# What drives the non-linear growth of supermassive black holes in galaxies?




OAS Astrophysical Colloquium

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*On behalf of:*

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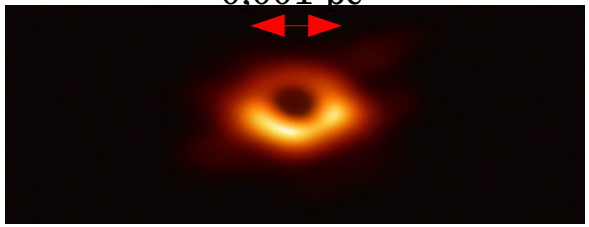
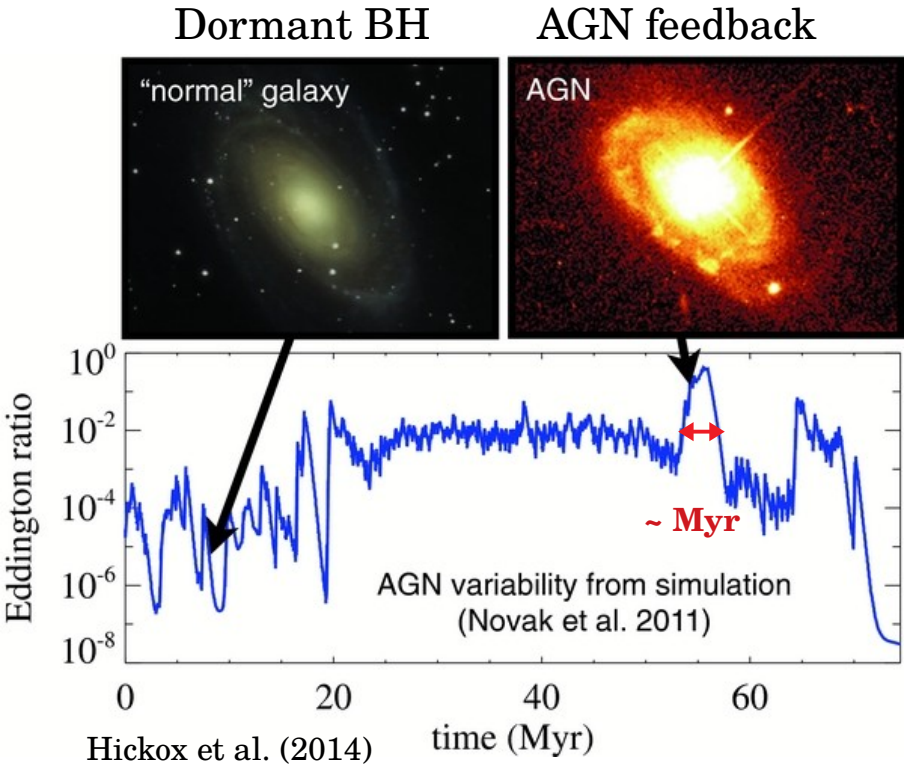
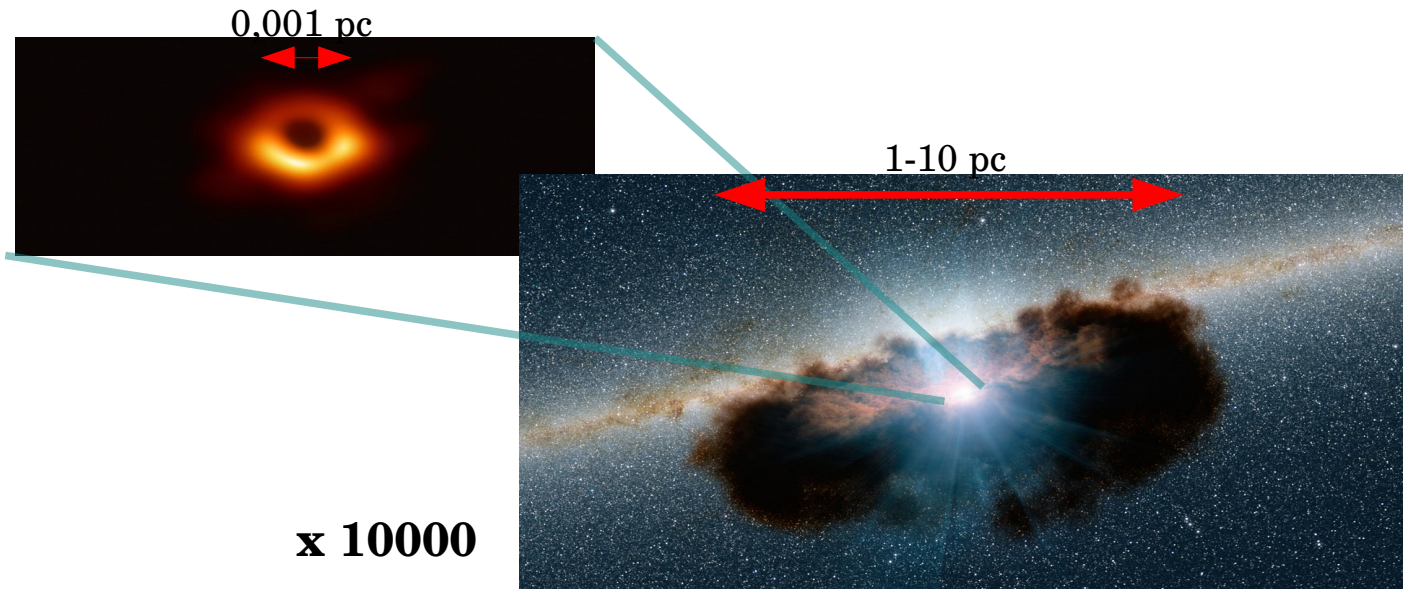
# Supermassive black hole




$M_{BH} = 10^6 - 10^{10}\ M_{sun}$

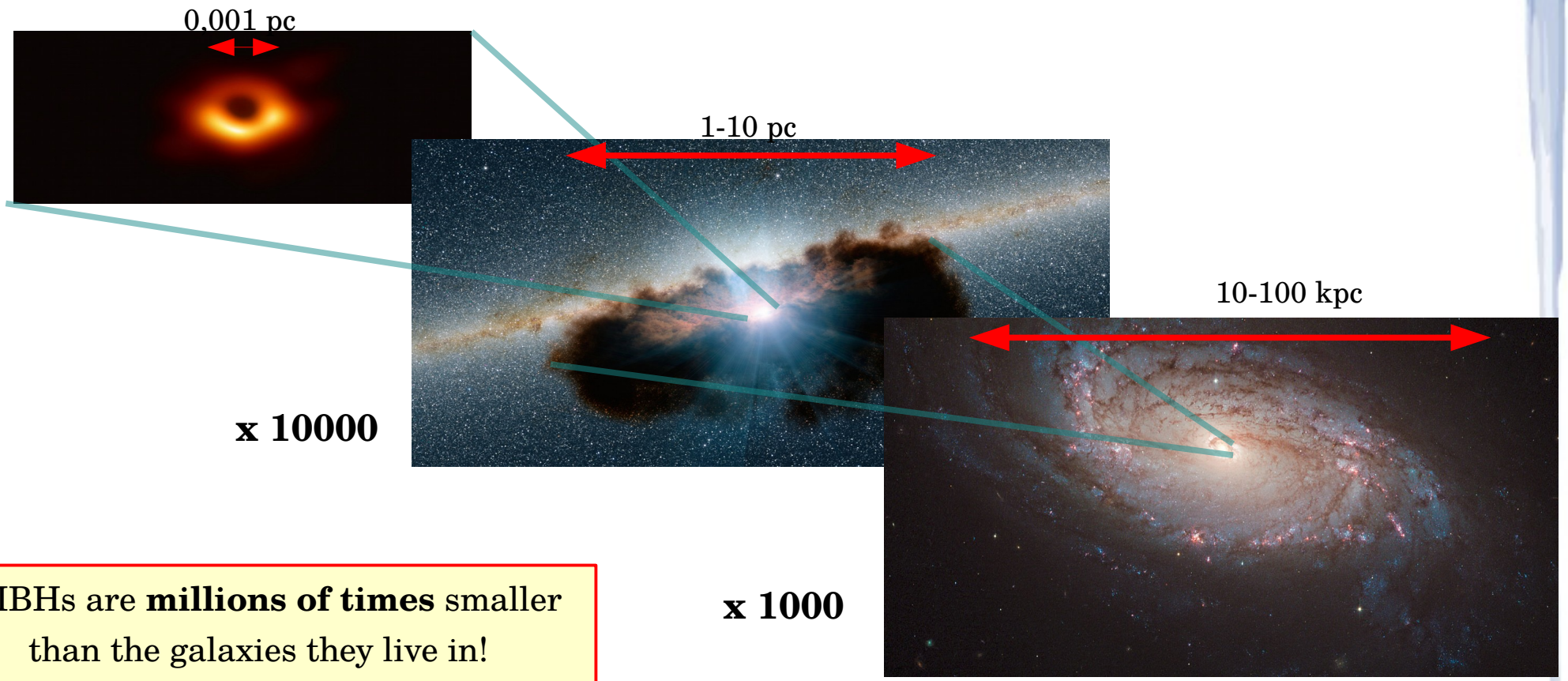


# BH sphere of influence




- BH sphere of influence: $$r_{BH} = \frac{G\,M_{BH}}{\sigma_\star^2} = 10.7\,\mathrm{pc}\left(\frac{M_{BH}}{10^8\,M_\odot}\right)\left(\frac{\sigma_\star}{200\,\mathrm{km/s}}\right)^{-2}$$
- Dynamical $M_{BH}$ limited to bigger BHs for which we can spatially resolve the sphere of influence

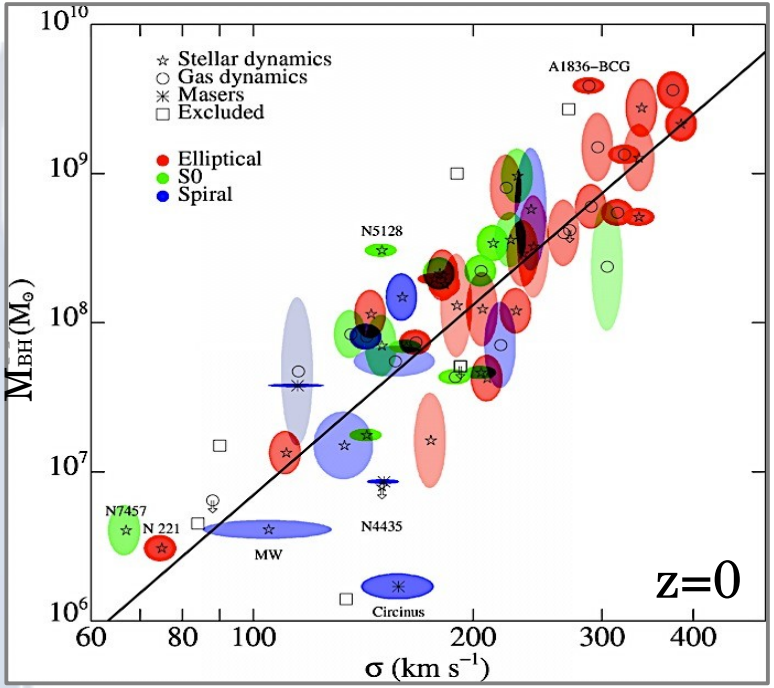
# Mind the gap




SMBHs are **millions of times** smaller than the galaxies they live in!

# Galaxies and SMBHs know each other

Magorrian (1998); Ferrarese & Merritt (2000); Marconi & Hunt (2003); Haring & Rix (2004); Gultekin et al. (2009); Kormendy & Ho (2013)




- Black hole masses correlate with various properties of "classical bulges":

  - stellar velocity dispersion $\sigma_*$
  - bulge mass (<1:200)
  - bulge luminosity

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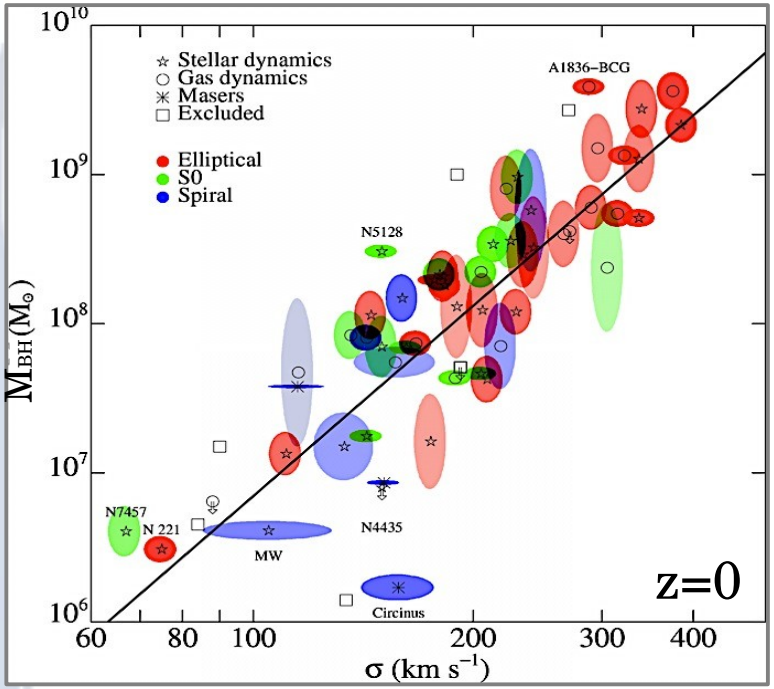
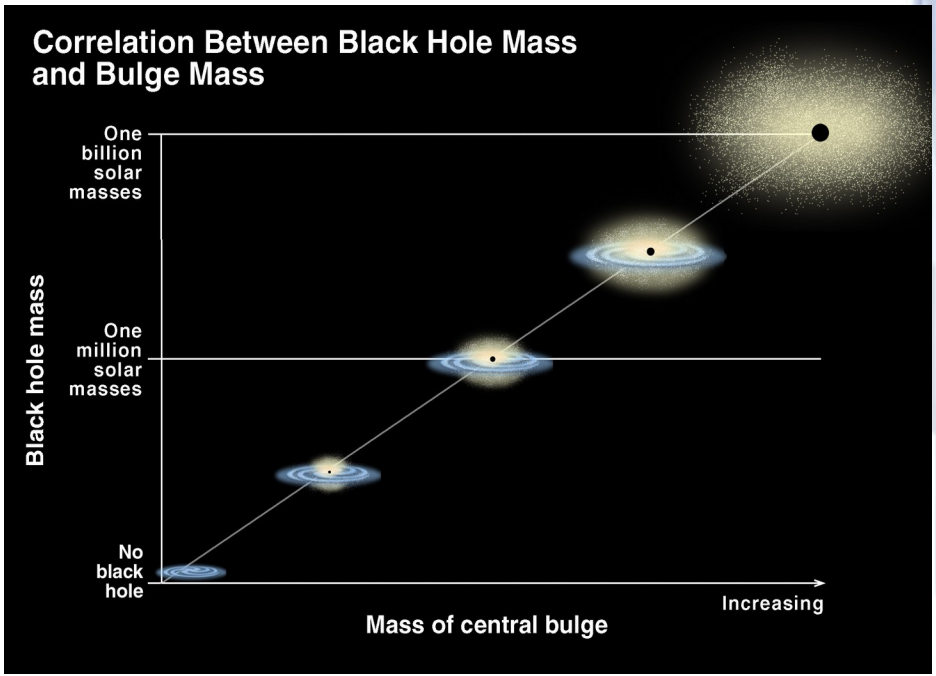
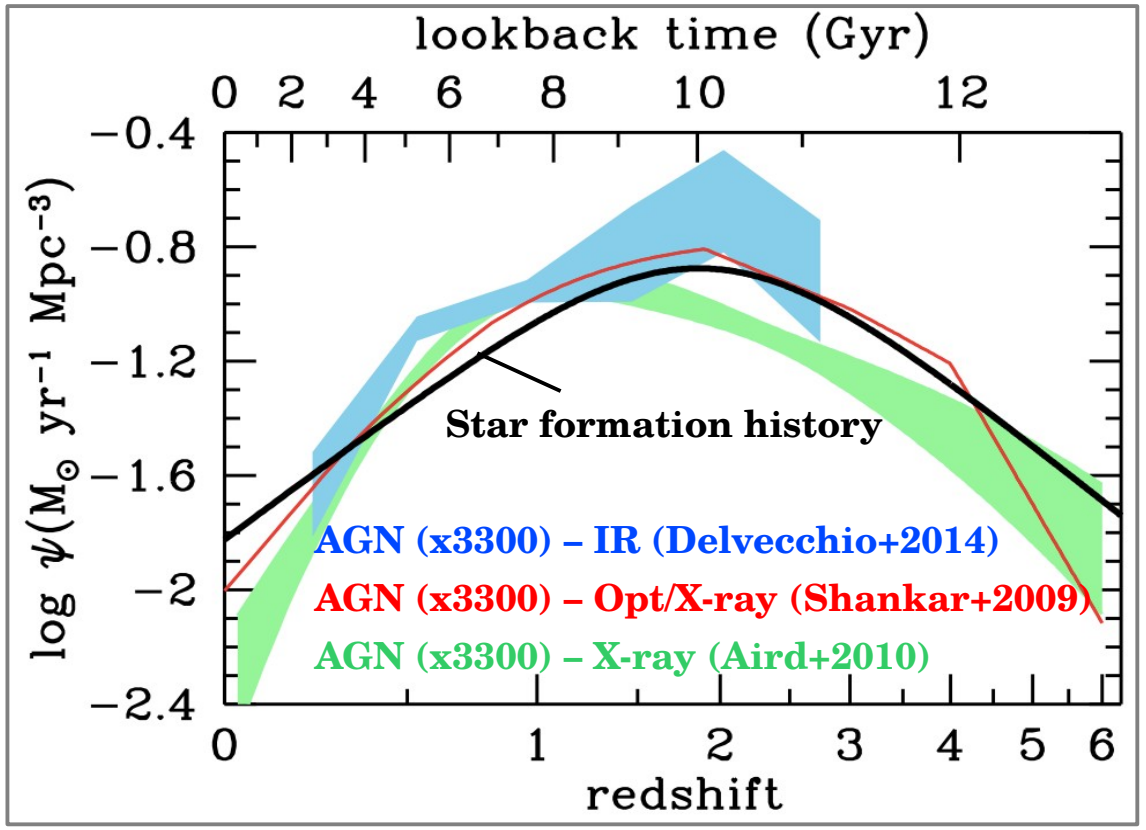



- At z~0 bigger galaxies contain bigger black holes.
- But nearly all today's BHs are quiescent…
- Possible imprinting of a past AGN/galaxy co-evolution epoch?

