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The mass assembly of the high-redshift black hole population

Growing Black Holes: Accretion and Mergers
Kathmandu - 20/05/2022

國立臺灣師範大學
National Taiwan Normal University

Black holes during the epoch of reionization

Topic: evolution of the population of high-redshift central black holes and their host galaxies by means of the semi-analytic model ***Delphi***.

Collaborators: Pratika Dayal (Kapteyn Institute, Groningen), Hung-Yi Pu (NTNU), Marta Volonteri (IAP, Paris), Tirthankar Roy Choudhury (NCRA, Pune).

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IAP

NCRA • TIFR

High-redshift central black holes

Observational facts

- Supposedly, the centre of every galaxy has a black hole at its centre

Open questions

- How are central SMBHs born?

High-redshift central black holes

Observational facts

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- Supermassive black holes are already in place at $z > 6$

Open questions

- How are central SMBHs born?
- How do SMBHs grow so big so fast?
- What is time-averaged accretion rate of the seeds?
- What is the contribution of black hole mergers?

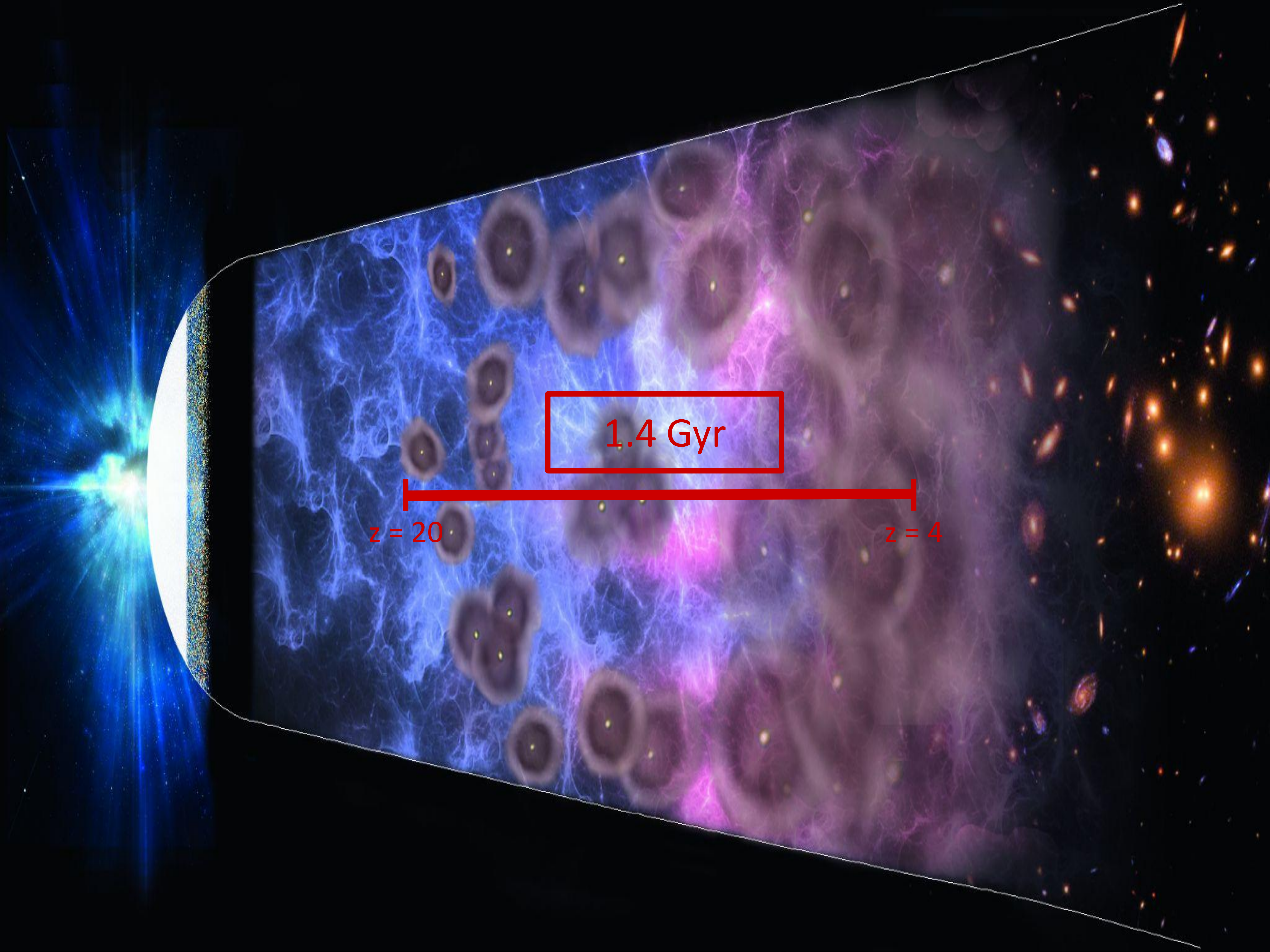
High-redshift central black holes

Observational facts

- Supposedly, the centre of every galaxy has a black hole at its centre
- Supermassive black holes are already in place at $z > 6$
- Energetic jets and gas outflows are observed in active galactic nuclei (AGN)
- Established correlations between the properties of SMBHs and host galaxies

Open questions

- How are central SMBHs born?
- How do SMBHs grow so big so fast?
- What is time-averaged accretion rate of the seeds?
- What is the contribution of black hole mergers?
- How exactly does their growth affect that of the host galaxy?


1.4 Gyr
z = 20
z = 4

The model /1
(Dayal+ 2014)

- Dark matter halo merger tree, with 550 halos between 10^8 and $10^{13.5}$ $M_\odot$, followed across the redshift range z = 20 to 4 in time steps of 20 Myr.
- Sheth-Tormen halo mass function is matched at all redshift.
- Dark matter, gaseous and stellar components jointly tracked along the trees.
- Calibrated against the main statistical observables for galaxies.
- Solidity test: we study two scenarios (ins1) and (tdf4) as upper and lower limits of the galaxy gas mass content

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Black holes?

(Dayal+ 2019, Piana+ 2021, Piana+ 2022)

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Black holes?

(Dayal+ 2019, Piana+ 2021, Piana+ 2022)

Seeding model

Accretion model

Feedback model

The model /2

- Multiple black hole seeds formation channel (*Volonteri+ 2012, Haiman+ 2013, Latif & Ferrara 2016, Inayoshi+ 2020* and others).

→ **Hybrid seeding mechanism**

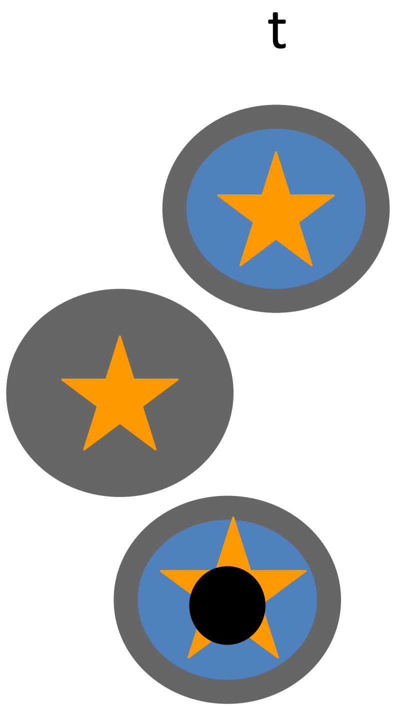
The model /2

- Multiple black hole seeds formation channel (*Volonteri+ 2012, Haiman+ 2013, Latif & Ferrara 2016, Inayoshi+ 2020* and others).

→ **Hybrid seeding mechanism**

- Black hole growth is quenched in low-mass system, as SN feedback heat and eject the gas from the central region of the galaxy (*Bower+ 2017*, but also *Rosas-Guevara+2016, Lupi+2019* and others).

→ **Transitional halo mass**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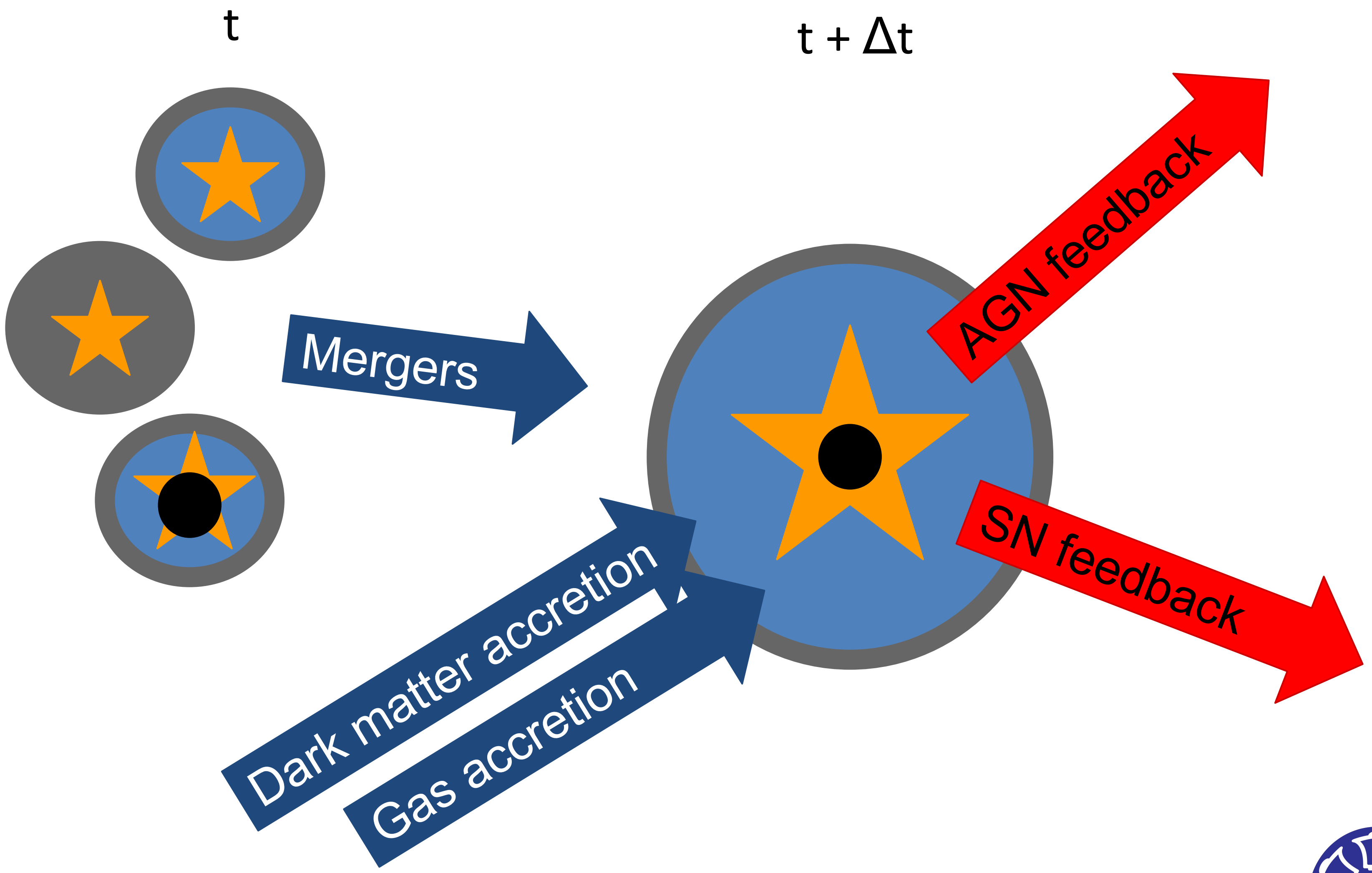
The model /2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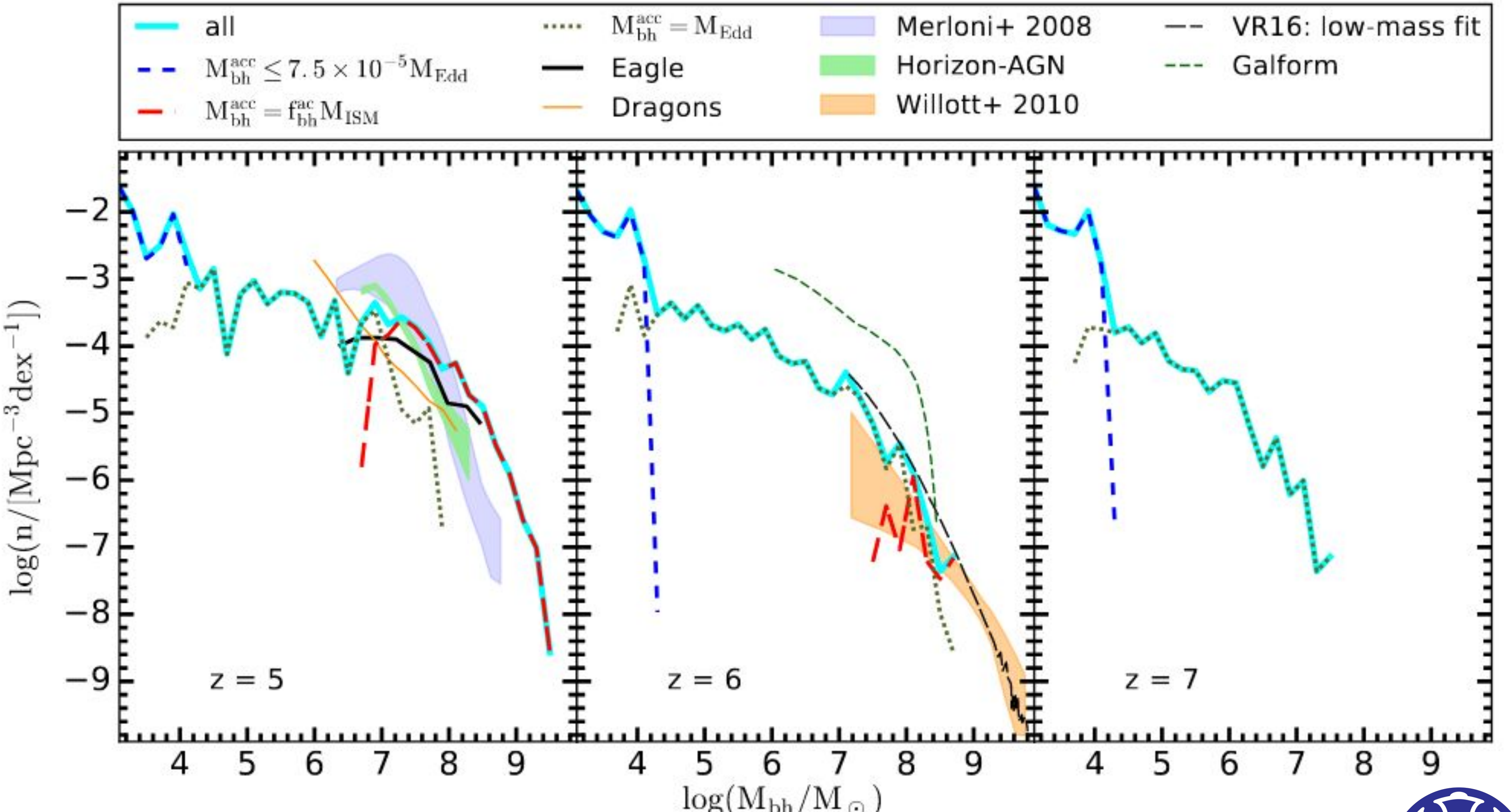
t + Δt
Mergers
Dark matter accretion
Gas accretion
AGN feedback
SN feedback

