University of Southampton

BiD4BEST
Big Data applications for Black hole Evolution Studies

Is the PTA stochastic gravitational wave background originating from Supermassive Black Hole mergers or from the Early Universe?

Francesco Shankar

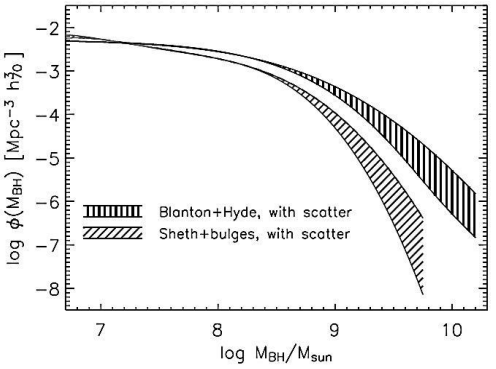
With: D. Roberts, Hao Fu, A. Smith, M. Bernardi, C. Marsden, A. Lapi, N. Menci, V. Allevato, A. V. Alonso Tetilla, F. Fontanot, L. Boco, and many more…

22/05/2025 – Round Table on New Avenues in Particle Cosmology

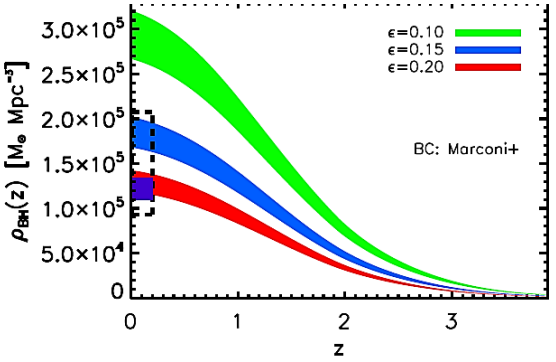
F.Shankar@soton.ac.uk

WHAT I WILL DISCUSS:

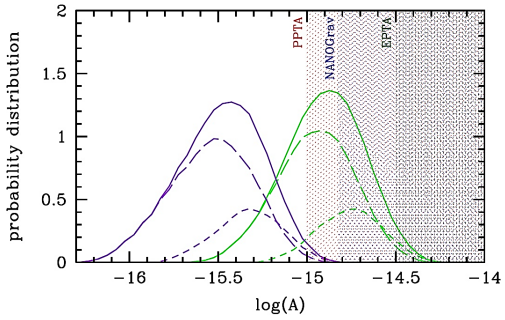
Introduction to SMBHs:
Relations and Demography



Evolution of SMBHs:
SMBH growth and feedback



Physical implications:
Mergers and GWs

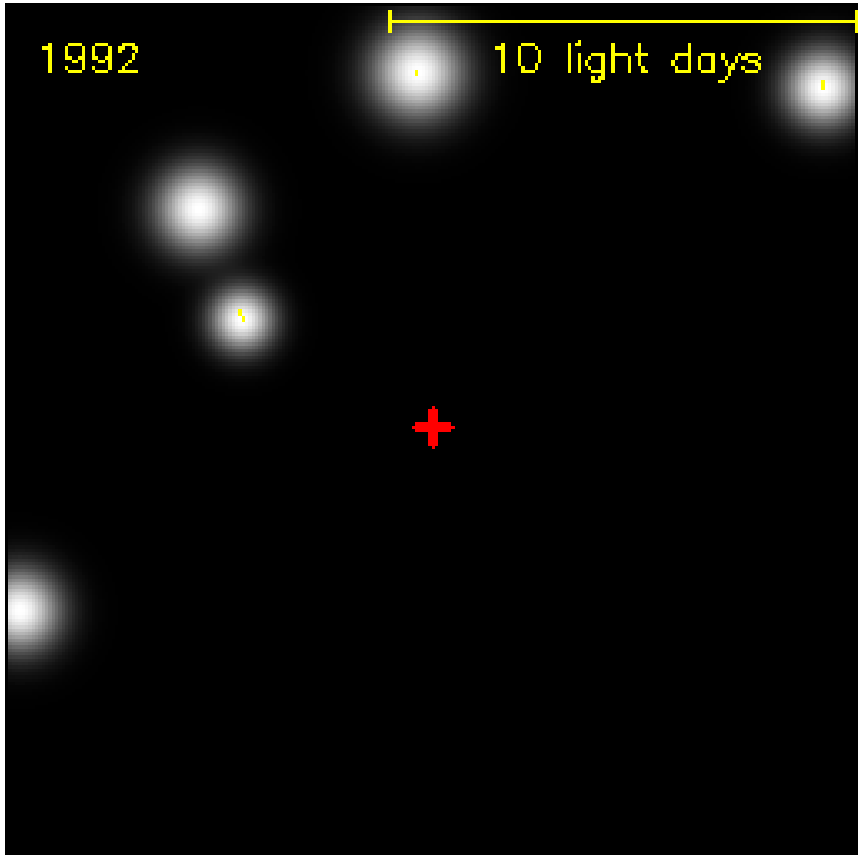


Introduction to SMBHs:
Relations and Demography

Evidence for central supermassive black hole in normal/inactive galaxies

- Orbits of luminous giant stars around the location of Sgr A*

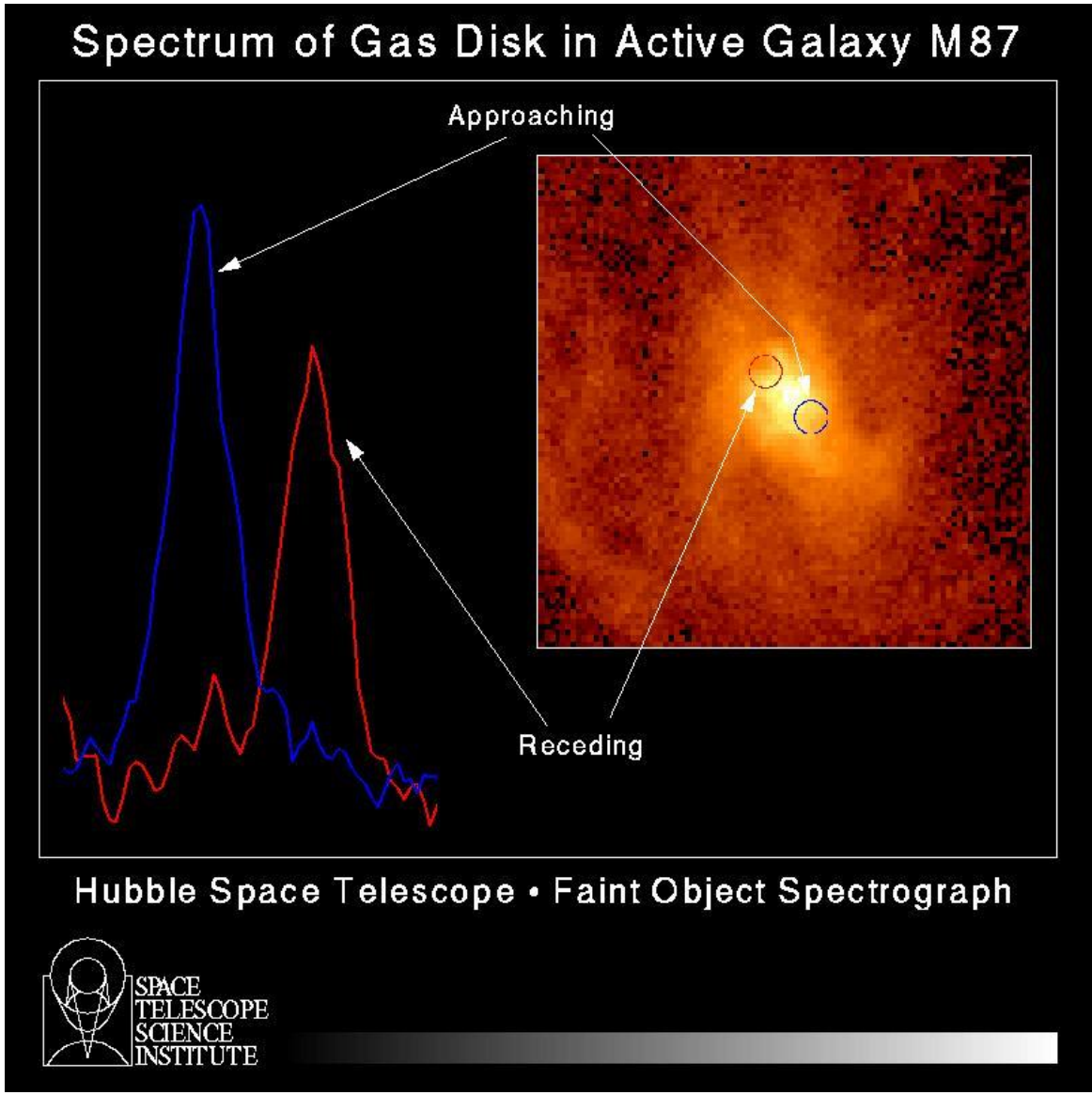
- Derived mass ~ $4 \times 10^6 M_\odot$



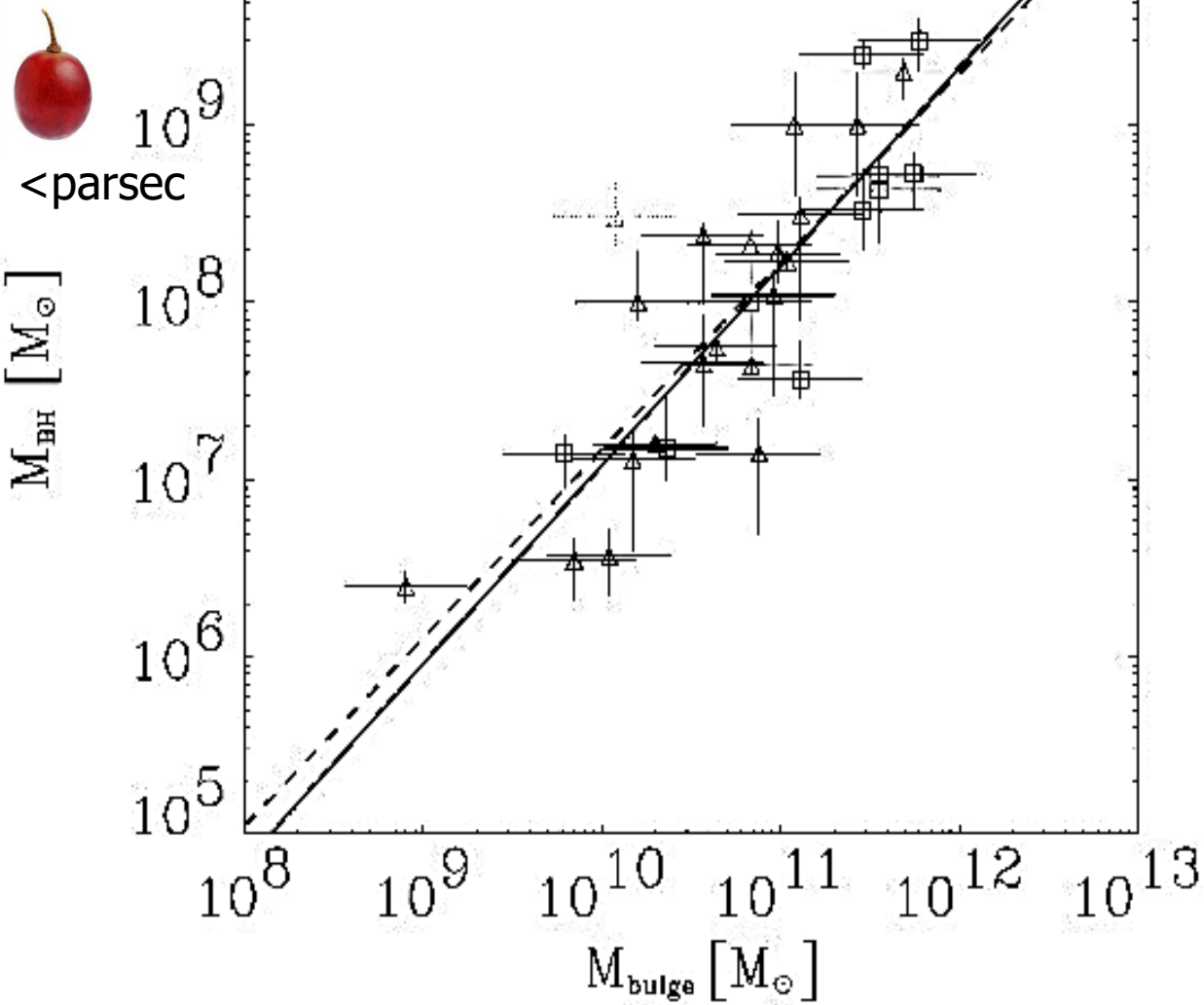
http://www.mpe.mpg.de/www-ir/GC/

Evidence for SMBH in M87

- Velocity change of almost 500 km/s within 0.25” of nucleus
- **$m v^2 / r = G M m / r^2$**
- → **$M = v^2 r / G$**
- ➔ **M** ~ 1 billion M_O !



The «Magorrian» relation: M_{BH}-Mbulge



<parsec

Marconi&Hunt 03
Haering&Rix 04

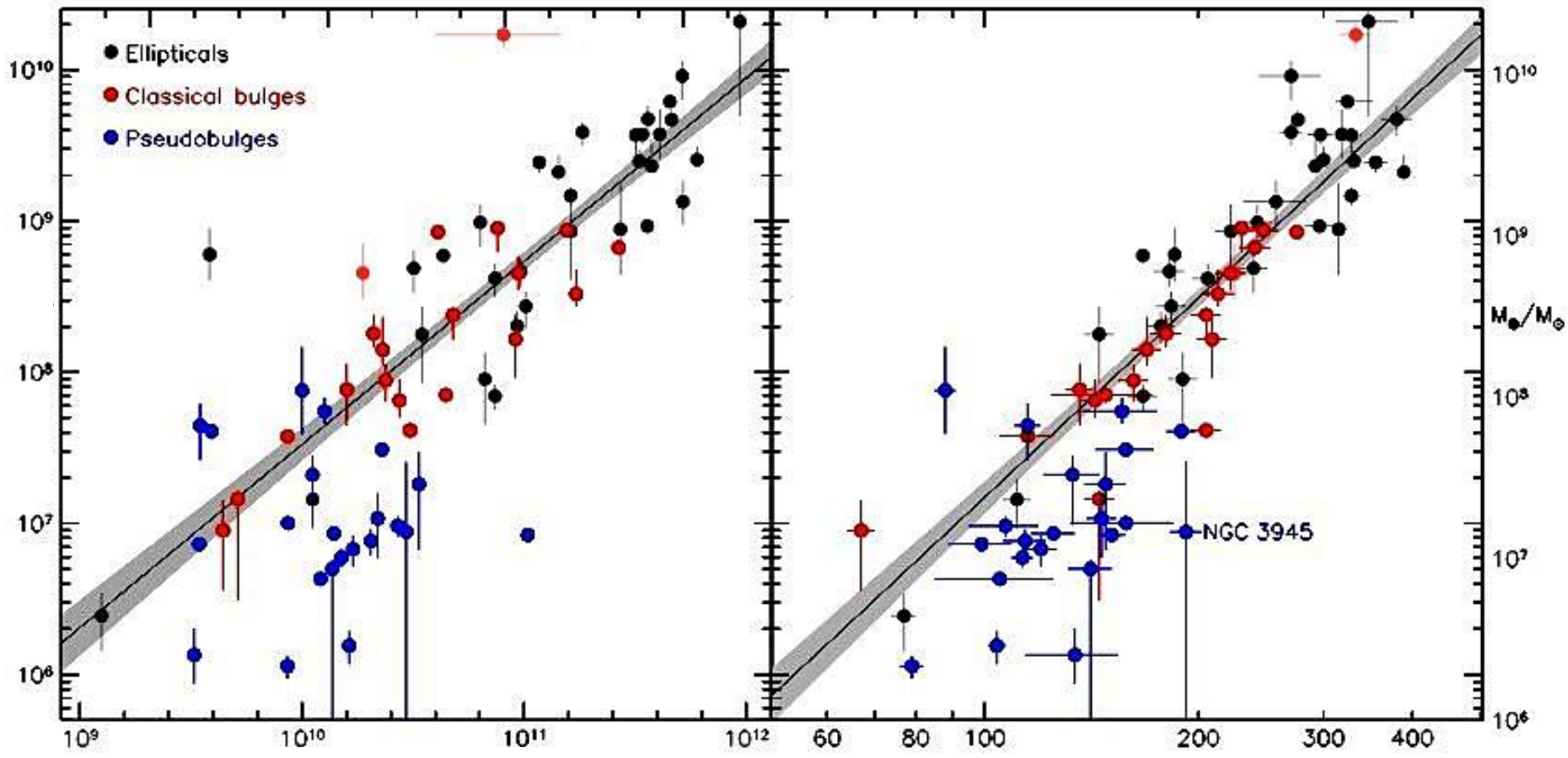
Thousands and thousands of papers on the co-evolution of black holes and galaxies

>kilo-parsec

Which is the most fundamental?

