Light, medium-weight or heavy? The nature of the first supermassive black hole seeds

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COST is supported by the EU Framework Programme Horizon 2020

Second-most distant quasar ever found

Pōniuā'ena: A Luminous $z = 7.5$ Quasar Hosting a 1.5 Billion Solar Mass Black Hole

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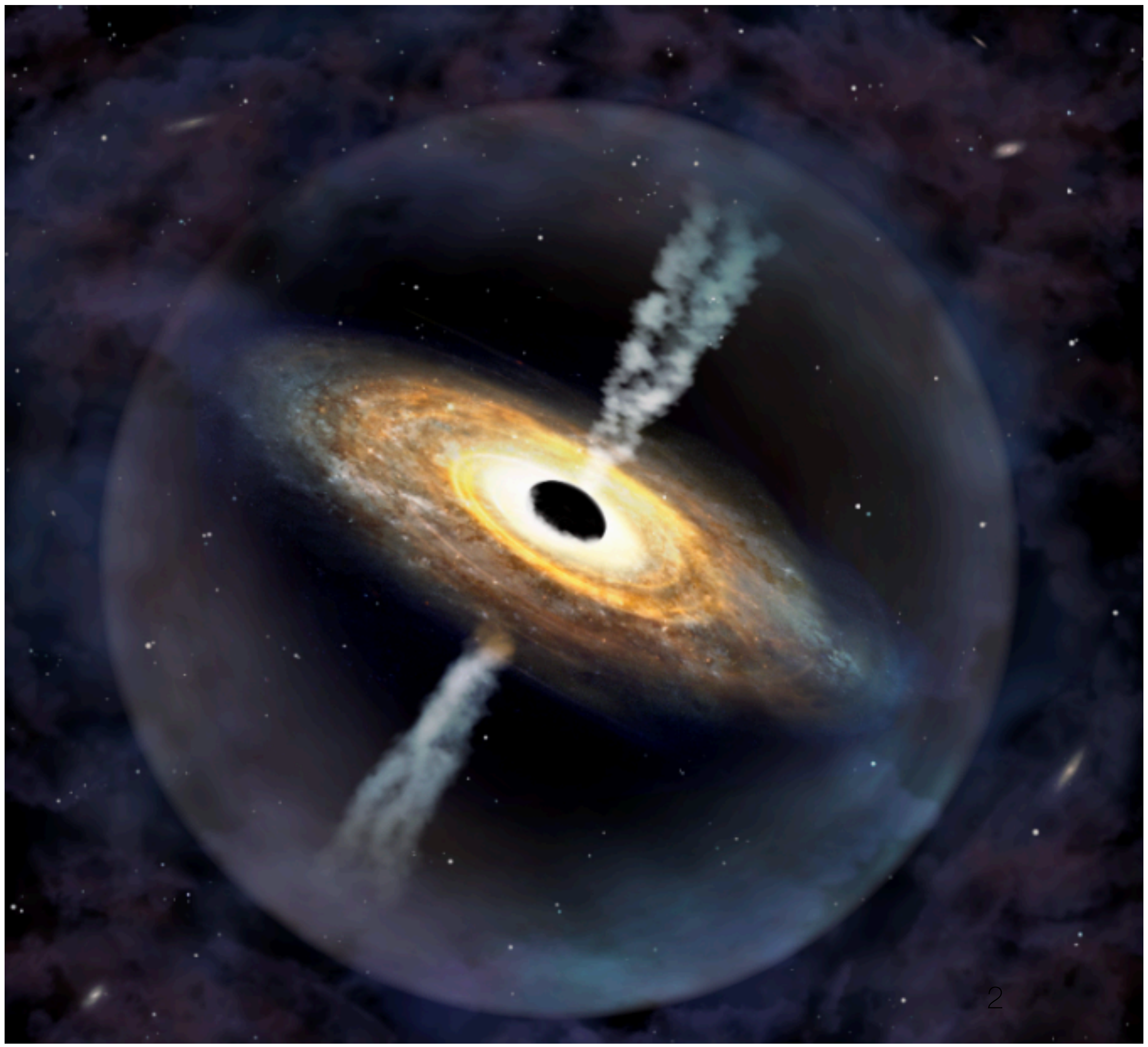
Eduardo Banados,[3] Xue-Bing Wu,[5,6] Bram Venemans,[3] Aaron J. Barth,[7] Fuyan Bian,[8] Konstantina Boutsia,[9]
Roberto Decarli,[10] Emanuele Paolo Farina,[11] Richard Green,[1] Linhua Jiang,[5] Jiang-Tao Li,[12]
Chiara Mazzucchelli,[8] and Fabian Walter[3]



**SMBH at
700 million years
after the Big Bang!**

Credit: International Gemini Observatory/NOIRLab/NSF/AURA/
P. Marenfeld

Most distant and massive SMBHs at high-z

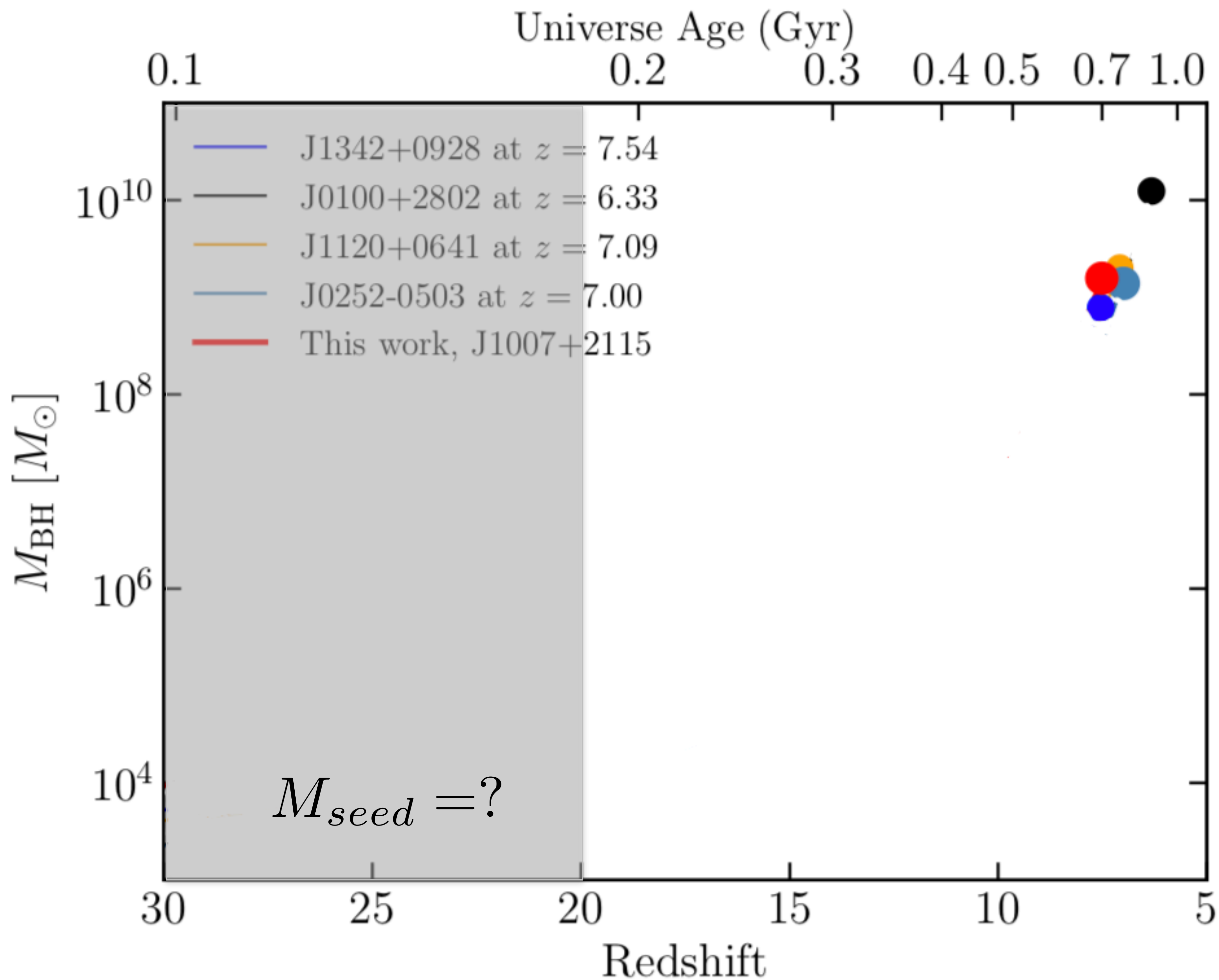


Figure from Yang et al. 2020

Initial mass of the BH at z>20 assuming unimpeded Eddington accretion rate?

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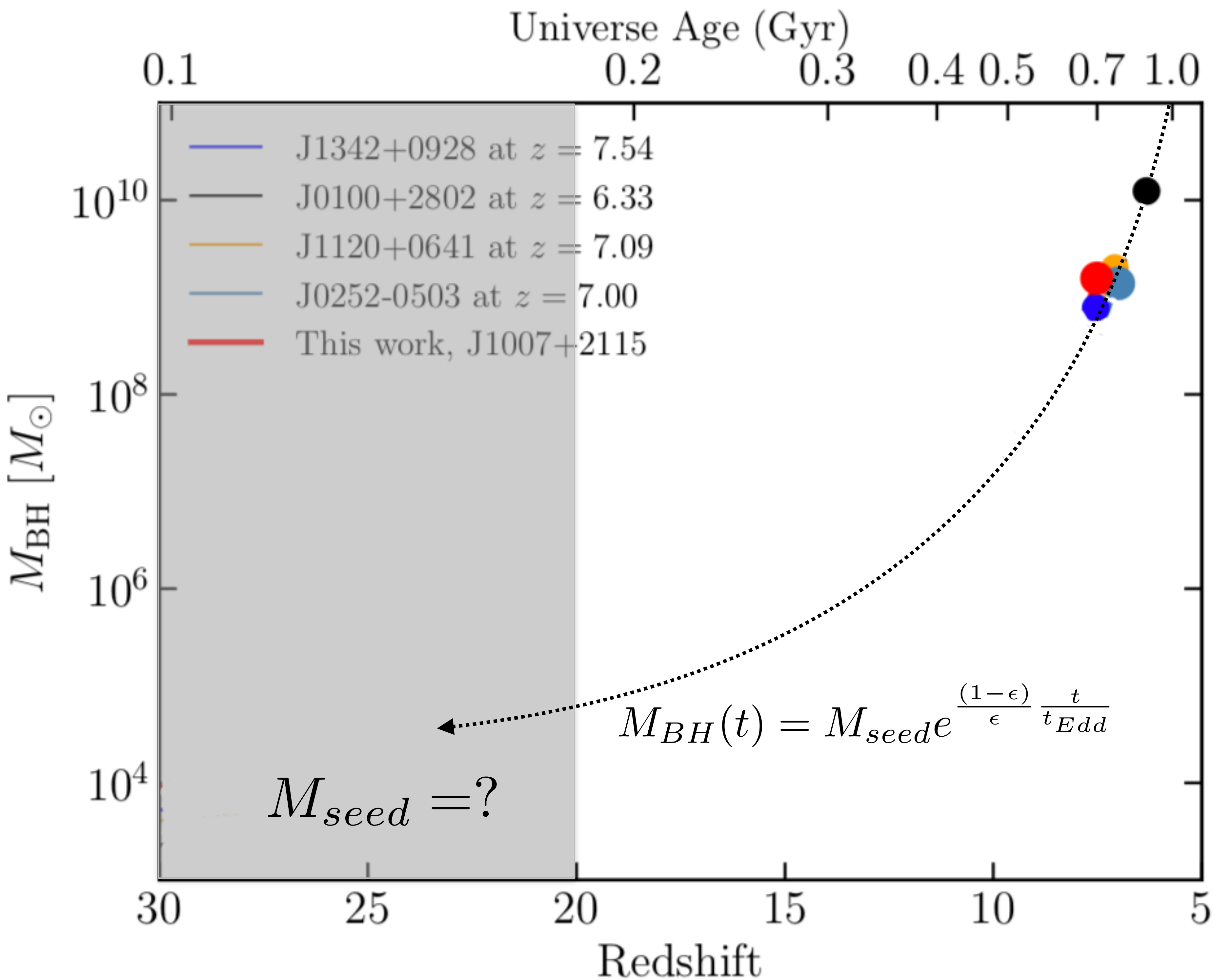
Most distant and massive SMBHs at high-z



$t_{Edd} = 0.45Gyr$

$\epsilon = 0.1$

Figure from Yang et al. 2020

Initial mass of the BH at z>20 assuming unimpeded Eddington accretion rate?