The black hole mass function

(Piana+ 2021)



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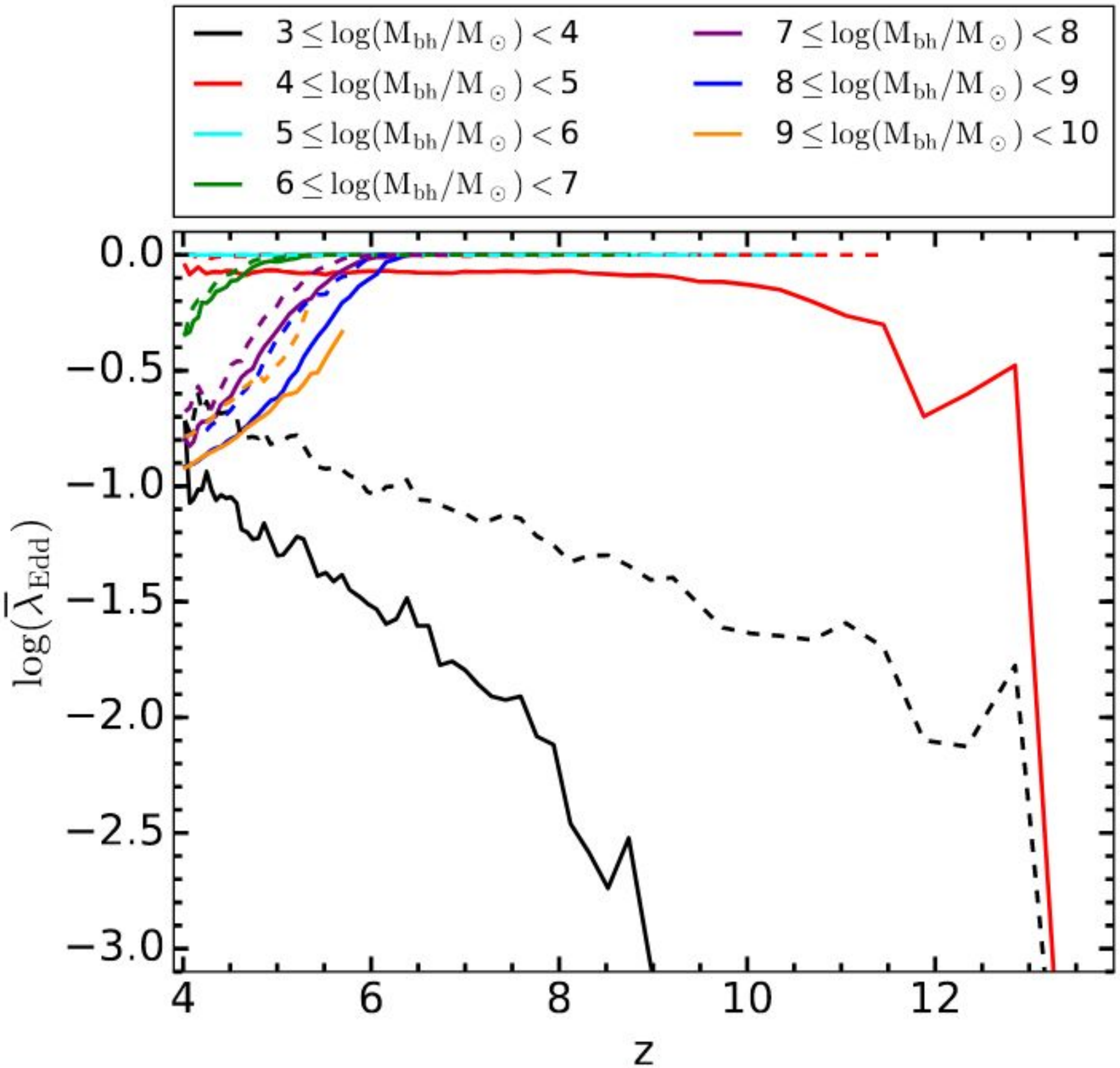
The Eddington ratio evolution

(Piana+ 2021)

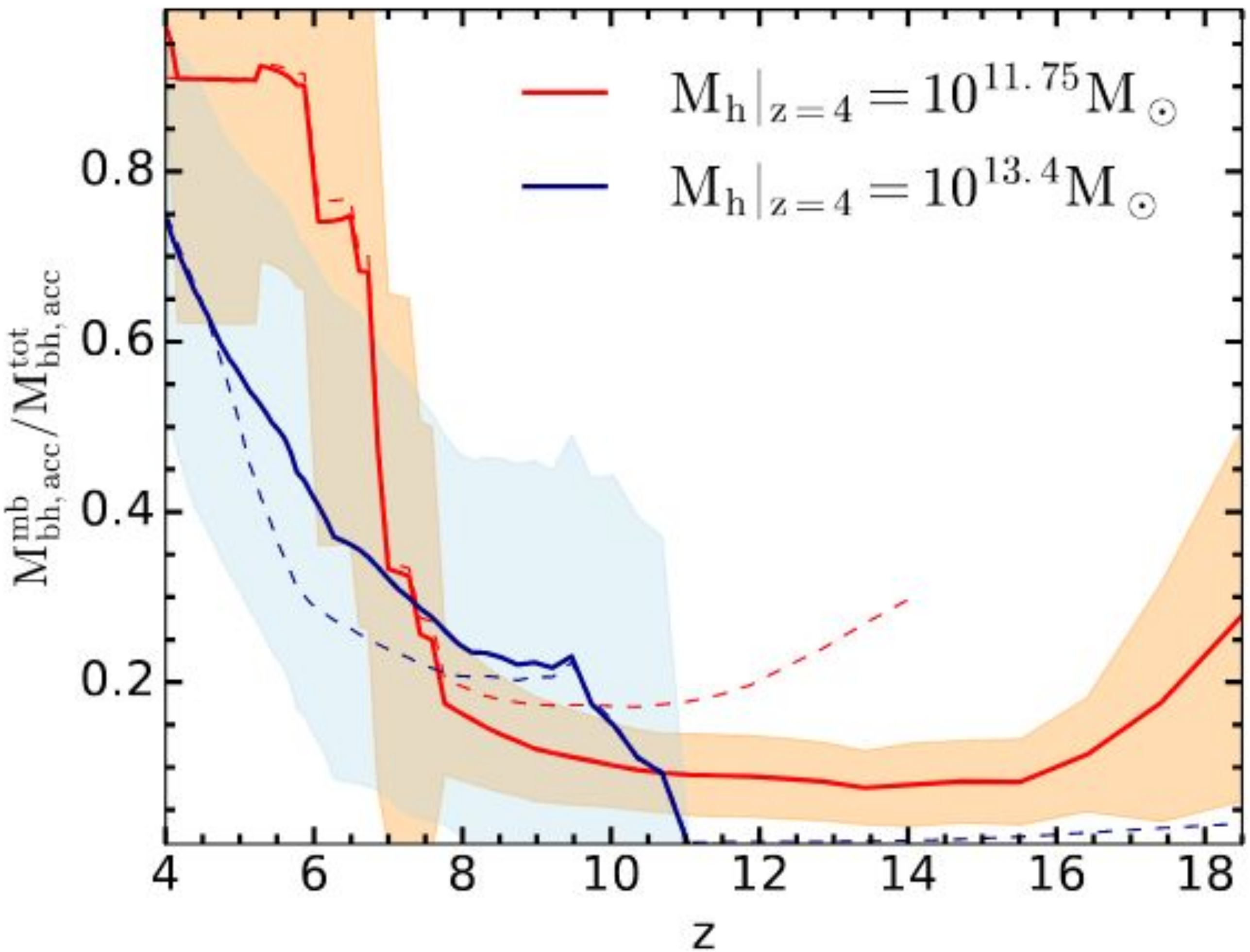


solid lines: ins1
dashed lines: tdf4

Opposite trend for high-mass and low-mass black holes

The contribution of mergers

(Piana+ 2021)