M_{BH}~Mstar

M_{BH}~σ^{4-5}

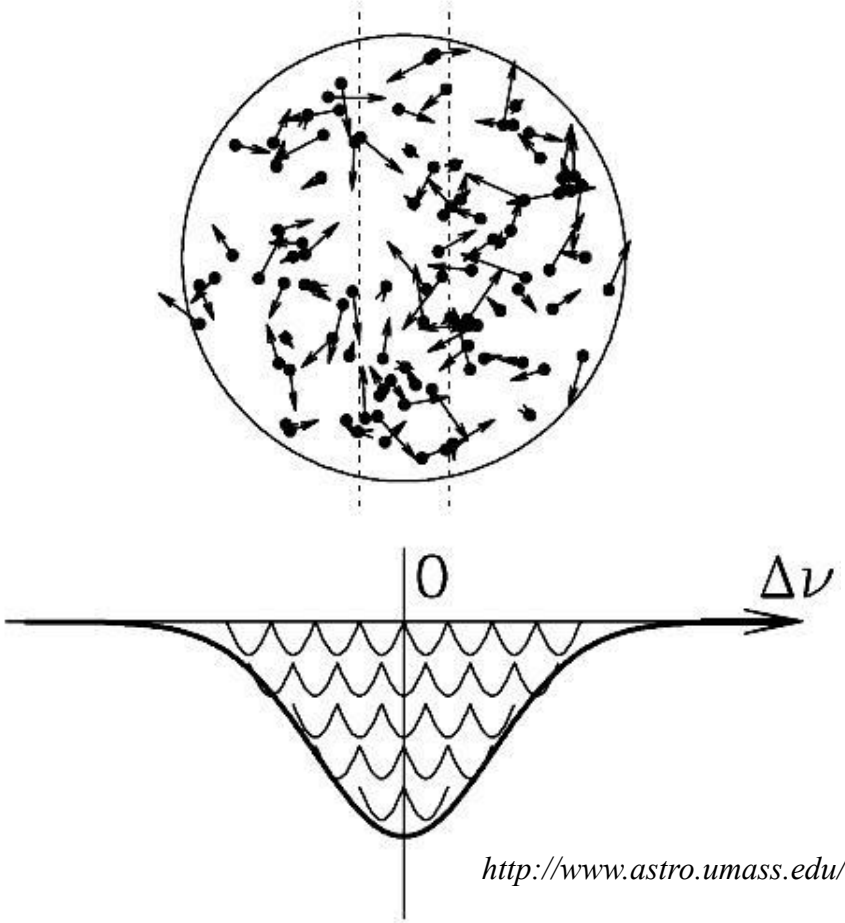


$L_{K,bulge}$ (Lsun)

σ (km/s)

Kormendy & Ho 13

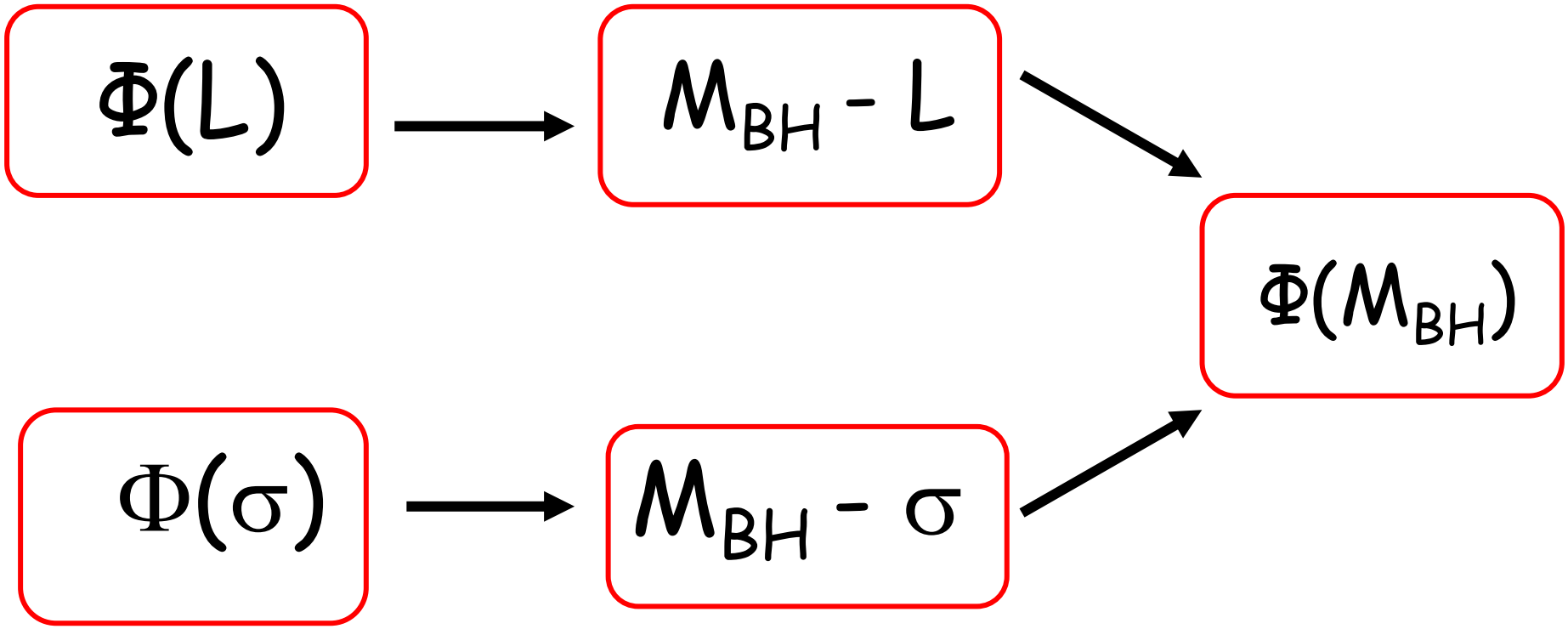
Radial velocity dispersion



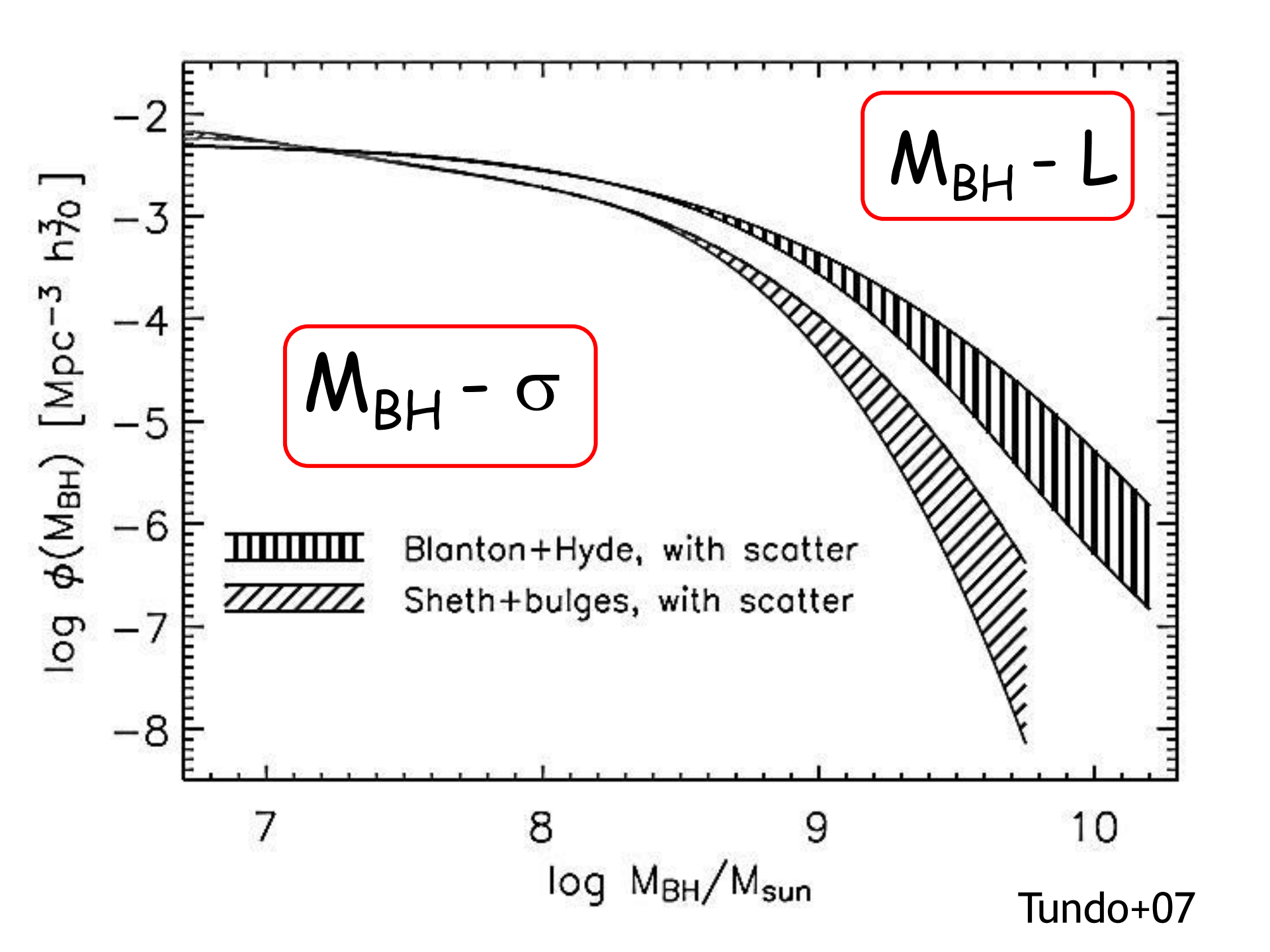
http://www.astro.umass.edu/~hjmo/astro330/htmldir/reading.pdf

In a galaxy, each star produces a small Doppler shift with respect to the rest frame of the galaxy. The superposition of many absorption lines produces a broadening of the observed line. In mathematical terms, it is the convolution of the original stellar spectral line with the velocity distribution of the stars in the galaxy along the line-of-sight.

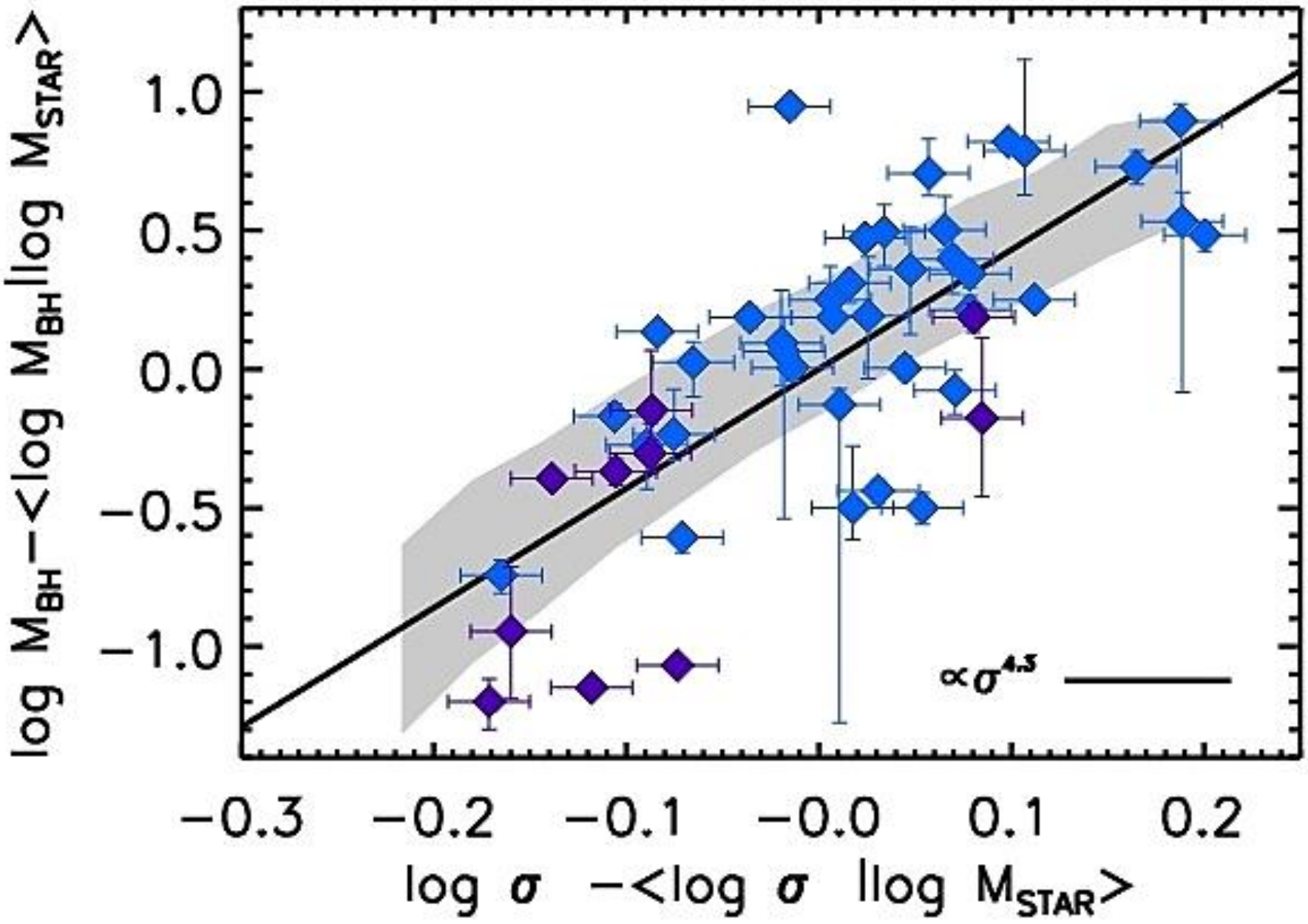
How many SMBH? How Massive?



Several caveats: scatter, colour change, bulge fractions, etc…


M_{BH} - L
M_{BH} - σ
Blanton+Hyde, with scatter
Sheth+bulges, with scatter
log φ(M_{BH}) [Mpc^{-3} h_{70}^3]
log M_{BH}/M_{sun}
−2
−3
−4
−5
−6
−7
−8
7
8
9
10

Tundo+07


log M_{BH} − <log M_{BH} |log M_{STAR}>
1.0
0.5
0.0
−0.5
−1.0
−0.3
−0.2
−0.1
−0.0
0.1
0.2
log σ − <log σ |log M_{STAR}>
$\propto \sigma^{4.5}$

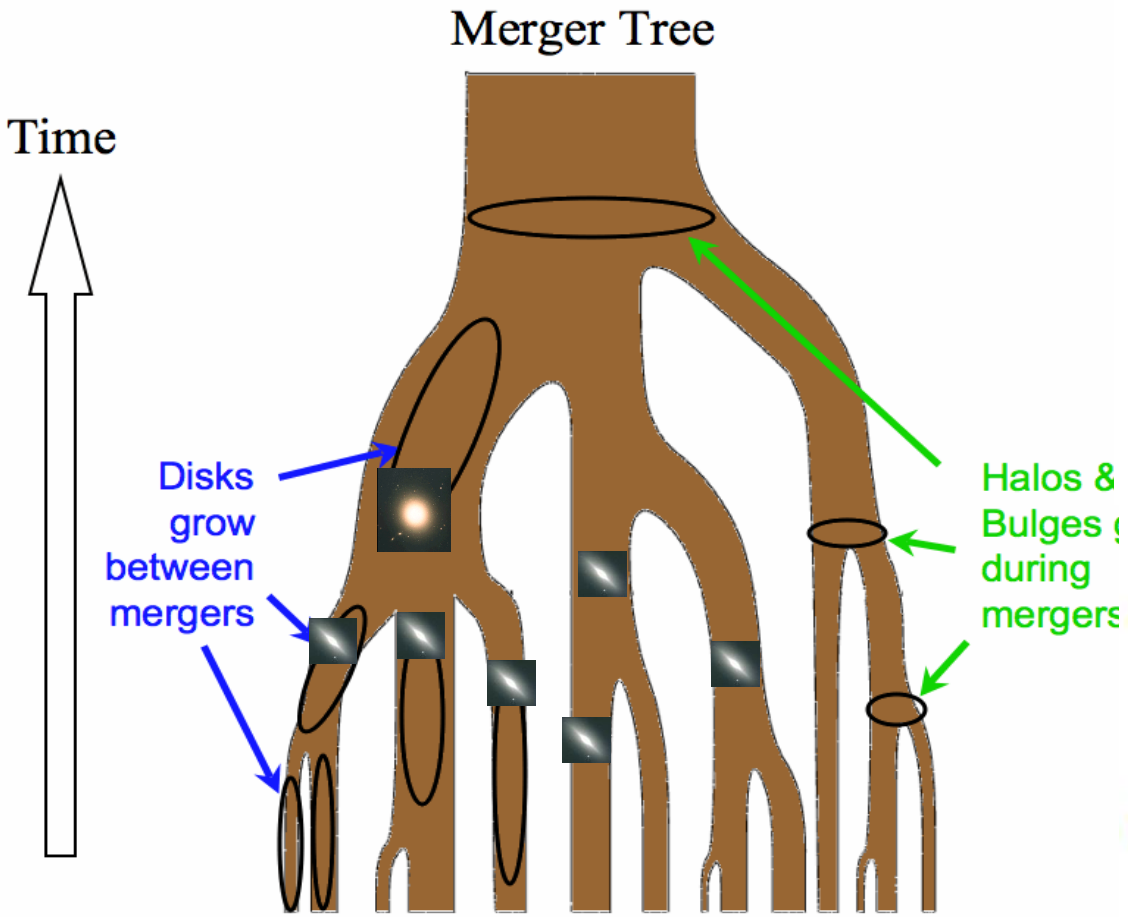
Shankar+16

Take-home message I:

SMBHs are as common as galaxies but their average masses are uncertain

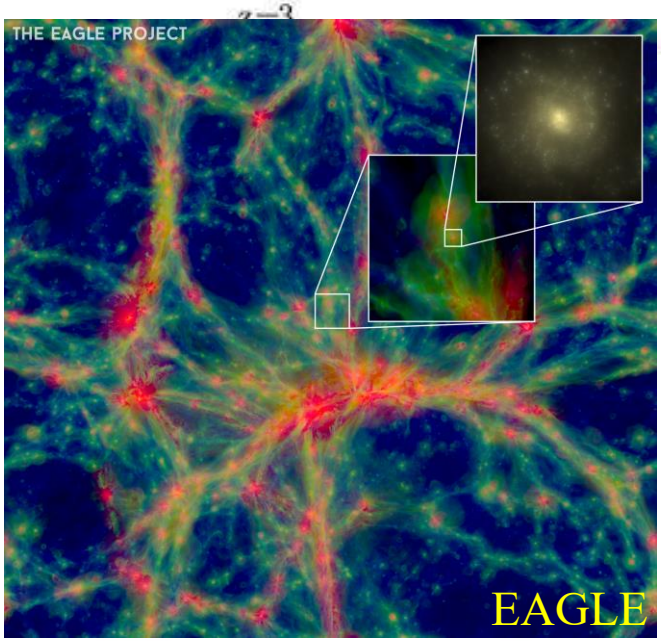
Evolution of SMBHs:
SMBH growth and feedback

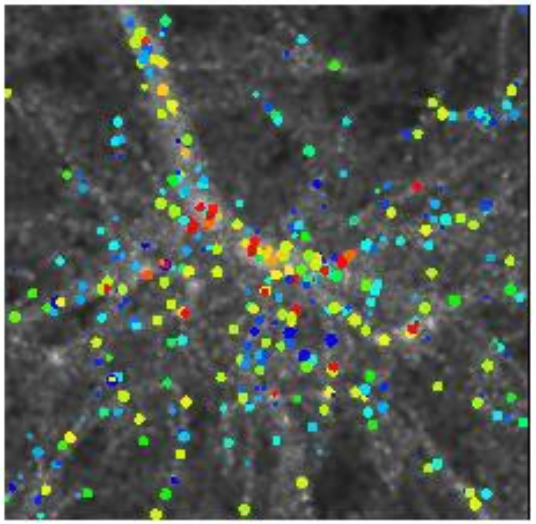
GALAXIES and SMBHs LIVE AND GROW WITHIN DARK MATTER HALOES IN ΛCDM



Hierarchical assembly of dark matter haloes

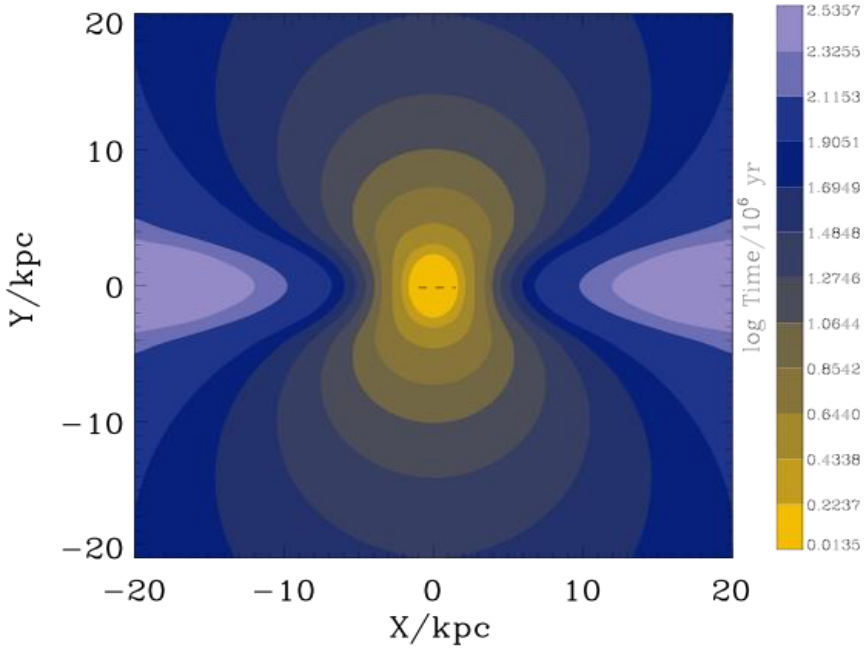
Whittle et al.





MPA-SAM (Kauffmann+)

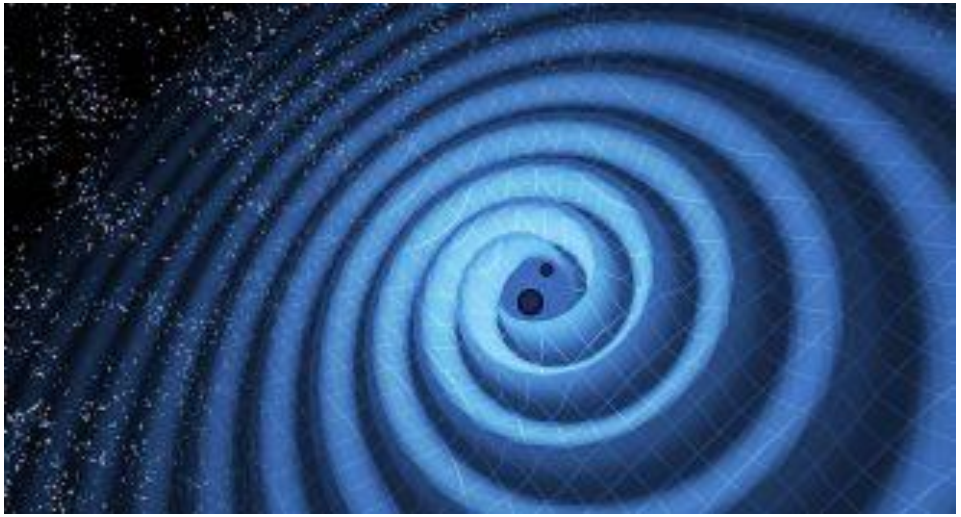
Why do we care about supermassive black holes?



N. Menci,..FS, et al. 2019

SMBHs might have shaped galaxies via their energetic/kinetic outputs halting and/or promoting star formation and supporting morphological transformations

SMBH binaries are considered among the loudest sources of gravitational waves



T. PYLE/LIGO

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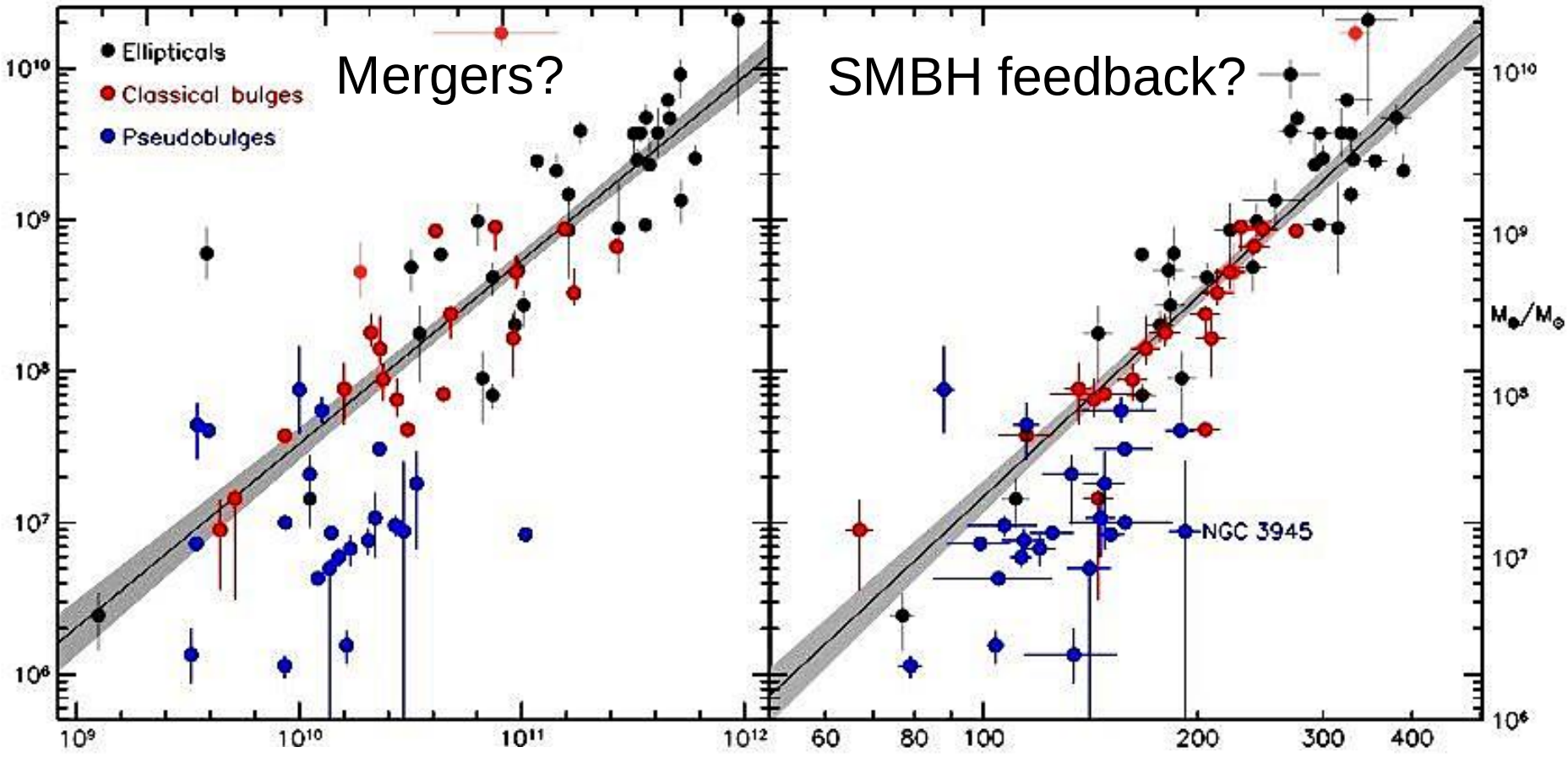
M_{BH}~Mstar

M_{BH}~σ^{4-5}

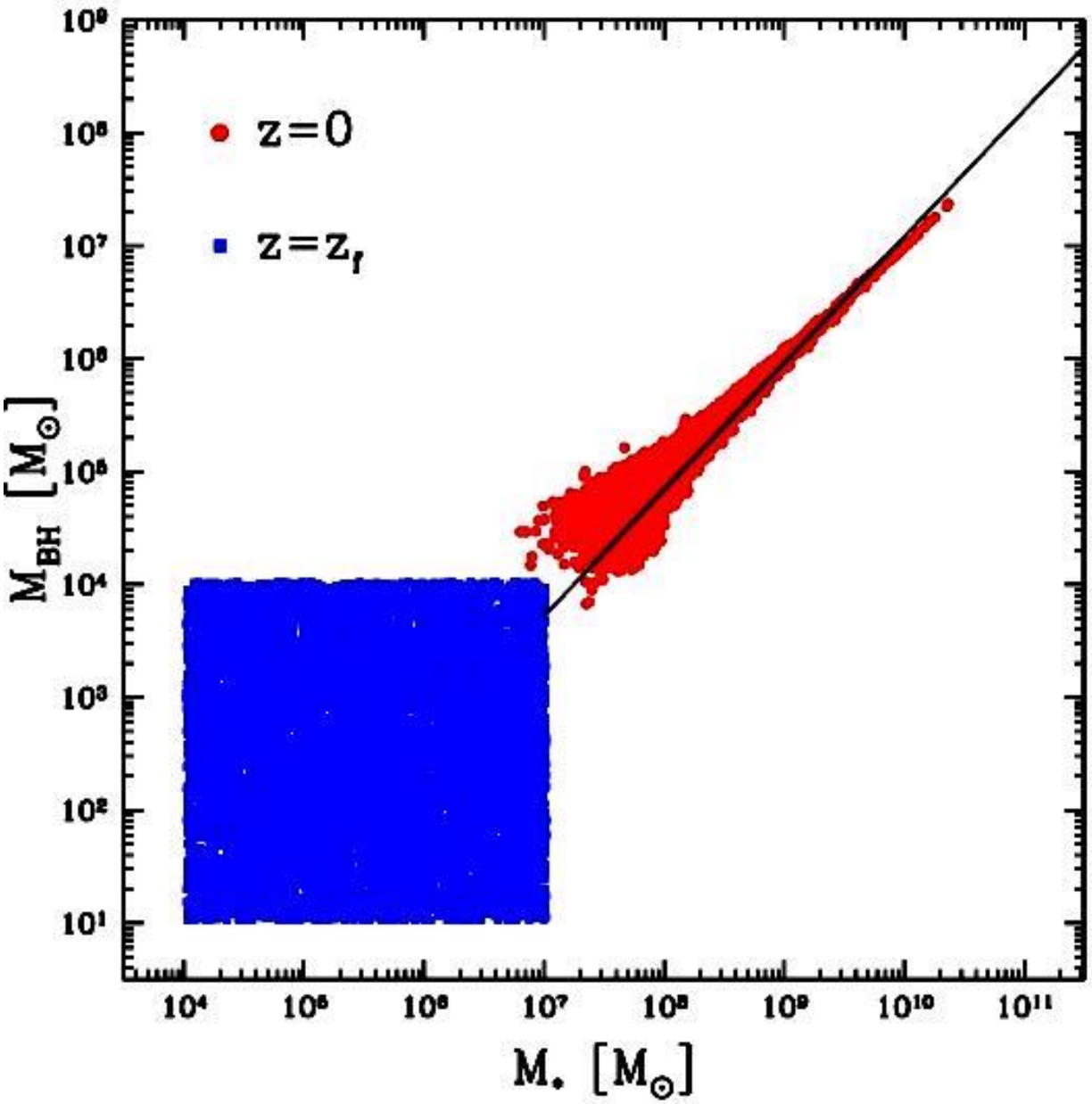


$L_{K,bulge}$ (Lsun)

σ (km/s)

Kormendy & Ho 13

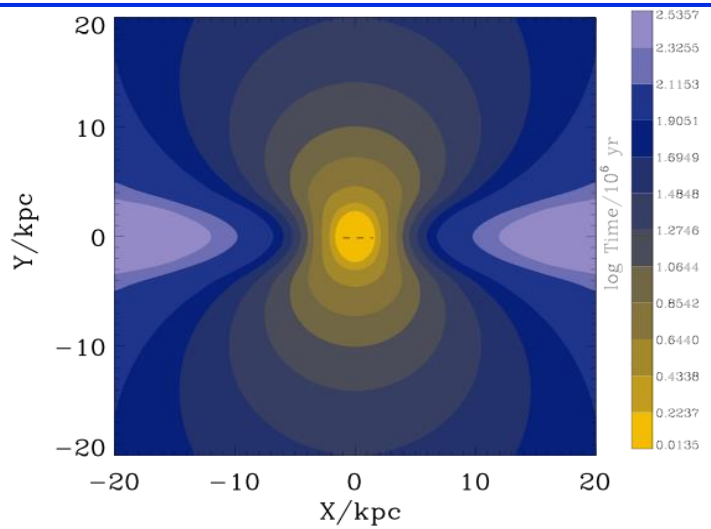
SMBH MERGERS?



Even with NO gas accretion, ONLY mergers at the rate predicted by ΛCDM can already predict a linear relation!

Jahnke+Maccio 11

SMBH feedback?



