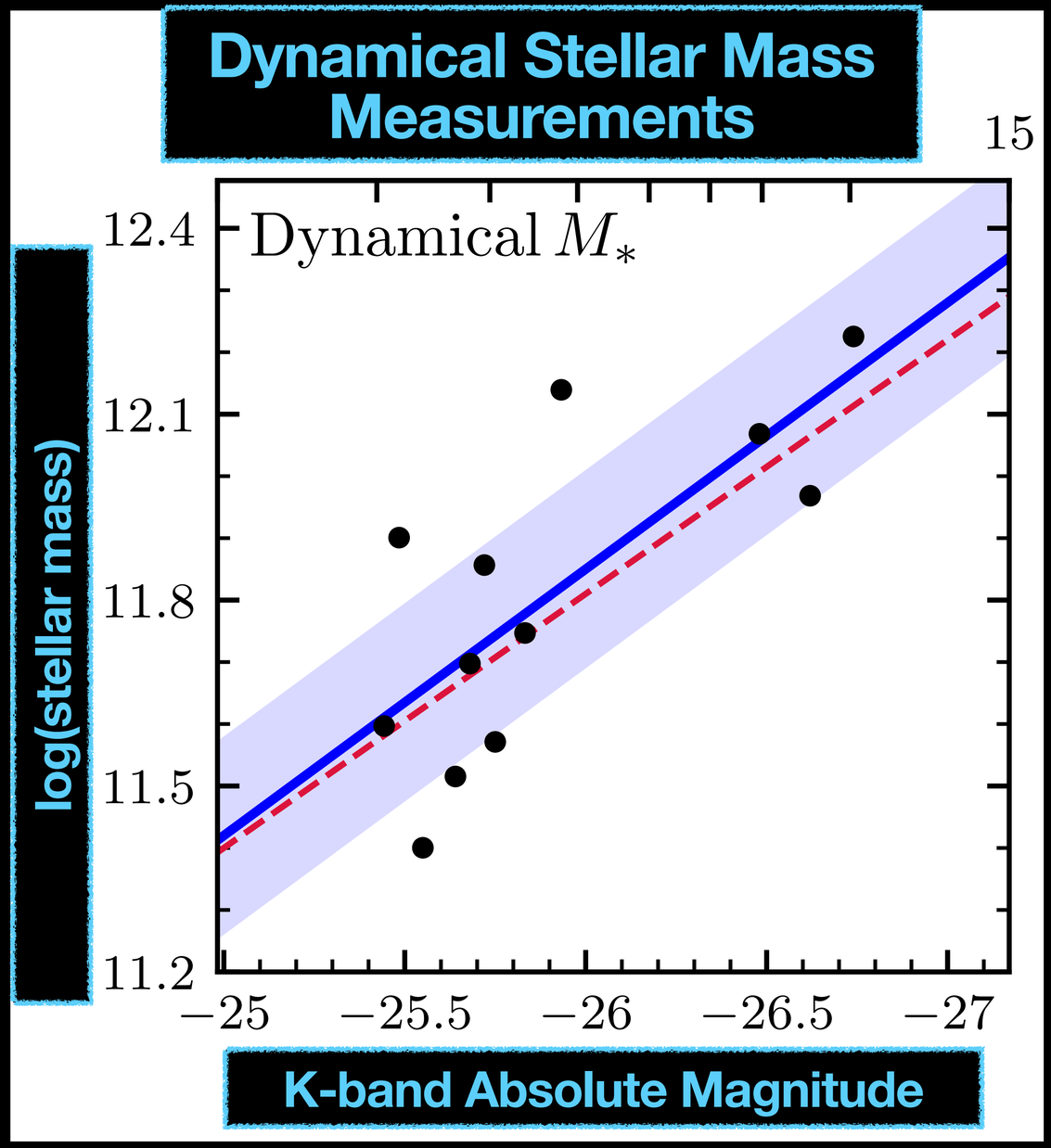
**Dynamical** measurements of the stellar mass now exist for 12 MASSIVE galaxies

**11** from orbit-based stellar dynamics

**1** from gas-dynamical methods

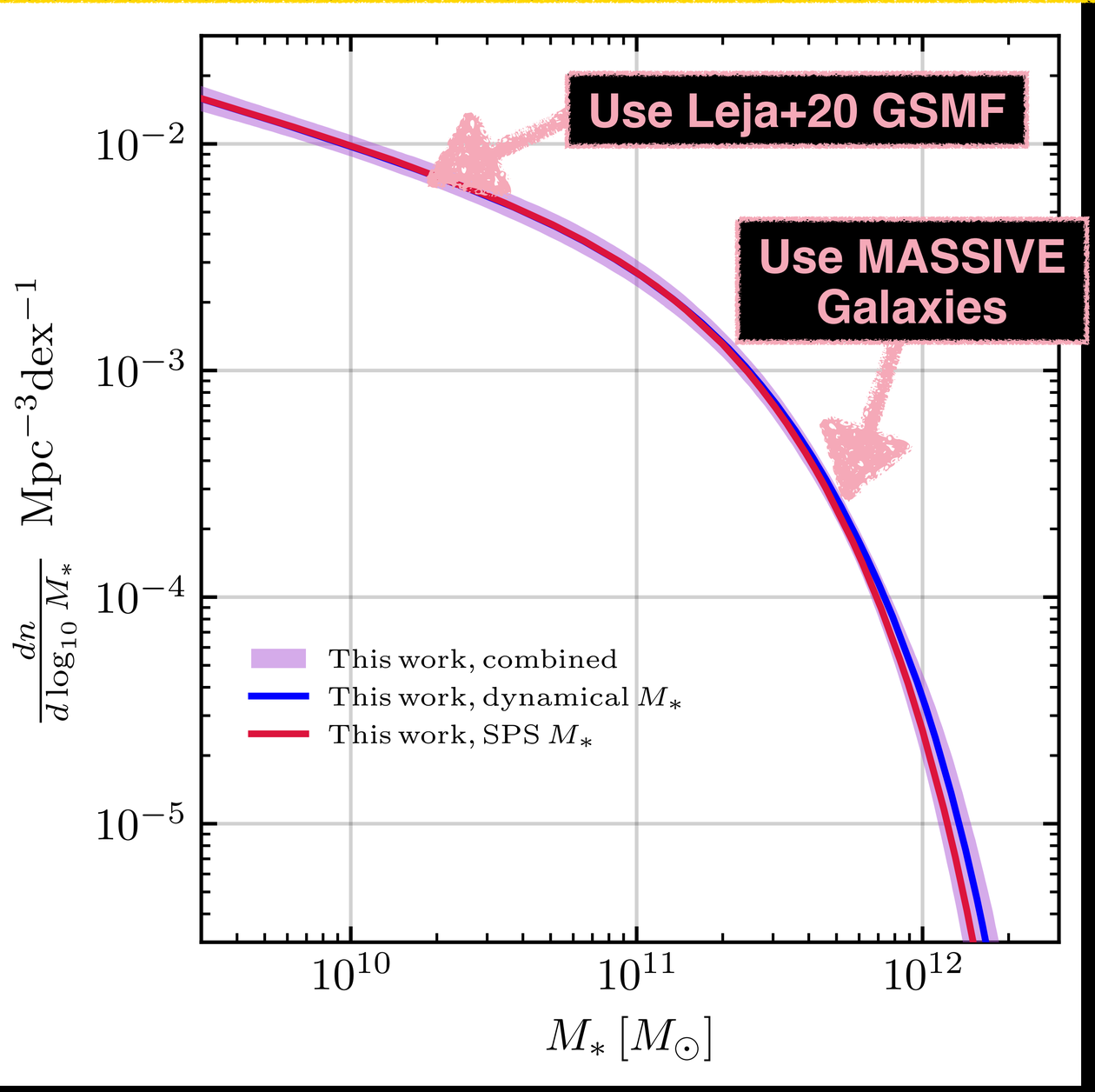
The inferred stellar masses from **SPS** and **dynamical** models are **consistent (~7% offset)!**

(excluding Jeans-modeling based measurements)



# The high-mass end of the local GSMF

Liepold+Ma 2024
ApJL 971 L29




- Use direct measurements of $M_*$ when available
- Use measured $M_K$ and new $M_K$-$M_*$ relations to infer $M_*$ for remaining MASSIVE galaxies
- Use GSMF from Leja+20 below $10^{11} M_\odot$ and MASSIVE above $10^{11.5} M_\odot$
- Our GSMF from Dynamical and SPS-based masses are consistent!

Leja et al 2020, ApJ, 893, 111

# The high-mass end of the local GSMF

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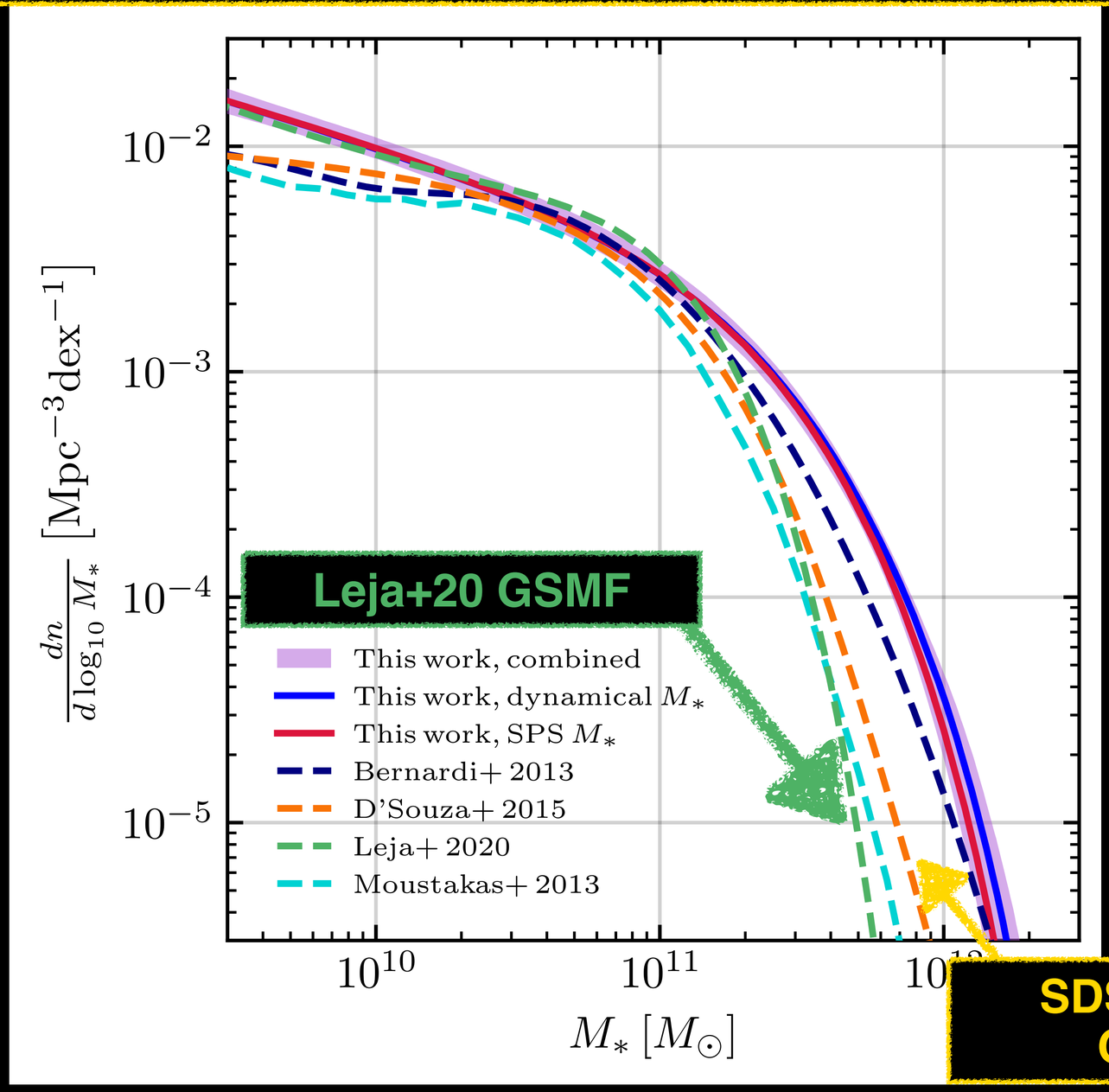
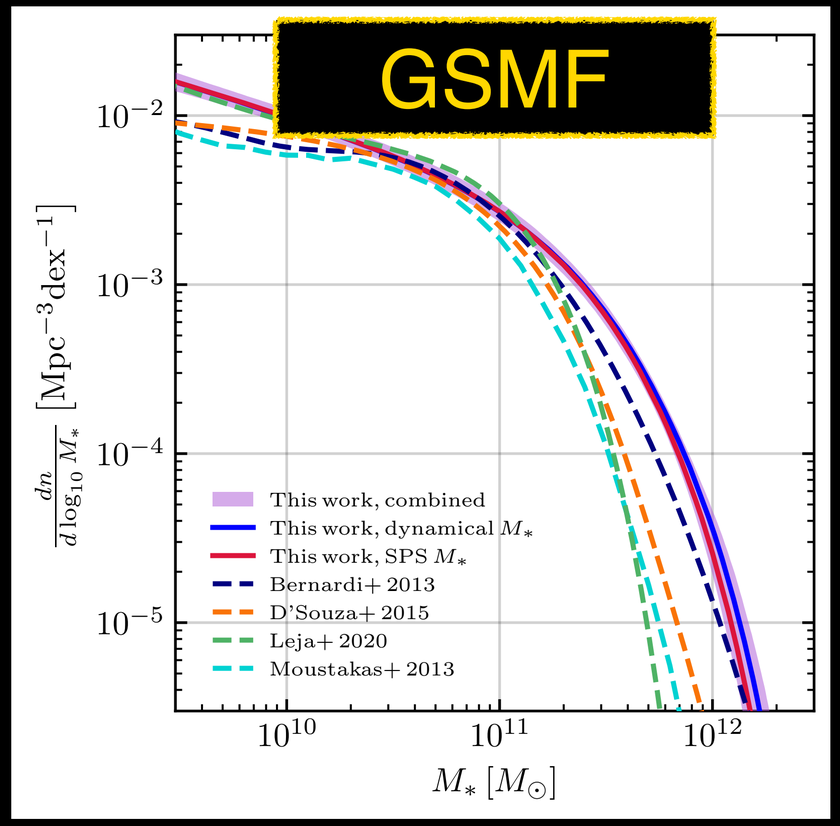


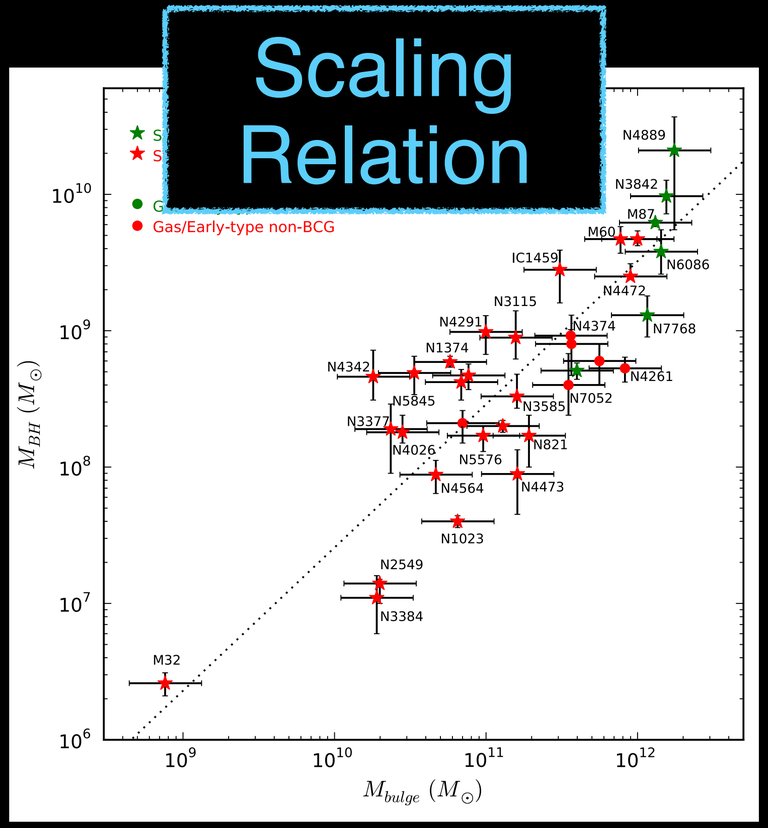

- Our stellar masses at the high-mass end are ~1.6x higher than SDSS-based GSMF measurements (shift their curves ***right***)
- Most prior work assumed Milky-Way-like IMF. Our bottom-heavy SPS-based masses fit for IMF are ~1.8x more massive.
- Prior work found minimal GSMF evolution since z = 1. Our high-mass z = 0 GSMF suggests substantial mass growth since z = 1

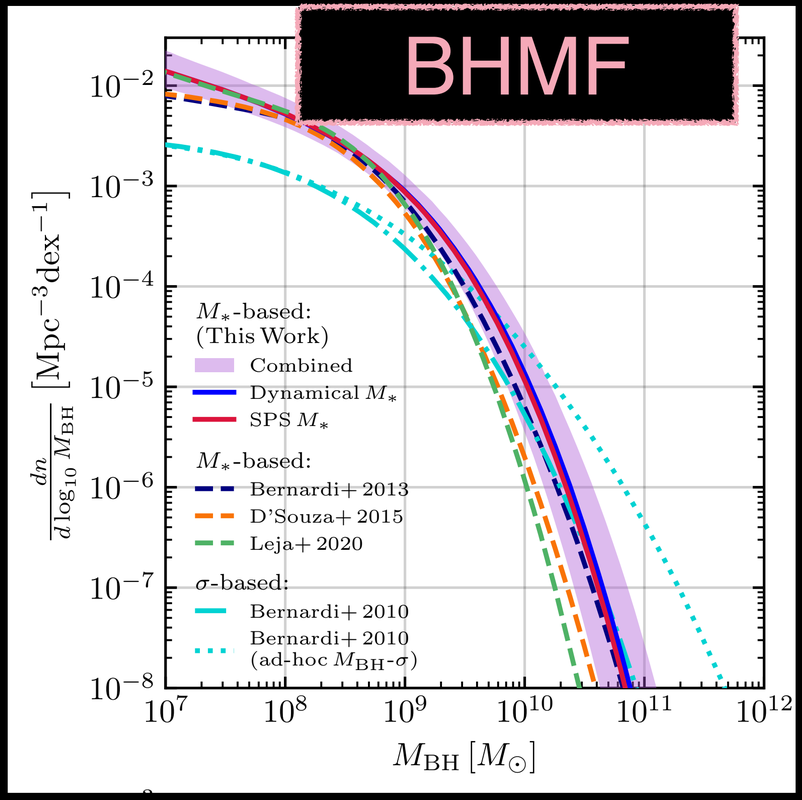
# The local Black Hole Mass Function

Liepold+Ma 2024
ApJL 971 L29

Black hole mass function is convolution of GSMF and (BH Mass)—(Stellar Mass) scaling relation



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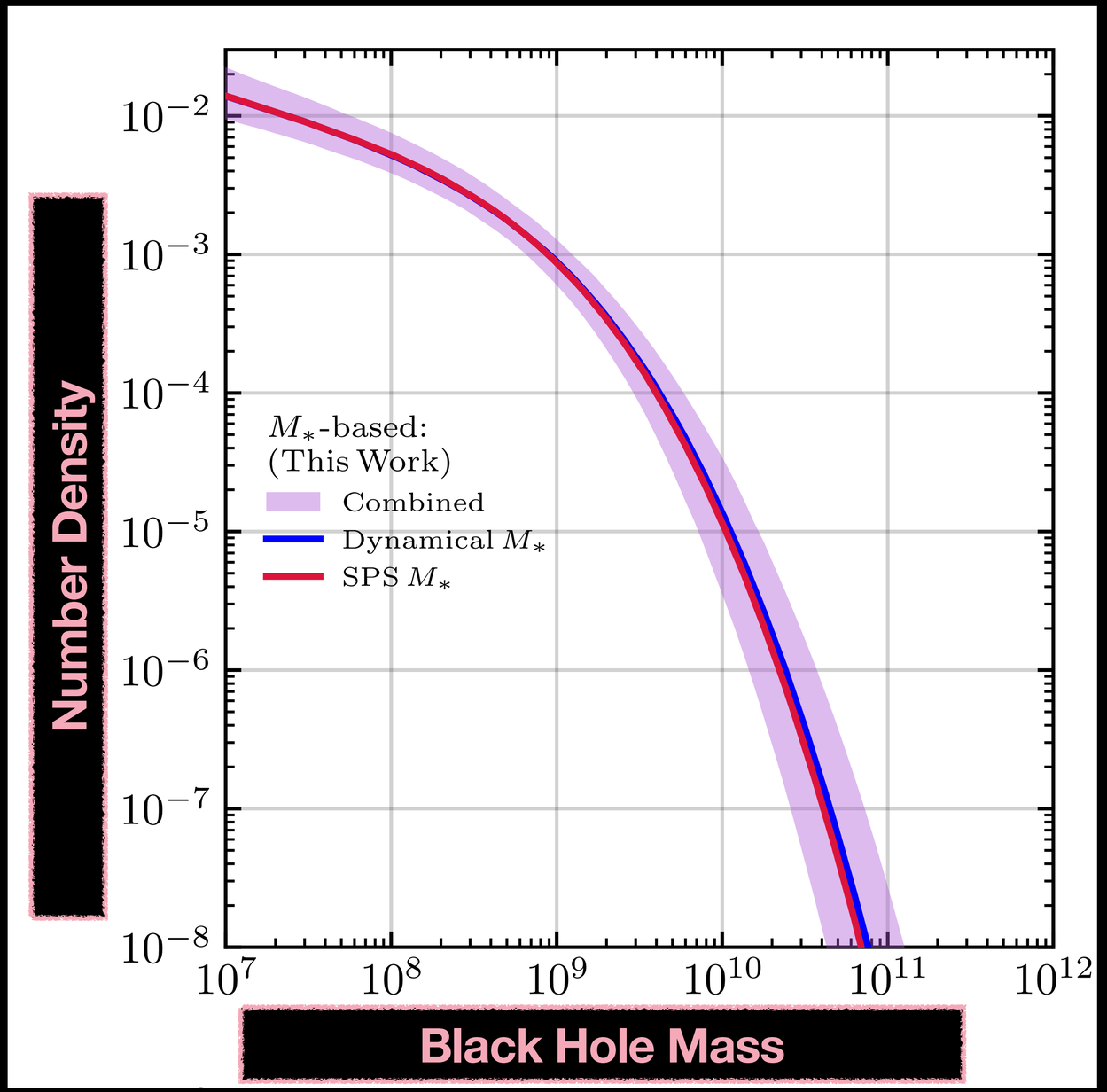


- Scatter in BHMF mostly due to scatter in scaling relation
- Consistent BHMF from SPS and dynamical $M_*$

# The local Black Hole Mass Function

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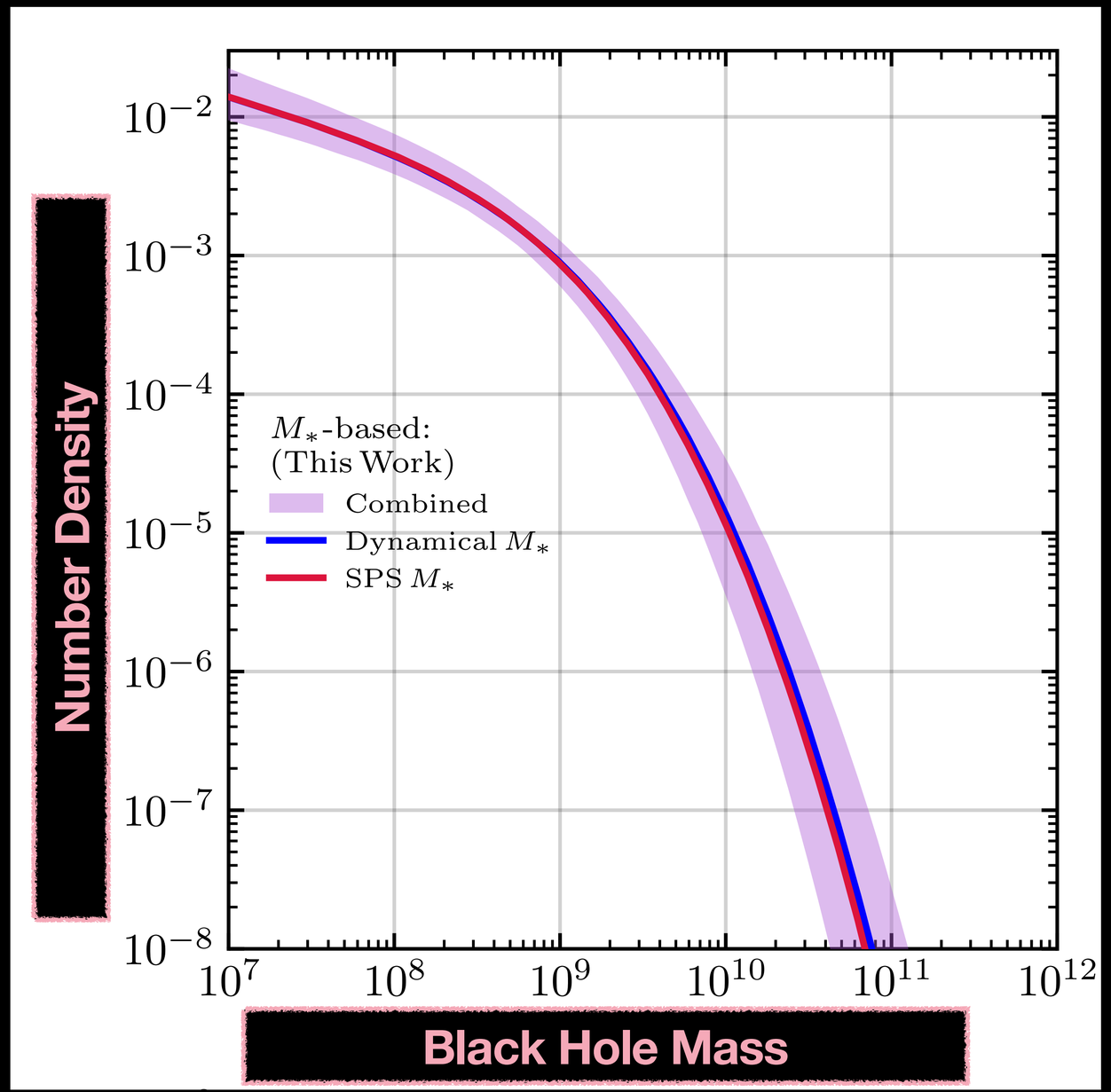


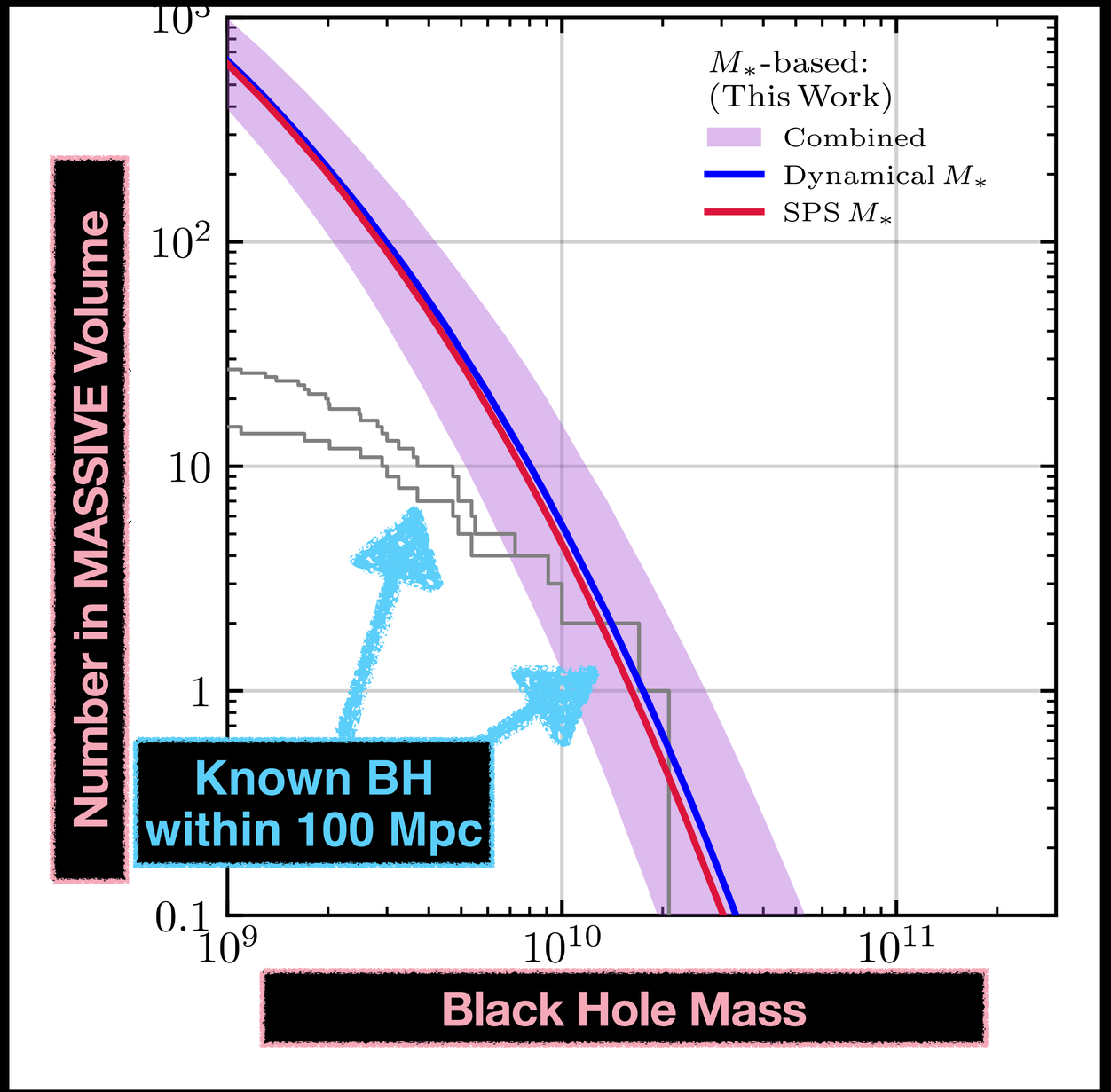

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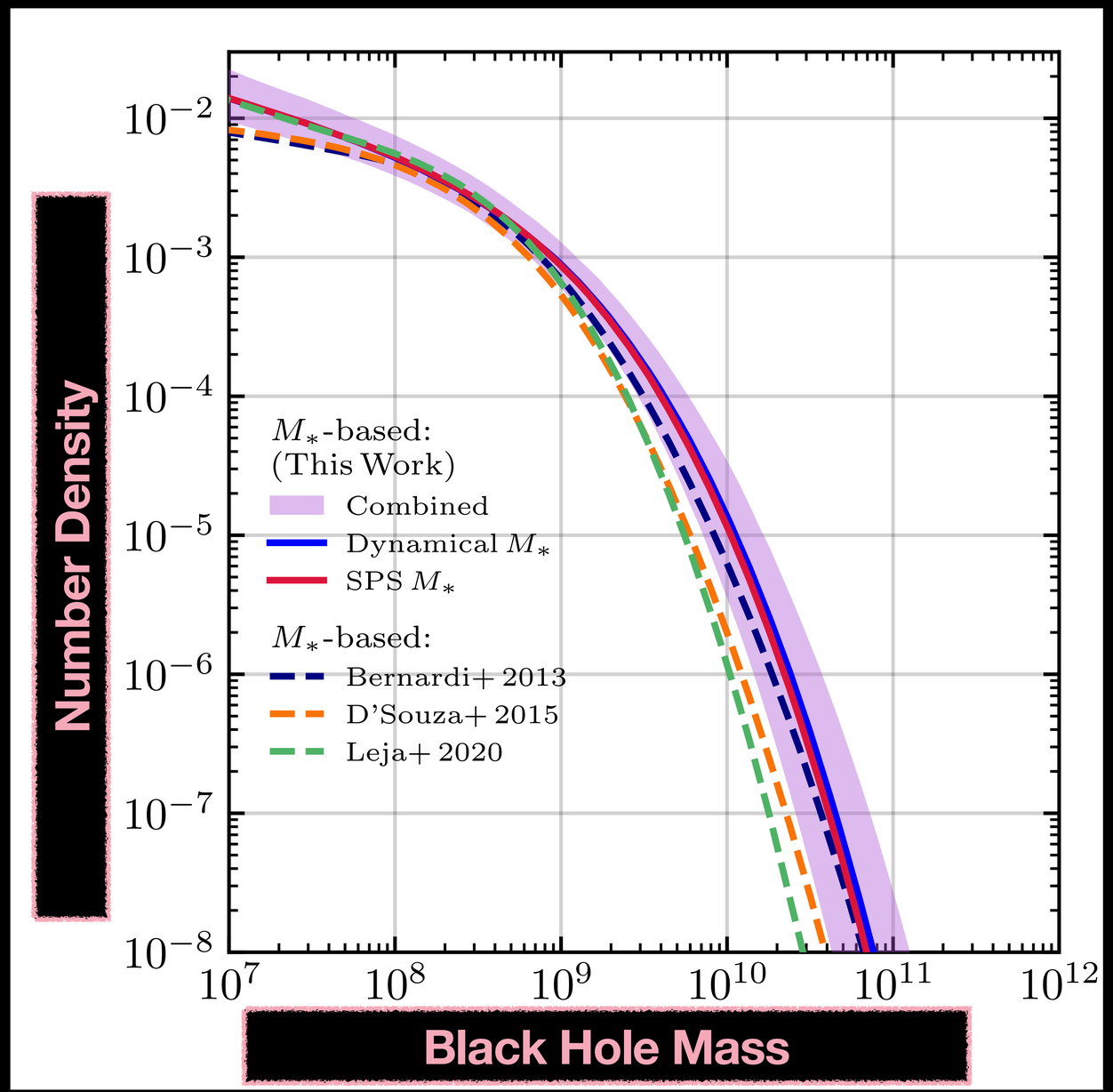


