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SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

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black hole formation through cosmic time:

from JWST to present and future GW telescopes

Raffaella Schneider

Sapienza Università di Roma

in collaboration with:

Federico Angeloni, **Riccardo Caleno**, Pedro Capelo, **Nazanin Davari ,** Luca Graziani, , **Ignas Juodzbalis** , Alessandro Lupi, Roberto Maiolino, Lucio Mayer, **Alessandro Trinca**, Rosa Valiante, Marta Volonteri, **Tommaso Zana** and the BLACKThunder team

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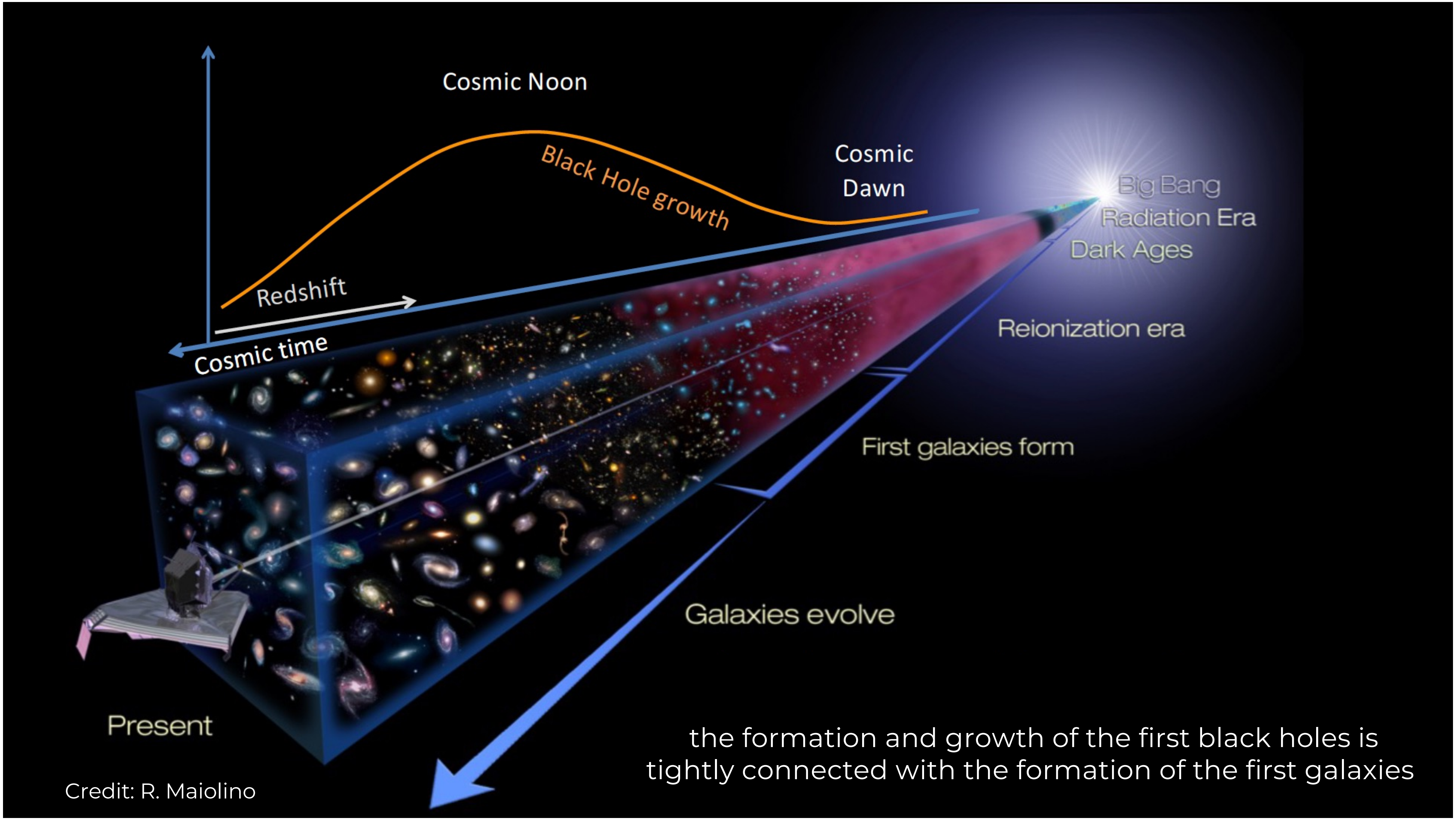
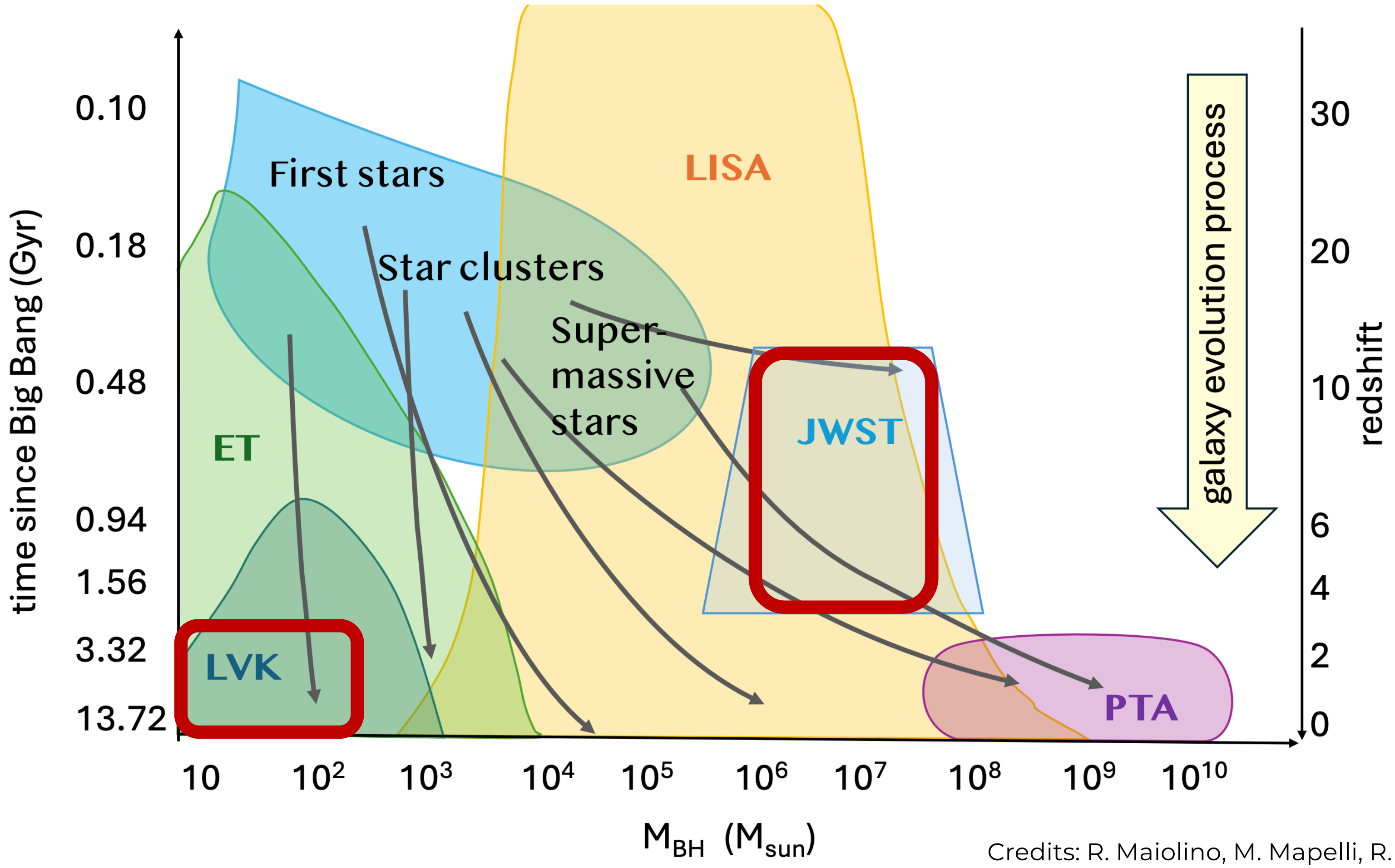

Cosmic Noon
Black Hole growth
Cosmic
Dawn
Big Bang
Radiation Era
Dark Ages
Redshift
Cosmic time
Reionization era
First galaxies form
Galaxies evolve
Present
Credit: R. Maiolino
the formation and growth of the first black holes is
tightly connected with the formation of the first galaxies

