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Theory of Gravitational Waves
SAPIENZA UNIVERSITÀ DI ROMA
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INFN
Istituto Nazionale di Fisica Nucleare

the origin and growth of early supermassive black holes

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Marta Volonteri, Tommaso Zana…

SAPIENZA UNIVERSITÀ DI ROMA
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NextGenerationEU
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Ministero dell'Università e della Ricerca

the earliest quasars

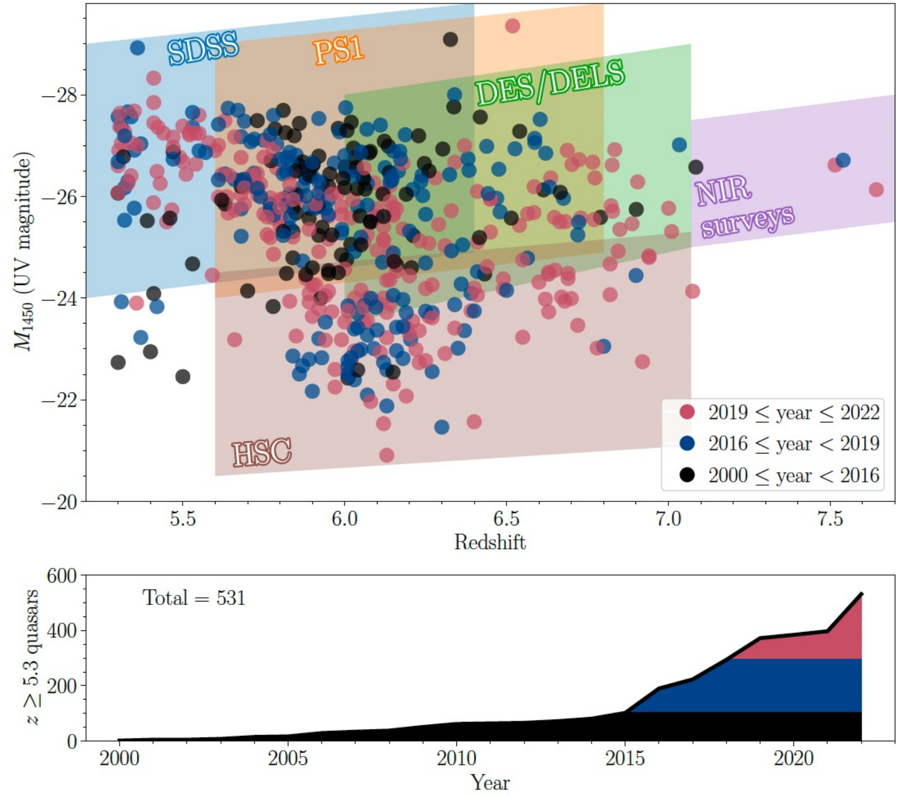
Artistic visualization. Image credit: NASA, ESA, Joseph Olmsted (STScI)

the most luminous active galactic nuclei (AGN) in the Universe

> 200 quasars observed within the first Gyr of the Universe (z≥6)

Fan et al. (1999, 2001, 2006); Mortlock et al. (2011); Bañados et al. (2016);
Wu et al. (2015); Yang et al. (2020, 2021); Mazzucchelli et al.(2017);
Matsuoka et al. (2019a,b); Reed et al. (2019); Wang et al. (2019)…

distribution of all known quasars as of Dec 2022



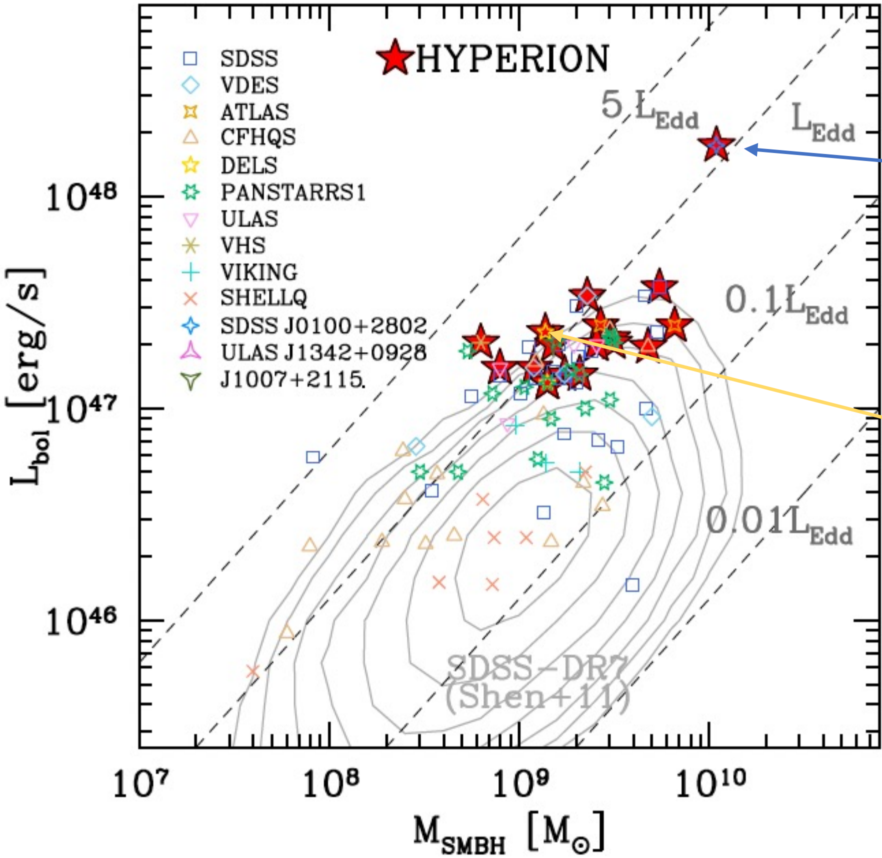
Fan et al. 2023

the earliest supermassive black holes

the emission from Quasars (AGN in general)
is powerd by accretion onto
Supermassive Black Holes (SMBHs)
up to 10^9 - 10^{10} M_{sun}

Hyperluminous ones (L_{bol}>10^{47} erg/s)
shine close or above the Eddington
luminosity limit (L_{Edd})

HYPerluminous quasars at the **E**poch of **R**eionizati**ON** (HYPERION)



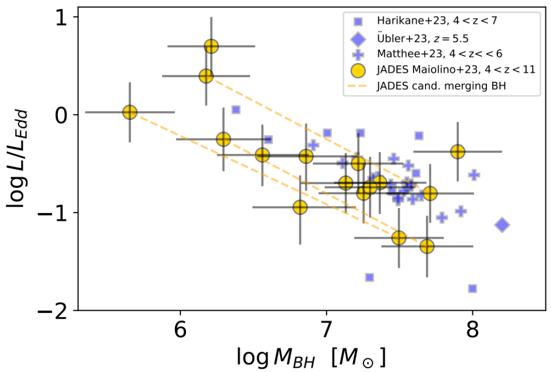
record holders

J0100 z=6.3
Wu+2015
most massive
(>10^{10} M_{sun})

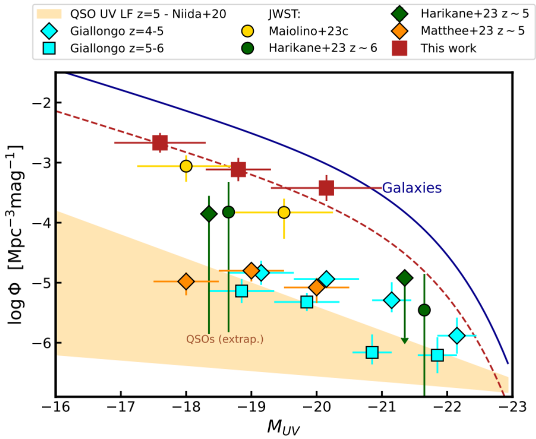
J0313 z=7.64
Wang+2021; Yang+2021
most distant
(1.6×10^9 M_{sun})

Zappacosta et al. 2023

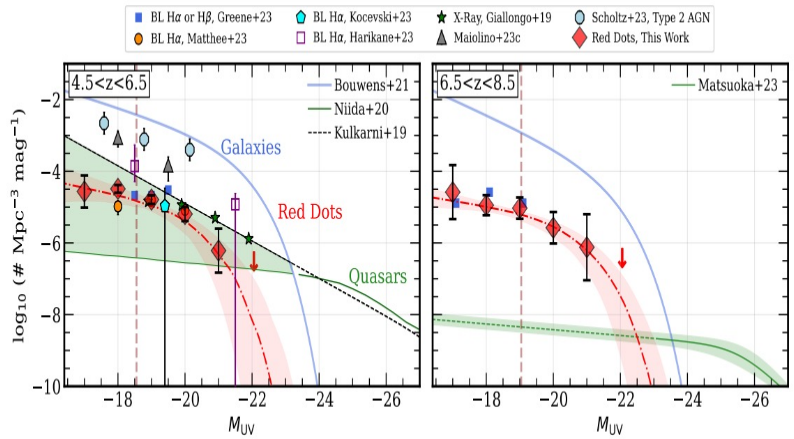
JWST has uncovered a large population of AGNs



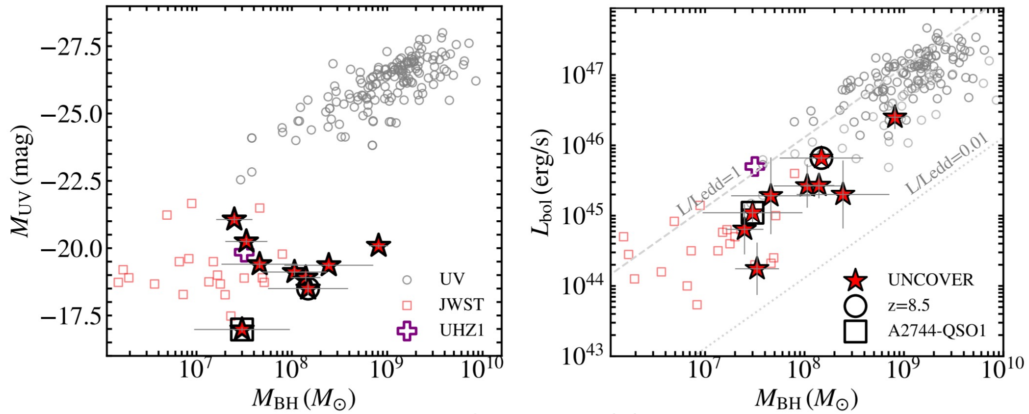
Maiolino+23



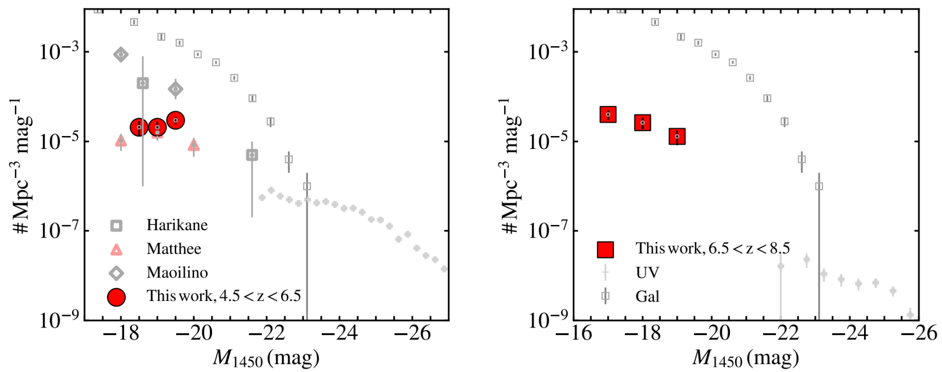
Scholtz+23



Kokorev+24

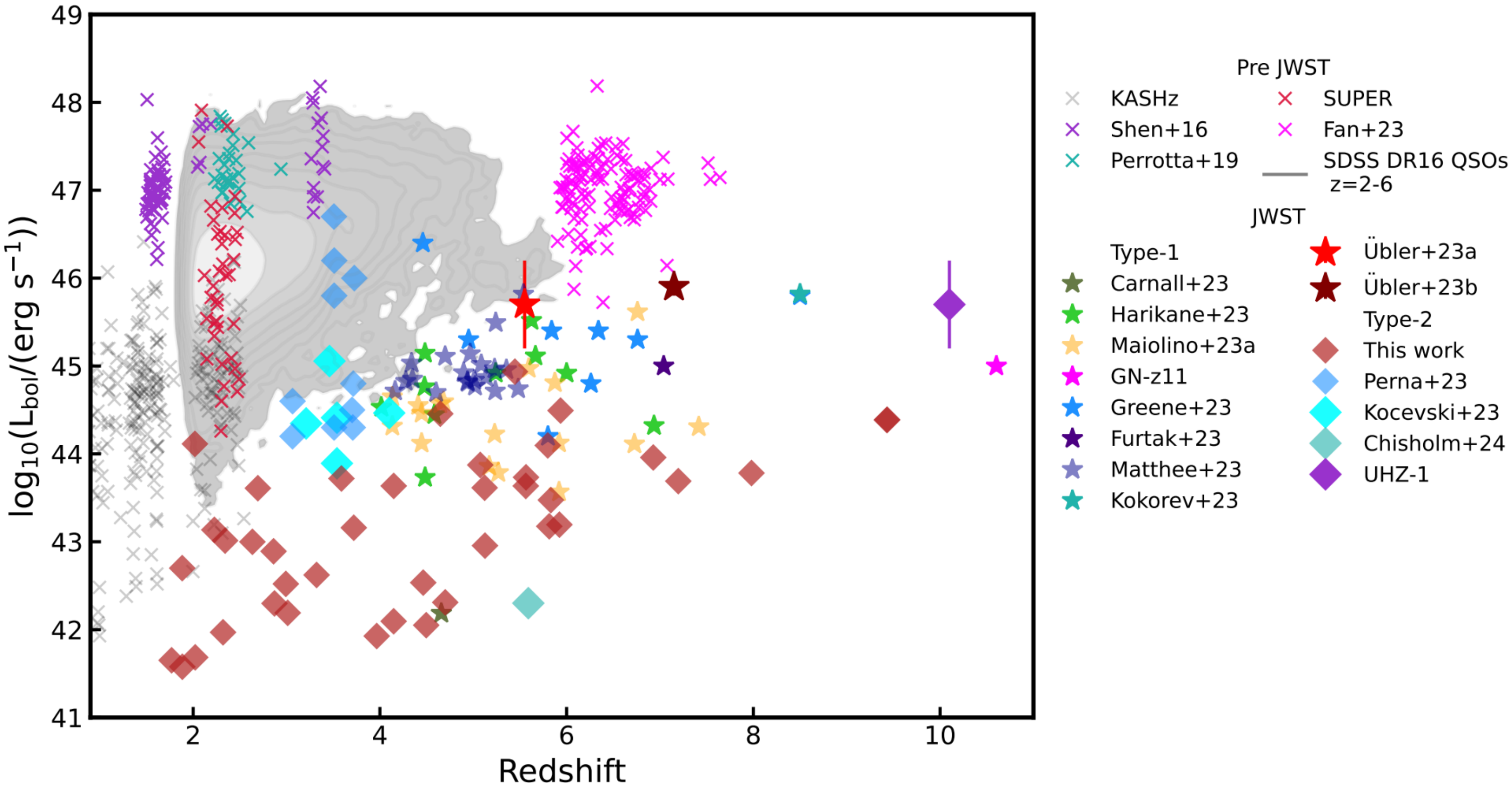


Greene+23



Greene+23

the new SMBH discovery space opened by JWST



Scholtz+23

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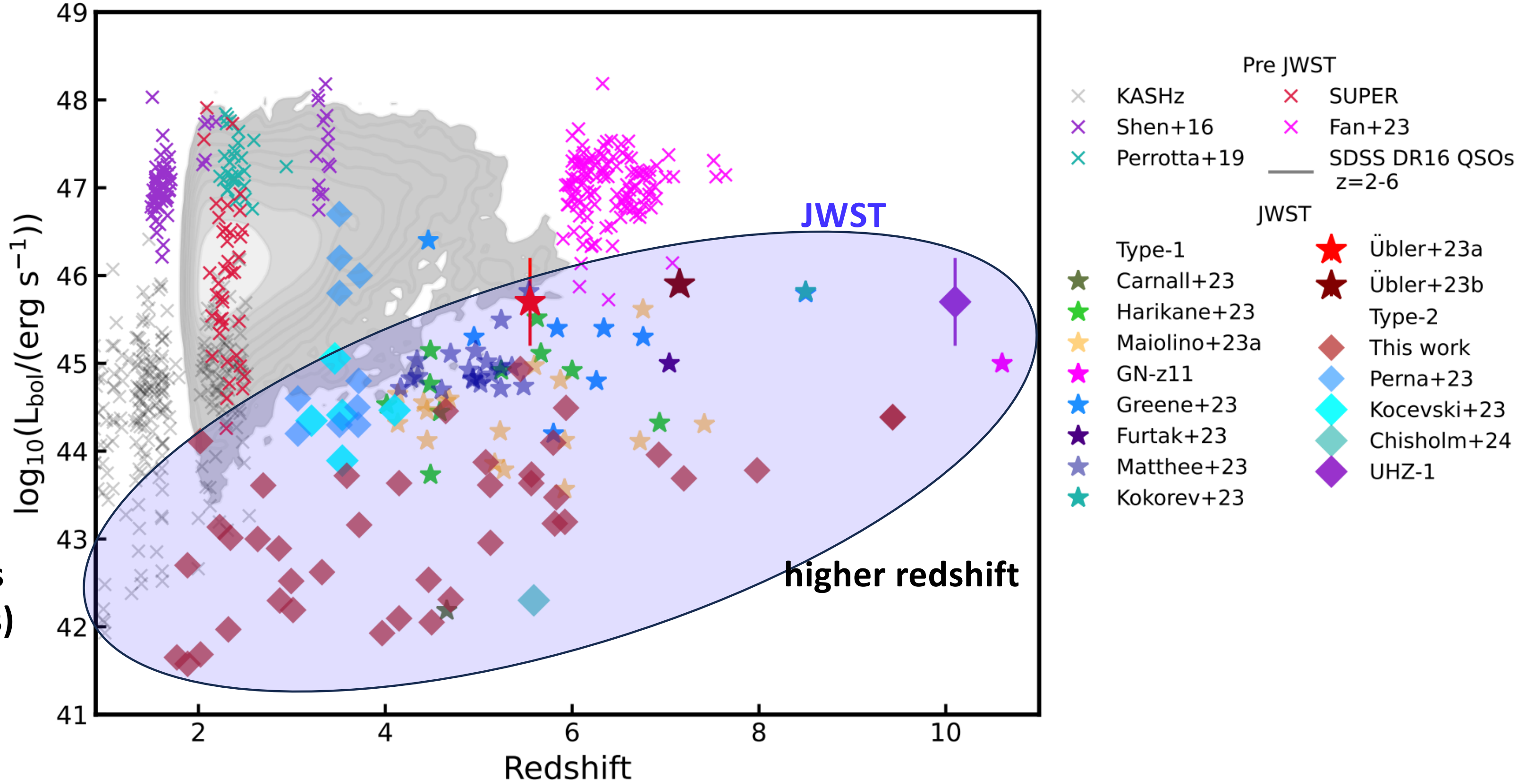


fainter luminosities (smaller BH masses)