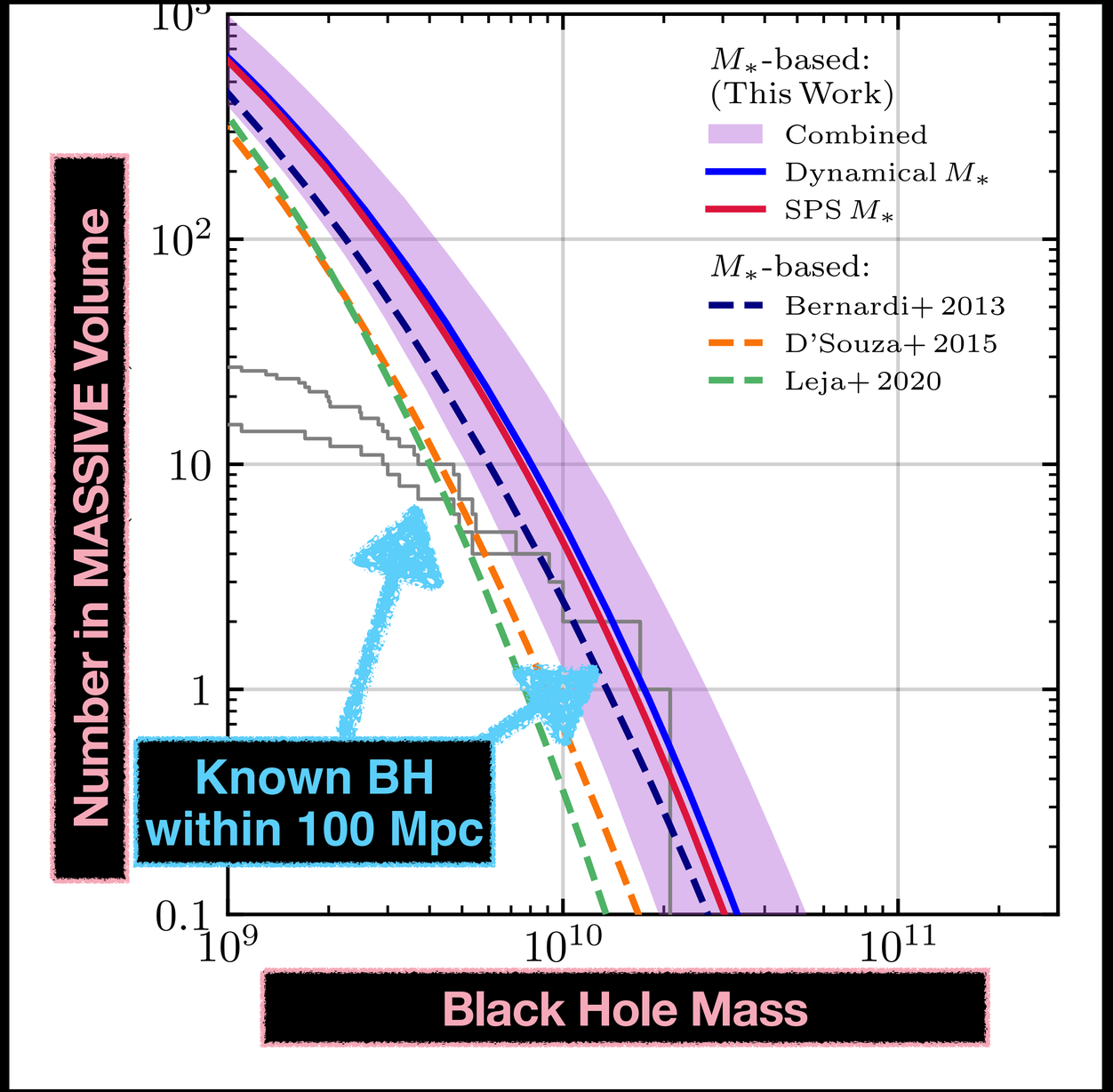

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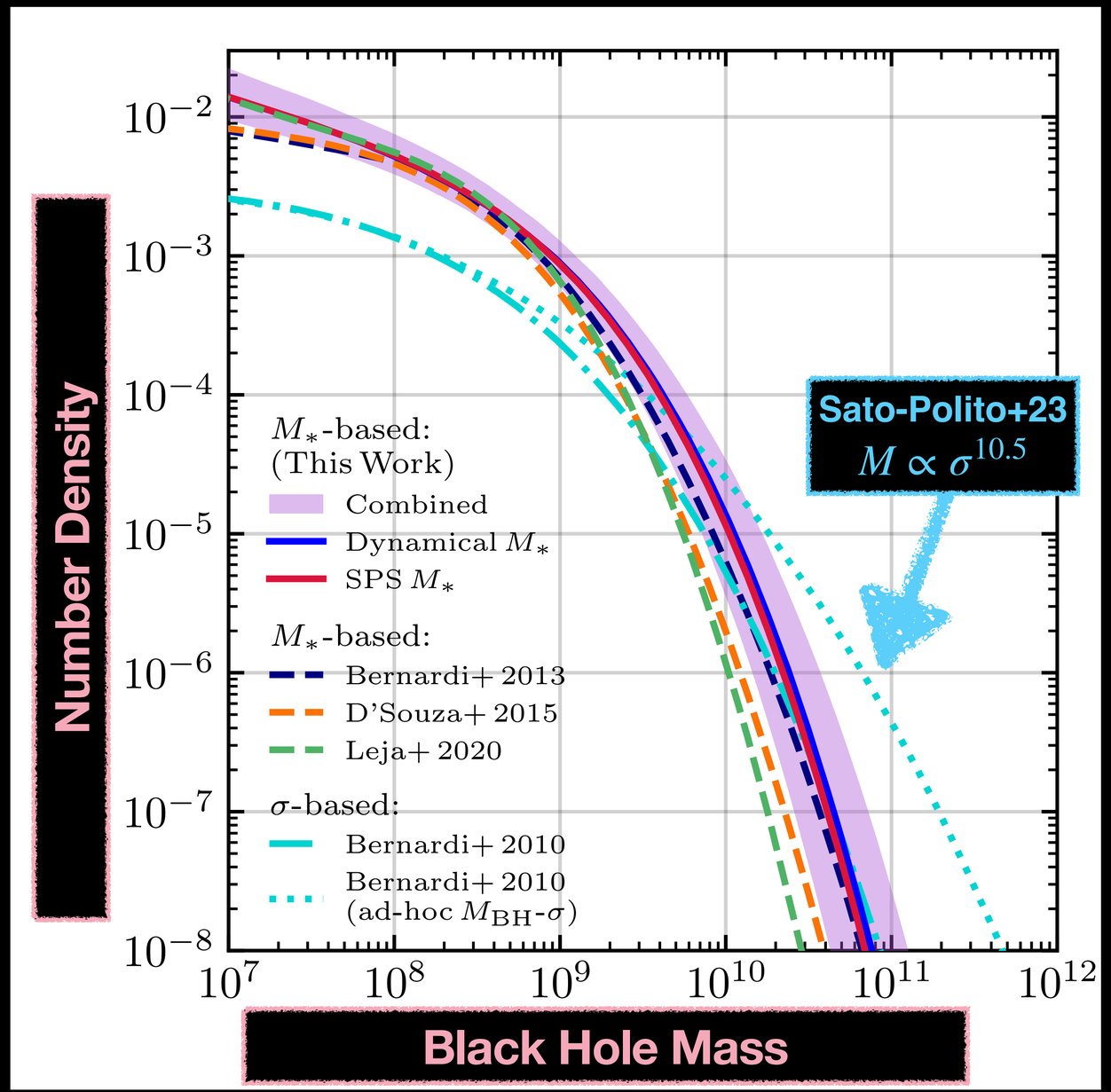


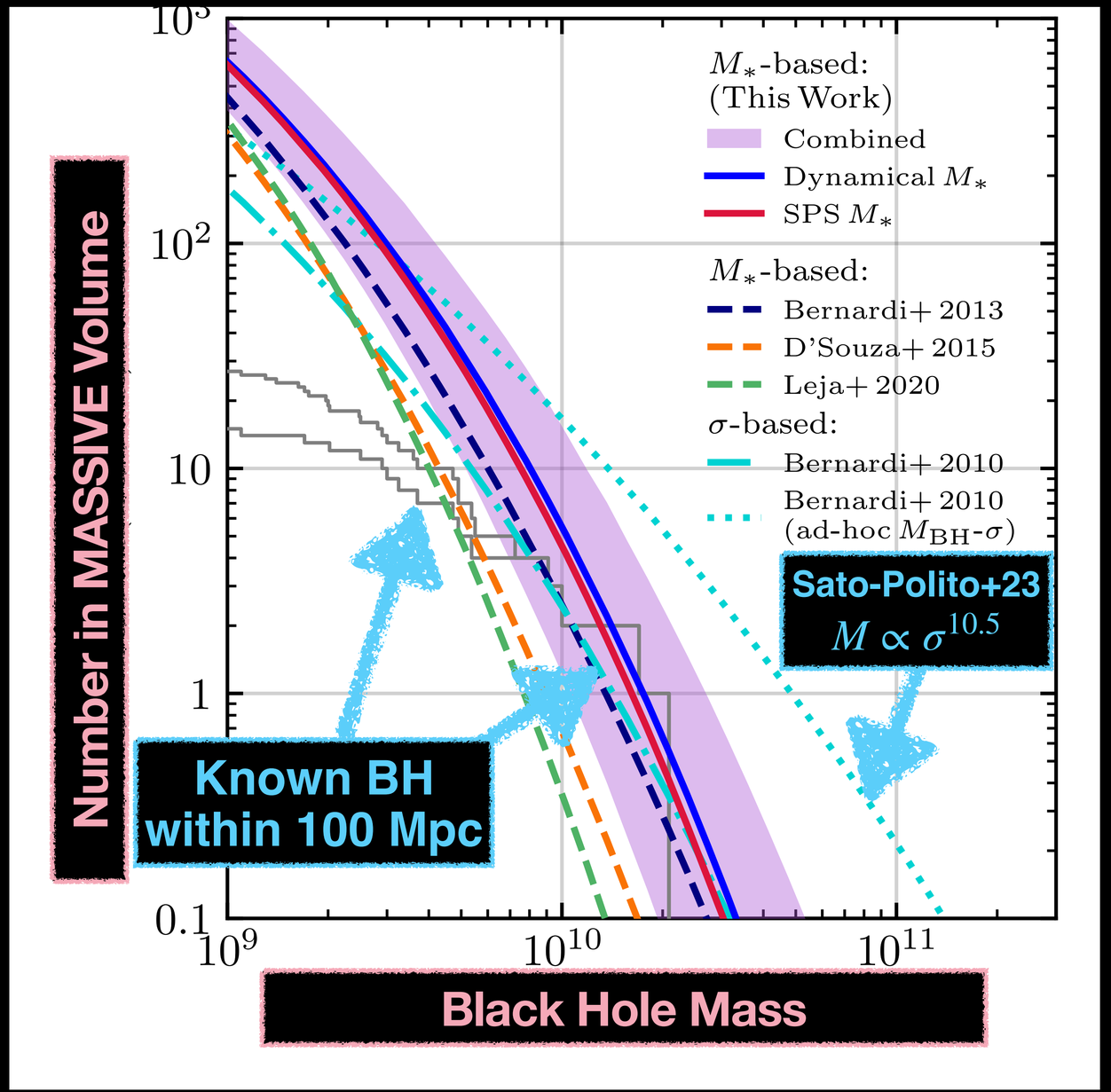

# Implications for the Cosmic GW Background

Liepold+Ma 2024
ApJL 971 L29

- Link characteristic strain to properties of a population of SMBH mergers
- Link population of mergers to BHMF

$$h_c^2(f) = \frac{4\pi}{3c^2}\frac{1}{(\pi f)^{4/3}} \times \int dM\, dq\, dz \frac{d^3n}{dM\, dq\, dz}\frac{q(GM)^{5/3}}{(1+q)^2}\frac{1}{(1+z)^{1/3}}.$$

Frequency

Total Binary Mass

Characteristic strain amplitude

Number density per total mass per mass ratio per redshift

Mass ratio

Redshift

Phinney 2001, arXiv:0108028

Sato-Polito+23, arXiv:2312:06756

Eqn 4 in Liepold+Ma 2024

# Implications for the Cosmic GW Background

Liepold+Ma 2024
ApJL 971 L29

$\partial h_c^2 / \partial \log M_{\rm BH}$

Characteristic Strain $h_c$

**Consistent value w/ PTAs!**

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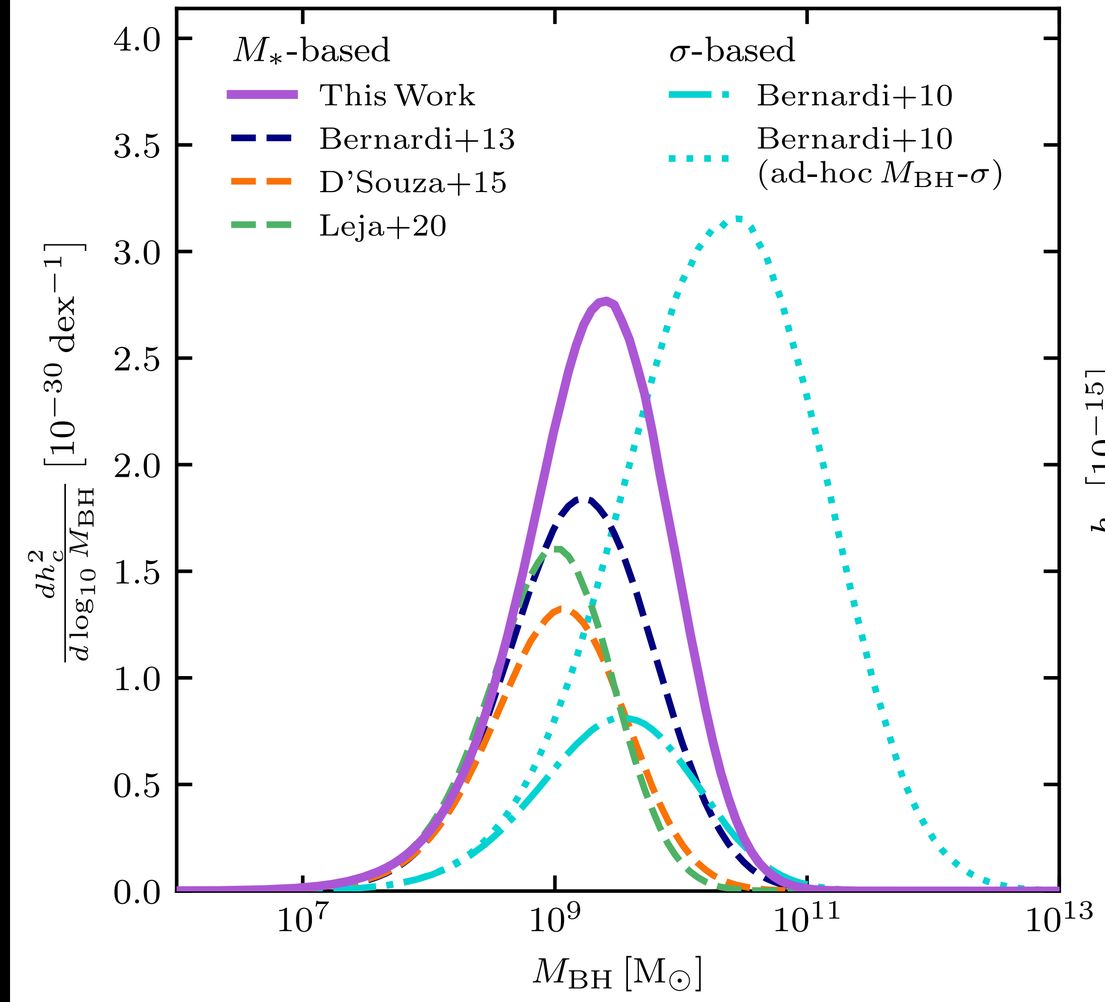
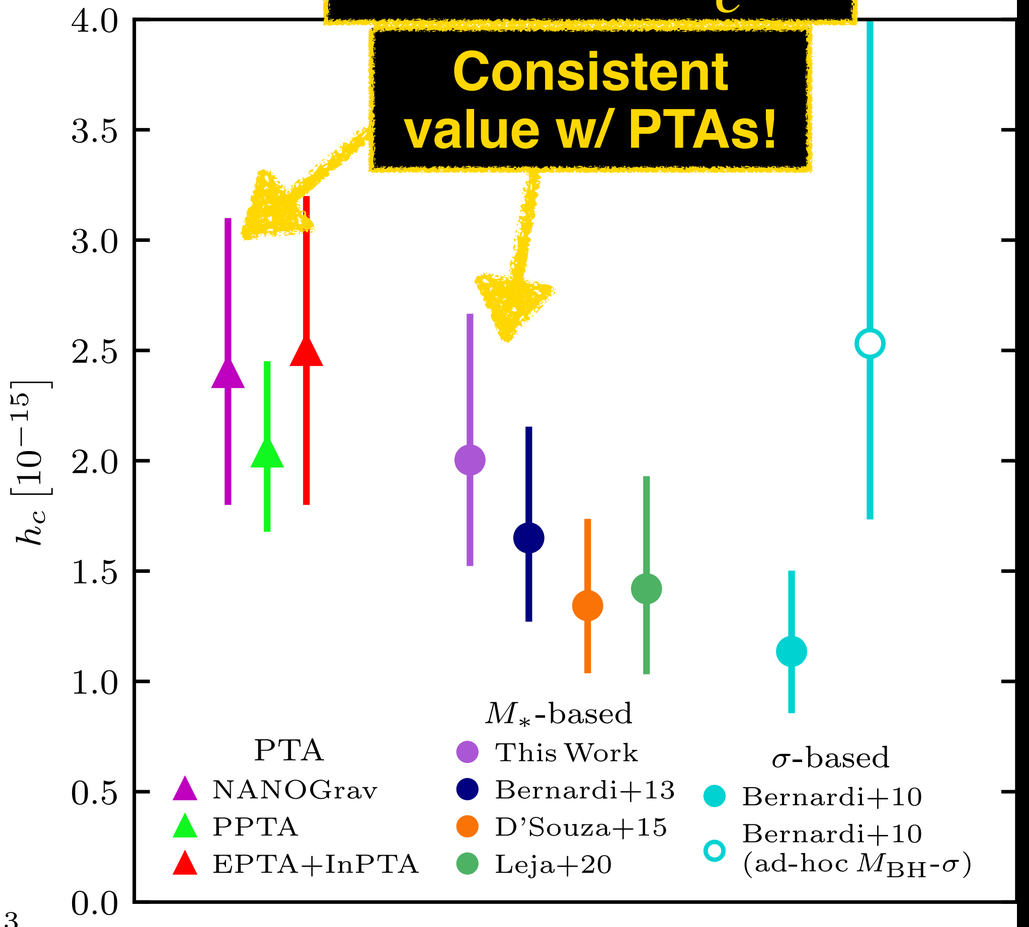



Characteristic Strain $h_c$

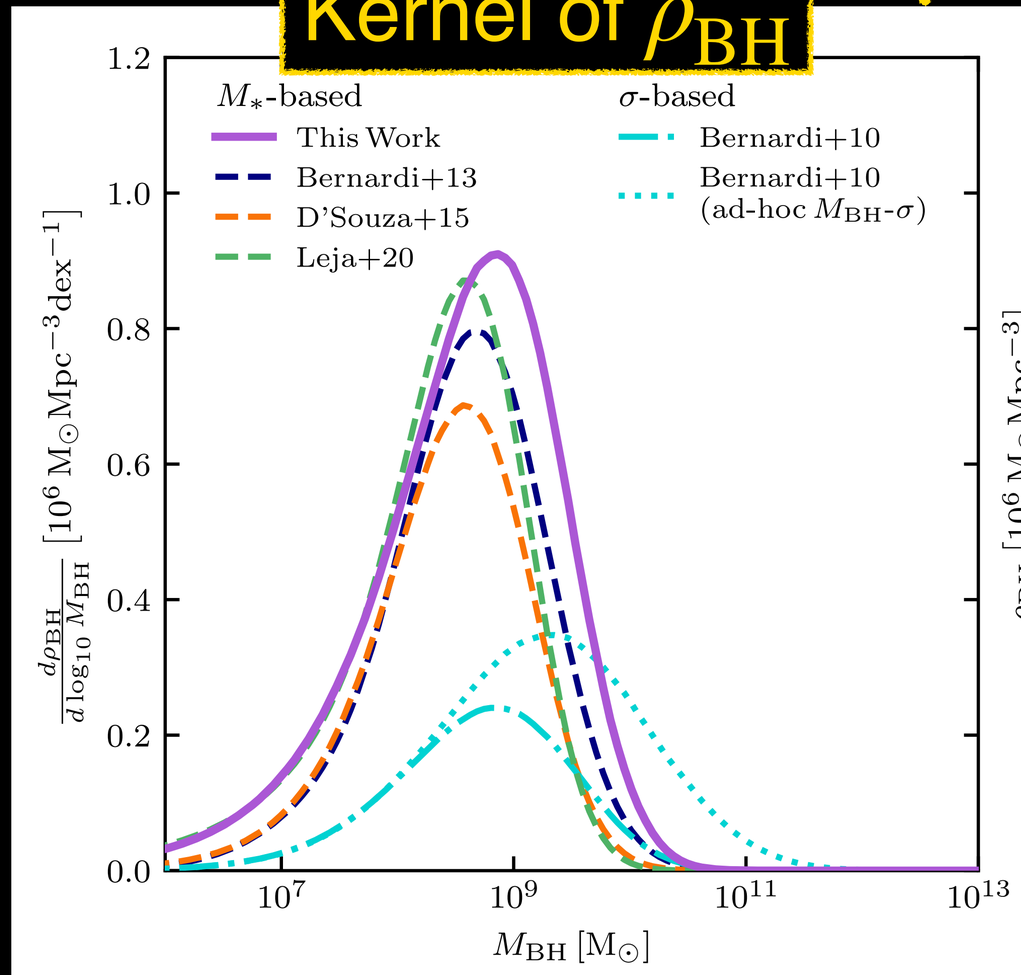
**Consistent value w/ PTAs!**



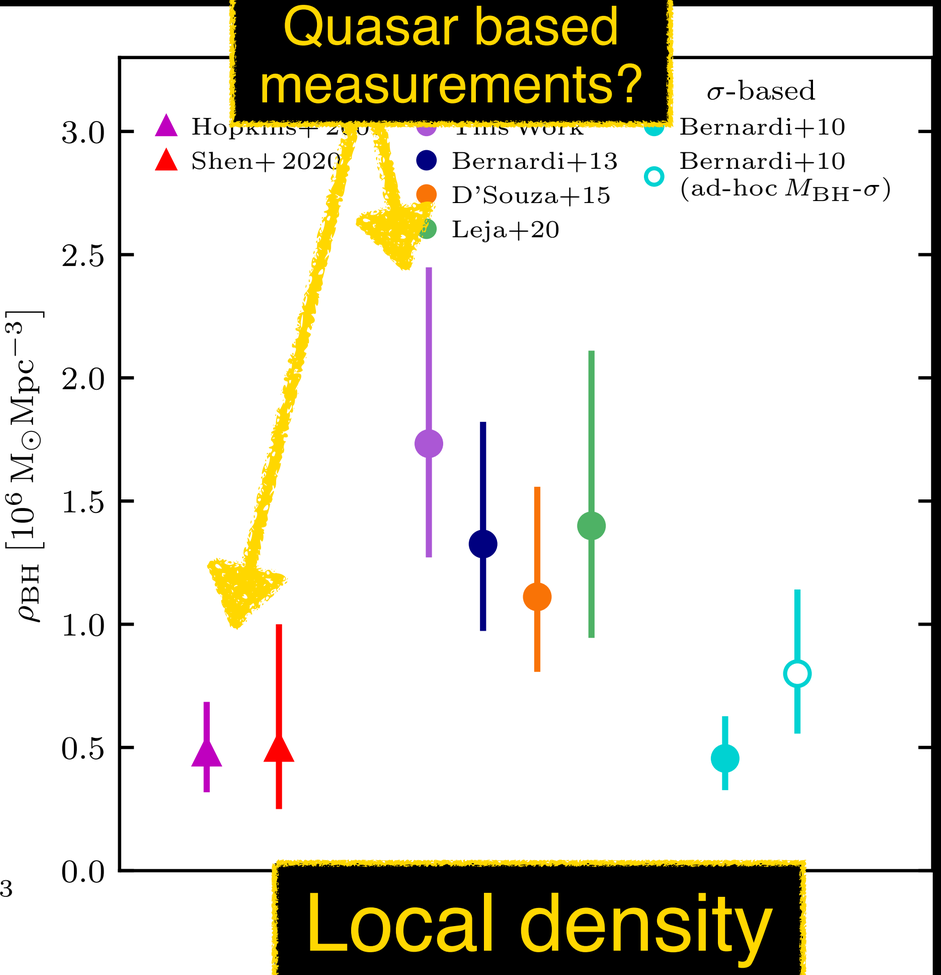
# A Mystery:
# Local BH Mass density

$$\rho_{\rm BH} = \int dM_{\rm BH} \frac{dn}{dM_{\rm BH}} M_{\rm BH}$$

Kernel of $\rho_{\rm BH}$




Factor of 3 above Quasar based measurements?




Local density $\rho_{\rm BH}$

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Our GSMF has **higher** amplitude at high mass than prior measurements

The predicted BHMF is **consistent** with observed population

The inferred strain is **consistent with PTA-based measurements**

- This suggests evolution since z = 1
- The predicted $\rho_{\mathrm{BH}}$ is 2-3x higher than QLF measurements — lower efficiency? Or higher obscuration?

