the early growth of the first supermassive black holes

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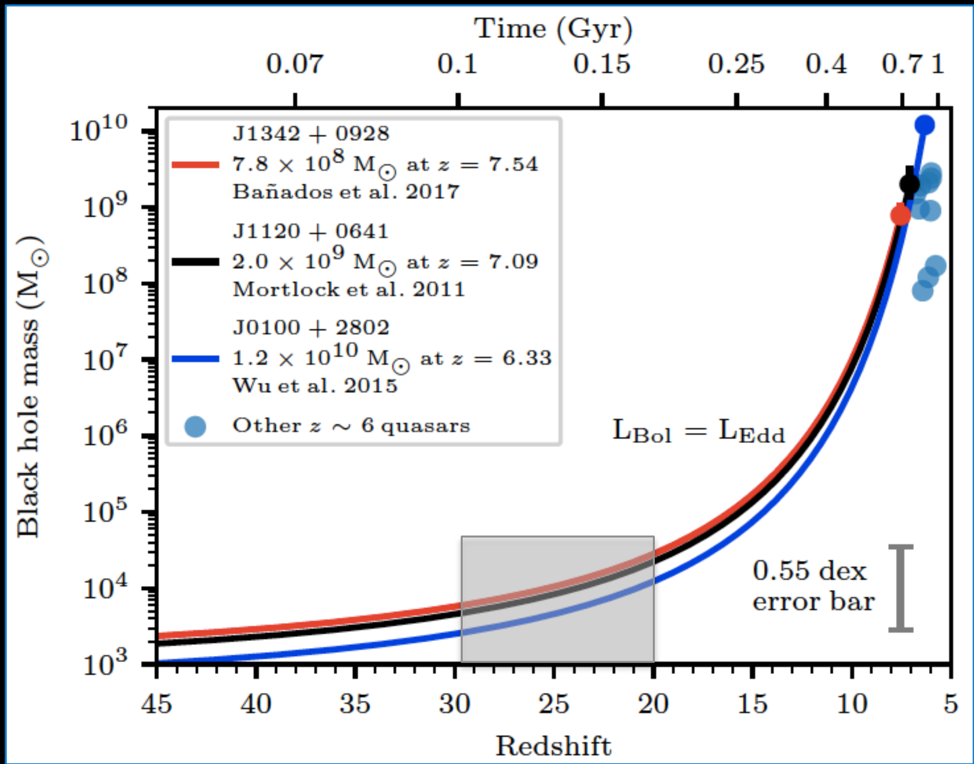
the first super-massive black holes

How do these SMBHs grow in less than 1 Gyr?

$M_{SMBH}(t) = M_{seed}(t_{form})\, e^{[(1-\varepsilon)/\varepsilon]\Delta t/tEdd}$ $\varepsilon = 0.1$ $t_{Edd} = 0.45$ Gyr



Banados et al. 2018

models of SMBH growth require massive seeds (> 10^4 M_{sun}) and/or episodes of super-Eddington accretion

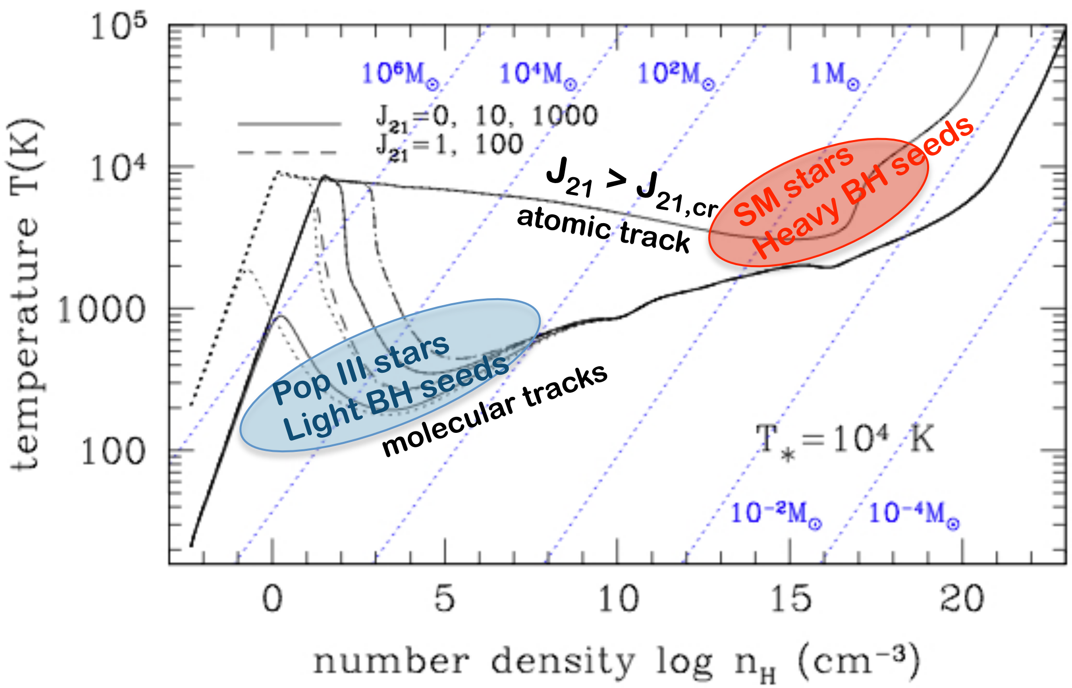
seed black holes

their nature is set by the environmental conditions

H_2 photo-dissociation from UV photons in the Lyman-Werner band: (11.2 – 13.6) eV

$J_{21} = J_{LW} / 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}

collapsing metal free gas clouds



Omukai, RS, Haiman (2008)

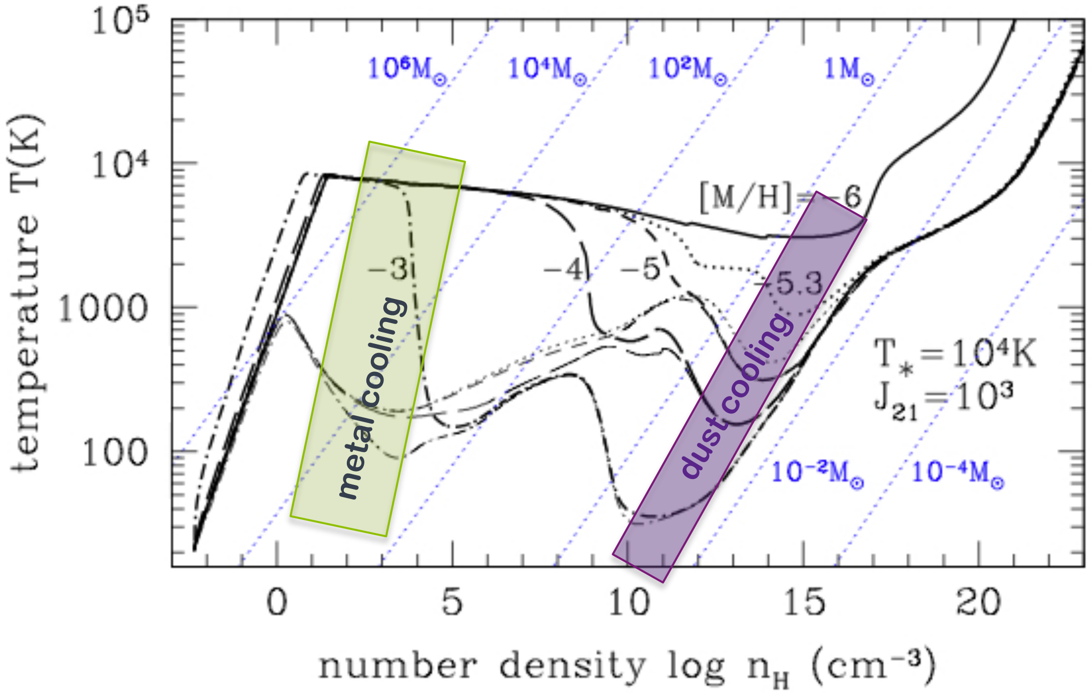
see also Omukai 2001; Oh & Haiman 2002; Bromm & Loeb 2003; Omukai+2008; Agarwal +2012; Latif+2014; Sugimura+2014, 2015; Agarwal +2015; Latif & Volonteri 2015; ; Regan & Haehnelt 2009; Hosokawa+2012; Latif+2013,2014, 2016; Prieto+2013; Regan+2014; Inayoshi+2014;Choi +2015; Becerra +2015, 2018

seed black holes

their nature is set by the environmental conditions

metal line cooling and dust cooling lead to fragmentation

collapsing metal enriched gas clouds irradiated with $J_{21} > J_{21,cr}$



Omukai, RS, Haiman (2008)