# Looking back in time: statistical (co-)evolution




Madau & Dickinson (2014)

The total luminosity density produced via **BH accretion** and **star formation** peaked at 1<z<3 and declined towards z=0 .

↓

Why?

# What fuels galaxy and BH growth?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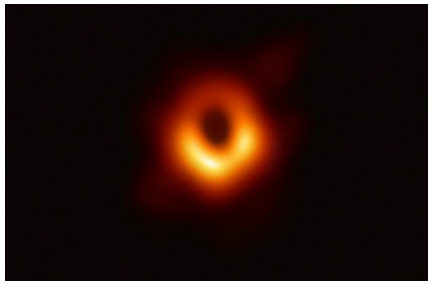
# Feeding BH growth via gas accretion

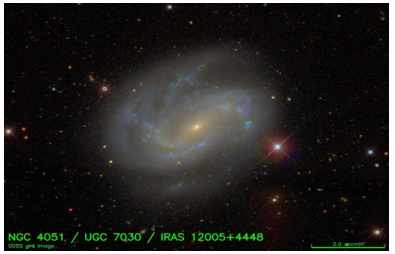


**BHAR** $\propto (1-\epsilon)/\epsilon \cdot L_X$

**ε:** radiative efficiency [0.06:0.42] ~ 0.1

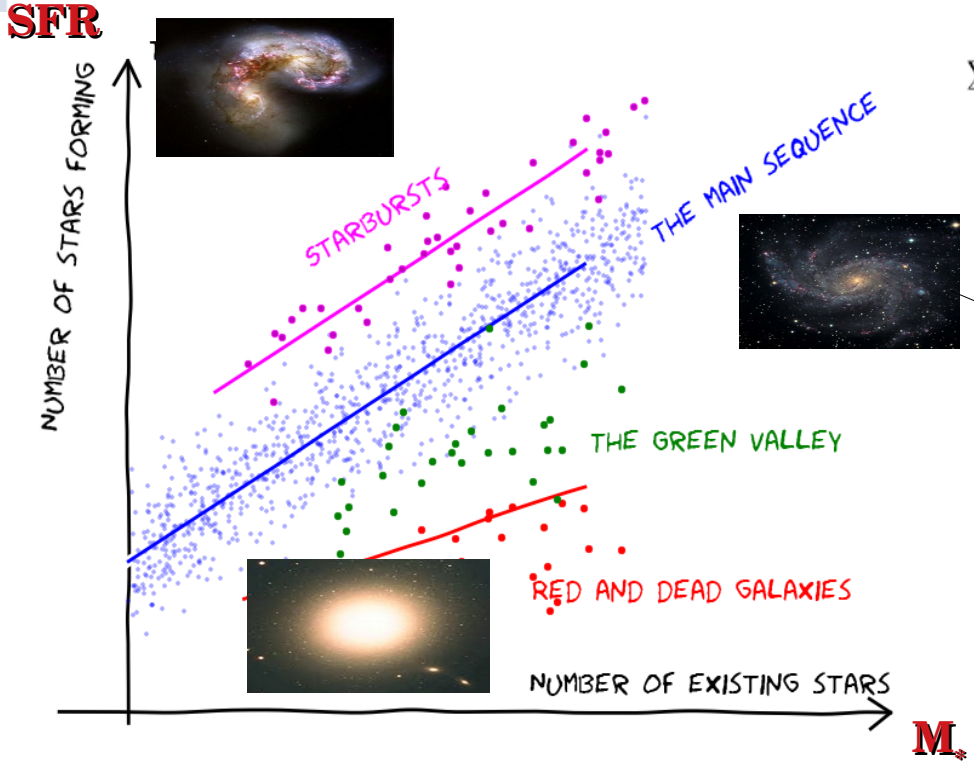
BHAR

Quasars




Low-Luminosity AGN

# Feeding SF via gas accretion




*Schmidt-Kennicutt law* (Schmidt 1959, Kennicutt 1998)

$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{gas}}{1\ M_\odot\ \mathrm{pc}^{-2}}\right)^{1.4\pm0.15} \quad \mathrm{M_\odot\ yr^{-1}\ kpc^{-2}}$$

"Star forming" *main-sequence* (MS):

- Tight correlation (scatter ~ 0.3 dex)
- Roughly 85-90% of the global star formation history (Sargent et al. 2012)
- Star formation driven by stochastic gas accretion (Dekel et al. 2009; Ciotti et al. 2010).

(Noeske et al. 2007; Elbaz et al. 2011; Whitaker et al. 2012; Speagle et al. 2014; Schreiber et al. 2015; Scoville et al. 2017 etc).

# Feeding vs Feedback self-regulation

Gas feeding

Stellar/AGN feedback

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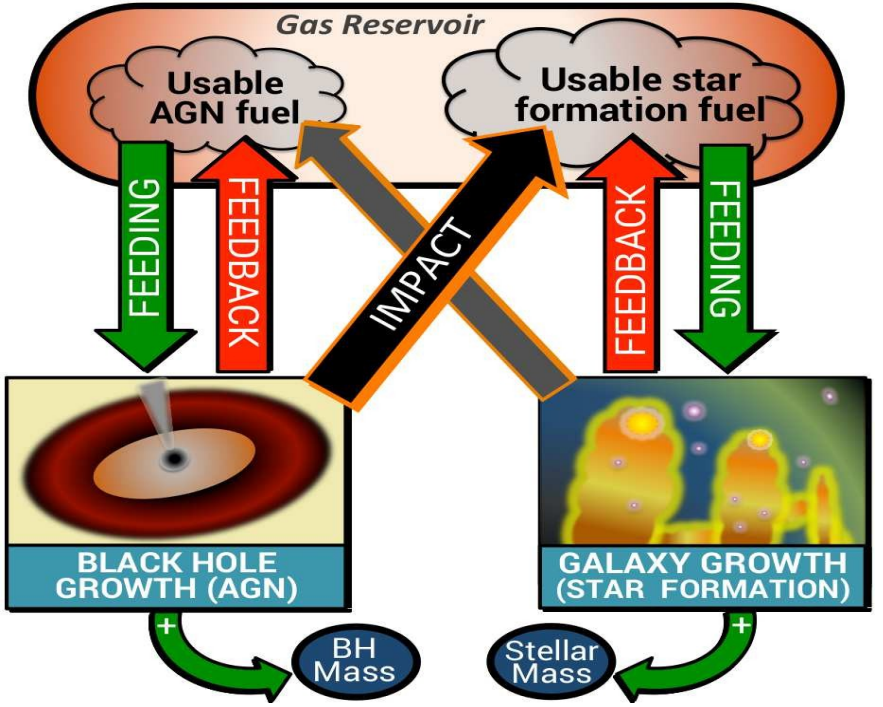
Gas feeding

Stellar/AGN feedback

Harrison et al. (2017)




$$M_{BH} = \int BHAR \, dt$$

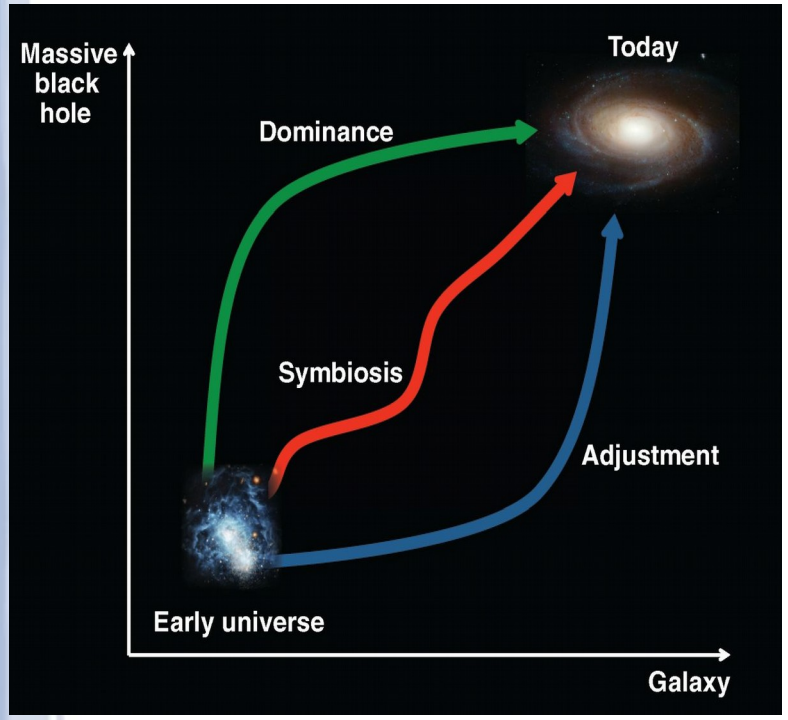
BH accretion rate (BHAR)

$$M_{*} = \int SFR \, dt$$

Star formation rate (SFR)

# Linear or non-linear growth?

Volonteri (2010)

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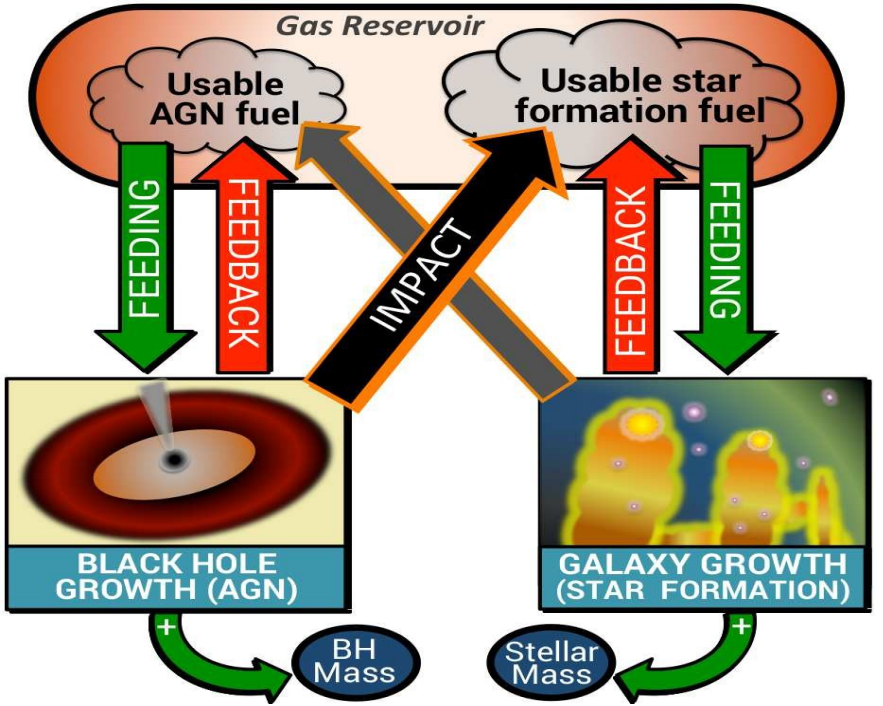


Have BHs and galaxies followed a symbiotic growth over cosmic time?

$$M_{BH} = \int BHAR \, dt$$

BH accretion rate (BHAR)

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Star formation rate (SFR)

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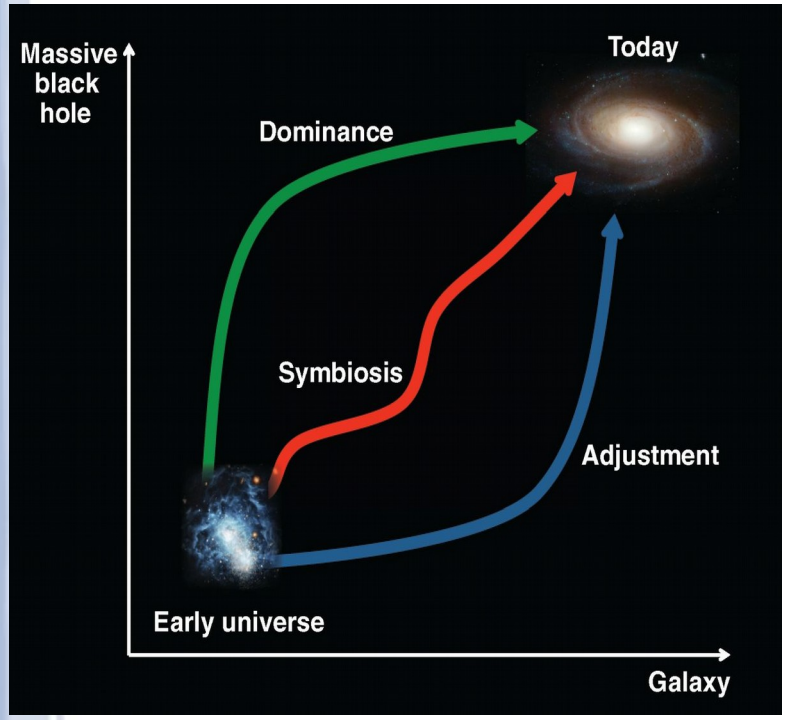


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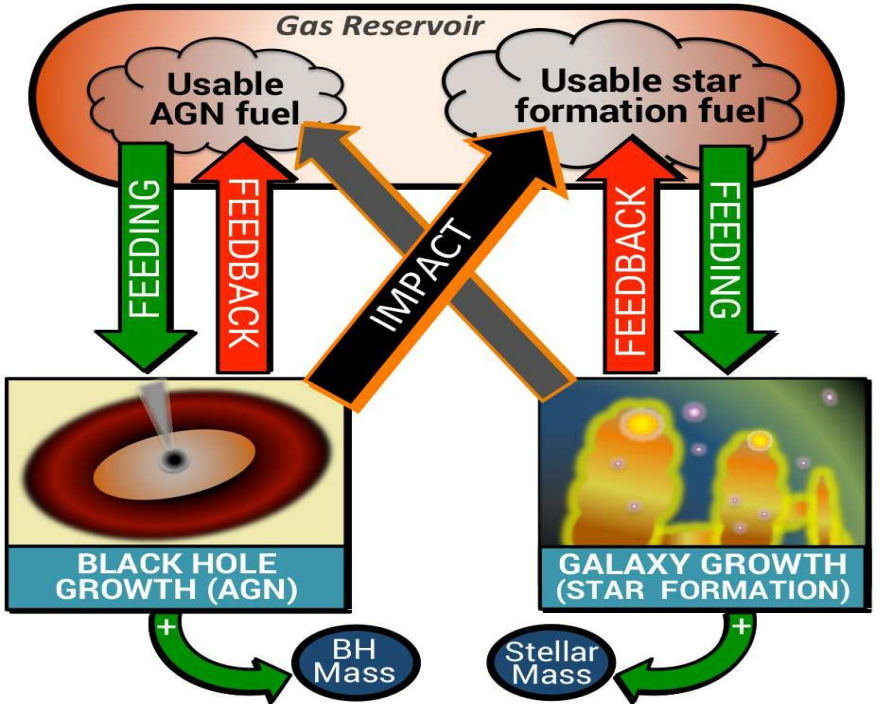