**refining** the high-mass local galaxy stellar mass function

**finding** and **measuring** supermassive black holes using stellar dynamics

# Big BHs are intriguing

- Ultramassive BHs are
  - PTA sources
  - EHT sources
  - Product of mergers + evolution

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

# Big BHs are intriguing

- Ultramassive BHs are
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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**
**Liepold+25, Holmberg 15A**
**Pilawa+25, NGC 315**

# Big BHs are booming

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

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

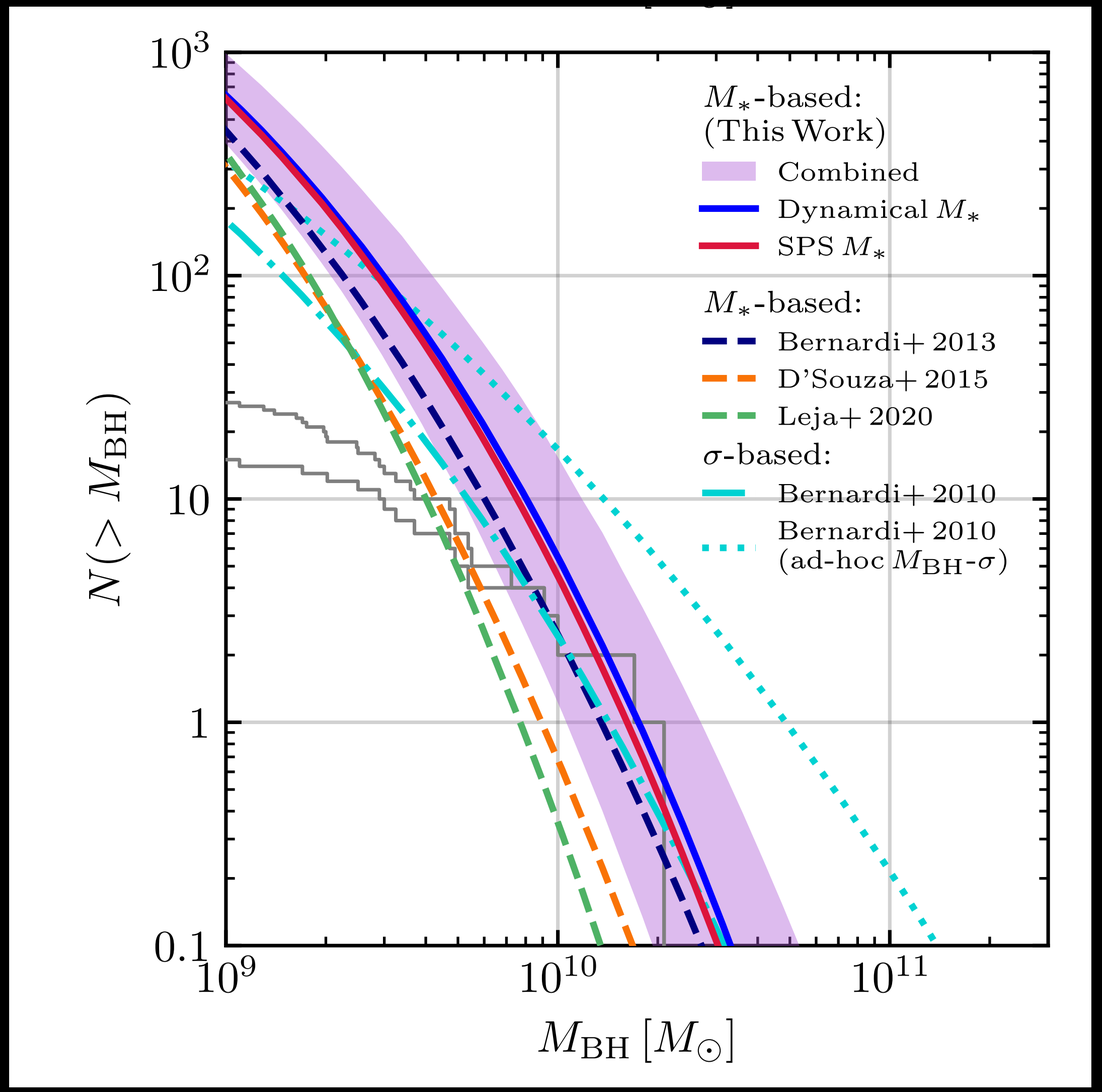
~10 from past 3 years!
(Plus more in the pipeline)

# Big BHs are uncommon

Within 100 Mpc of us:

- Only ~1 - 15 ultramassive BH with $M_{\rm BH} \gtrsim 10^{10} M_\odot$ *(3 known)*
- Only ~15 - 70 SMBH with $M_{\rm BH} \gtrsim 5 \times 10^{9} M_\odot$ *(~10 known)*

***Most*** of these are ***overmassive*** in lower-mass or lower-dispersion galaxies (hard to find!)



# How to find SMBHs

## Different methods for different galaxies


Individual stellar orbits (S2, etc around Sgr A*)

Shadow imaging (Sgr A* and M87)

Gas dynamics (CO or ionized gas)

Integrated stellar motion (Galaxies with stars + resolved SOI)

Reverberation mapping (AGN)

Single Epoch emission line width (AGN)

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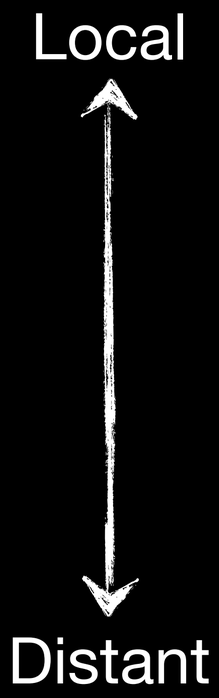


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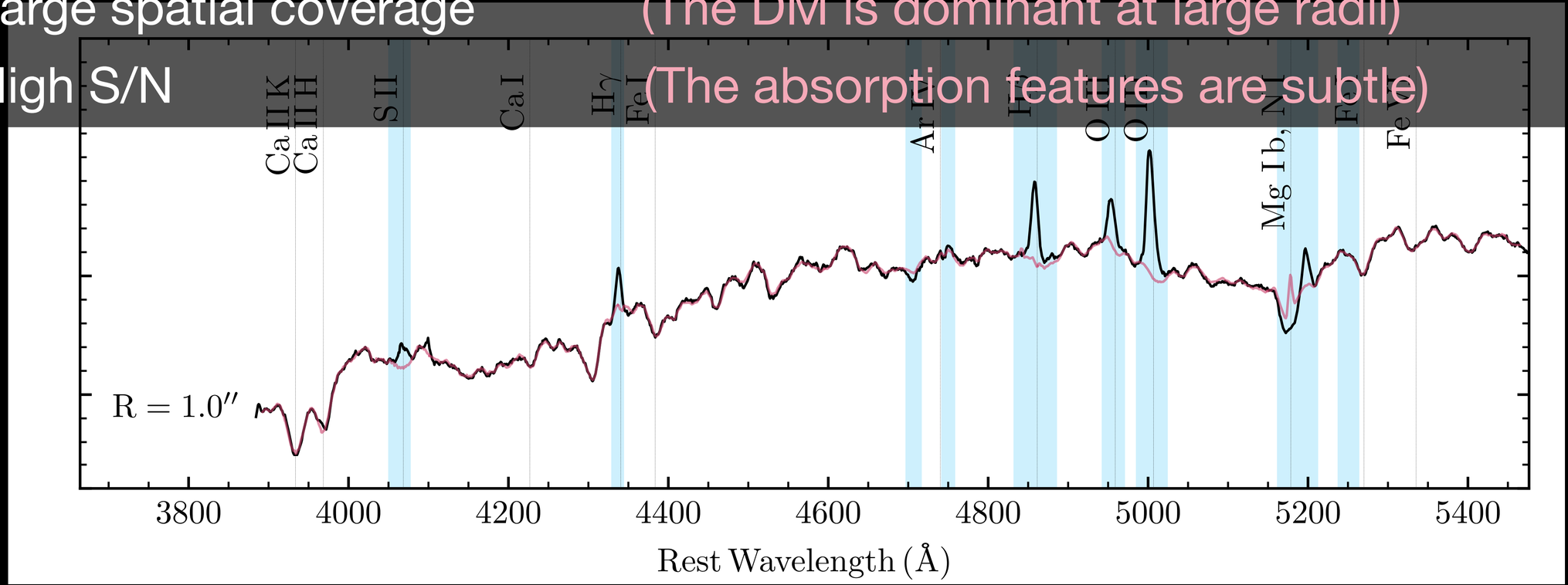
# How to find SMBHs

## (with Stellar Dynamics)

What do we need?

- Spatially-resolved Spectra! (The velocity distribution traces mass)
- High spatial resolution (The BH sphere of influence is small)
- Large spatial coverage (The DM is dominant at large radii)
- High S/N (The absorption features are subtle)



# How to measure SMBHs

## *Triaxial* Schwarzschild Modeling

Schwarzschild+79
Schwarzschild+93

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Propose a potential

# How to measure SMBHs

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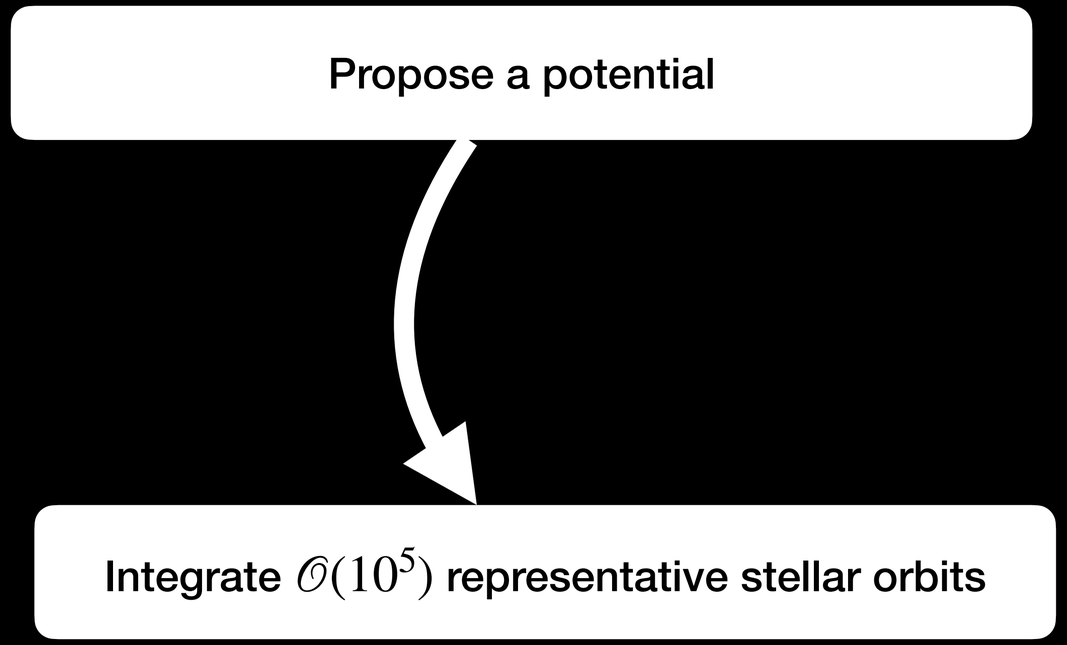

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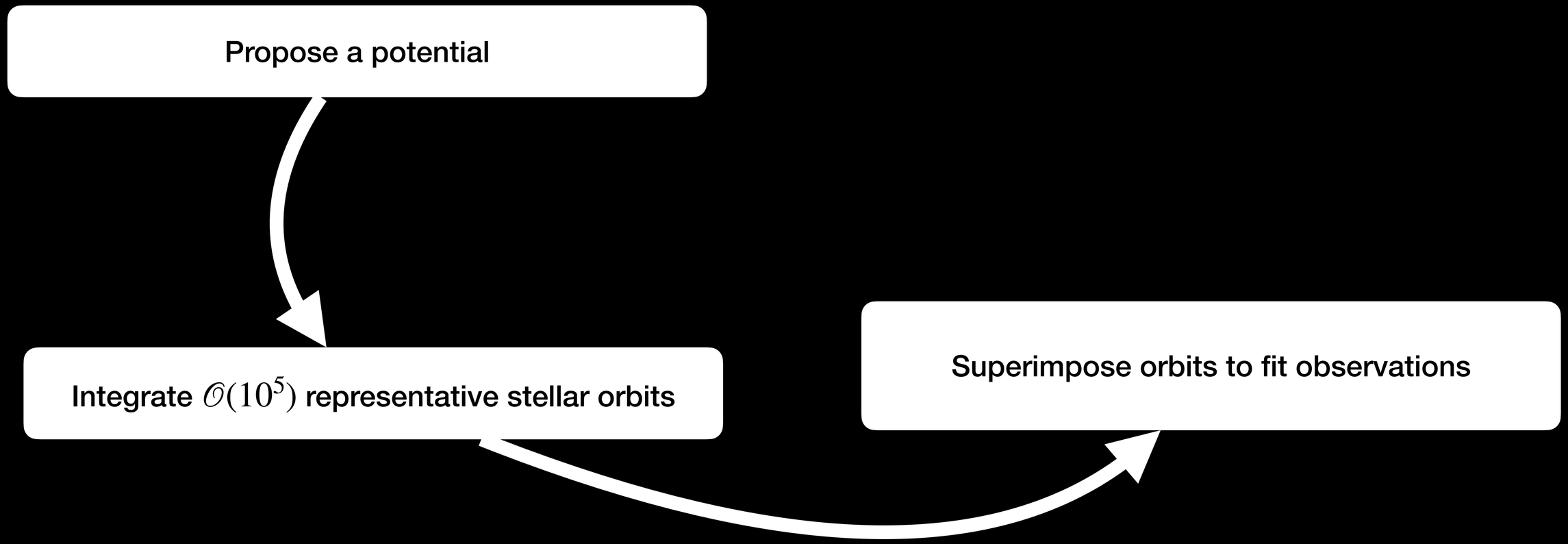

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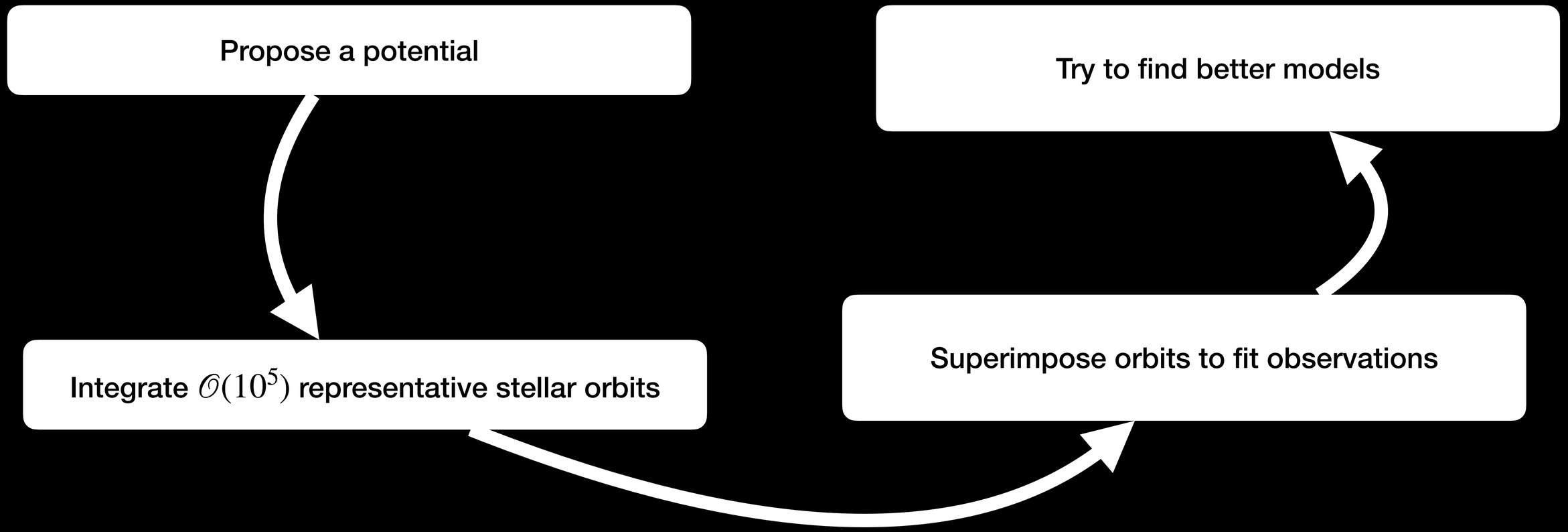

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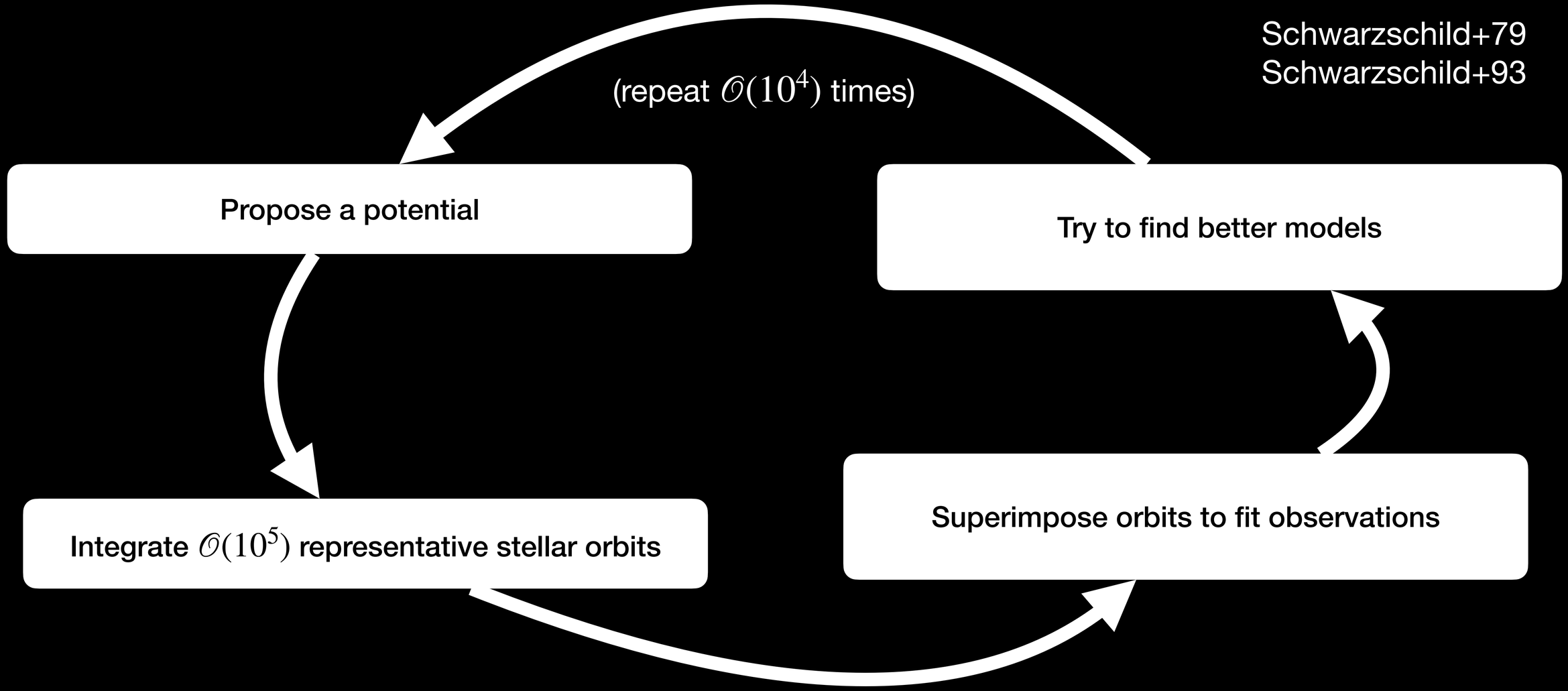

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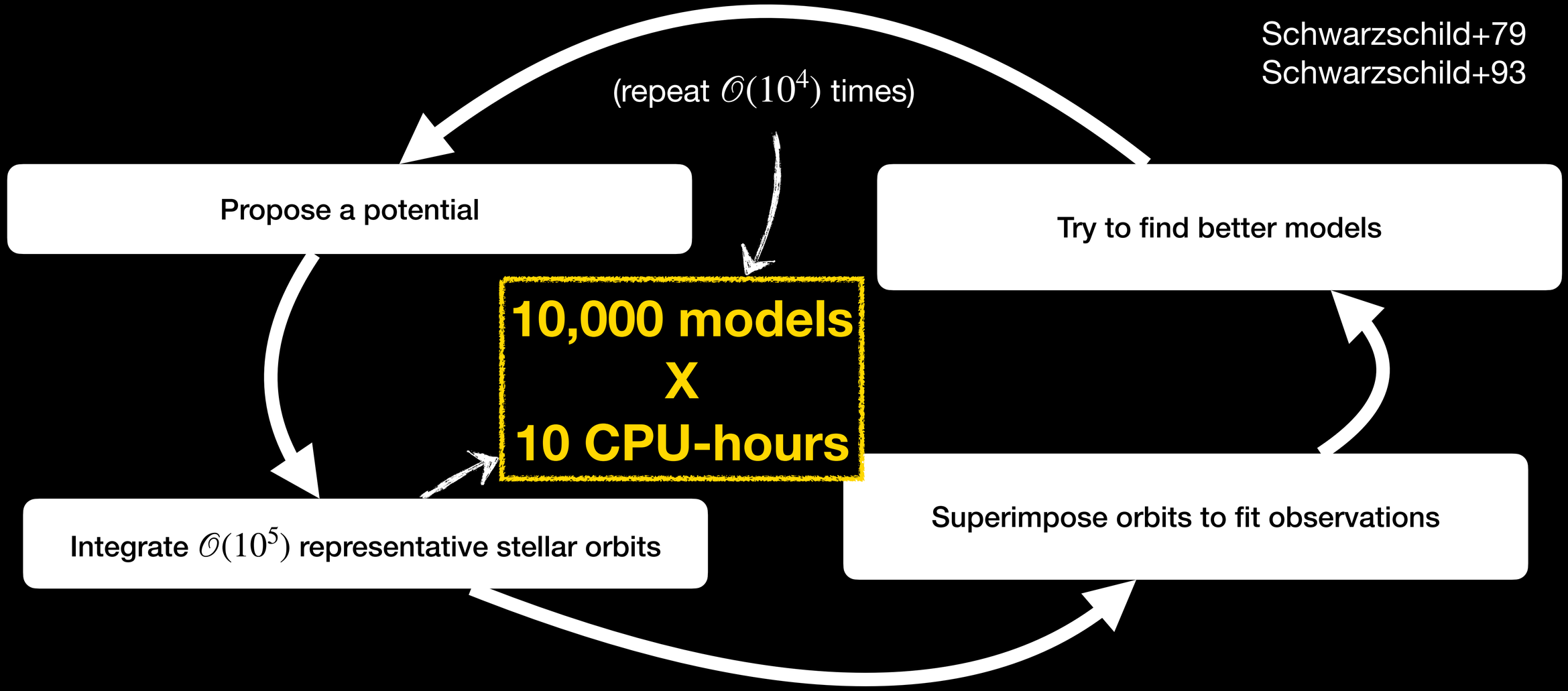

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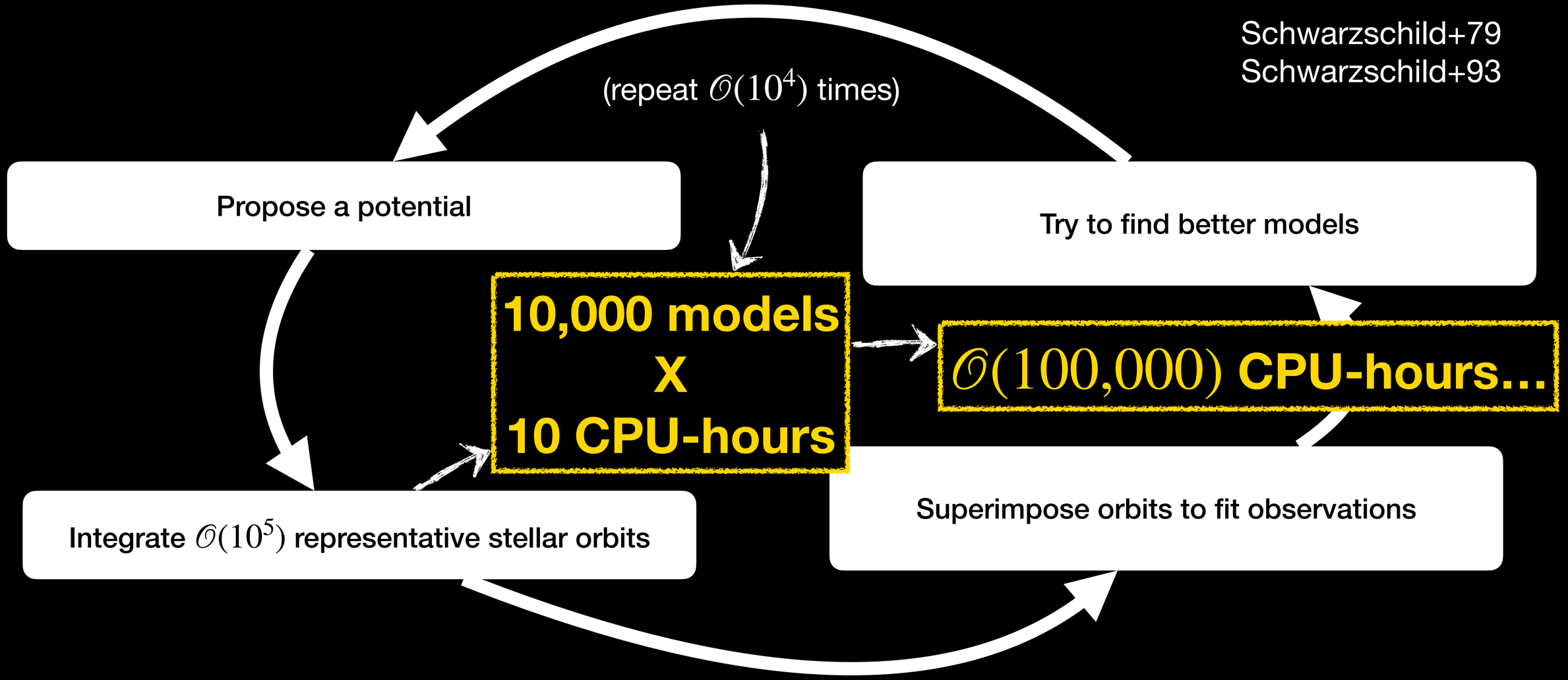

# How to (really) measure SMBHs

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
2. Efficiency improvements in acceleration functions and orbit projection. *(~order of magnitude speedup!)*
3. 6-7-dimensional grid-free model sampling + parameter inference improvements! (~couple order of magnitude cheaper)
4. ***(brand new)*** CPU parallelism (*order of magnitude faster!)*
5. Robustness and validation tests with mock galaxy data!

(Liepold+20, 23; Quenneville+21, 22; Pilawa+22, 24)

# How to (really) measure SMBHs

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**Triaxial Schwarzschild orbit modeling is now in production mode!**

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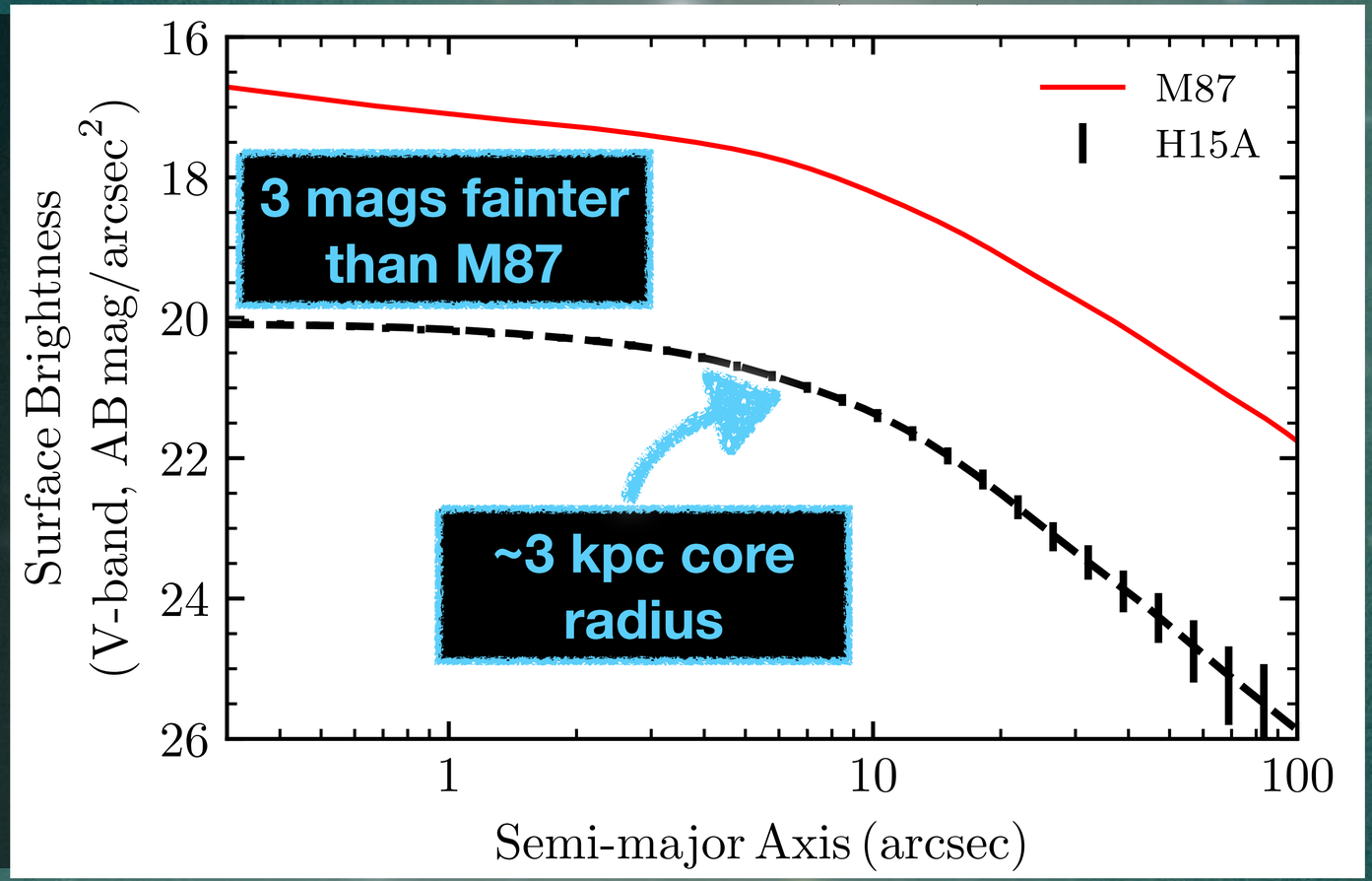
**NGC1453: Liepold+20, Quenneville+22**
**NGC2693: Pilawa+22**
**M87: Liepold+23; Liepold+soon**
**Holmberg 15A: Liepold+25**
**NGC315: Pilawa+25**
**NGC57: Pilawa+soon**

(Liepold+20, 23; Quenneville+21, 22; Pilawa+22, 24)

Liepold, Ma, Walsh 2025

# An extremely large and extremely faint core: Holmberg 15A

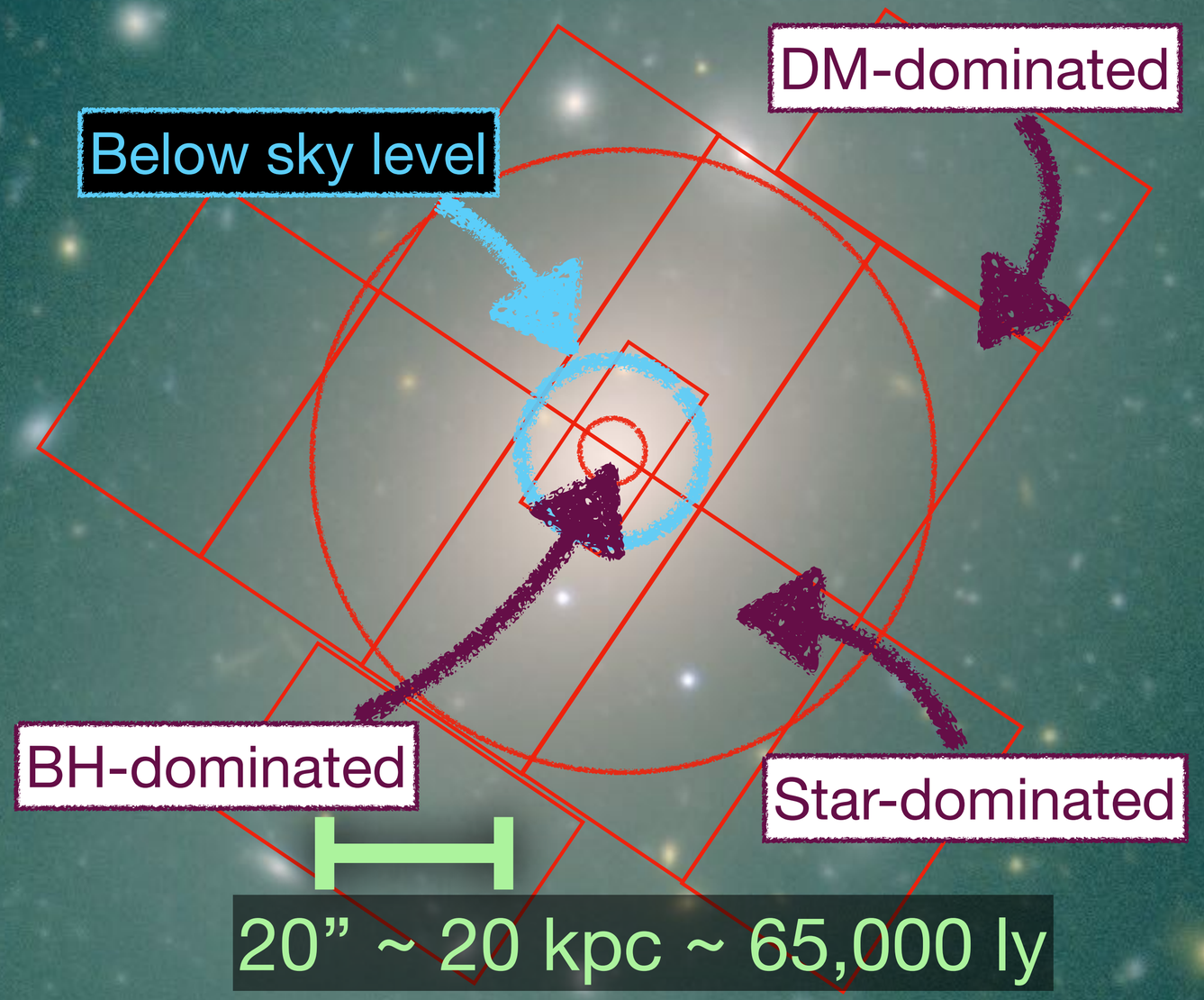
- BCG of Abell 85 (220 Mpc away)
- Largest known core! (~3 kpc)
- Faintest known Central SB! ( $\mu_V = 20\mathrm{mag/arcsec}^2$ )
- The size of an ETG's core is correlated with the black hole mass
- The central surface brightness is ***anti***correlated with black hole mass