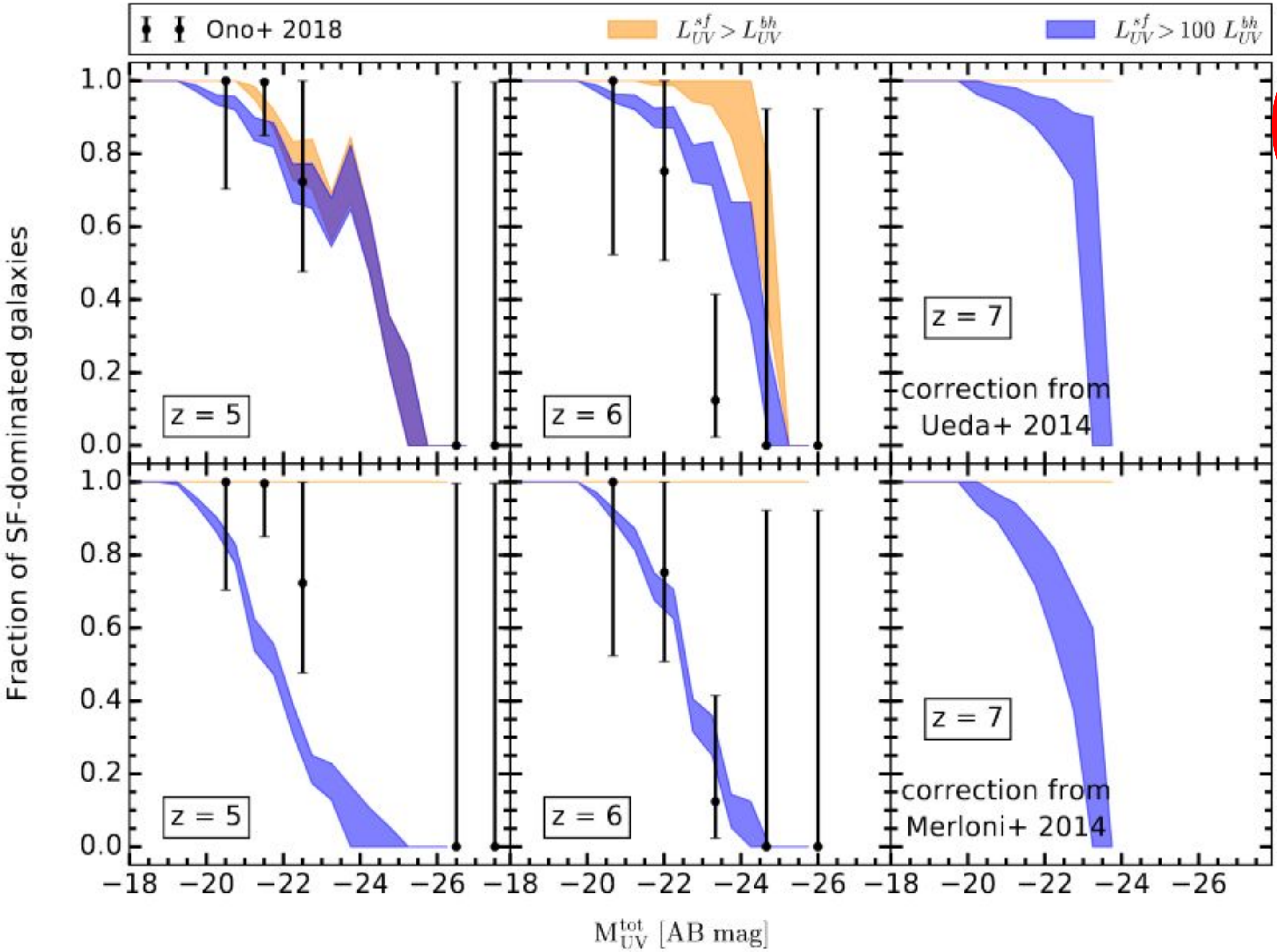


solid lines: ins1
dashed lines: tdf4

Mergers contribute with 5% (25%) of total mass for intermediate- (high-) mass halos

The galaxy fraction

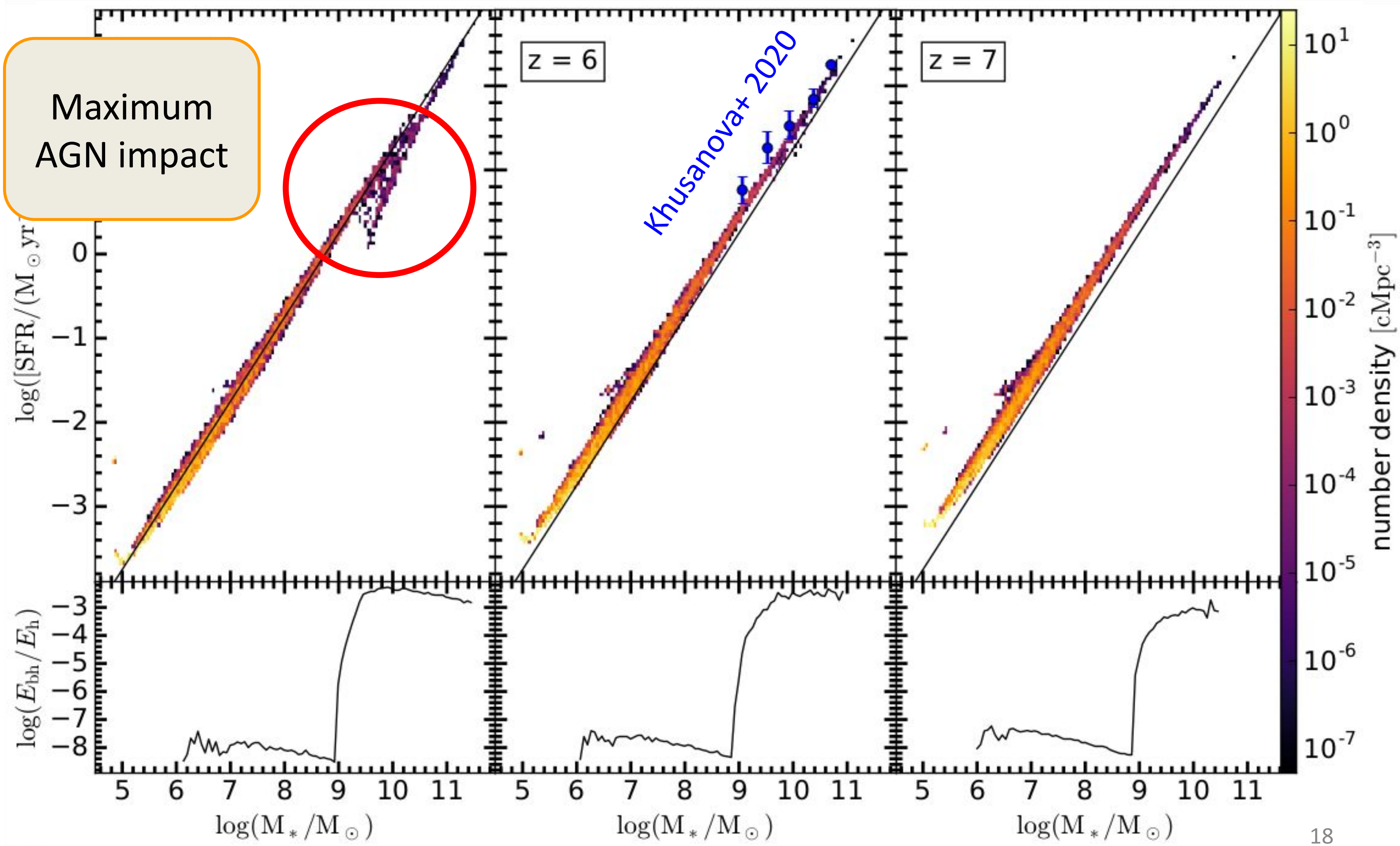
(Piana+ 2022)



Emergence of AGN

The effect of AGN feedback

(Piana+ 2022)



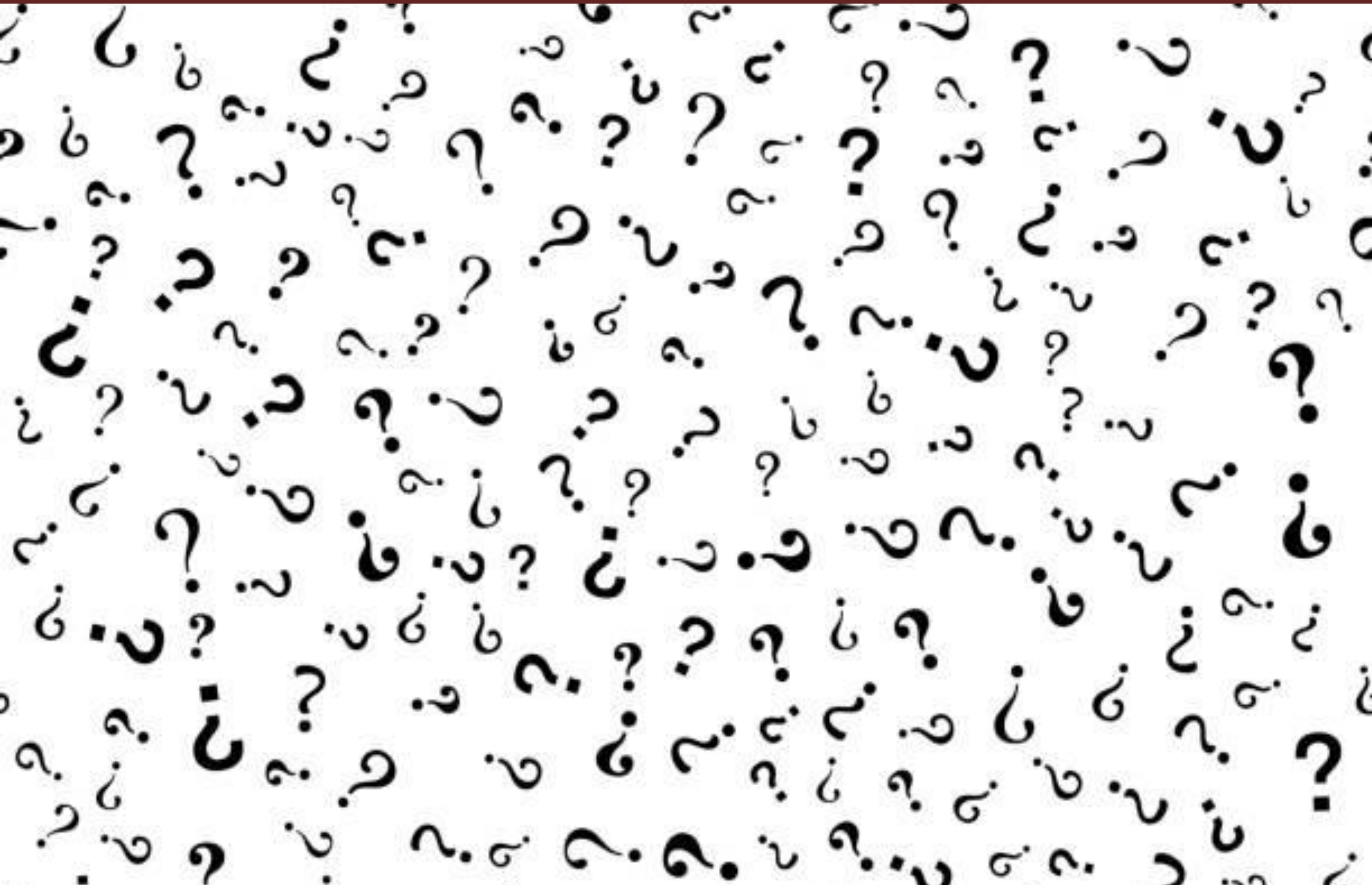
Summary and conclusions

- We grow black holes at up to $10^{9.5}$ $M_\odot$ by z = 5 (with caveats).
- Mergers dominate growth down to z = 8, but approximately 80% (depending on the halo mass) of the final mass is assembled within the major branch.
- High- (low-) mass black holes show a decreasing (increasing) trend of the average Eddington ratio.
- The impact of AGN feedback is most effective for intermediate-mass galaxies with $M_* = 10^{9.5}$ $M_\odot$ at z < 7.
- AGN-driven outflows dominate at z < 5.

