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

Emily Liepold, postdoc @ UC Berkeley Astronomy
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Berkeley Big BH Bunch:
Emily Liepold
Jacob Pilawa
Matthew Quenneville
Chung-Pei Ma

And our Texan Friends:
Jonelle Walsh
Silvana Delgado Andrade
Refa Al-Amri

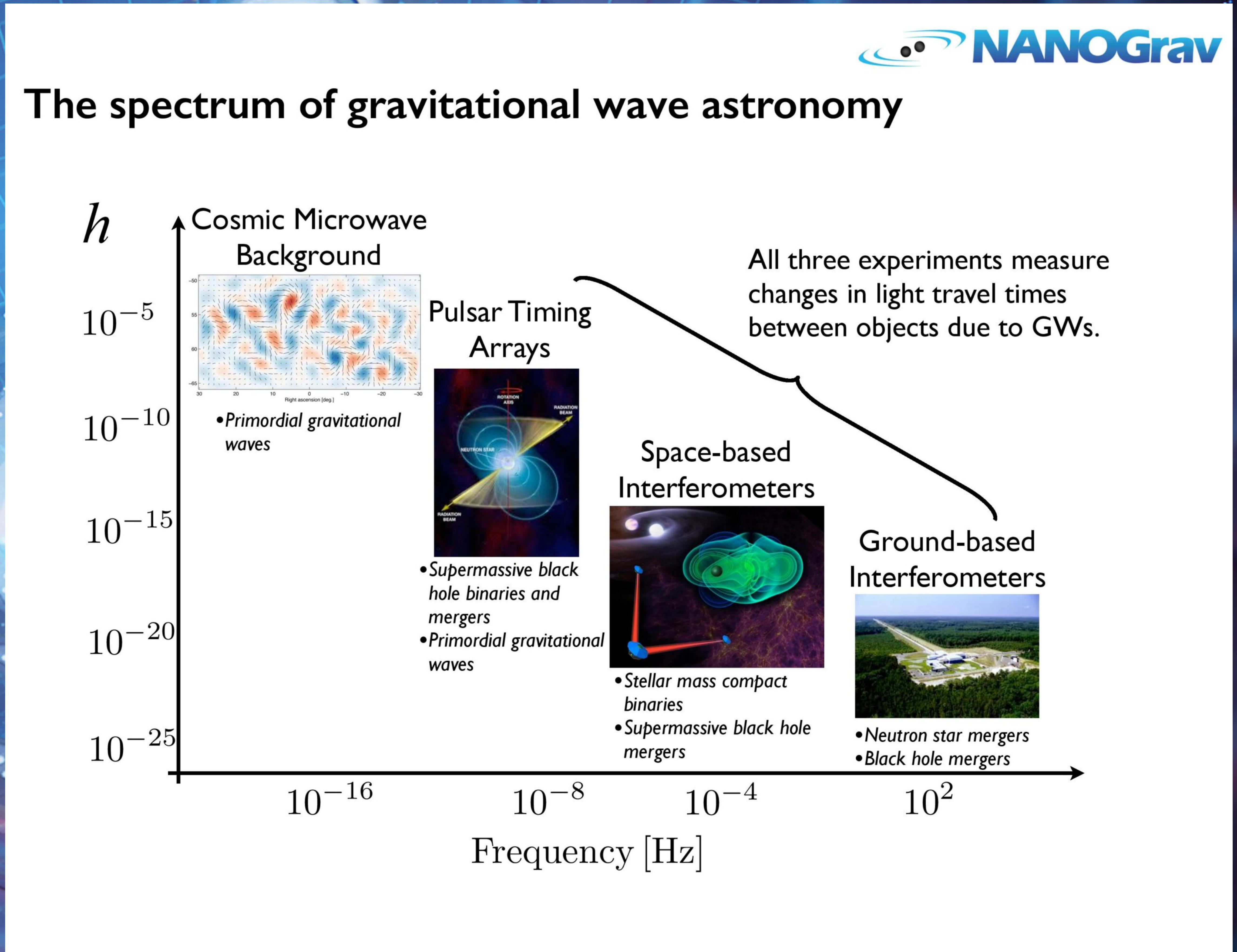
refining the high-mass local galaxy stellar mass function

finding and measuring supermassive black holes using stellar dynamics

refining the high-mass local galaxy stellar mass function

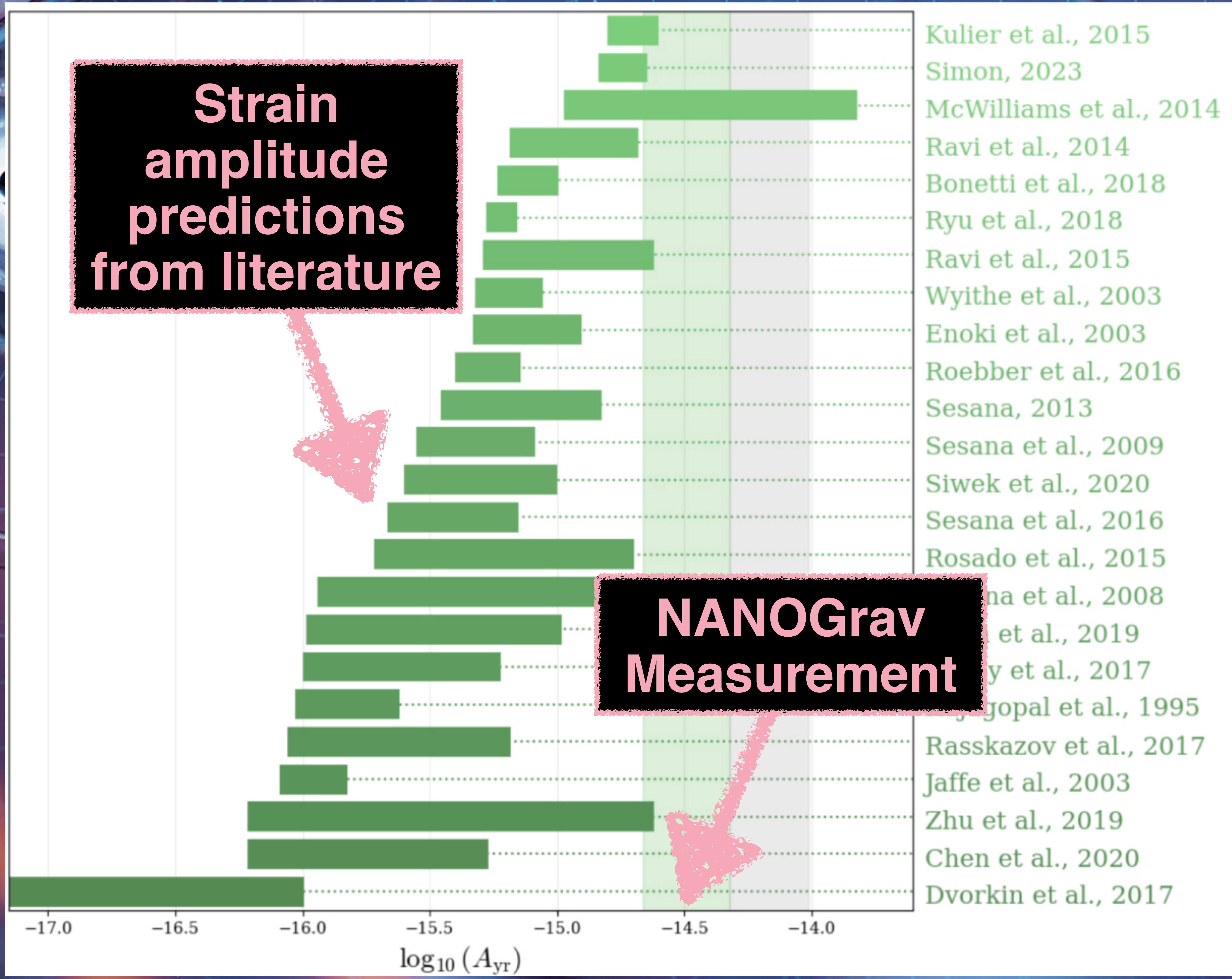
A Puzzle: Is the local SMBH population consistent with measurements of the stochastic gravitational wave background?

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



Characteristic Strain

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]

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[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 $3 \times 10^{10} M_\odot$ 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**

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)

Galaxy property function

↓

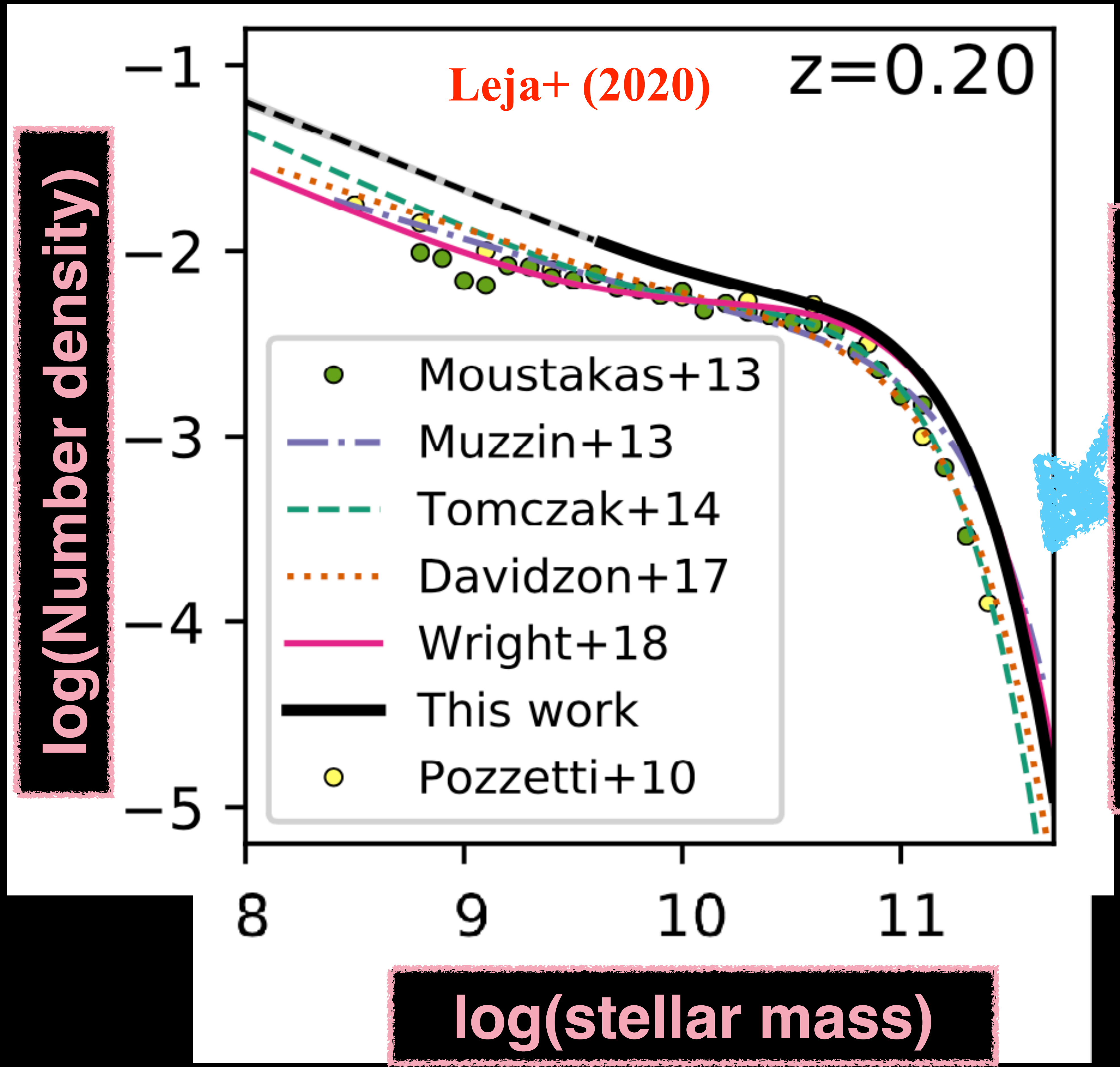
Black Hole Mass function

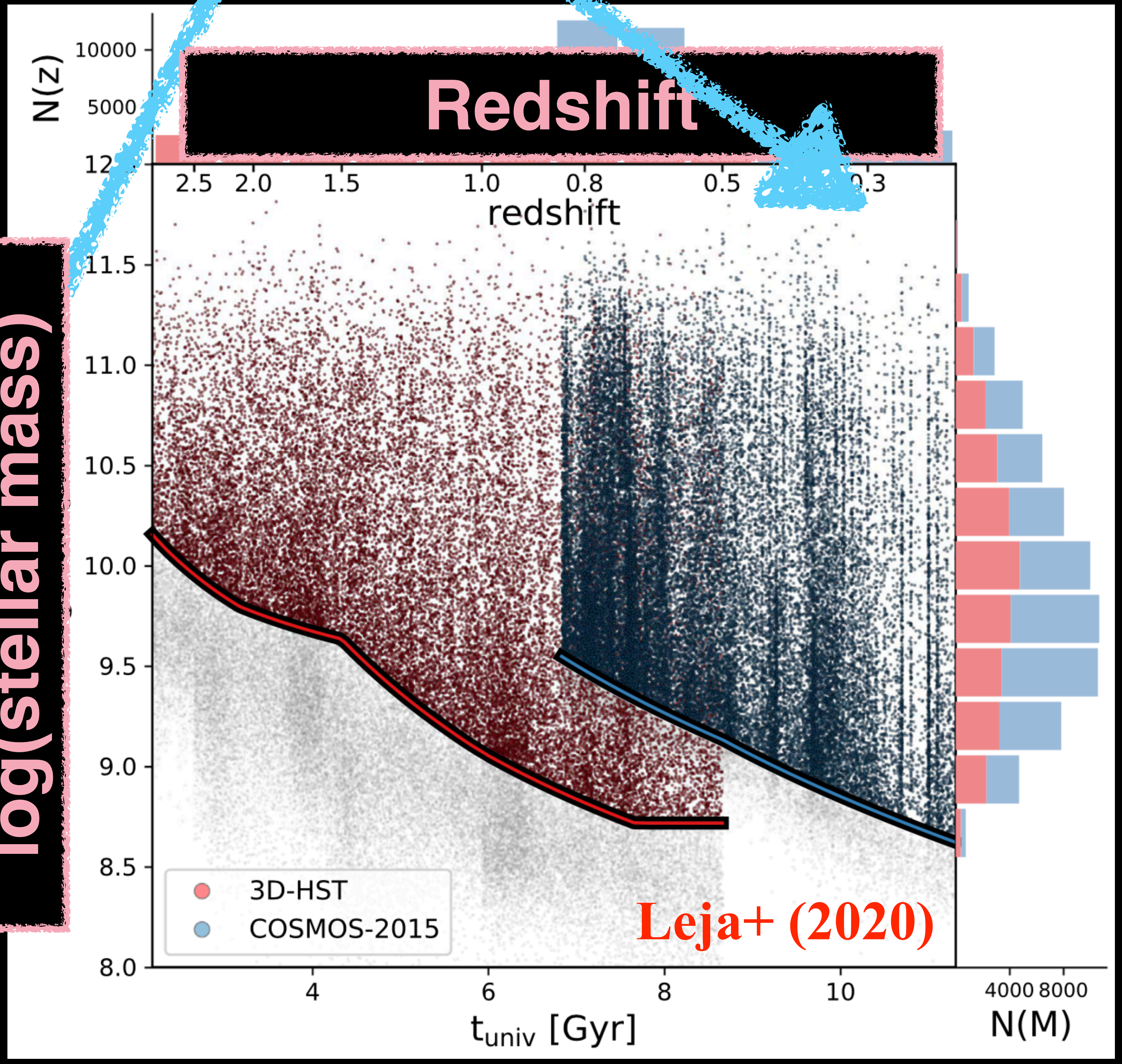
↓

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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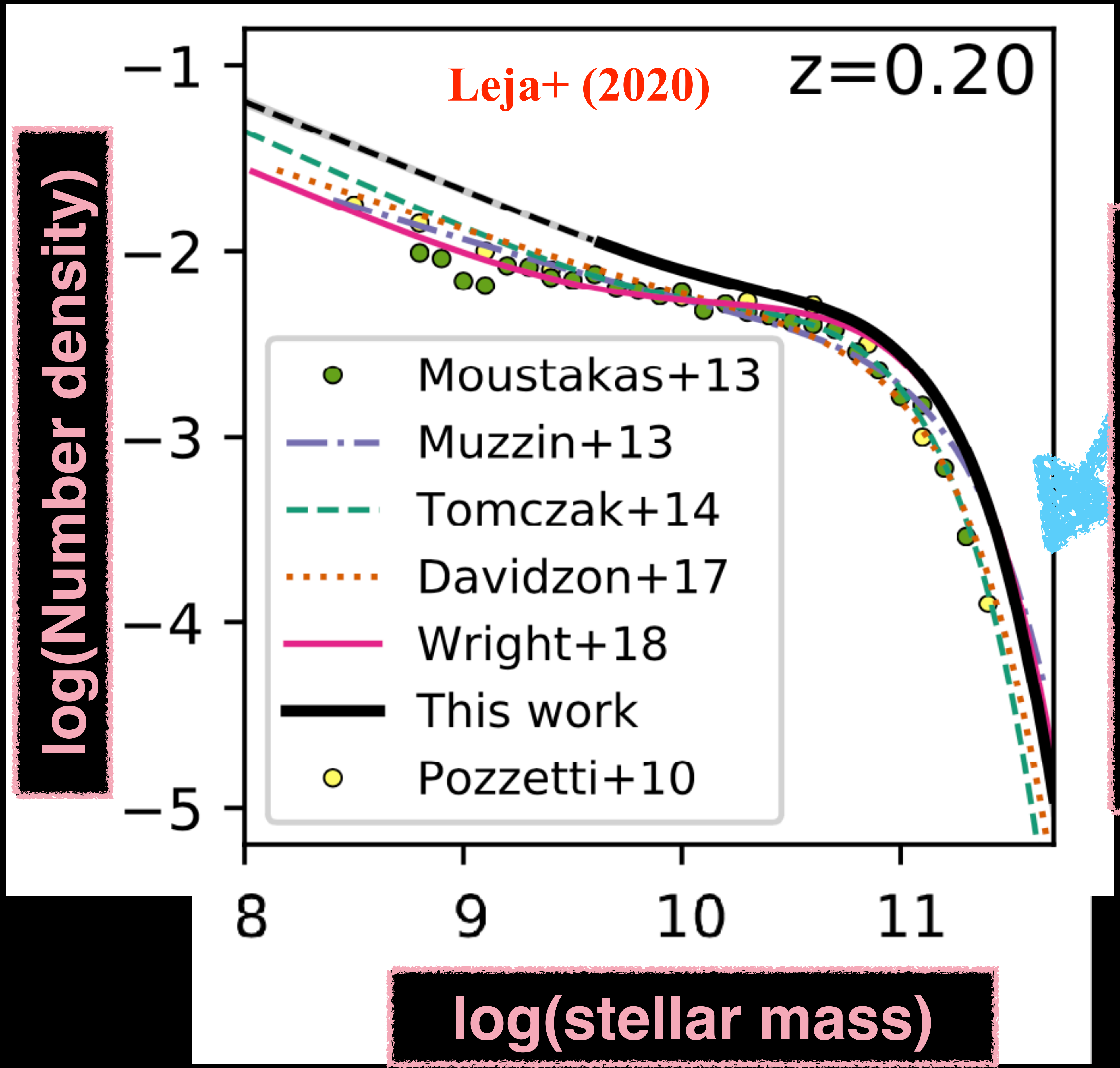
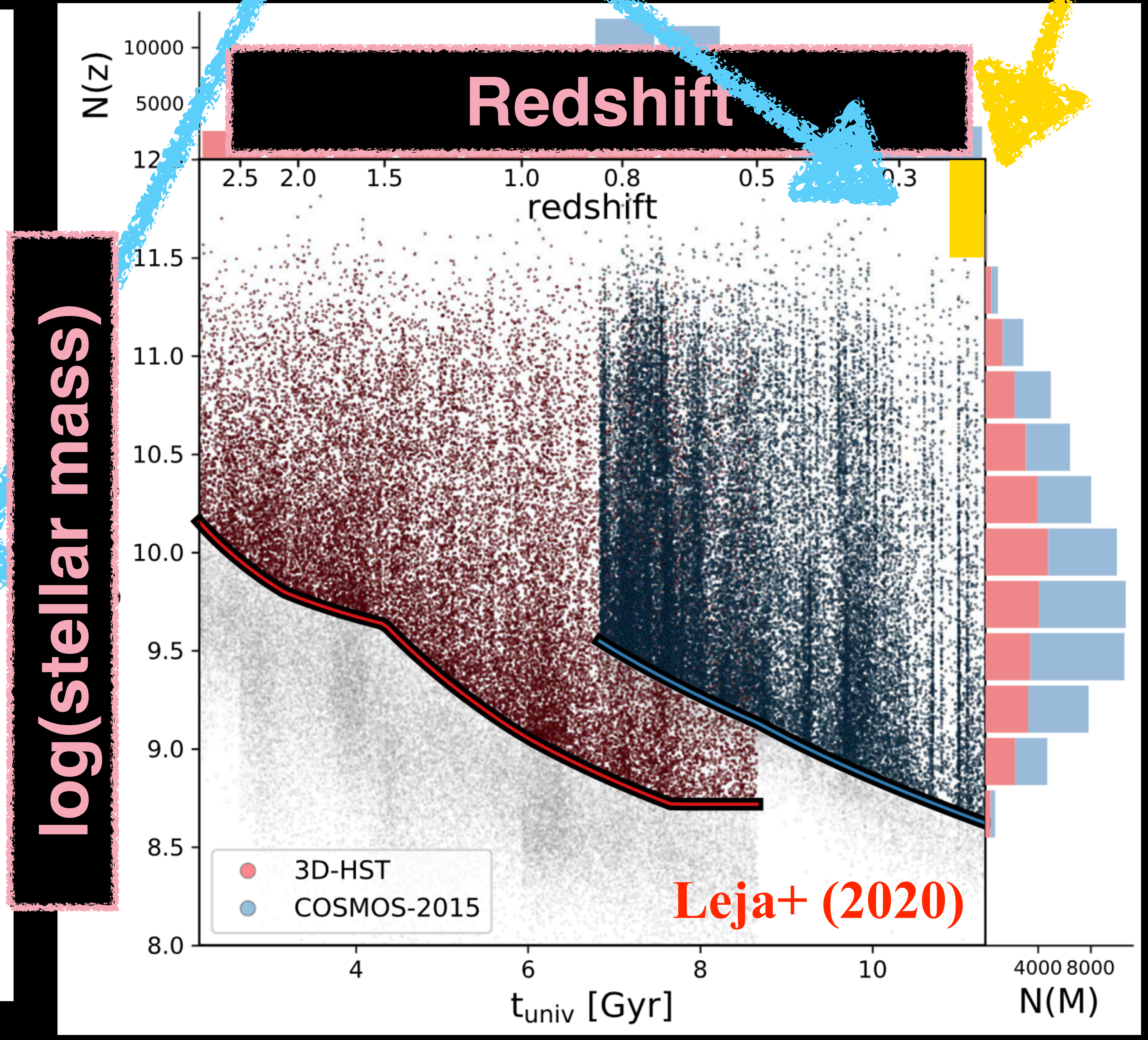
MASSIVE





