Big Galaxies &
Big Black Holes &
Nanohertz Gravitational Waves

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

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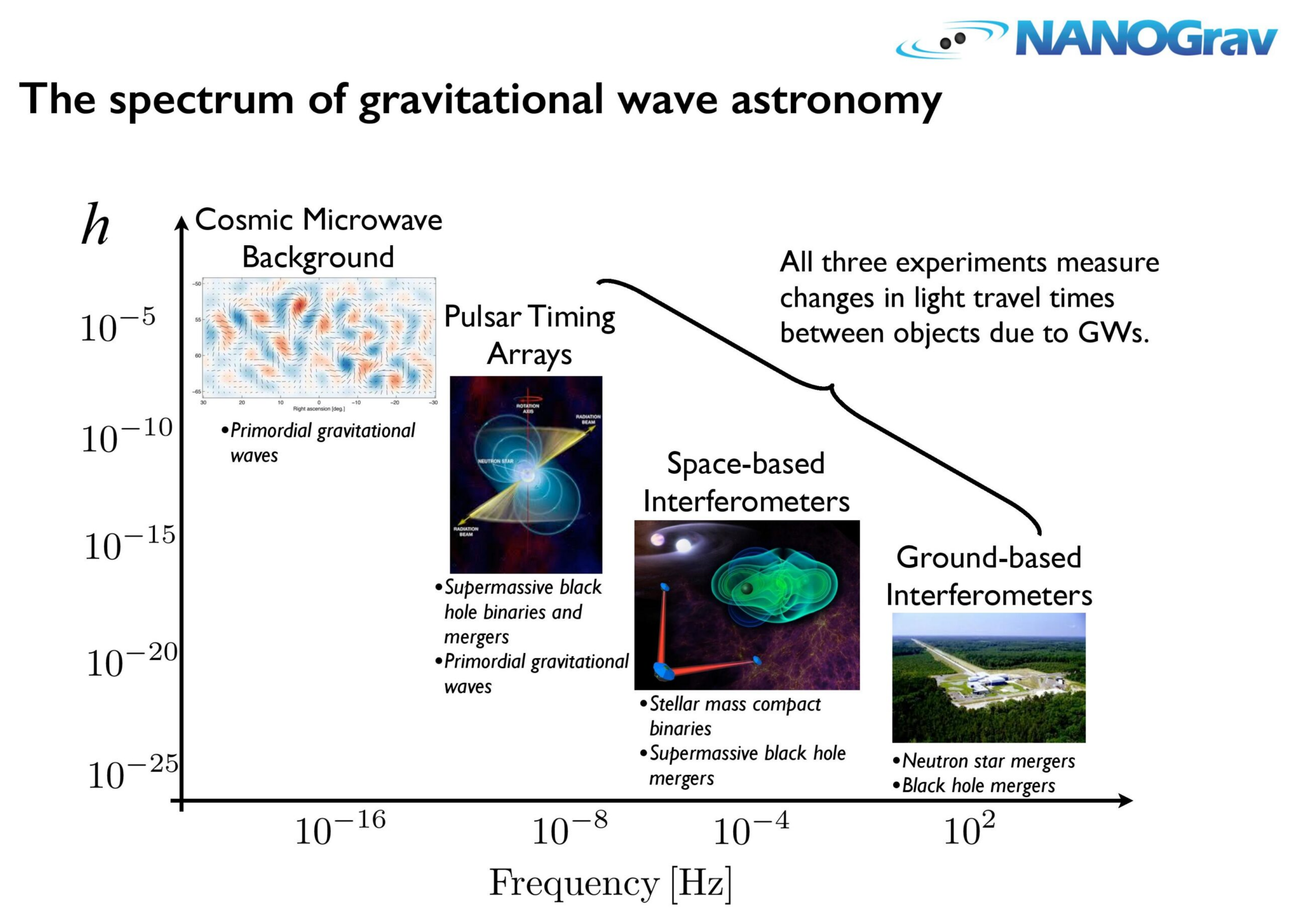
refining the **high-mass** local galaxy stellar mass function

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



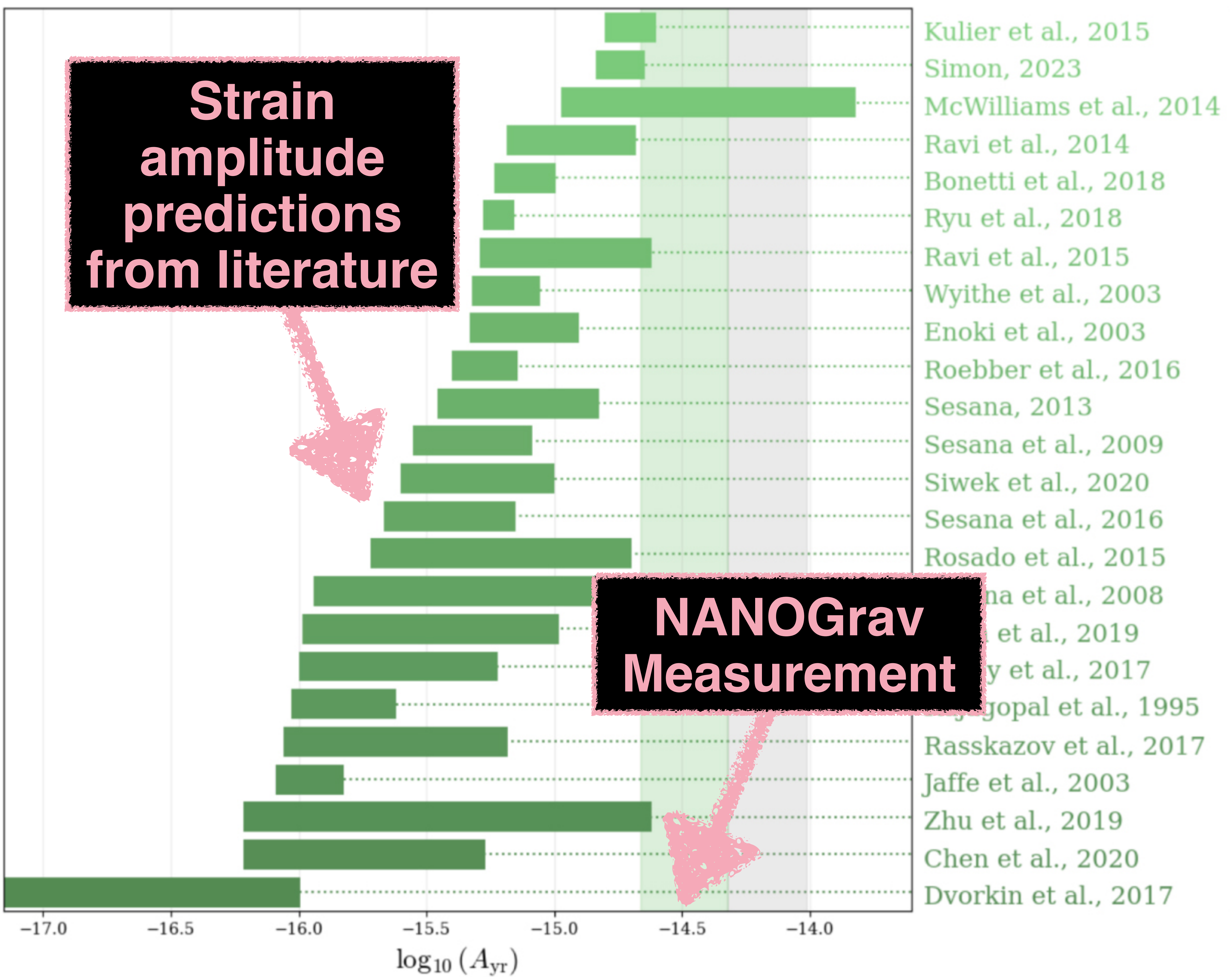
NANOGrav

The spectrum of gravitational wave astronomy

All three experiments measure changes in light travel times between objects due to GWs.

Olena Shmahalo for NANOGrav

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



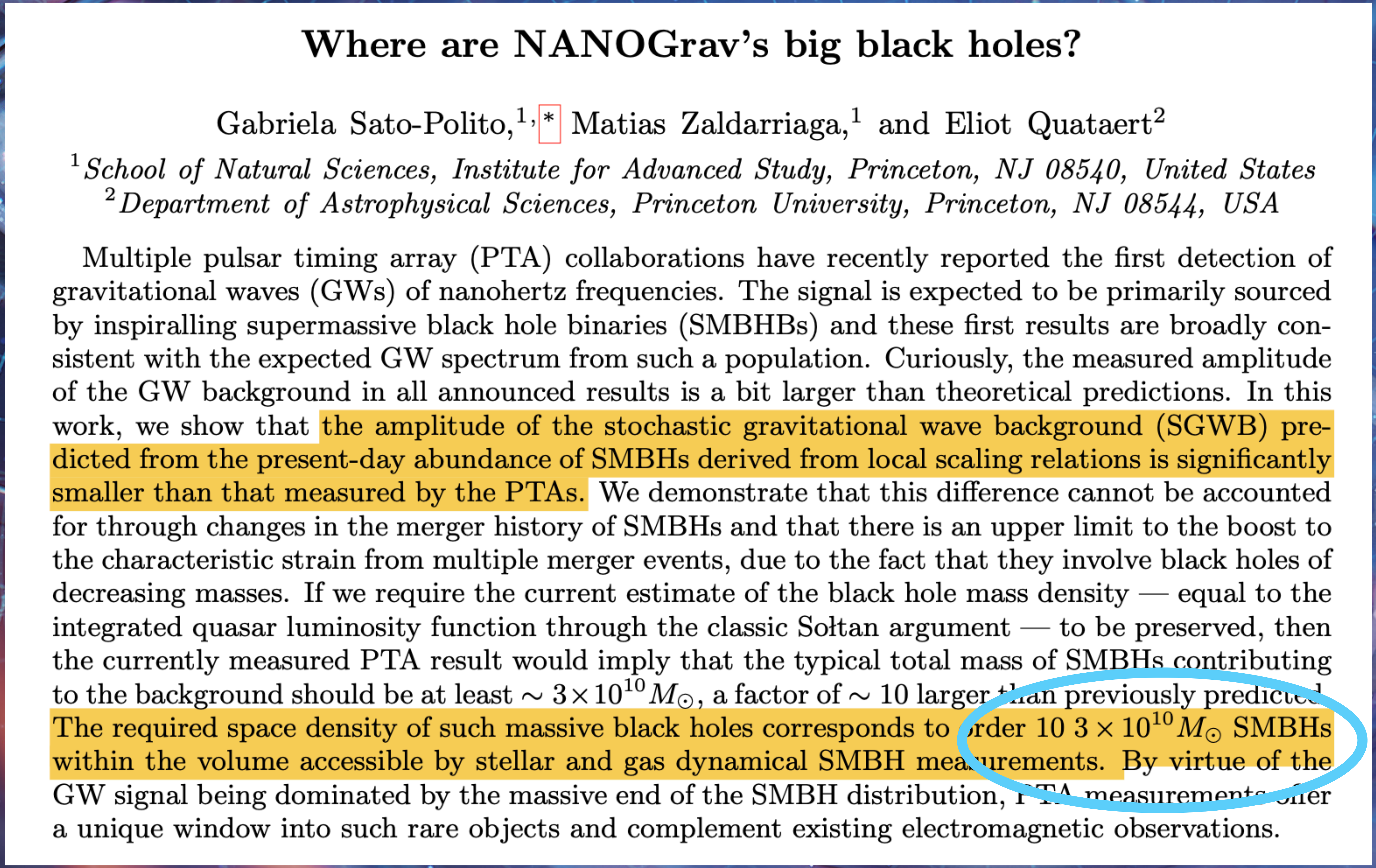
Strain amplitude predictions from literature

NANOGrav Measurement

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]

[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 $\sim 3 \times 10^{10} M_\odot$, a factor of ~ 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

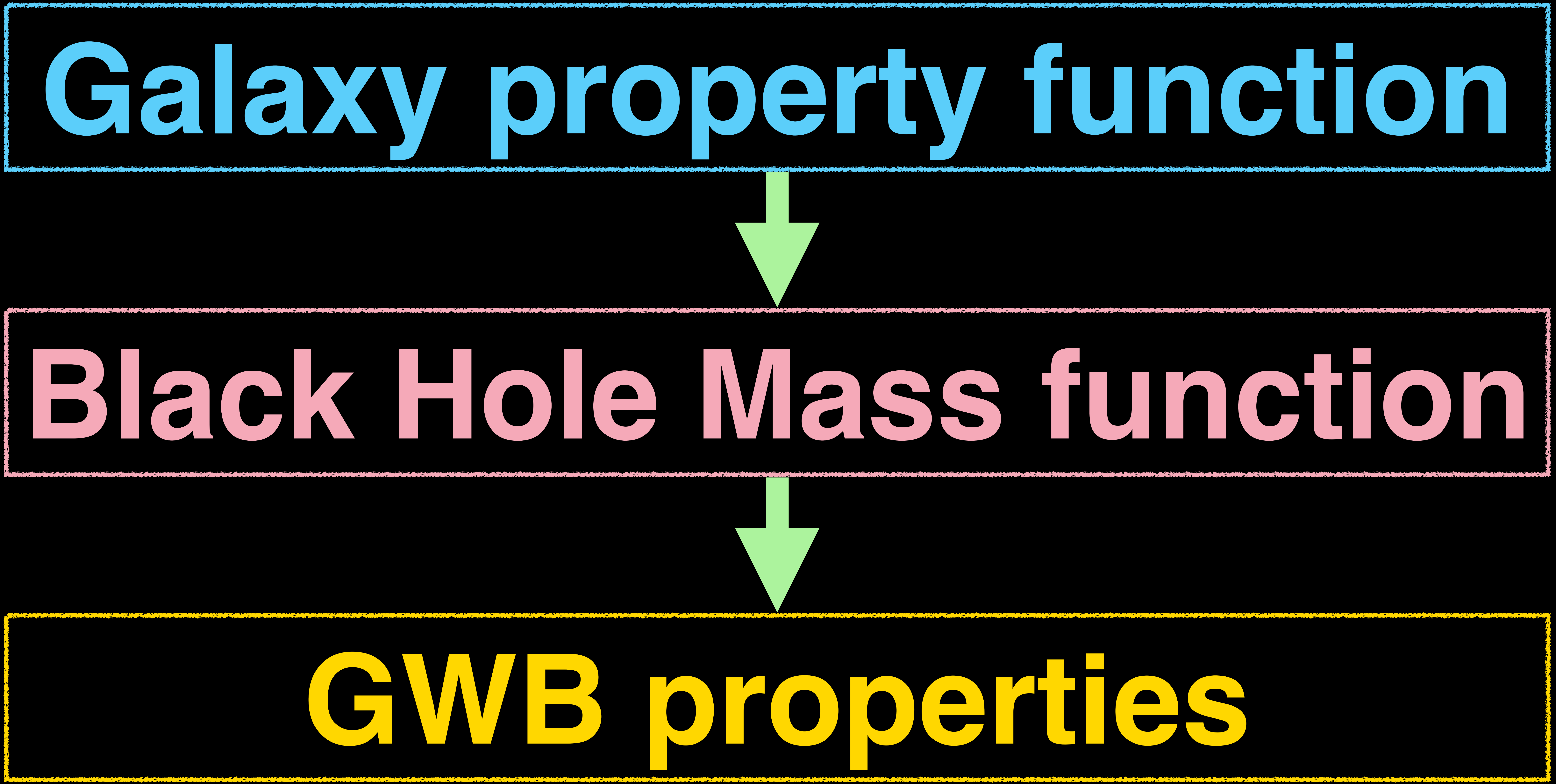
MASSIVE is a…

- 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)



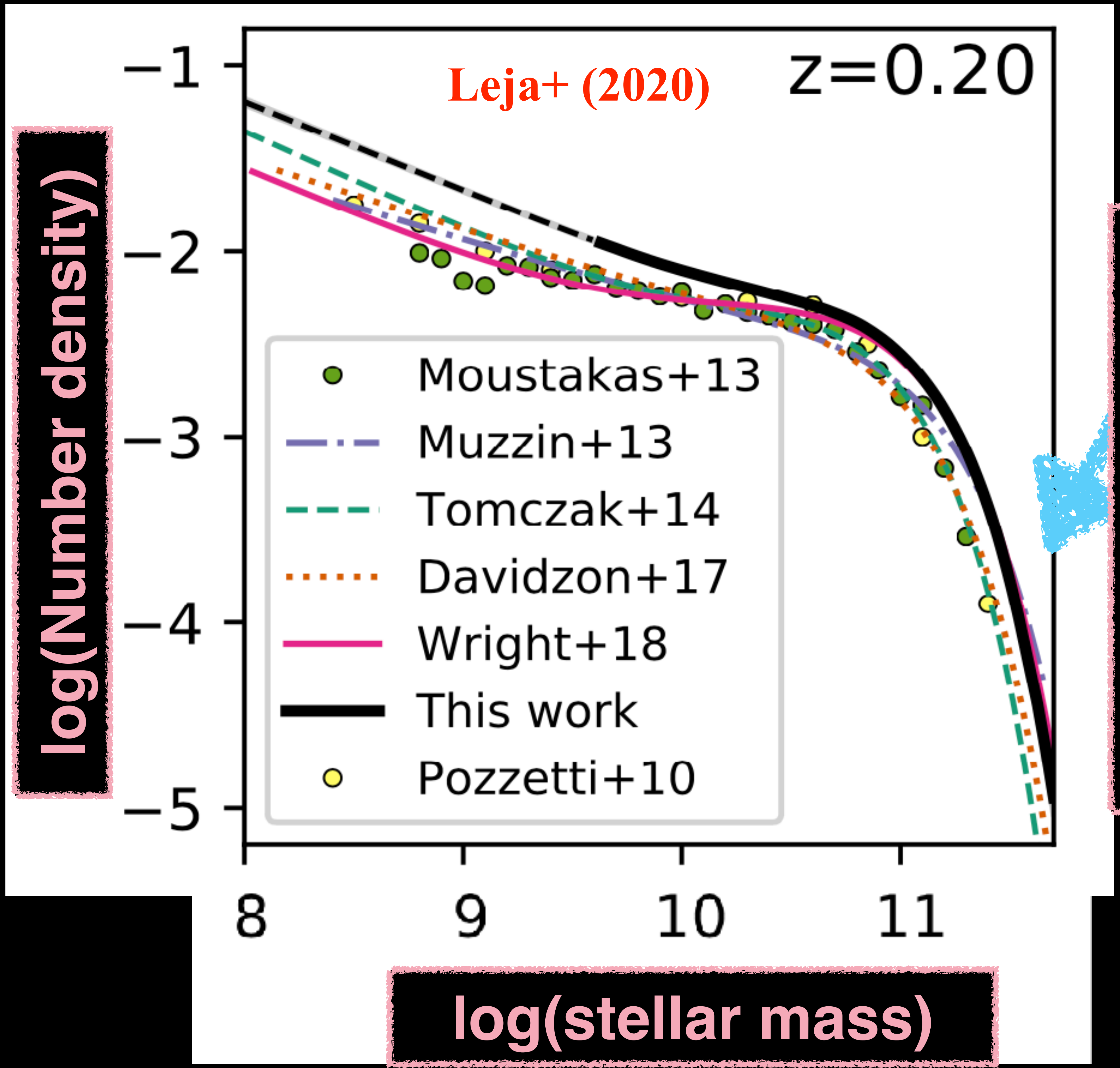
Galaxy property function

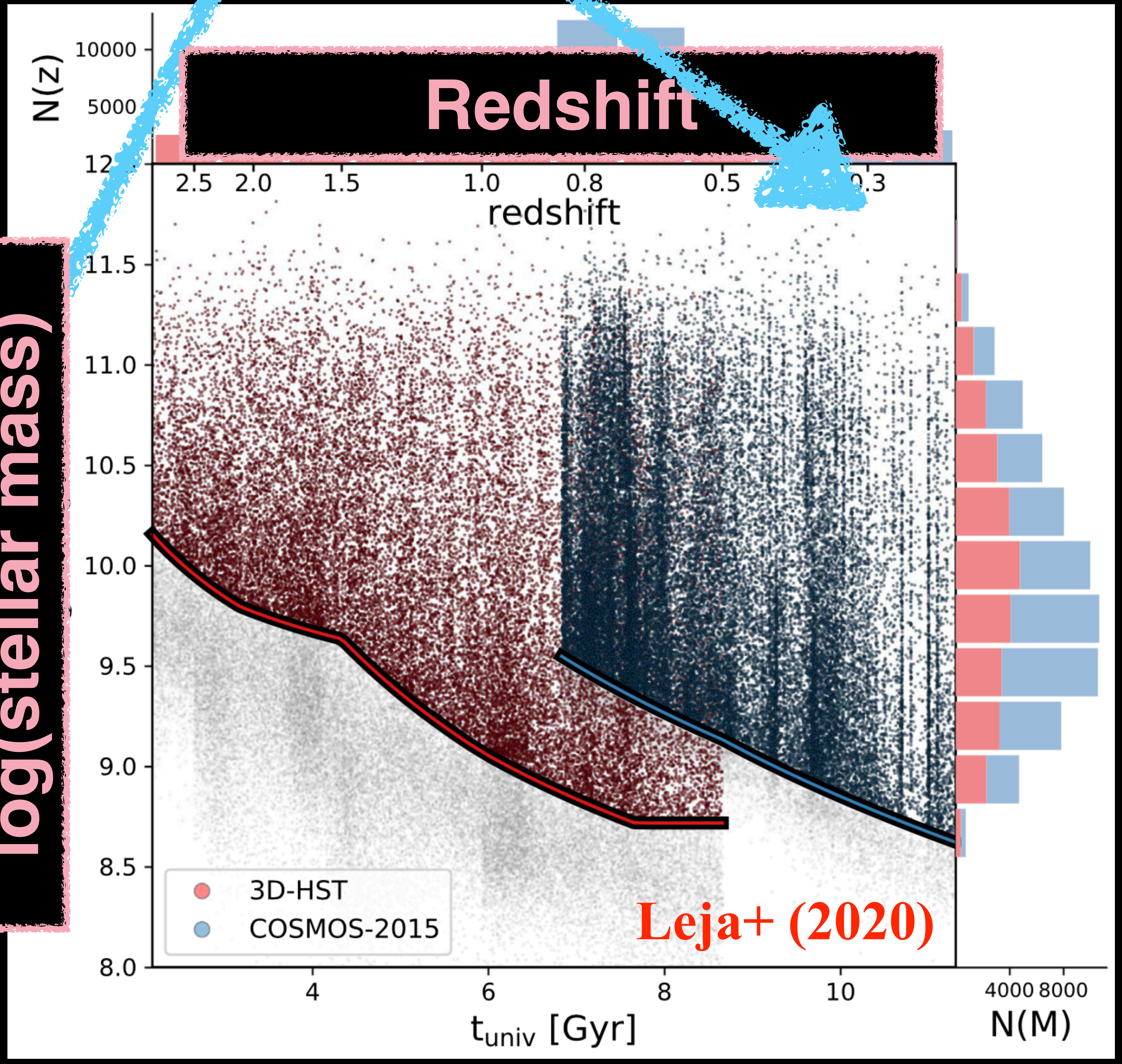
Black Hole Mass function

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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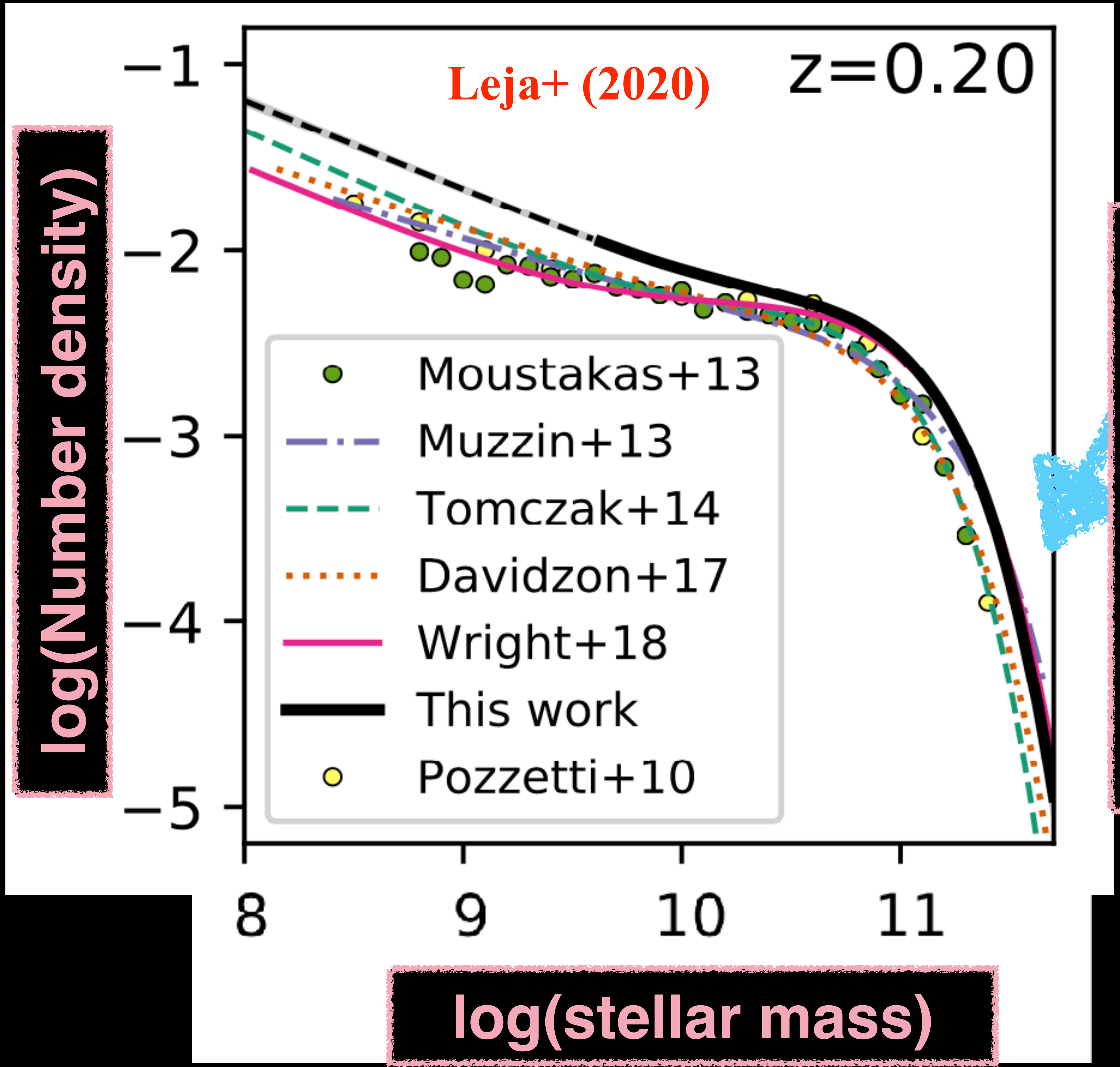
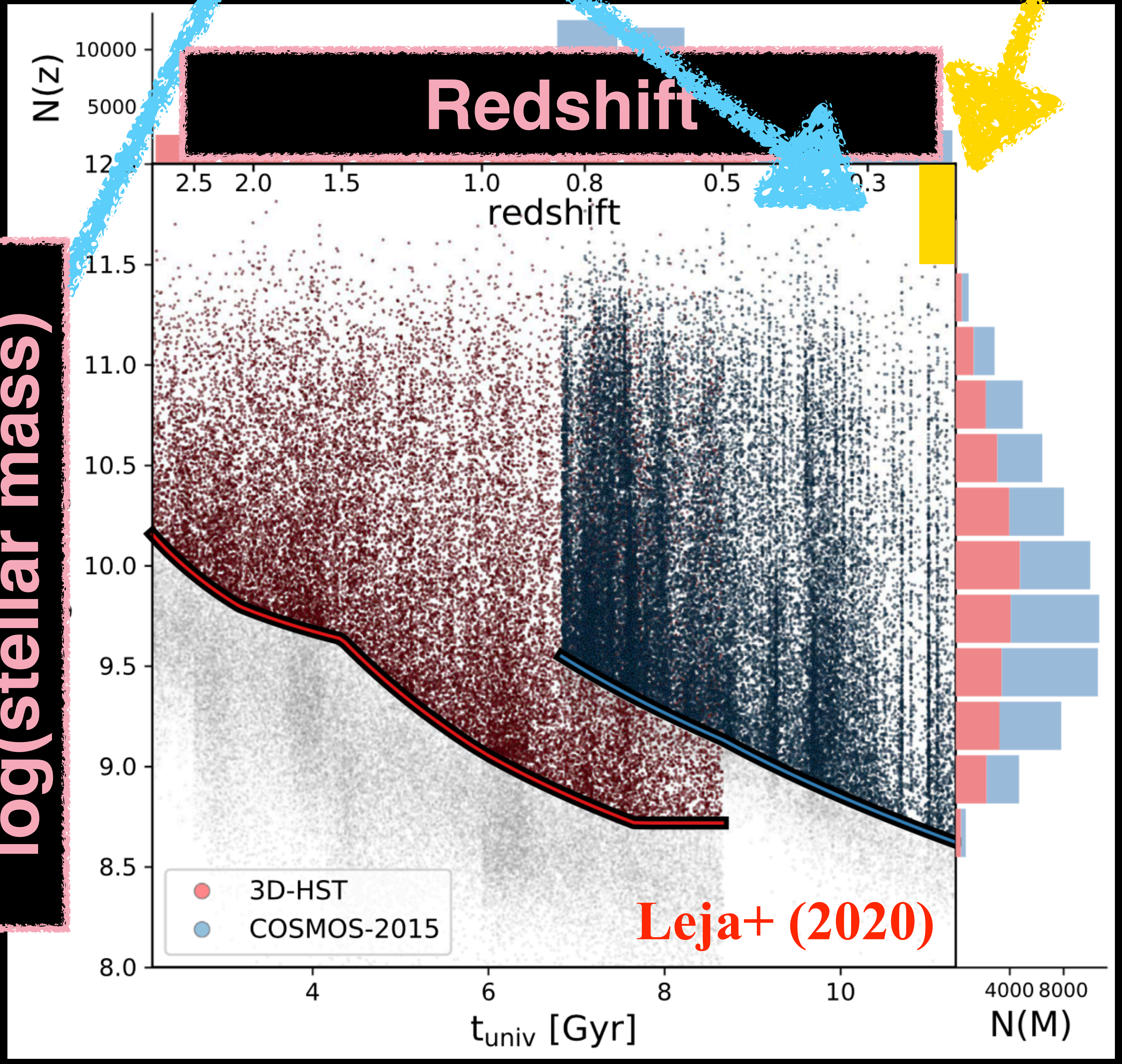
MASSIVE