Studying the relationship between **BHAR** and **SFR** at various epochs

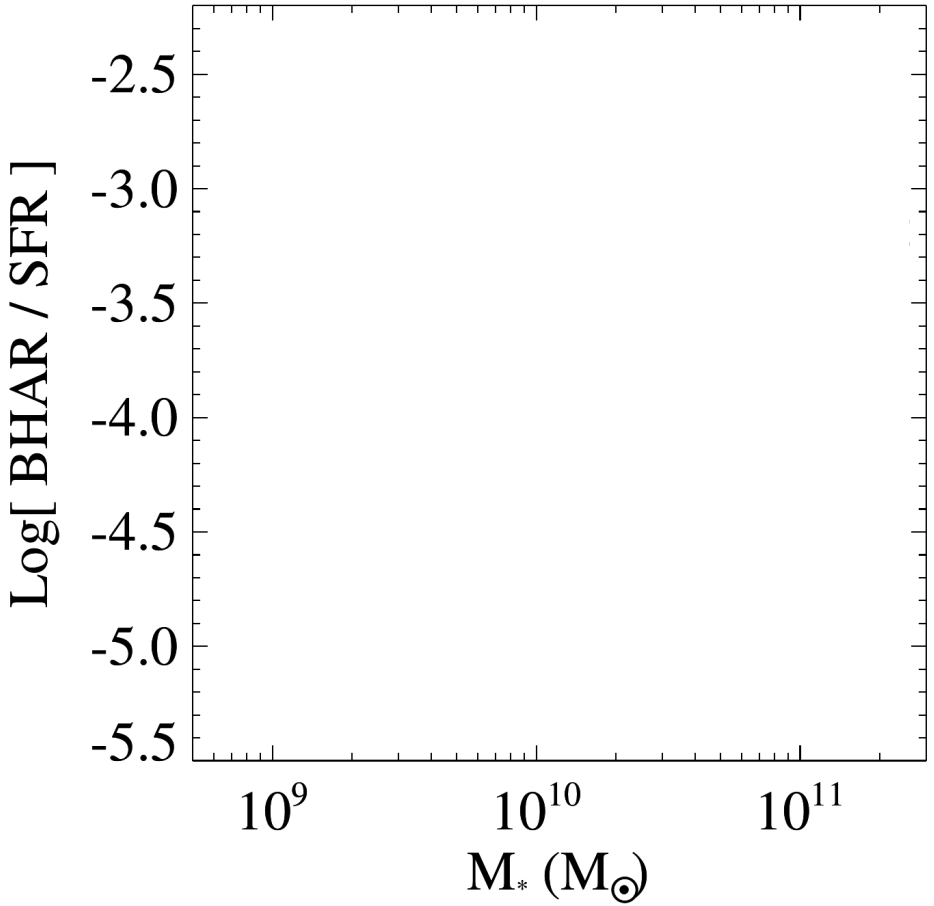
$$M_{BH} = \int BHAR \, dt$$

BH accretion rate (BHAR)

$$M_{*} = \int SFR \, dt$$

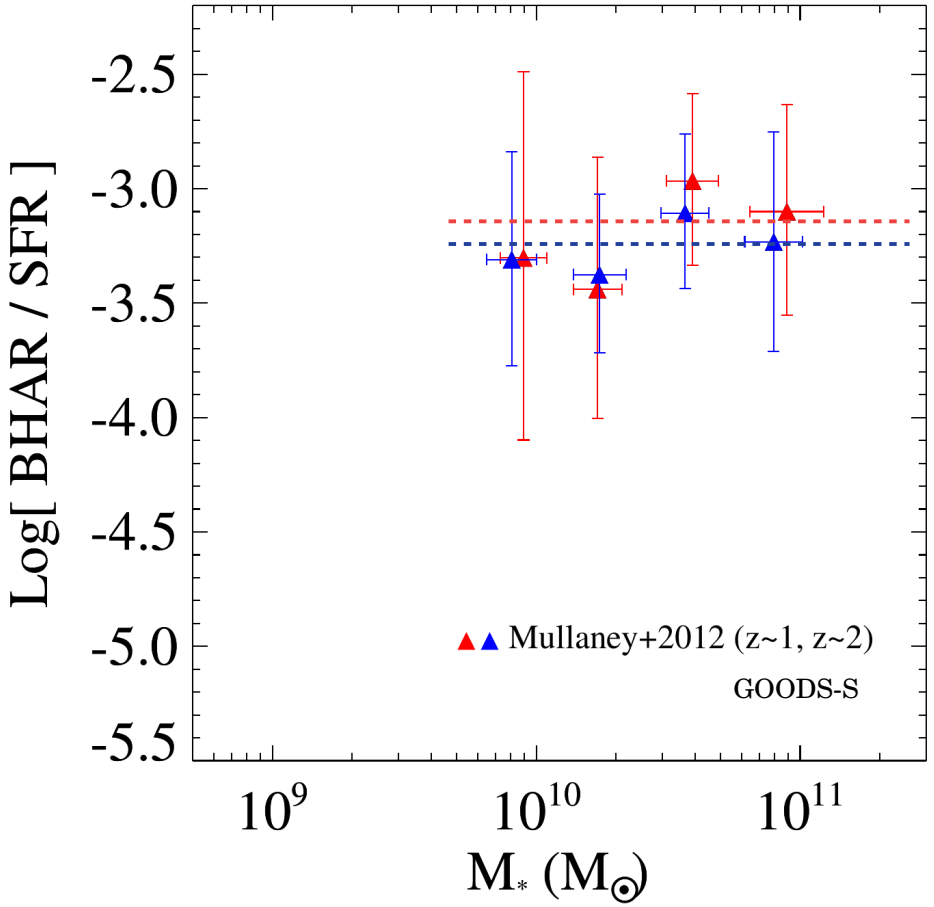
Star formation rate (SFR)

# Is the BHAR/SFR ratio universal?



# Is the BHAR/SFR ratio universal?

- BH and galaxy growth in a similar fashion: universal AGN/galaxy main sequence (Mullaney et al. 2012).
  - <SFR> from $L_{IR}$ + stacking
  - <BHAR> from $L_X$ + stacking



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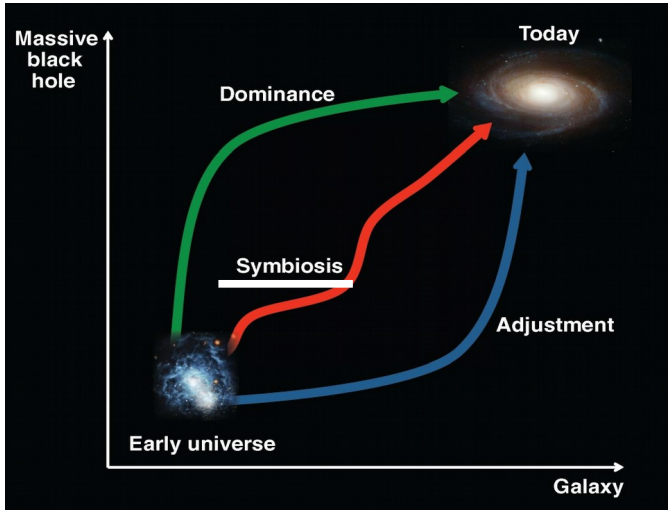
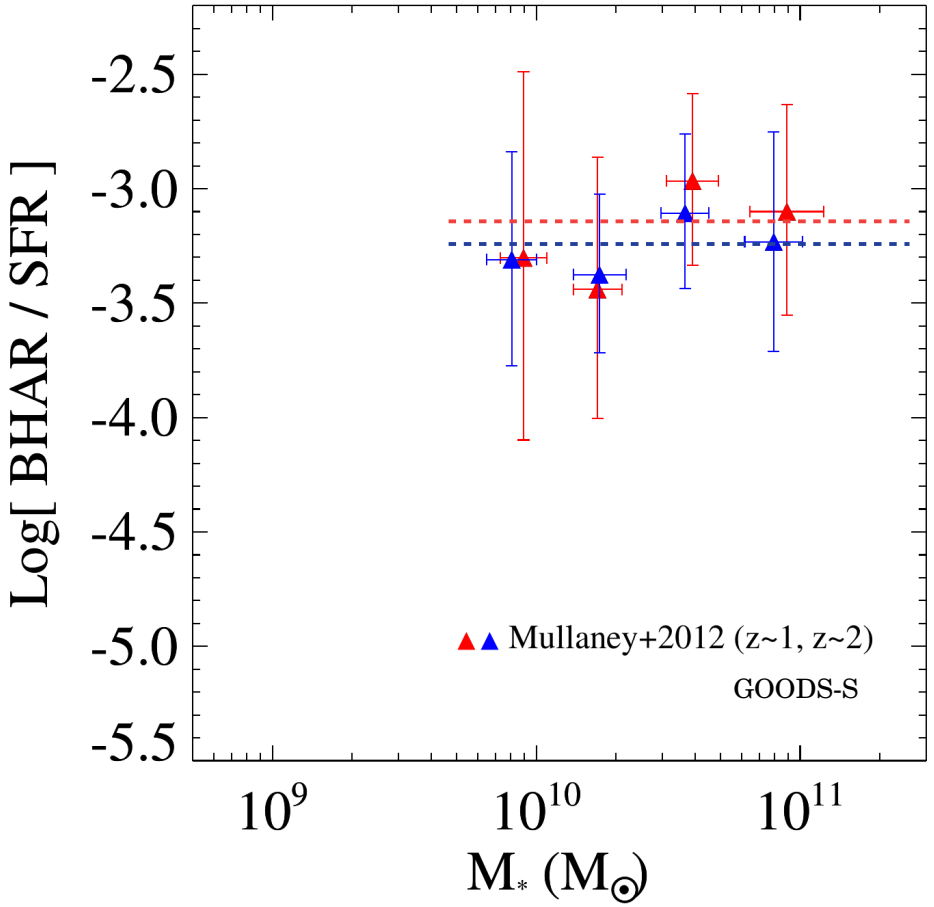
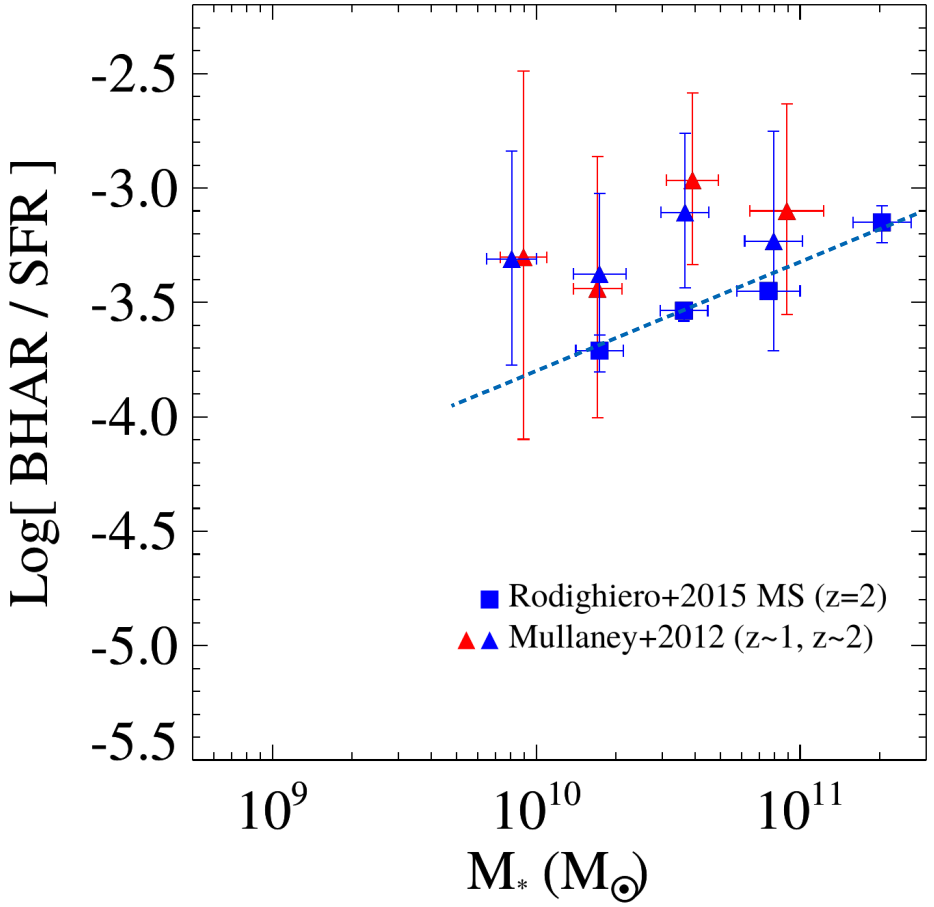


# Is the BHAR/SFR ratio universal?

- From GOODS-S to COSMOS (more statistics): at z=2 the BHAR/SFR ratio increases with $M_*$ (Rodighiero et al. 2015)



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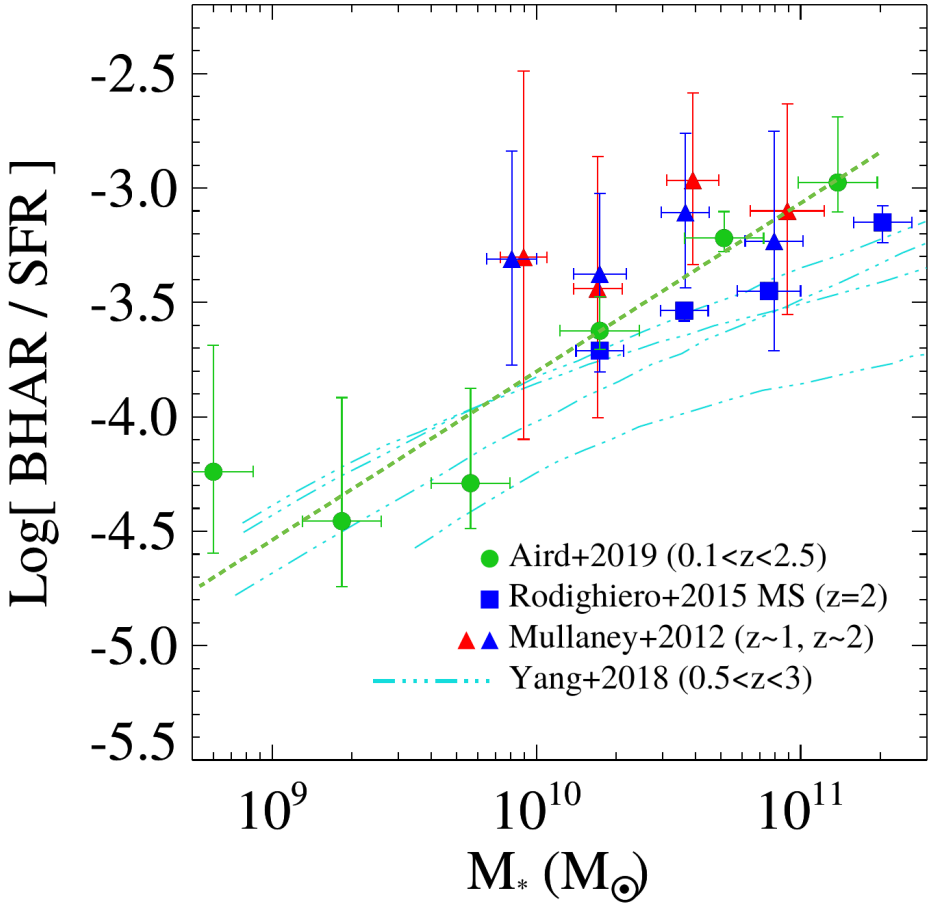