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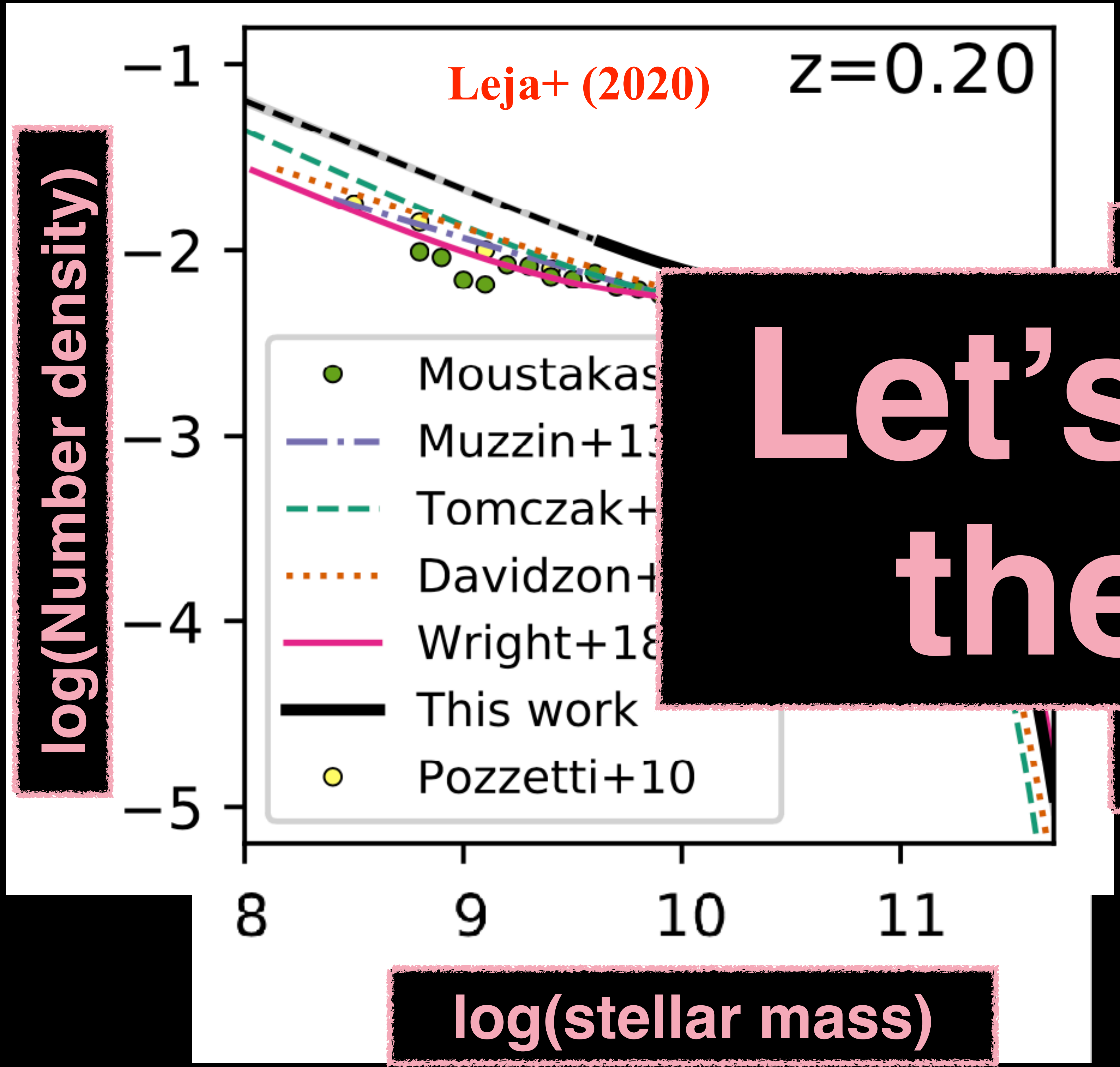
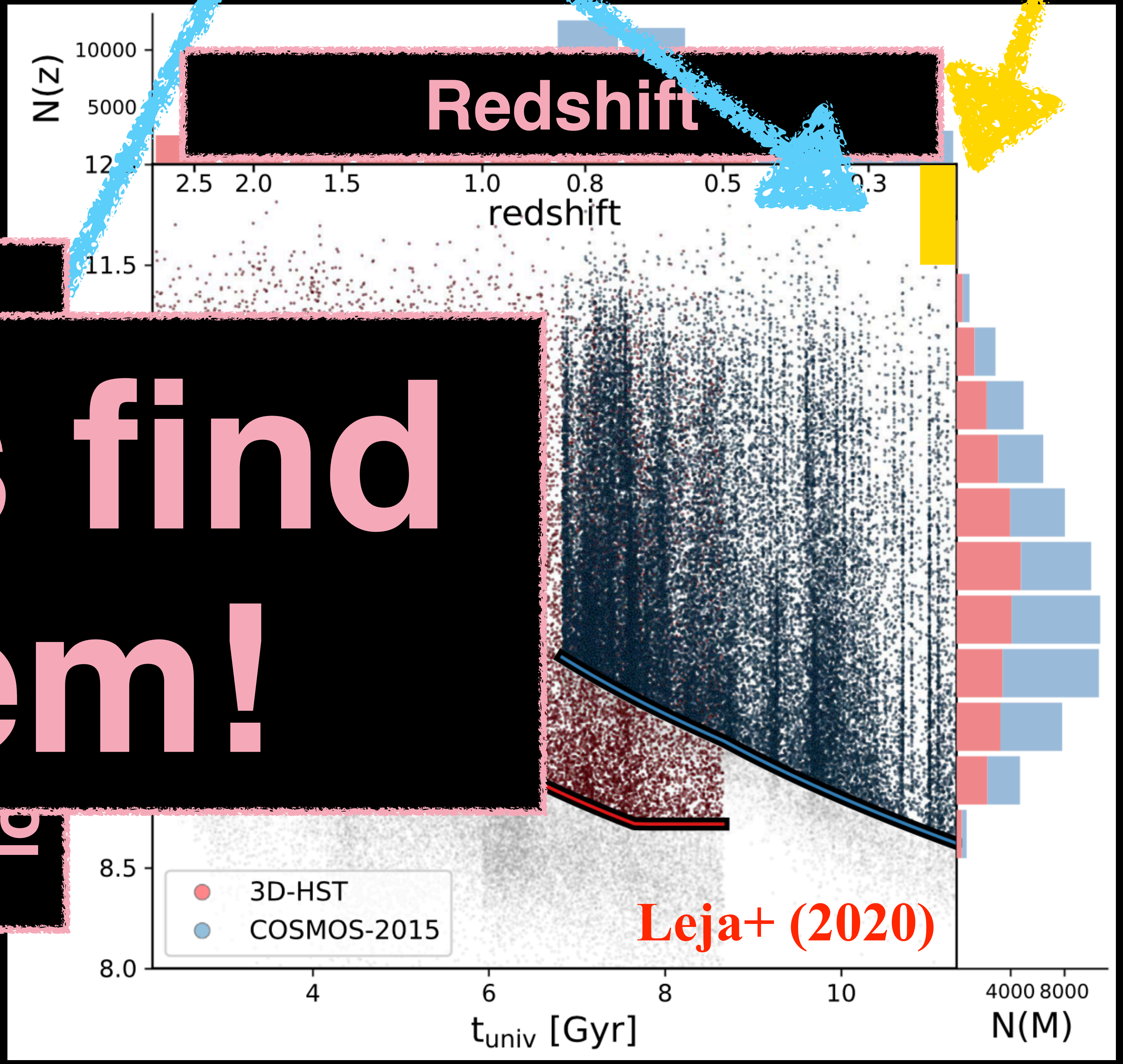




Let's find them!

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

But this is *expensive*....

Our strategy:

1. Use direct measurements when available
2. Correlate M_K and M_*
3. Use high-precision M_K to infer M_* for remaining targets

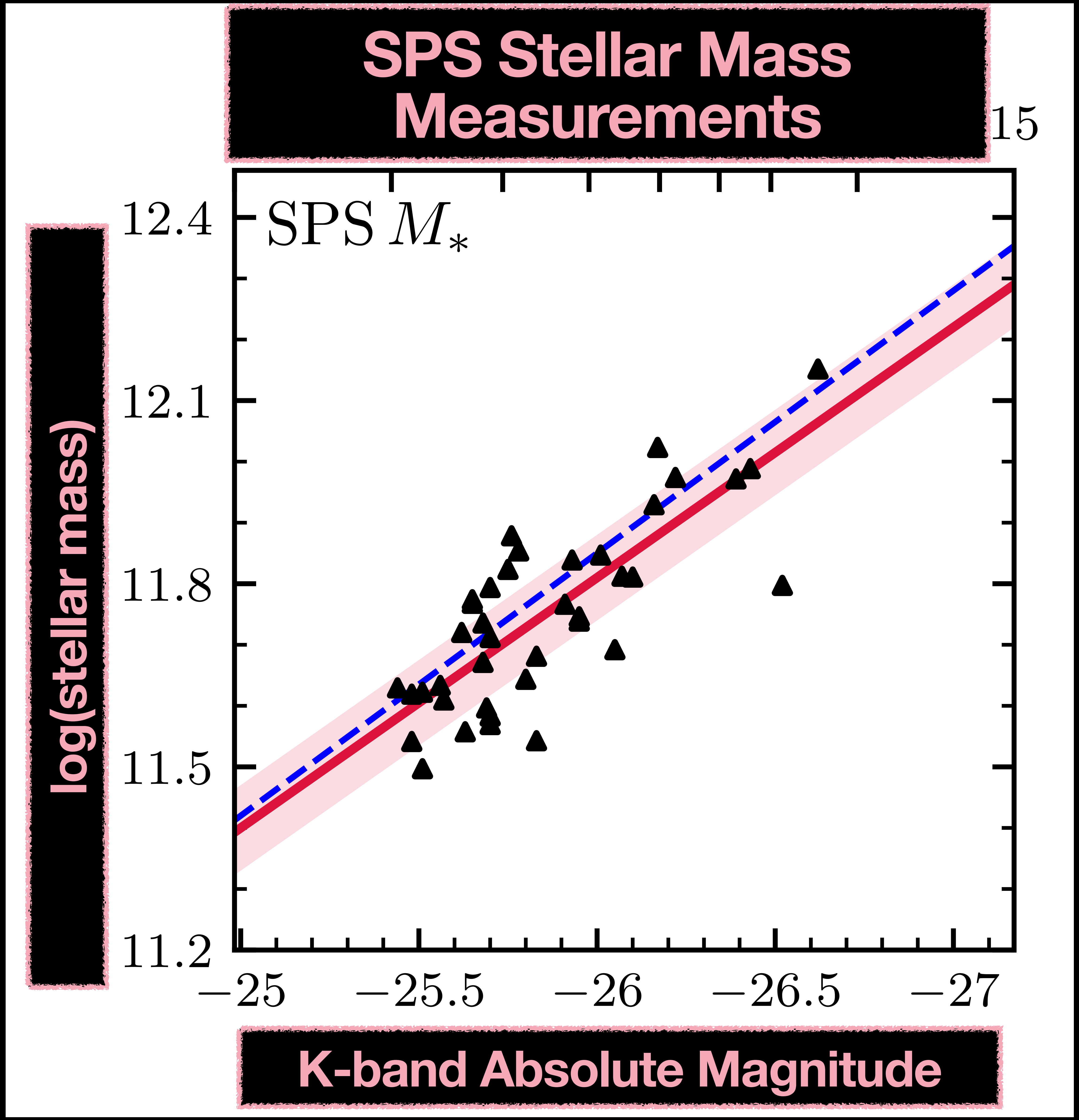
Two ways to measure galaxy stellar masses

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

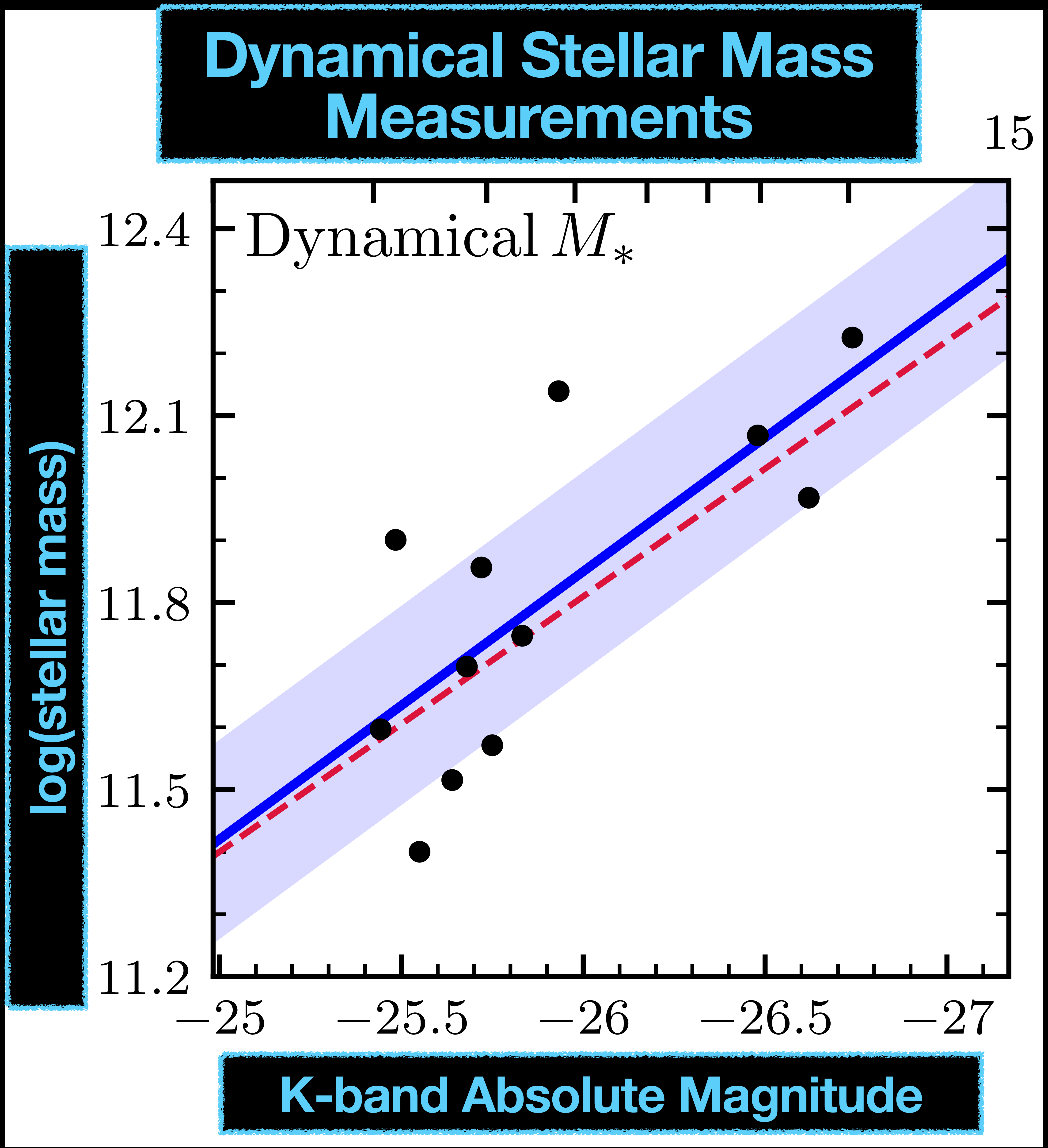
Dynamical measurements of the stellar mass now exist for 12 MASSIVE galaxies

11 from orbit-based stellar dynamics

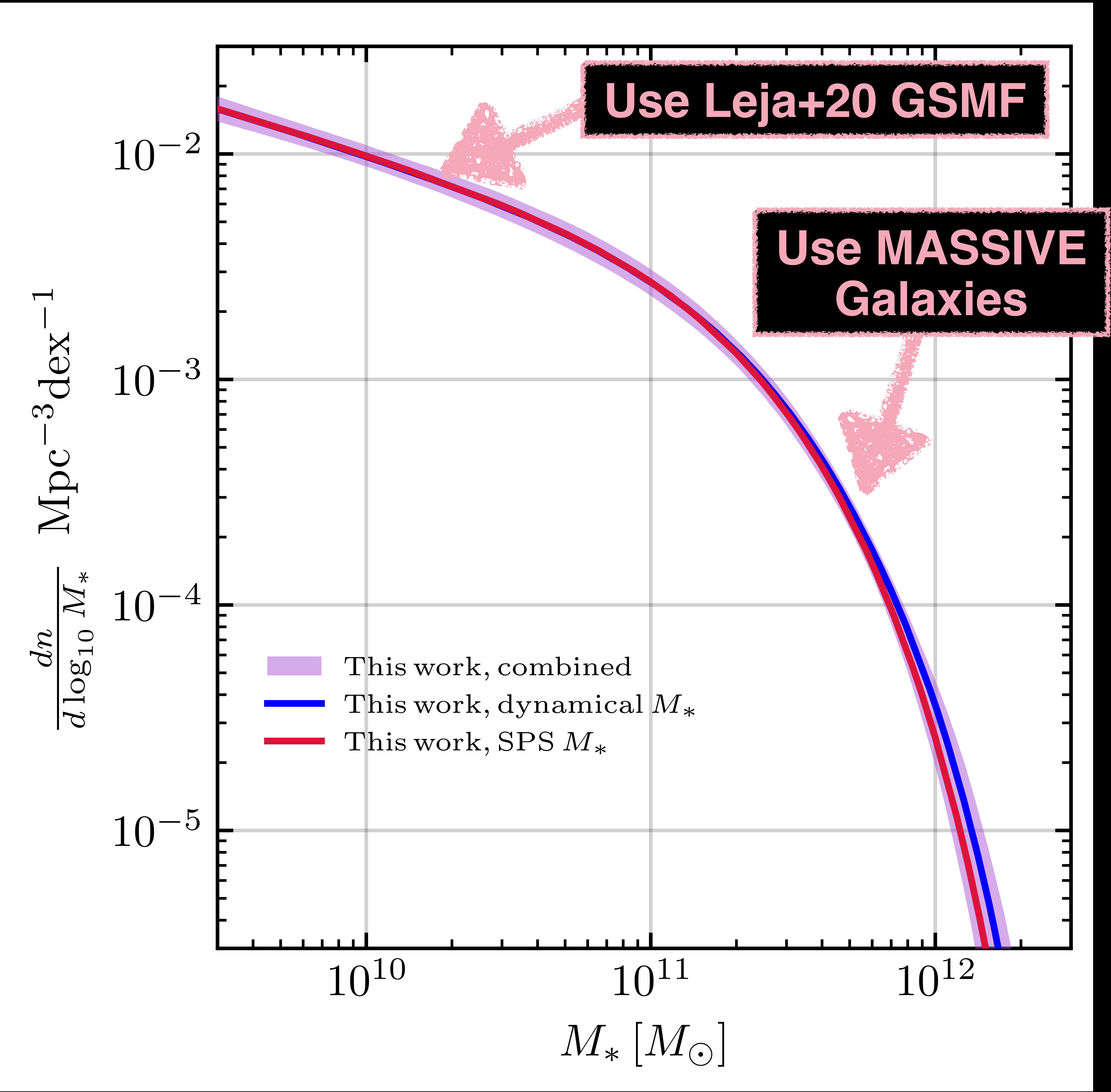
1 from gas-dynamical methods

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

(excluding Jeans-modeling based measurements)



