Lunar Gravitational-wave Antenna workshop
LGWA
07–11 ott 2024
Centro Internazionale Mariapoli

chasing the first BHs with multiband observations

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MUR
Ministero dell'Università e della Ricerca

the earliest supermassive black holes

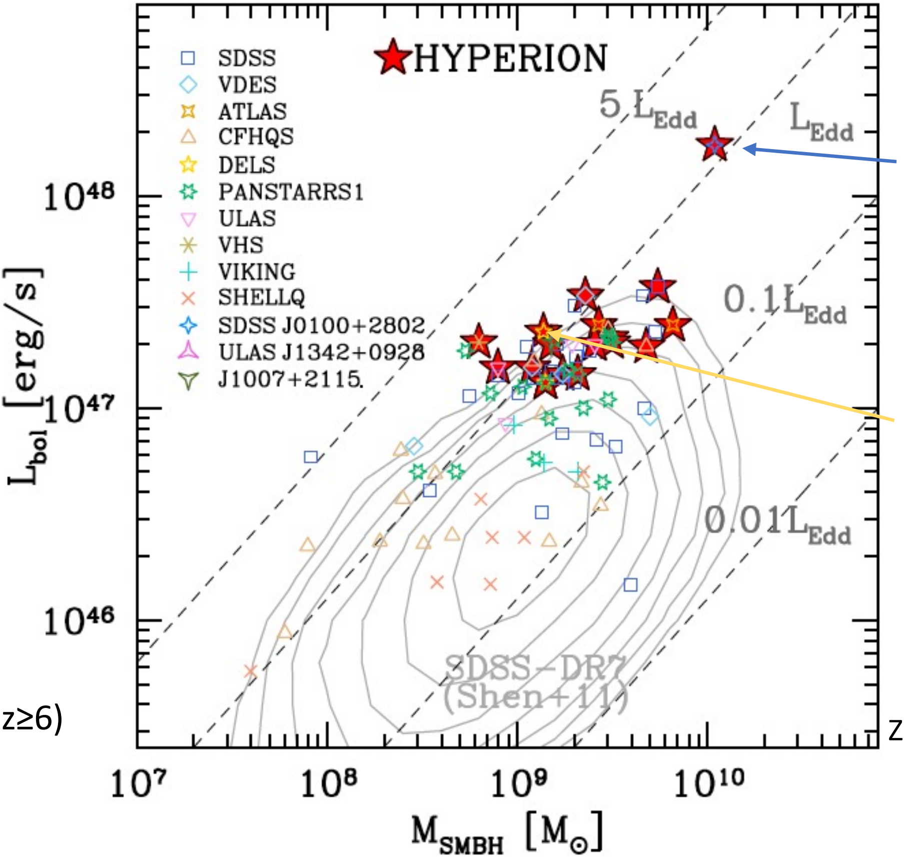
the emission from Quasars (AGN in general)
is powerd by accretion onto
Supermassive Black Holes (SMBHs)
up to 10^9 - 10^{10} M_{sun}

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

> 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)…

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



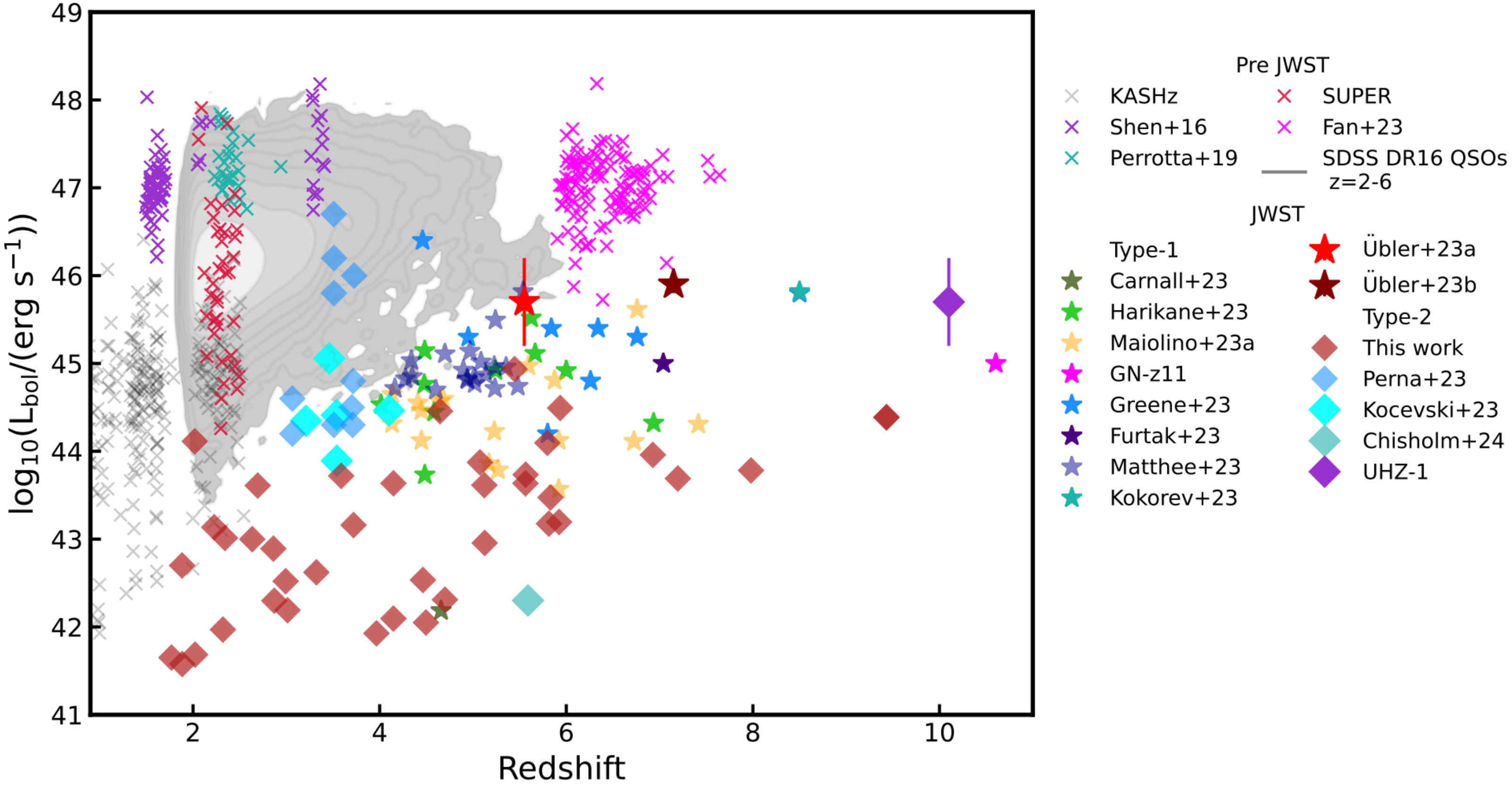
record holders

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

the new SMBH discovery space opened by JWST



Scholtz+23

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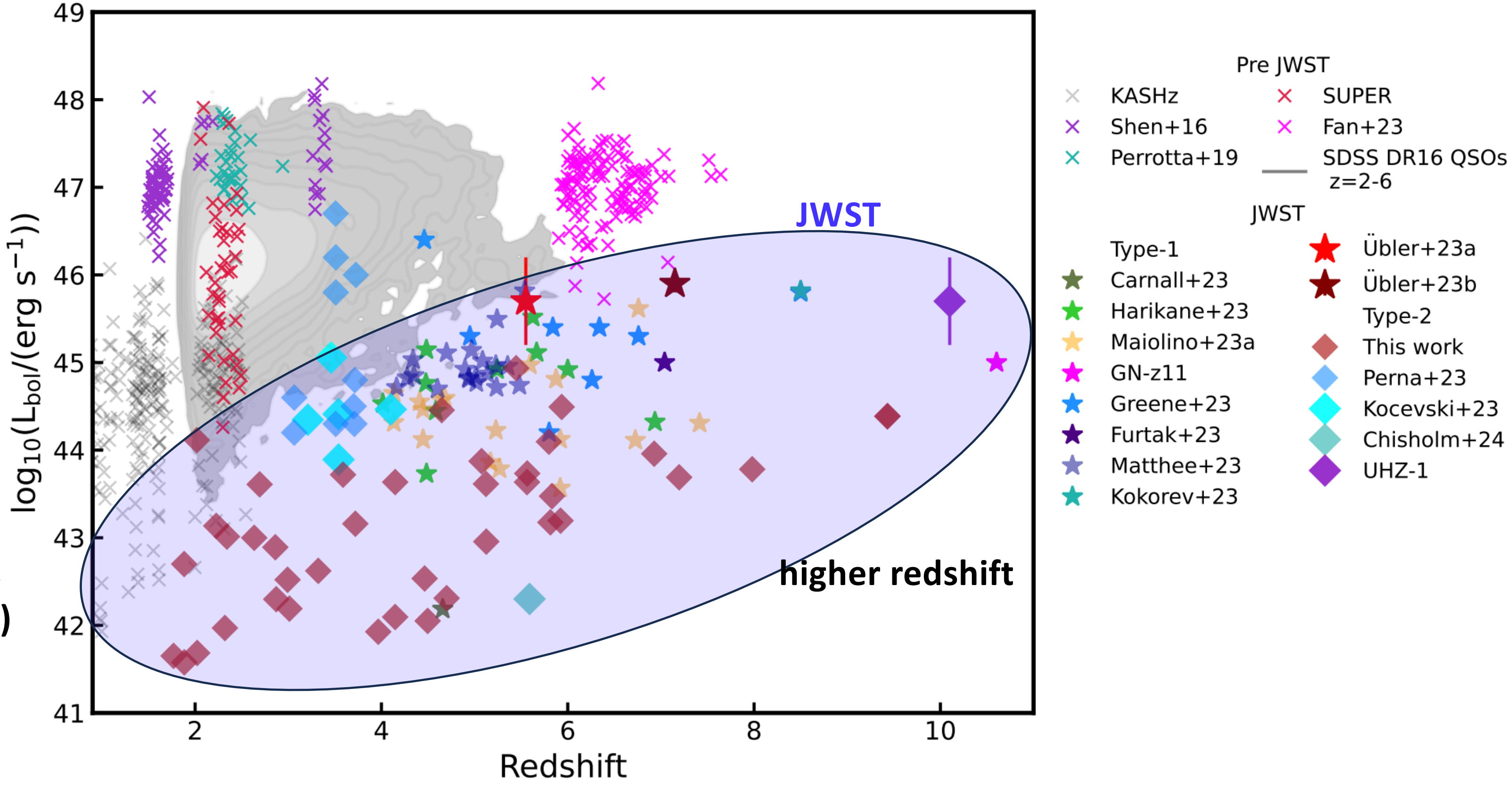


fainter luminosities (smaller BH masses)

Scholtz+23

when do the first BHs form in the Universe?