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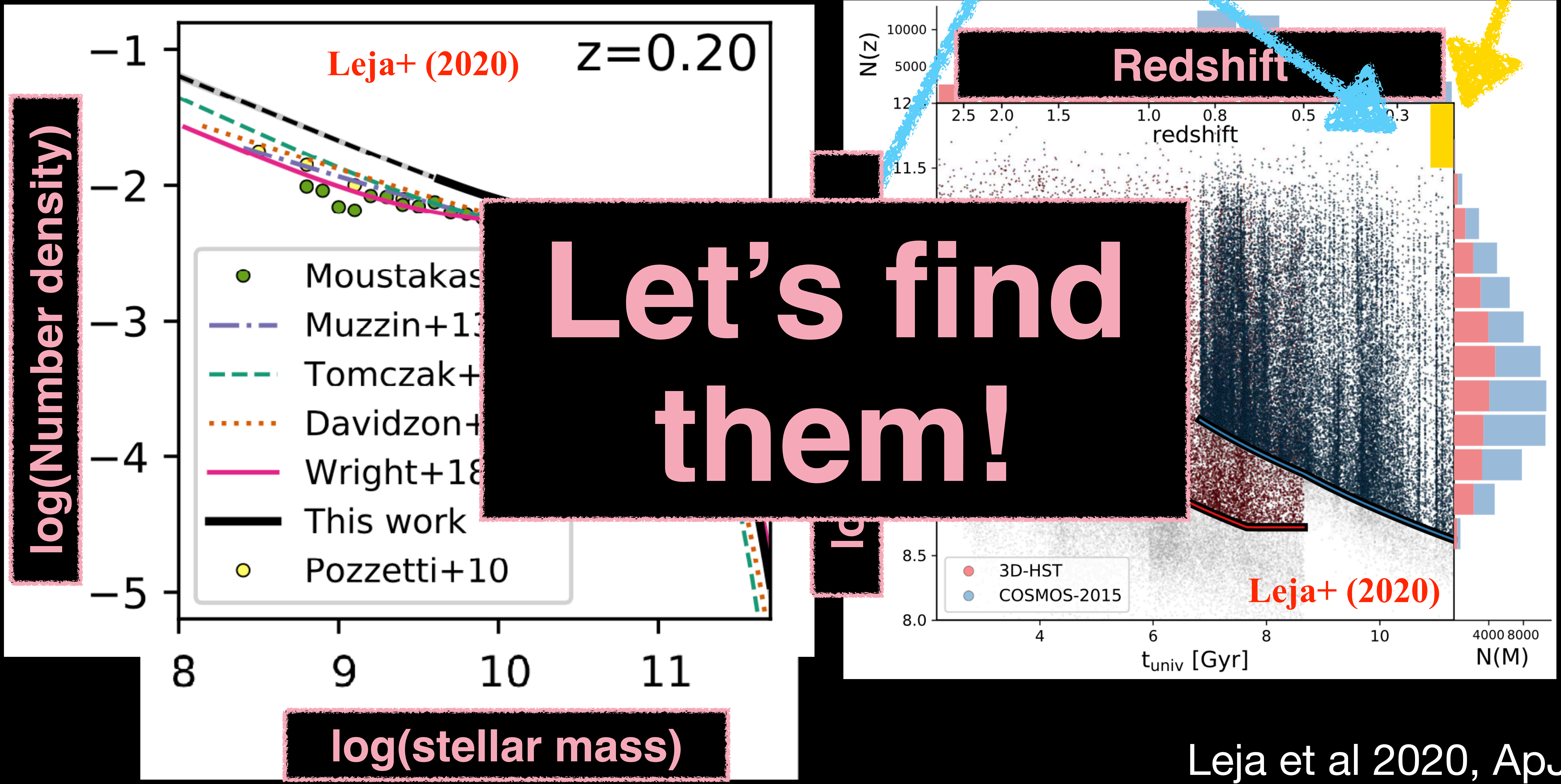


Let's find them!

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

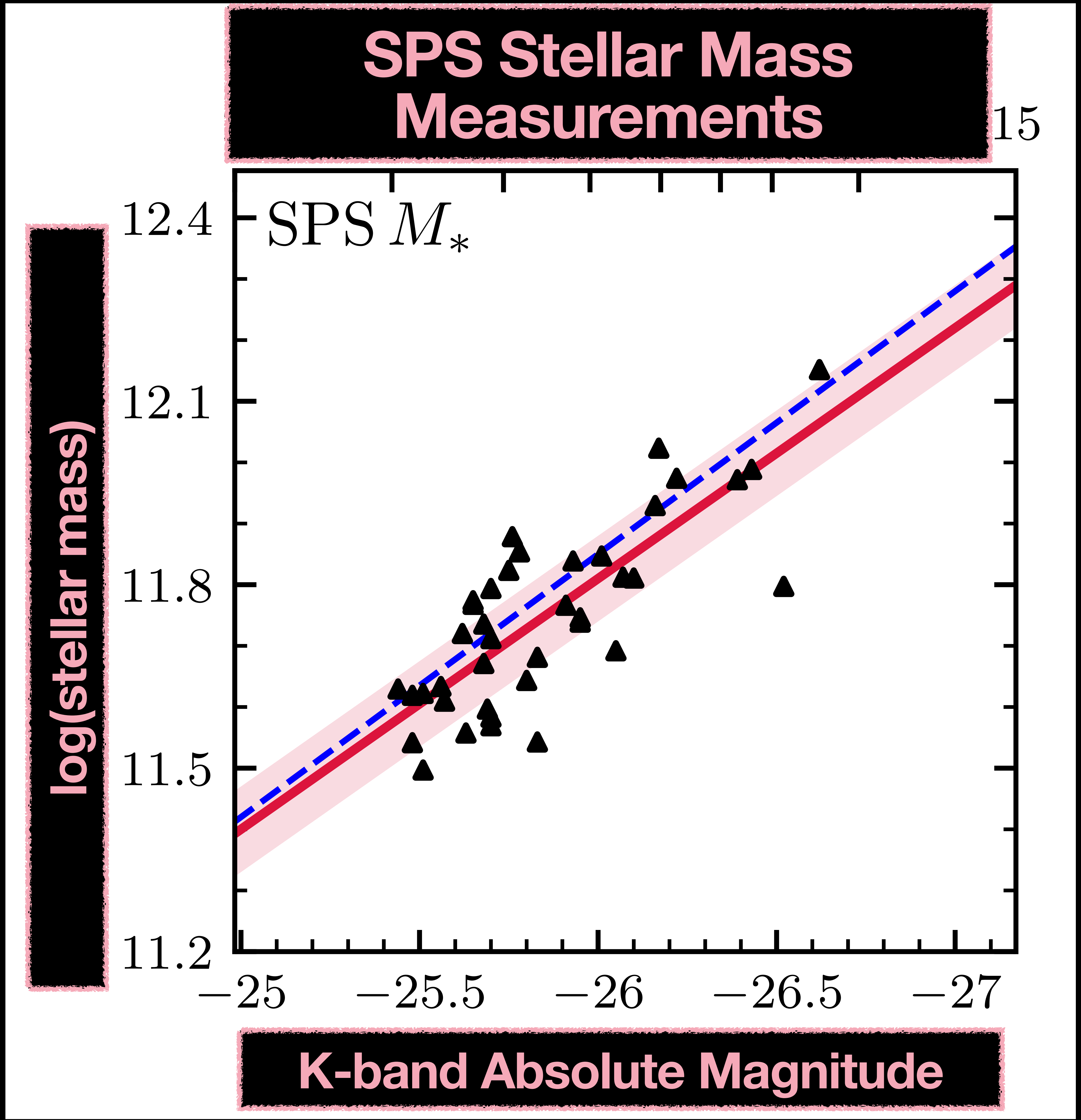
Liepold+Ma 2024
ApJL 971 L29

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

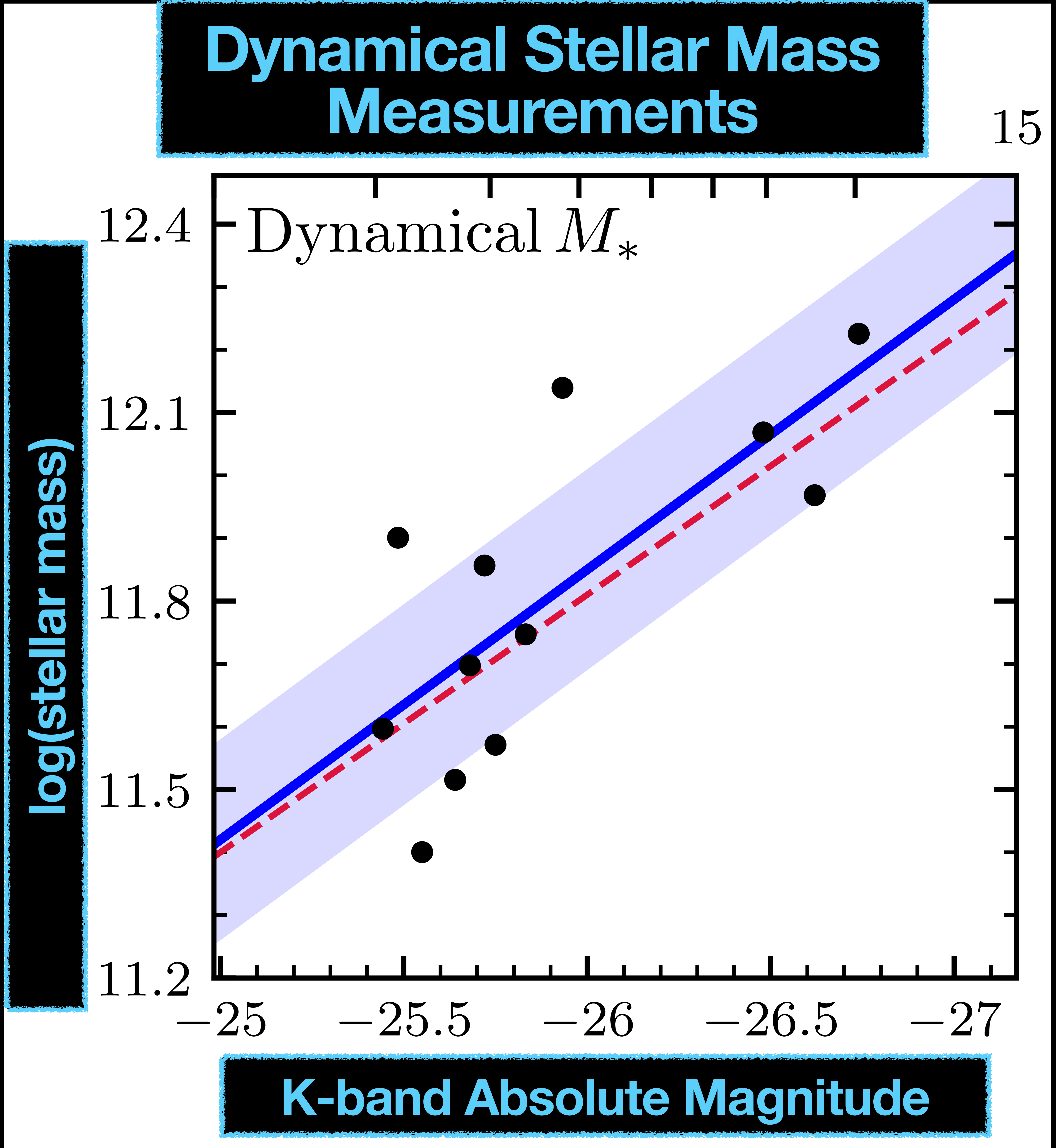
Dynamical measurements of the stellar mass now exist for 12 MASSIVE galaxies

11 from orbit-based stellar dynamics

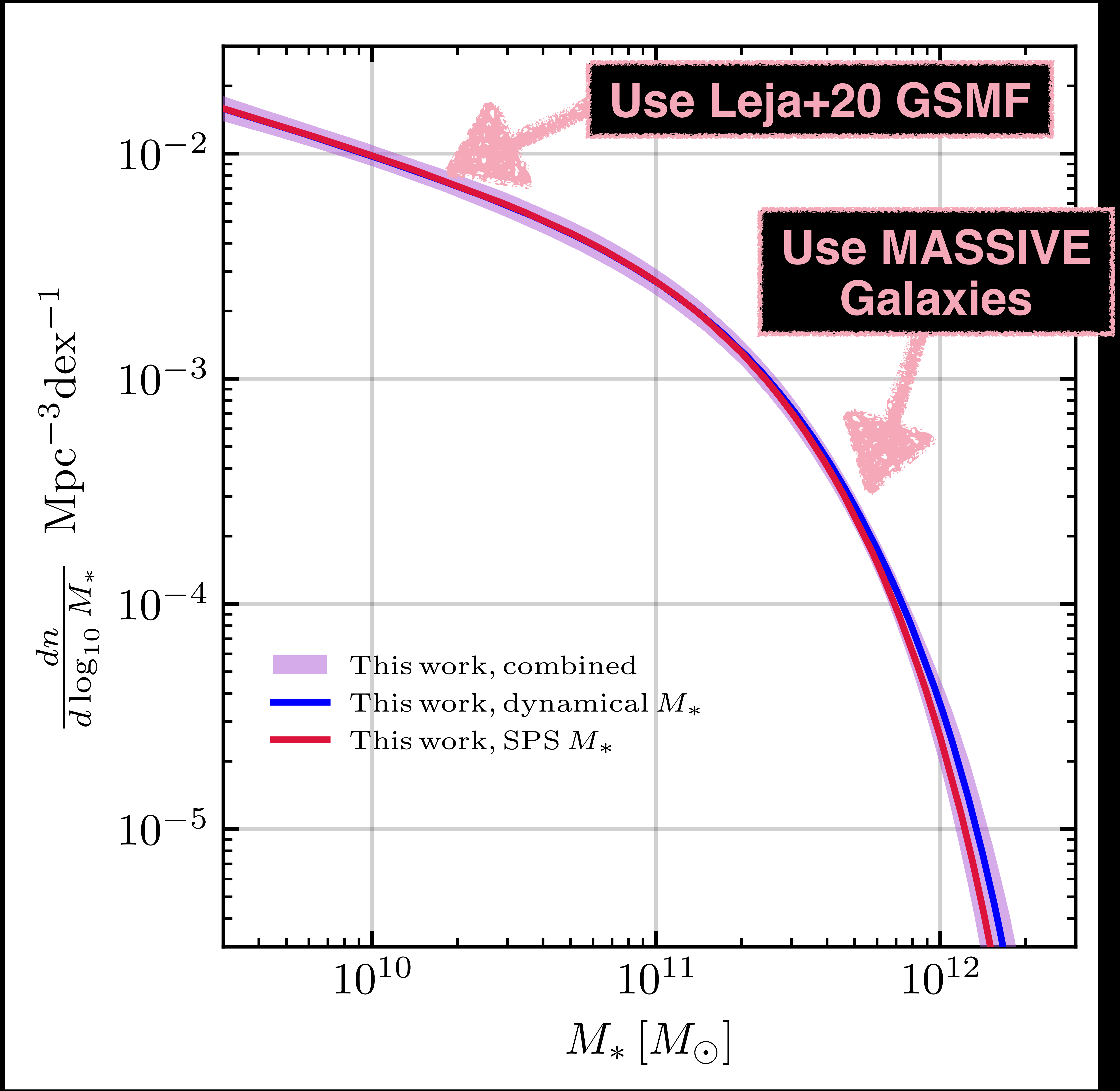
1 from gas-dynamical methods

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

(excluding Jeans-modeling based measurements)



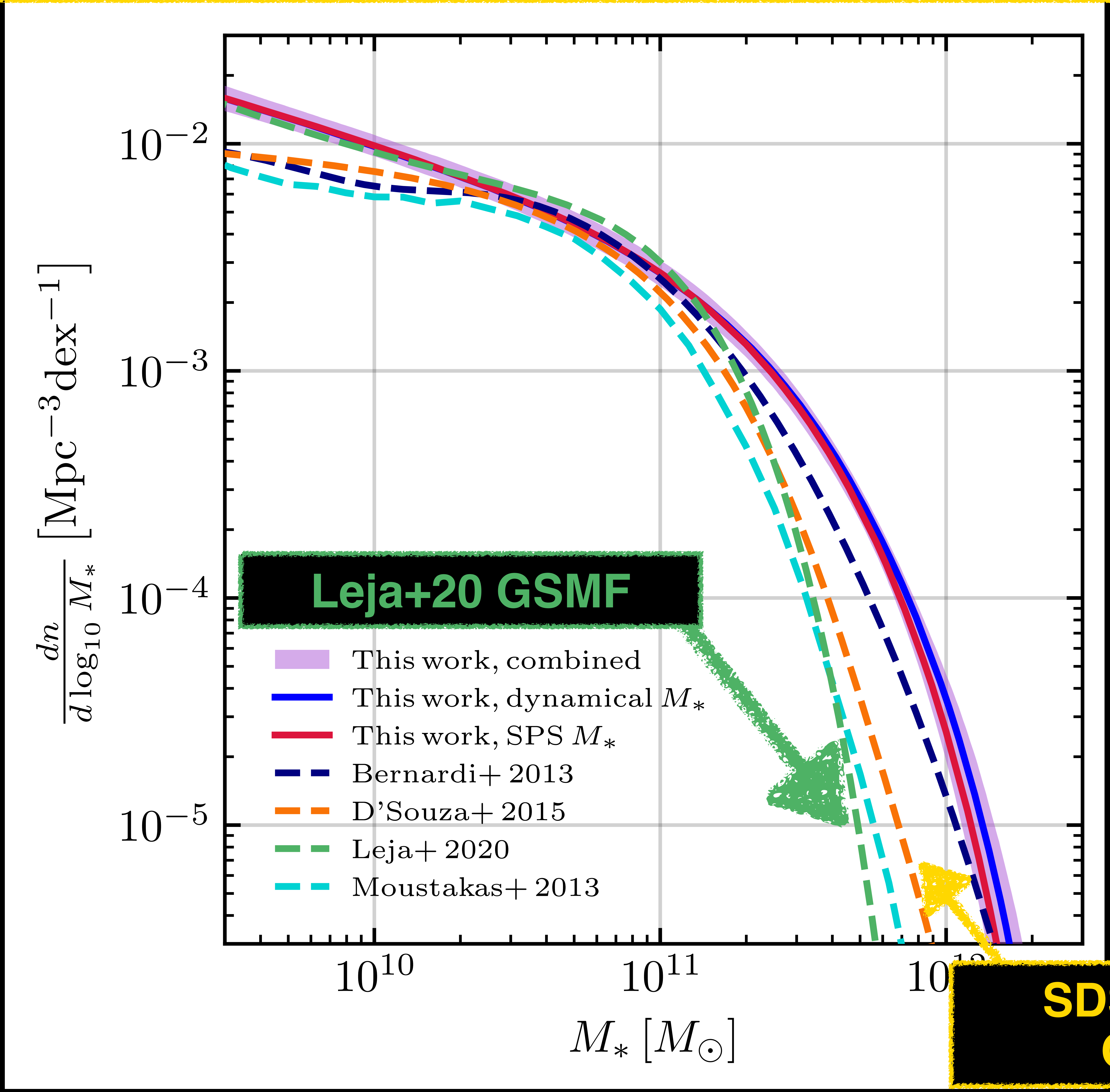
The high-mass end of the local GSMF



- 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



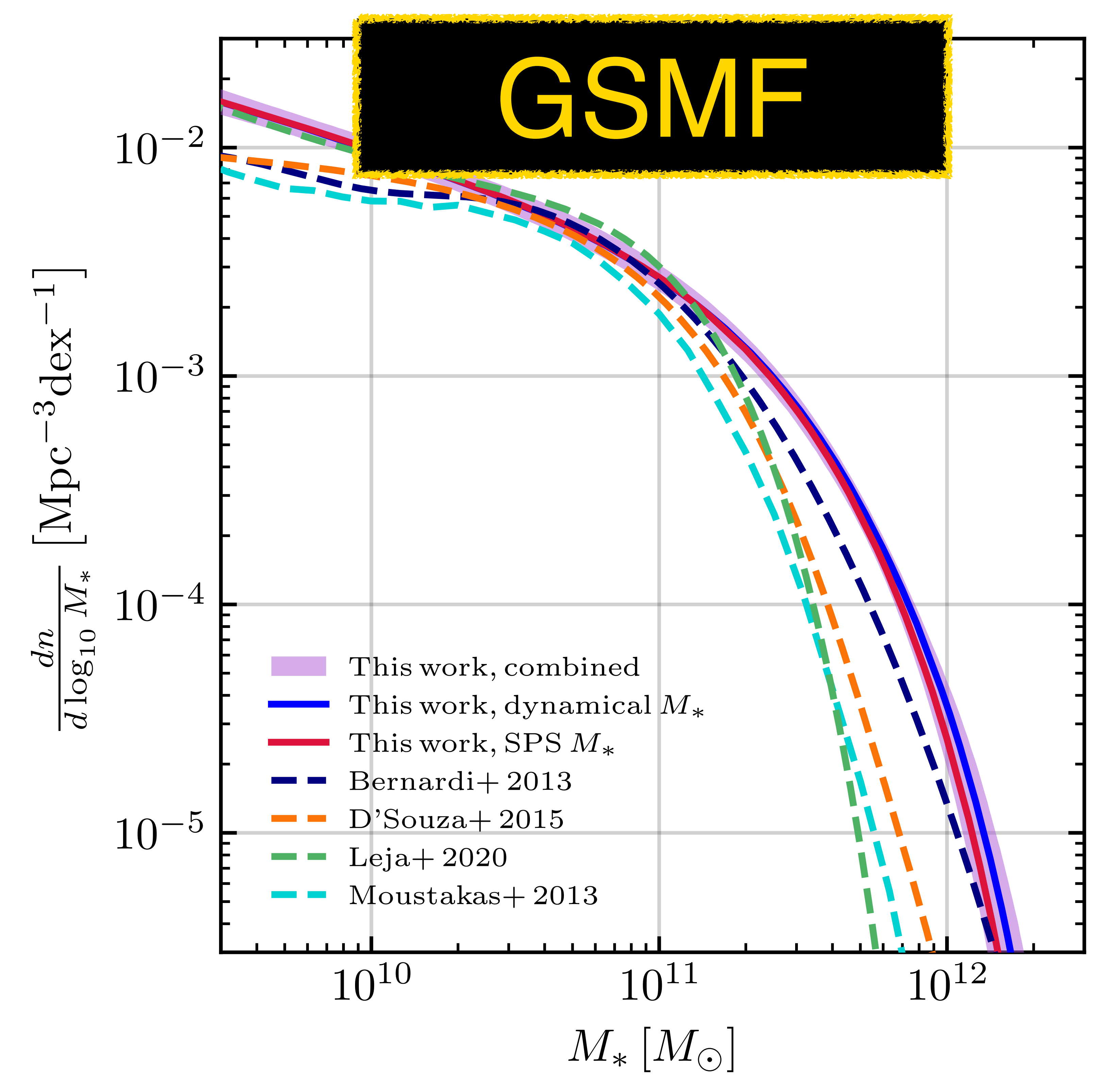
Leja+20 GSMF

SDSS-based GSMFs

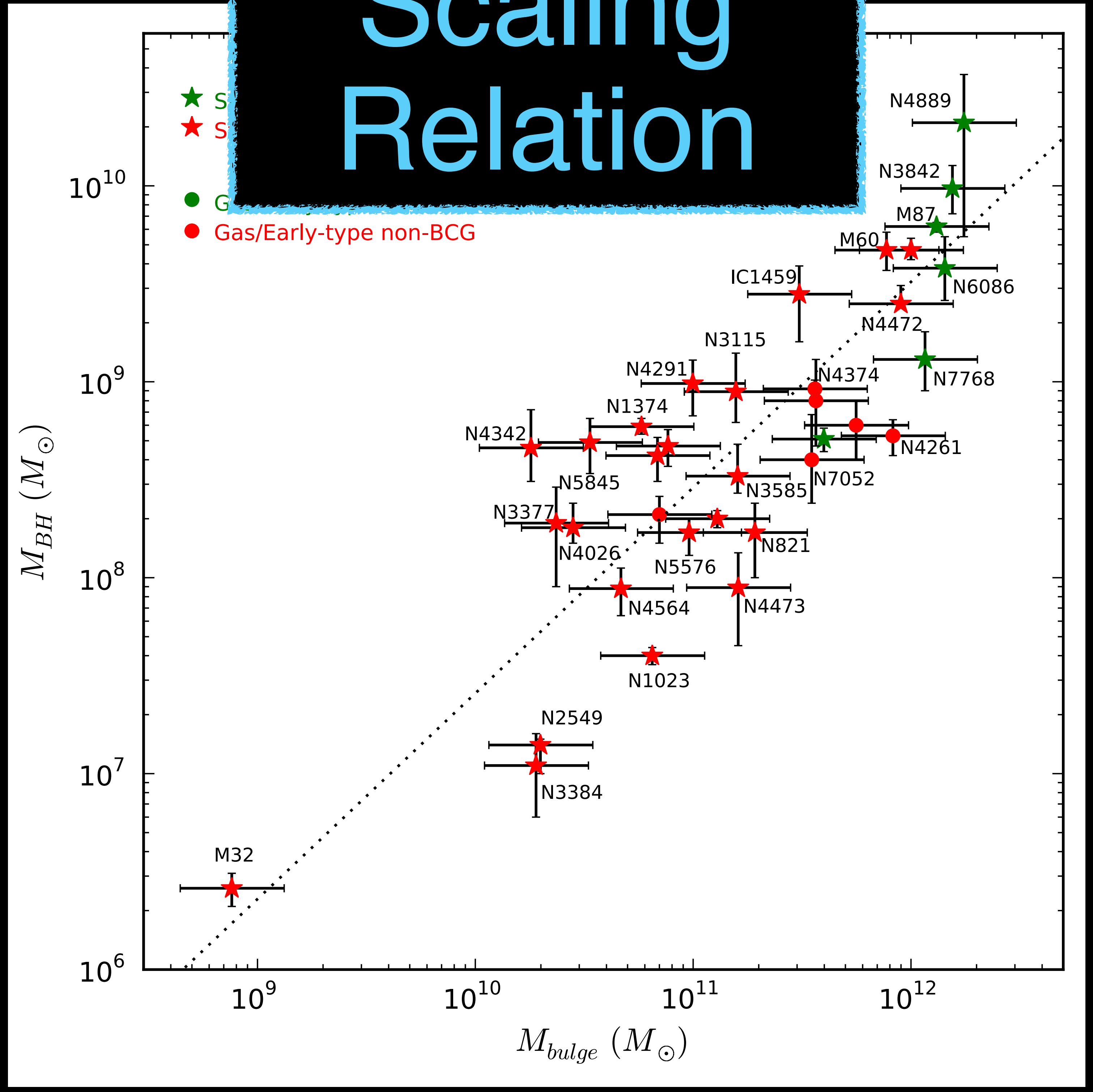
- Our stellar masses at the high-mass end are ~1.6x higher than SDSS-based GSMF measurements (shift their curves ***right***)
- Most prior work assumed Milky-Way-like IMF. Our bottom-heavy SPS-based masses fit for IMF are ~1.8x more massive.
- Prior work found minimal GSMF evolution since z = 1. Our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