Future prospects

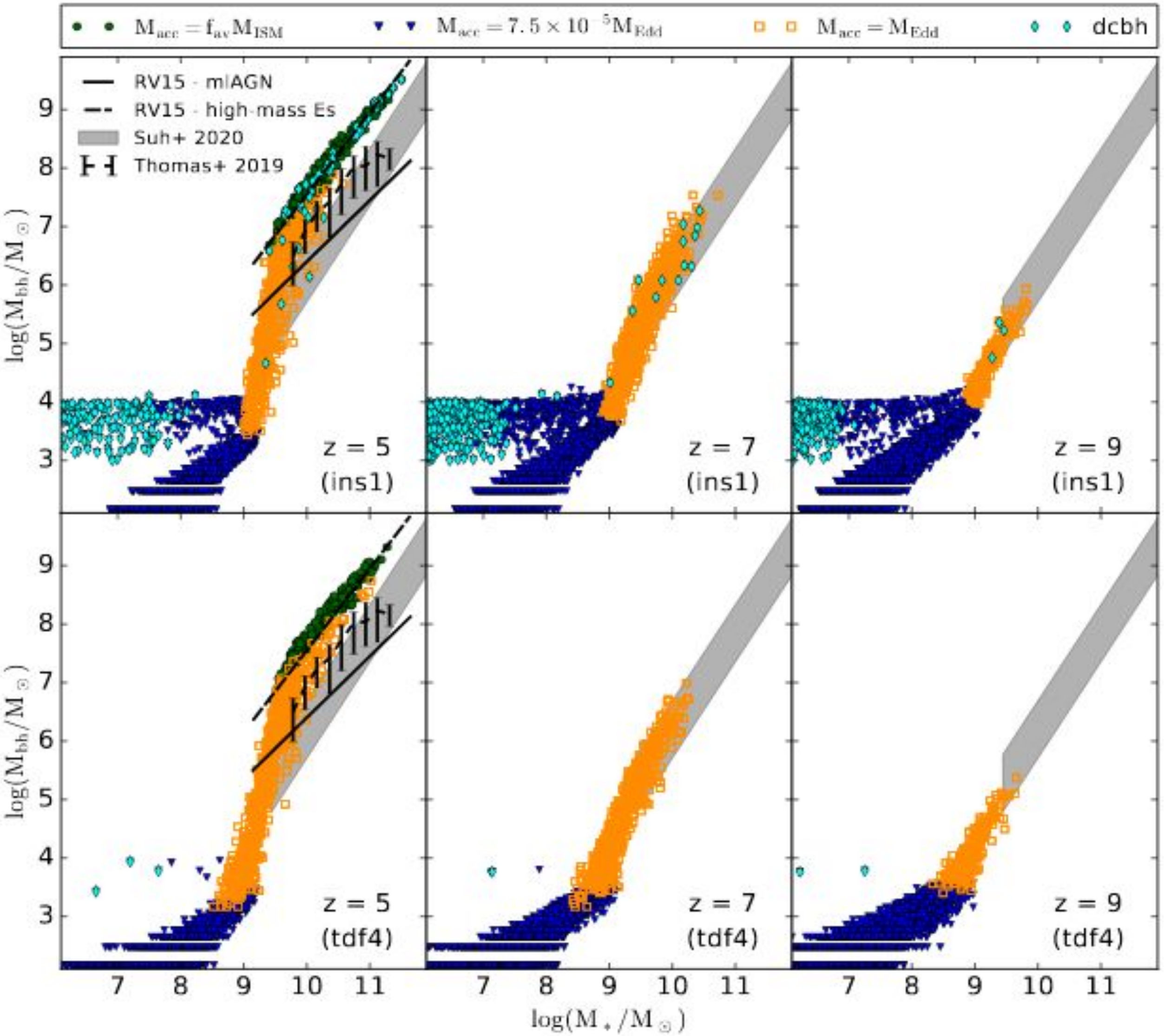
- Implementing recipes for density, temperature and entropy profiles at the center of galaxies.
- More accurate estimation of black hole accretion rates as a function of host galaxy properties.
- Including jet models for ADAF and super-Eddington accretion regimes.
- Studying the emergence of jets in the early Universe and their effect on the host galaxies.

Thank you!



The stellar mass - black hole mass relation

(Piana+ 2021)

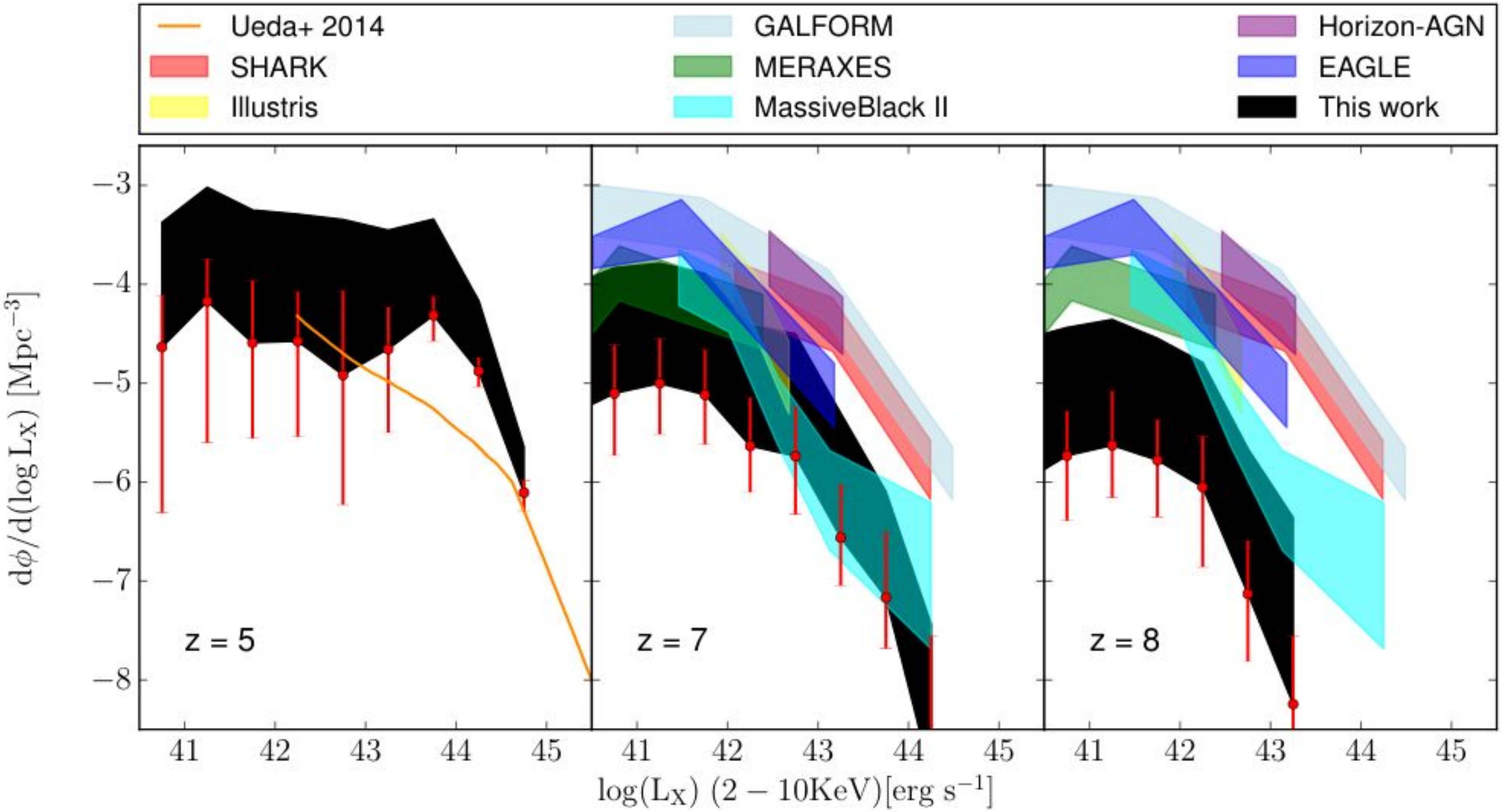


SMBHs at z ~ 6

Three different sequences are found on the stellar mass - black hole mass plane

The mass assembly of high-z SMBHs

(Piana+ 2021)



Delphi

(Dayal+ 2019, Piana+ 2021)

Solidity test

Upper limit

ins1

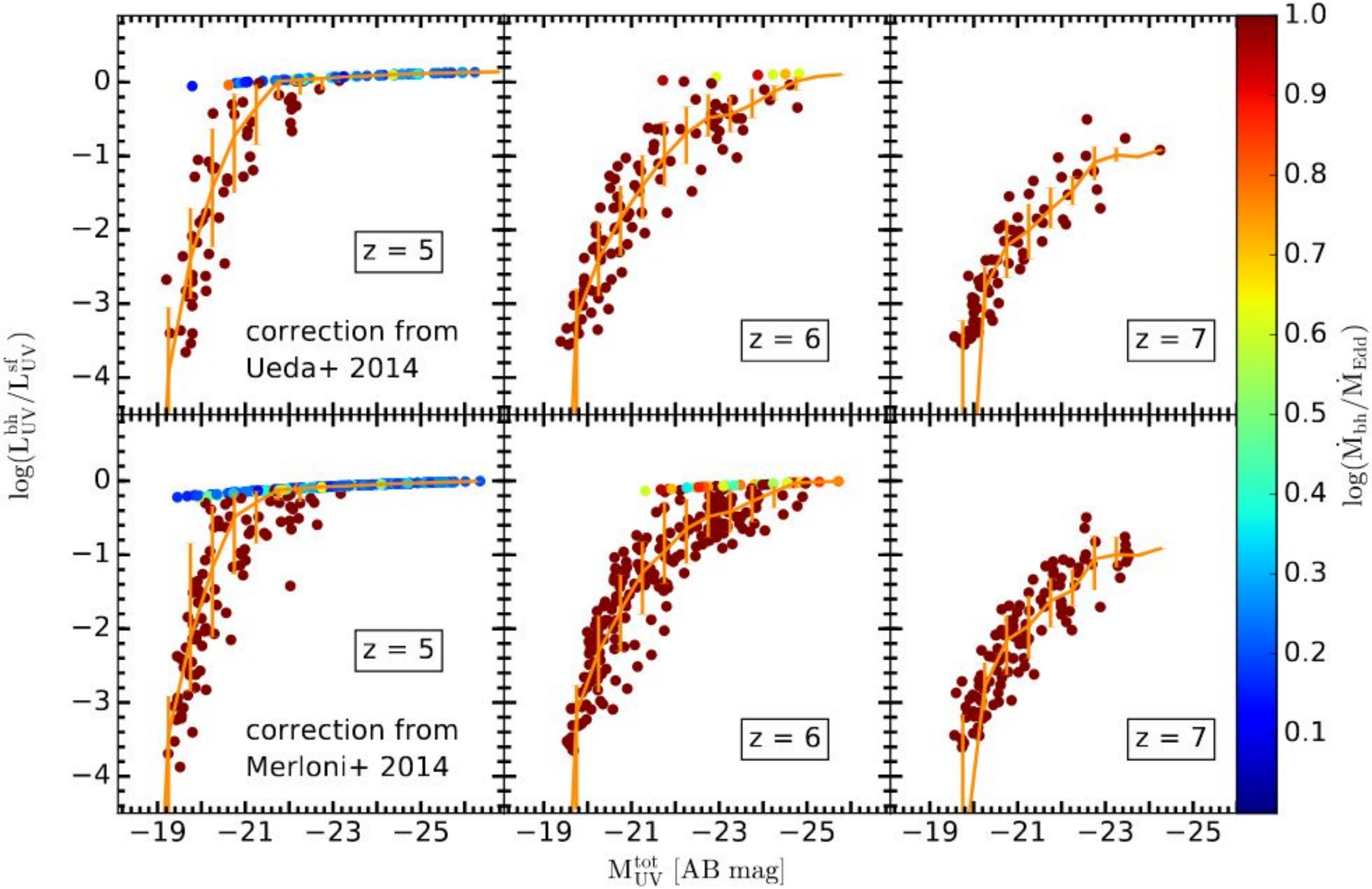
- Instantaneous galaxy mergers
- No reionization feedback
- Lower threshold for the LW flux needed for DCBH seed formation

Lower limit

tdf4

- Delayed galaxy mergers due to dynamical friction
- Maximal reionization feedback
- Higher threshold for the LW flux needed for DCBH seed formation

The impact of black hole feedback on the UV luminosity and stellar mass assembly of high-z galaxies *(submitted)*



Black hole seeds

(Volonteri+ 2012, Haiman+ 2013, Latif & Ferrara 2016, Inayoshi+ 2020 and others*)*

- **Stellar black hole seeds**: from PopIII stars that can leave behind seeds of about 100 solar masses BUT constant Eddington growth required to grow to 10^9 solar masses by z = 6

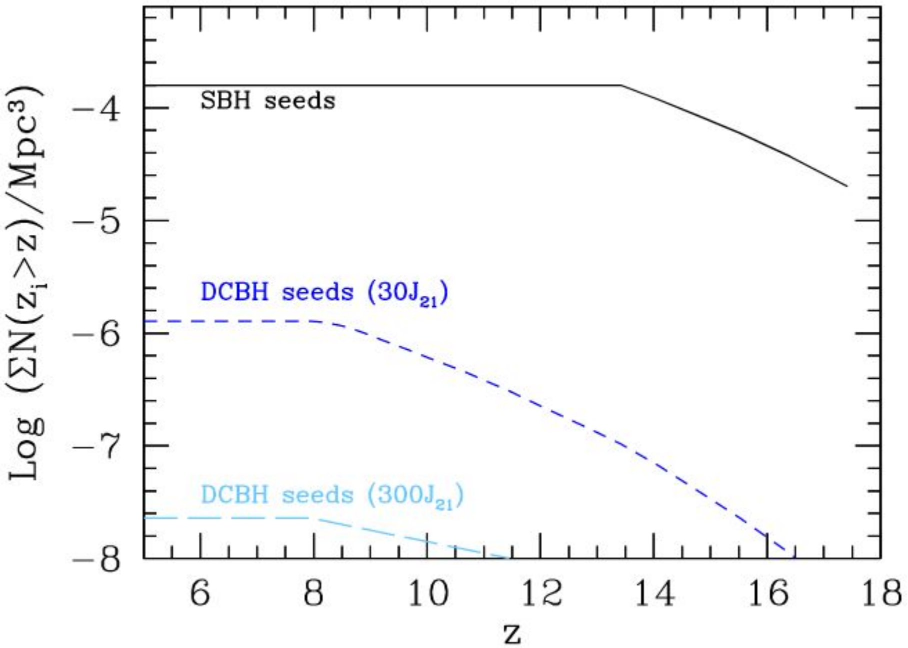
- **Direct-** … of pristine … mic cooling …

Hybrid seeding mechanism

- **Black hole seeds in stellar clusters**: from runaway collisional processes in dense stellar clusters BUT very dependent on initial conditions.