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Most distant and massive SMBHs at high-z

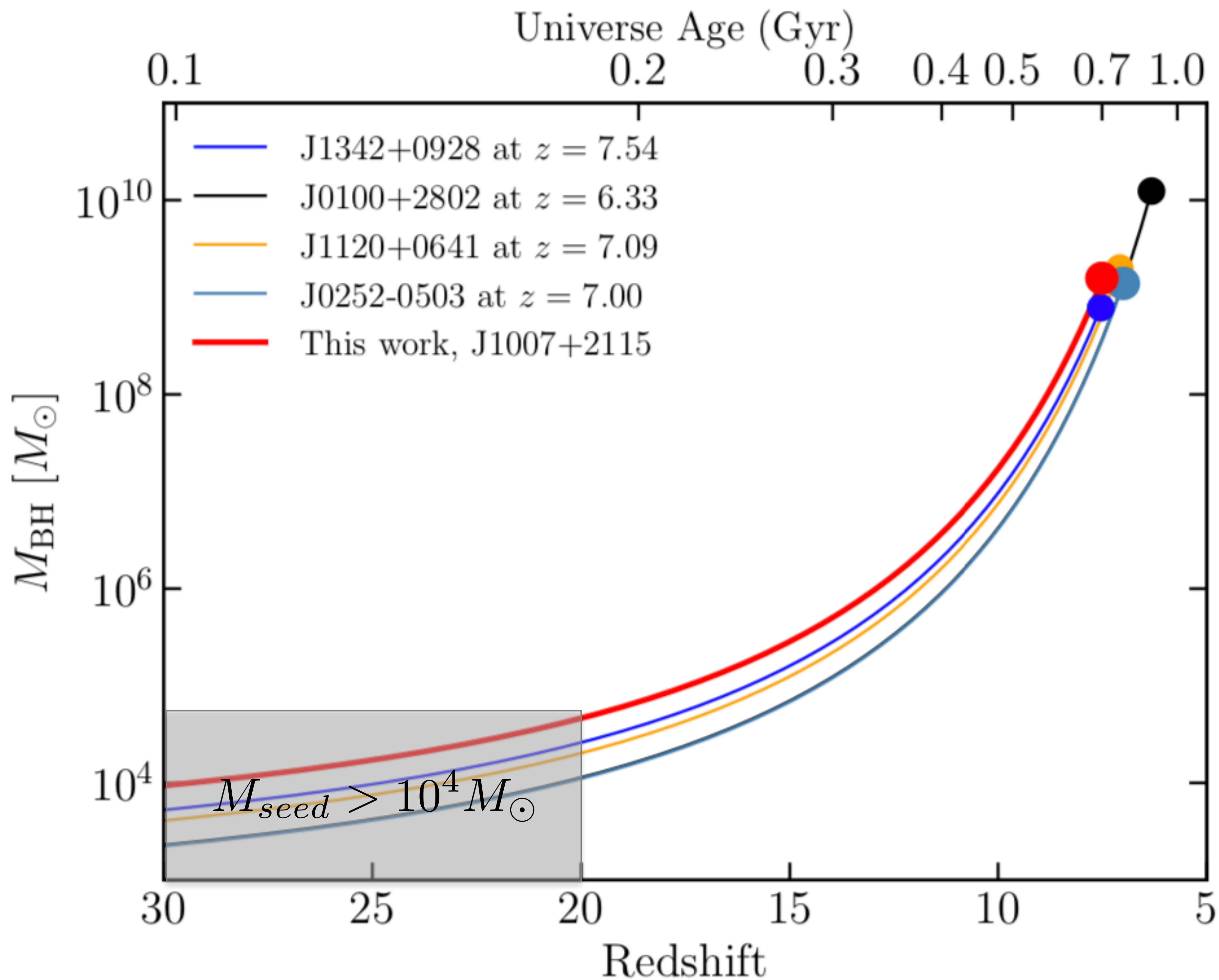

Figure from Yang et al. 2020

The initial mass of the BH at z>20 assuming unimpeded Eddington accretion rate is $M_{seed} > 10^4 M_\odot$

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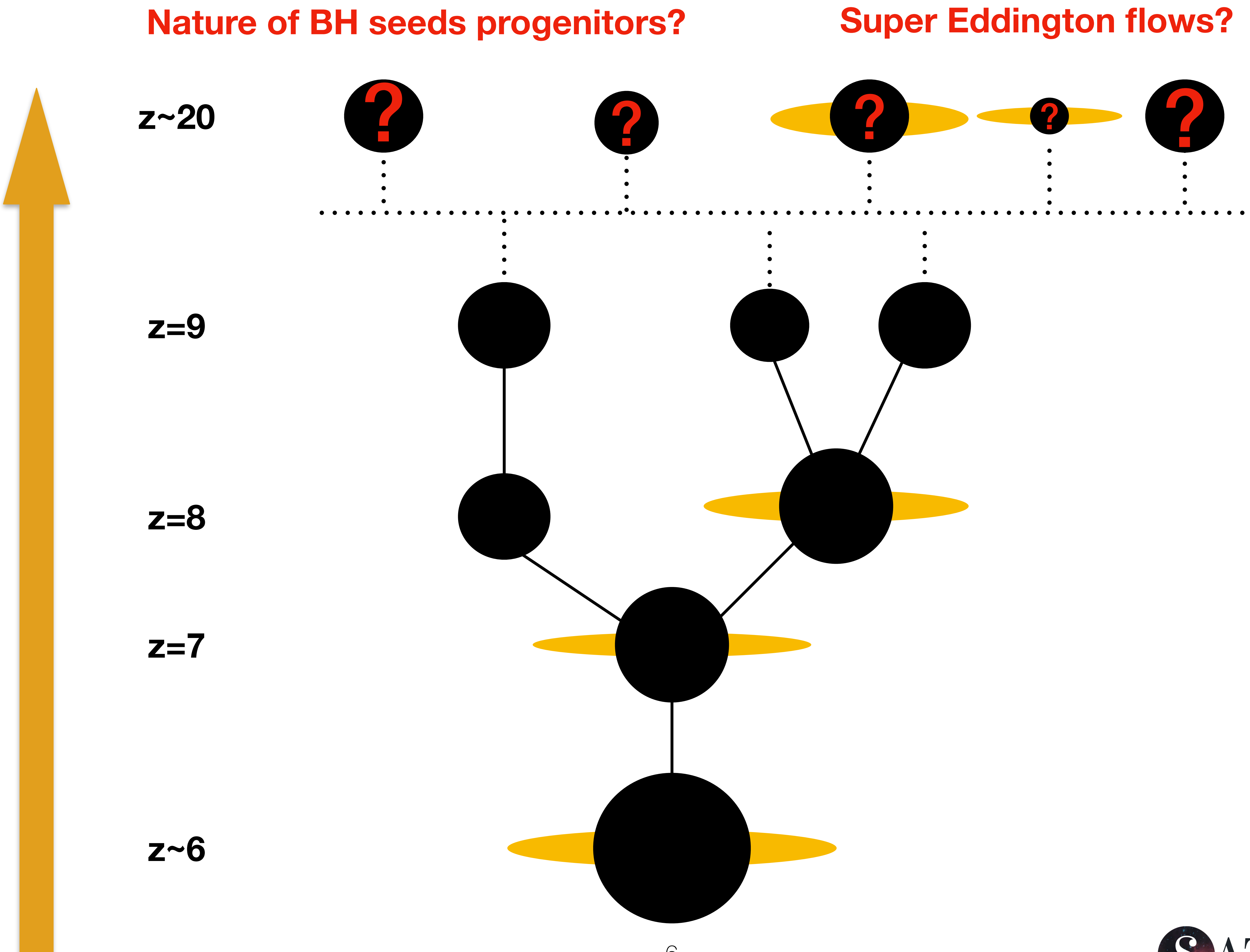
Build up of first SMBHs



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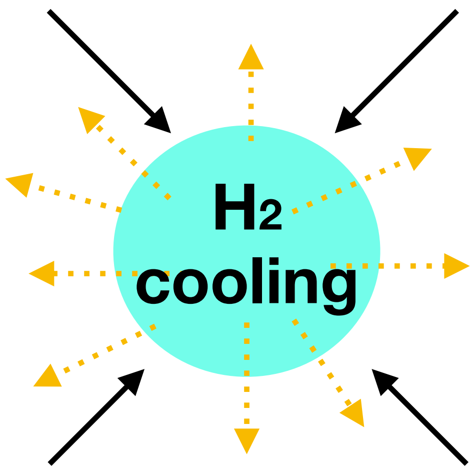
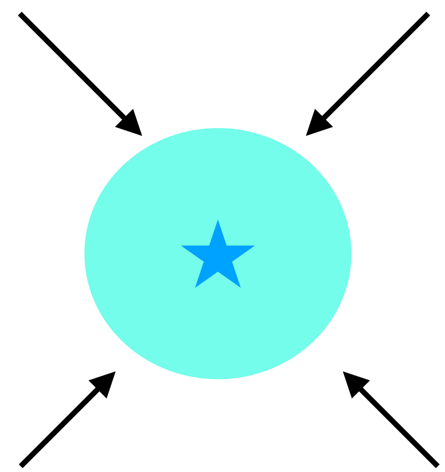
Black Hole seeds

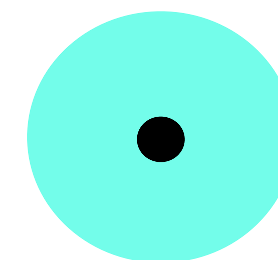
Madau & Rees 2001; Tanaka & Haiman 2009; Hirano et al. (2014, 2015); Hosokawa et al. (2015, 2016); Sugimura et al. 2020; de Bennassuti et al. 2017 ,Woosley et al. 2020