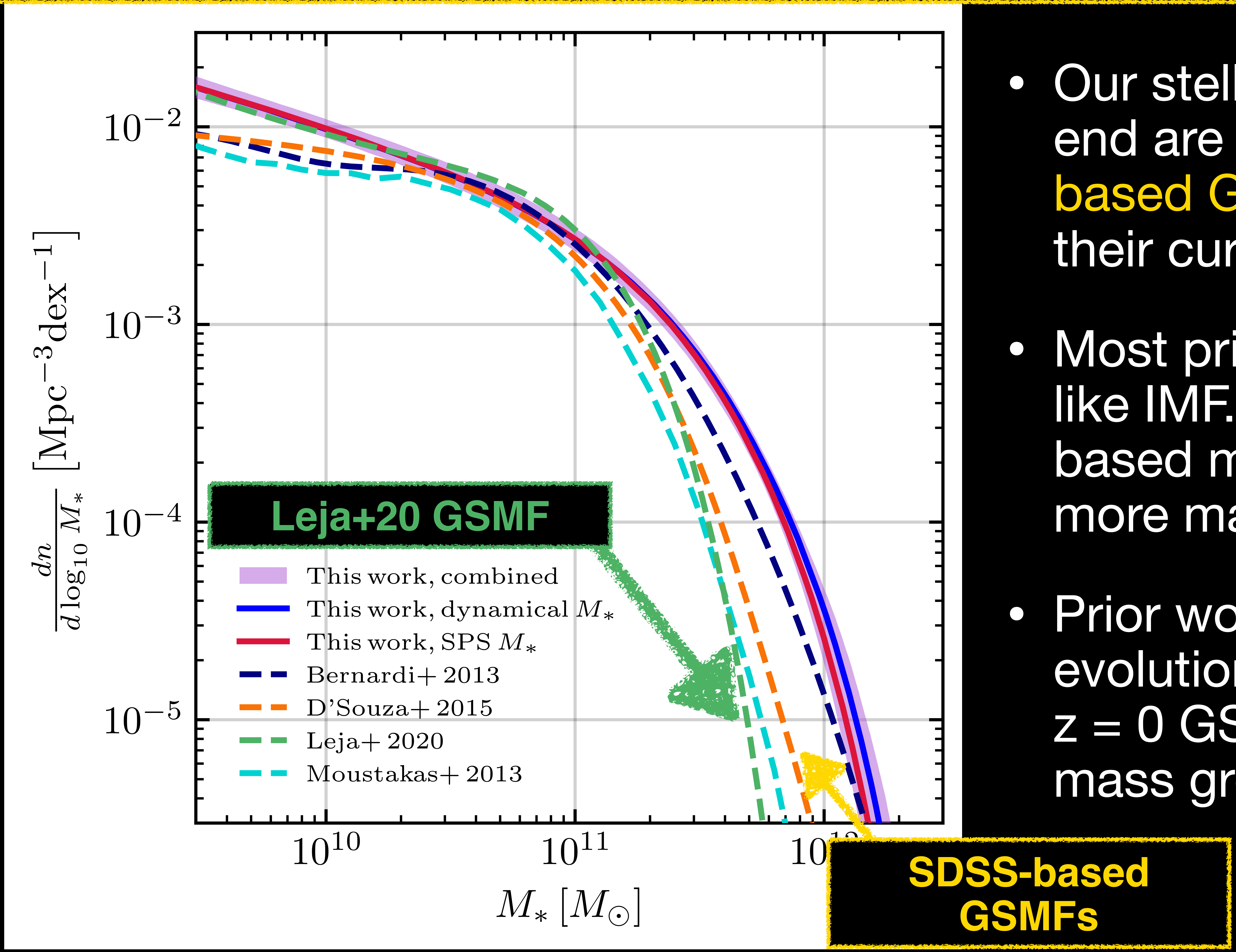
The high-mass end of the local GSMF



- 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

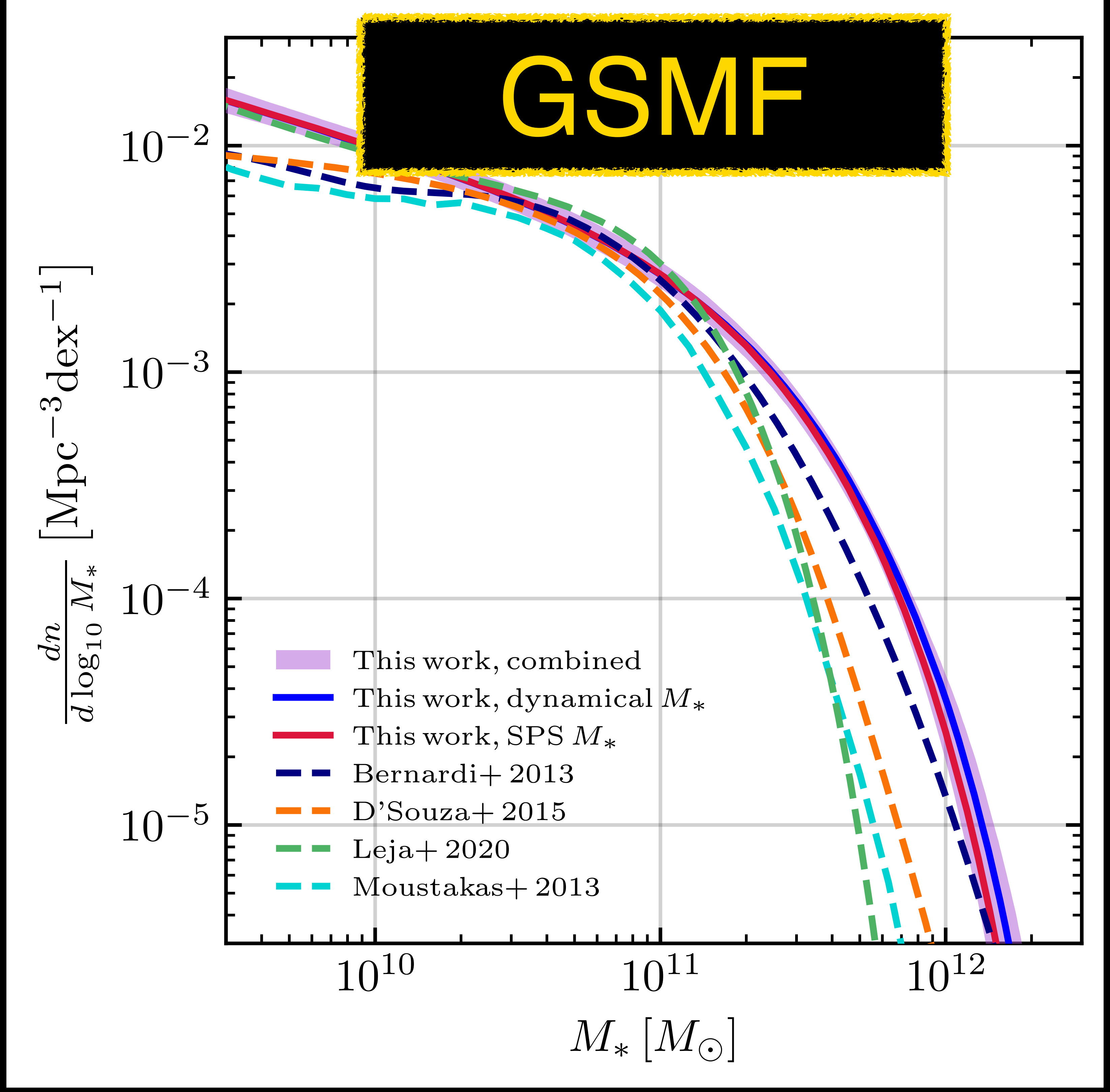
The high-mass end of the local GSMF

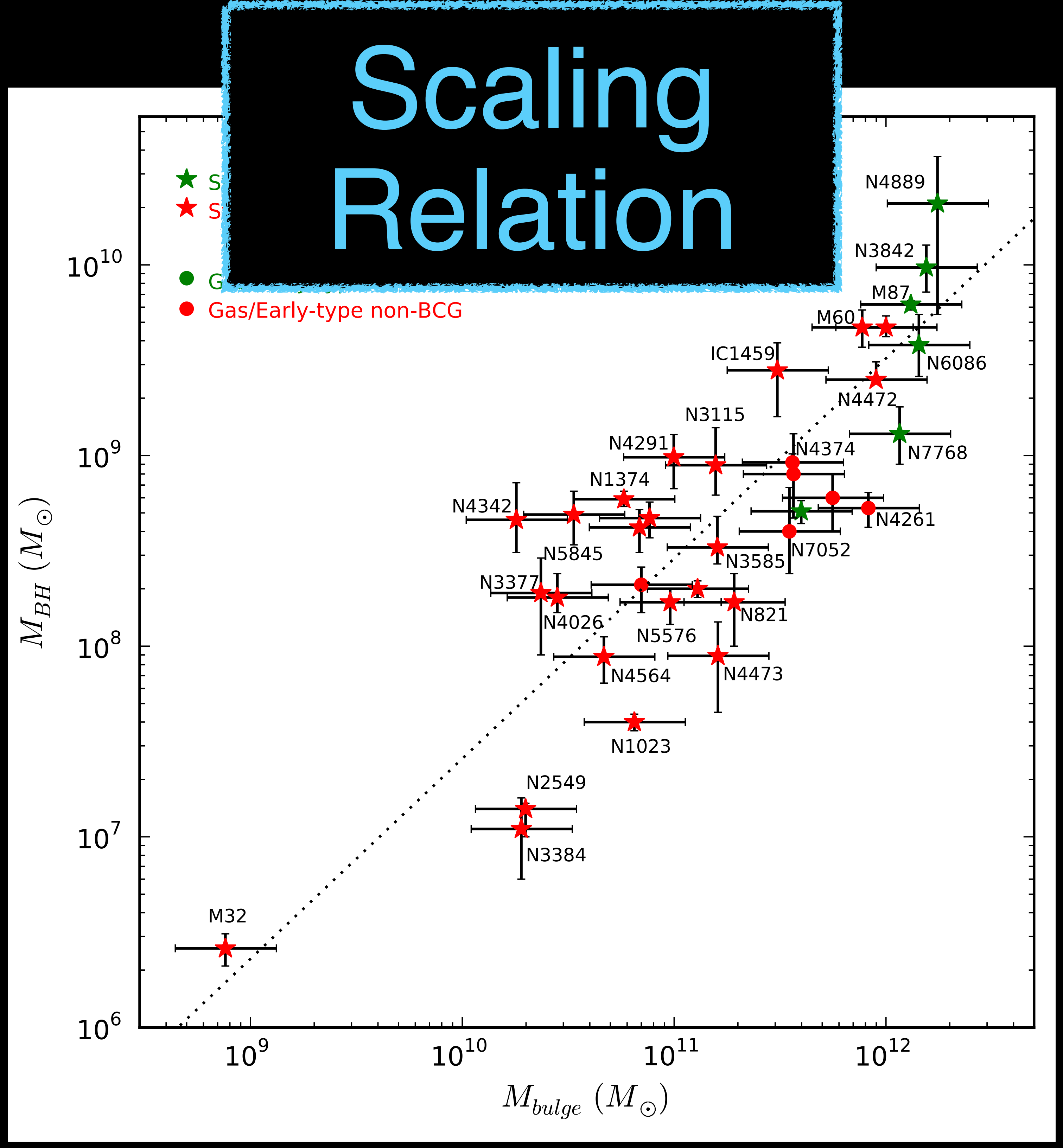


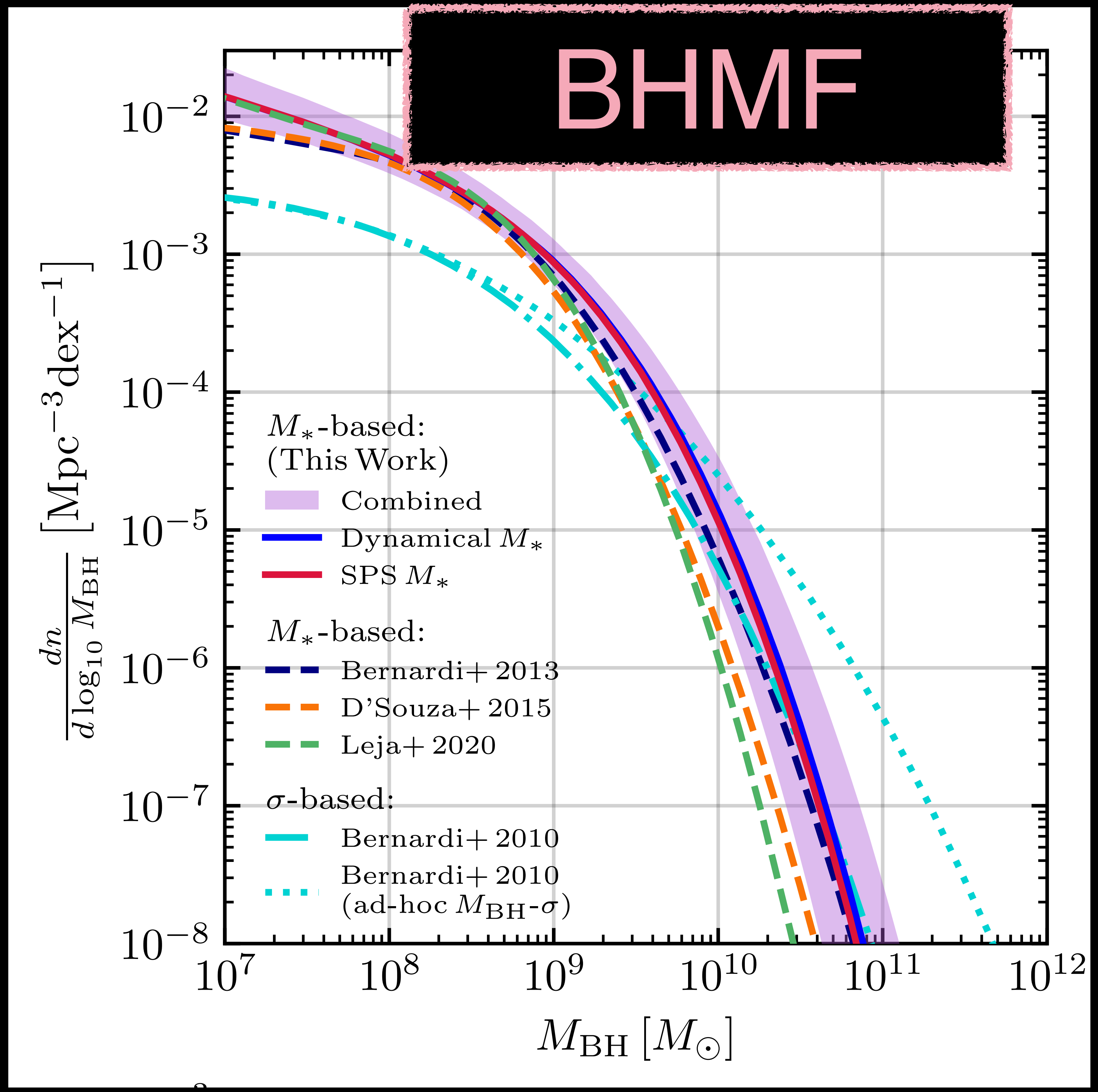
- Our stellar masses at the high-mass end are ~1.6x higher than SDSS-based GSMF measurements (shift their curves ***right***)
- Most prior work assumed Milky-Way-like IMF. Our bottom-heavy SPS-based masses fit for IMF are ~1.8x more massive.
- Prior work found minimal GSMF evolution since z = 1. Our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

The local Black Hole Mass Function

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







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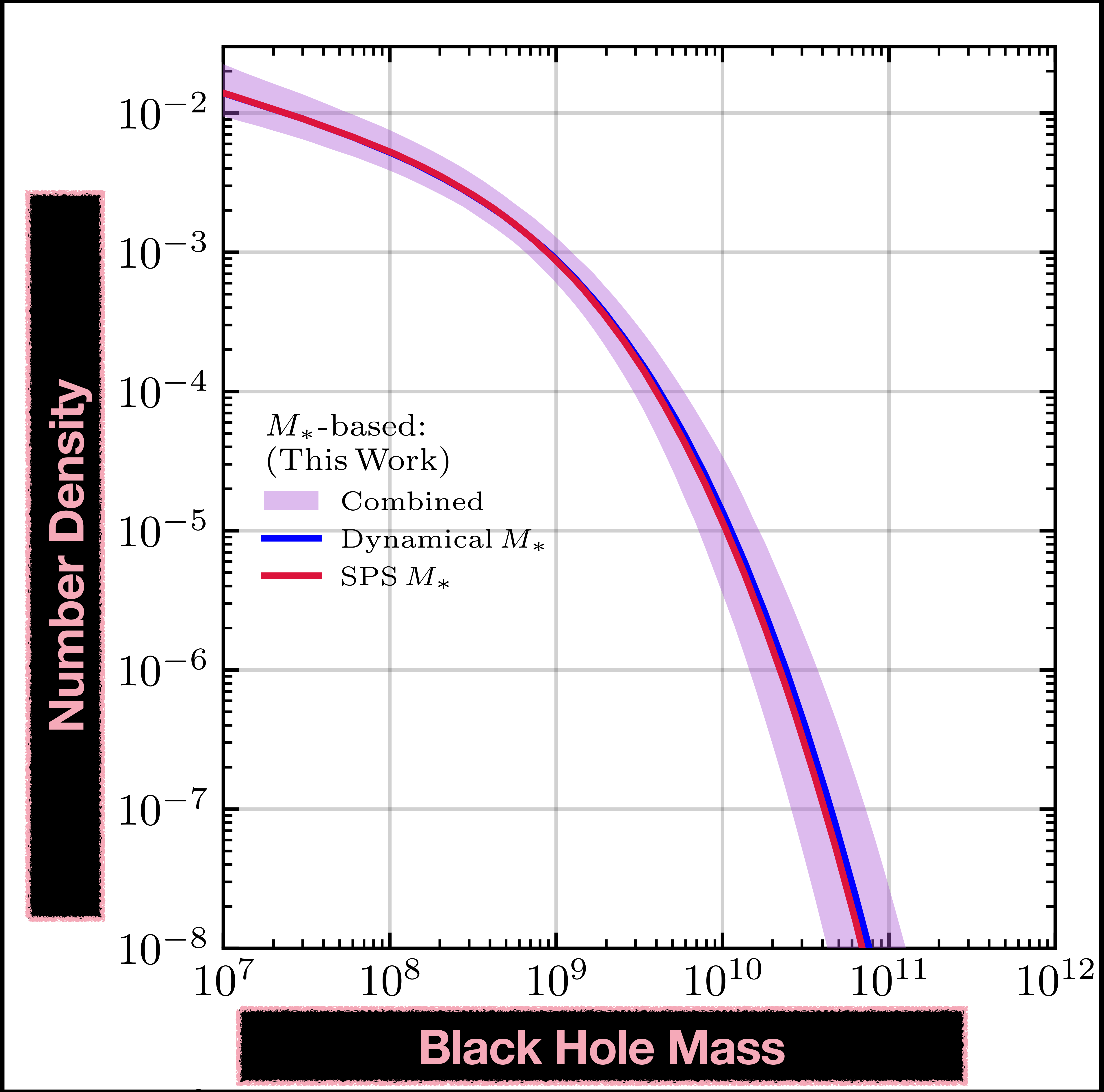
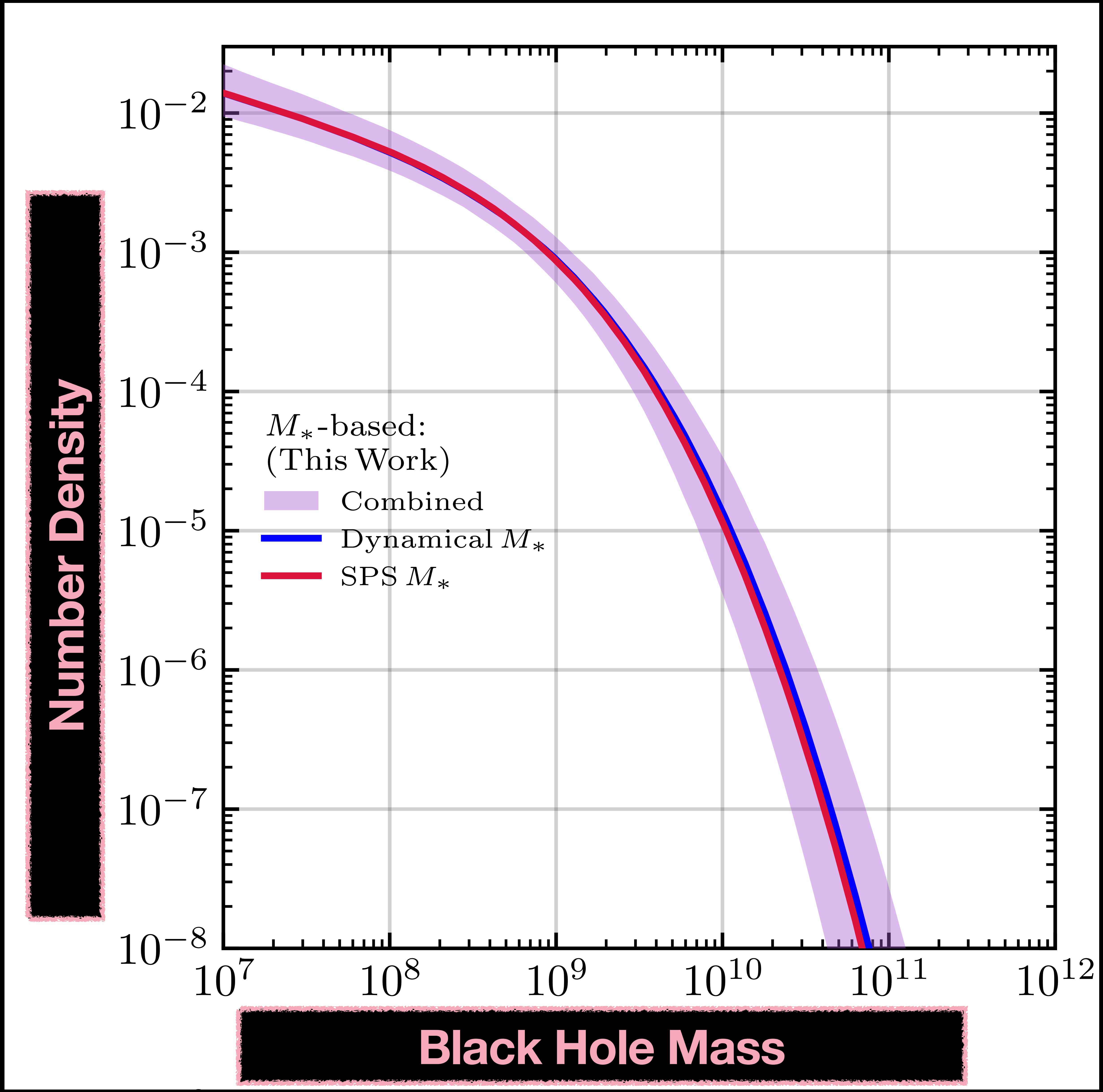
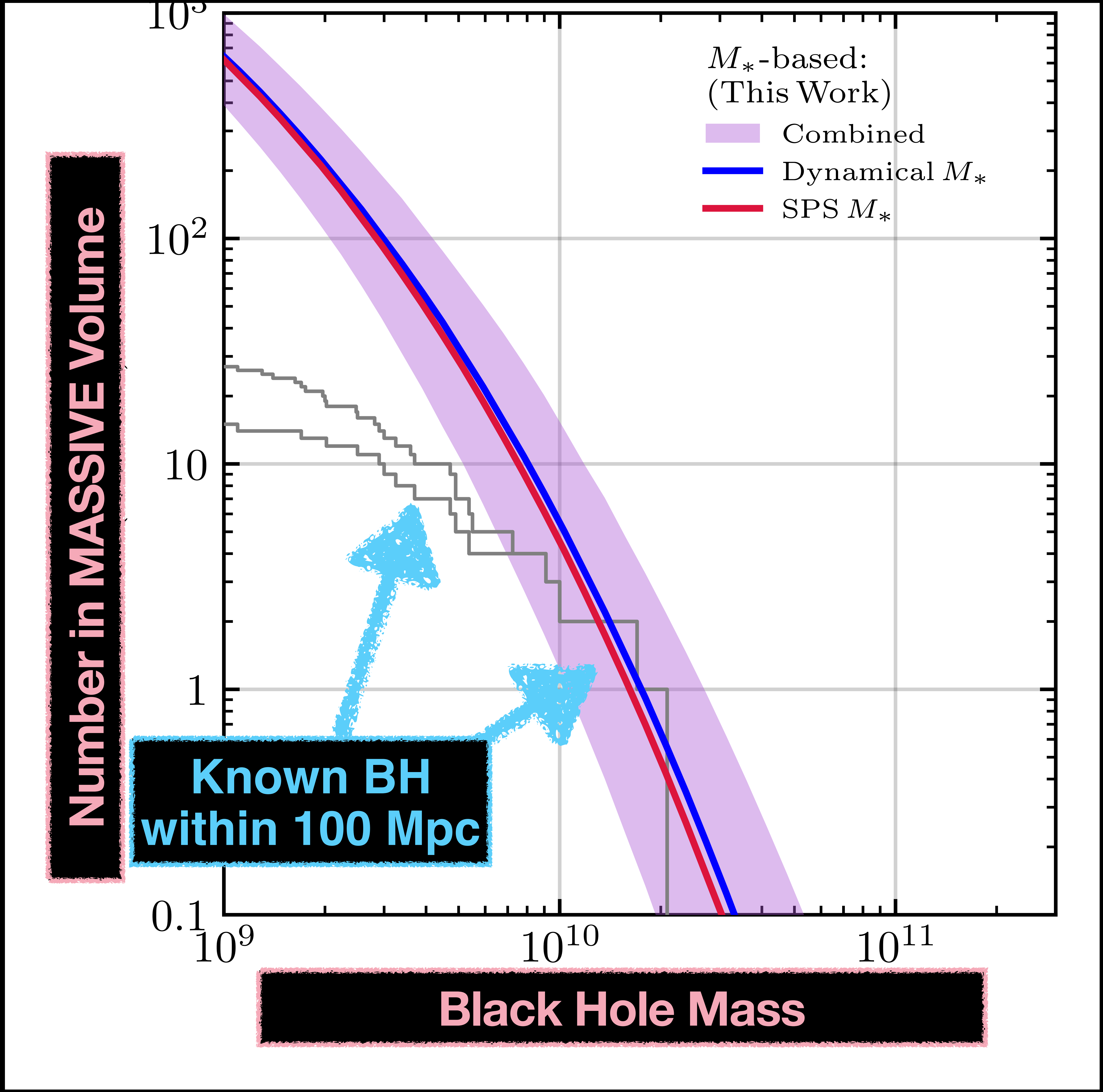


- Scatter in BHMF mostly due to scatter in scaling relation
- Consistent BHMF from SPS and dynamical M_*

The local Black Hole Mass Function





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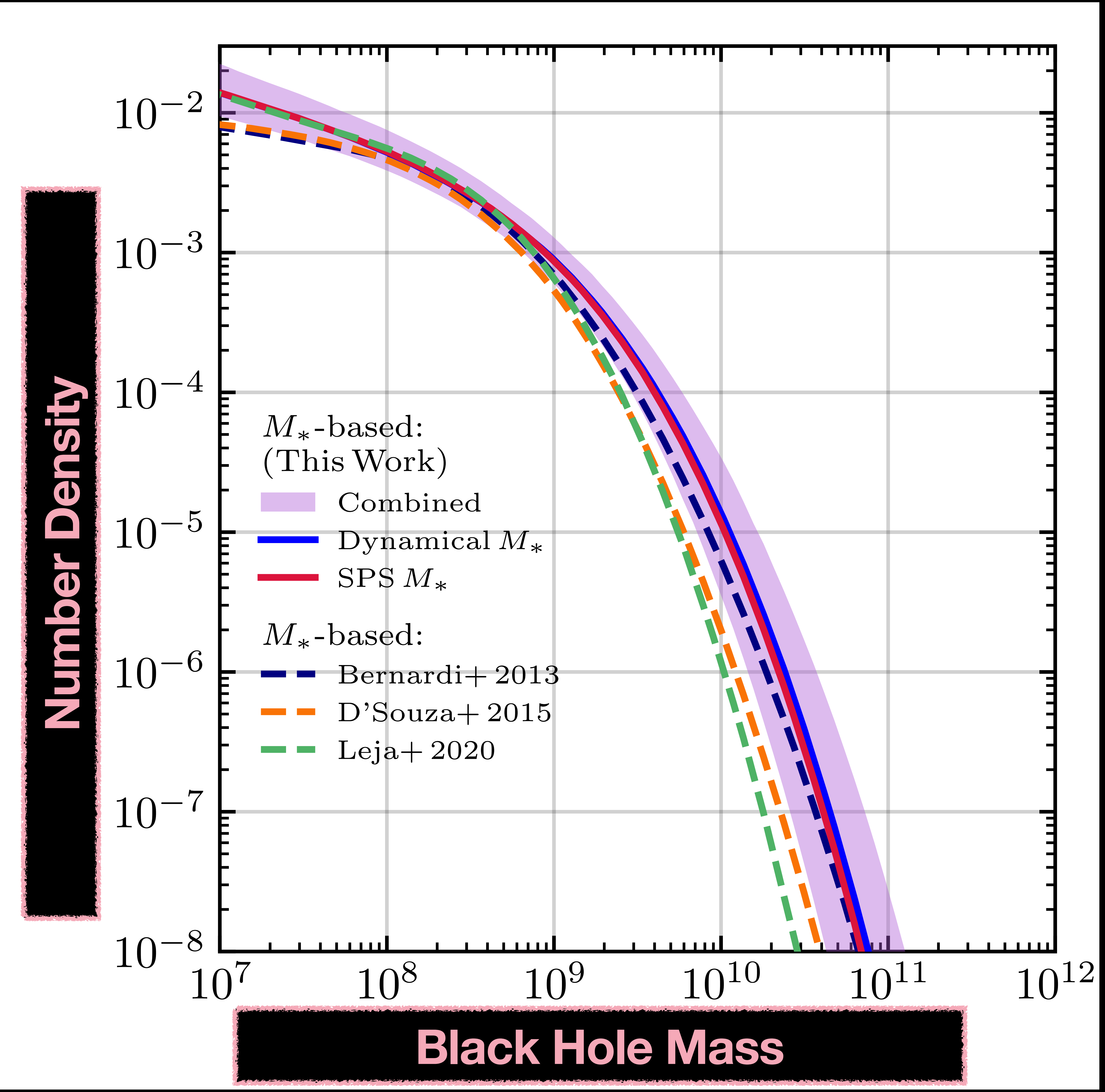