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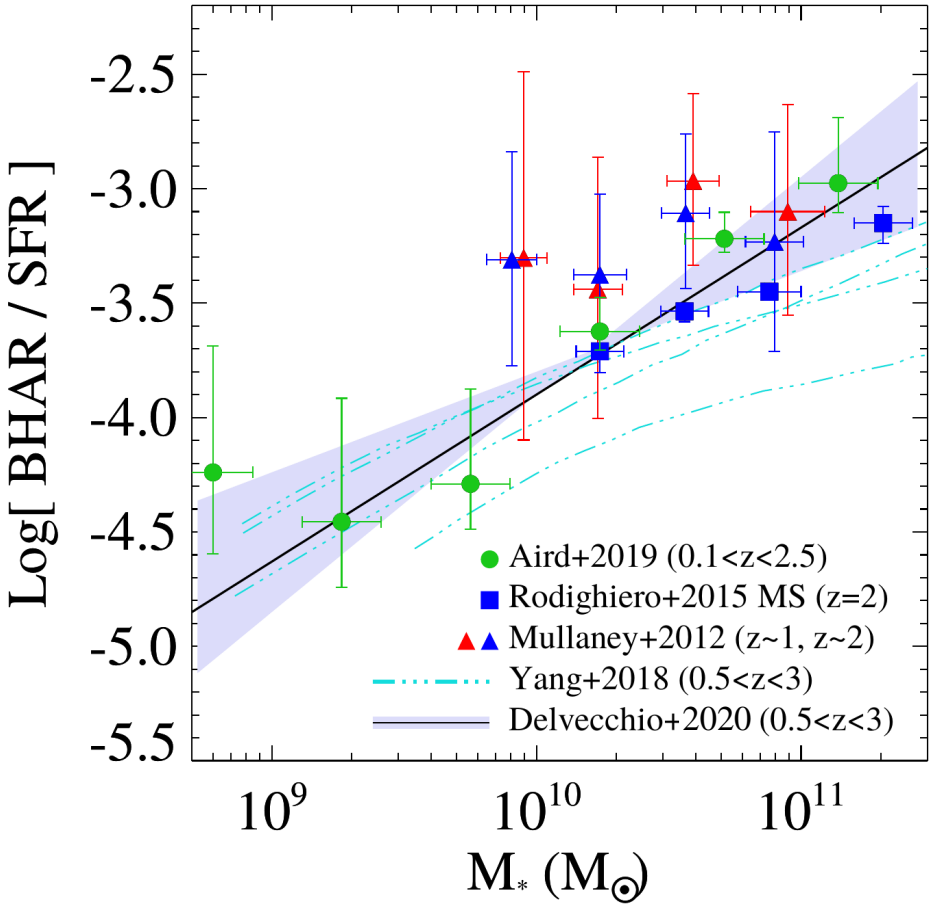

# The BHAR/SFR ratio *increases* with $M_*$

- From GOODS-S to COSMOS (more statistics): at z=2 the BHAR/SFR ratio increases with $M_*$ (Rodighiero et al. 2015)
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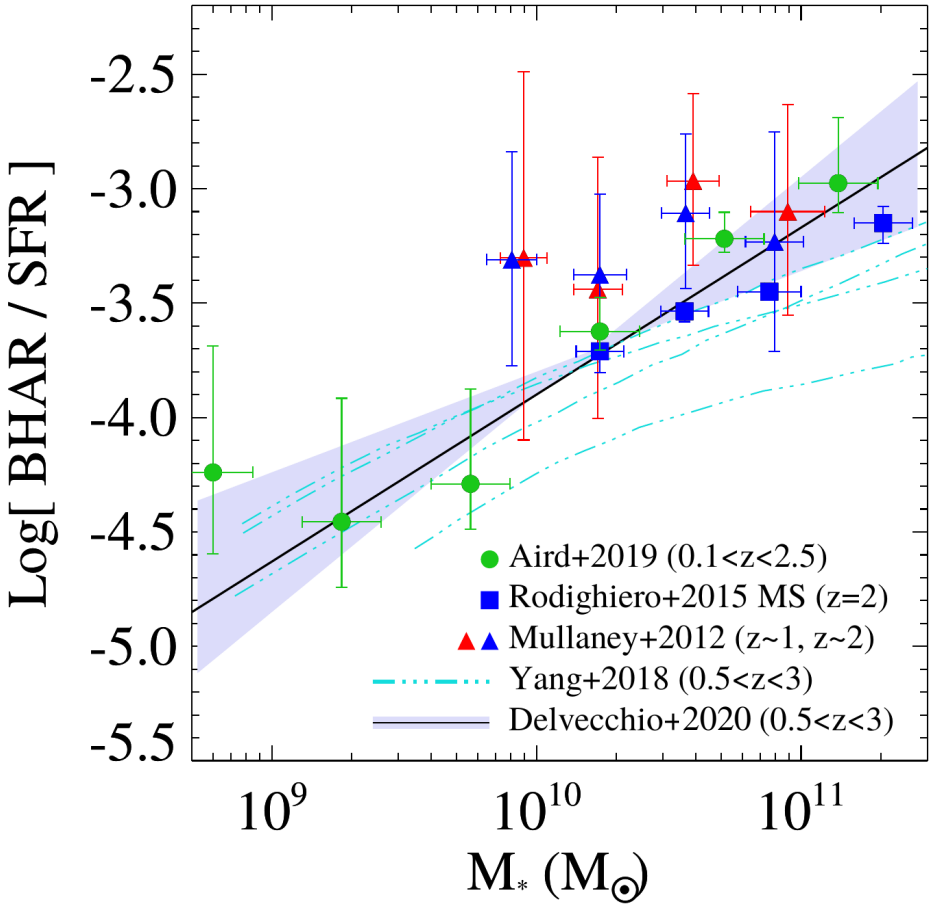
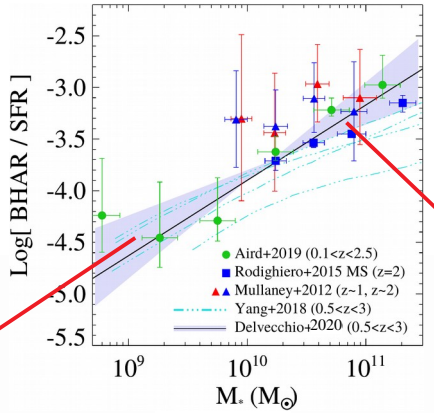
$$BHAR/SFR \propto M_*^{0.73 \pm 0.25}$$

Redshift-independent, at least since z~3

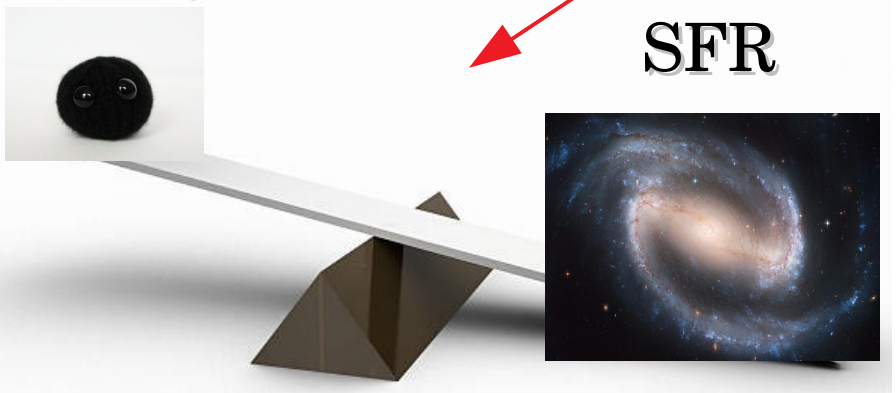


# BH growth is *not* linear with galaxy $M_*$




BHAR

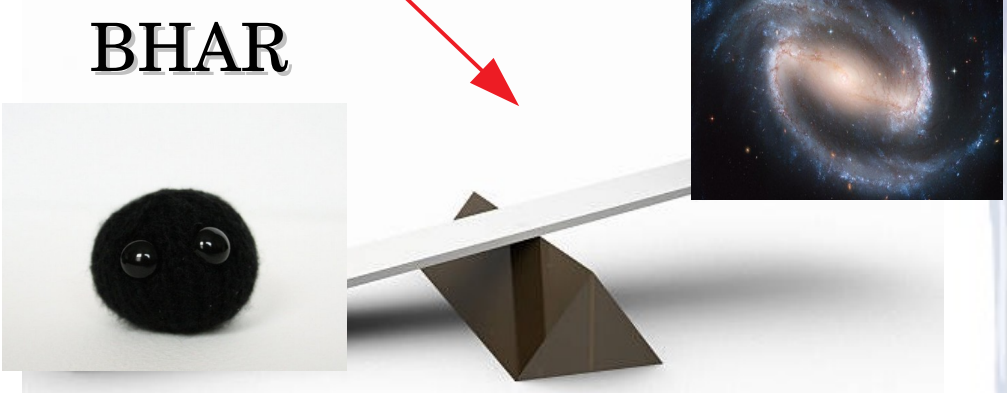
SFR



The BH lags behind the galaxy

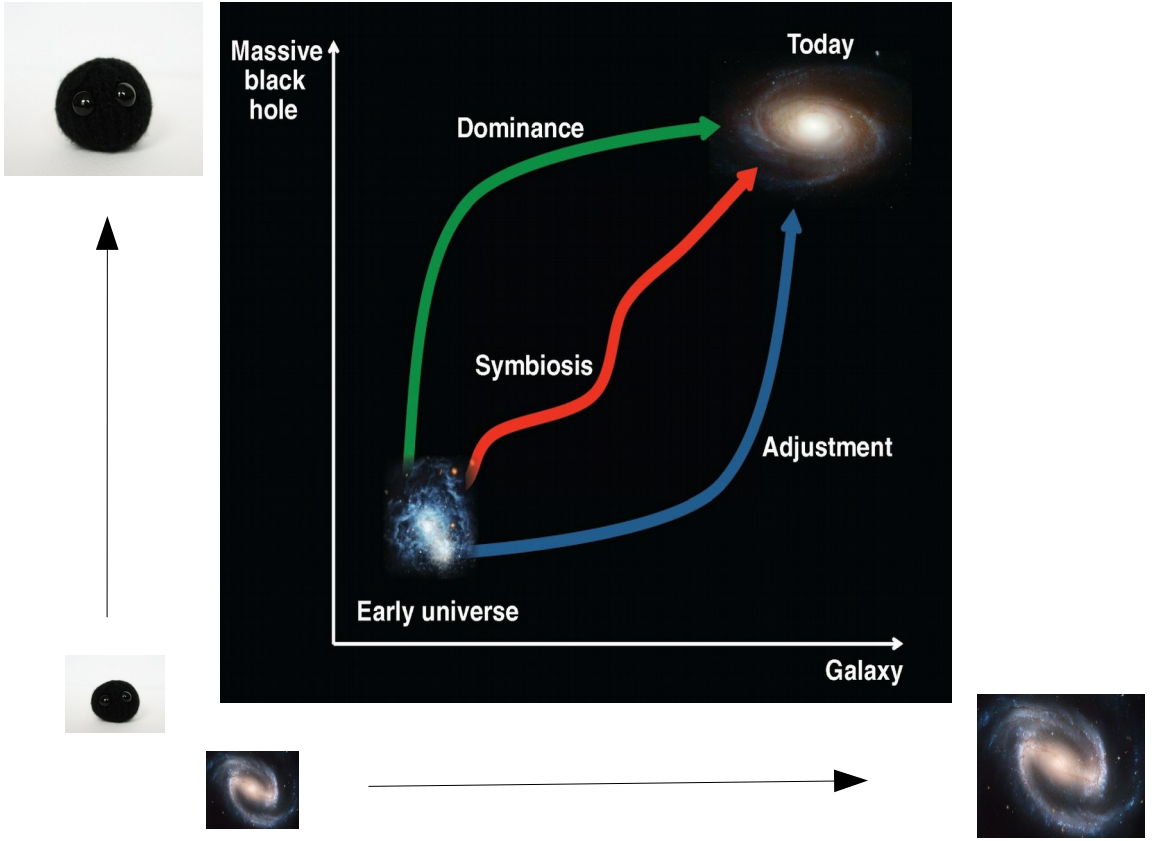
BHAR

SFR

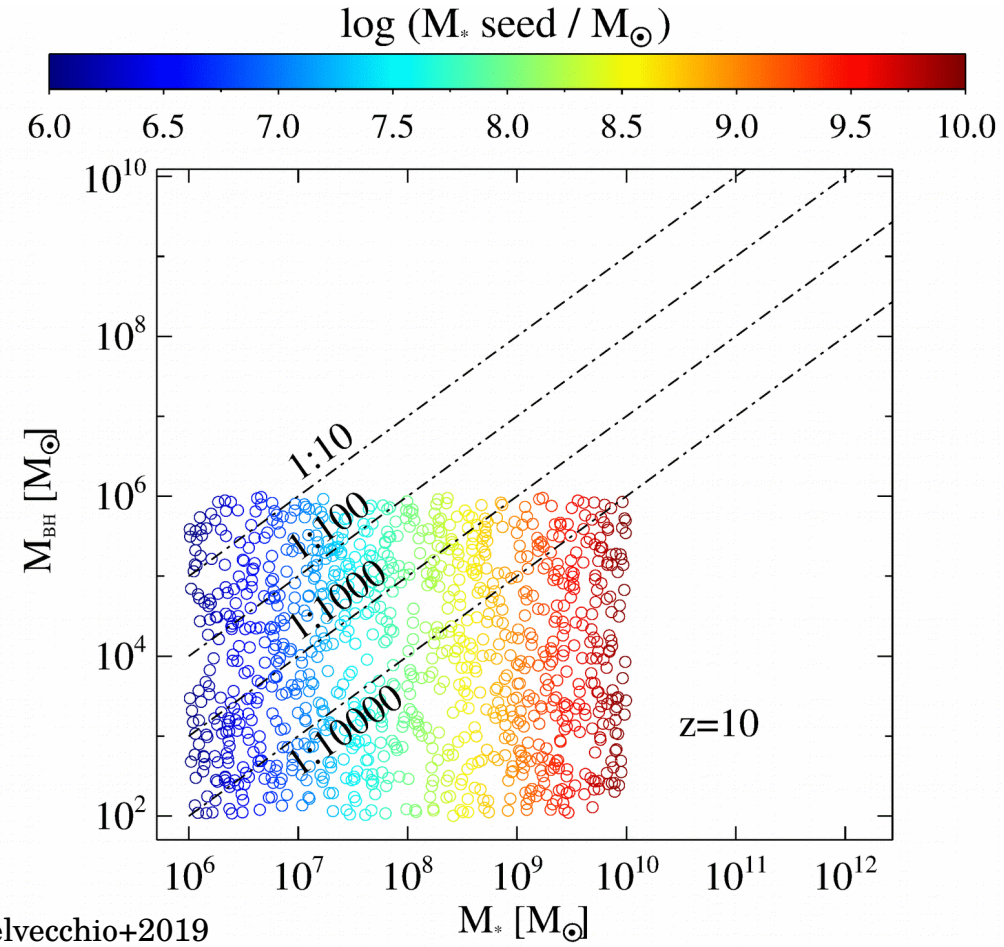


The BH grows faster and catches up

# What are the implications for the assembly of BH scaling relations?



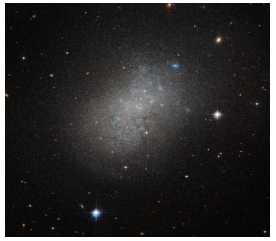
# Tracking BH growth down to z~0




Delvecchio+2019

- We assumed a uniform distribution of BH and galaxy *seeds* at z=10 (arbitrary)