PopIII star



Light seed



$$J_{LW} < J_{cr}$$

$$Z < Z_{cr}$$

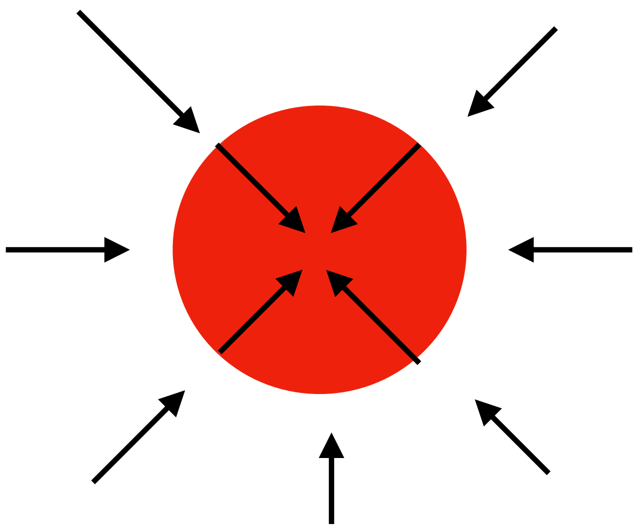
$$\mathcal{D} < \mathcal{D}_{cr}$$

$$M_{BH} \sim 100 M_{\odot}$$

J_{LW} flux in the range (11.2 eV-13.6 eV) in units $10^{-21} erg \cdot s \cdot cm^{-2}$

Black Hole seeds

Direct collapse of pristine cloud



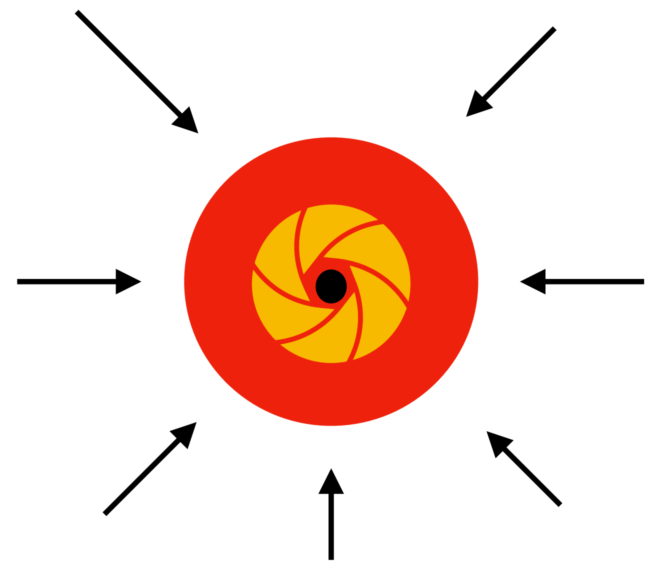
$T_{vir} \geq 10^4 K$

$J_{LW} > J_{cr}$

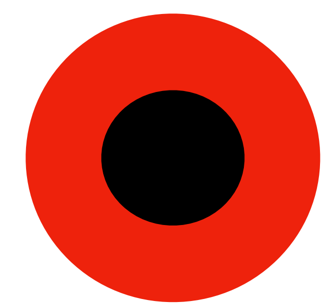
$Z < Z_{cr}$

$\mathcal{D} < \mathcal{D}_{cr}$

Super Massive Star



Heavy seed

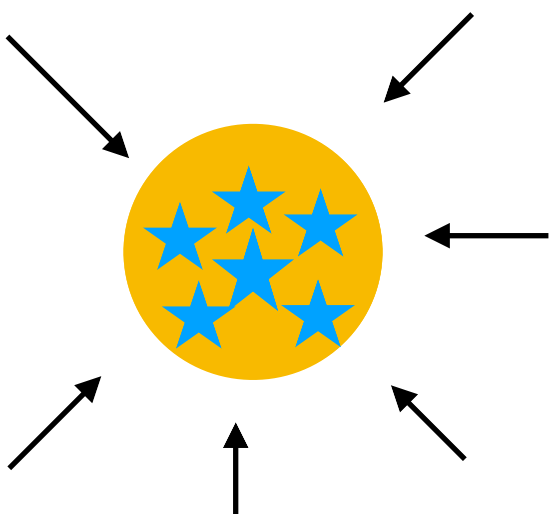


$M_{BH} \sim 10^5 M_\odot$

Omukai 2001; Bromm & Loeb 2003; Wise et al. 2008; Regan & Haehnelt 2009; Shang et al. 2010; Hosokawa et al. 2012; Latif et al. 2013; Hosokawa et al. 2013; Schleicher et al. 2013; Ferrara et al. 2014; Inayoshi et al. 2014; Regan et al. 2014; Umeda et al. 2016; Maio et al. 2019

Black Hole seeds

Dense stellar cluster



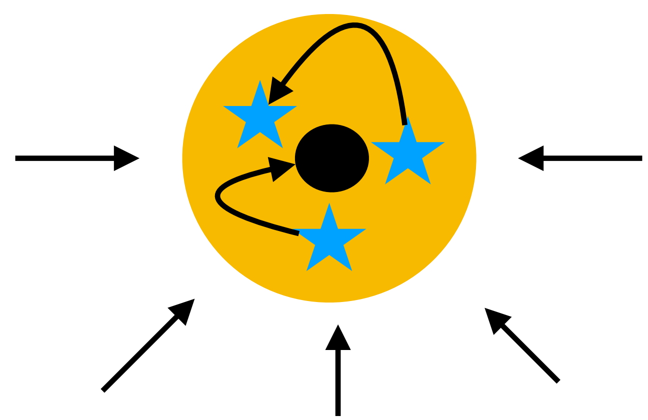
$T_{vir} \geq 10^4 K$

$J_{LW} > J_{cr}$

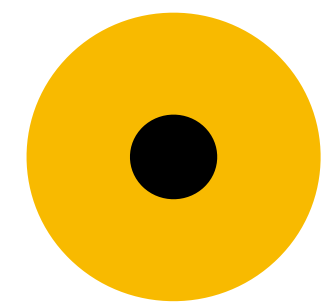
$Z < Z_{cr}$

$\mathcal{D} > \mathcal{D}_{cr}$

Stellar runaway Collisions



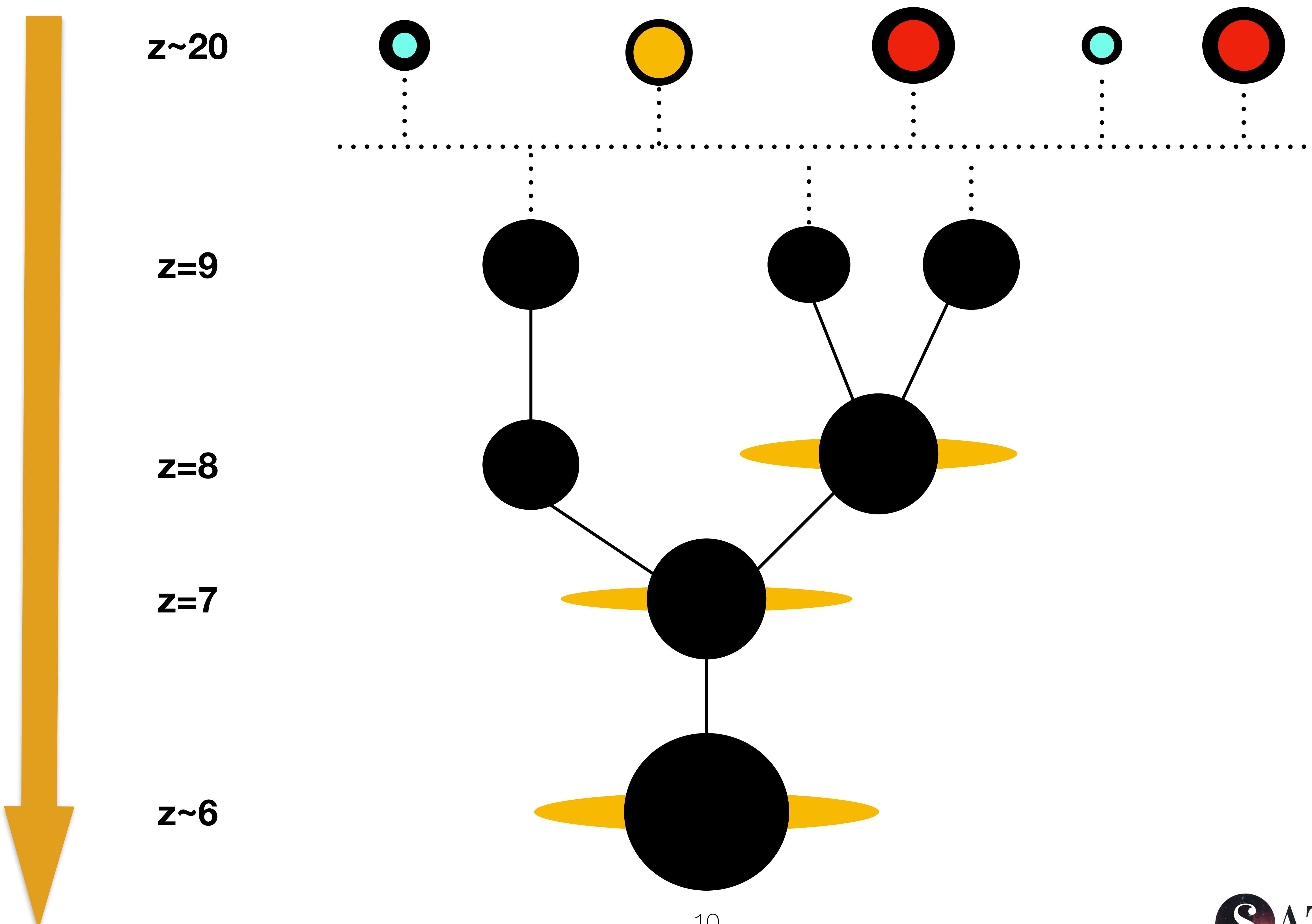
Medium-weight seed



$M_{BH} \sim 10^3 M_{\odot}$

Quinlan & Shapiro 1990; Omukai et al. 2008; Devecchi & Volonteri 2009;Volonteri 2010; Davies et al. 2011; Devecchi et al. 2012; Katz et al. 2015; Sakurai et al. 2017; Stone et al. 2017; Reinoso et al. 2018; Tagawa et al. 2020, Rizzuto et al. 2020