N. Menci,..FS, et al. 2019

$$\dot{M}_{BH}c^2\tau_{dyn}\sim M_{star}\sigma^2$$

$$\tau_{dyn}\sim R/\sigma$$

$$M_{BH}\sim\dot{M}_{BH}\sim M_{star}\sigma^3/R$$

$$GM_{star}/R\sim\sigma^2$$

$$M_{BH}\sim\sigma^5$$

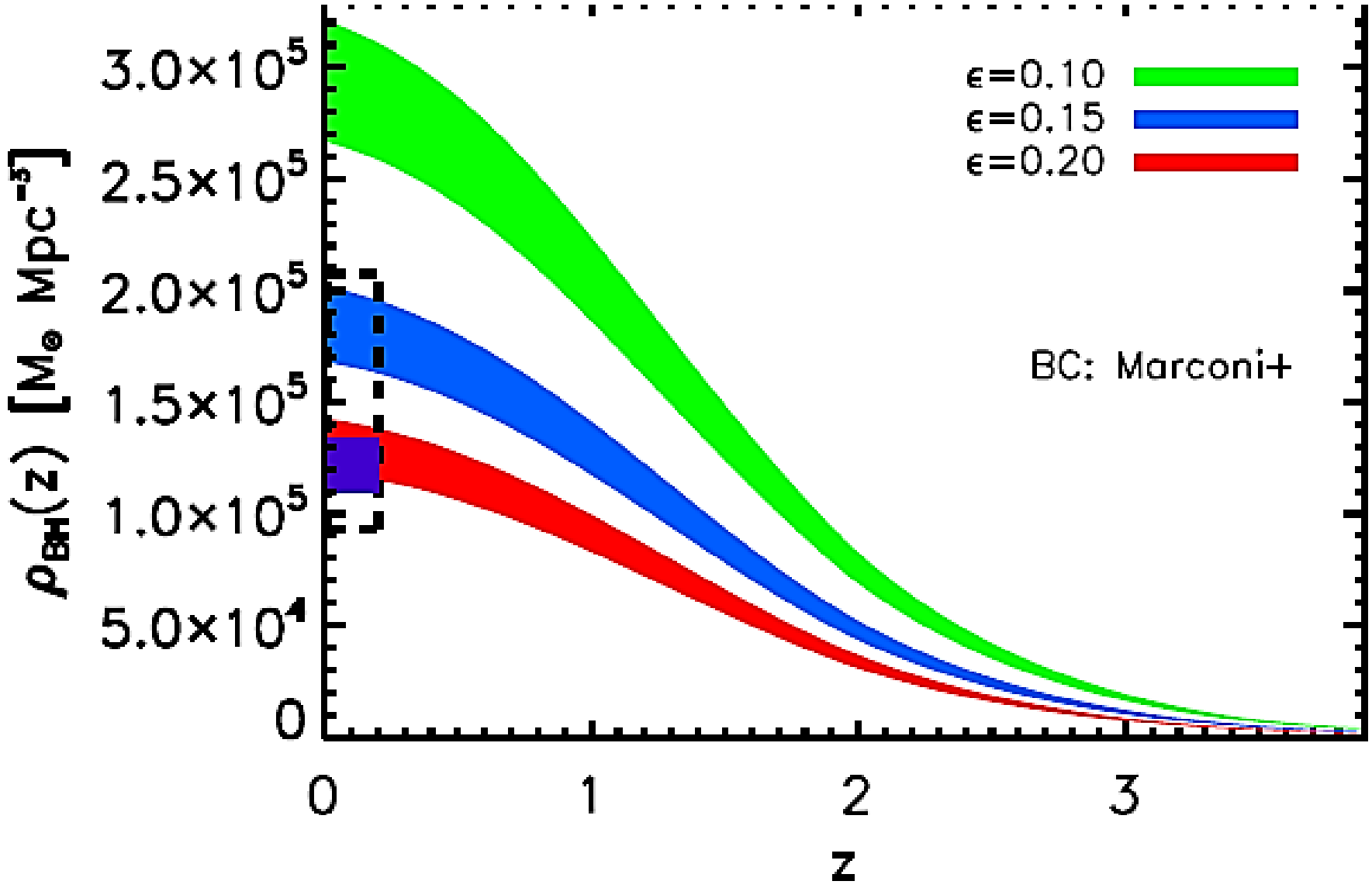
Silk&Rees98

The “Soltan-Paczynski (1982) argument”

$$L = \varepsilon \frac{d(mc^2)}{dt}$$

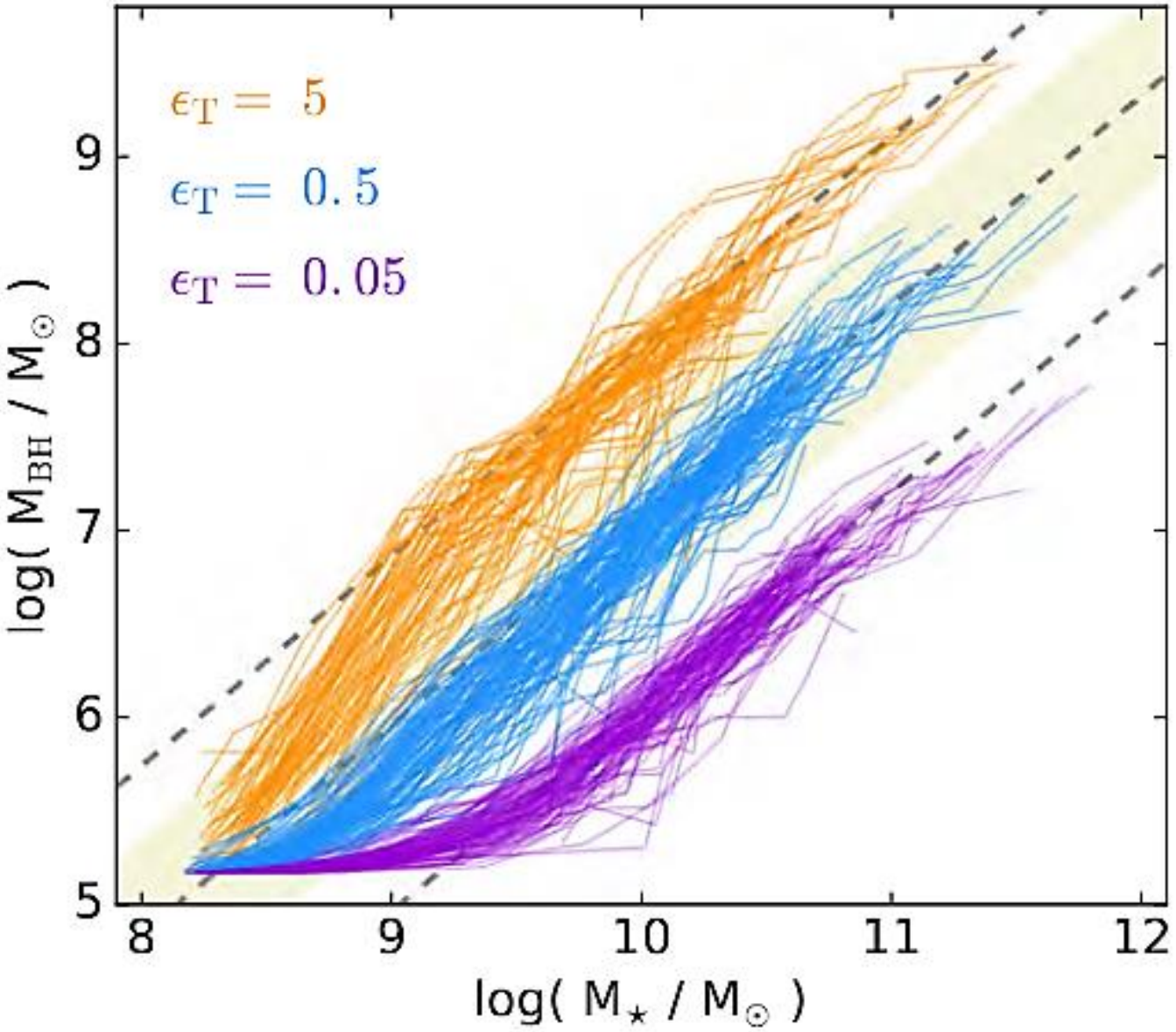
$$\frac{1-\varepsilon}{\varepsilon c^2} \int L\Phi(L,t)dt = \rho_{BH,relic}$$

$$\rho_{BH,relic} \Leftrightarrow \rho_{BH,local} \Rightarrow \varepsilon$$



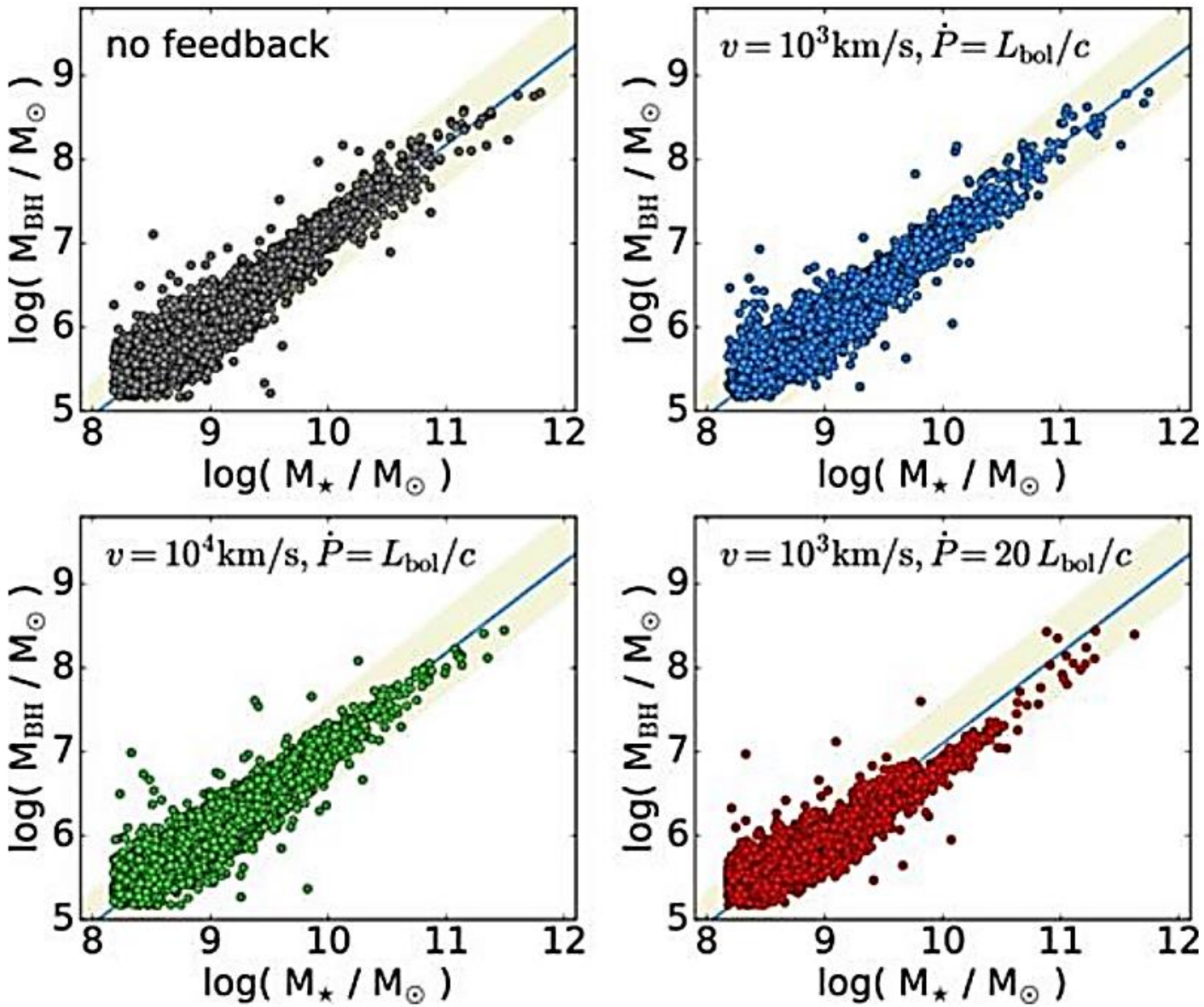
Shankar+19, NatAstro, resubmitted

Accretion is connecting SMBHs and galaxies



Angles-Alcazar+17

Weak effect of AGN feedback on scaling relations



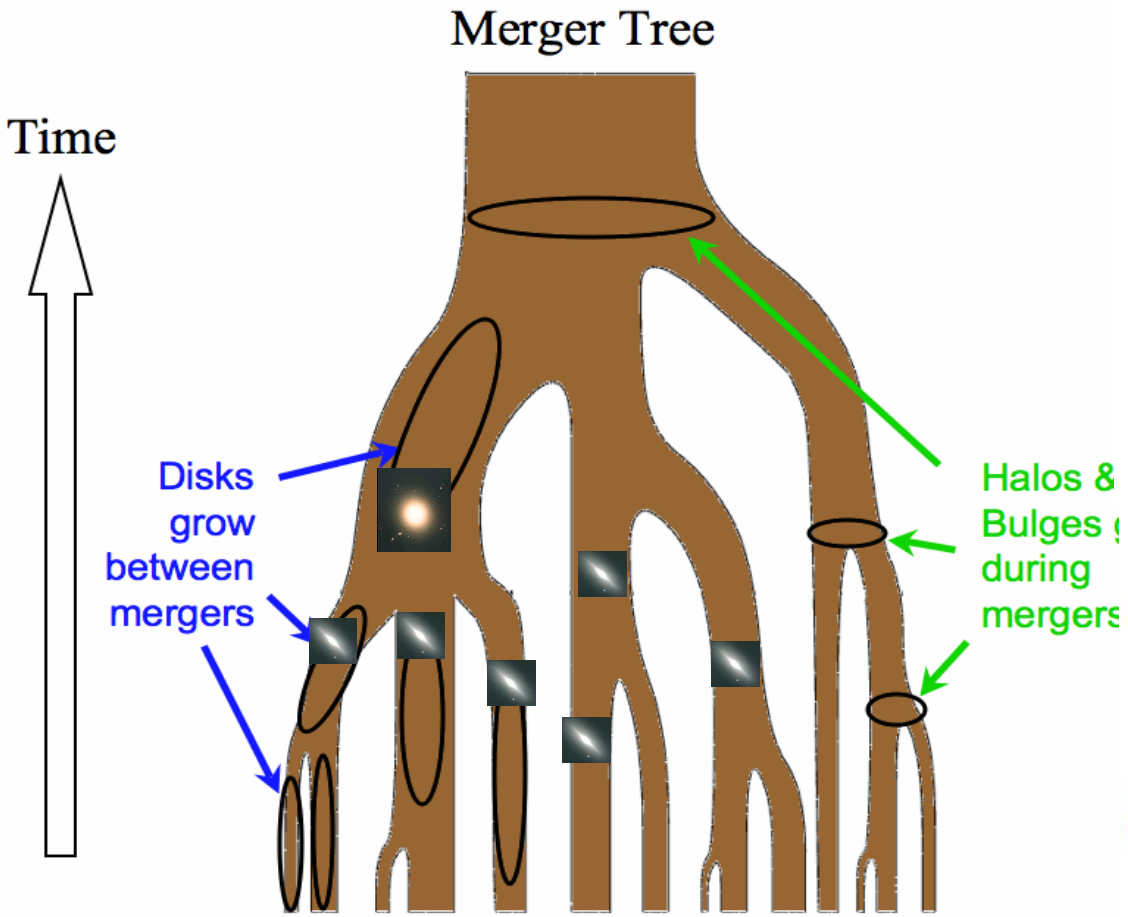
Angles-Alcazar+17

Take-home message II:

SMBHs grow primarily via gas accretion!

Physical implications:
Mergers and GWs

GALAXIES and SMBHs LIVE AND GROW WITHIN DARK MATTER HALOES IN ΛCDM



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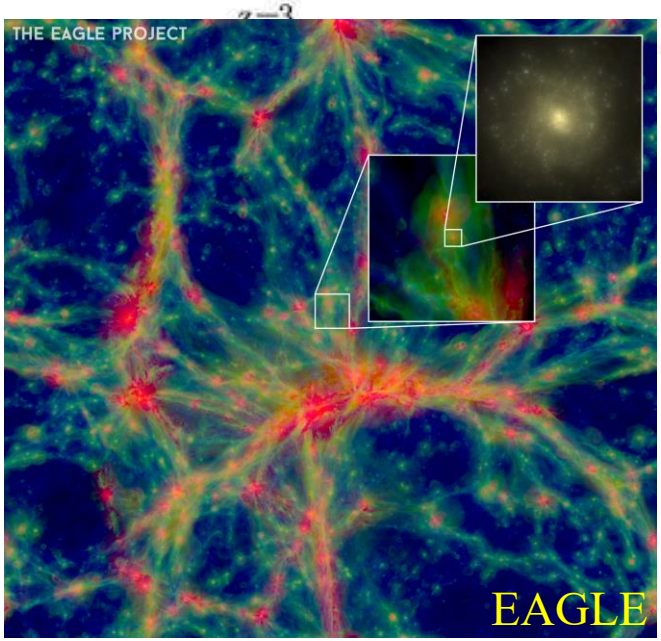
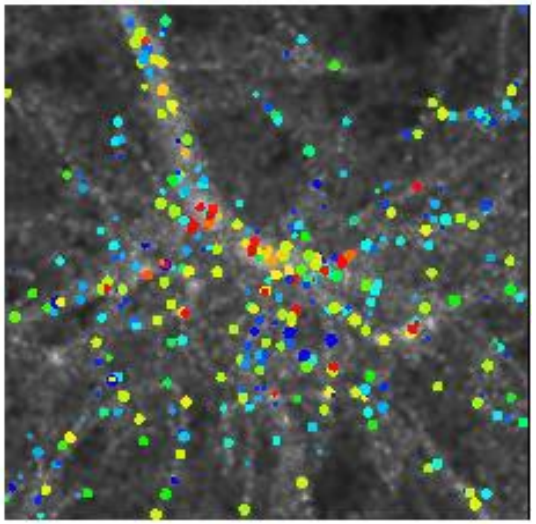
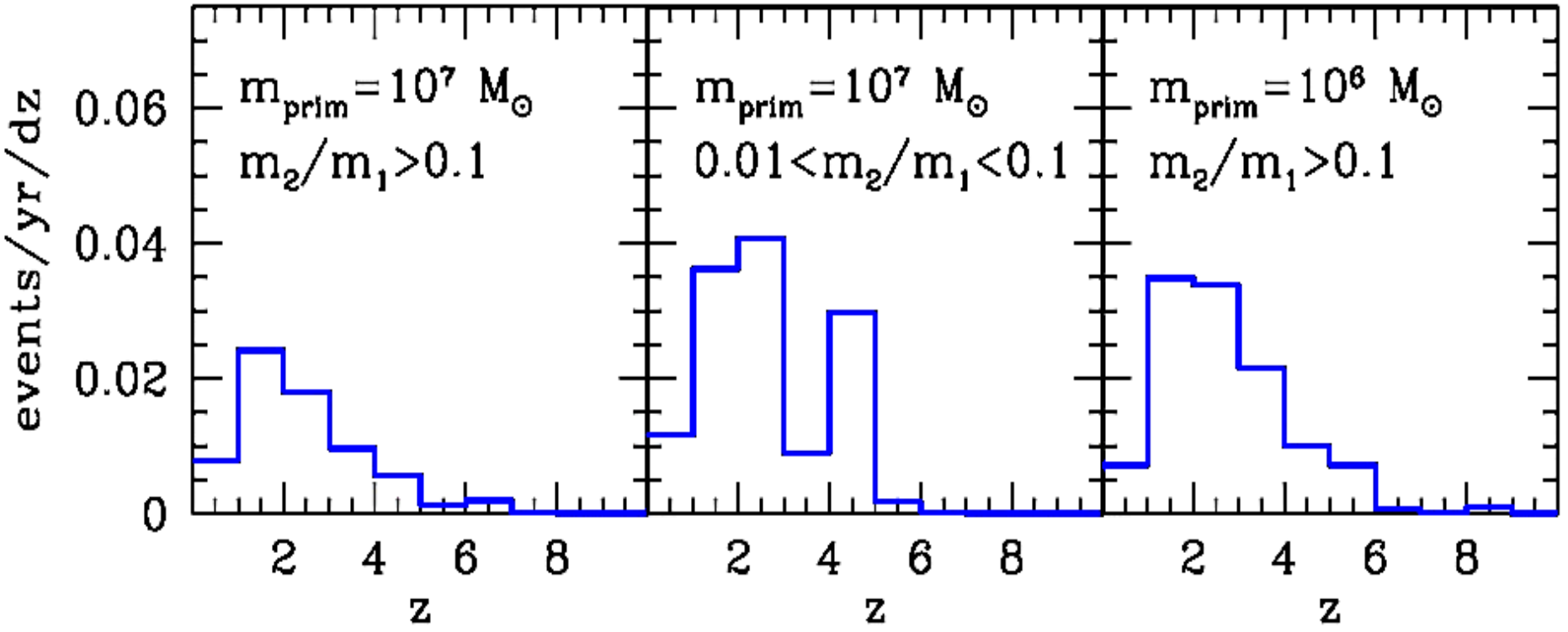




