Big Galaxies&
Big Black Holes&
Nanohertz Gravitational Waves

Emily Liepold + Chung-Pei Ma, UC Berkeley
emilyliepold@berkeley.edu, cpma@berkeley.edu

Big Galaxies and Big Black Holes: The Massive Ends of the Local Stellar and Black Hole Mass Functions and the Implications for Nanohertz Gravitational Waves
Liepold & Ma, ApJL, 971 L29 (arXiv:2407.14595)
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Pulsar Timing Array GW Strain
$\longrightarrow$ Many Ultra-massive Black Holes ?

Where are NANOGrav's big black holes?

arXiv 2312.06756

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.

But we don't see them!

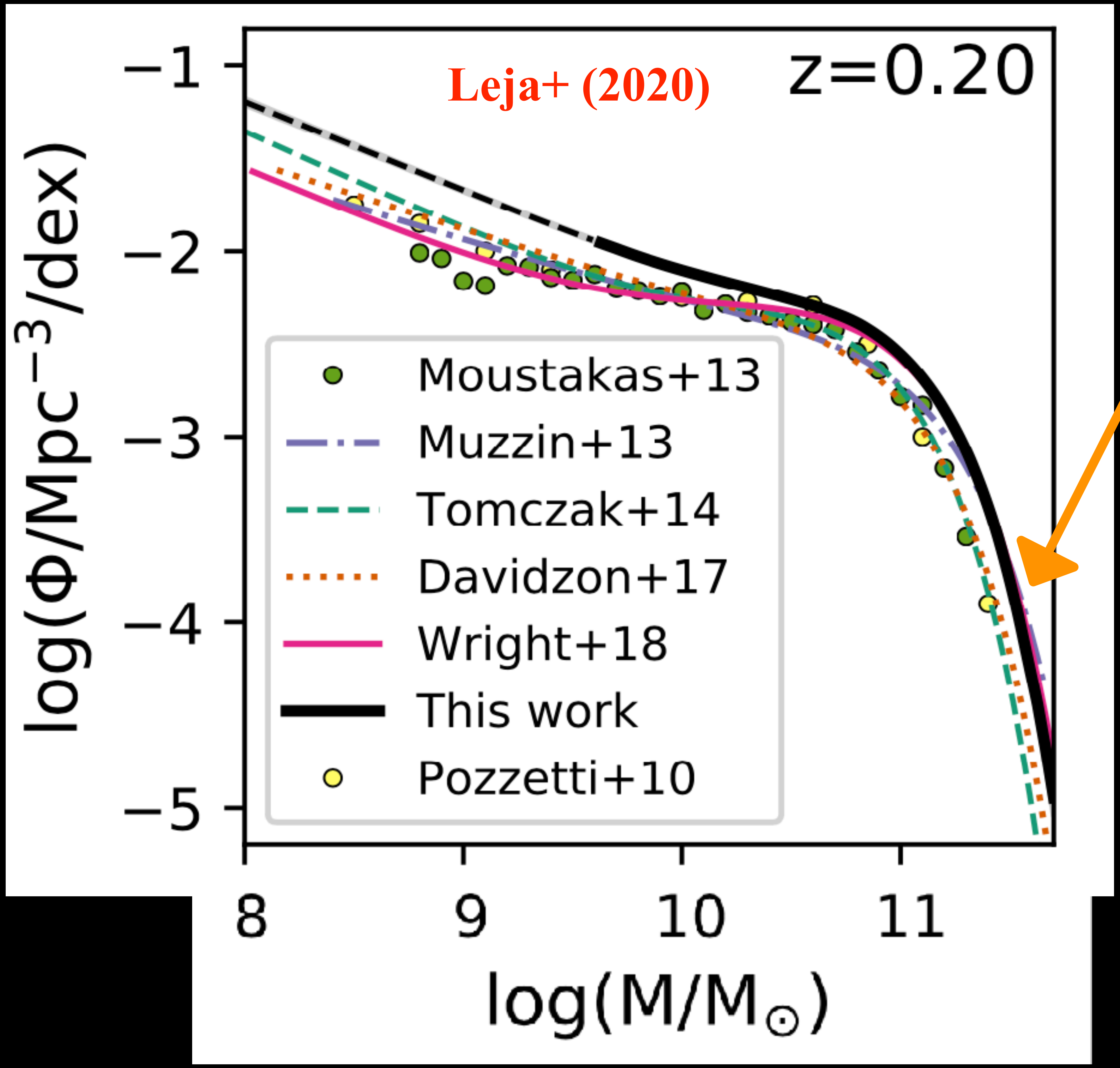
Pulsar Timing Array GW Strain
→ Many Ultra-massive Black Holes ?

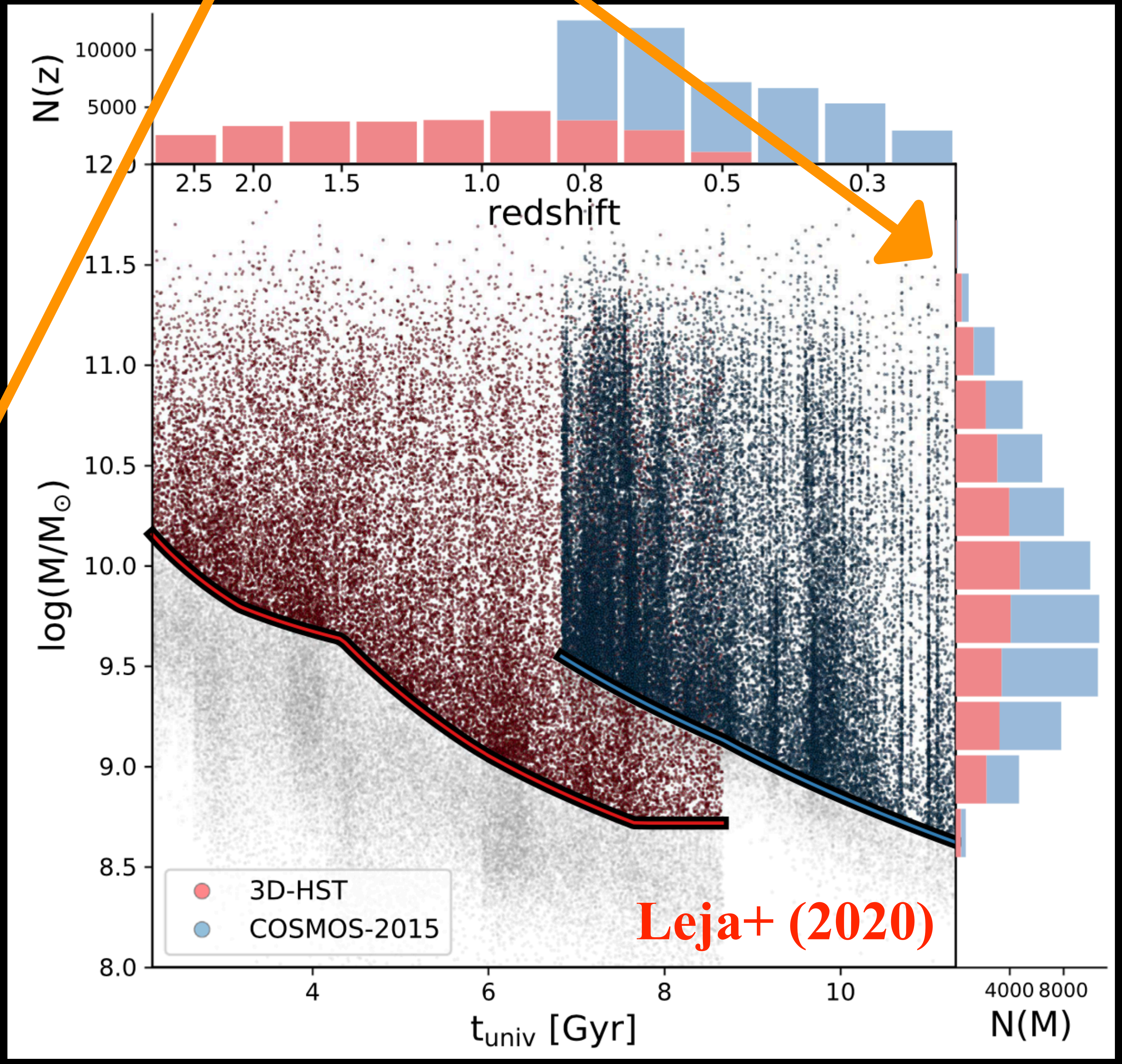
ACKNOWLEDGMENTS

We would like to thank Jenny Greene, Scott Tremaine, Luke Zoltan Kelley, and Nick Kokron, for helpful discussions. EQ and MZ thank Roger Blandford for a cryptic comment about the NANOGrav results at the Simons Symposium on Multiscale Physics, which motivated this work. GSP gratefully acknowledges support from the

Local Galaxy Stellar Mass Function (GSMF)

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





Local Galaxy Stellar Mass Function (GSMF)

The MASSIVE Survey (Ma et al. 2014)

An integral field spectroscopic & photometric survey
of the ~100 most massive galaxies within ~100 Mpc

Volume-limited: target all early-type galaxies (northern sky)
with $M^* > 10^{11.5}\ M_{sun}$

Multi-wavelength study of all mass components:
stars, cold/warm/hot gas, dark matter halos, black holes

Chung-Pei Ma, Jenny Greene, Jonelle Walsh, Nicholas McConnell, Jens Thomas

Graduate students: Melanie Veale, Irina Ene, Viraj Pandya, Charles Goullaud,
Emily Liepold, Matthew Quenneville, Jacob Pilawa, Silvana Andrade

Undergrads + High school students

MASSIVE-HST: John Blakeslee, Joe Jensen

MASSIVE-CFHT: John Blakeslee

MASSIVE-CO: Tim Davis

MASSIVE-Xray: Andy Goulding

MASSIVE-IMF: Meng Gu, Drew Newman

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 $\langle \alpha \rangle = 1.84$
- (Among other things) These models measure stellar M/L for each galaxy
- Combine with new Luminosities from Quenneville+24 to infer stellar mass