black holes at all scales

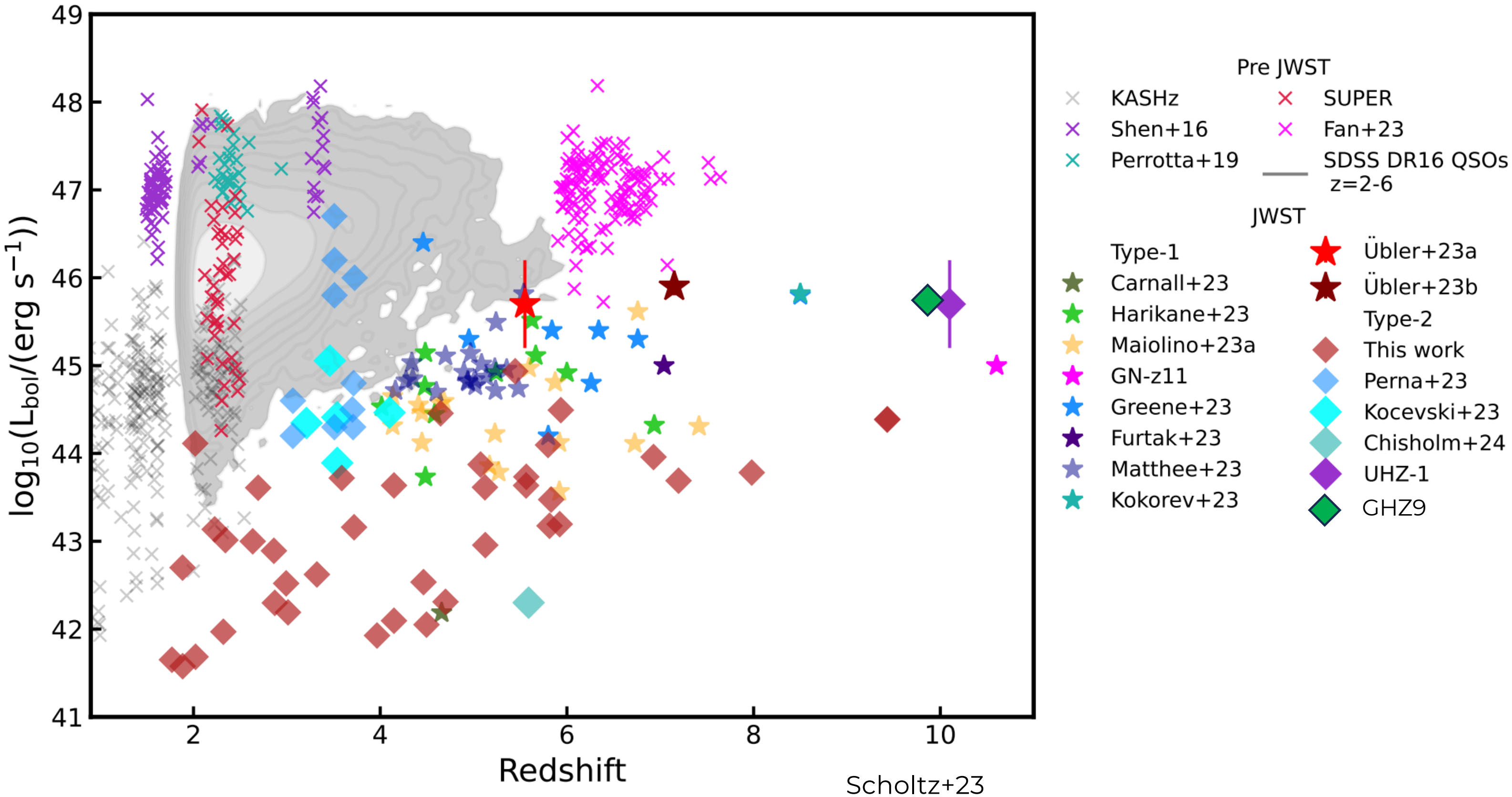


Credits: R. Maiolino, M. Mapelli, R. Schneider, M. Volonteri

many open questions...

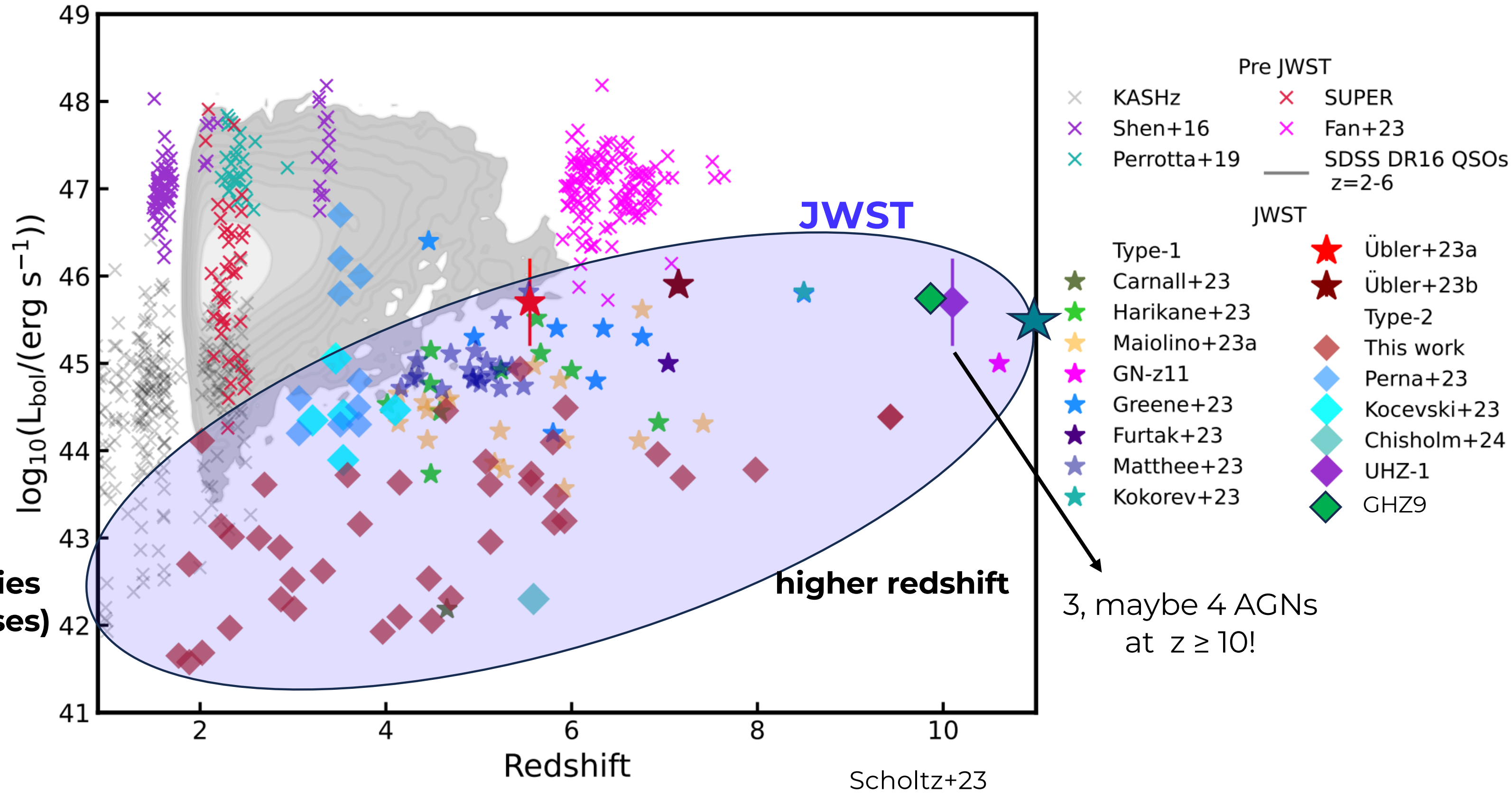
- how do super-massive black holes (SMBHs) form?
- what is the relation between BHs at different (mass) scales?
- what is the role of the cosmic environment for BH formation?
- can we use BH archaeology to probe physical conditions at early cosmic times?

the new discovery space opened by JWST



Scholtz+23

the new discovery space opened by JWST

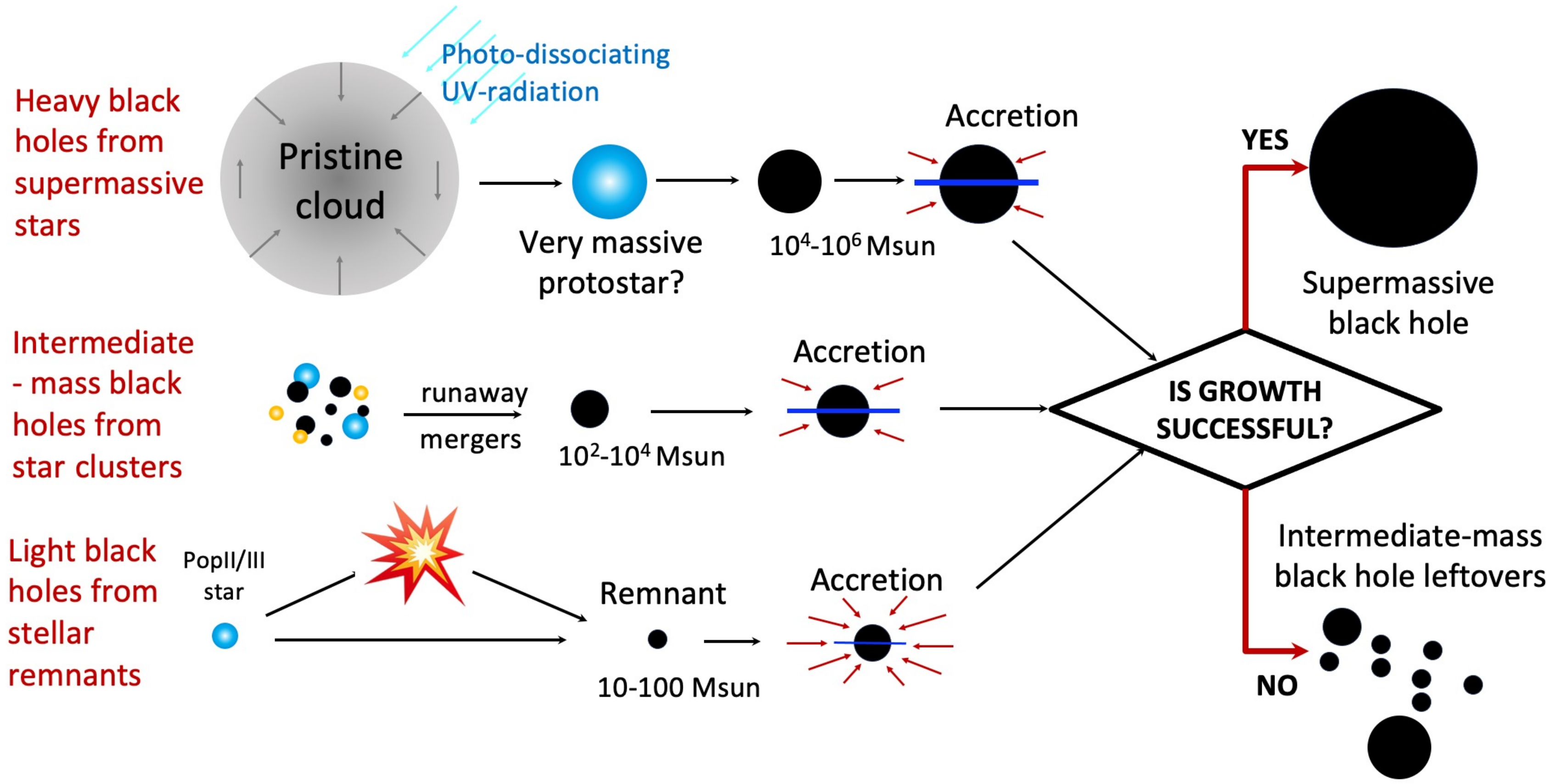


fainter luminosities (smaller BH masses)

3, maybe 4 AGNs at z ≥ 10!