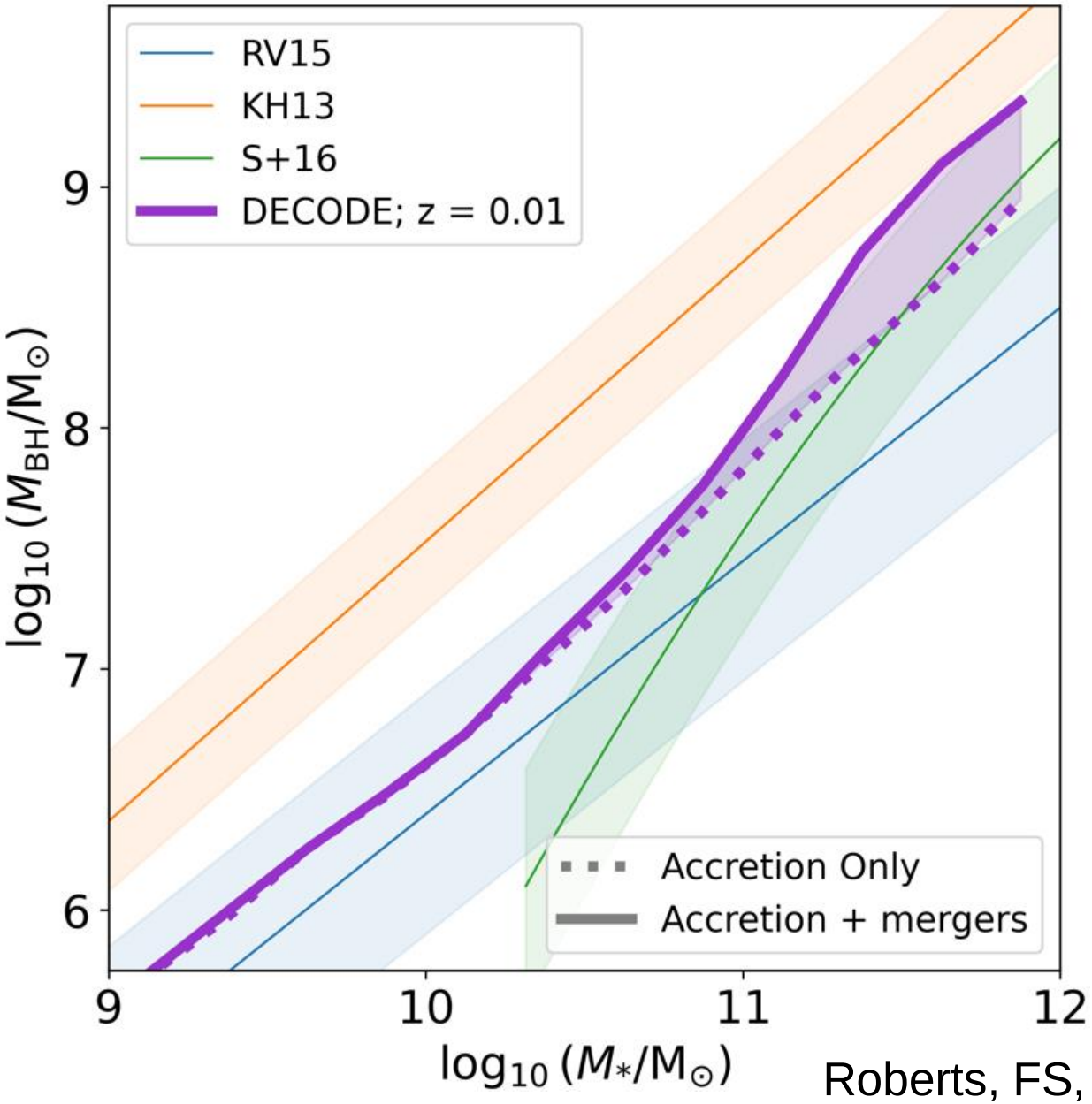
MPA-SAM (Kauffmann+)

Example of galaxy (bulge) merger rates that may favour supermassive black hole binaries and mergers

Haehnelt+03



Effect of mergers is modest



Roberts, FS, et al. in prep

Example of galaxy (bulge) merger rates that may favour supermassive black hole binaries and mergers

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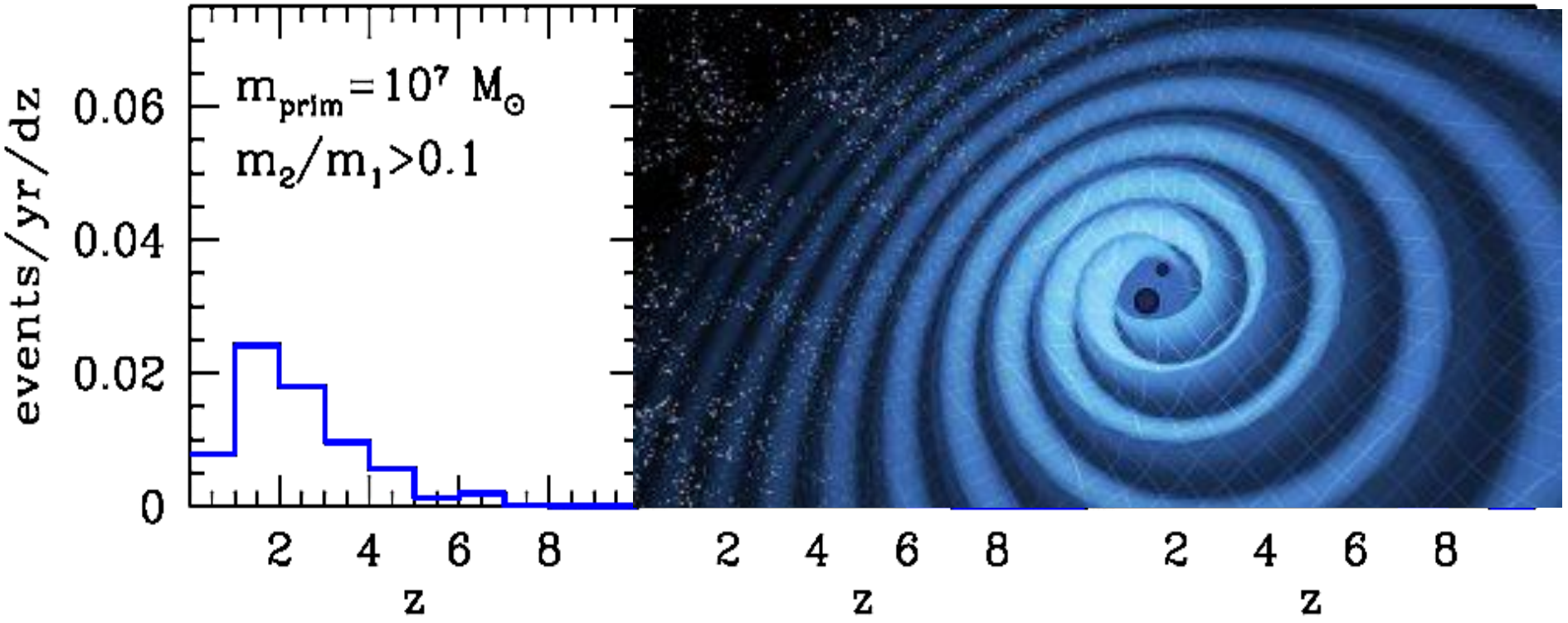
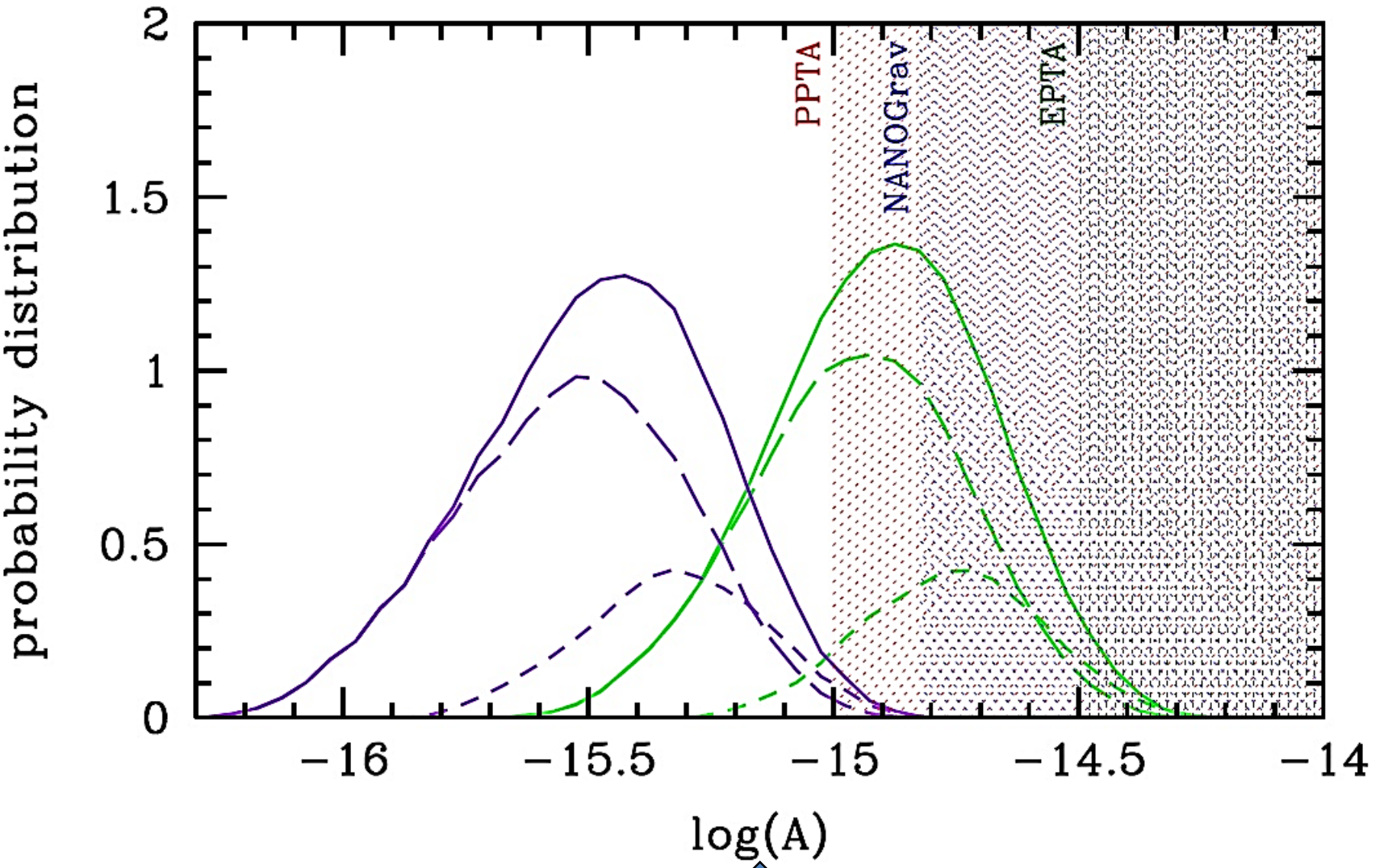


$$h_c^2(f) = \frac{4\,G^{5/3}}{3\,\pi^{1/3}\,c^2\,f^{4/3}} \int \frac{\mathrm{d}t}{(1+z)^{1/3}} \int \mathrm{d}M_\bullet\, M_\bullet^{5/3} \int \mathrm{d}q\, \frac{q}{(1+q)^2}\, \frac{\mathrm{d}^2\mathcal{R}_{\bullet\bullet\to\bullet}}{\mathrm{d}M_\bullet\,\mathrm{d}q}$$

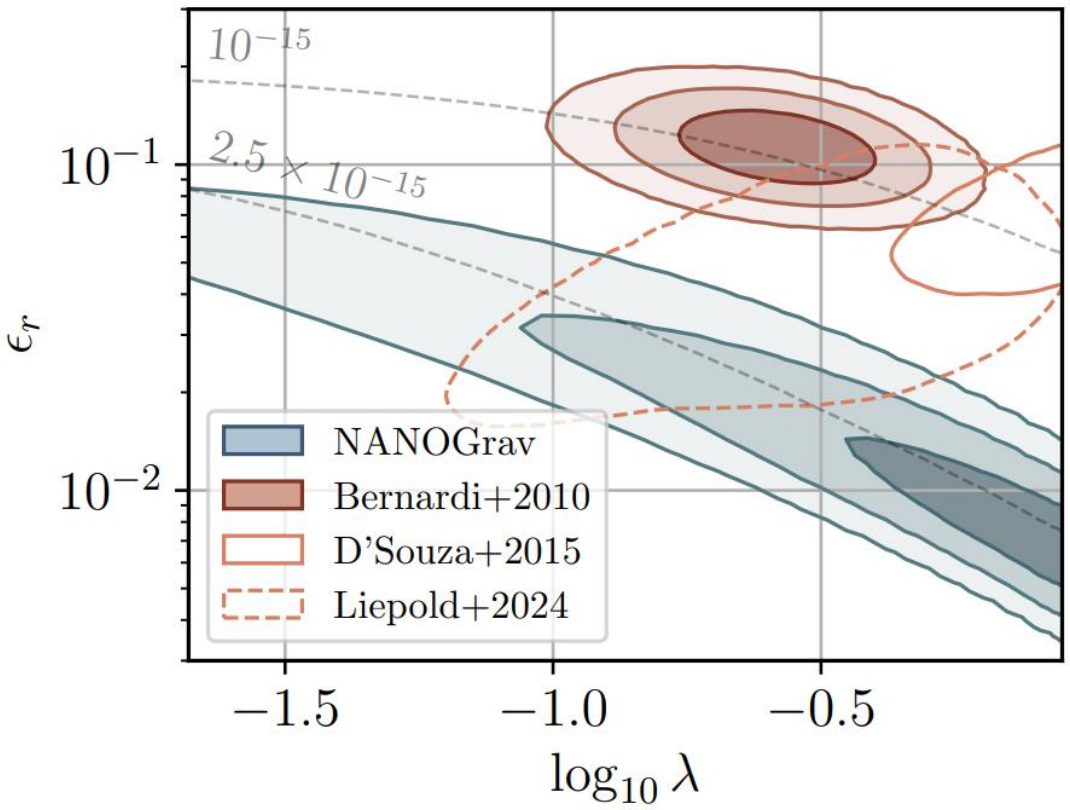
How much Gravitational Waves?



characteristic Amplitude GWs at f=1/yr

Sesana, FS, et al. 2016

How much Gravitational Waves?