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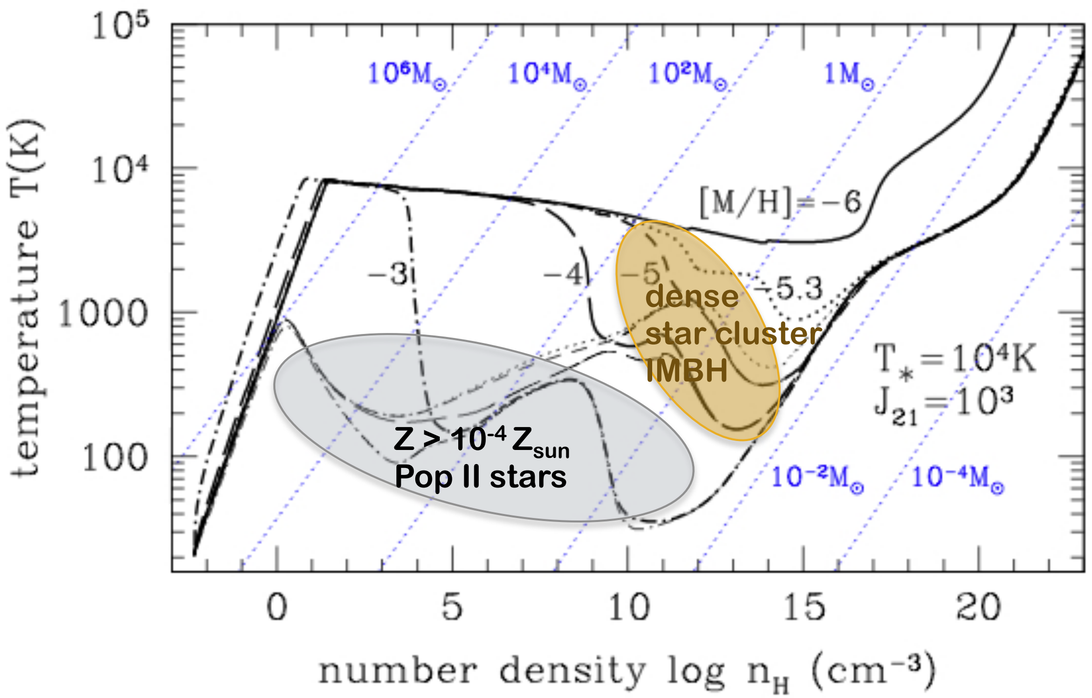
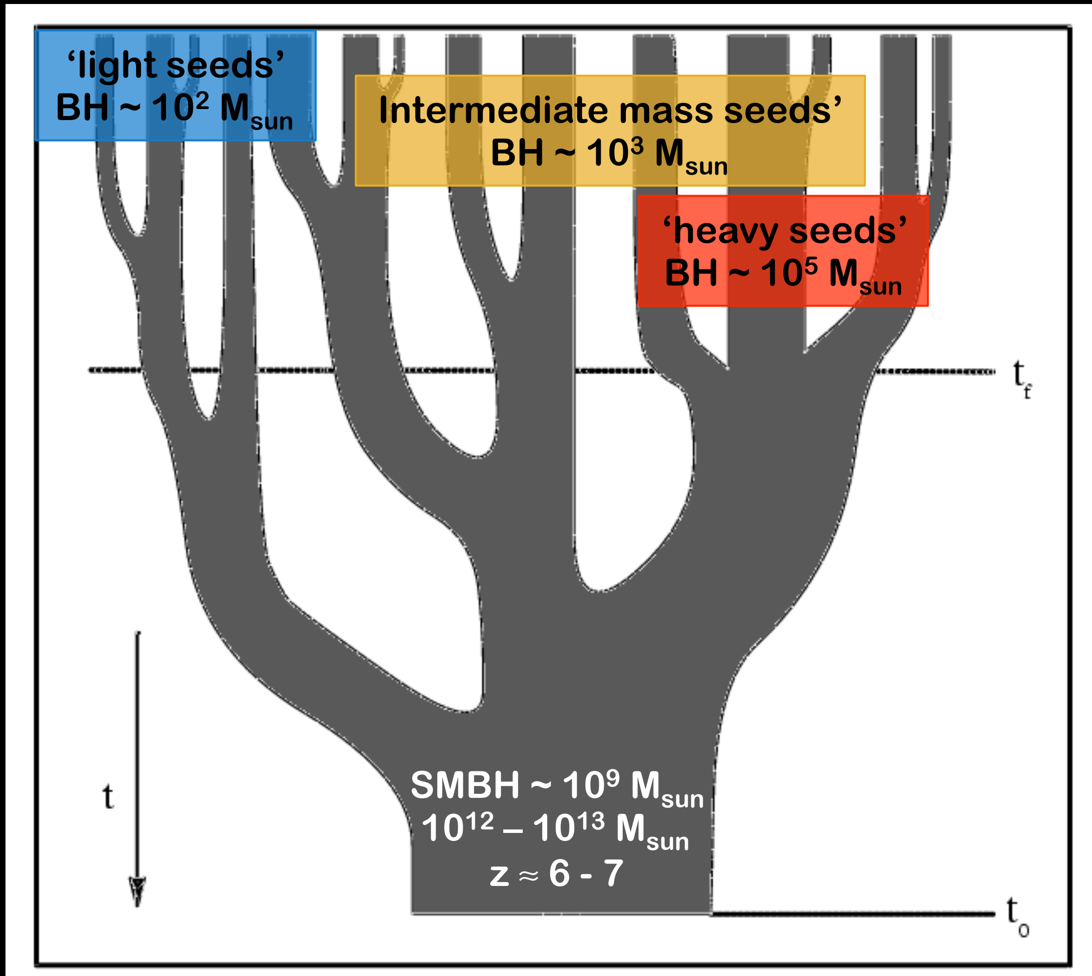


Omukai, RS, Haiman (2008)