Liepold, Ma, Walsh 2025

# An extremely large and extremely faint core: Holmberg 15A

- We observed H15 with Keck Cosmic Web Imager (KCWI) during five observing runs from Nov 2018 - Nov 2021
- ~12 hours on target with KCWI large and small slicers + skies + overheads
- The full FOV spans about 100 kpc along the photometric major and minor axes
- These observations are **mostly below sky level**



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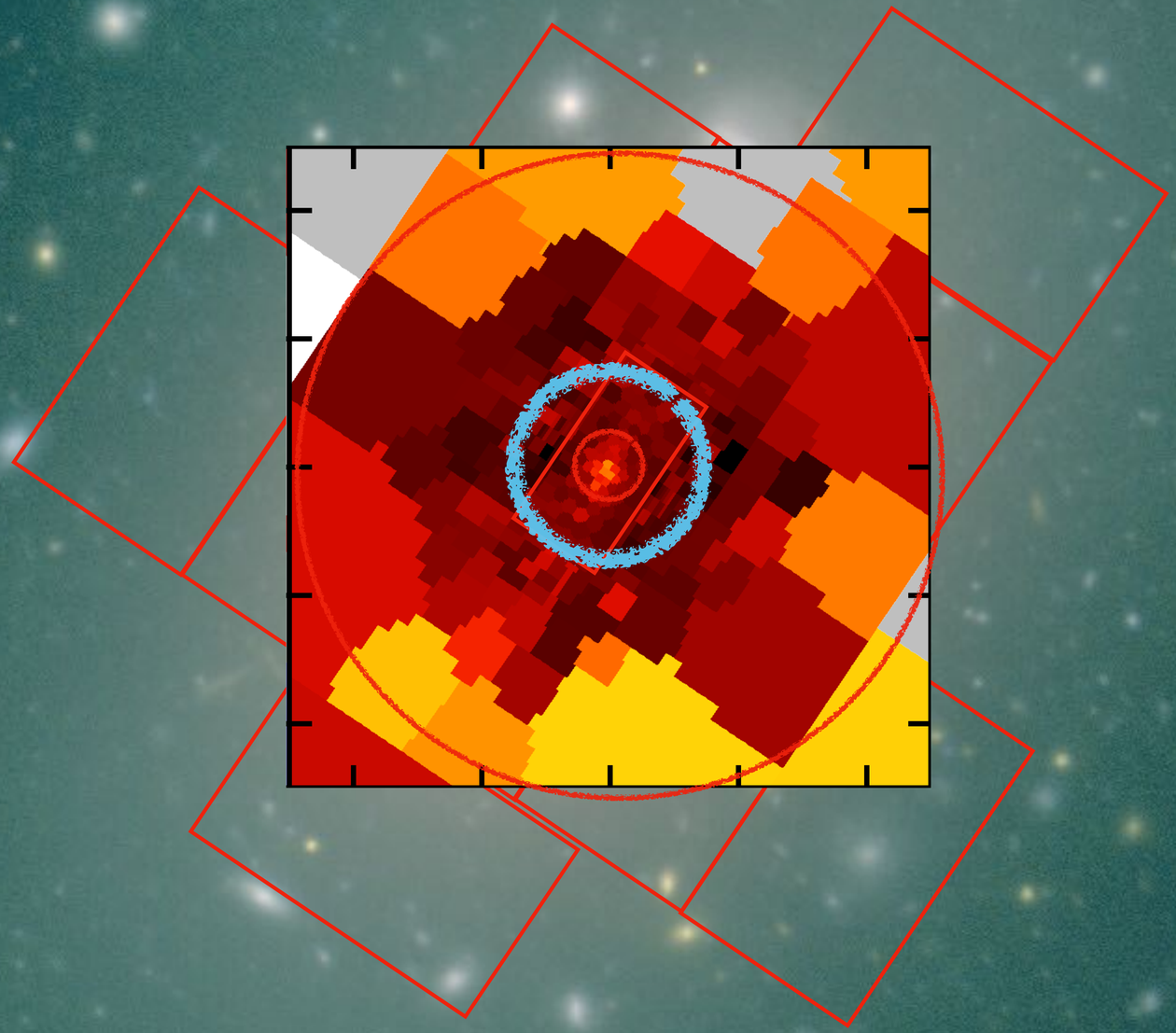
Liepold, Ma, Walsh 2025



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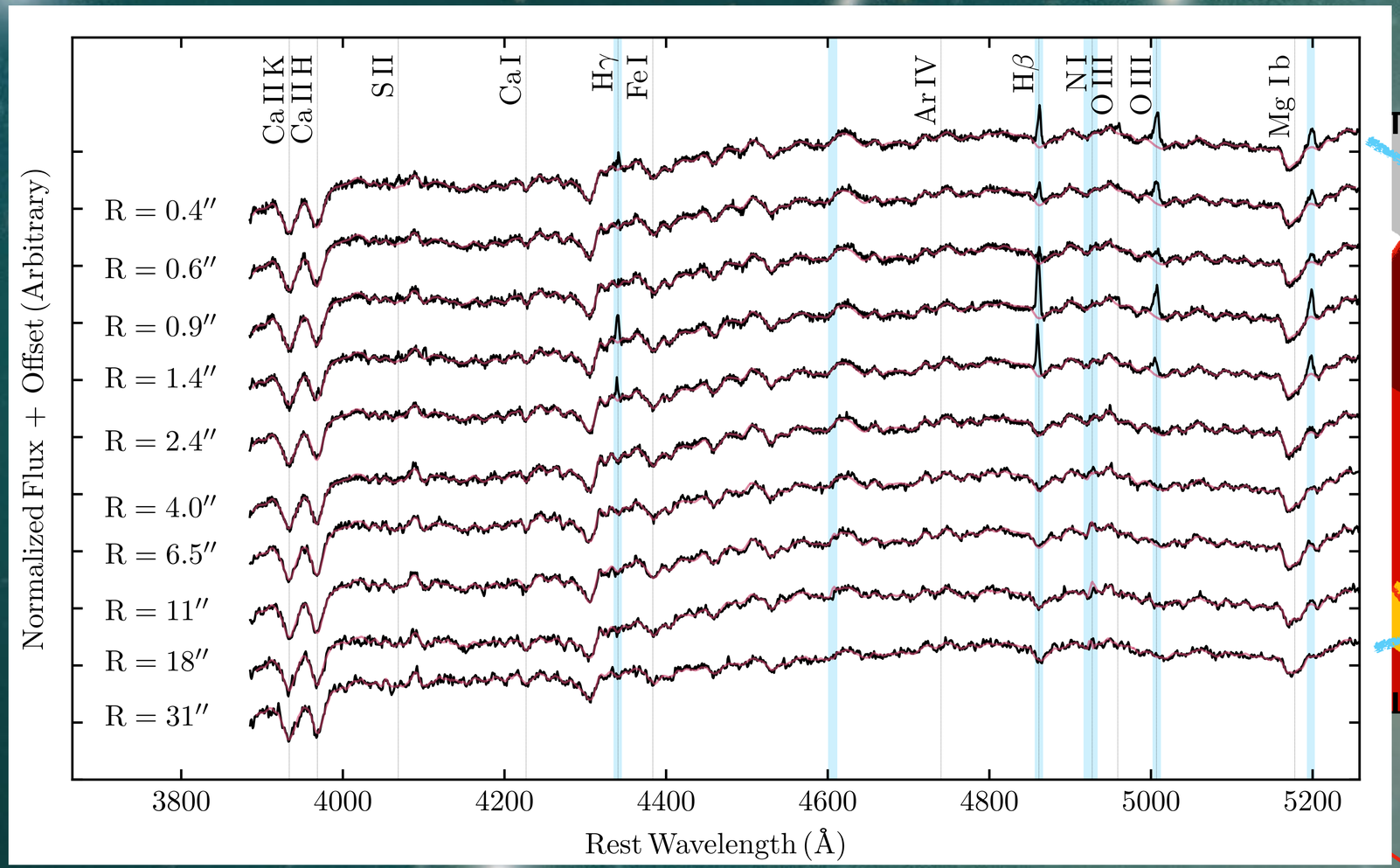


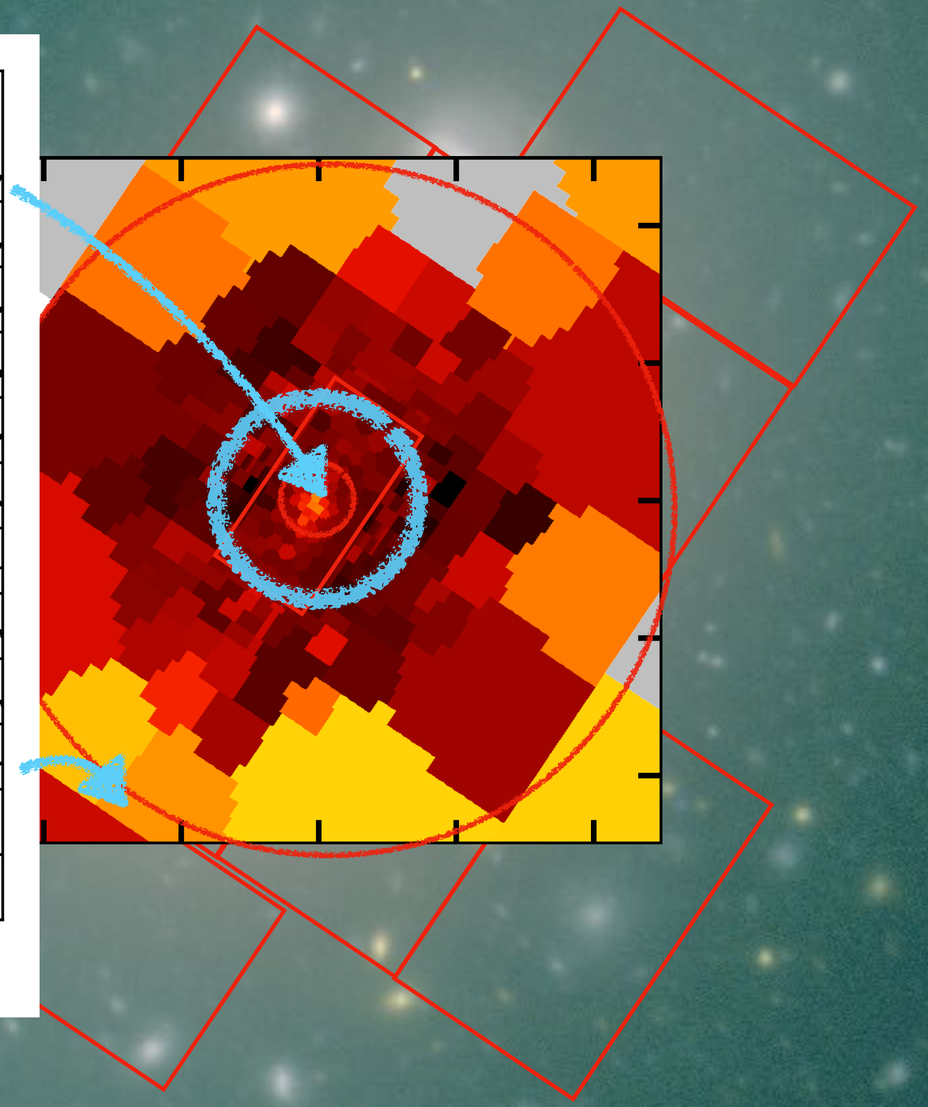

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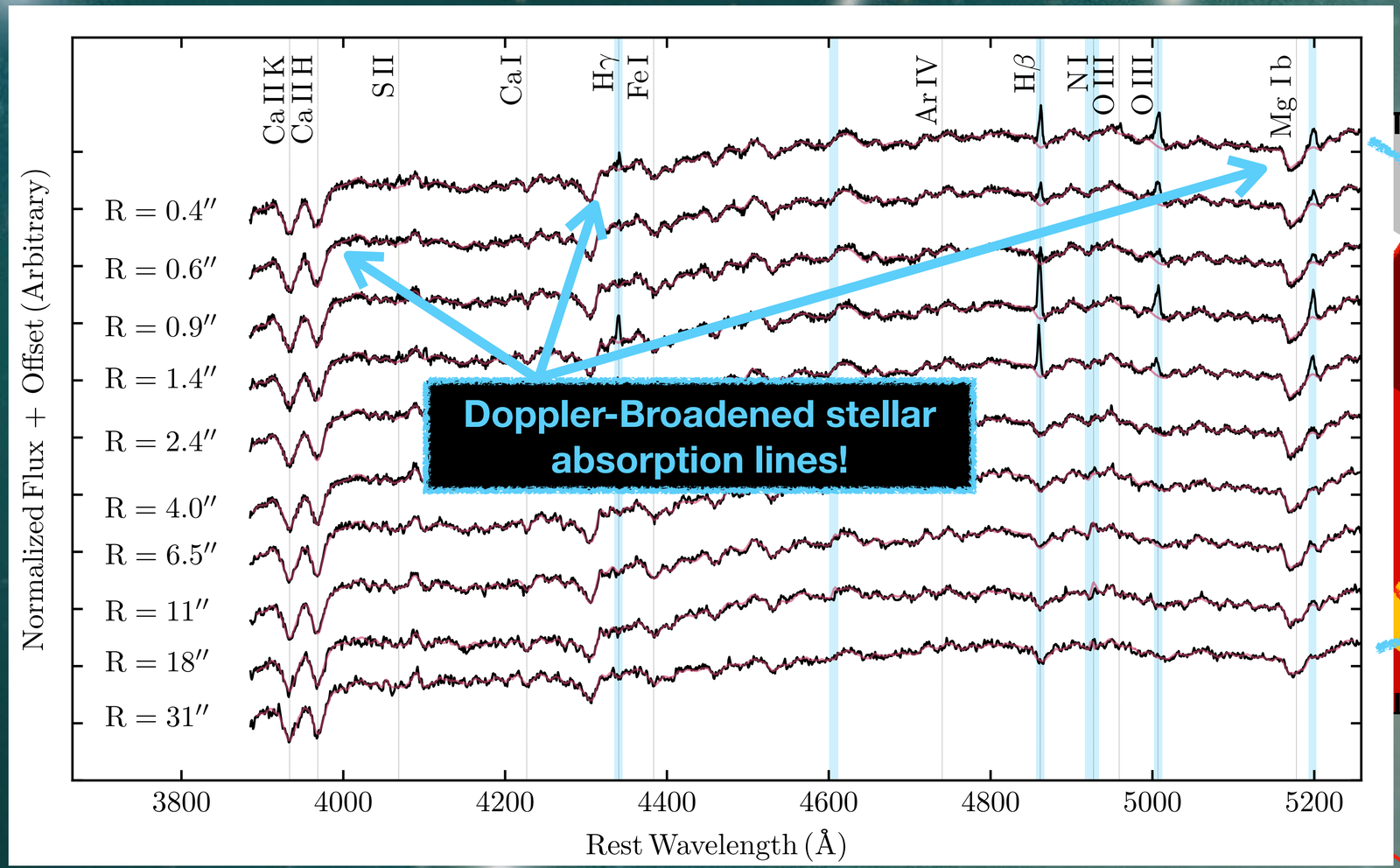


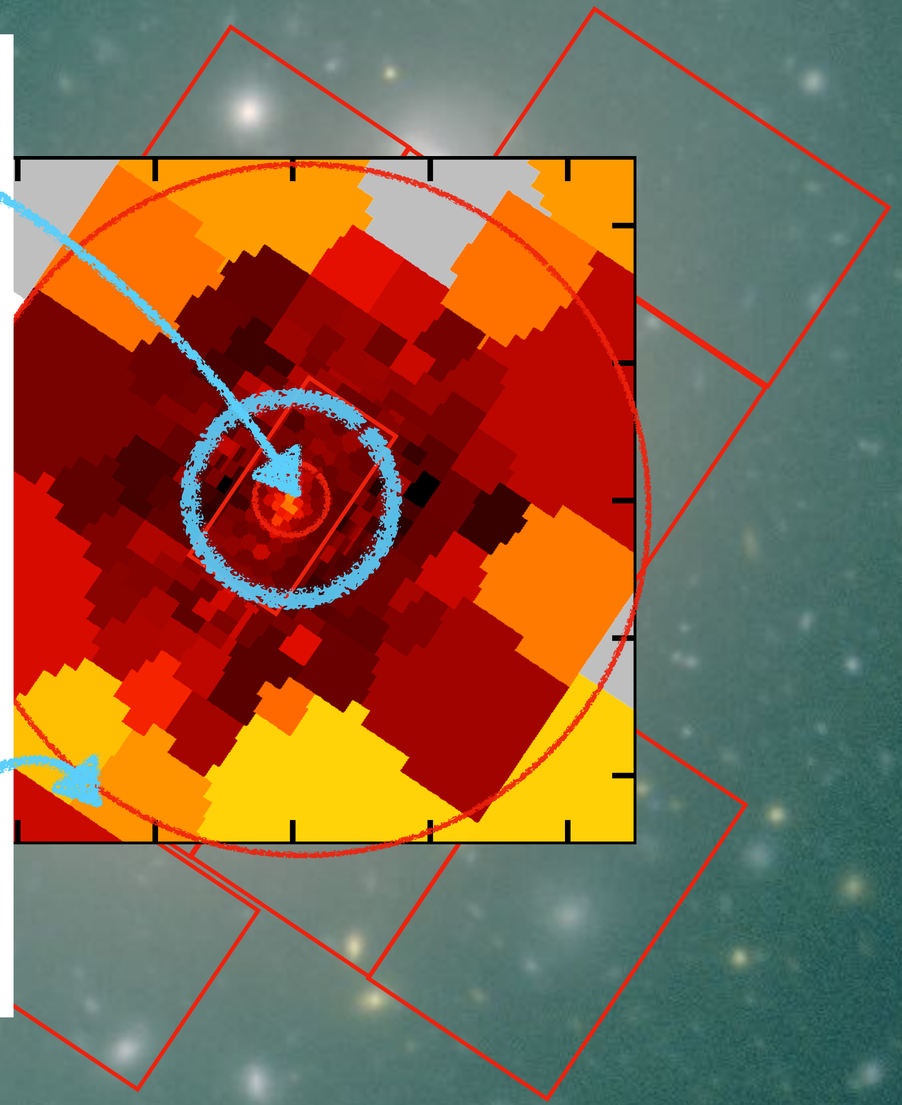

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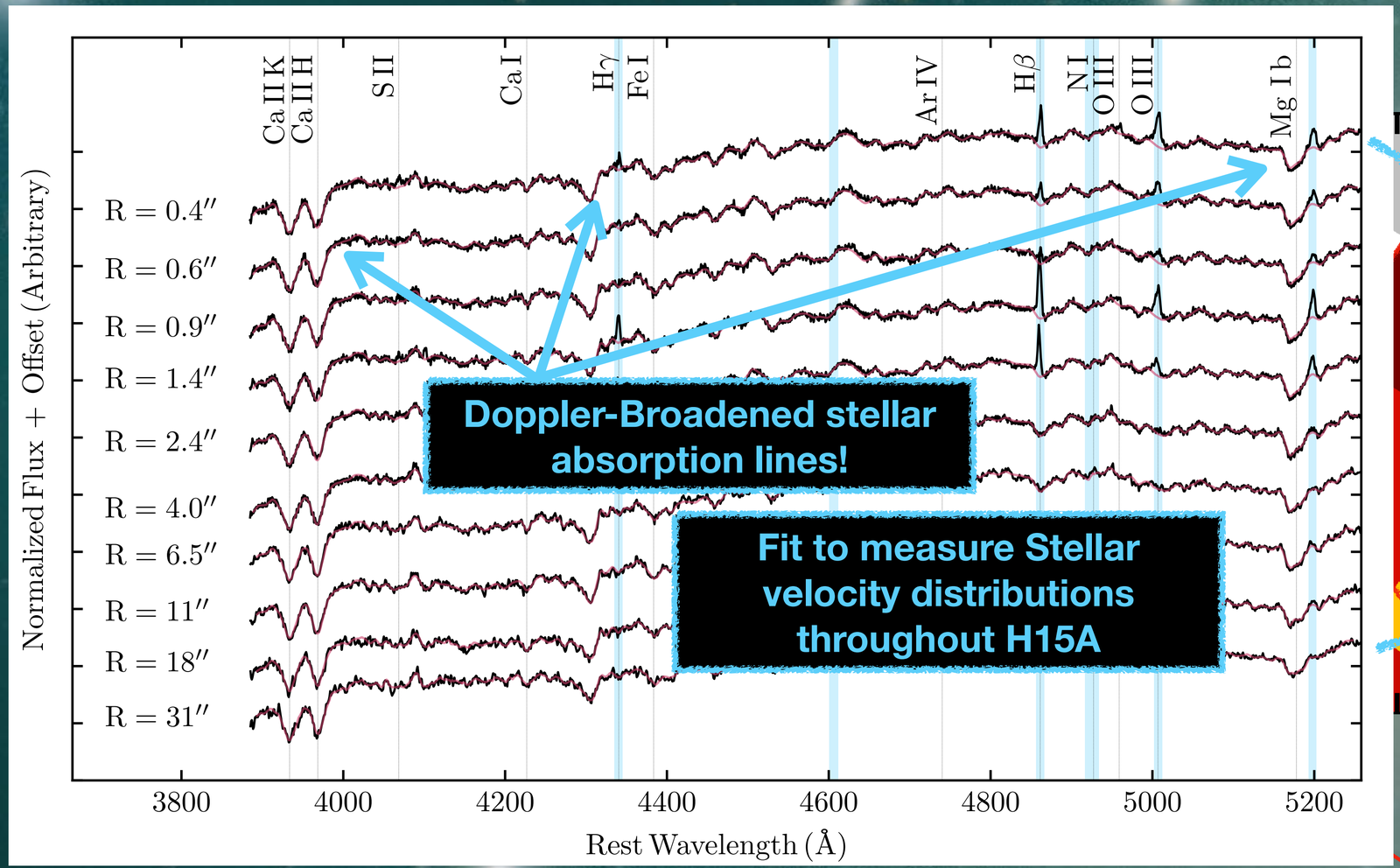


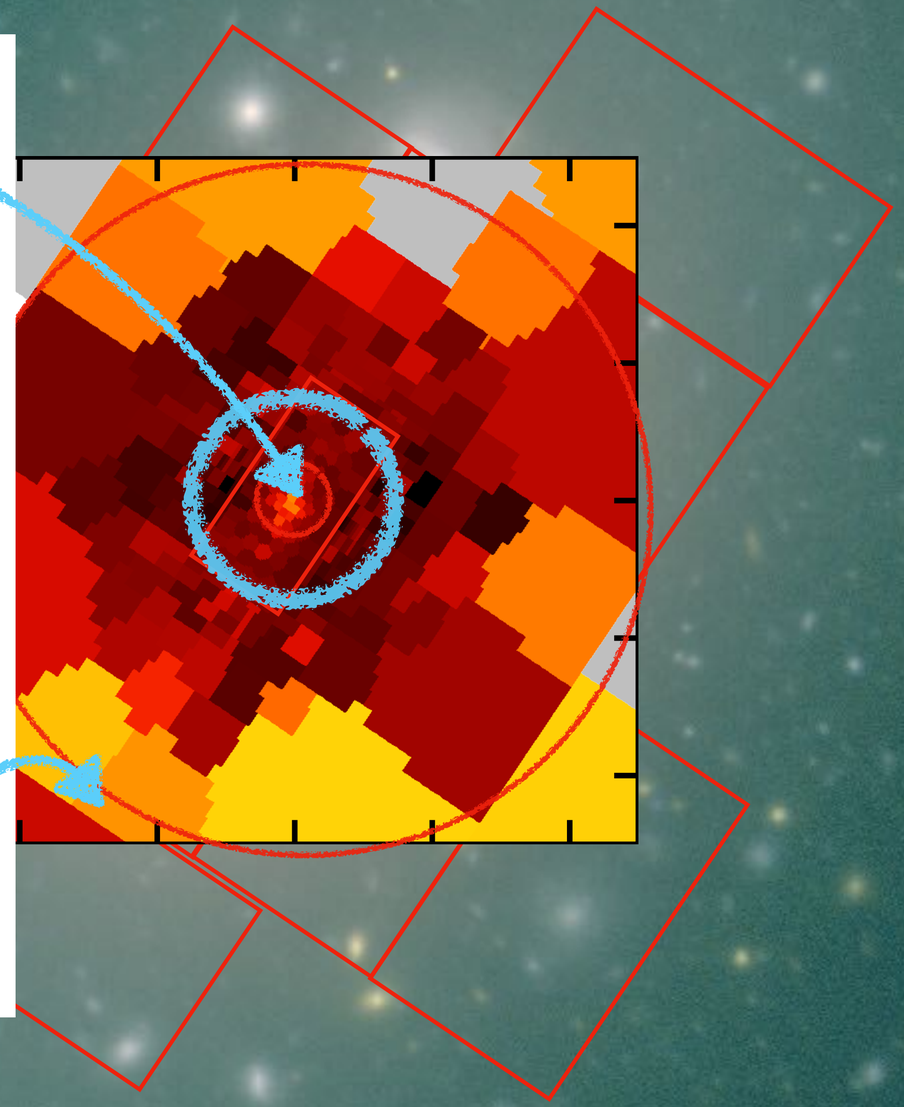

Liepold, Ma, Walsh 2025

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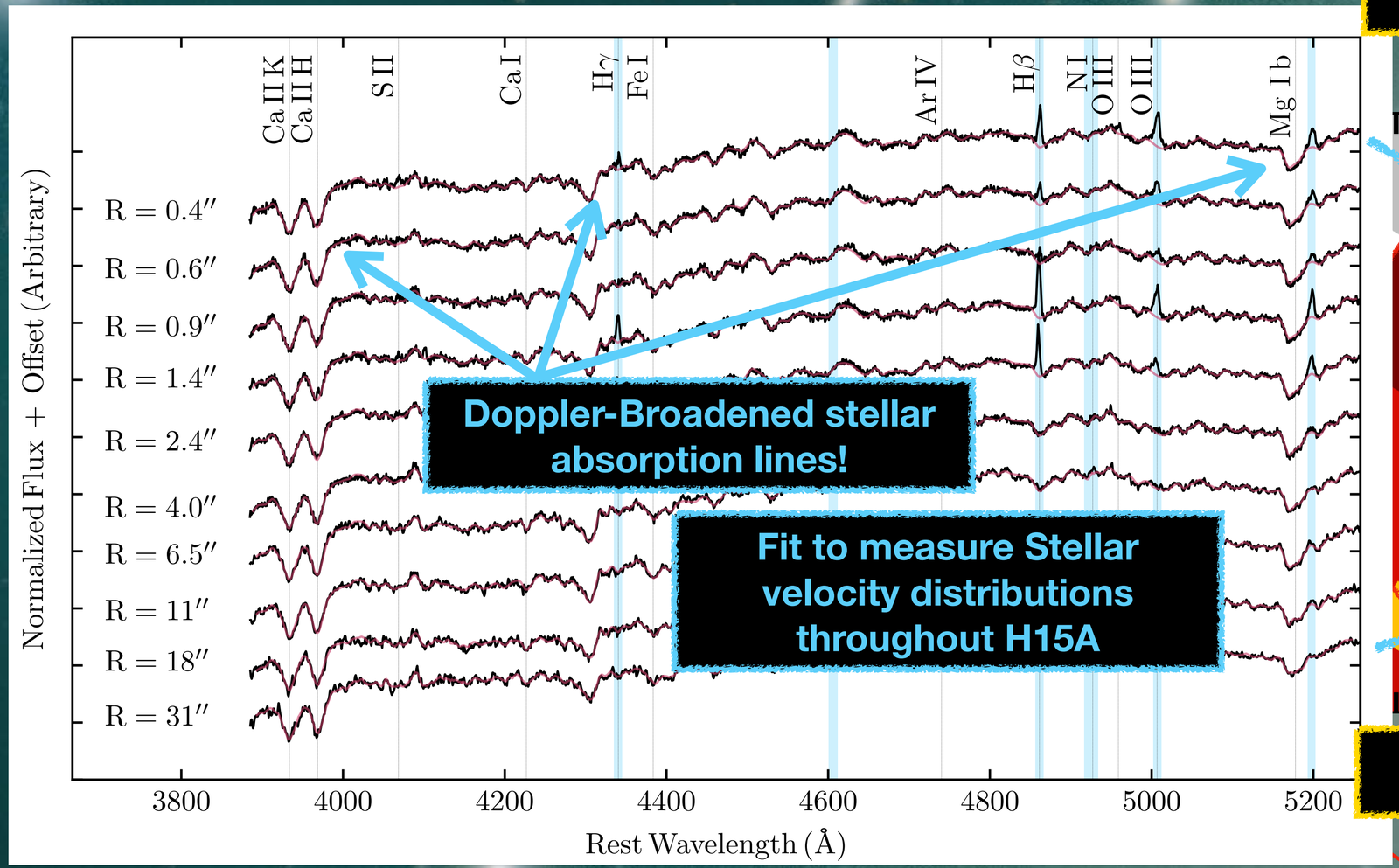
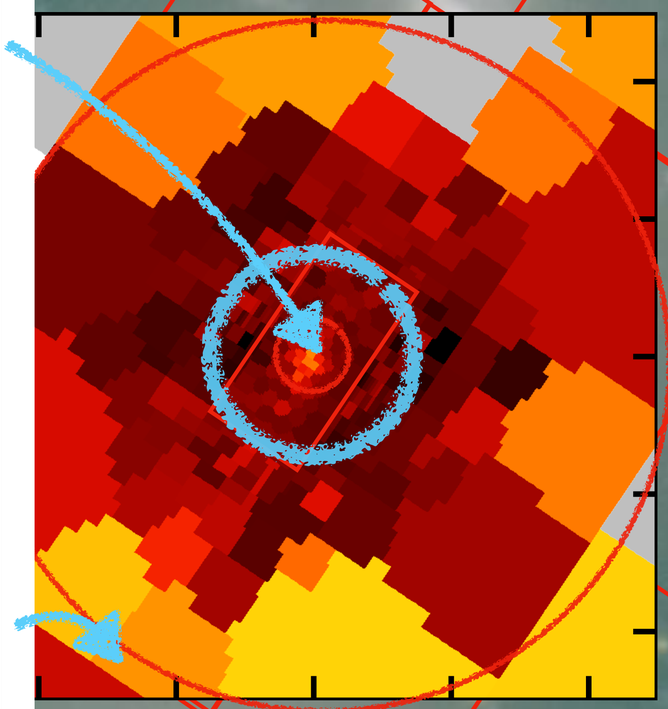