G. Sato-Polito, M. Zaldarriaga, and E. Quataert, 2025

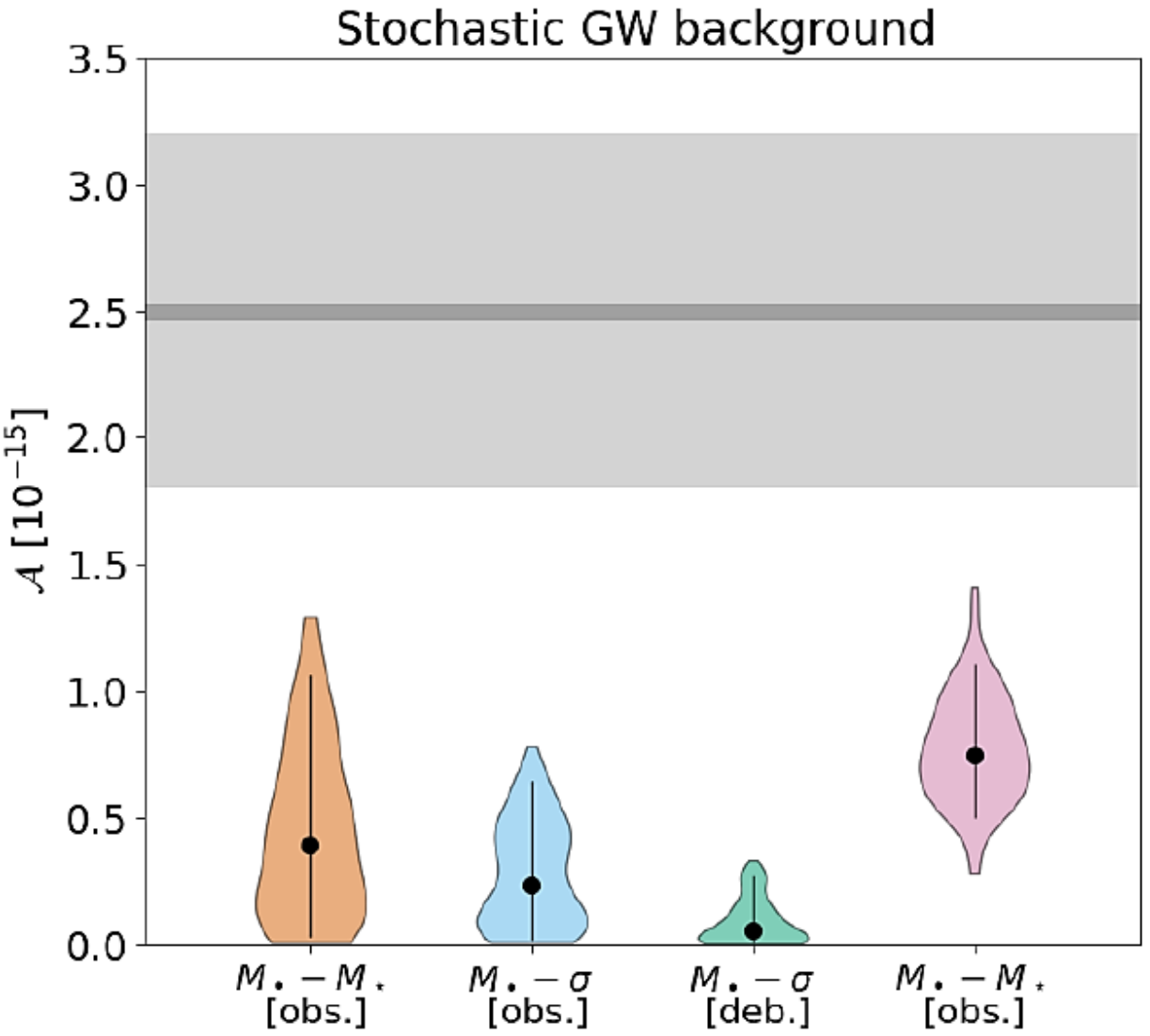
Red shaded region uses M_{BH}-σ relation

Dashed-line region uses M_{BH}-M* relation

Blue shaded region is from NANOGrav

Merger rates using a full semi-empirical model

How much Gravitational Waves?



characteristic Amplitude GWs at f=1/yr

Lapi..., FS, in prep.

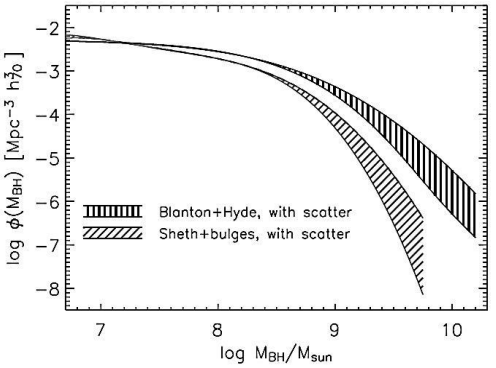
Take-home message III:

The predicted GW cumulative contribution of SMBH mergers to PTA may be subdominant

WHAT I DISCUSSED:

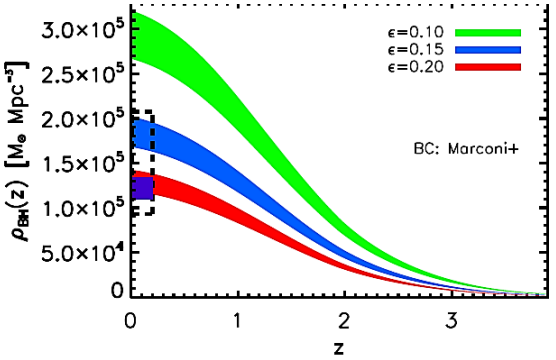
SMBH demography:

Unclear average masses



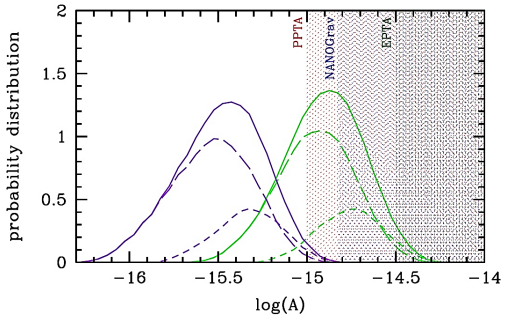
Evolution of SMBHs:

Accretion dominant

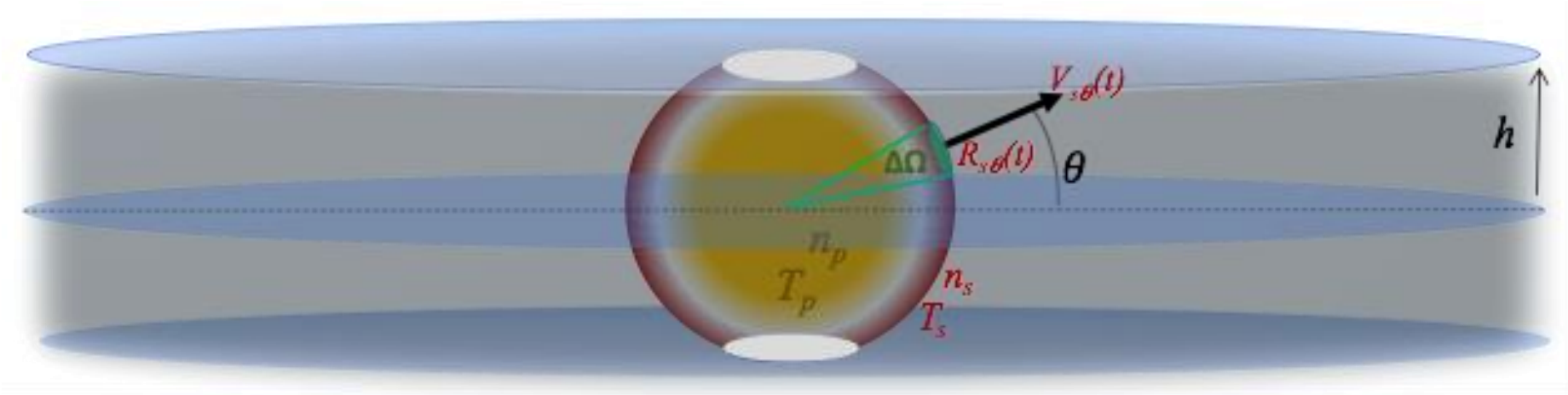


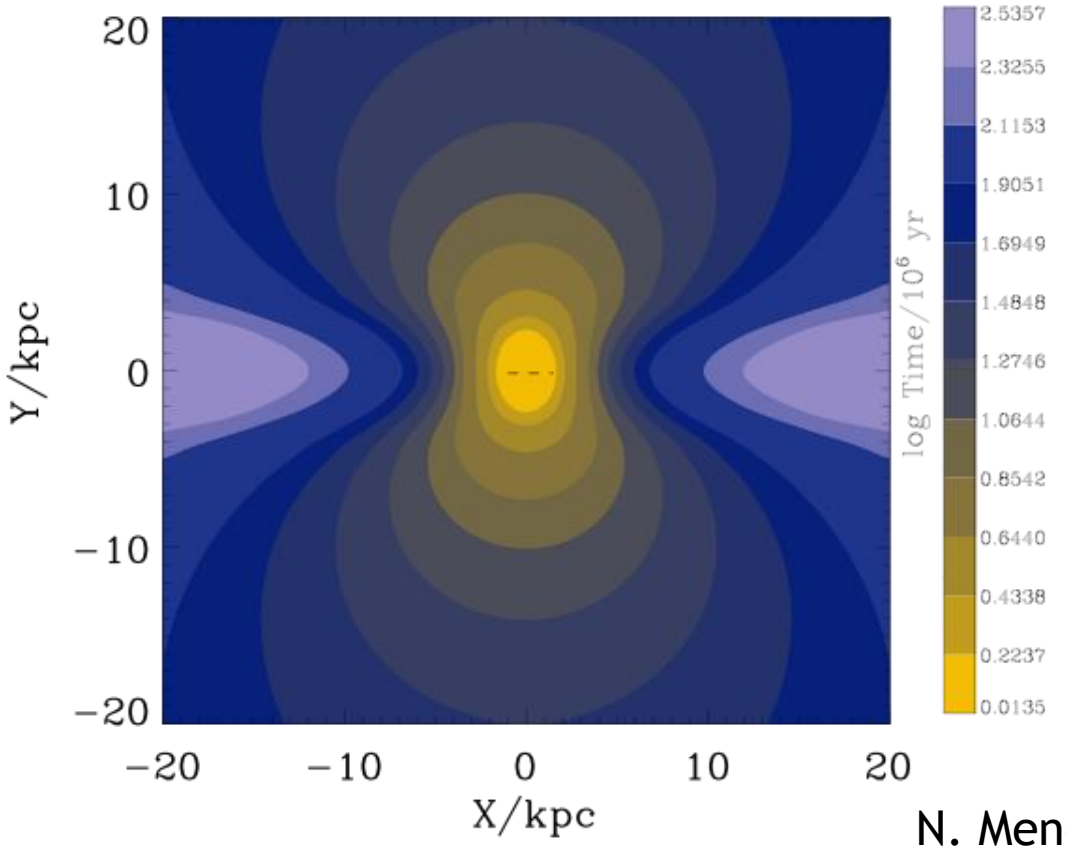
Physical implications:

Tension with PTA



Example of kinetic AGN feedback: Expansion of outflows at different azimuthal angles





N. Menci,..FS, et al. 2019

HOW EFFICIENT IS ACCRETION?
IT DEPENDS ON HOW CLOSE WE GET…

$$L = \frac{dU}{dt} = \frac{GM}{r}\frac{dm}{dt}$$

$$r = R_S = \frac{2GM}{c^2}$$

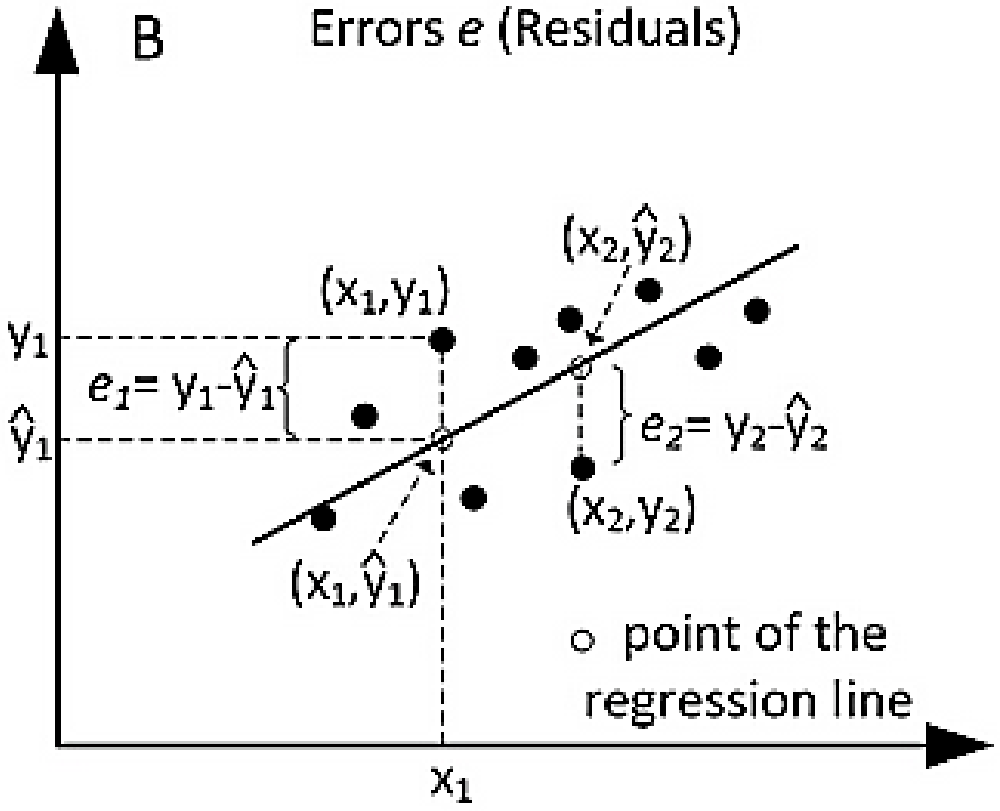
We can extract light/energy only for R>Rs

$$\Rightarrow L = \frac{GM}{2GM} \times c^2 \times \frac{dm}{dt} = \frac{1}{2}\frac{d(mc^2)}{dt}$$

$$\varepsilon = 0.1 - 0.4 >>>> \varepsilon_{STAR} \sim 0.008!!!!!$$

SMALL r BIG M-> VERY HIGH EFFICIENCY!!!

How do residuals work?



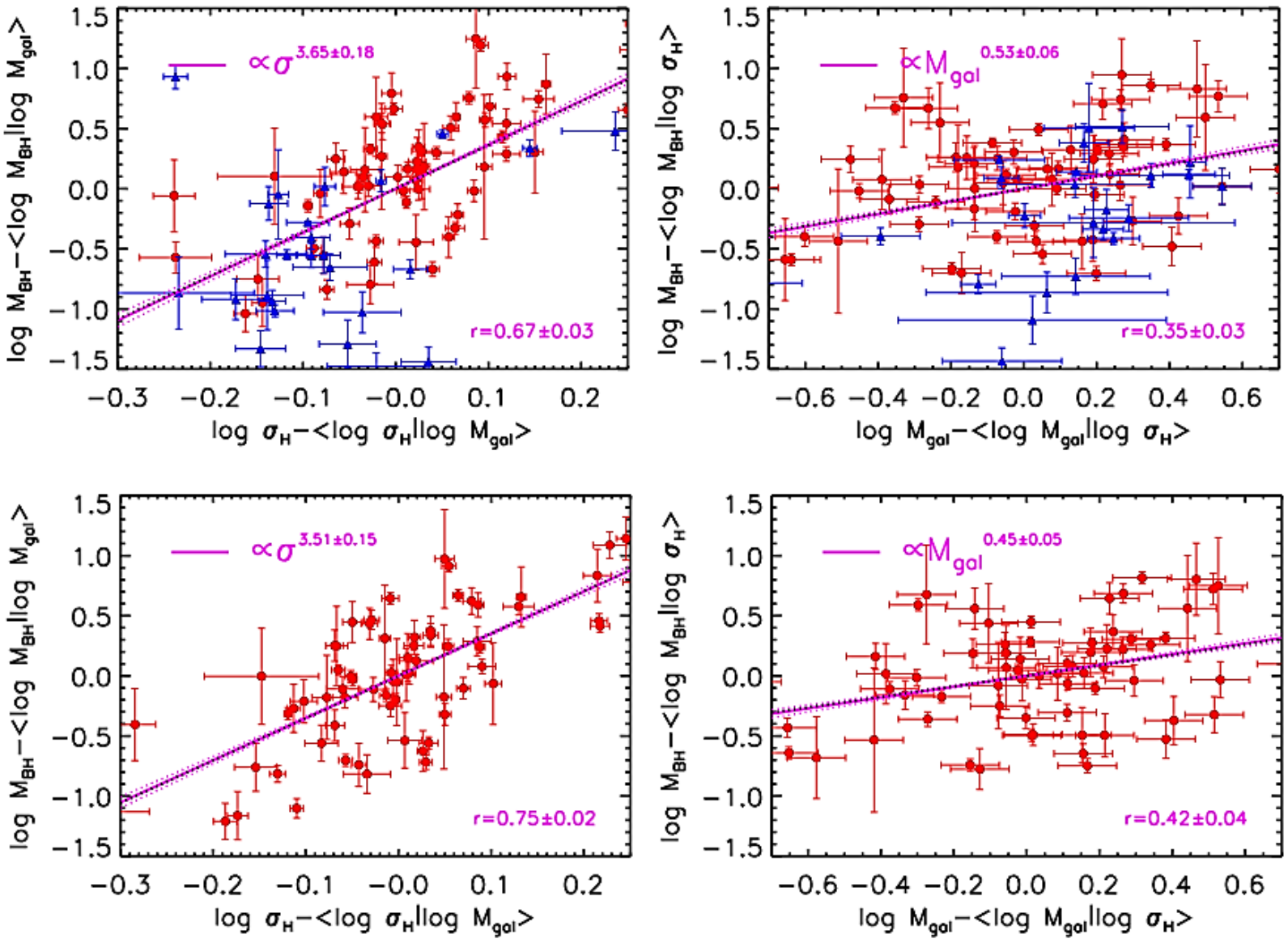
George Grekousis 2020

1) Calculate residuals of y(x)-y_fit(x)

2) Calculate residuals of z(x)-z_fit(x)

3) Calculate correlation coefficient between the two residuals, if strong then NO underlying correlation with x!