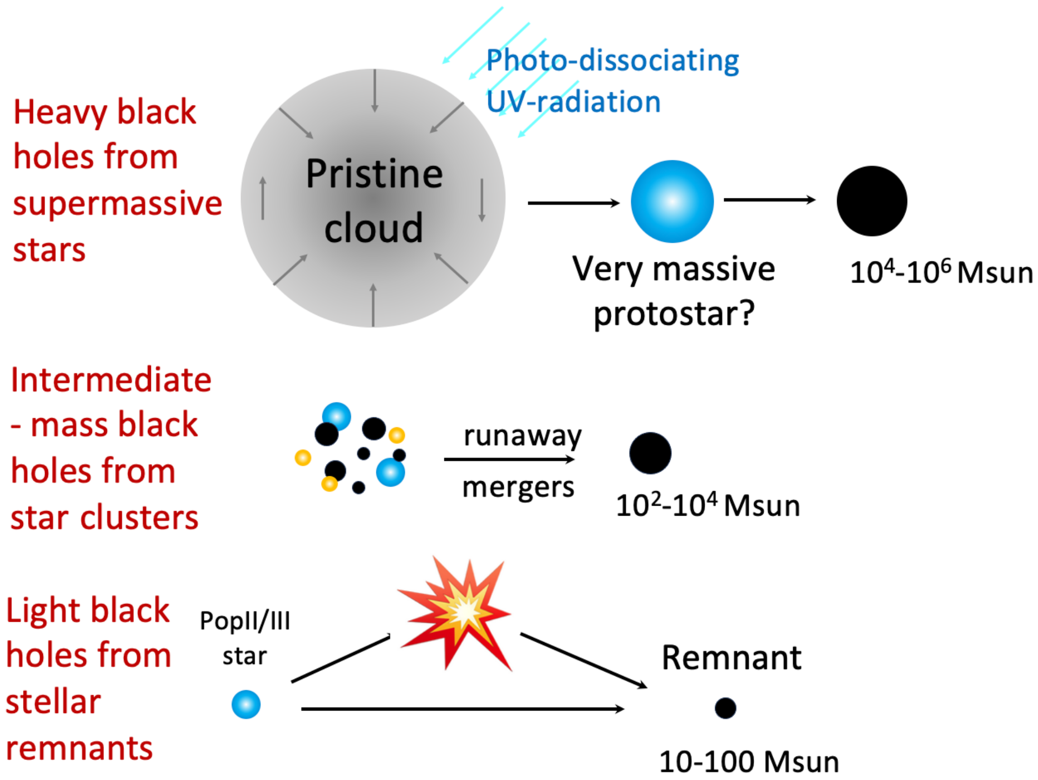
how do these early black holes form and grow?

main astrophysical scenarios for BH formation



Credits: R. Maiolino, M. Mapelli, R. Schneider, M. Volonteri

1. black hole seed formation



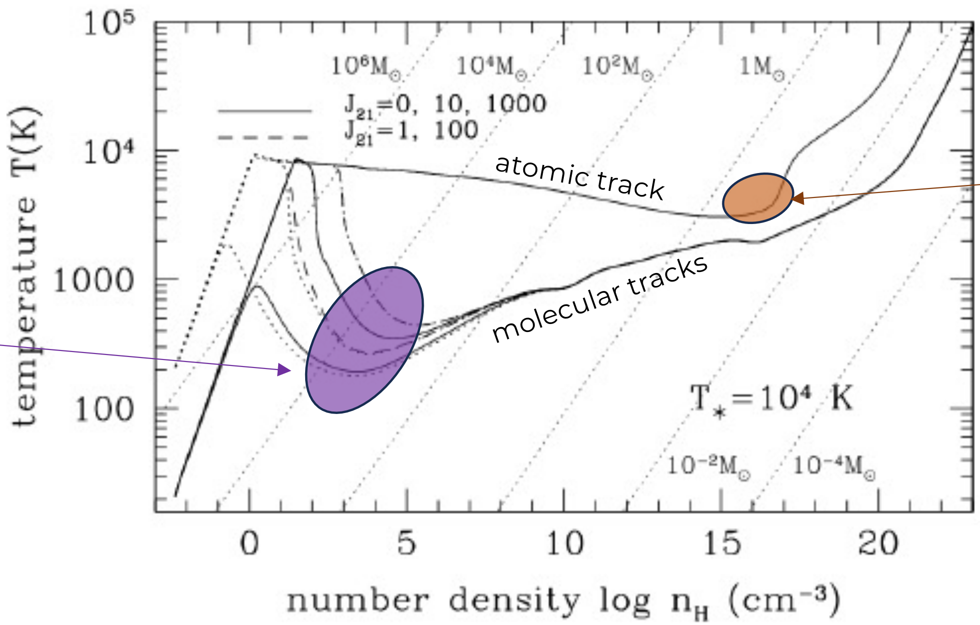
Credits: R. Maiolino, M. Mapelli, R. Schneider, M. Volonteri

a continuum shaped by environmental conditions

the light-to-intermediate-to-heavy seed sequence can also be viewed as a sequence where the fragmentation-accretion-collision processes have different relative importance

tracks of **metal free** clouds exposed to **varying LW radiation** (J_{21})

standard Pop III star formation
light black hole seeds
$M_{BH} \approx 10^2\ M_{sun}$



$J_{LW} > J_{cr}$

formation of
a super-massive star
$\approx 10^4 - 10^6\ M_{sun}$
heavy black hole seeds
$M_{BH} \approx 10^4 - 10^6\ M_{sun}$

Omukai, RS, Haiman 2008

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

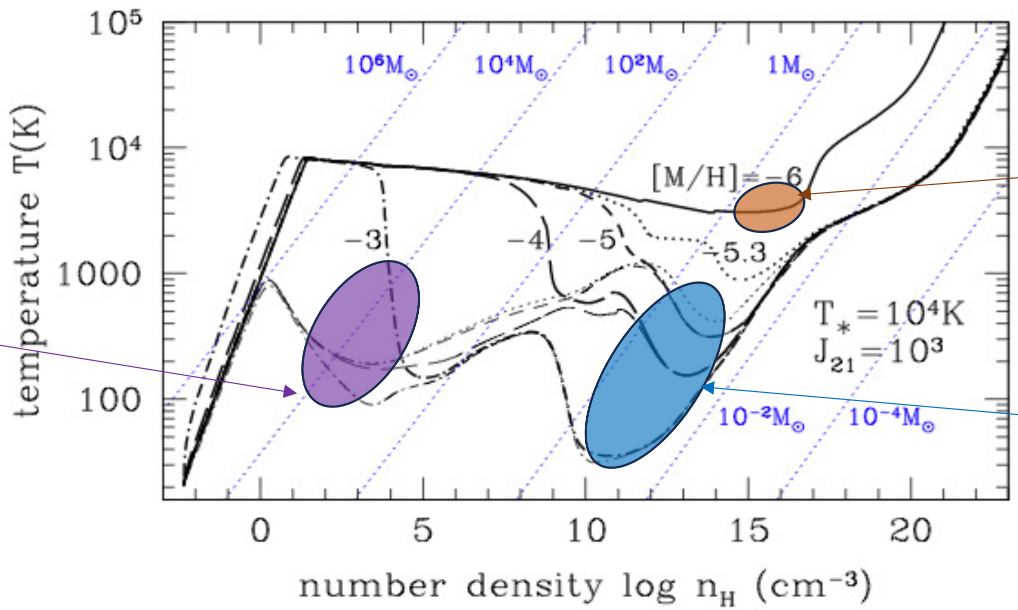
a continuum shaped by environmental conditions

the light-to-intermediate-to-heavy seed sequence can also be viewed as a sequence where the fragmentation-accretion-collision processes have different relative importance

tracks of **metal-enriched** clouds exposed **to J_{21} > J_{cr}**

standard Pop II star formation

stellar black holes
$M_{BH} \approx 10$ - 50 M_{sun}



$Z < Z_{cr}$

formation of
a super-massive star
$\approx 10^4 - 10^6$ M_{sun}
heavy black hole seeds
$M_{BH} \approx 10^4 - 10^6$ M_{sun}

formation of dense star clusters

Intermediate-mass BHs
$M_{BH} \approx 1000$ M_{sun}

Omukai, RS, Haiman 2008

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

what is the value of J_{cr}?

the minimum value of LW flux for H_2 suppression depends:

- on the mass and redshift of the host dark matter halo: $J_{cr} \approx (0.01 - 1)$ in minihalos
  $J_{cr} \approx 1000$ in atomic cooling halos

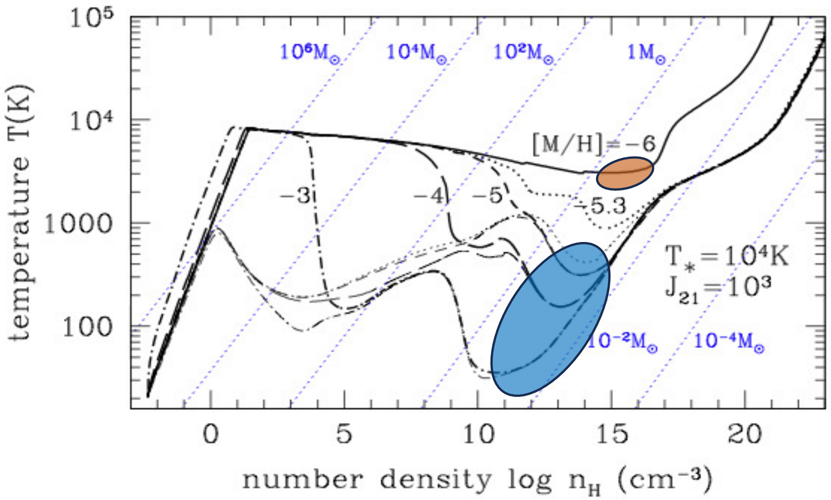
- on the spectral shape of the radiation field: $J_{cr} < 100$ for $T_{bb} \approx 10^4$ K (Pop II stars)
  $J_{cr} \approx 1000$ for $T_{bb} \approx 10^5$ K (Pop III stars)