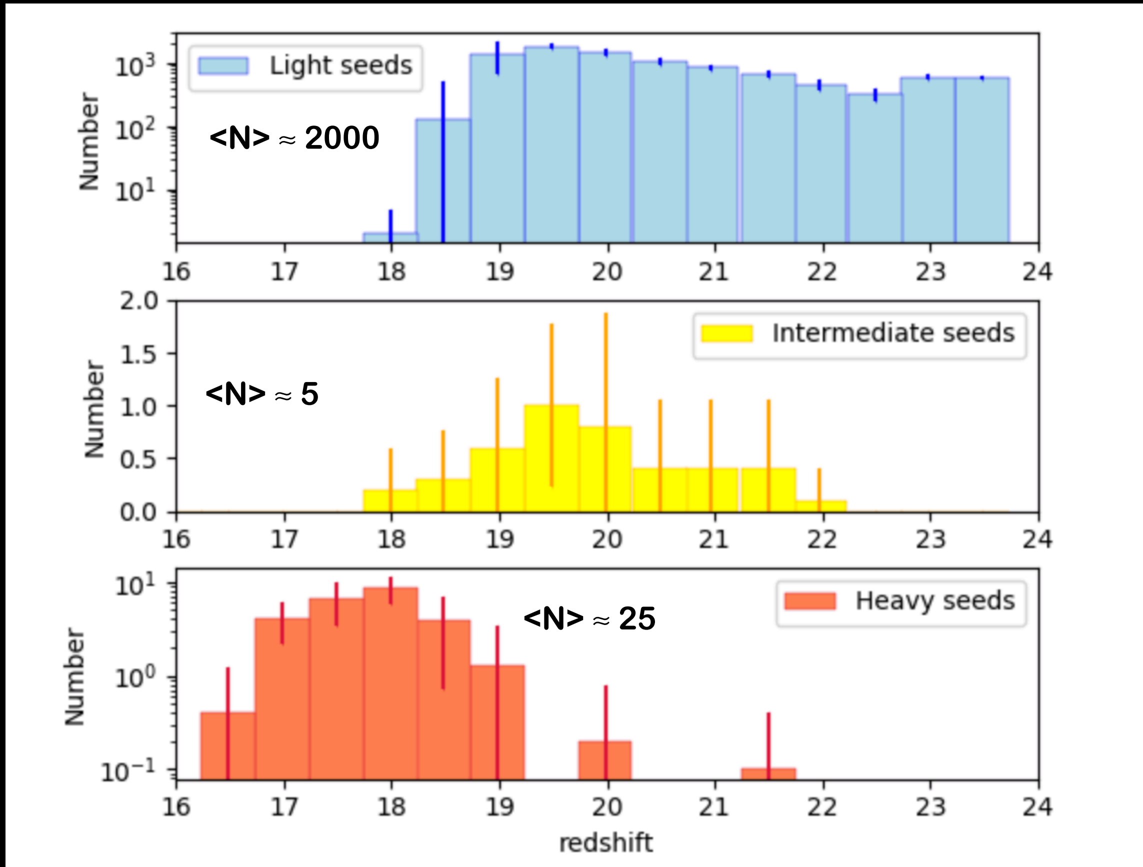
the formation of the first SMBHs: planting and growing seeds in a highly biased region



Haiman & Loeb 2001, Volonteri et al. 2003, Wyithe & Loeb 2003, Haiman 2004, Menci et al. 2004, 2008, Shapiro 2005, Yoo & Miralda-Escude' 2004, Bromley et al. 2004, Volonteri & Rees 2005, Li et al. 2007, Pelupessy et al. 2007, Sijacki et al. 2009, Tanaka & Haiman 2009, Lamastra et al. 2010, Valiante et al. 2011, Petri et al. 2012; Valiante et al. 2015; 2016, 2017, 2018; Pezzulli et al. 2016, 2017; Sassano et al. 2019

the census of BH seeds progenitors

redshift distribution averaged over 10 independent simulations



Sassano et al. in prep

$J_{21} < J_{21,cr}$
$Z < Z_{cr}$
$D < D_{cr}$

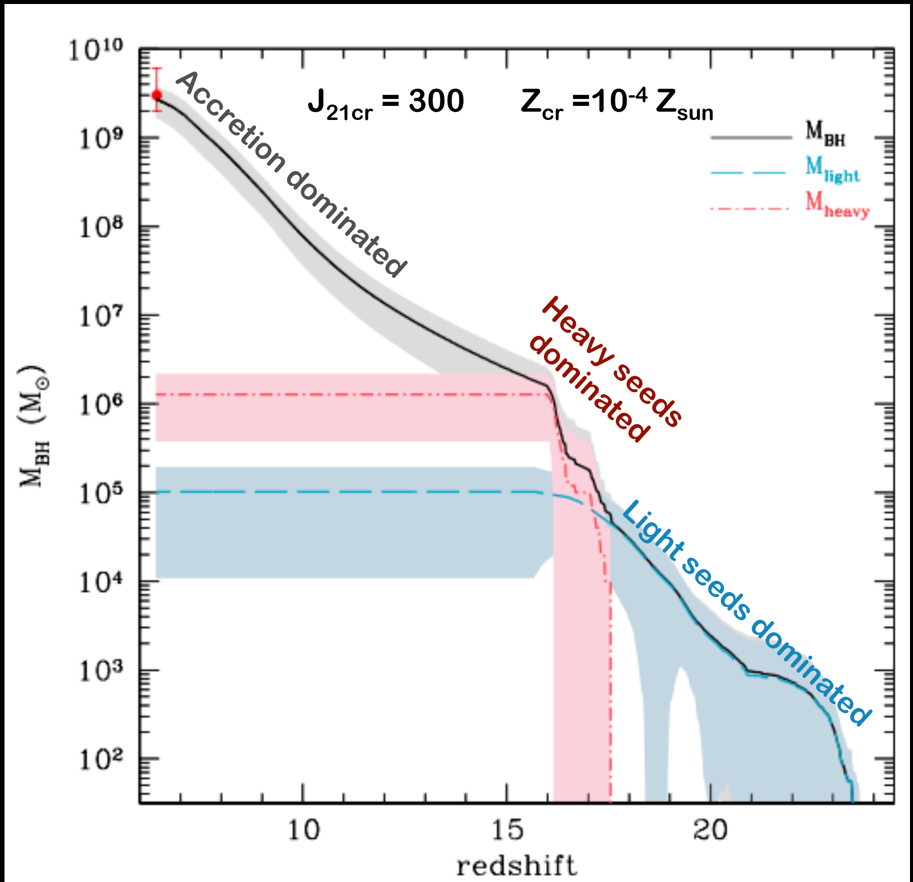
$T_{vir} > 10^4$ K
$J_{21} > J_{21,cr}$
$Z < Z_{cr}$
$D > D_{cr}$