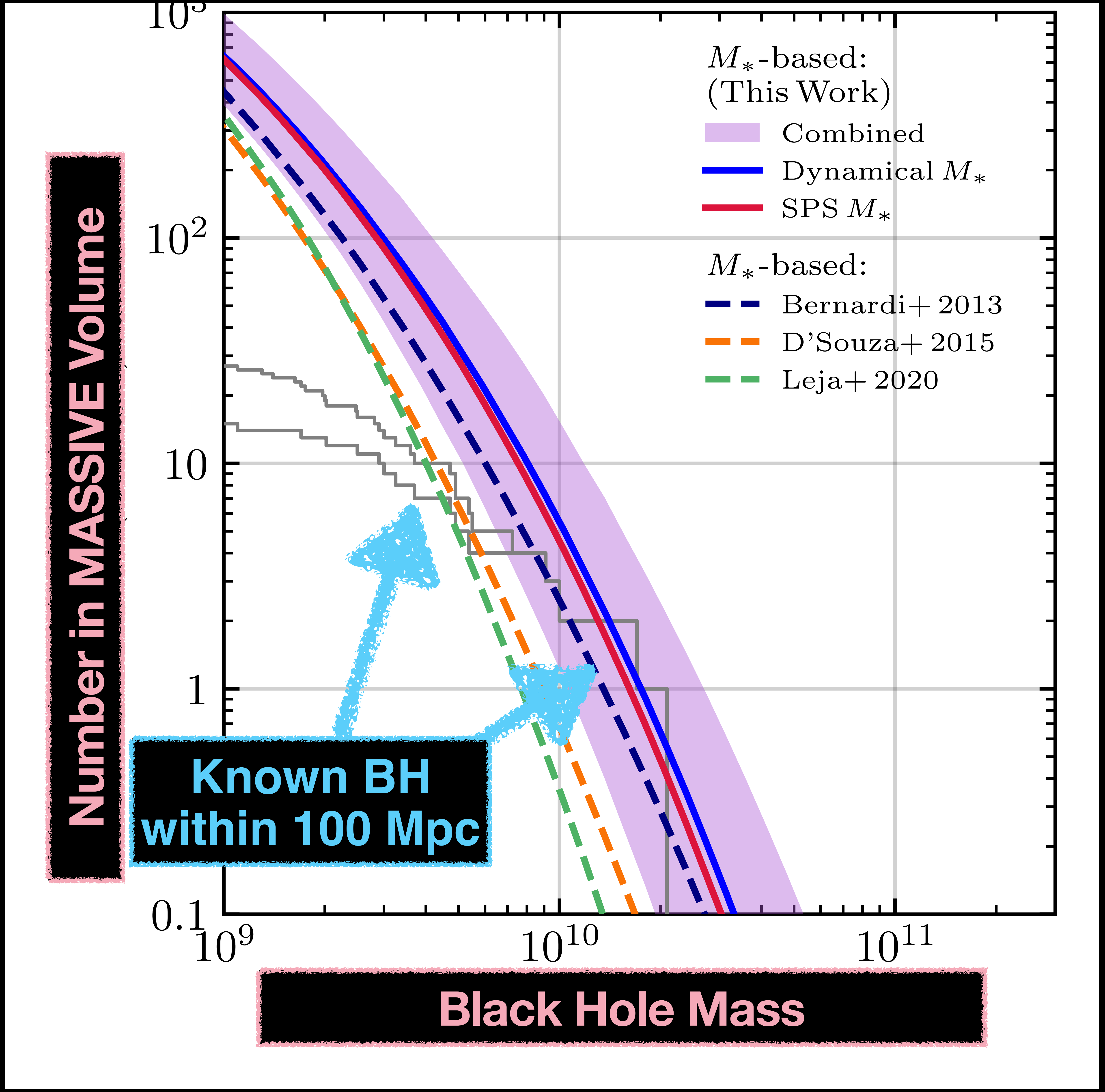

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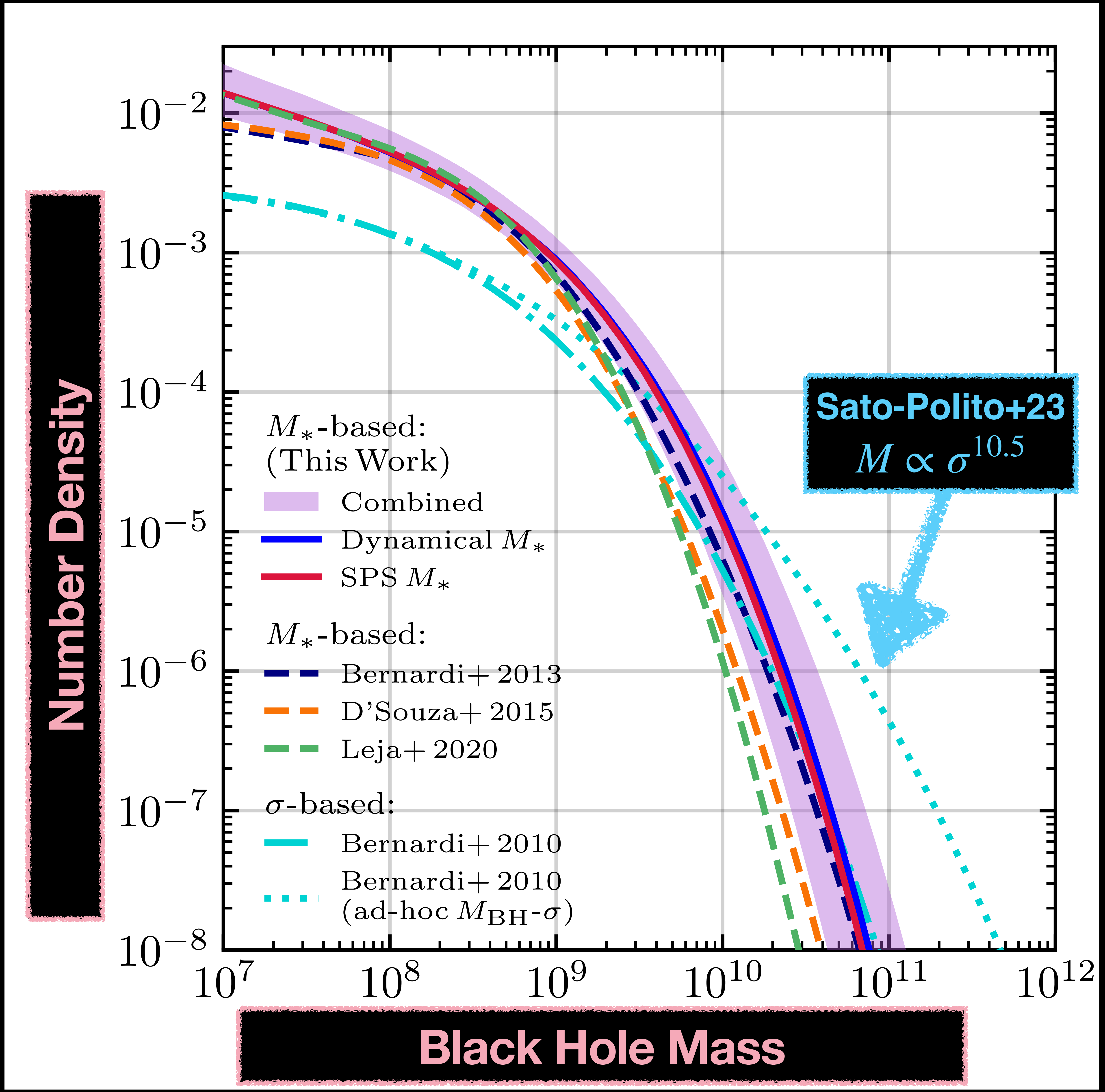
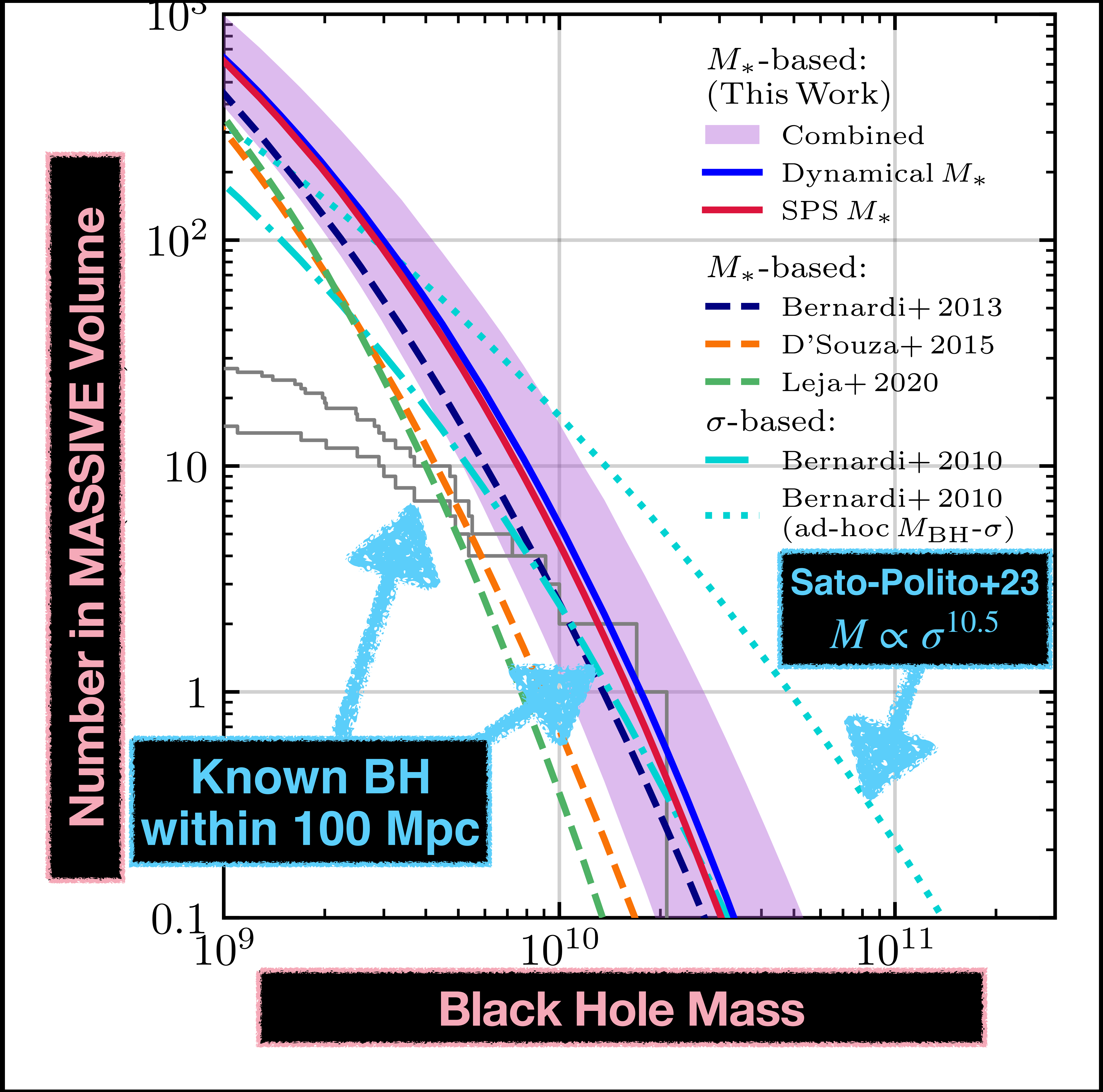




Implications for the Cosmic GW Background

- 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

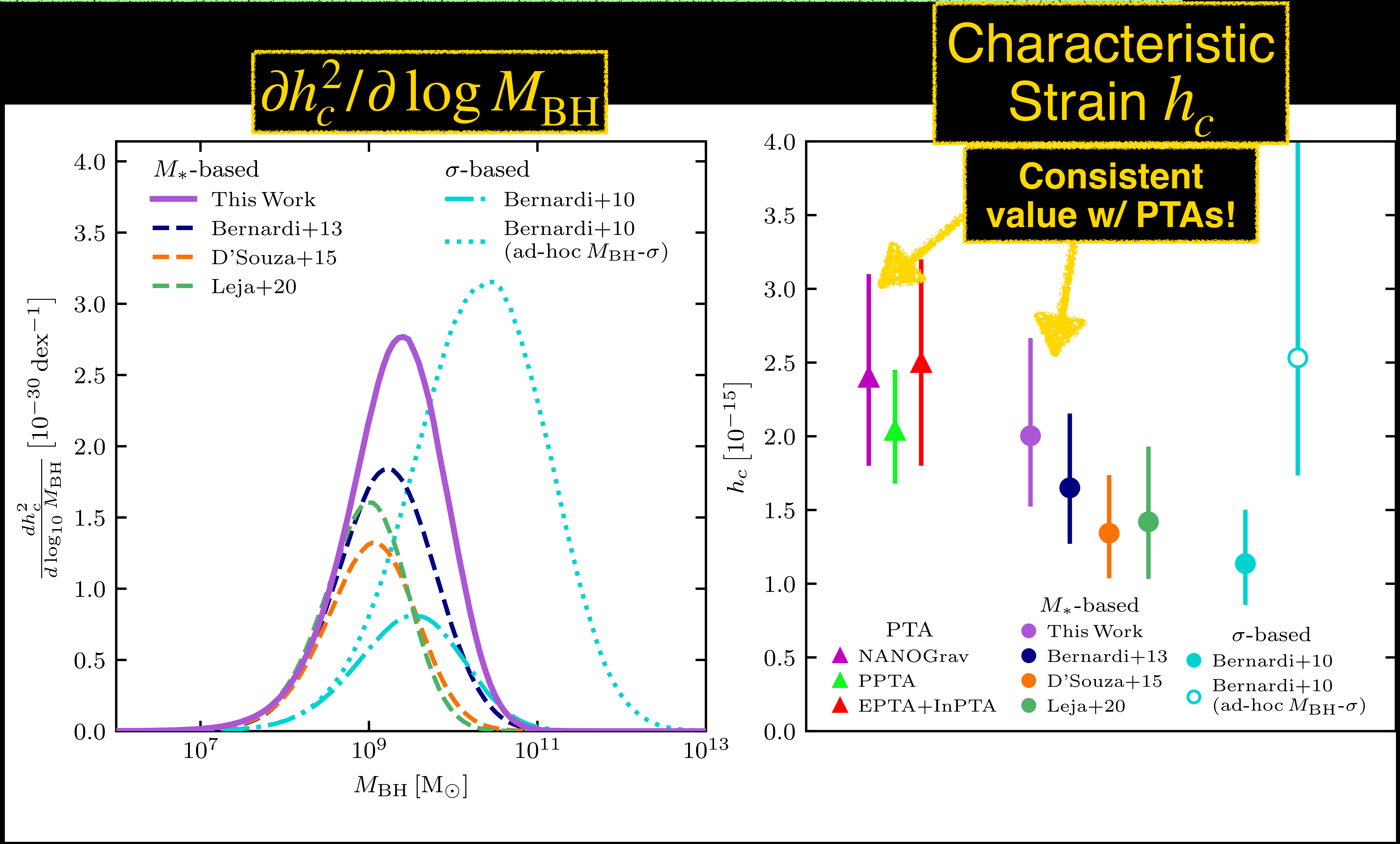
Implications for the Cosmic GW Background

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

Characteristic Strain h_c

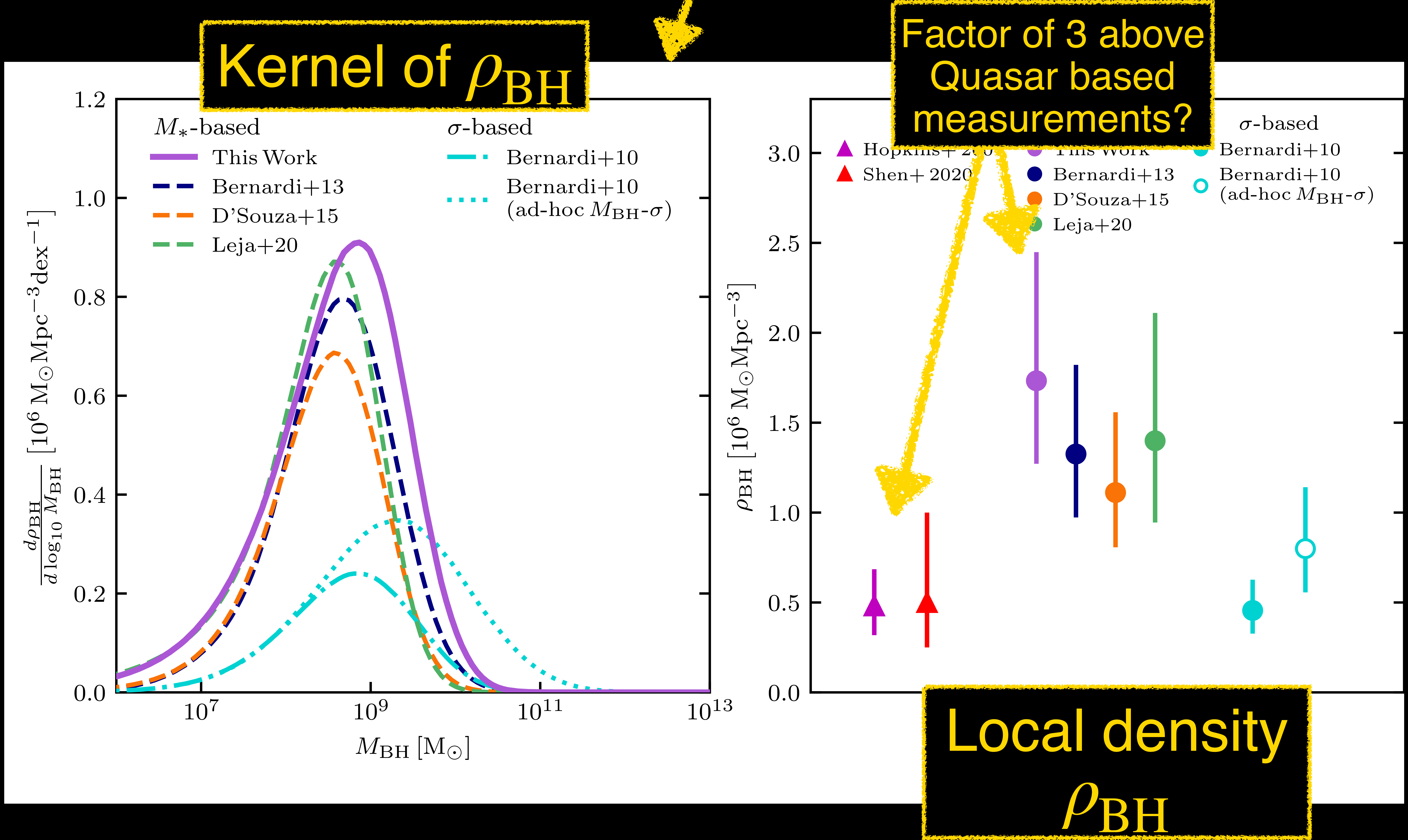
Consistent value w/ PTAs!

Implications for the Cosmic GW Background



A Mystery:
Local BH Mass density

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



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The predicted ρ_{BH} is 2-3x higher than QLF measurements — lower efficiency? Or higher obscuration?

finding and measuring supermassive black holes using stellar dynamics

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
$M_{\rm BH} \gtrsim 10^9 M_\odot$
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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
Pilawa+soon, NGC 315
Liepold+soon, IC1101

Big BHs are booming

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

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

→

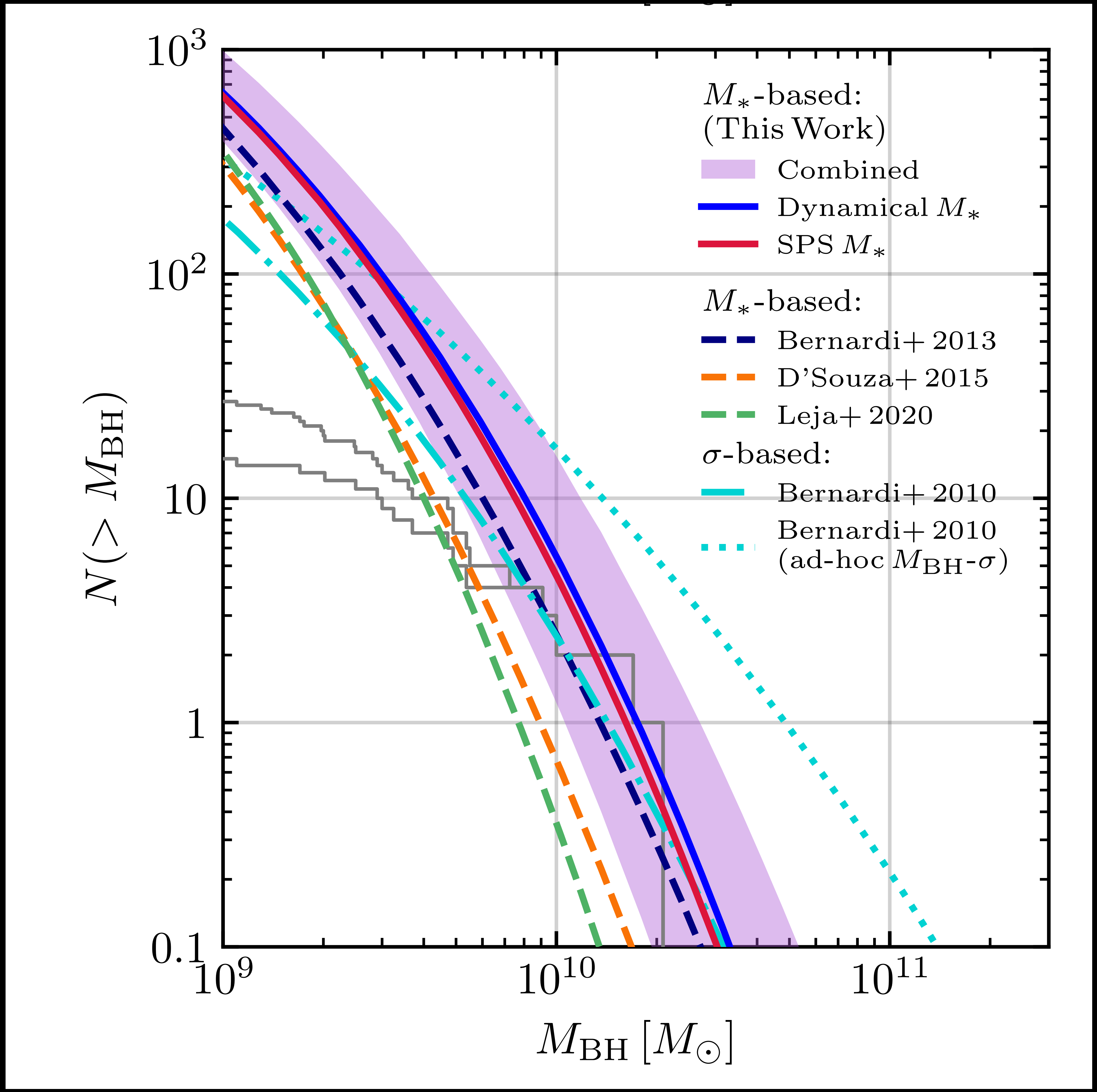
12 from past 3 years!
8 this year!
(Plus more in the pipeline)

Big BHs are uncommon

Within 100 Mpc of us:

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

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



How to find SMBHs

Different methods for different galaxies

Local

Distant

Individual stellar orbits (S2, etc around Sgr*)

Shadow imaging (Sgr* 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)

How to find SMBHs

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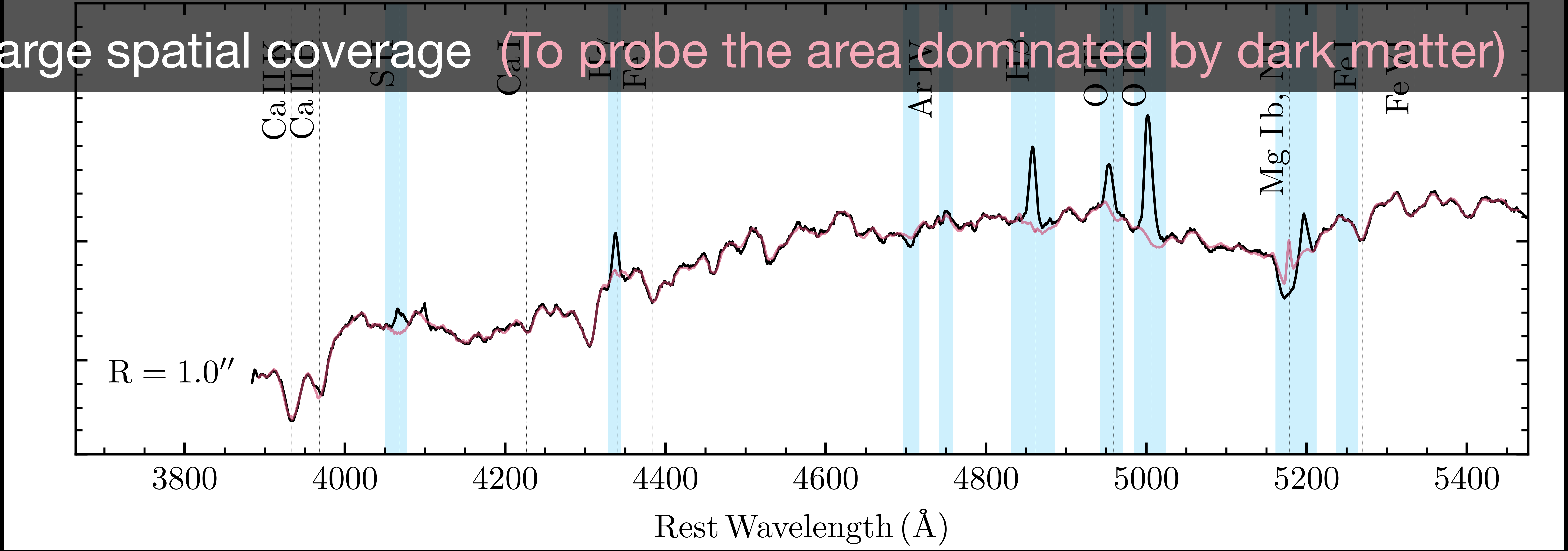
How to find SMBHs

Stellar Dynamics

What do we need?