The local Black Hole Mass Function

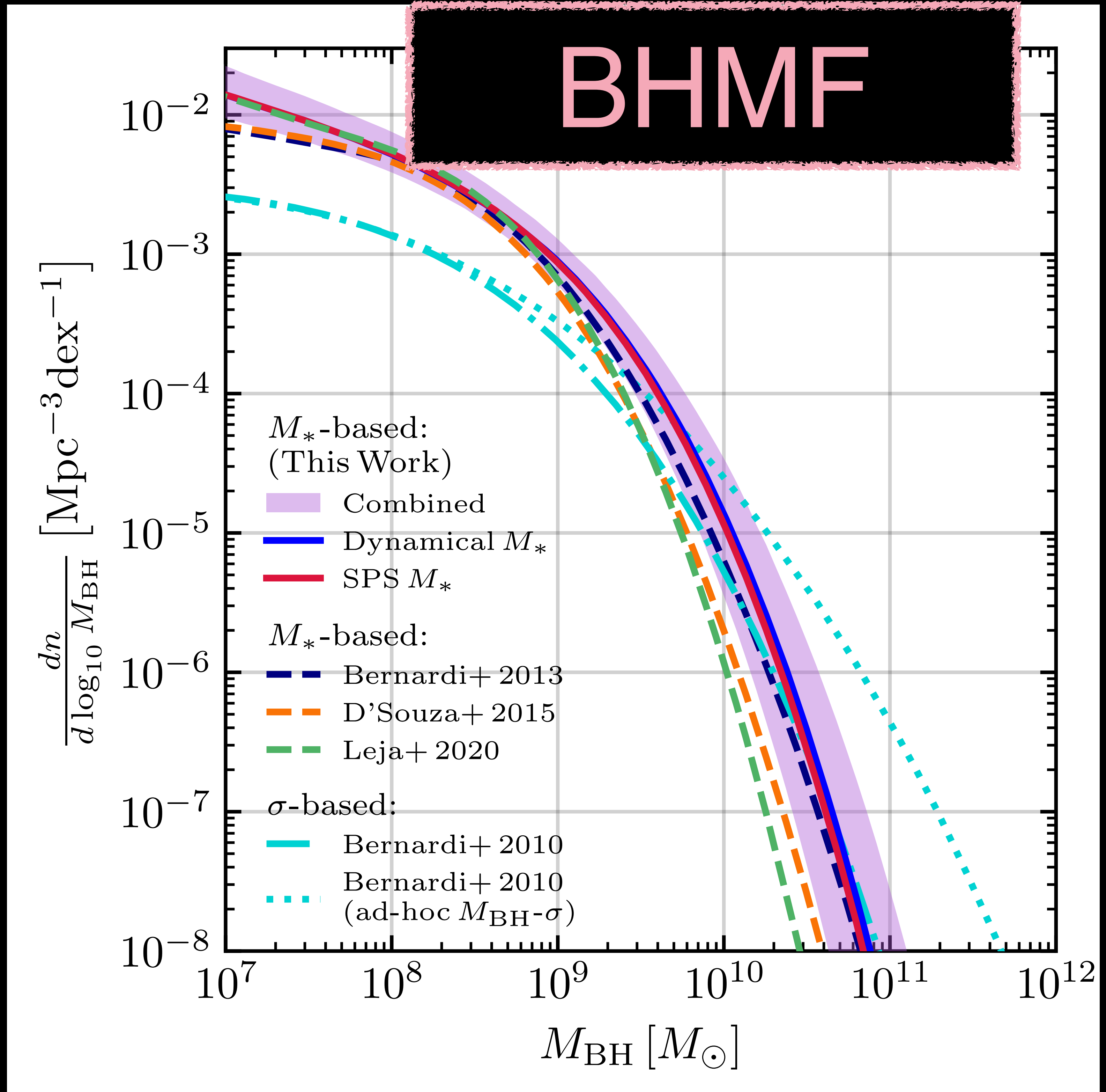
Black hole mass function is convolution of GSMF and (BH Mass)—(Stellar Mass) scaling relation



GSMF

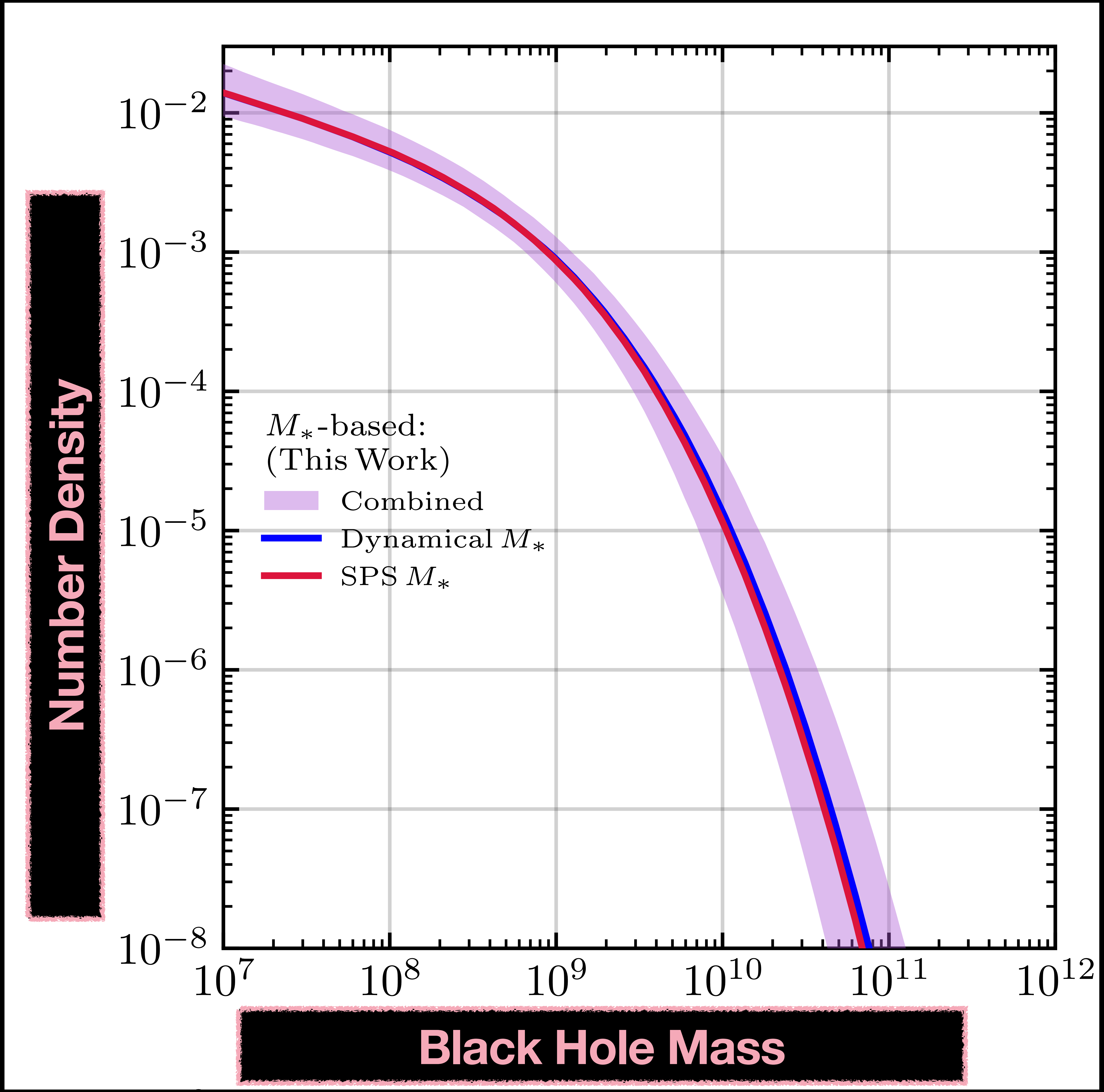


Scaling Relation



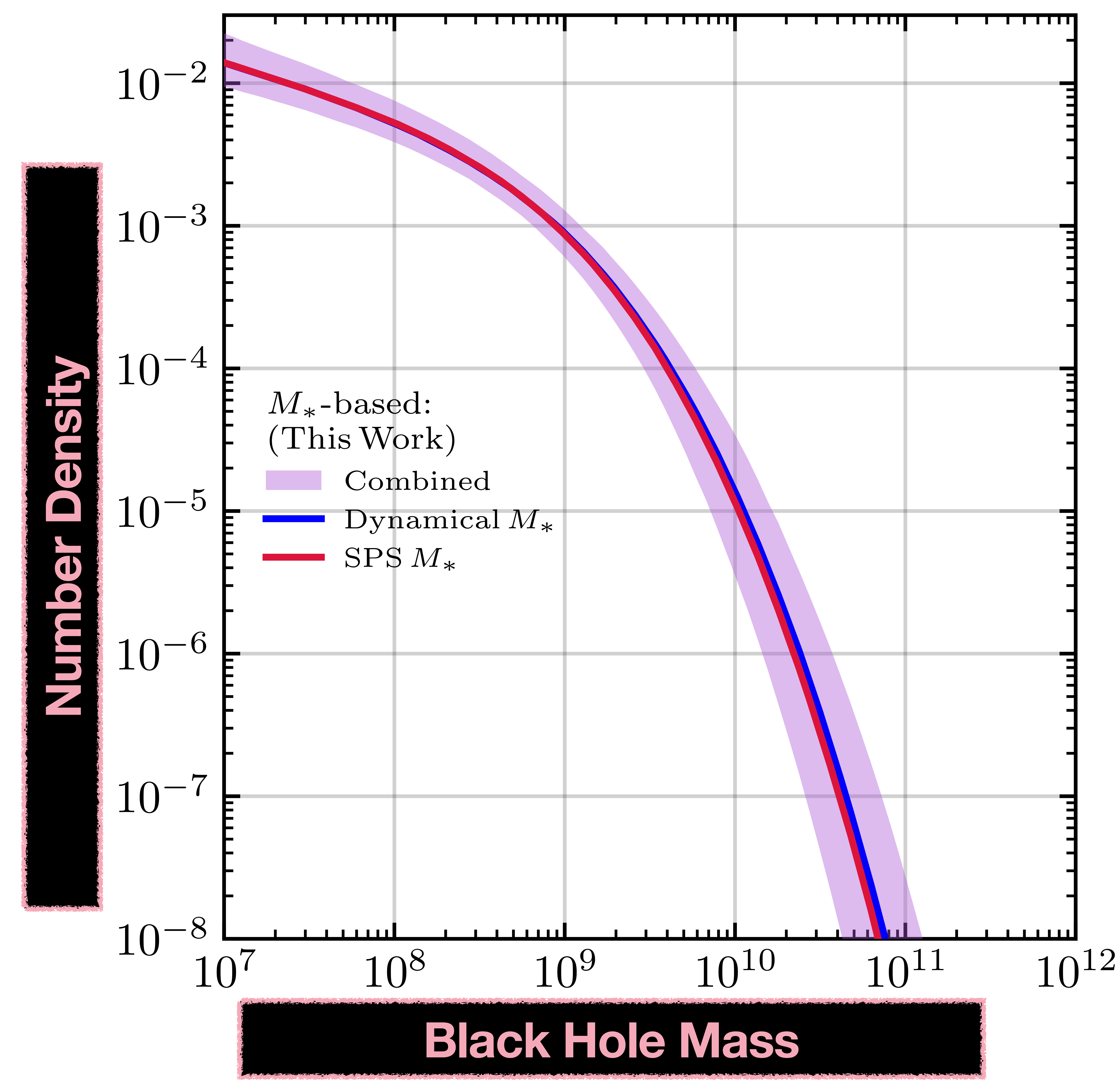
BHMF

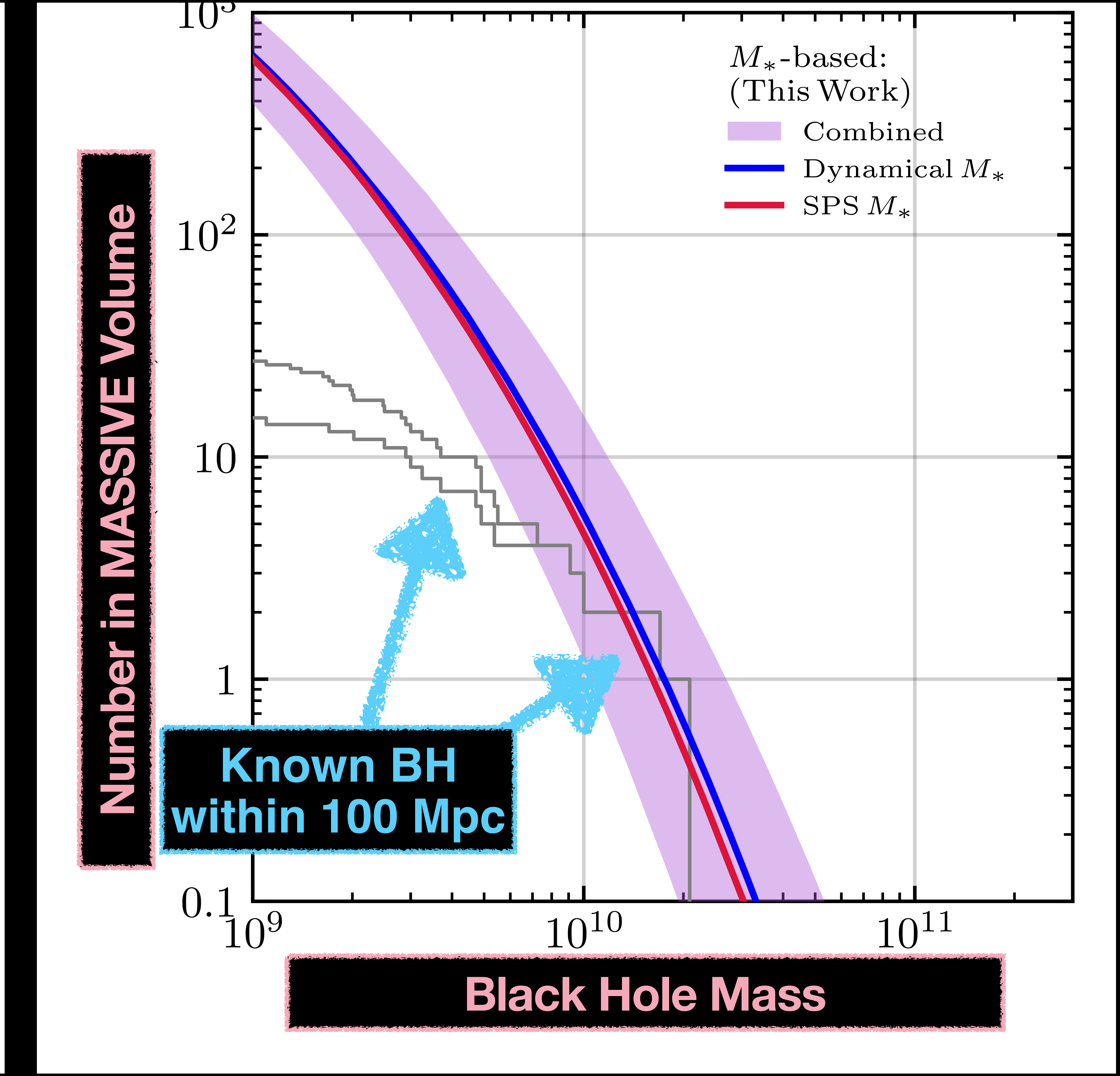
The local Black Hole Mass Function



- Scatter in BHMF mostly due to scatter in scaling relation
- Consistent BHMF from SPS and dynamical M_*
- Consistent results from other scaling relations (e.g., Saglia+16)