SPS Stellar Mass Measurements

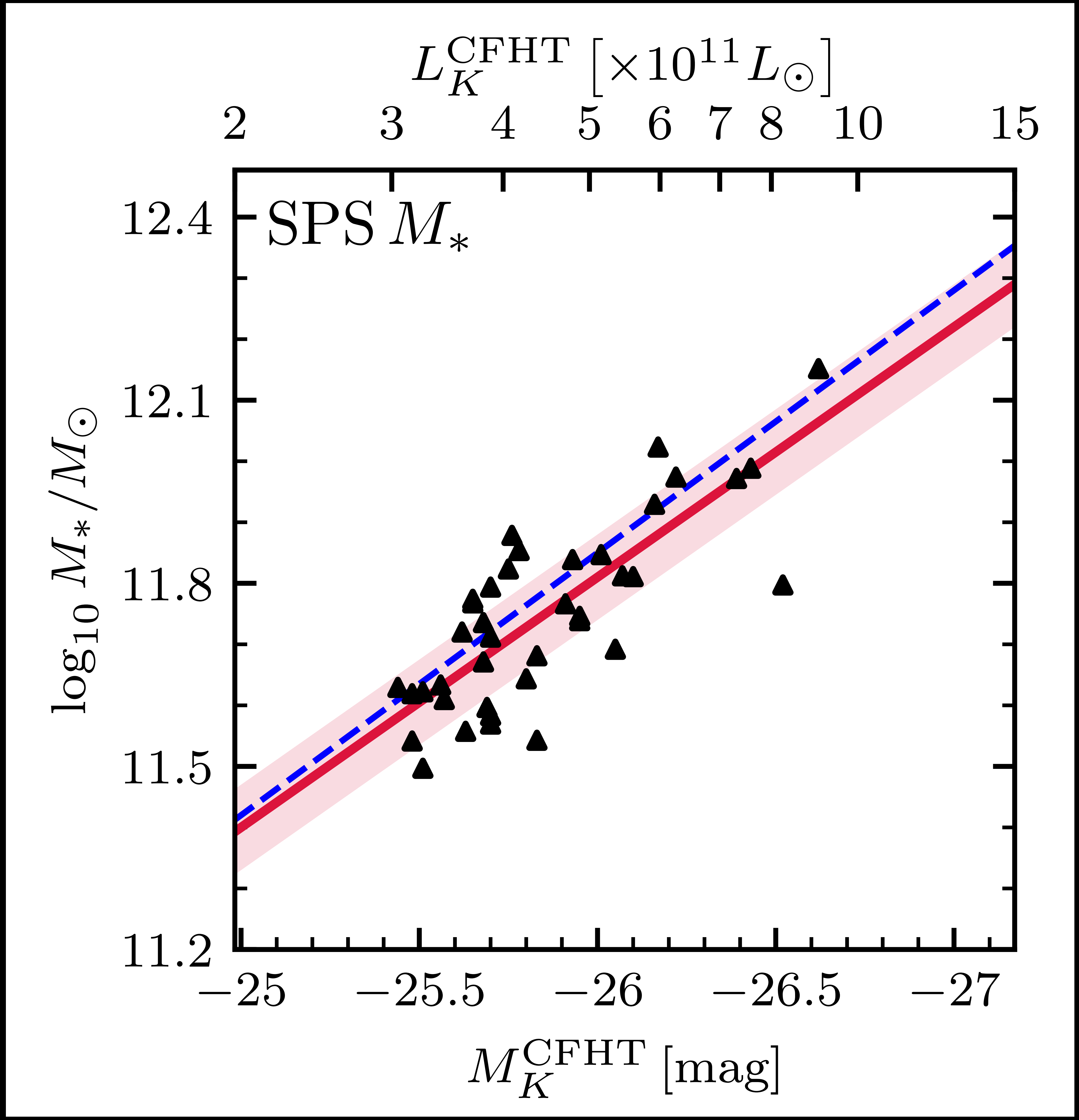


Fig 1c of LM24

Gu et al 2022, ApJ, 932, 103
arXiv:2110.11985
Quenneville et al 2024, MNRAS, 527, 249
arXiv:2210.08043

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

11 use orbit-based stellar-dynamical

1 uses gas-dynamical methods

The inferred stellar masses from **SPS** and **dynamical** models are **consistent!**

Dynamical Stellar Mass Measurements

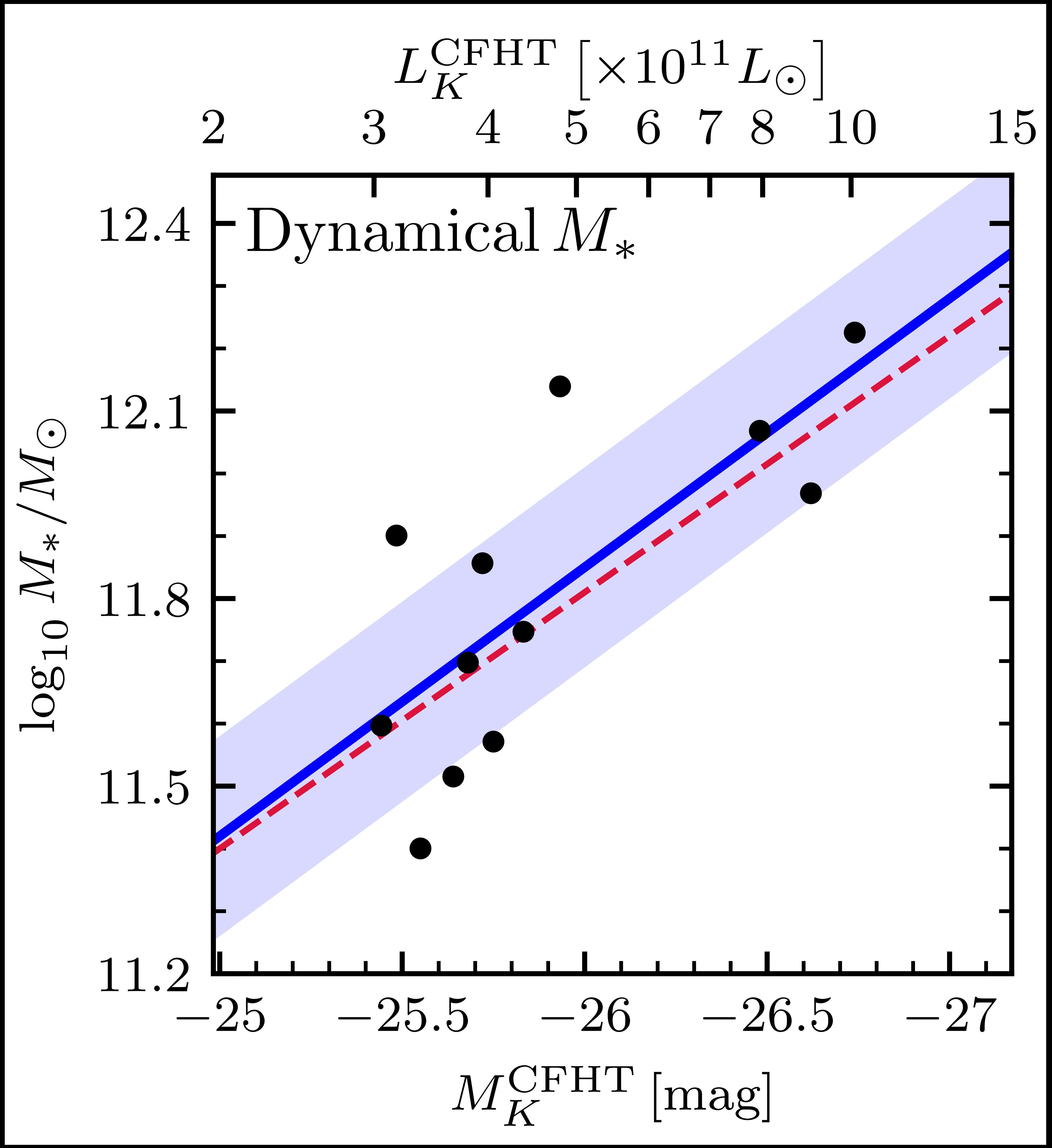
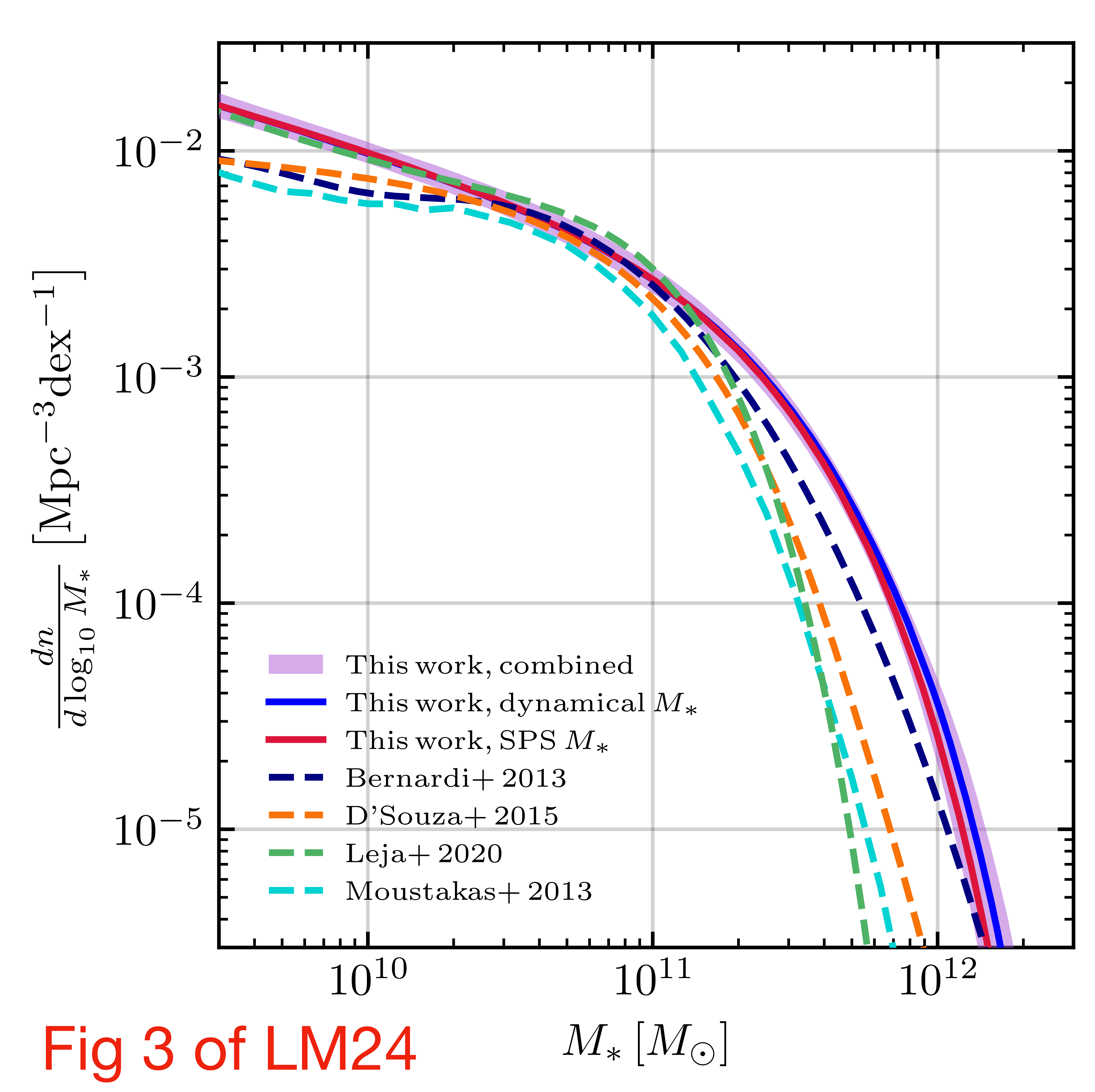


Fig 1b of LM24

The high-mass local Galaxy Stellar Mass Function (GSMF)



- Use measured M_K and new M_K-M_* relations to predict M_* for all MASSIVE galaxies
- GSMF is ***number density of galaxies*** per ***stellar mass bin*** at a given ***mass***:

$$\frac{dn}{d\log M_*}(M_*)$$

- Our GSMF from Dynamical and SPS-based masses are consistent! (And systematically higher than prior measurements!)