Black hole seeds in *Delphi*
(Dayal+ 2019, Piana+ 2021)

- Heavy seeds (dcbh): direct-collapse black holes, Mseed = 10^{3-4} $M_\odot$
- Light seeds (sbh): from the collapse of very massive (M > 260 $M_\odot$) PopIII stars in minihalos, Mseed = 150 $M_\odot$



Black hole growth and feedback in *D*

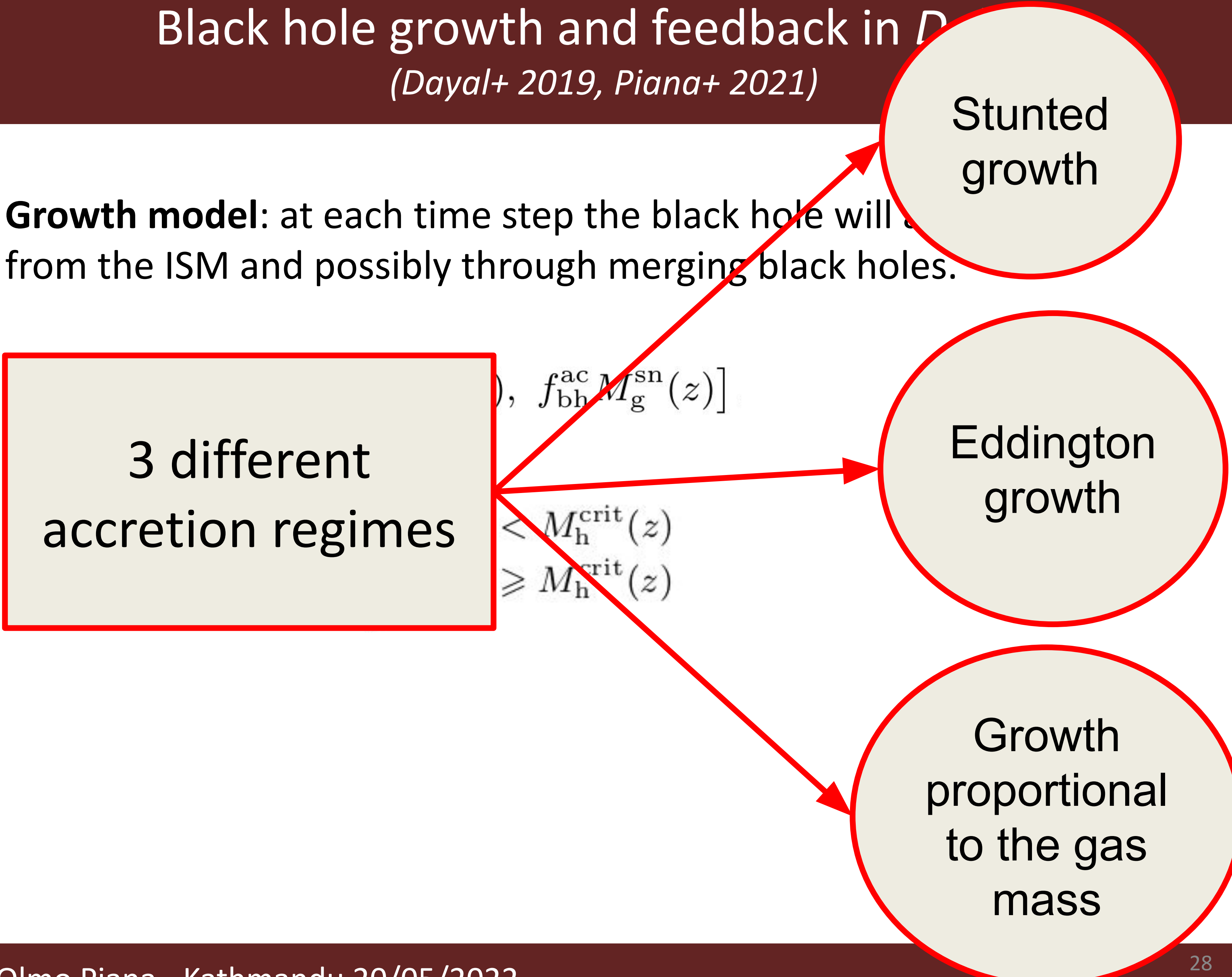
(Dayal+ 2019, Piana+ 2021)

Growth model: at each time step the black hole will a
from the ISM and possibly through merging black holes.

$), \; f_{\rm bh}^{\rm ac} M_{\rm g}^{\rm sn}(z)]$

$< M_{\rm h}^{\rm crit}(z)$

$\geqslant M_{\rm h}^{\rm crit}(z)$



Black hole growth and feedback in *Delphi*

(Dayal+ 2019, Piana+ 2021)

Growth model: at each time step the black hole will accrete mass from the ISM and possibly through merging black holes.

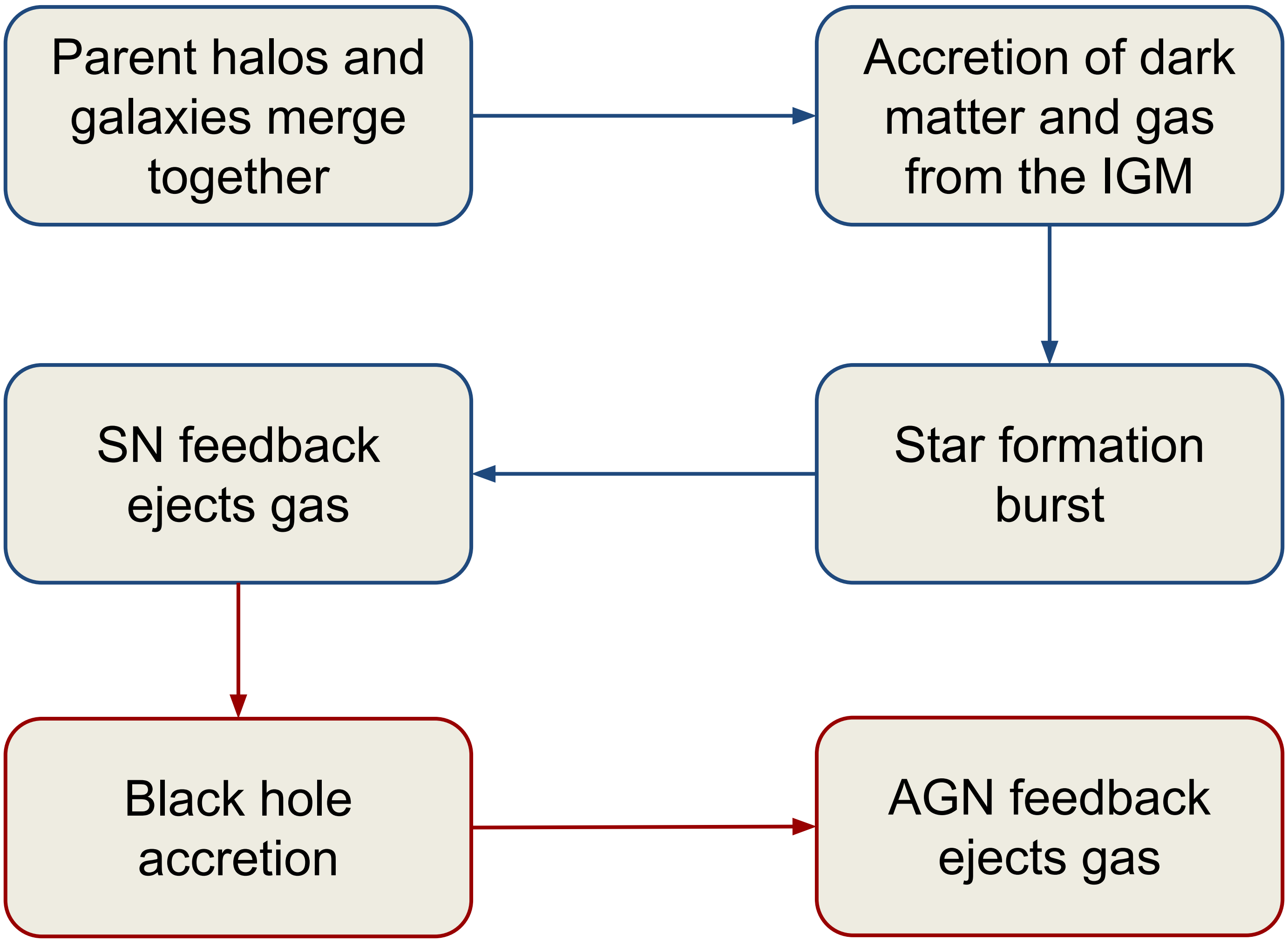
$$M_{\rm bh}^{\rm ac}(z) = \min\left[f_{\rm Edd} M_{\rm Edd}(z),\ f_{\rm bh}^{\rm ac} M_{\rm g}^{\rm sn}(z)\right]$$

$$f_{\rm Edd} = \begin{cases} 7.5\times10^{-5} & M_{\rm h}(z) < M_{\rm h}^{\rm crit}(z) \\ 1 & M_{\rm h}(z) \geqslant M_{\rm h}^{\rm crit}(z) \end{cases}$$

Feedback: 10% of the accreted mass is turned into energy. Part of the emitted radiation couples to the gas and drives outflows.

Delphi

(Dayal+ 2019, Piana+ 2020)



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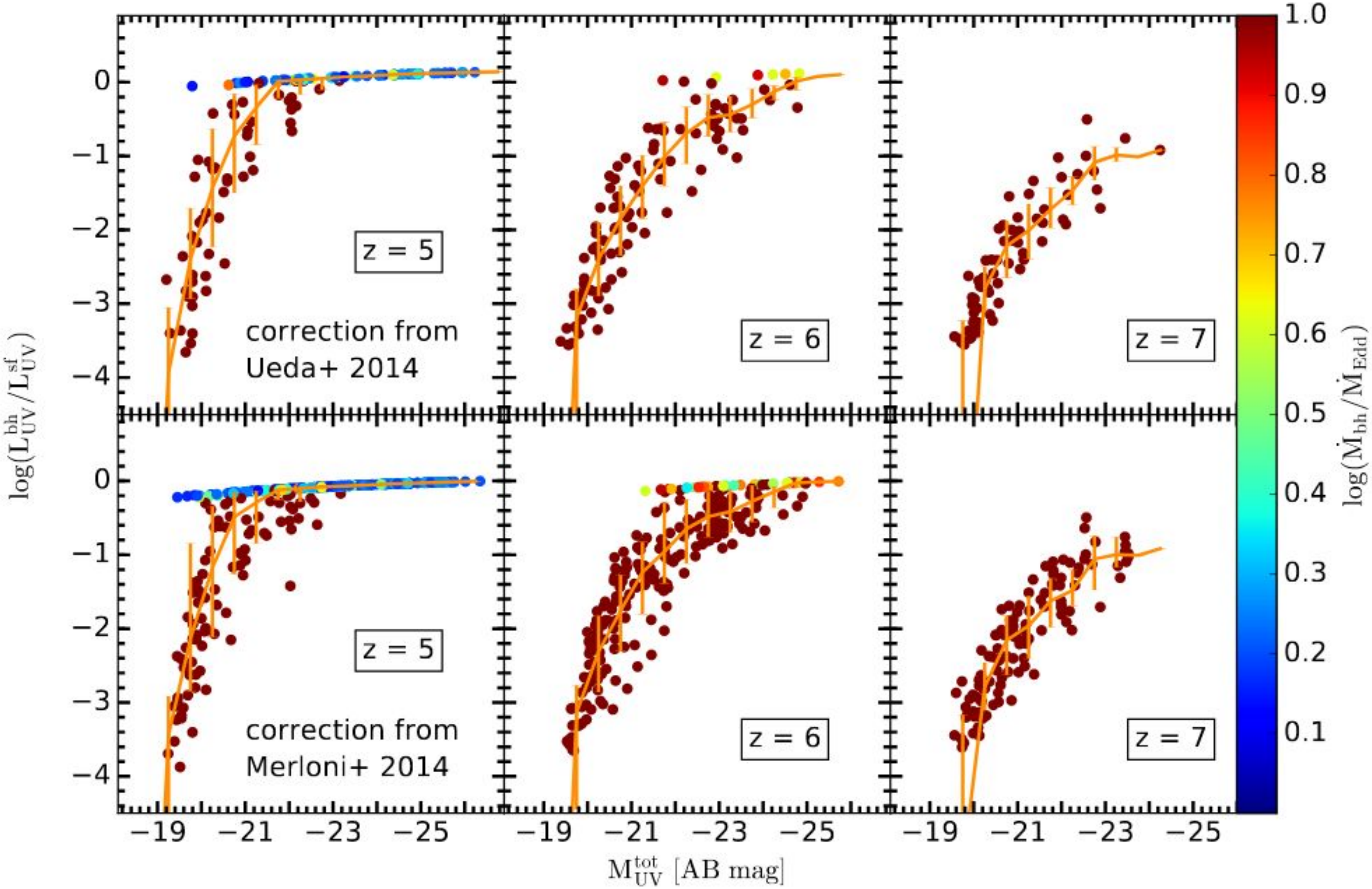