- on the presence of dynamical heating from rapid halo growth: $J_{cr} \approx 10$

see: Haiman et al. 2000, Machacek et al. 2001, Omukai 2001, O'Shea & Norman 2008, Inayoshi & Omukai 2011, 2012, Latif et al. 2014, Hartwig et al. 2015, Regan et al. 2016, 2017, Wolcott-Green & Haiman 2017, 2019, Regan & Downes 2018, Sugimura et al. 2014, Chon et al. 2016, Agarwal et al. 2017, Hirano et al. 2017, Wise et al. 2019, Regan et al. 2020

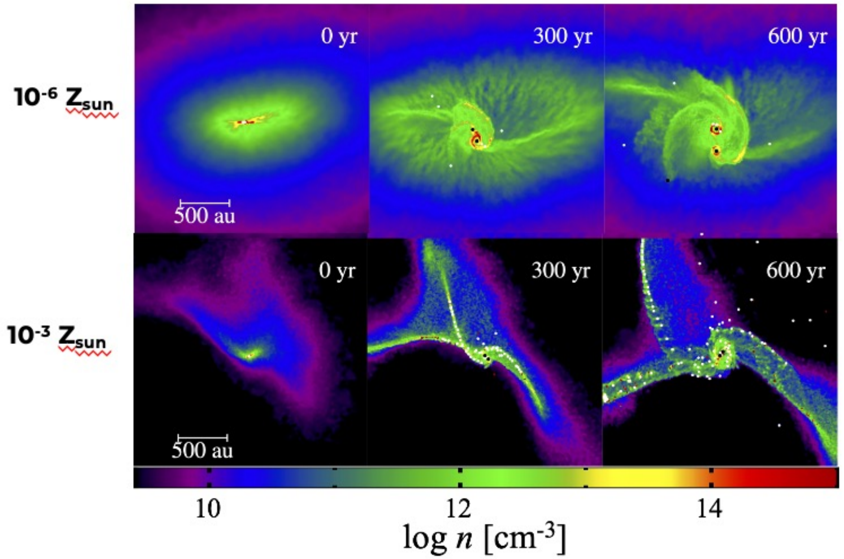
what is the value of Z_{cr}?

$Z_{cr} \approx 10^{-6} Z_{sun}$ to avoid (dust-driven) fragmentation



Omukai, RS, Haiman 2008

$Z_{cr} \approx 10^{-3} Z_{sun}$ because of **super-competitive accretion**



Chon & Omukai 2020, 2025

when $Z > Z_{cr} \approx 10^{-3} Z_{sun}$ metal-line cooling becomes effective:
increased fragmentation and lowered accretion rate lead to normal Pop II star formation

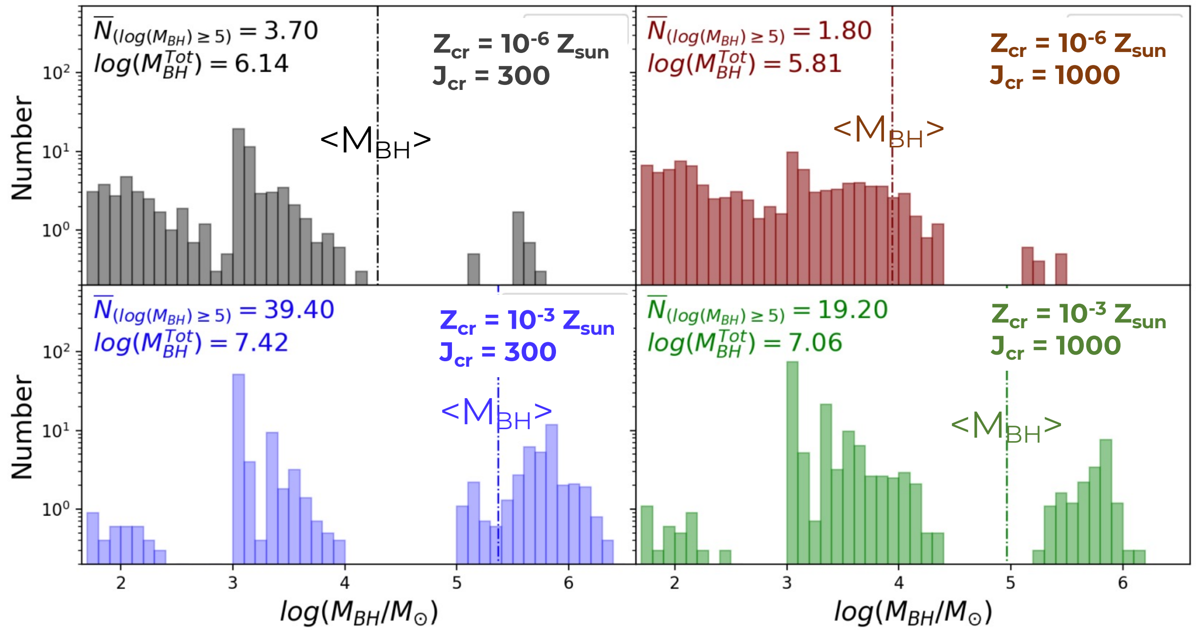
why do we care?

the values of J_{cr} and Z_{cr} affect:

- the number density of different seed types
- the mass distribution of black hole seeds accross different halos

the seed mass distribution across different halos depends on J_{cr} and Z_{cr}

mass function of BH seeds at $z \approx 15$ within progenitors of a $z \approx 6$ quasar host*



standard model

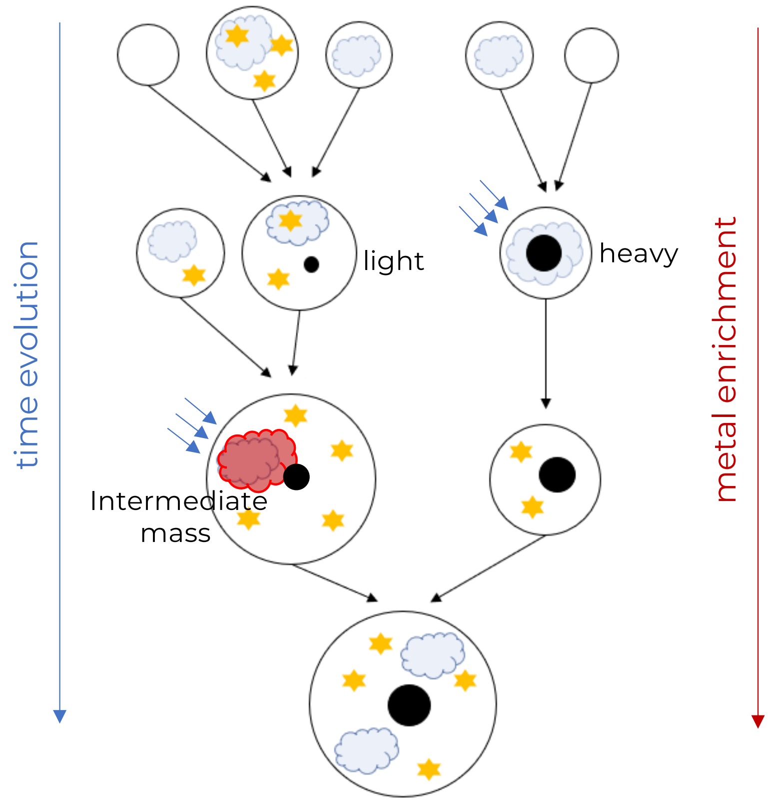
supercompetitive accretion model

Sassano, RS, Valiante, Inayoshi, Chon, Omukai, Mayer, Capelo, MNRAS 2021

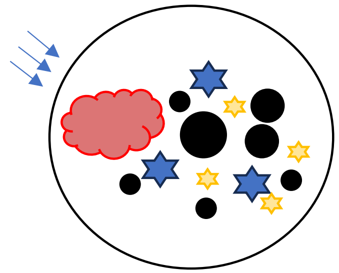
*averaged over 10 simulations

two paradigm shifts

(1) multifaceted nature of BH seed populations in galaxy evolution



(2) a continuous BH seed initial mass function ranging from light to intermediate and heavy seeds within individual halos



- in mildly enriched halos with $J_{LW} > J_{cr}$ in the supercompetitve accretion scenario