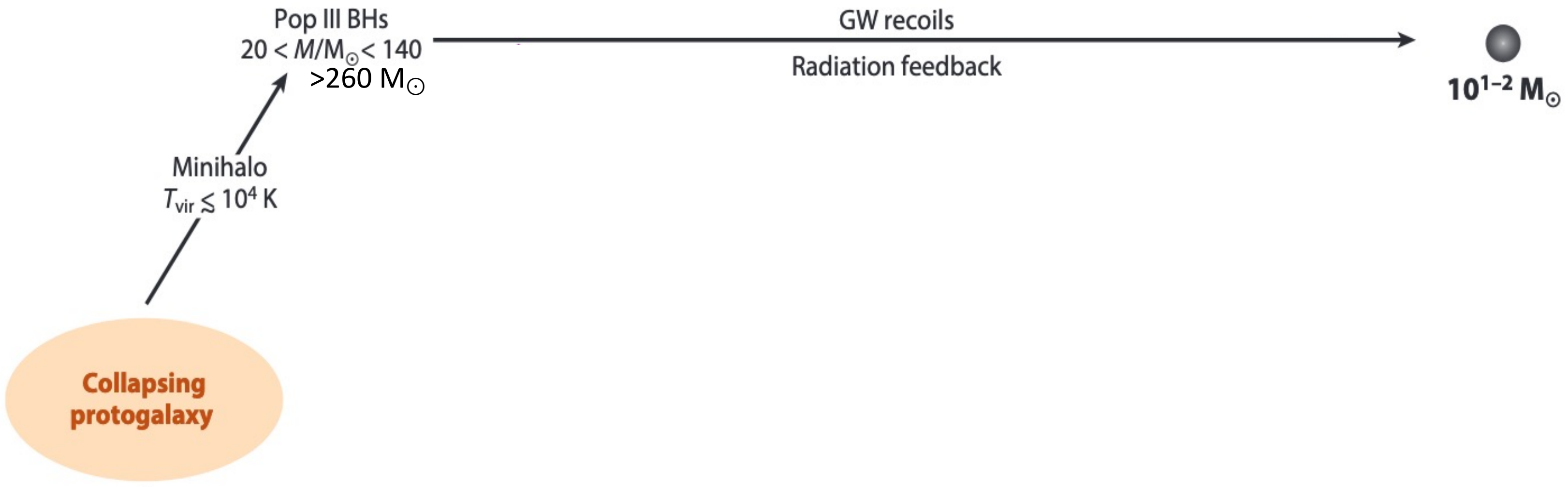
what is the mass of the first BHs?

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?

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

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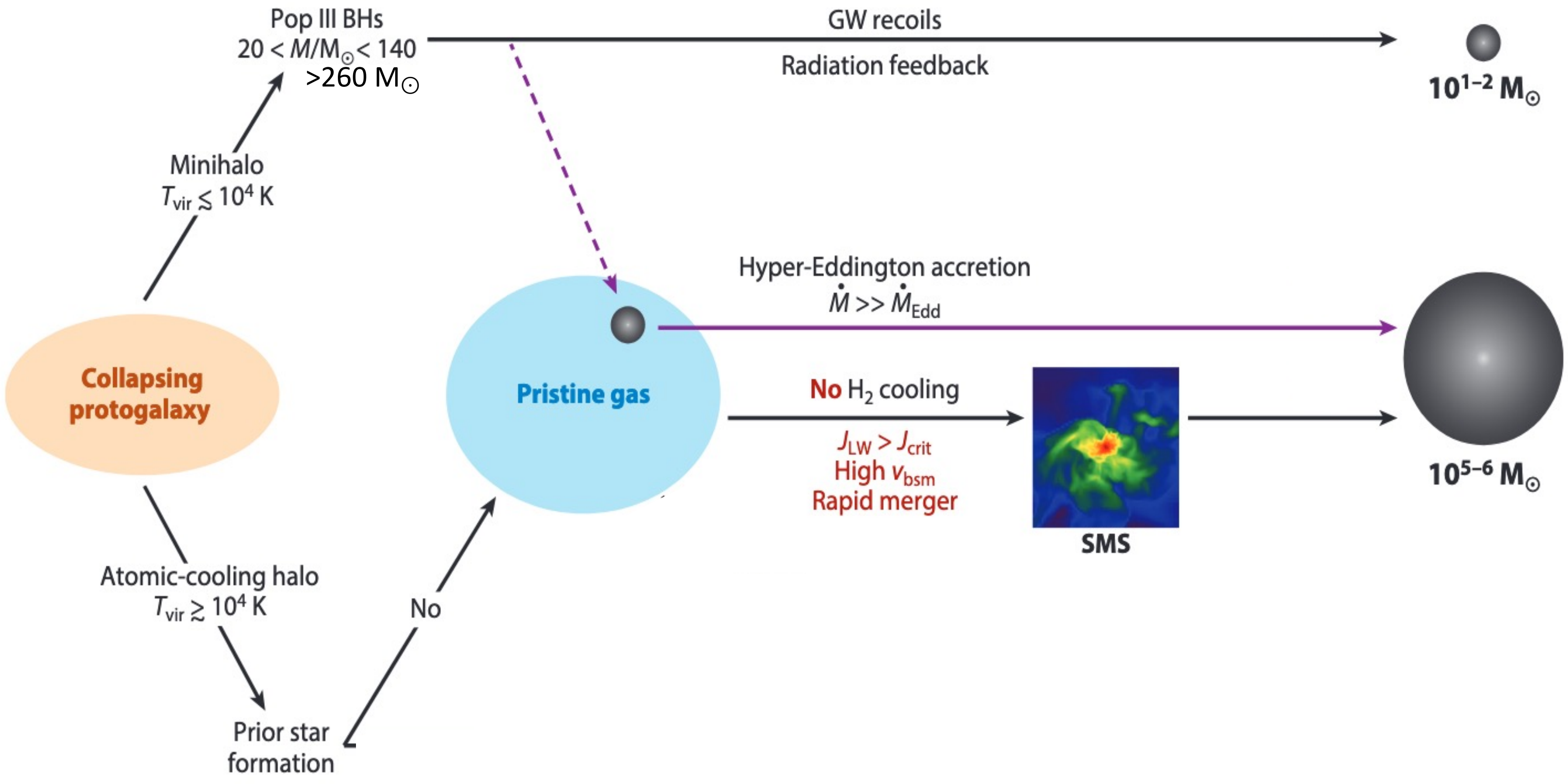

Pop III BHs

$20 < M/M_\odot < 140$

$>260\ M_\odot$

GW recoils

Radiation feedback

$10^{1-2}\ M_\odot$

Minihalo

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

Collapsing protogalaxy

Pristine gas

Hyper-Eddington accretion

$\dot{M} >> \dot{M}_{Edd}$

No H_2 cooling

$J_{LW} > J_{crit}$

High v_{bsm}

Rapid merger

SMS

$10^{5-6}\ M_\odot$

Atomic-cooling halo

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

No

Prior star formation

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

from Inayoshi et al. 2020

The *seeds* of the earliest SMBHs

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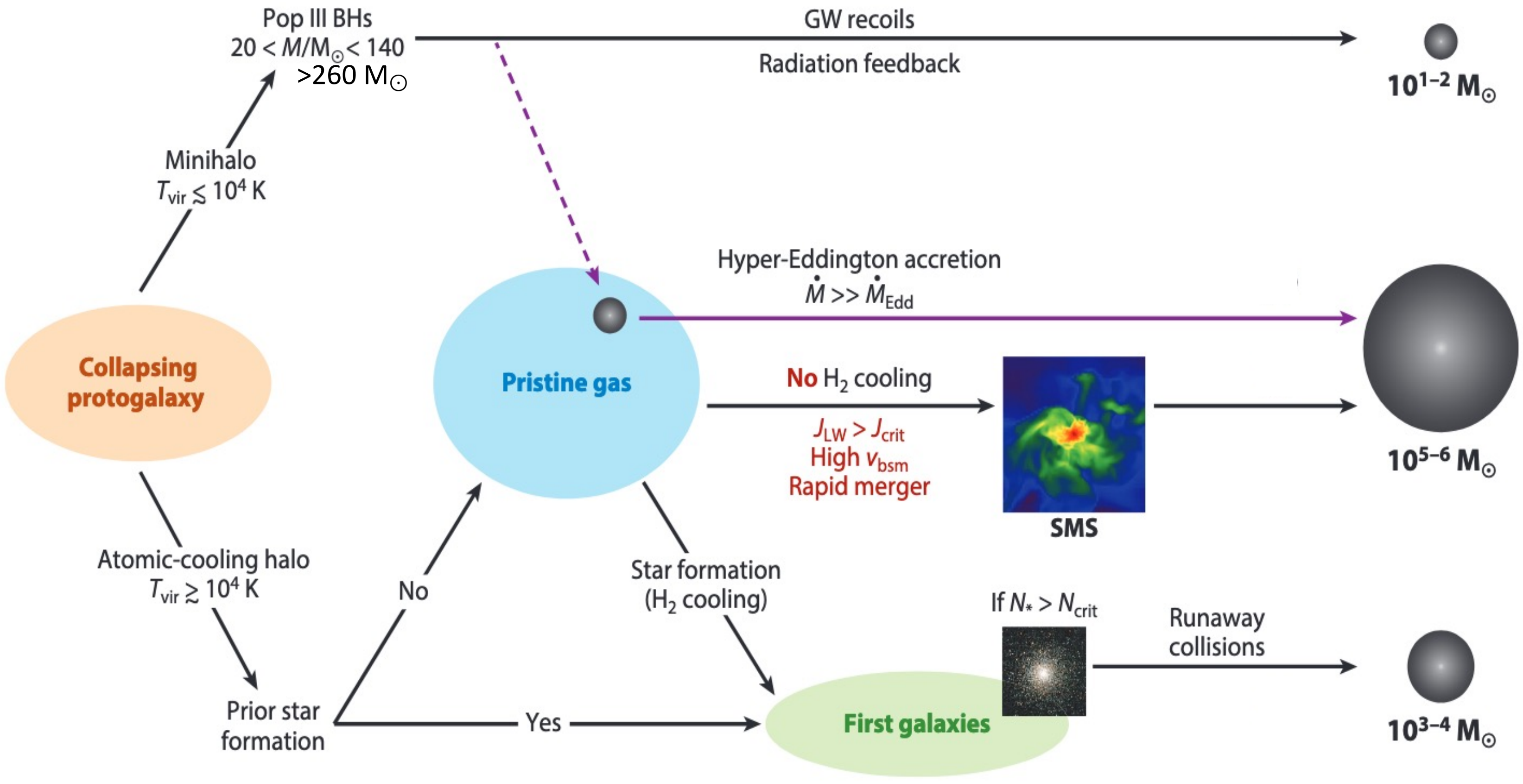