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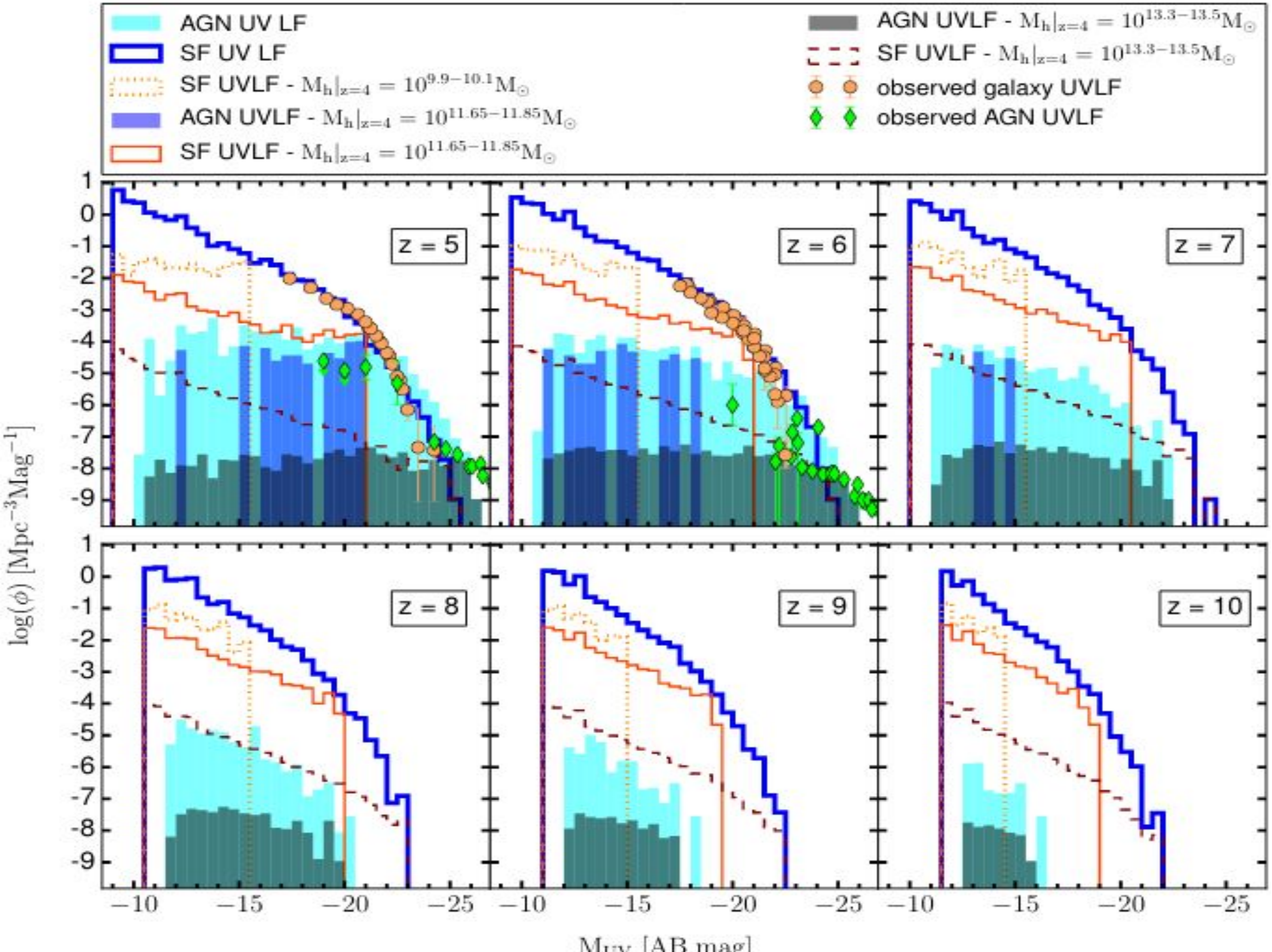


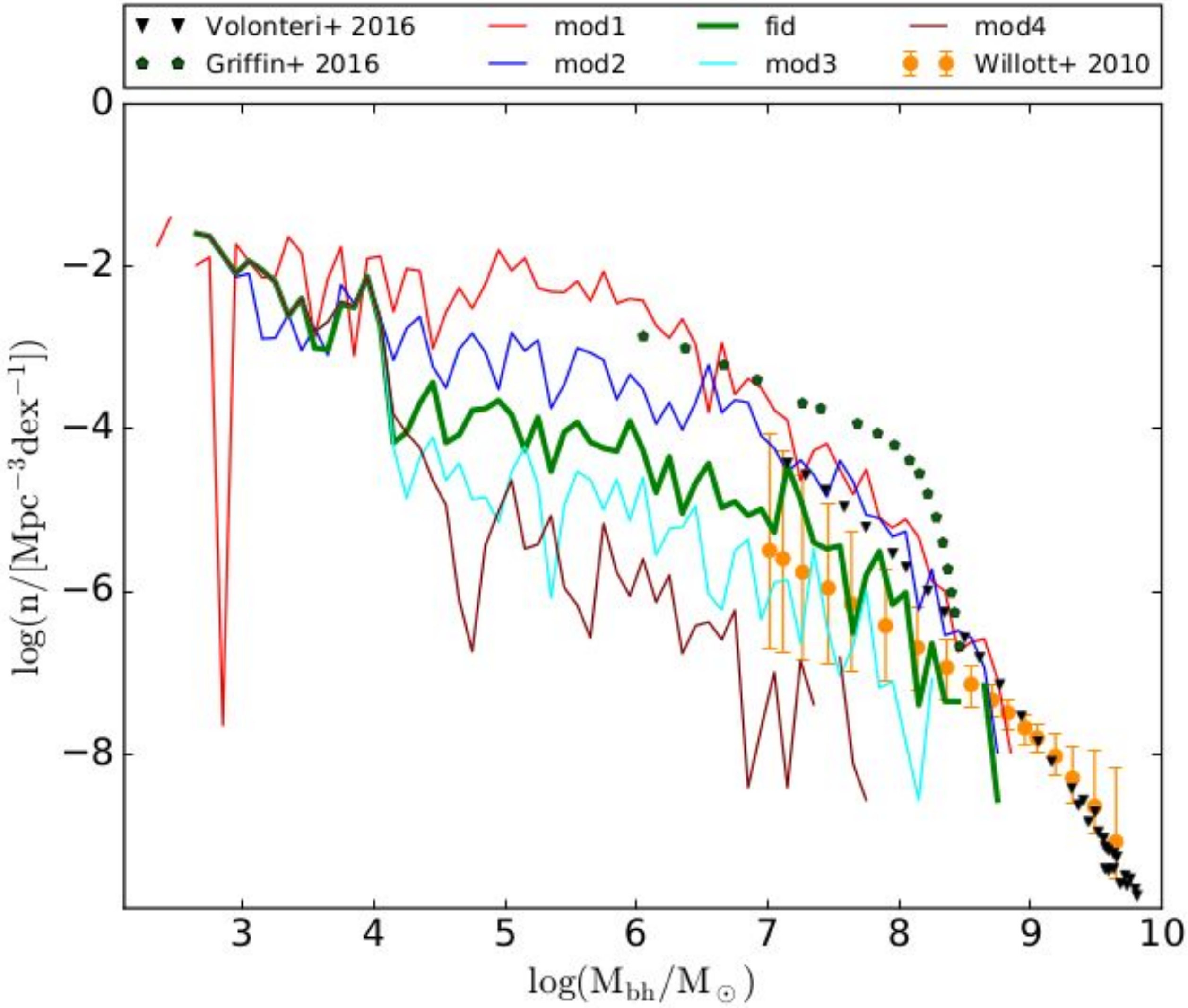
Delphi

(Dayal+ 2019, Piana+ 2021)

Parameters definition

Parameter	Description	*ins*1	*tdf*4
ϵ_r	radiative efficiency of black hole accretion	0.1	0.1
f_*	star formation efficiency threshold	0.02	0.02
f_*^w	fraction of SN energy that couples to the gas	0.1	0.1
f_{bh}^w	fraction of AGN energy that couples to the gas	0.003	0.003
f_{bh}^{ac}	fraction of available gas mass that black holes can accrete	5.5×10^{-4}	5.5×10^{-4}
$f_{Edd}(M_h < M_h^{crit})$	black hole accretion rate in fraction of Eddington	7.5×10^{-5}	7.5×10^{-5}
$f_{Edd}(M_h > M_h^{crit})$	black hole accretion rate in fraction of Eddington	1	1
α	LW background threshold for DCBH formation (in units of J_{21})	30	300
Reionization feedback	-	No	Yes
Delayed mergers	dynamical friction acting to delay the merging of the baryonic components	No	Yes

The role of parameters (M^{crit}_h)



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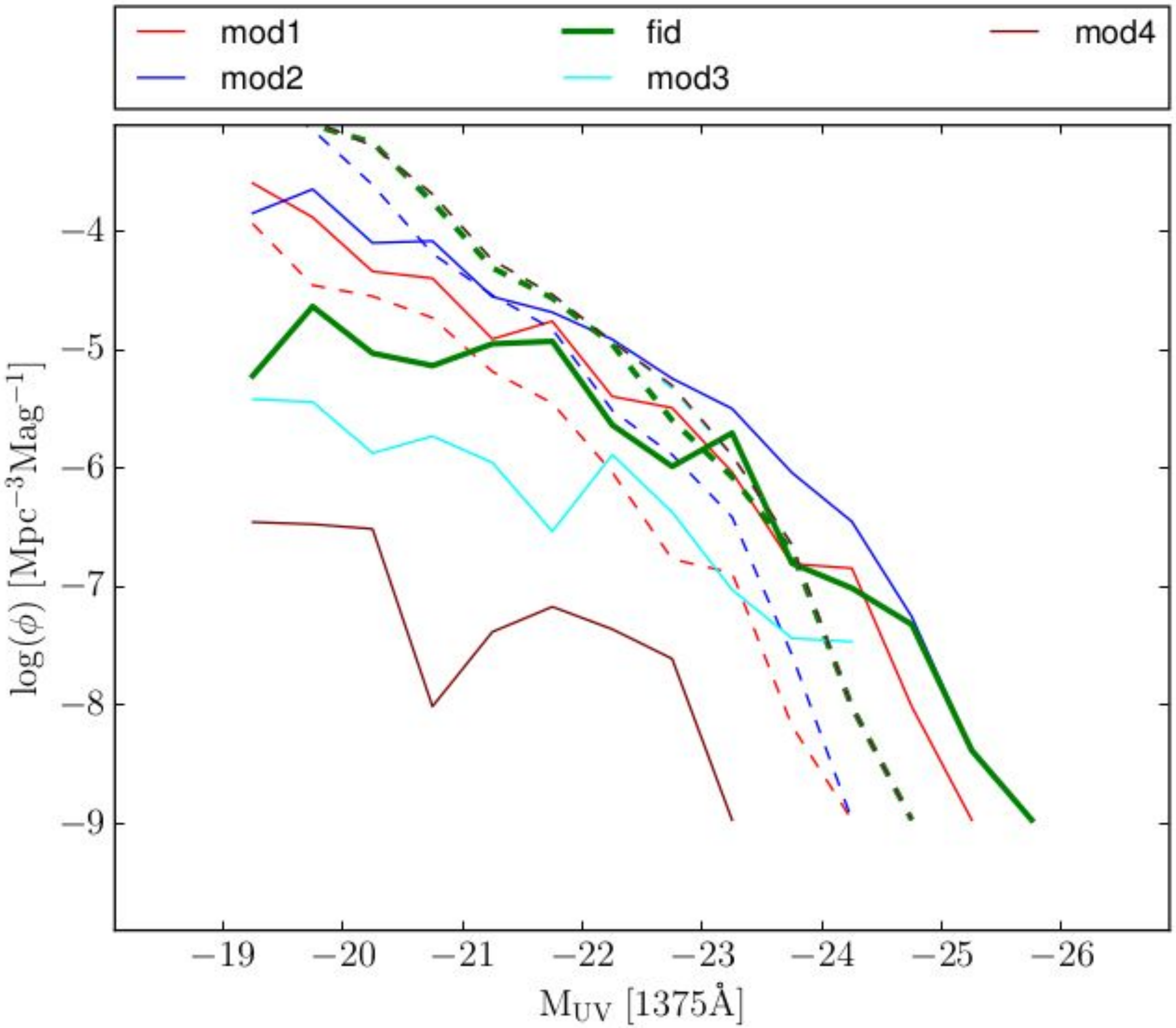