Build up of first SMBHs



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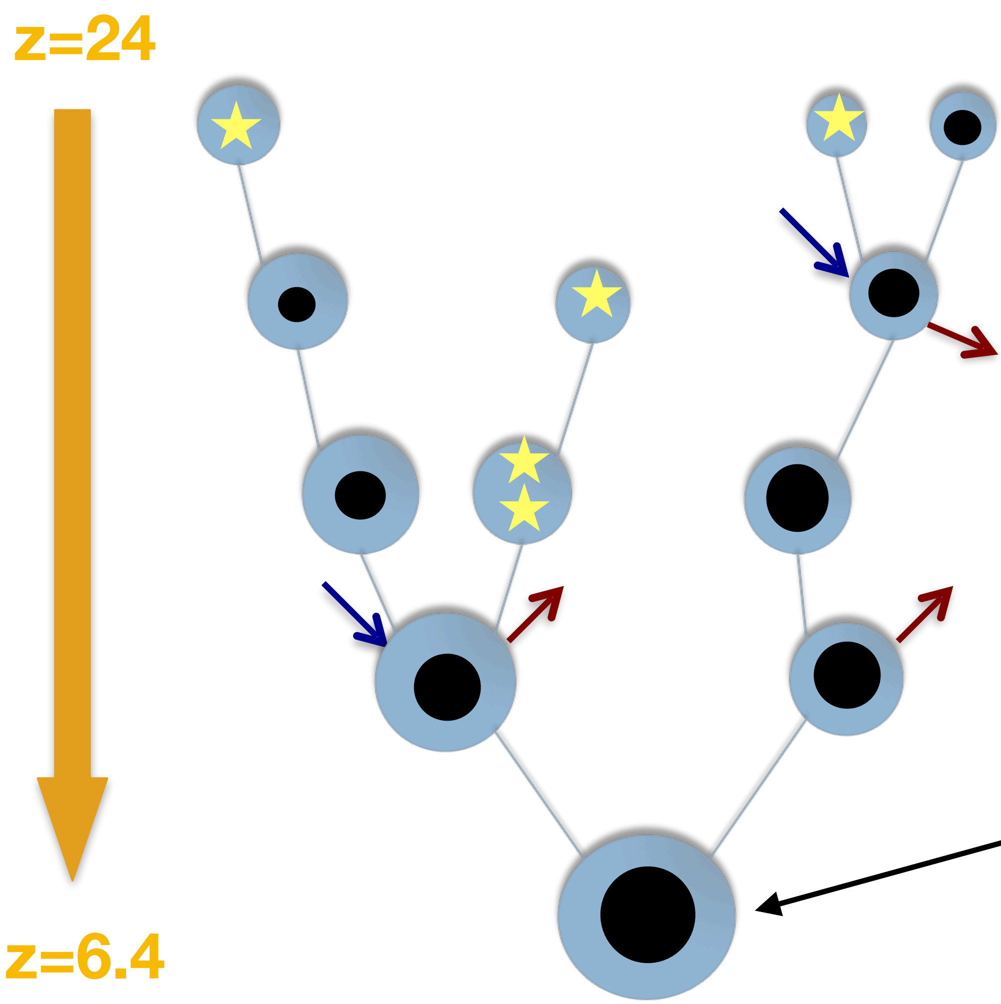
THE MODEL: GAMETE\QSOdust

GAlaxy MErger Tree and Evolution

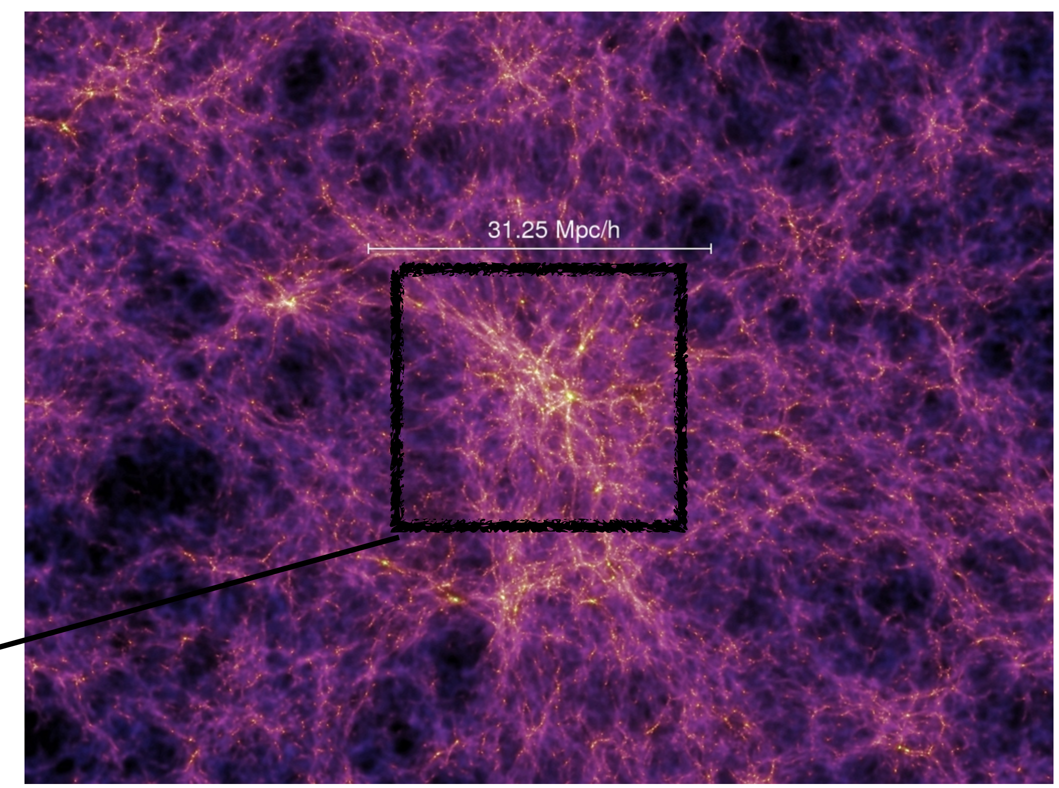
Salvadori et al. 2007, 2008, 2009, 2014, 2015; Valiante et al. 2011, 2014,2016,2017; de Bennassuti et al. 2014; Salvadori & Ferrara 2009,2012; Sassano et al. 2020

Dark Matter halo merger tree + star formation and chemical evolution + BH seeding, feeding and feedback



$$M_{Halo} \sim 10^{13} M_{\odot}$$

Highly biased region



Credits from Millenium Simulation: https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/

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THE MODEL: GAMETE\QSOdust

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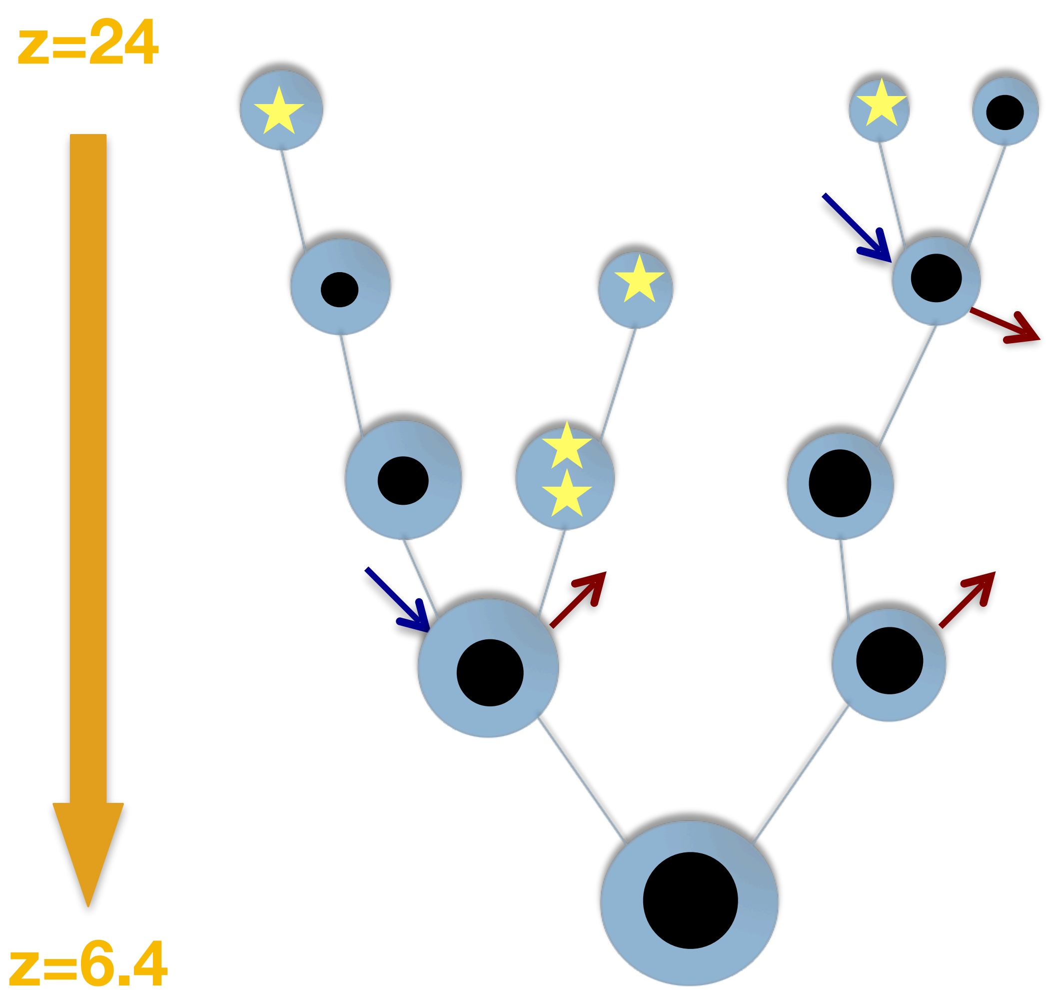

$$M_{Halo} \sim 10^{13} M_{\odot}$$

+

Inhomogeneous treatment for metal diffusion

Salvadori et al. 2014, Dijkstra et al. 2014

& LW background fluctuations

Dijkstra et al. 2008, 2014; Ahn et al. 2009; Agarwal et al. 2012; Inayoshi & Tanaka 2015