Leja et al 2020, ApJ, 893, 111
arXiv:1910.04168

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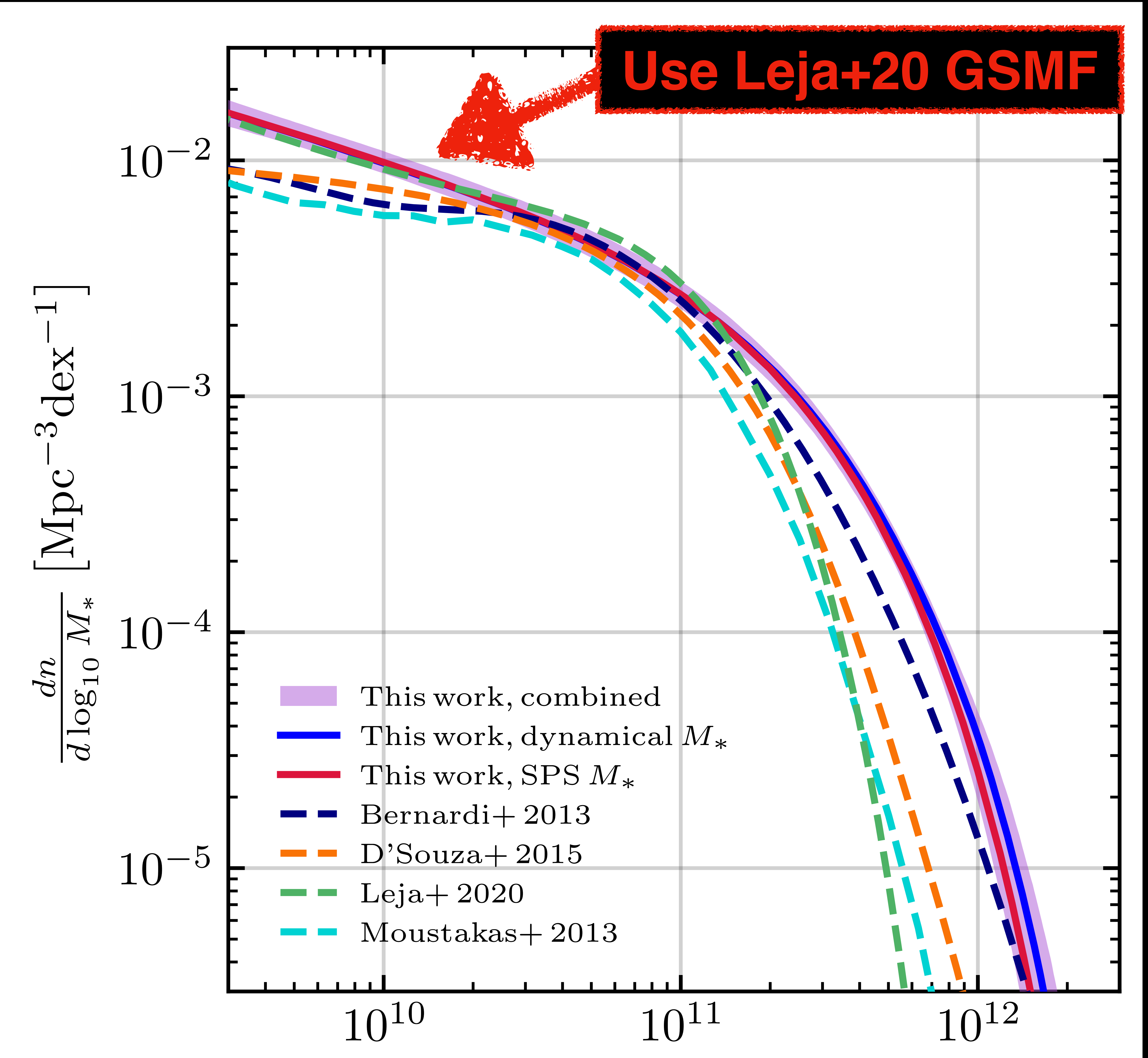

Fig 3 of LM24

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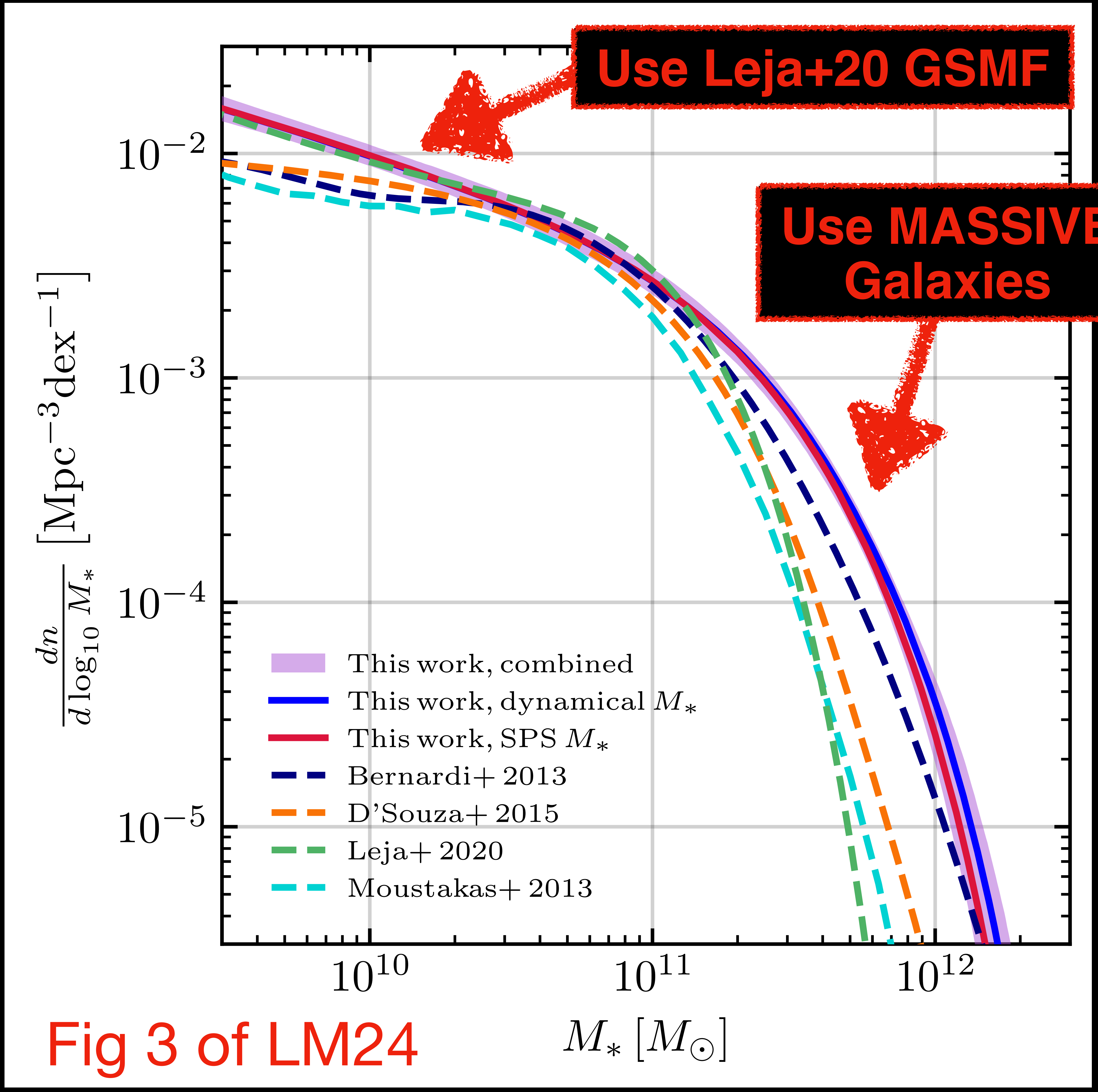

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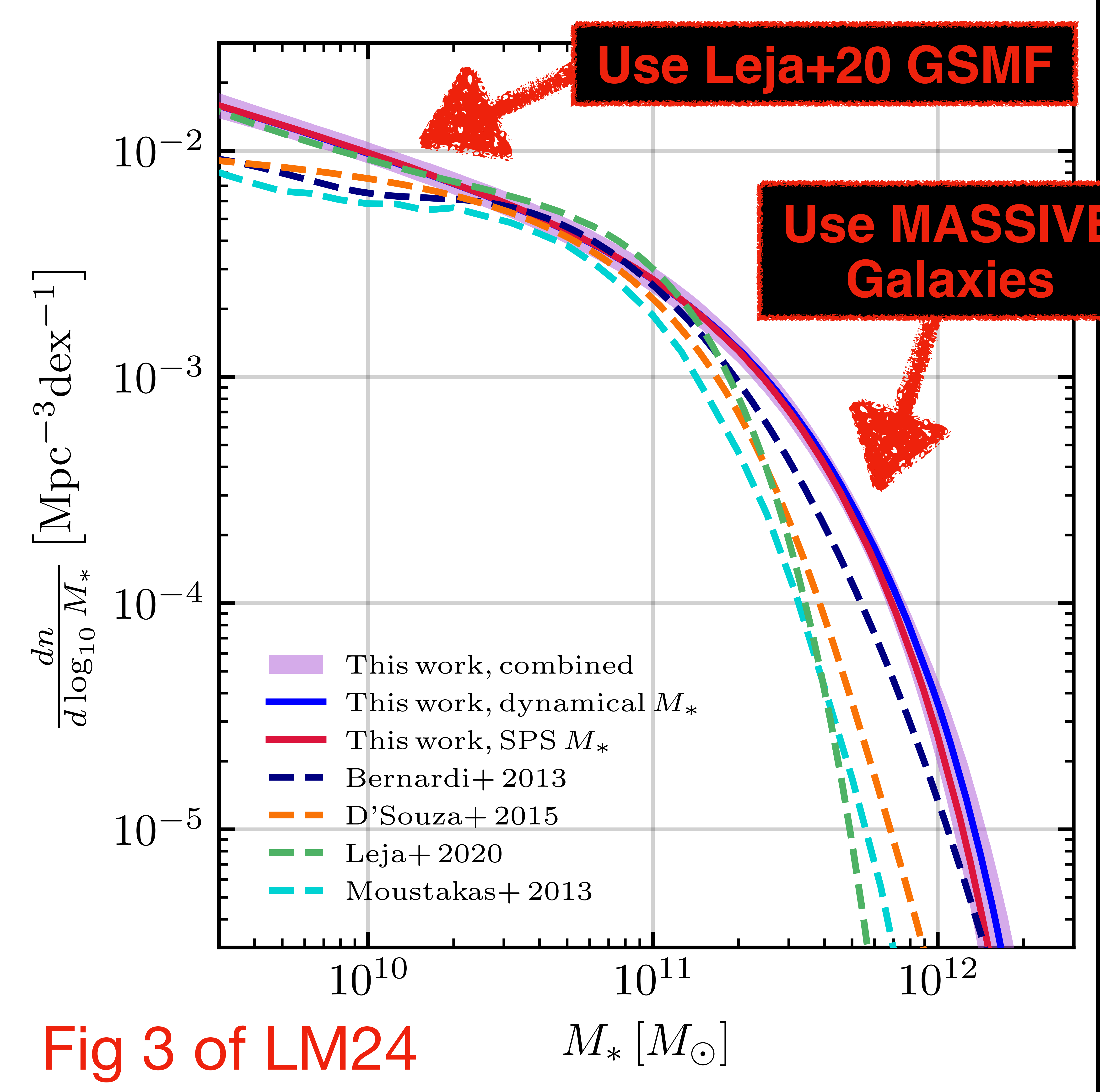


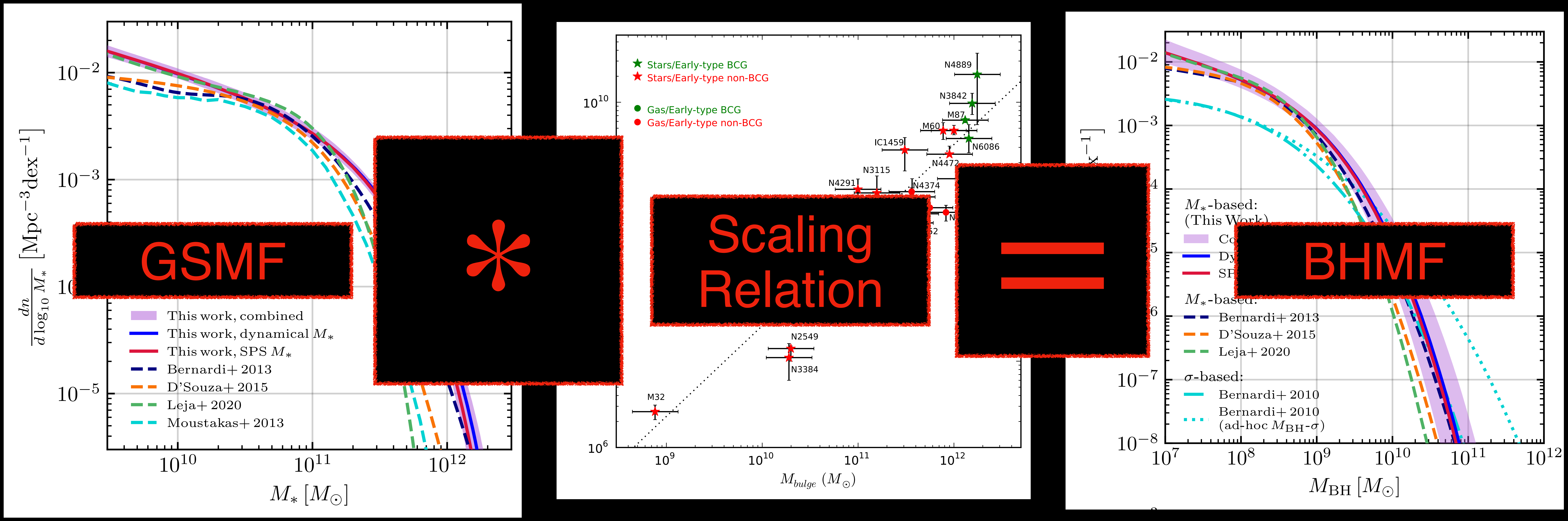
Fig 3 of LM24

GSMF: important takeaways

- Our stellar masses at the high-mass end are ~1.6x higher than prior GSMF measurements (shift their curves ***right***)
- Most prior work assumed Milky-Way-like IMF. Our SPS-based stellar masses fit for IMF and are ~1.84x 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 high-mass local Black Hole Mass Function (BHMF)