$T_{vir} > 10^4$ K
$J_{21} > J_{21,cr}$
$Z < Z_{cr}$
$D < D_{cr}$

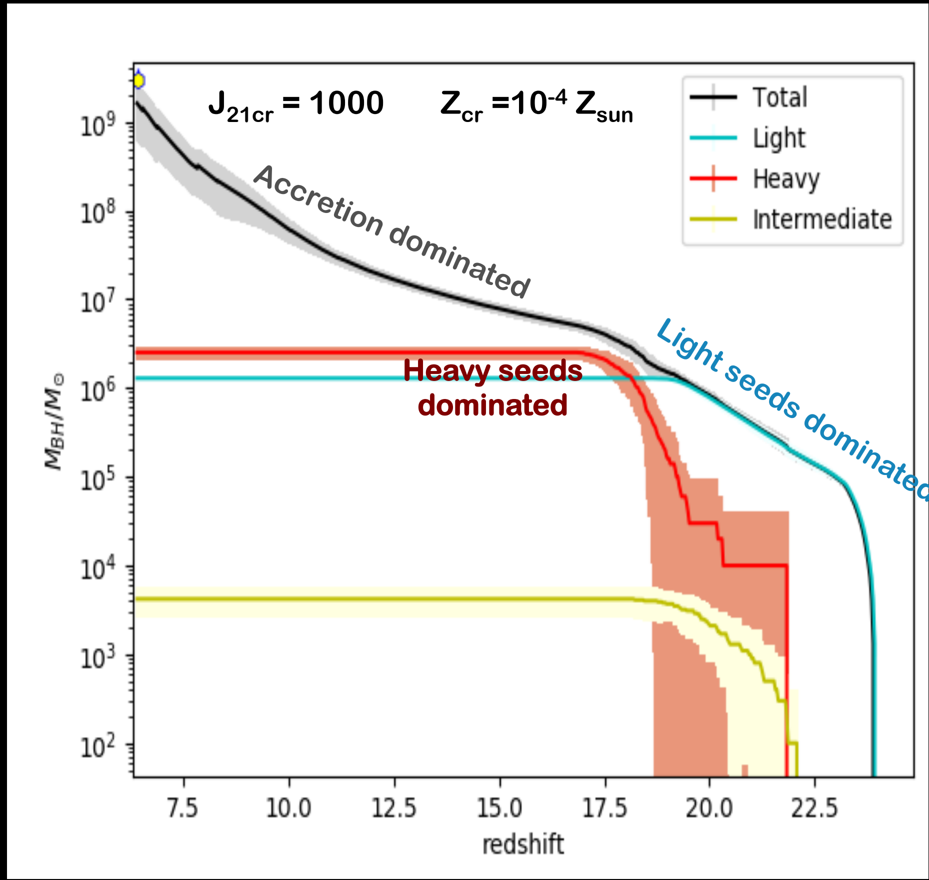
- inhomogeneous metal enrichment
- inhomogeneous Lyman Werner radiation
- $Z_{cr} = 10^{-4} Z_{sun}$, $D_{cr} = 4.4\ 10^{-9}$, $J_{21,cr} = 1000$

growing the first SMBHs

evolution of the total nuclear BH mass averaged over 10 simulations



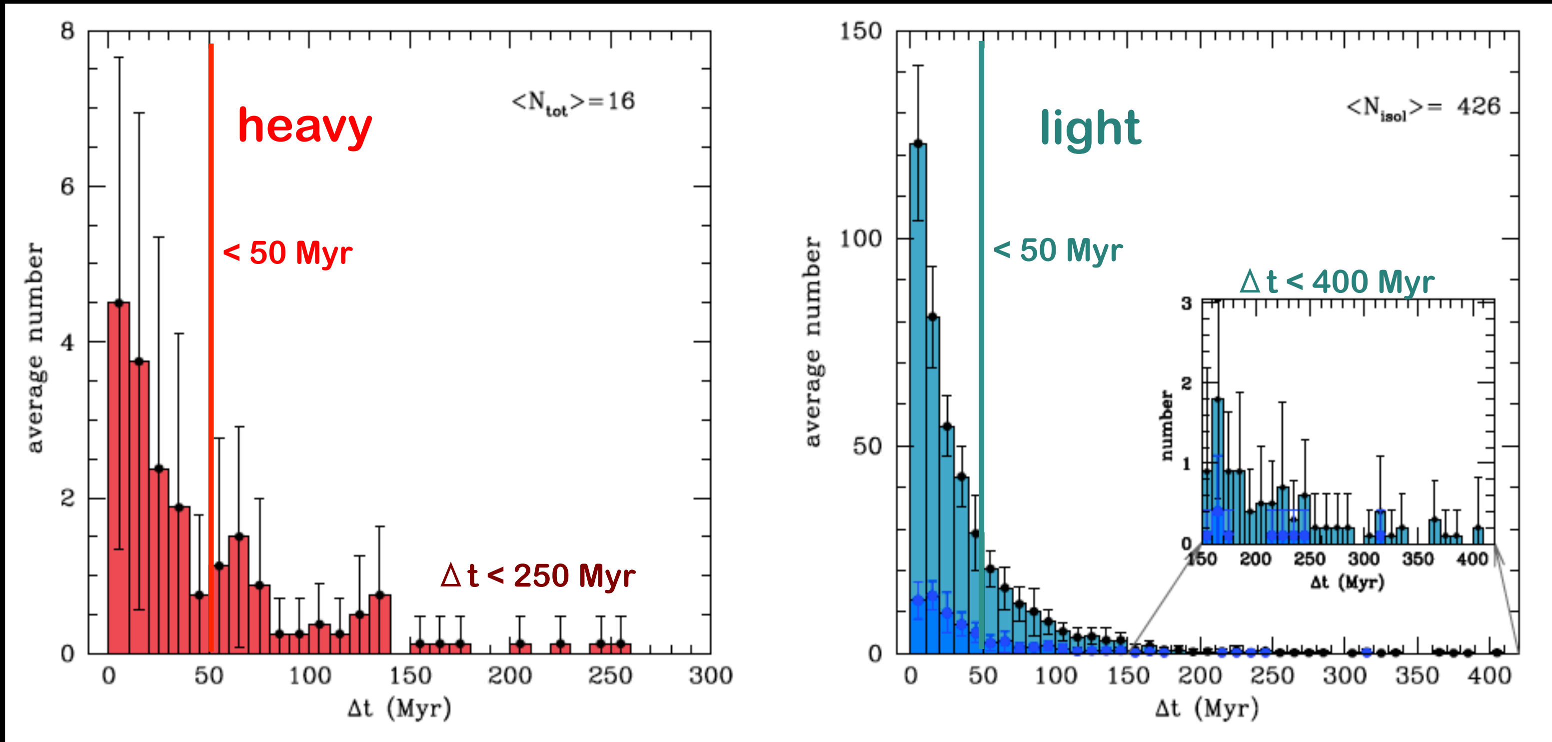
Valiante et al. 2016



Sassano et al. in prep

chasing the nature of BH seeds: candidate statistics

distribution of heavy and light seeds that live in “isolation” (no major or minor mergers)