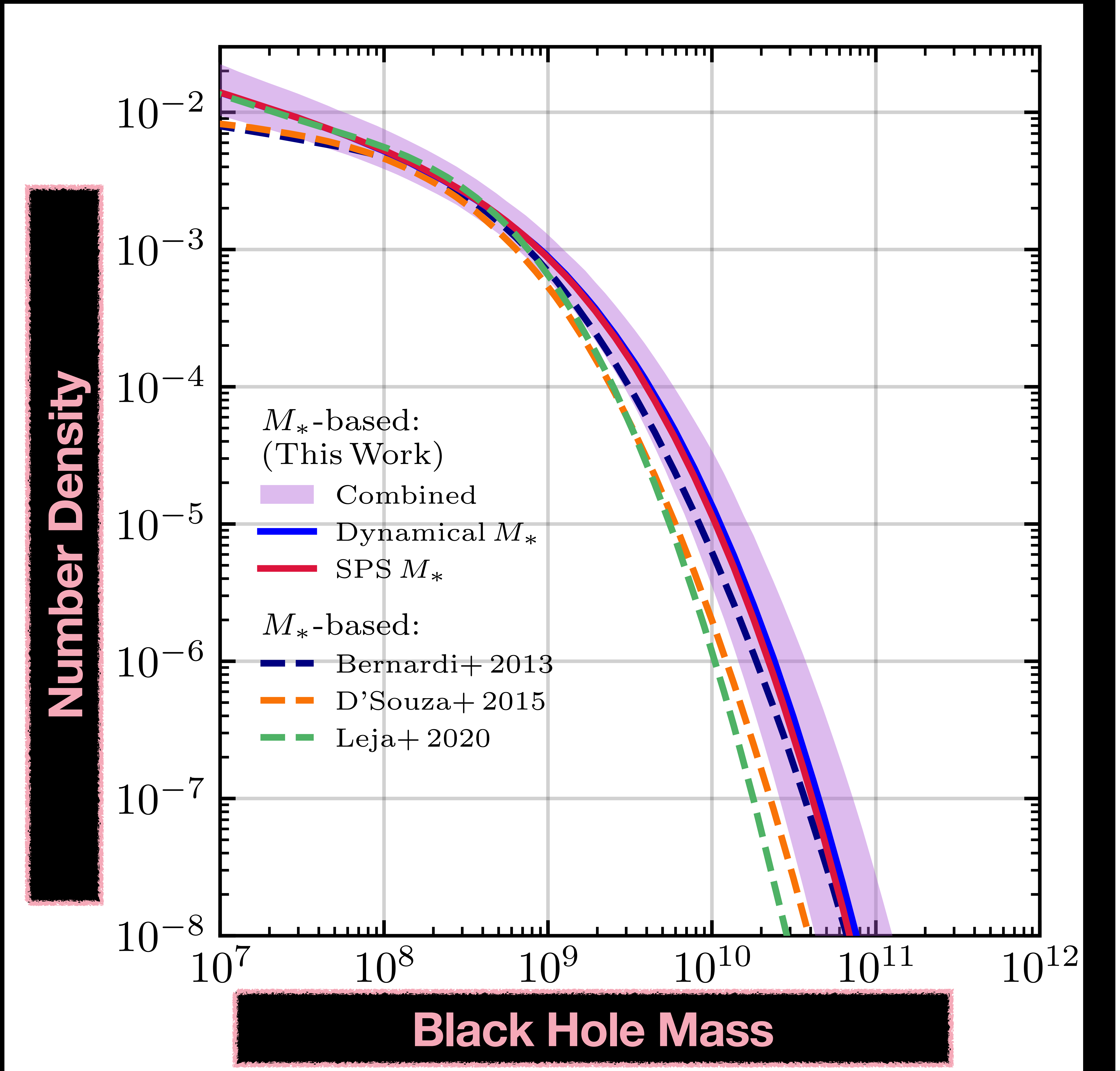
The local Black Hole Mass Function

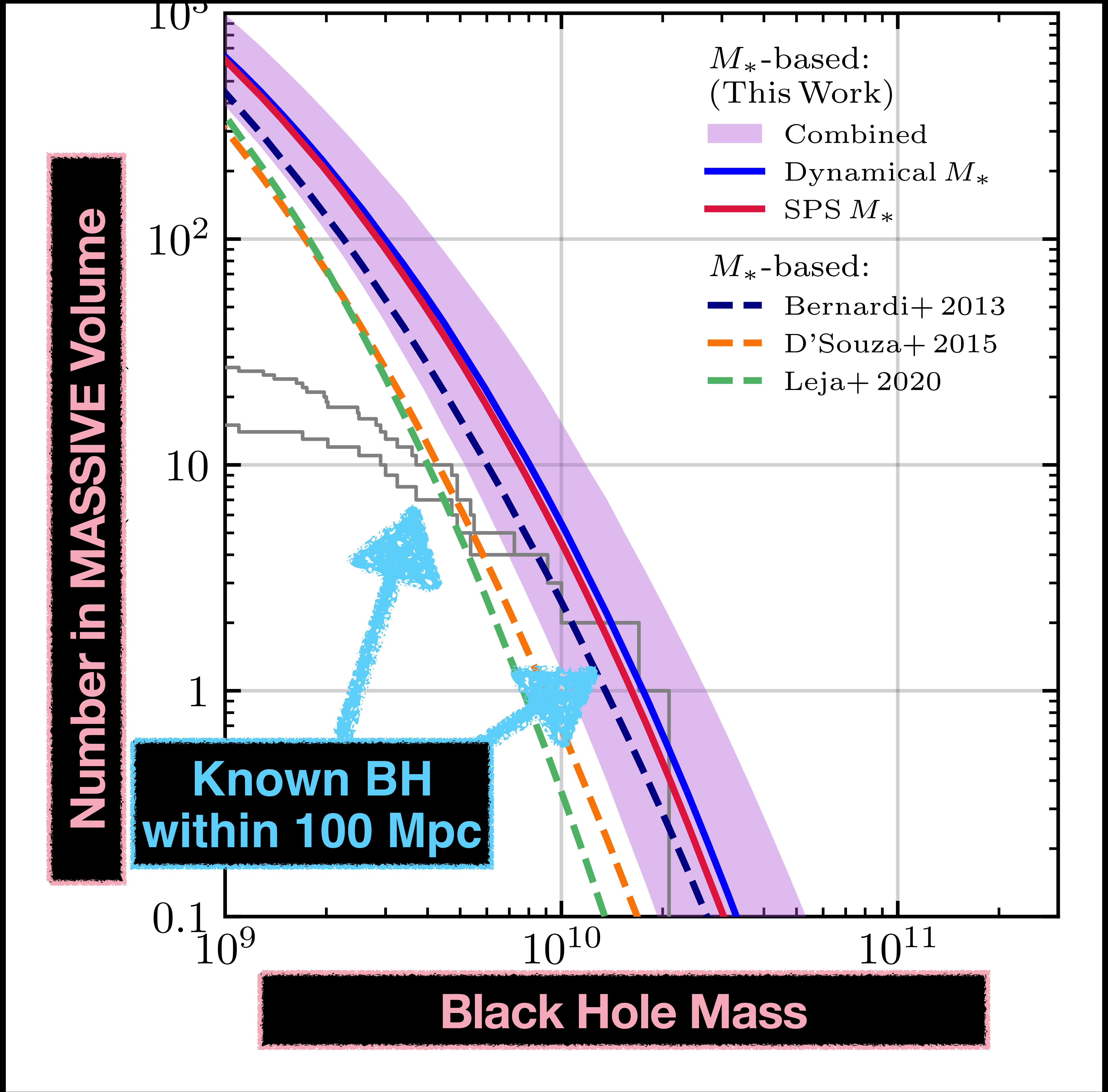




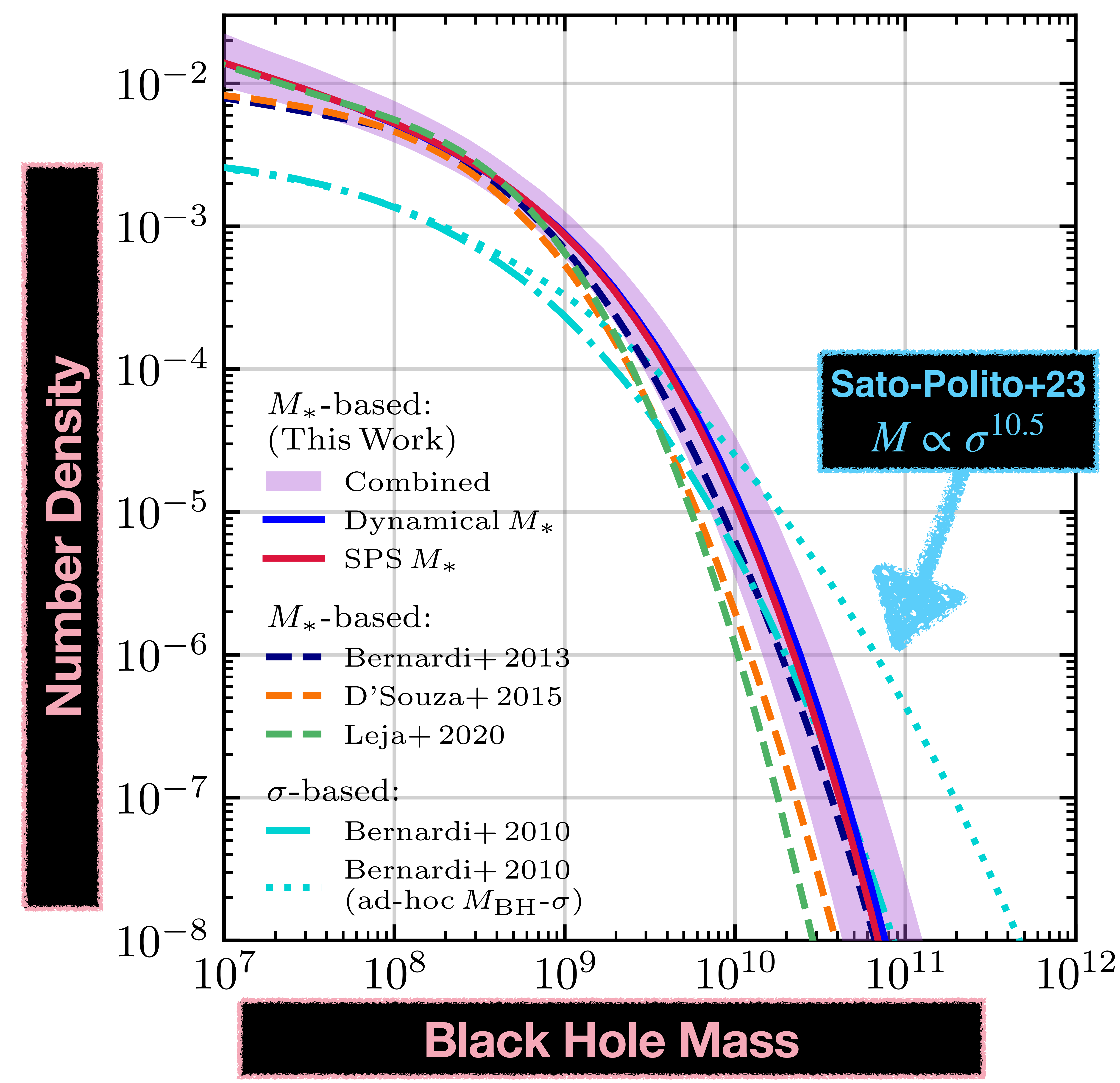
Known BH within 100 Mpc

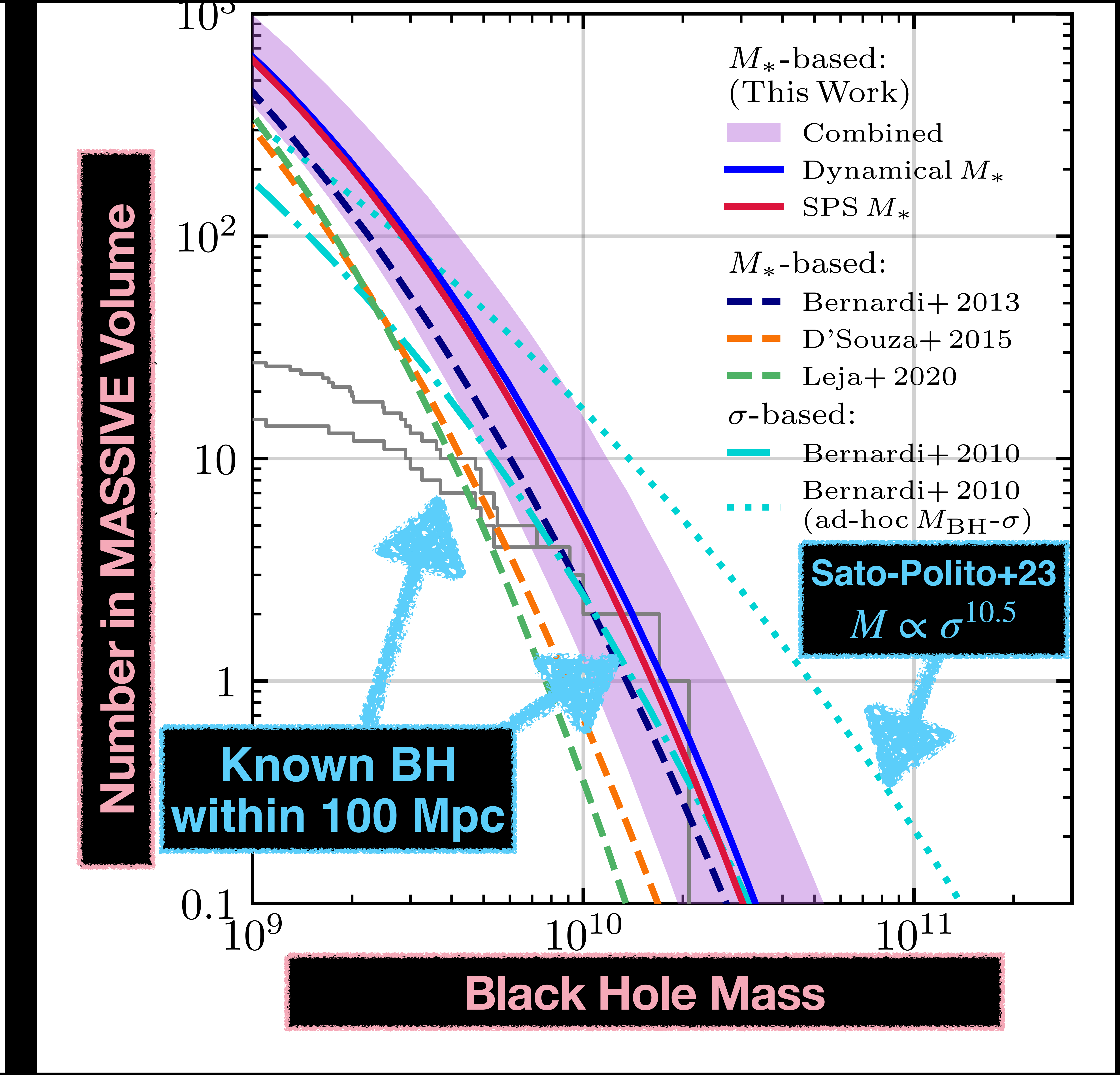
The local Black Hole Mass Function





The local Black Hole Mass Function

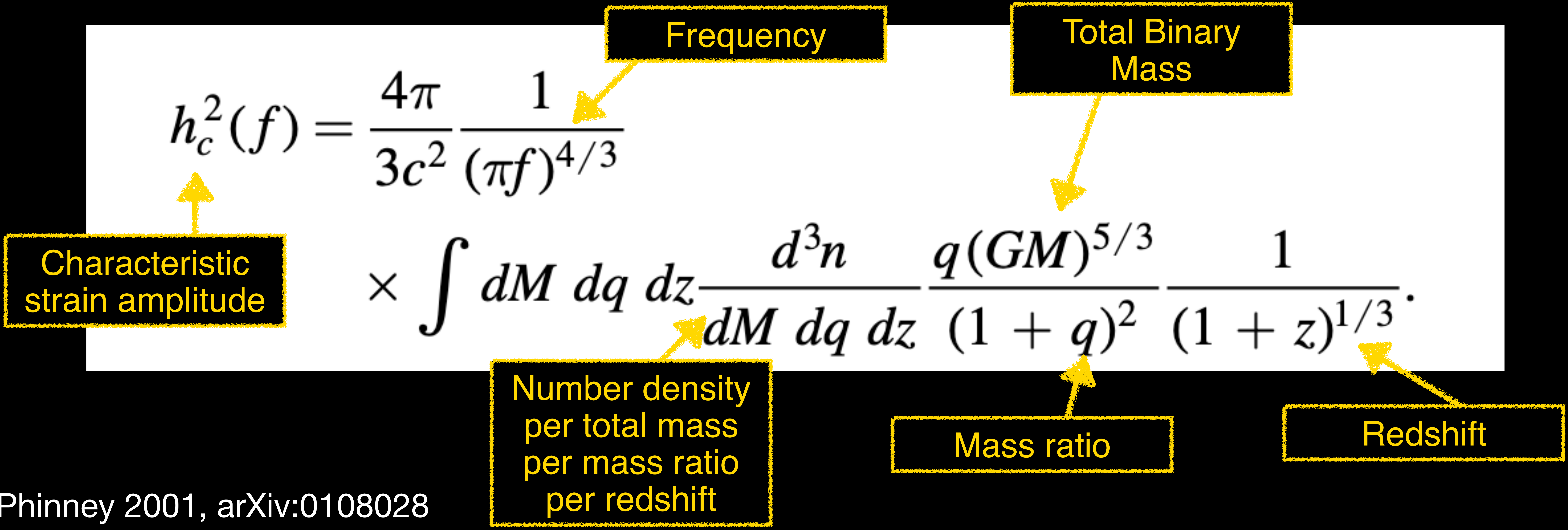




Implications for the Cosmic GW Background

- 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

$$
\begin{aligned}
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}}.
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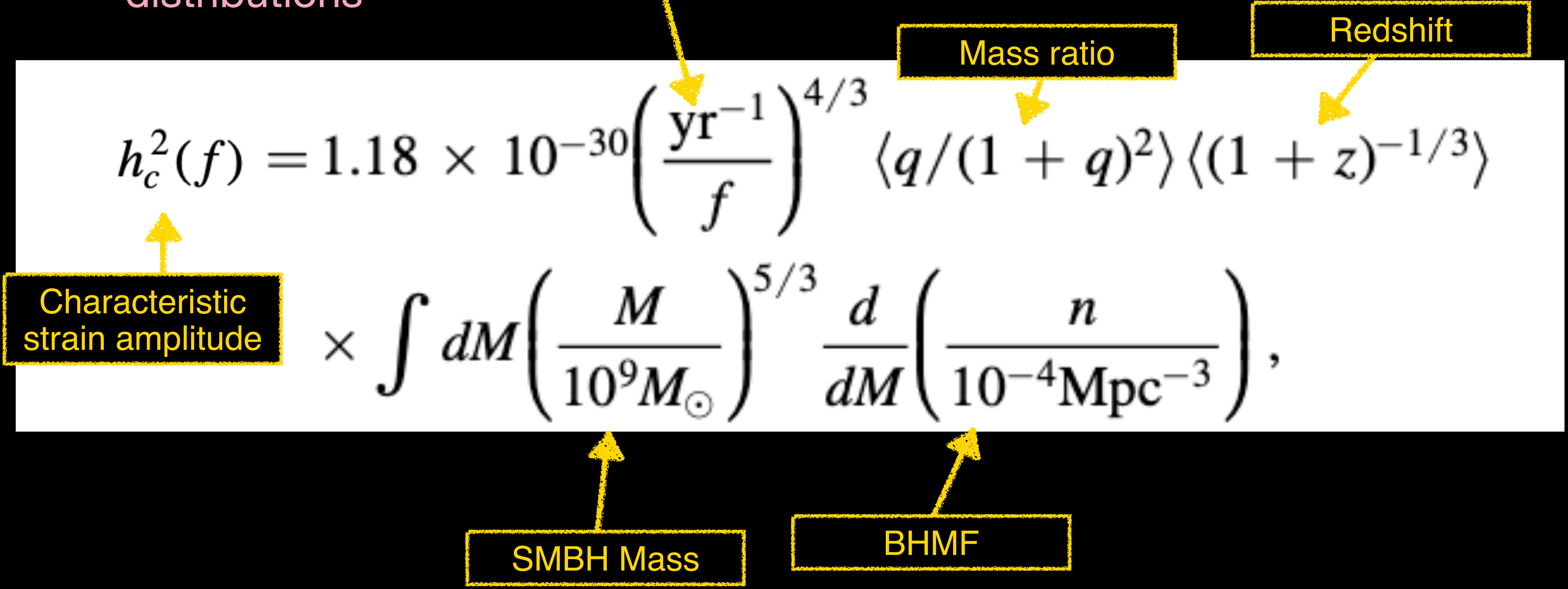
Implications for the Cosmic GW Background

- Assume separable distributions
- Assume Binary Mass = M_{BH}



$$h_c^2(f) = 1.18 \times 10^{-30} \left(\frac{\mathrm{yr}^{-1}}{f} \right)^{4/3} \langle q/(1+q)^2 \rangle \langle (1+z)^{-1/3} \rangle \times \int dM \left(\frac{M}{10^9 M_\odot} \right)^{5/3} \frac{d}{dM} \left(\frac{n}{10^{-4}\mathrm{Mpc}^{-3}} \right),$$

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If all mergers occur at z = 3:

$$(1+z)^{-1/3} \rangle^{1/2} = (1+3)^{-1/3} \rangle^{1/2} = 0.79$$

$$\begin{aligned} h_c^2(f) = {} & 1.18 \times 10^{-30} \left(\frac{\mathrm{yr}^{-1}}{f} \right)^{4/3} \langle q/(1+q)^2 \rangle \langle (1+z)^{-1/3} \rangle \\ & \times \int dM \left(\frac{M}{10^9 M_\odot} \right)^{5/3} \frac{d}{dM} \left(\frac{n}{10^{-4}\,\mathrm{Mpc}^{-3}} \right), \end{aligned}$$

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If all mergers are very unequal ($q = 0.1$)

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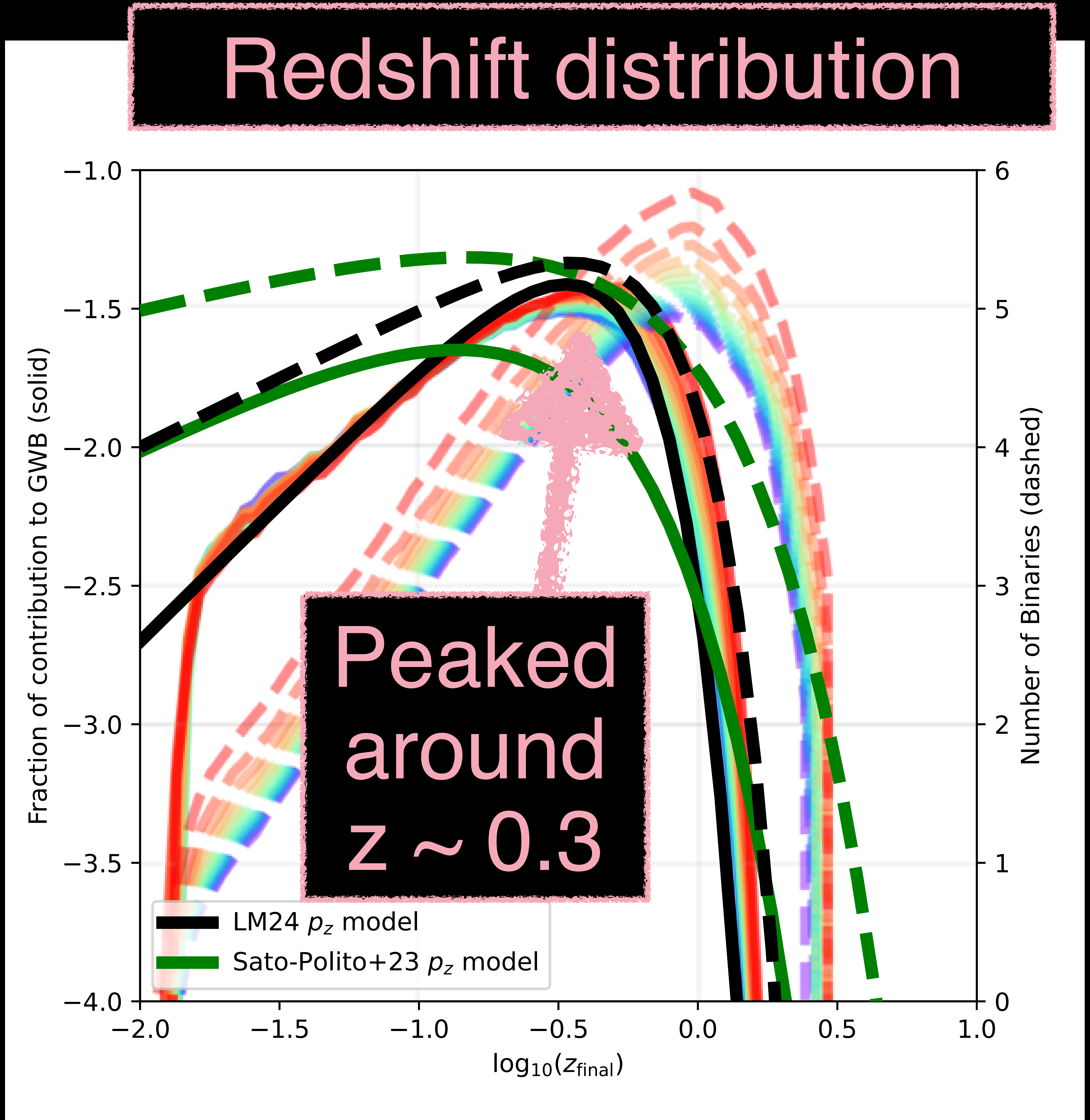
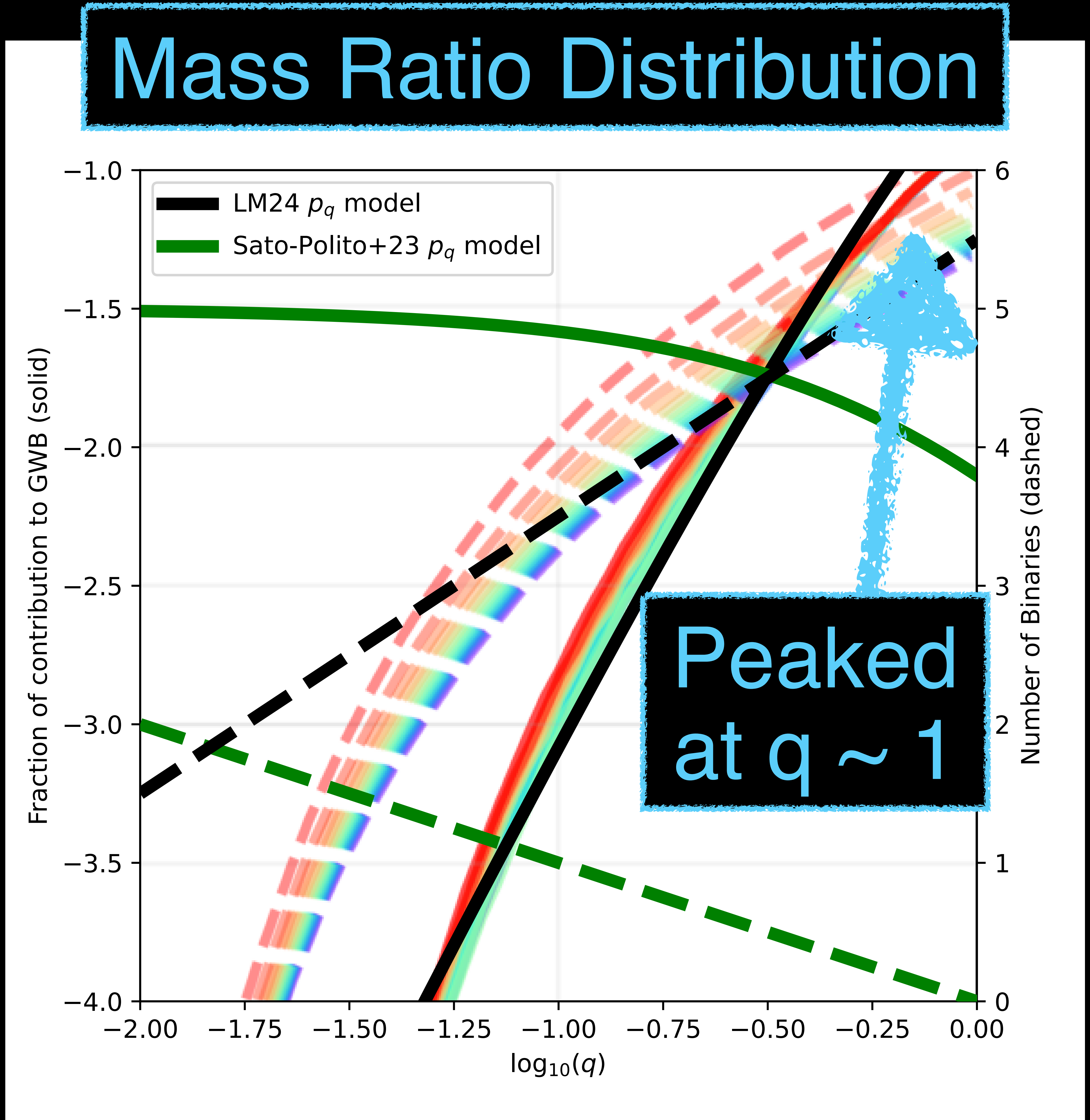
If all mergers are very unequal ($q = 0.1$)

$$\langle q/(1+q^2)\rangle^{1/2} = \langle 0.1/(1+0.1^2)\rangle^{1/2} = 0.31$$

Implications for the Cosmic GW Background


Redshift distribution

Peaked around z ~ 0.3

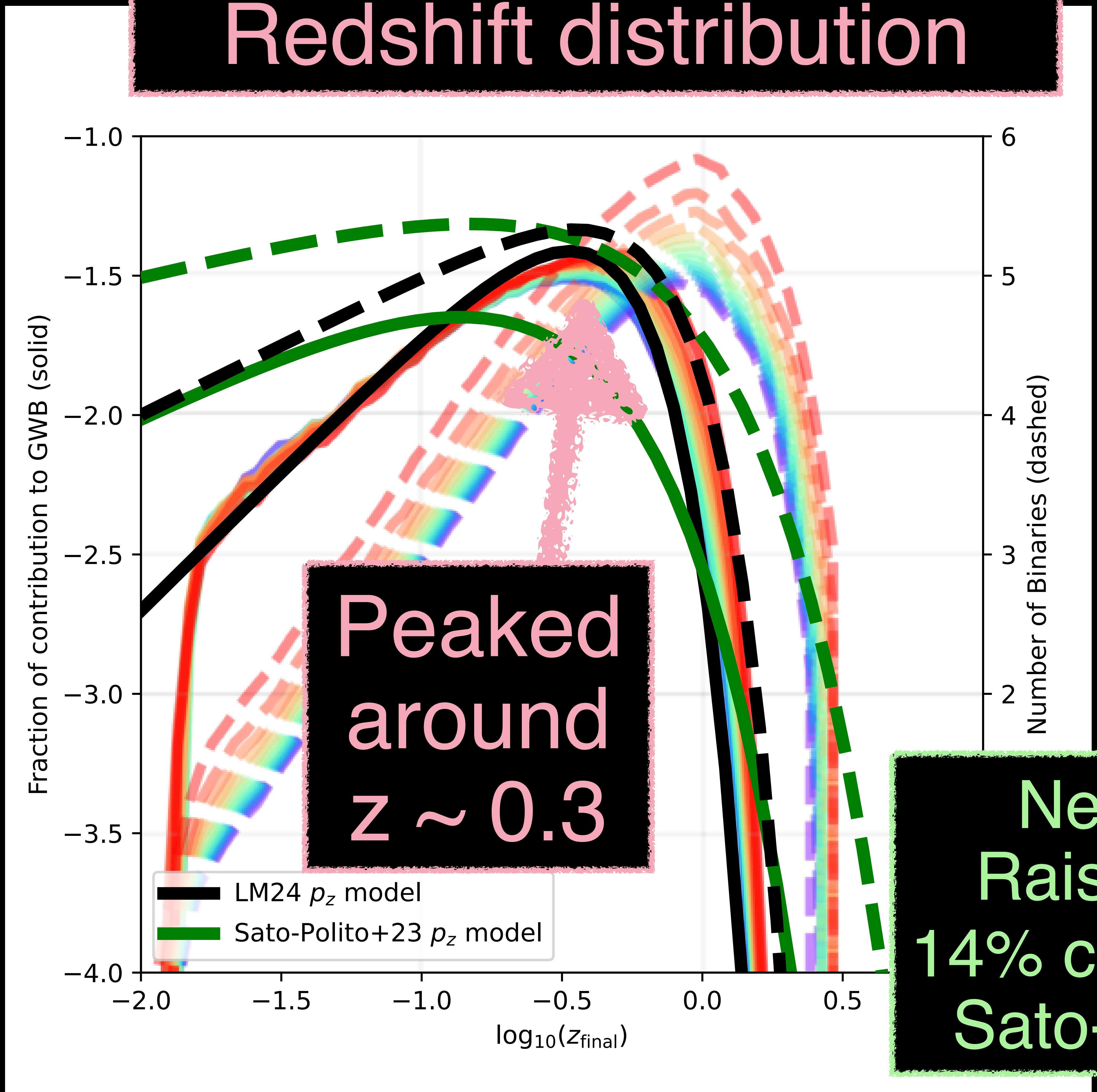

Mass Ratio Distribution

Peaked at q ~ 1

Implications for the Cosmic GW Background

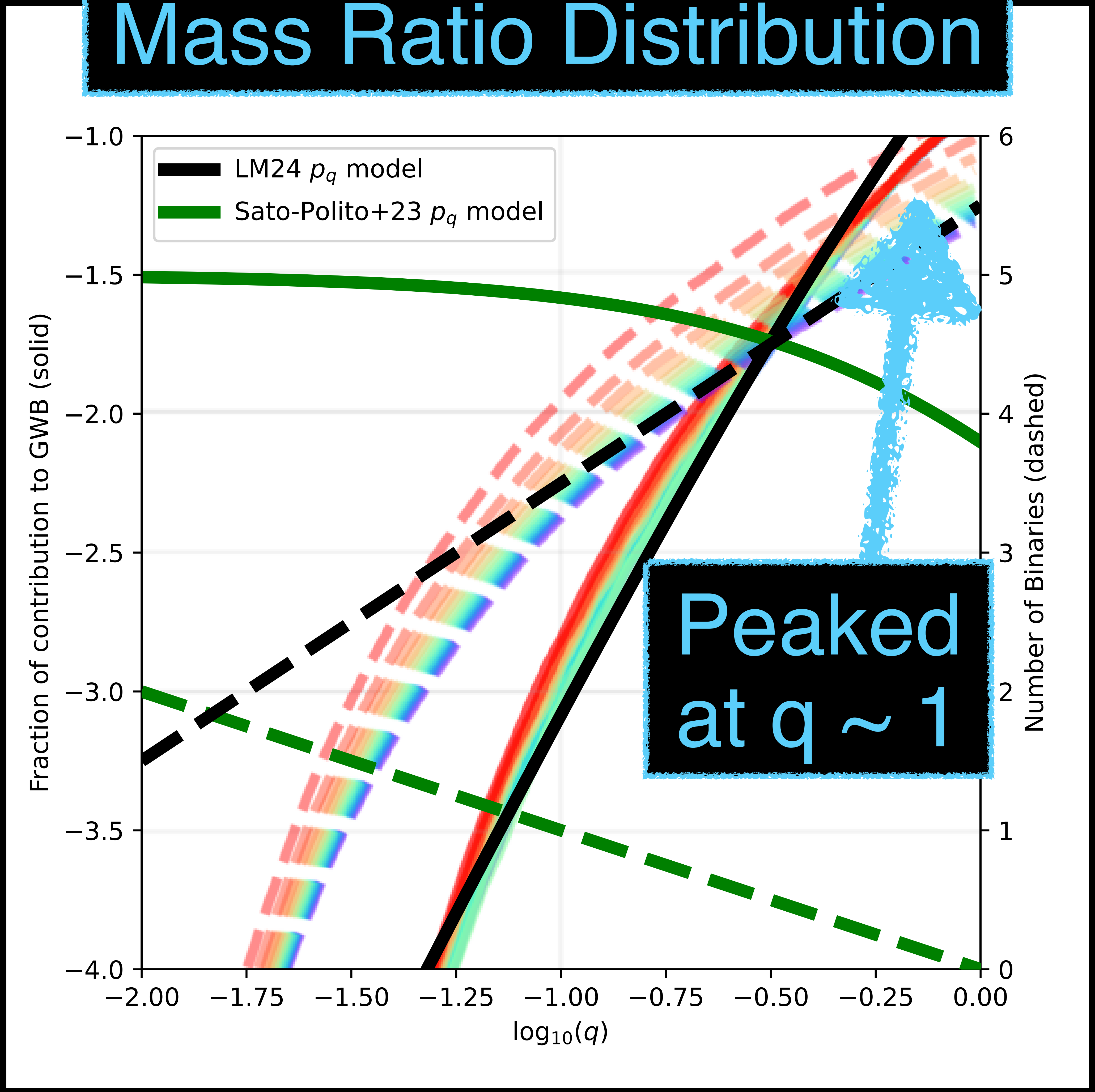
We adopt distributions to approximate those from NANOGrav binary population synthesis models (Agazie 2023, ApJL 952 L37)

Redshift distribution



Peaked around z ~ 0.3

Mass Ratio Distribution



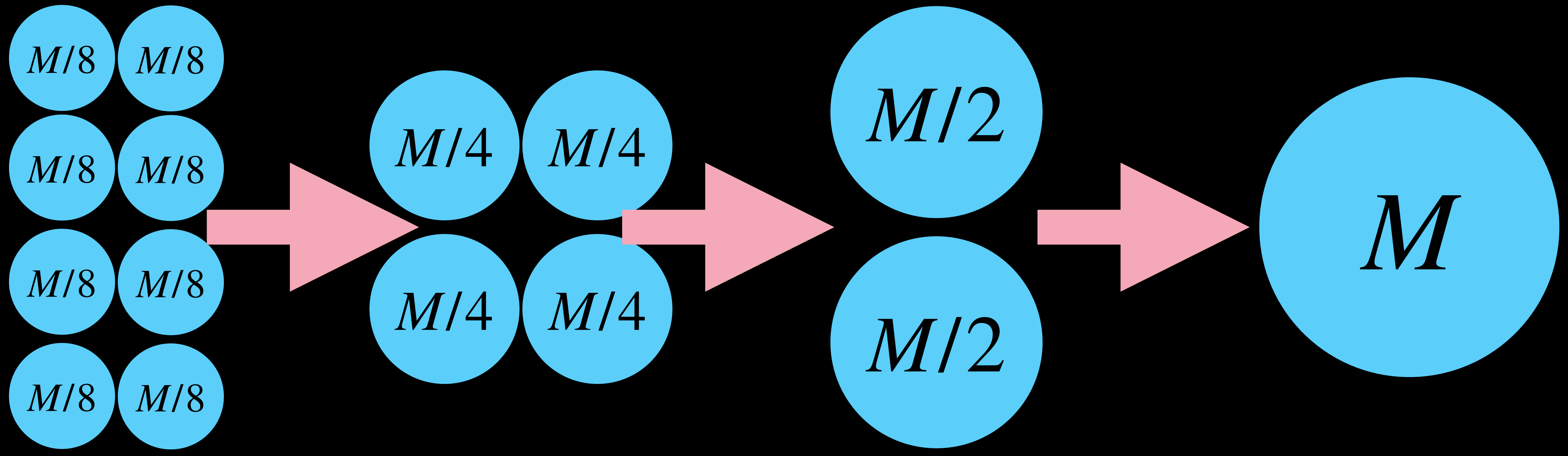
Peaked at q ~ 1

Net Effect: Raising h_c by 14% compared to Sato-Polito+23

Implications for the Cosmic GW Background

- Mergers prior to the most recent have smaller mass scales and smaller contributions to the strain
- Consider a chain of equal mass mergers which produce a present-day mass M

$$h_c^2 \propto \ldots + 4(M/4)^{5/3} + 2(M/2)^{5/3} + M^{5/3} = M^{5/3} \sum_{n=0}^{\infty} 2^{-2n/3} \approx 2.7 M^{5/3}$$



$$h_c \lesssim 1.65 h_{c,0}$$

Sato-Polito+23, arXiv:2312:06756

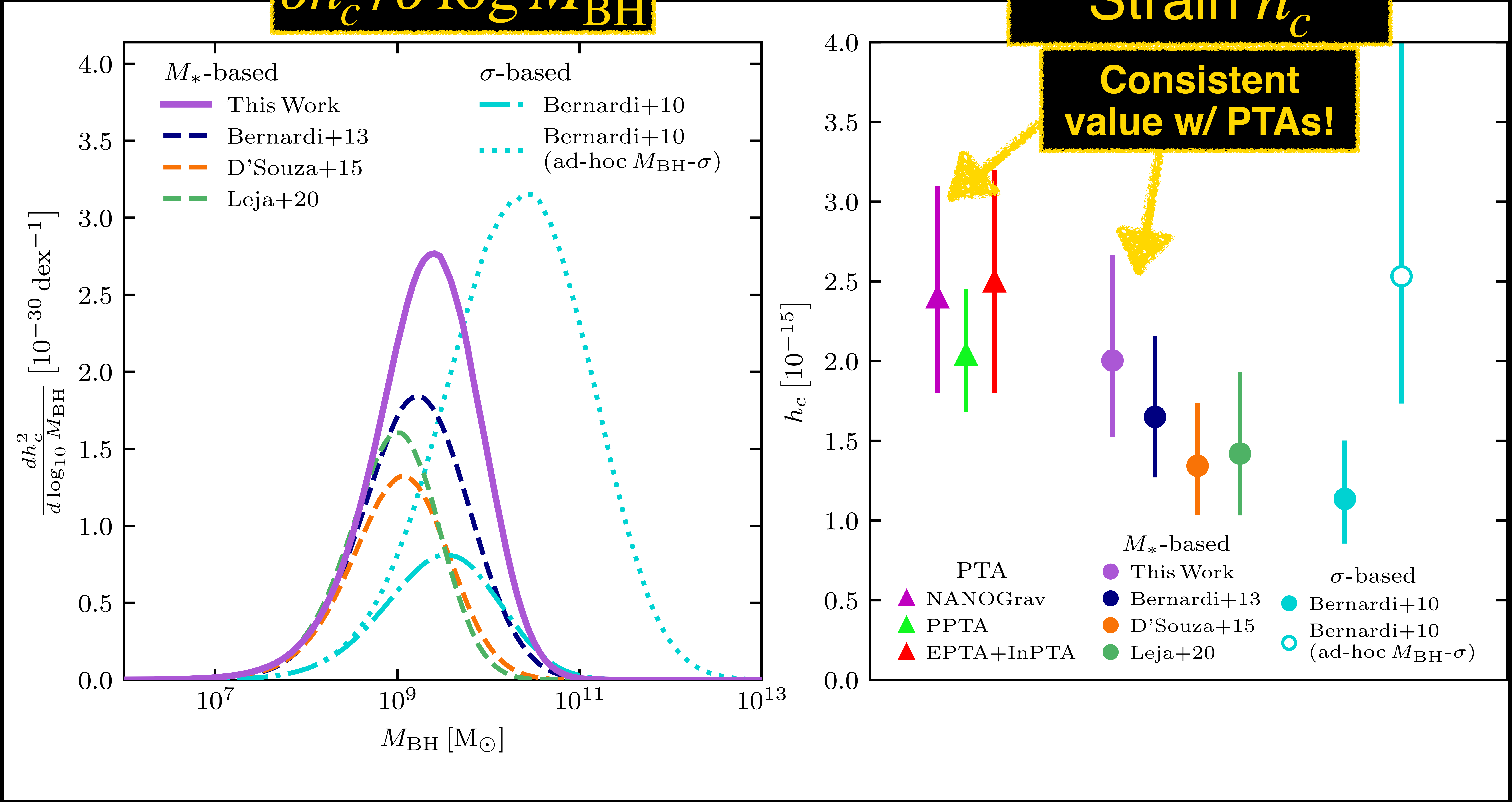
Implications for the Cosmic GW Background

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

Characteristic Strain h_c

Consistent value w/ PTAs!