- Spatially-resolve Spectra! (To observe the velocity broadening 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)



How to measure SMBHs

Triaxial Schwarzschild Modeling

Schwarzschild+79
Schwarzschild+93

How to measure SMBHs

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Propose a potential

How to measure SMBHs

Triaxial Schwarzschild Modeling

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Propose a potential

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

How to measure SMBHs

Triaxial Schwarzschild Modeling

Schwarzschild+79
Schwarzschild+93

Propose a potential

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

→ Superimpose orbits to fit observations

How to measure SMBHs

Triaxial Schwarzschild Modeling

Schwarzschild+79
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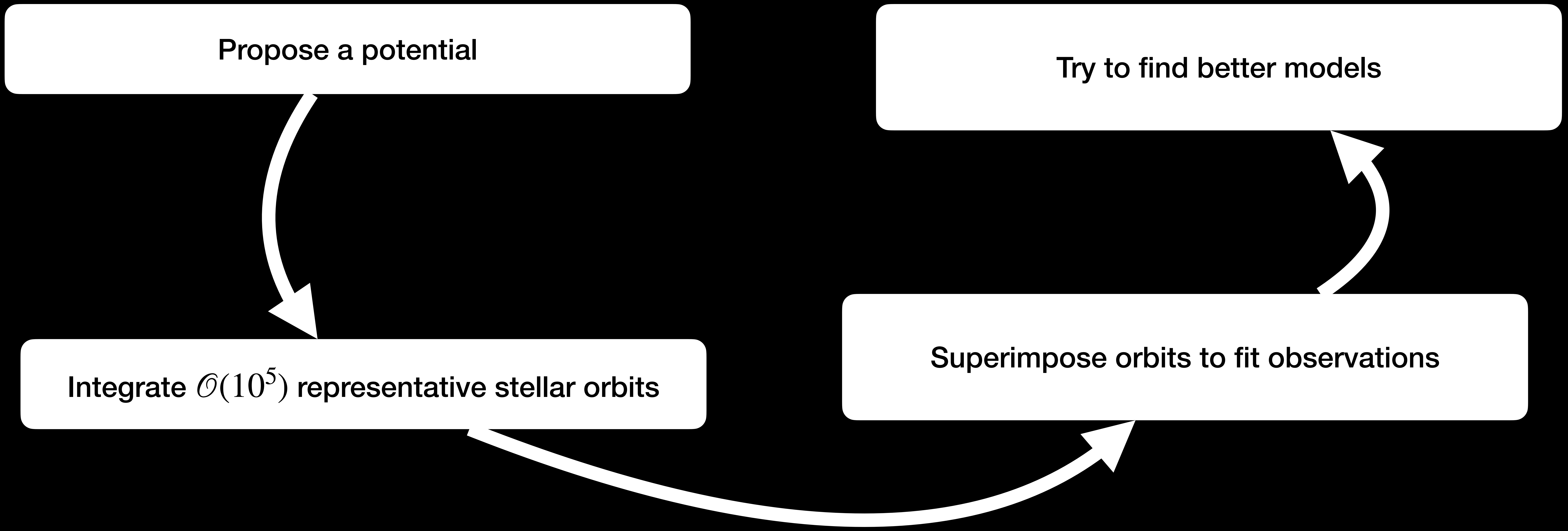

How to **measure** SMBHs

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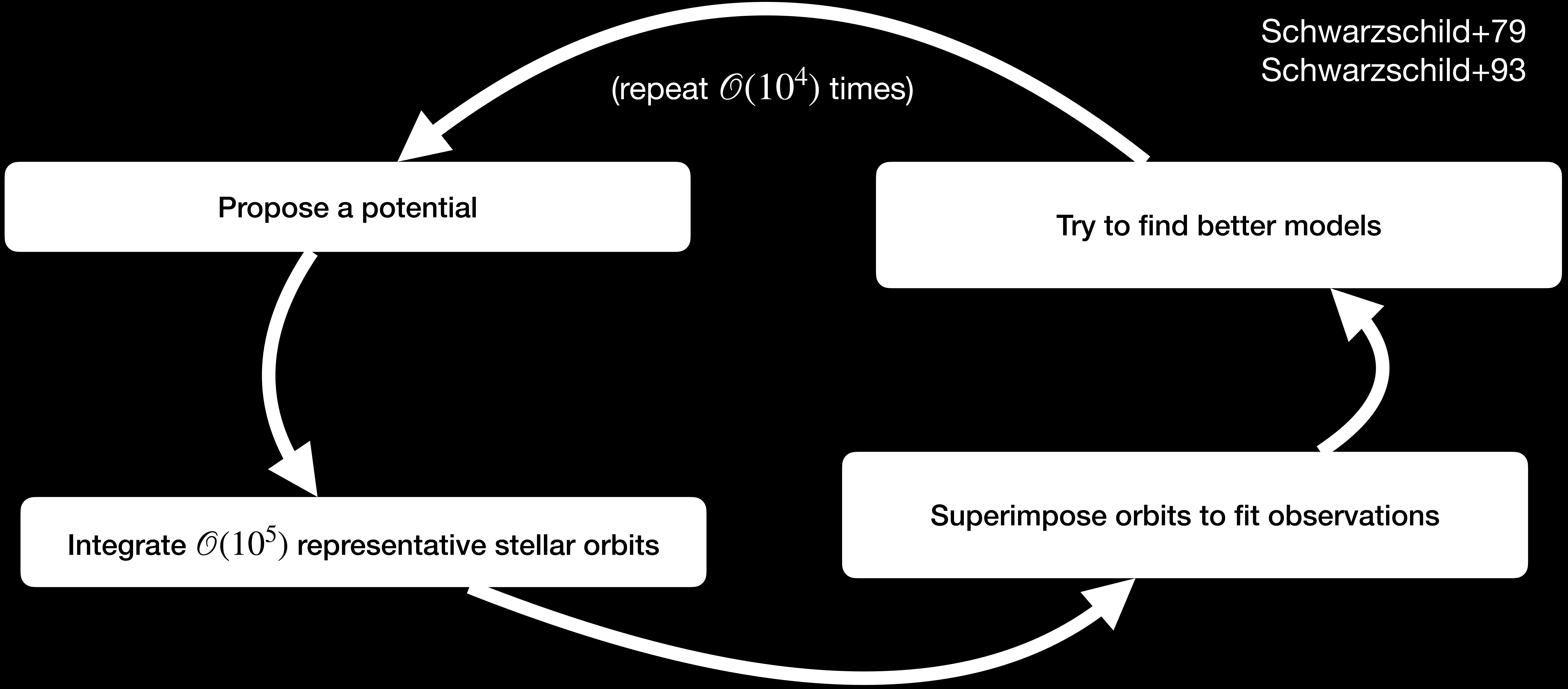

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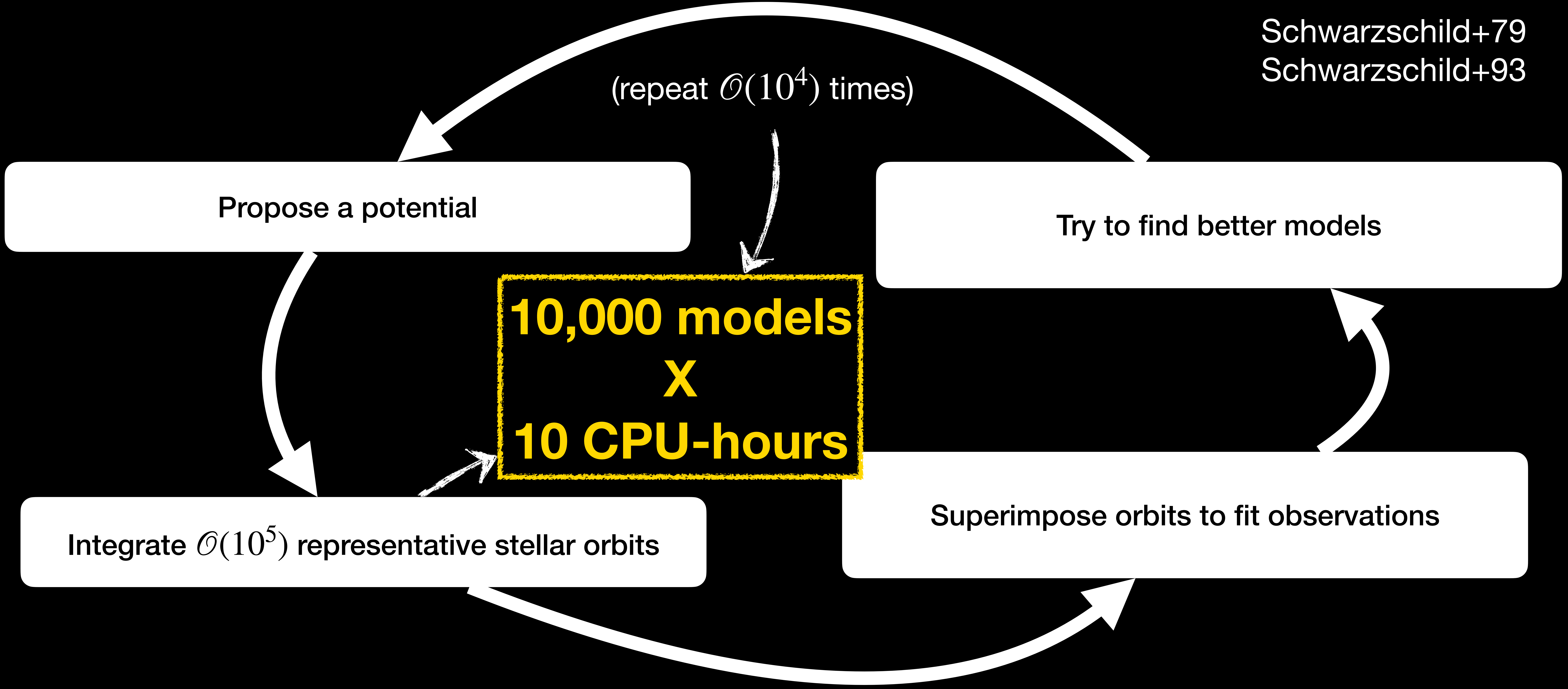

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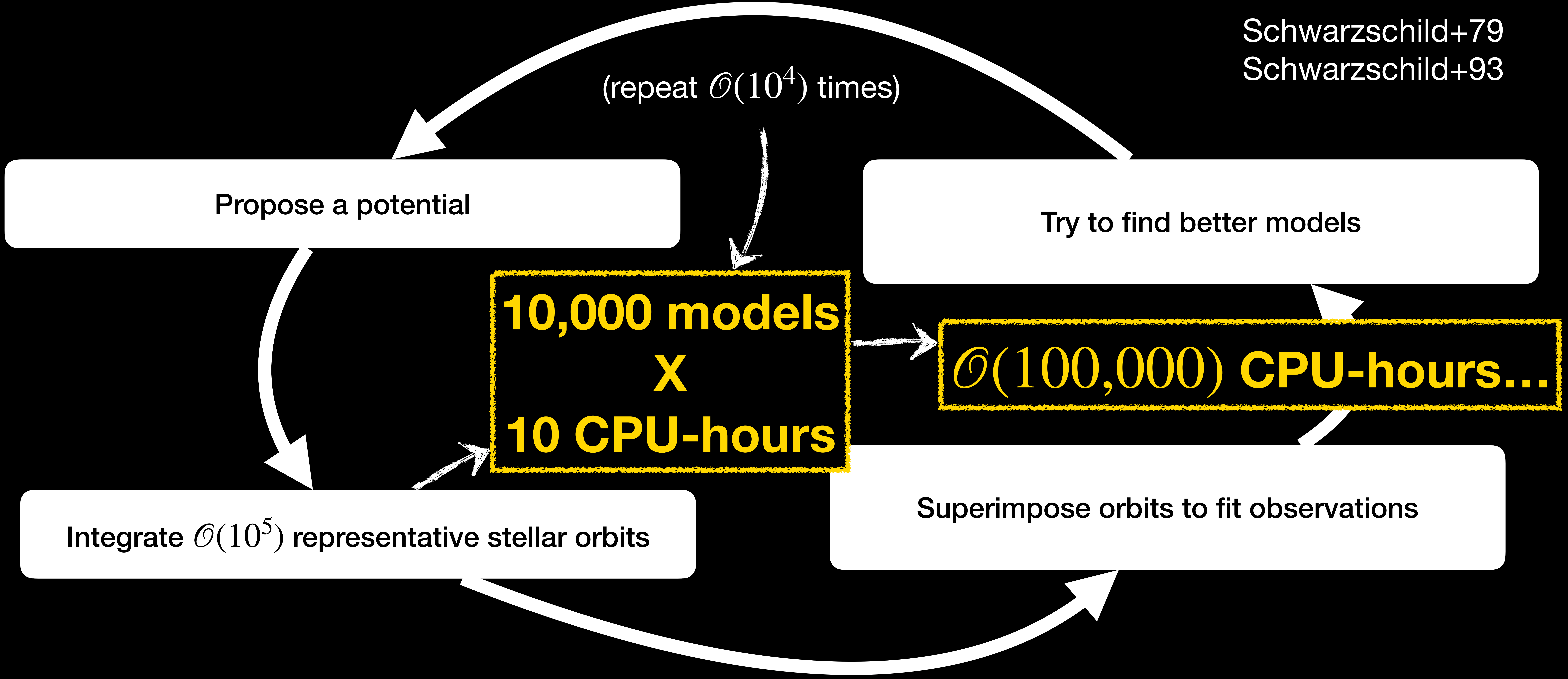


How to (really) measure SMBHs

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 calls to acceleration functions and orbit projection. *(~order of magnitude speedup!)*

3. 6-7-dimensional grid-free model sampling+ parameter inference improvements!

   (~couple order of magnitude speedups)

4. Robustness and validation tests with mock galaxy data!

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

How to (really) measure SMBHs

We've substa ode of van den Bosch+08

(Now we cal

1. Accurate orbit cor and triaxial galaxies

Triaxial Schwarzschild orbit modeling is now in production mode!

2. Efficiency improvements in calls to acceleration functions and orbit projection. *(~order of magnitude speedup!)*

3. 6-7-dimensional gri nference improvements!

   (~couple order o

NGC1453: Liepold+20, Quenneville+22
NGC2693: Pilawa+22
M87: Liepold+23
Holmberg 15A: (Next slide)
NGC57 & NGC315: Pilawa+soon
IC1101: Liepold+soon

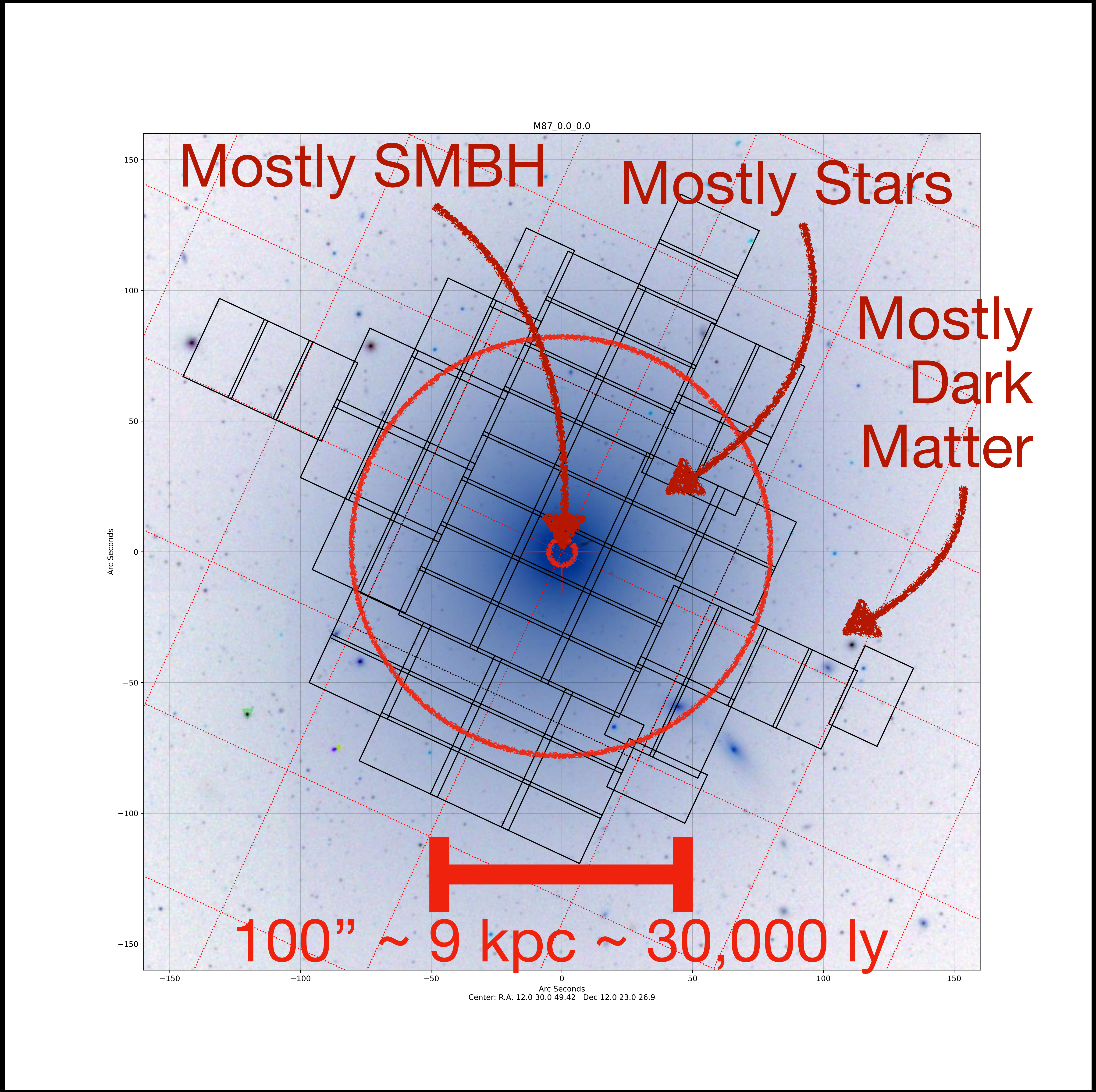
4. Robustness and va

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

Keck observations 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
- 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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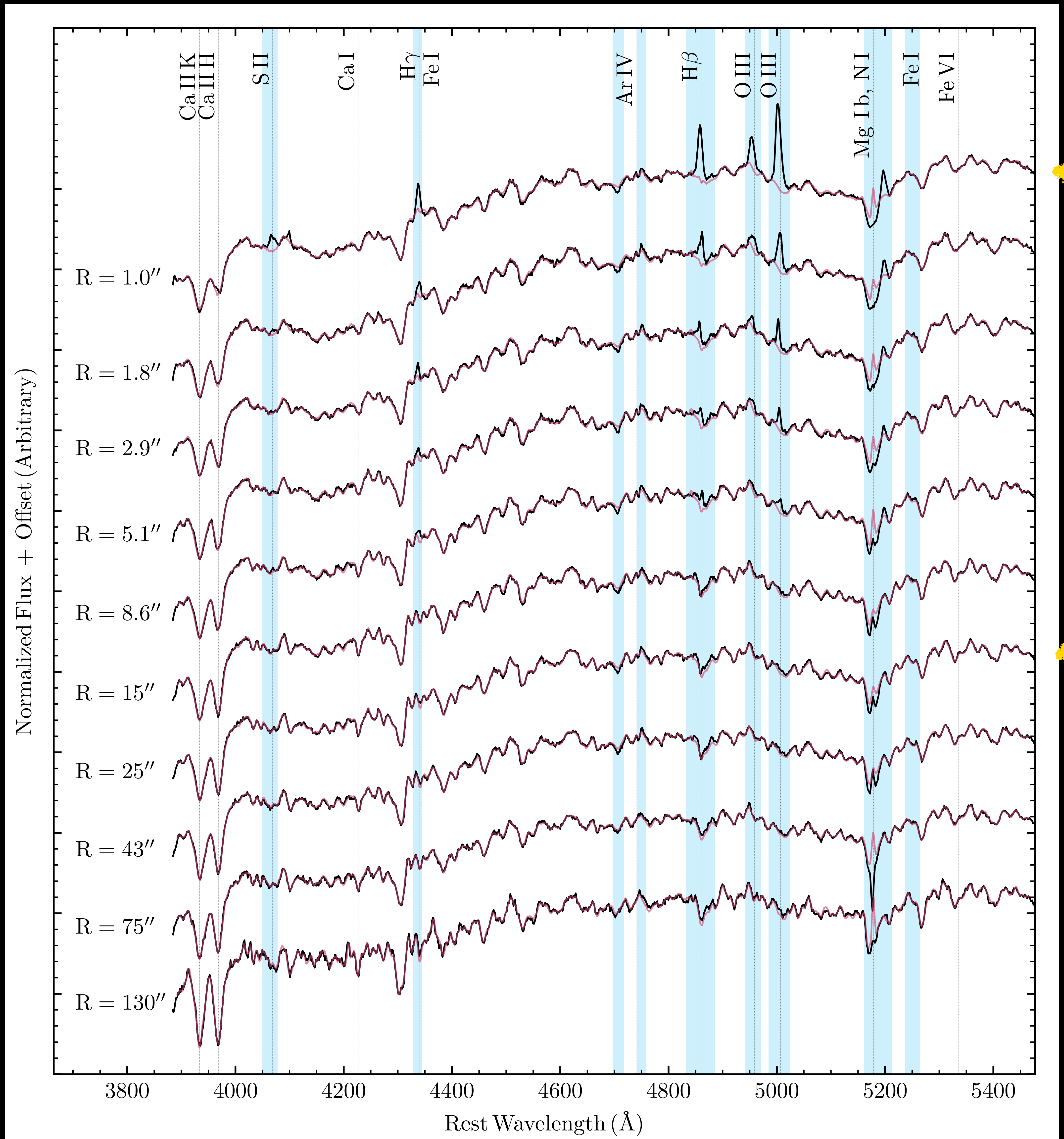

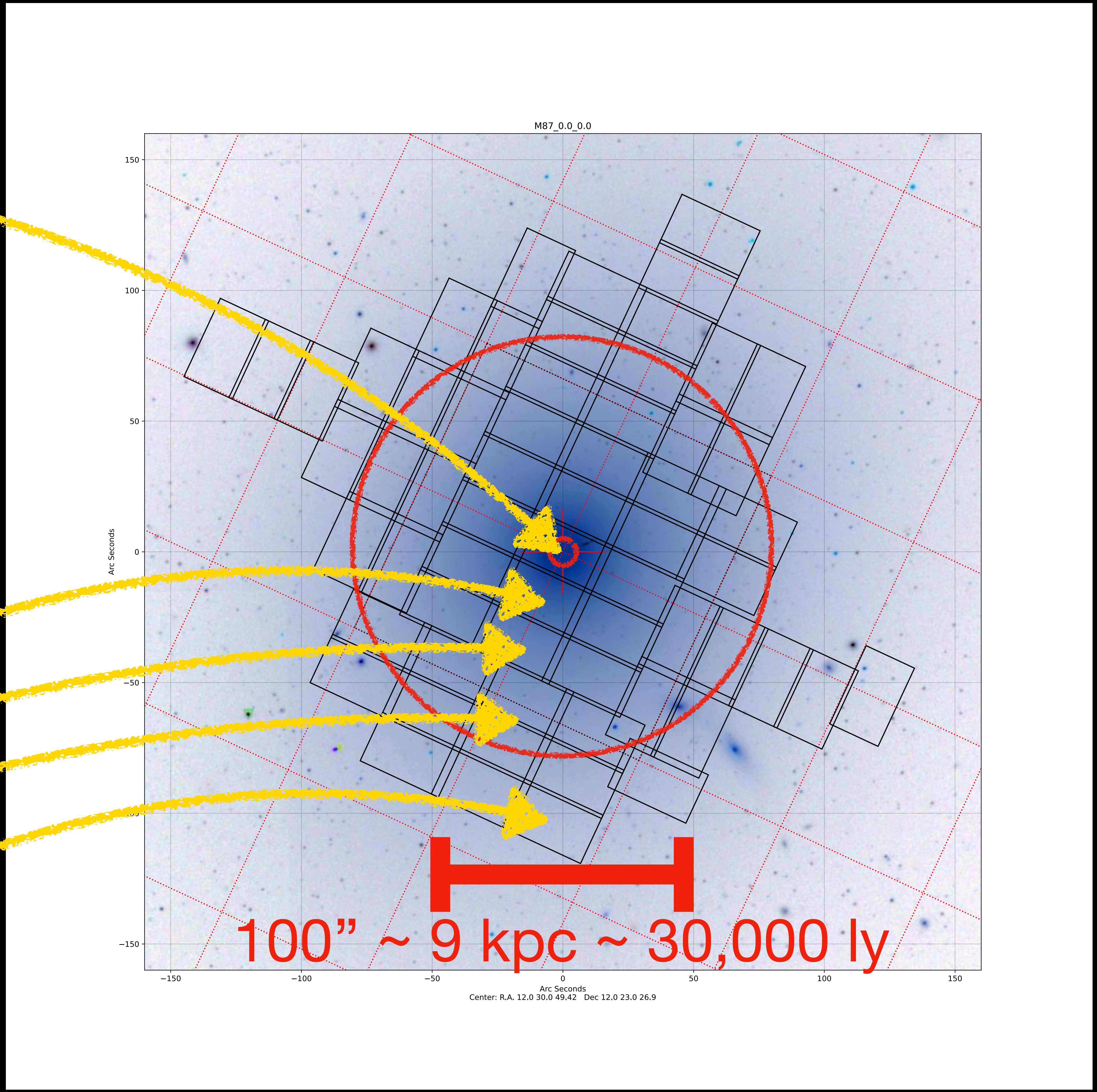

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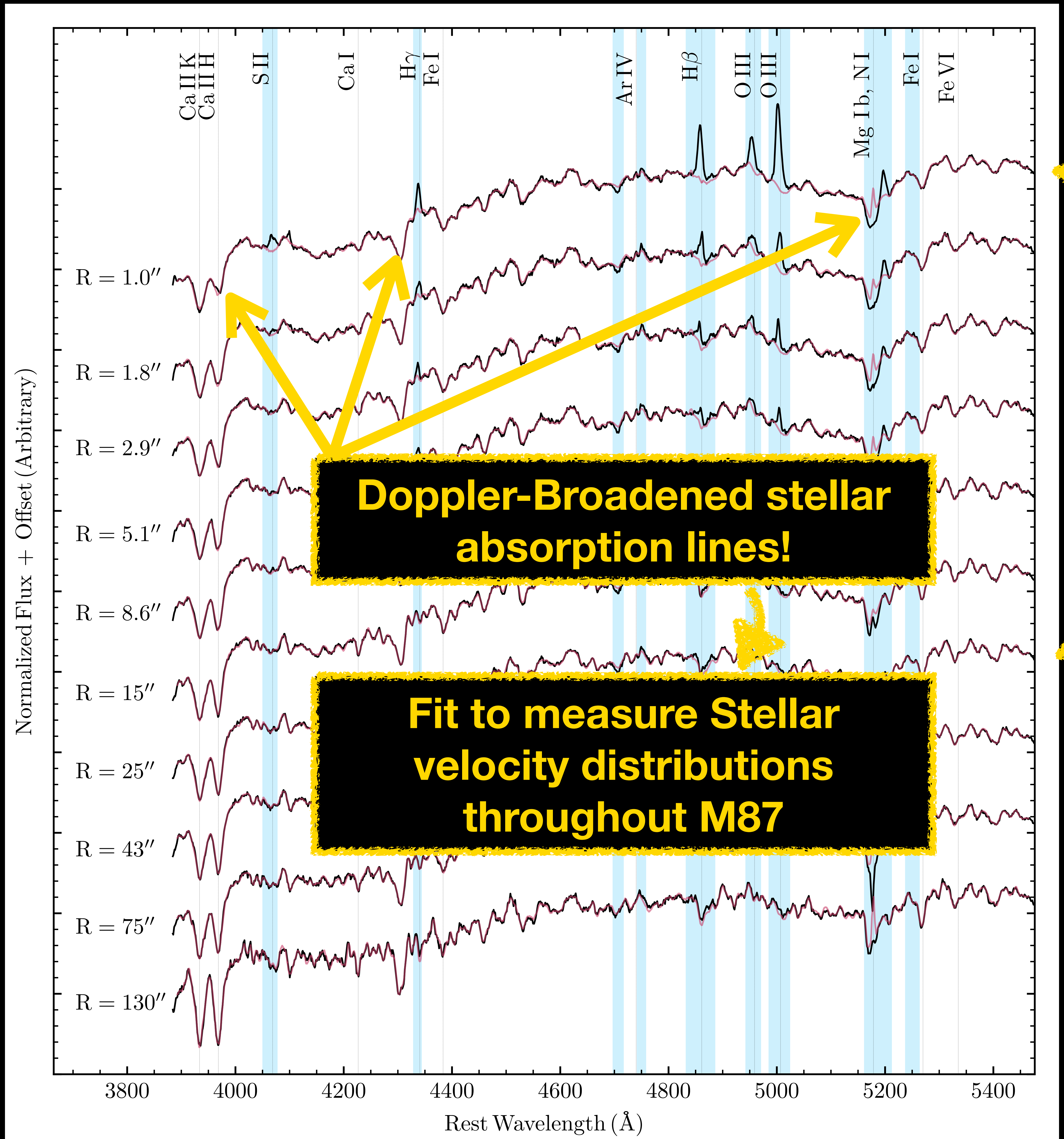