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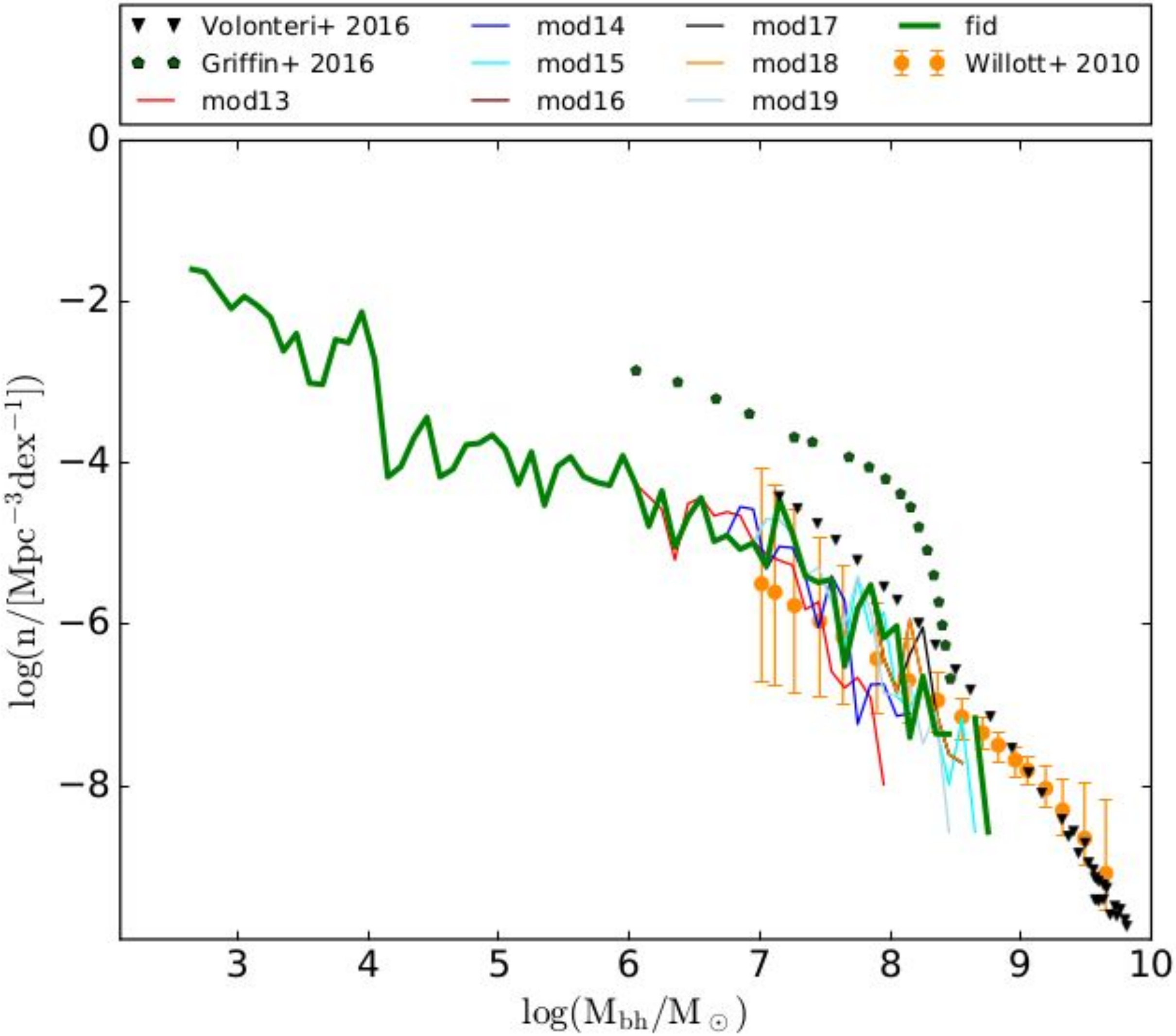

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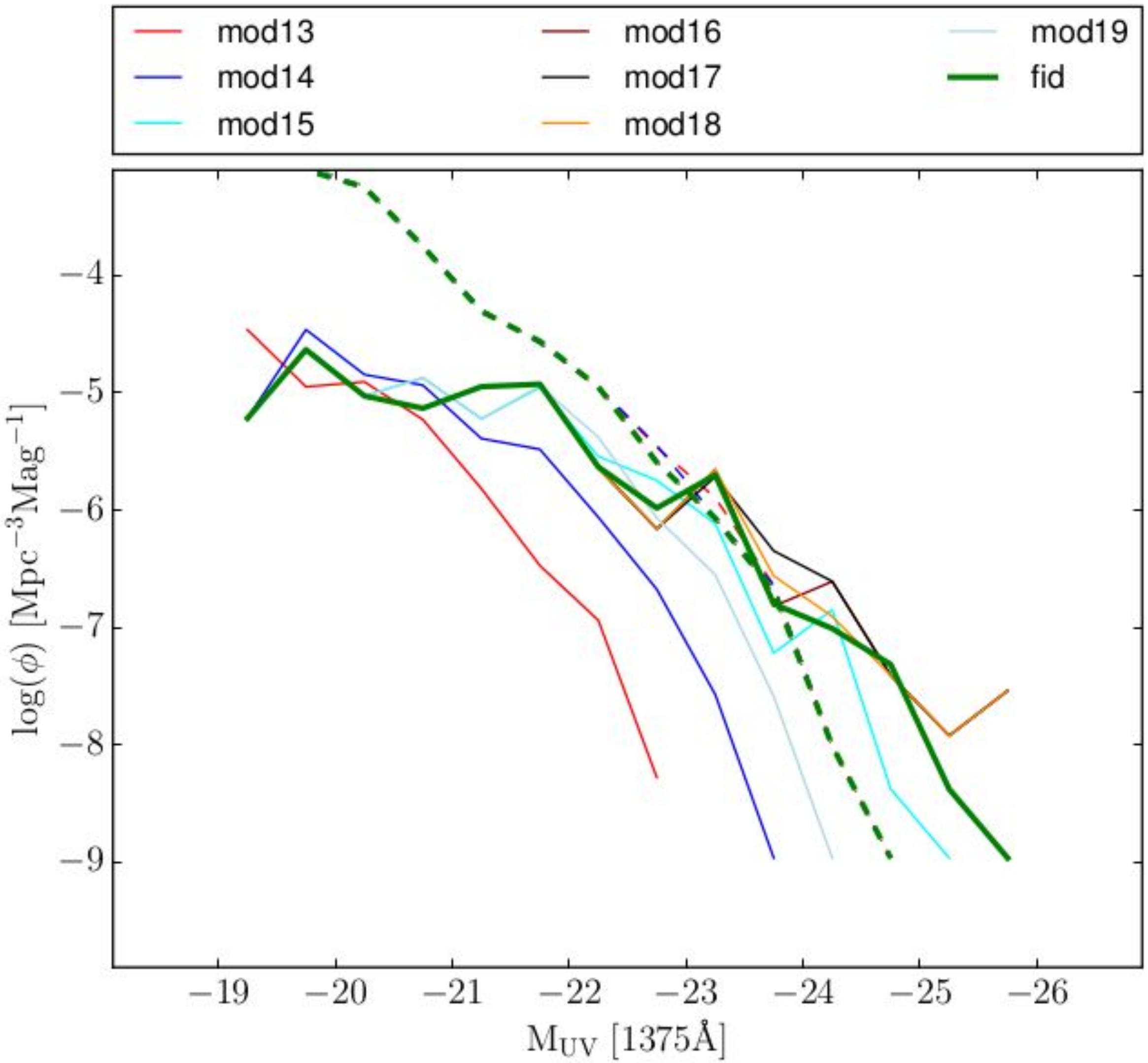
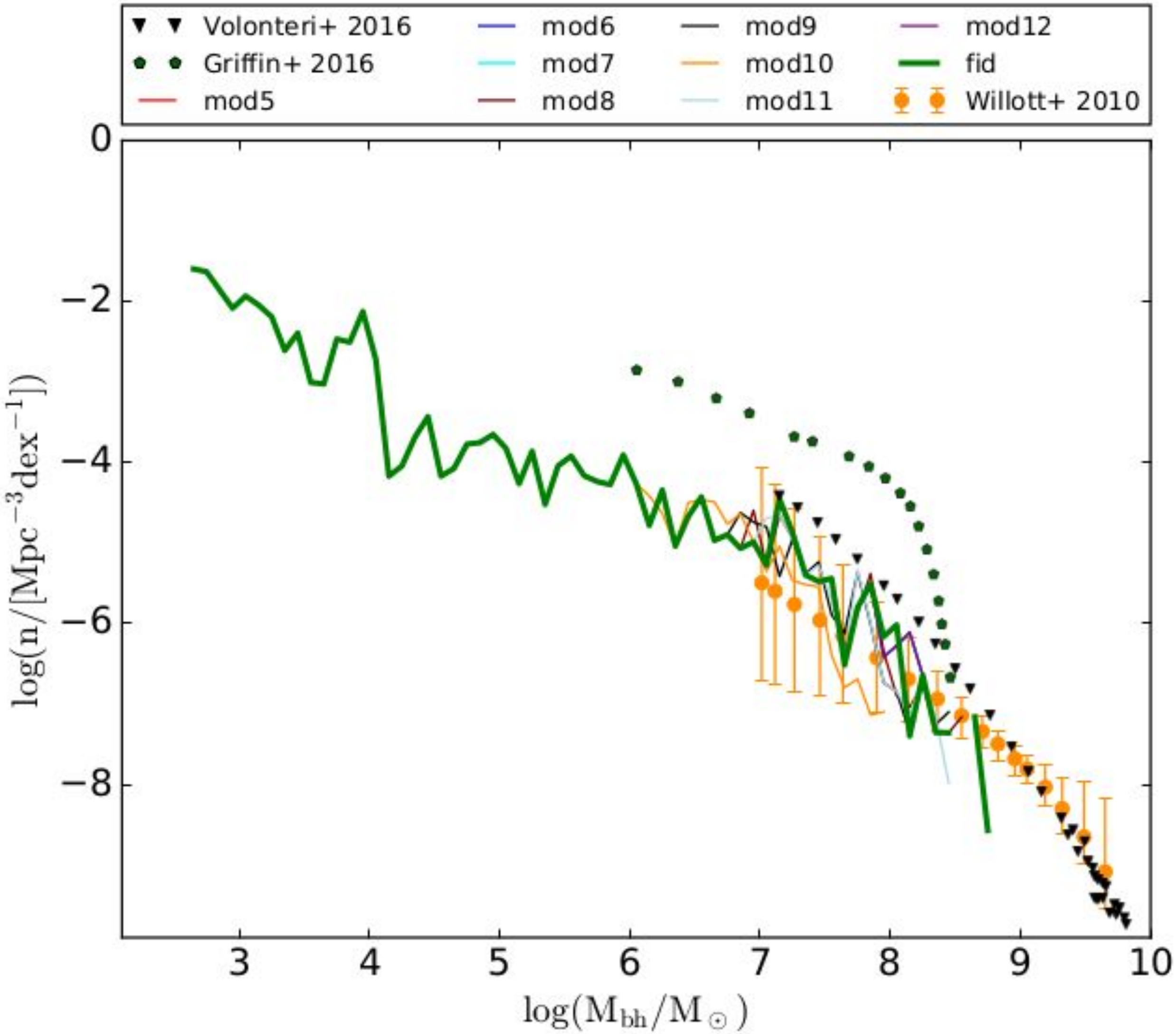
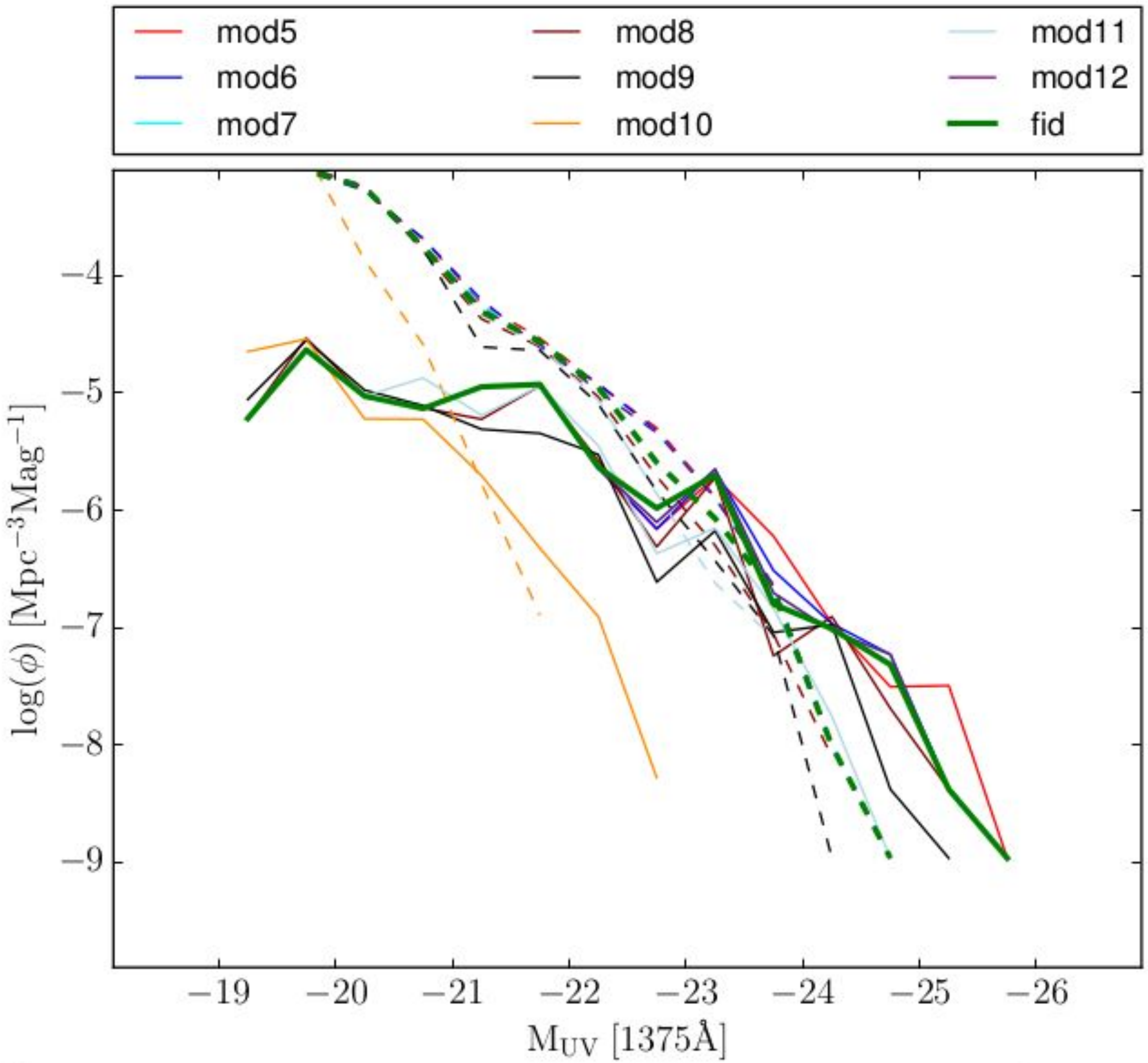