PopIII remnants
"light"
e.g. Madau & Rees 2001
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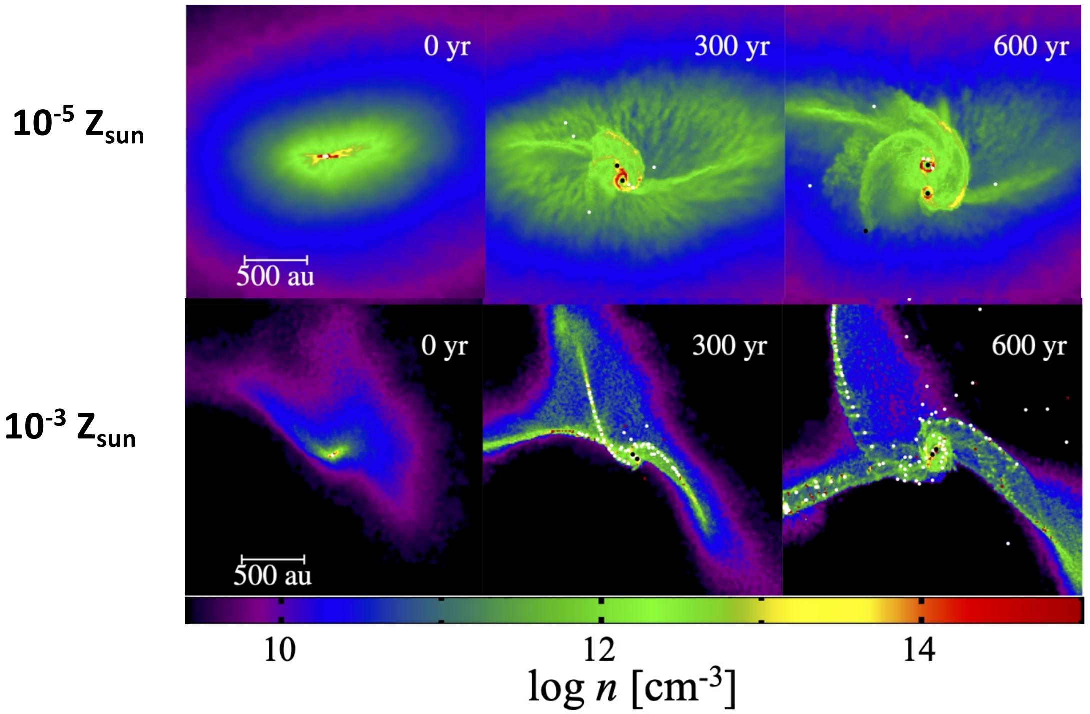
Volonteri 2003

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

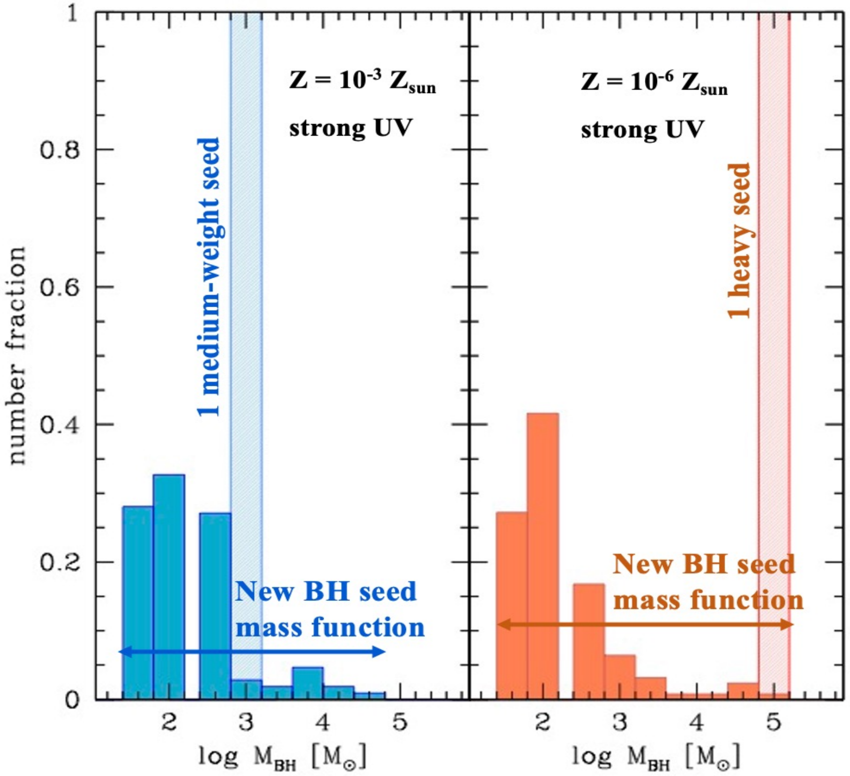
from Inayoshi et al. 2020

multiple «BH seeds» forming in a single halo



Chon & Omukai 2020

mass distribution of BH seeds at formation



in situ dynamical interactions among BH seeds may be expected

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

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:

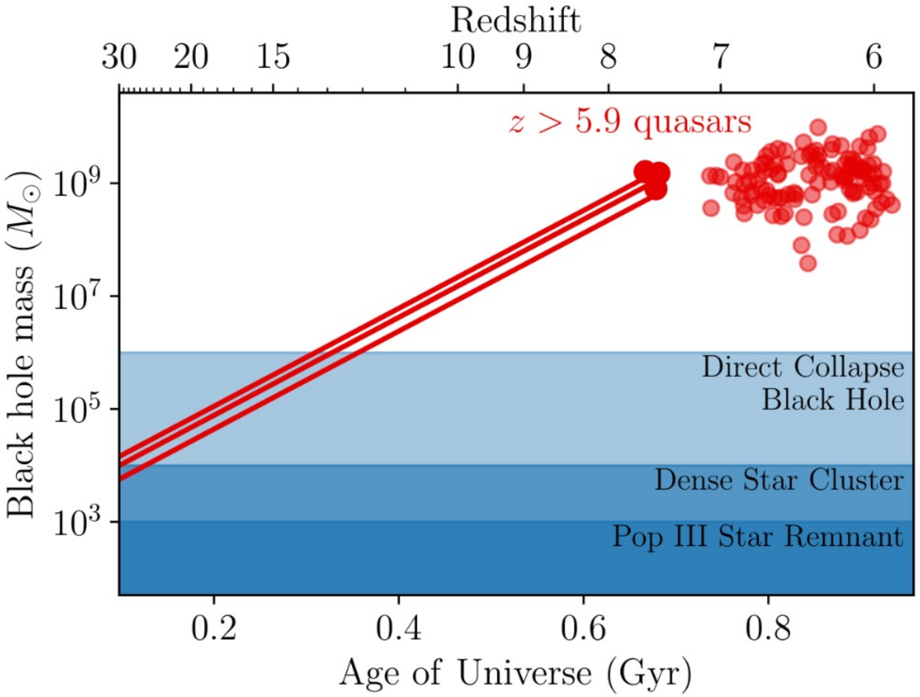
$$\dot{M}_{\rm Edd} \equiv 10\ L_{\rm Edd}/c^2 \quad L_{\rm Edd} = 4\pi c G M_\bullet/\kappa_{\rm es}$$

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

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

$\epsilon = 0.1,$ radiative efficiency

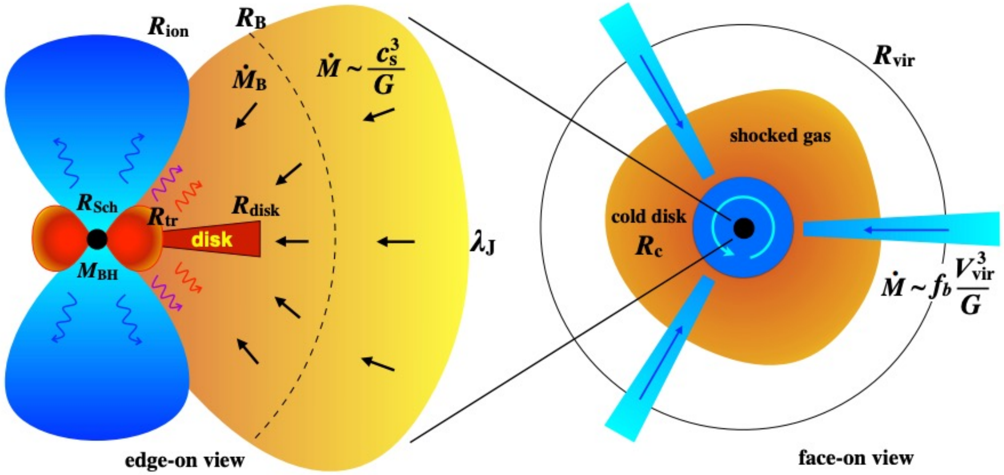
$f_{\rm duty} = 1,$ duty cycle



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

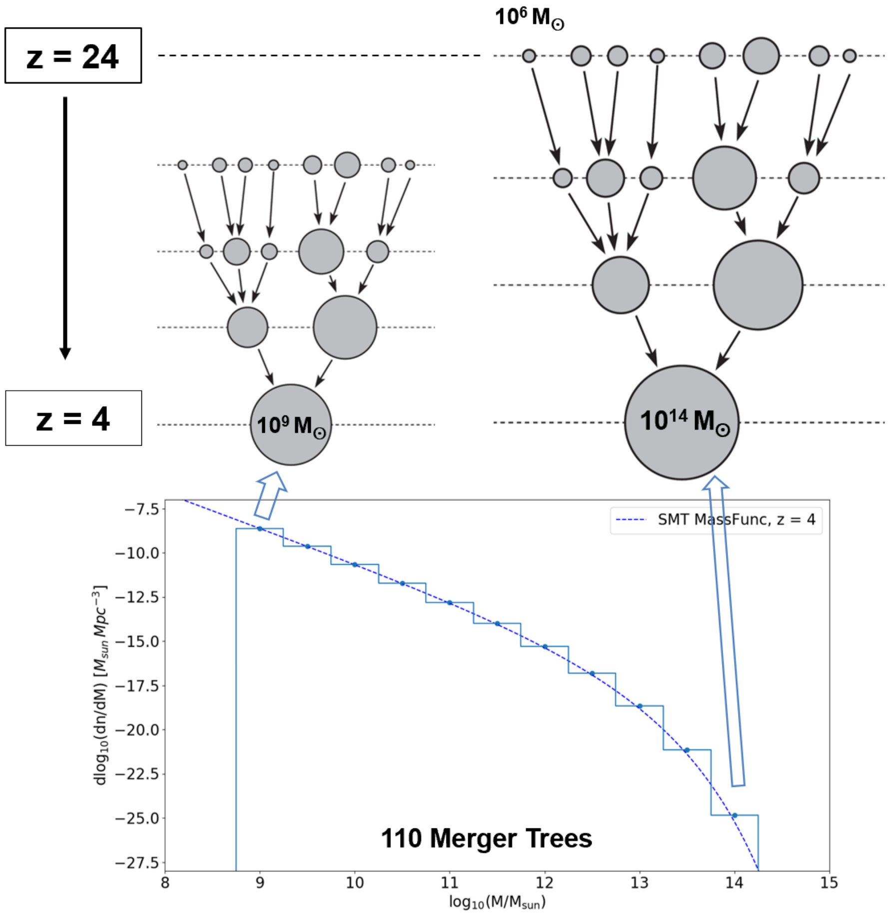
Populations studies
The Cosmic Archaeology Tool - **CAT**