**1.5 mag above sky,** S/N ~ 130/0.5Å



**2 mag *below* sky,** S/N ~ 60/Å

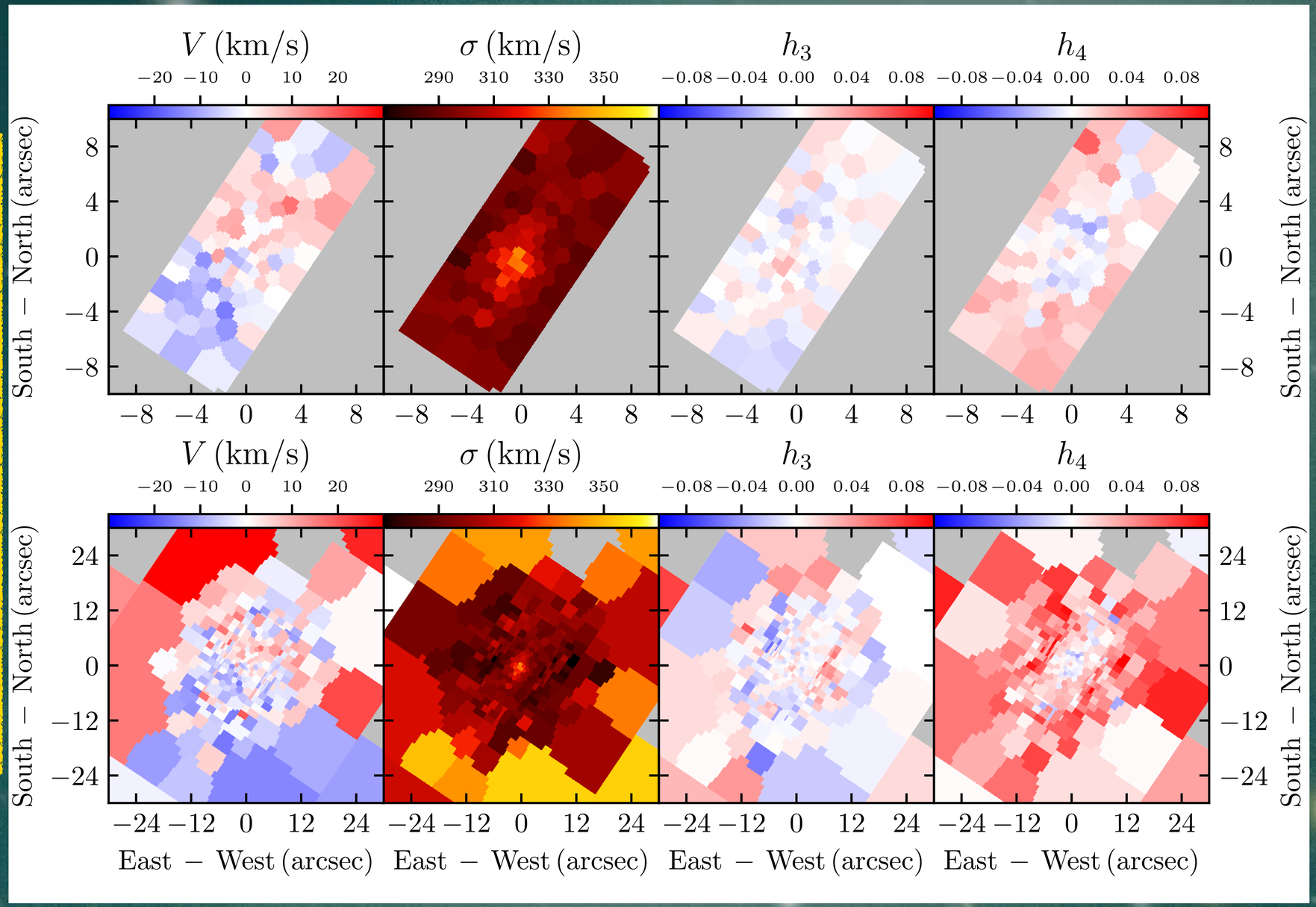
Liepold, Ma, Walsh 2025

# Holmberg 15A

**Measurements of 12 velocity moments in sky-dominated regions!**

**(Over 2500 kinematic observables!)**

**Only possible with KCWI!**



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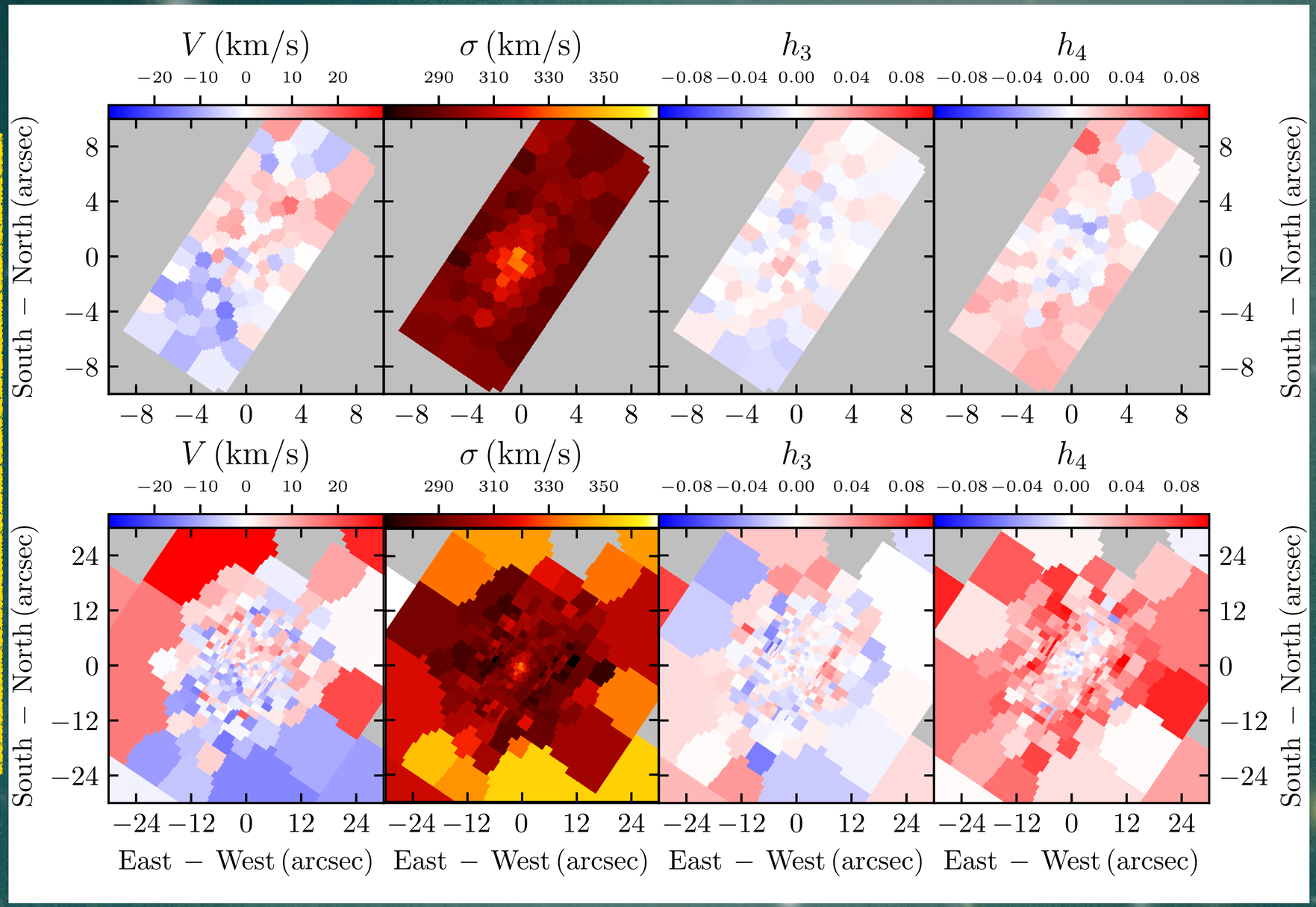
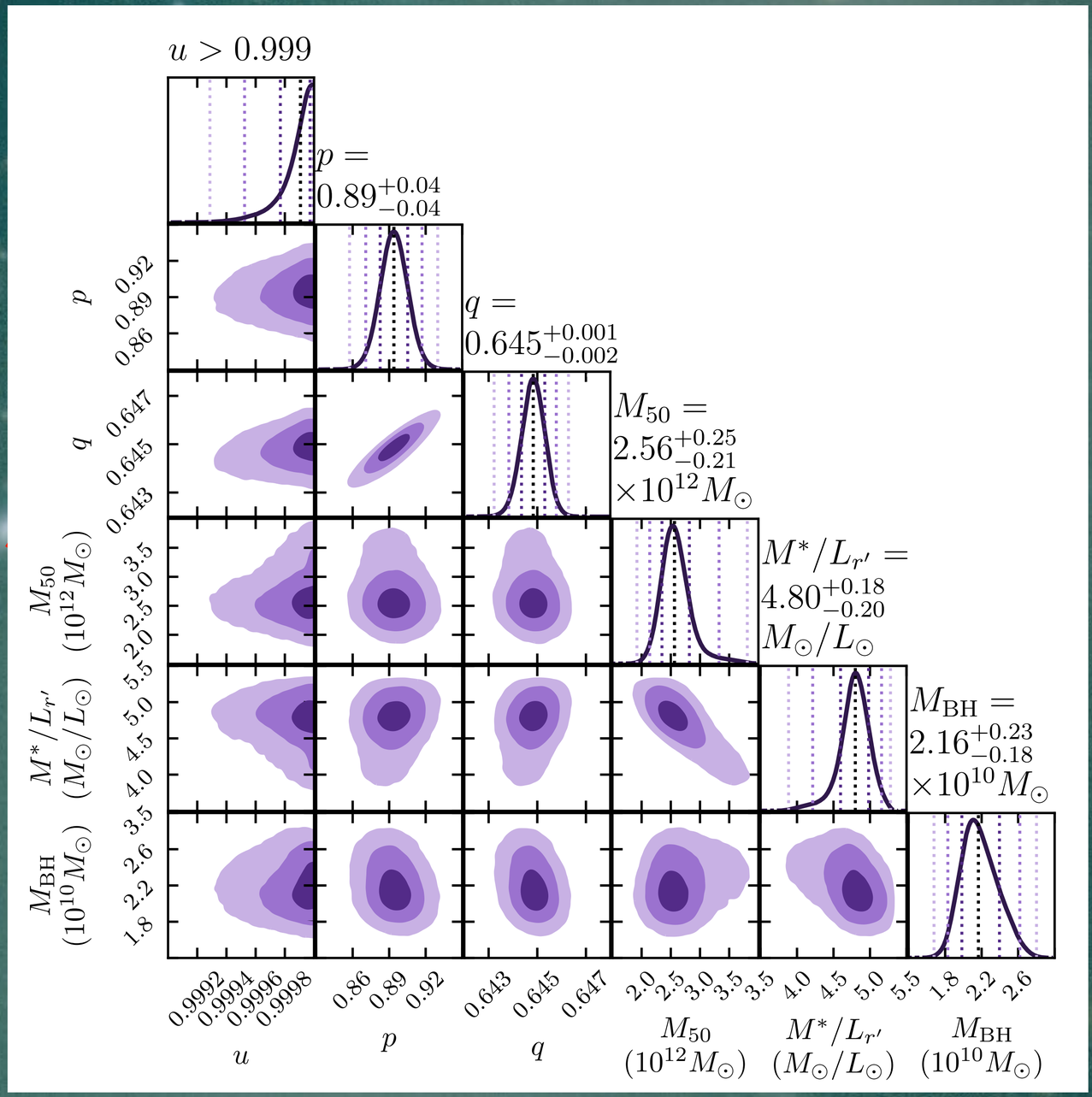


# Holmberg 15A

- Ran ***~40,000*** triaxial orbit models with ***2,500*** kinematic observations
- Measurement of a ***22 Billion*** $M_\odot$ SMBH! (Tied for largest measured dynamically!)
- Determination of the ***Triaxial intrinsic shape*** (1 : 0.89 : 0.65)
- Consistent results from axisymmetric models (***25 Billion*** $M_\odot$)
- Factor-of-two difference from prior MUSE-based measurement

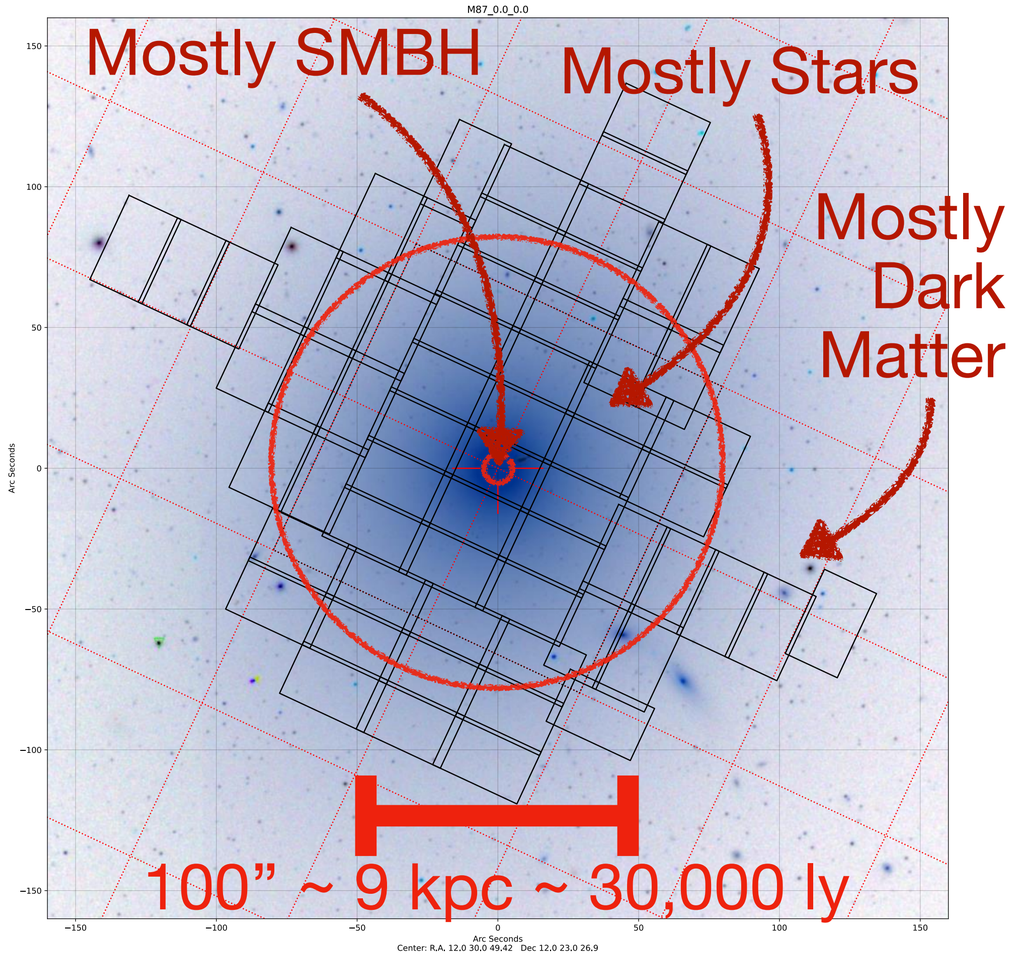
Liepold, Ma, Walsh 2025



# First triaxial shape measurements of 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′′ × 33′′ FOV with 0.3′′ × 1.4′′ spatial pixels
- The full FOV spans about 23 kpc along the photometric major axis and 28 kpc along the minor (11.6 square arcmin in total!)
- The full field is divided into ~450 bins: over 5000 kinematic observations!



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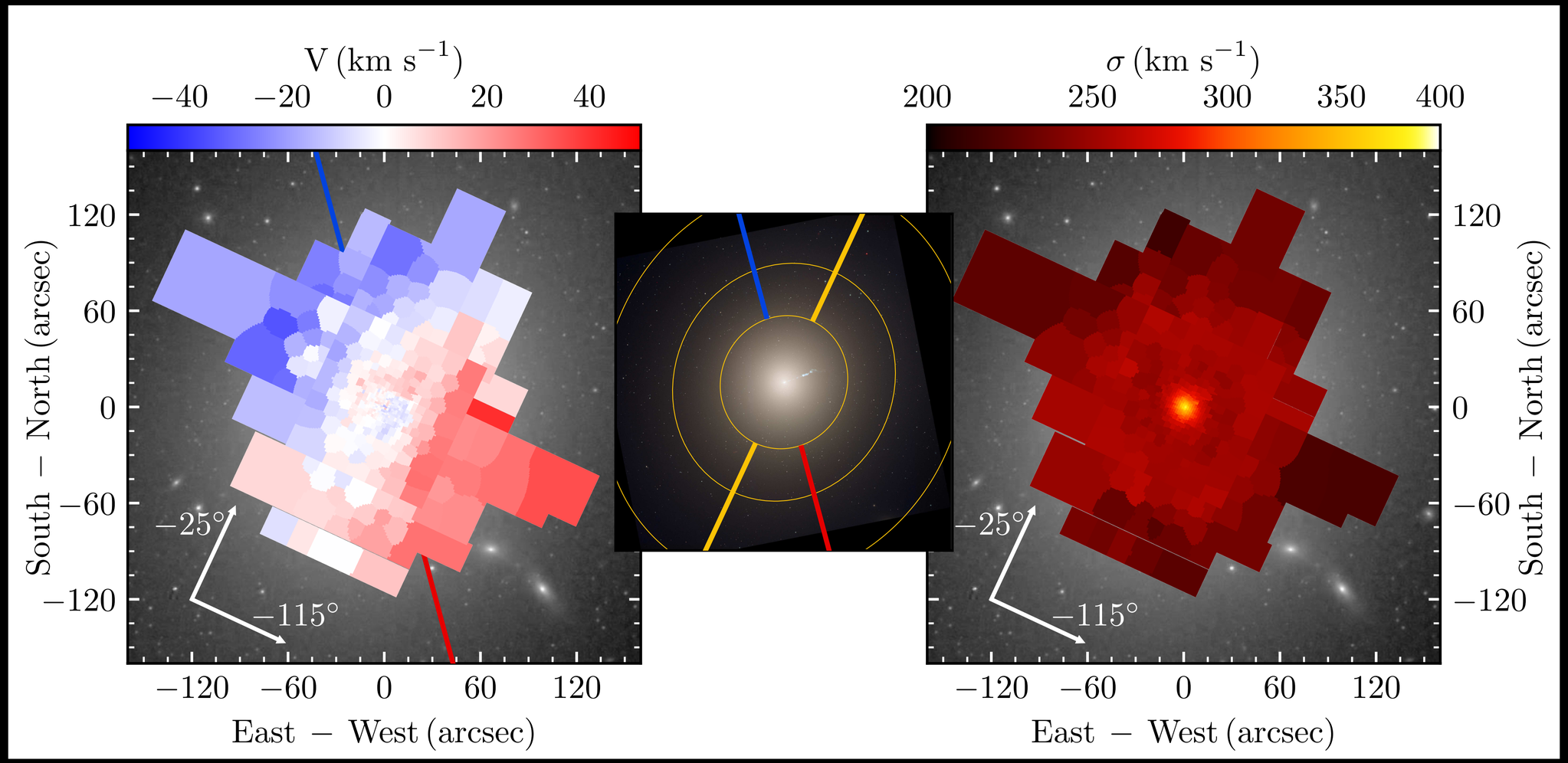

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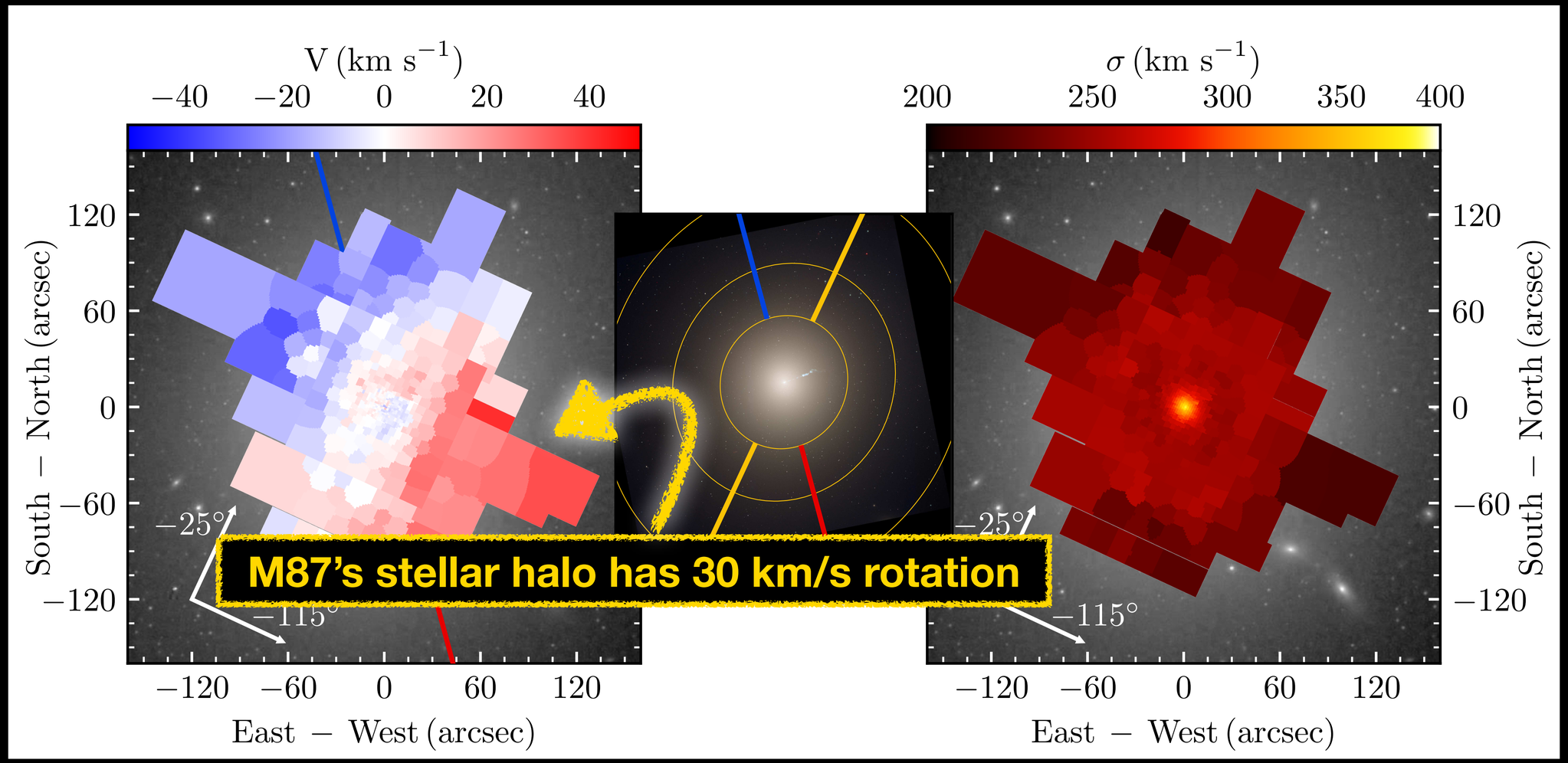

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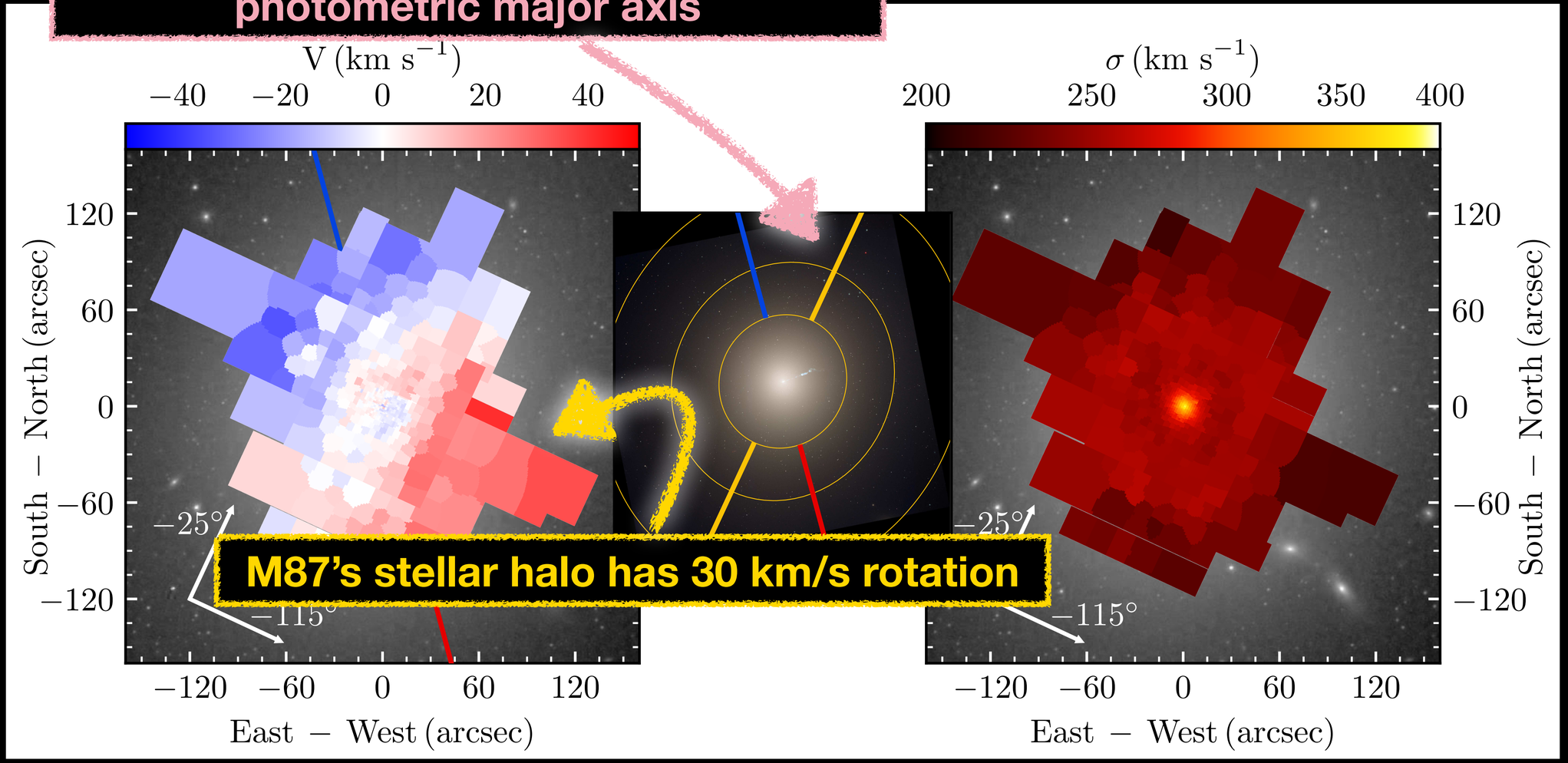
**The rotation is *misaligned* with the photometric major axis**




**M87's stellar halo has 30 km/s rotation**

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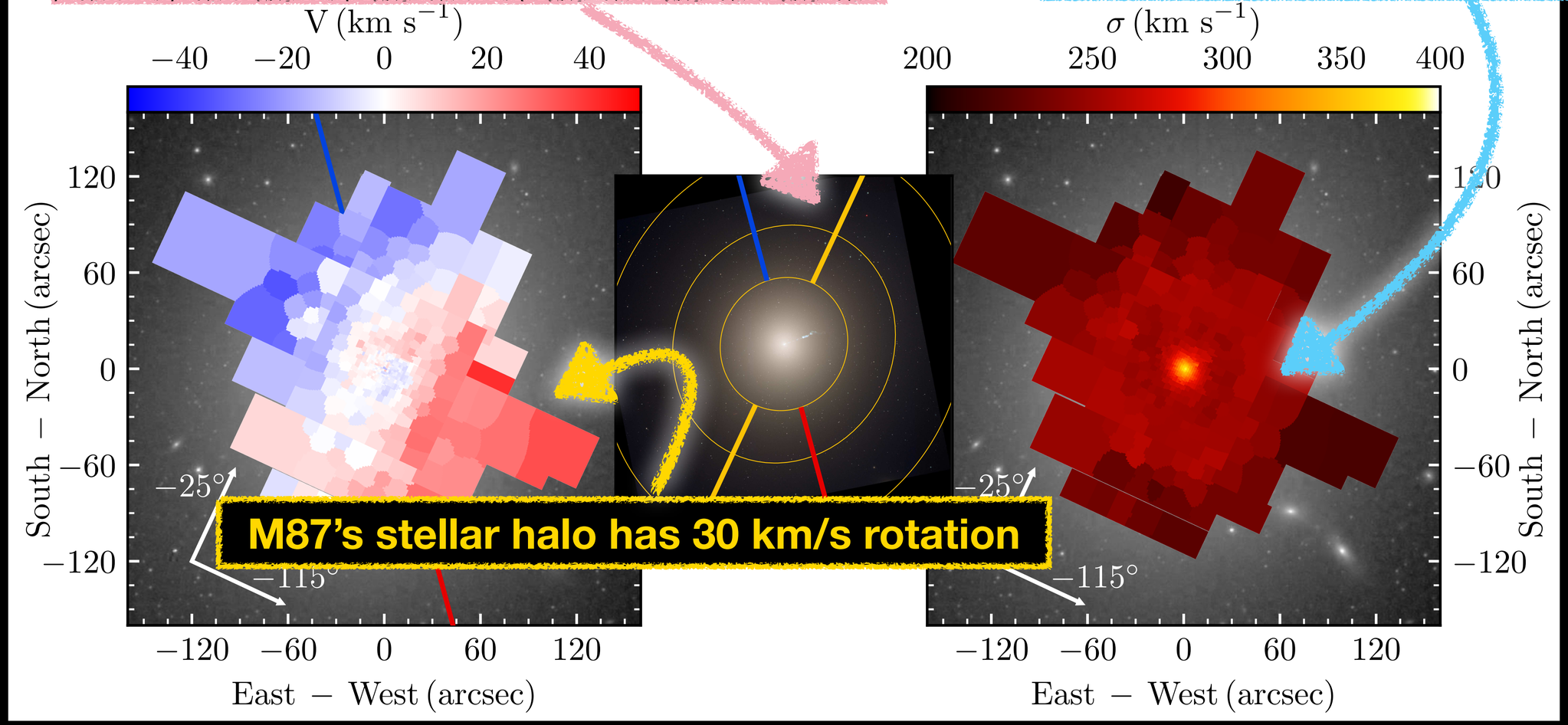
**The velocity dispersion rises *quickly* towards the center!**