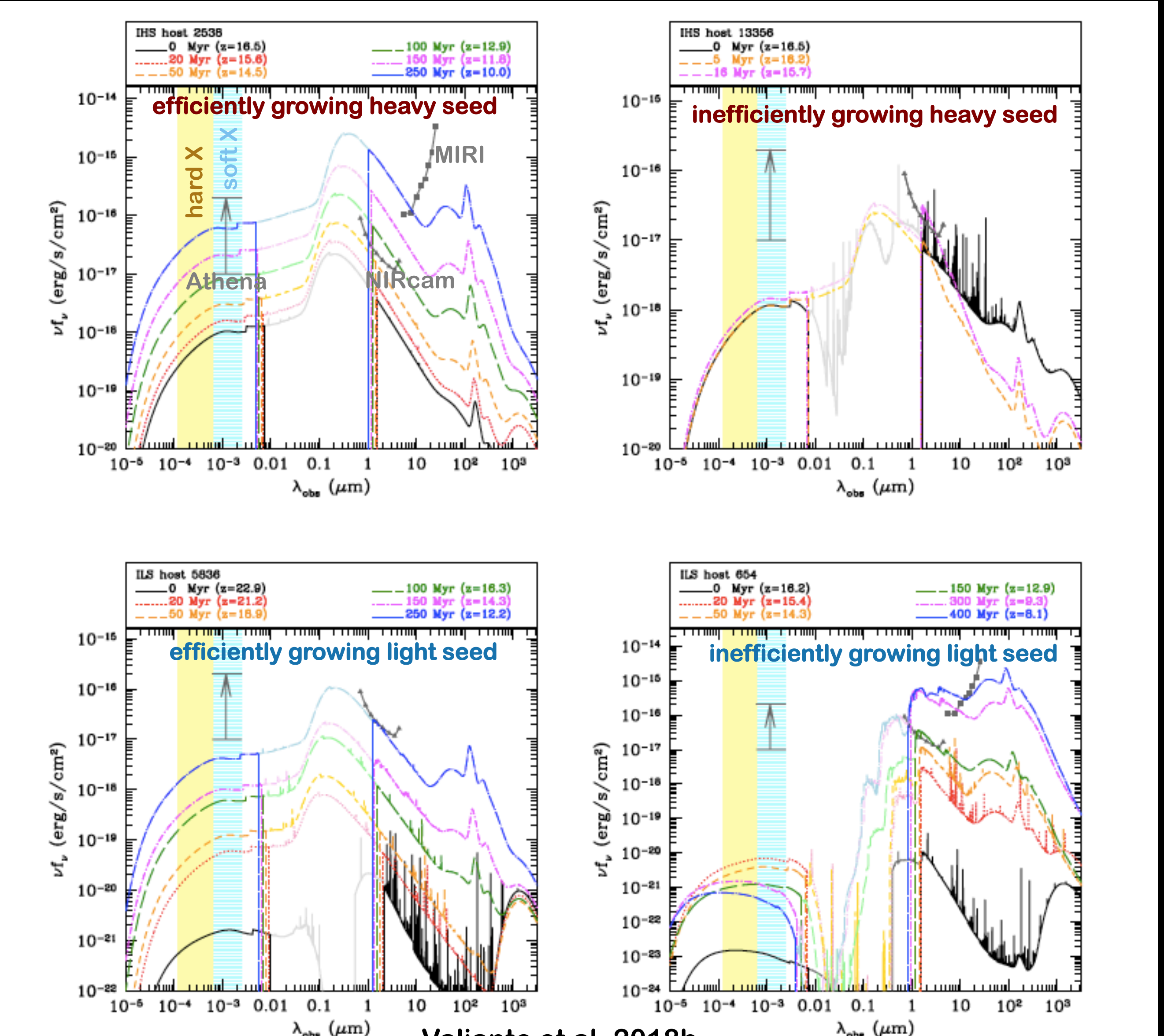


Valiante et al. 2018a

at z > 10, 80% of light seeds and 98% of heavy seeds are isolated
(most systems for ~ 50 Myr)
these fractions decrease dramatically at z < 10

chasing the nature of BH seeds: candidate observability

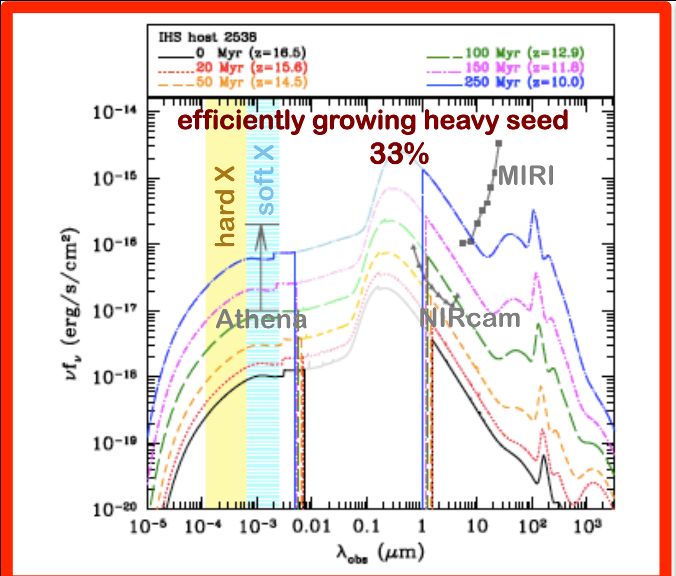
SED of isolated heavy and light seeds prototypes

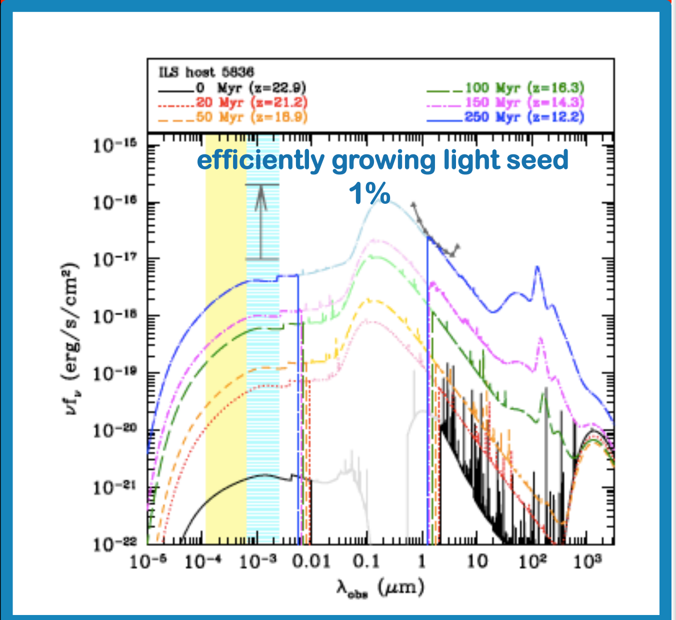


Valiante et al. 2018b

chasing the nature of BH seeds: candidate observability

SED of efficiently growing seeds (Valiante et al. 2018b)