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

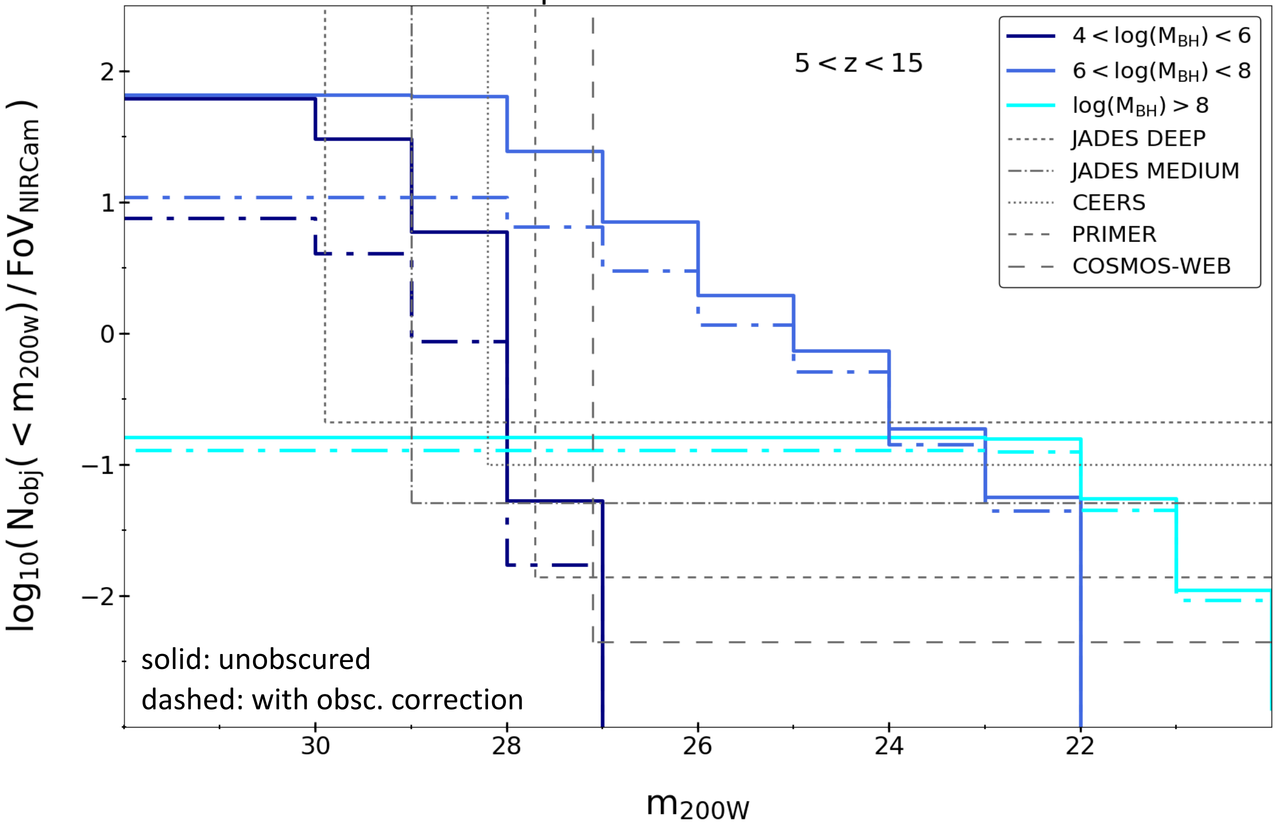
Model calibration
reproduce the cosmic star formation history (SFRD)
reproduce obs. properties of high-z QSOs (L_{bol}, M_{BH})



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*

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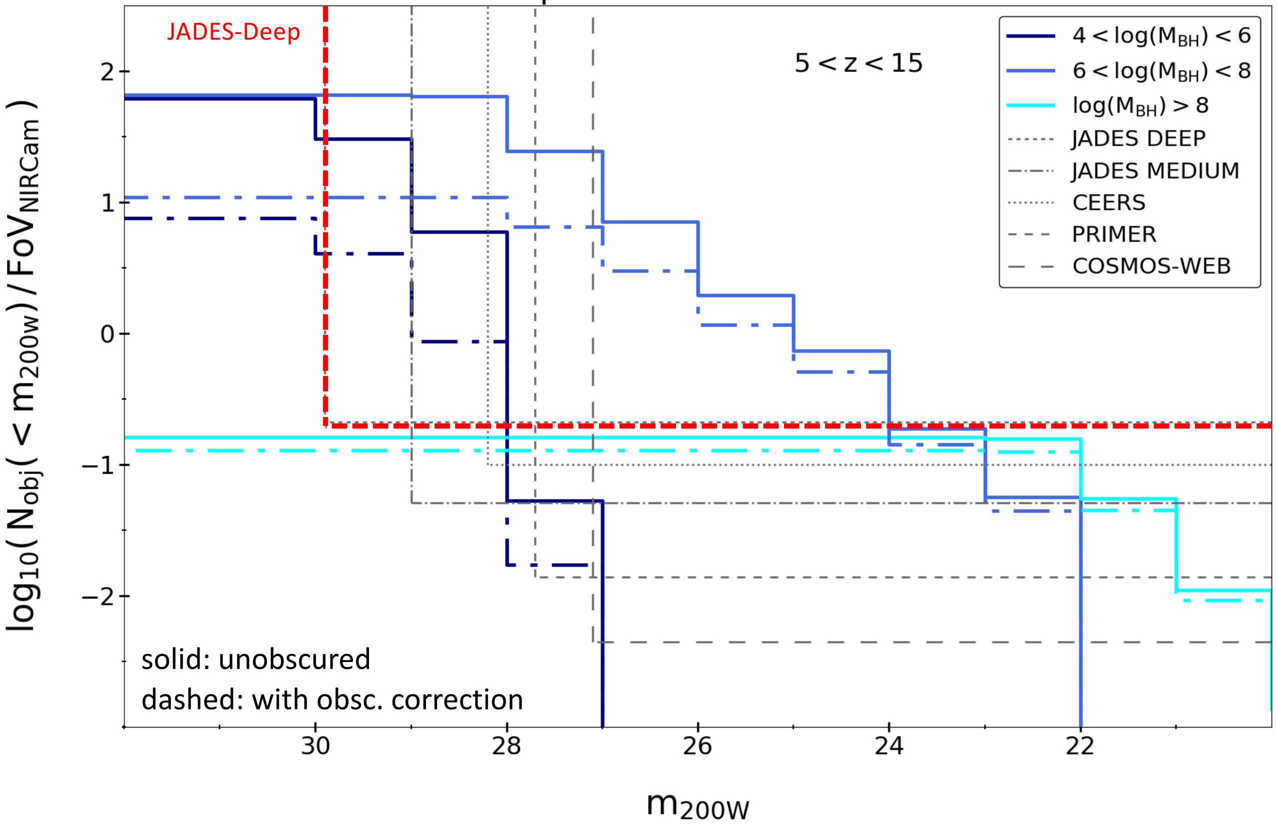

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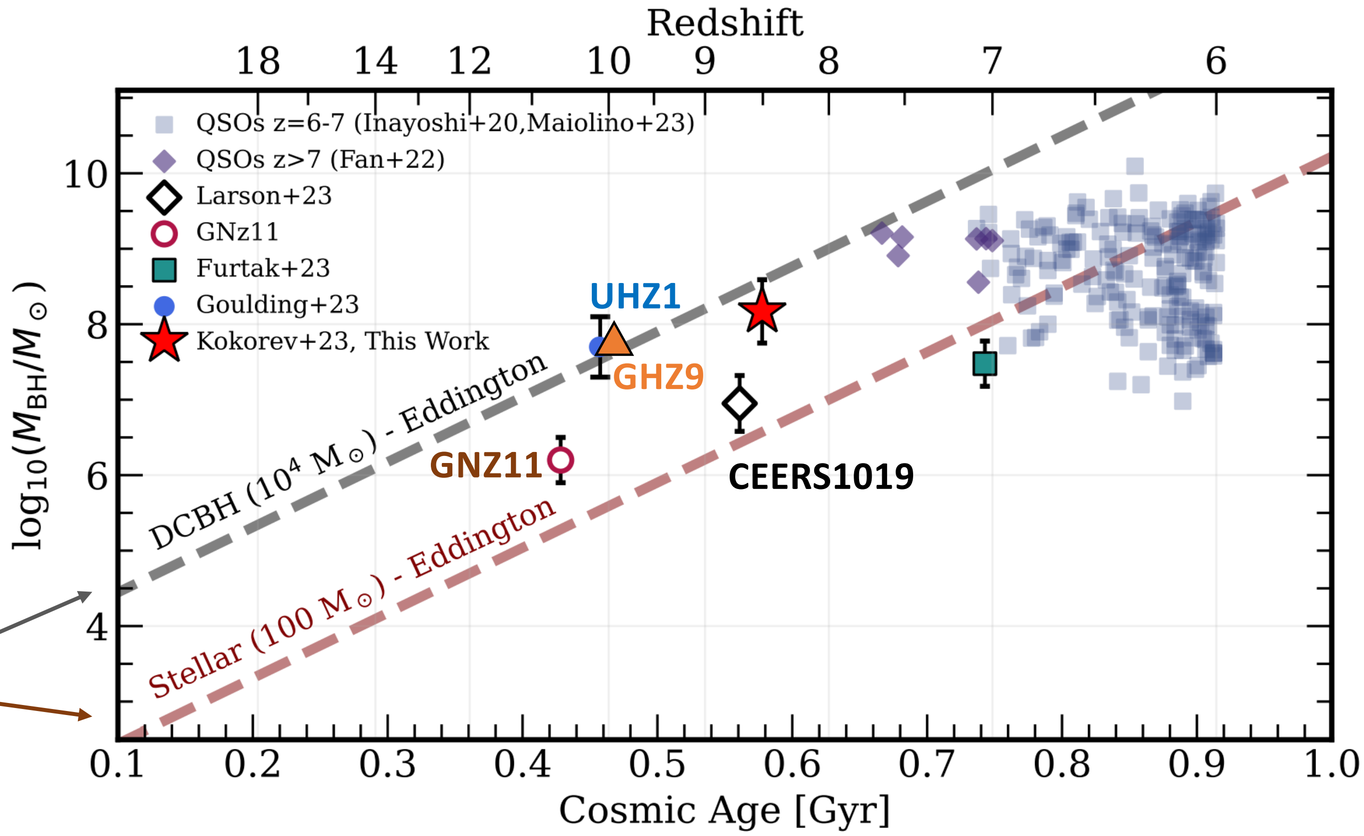
JADES-Deep has the sensitivity to detect $4 \leq \mathrm{Log}(M_{\mathrm{BH}}/M_\odot) < 6$ BHs at z>10