**Tell-tale sign of a black hole!**

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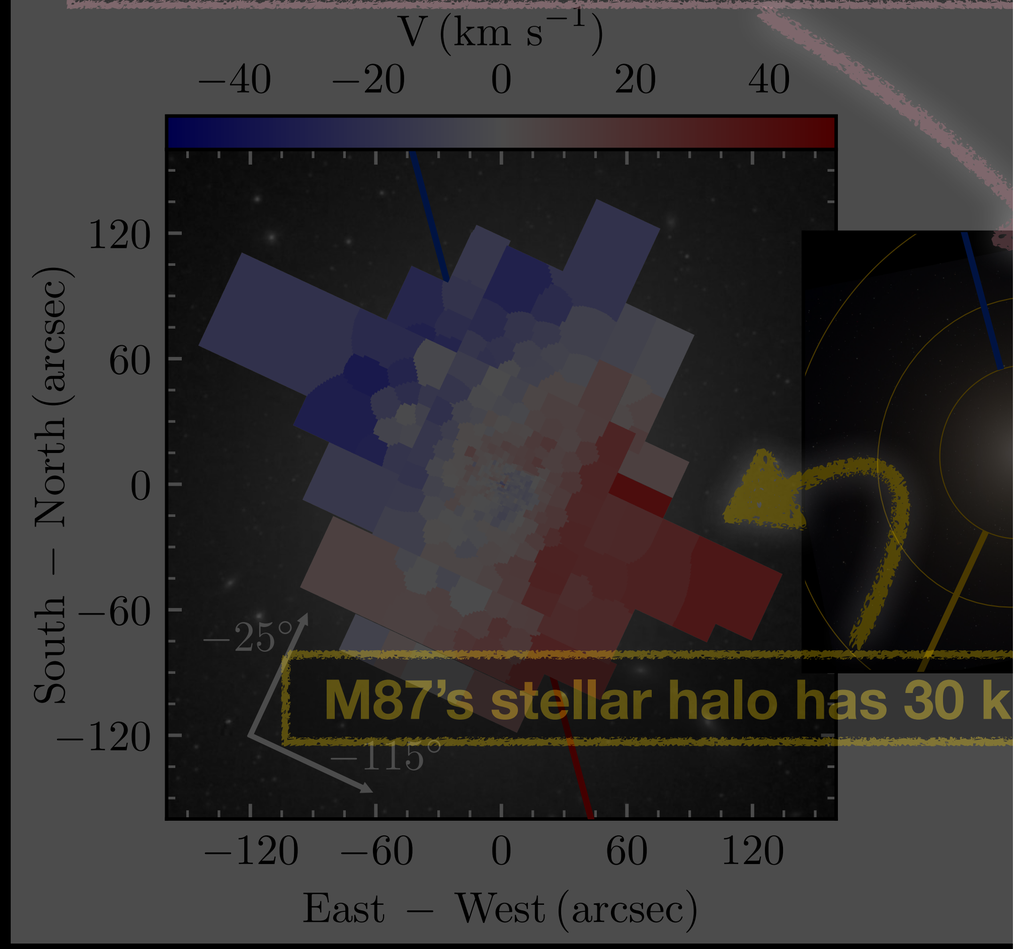


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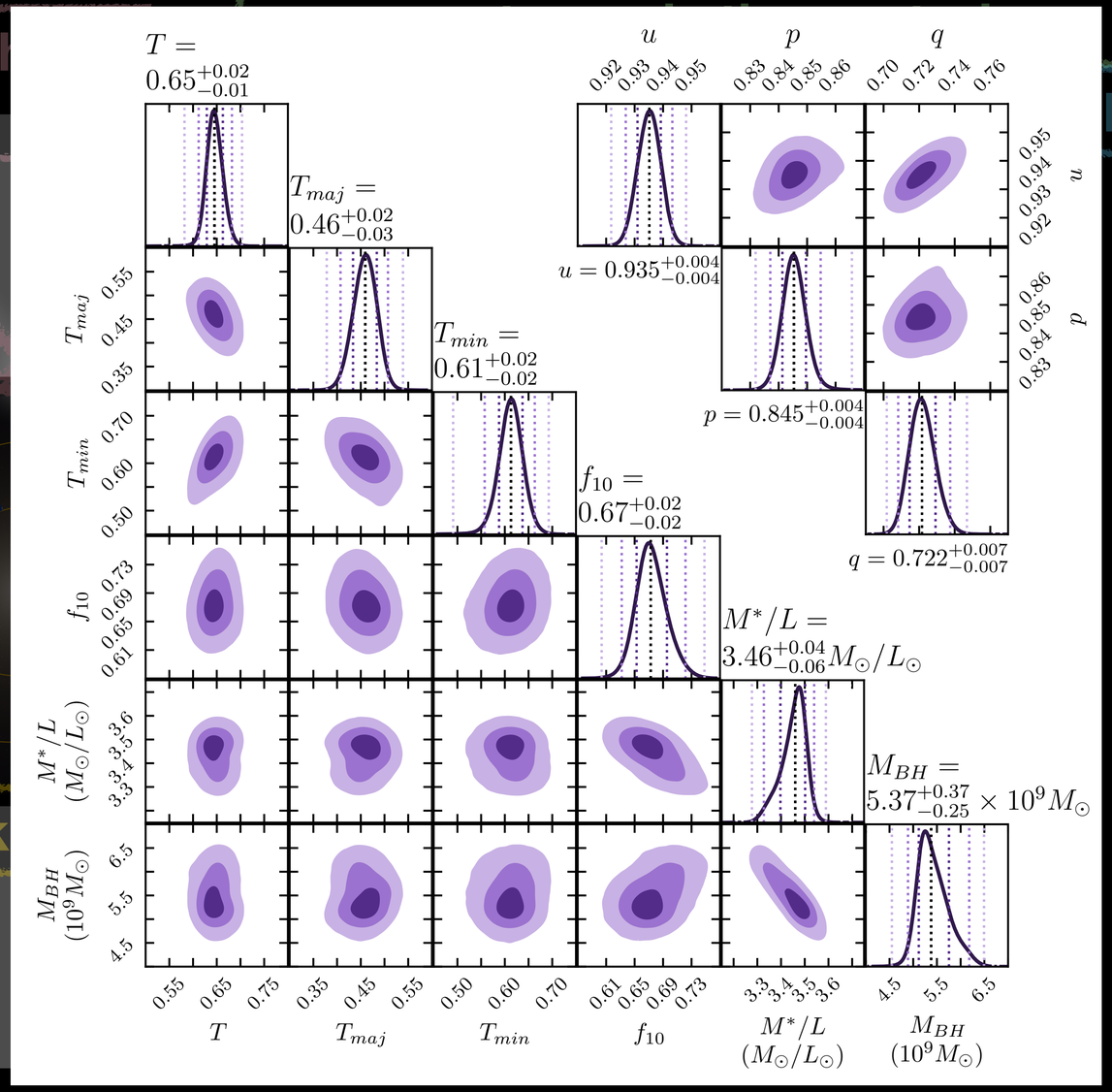
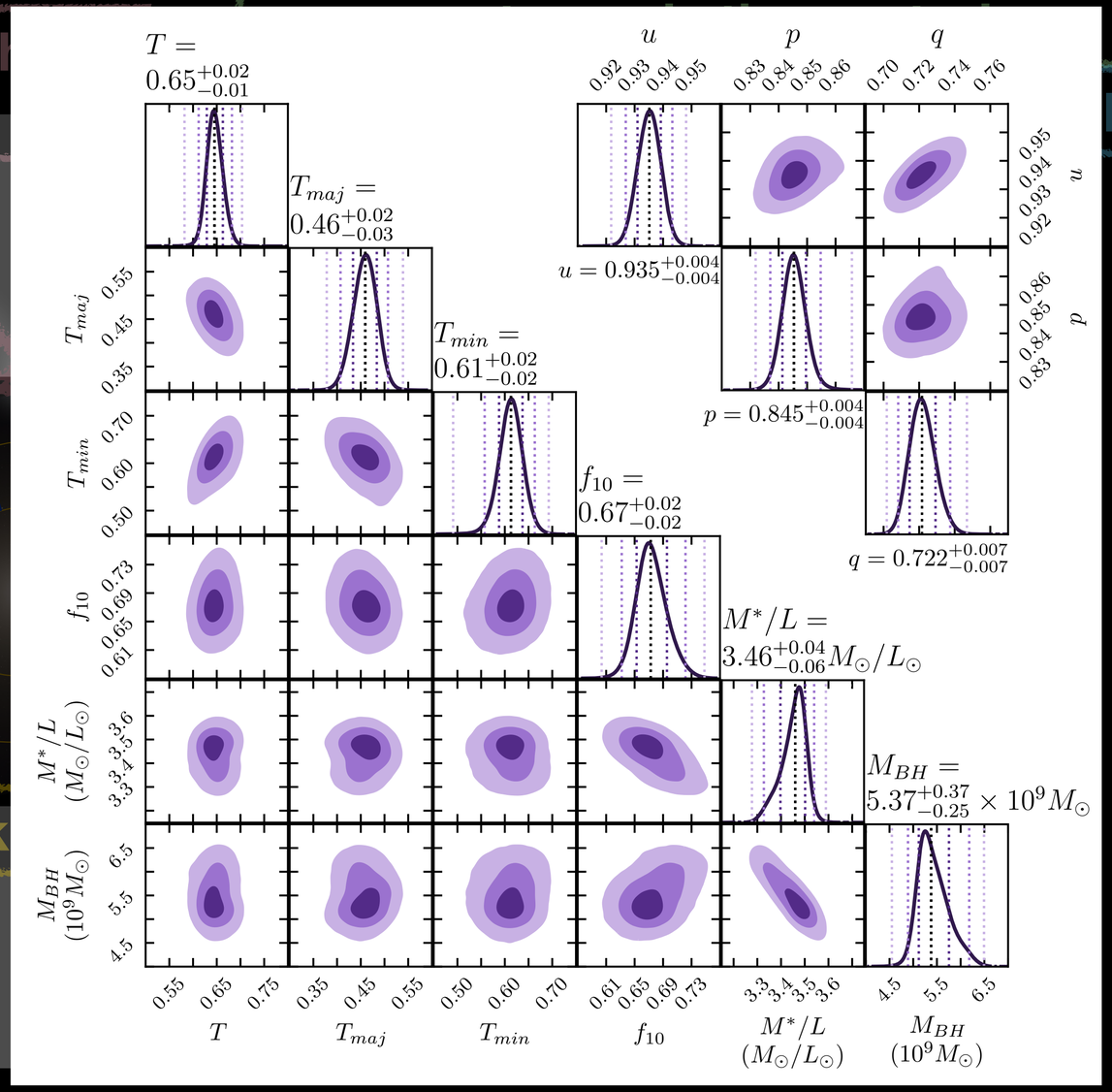


# First triaxial shape measurements of M87

Liepold, Ma, Walsh 2023

- Ran ***~20,000*** triaxial orbit models with ***5,000*** kinematic observations
- ***First*** measurement of the triaxial shape of M87's stellar halo
- Refined stellar dynamical measurement of the SMBH mass (5.4 Billion $M_\odot$)
- A puzzle: apparent alignment of the jet, the stellar **L** vector, and the Virgo cluster



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Arxiv:2510.02439

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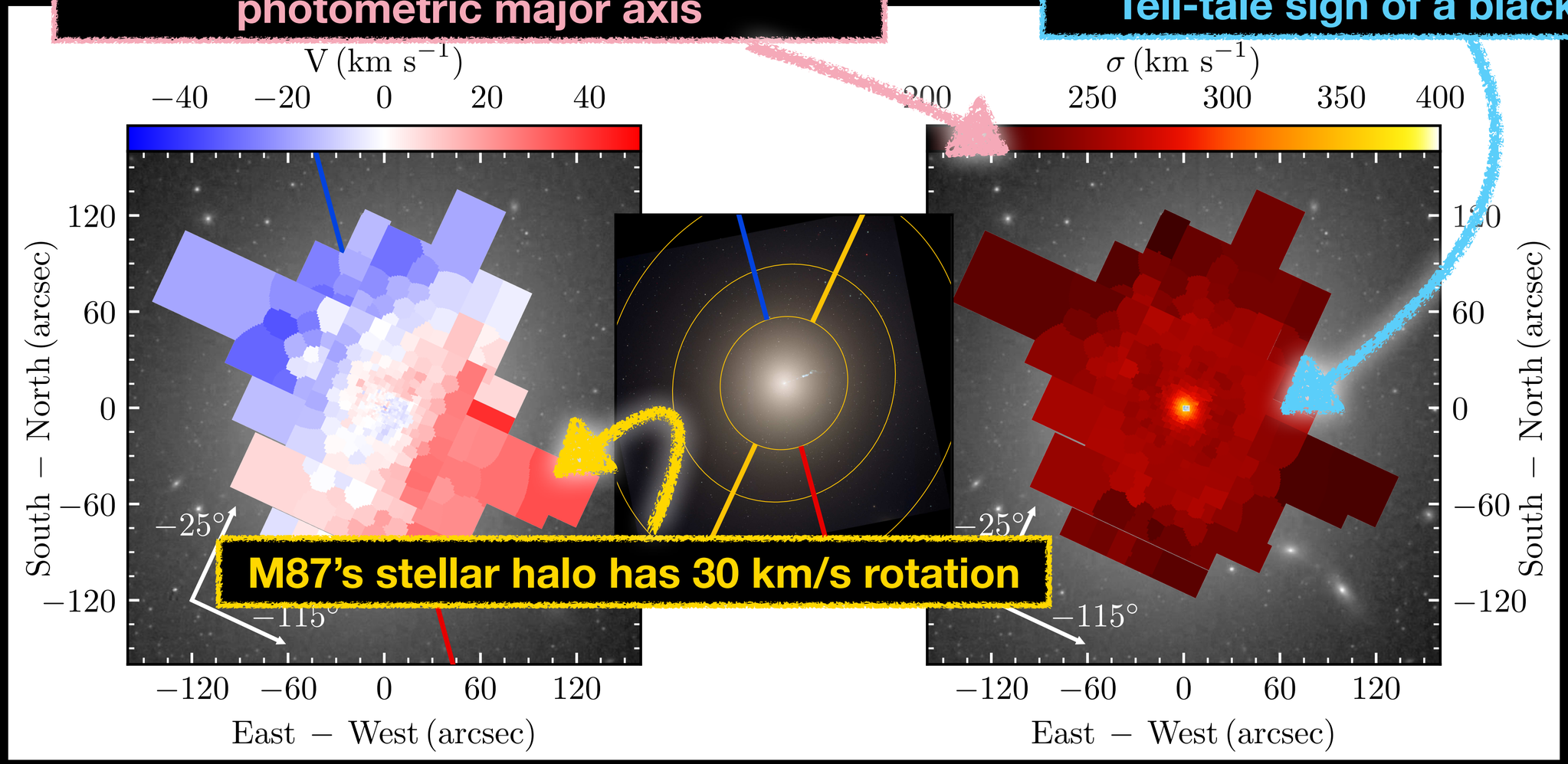


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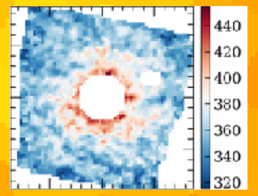

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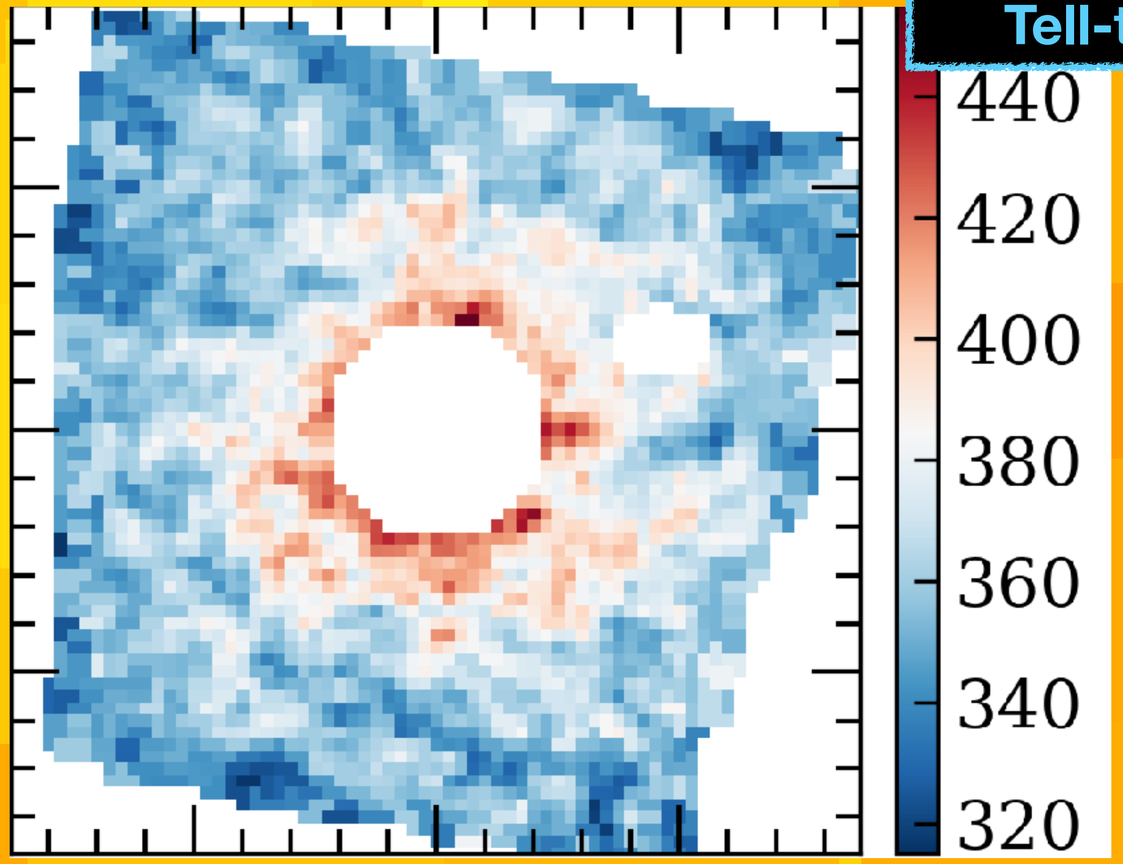

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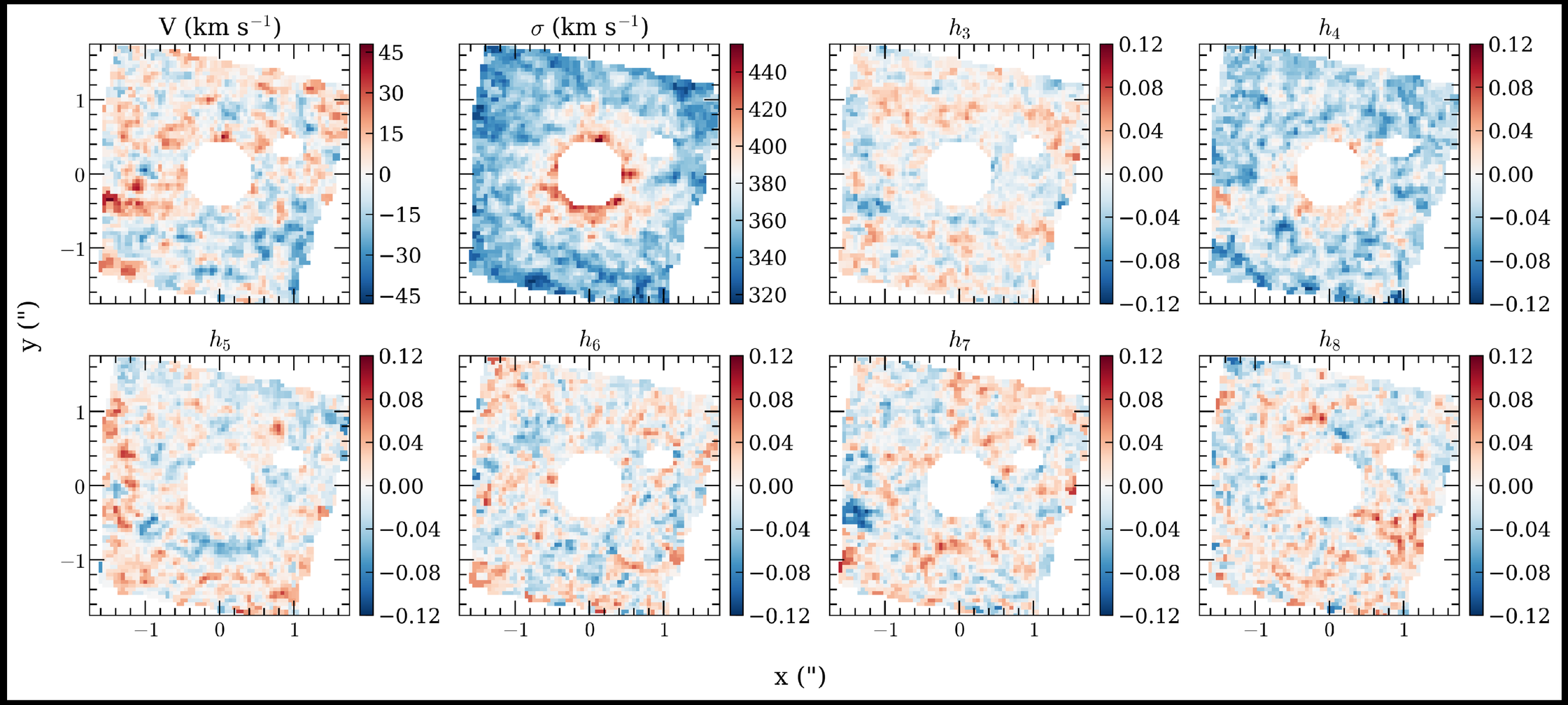

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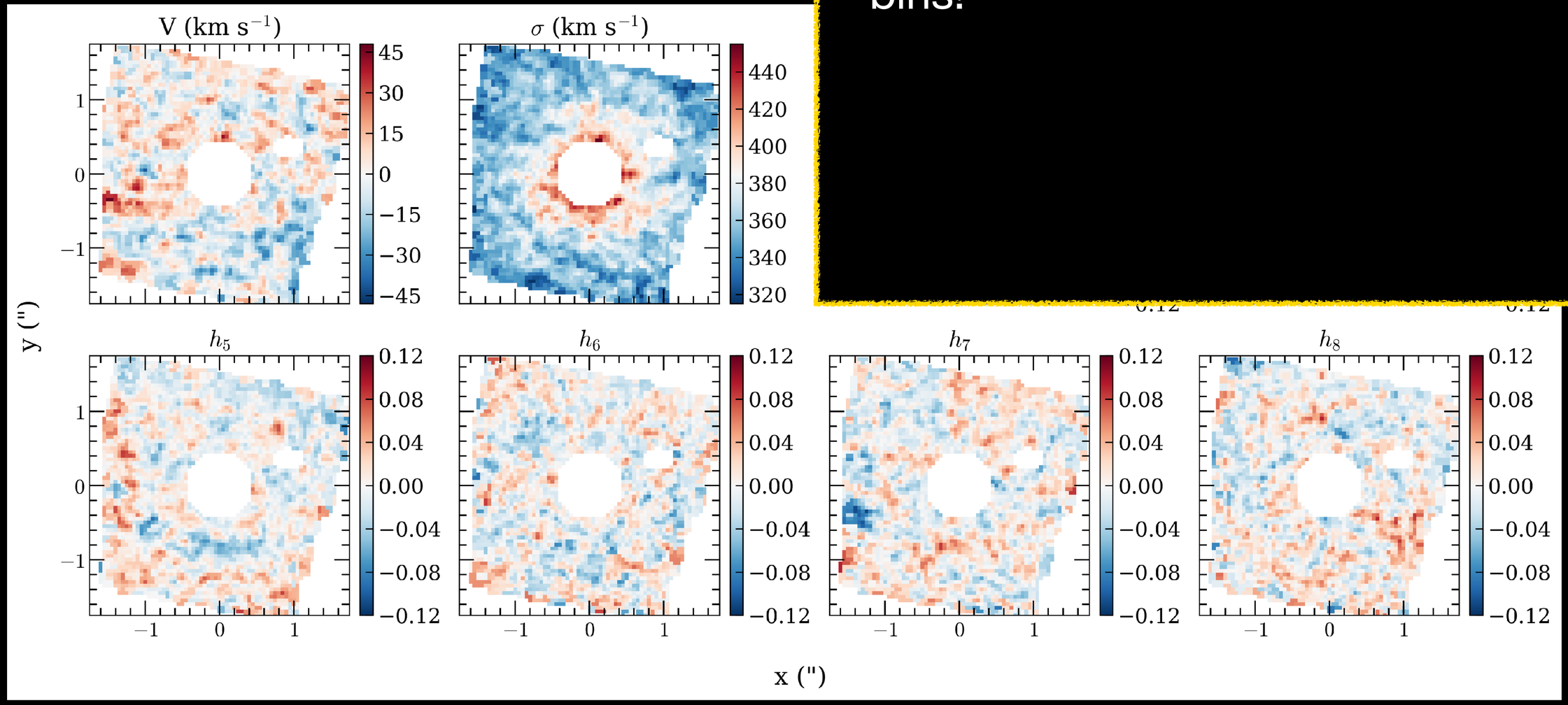

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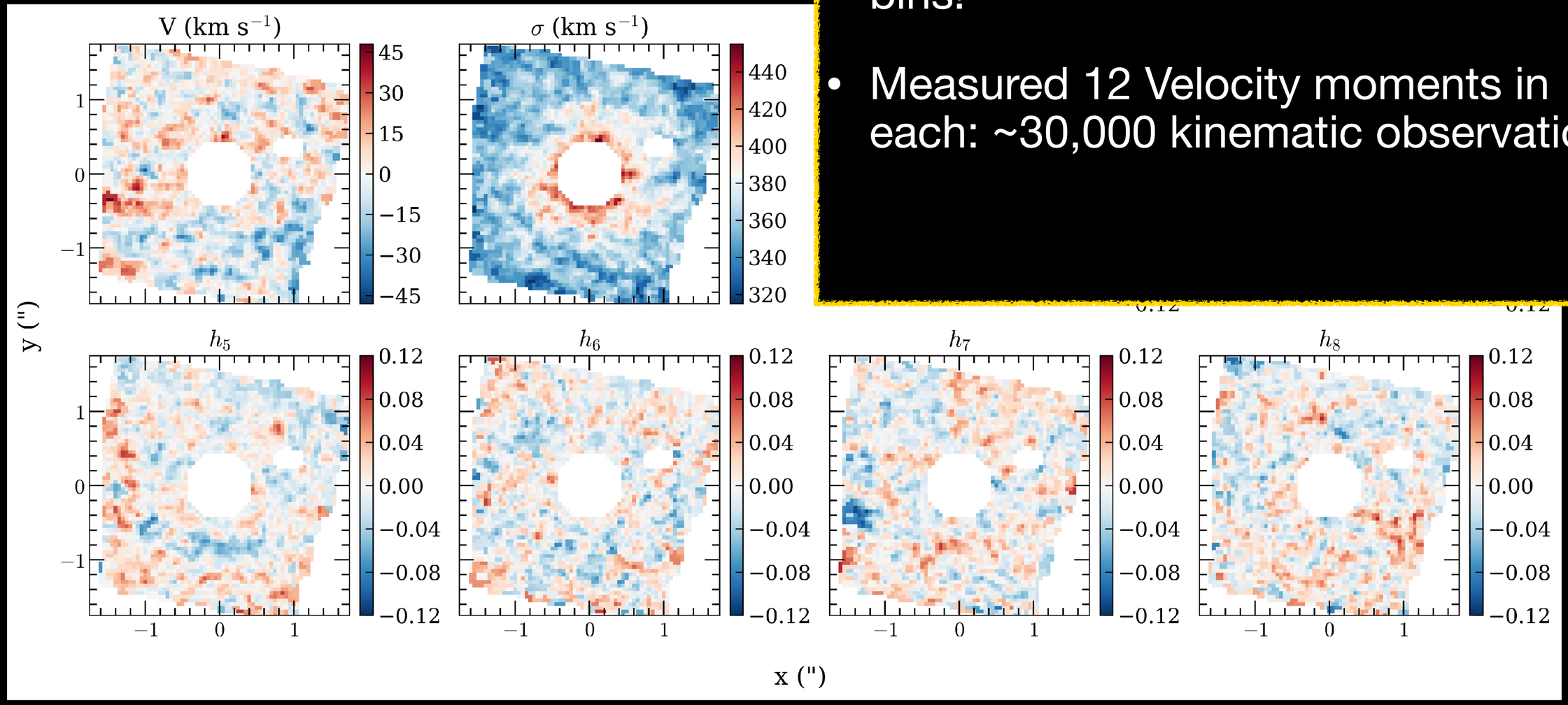