  Chon & Omukai 2020, 2025

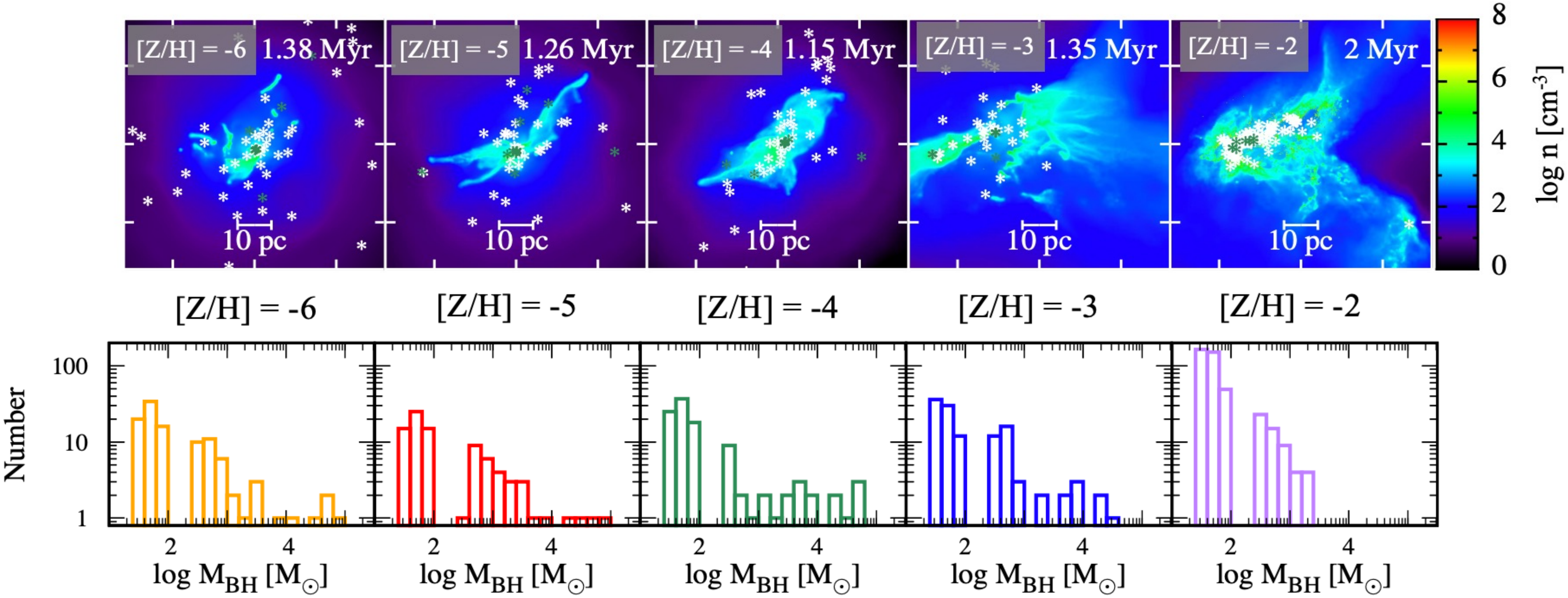
- when dynamical heating is important

  Wise et al. 2019, Regan et al. 2020

multiple BH seeds forming in a single halo

supercompetitive accretion scenario

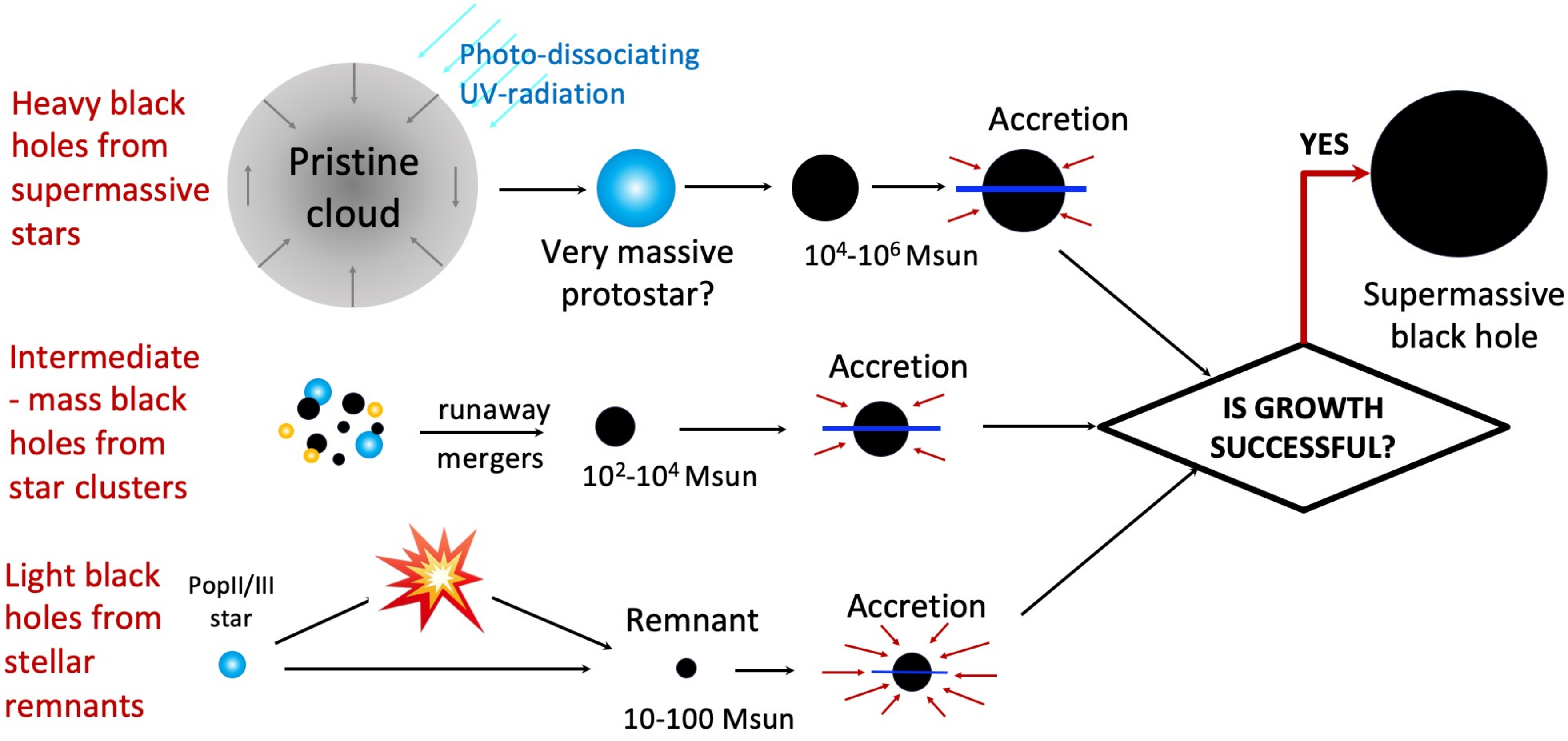
$J_{LW} > J_{cr} \approx 1000$



Chon & Omukai 2025

a continuous BH mass distribution forms, ranging from light to intermediate and heavy black hole seeds

2. black hole seed growth through gas accretion



Credits: R. Maiolino, M. Mapelli, R. Schneider, M. Volonteri

growing black hole seeds is challenging

Gas accretion is inefficient because:

- Bondi radius scales $\propto M_{BH}^2$

  (see Pacucci et al. 2017, Trinca et a. 2022, Zhu et al. 2022)

- BHs are easily displaced from the center of the halo

  (see Pfister et al. 2019, Ma et al. 2021)

- feedback from SNe and from the BH itself can evacuate the gas from low-mass galaxies

  (see Dubois et al. 2015, Anges-Alcazar et al. 2017, Habouzit et al. 2017, Prieto et al. 2017, Silk 2017, Smith et al. 2018, Regan et al. 2019, Bhowmick et al 2022, Koudmani et al. 2022, Lupi et al. 2024)

light seeds are generally found not to grow

seeds with $M_{BH} > 10^5\ M_{sun}$ grow in sufficiently massive galaxies with $M_* > 10^9\ M_{sun}$

WARNING! **this conclusion is challenged by JWST observations** **WARNING!**

seeds grow in favourable environments

- when they are embedded in a nuclear star cluster or within a circumnuclear disk,
  (see Alexander & Natarajan 2014, Lupi et al. 2016, Natarajan 2020)

- when they are born in a high density environment:
  at the halo center (Latif & Kochfar 2020)
  in overdense regions of the cosmic web (Lupi et al 2024, Quadri et al. 2025)
  in gas-rich protogalactic cores (Sassano et al. 2023, Shi et al. 2024, Mehta et al. 2024, Zana et al. 2025)

- if BH feedback is not very efficient (Massonneau et al. 2023, Lupi et al. 2024, Husko et al. 2025, Zana et al. 2025)

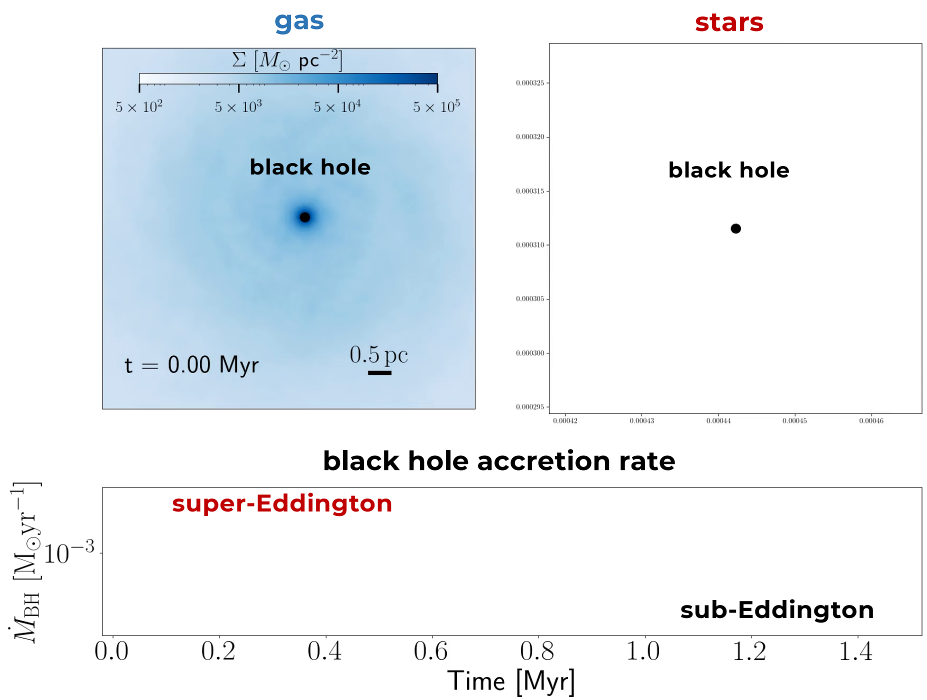
under these conditions, accelerated BH growth can occurr
in short bursts of super-Eddington accretion

super-Eddington accretion in protogalactic cores

different initial seed masses $5 \times 10^2\ M_{sun}$ - $10^5\ M_{sun}$ and feedback coupling efficiencies in a gas rich, metal-poor galaxy at $z \approx 15$
modified version of GASOLINE2, 0.18 pc resolution