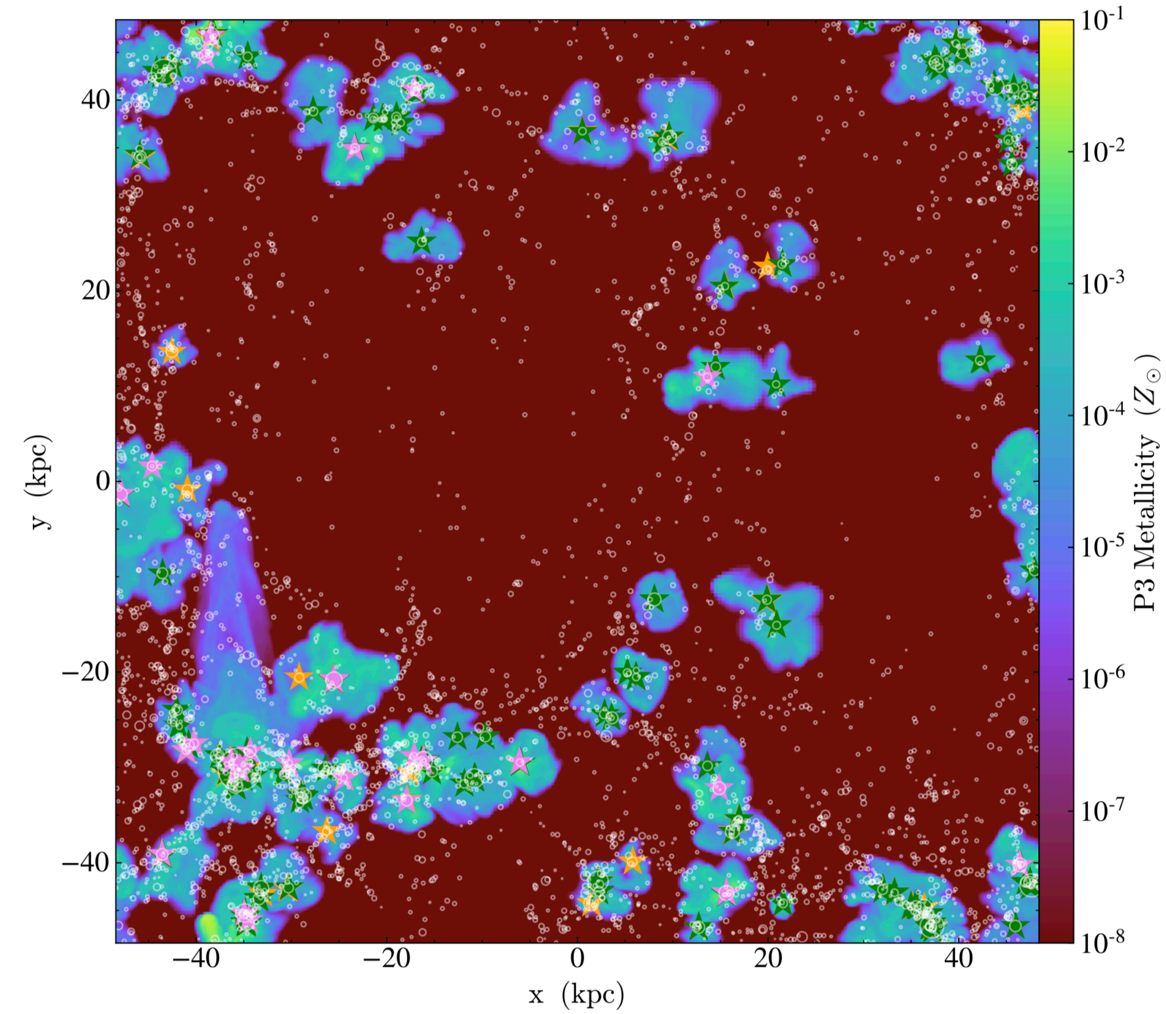

Figure from Trapp & Furlanetto 2020

Environmental conditions for seeds formation

	Reference	Model	
Seeds	$Z/Z_\odot$	$\mathcal{D}$	$J_{\rm LW}$
Light	$< 10^{-3.8}$	$< 4.4 \cdot 10^{-9}$	$< J\mathrm{cr}$
medium-weight	$< 10^{-3.8}$	$\geq 4.4 \cdot 10^{-9}$	$\geq J\mathrm{cr}$
Heavy	$< 10^{-3.8}$	$< 4.4 \cdot 10^{-9}$	$\geq J\mathrm{cr}$

Reference model adopting Z_{cr} and $\mathcal{D}_{cr}$ from *Omukai, Schneider and Haiman 2008*

Two different simulations for Jcr=300 *(Latif & Ferrara 2016)* and Jcr=1000 *(Sugimura et al. 2014; Agarwall & Khochfar 2015)*

Reference model

R300 $J_{cr} = 300$

R1000 $J_{cr} = 1000$

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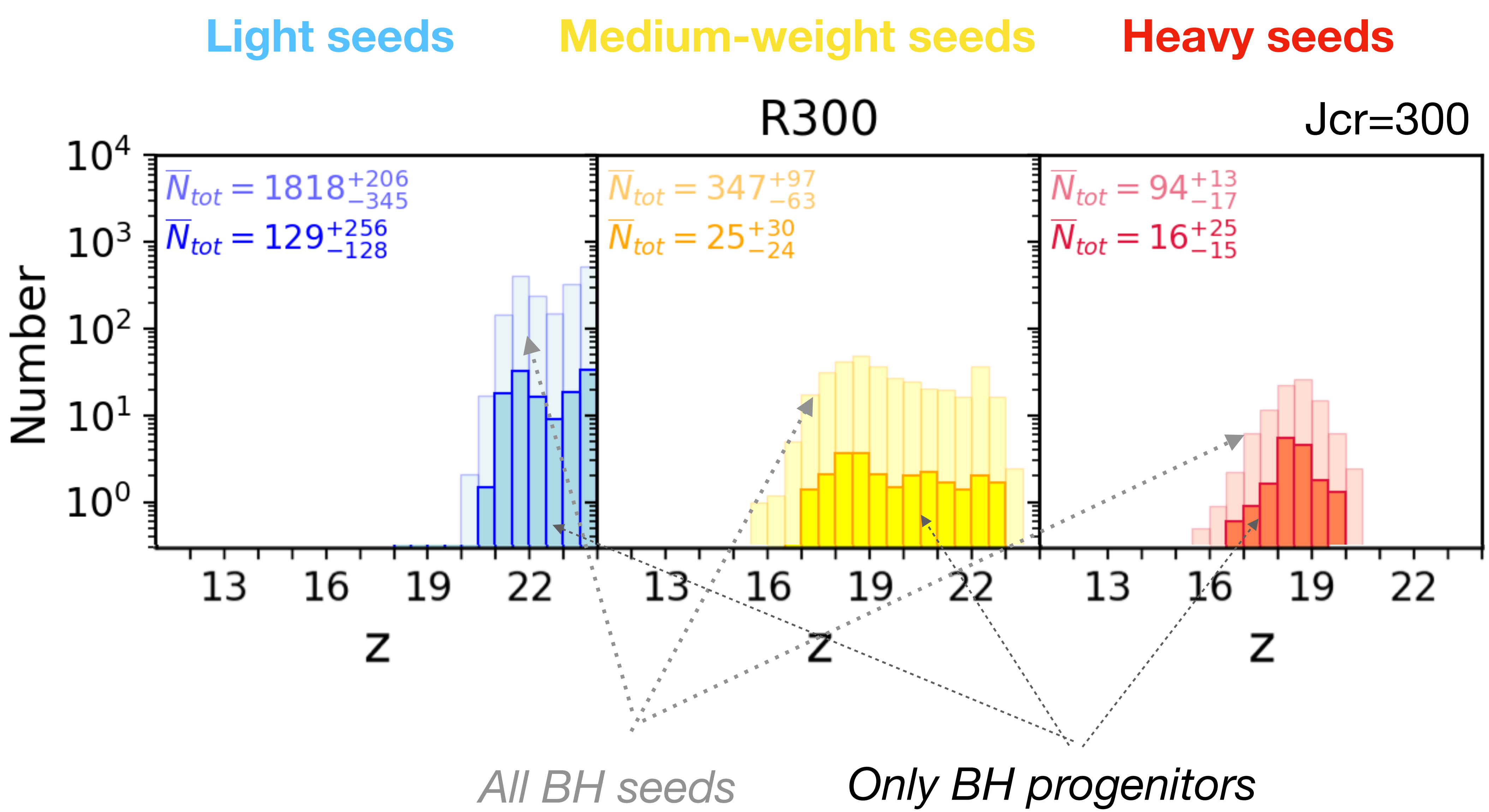
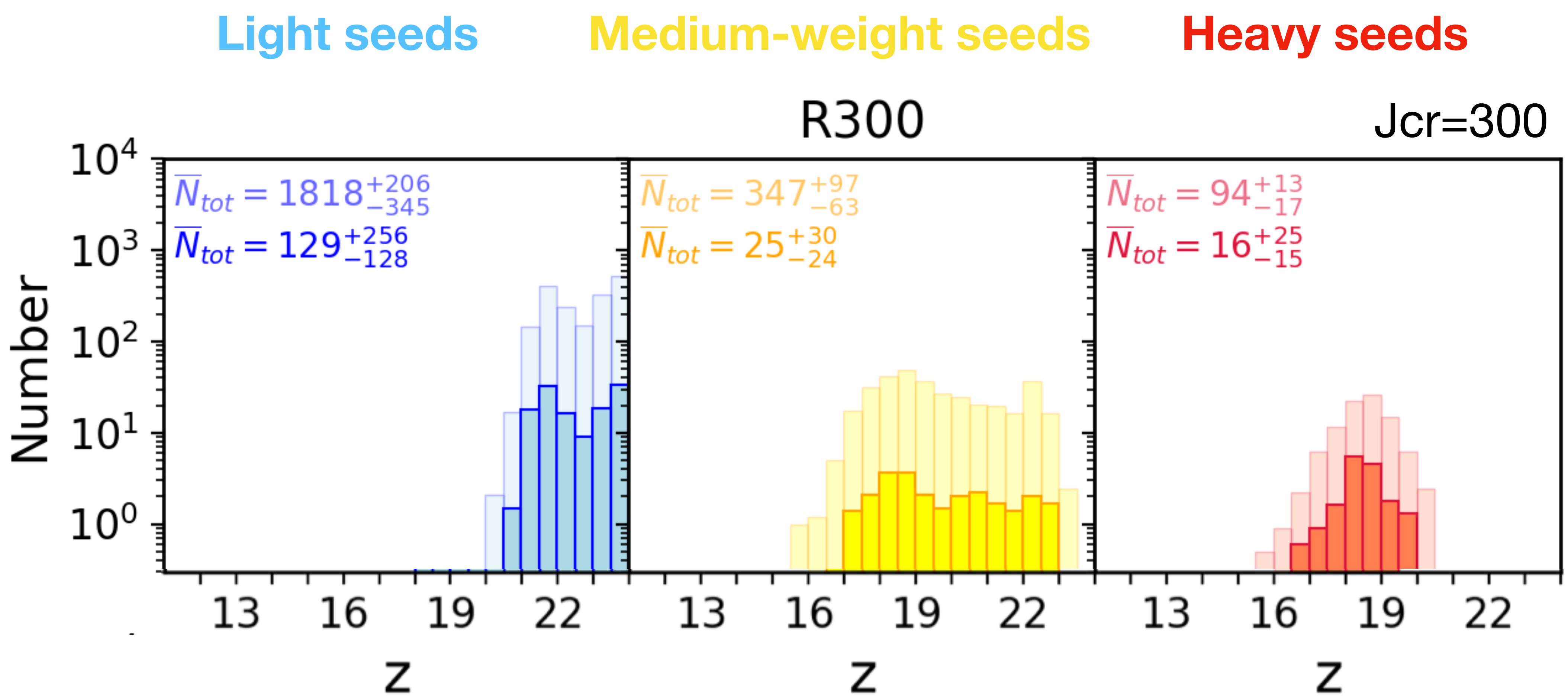
Redshift distribution of BH seeds



Redshift distribution of BH seeds



- *Light seeds start to form earlier down to redshift z~19, when the increase of the LW background suppresses Pop III star formation due to radiative feedback*
- *Medium weight and heavy seeds continue to form down to z~15, when the epoch of seeds formation is terminated by chemical feedback*