Scholtz+23

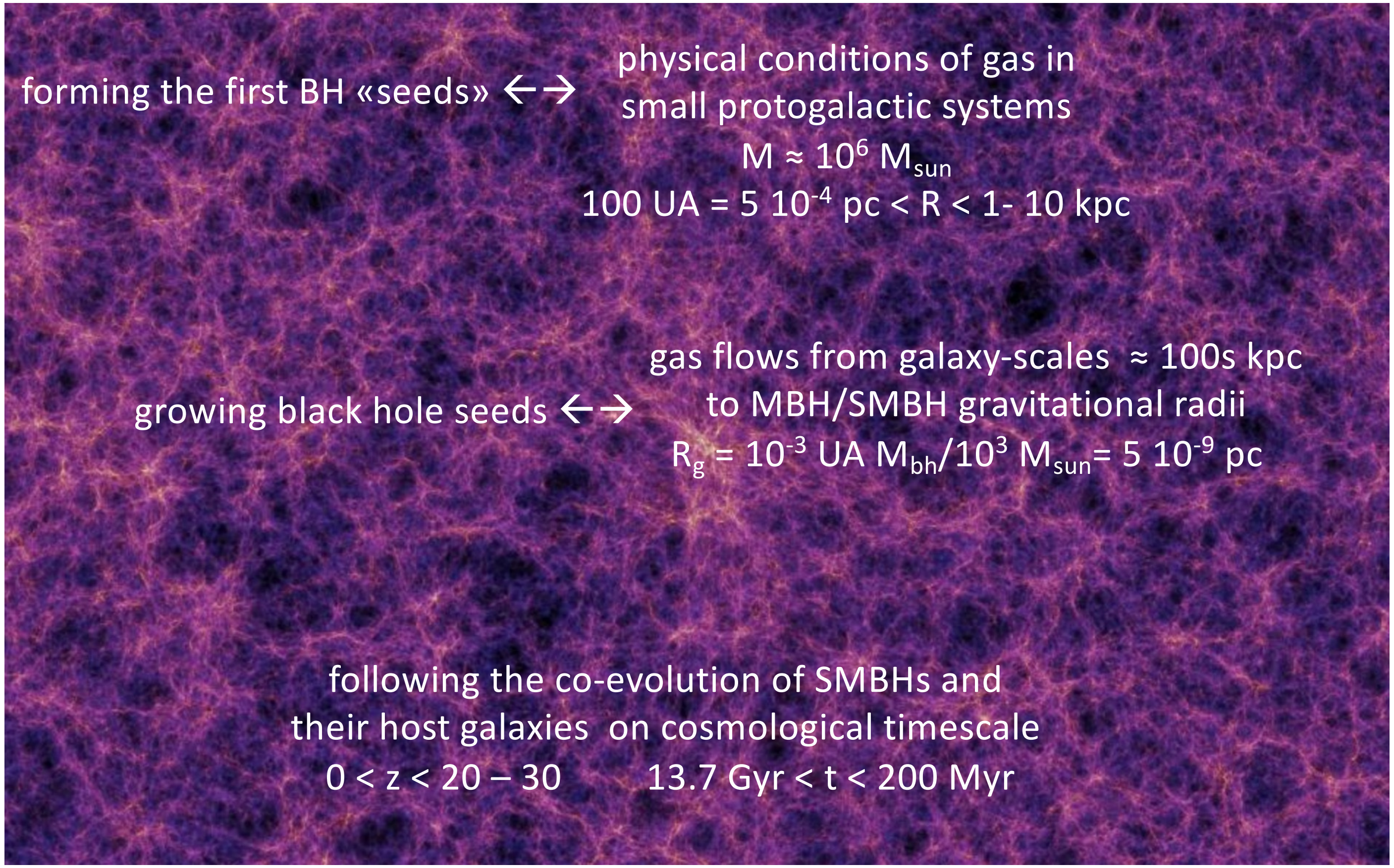
when do the first BHs form in the Universe?

what is the mass of the first BHs?

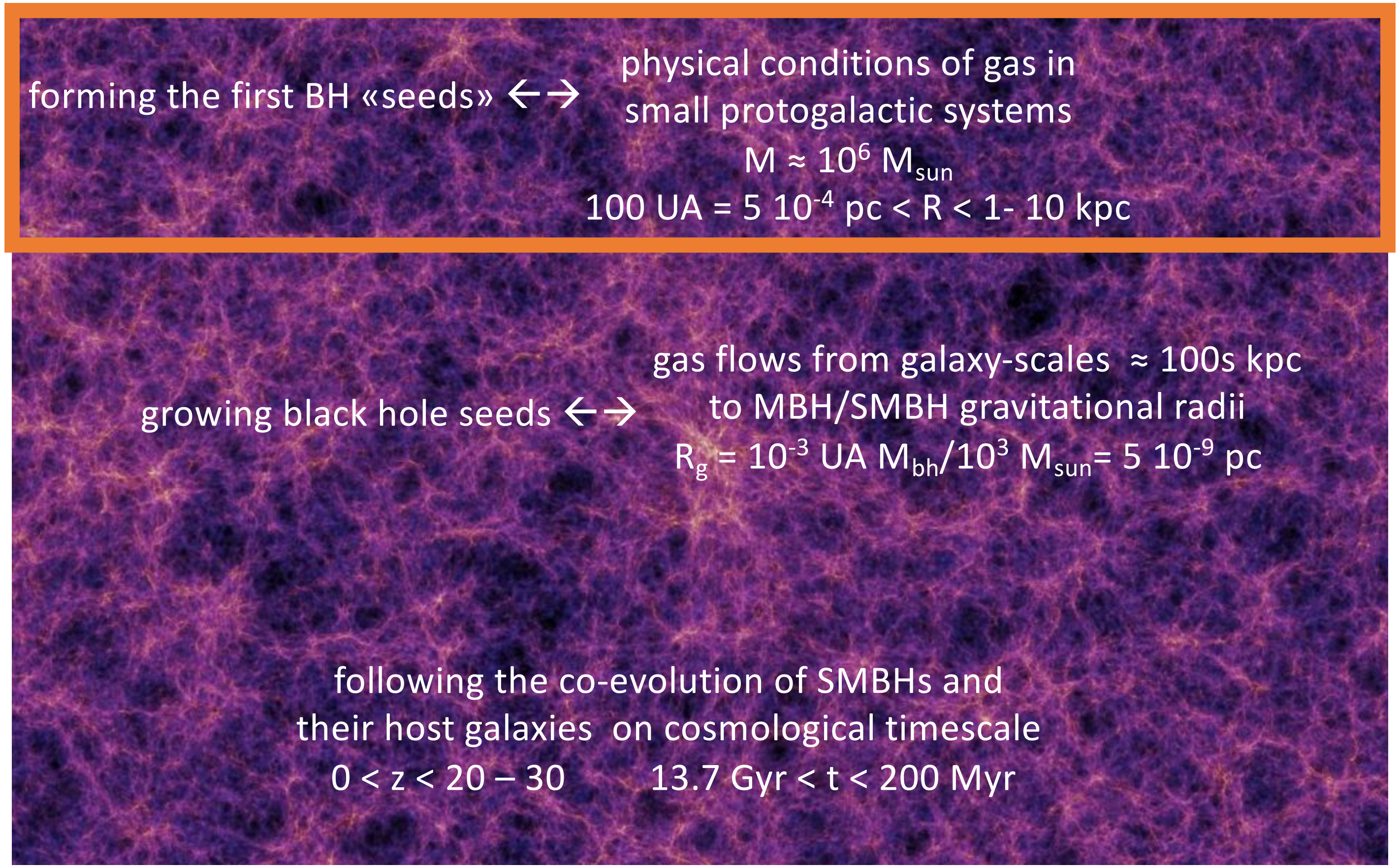
are the BHs detected at high-z the “seeds” upon which super massive BHs form?

do the first BHs pair and merge on timescales shorter than the Hubble time?

a theoretical challenge



a theoretical challenge



forming the first BH «seeds» ←→ physical conditions of gas in small protogalactic systems

$M \approx 10^6 M_{sun}$

100 UA $= 5\ 10^{-4}$ pc $< R < 1$- 10 kpc

growing black hole seeds ←→ gas flows from galaxy-scales ≈ 100s kpc to MBH/SMBH gravitational radii

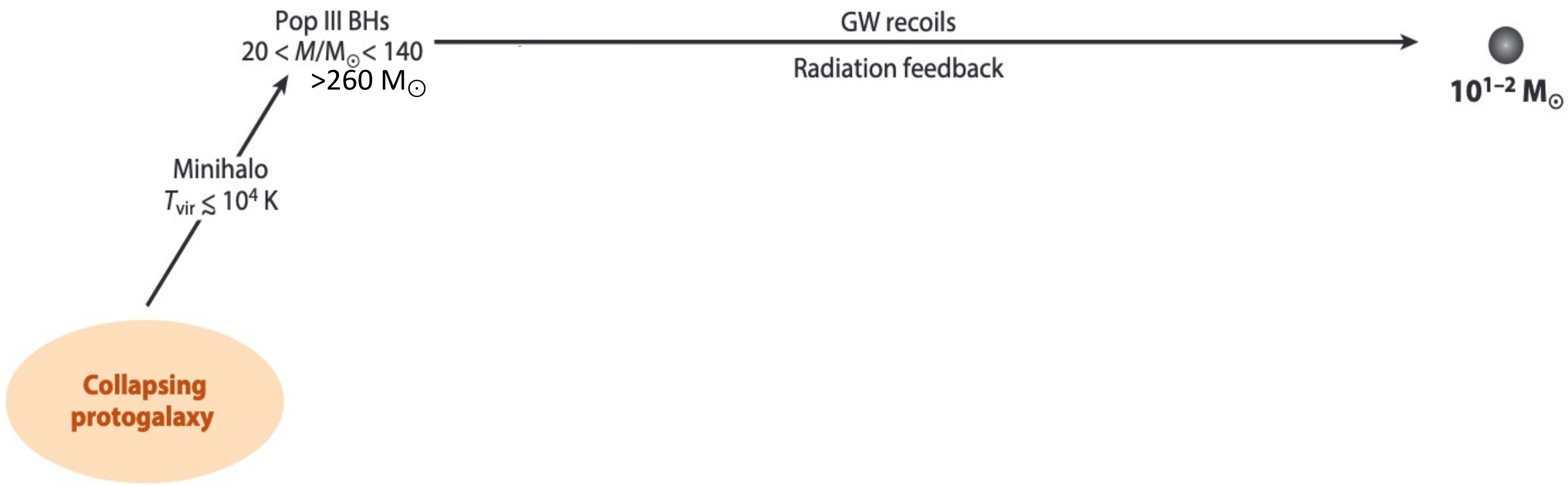
$R_g = 10^{-3}$ UA $M_{bh}/10^3 M_{sun} = 5\ 10^{-9}$ pc

following the co-evolution of SMBHs and their host galaxies on cosmological timescale

$0 < z < 20 - 30$ $\quad$ 13.7 Gyr $< t < 200$ Myr

The *seeds* of the earliest SMBHs

Astrophysical BHs formation channels



PopIII remnants "light"

e.g. Madau & Rees 2001
Heger et al. 2003;
Volonteri 2003

from Inayoshi et al. 2020

The *seeds* of the earliest SMBHs

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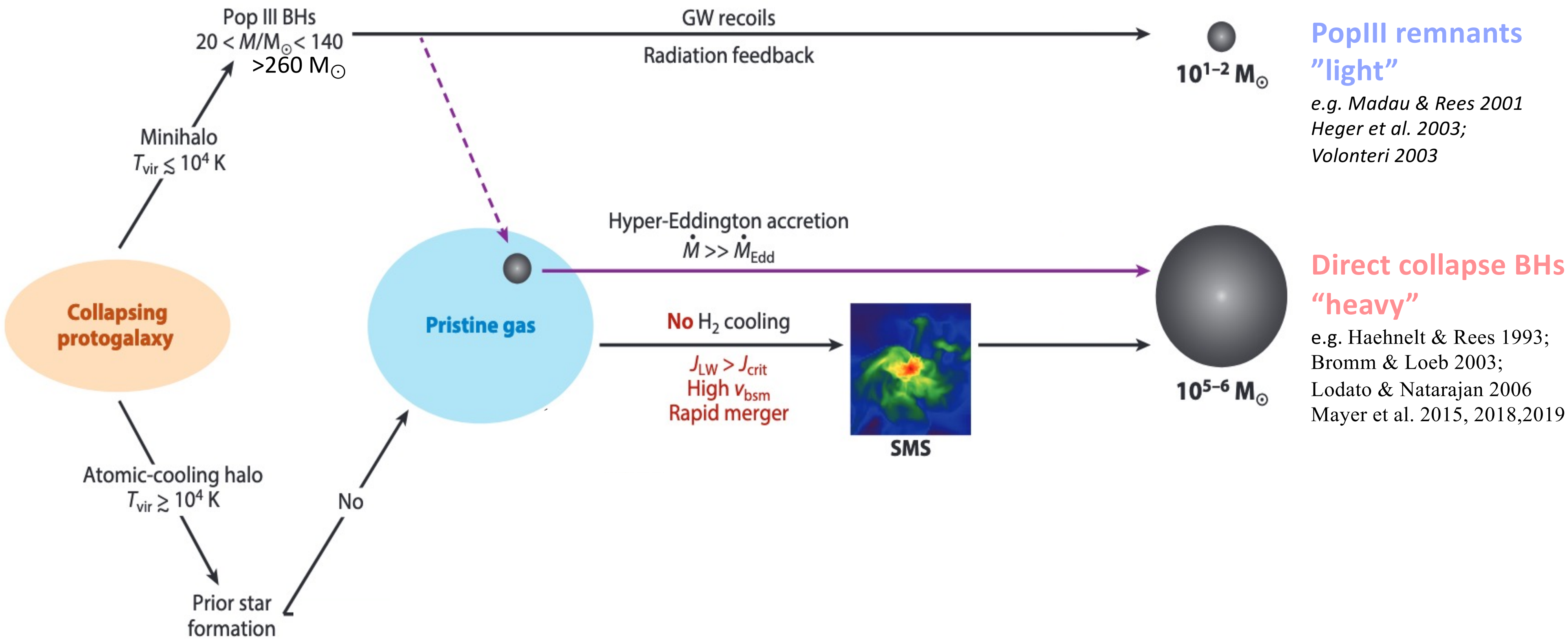

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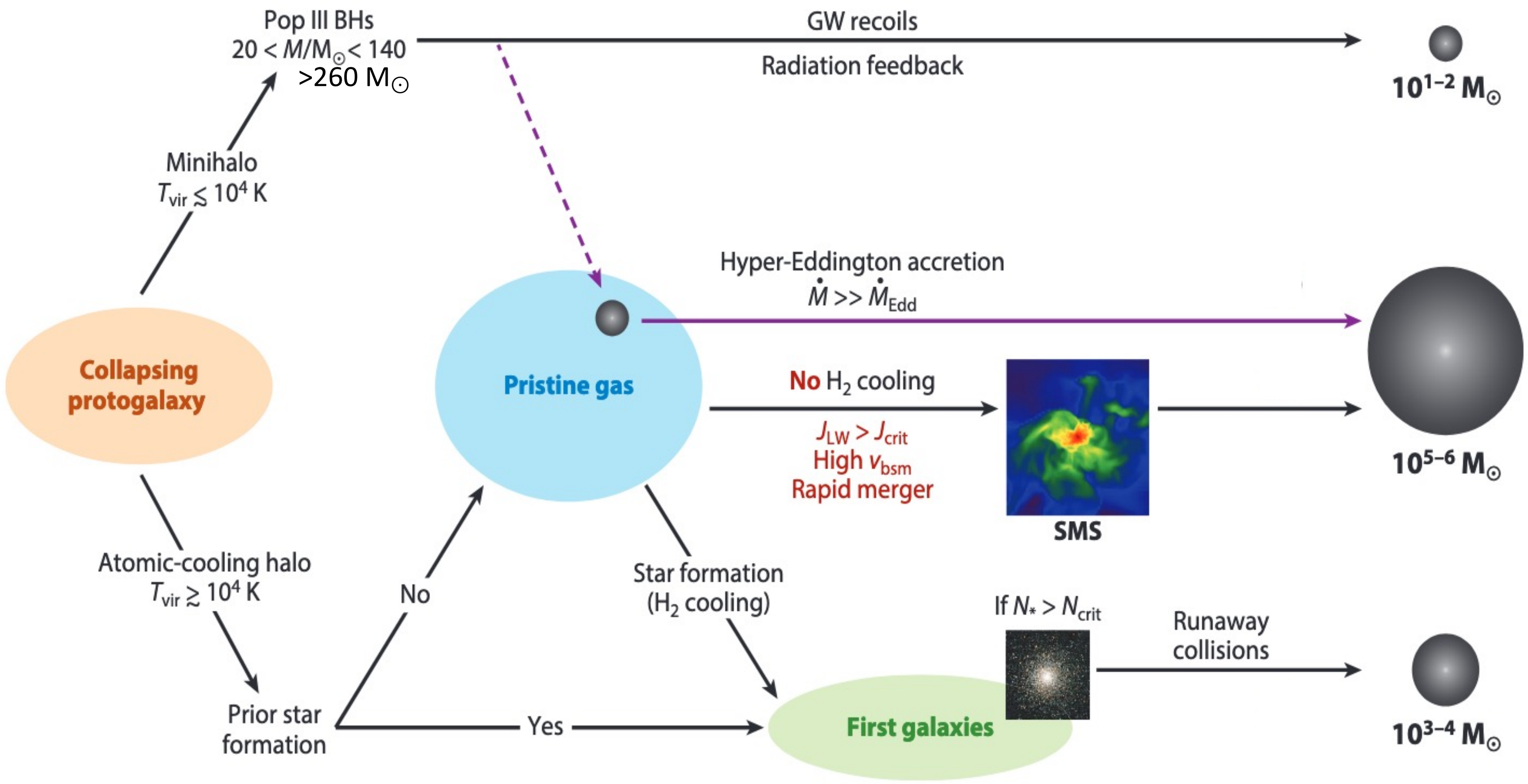


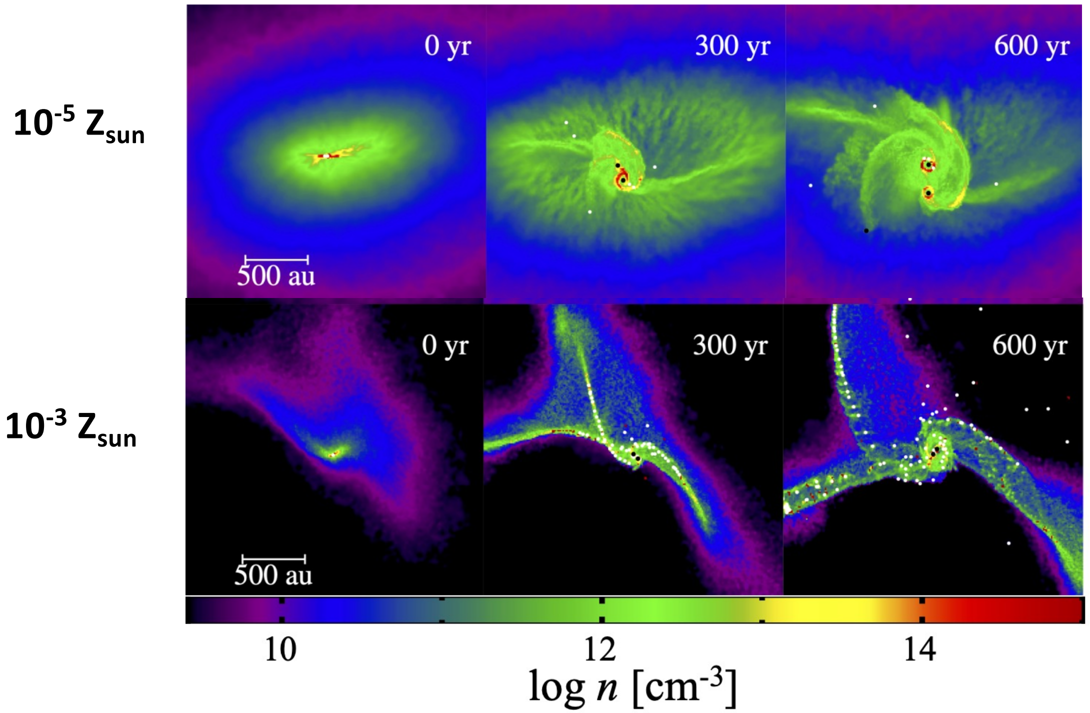
PopIII remnants
"light"
e.g. Madau & Rees 2001
Heger et al. 2003;
Volonteri 2003