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



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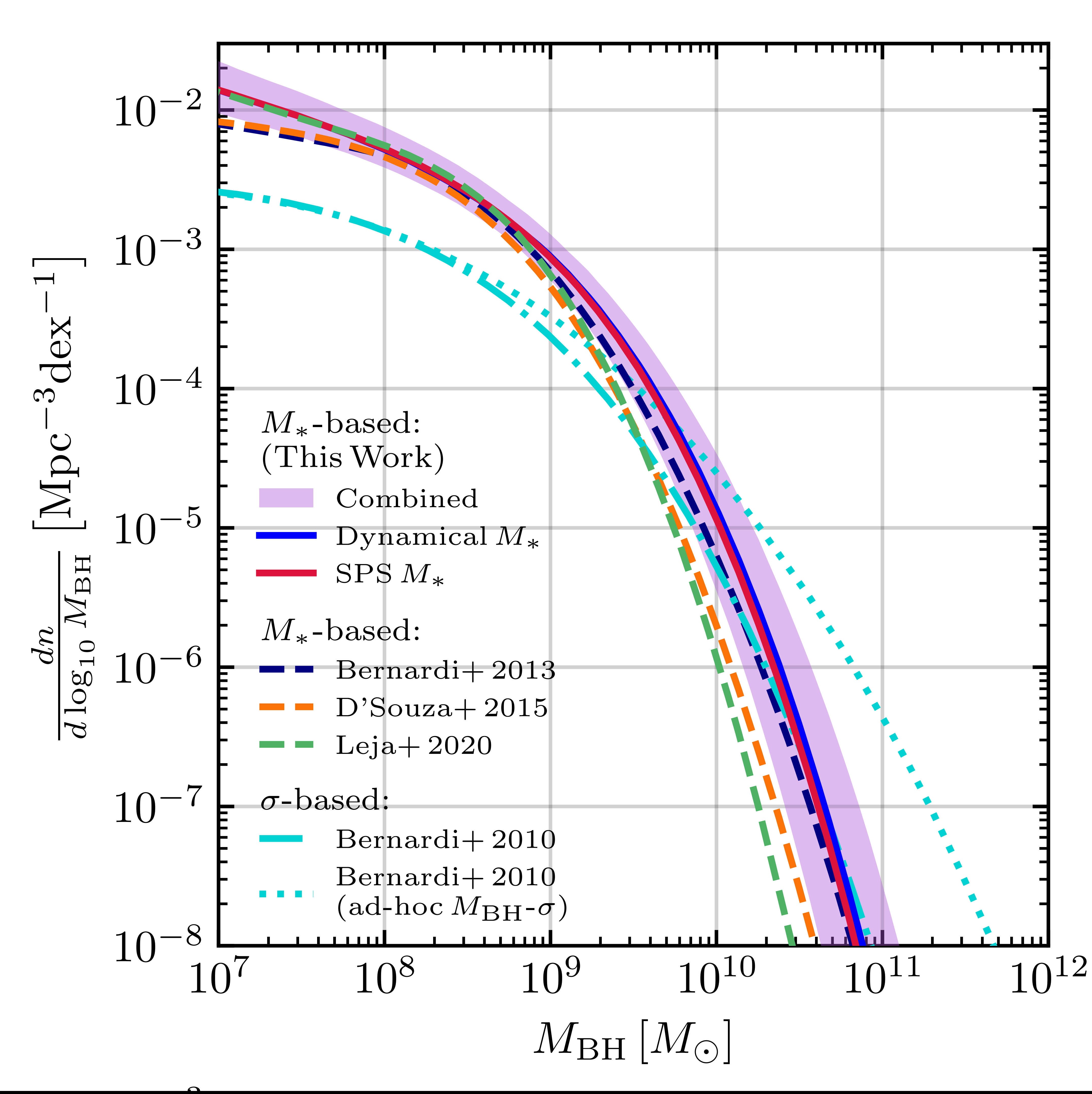

- Scatter in BHMF mostly due to scatter in scaling relation
- Velocity-Dispersion-based BHMF is inconsistent with GSMF-based BHMF below $10^9 M_\odot$
- BHMF from Sato-Polito+23 (cyan dotted) is substantially higher than all prior measurements above $10^{10} M_\odot$

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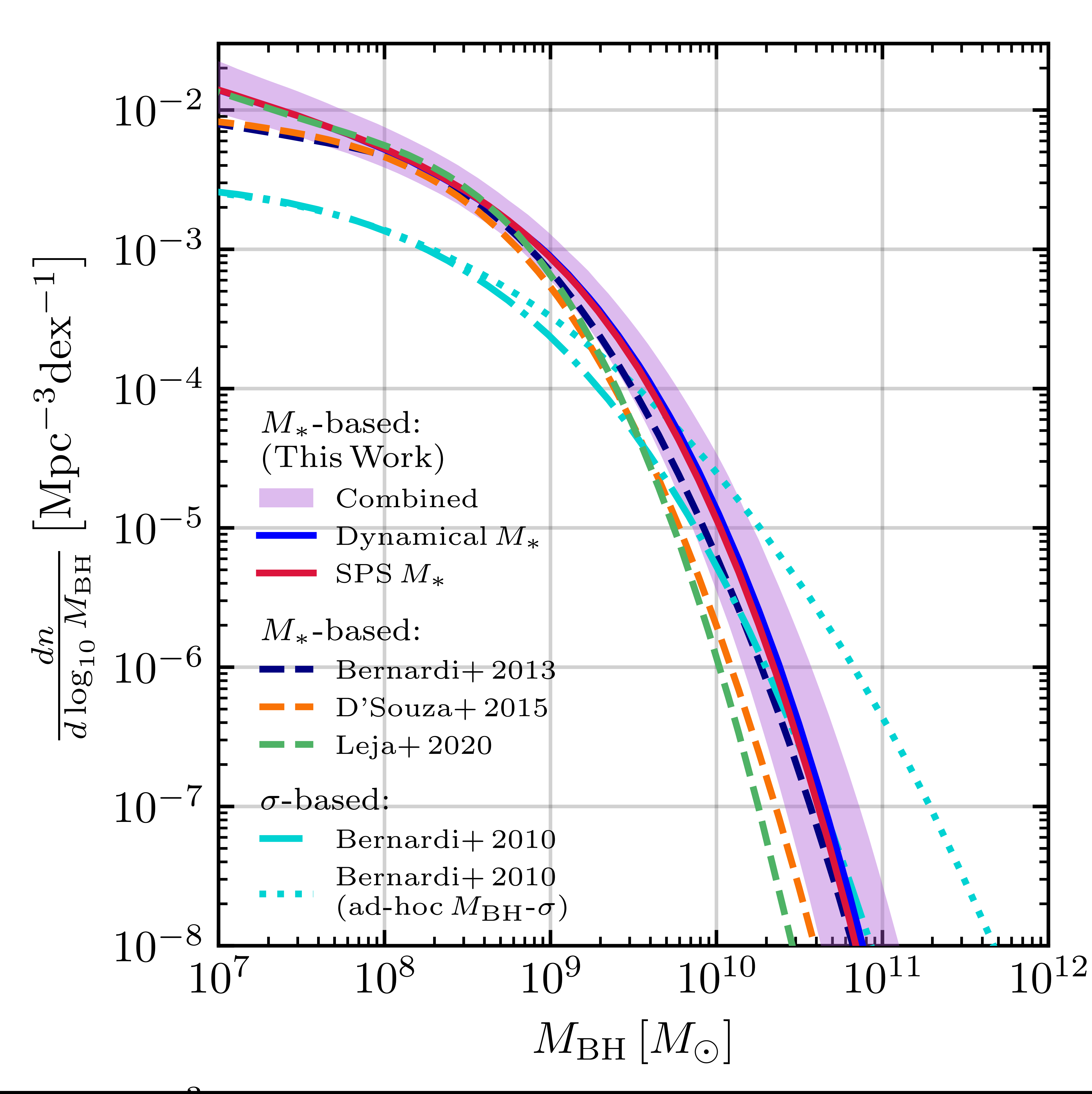
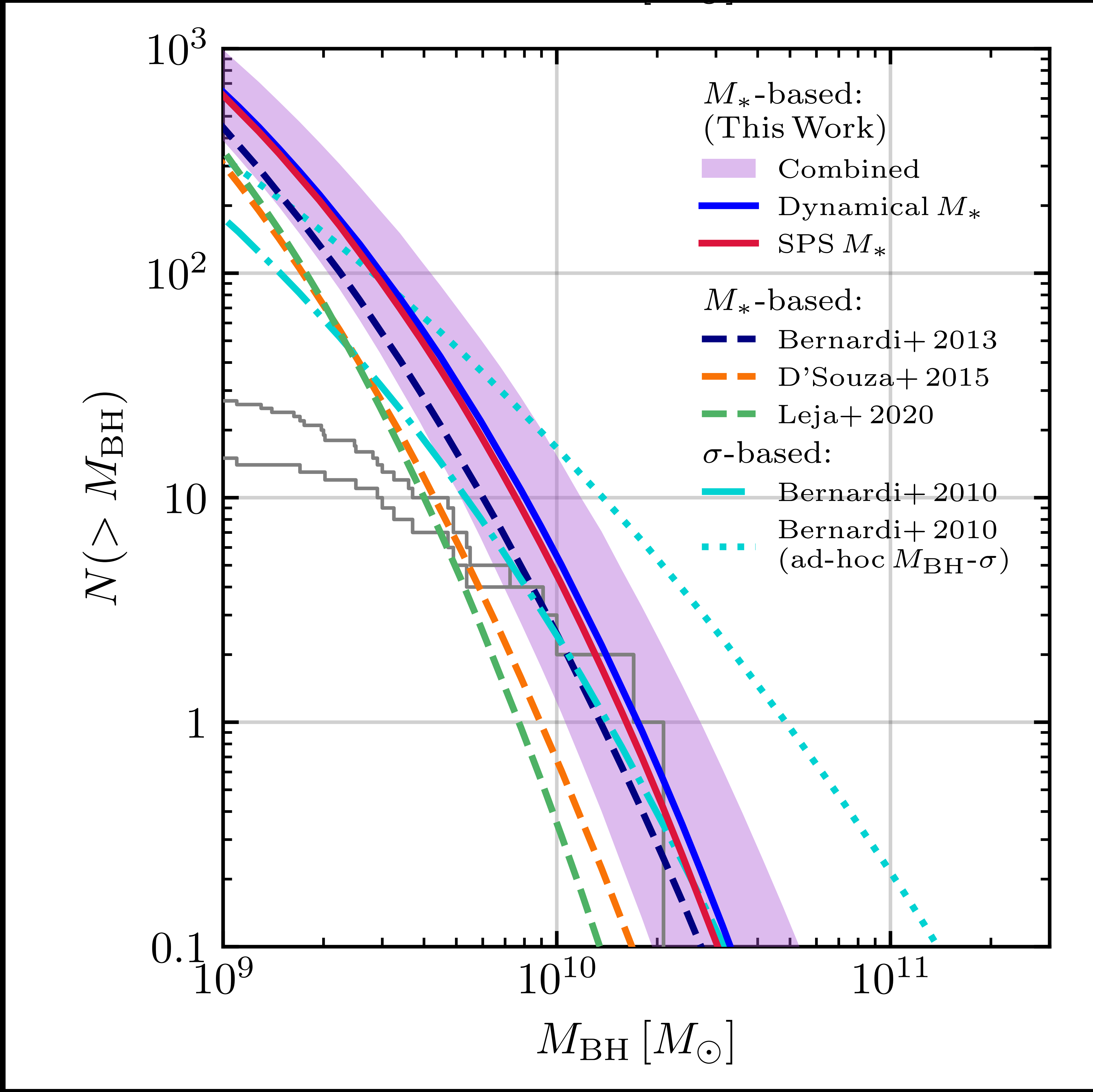