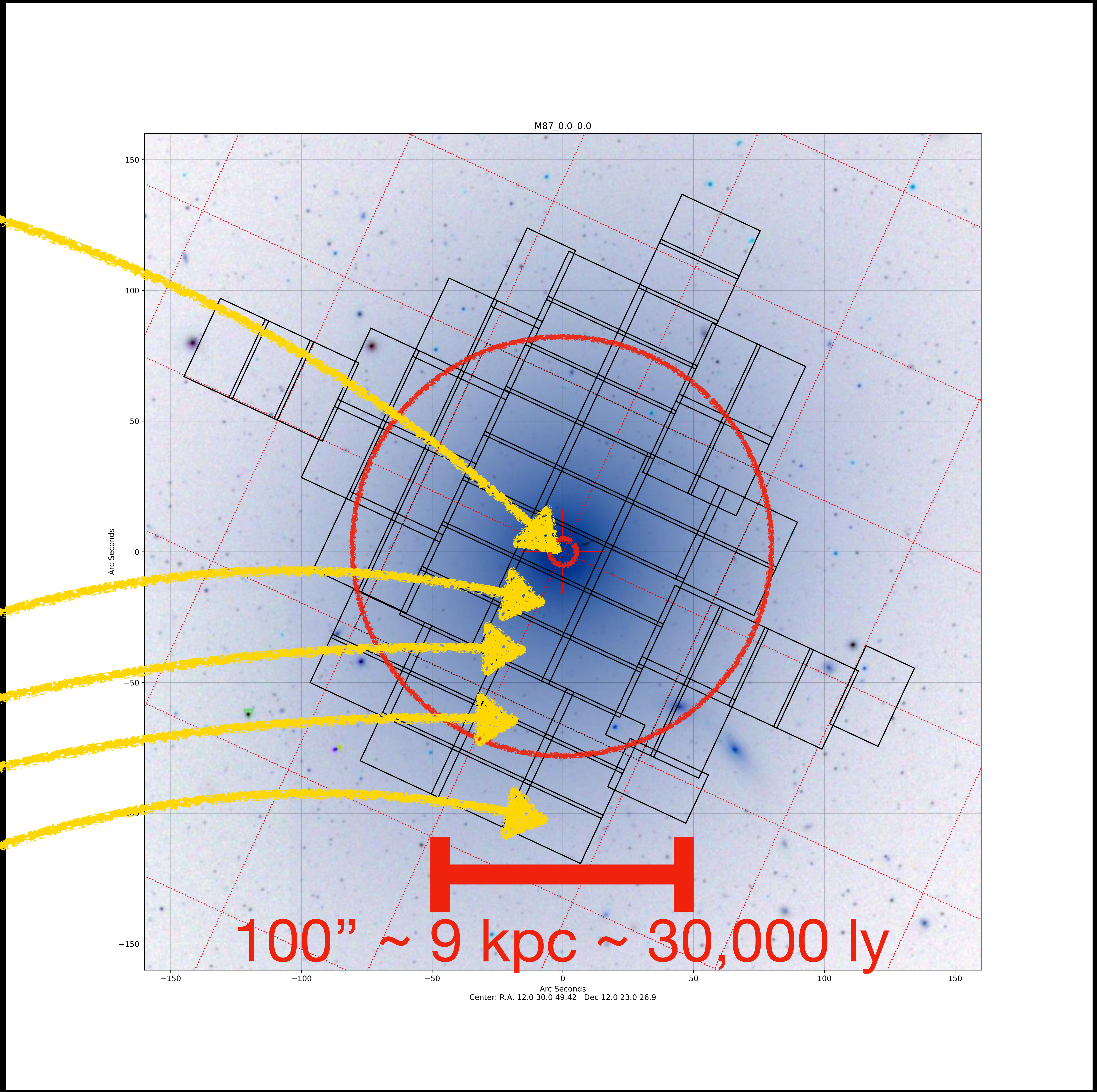

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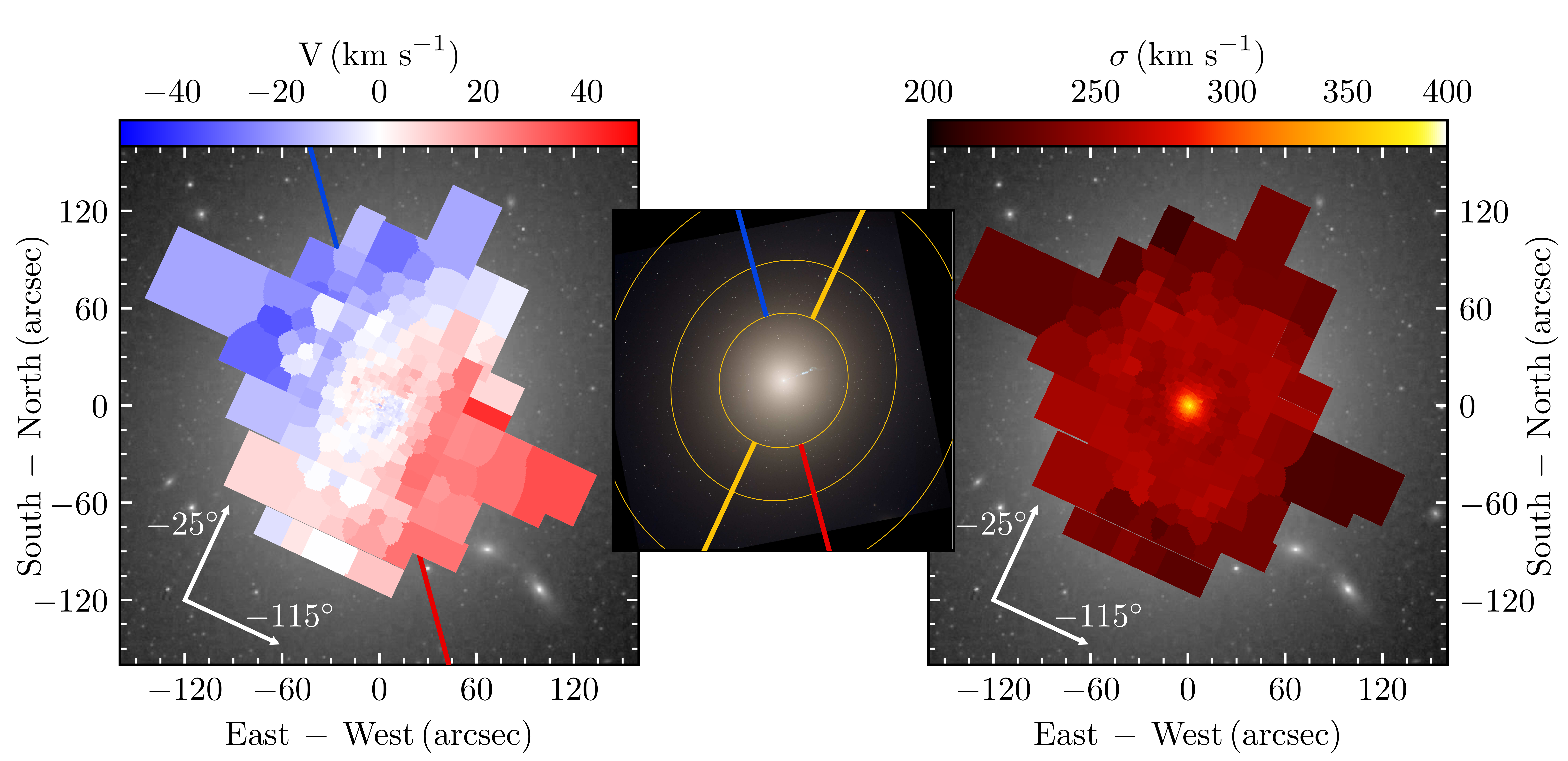

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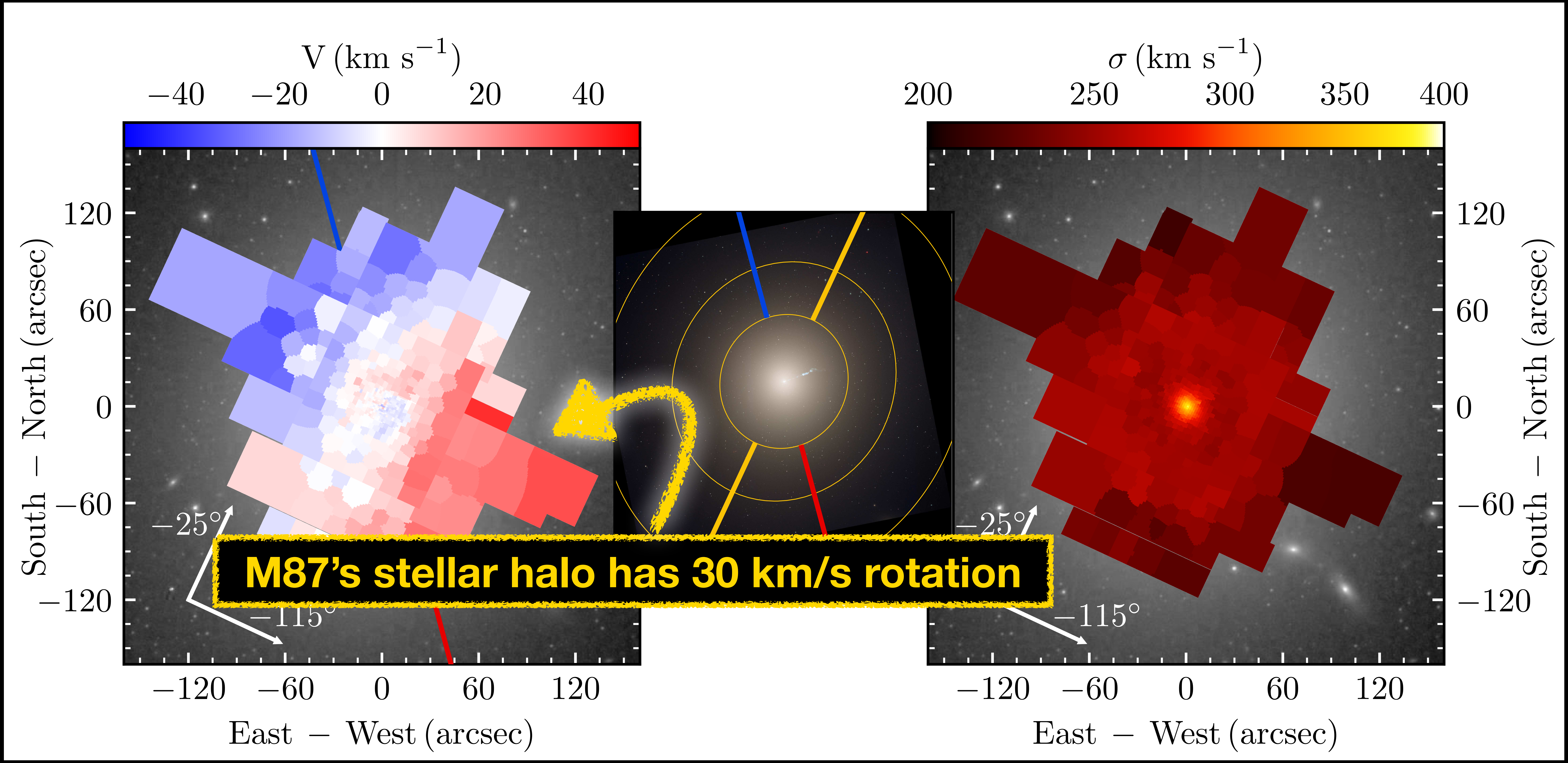

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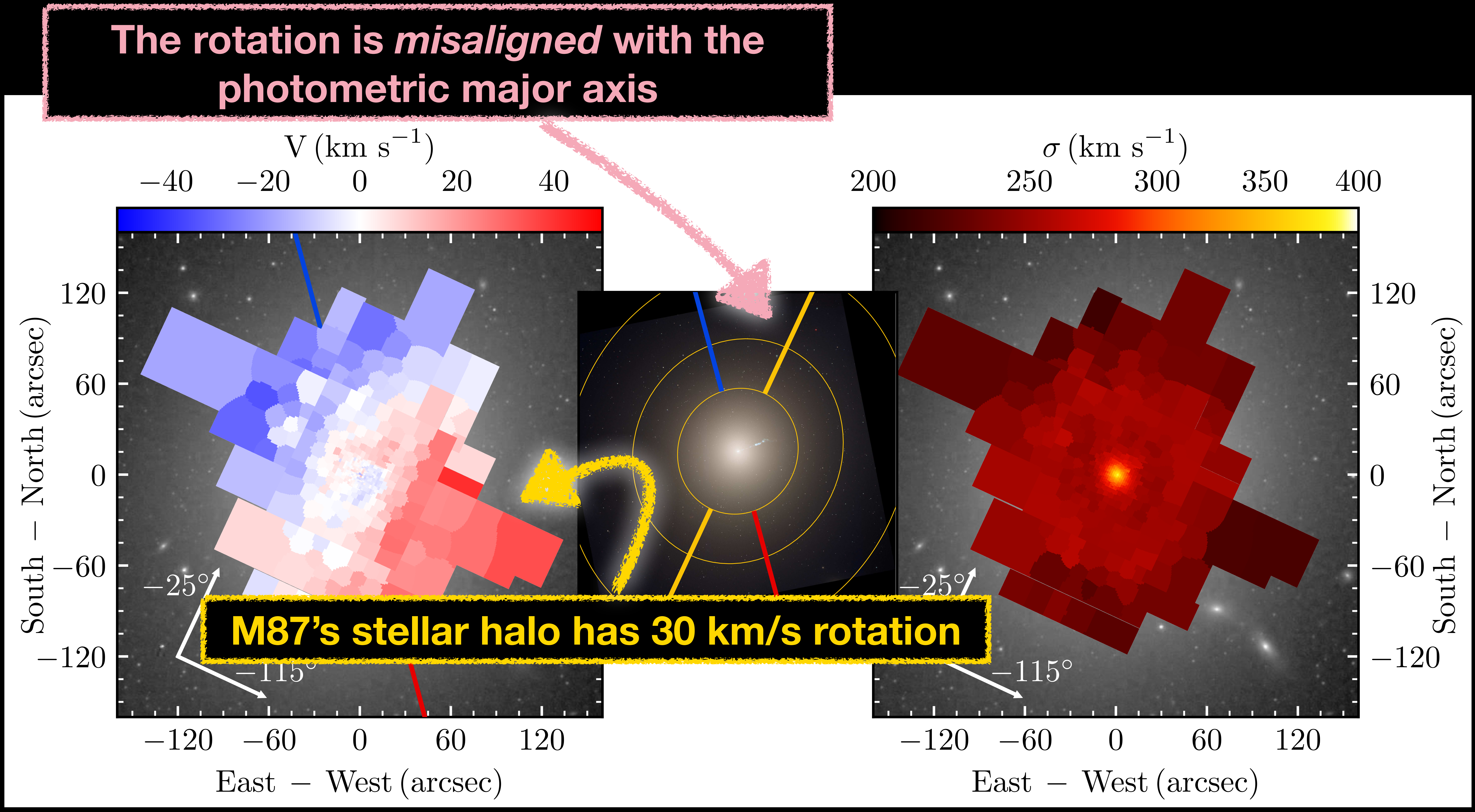


Keck observations of M87

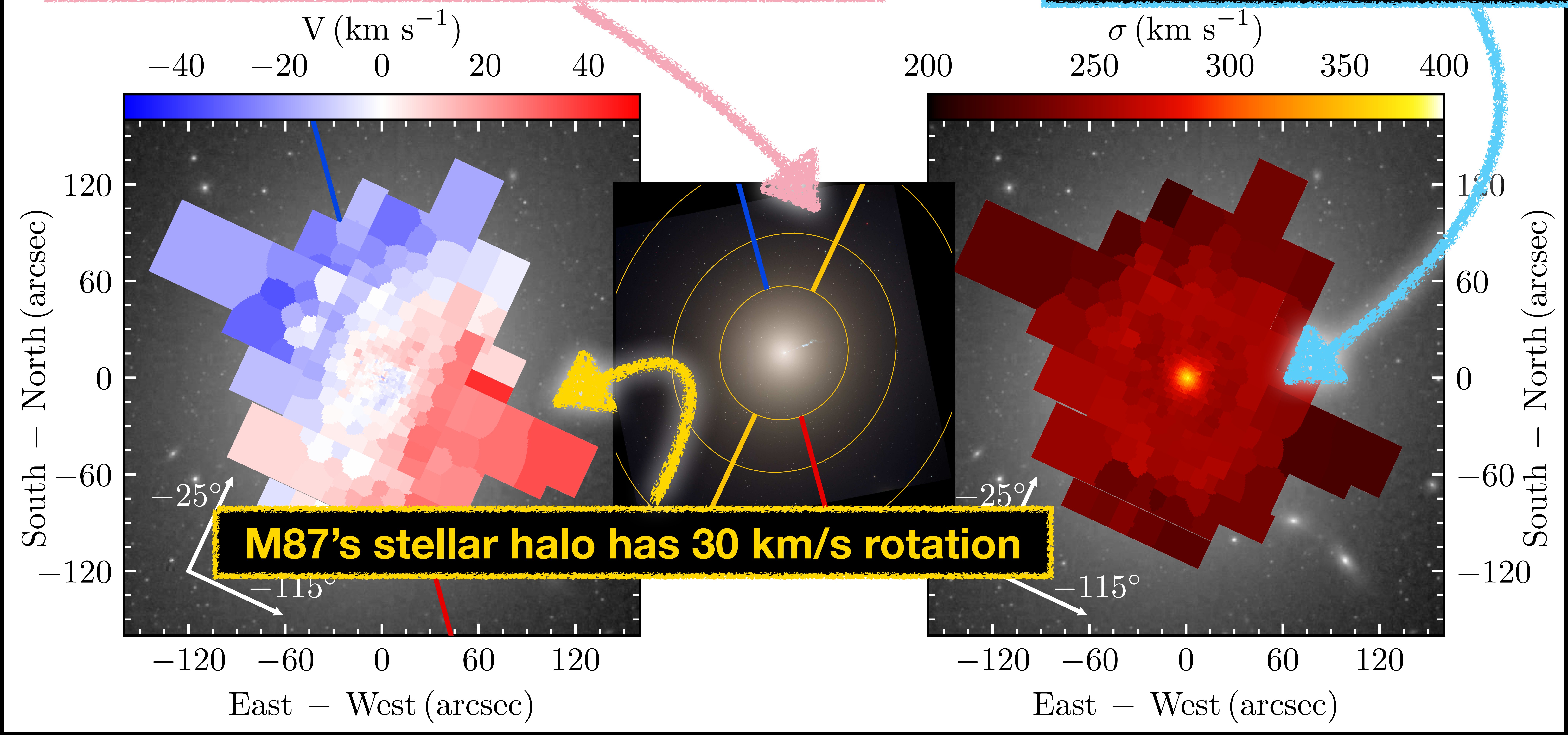
Liepold, Ma, Walsh 2023

The velocity dispersion rises *quickly* towards the center!

Tell-tale sign of a black hole!

The rotation is *misaligned* with the photometric major axis

M87's stellar halo has 30 km/s rotation



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Ask about our JWST data! (PI Jonelle Walsh, Co-I's Greene, Liepold, Ma) + a lot of work by Refa!