Zana et al. (2025)

initial BH seed mass $5 \times 10^3\ M_{sun}$

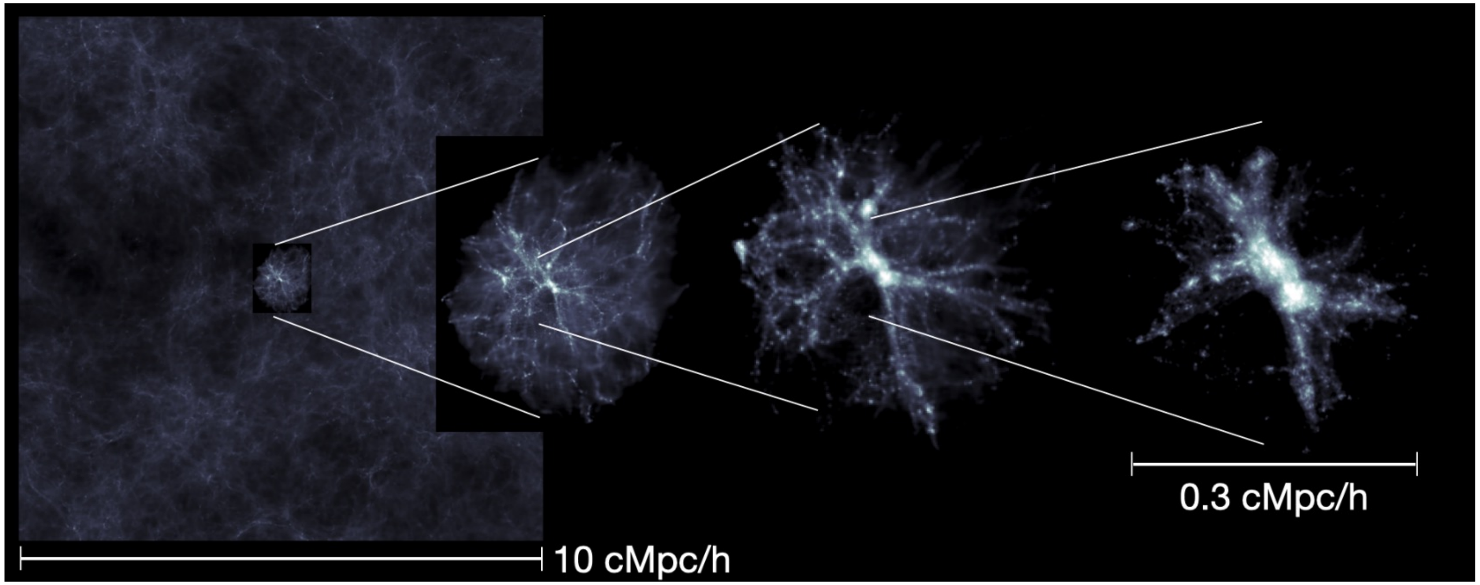


even the smallest initial seeds grow to $\approx 10^4\ M_{sun}$ - $10^5\ M_{sun}$ in < 1 Myr!

how do these results change in more realistic environments?

Caleno et al. in prep

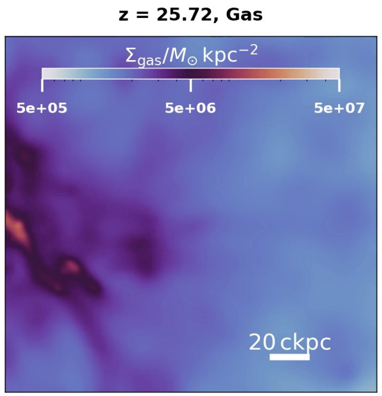
zoom-in simulation with GIZMO from a 10 Mpc box on a region undergoing a merger between two halos at z = 10

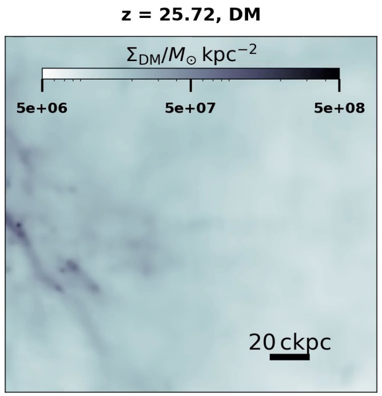


the final resolution is 1 pc and 2×10^3 M_{sun}

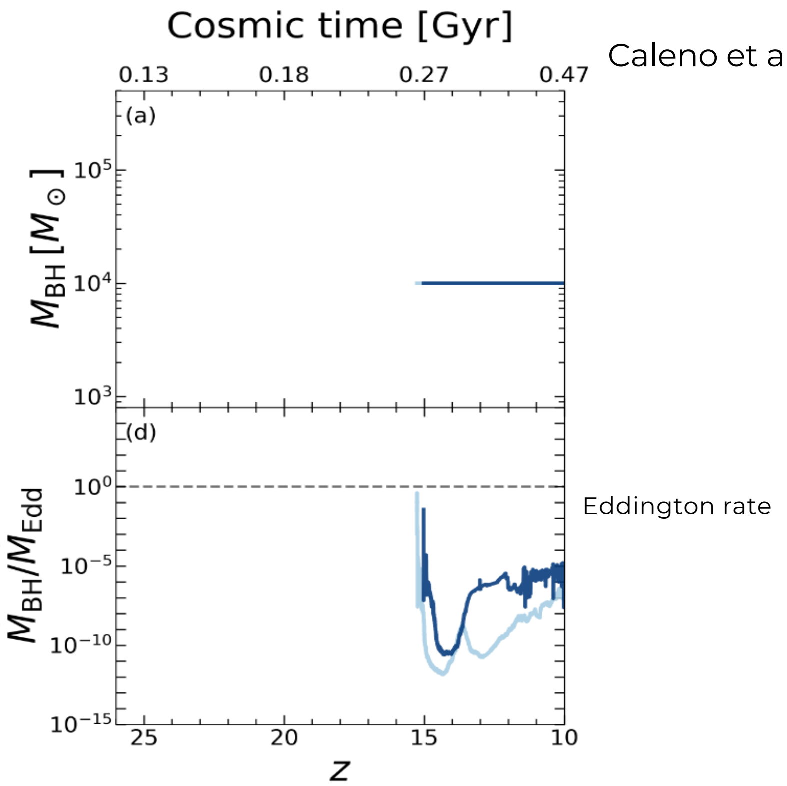
1) Different BH seeding conditions   2) Impact of black hole/supernova feedback on BH growth

how do these results change in more realistic environments?





- 10^4 M_{sun} BHs are seeded in 10^6 M_{sun} star clusters

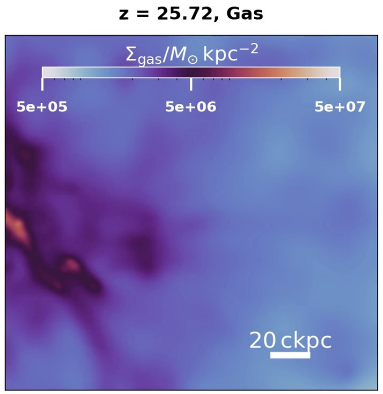


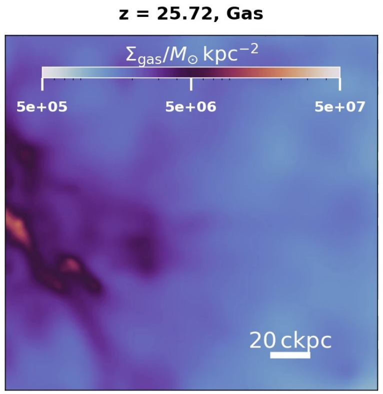
Caleno et al. in prep

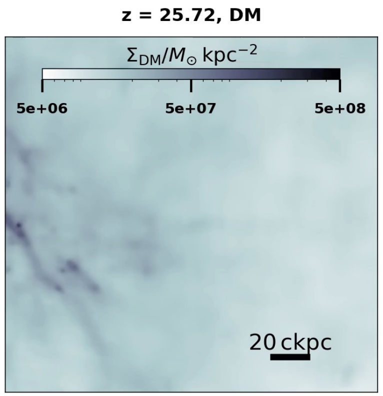
the two BHs are unable to grow due to strong SN feedback