σ more fundamental than M_{gal}

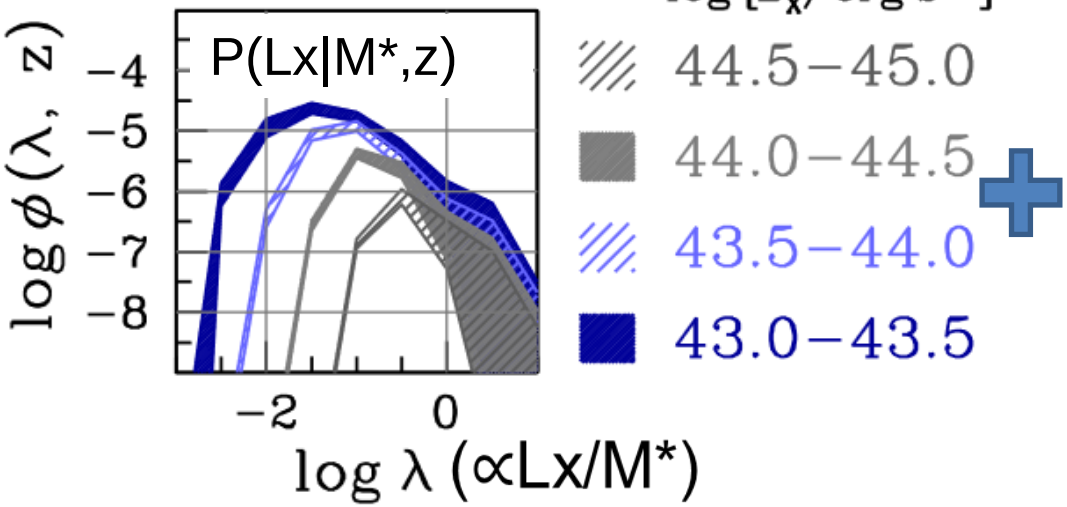


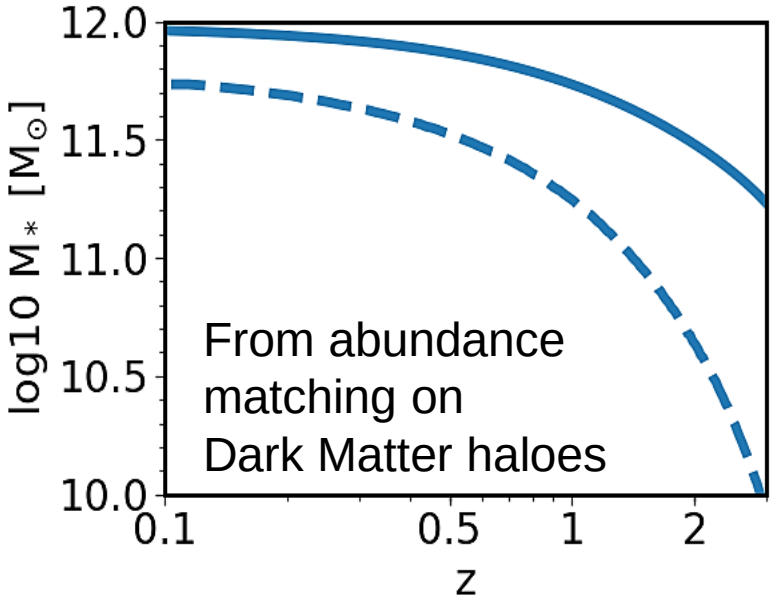
FS et al. MNRAS, in press

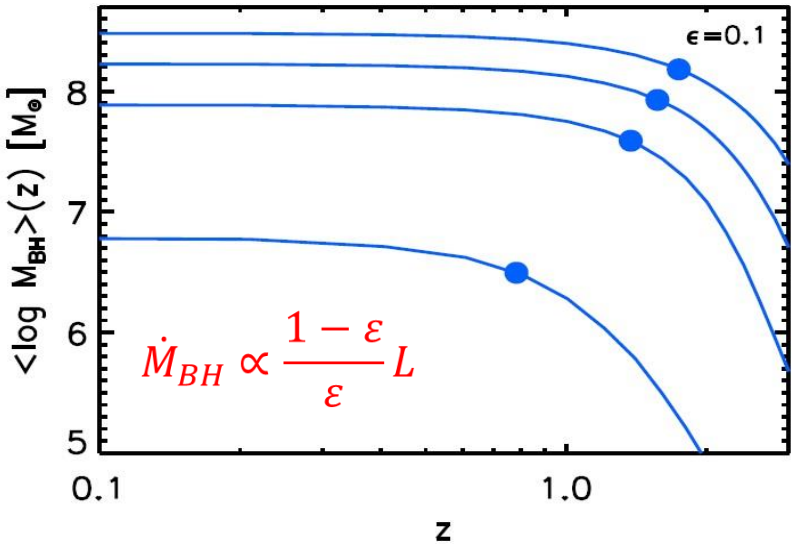
Data from Sahu et al. 2020

From P(Lx|M*,z) relation to SMBH scaling relations

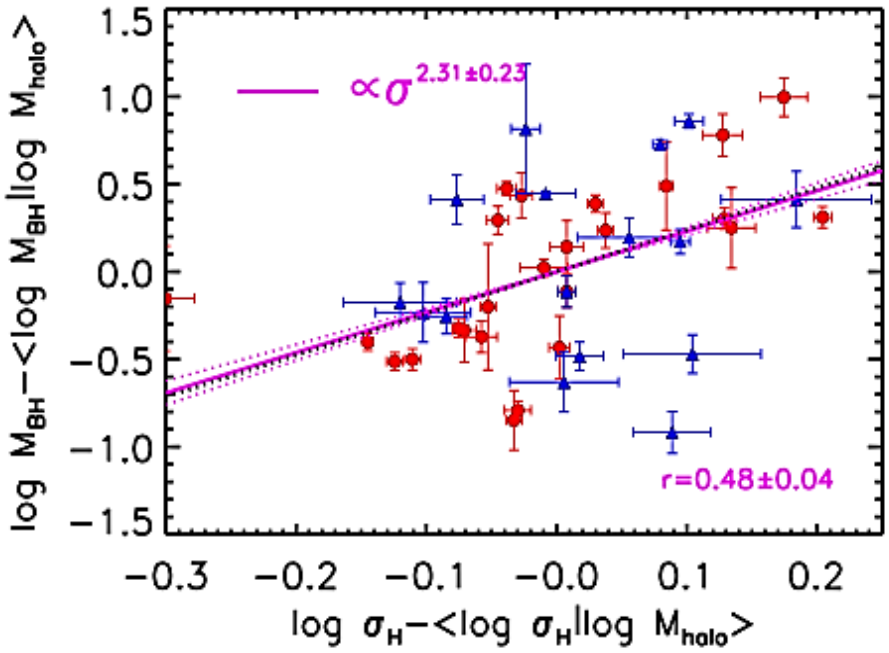
Georgakakis+,
Aird+, Bongiorno+

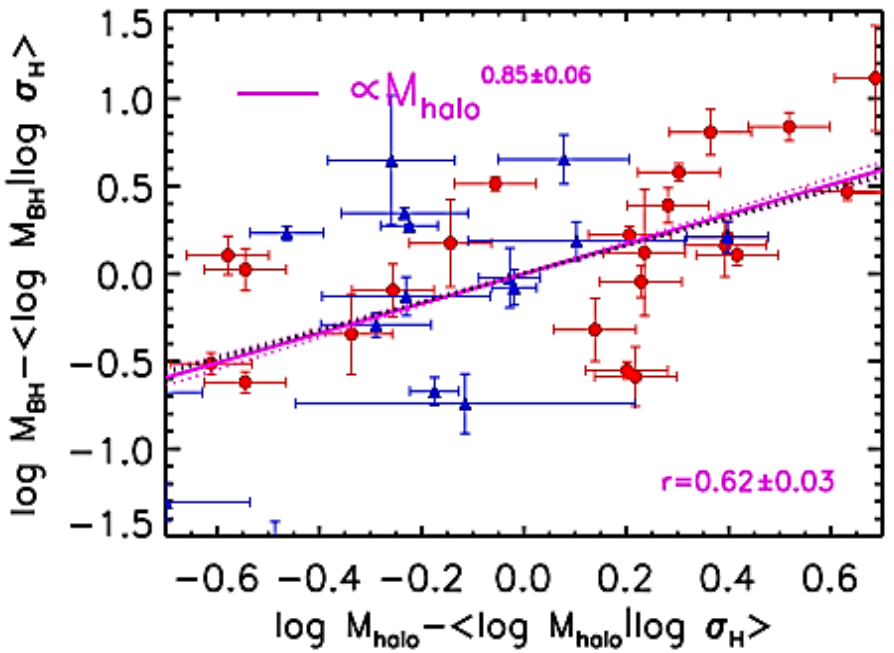






M_{halo} more fundamental than σ?

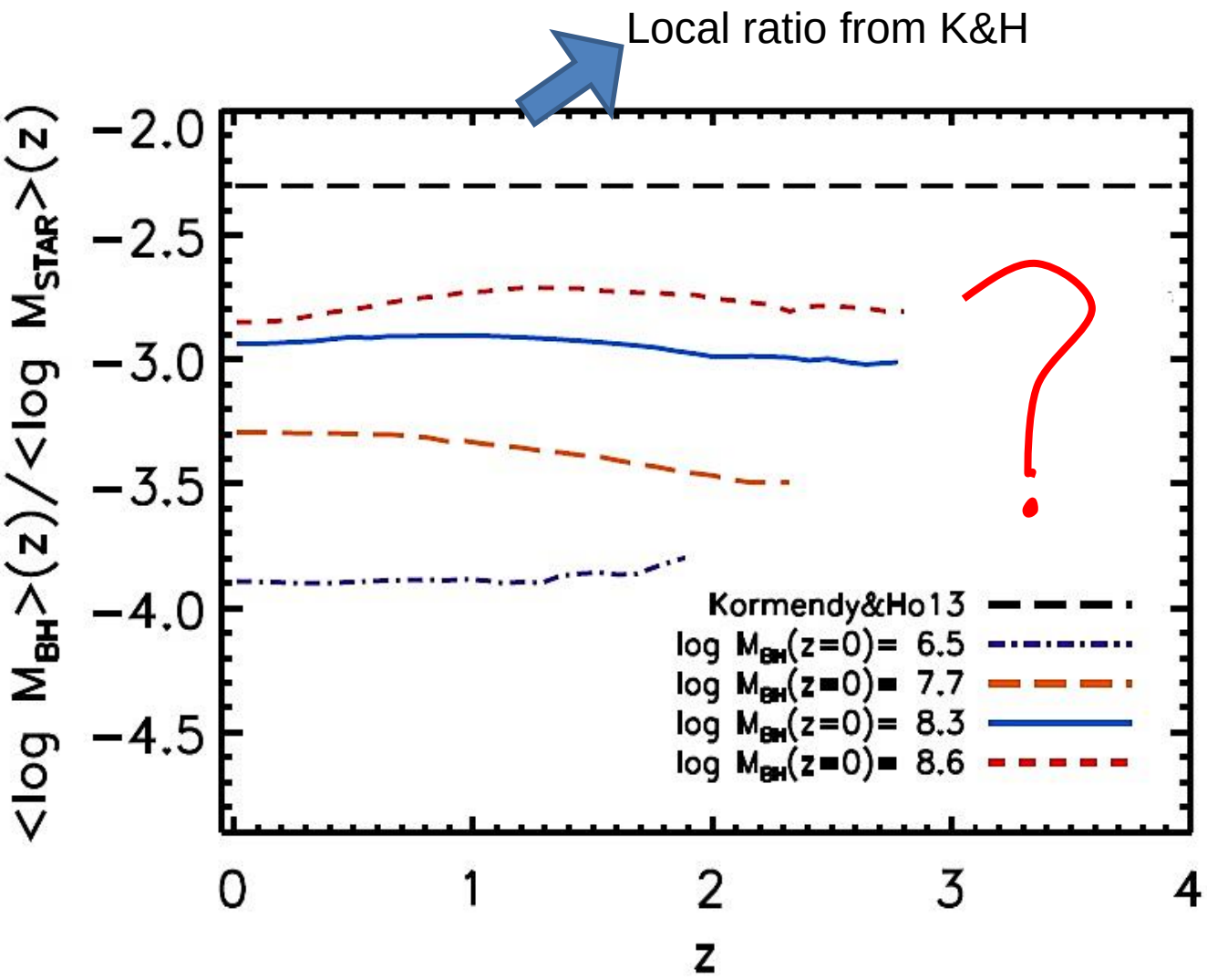




FS et al. MNRAS, in press

Data from Sahu et al. 2023+Marasco et al. 2021

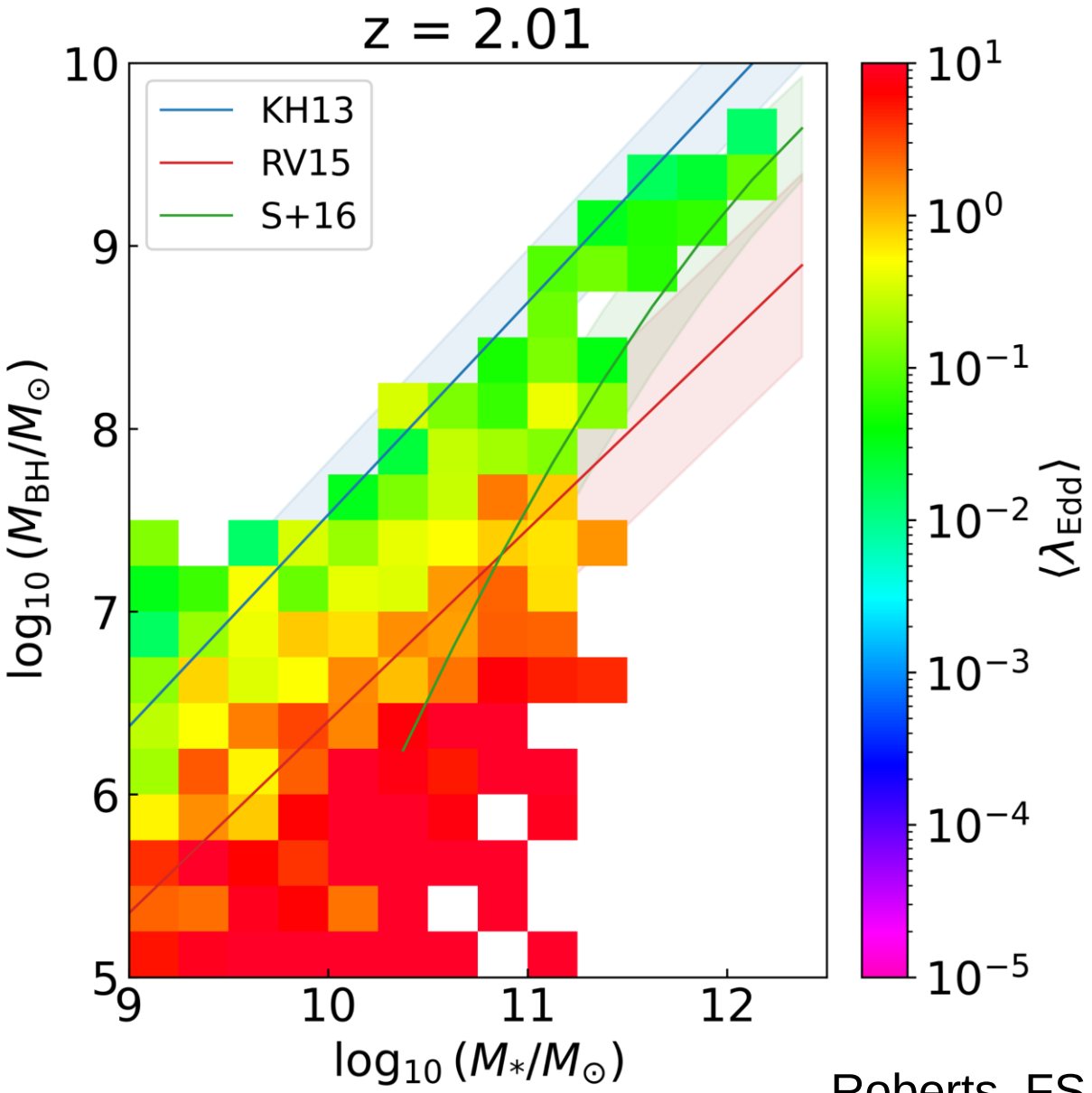
Almost constant evolution of Mbh-Mgal relation



…but
mass-dependent

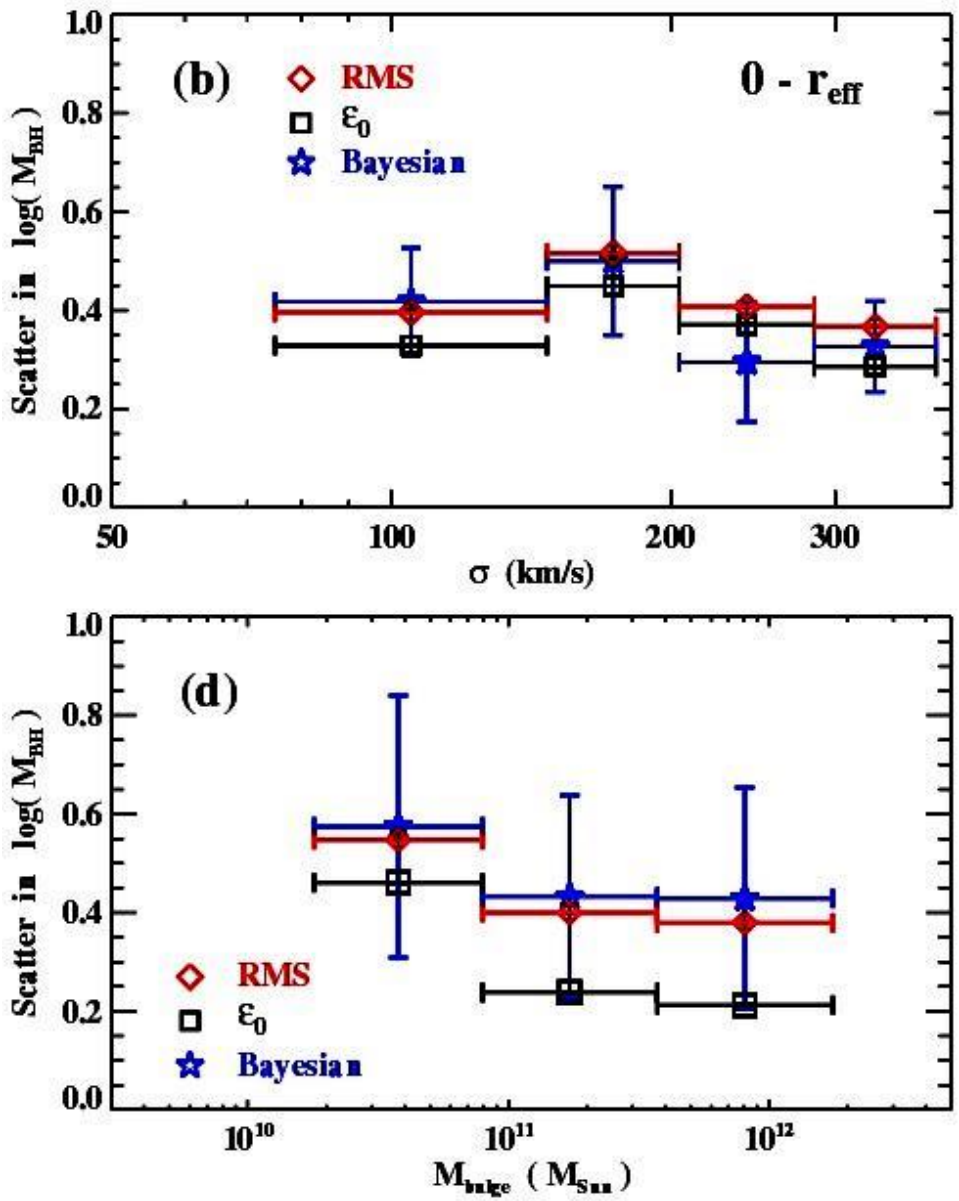
FS+20, as in direct observations from, e.g.,
Suh+20, Carraro+20, Tanaka+24...