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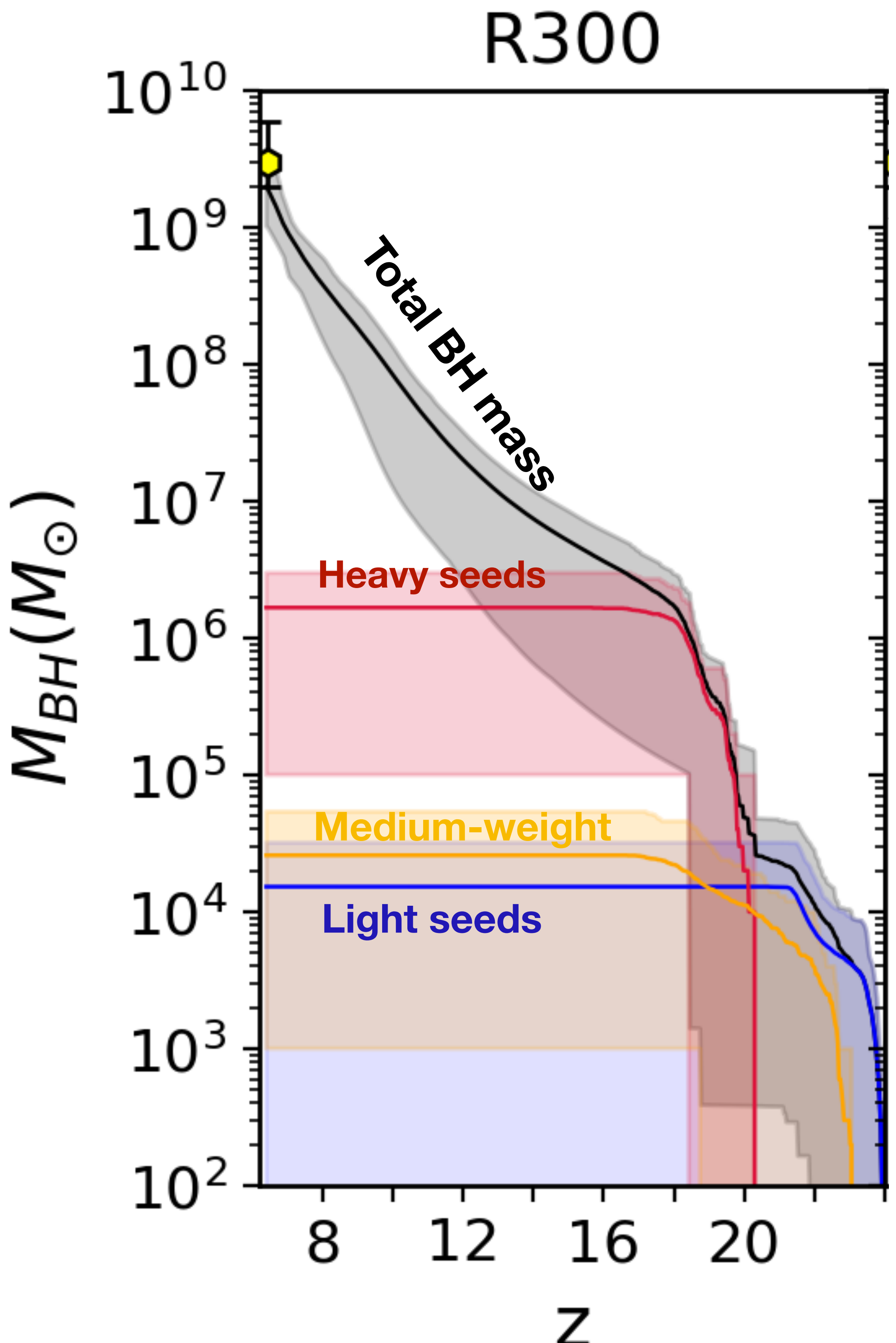
Evolution of the total nuclear BH mass as function of redshift



All values are mean values over ten simulations with shaded regions ranging between the minimum and maximum

- *z>20: Light seeds (blue line) contribution to the total mass is relevant at z>20*
- *z<20: heavy seeds (red line) start to form and provide the most important contribution with respect to other channels*
- *z<16: the mass growth is driven by accretion*
- *Medium-weight seeds are always subdominant*

Sassano et al. 2020 (submitted to MNRAS)

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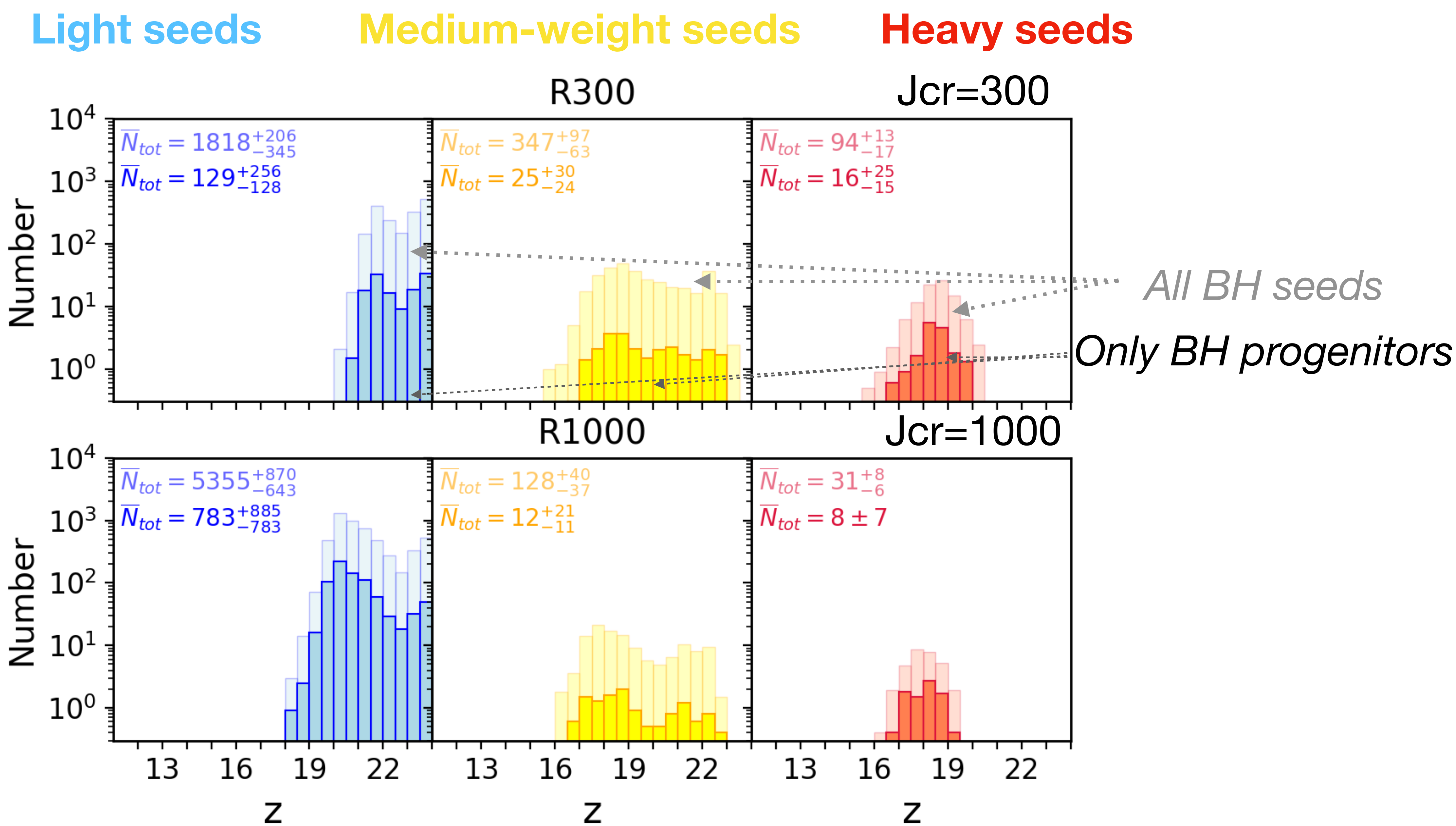
Redshift distribution of BH seeds



In R1000:

- *Light seeds increase with respect to R300 due to milder radiative feedback on Pop III star formation.*
- *Medium-weight and heavy seeds are less numerous because of higher Jcr and more efficient metal enrichment*

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Super competitive accretion scenario

Impact of the metal enrichment on the clouds in hydrodynamical simulations to follow the evolution of massive BHs in cases with different degree of the metal enrichment *(Chon & Omukai 2020)*

Chon S. and K. Omukai. MNRAS 494.2 (2020): 2851-2860.

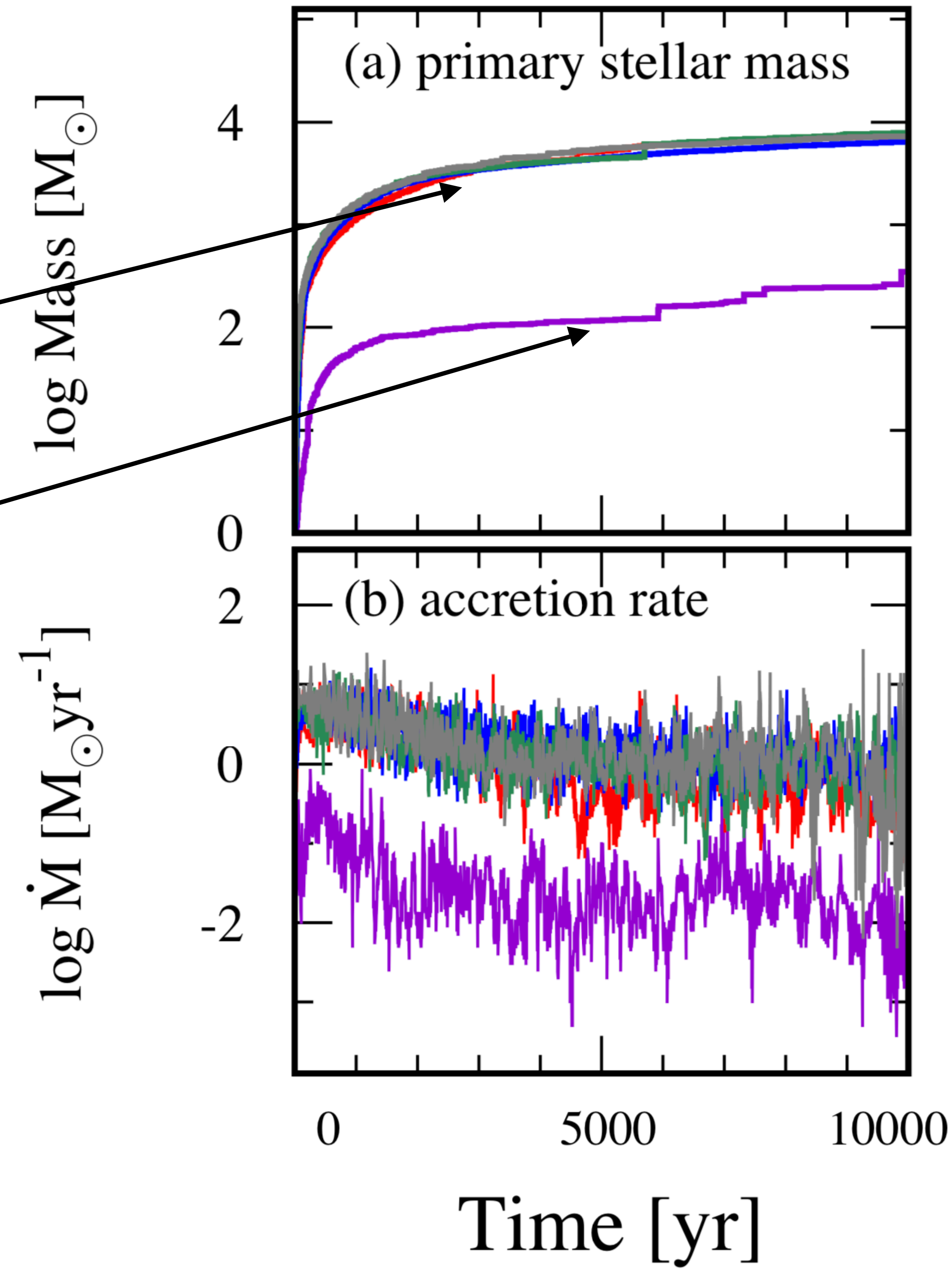
$\frac{Z}{Z_\odot} \sim 10^{-6}$

$\frac{Z}{Z_\odot} \sim 5 \times 10^{-6}$

$\frac{Z}{Z_\odot} \sim 10^{-5}$

$\frac{Z}{Z_\odot} \sim 10^{-4}$

$\frac{Z}{Z_\odot} \sim 10^{-3}$



High accretion rates sustain the growth of massive BHs

↓

<u>Wider metallicity range for massive seeds formation</u>

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Condition for BH seeds formation