Direct collapse BHs
"heavy"
e.g. Haehnelt & Rees 1993;
Bromm & Loeb 2003;
Lodato & Natarajan 2006
Mayer et al. 2015, 2018, 2019

Nuclear star clusters
"medium-weight"
e.g. Devecchi & Volonteri 2009;
Davies et al 2011; Lupi et al. 2014

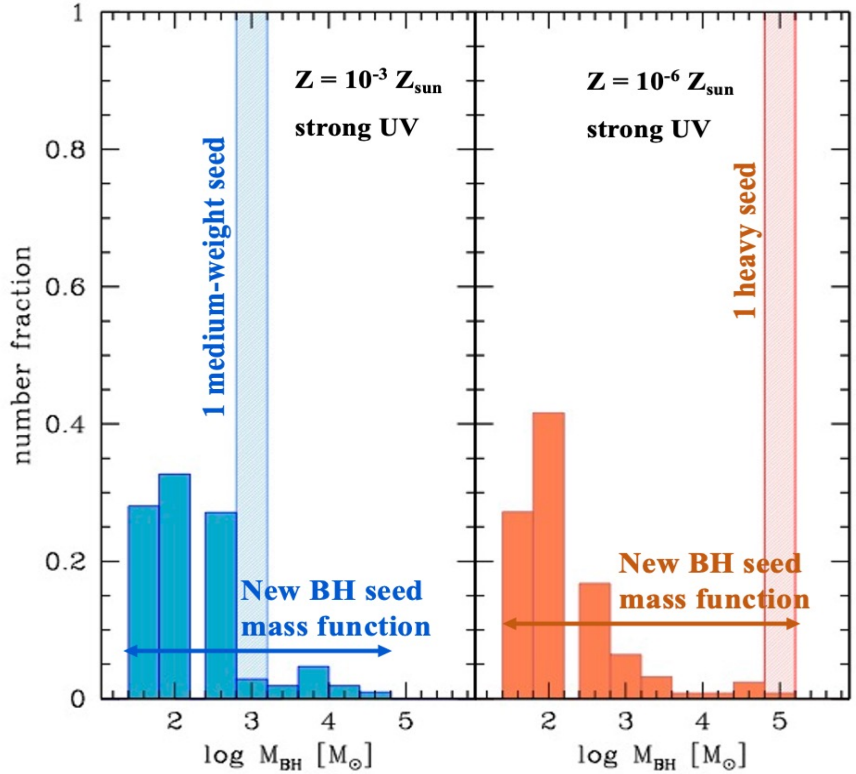
from Inayoshi et al. 2020

multiple «BH seeds» forming in a single halo



Chon & Omukai 2020

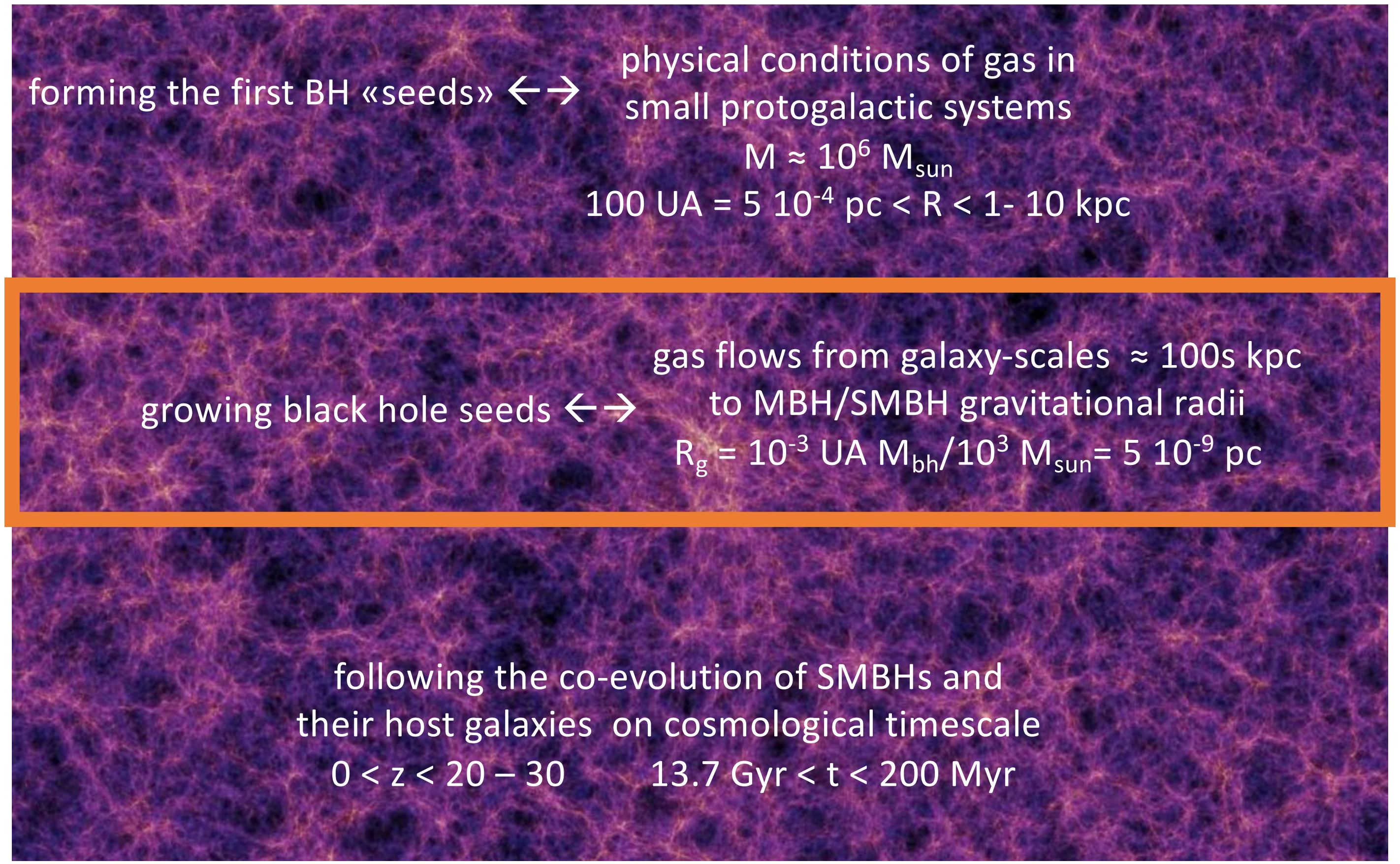
mass distribution of BH seeds at formation



<u>in situ dynamical interactions among BH seeds may be expected</u>

(see also Mestichelli+24 for Pop III – BHs clusters)

a theoretical challenge



growing the first black hole seeds: Eddington limit

the outward radiation pressure force on the infalling gas, through electron scattering, matches the inward gravitational force at the critical accretion rate of:

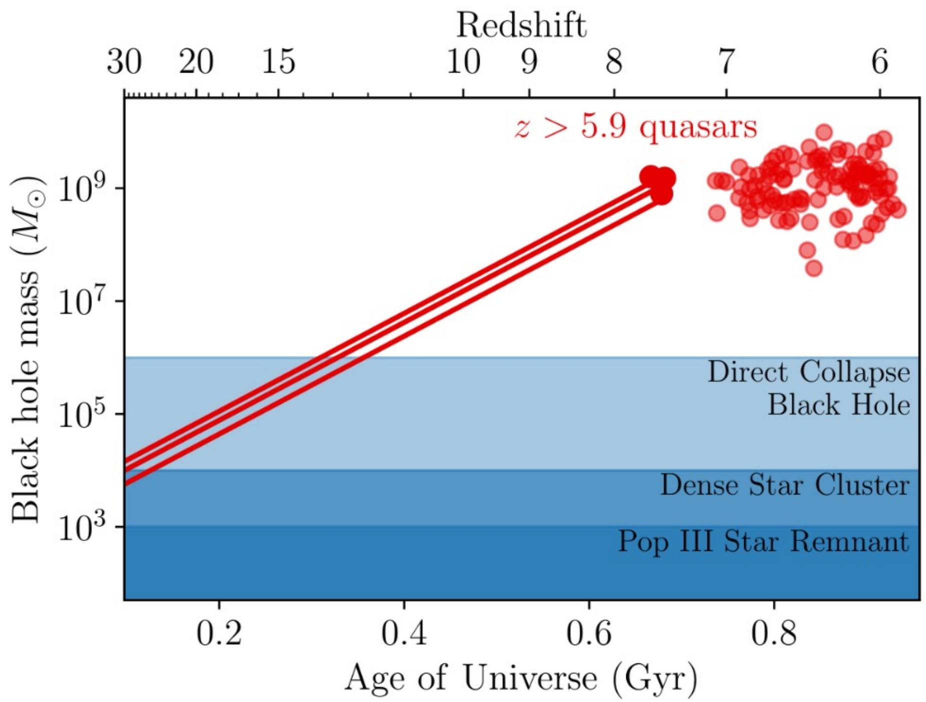
$$\dot{M}_{\rm Edd} \equiv 10\ L_{\rm Edd}/c^2 \quad L_{\rm Edd} = 4\pi c G M_\bullet/\kappa_{\rm es}$$

$$t_{\rm grow} \approx \frac{0.45\ \epsilon}{(1-\epsilon) f_{\rm duty}}\ \ln\left(\frac{M_\bullet}{M_{\rm seed}}\right)\ {\rm Gyr} \approx 0.81\ {\rm Gyr}.$$

$$M_\bullet = 10^9\ {\rm M}_\odot \quad M_{\rm seed} = 100\ {\rm M}_\odot$$

$\epsilon = 0.1,$ radiative efficiency

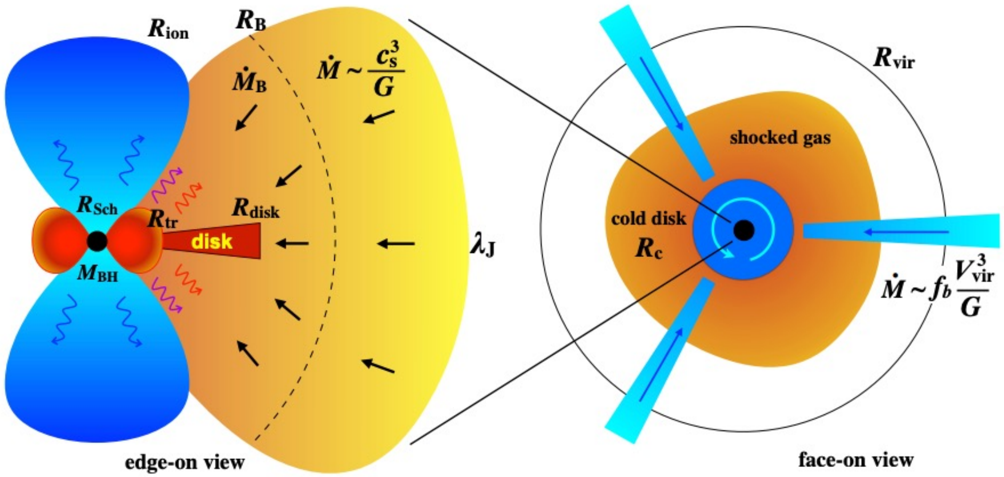
$f_{\rm duty} = 1,$ duty cycle



breaking the limit: super-Eddington growth

if photon diffusion timescale is longer than the advection timescales: $R_{tr} > R_{Sch}$

$$R_{\rm tr} \equiv \frac{\kappa_{\rm es}}{4\pi c}\dot{M}_\bullet = 5\dot{m}R_{\rm Sch} \qquad \dot{m} \equiv \dot{M}_\bullet/\dot{M}_{\rm Edd} \qquad \dot{M}_{\rm Edd} \equiv 10\ L_{\rm Edd}/c^2 \qquad L_{\rm Edd} = 4\pi c G M_\bullet/\kappa_{\rm es}$$

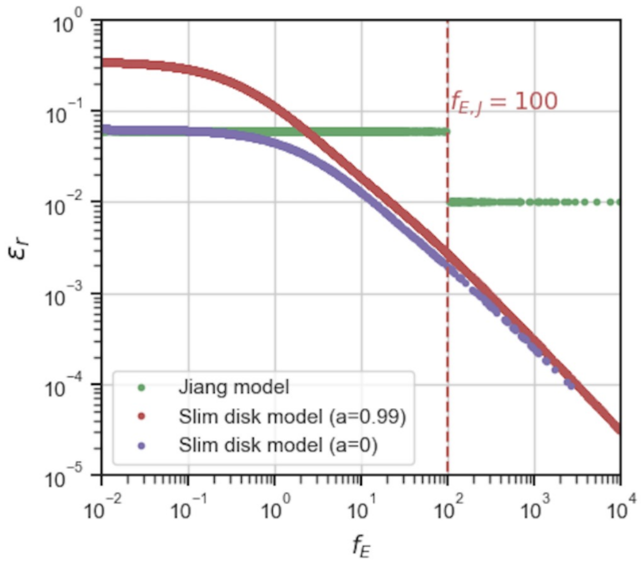


Inayoshi+2020

Begelman 1979, Abramowicz et al. 1988; Ohsuga+2005; Sadowski 2011; Sadowski+2013;
Sadowski and Narayan 2016; Jiang+2017; Inayoshi & Haiman 2016; Jiiang+2014, 2017; Takeo+2018; Madau+2014

super-Eddington accretion in early protogalaxies?

simulations on the scale of BH accretion disks



Jiang+2014,2019
higher anisotropy in the propagation of photons
turbulence helps photons propagate outward

Sadowski 2009, Madau+2014
radiation is advected inward, very radiately inefficient

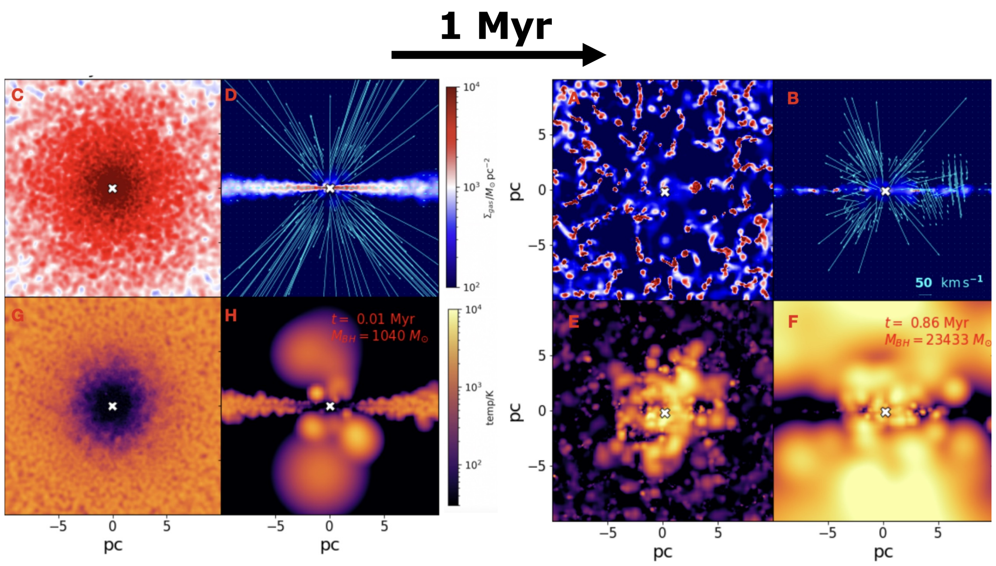
radiative BH feedback $\dot{E}_{\rm c} = \dot{m}\epsilon_{\rm r}\epsilon_{\rm c}c^2$

Coupling efficiency

is super-Eddington growth sustainable?

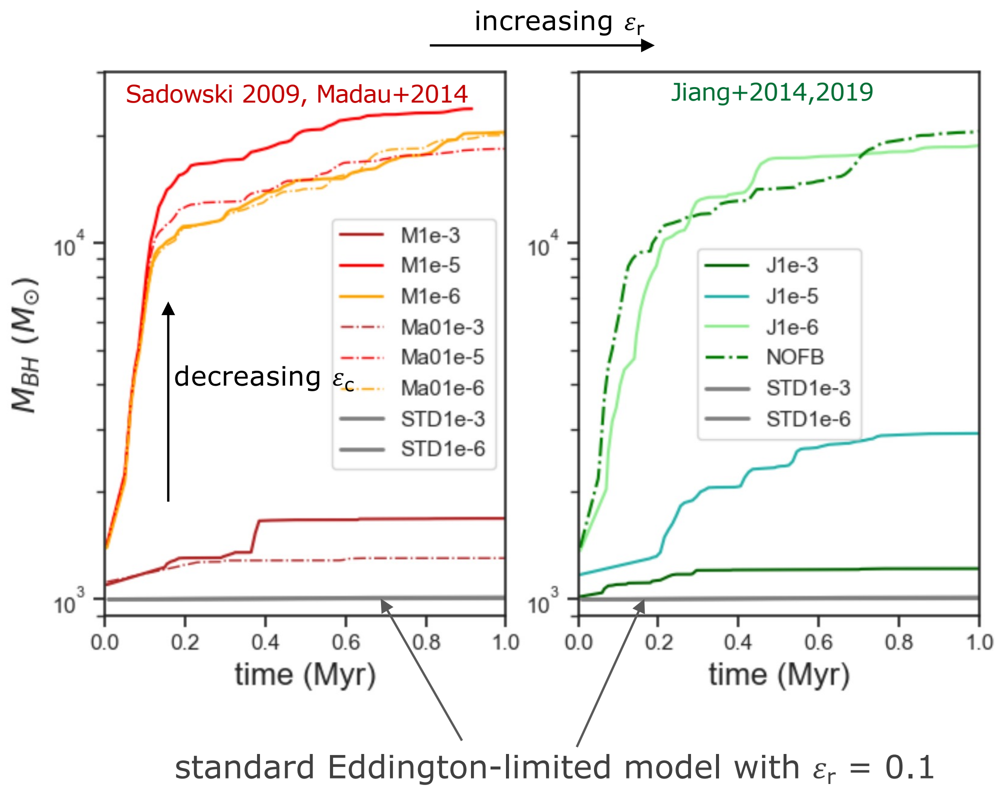
SPH simulation (GASOLINE2) of a **≈ 10^3 M_{sun} black hole in a gas-rich protogalaxy at z ≈ 15** (m_{res} = 25 M_{sun})

Sassano, Capelo, Mayer, RS, Valiante (2023)



$M_{BH,seed}$ = 10^3 M_{sun} → **M_{BH} ≈ 10^4 M_{sun}**

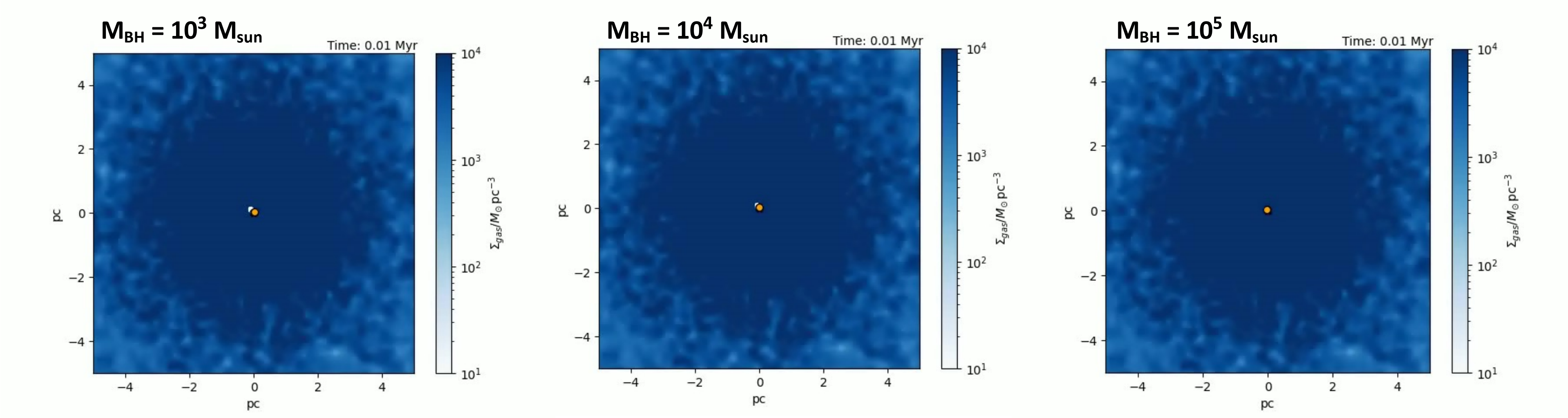
BH displacement, star formation and feedback lead to a **rapid quenching** of BH accretion after ≈ 1 Myr



see also Lupi+2014, Regan+2019, Massoneau+2022, Lupi+2023

does super-Eddington growth depend on BH seed mass?