Implications for the Cosmic GW Background



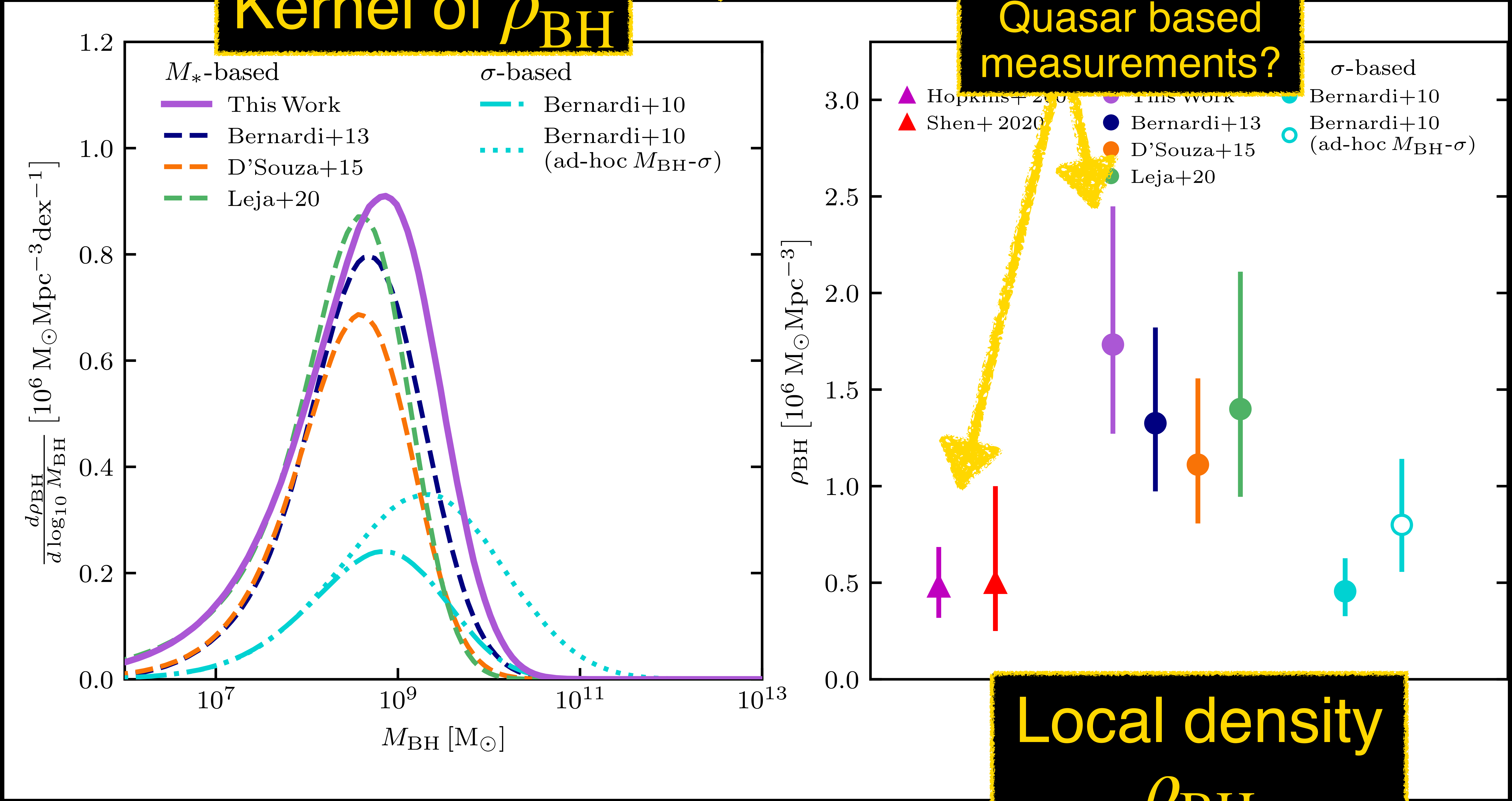
$\partial h_c^2/\partial \log M_{\mathrm{BH}}$

Characteristic Strain h_c

Consistent value w/ PTAs!

A Mystery:
Local BH Mass density

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



Kernel of ρ_{BH}

Factor of 3 above Quasar based measurements?

Local density ρ_{BH}

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

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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 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

Big BHs are **intriguing**

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

Big BHs are **booming**

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

Big BHs are intriguing

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

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)

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

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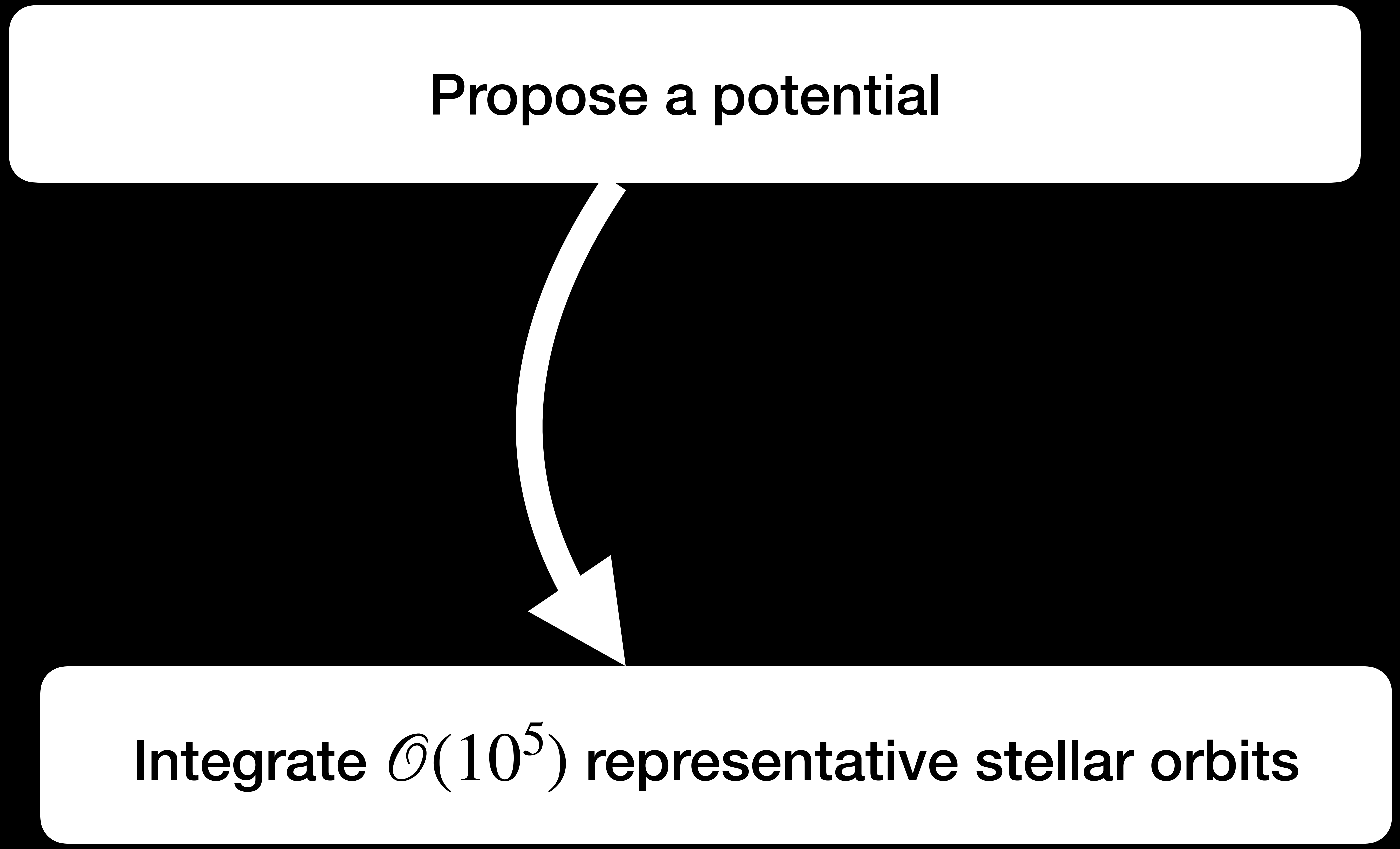

Propose a potential

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

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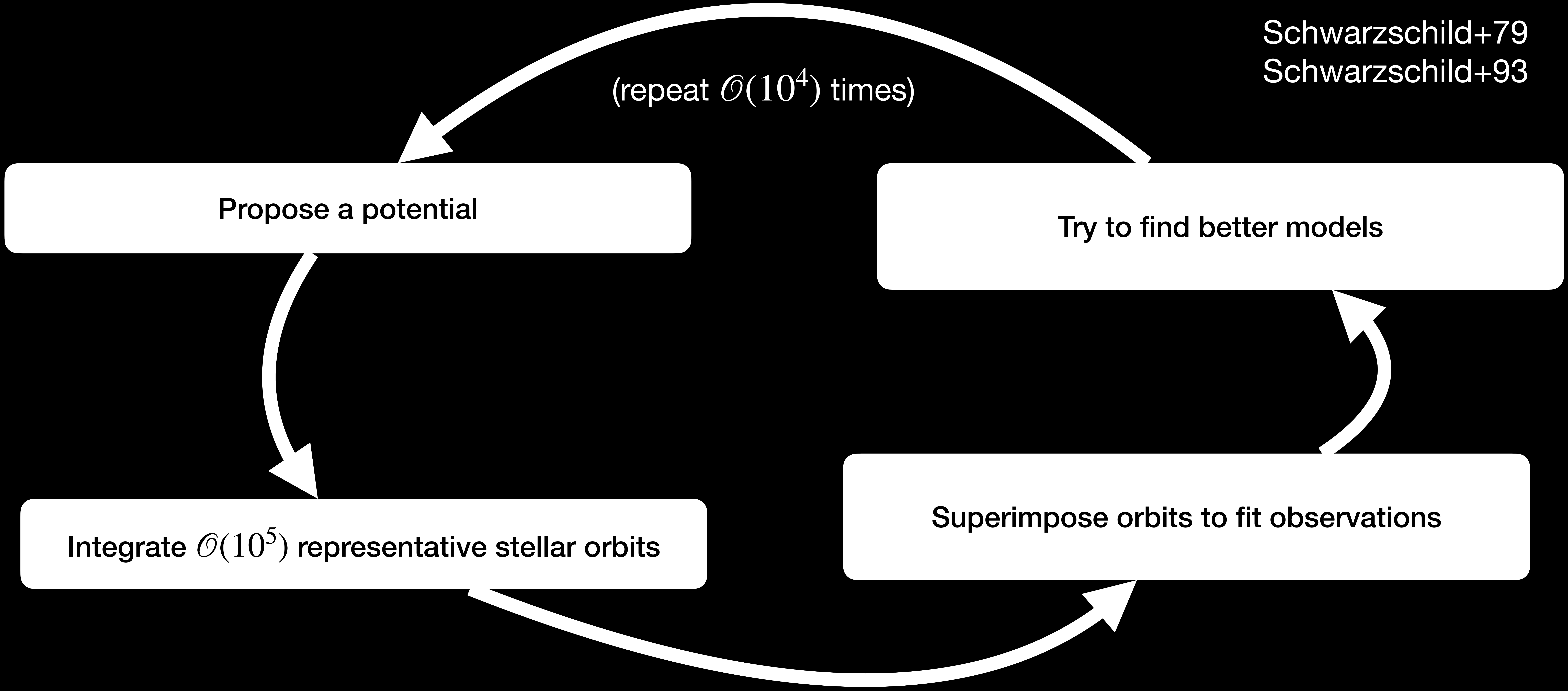

(repeat $\mathcal{O}(10^4)$ times)

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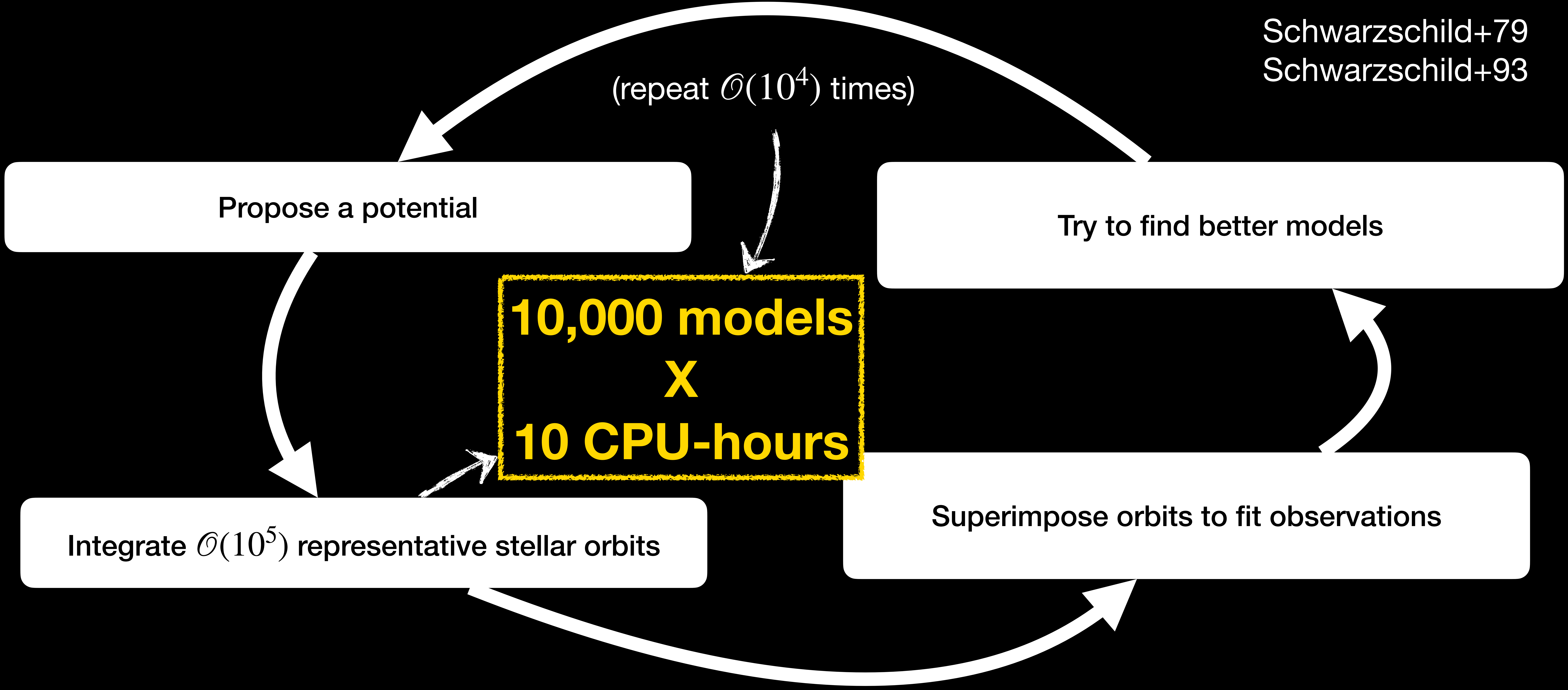

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10,000 models
X
10 CPU-hours

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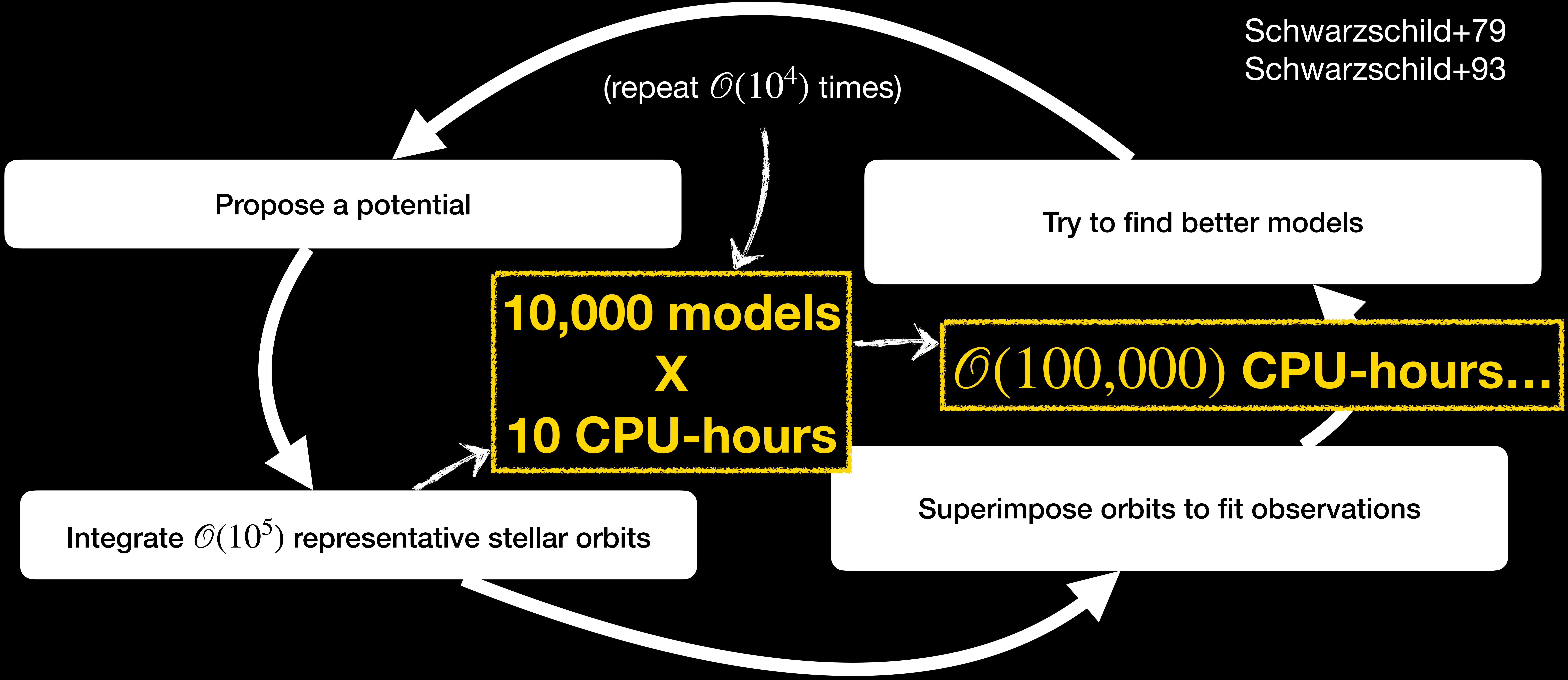

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$\mathcal{O}(100{,}000)$ CPU-hours…

Improvements in Schwarzschild Modeling

We've substantially modified the *triaxial orbit* code of van den Bosch+08

(Now we call it **TriOS)**

1. Accurate enforcement of axisymmetry
2. Accurate orbit composition + symmetry in triaxial galaxies
3. Radical efficiency improvements and new grid-free model sampling + parameter inference schemes *(~several order of magnitude cost reduction!)*
4. Robustness and validation tests with mock galaxy data!

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

Prior use of the code often tried to approximate axisymmetry (Seth+14, Walsh+15,17, Ahn+18)

- Determined criteria for axisymmetry in triaxial code.
- Added projections which enforce axisymmetry in the orbits

(Liepold+20, Quenneville+21)

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

- Fixed errors in orbit mirroring
- Identified and fixed aliasing effects due to insufficient phase space coverage
- Identified shape parameters for efficient + comprehensive search over deprojections

(Quenneville+22, Liepold+23)

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- **Replaced *extremely* inefficient PSF convolution scheme (3x overall speedup)**
- Optimized scheme for acceleration interpolations (2x overall speedup)
- Developed grid free Gaussian Process Regression-based model search and parameter inference routines

(~10x speedup in individual models, 100+x reduction in number of models for 6D search)

(Quenneville+21, 22, Pilawa+22, Liepold+23)

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

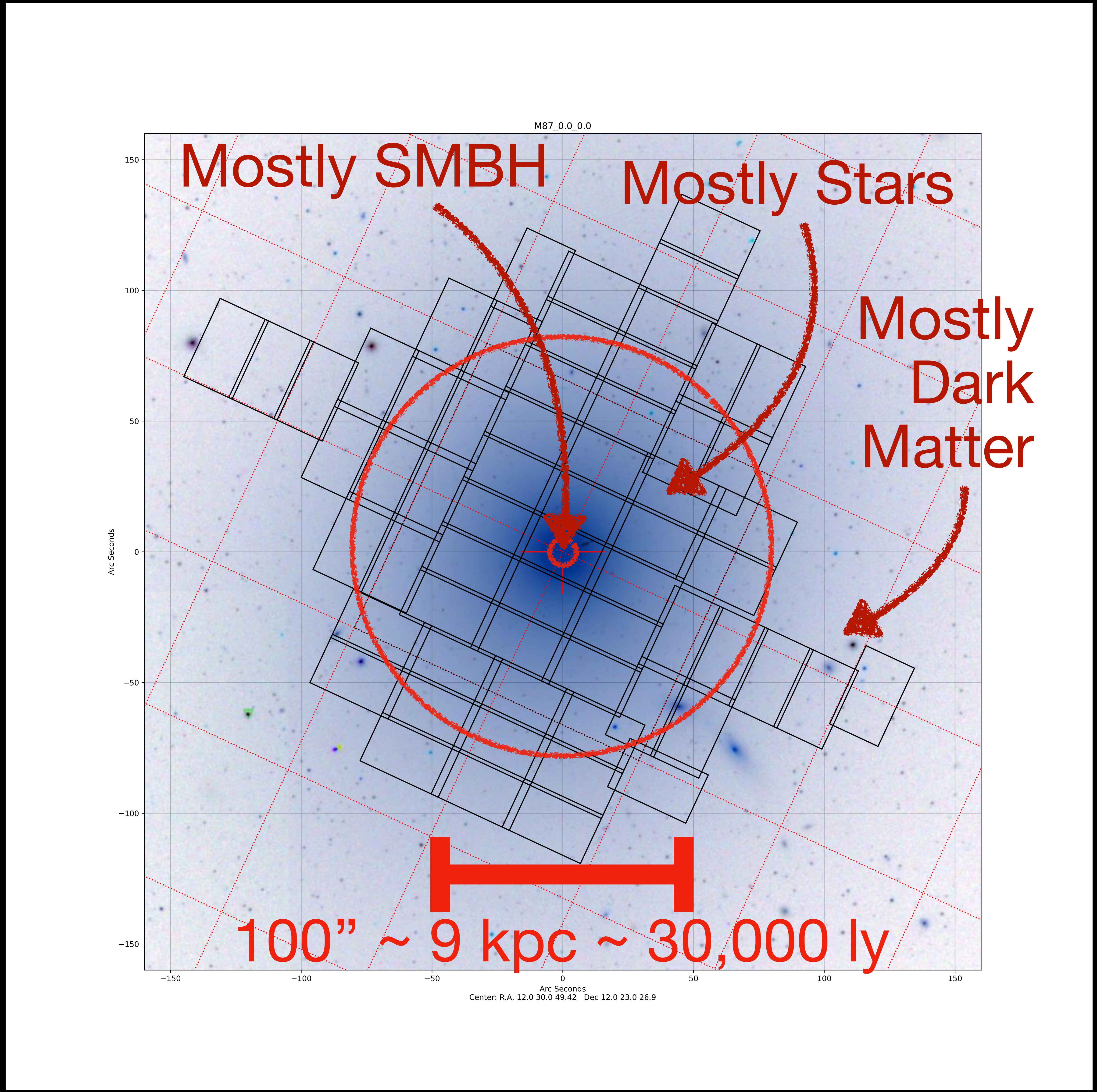
Pilawa+24: Followed a similar procedure as Lipka+Thomas 21 to bootstrap synthetic stellar kinematic observations from Schwarzschild models

1. **We find a similar bias towards *edge-on* models when axisymmetry is used**
2. **We don’t find obvious biases in shape / orientation for triaxial models**
3. **Mass parameters are well recovered (input value within 68% CI about 68% of the time)**
4. 1σ **perturbation in input kinematics yields** 1σ **perturbation in preferred model**