$10^6 < M_* < 10^{10}$ Msun



$10^2 < M_{BH} < 10^6$ Msun

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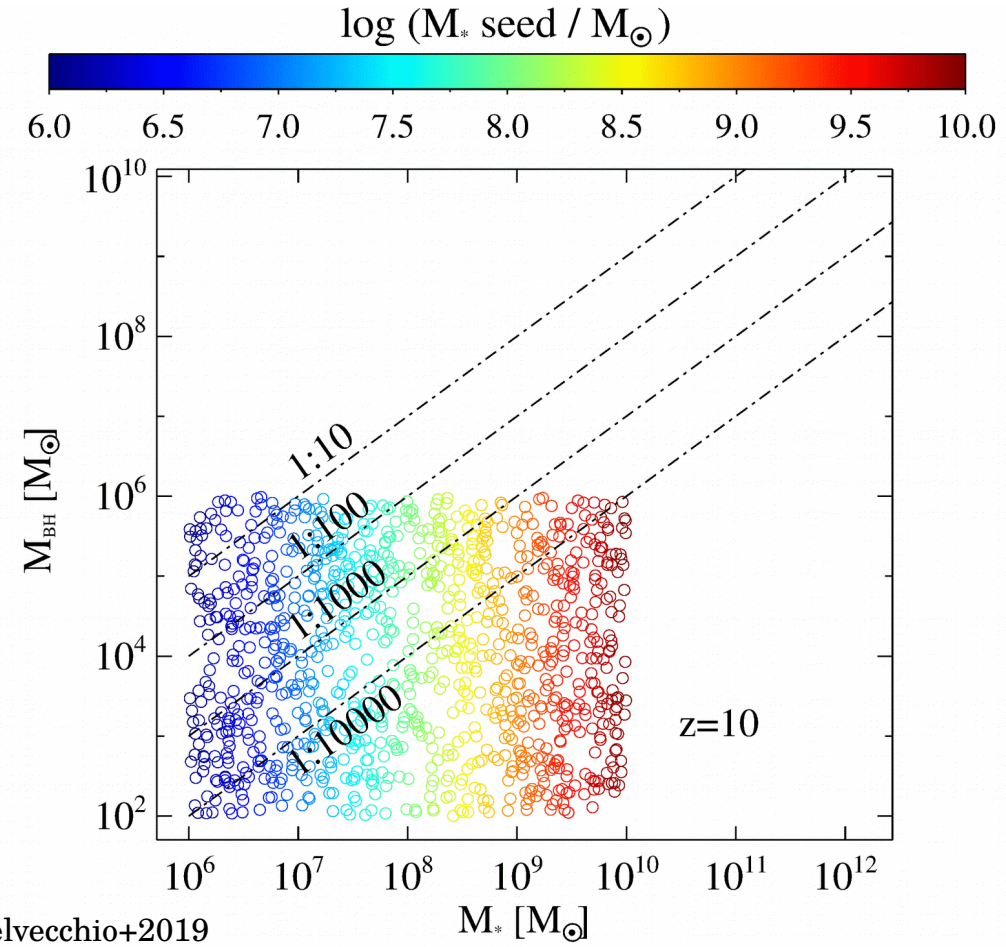


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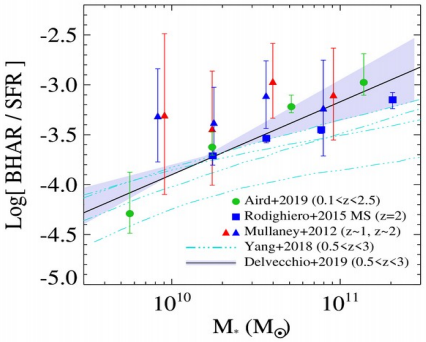
Galaxy **M**$_*$ evolves on the *main sequence* (Schreiber et al. 2015)


**M**$_{BH}$ follows the BHAR/SFR trend with M$_*$



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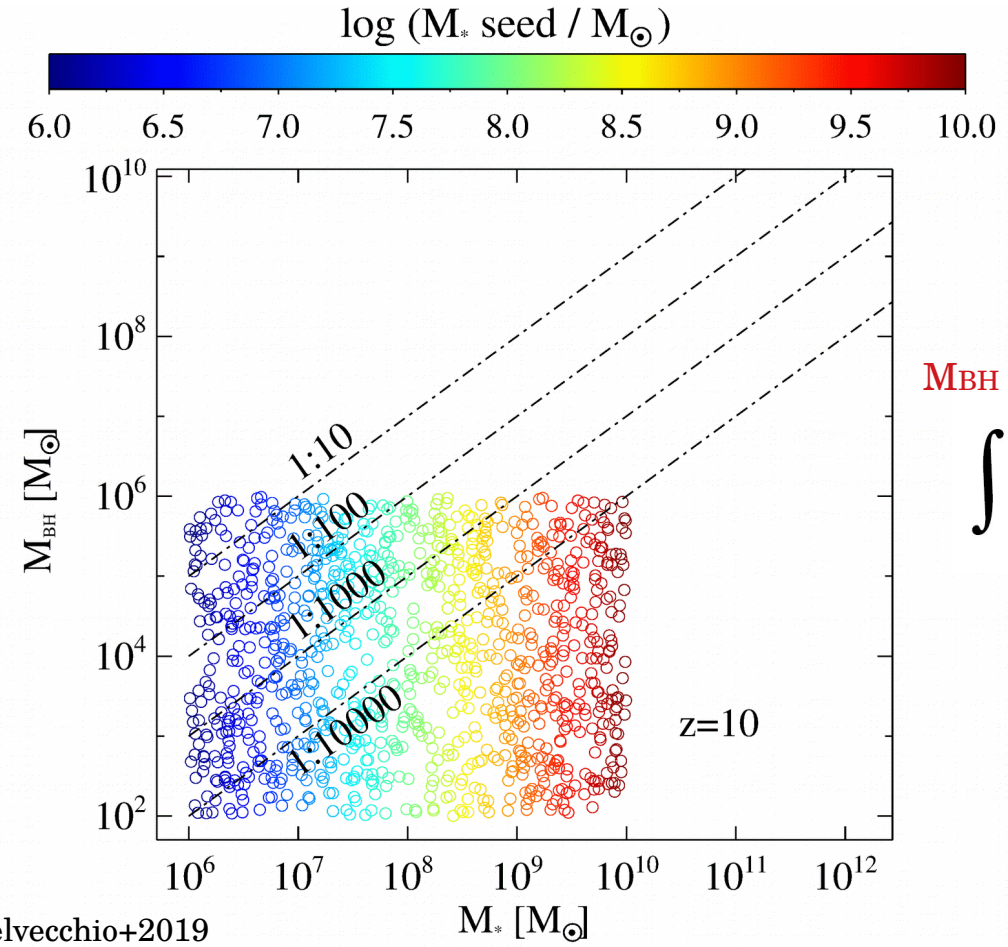
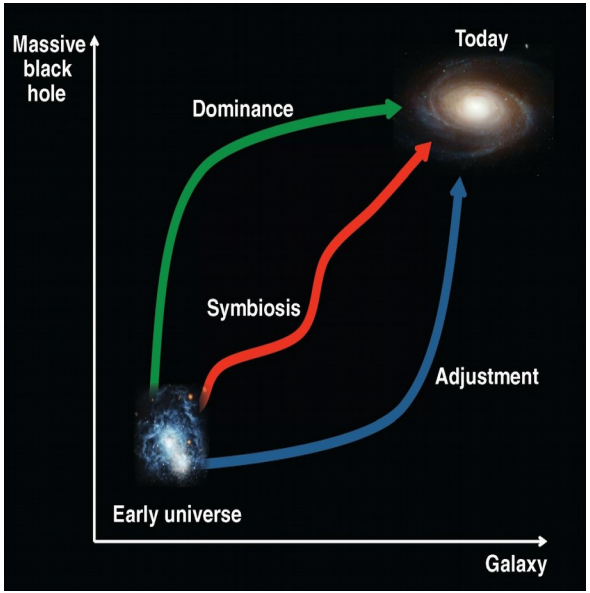



Delvecchio+2019

$$M_{BH} = M_{BH,seed} + \int BHAR \, dt$$




*Input seeds*

$$M_{*} = M_{*,seed} + \int SFR \, dt$$

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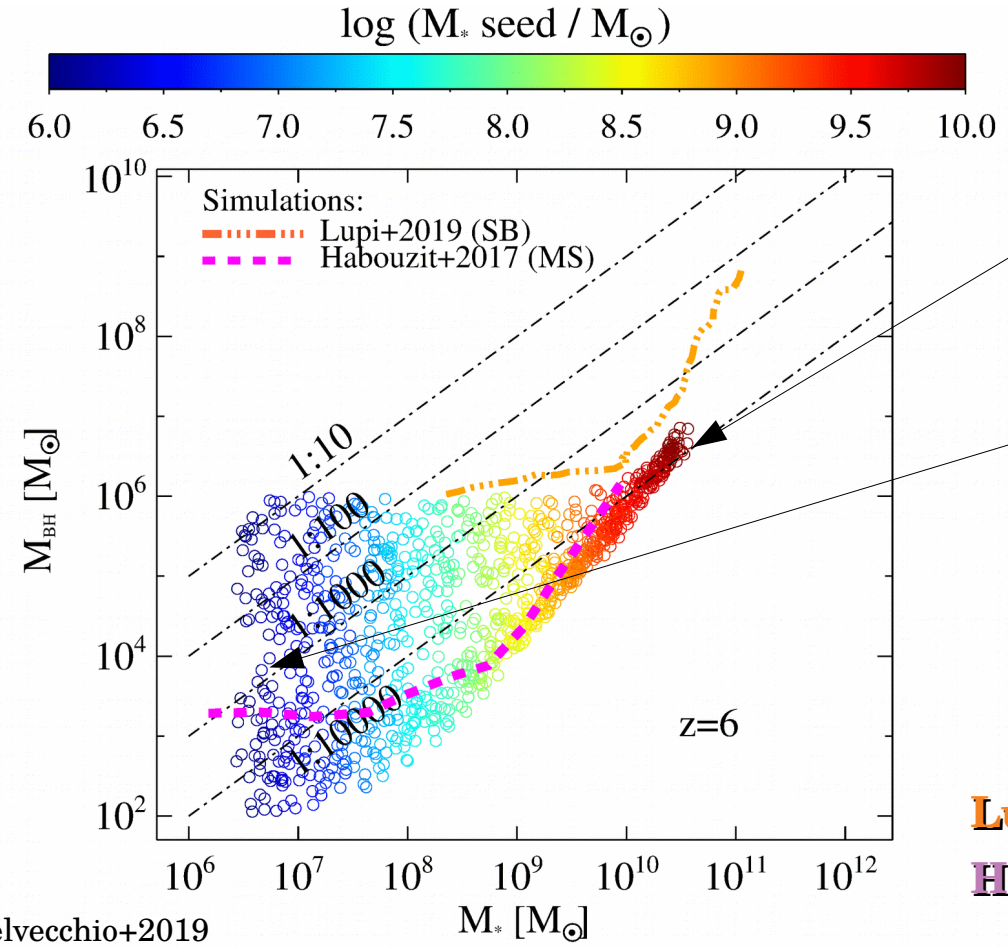


Delvecchio+2019

Bigger galaxies: the BH grows super-linearly via gas accretion along with its host

Smaller galaxies: the BH lags behind the host. SN-driven feedback halts BH growth

**Lupi et al. (2019):** SB galaxy hosting a Quasar

**Habouzit et al. (2017):** typical star-forming galaxy

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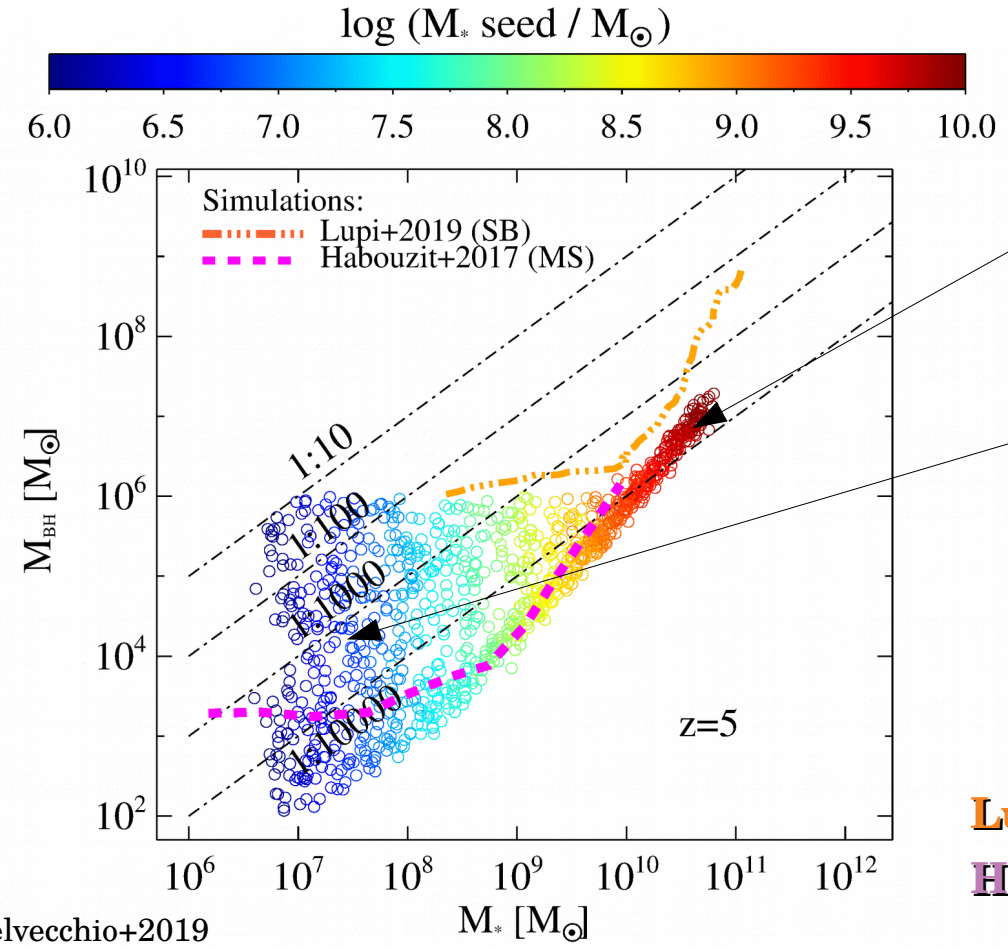


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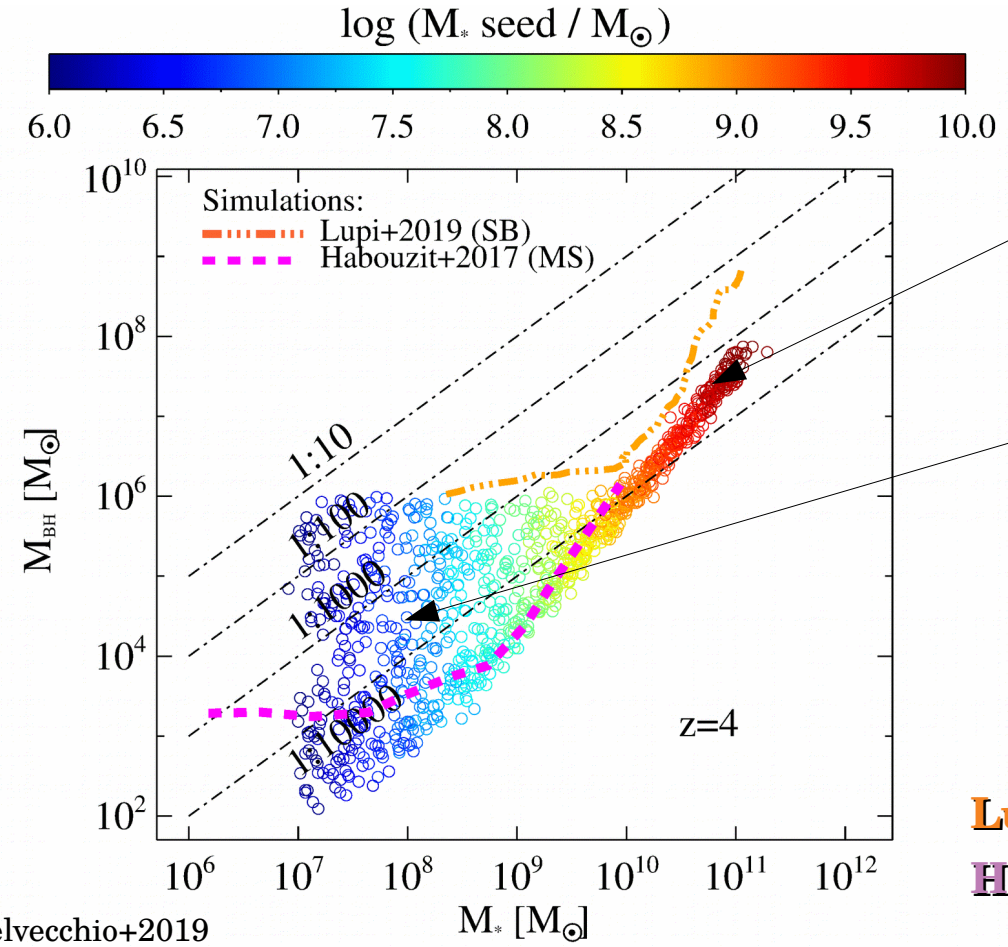