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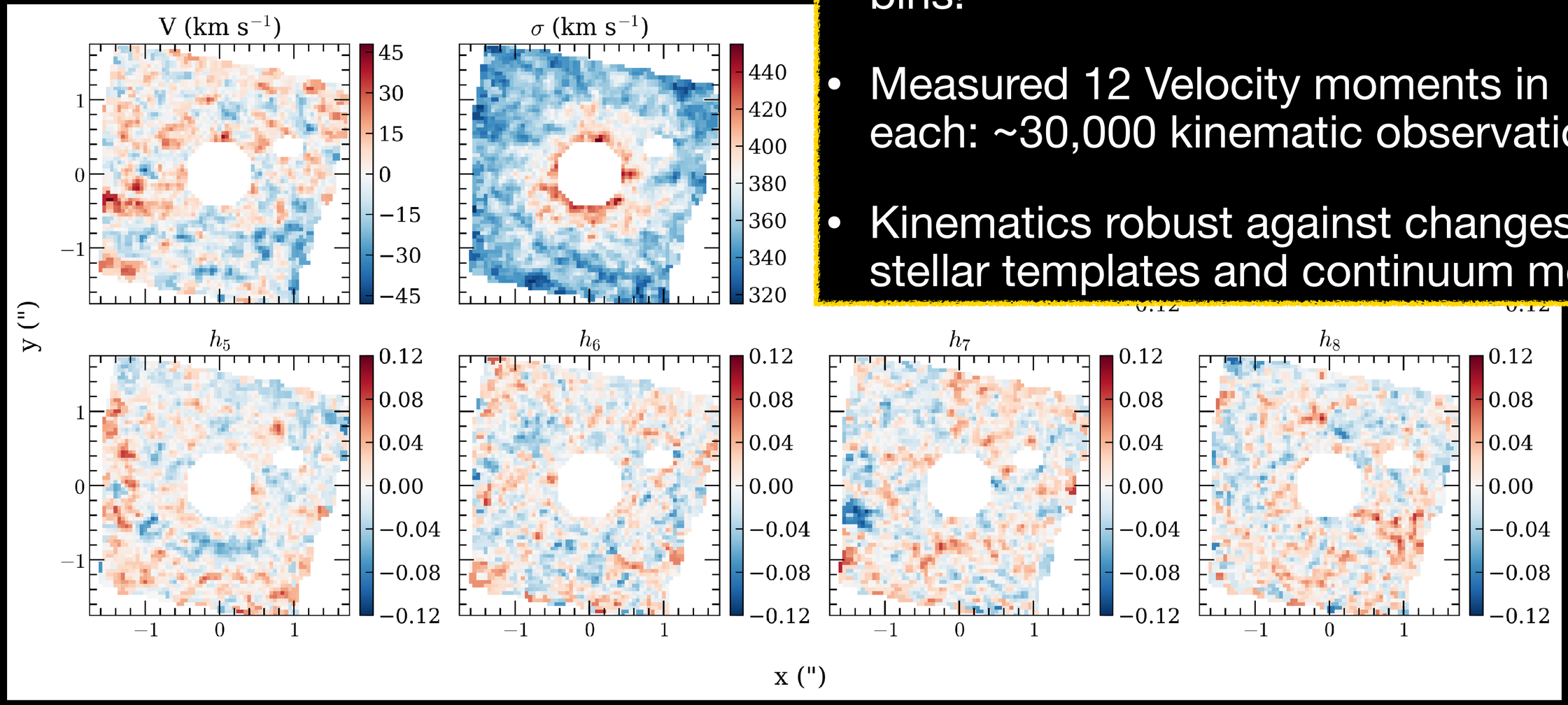

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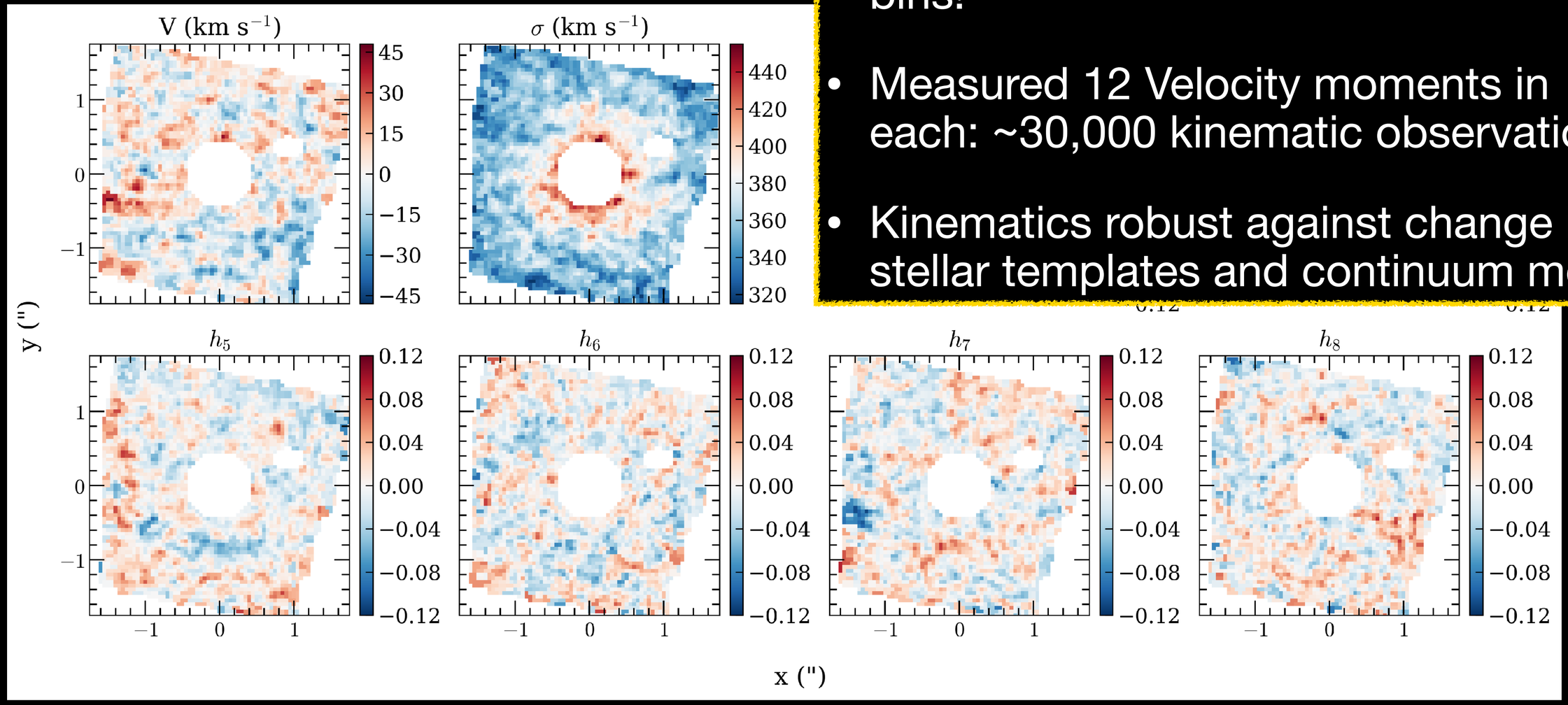

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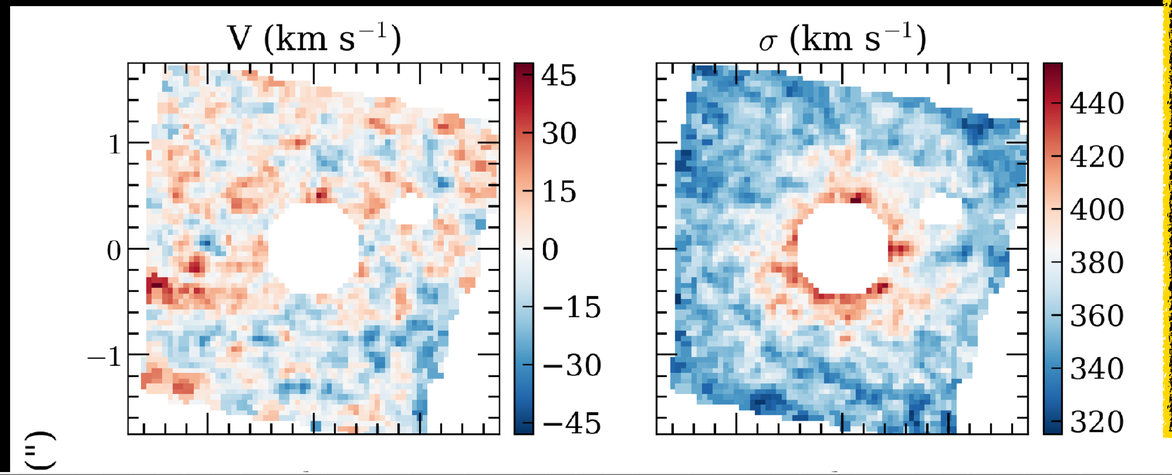


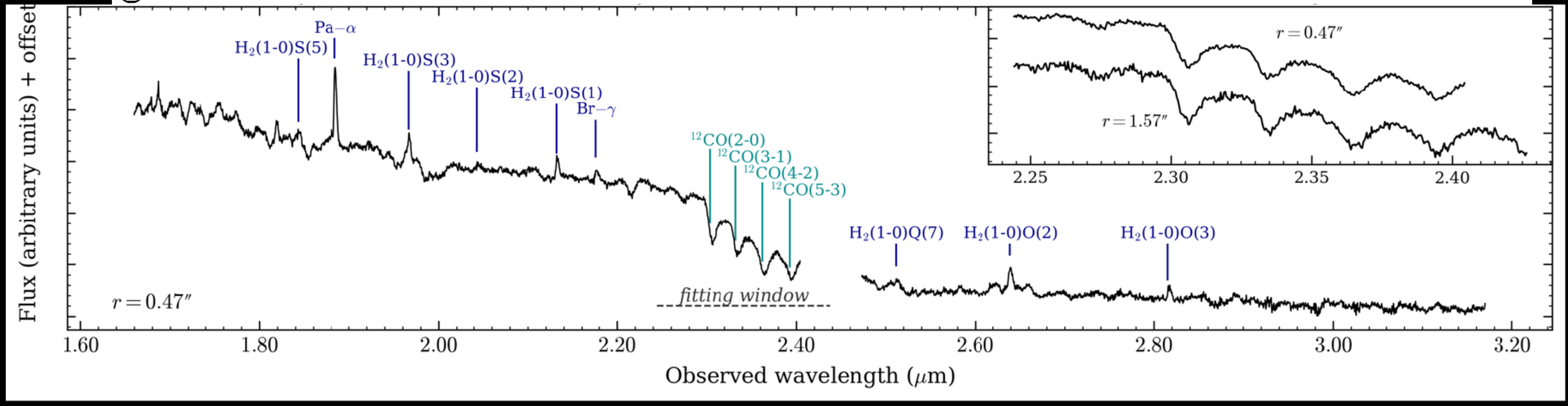

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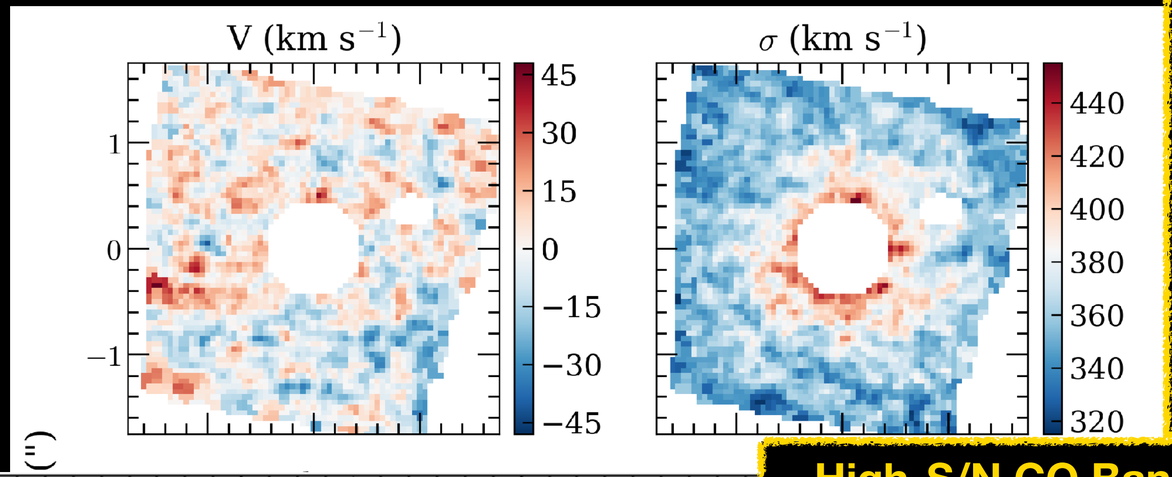
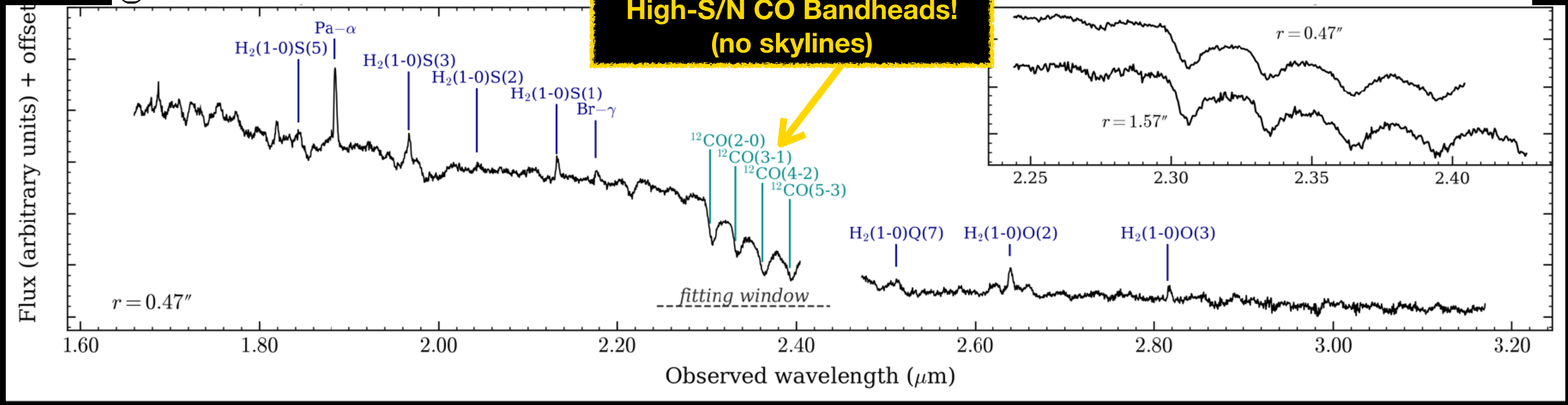


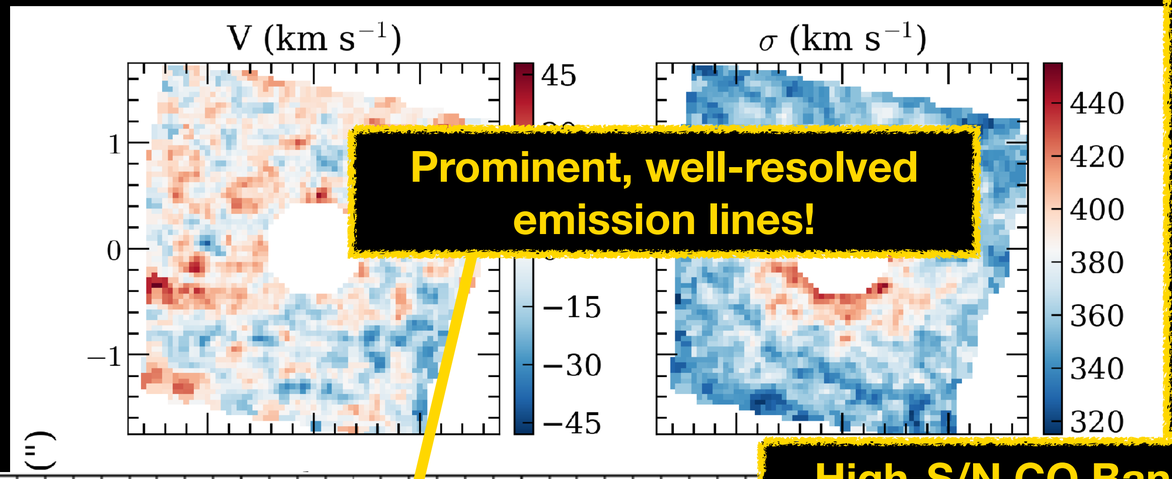

**High-S/N CO Bandheads! (no skylines)**



# JW NIRSpec observations of M87

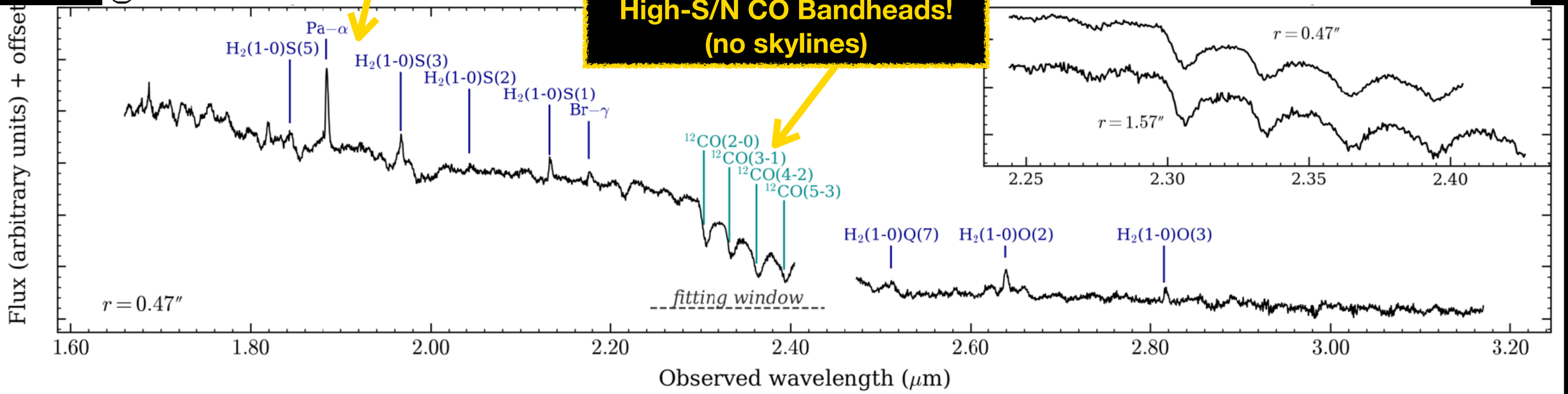
Al-Amri, Walsh, Liepold et al. 2025
Arxiv:2510.02439

- High-S/N spectra in ~2500 spatial bins!
- Measured 12 Velocity moments in each: ~30,000 kinematic observations
- Kinematics robust against change in stellar templates and continuum model




**Prominent, well-resolved emission lines!**

**High-S/N CO Bandheads! (no skylines)**



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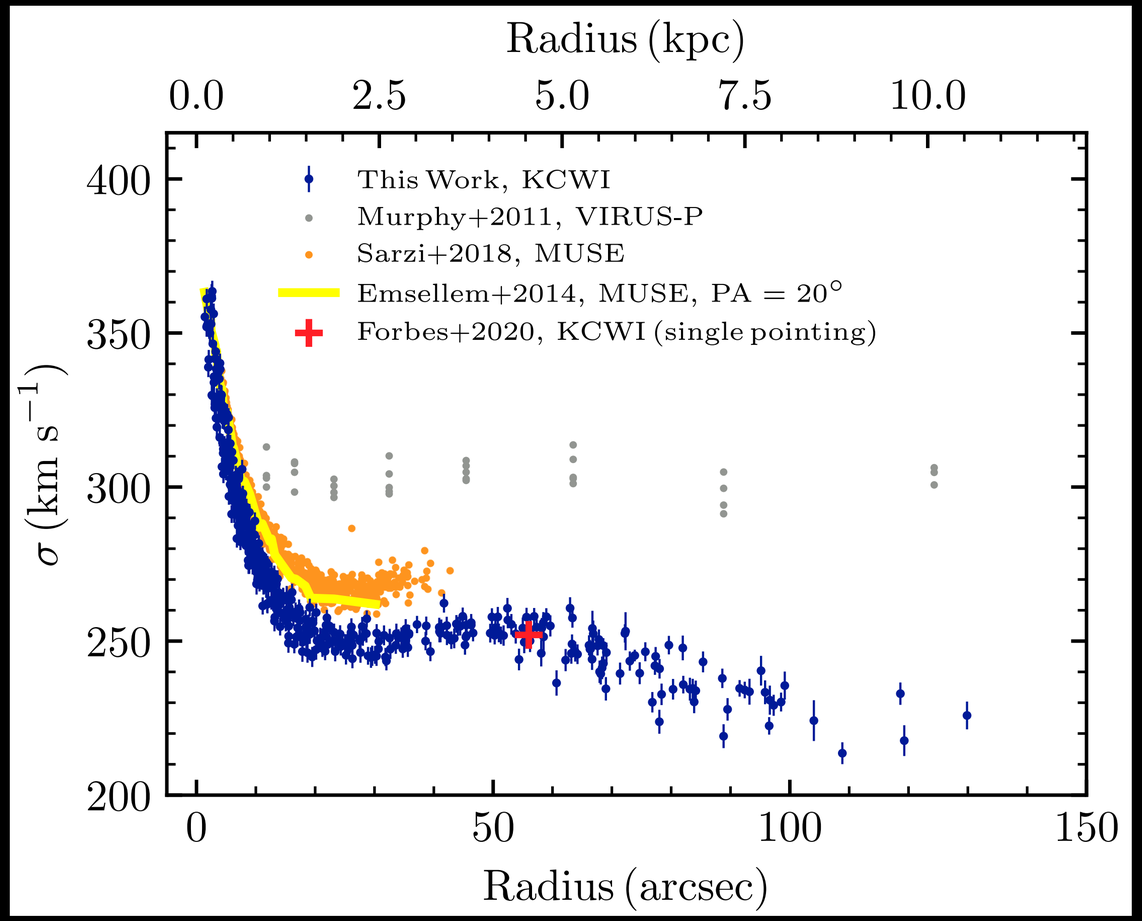


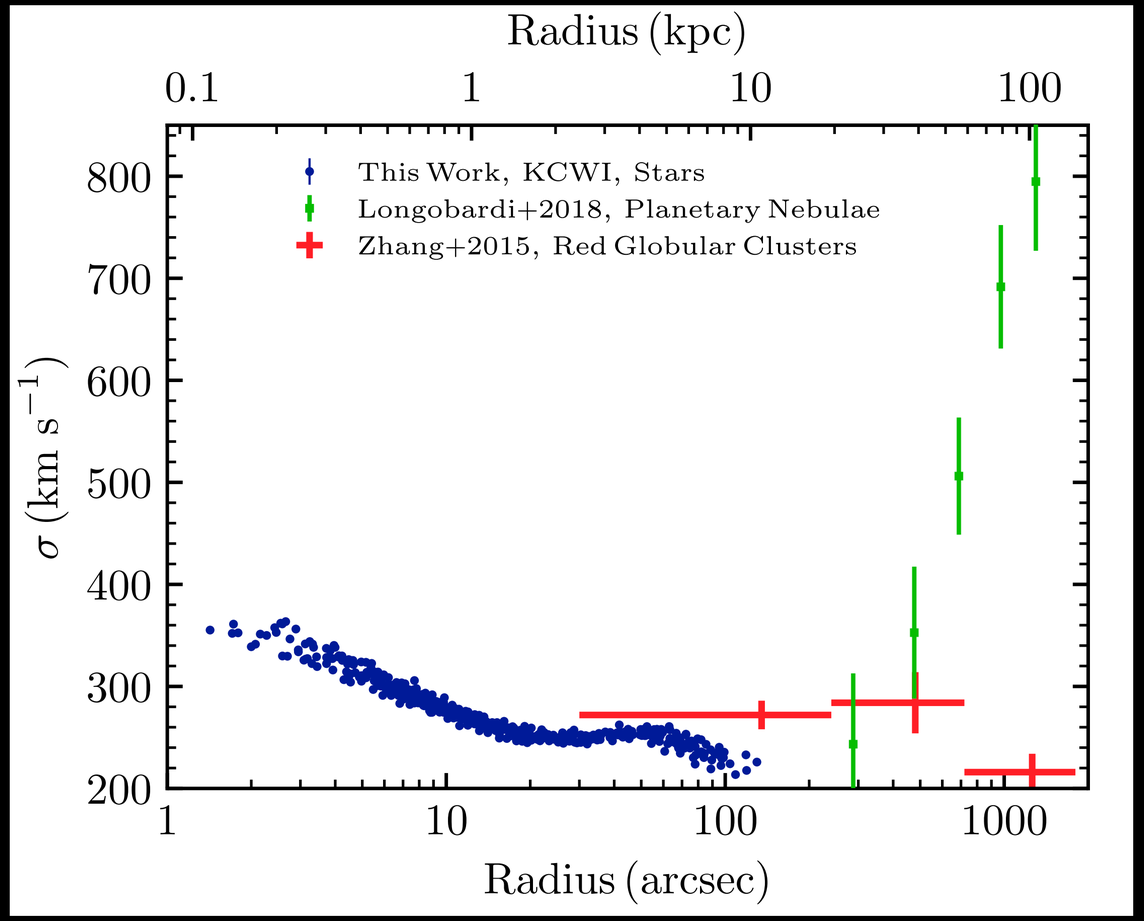

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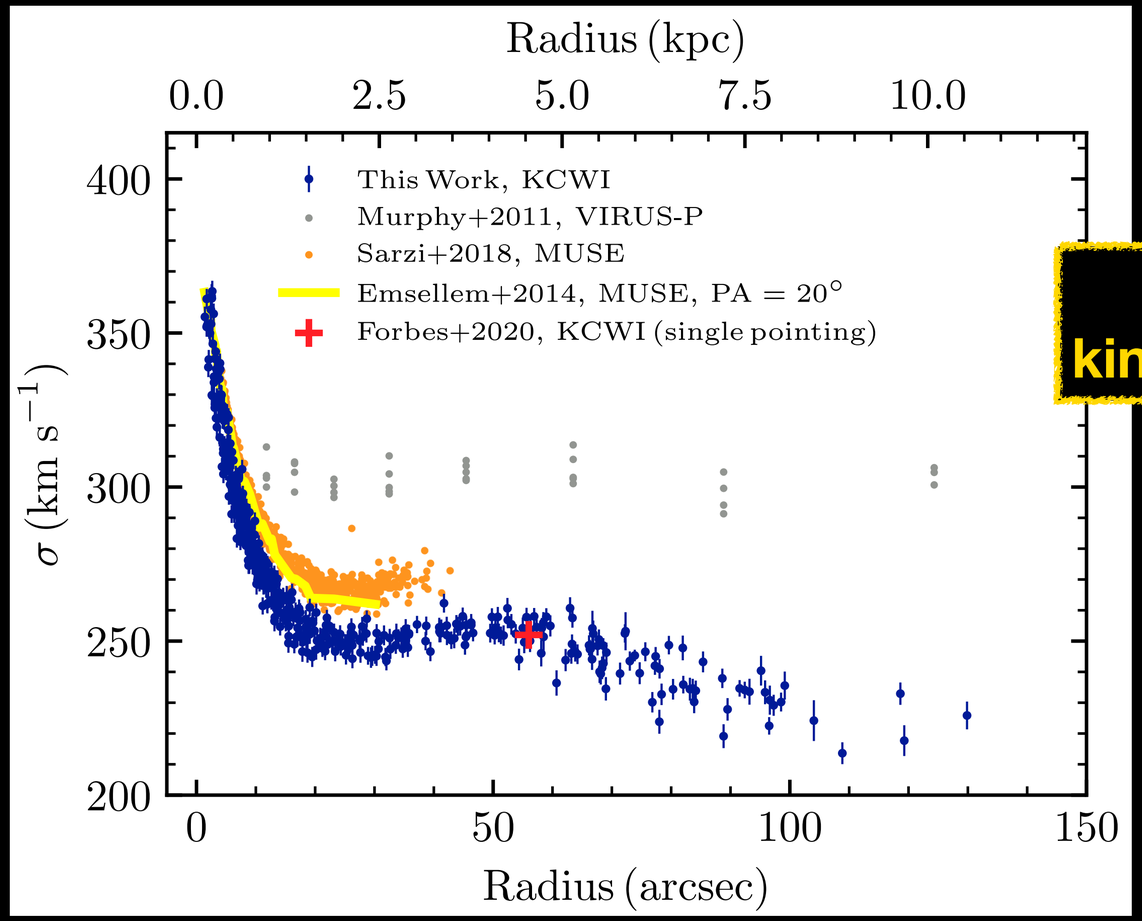


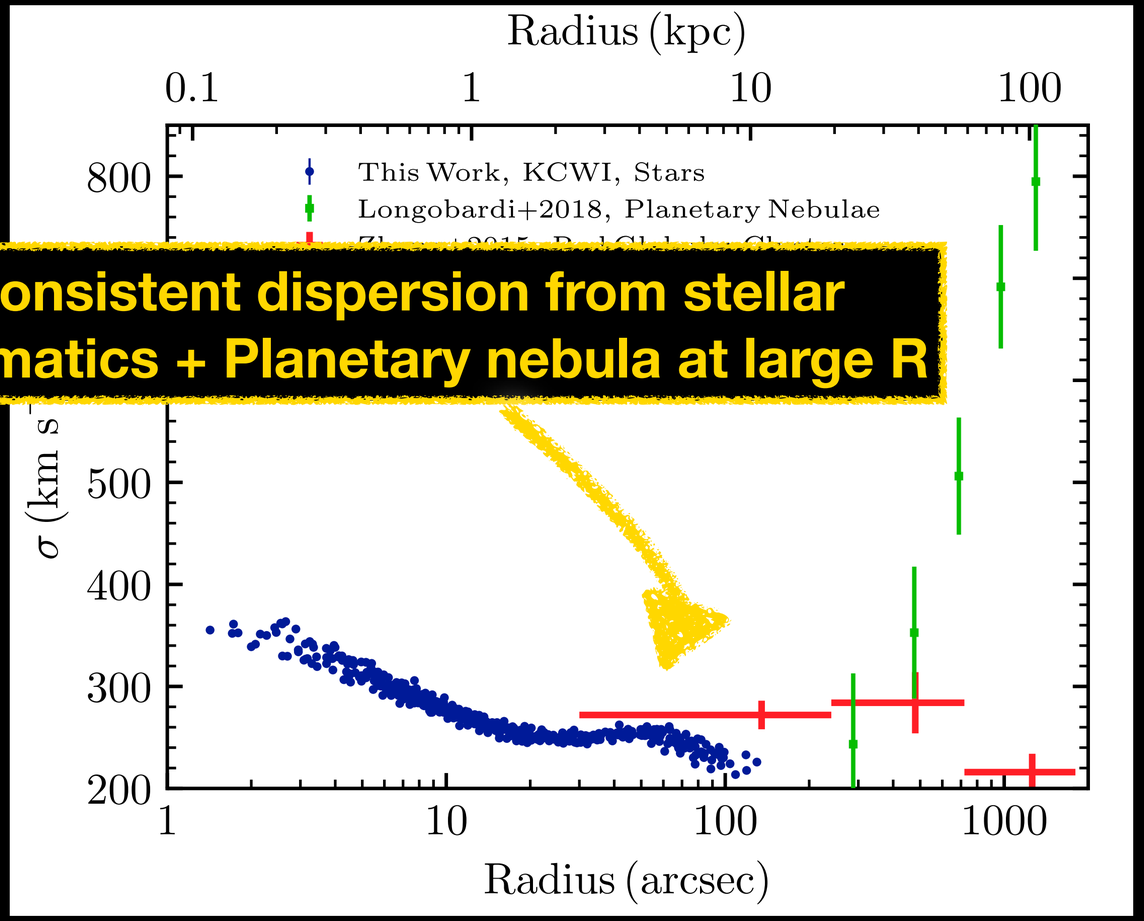


**Consistent dispersion from stellar kinematics + Planetary nebula at large R**

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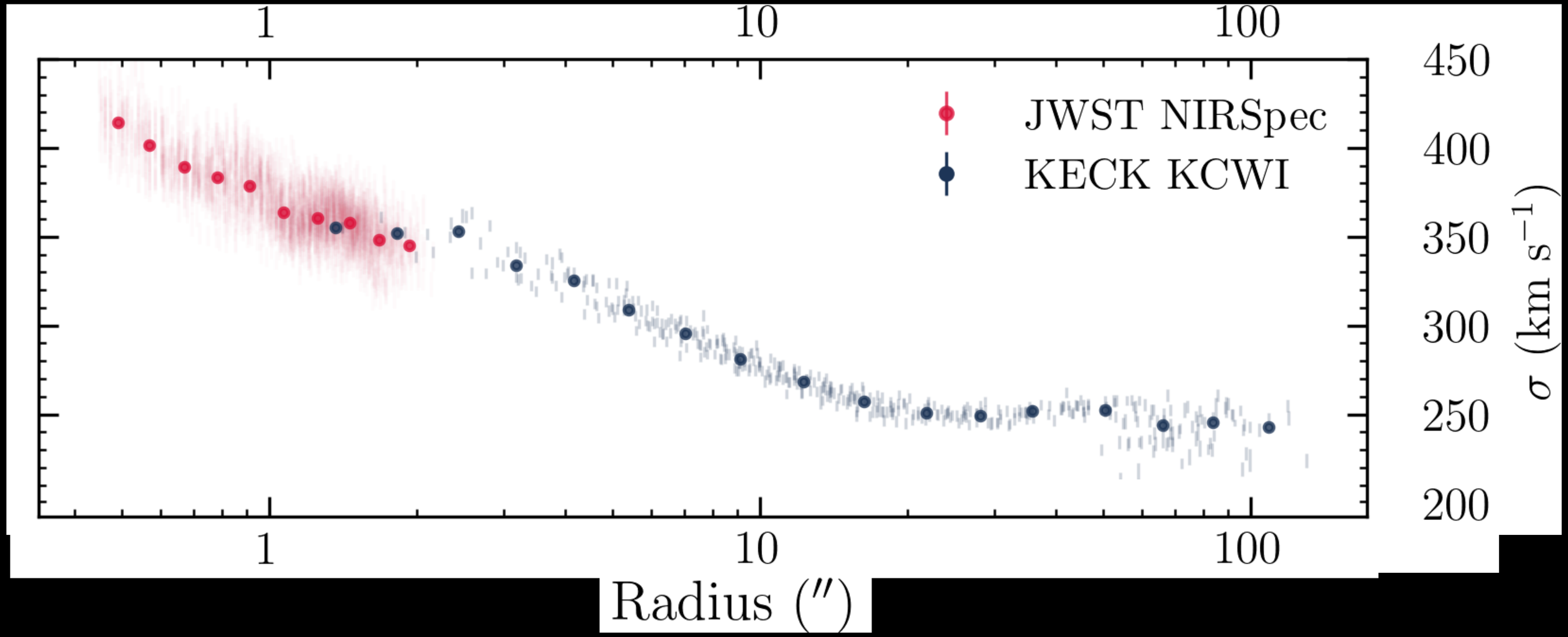