Number of BH within MASSIVE Volume The *cumulative BHMF* (Integral of left figure)



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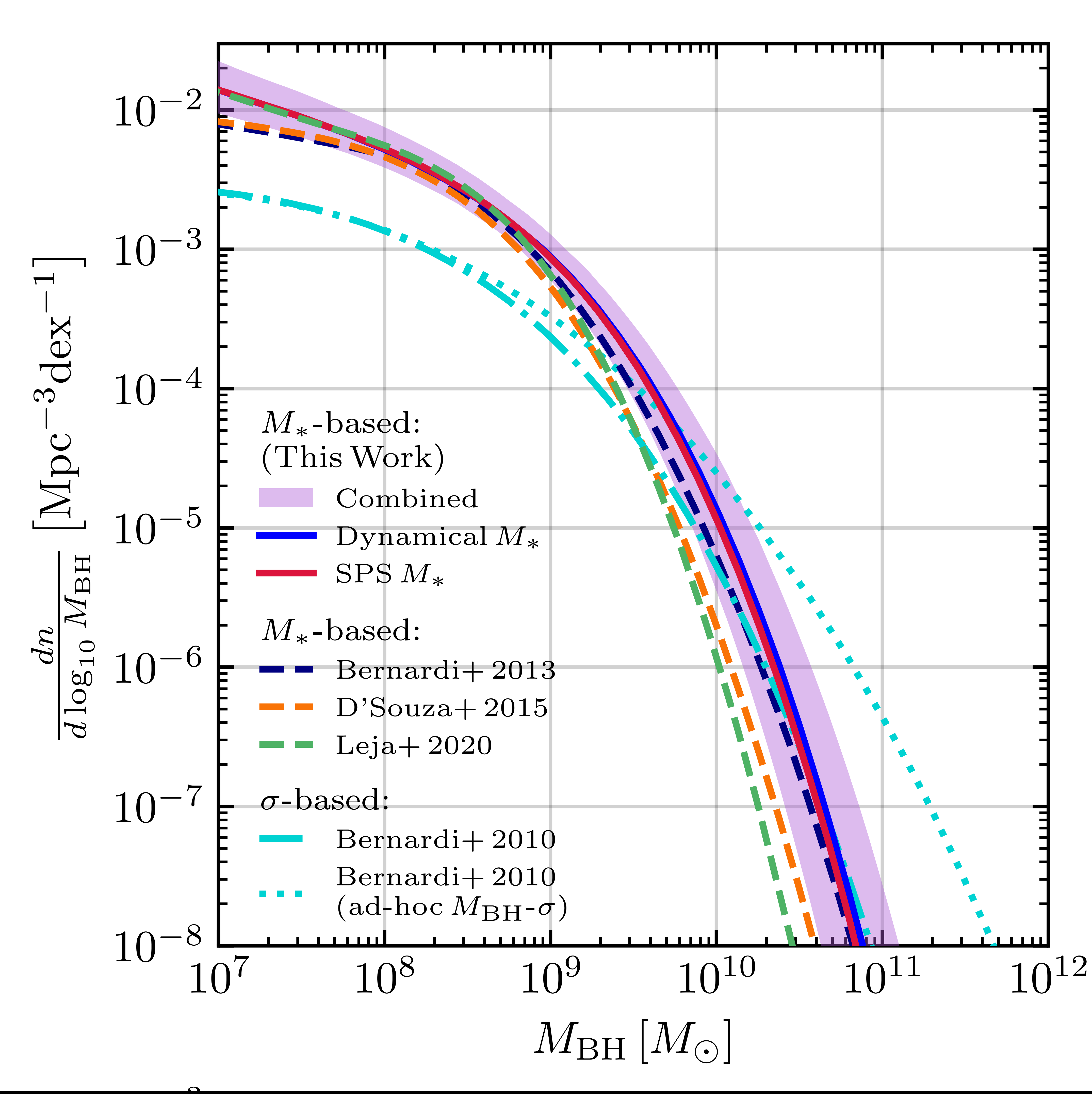

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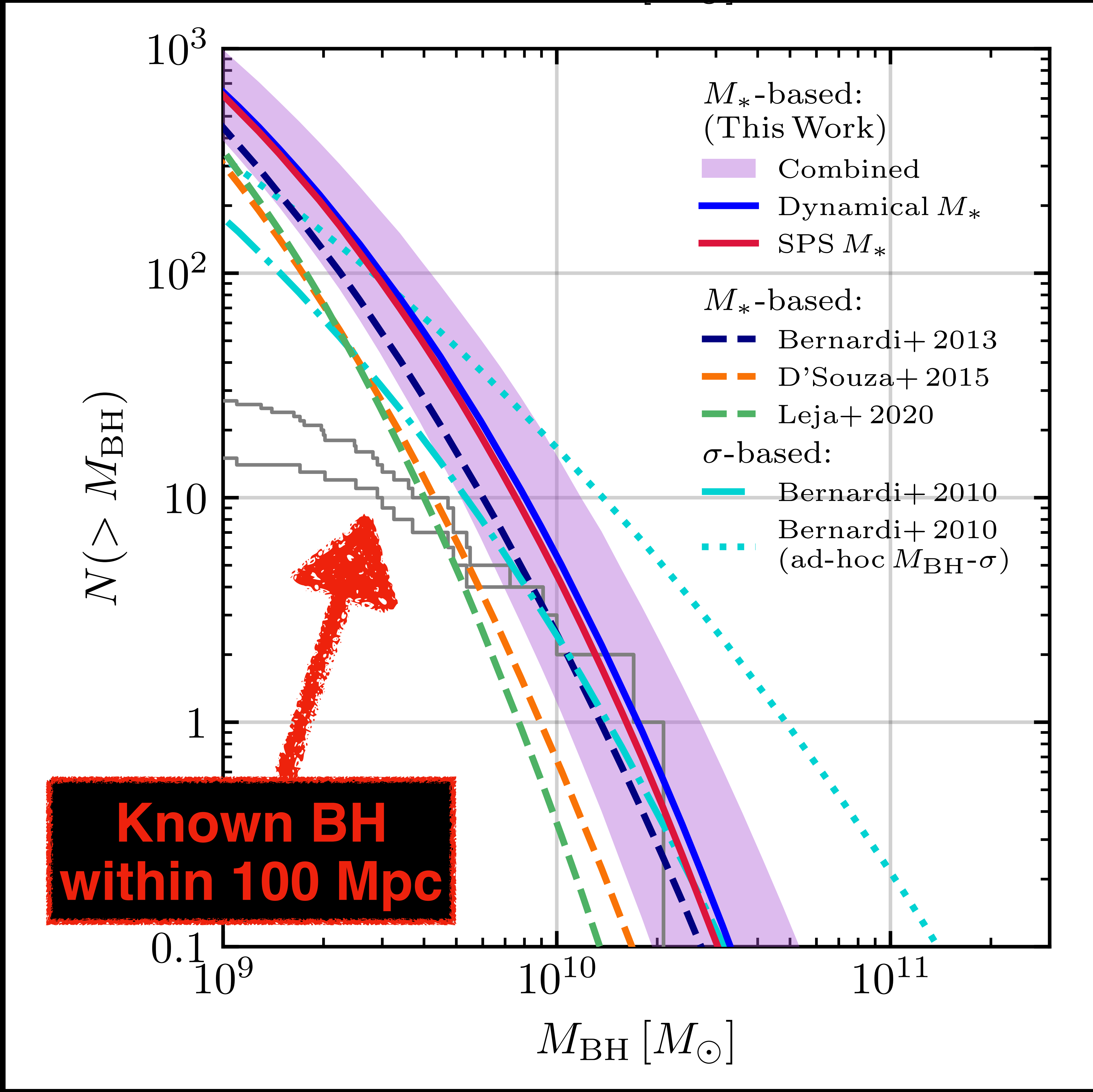

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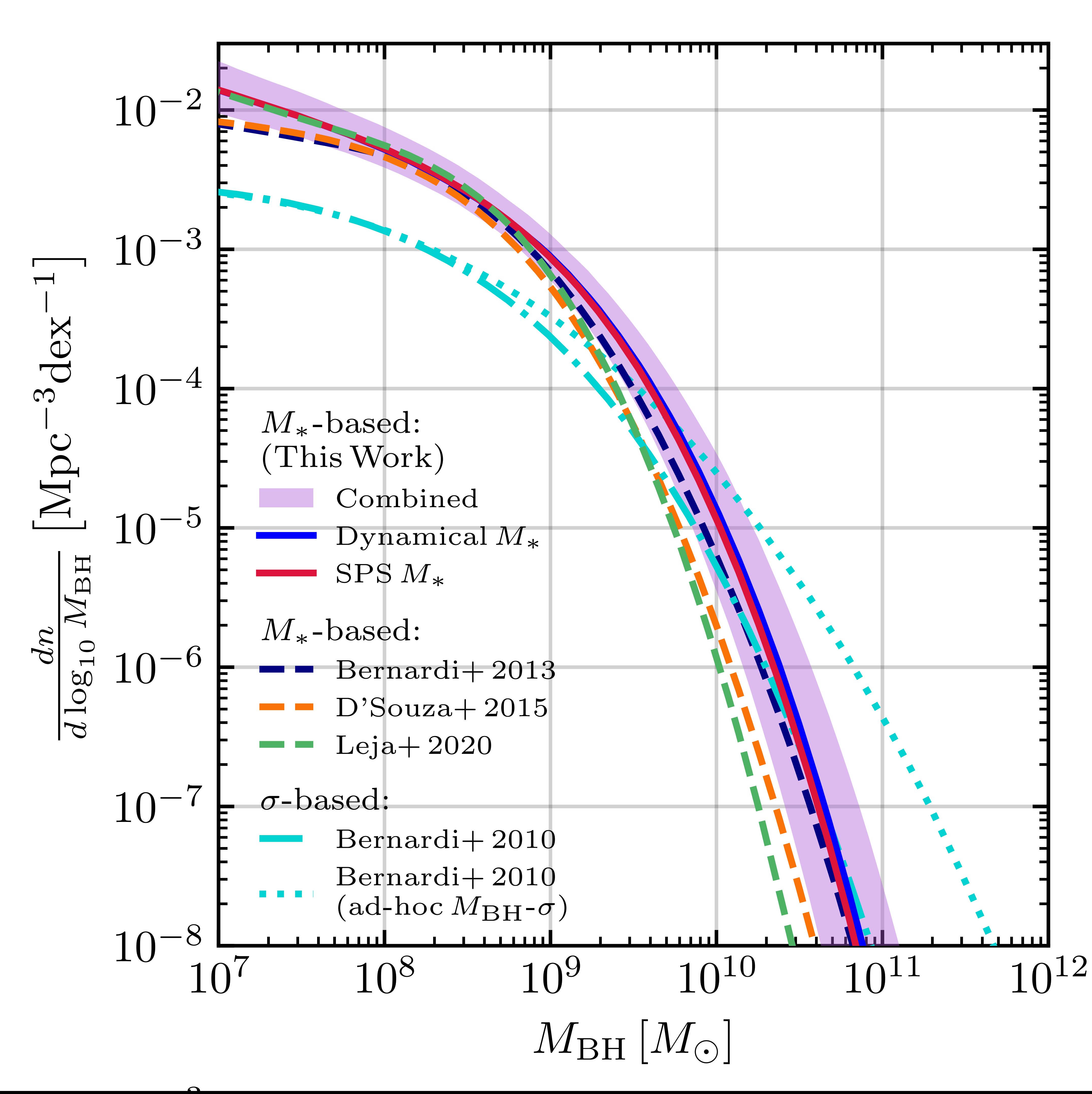