Keck observations of M87

Liepold, Ma, Walsh 2023

- New observations of M87 with Keck Cosmic Web Imager (KCWI) IFU
- 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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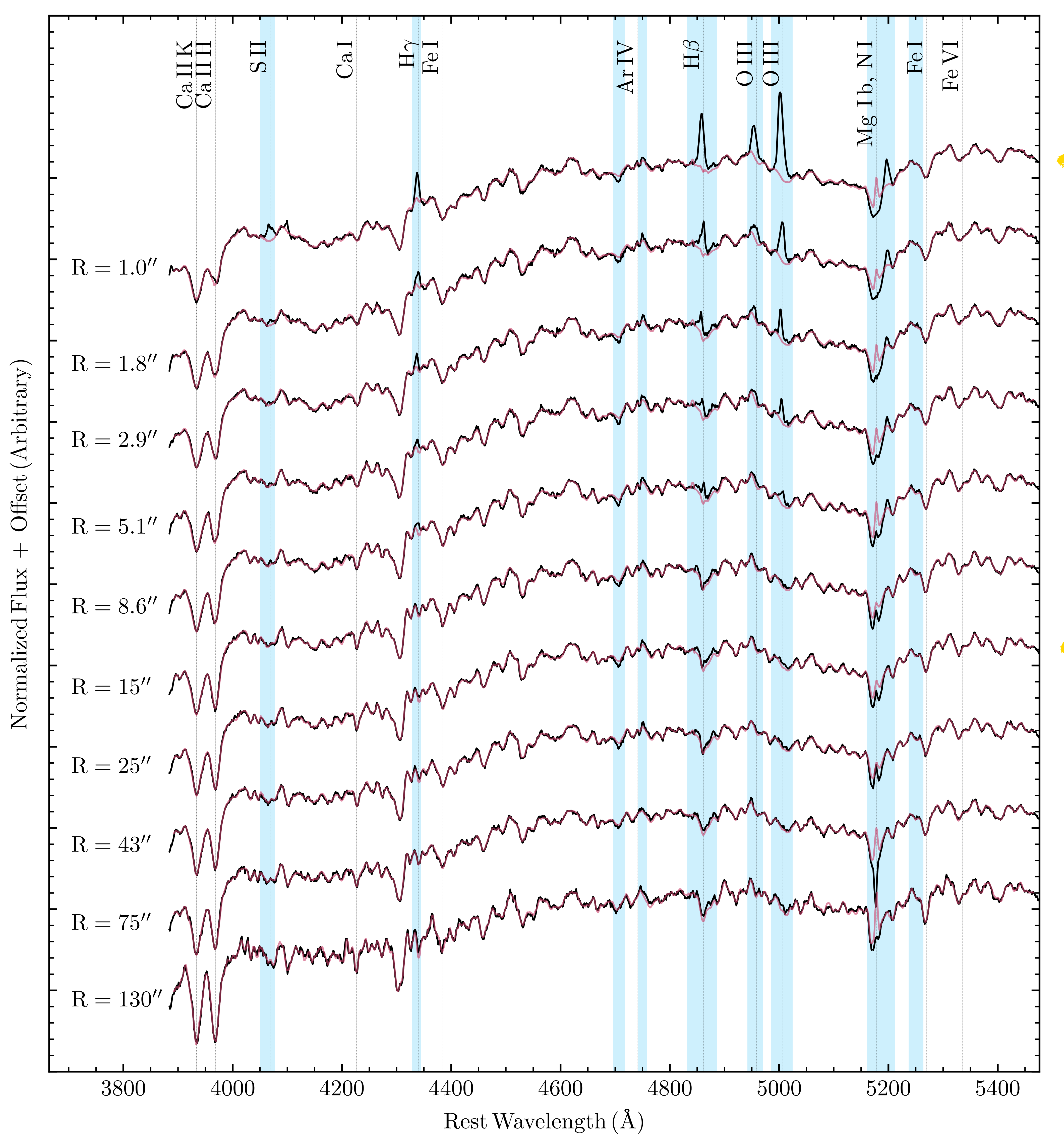

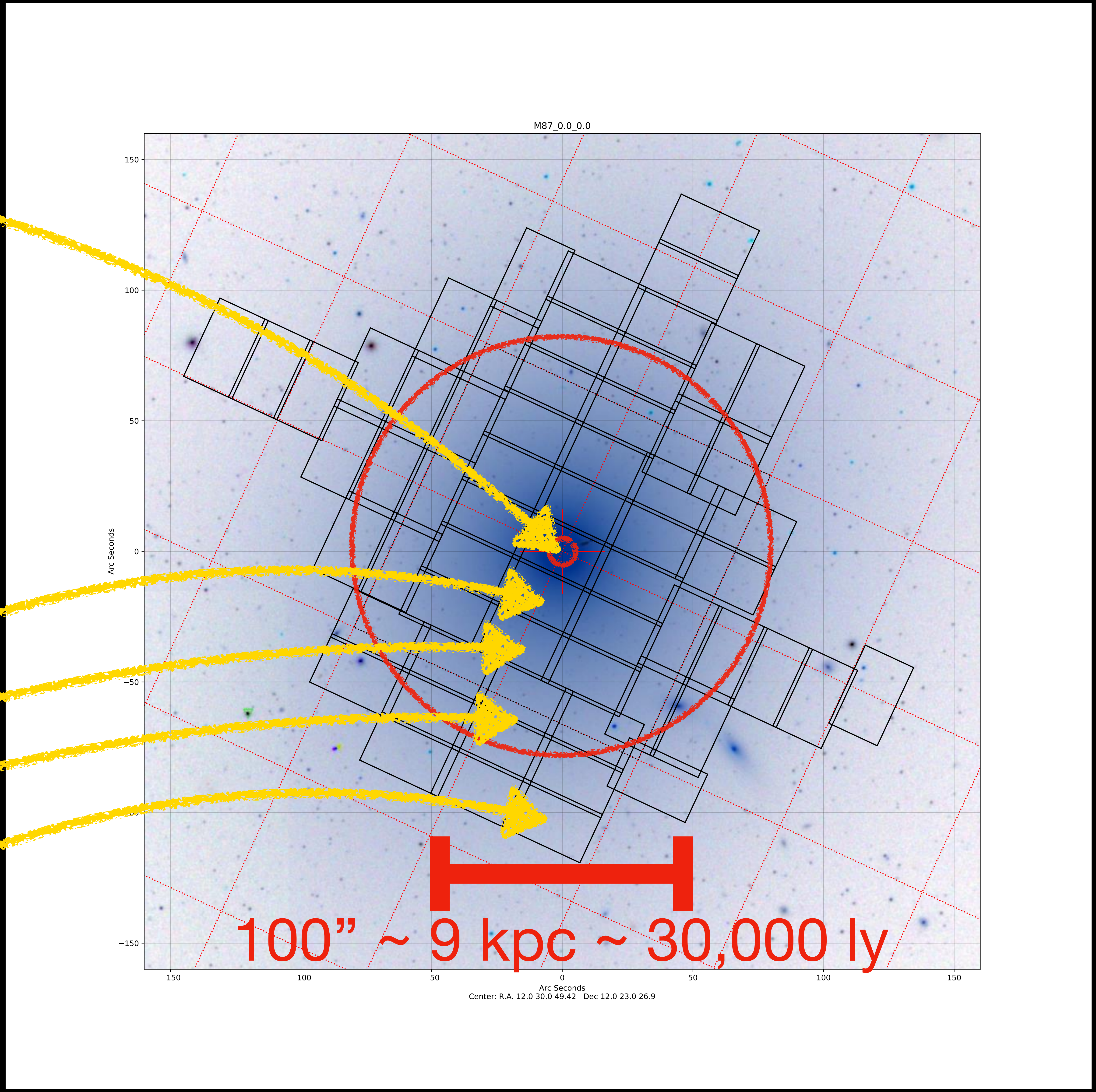

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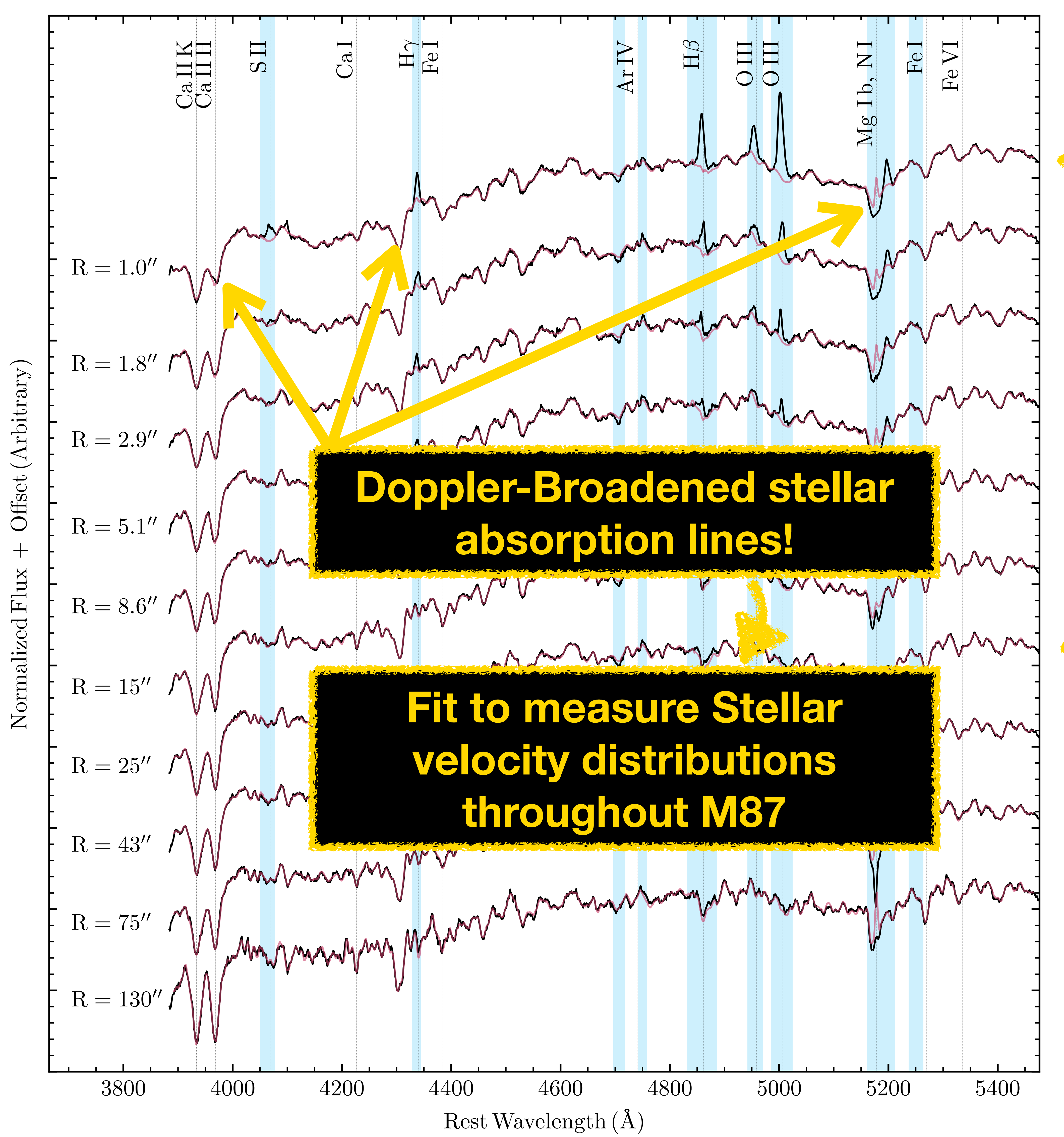
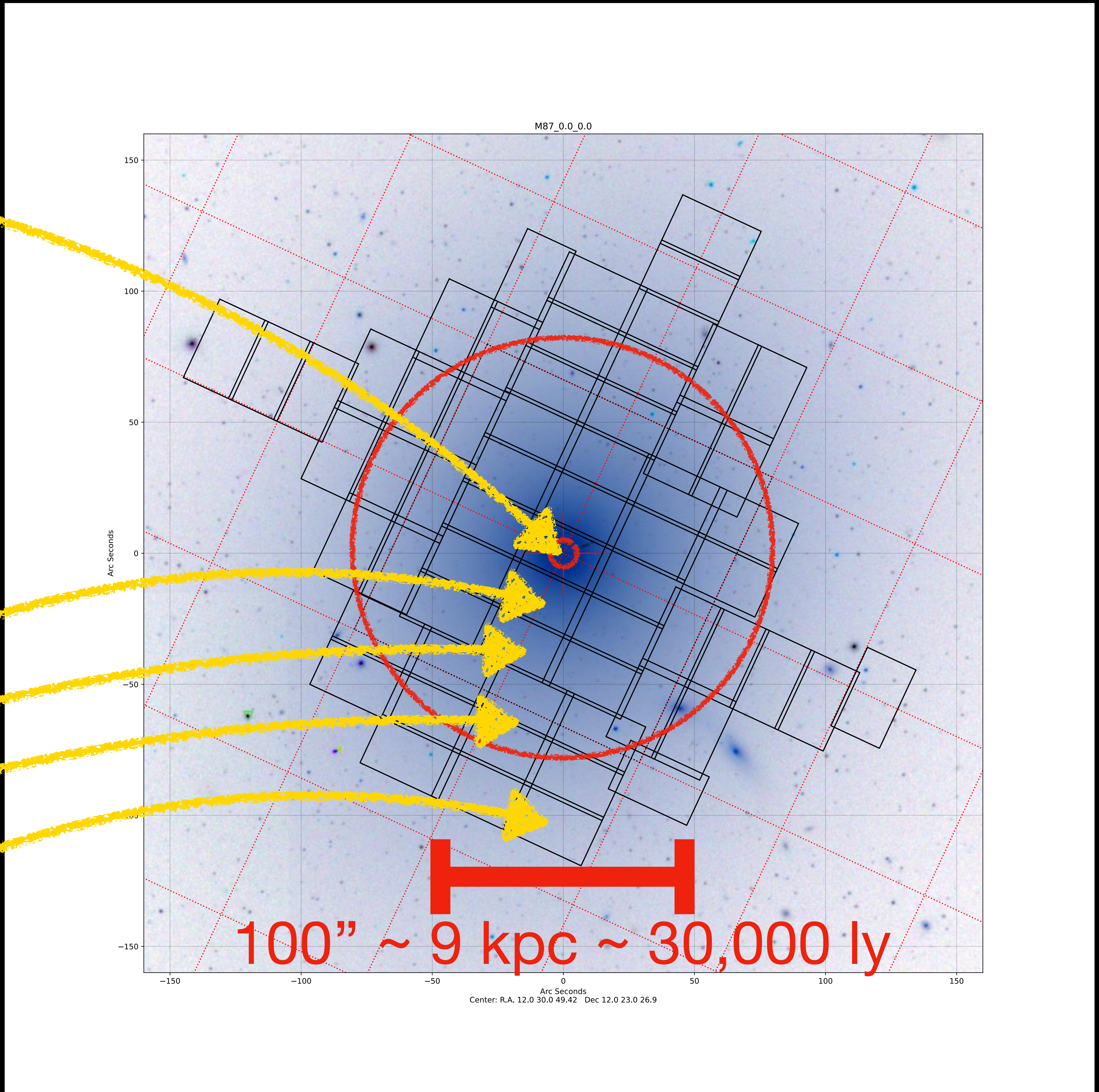


Doppler-Broadened stellar absorption lines!

Fit to measure Stellar velocity distributions throughout M87



100” ~ 9 kpc ~ 30,000 ly

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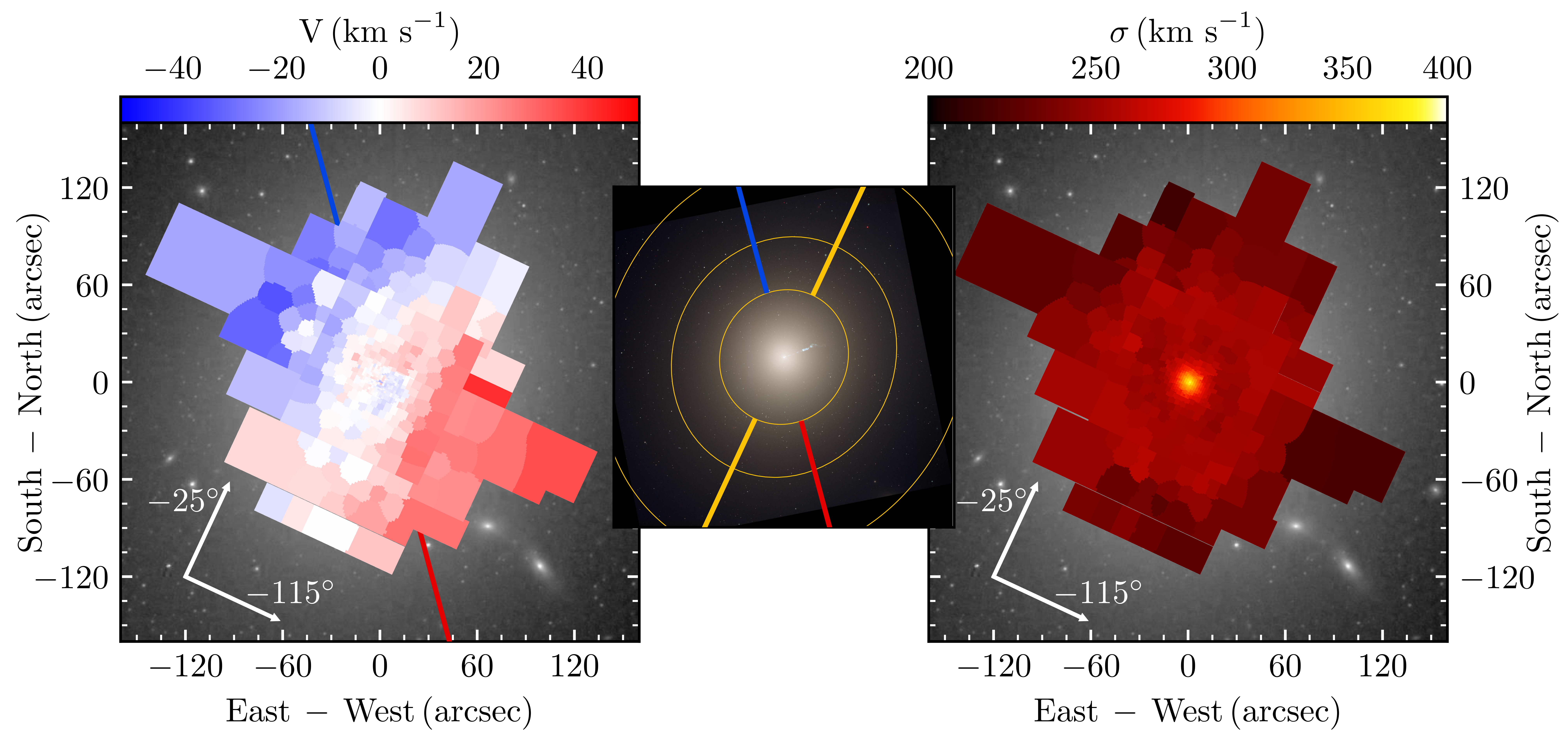

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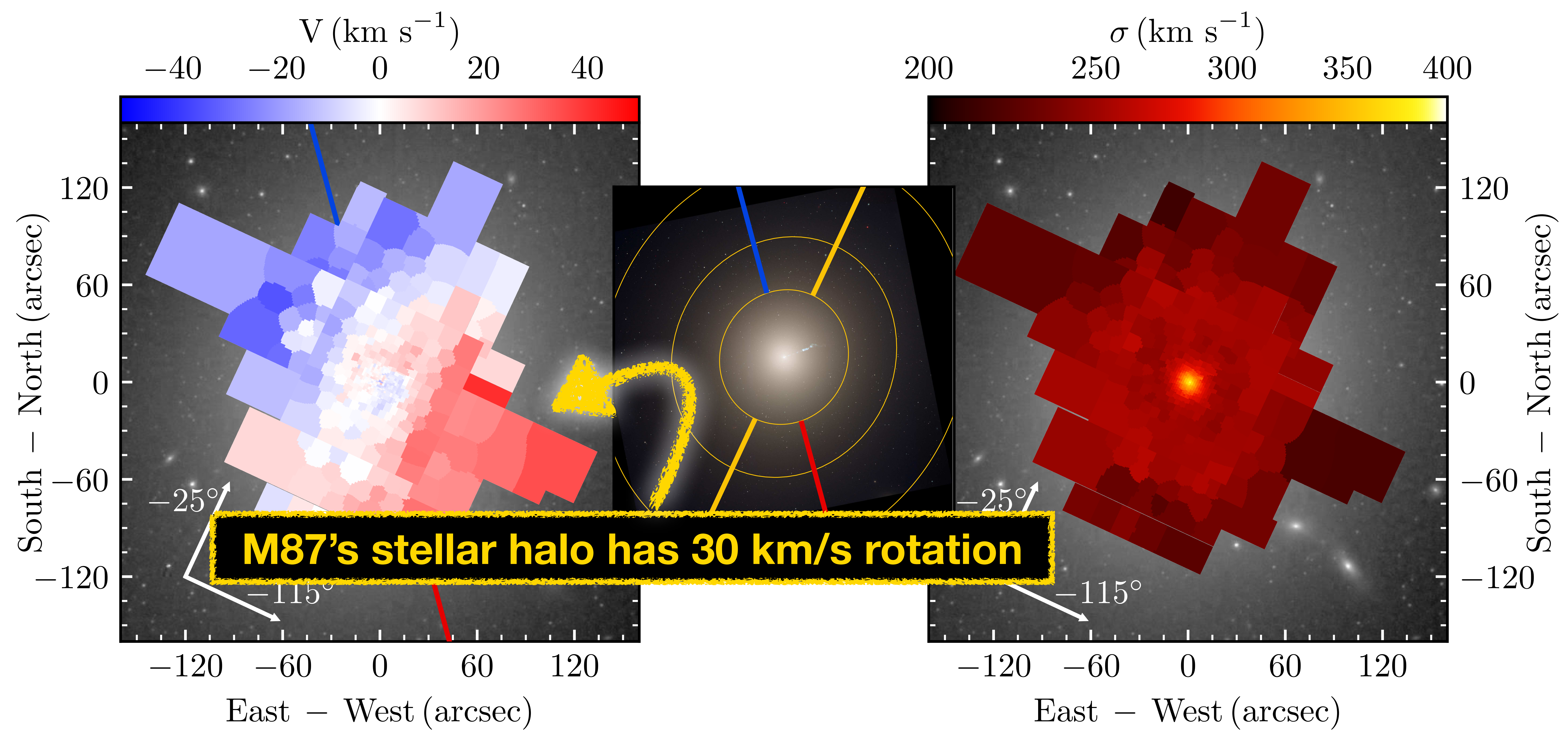
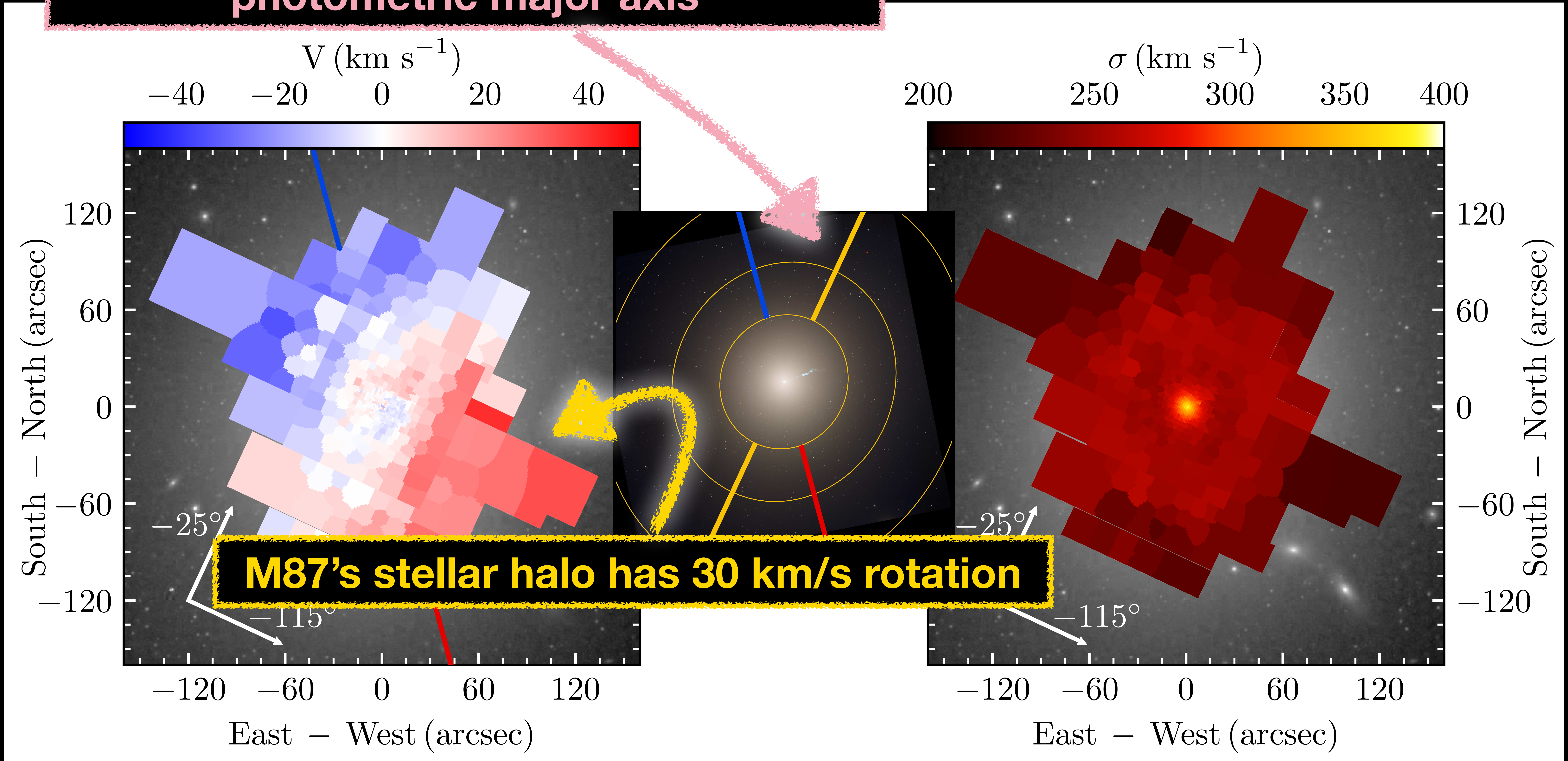


M87’s stellar halo has 30 km/s rotation

Keck observations of M87

Liepold, Ma, Walsh 2023



The rotation is *misaligned* with the photometric major axis

M87’s stellar halo has 30 km/s rotation

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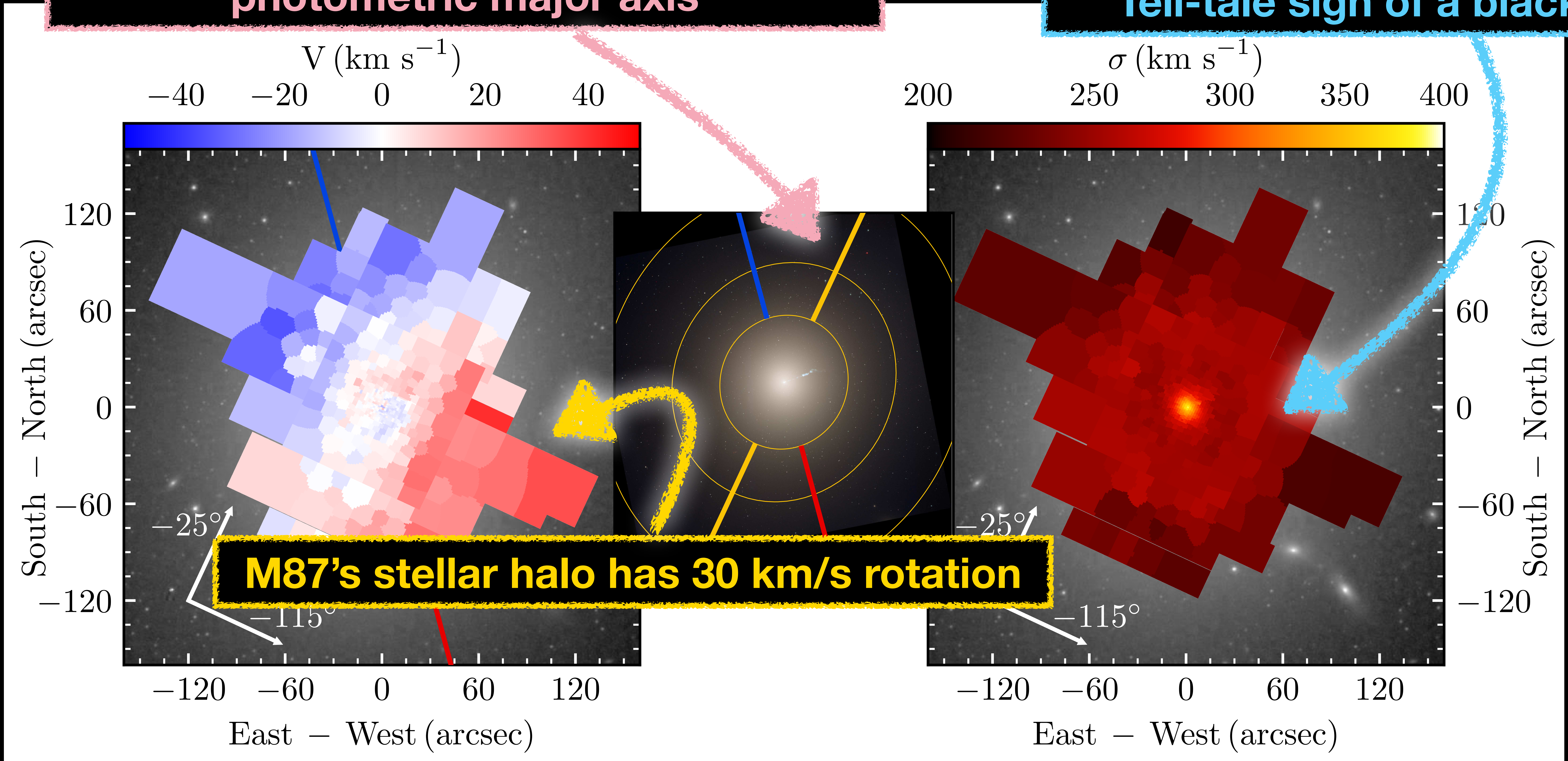
The rotation is *misaligned* with the photometric major axis

The velocity dispersion rises *quickly* towards the center!