	Reference	Model	
Seeds	$Z/Z_\odot$	$\mathcal{D}$	$J_{\rm LW}$
Light	$< 10^{-3.8}$	$< 4.4 \cdot 10^{-9}$	$< J\rm{cr}$
medium-weight	$< 10^{-3.8}$	$\geq 4.4 \cdot 10^{-9}$	$\geq J\rm{cr}$
Heavy	$< 10^{-3.8}$	$< 4.4 \cdot 10^{-9}$	$\geq J\rm{cr}$
Super	competitive	accretion	model
Seeds	$Z/Z_\odot$	$\mathcal{D}$	$J_{\rm LW}$
Light	$< 10^{-3.8}$	$< 4.4 \cdot 10^{-9}$	$< J\rm{cr}$
medium-weight	$[10^{-3.5} - 10^{-2.5}]$	all	$\geq J\rm{cr}$
Heavy	$< 10^{-3.5}$	all	$\geq J\rm{cr}$

Reference model

R300 $\rightarrow$ $J_{cr} = 300$

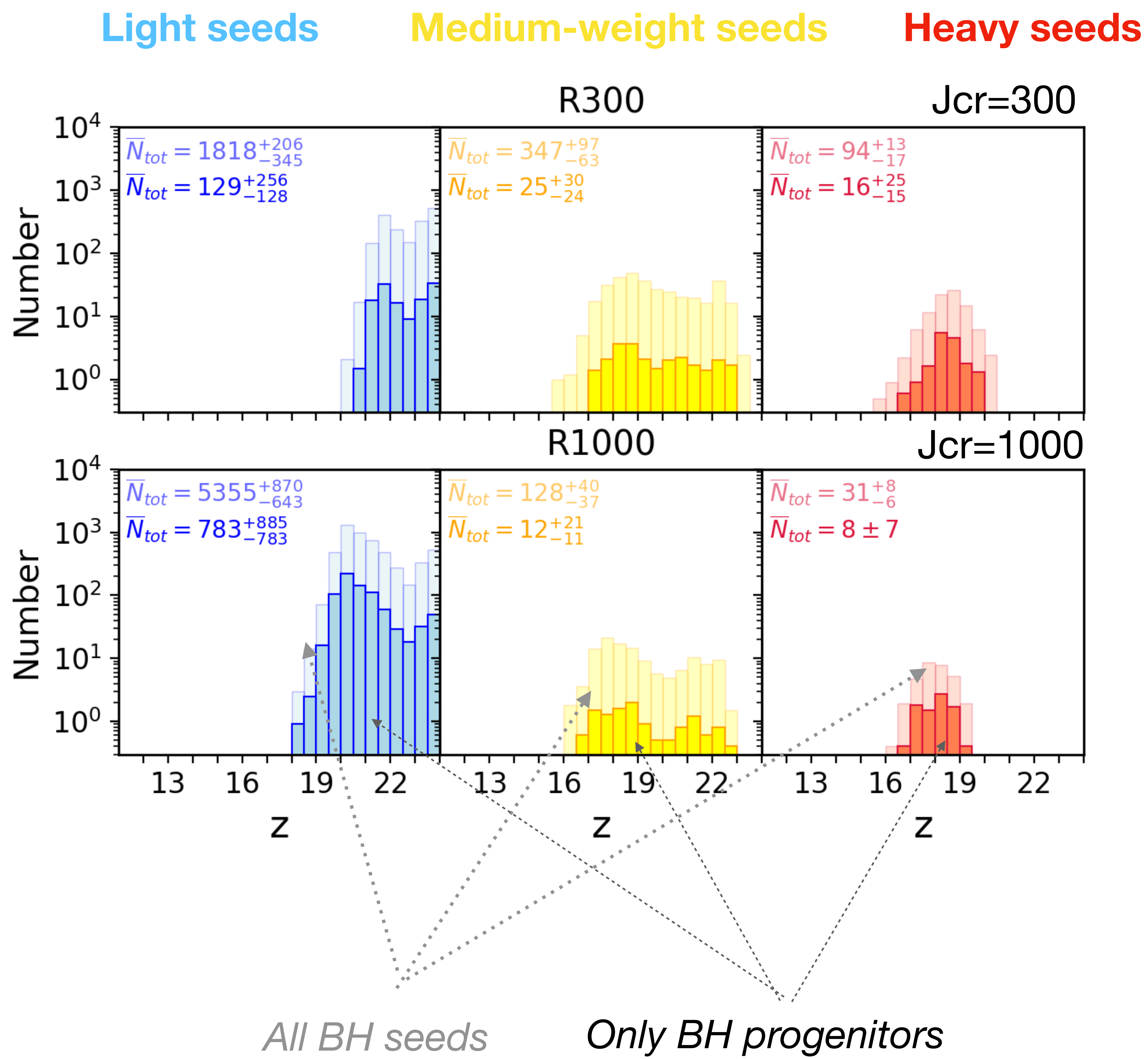
R1000 $\rightarrow$ $J_{cr} = 1000$

Super Competitive Accretion model

SCA300 $\rightarrow$ $J_{cr} = 300$

SCA1000 $\rightarrow$ $J_{cr} = 1000$

Redshift distribution of BH seeds



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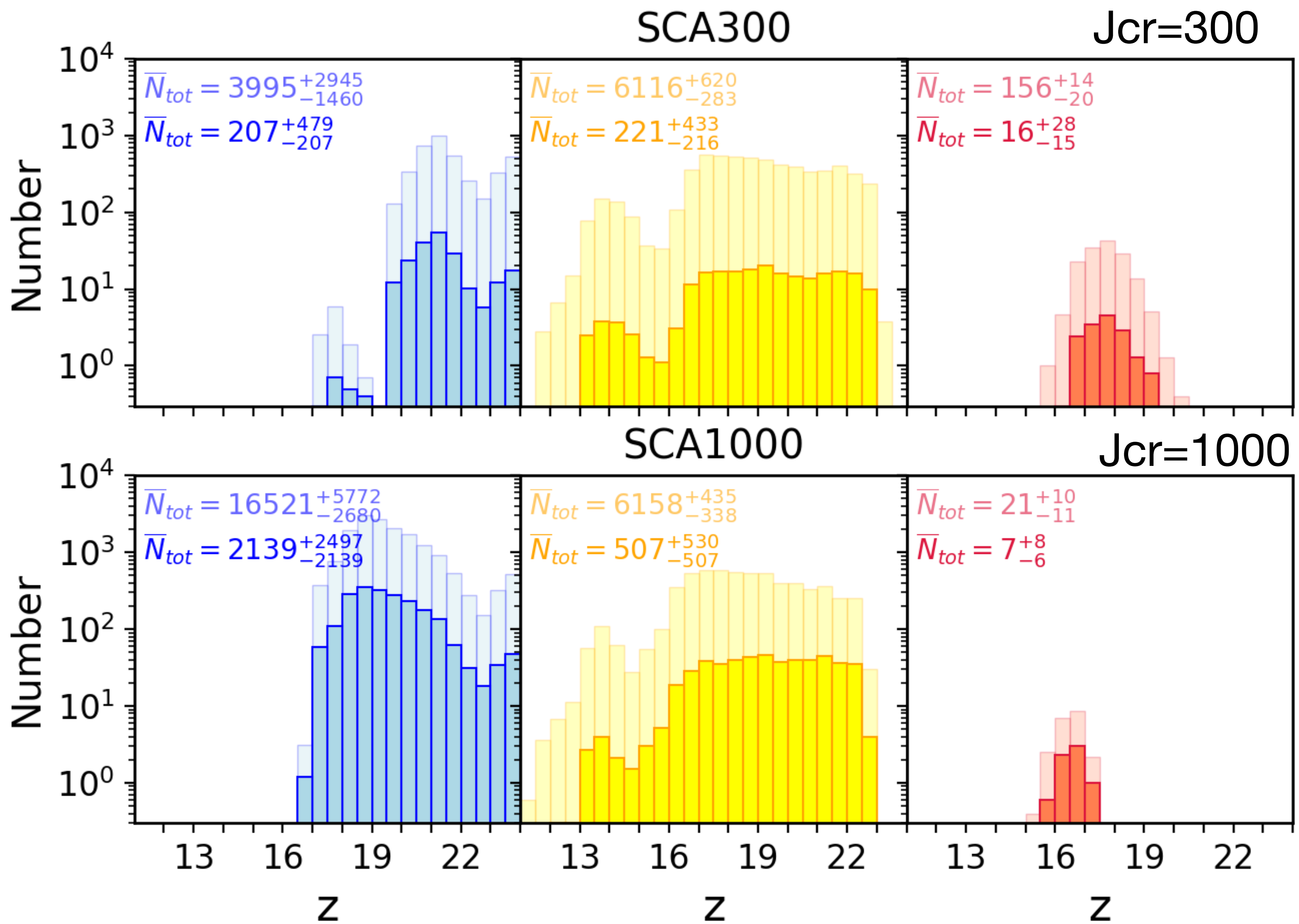
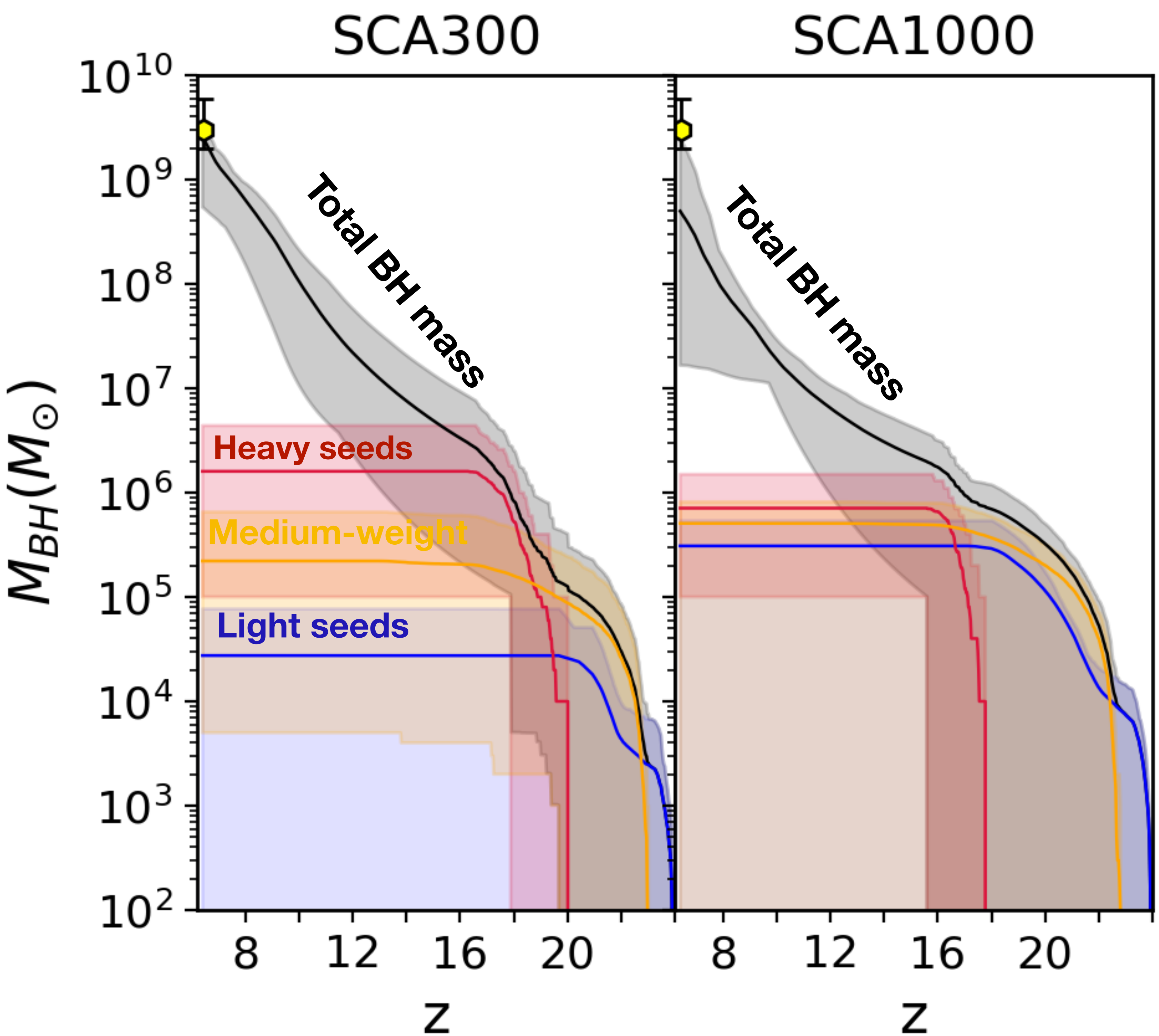
Redshift distribution of BH seeds