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



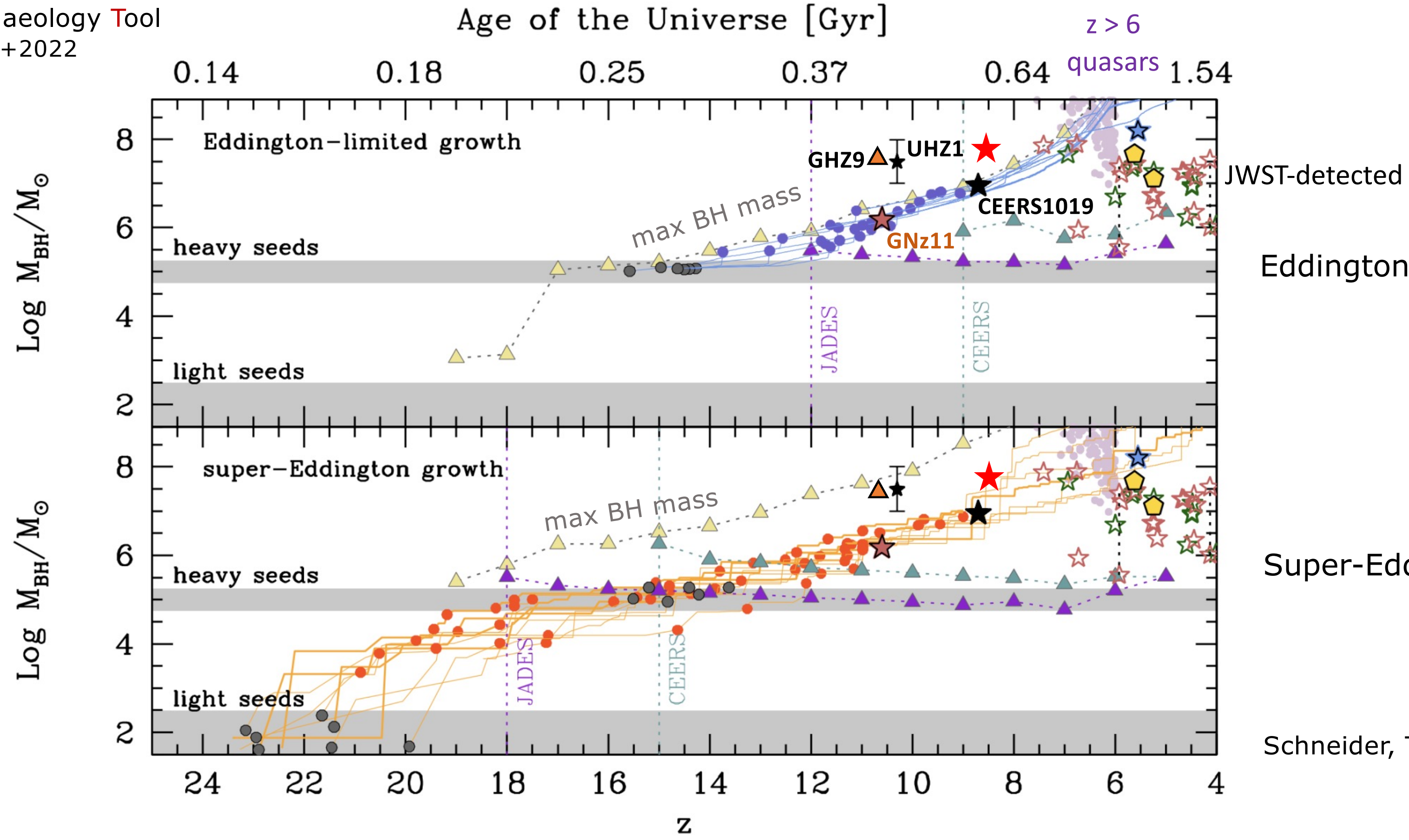
▲ Kovacz+24

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



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

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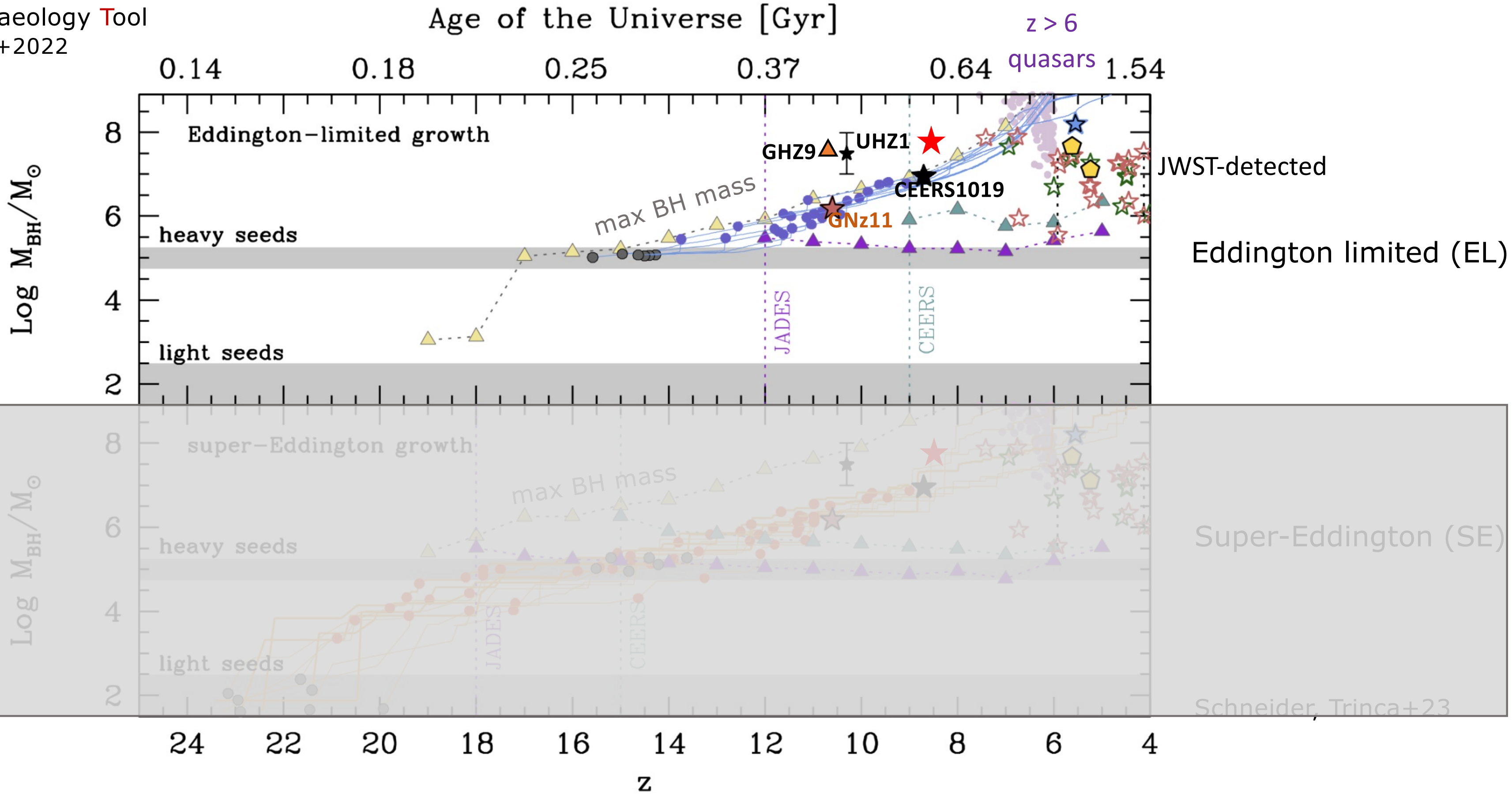

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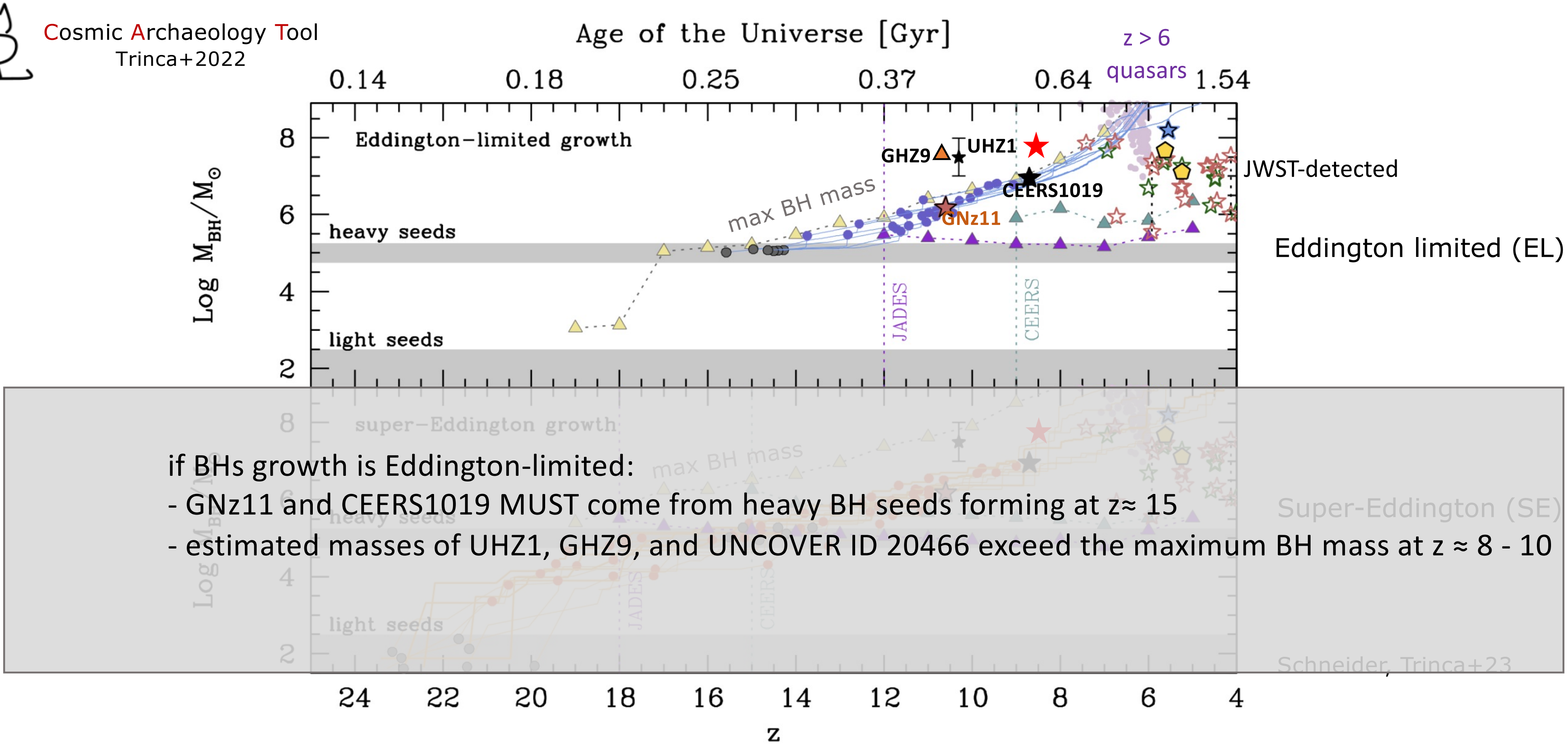

if BHs growth is Eddington-limited:

- GNz11 and CEERS1019 MUST come from heavy BH seeds forming at z≈ 15
- estimated masses of UHZ1, GHZ9, 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

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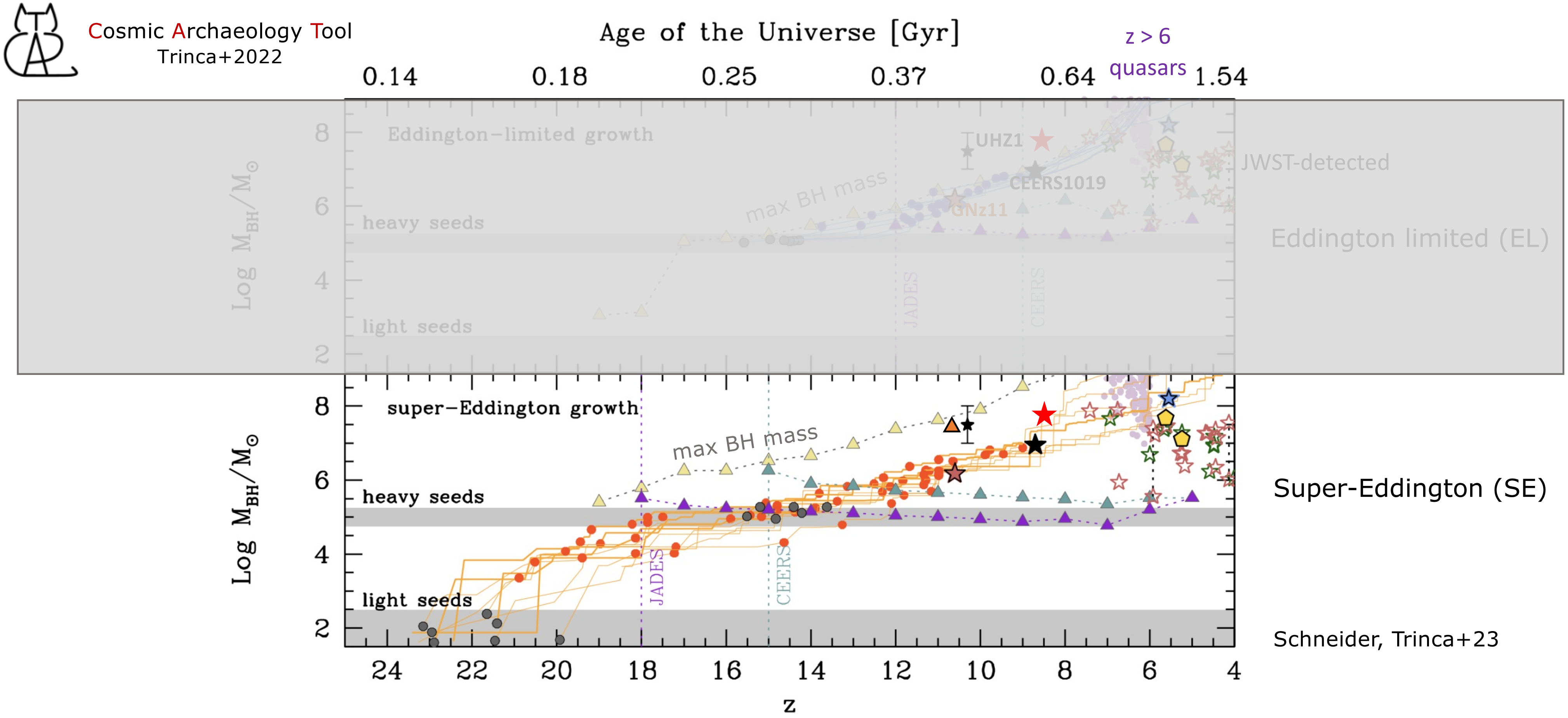
Trinca+2022



Eddington limited (EL)

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Schneider, Trinca+23

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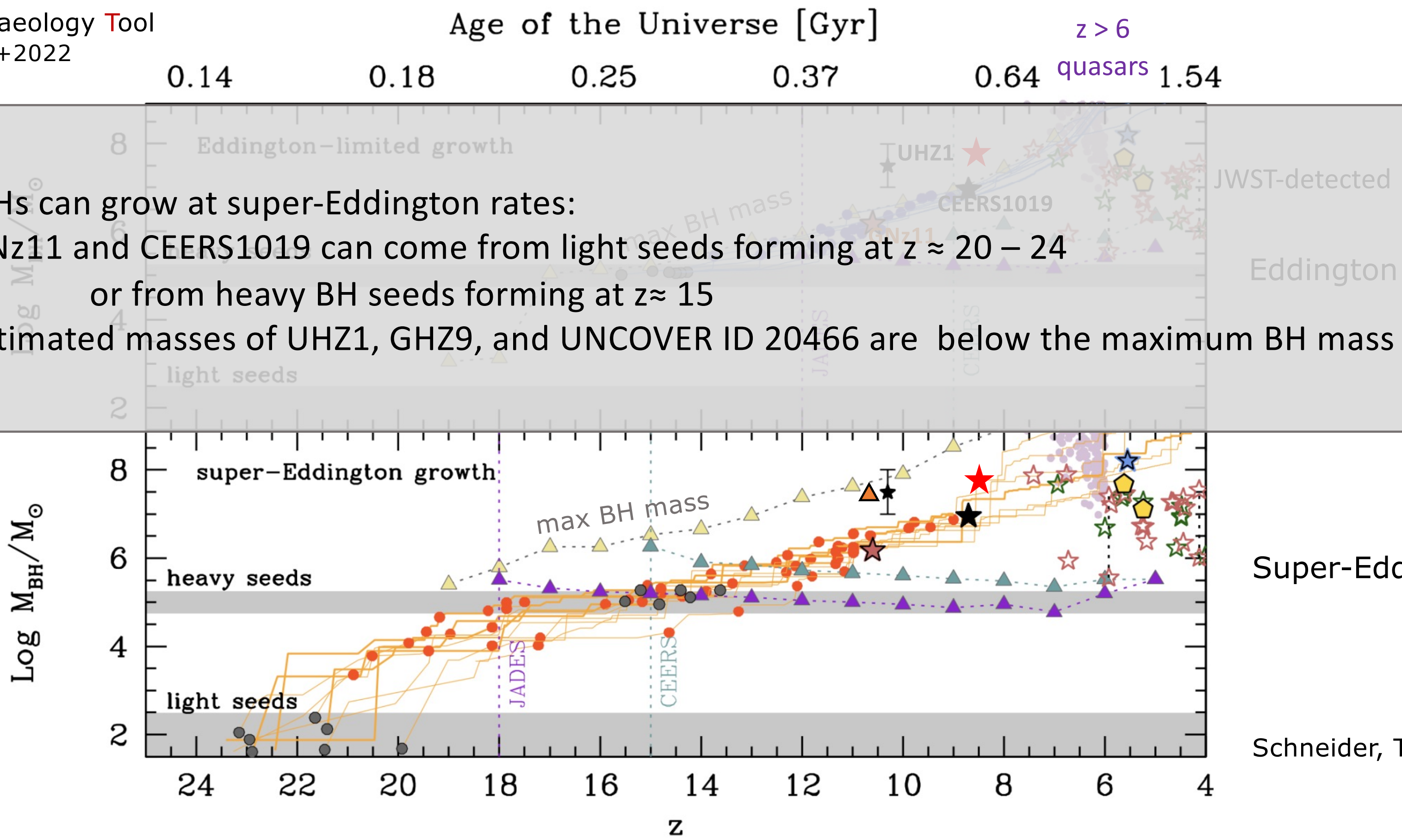
JWST-detected BHs at z ≈ 9 – 11: implications for BH seeding and growth

Cosmic **A**rchaeology **T**ool
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, GHZ9, and UNCOVER ID 20466 are below the maximum BH mass at z ≈ 8 - 10

Eddington limited (EL)