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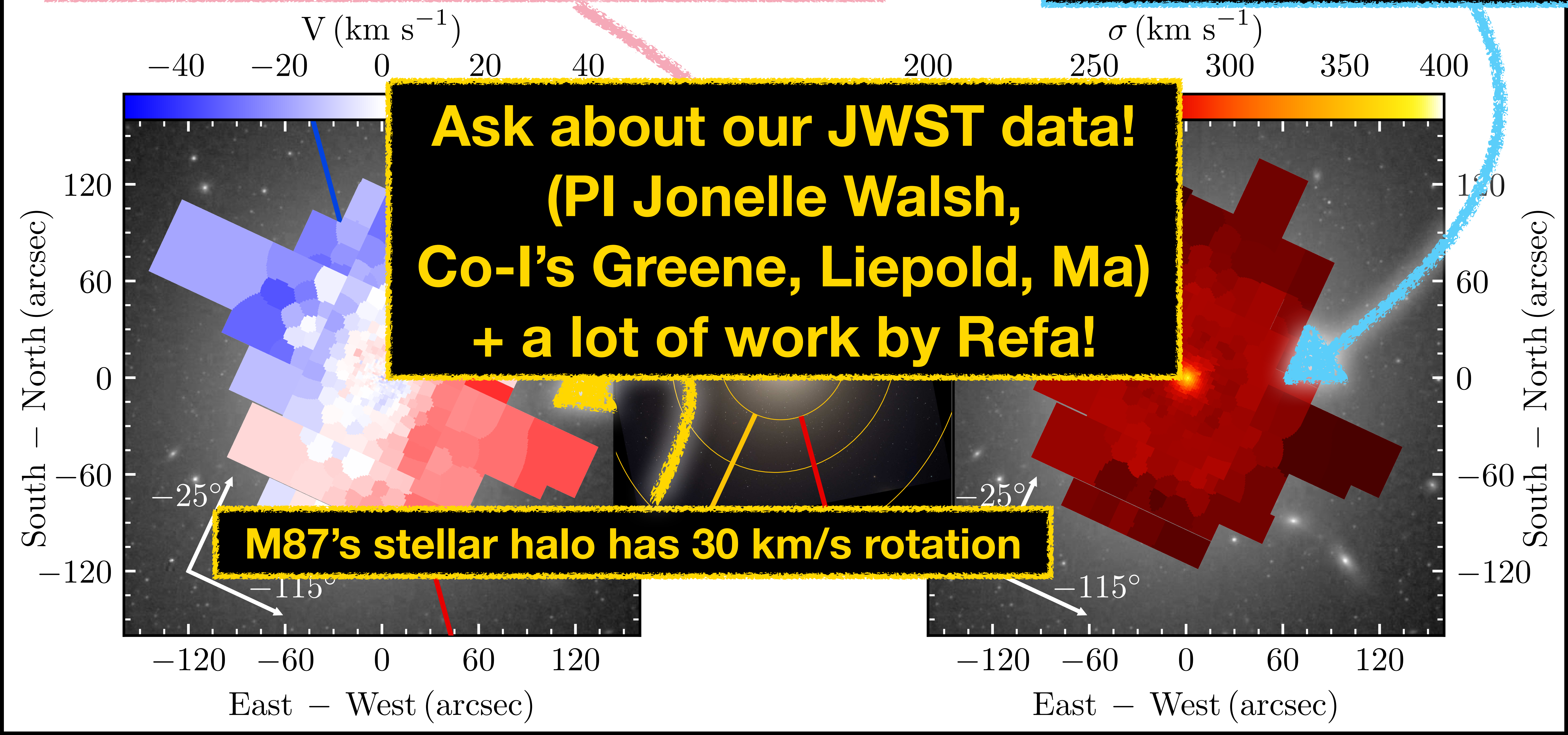

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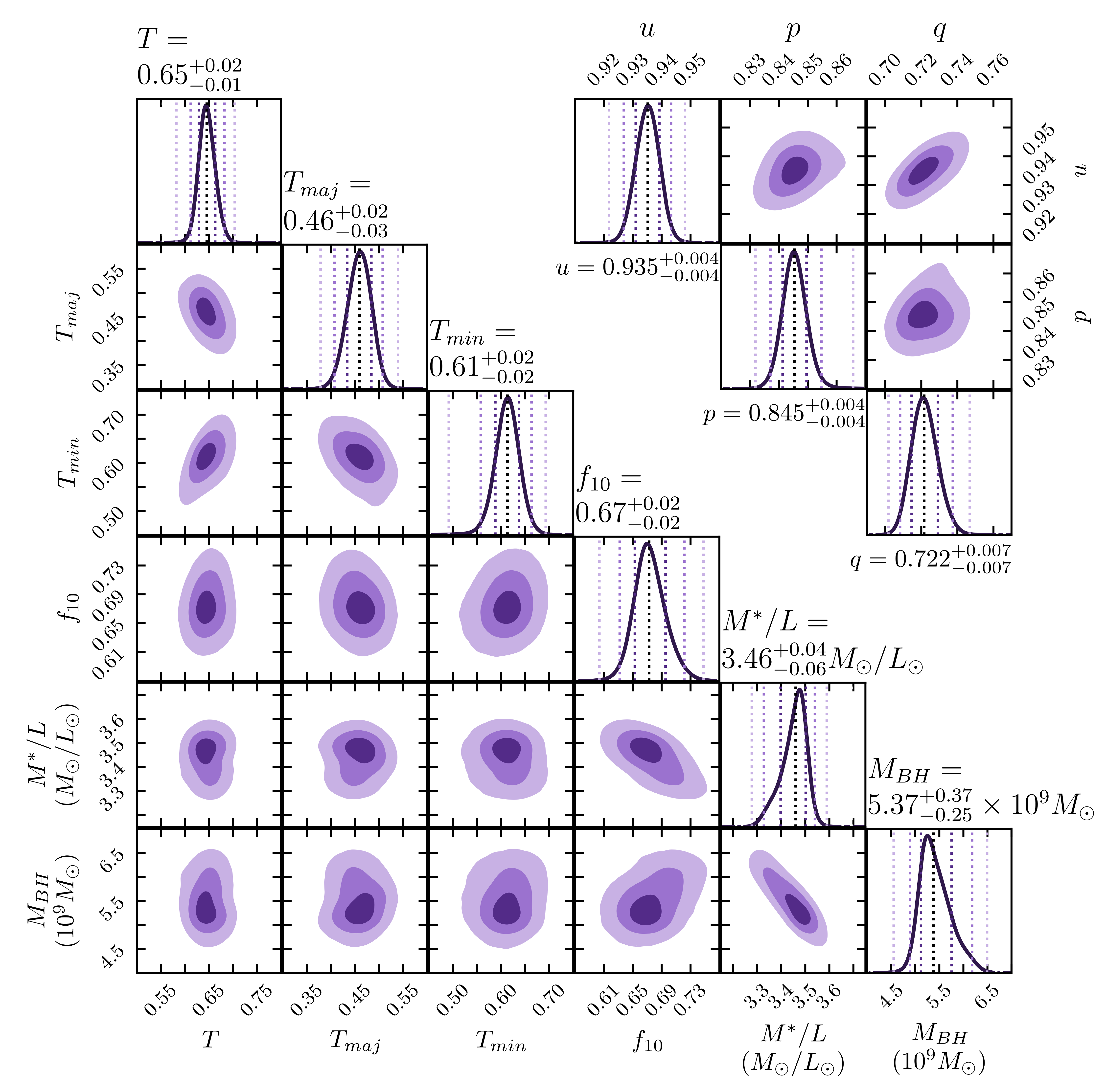

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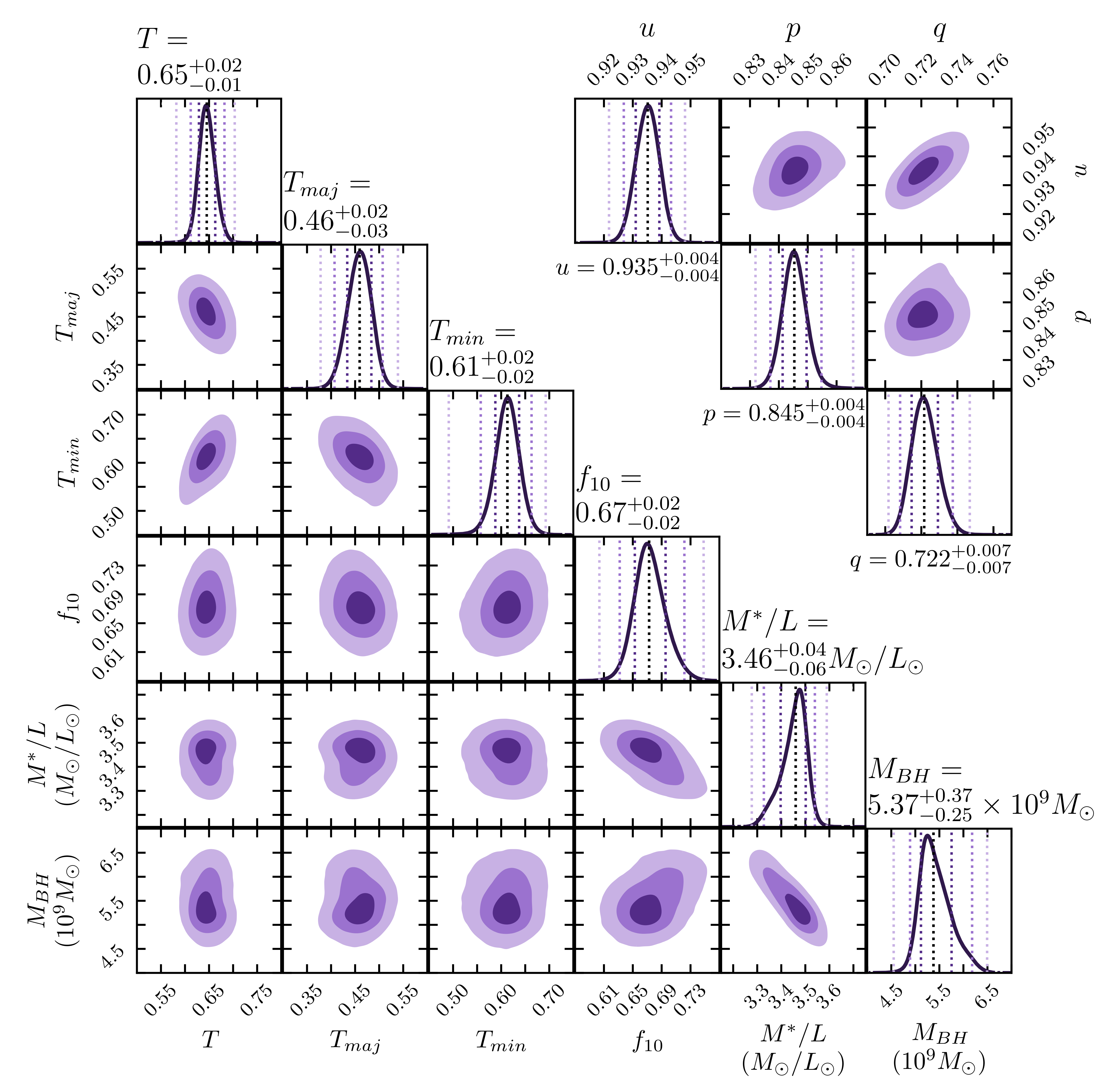

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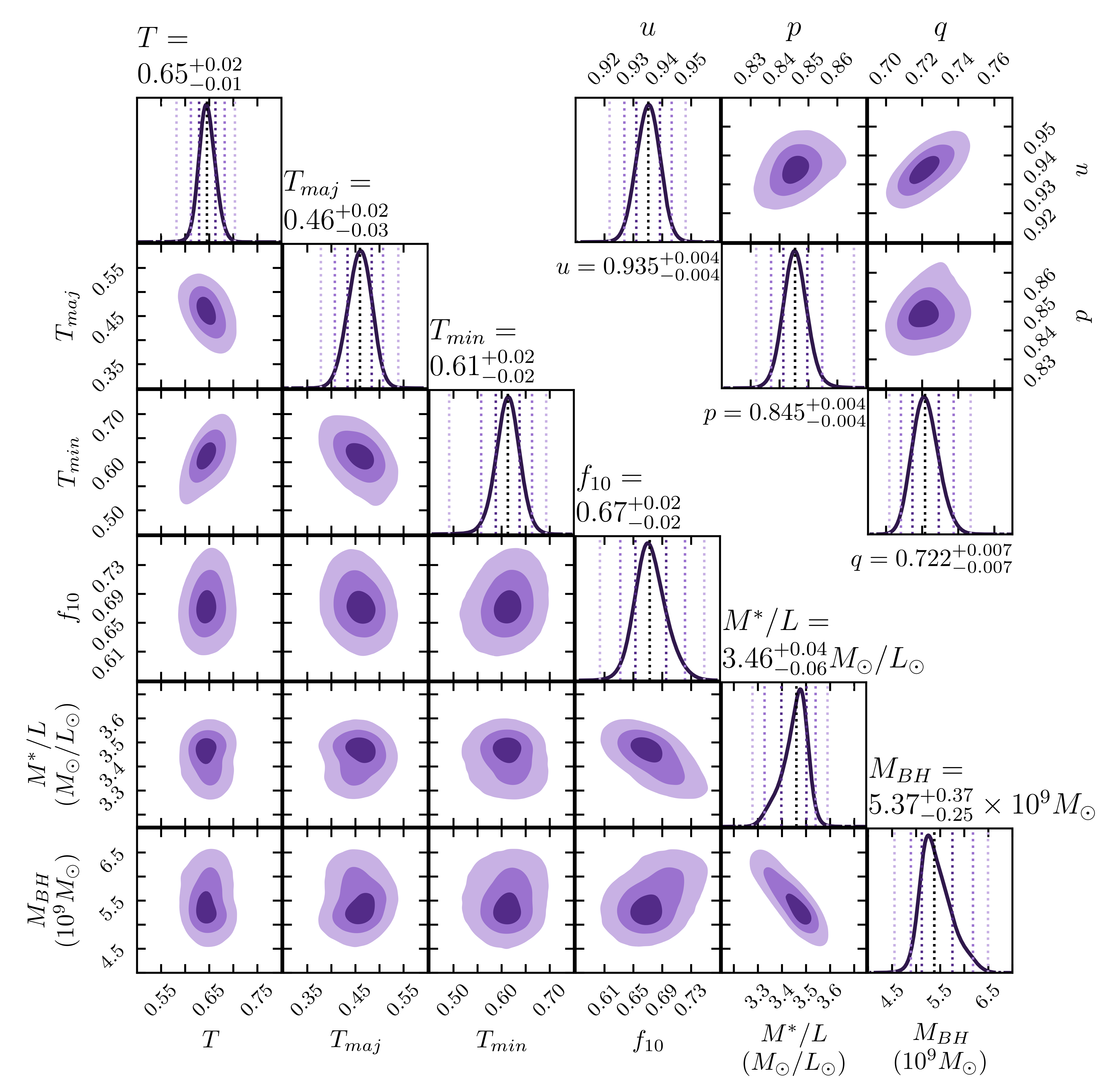

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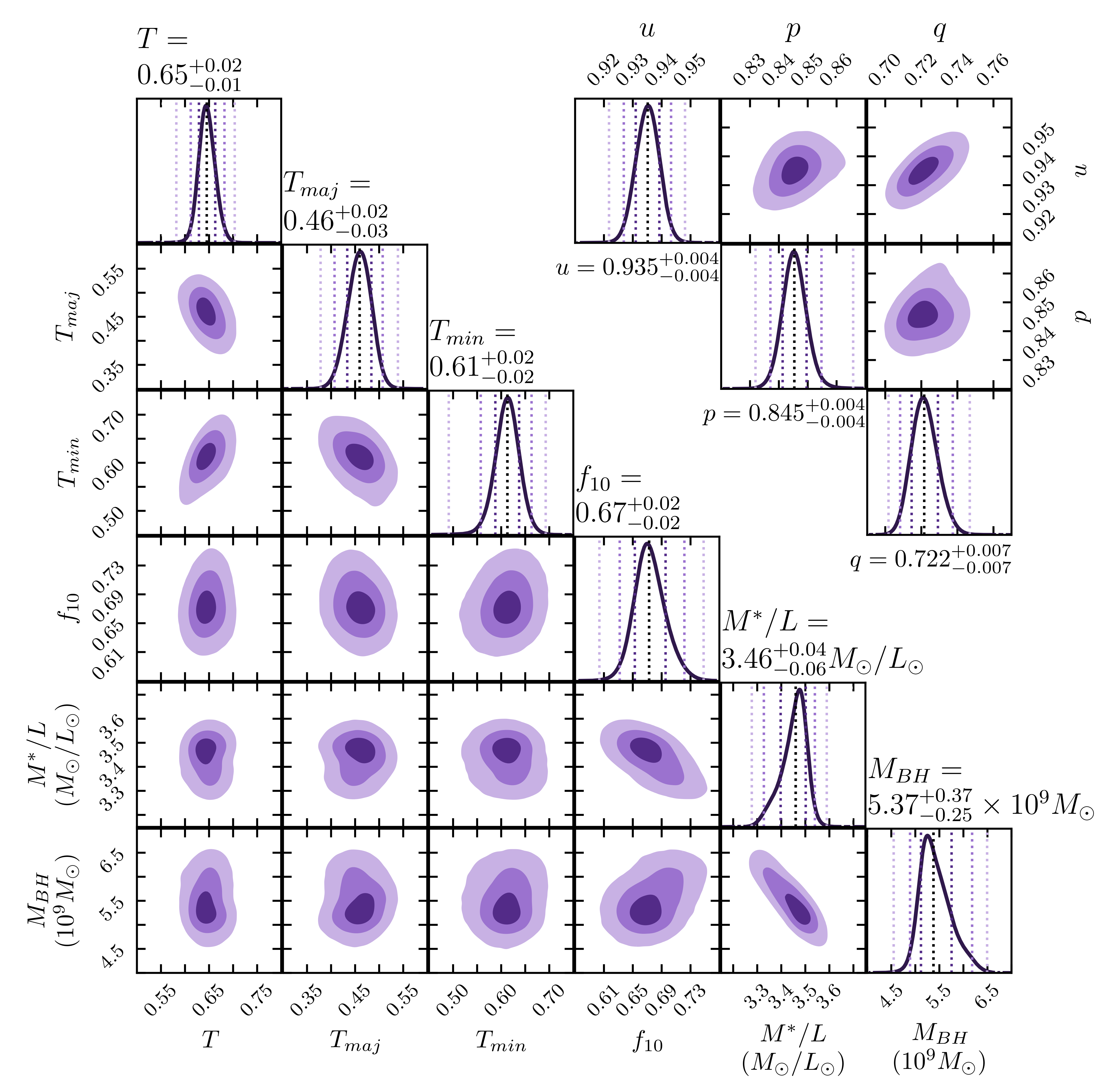

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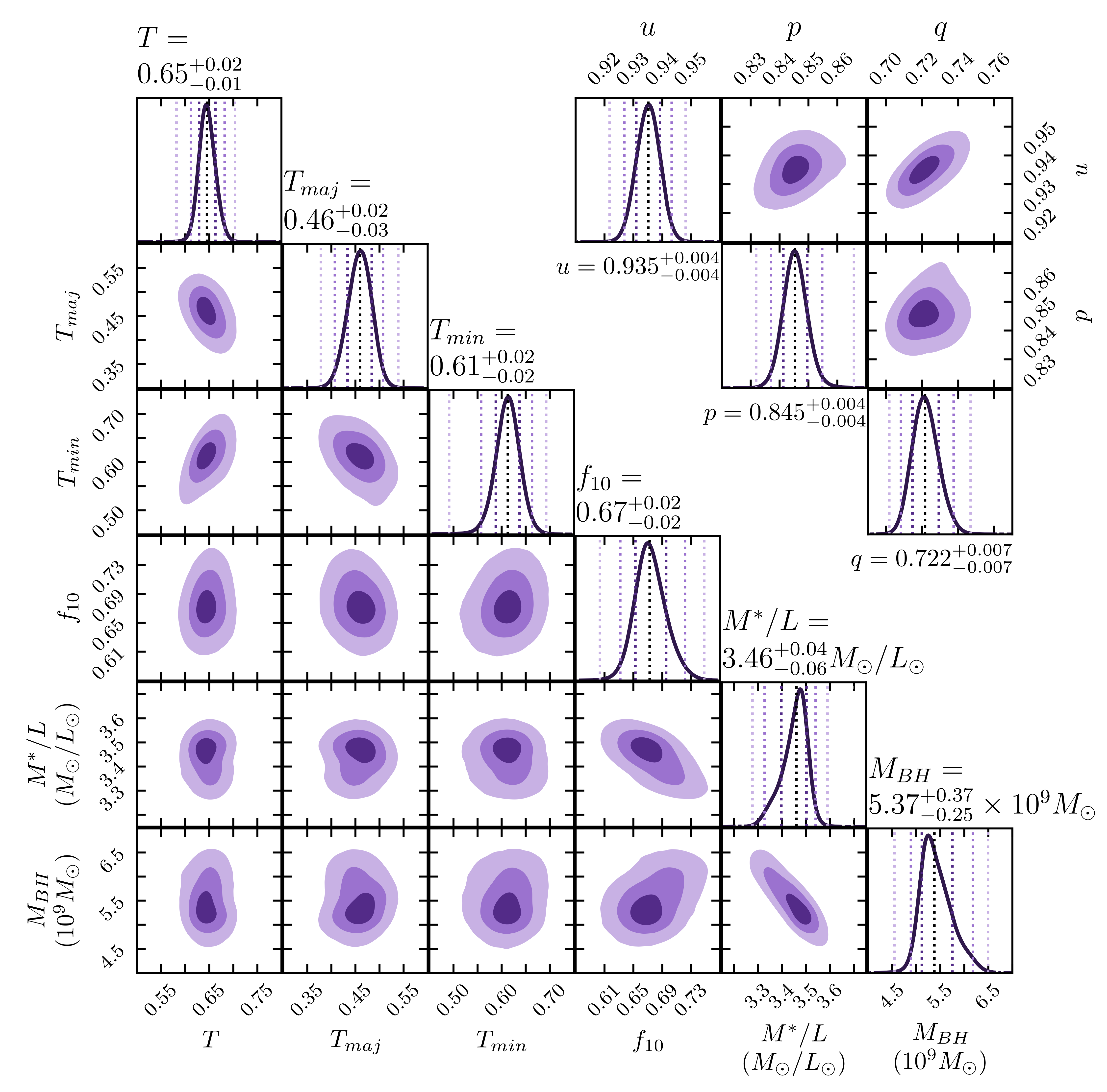

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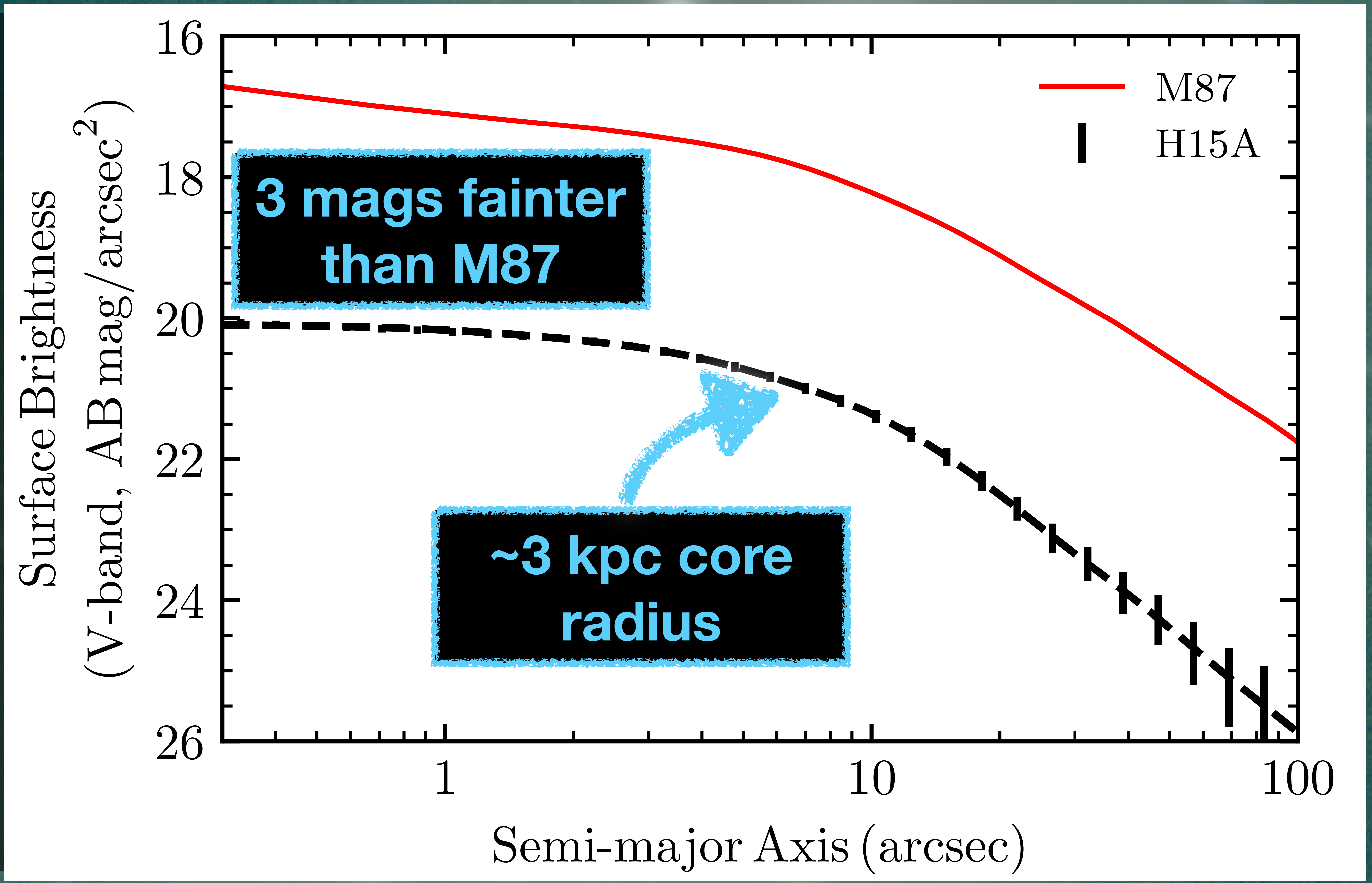
- A puzzle: apparent alignment of the jet, the stellar **L** vector, and the Virgo cluster
- (a tweet from Hubble!)