Tell-tale sign of a black hole!



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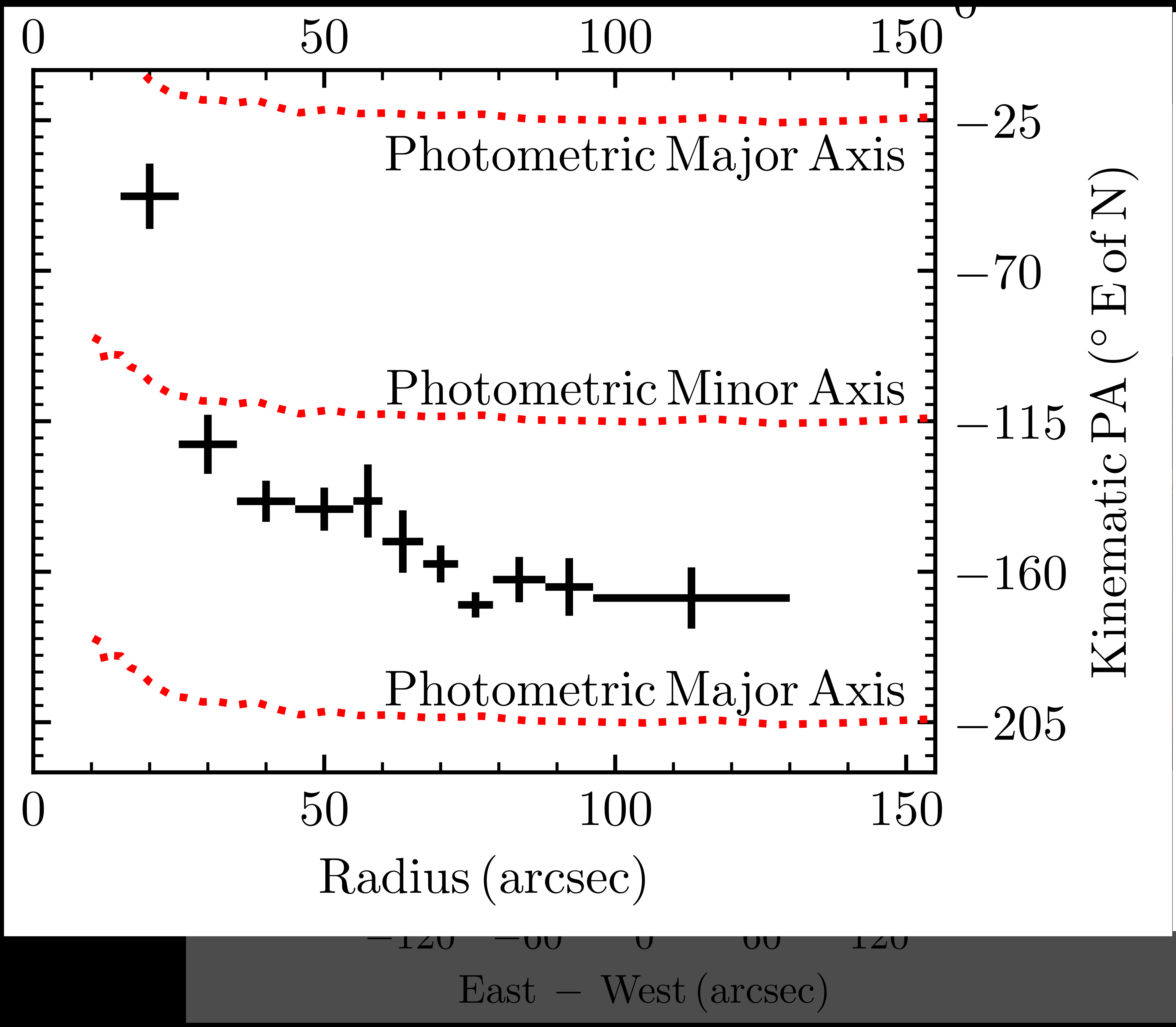
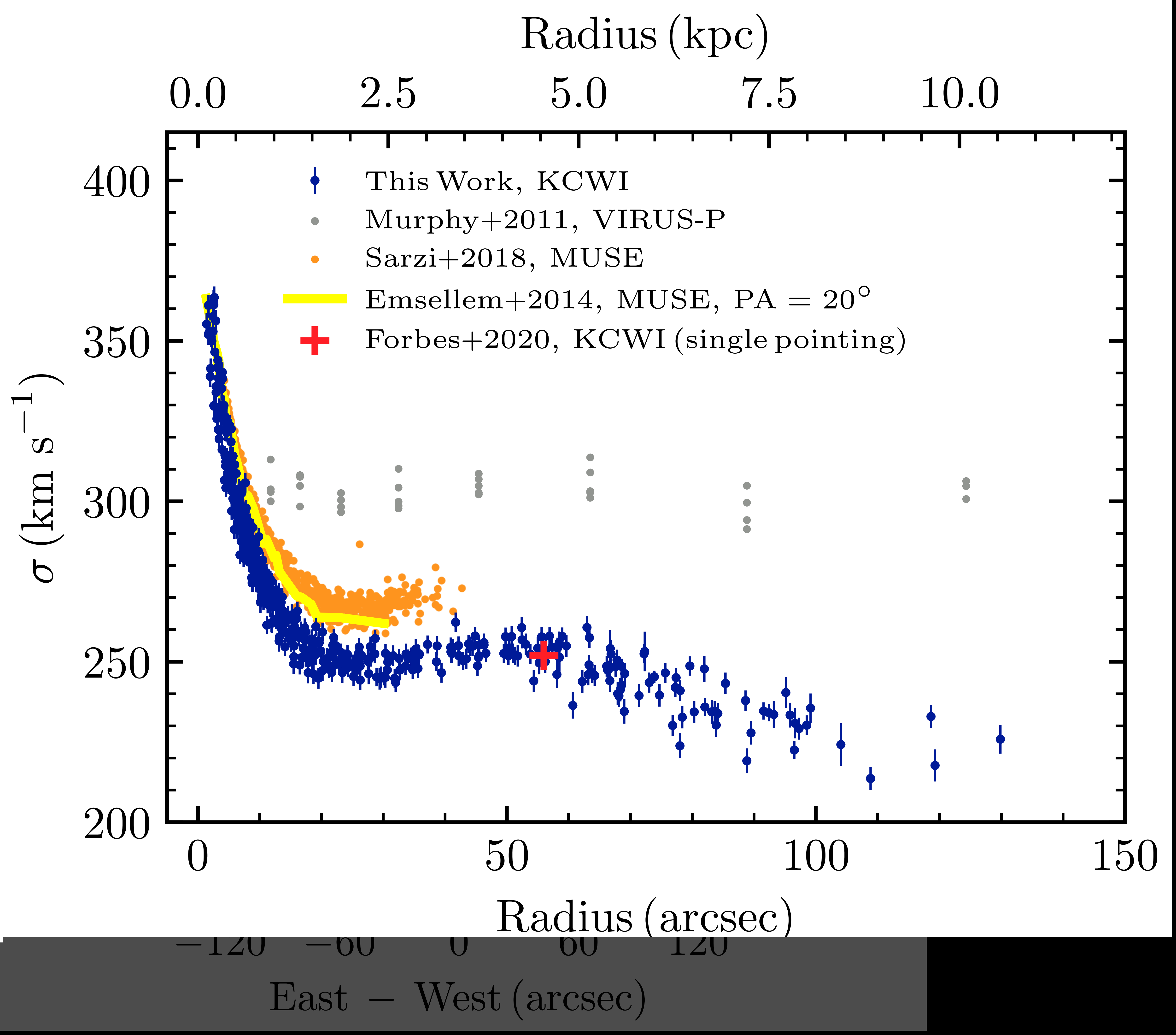

0
50
100
150
0
−25
−70
−115
−160
−205
Kinematic PA (° E of N)
Photometric Major Axis
Photometric Minor Axis
Photometric Major Axis
Radius (arcsec)
−120
−60
0
60
120
East − West (arcsec)


Radius (kpc)
0.0
2.5
5.0
7.5
10.0
σ (km s^{-1})
400
350
300
250
200
This Work, KCWI
Murphy+2011, VIRUS-P
Sarzi+2018, MUSE
Emsellem+2014, MUSE, PA = 20°
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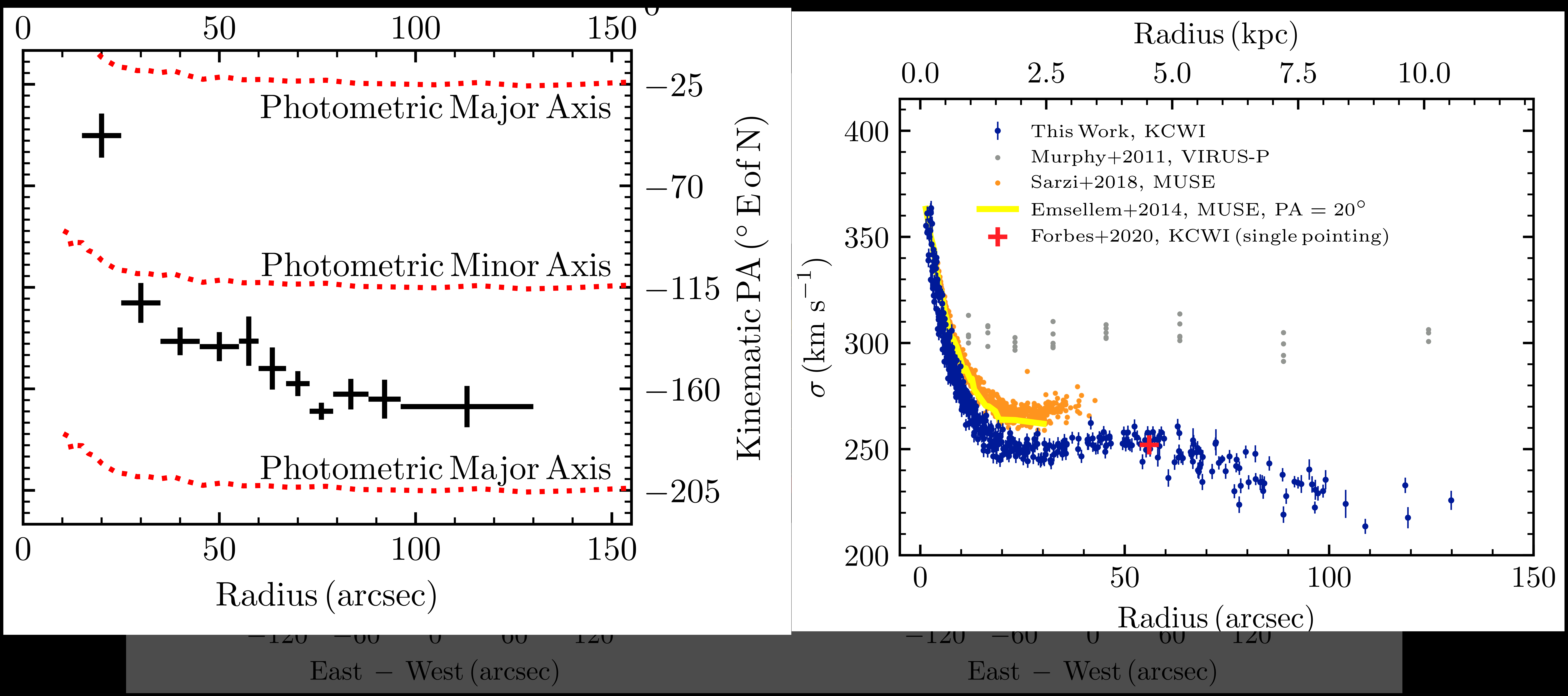

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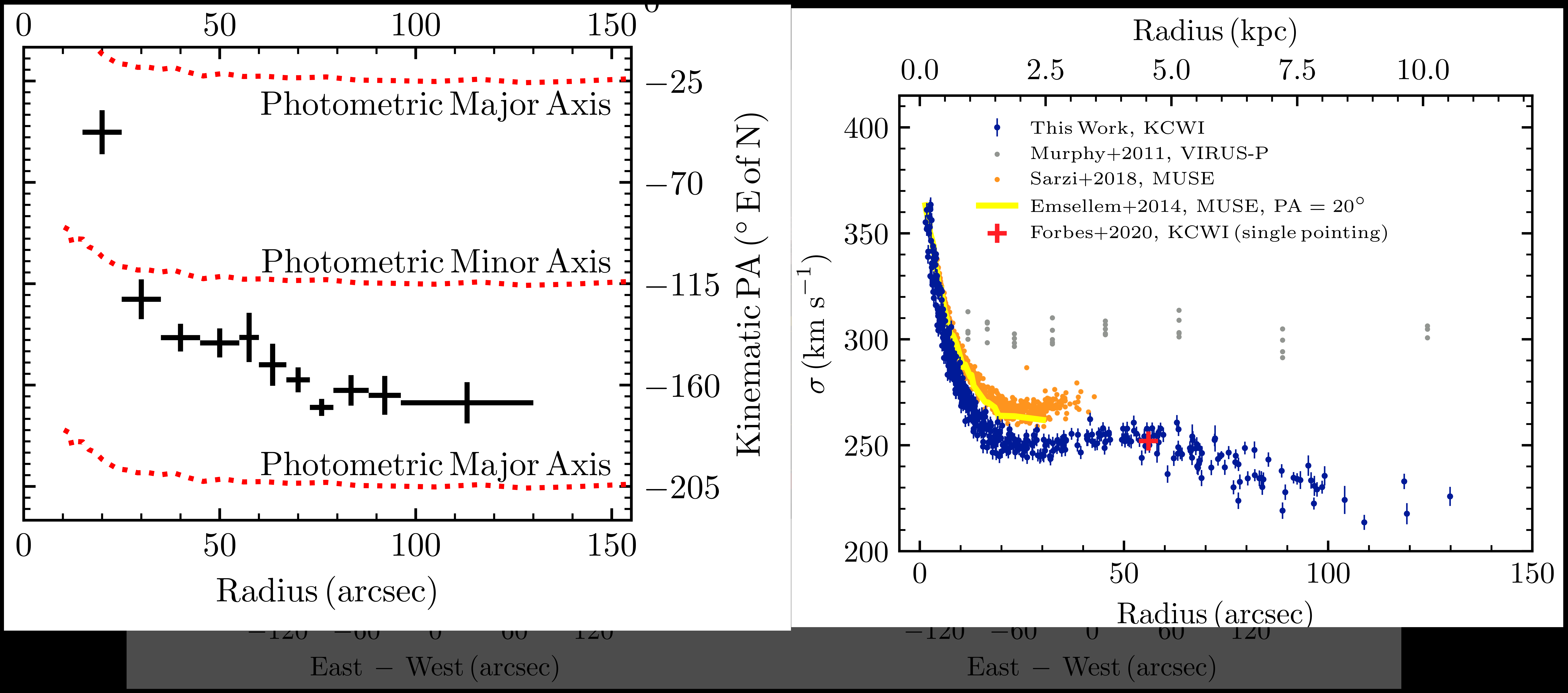
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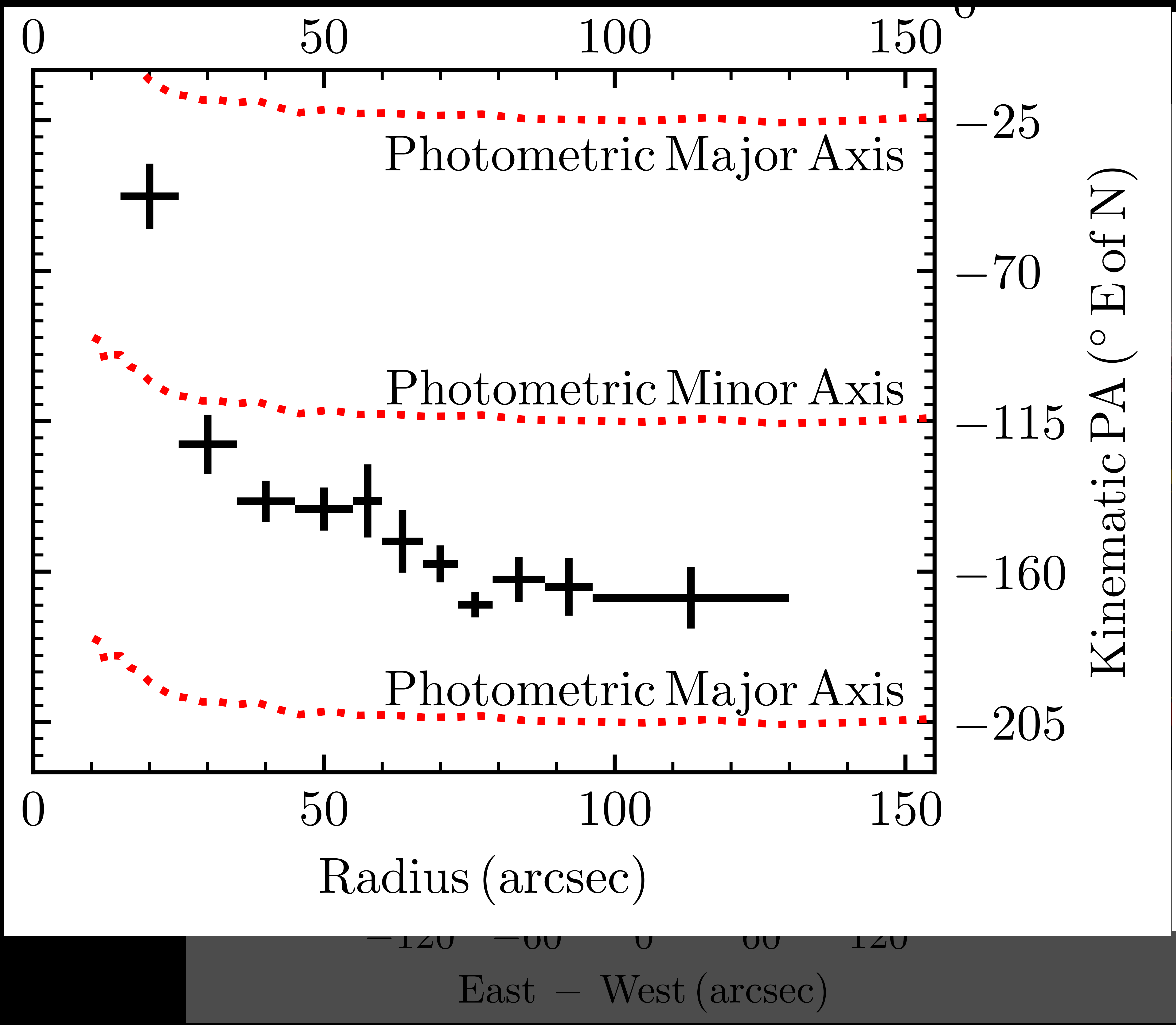
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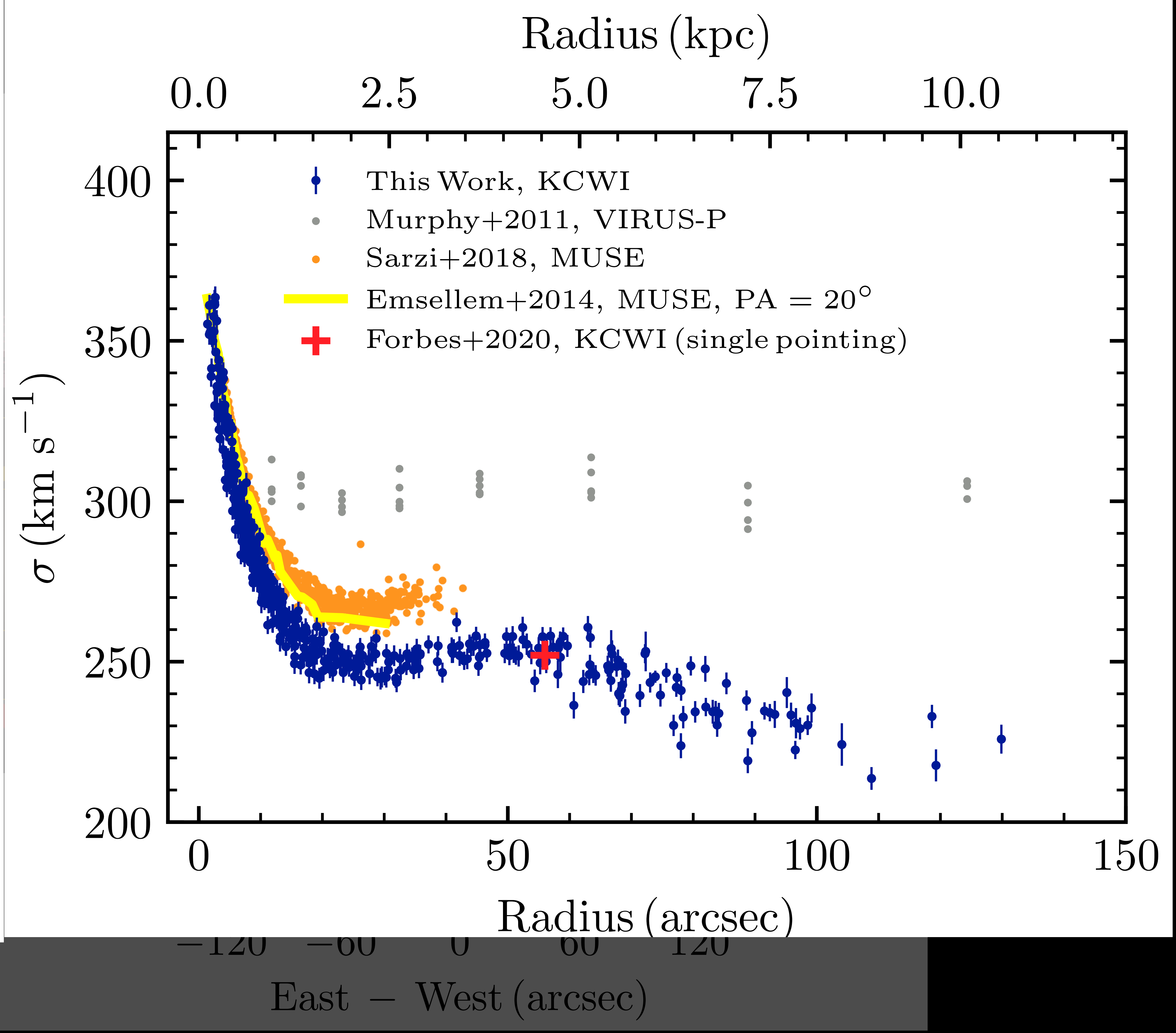
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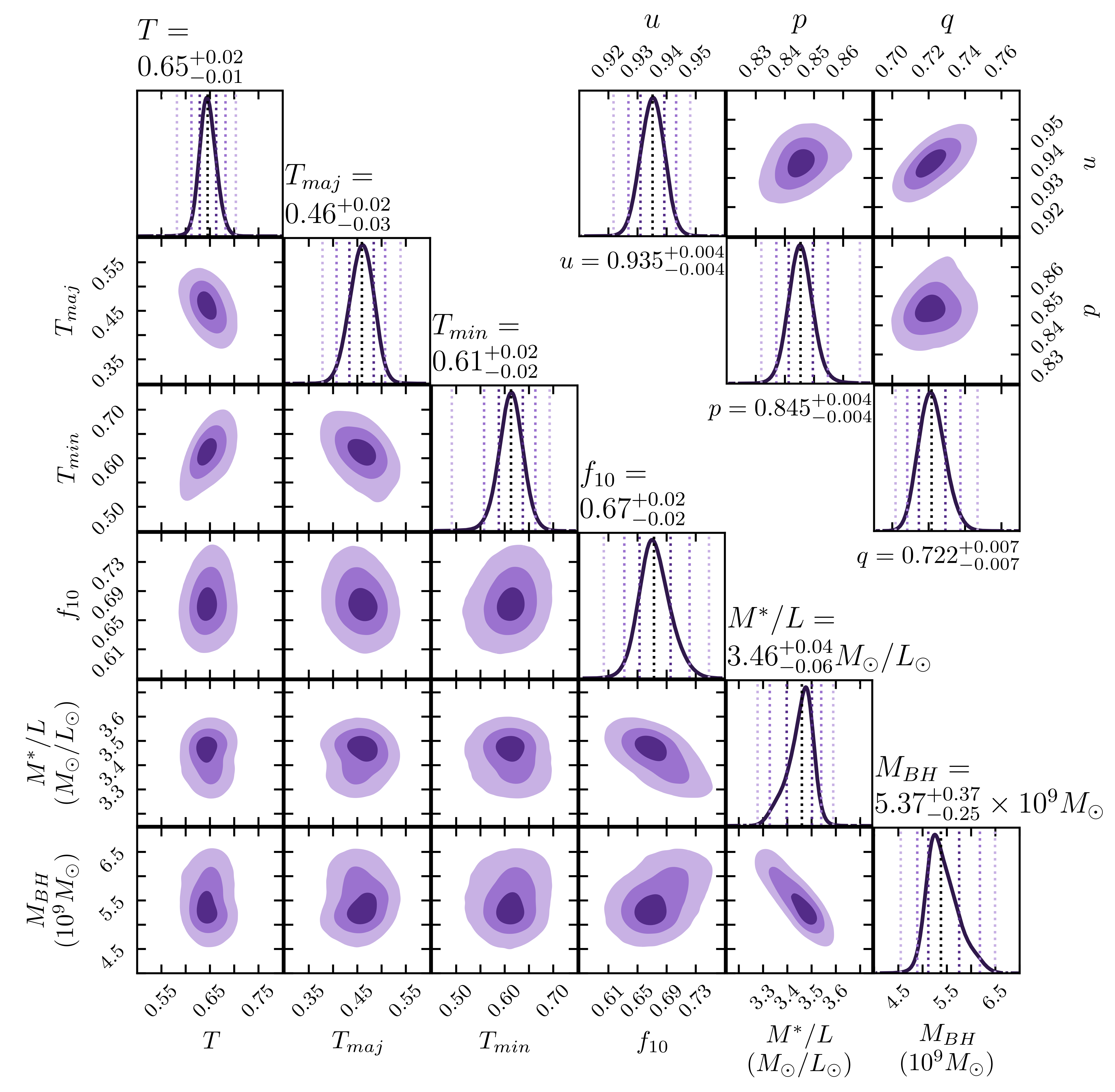
Liepold, Ma, Walsh 2023



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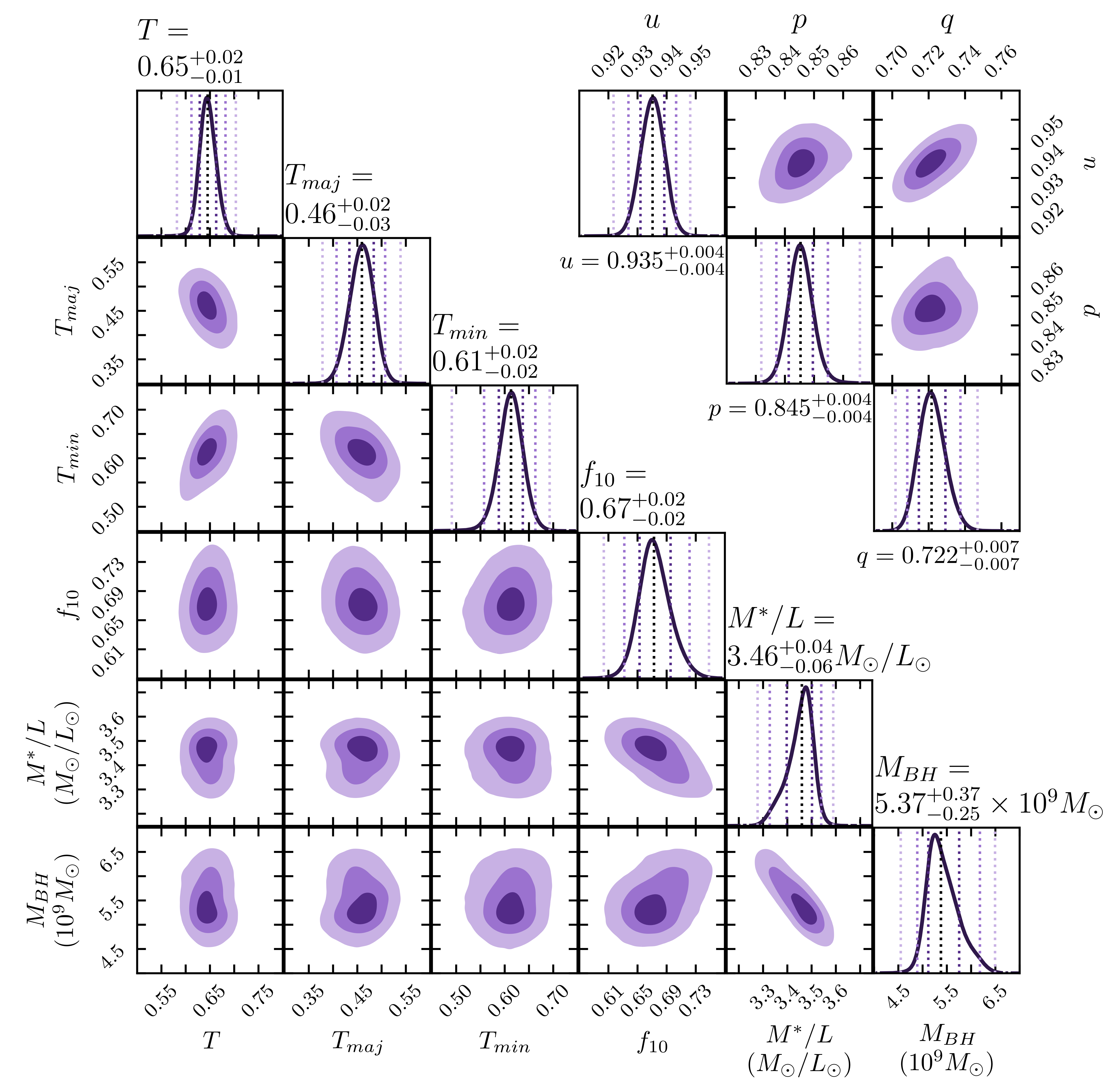