Scatter depends on Eddington ratio!



Roberts, FS, et al. in prep

Is the Mbh-σ the most fundamental?

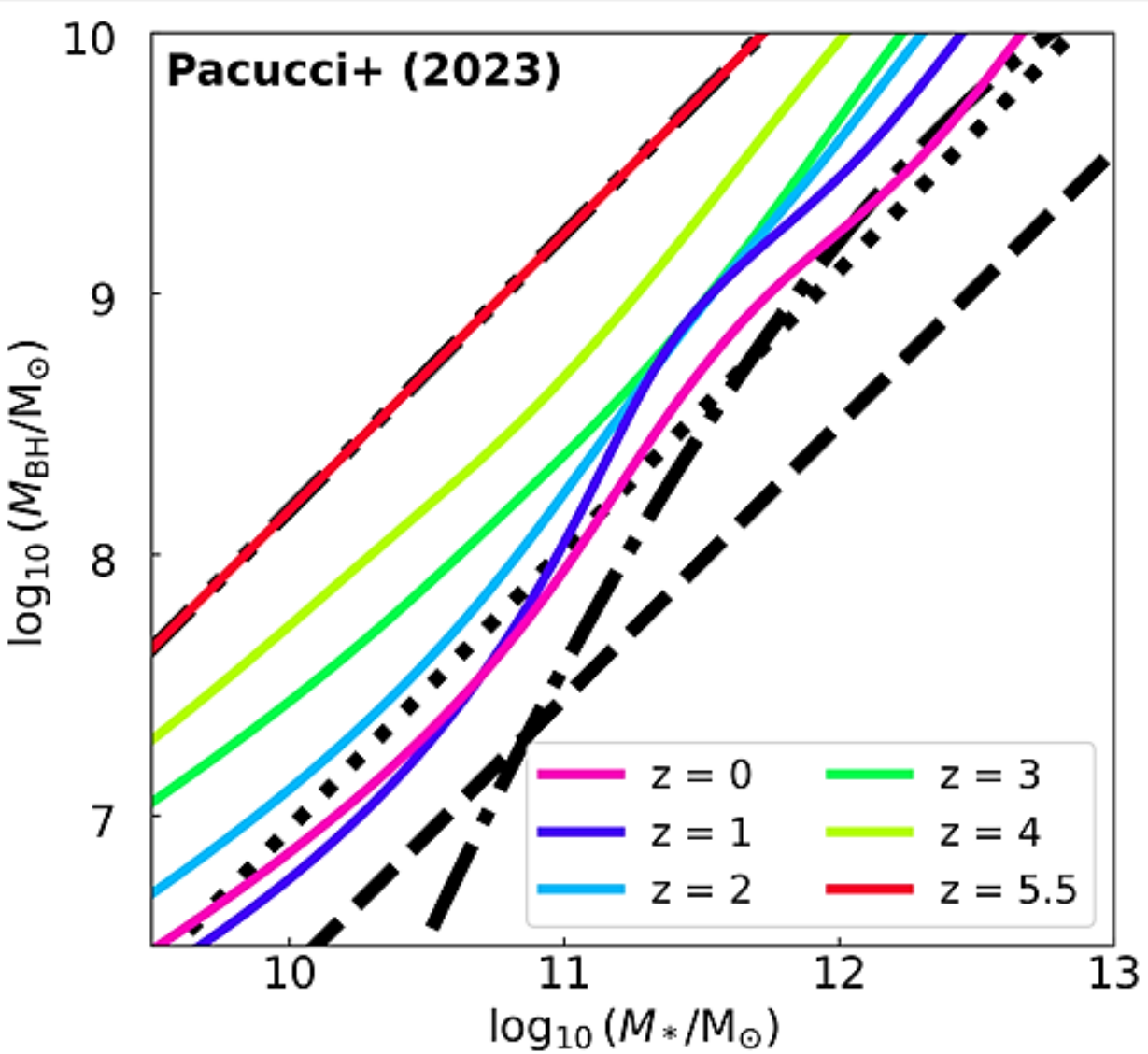


Scatter always ranging within 0.3-0.5 dex

RESIDUALS!

McConnell+Ma 13

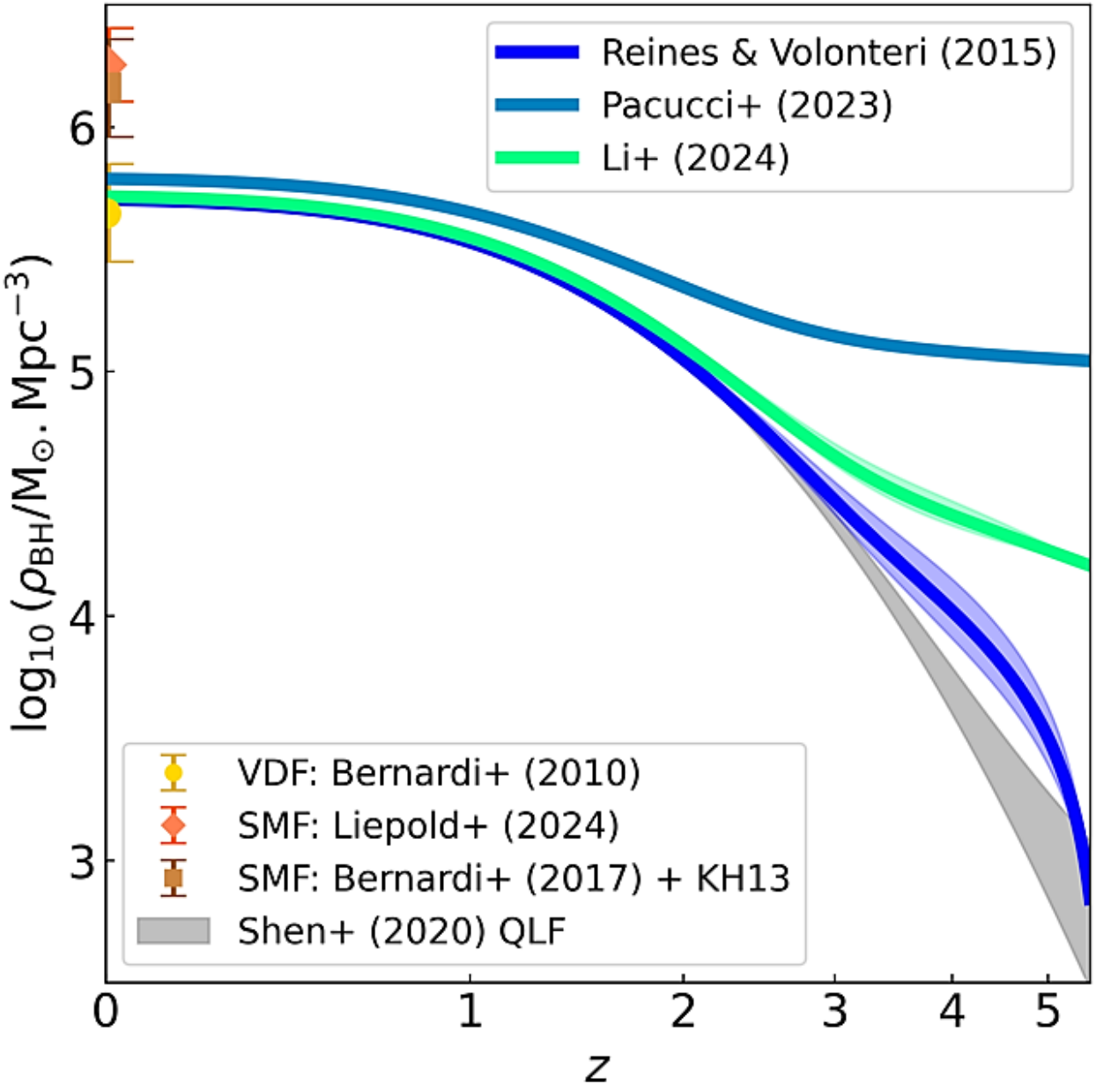
High-z conditions little effect on local demography



Accretion models predict that even starting from very high ICs, the z=0 tends to line up with the local relation

Roberts, FS, in prep

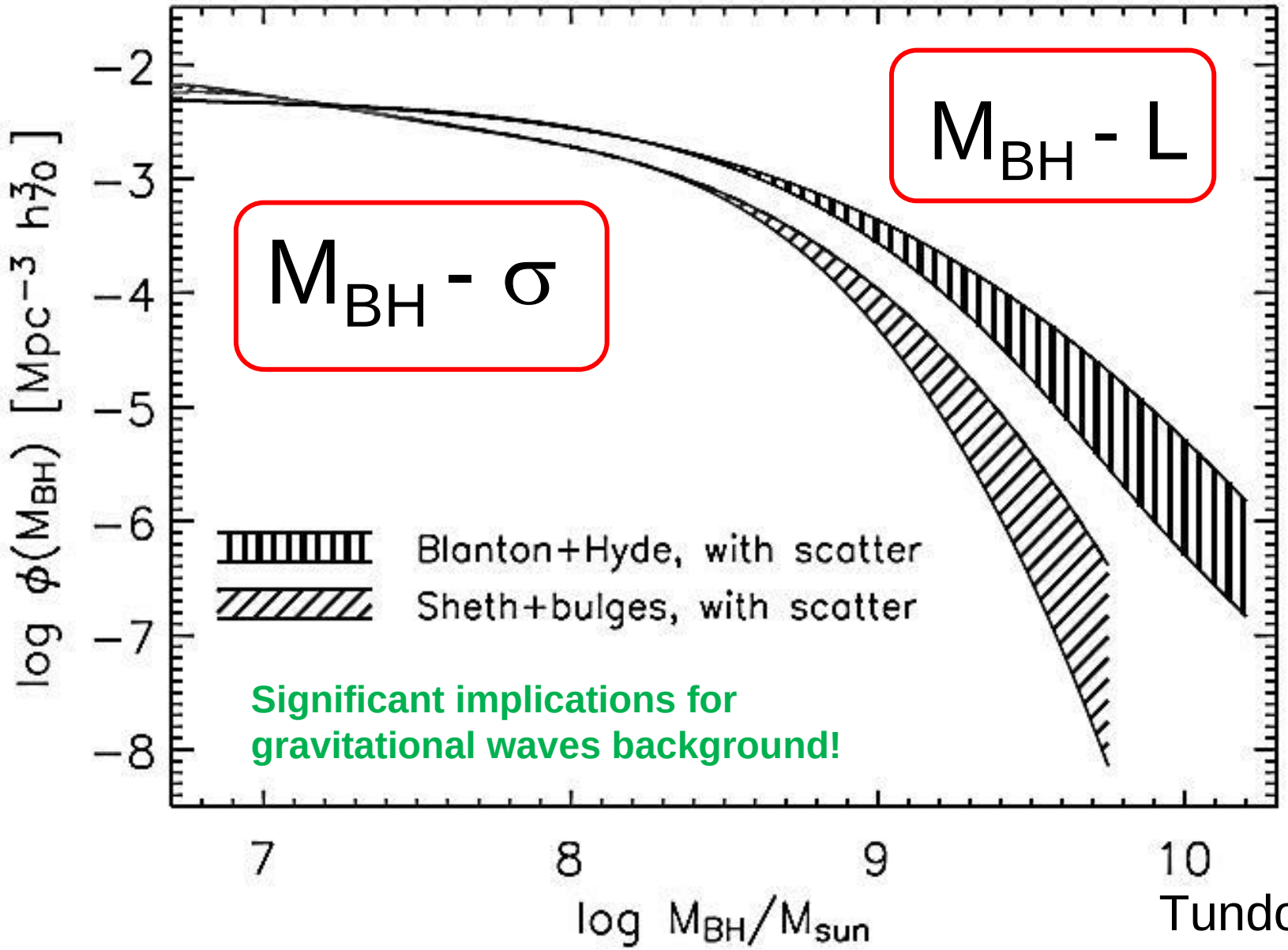
High-z conditions little effect on local demography



High Initial Conditions necessarily imply mild evolution in the integrated SMBH mass density!

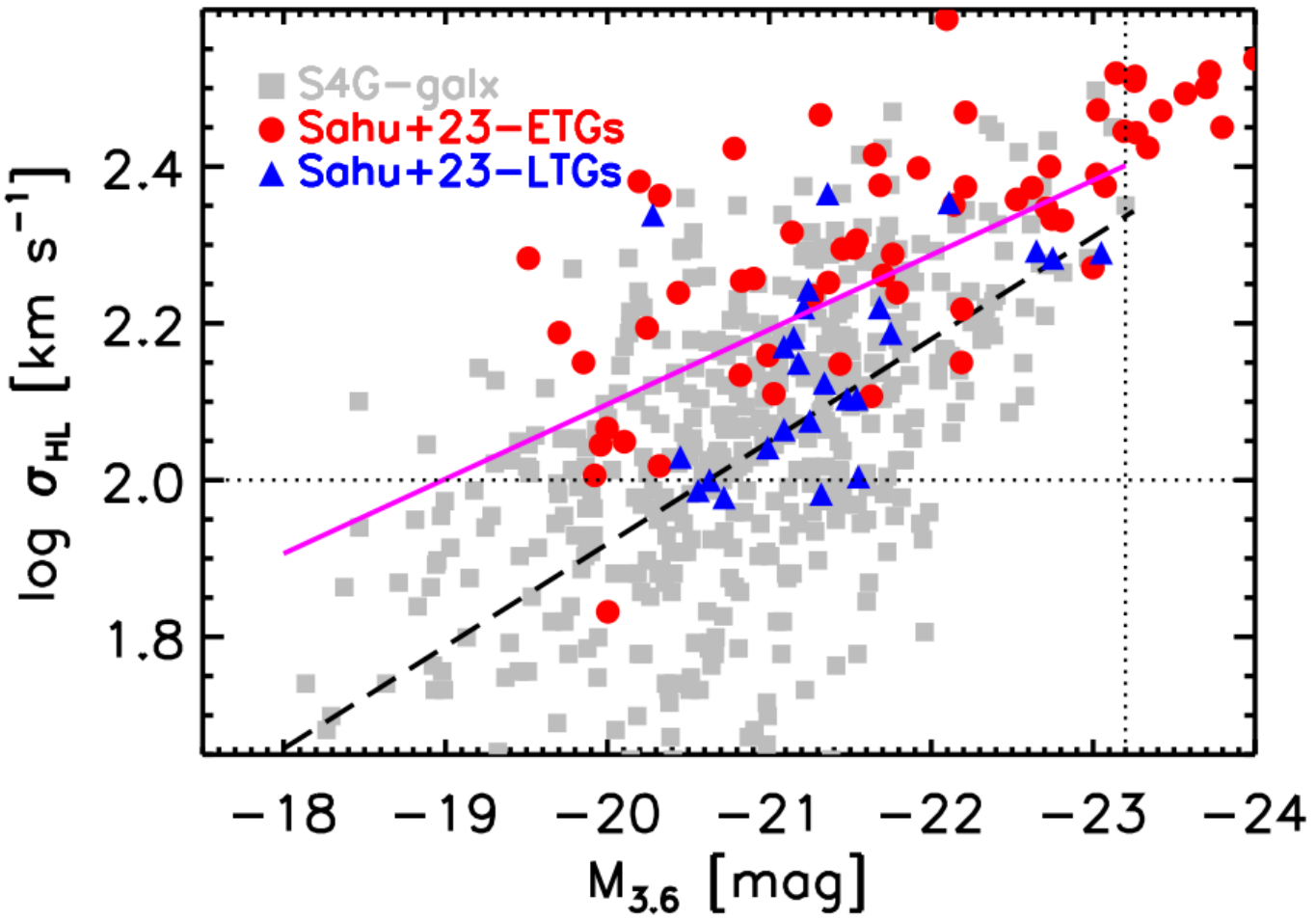
Roberts, FS, in prep

Two SMBH mass functions?



Tundo+07

Beware of bias!



SMBH local sample biased high compared to all local galaxies?
Observational or physical bias?

FS et al. MNRAS, resubmitted