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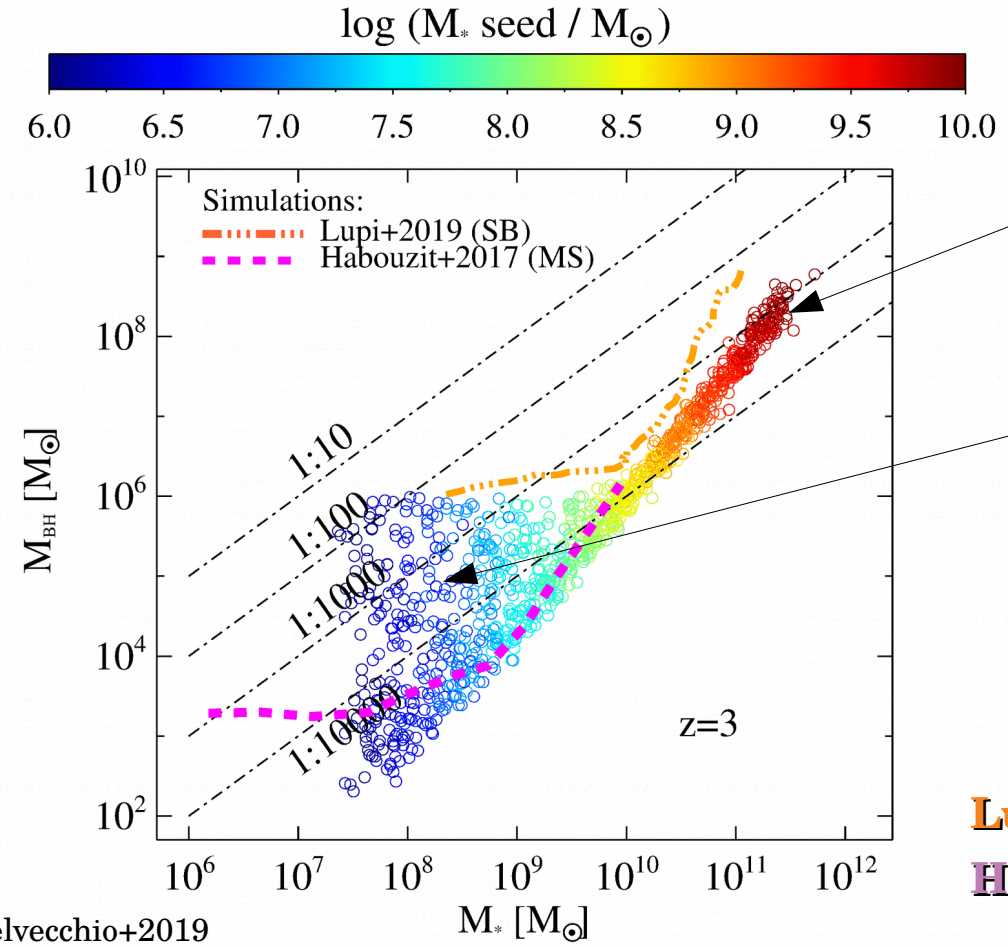


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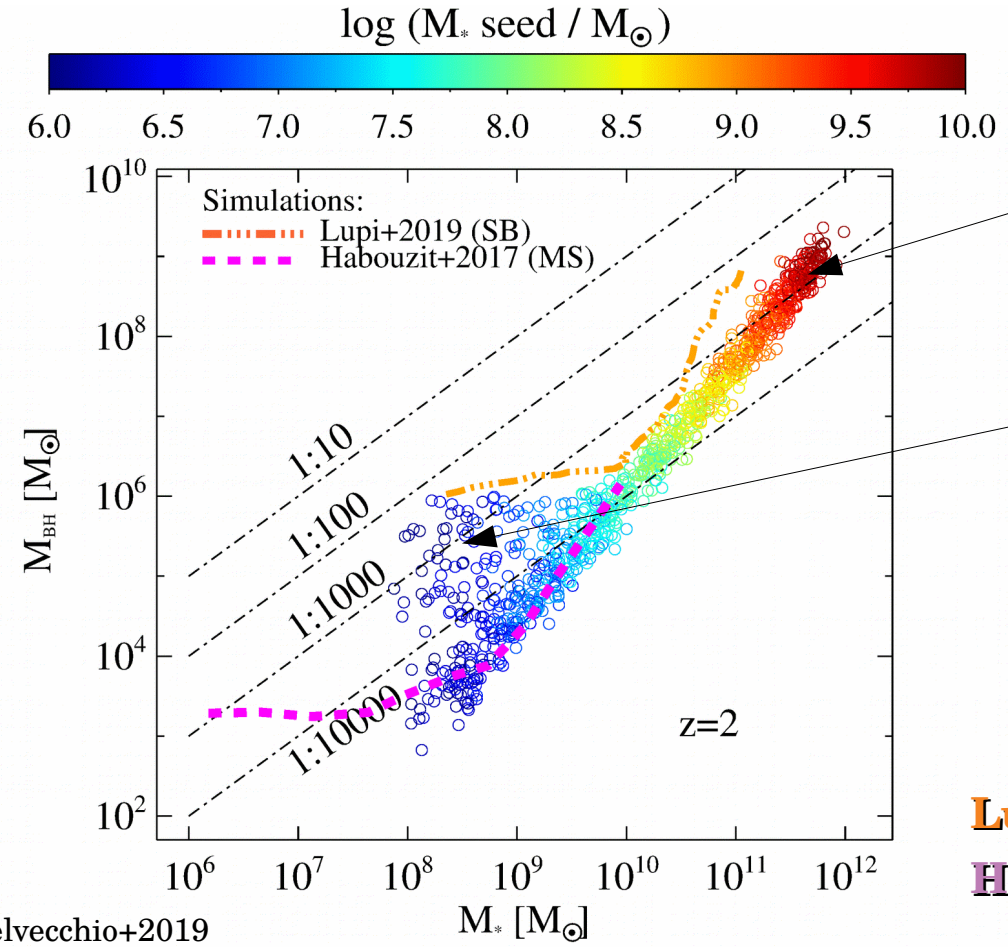


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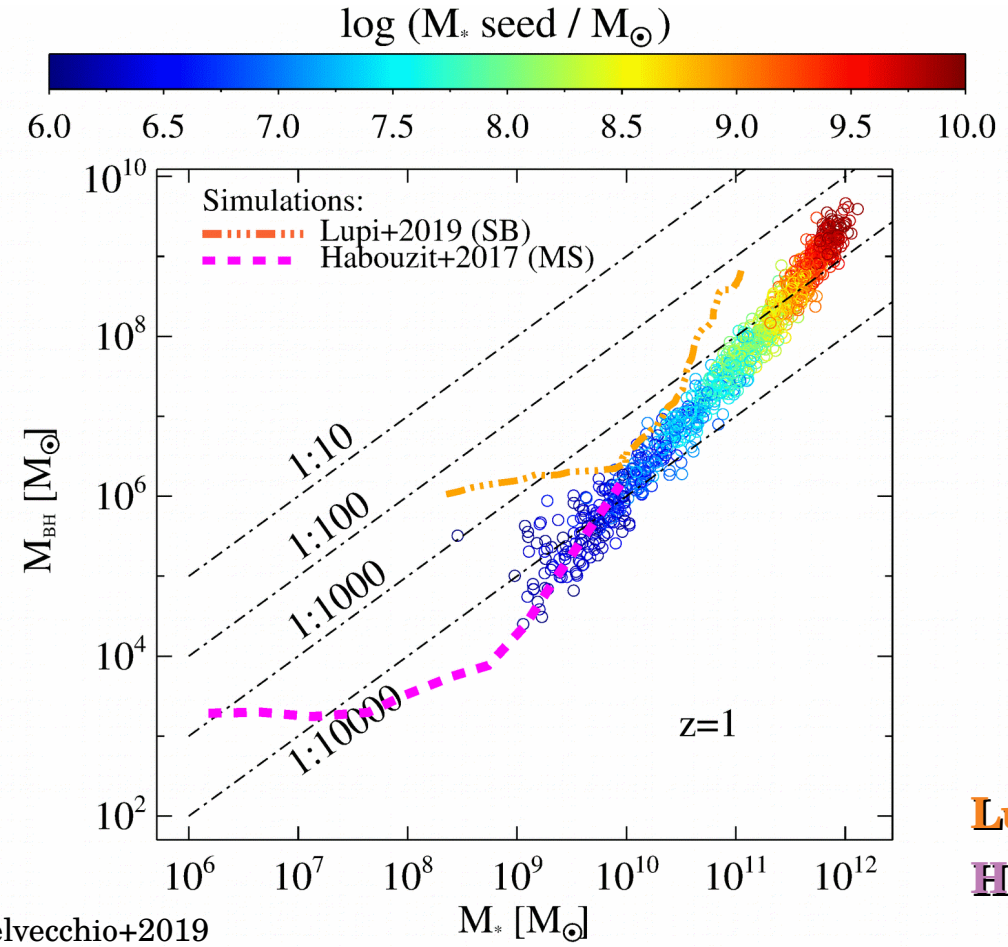


Delvecchio+2019

All galaxies are placed on the final relation ($M_{BH} \propto M_*^{1.7}$). Today's $M_{BH} - M_*$ relation was already in place several Gyrs ago

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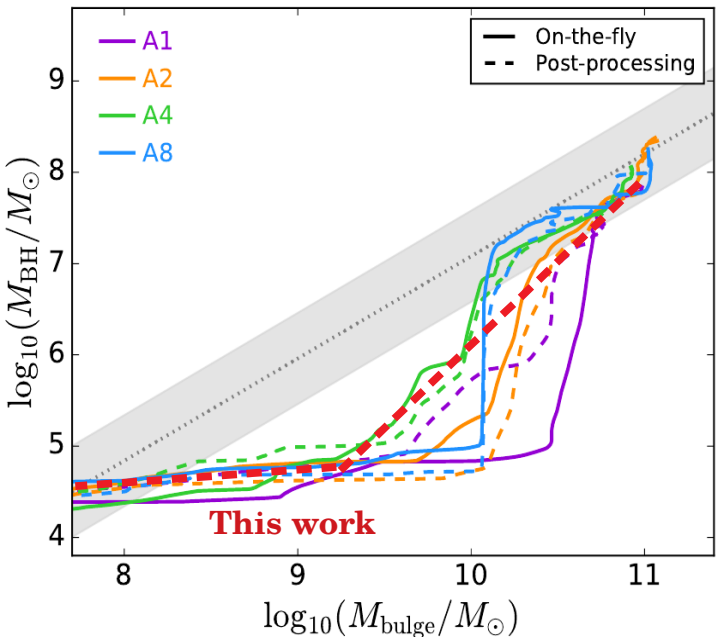
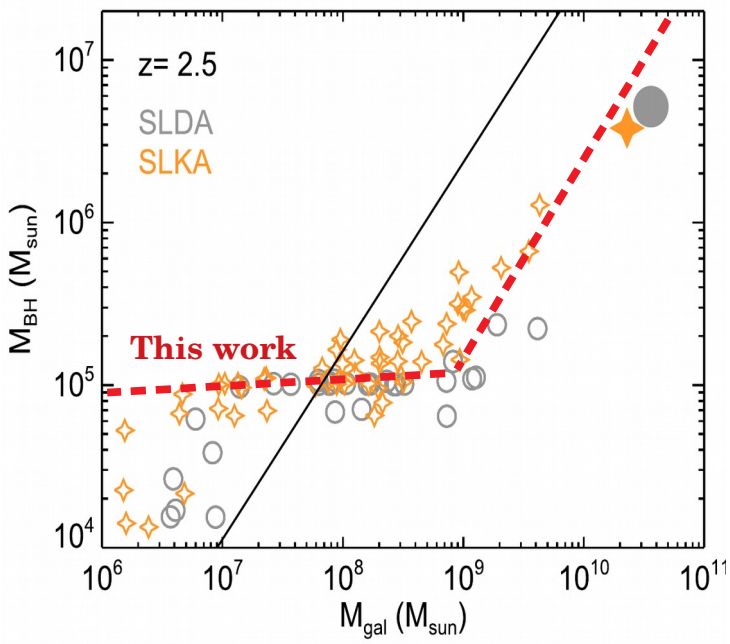
# Agreement with hydro and cosmological simulations:

FIRE (Hopkins+2014)



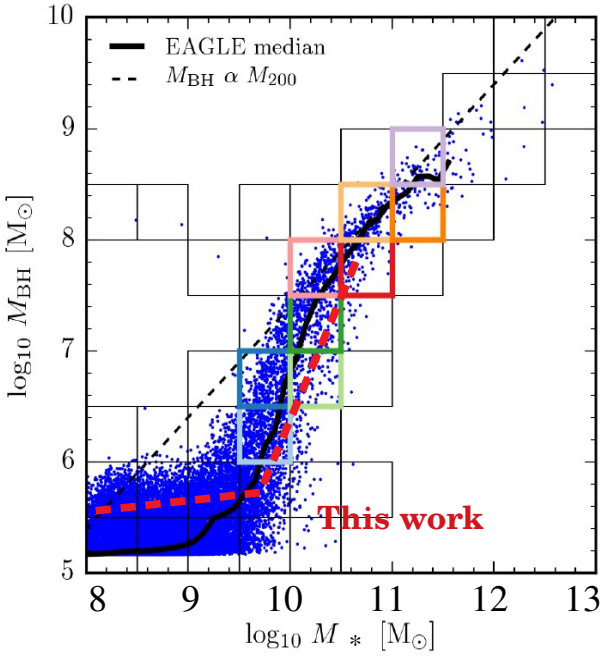

Anglès-Alcazar + 2017

Horizon-AGN (Dubois+2015)




Dubois + 2015

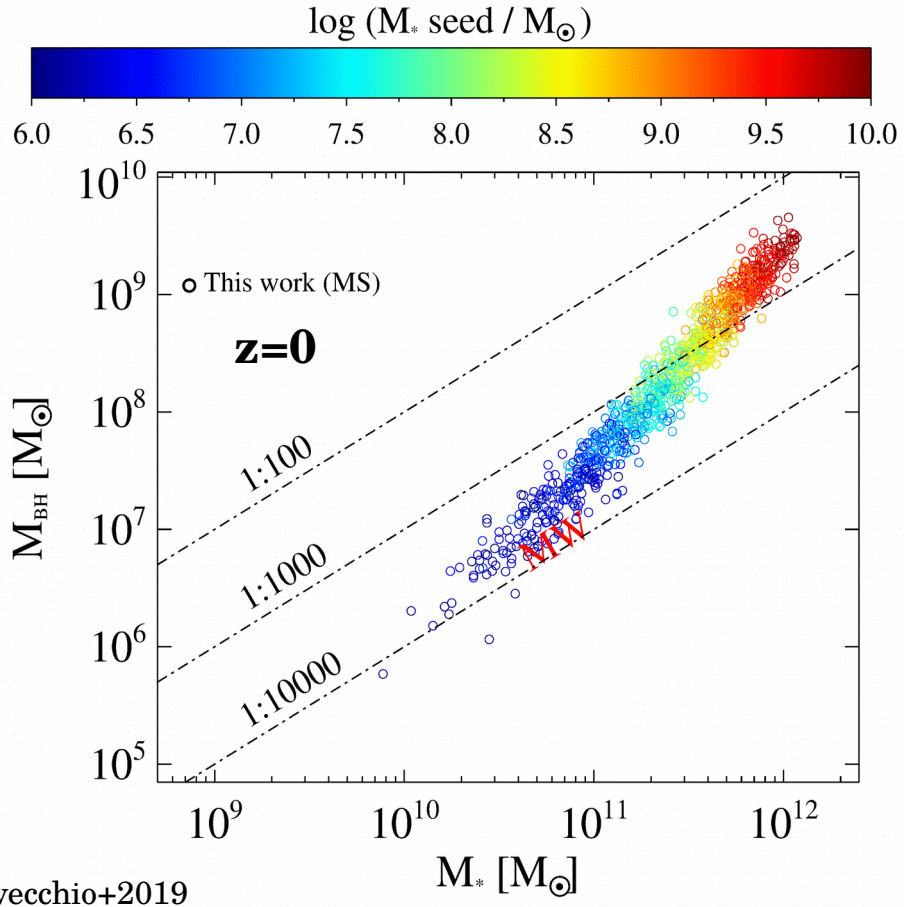
EAGLE (Schaye+2015)