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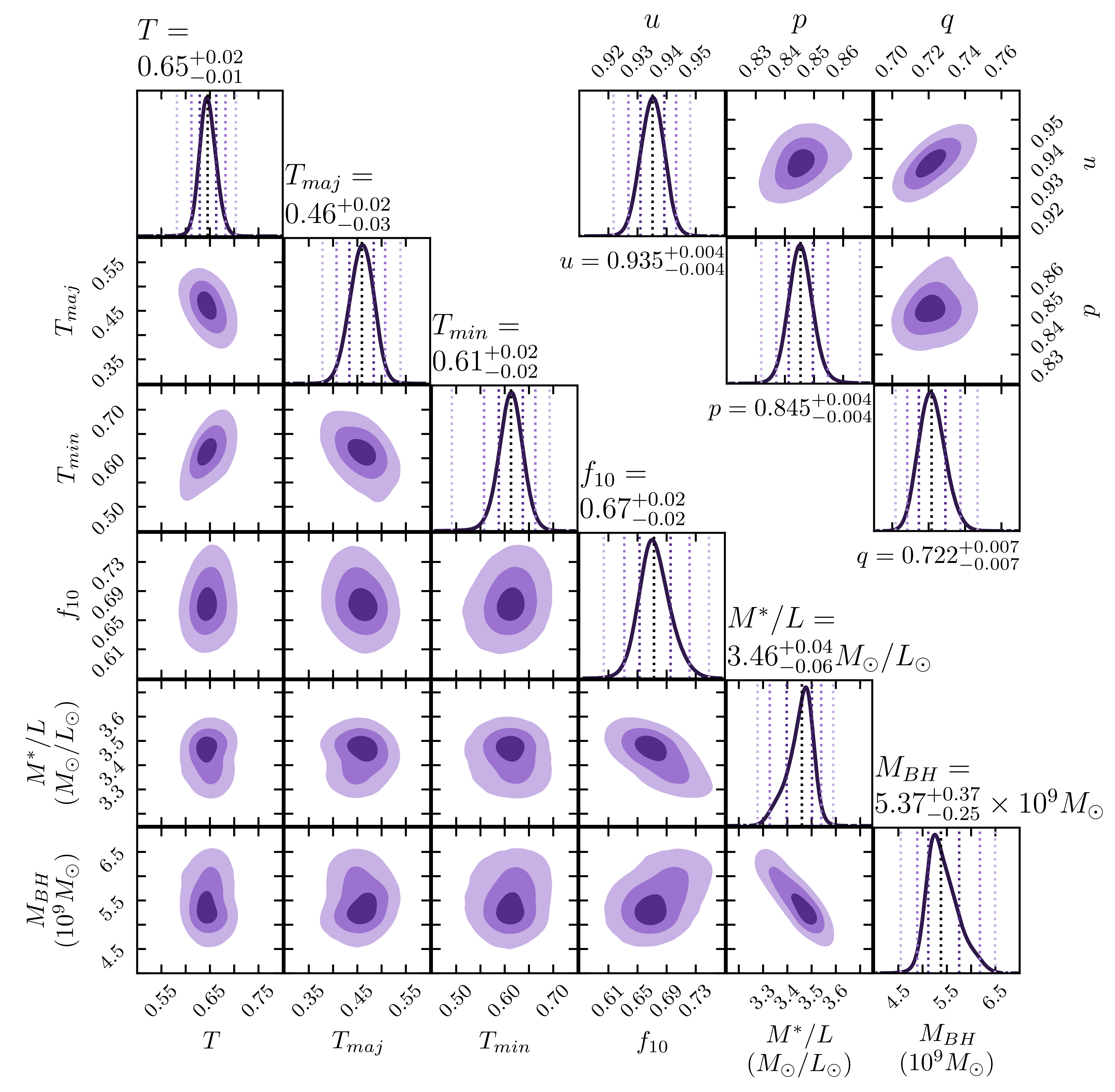

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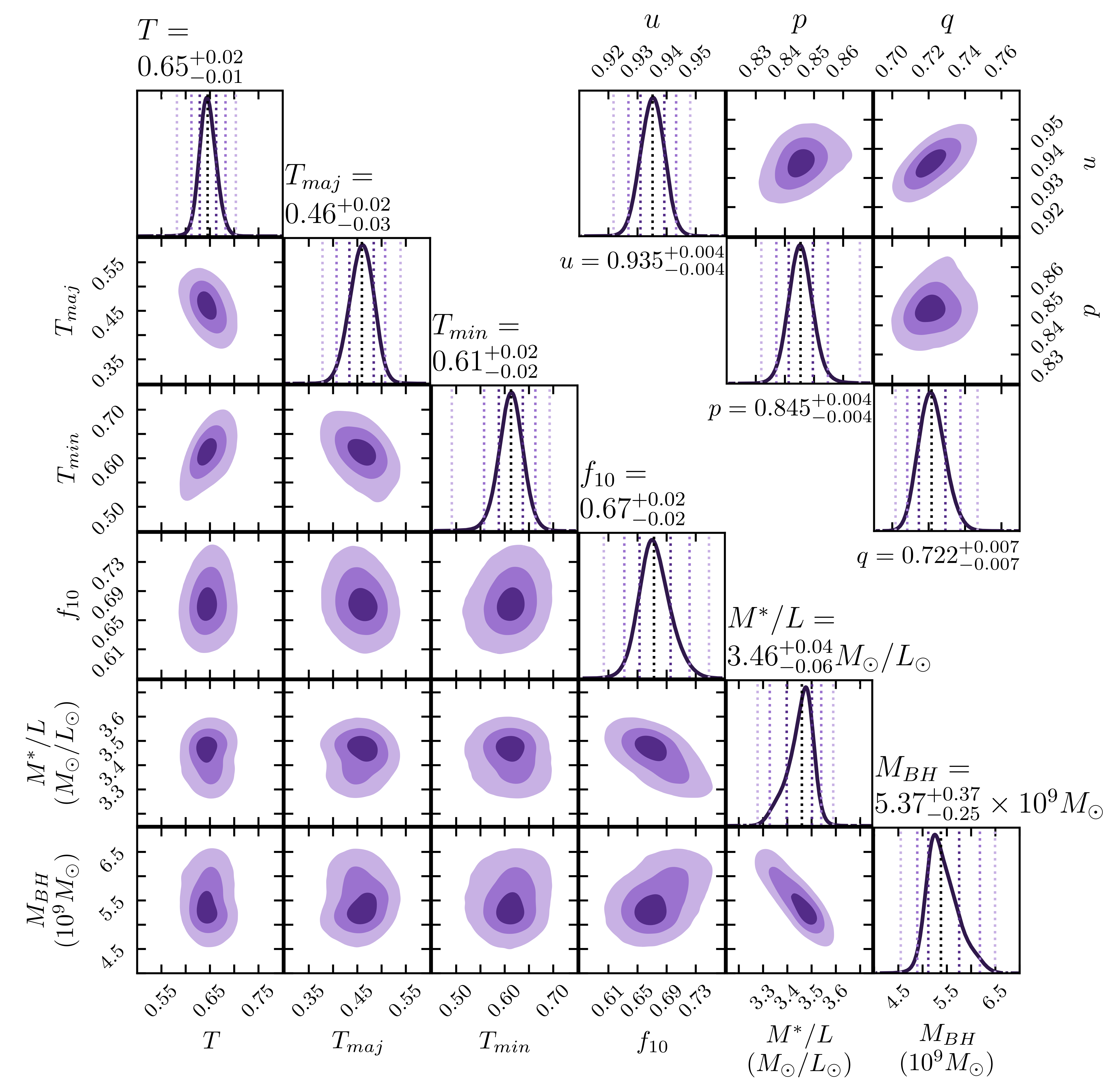

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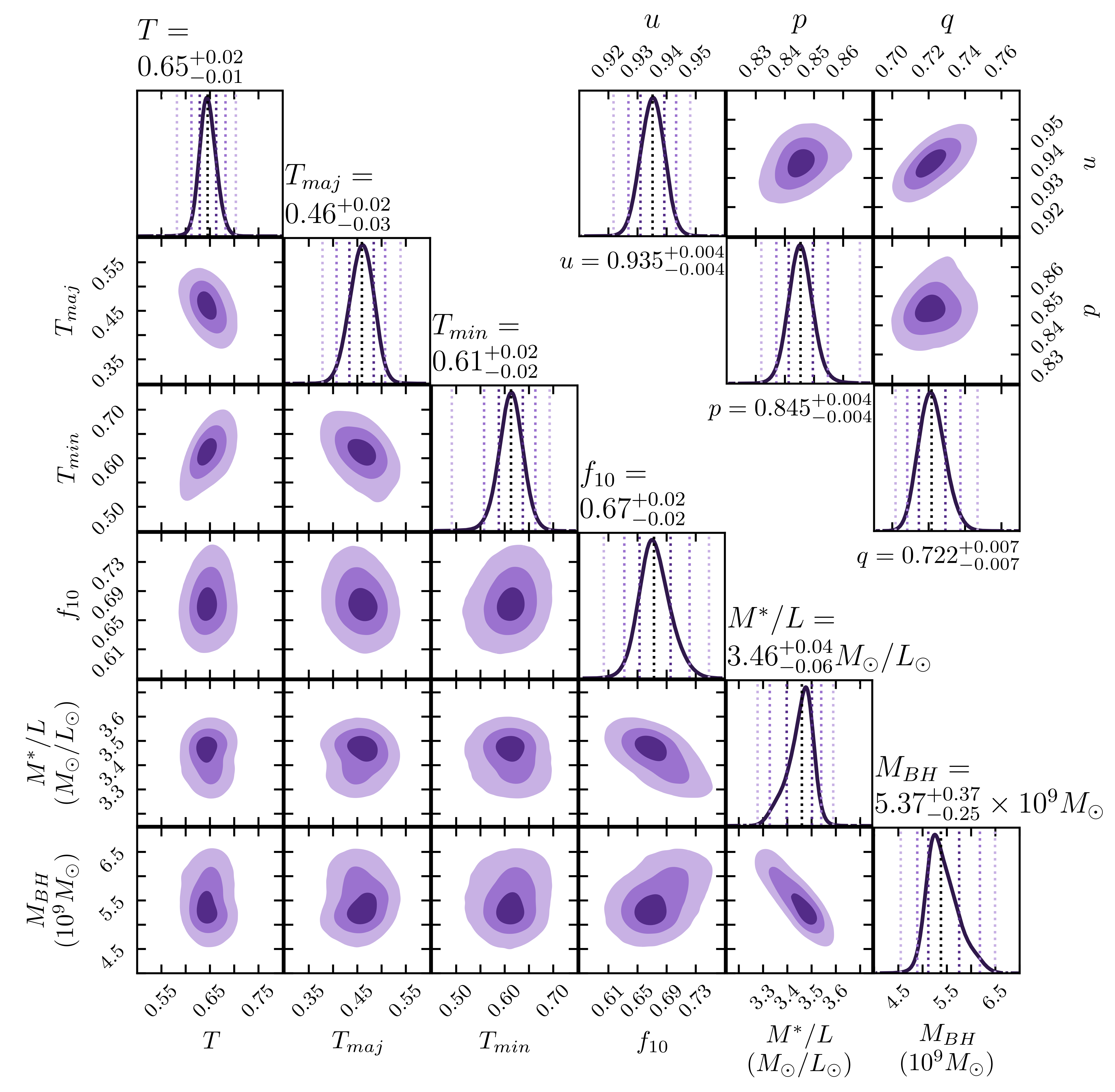

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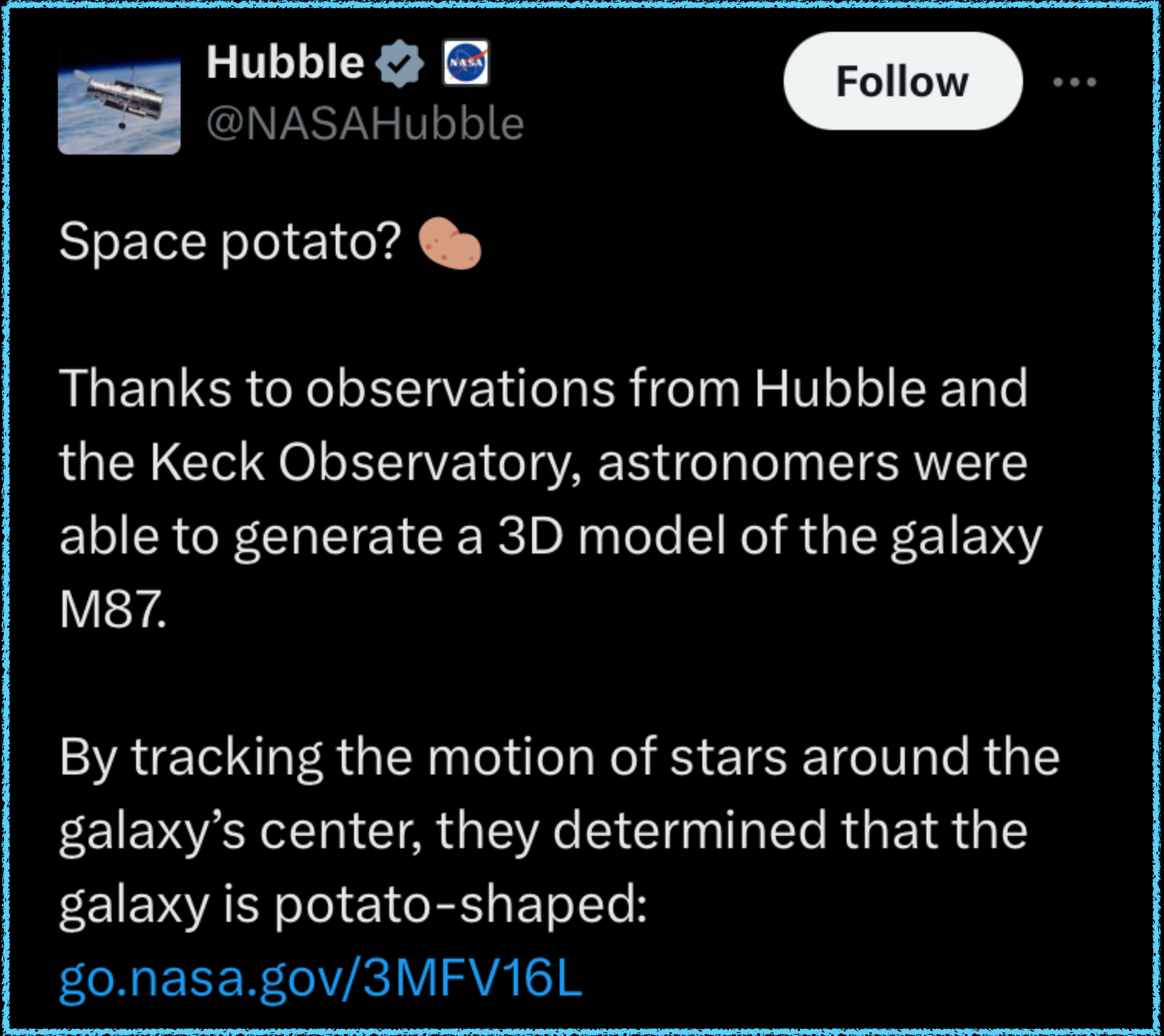
- A puzzle: apparent alignment of the jet, the stellar **L** vector, and the Virgo cluster
- (a tweet from Hubble!)



Space potato? 🥔

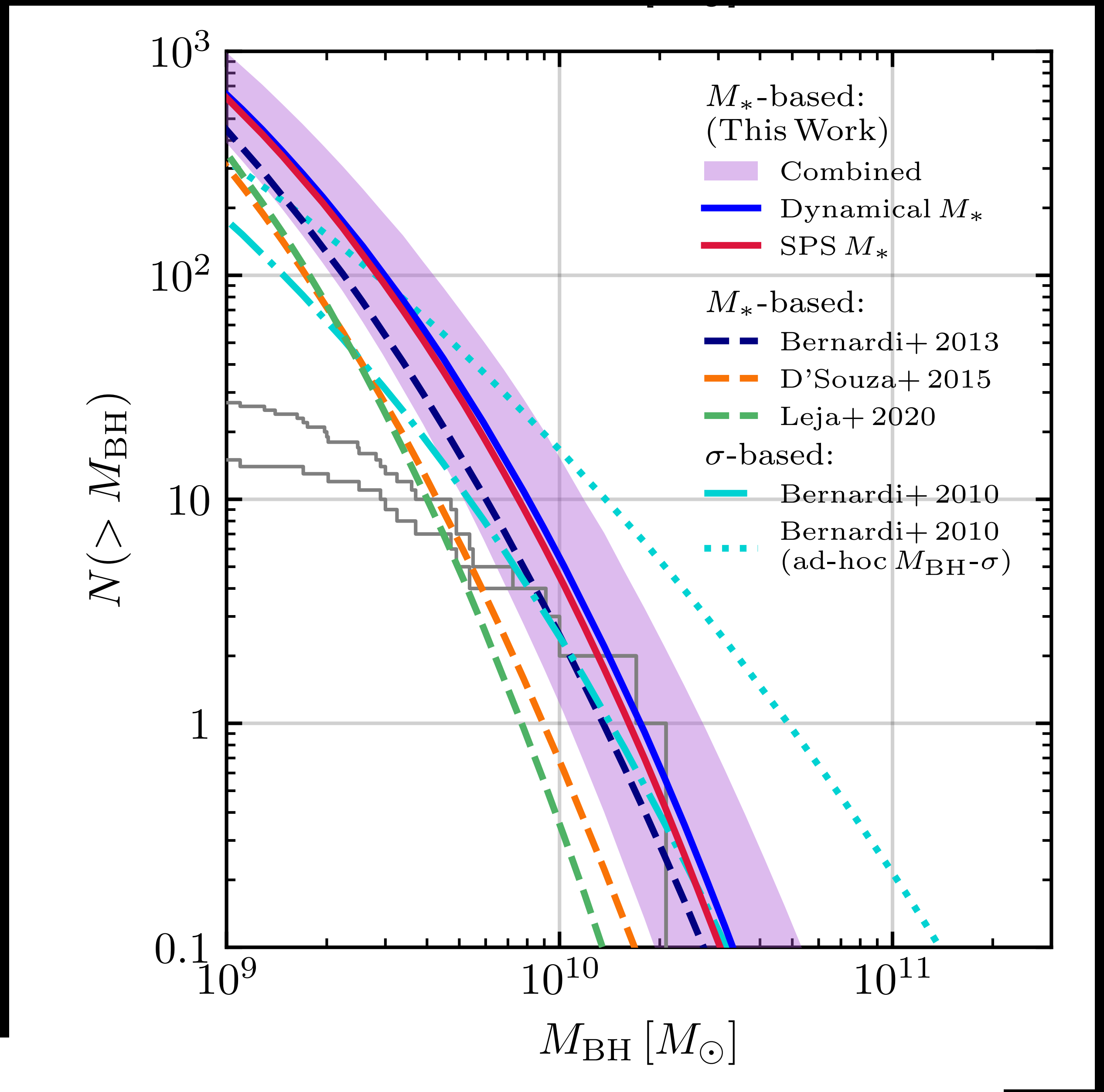
Thanks to observations from Hubble and the Keck Observatory, astronomers were able to generate a 3D model of the galaxy M87.

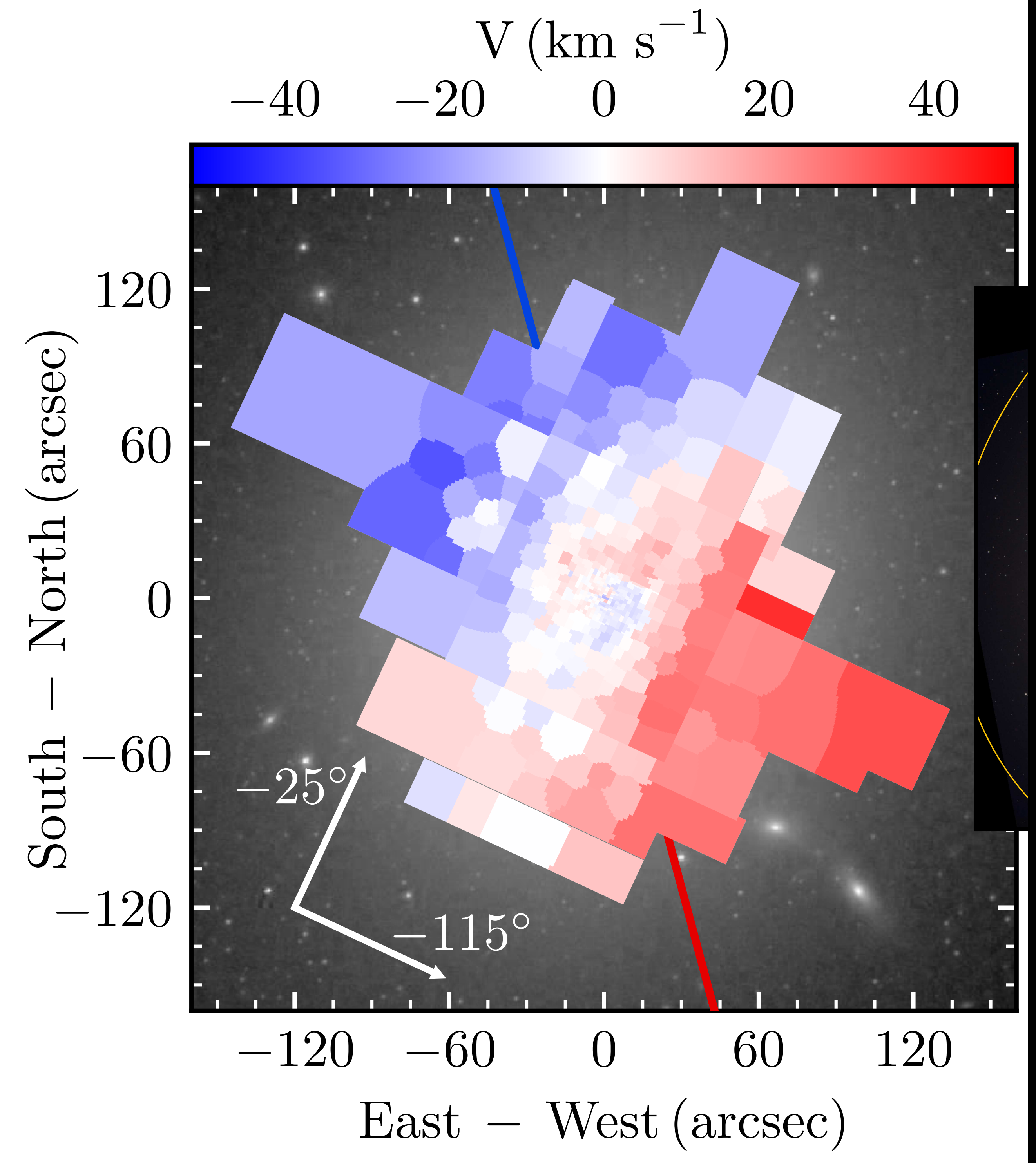
By tracking the motion of stars around the galaxy’s center, they determined that the galaxy is potato-shaped: go.nasa.gov/3MFV16L

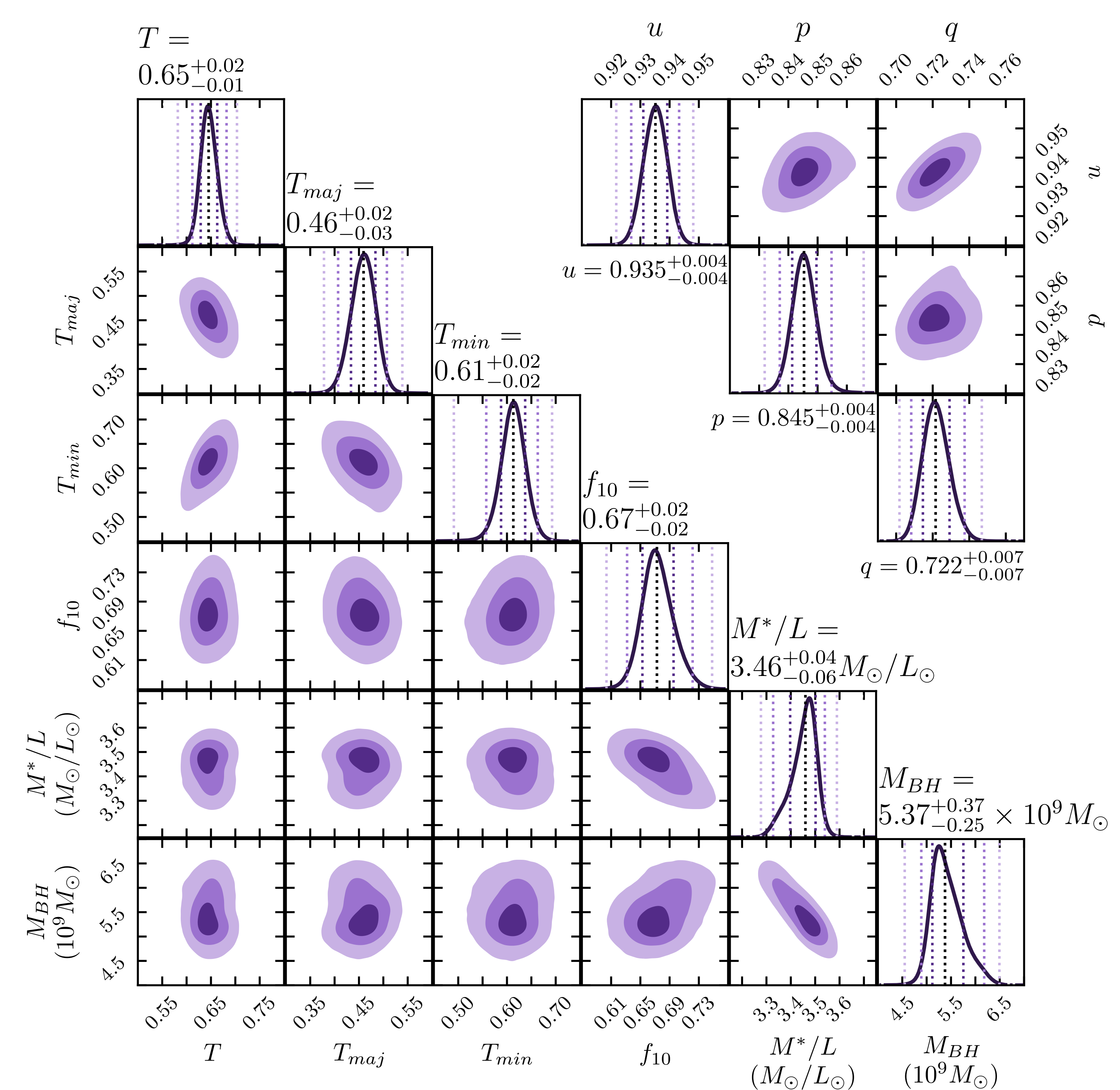
Ongoing Efforts + Connections

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







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