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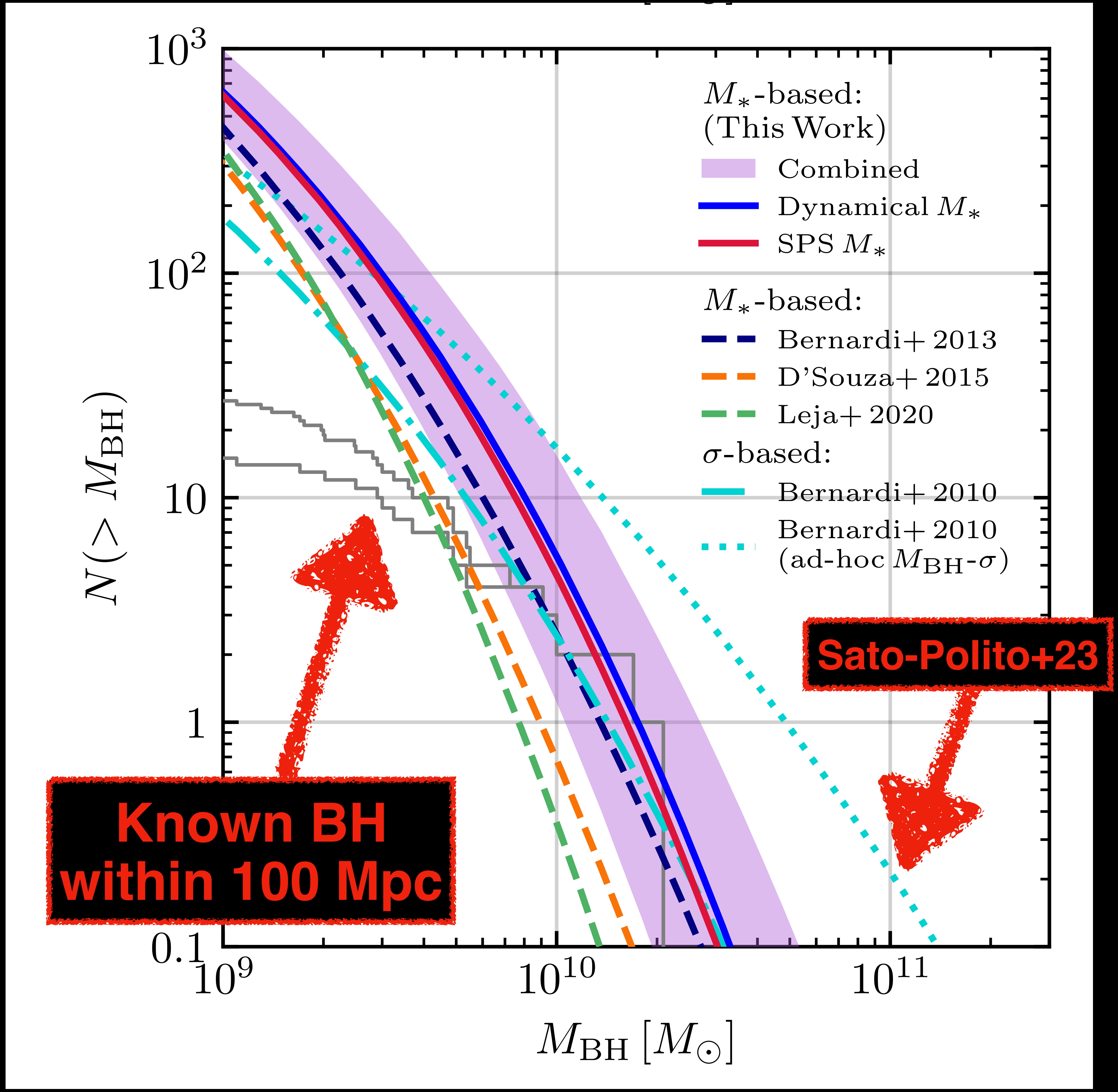

Implications for the Cosmic GW Background

- Phinney 2001 links characteristic strain to properties of a collection of SMBH binaries

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

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Total Binary Mass

Redshift

Mass ratio

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Mass ratio

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Redshift

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- Compare against. NANOGrav 2023 ApJL 952 L37

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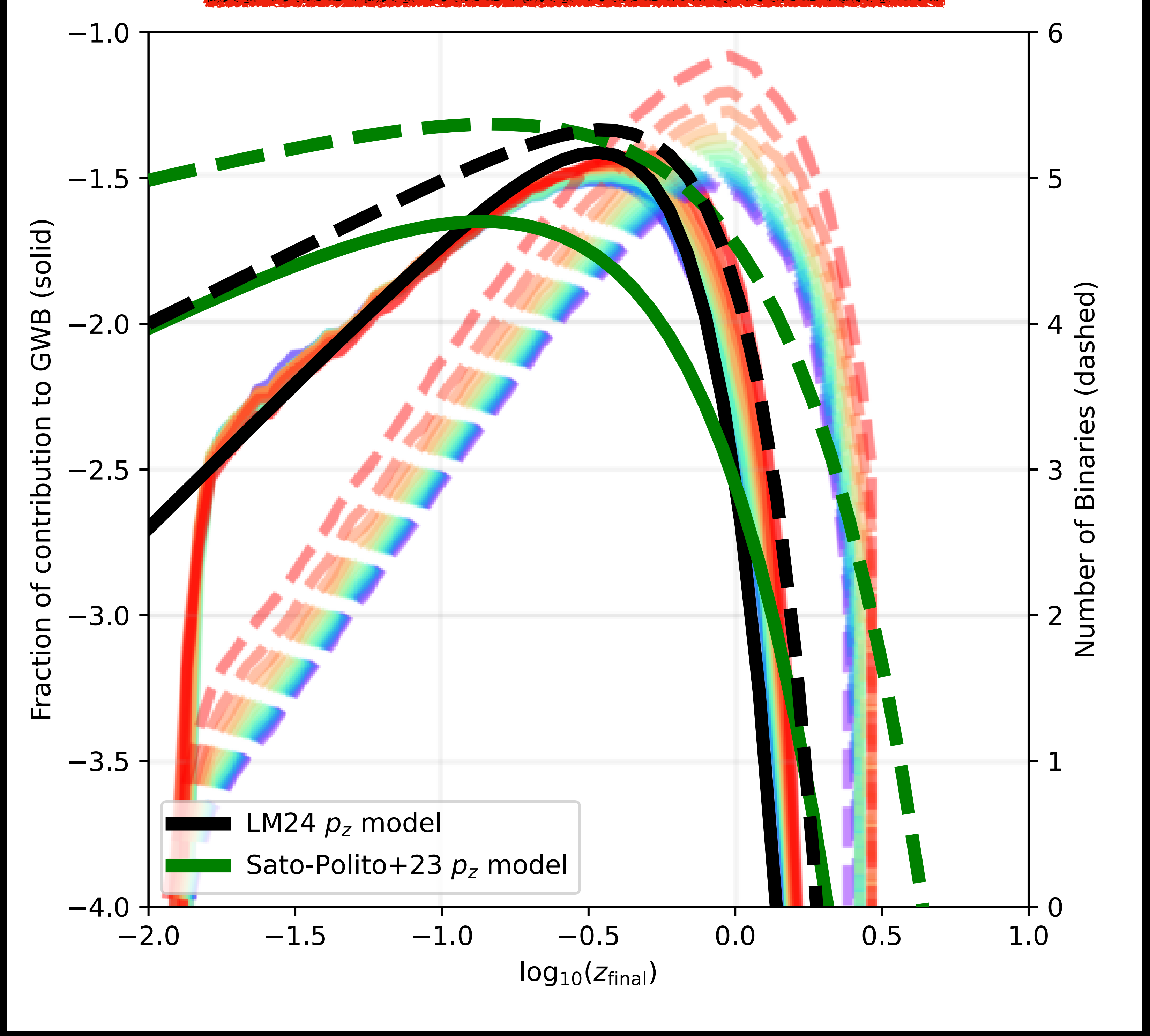
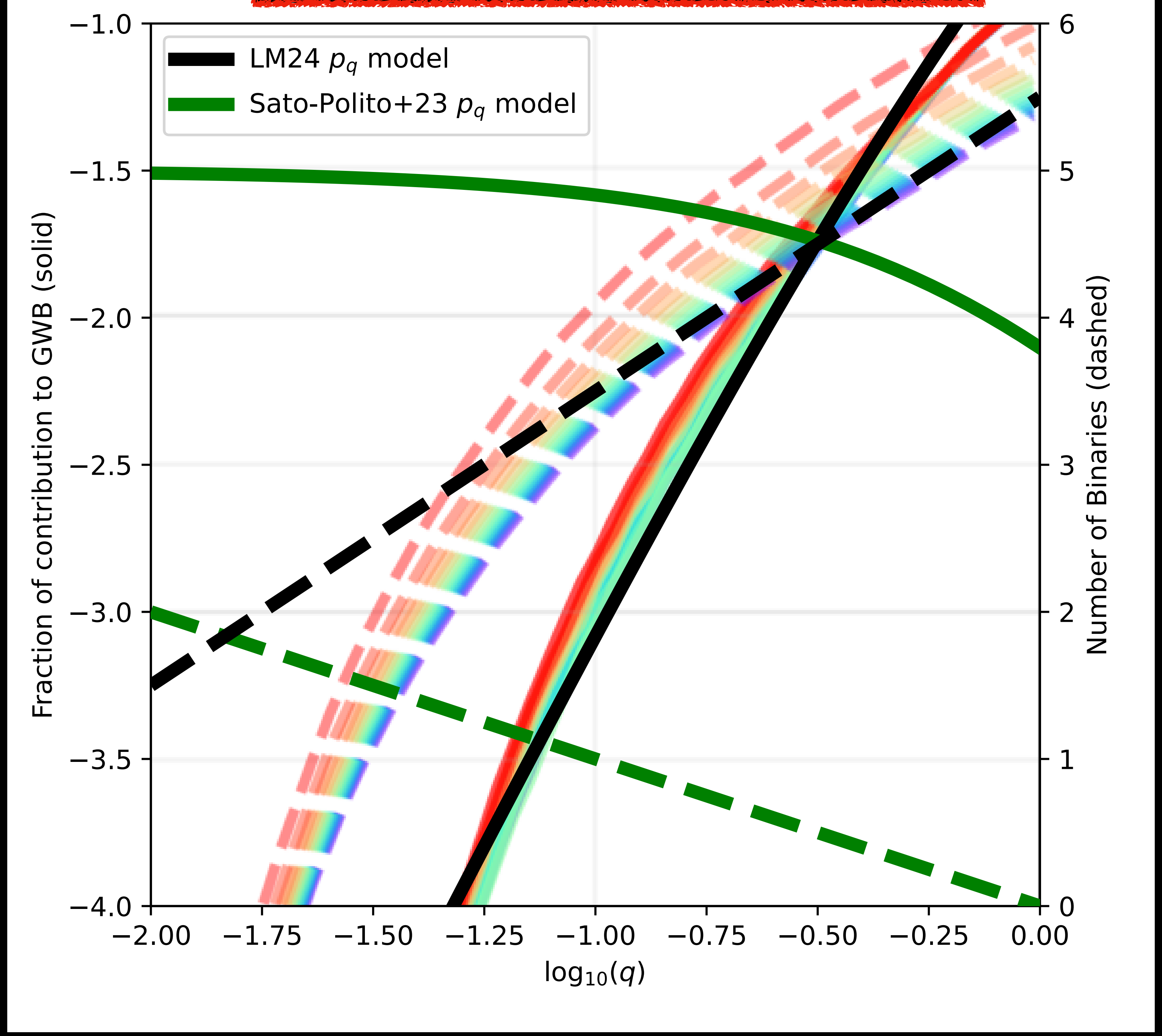
Redshift distribution