McAlpine + 2017

Despite different BH seeds and redshifts, the twofold trend is there

# Comparison with local $M_{BH}$ - $M_*$ relations




Delvecchio+2019

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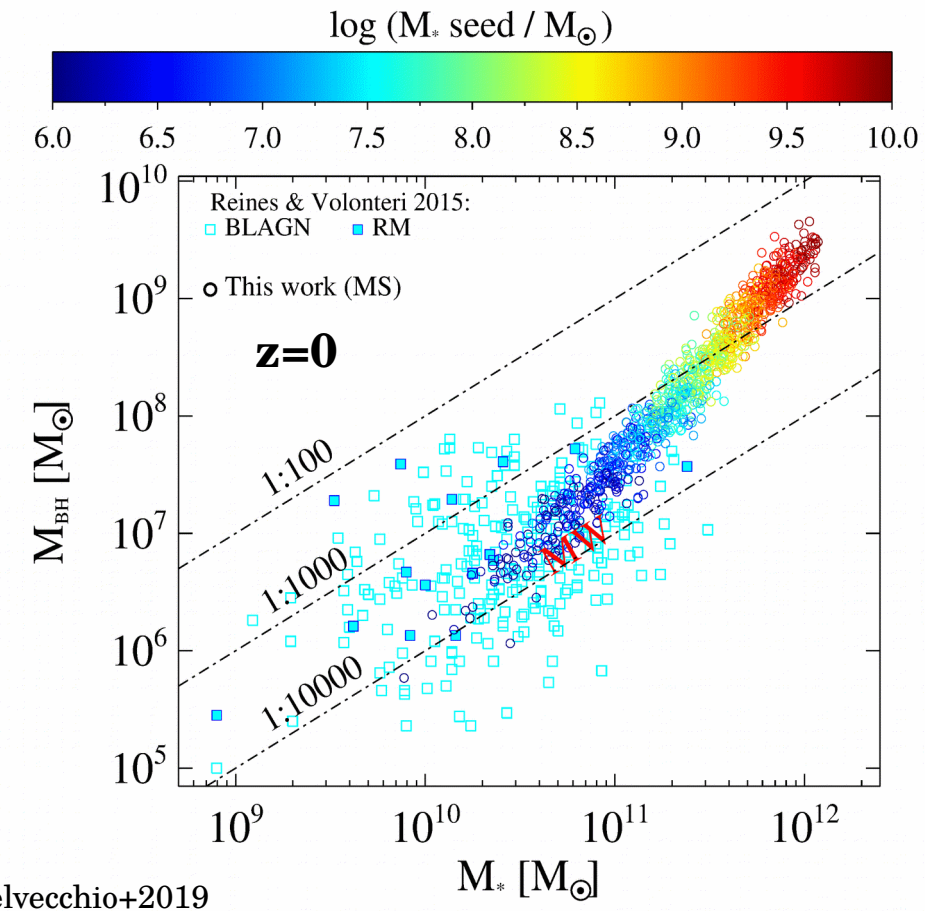


Delvecchio+2019

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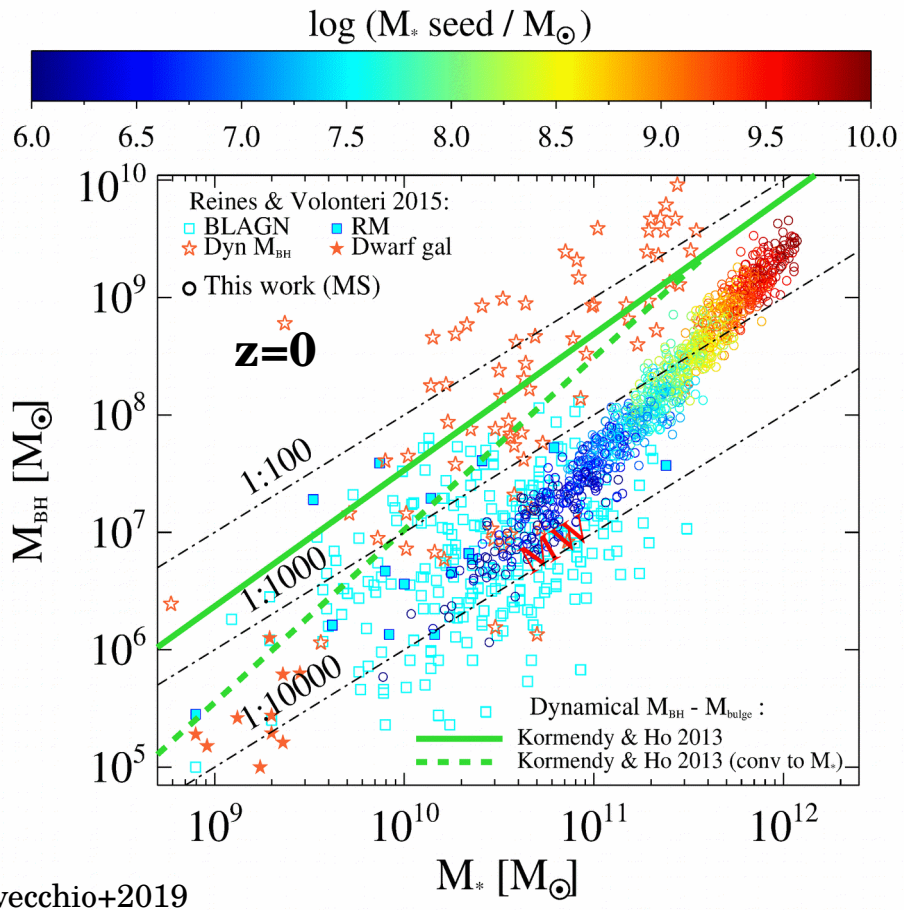


Delvecchio+2019

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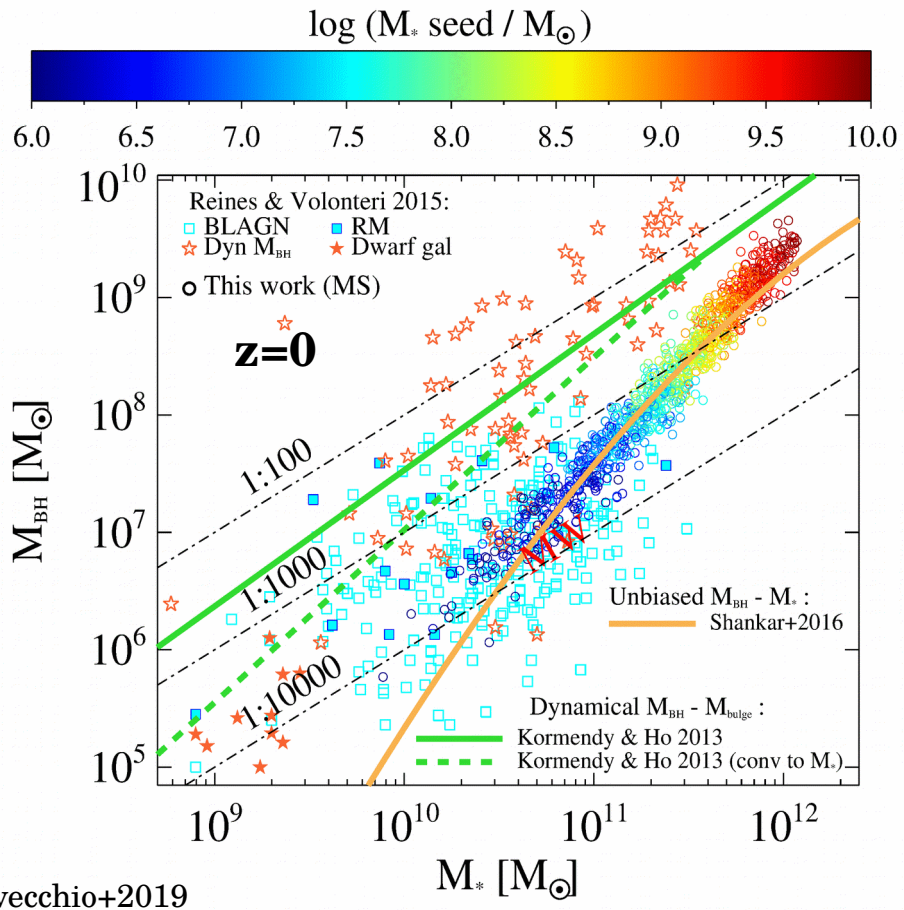


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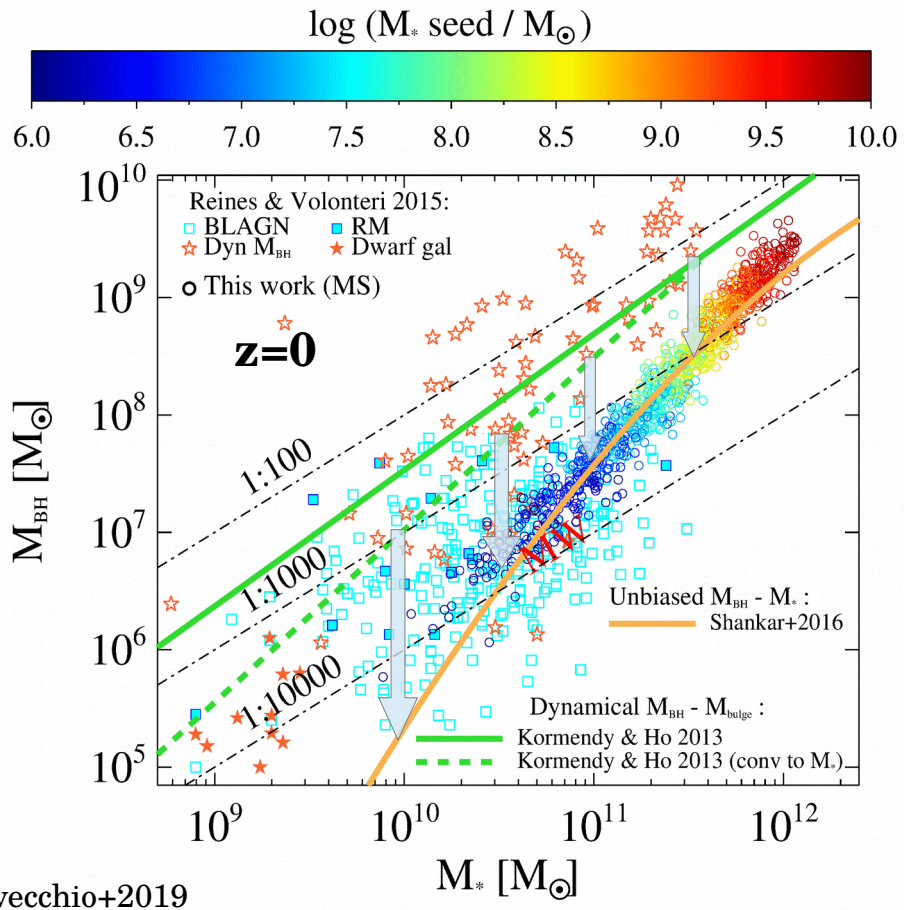


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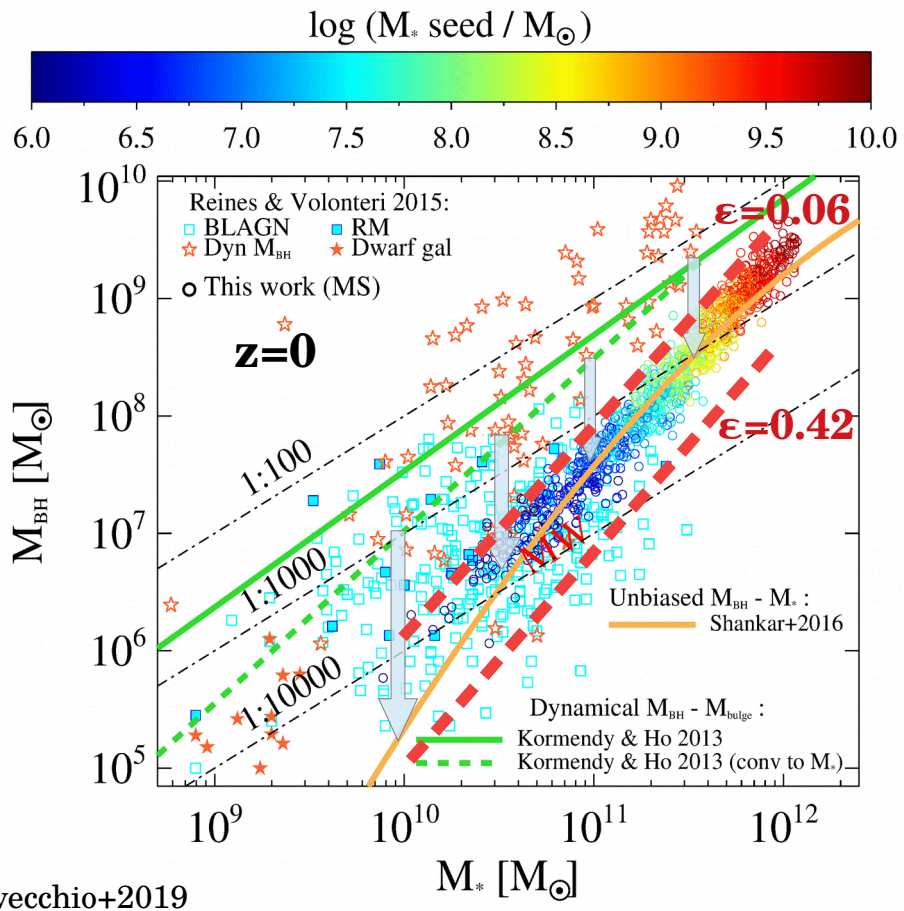


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Radiative efficiency: we assumed $\varepsilon=0.1$

**BHAR** $\propto (1-\varepsilon)/\varepsilon \cdot L_X$

but no $\varepsilon$~[0.06:0.42] would fill the gap

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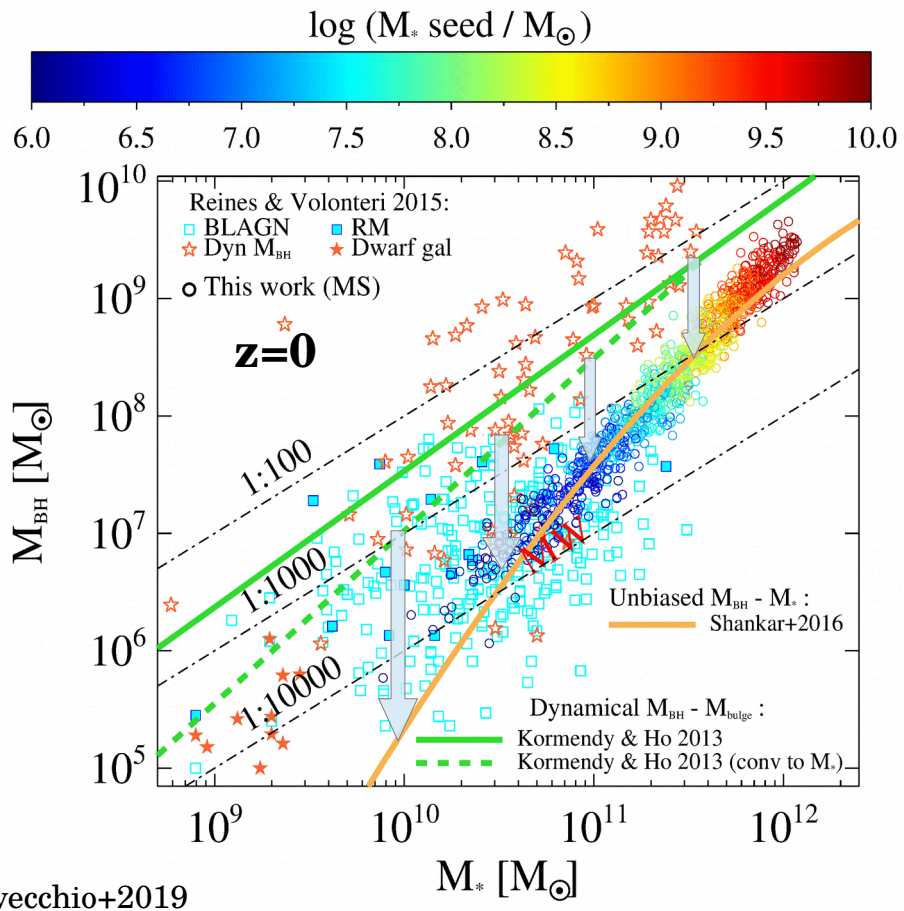


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**Compton Thick AGN:**
Constrained by the cosmic XRB (≤ 2x boost, Comastri et al. 2015)