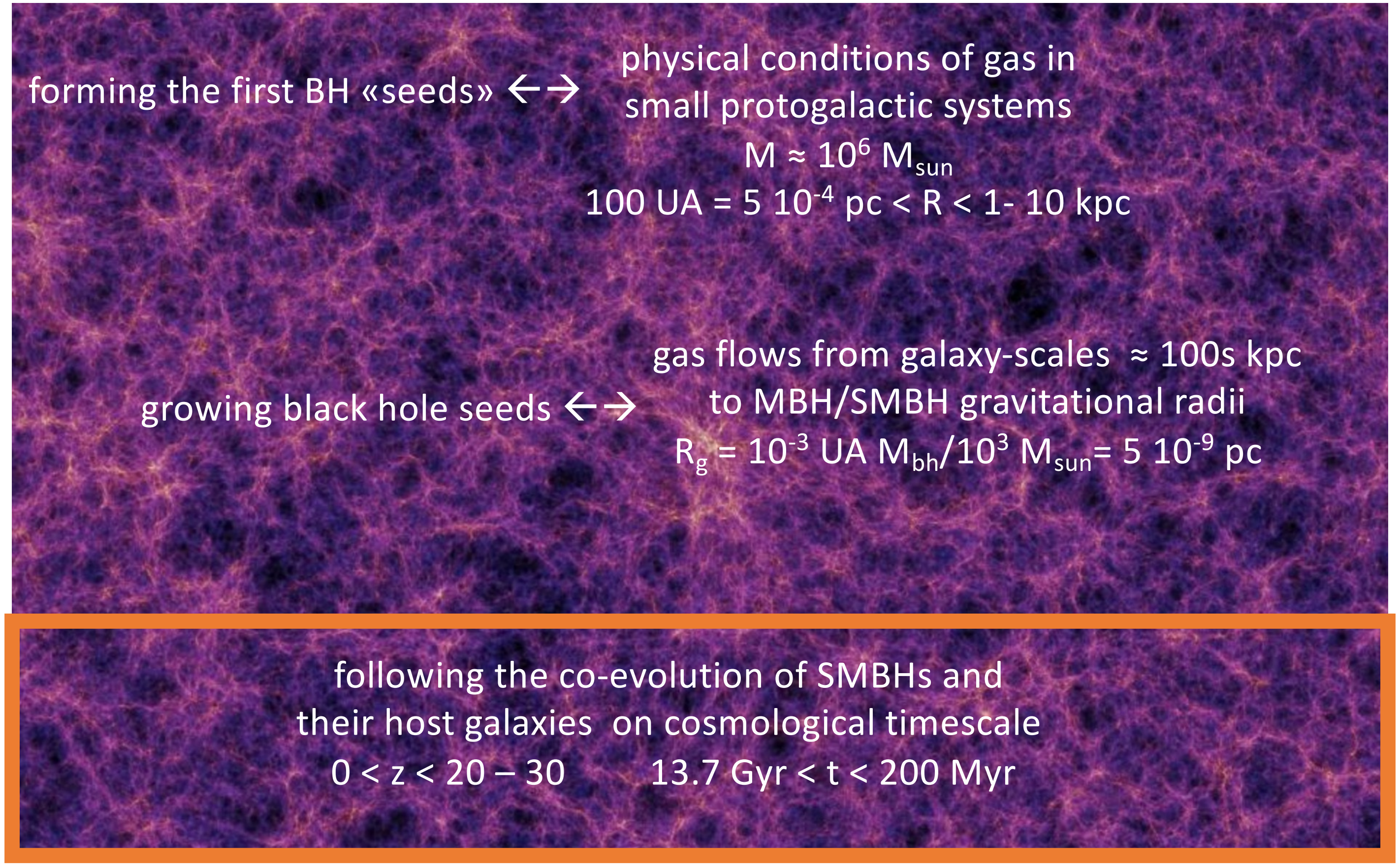
SPH simulation (GASOLINE2) of a BH seed in a gas-rich protogalaxy at $z \approx 15$ ($m_{res} = 25\ M_{sun}$)



estimate the time duration of the super-Edd phase and BH mass growth, testing the impact of BH **displacement**, **star formation** and **feedback**

Tommaso Zana, Mairo Boresta et al. in prep

a theoretical challenge



investigating the first sources of light and GWs with semi-analytical models

SAMs easily account for:

cosmic variance (DM halos merger trees based on Extended PS)

low-mass DM halos (mini halos; $T_{vir} < 10^4$ K, $M \sim 10^6$ M_{sun})

evolution of the host galaxy ISM (with metals and dust)

different physically-motivated seeding prescriptions

different BH accretion paradigms

BH dynamics (BH pairing/mergers delay times)

the formation of single quasars - GQd

A data-constrained **SAM** for **G**alaxies & **Q**uasars *with* **d**ust
we use observed quasar properties to constrain model parameters

merger trees based on the EPS theory for a 10^{13} M_{sun} DM halo

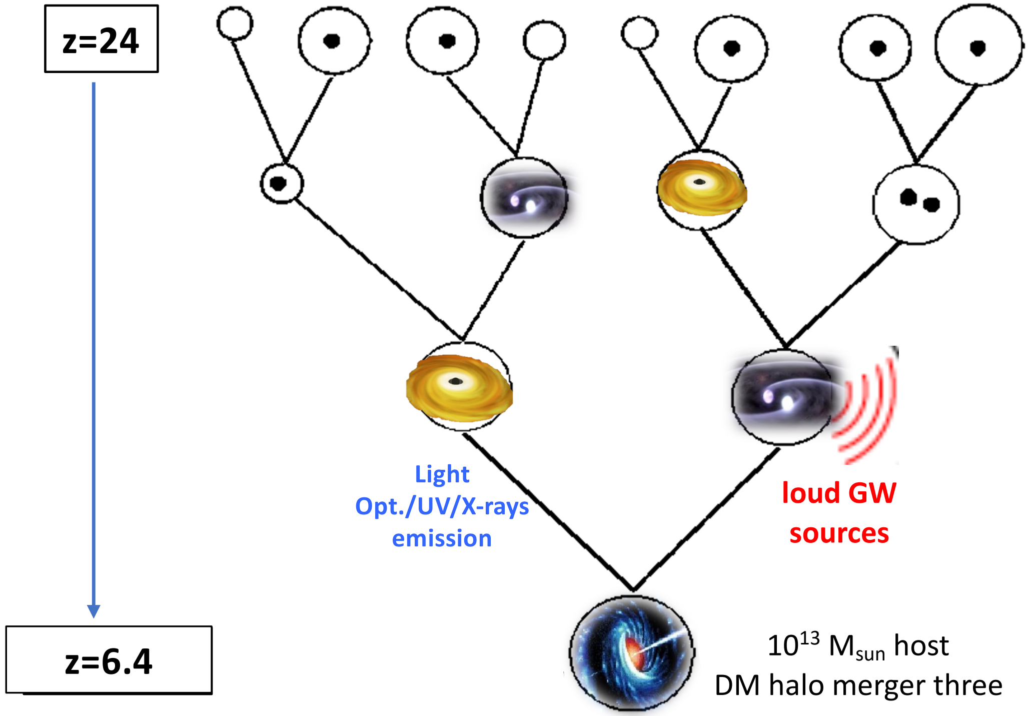
Population III/II stars formation according to gas metallicity (Z_{ISM})
ISM chemical enrichment with metals and dust

BH seeds according to environmental properties (Z_{ISM}, J_{LW})
light+heavy (Valiante et al. 2016,2018)
light+heavy+medium-weight (Sassano+2021)

Eddington-limited (Bondi) accretion
(Valiante et al. 2016,2018,2021, Sassano et el. 2021)

Stellar and AGN feedback (energy-driven winds)
(Valiante et al. 2011, 2012)

BH mergers in major halo-halo mergers (mass ratio >1:4)
(Valiante et al. 2016, 2018a,b; Sassano et al. 2021)



Valiante et al. 2011; 2012; 2014

z>6 SMBH seeds: where and when

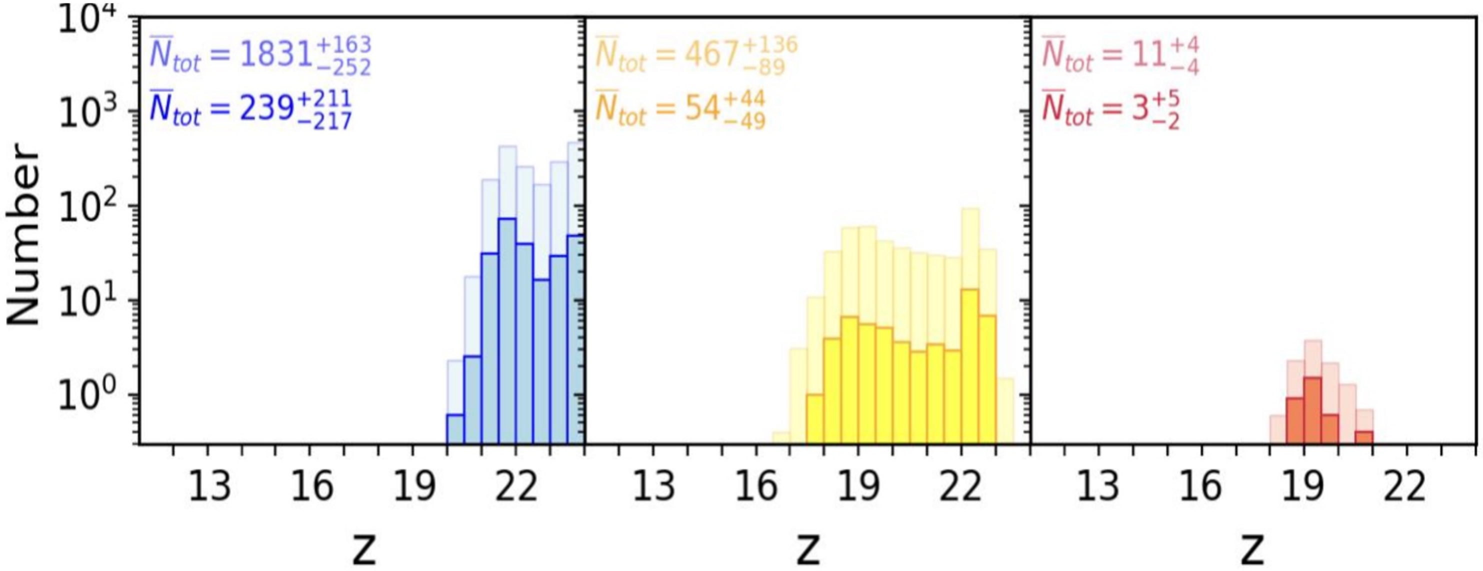
more than one of seed formation processes may be operating ...

light seeds
[40-140] & [260-300] M_{sun}
$Z<10^{-3.8} Z_\odot$ DtG<4.4 × 10^{-9} $J_{LW} < J_{cr}$

medium-weight seeds
10^3 Msun
$Z<10^{-3.8} Z_\odot$ DtG≥4.4 × 10^{-9} $J_{LW} > J_{cr}$

heavy seeds
10^5 M_{sun}
$Z<10^{-3.8} Z_\odot$ DtG<4.4 × 10^{-9} $J_{LW} > J_{cr}$

Lyman-Werner flux density
J_{cr}=300 x 10^{-21} erg/s/Hz/cm^2/sr

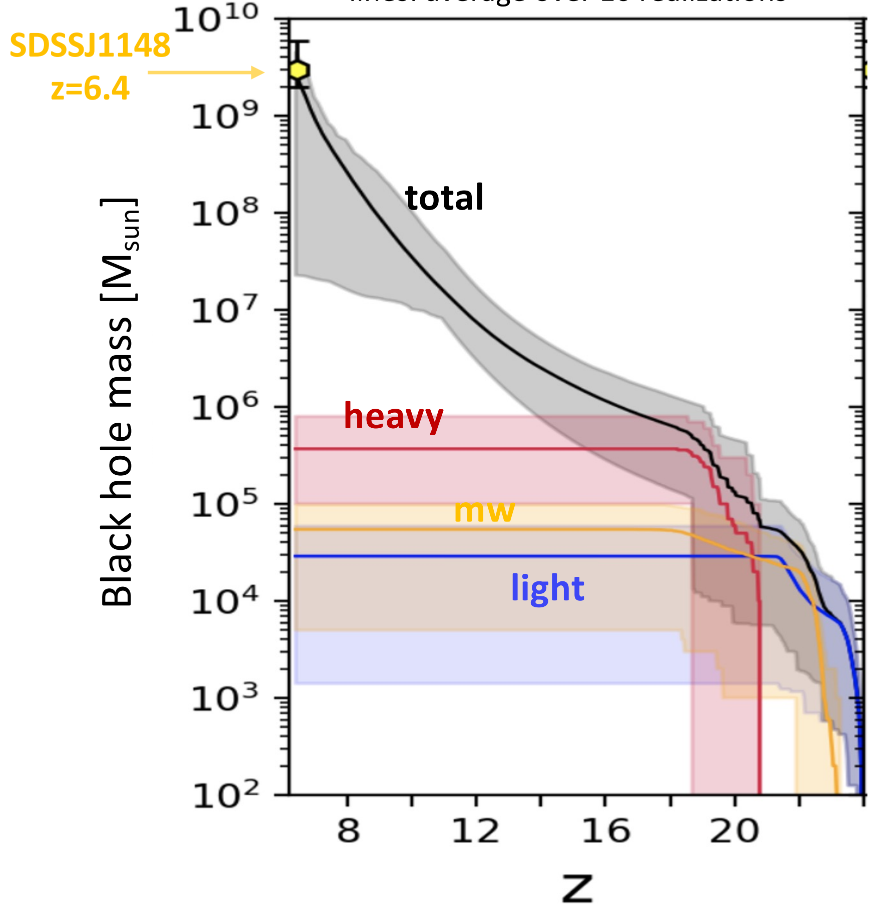


number of seed BHs forming along the formation history of a z>6 quasar

LS form mainly in mini halos (T_{vir} <10^4 K) at z>20 while MWS and HS form only in atomic cooling halos at later epochs
Heavy seeds are less numerous as a consequence of their tight birth environmental conditions

Sassano, Schneider, RV, Inayoshi, Chon, Omukai, Mayer, Capelo, MNRAS 2021

growing a z>6 SMBH: Eddington-limited scenario



$$\dot{M}_{\rm accr} = \min(\dot{M}_{\rm BHL}, \dot{M}_{\rm Edd}),$$

$$\dot{M}_{\rm BHL} = \alpha \frac{4\pi G^2 M_{\rm BH}^2 \rho_{\rm gas}(r_A)}{c_s^3}$$ Bondi-Hoyle-Lyttleton accretion

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\epsilon_{\rm r}\, c^2},$$ Eddington rate

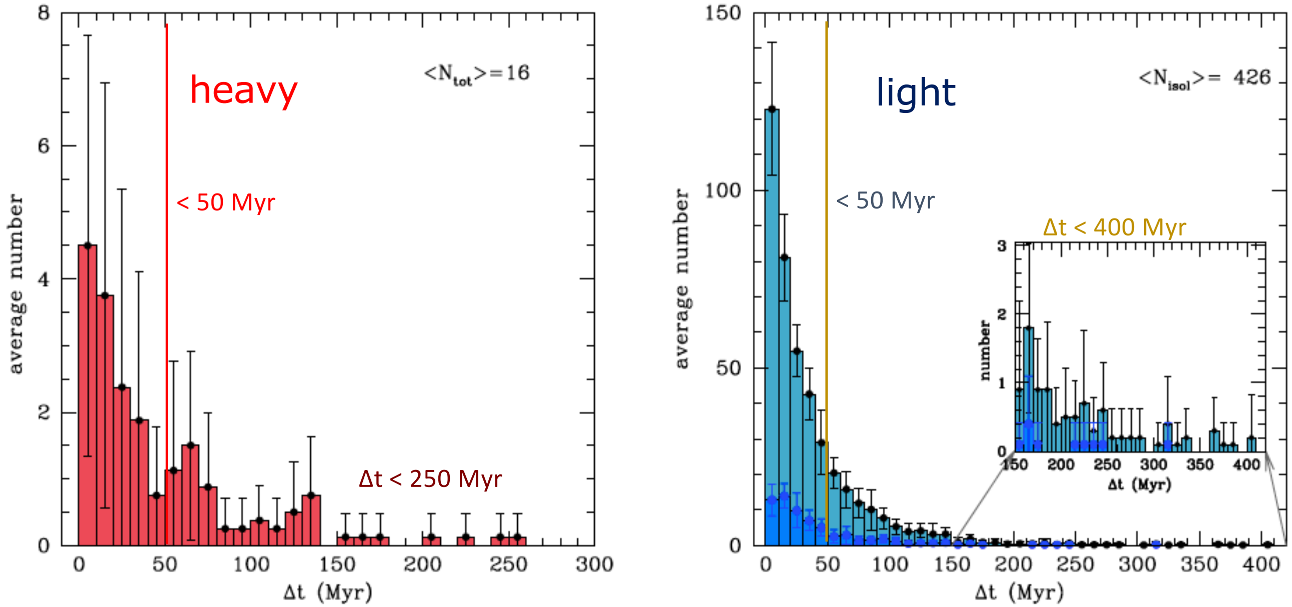
the mass growth of a 10^9 M_{sun} SMBH is driven by efficient accretion (at a sub-Eddington rate) onto its heavy progenitors (10^5 M_{sun})

in good agreement with other models/sims
e.g. Sijaki+2009, DiMatteo2012,2017, Smidth+2018, Lupi+2019, Zhu+2020, Valentini+2021

Sassano, Schneider, RV, Inayoshi, Chon, Omukai, Mayer, Capelo, MNRAS 2021

black hole seeds need to be observed at z > 10

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



Valiante, RS et al. 2018a

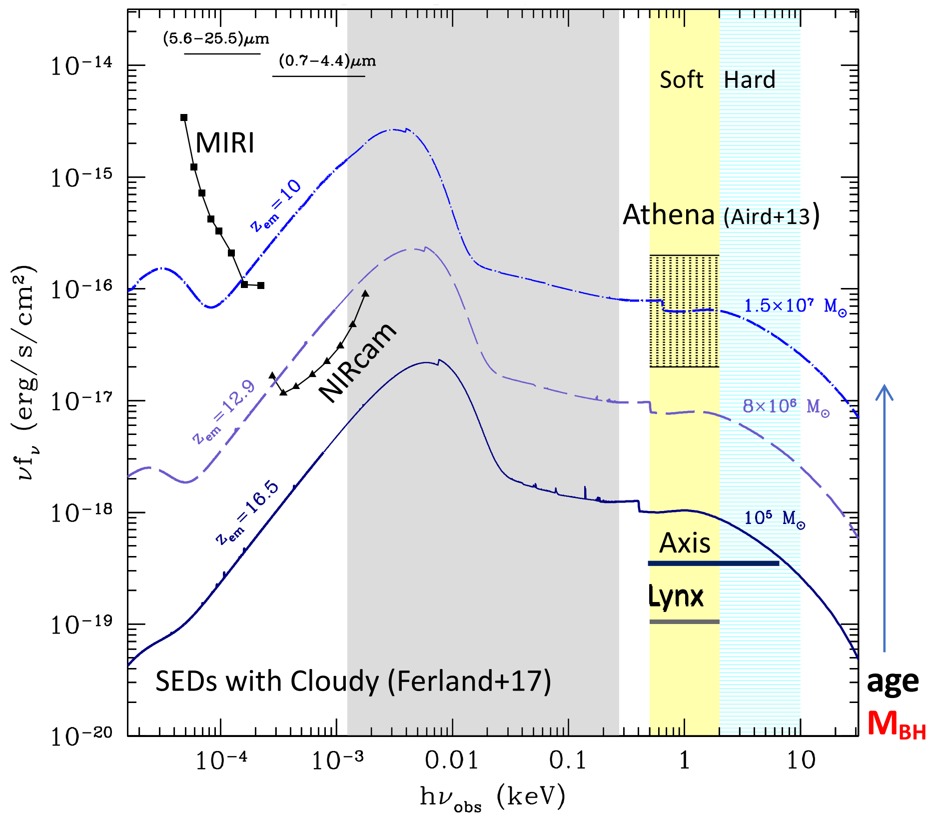
at z > 10, 80% of light seeds and 98% of heavy seeds are isolated (most systems for ~ 50 Myr)

these fractions decrease dramatically at z < 10

”Light” from z>6 SMBH seeds

Can we detect the emission from the first accreting BHs? – Valiante et al. 2018a,b; 2021

growing heavy seed via gas accretion only for t=250 Myr



JWST, Athena(?) and Lynx/Axis (if in operation) will “see” massive seeds out to z>10