Mass Ratio Distribution



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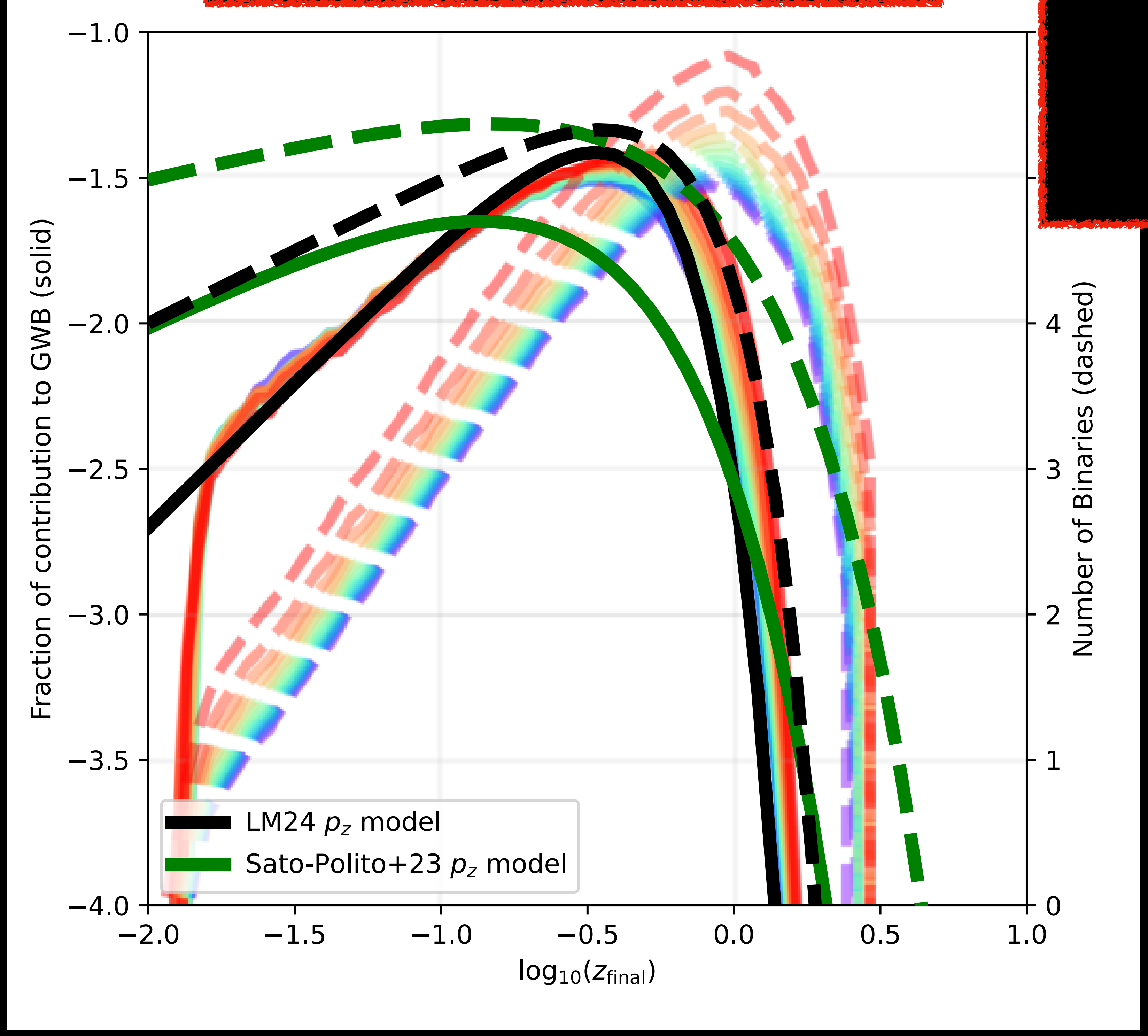
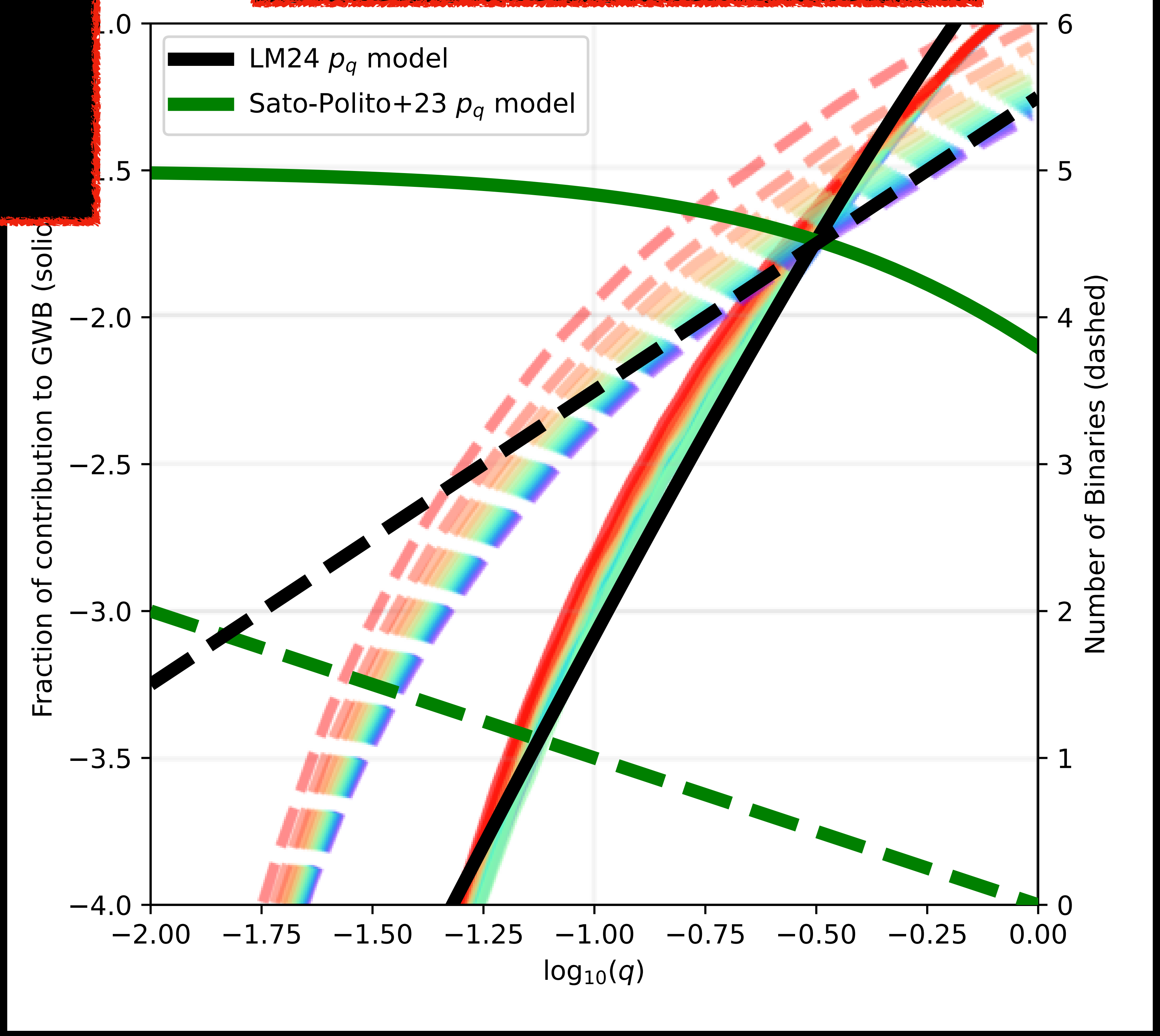


Switching from Green to Black raises h_c by only 14%

Mass Ratio Distribution



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Kernel of h_c^2

Characteristic Strain h_c

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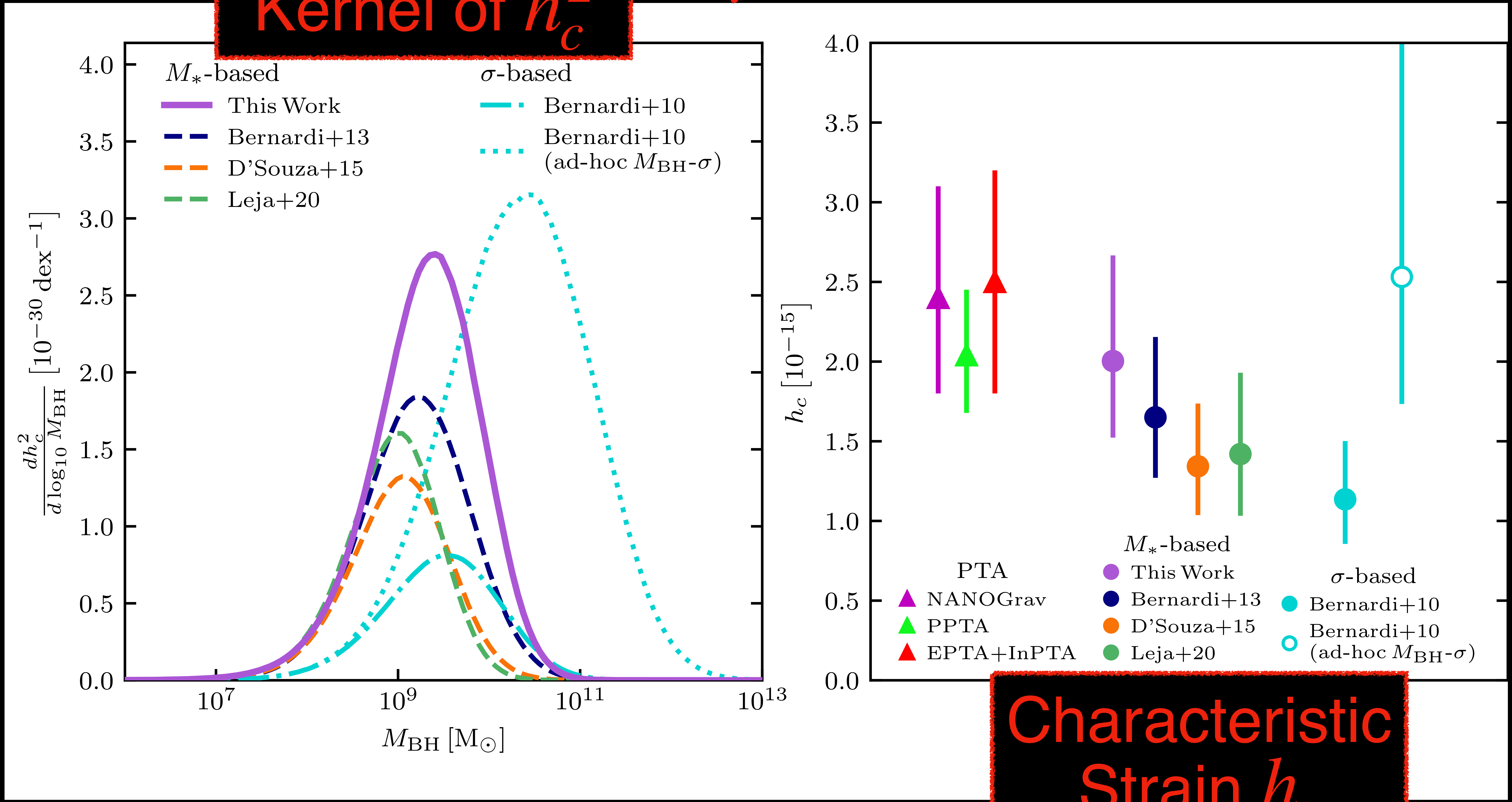
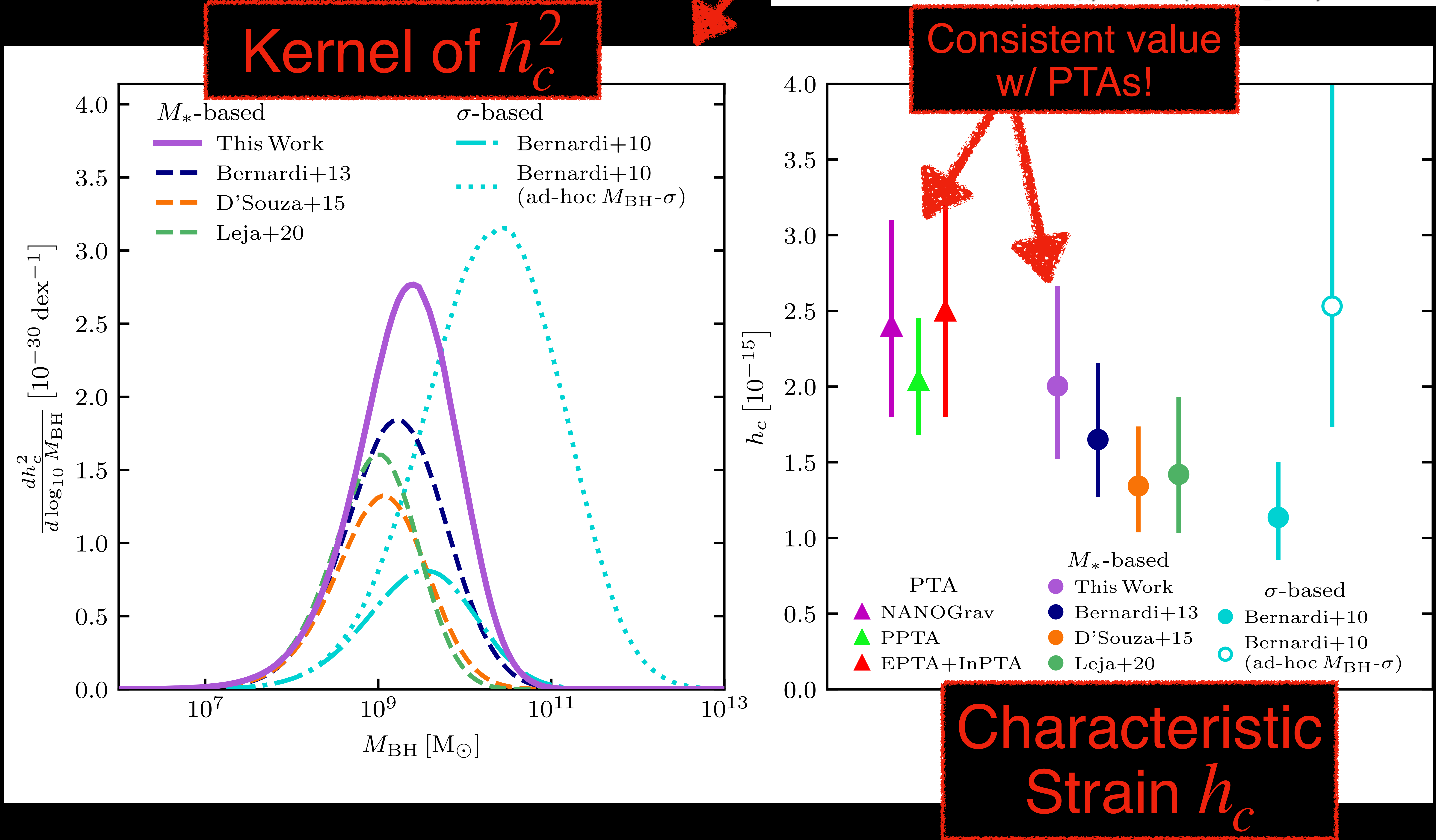