The role of parameters (f^{w}_{bh})

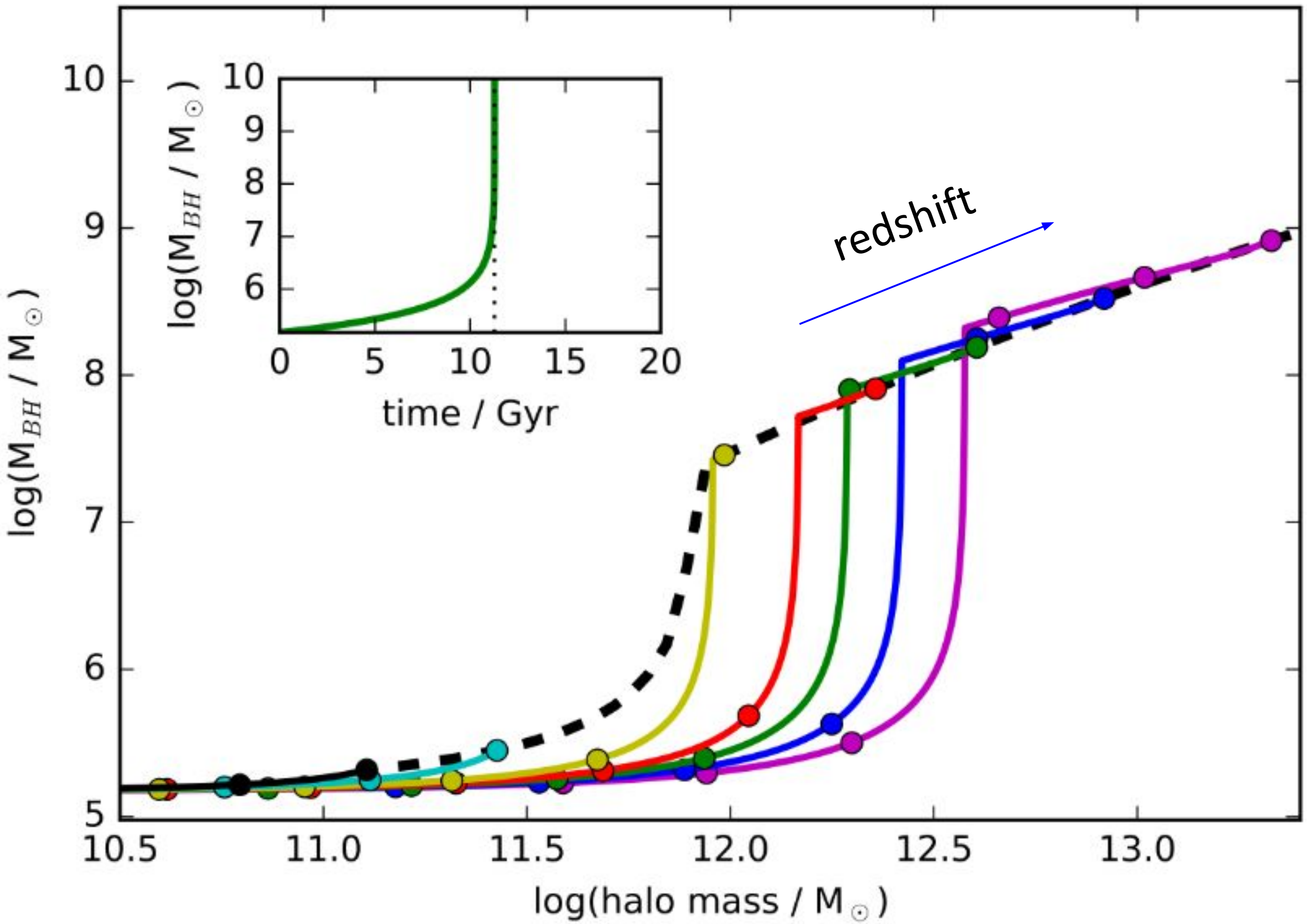


The role of parameters (f^{w}_{bh})



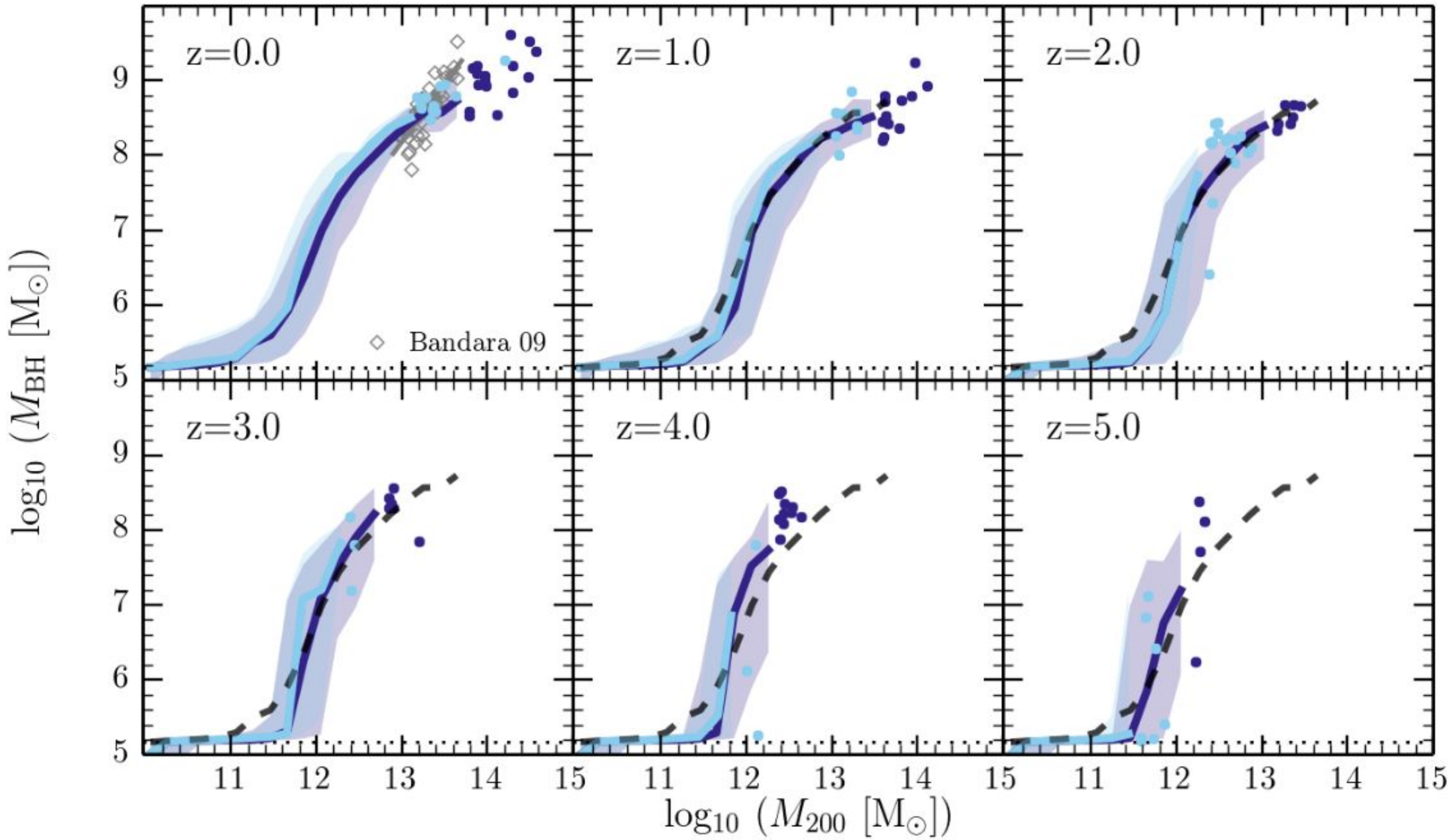
Black hole growth in simulations

(e.g. Bower+ 2017, but also *Rosas-Guevara+2016, Lupi+2019* and others*)*



Black hole growth in simulations

(Rosas-Guevara+ 2016)



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