RV, Colpi, Schneider, Mangiagli, Bonetti, Cerini, Fairhurst, Haardt, Mills, Sesana, MNRAS 2021

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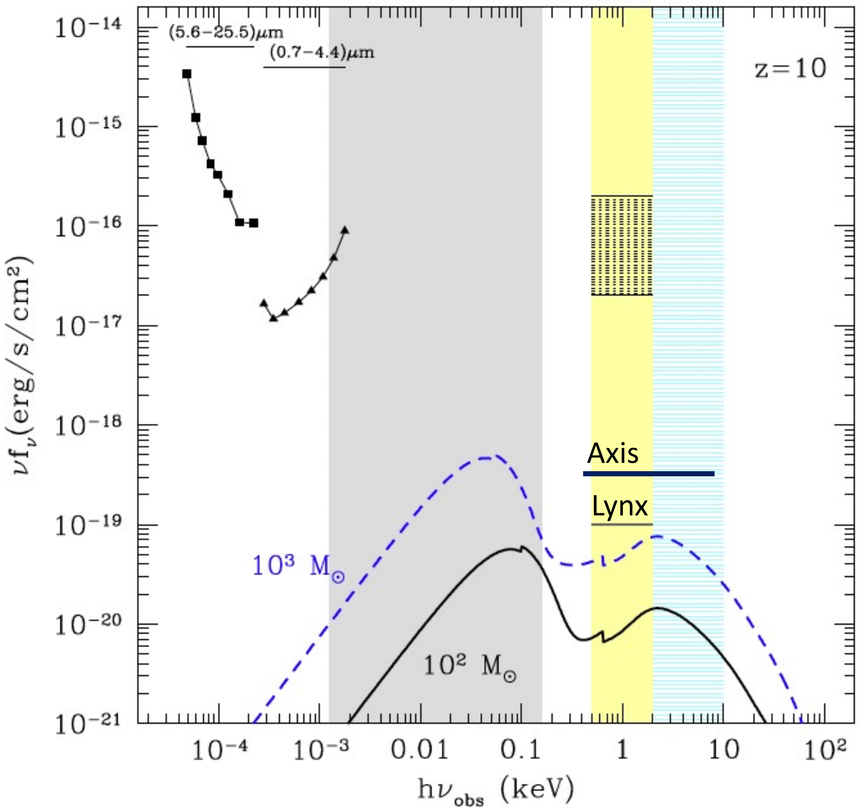
seeds growing @Eddington w/o host galaxy emission



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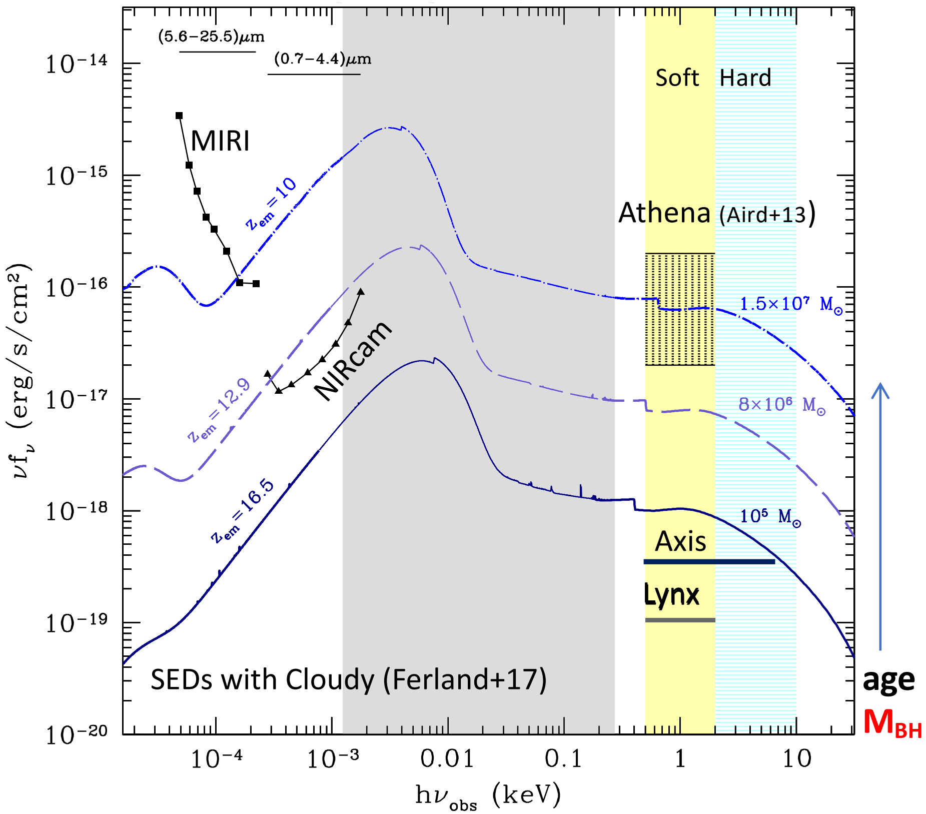

accreting light and mw seeds can not be detected at z>10 by EM facilities

JWST, Athena(?) and Lynx/Axis (if in operation) will "see" massive seeds out to z>10

RV, Colpi, Schneider, Mangiagli, Bonetti, Cerini, Fairhurst, Haardt, Mills, Sesana, MNRAS 2021

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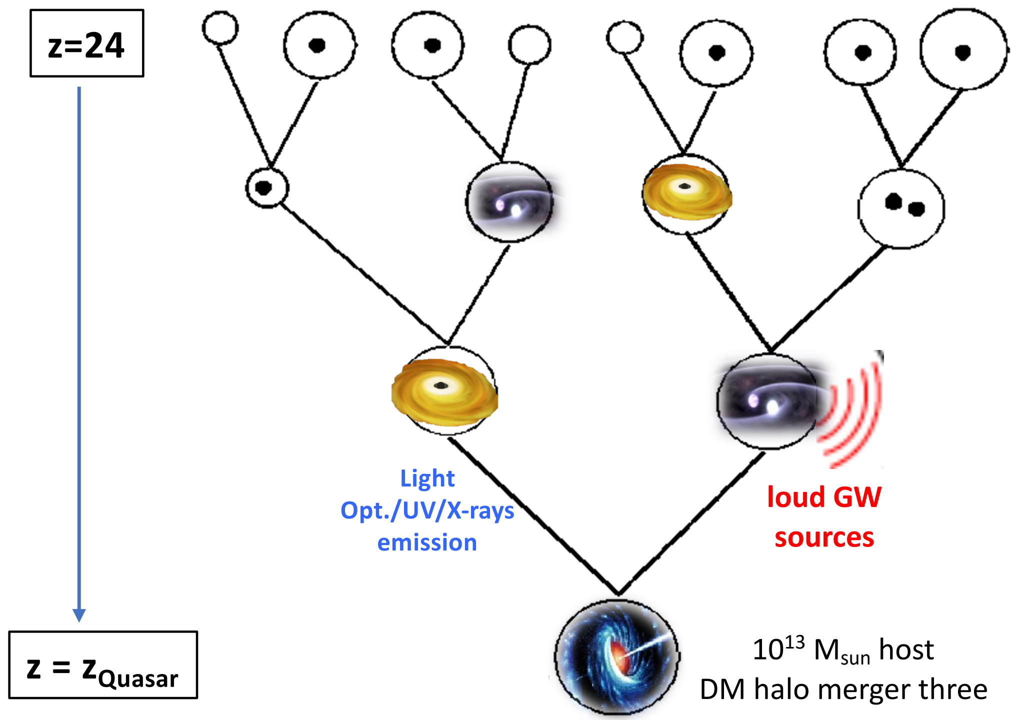
BH binaries form in major halo mergers
(DM halos mass ratio >1:4
BHBs merging via triple BH interactions
(merger probabilities from Bonetti+18)

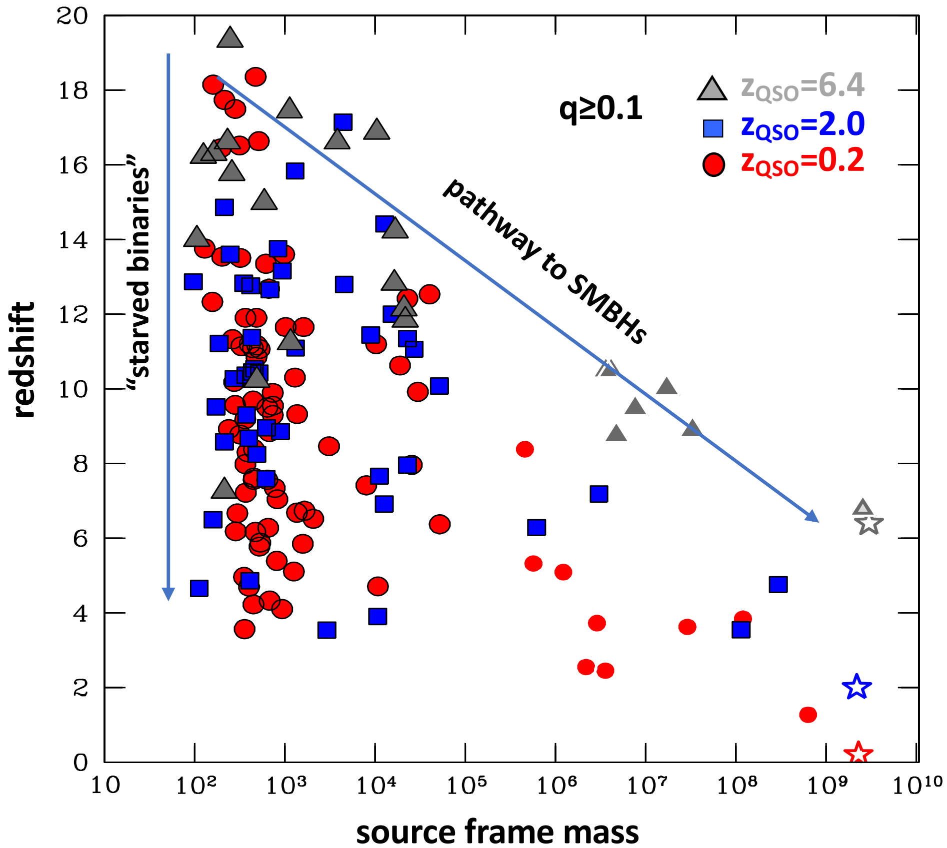


z=6.4	z=2	z=0.2
J1148	J2345	PDS456
Fan et al. 2001	*Shen et al. 2011*	*Nardini et al. 2011*

RV, Colpi, Schneider, Mangiagli, Bonetti, Cerini, Fairhurst, Haardt, Mills, Sesana, MNRAS 2021

cosmologically driven BH binaries

GQd MODEL on 3 target QSOs of >10^9 M_{sun} BH @ z=0.2, 2 and 6.4 in 10^{13} M_{sun} DM halos



mergers among the progenitors of 3 quasars

light and heavy seeds form in pristine/metal poor haloes

pair during galaxy major mergers (DM halo mass ratio μ> 1:4)

coalesce after triple BH interactions following later galaxy mergers

single simulation				
z_{QSO}	$n_{0.1}$	f_{L-L}	f_{L-H}	f_{H-H}
6.4	24	71%	17%	13%
2.0	45	91%	7%	2%
0.2	84	89%	11%	0

~70-90% merger of light seed pairs

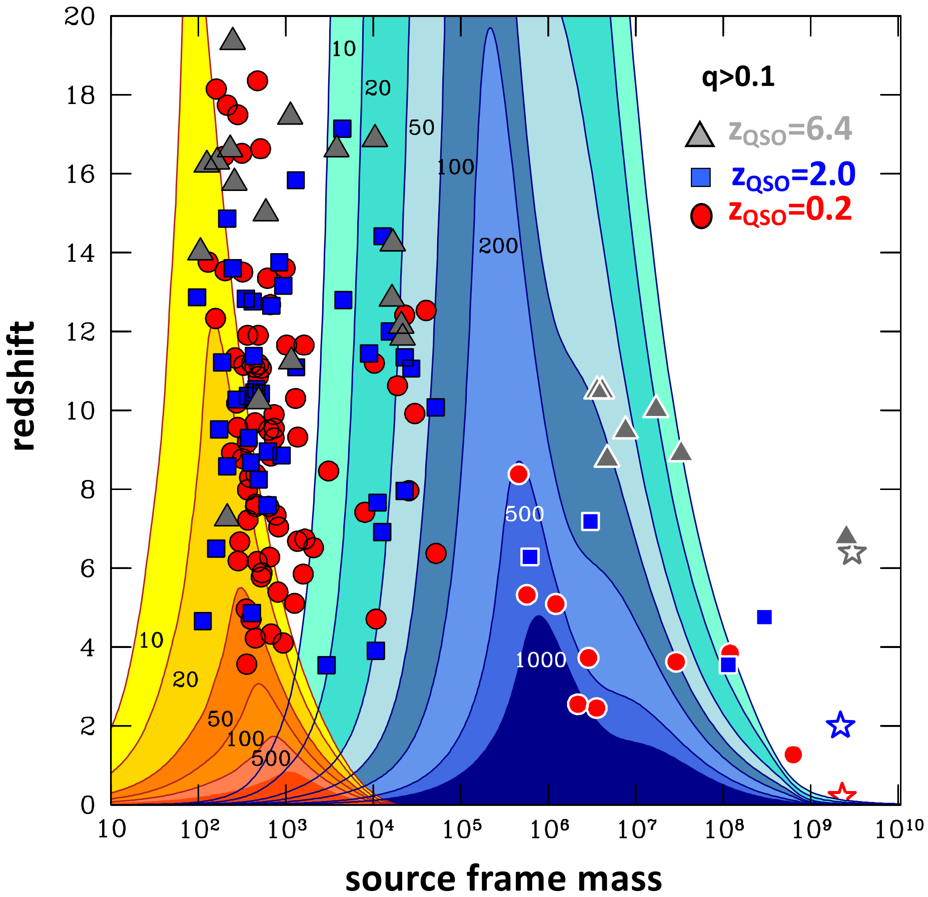
Ungrown light seeds forming at z>10 merge through cosmic epochs down to z~3

RV, Colpi, Schneider, Mangiagli, Bonetti, Cerini, Fairhurst, Haardt, Mills, Sesana, MNRAS 2021

“Sound” from early BHs in the ET and LISA domain

GQd MODELS → <u>triple interaction-driven BHB mergers</u> along the cosmic evolution history of >10^9 M_{sun} SMBHs @ z=0.2, 2 and 6.4

Einstein Telescope
ET_D sensitivity
PhenomC waveform
(spin=0, q=0.5)



LISA
sensitivity curve (q=0.5)
Santamaria et al (2010)

RV, Colpi, Schneider, Mangiagli, Bonetti, Cerini, Fairhurst, Haardt, Mills, Sesana, MNRAS 2021

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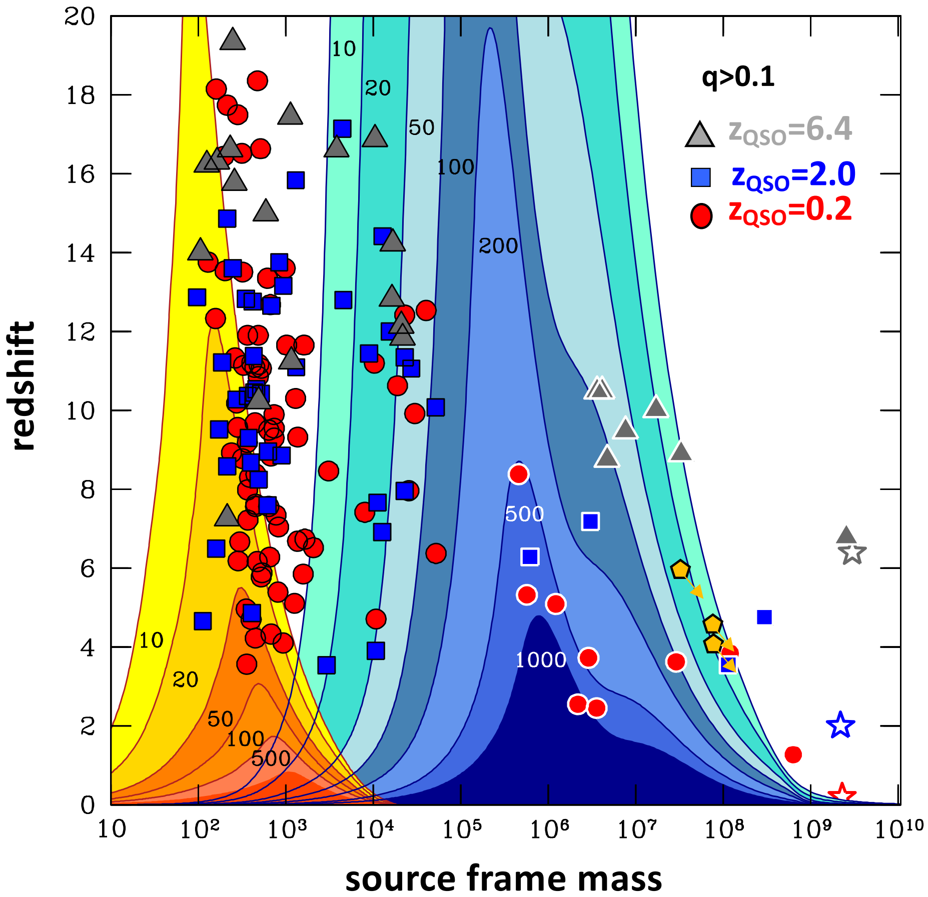

LISA
sensitivity curve (q=0.5)
Santamaria et al (2010)

candidate dual/merging BHs
0.01<q<0.04
(Maiolino et al. 2023)

RV, Colpi, Schneider, Mangiagli, Bonetti, Cerini, Fairhurst, Haardt, Mills, Sesana, MNRAS 2021