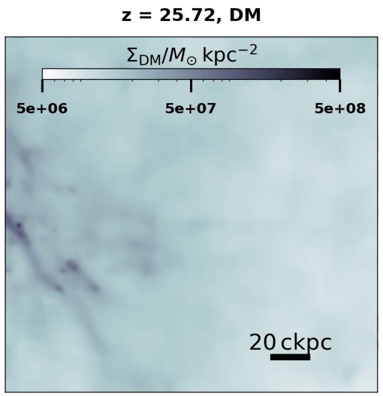
→ the applied seeding condition matters

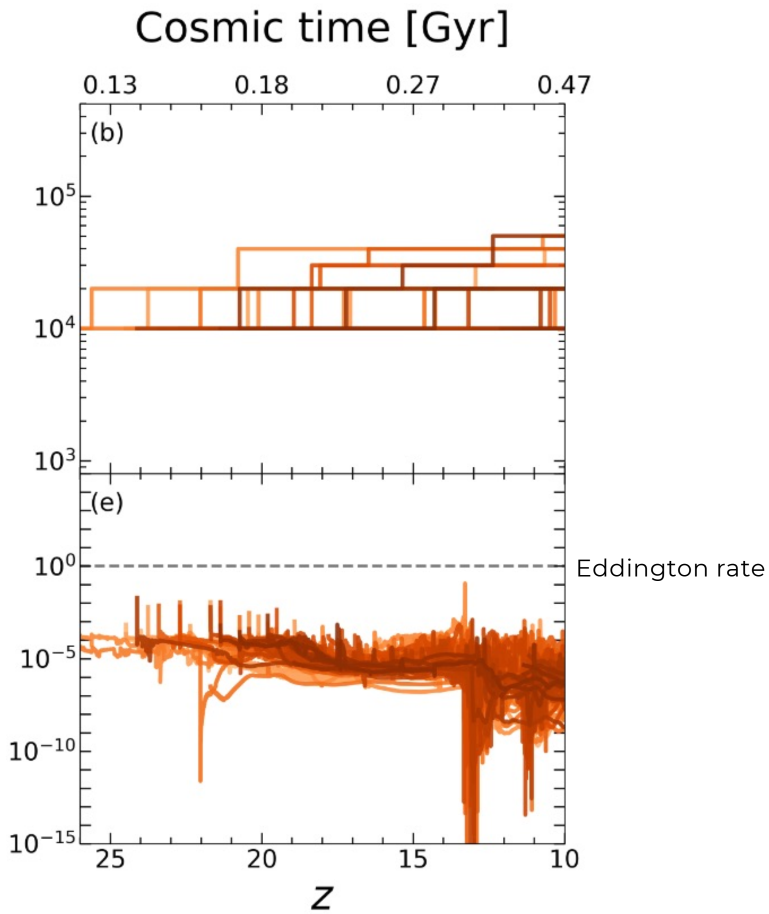
dependence on the seeding prescription









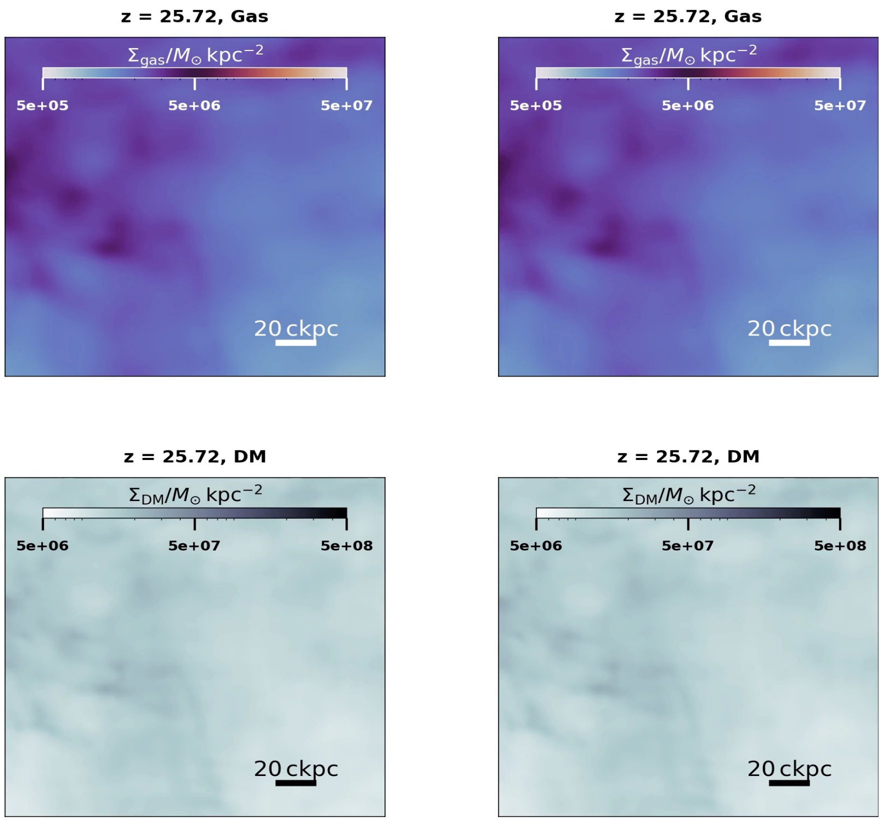


- 10^4 M_{sun} BHs are seeded in 10^6 M_{sun} star clusters

- 10^4 M_{sun} BHs are seeded in 10^6 M_{sun} gas clouds

competitive accretion and BH feedback suppress BH growth
BH mass increase only through mergers

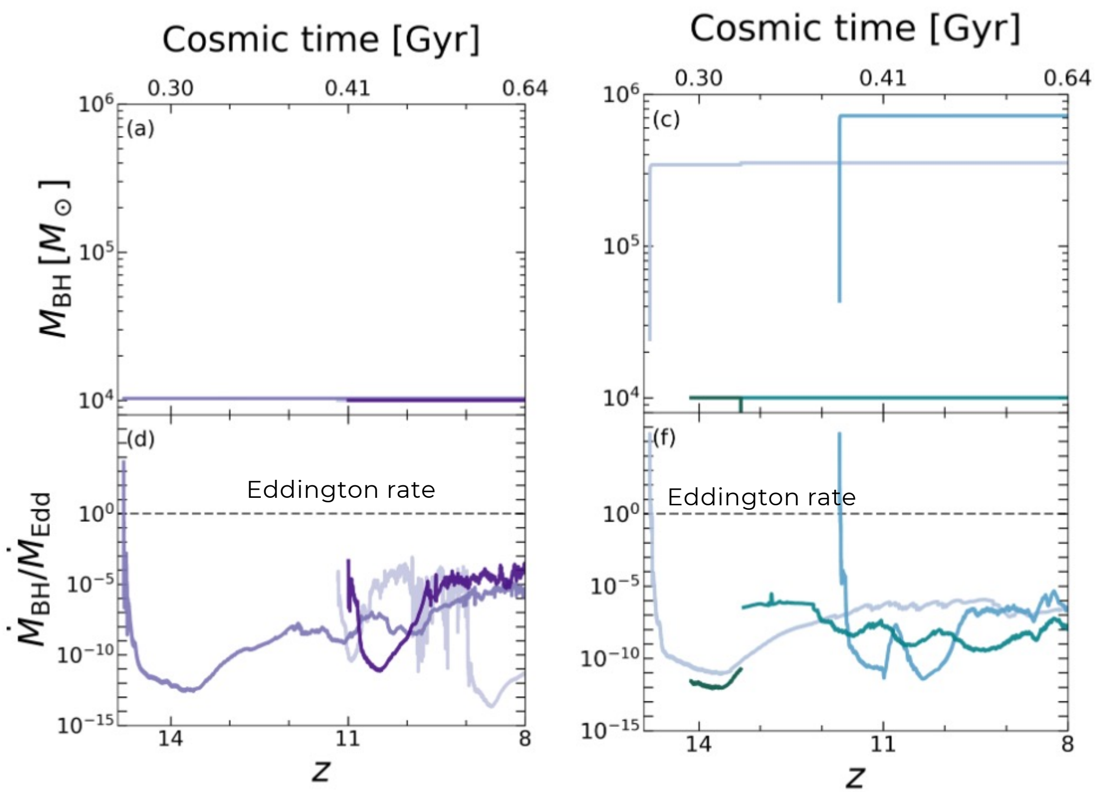
dependence on black hole feedback



radiative and kinetic feedback

no kinetic feedback

- 10^4 M_{sun} BHs are seeded in 10^6 M_{sun} star clusters



radiative and kinetic feedback

no kinetic feedback

the key mechanism regulating BH growth is kinetic feedback how can we test these scenarios?

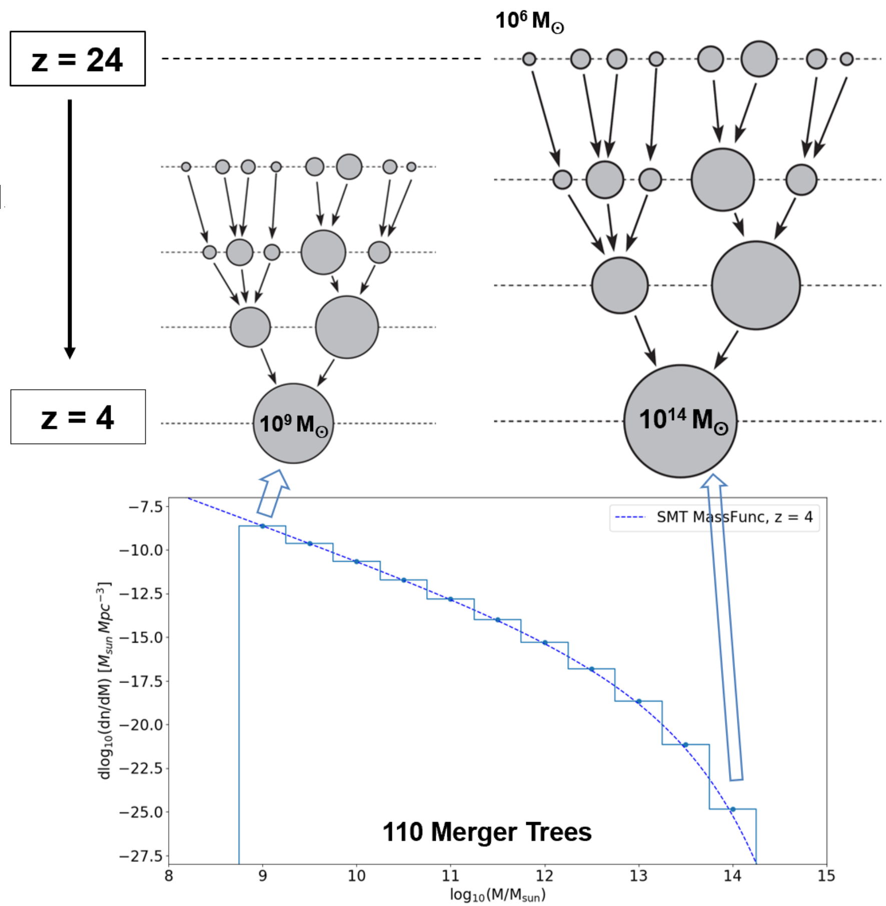
the Cosmic Archaeology Tool - **CAT**

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

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

Different accretion paradigms:

- Eddington-limited Bondi accretion
- super-Eddington. via slim disc accretion

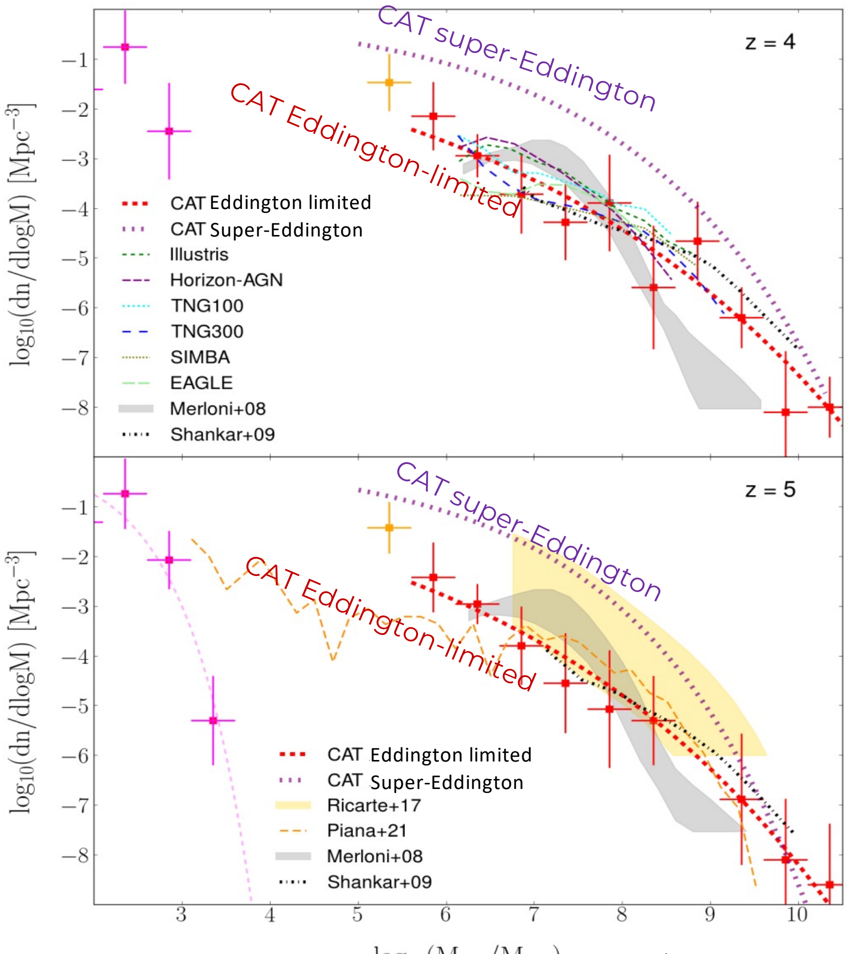


Model calibration:
reproduce the cosmic star formation history (SFRD)
reproduce obs. properties of high-z QSOs (L_{bol}, M_{BH})