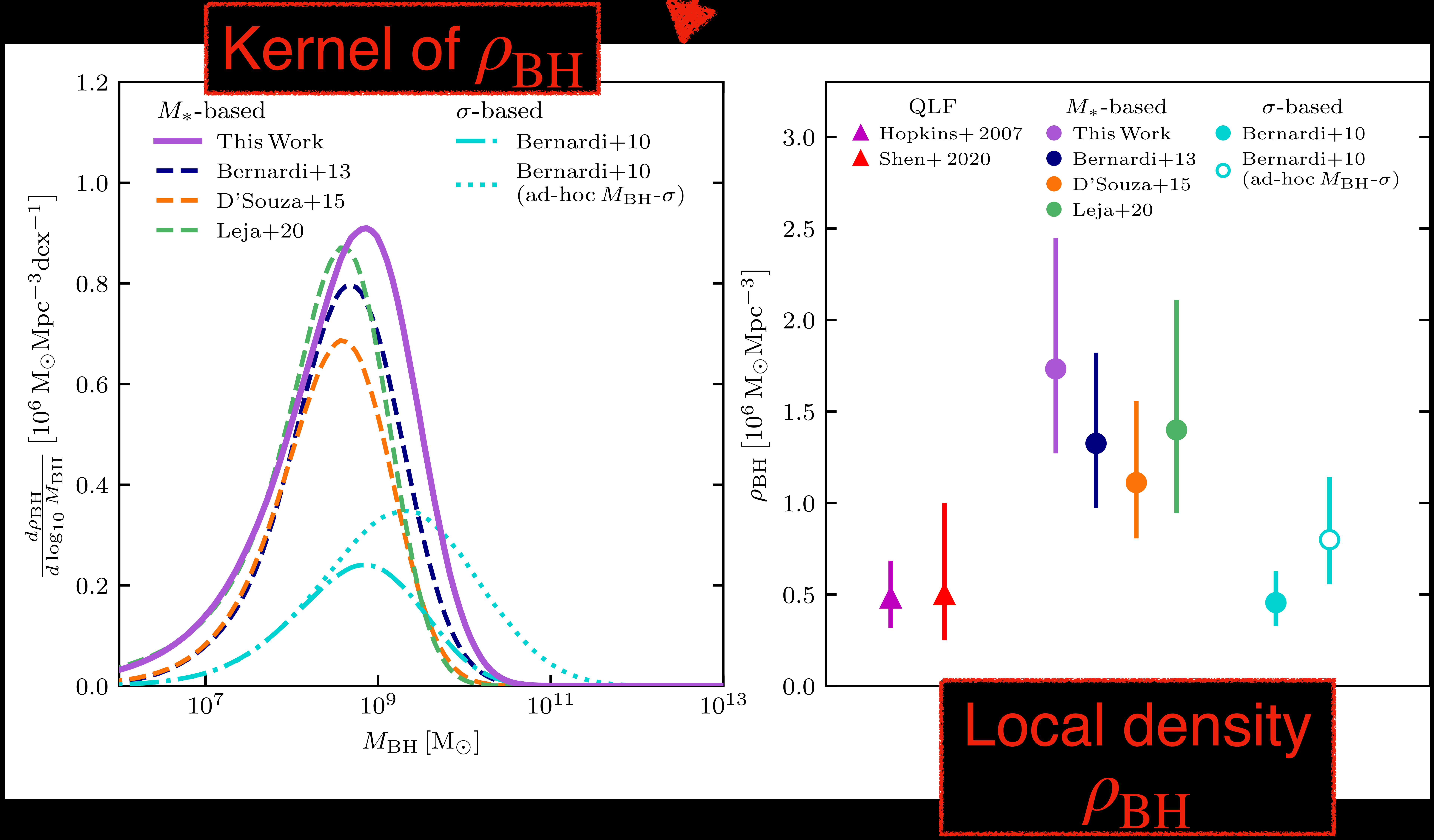
Characteristic Strain h_c

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



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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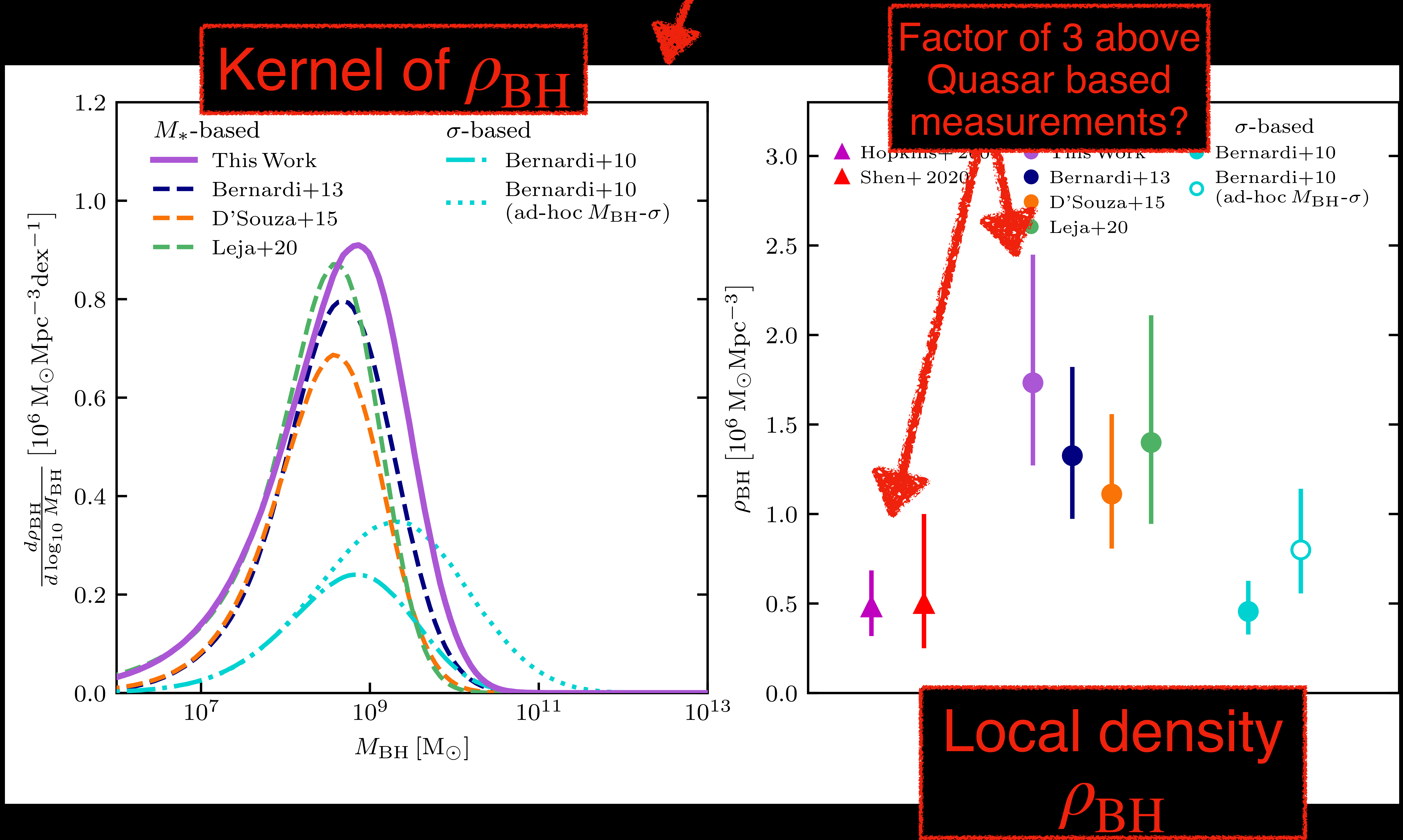

Summary

Our new z=0 stellar mass function combines Leja+ (2020) & MASSIVE survey

Our higher amplitude at $M^* > 10^{11.5}\ M_{sun}$ solves some puzzles:

(1) Reported lack of massive galaxy evolution between z=1 and 0

(2) Reported deficit in predicted GW amplitude compared to PTA results

(3) M* from dynamical method & stellar pop synthesis (bottom heavy IMF) agree within ~7%

Predicted number of local SMBHs (within 100 Mpc)

(1) Large uncertainties at $M_{BH} > 10^{10}\ M_{sun}$ but consistent with known pop.

(2) Many more to be detected at $M_{BH} \sim 10^9\ M_{sun}$

All local BH mass density predicted from galaxy M* has $\rho \gtrsim 10^6\ M_{sun}/Mpc^3$

Quasars: $\rho_{BH} \sim (0.25\text{-}1) \times 10^6\ M_{sun}/Mpc^3$

Obscuration? Lower efficiency ($\varepsilon < 0.1$)?