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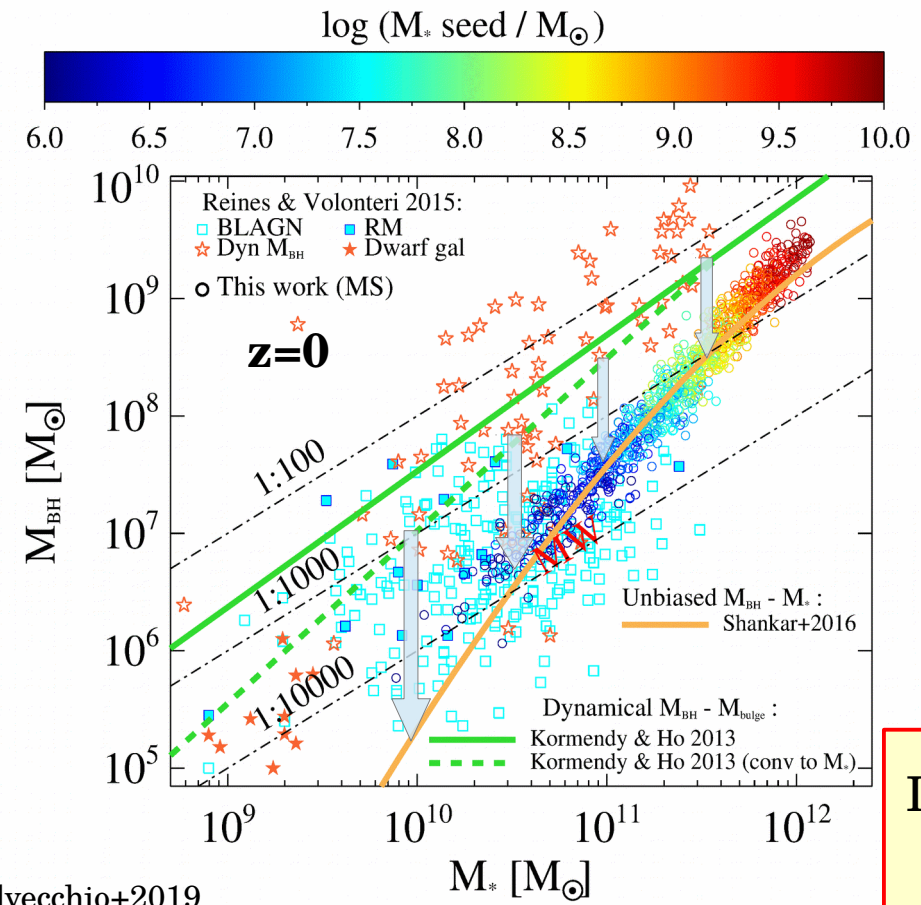


Delvecchio+2019

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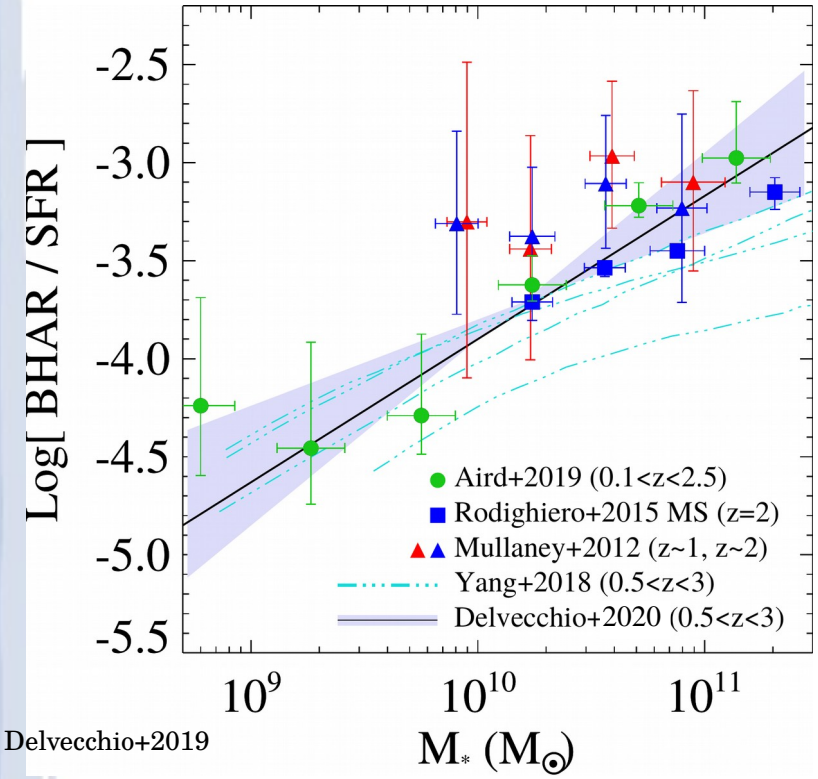
Dynamical $M_{BH} - M_{bulge}$ relations, if not biased, do not apply to normal MS galaxies

SPECULATION

# And the leading actor is…




Delvecchio+2019

- The $M_*$ drives the super-linear BH growth, but BHAR/SFR does not display a twofold behavior

SPECULATION

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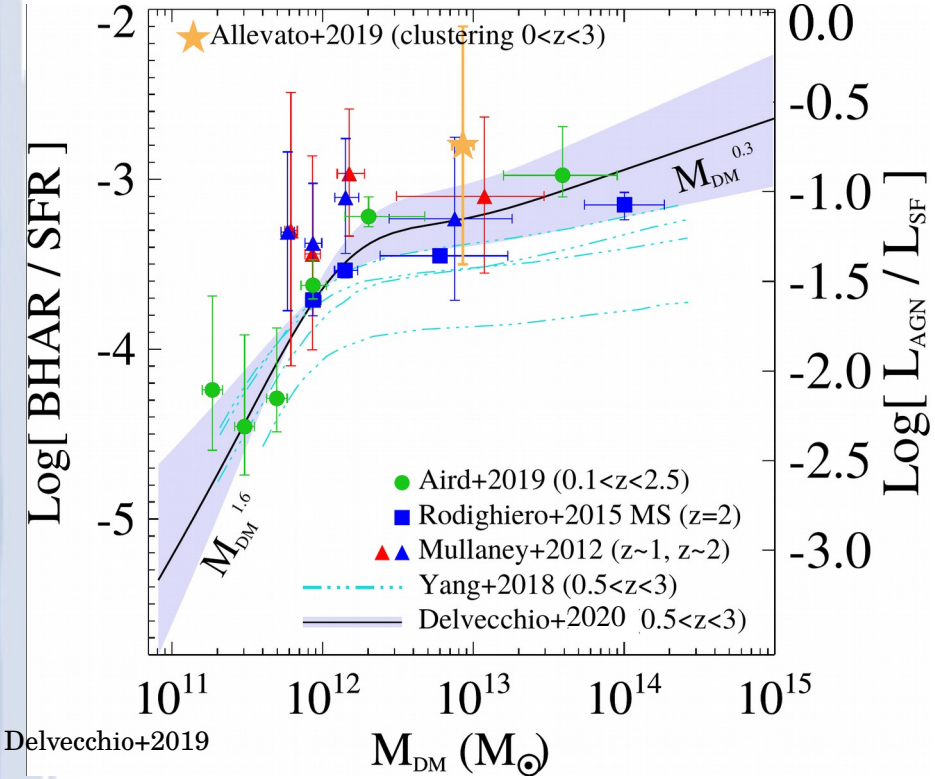


Delvecchio+2019

- The $M_*$ drives the super-linear BH growth, but BHAR/SFR does not display a twofold behavior
- When converting to $M_{DM}$ (Behroozi et al. 2019), the BHAR/SFR shows a **strikingly twofold trend** with $M_{DM}$

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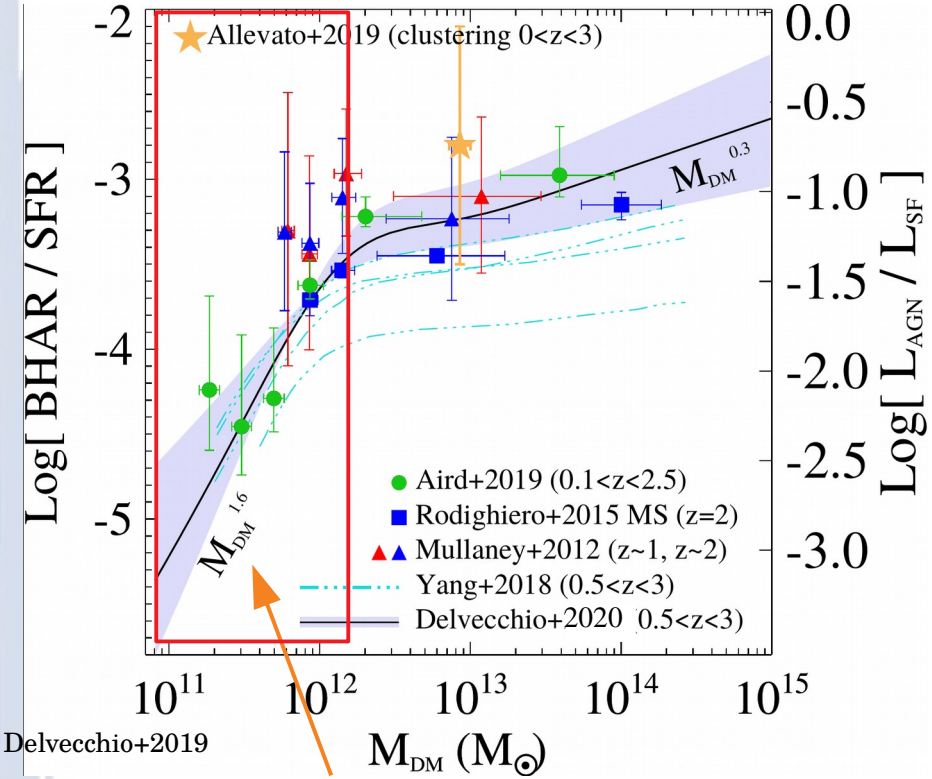


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SN-driven feedback hampers BH growth

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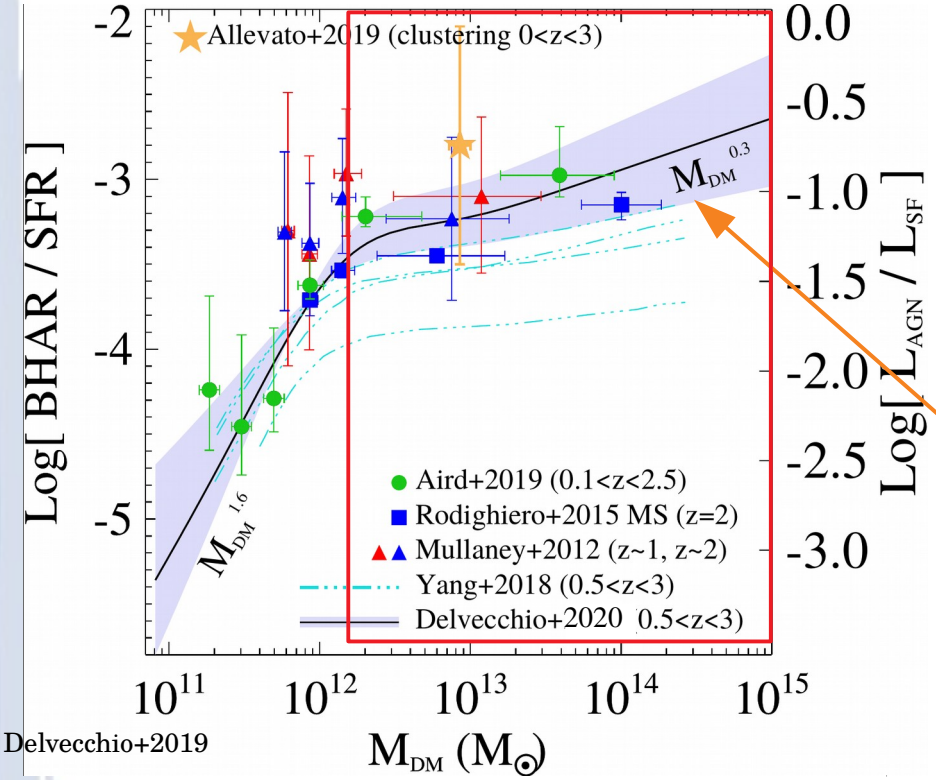


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>> AGN feedback

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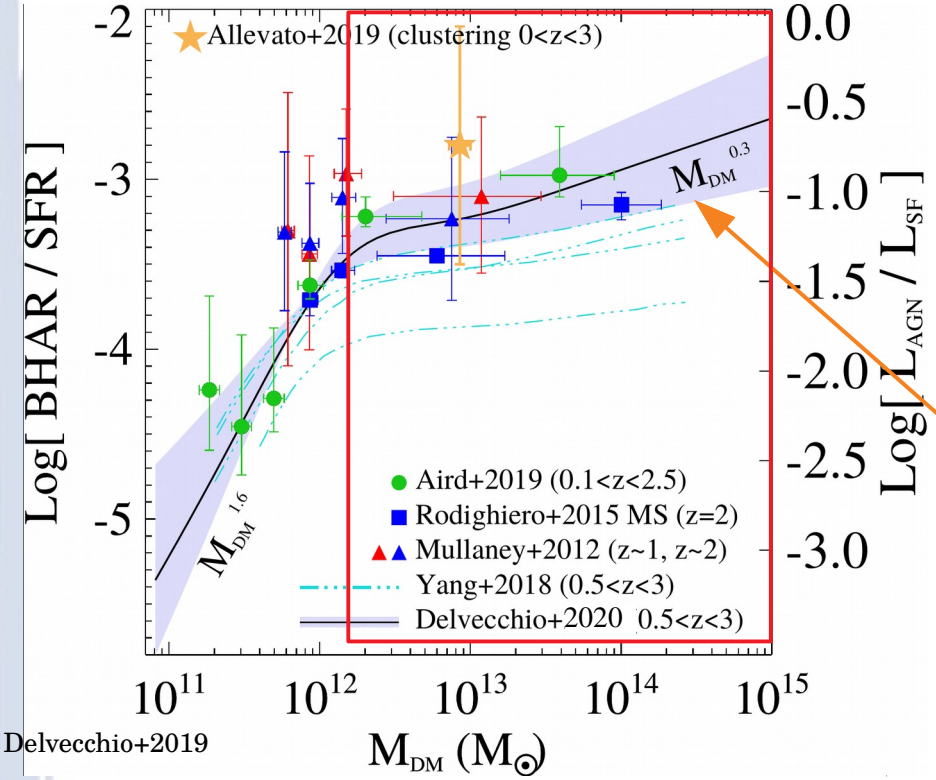


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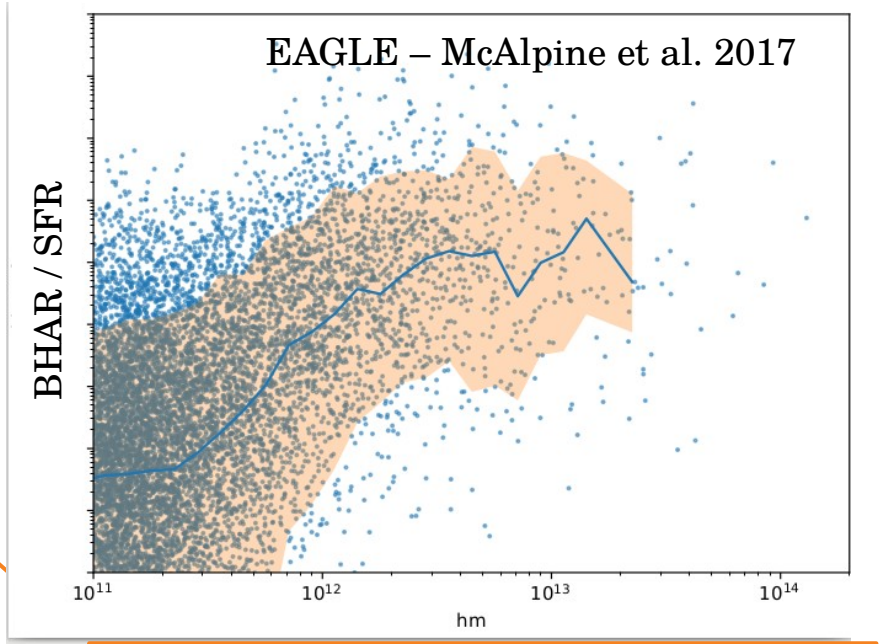


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# Take-home points

BHs and galaxies do *not* grow in lockstep at all times.
Our work favors the ***adjustement***
of BH growth driven by the available galaxy‘s gas content

...possibly regulated by the **DM halo mass**

Our empirical trend agrees with intrinsic relations at z=0 and with cosmological simulations at high/low redshift

Dynamical BH scaling relations, if not biased, do not hold for MS galaxies