> **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

Moving Forward: Holmberg 15A

Liepold, Ma, Walsh 2024 (Forthcoming)

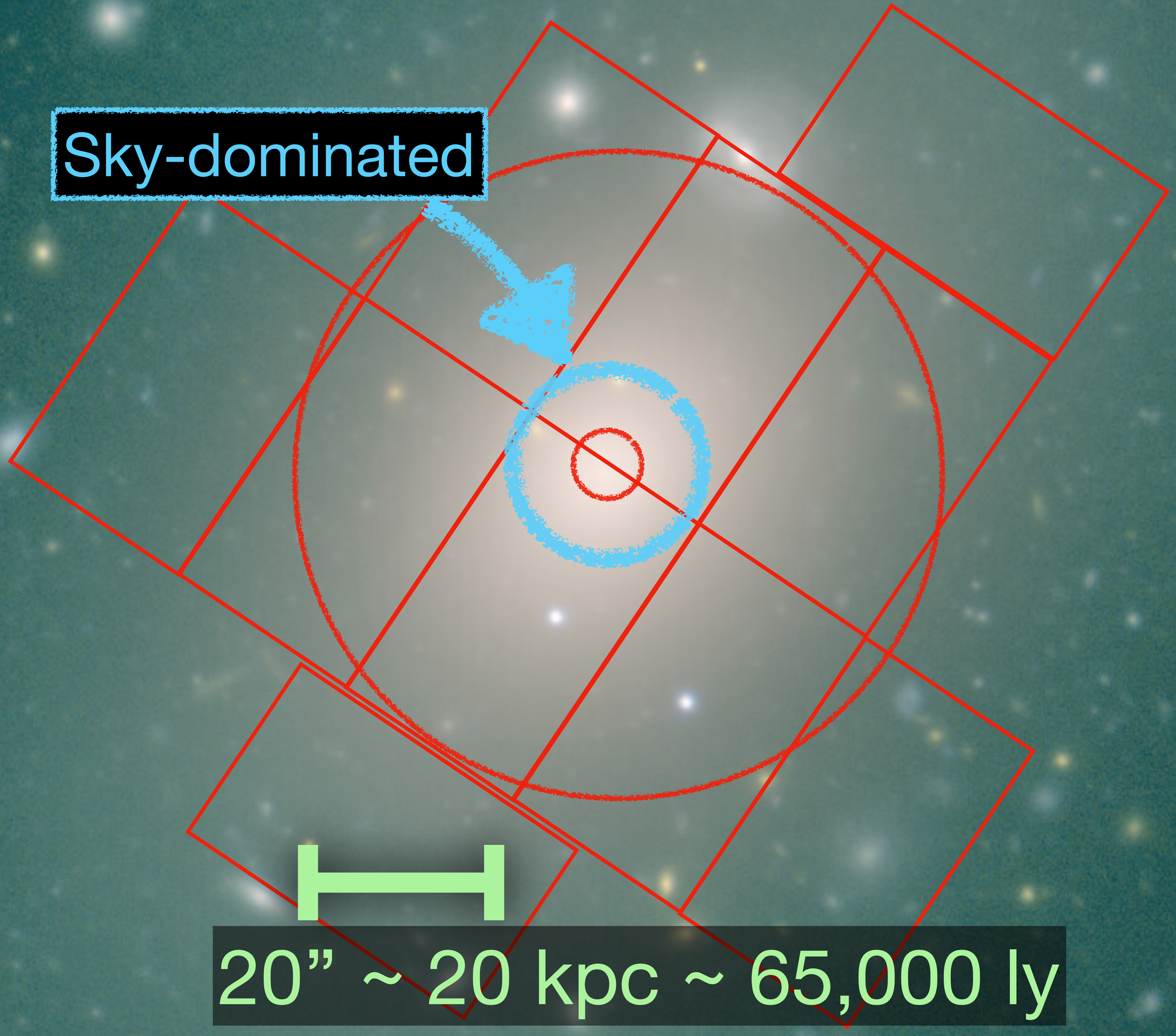
- BCG of Abell 85
- Largest known core! (~3 kpc)
- Faintest known Central SB! ($\mu_V = 20 \mathrm{mag/arcsec^2}$)
- The size of an ETG's core is correlated with the black hole mass
- The central surface brightness is ***anti***correlated with black hole mass
- (15x further away than M87)



Moving Forward: Holmberg 15A

Liepold, Ma, Walsh 2024 (Forthcoming)

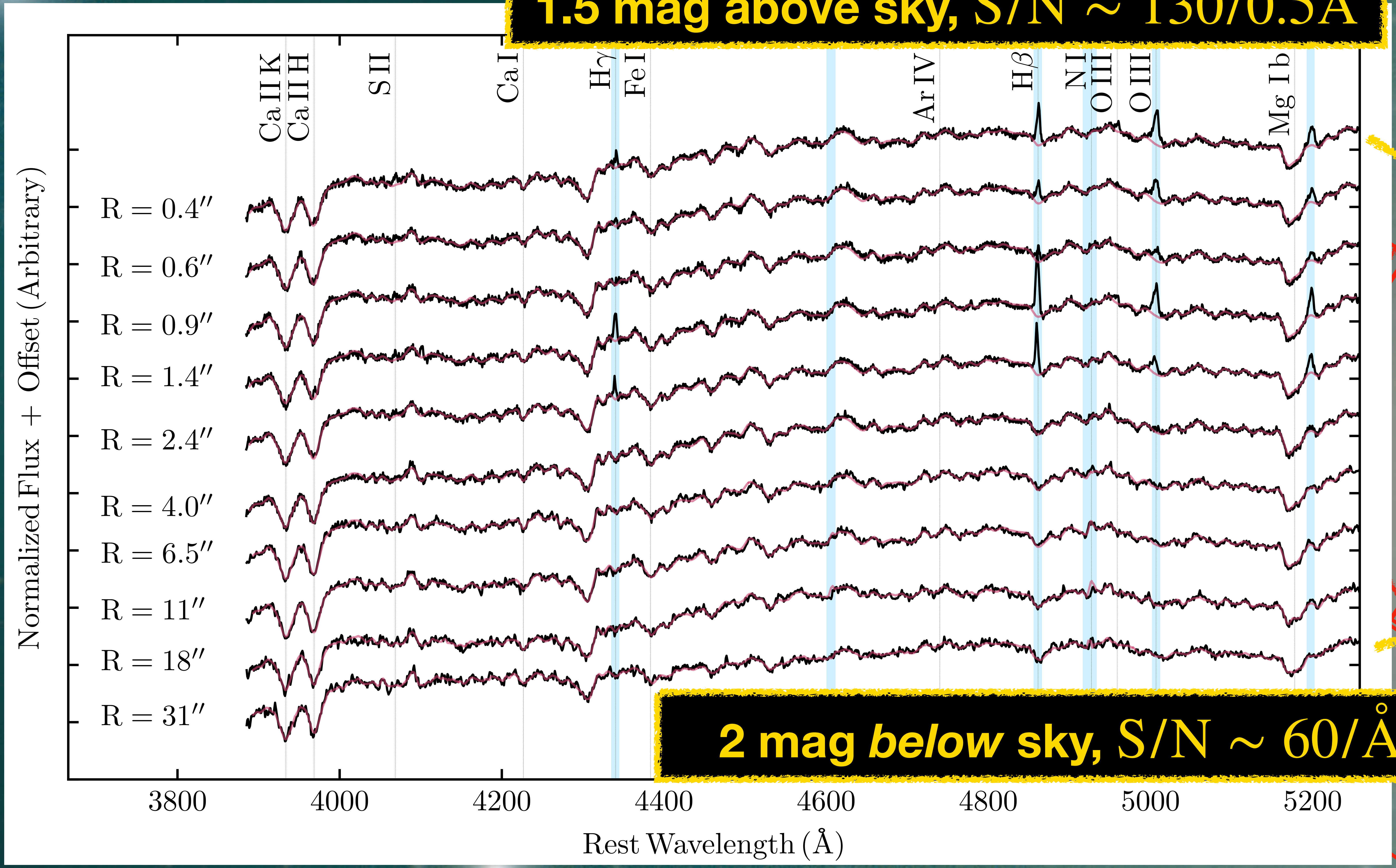
- We observed H15 with KCWI small and large slicers during five observing runs from Nov 2018 - Nov 2021
- ~12 hours on target with KCWI large and small slicers + 3.5 hours on sky
- The full FOV spans about 100 kpc along the photometric major and minor axes
- These observations are **mostly below sky level**



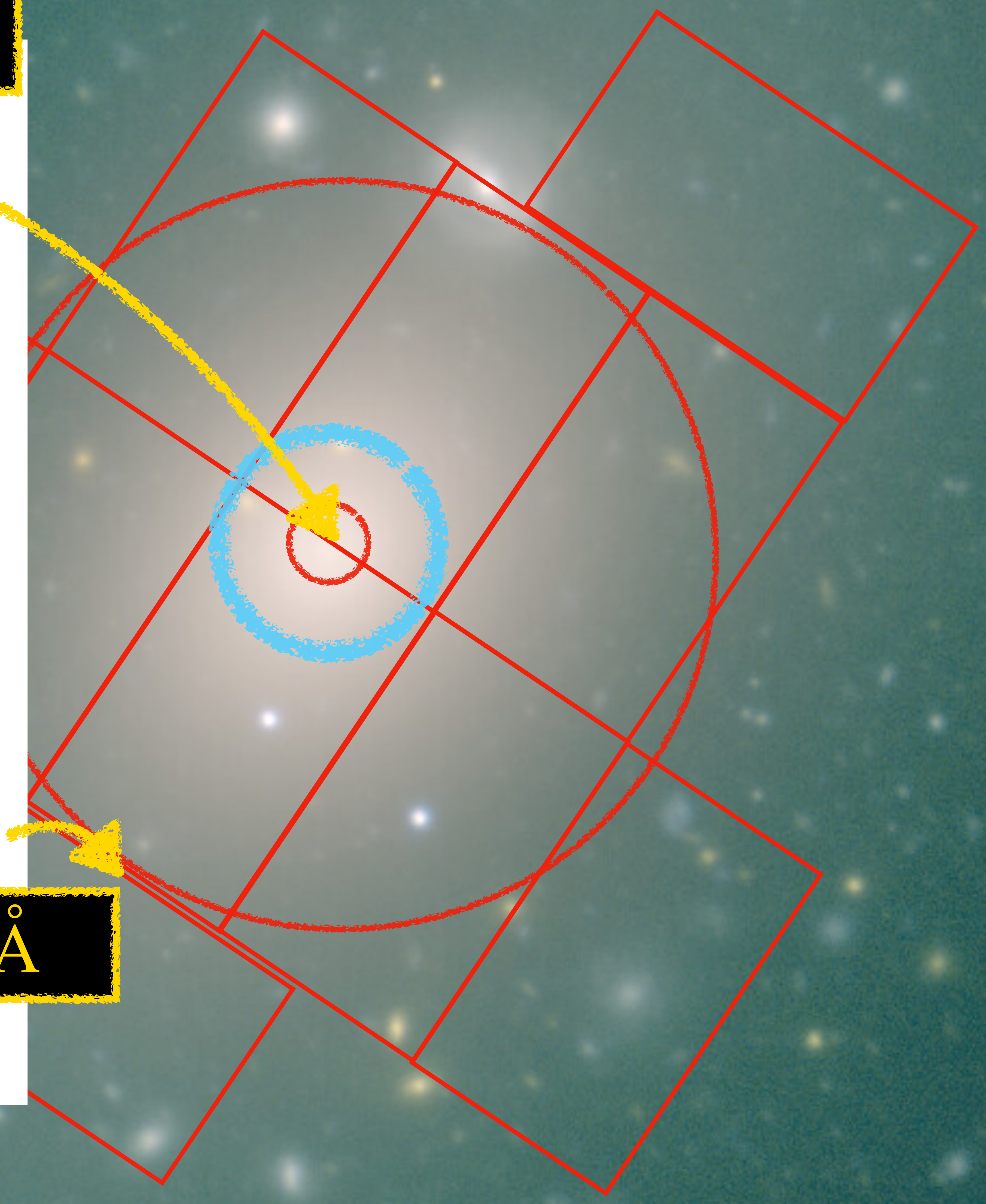
Moving Forward: Holmberg 15A

Liepold, Ma, Walsh 2024
(Forthcoming)

1.5 mag above sky, S/N ~ 130/0.5Å



2 mag *below* sky, S/N ~ 60/Å



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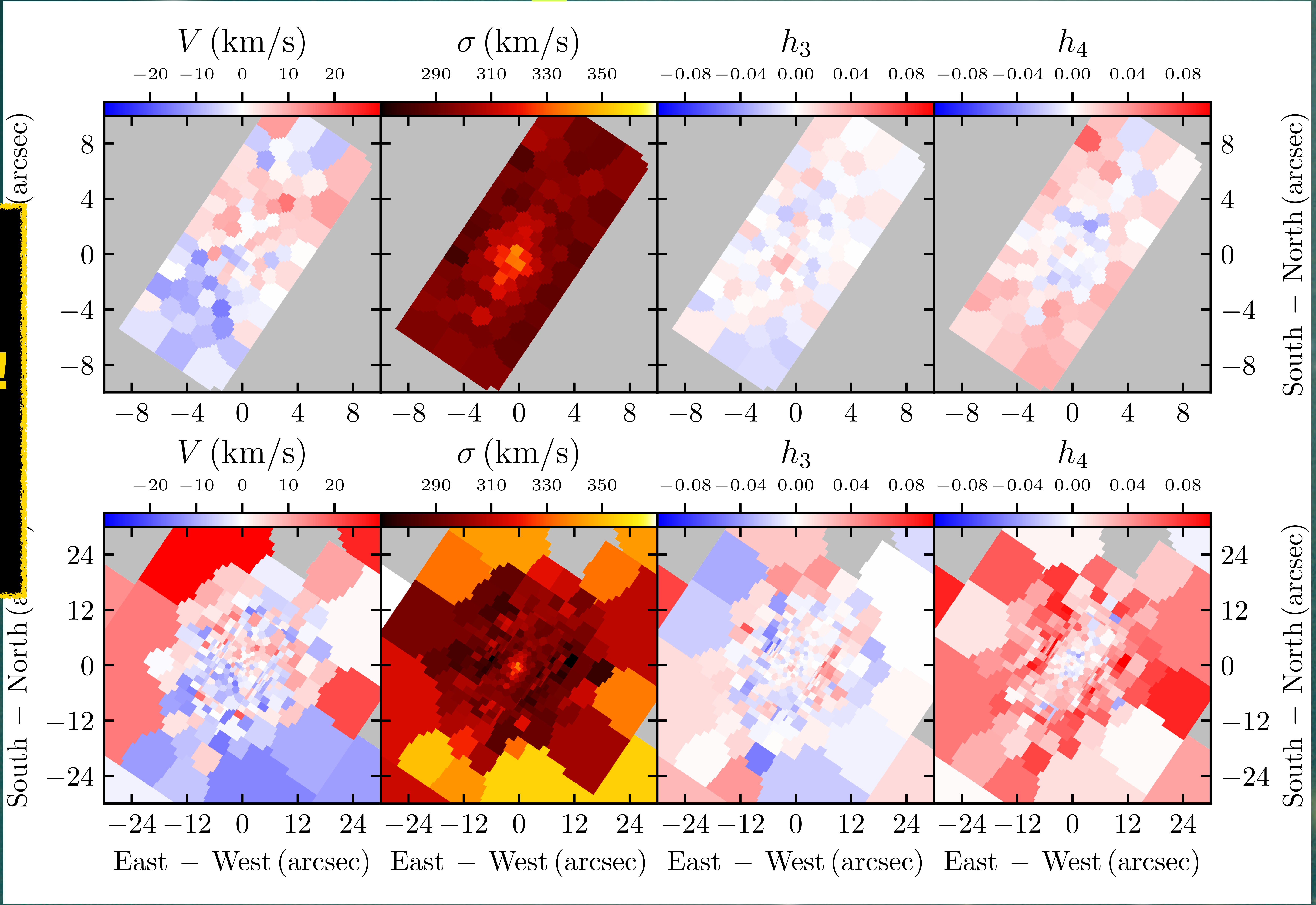

Measurements of 8 velocity moments in sky-dominated regions!

Only possible with KCWI!

Ongoing Efforts + Connections

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

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

- **Ultra-MASSIVE galaxies with KCWI (several more to model…)**

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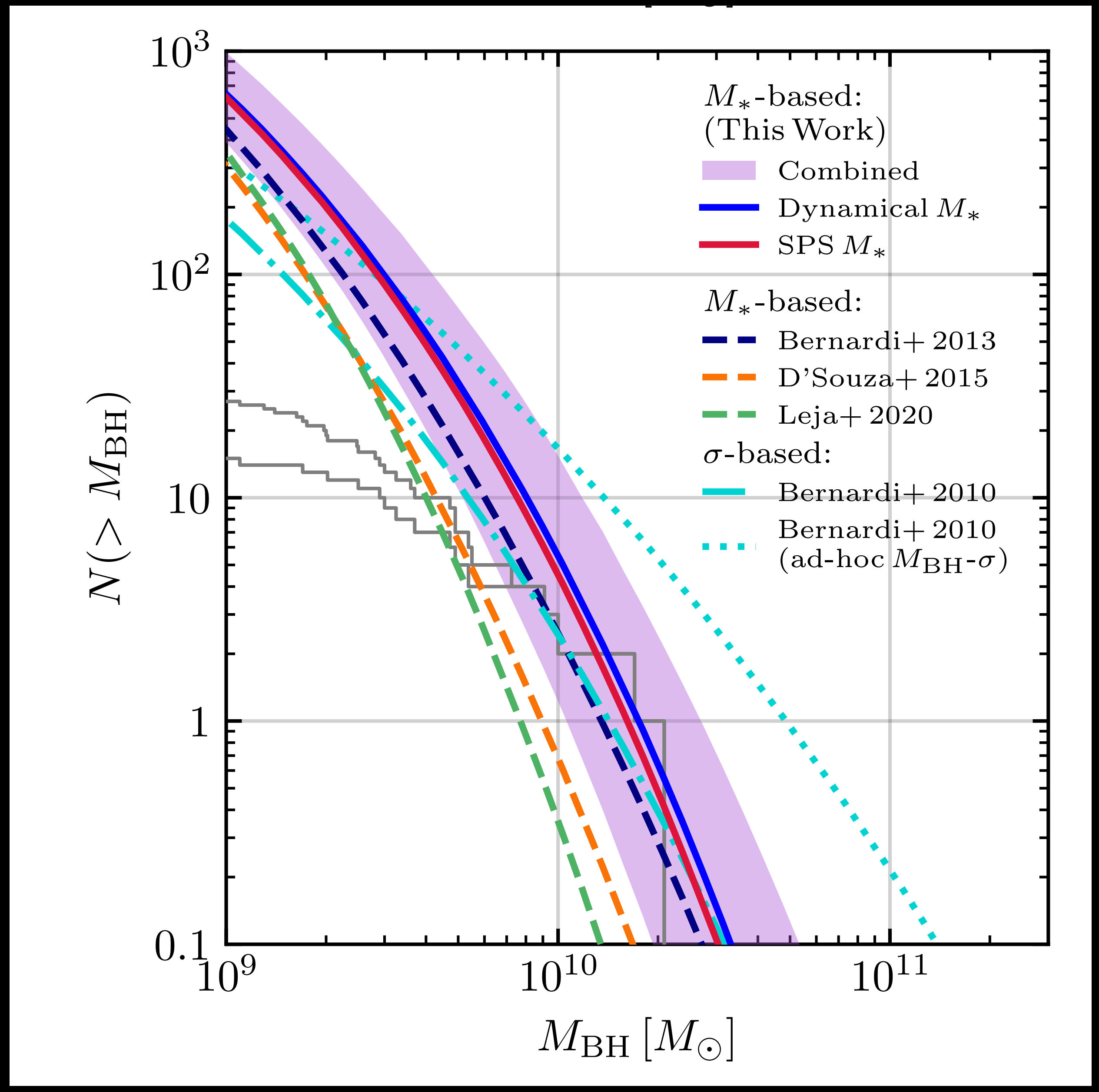
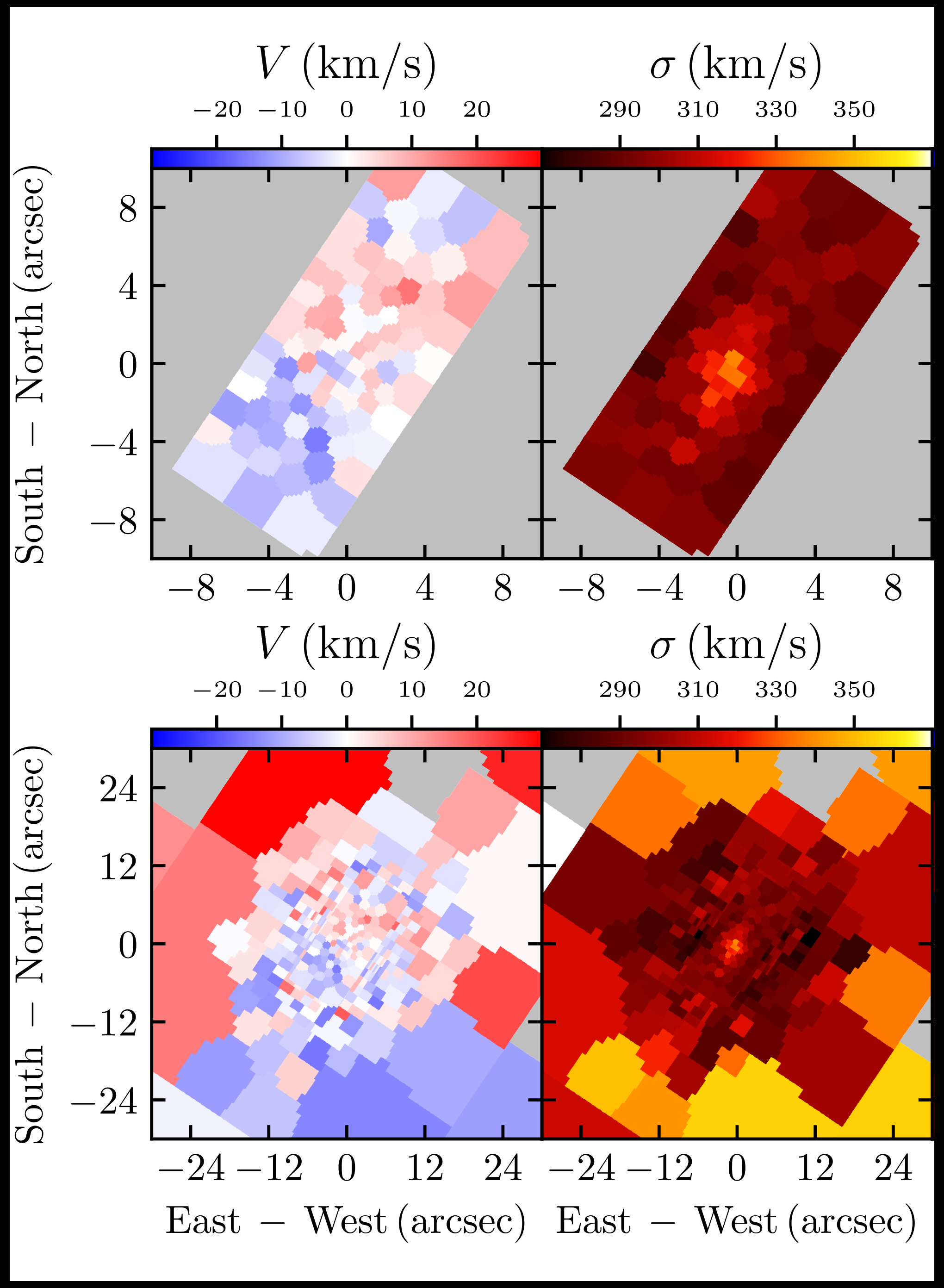
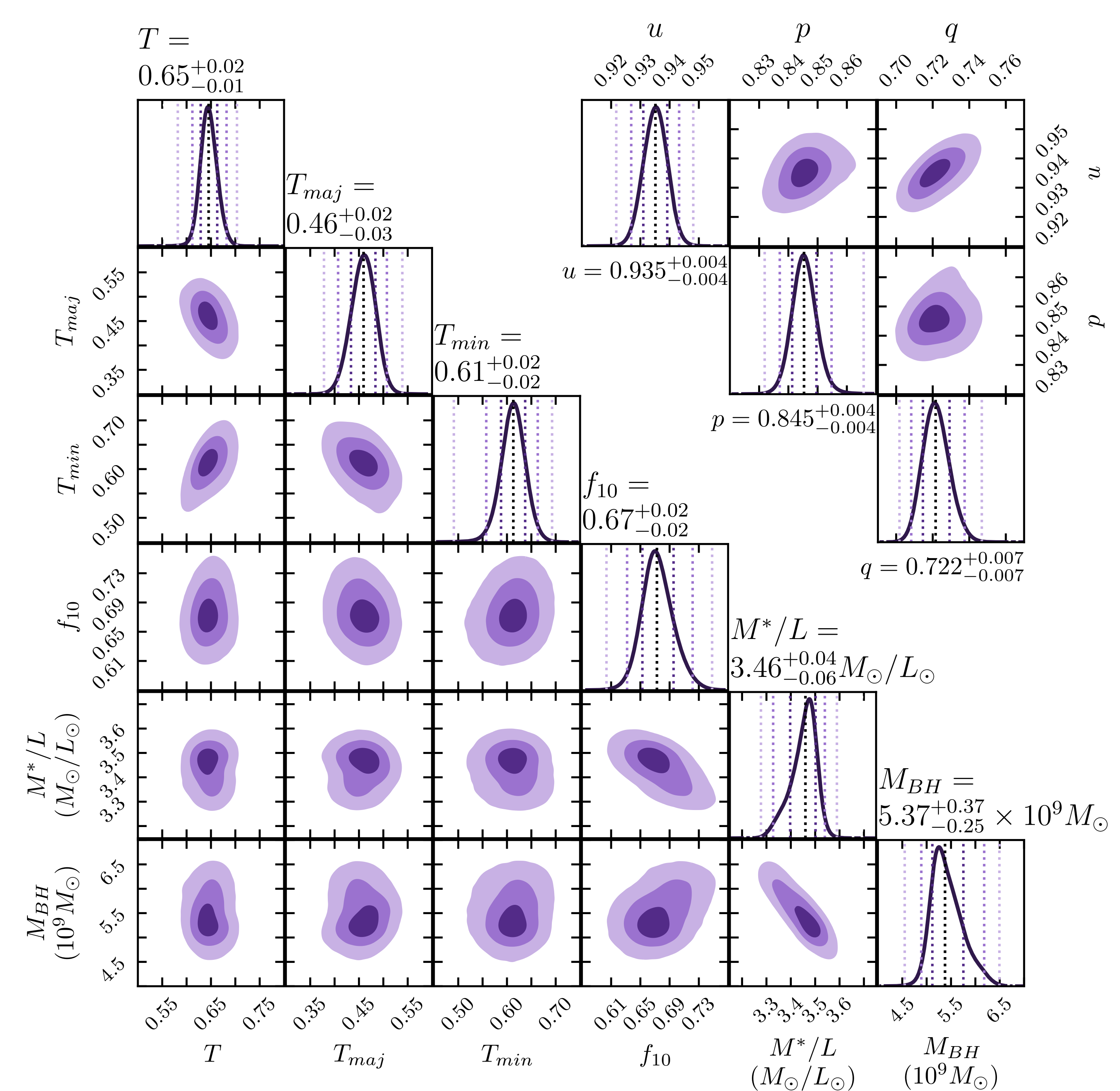
- **PTA sources? — implications for identifying continuous signals**
- **Massive nearby SMBH are EHT targets? Potential for observation with ngEHT / BHEX?**







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