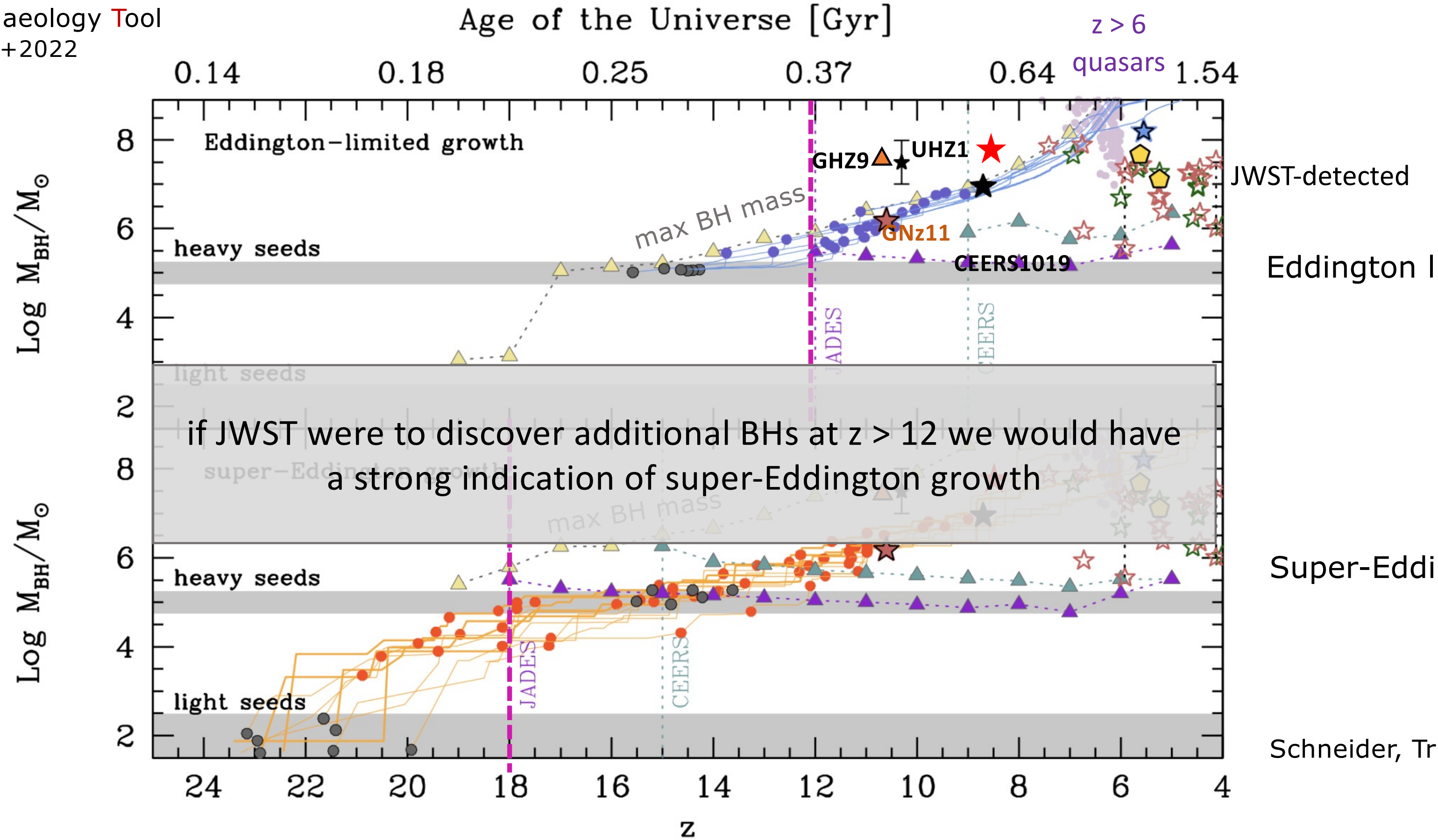
Super-Eddington (SE)

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



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

Eddington limited (EL)

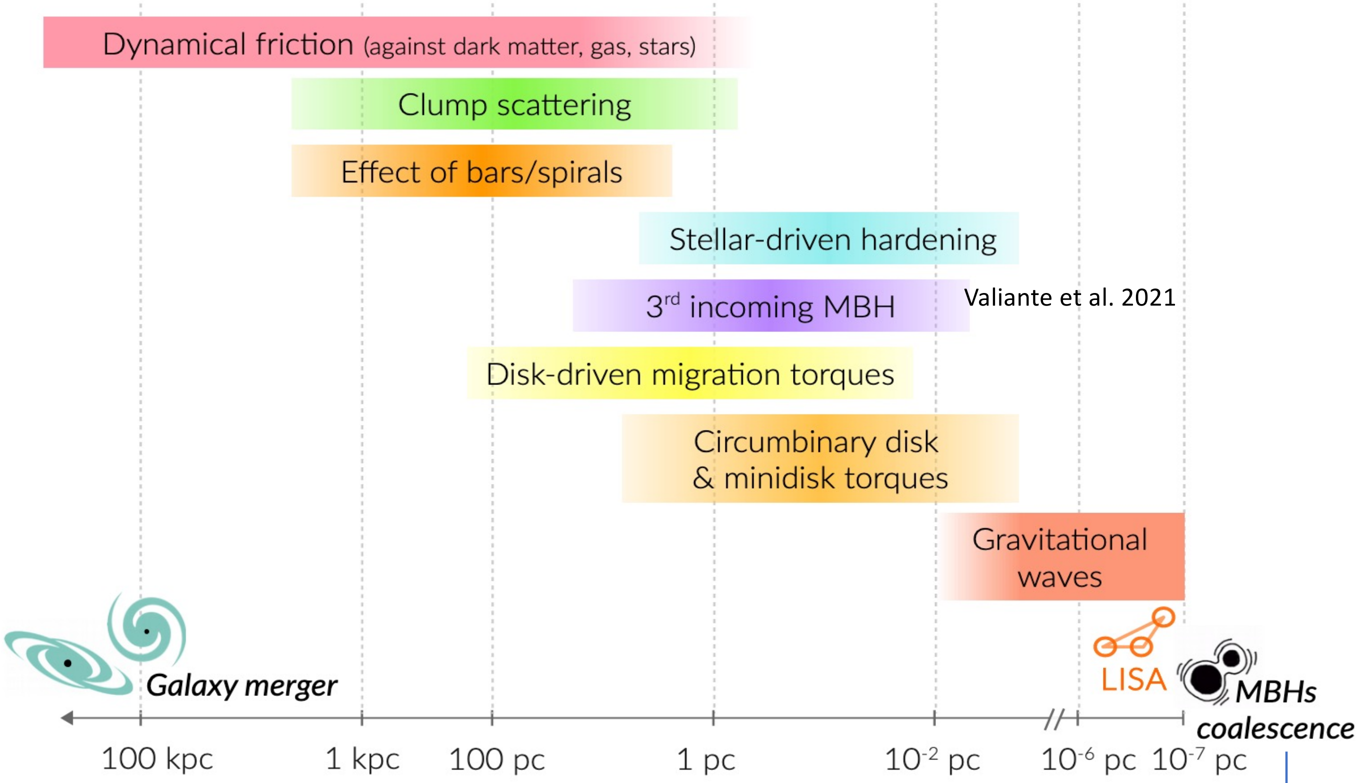
Super-Eddington (SE)

Schneider, Trinca+23

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

BH dynamics: timescale matters

especially at high redshift



Valiante et al. 2021

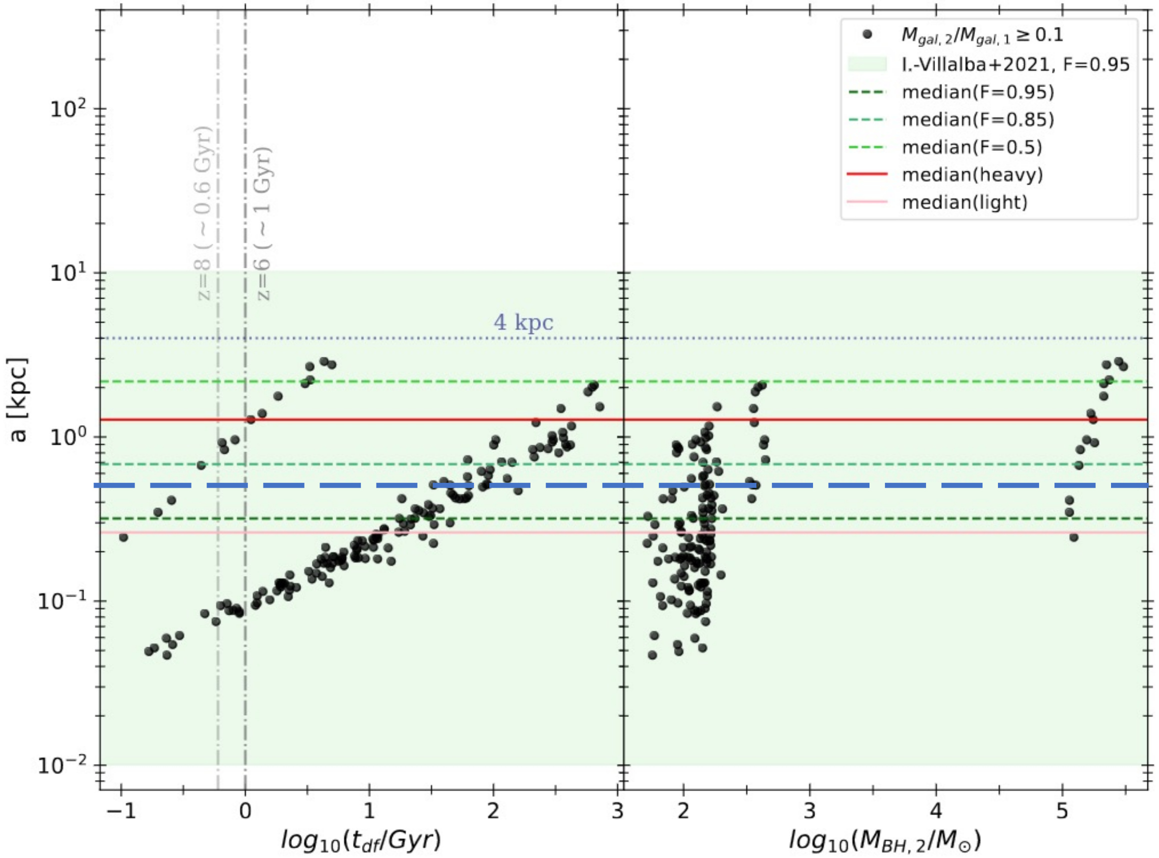
image credit: E. Bortolas

kick/recoil

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

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

calibrated against hydro simulations (Volonteri et al. 2020)