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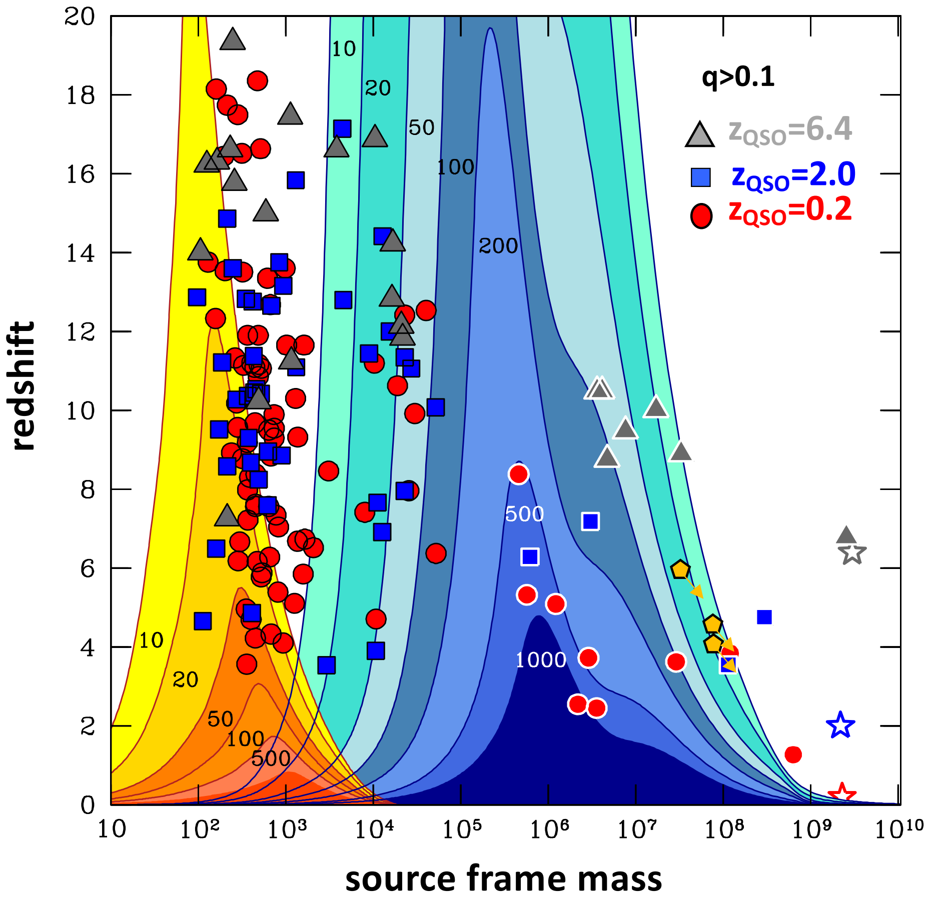
Einstein Telescope
ET_D sensitivity
PhenomC waveform
(spin=0, q=0.5)

earliest merging light seeds ($\approx 100 M_{sun}$) accessible to ET with S/N=10-20 at z>10

our only chance to discover light seeds!

merging “starved binaries” (10^2-10^3 Msun) could be detected at 2<z<8 with S/N>20



LISA
sensitivity curve (q=0.5)
Santamaria et al (2010)

growing light seeds enter the LISA domain with S/N>20 as the grow to $10^4 M_{sun}$

merging heavy seeds could be detected up to z≈15-20

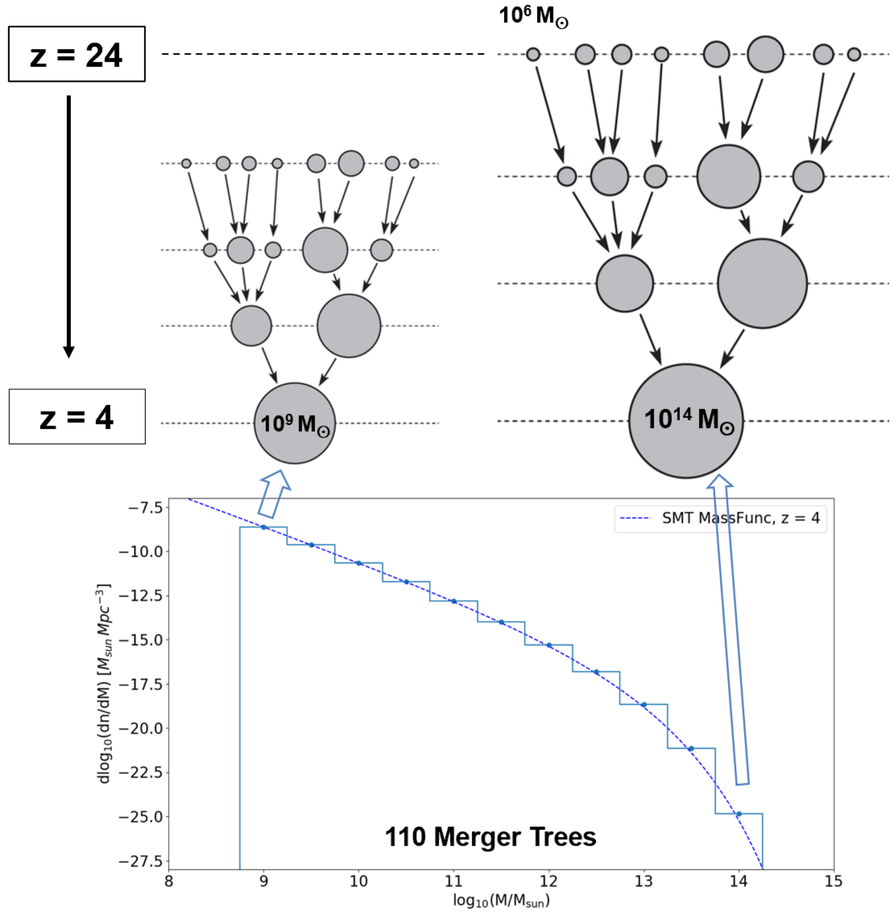
RV, Colpi, Schneider, Mangiagli, Bonetti, Cerini, Fairhurst, Haardt, Mills, Sesana, MNRAS 2021

Populations studies
The Cosmic Archaeology Tool - **CAT**

statistical sample of halos in a wide mass range $[10^6\text{-}10^{14}]M_{sun}$

light (40-140 M_{sun} >260M_{sun}) and heavy (10^5 M_{sun}) seed formation channels

Different accretion paradigms:
- Eddington-limited Bondi accretion (ref. model)
- merger-driven super-Edd. via slim disc accretion



Model calibration

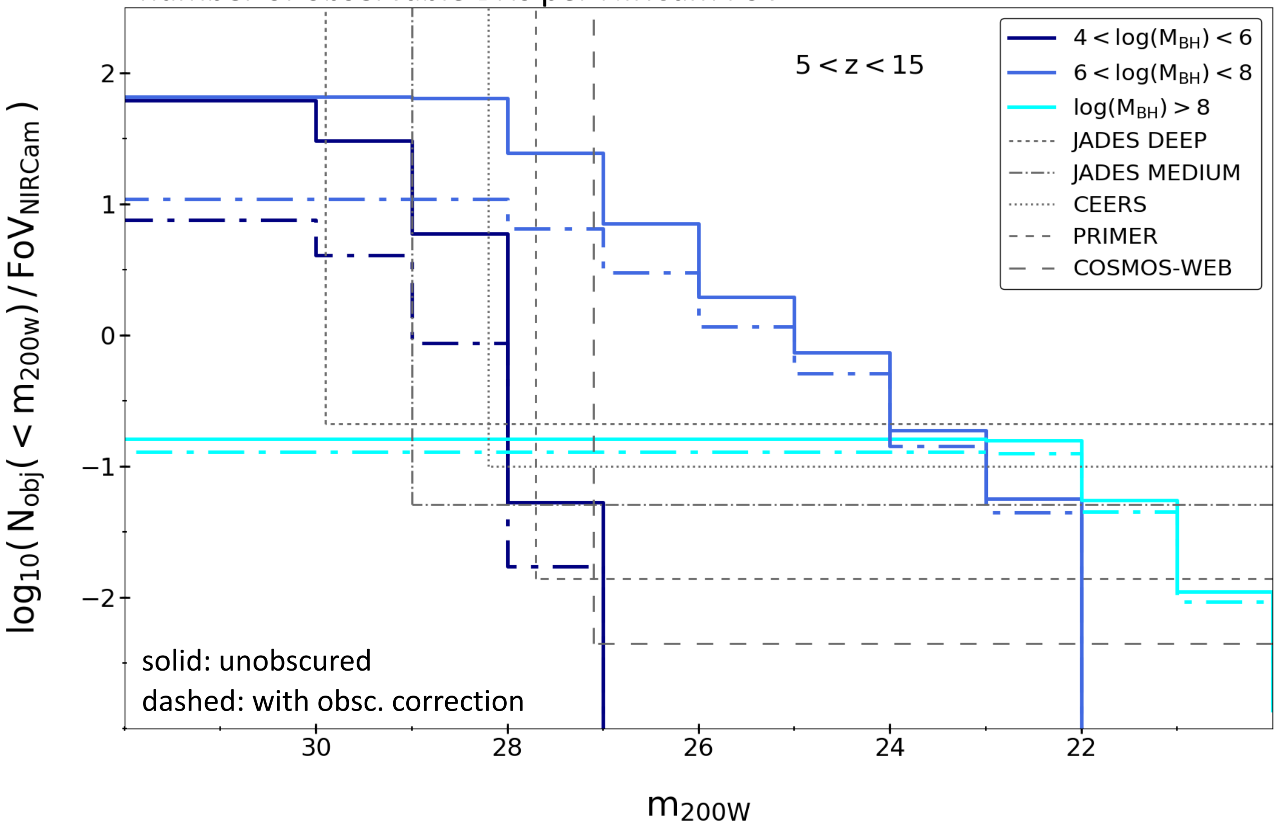
reproduce the cosmic star formation history (SFRD)

reproduce obs. properties of high-z QSOs (L_{bol}, M_{BH})

Trinca, Schneider, RV, Graziani, Zappacosta, Shankar, MNRAS 2022

the observability of high-z AGN with JWST

AGN/galaxies properties predicted with CAT
number of observable BHs per NIRCam FoV



Survey	Area [arcmin^2]	limiting mag
JADES-Deep	46	29.9
JADES-Medium	190	29.0
CEERS	97	28.2
PRIMER	695	27.7
COSMOS-WEB	2180	27.1*

Trinca, Schneider, Maiolino, RV, Graziani, Volonteri MNRAS 2023

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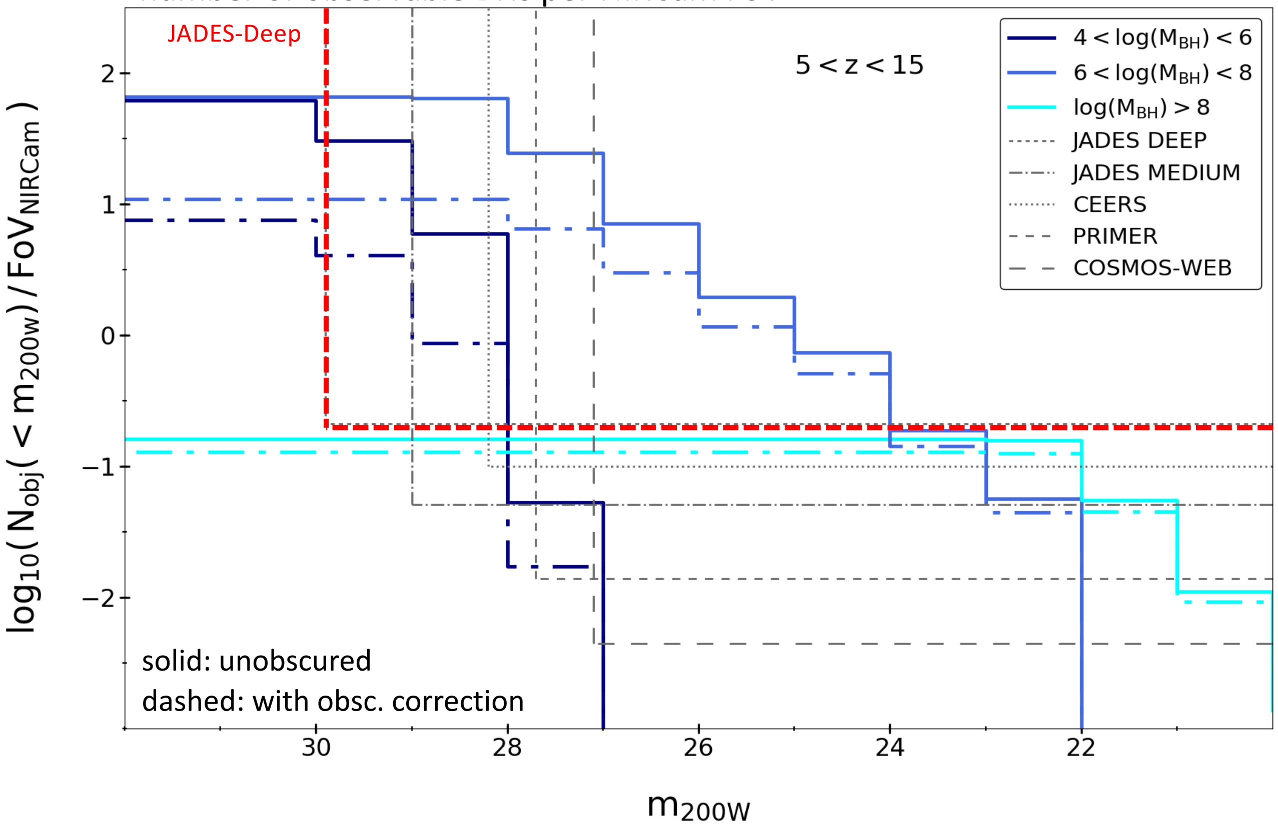

Trinca, Schneider, Maiolino, RV, Graziani, Volonteri MNRAS 2023

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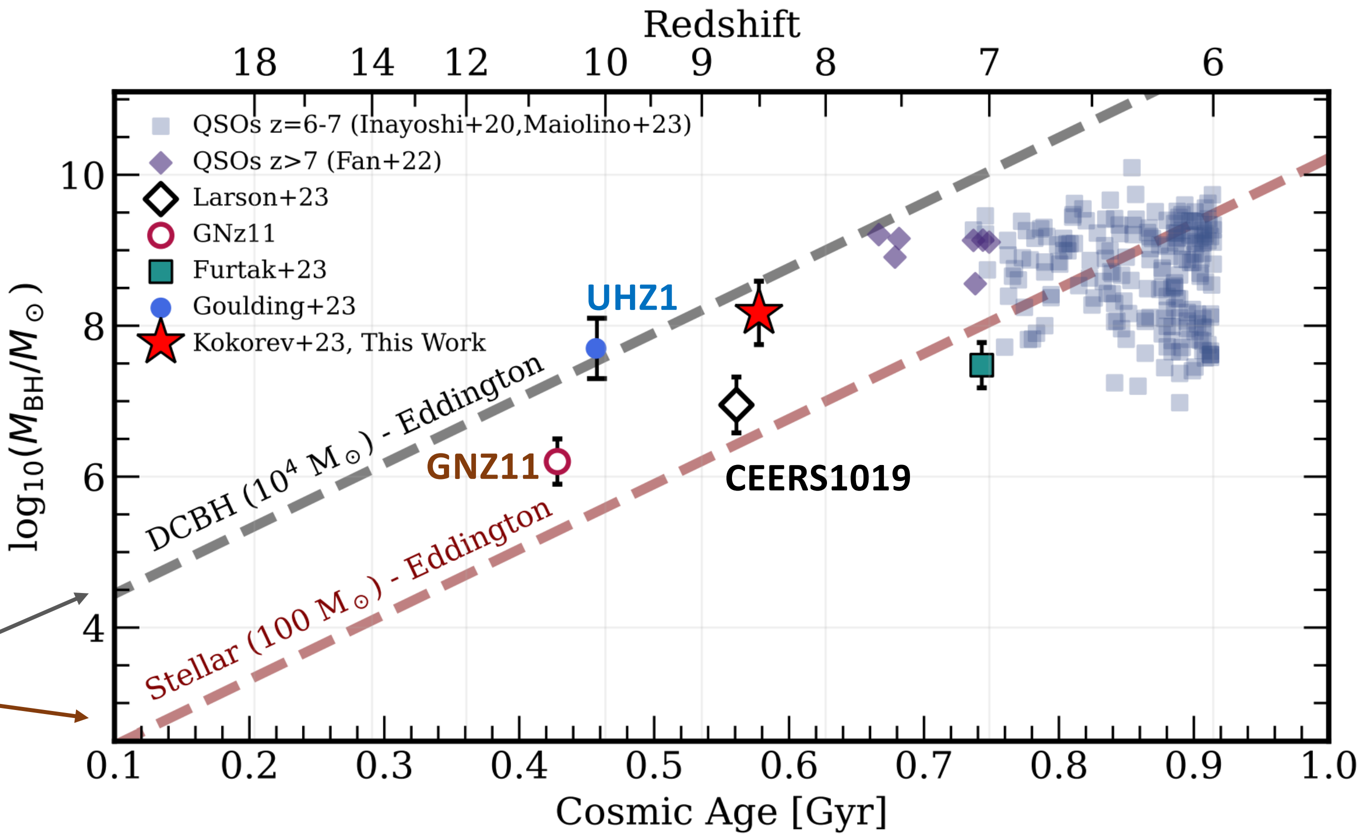
JADES-Deep has the sensitivity to detect $4 \leq \mathrm{Log}(M_{BH}/M_\odot) < 6$ BHs at z>10

into a regime where BHs are expected to keep memory of their initial seed mass
(Valiante et al. 2018a)