- *In SCA models the total number of BH seeds increase due to more favorable BH seeding conditions*
- *In SCA1000 the chemical feedback does not affect medium-weight seeds but suppresses heavy BH seeds, which preferably form in Z=D=0 regions*

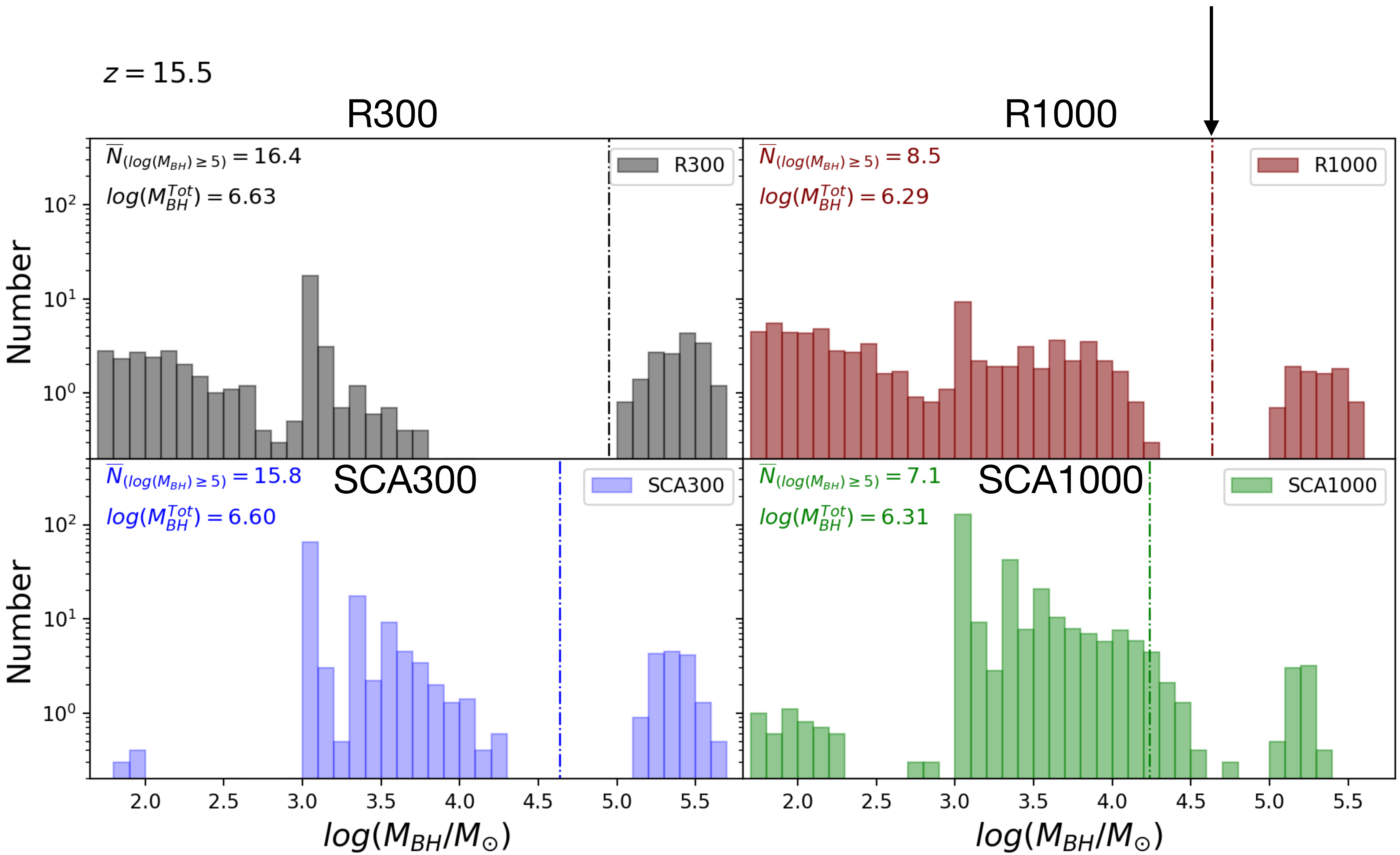
Evolution of the total nuclear BH mass as function of redshift



- *In SCA300 the nuclear BH mass evolution is similar to R300*
- *Medium-weight seeds provide a larger contribution with respect to the reference models*
- *In SCA1000 the average final BH mass is smaller than* $10^9 \, M_\odot$

BH mass function at z=15.5

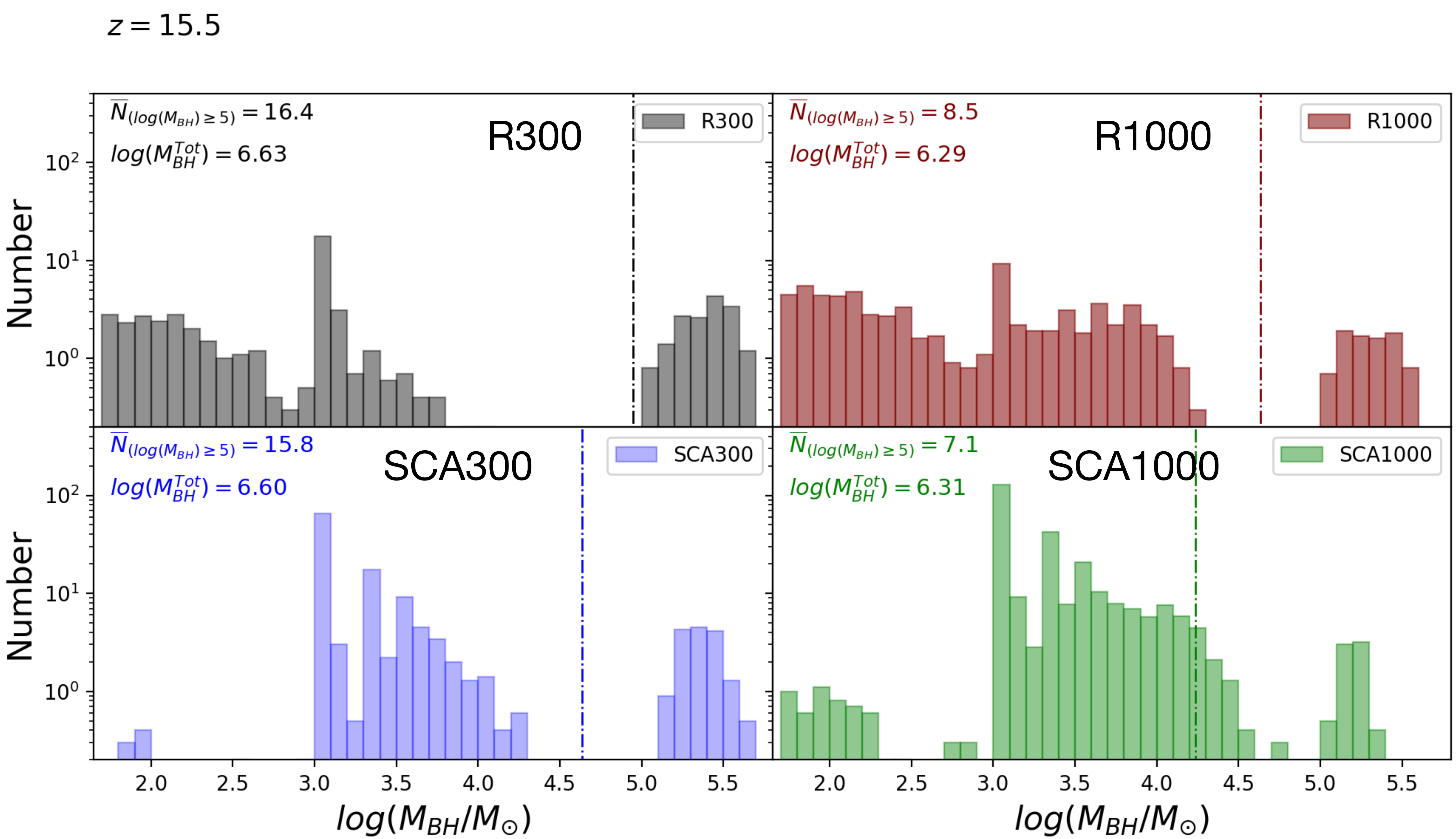
Around z=15.5 seeds formation in primordial environments is terminated.
The mean BH mass at this epoch is representative of the "average BH seed mass"



BH mass function at z=15.5

QUALITY NOT QUANTITY!

Mean BH mass is a key parameter in order to established if the final mass of the SMBH is reproduced



Conclusions

- In this work we have addressed the formation and evolution of <u>3 different BH seed populations within a self-consistent cosmological model</u>
- These BHs populations are strongly connected: the increase in light BH seeds leads to the decrease of medium-weight and heavy seeds
- The genealogy of a z~6 SMBHs is characterized by a reach variety of BH progenitors but <u>heavy seeds provide the dominant mass contribution</u>
- <u>Quality not quantity</u>: The mean BH mass at the end of seed formation is a key parameter for successful SMBH formation
- BH seeds progenitors <u>represent only from 10 to 20% of all BH seeds formed at high-z</u>.
- Our results will be used to predict a <u>catalog of BH-BH binary systems</u> detectable with the third generation GW telescopes

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