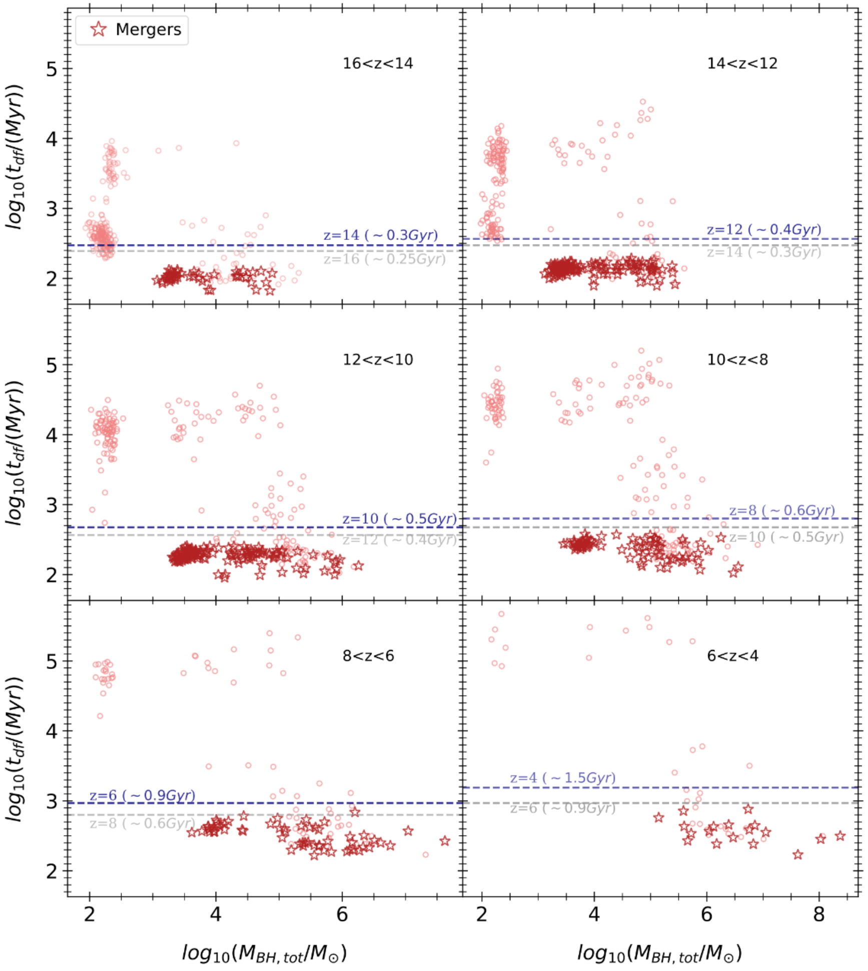
BH binary formation timescale

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

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

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

merging BHs across cosmic epochs

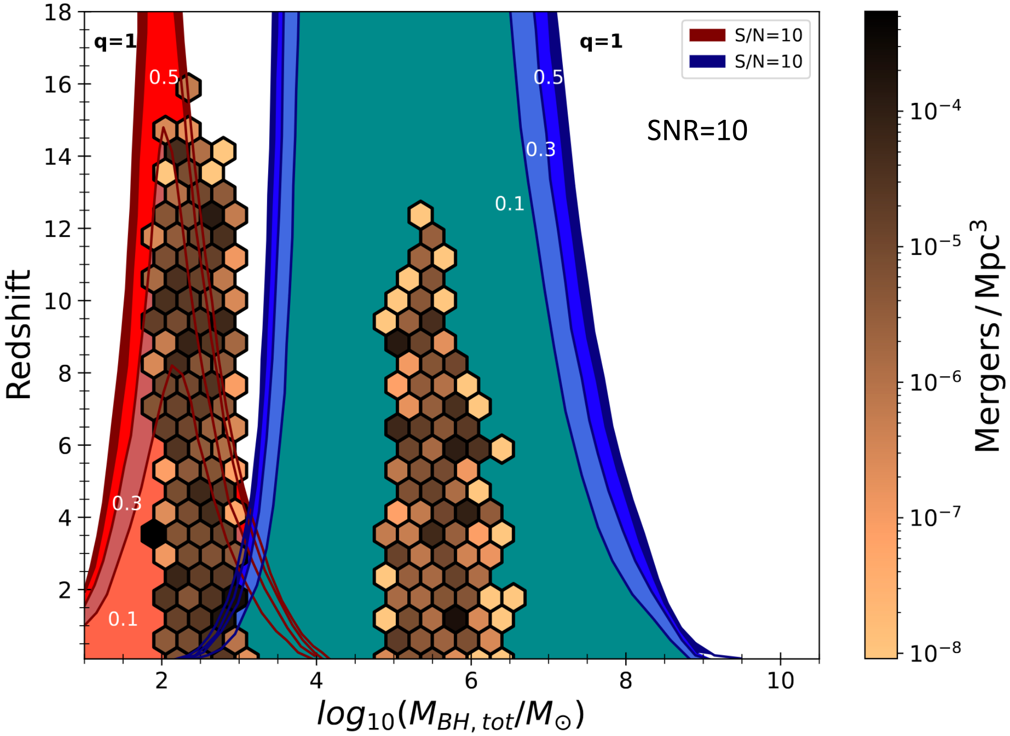


Trinca et al. in prep.

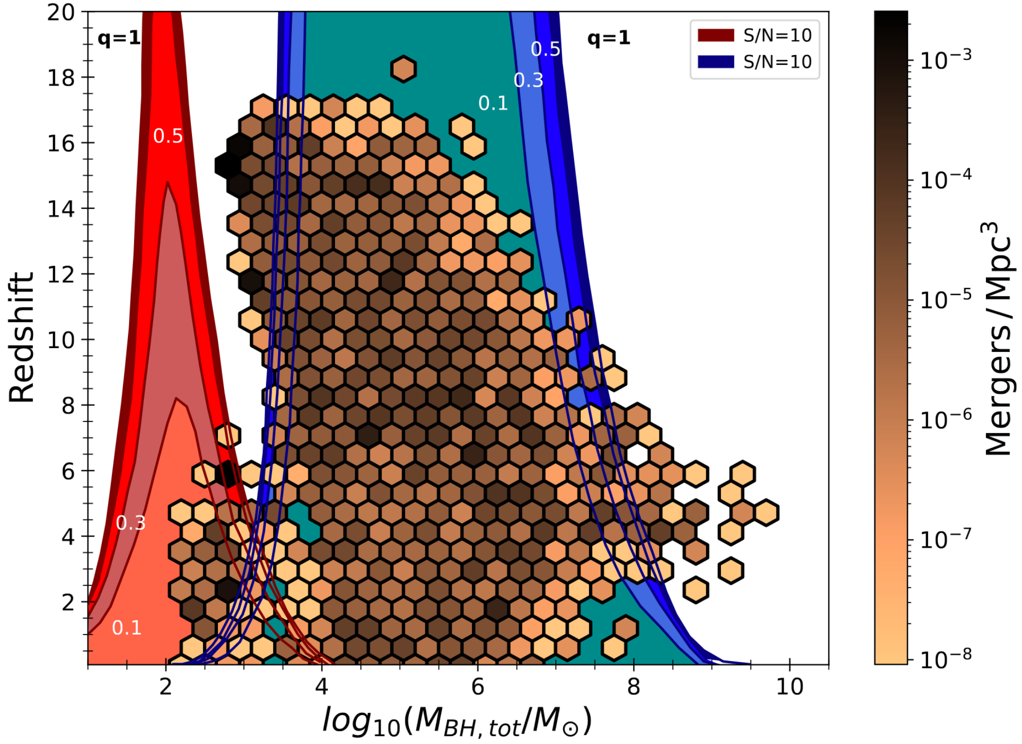
a population of GW sources

Testing prescriptions for BH dynamics: pairing+hardening phase

Eddington-limited model



super-Eddington model



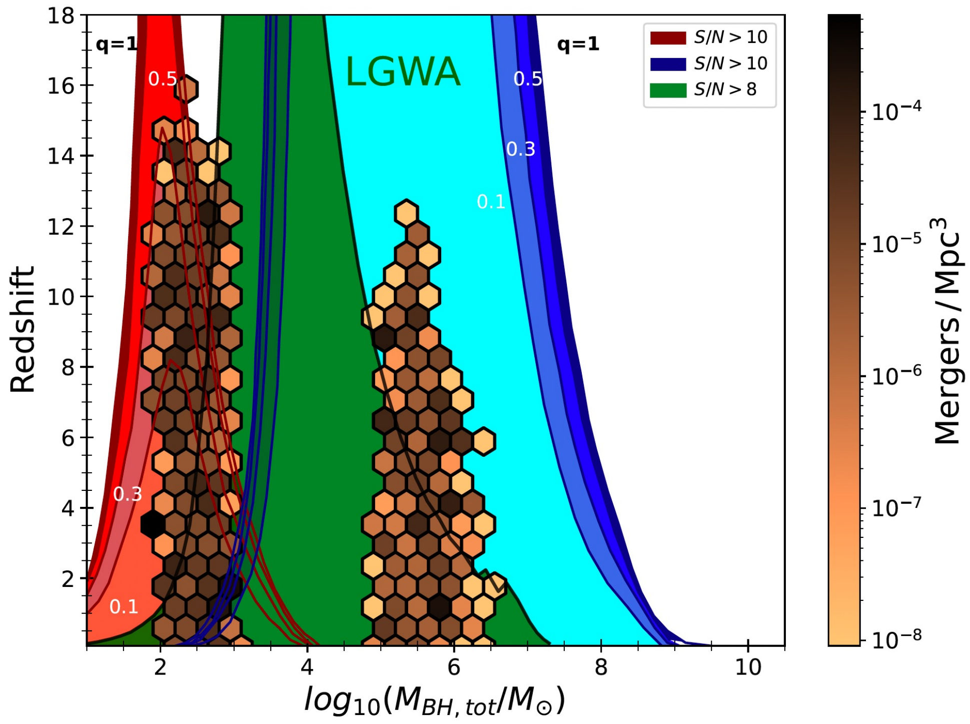
the two BH accretion regimes are expected to leave specific imprints in the properties of GW sources that would be detectable with ET and LISA

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

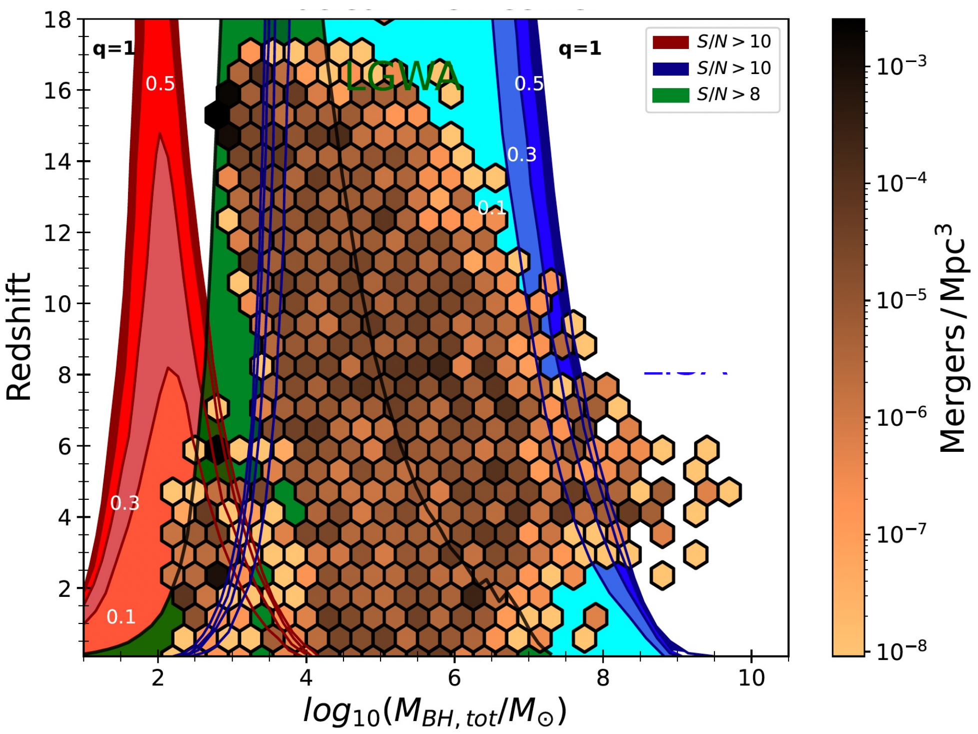
a population of GW sources

Testing prescriptions for BH dynamics: pairing+hardening phase

Eddington-limited model



super-Eddington model



LGWA would be sensitive to BBH coalescences from growing light BH seeds out to z ≈ 16 - 18

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!