JWST-detected BHs at z ≈ 9 - 11

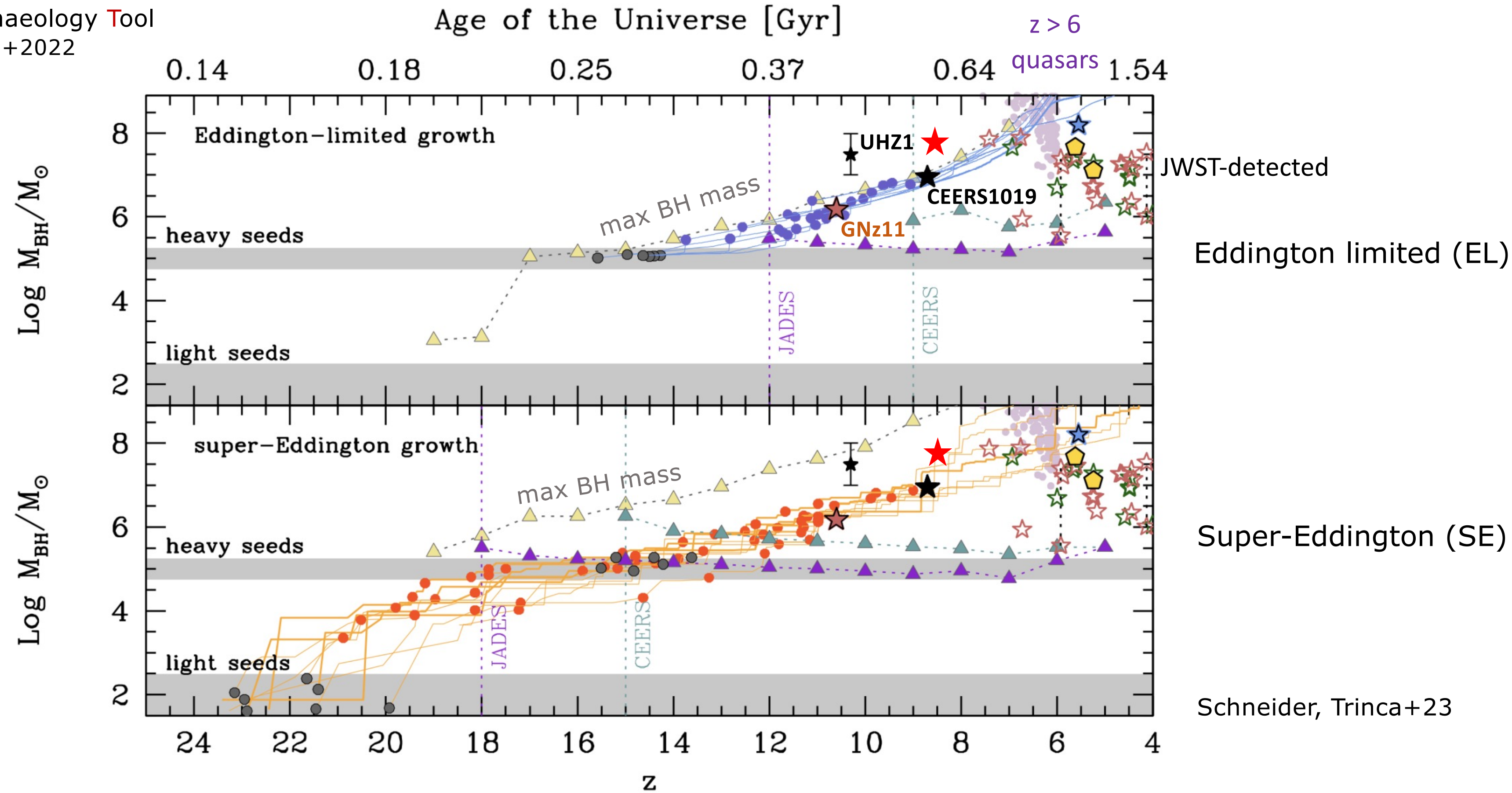


seeds forming
at z ≈ 50 and
continuosly
growing
at Eddington

Kokorev+24

JWST-detected BHs at z ≈ 9 – 11: implications for BH seeding and growth

Cosmic Archaeology Tool
Trinca+2022

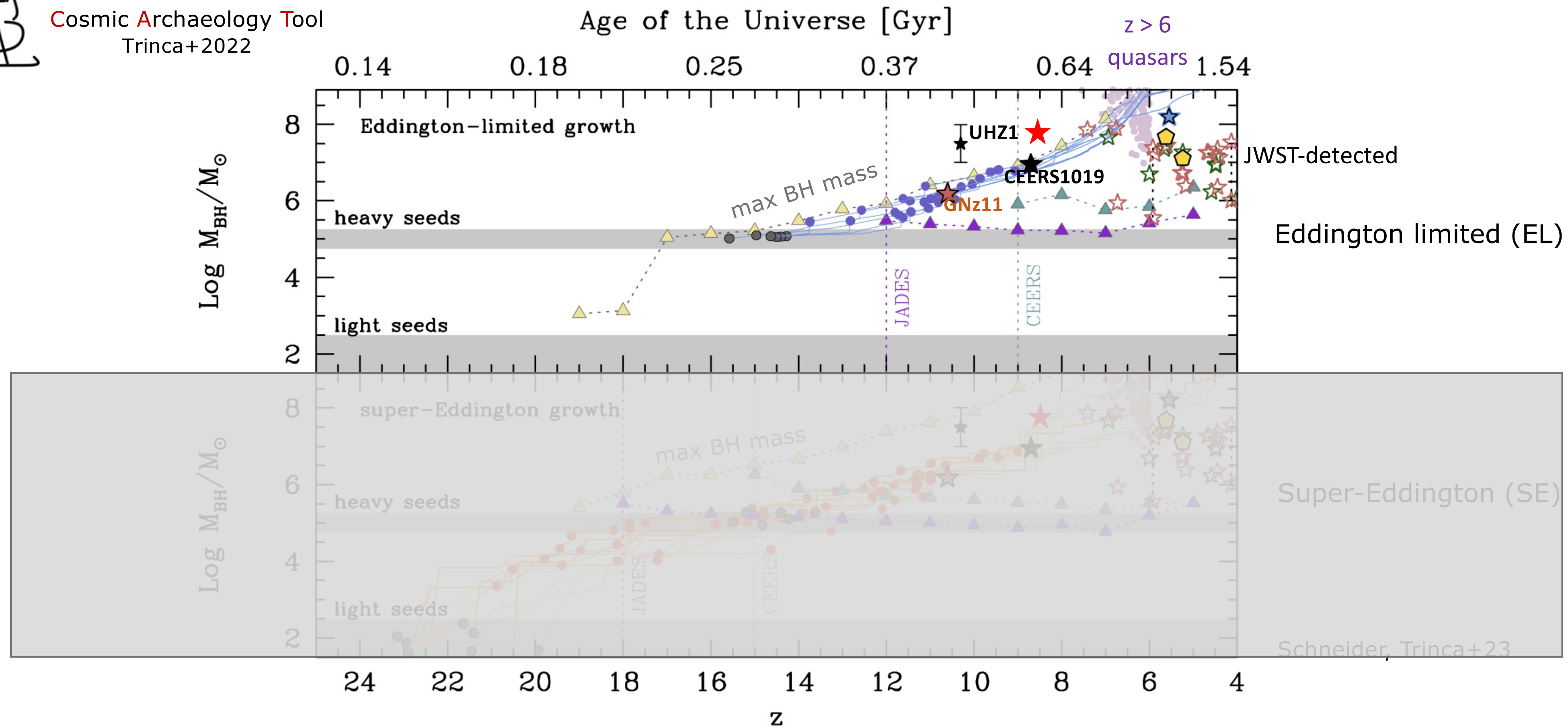


Schneider, Trinca+23

data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+23, Bogdan+23, Kokorev+24

JWST-detected BHs at z ≈ 9 – 11: implications for BH seeding and growth

Cosmic Archaeology Tool
Trinca+2022



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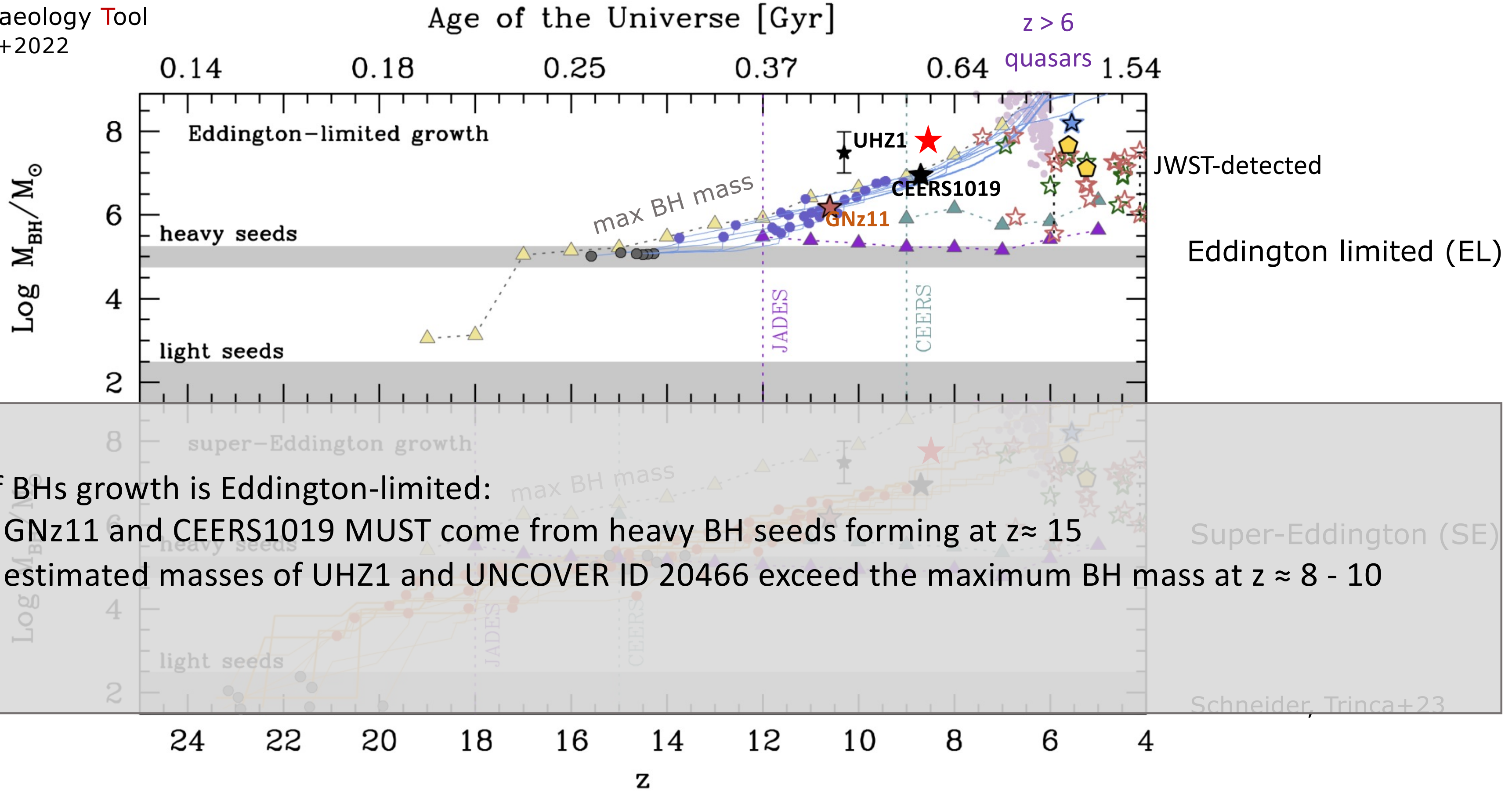
JWST-detected BHs at z ≈ 9 – 11: implications for BH seeding and growth

Cosmic Archaeology Tool
Trinca+2022

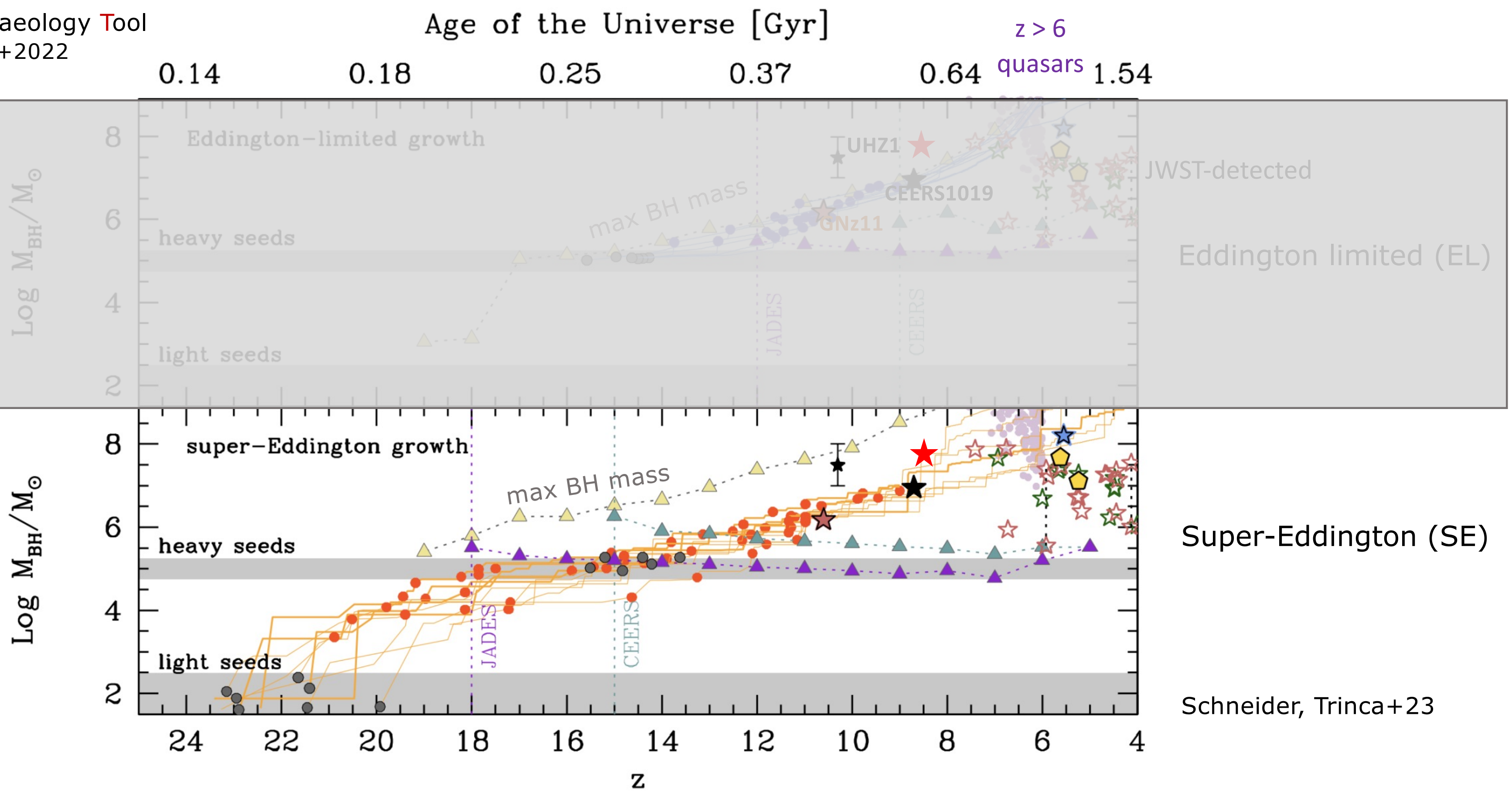


if BHs growth is Eddington-limited:
- GNz11 and CEERS1019 MUST come from heavy BH seeds forming at z≈ 15
- estimated masses of UHZ1 and UNCOVER ID 20466 exceed the maximum BH mass at z ≈ 8 - 10

data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+23, Bogdan+23, Kokorev+24

JWST-detected BHs at z ≈ 9 – 11: implications for BH seeding and growth

Cosmic Archaeology Tool
Trinca+2022



Schneider, Trinca+23

data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+23, Bogdan+23, Kokorev+24

JWST-detected BHs at z ≈ 9 – 11: implications for BH seeding and growth

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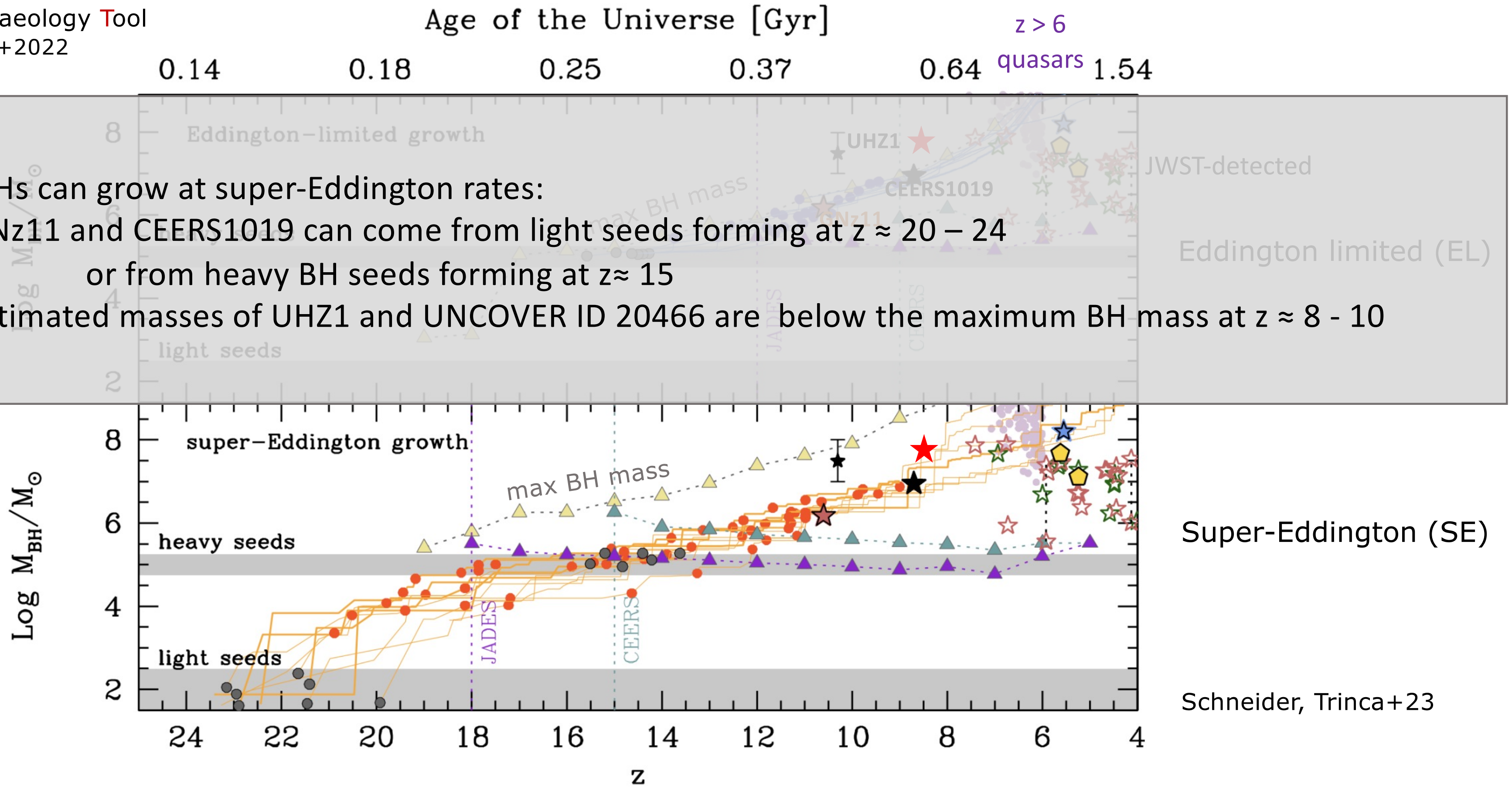
Trinca+2022



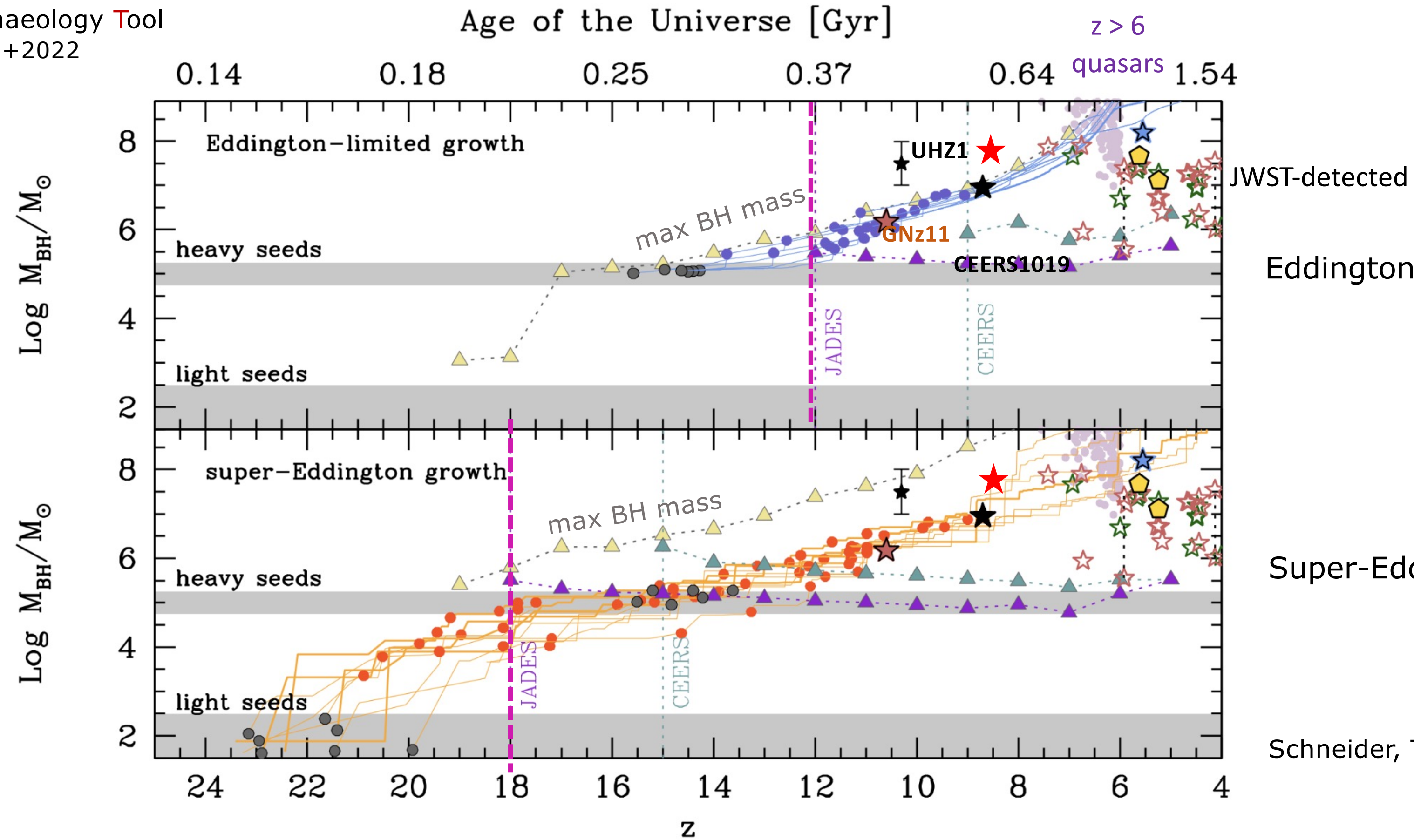
if BHs can grow at super-Eddington rates:

- GNz11 and CEERS1019 can come from light seeds forming at z ≈ 20 – 24
  or from heavy BH seeds forming at z≈ 15
- estimated masses of UHZ1 and UNCOVER ID 20466 are below the maximum BH mass at z ≈ 8 - 10

data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+23, Bogdan+23, Kokorev+24

JWST-detected BHs at z ≈ 9 – 11: implications for BH seeding and growth

Cosmic Archaeology Tool
Trinca+2022



Eddington limited (EL)

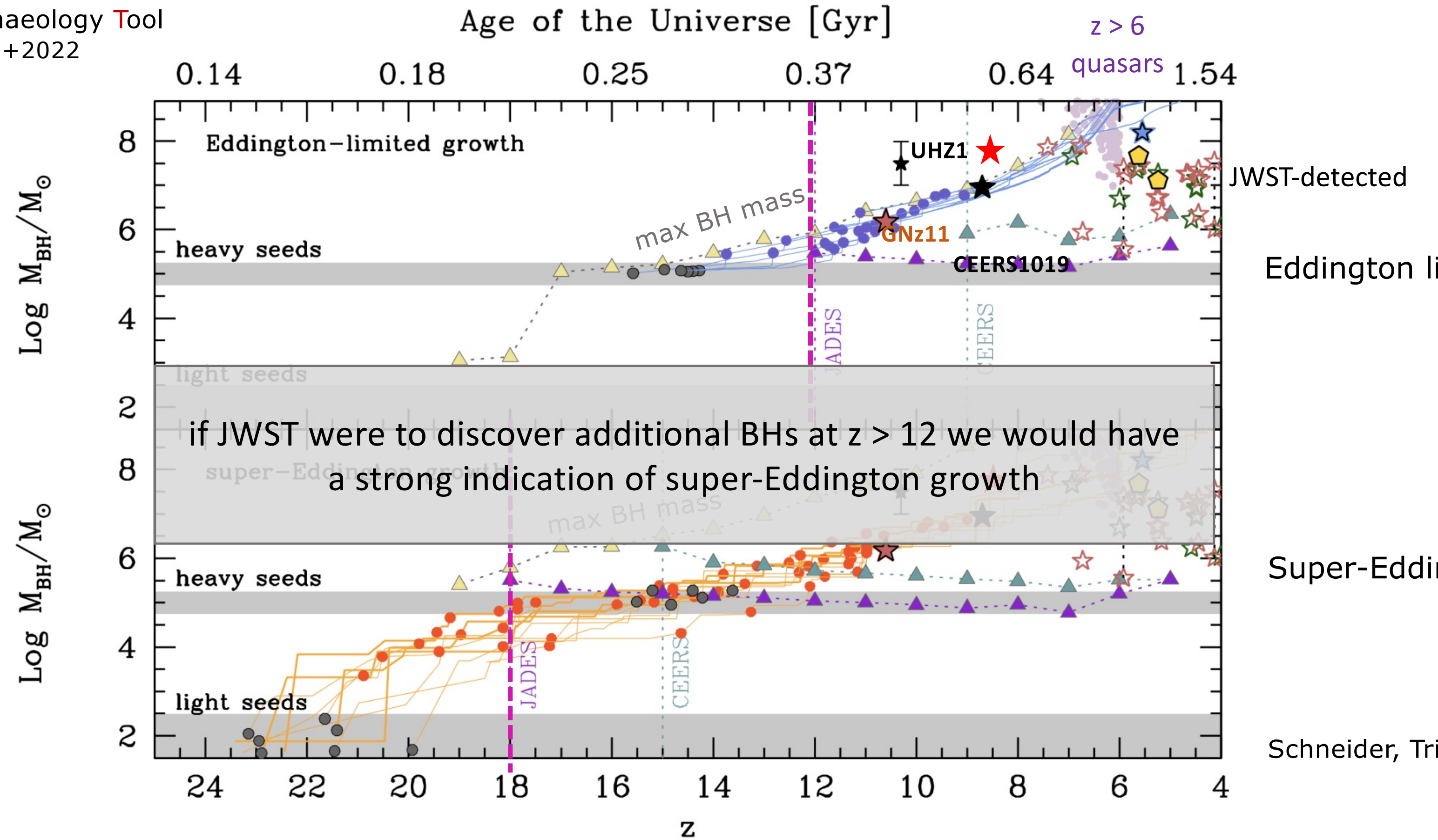
Super-Eddington (SE)

Schneider, Trinca+23

data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+23, Bogdan+23, Kokorev+24

JWST-detected BHs at z ≈ 9 – 11: implications for BH seeding and growth

Cosmic Archaeology Tool
Trinca+2022



Eddington limited (EL)

Super-Eddington (SE)

if JWST were to discover additional BHs at z > 12 we would have a strong indication of super-Eddington growth

Schneider, Trinca+23

data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+23, Bogdan+23, Kokorev+24

BH dynamics: timescale matters

especially at high redshift

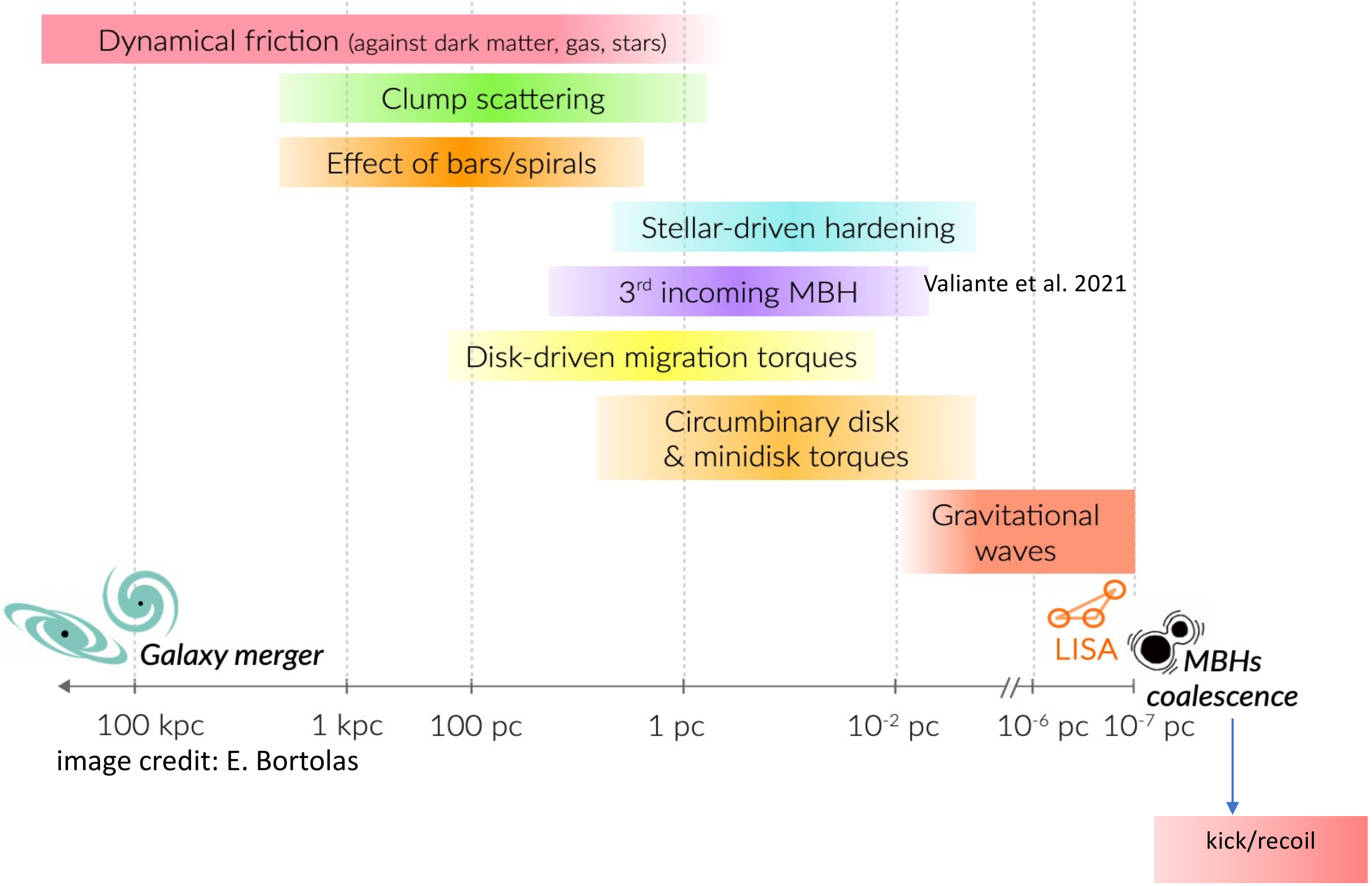
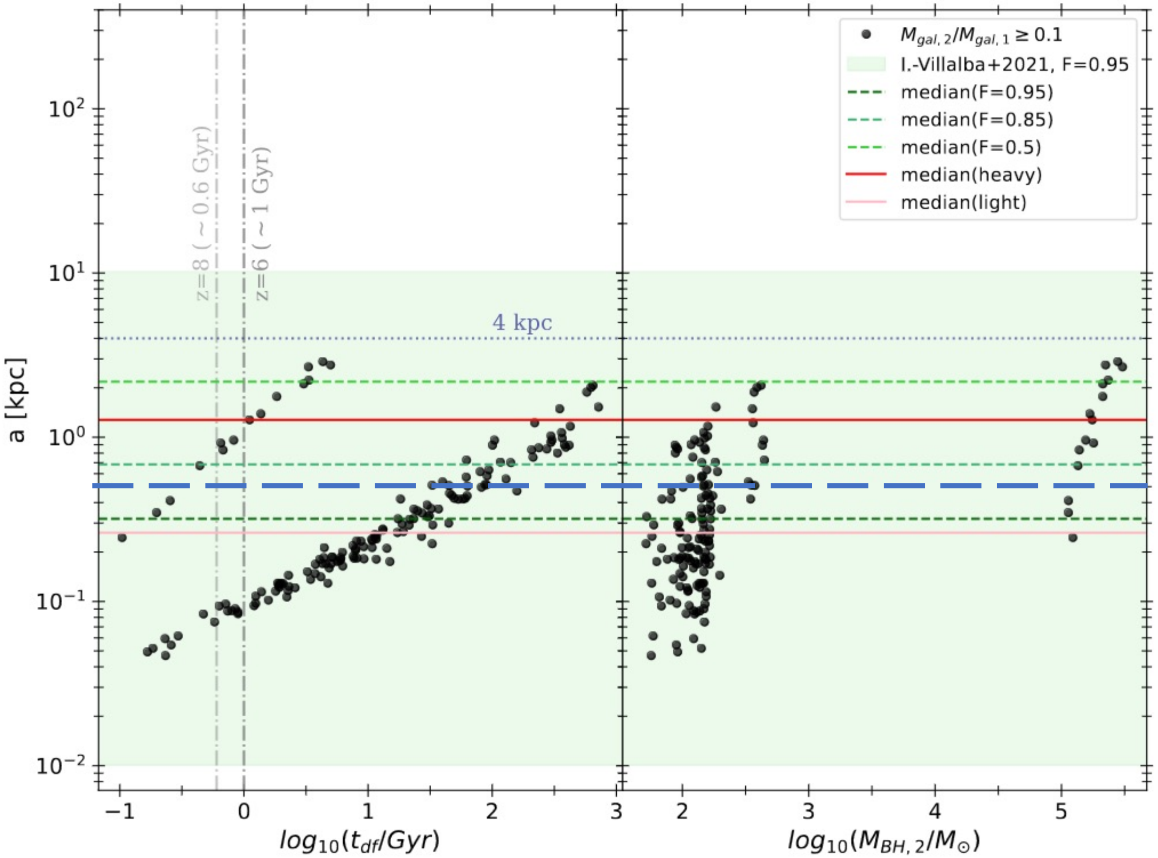


image credit: E. Bortolas

Pezzulli et al. 2016; 2017

the earliest BH binaries: population studies

new features for BH dynamics: pairing+hardening phase



candidates
z>4 dual AGN
separation
Maiolino et al. 2023

Trinca et al. in prep.

initial distance of "dual" BHs

$a = f \cdot R_{\rm vir}$ f = 0.1

calibrated against hydro simulations
(Volonteri et al. 2020)

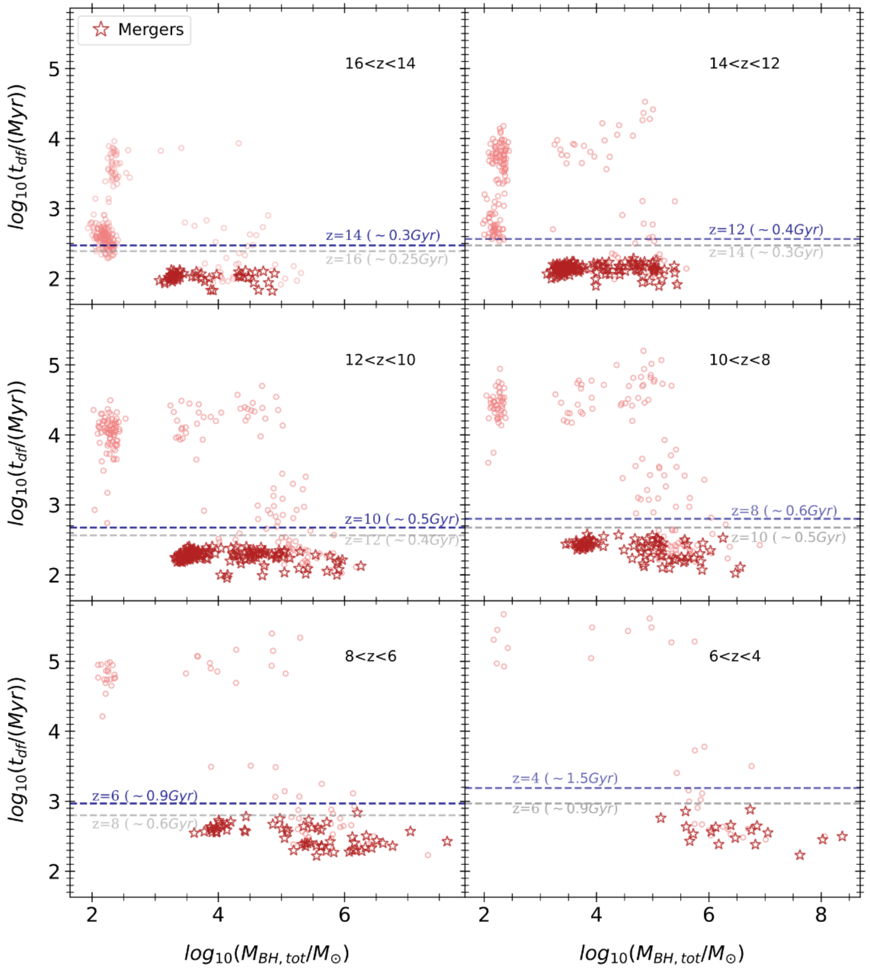
BH binary formation timescale

$$t_{\rm df} = 0.67\,{\rm Gyr}\left(\frac{a}{4{\rm kpc}}\right)^2\left(\frac{\sigma}{100{\rm kms}^{-1}}\right)\left(\frac{M_{\rm BH,2}}{10^8 M_\odot}\right)^{-1}\frac{1}{\Lambda}$$

In most cases BHB shrinking timescale
(<pc scales; stellar/gas hardening)
is fast: $t_{hardening} << t_{df}$

lower-mass secondary BHs are
closer (0.25-3 kpc) to the primary BH
wrt those with $>10^5$ M_{sun}

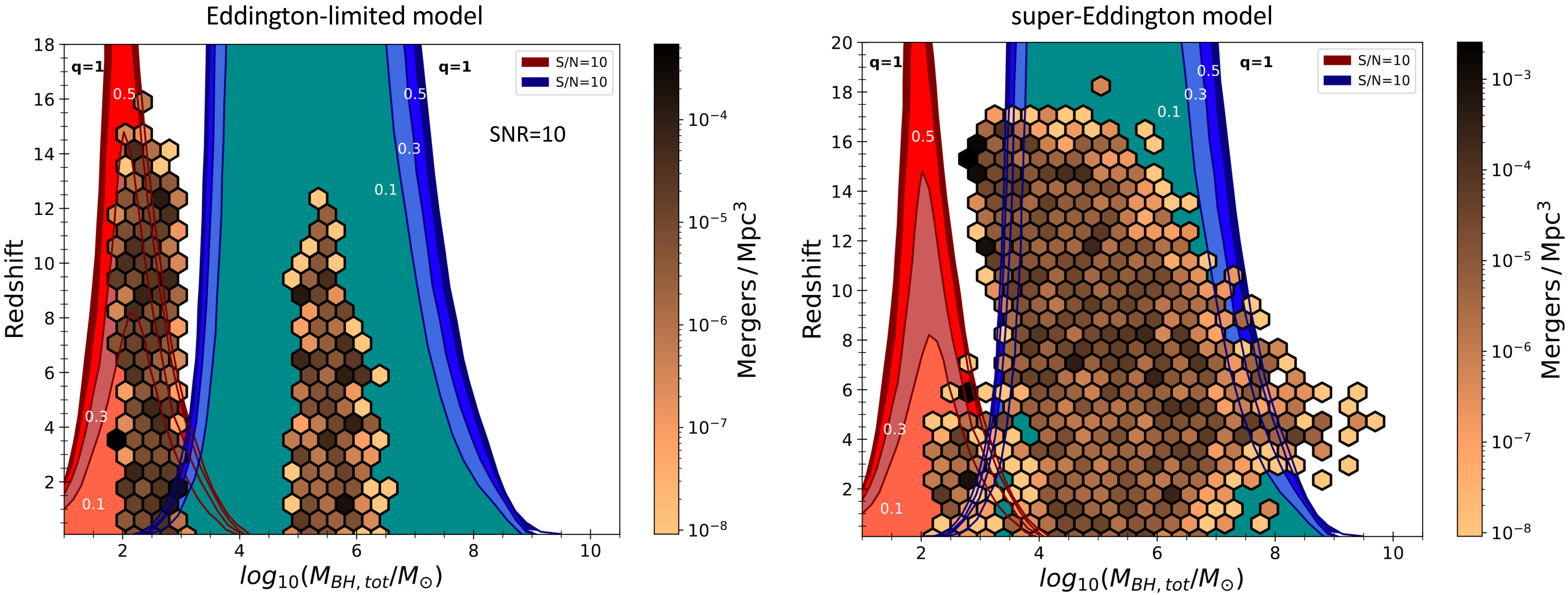
merging BHs across cosmic epochs



Trinca et al. in prep.

a population of GW sources

Testing prescriptions for BH dynamics: pairing+hardening phase



the two BH accretion regimes are expected to leave specific imprints in the properties of GW sources that would be detectable with ET and LISA

Trinca et al. in prep.; Davari et al. in prep.

Summary

- Origin and growth of SMBHs at $z > 6$ is a major theoretical challenge!
- JWST is revolutionising the field with detections and fainter and more distant AGNs
- Current observations/models point to a mix of BH seed populations, whose growth can be super-Eddington
- Incredible synergy with future GW telescopes!