heavy seeds

$10 < z < 13$

detectable with JWST & Athena

similar BH-dominated

SED at t > 100 Myr

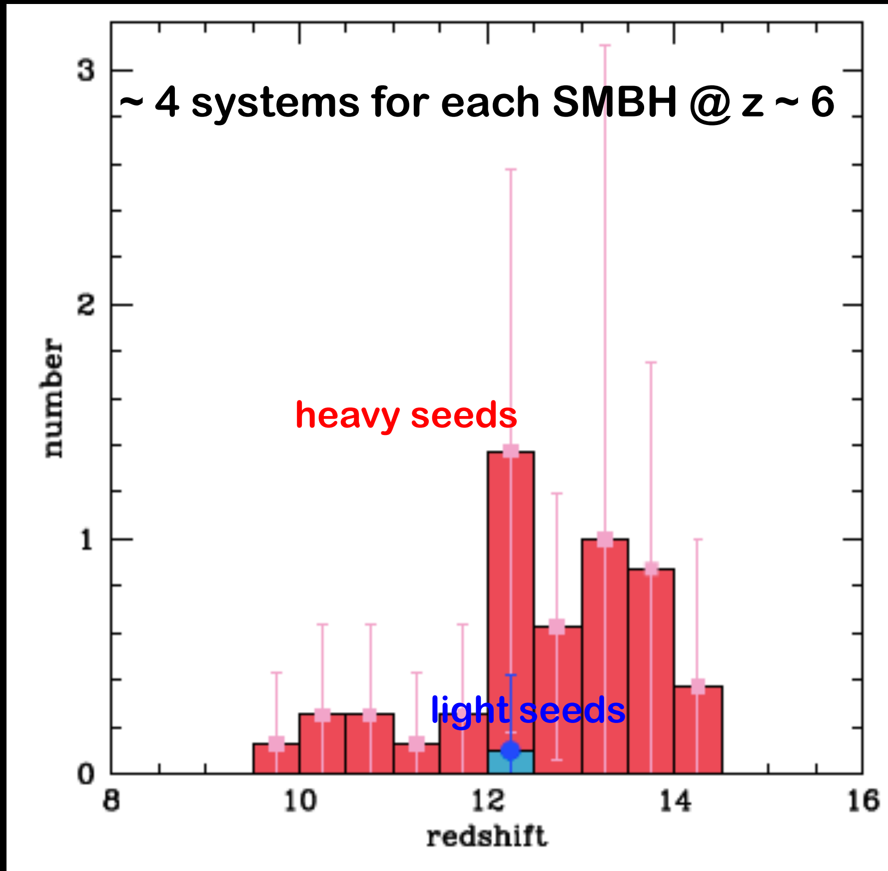
light seeds

$12 < z < 16$

not detectable

chasing the nature of BH seeds: candidate observability

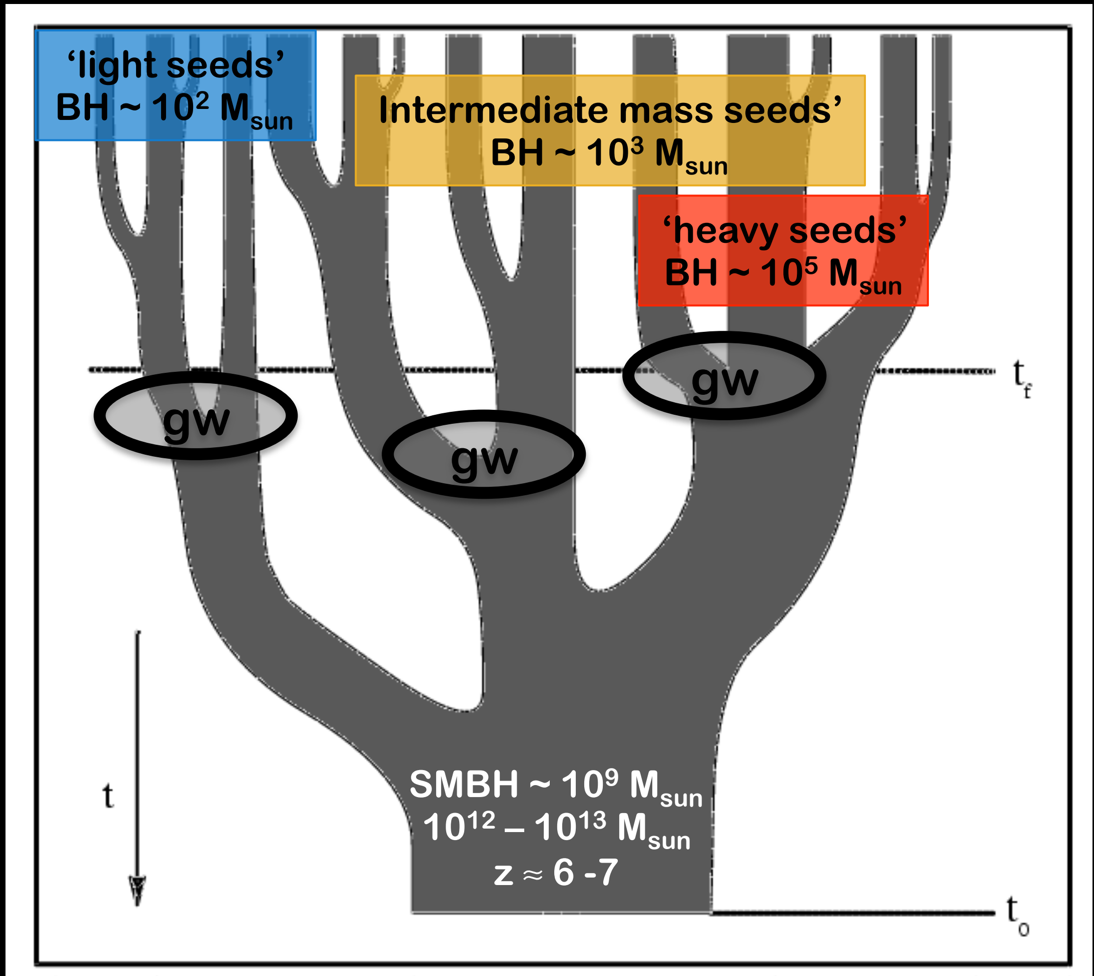
redshift distribution of detectable BH seeds



Valiante et al. 2018b

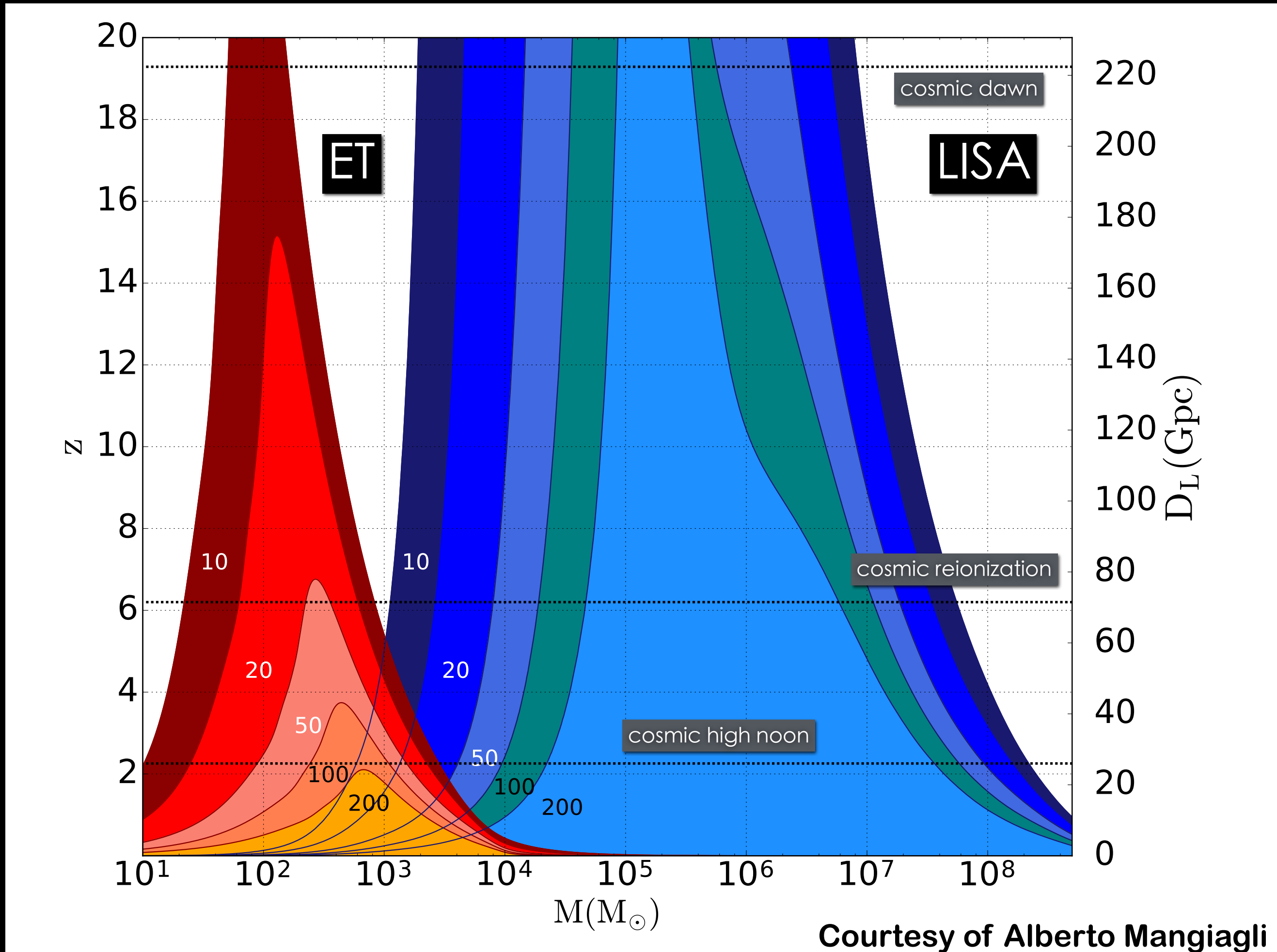
Pacucci et al. 2015, 2016; Natarajan et al. 2017; Volonteri et al. 2017