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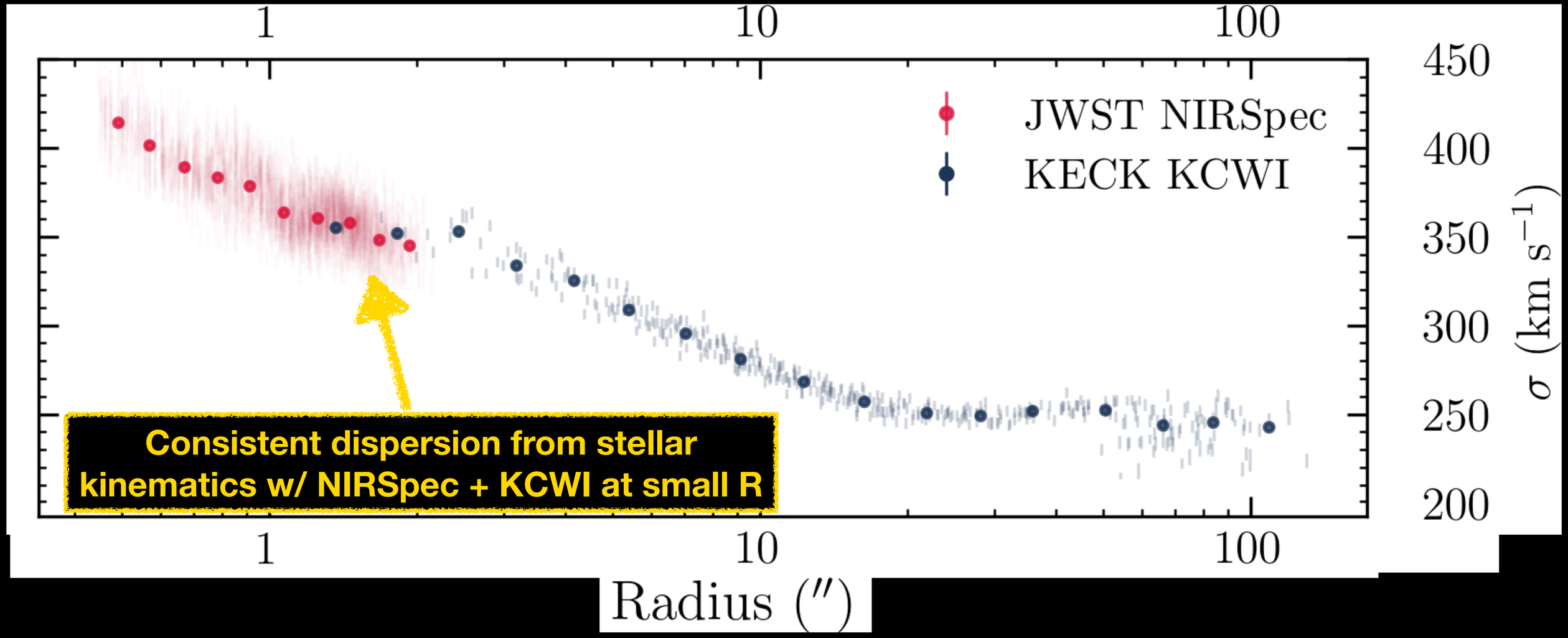

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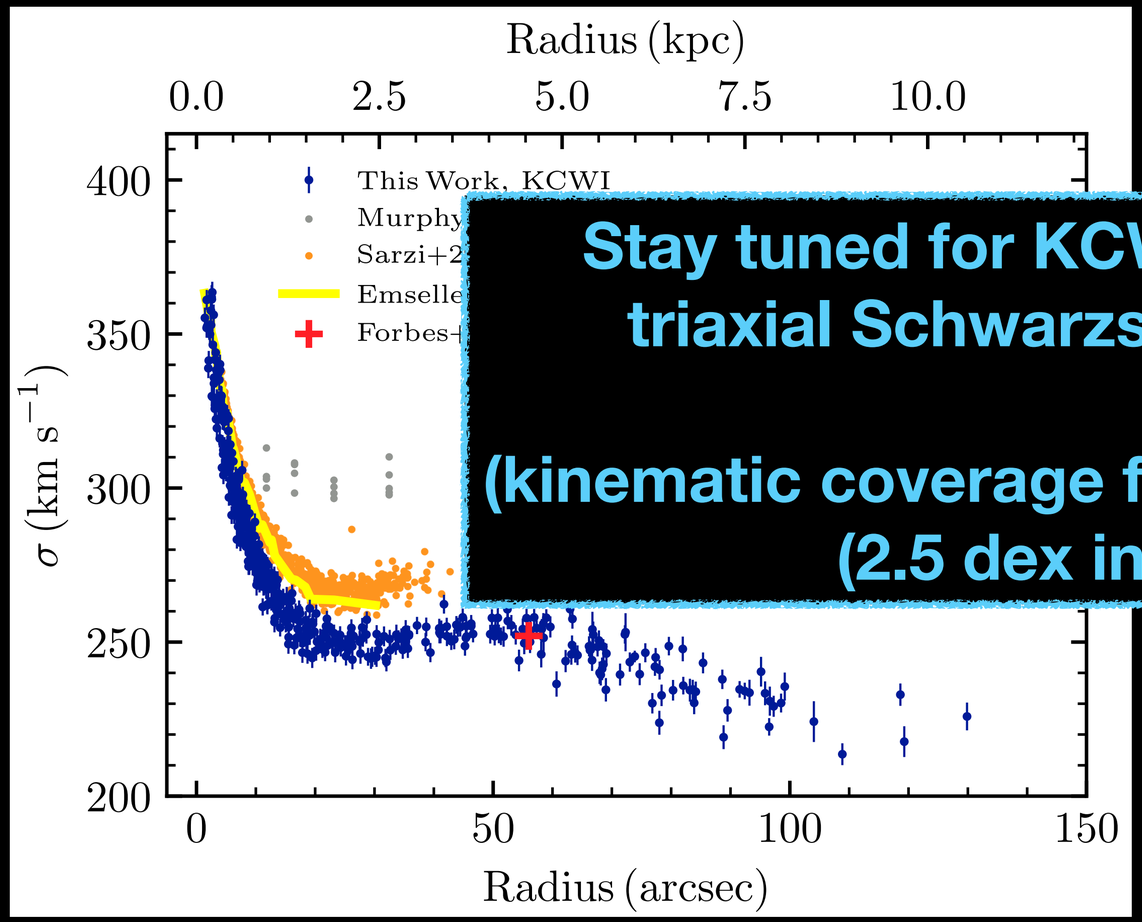
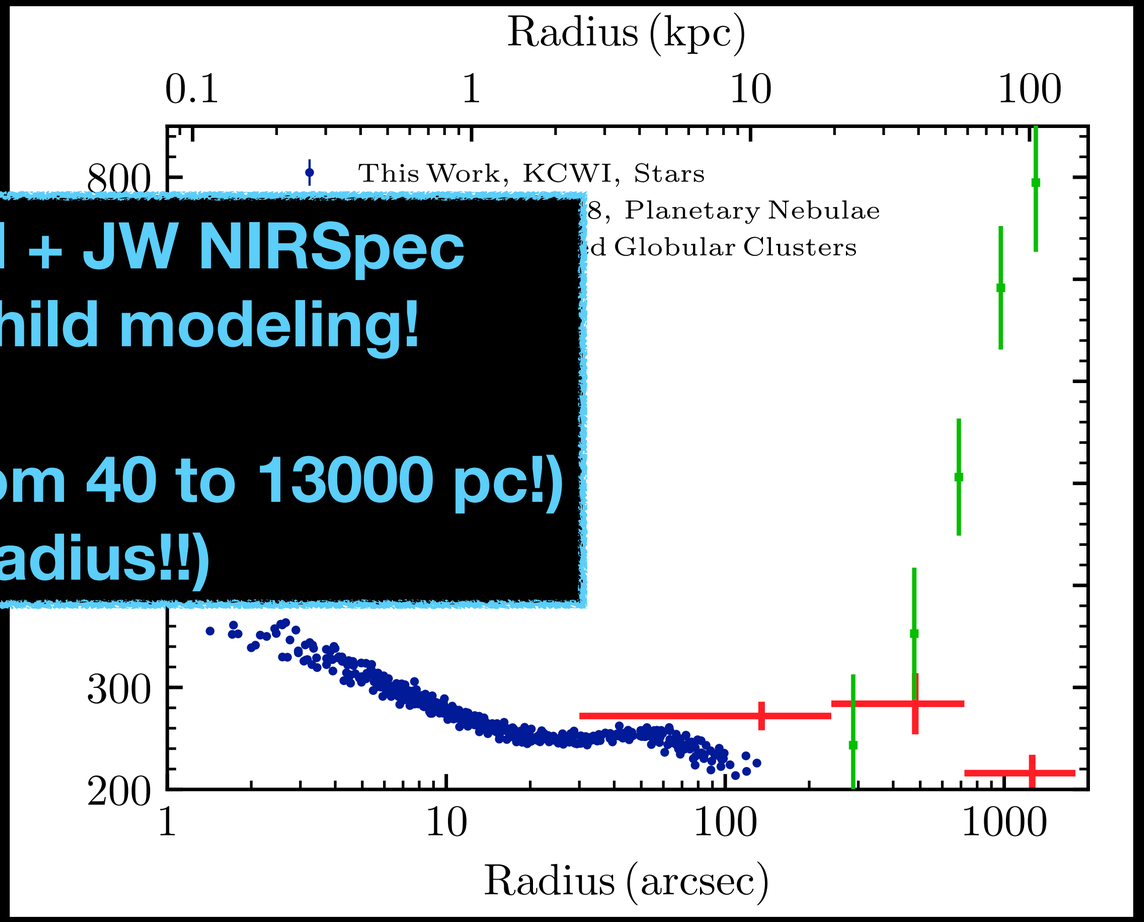



**Stay tuned for KCWI + JW NIRSpec triaxial Schwarzschild modeling!**

**(kinematic coverage from 40 to 13000 pc!)**
**(2.5 dex in radius!!)**



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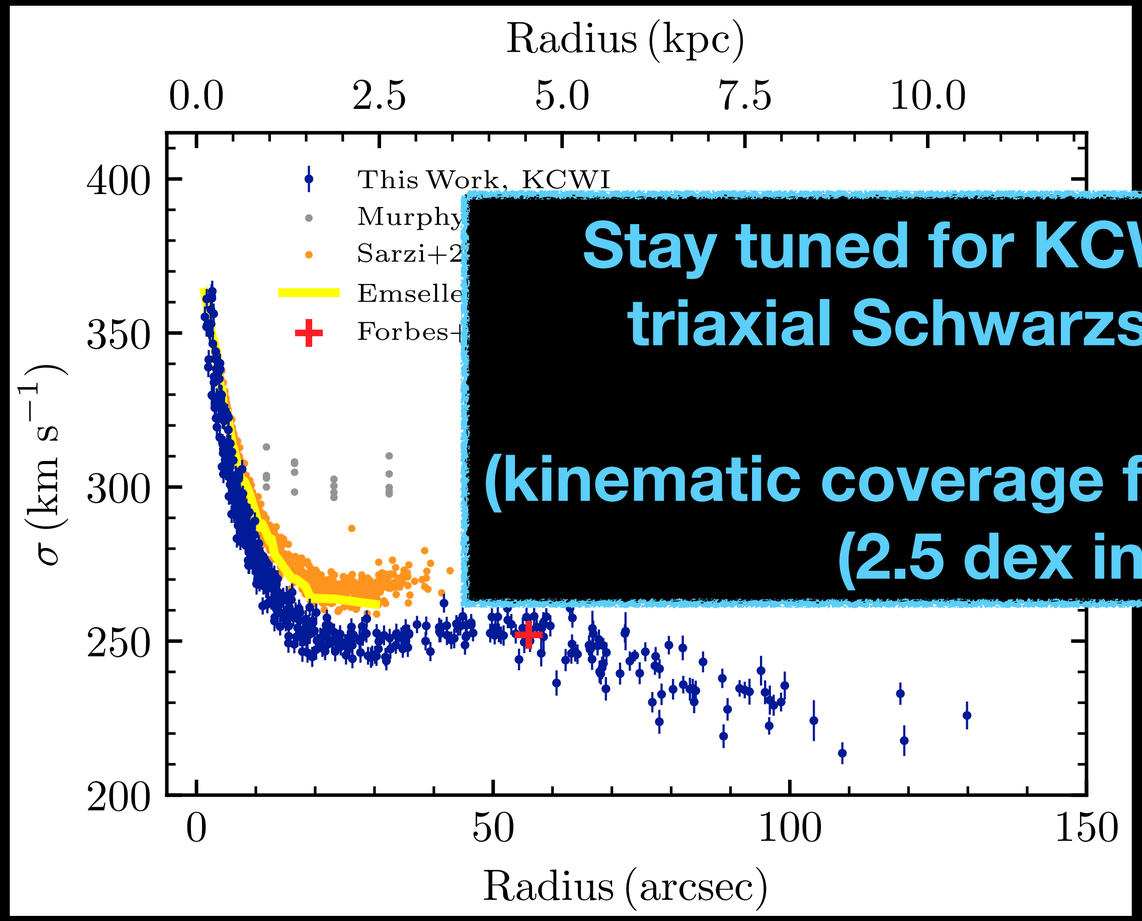


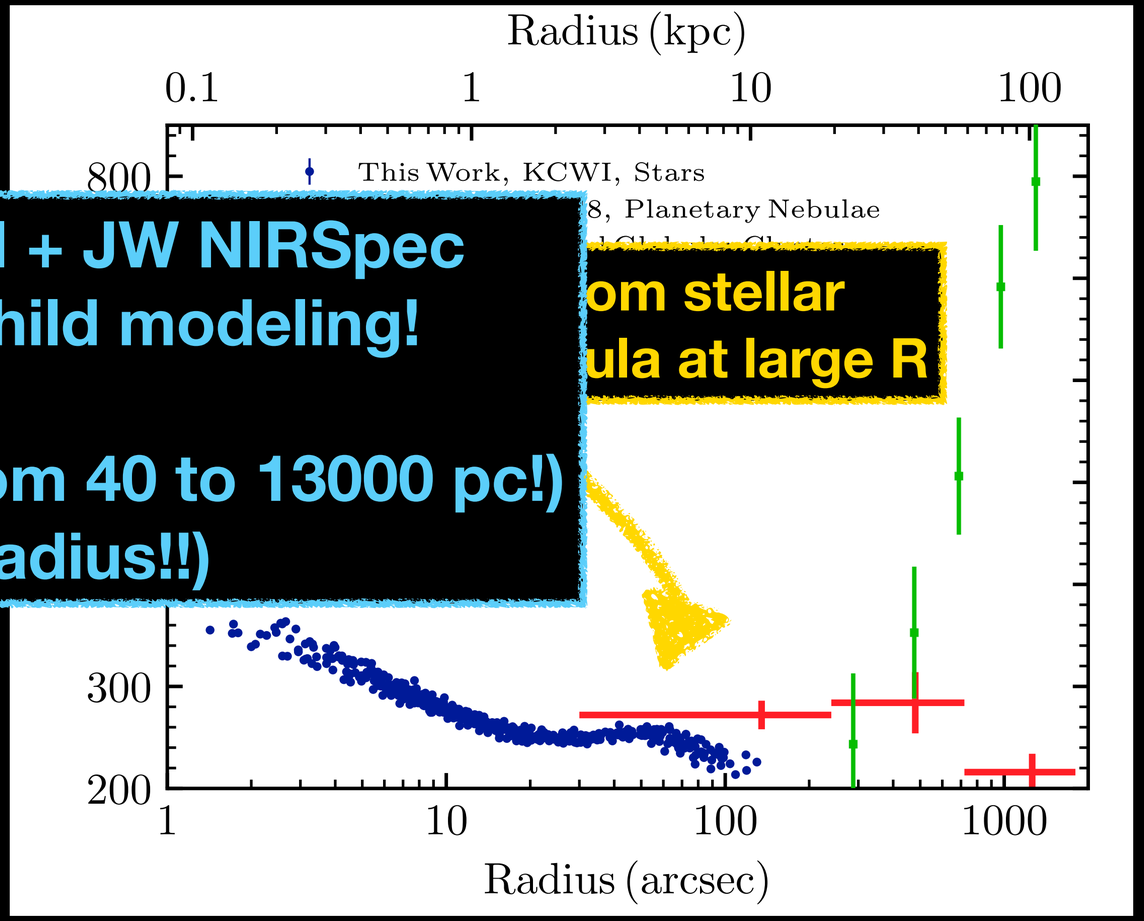


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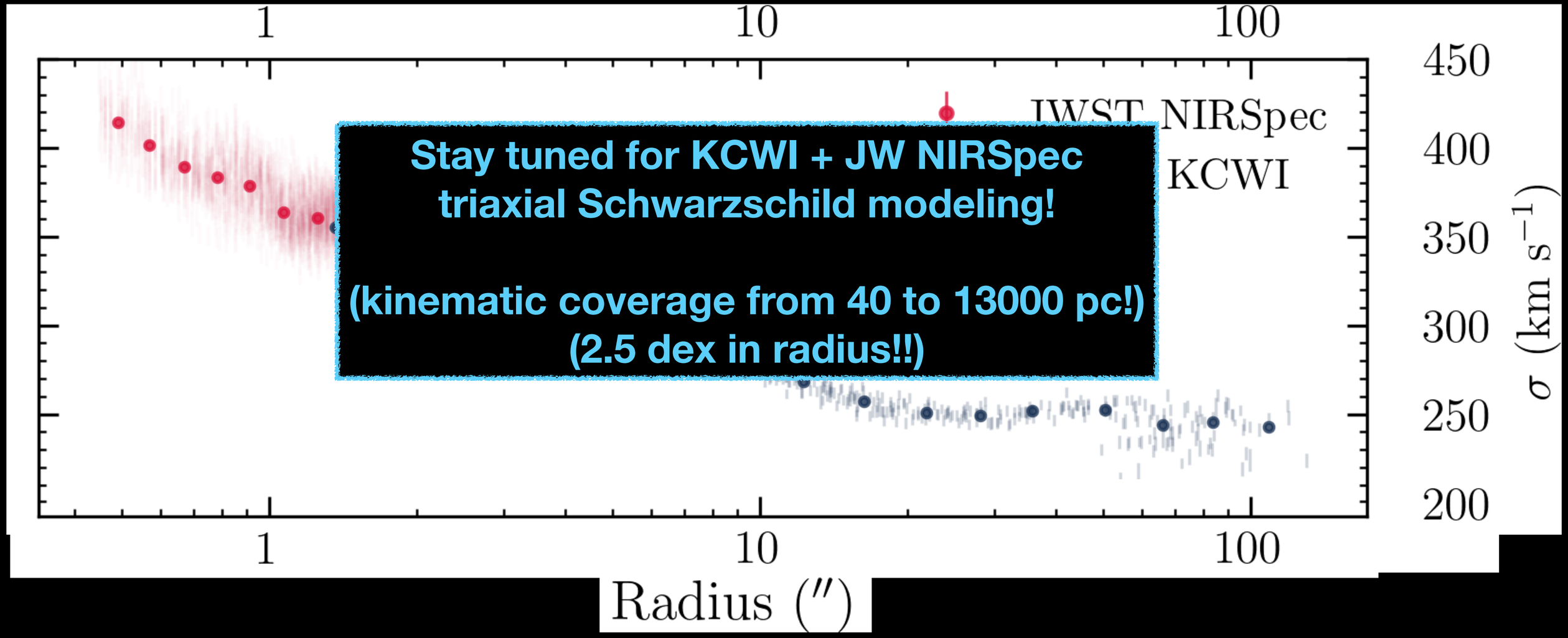

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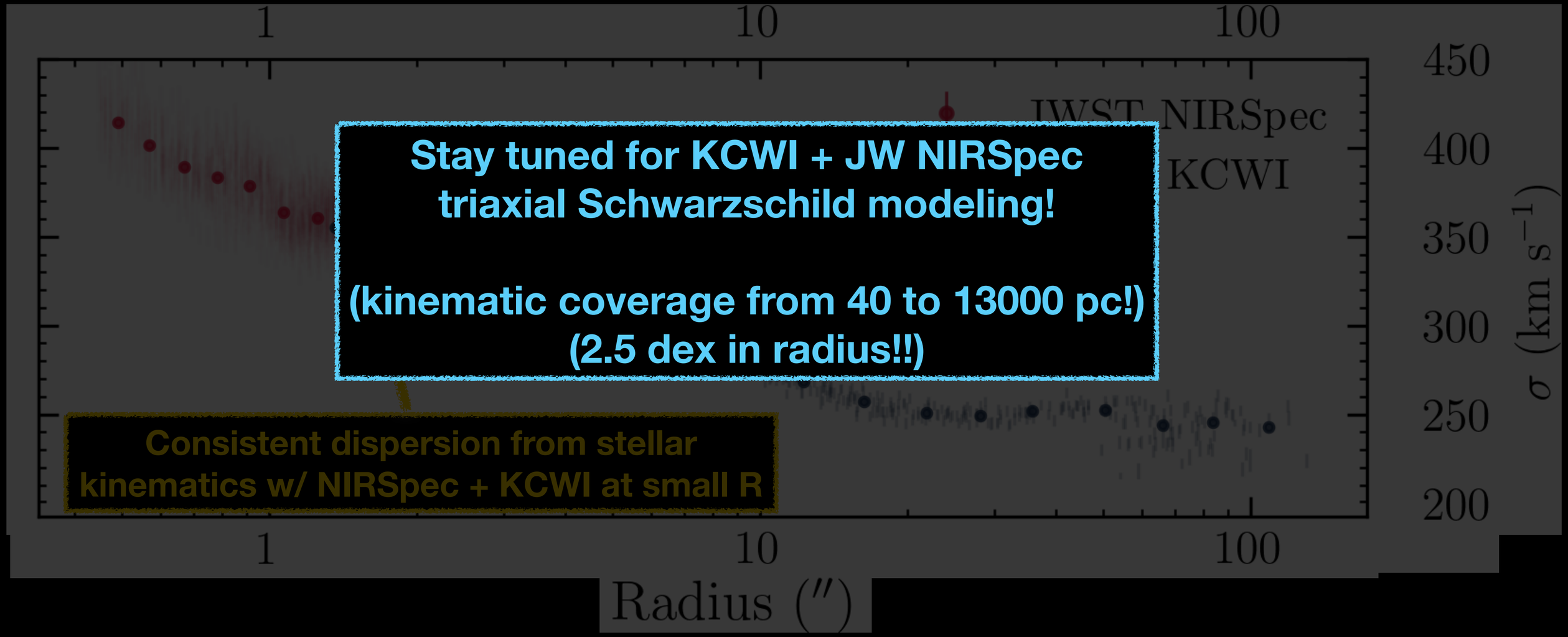


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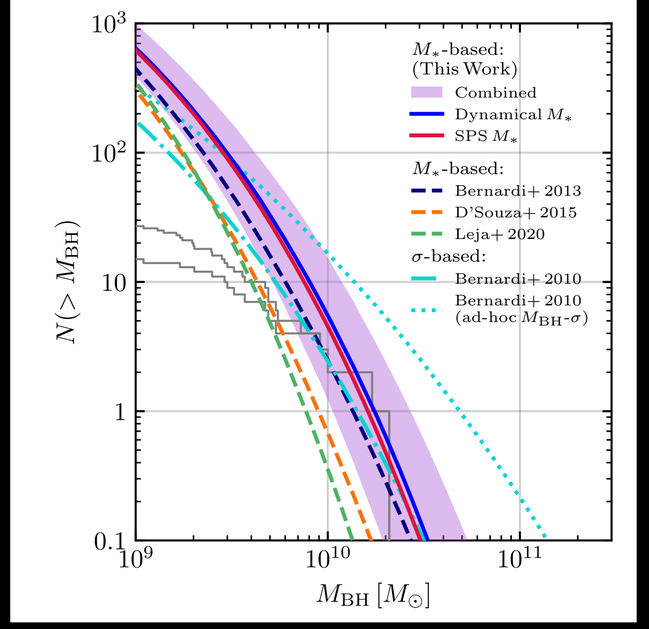
**Consistent dispersion from stellar kinematics w/ NIRSpec + KCWI at small R**

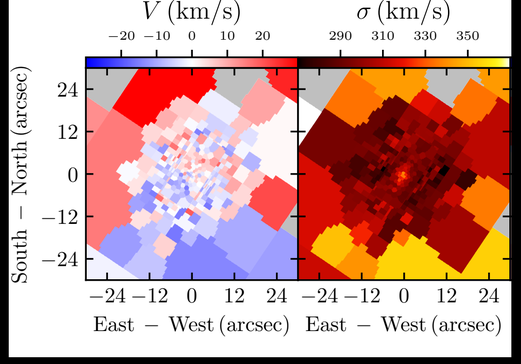
# Ongoing Efforts + Connections

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

  Keep an eye out for NGC57 (Pilawa+)

- **Ultra-MASSIVE galaxies with KCWI (several more to model…)**
- **PTA sources? — implications for identifying continuous signals (anisotropy in GWB?)**
- **Massive nearby SMBH are EHT targets? Potential for observation with ngEHT / BHEX?**



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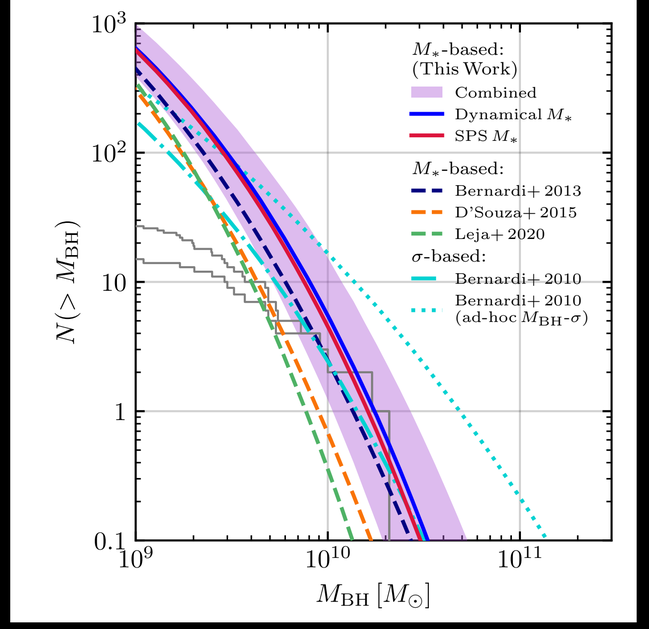


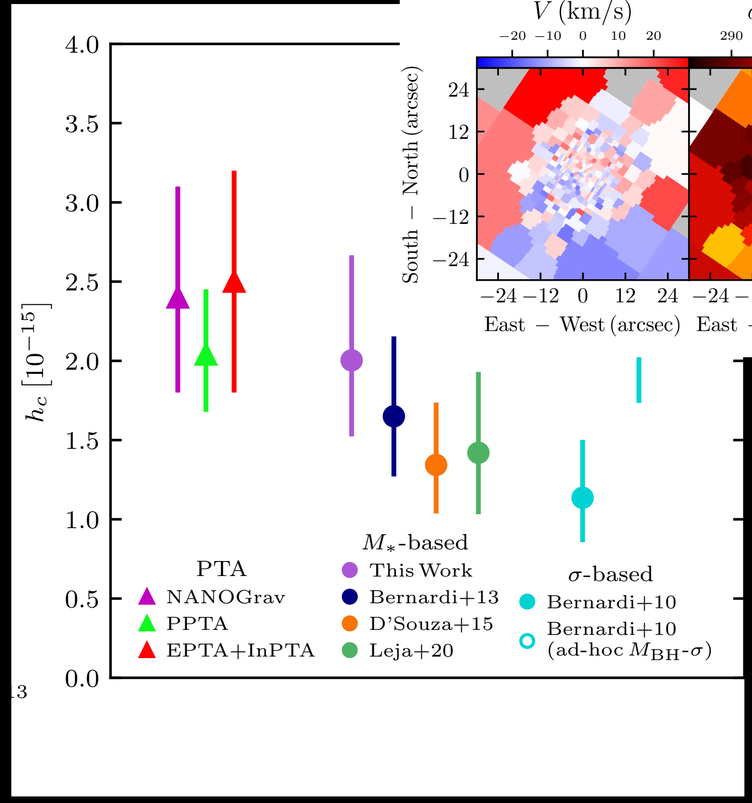

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