GW emission from BH seed pairs



Haiman & Loeb 2001, Volonteri et al. 2003, Wyithe & Loeb 2003, Haiman 2004, Menci et al. 2004, 2008, Shapiro 2005, Yoo & Miralda-Escude' 2004, Bromley et al. 2004, Volonteri & Rees 2005, Li et al. 2007, Pelupessy et al. 2007, Sijacki et al. 2009, Tanaka & Haiman 2009, Lamastra et al. 2010, Valiante et al. 2011, Petri et al. 2012; Valiante et al. 2015; 2016

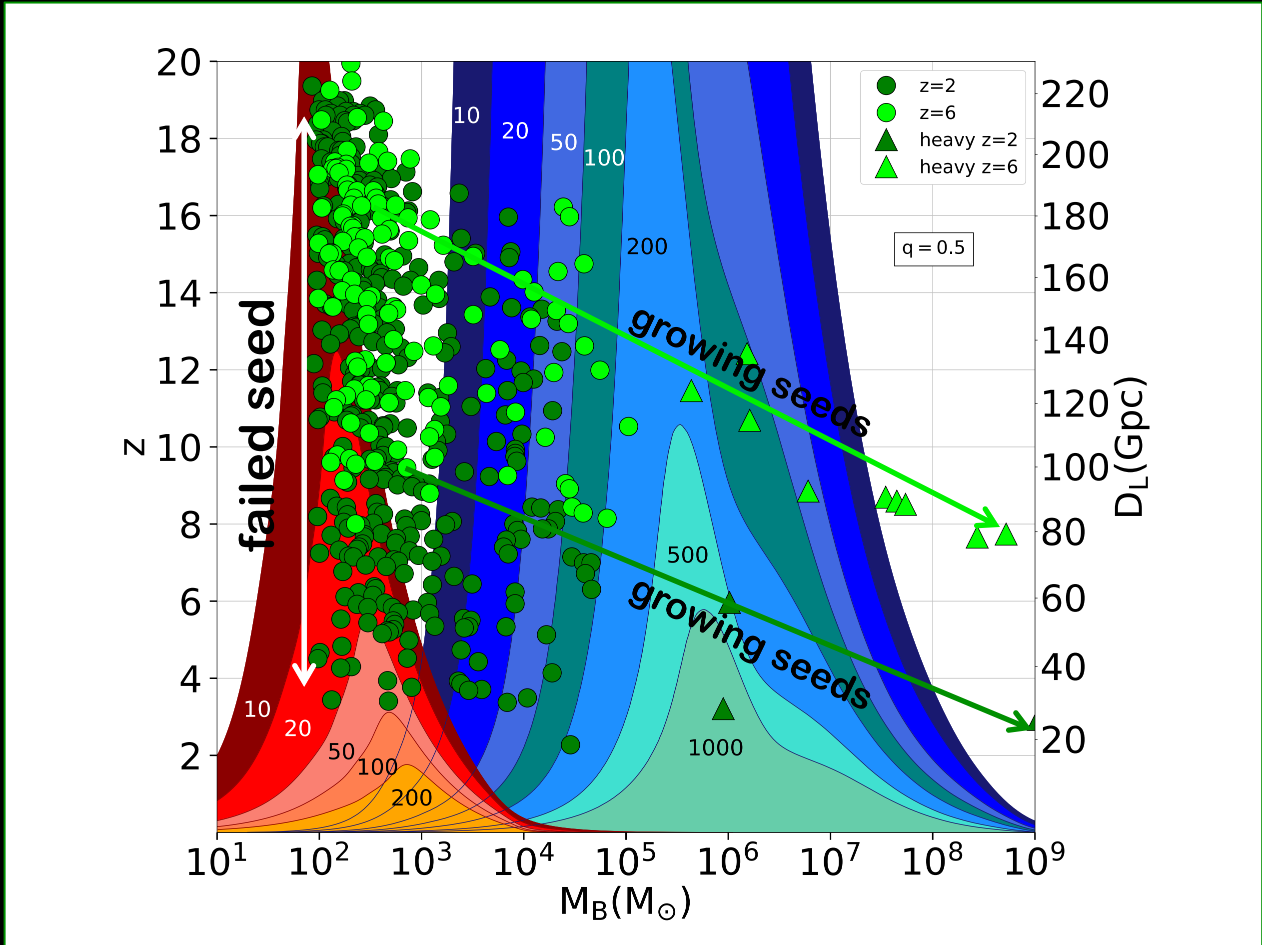
exploring the high-z Universe through gravitational waves



ET sensitivity curve ET_D as extracted from S. Hild, S. Chelkowski, A. Freise: "Pushing towards the ET sensitivity using 'conventional' technology" http://arxiv.org/abs/0810.0604.

LISA sensitivity curve is from arXiv:1702.00786. Lines of constant SNR are computed using waveforms for non-precessing binaries (Santamaria et al. 2010).

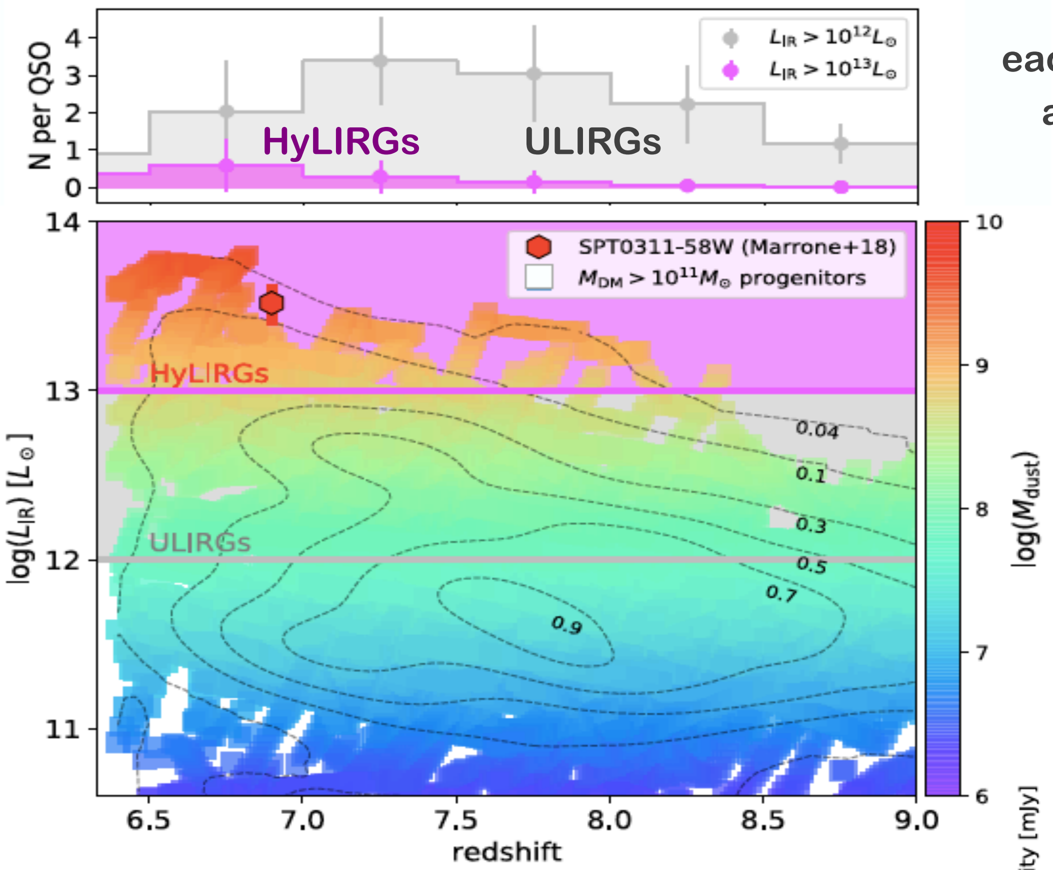
exploring the high-z Universe through gravitational waves



Valiante, Colpi, RS et al. in prep

the IR luminous progenitors of z ~ 6 quasars

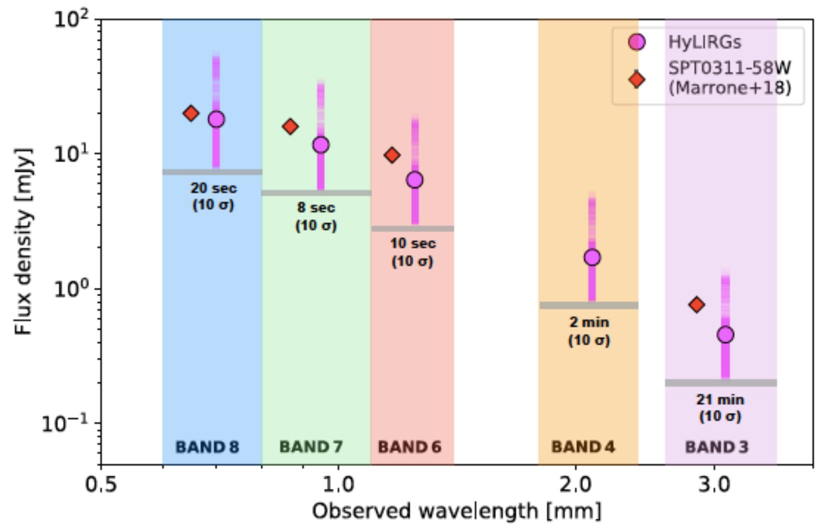
Ginolfi et al. 2019



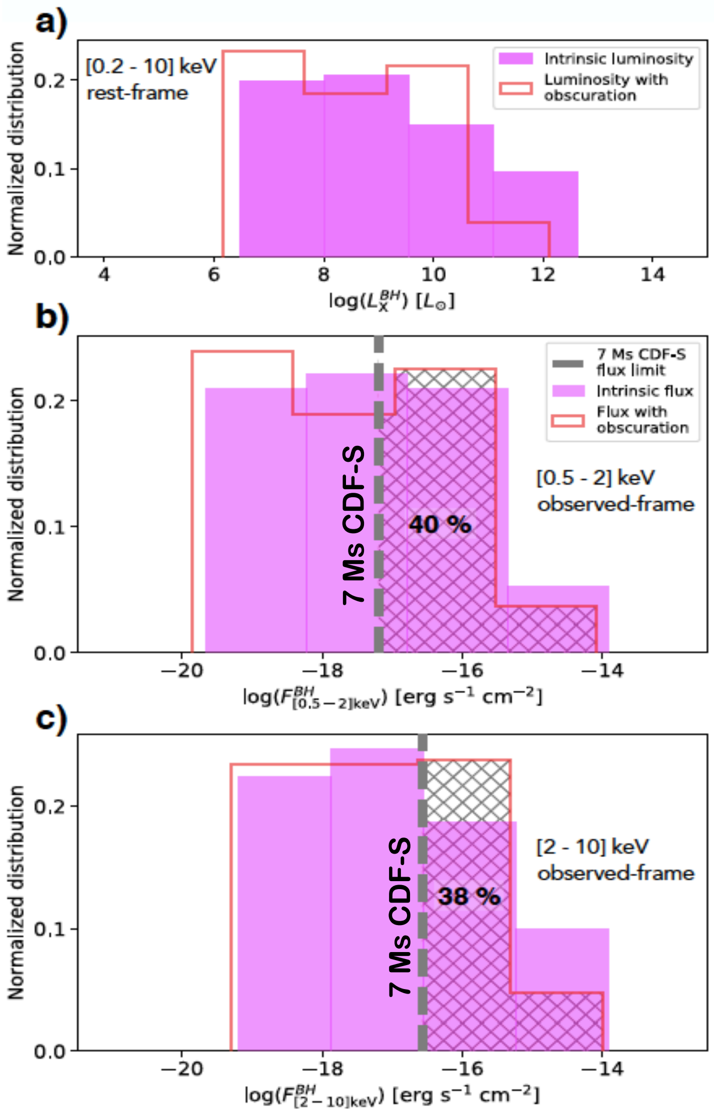
each z ~ 6 quasar has, on average, ~ 2.8 ULIRGs and ~ 0.4 HyLIRGs progenitors at 6.5 < z < 8

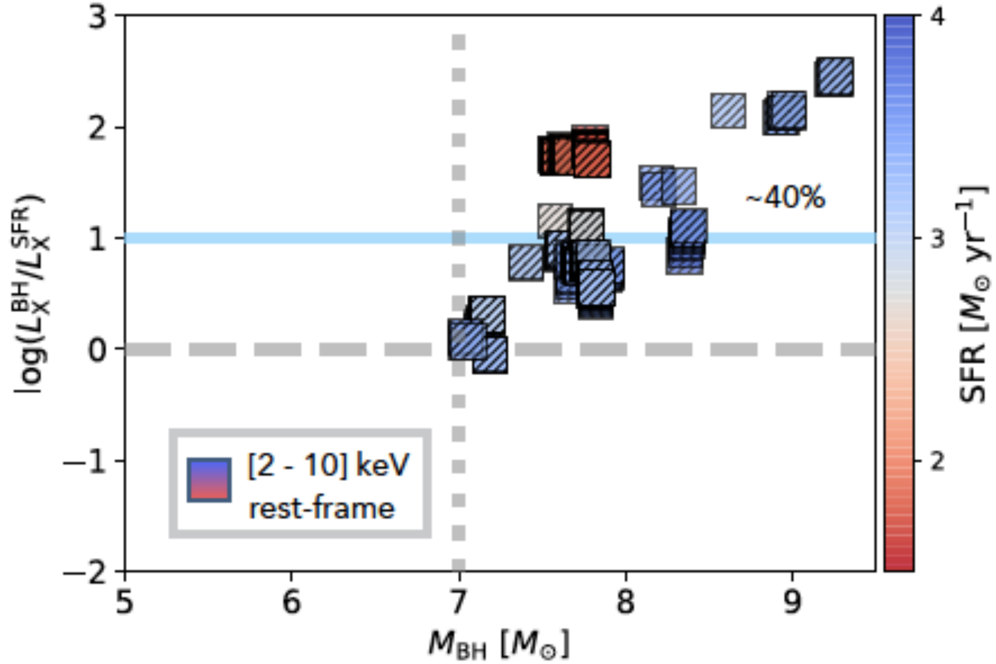
~ 180 quasars @ z > 6 → ~ 70 HyLIRGs

all these systems can be observed with ALMA



X-ray properties of HyLIRGs at z > 6





Ginolfi et al. 2019

Summary

- ❖ BH seeds can form in a variety of flavours: light (100 M_{sun}), intermediate-mass (1000 M_{sun}) and heavy ($10^4 – 10^5$ M_{sun}) depending on environmental conditions

- ❖ Identifying their nature observationally is hard: on average we expect ~ 4 progenitors for each SMBH could be detectable by JWST and Athena, most likely powered by efficiently growing heavy seeds

- ❖ Failed or growing BH seeds paired in halo mergers will be detectable by 3rd generation GW telescopes out to z = 20!

- ❖ z ~ 6 luminous quasars are the signposts of rare high-z over-densities, and that massive-IR luminous galaxies at higher z are their natural ancestors: 180 quasars @ z > 6 → ~ 70 HyLIRGs at 6.5 < z < 8 detectable with ALMA, 40% of detectable in X-rays

the combination of high spatial resolution with spectroscopic capabilities available with the E-ELT will provide a unique way of probing the formation history of SMBHs