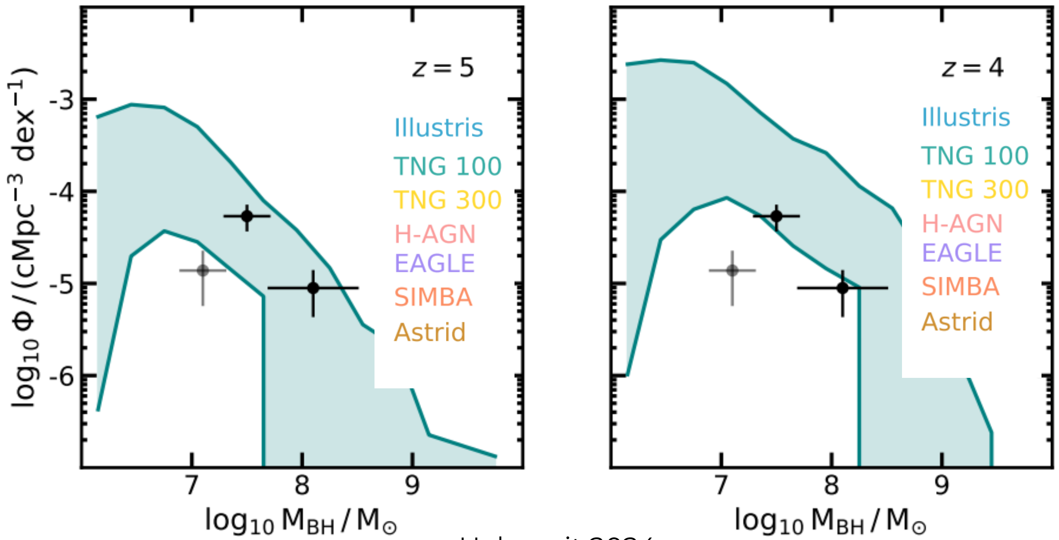
Trinca, RS. Valiante, Graziani, Zappacosta, Shankar, MNRAS 2022

the low-mass end of the black hole mass function

very sensitive to BH seeding and to the growth mode

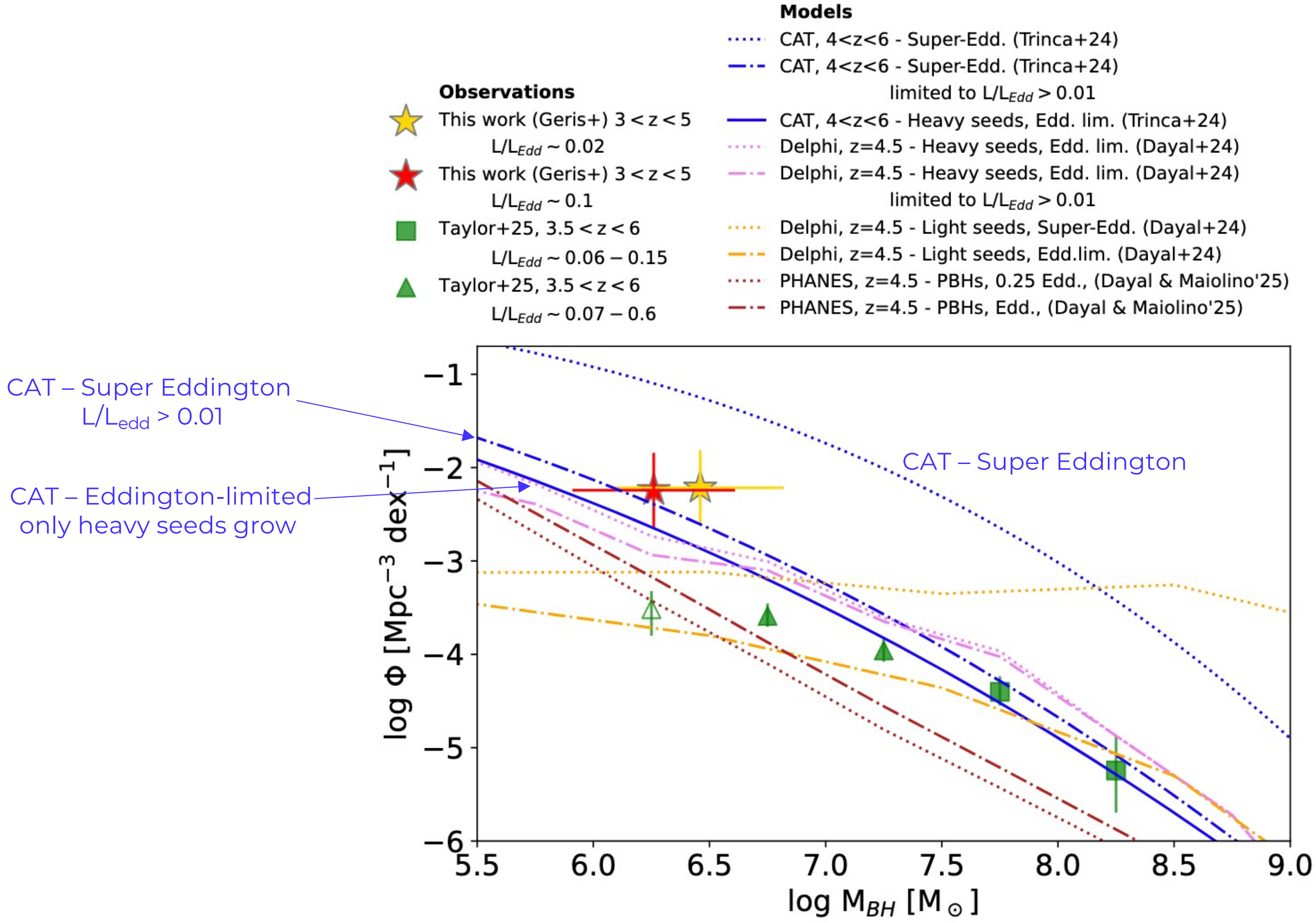


Trinca+2022



Habouzit 2024

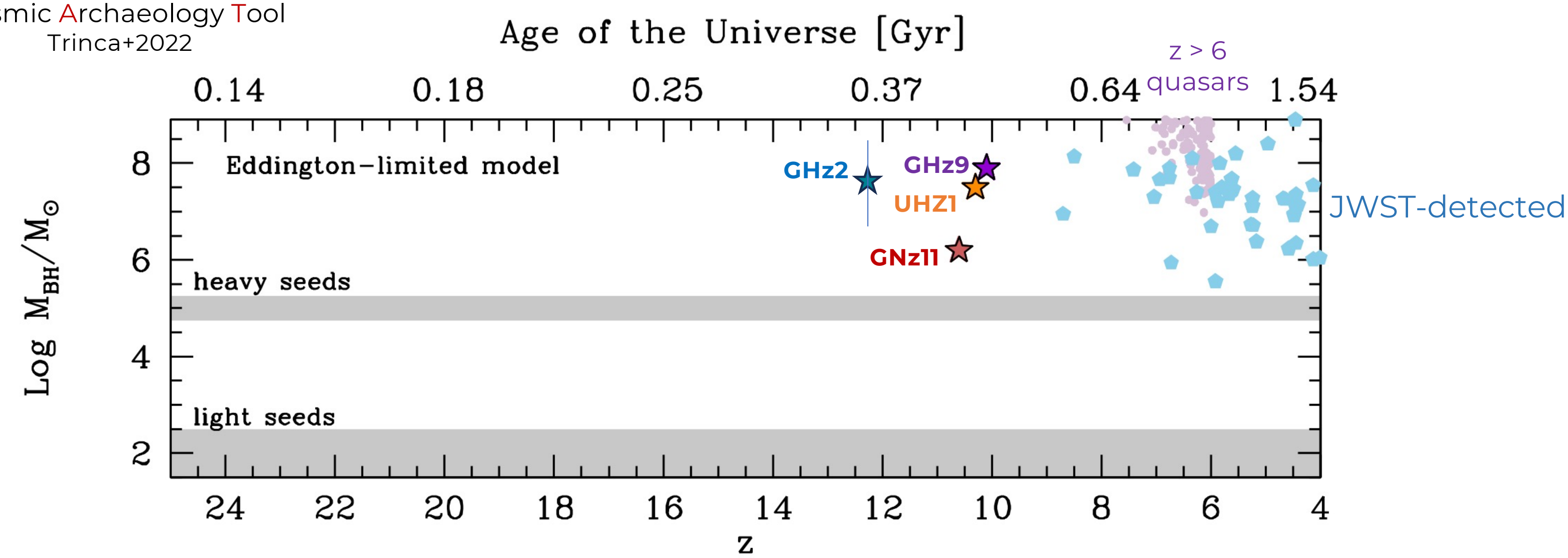
probing the low-mass end with JWST



Geris et al. 2025

implications of JWST-detected BHs at z > 10

Cosmic Archaeology Tool
Trinca+2022

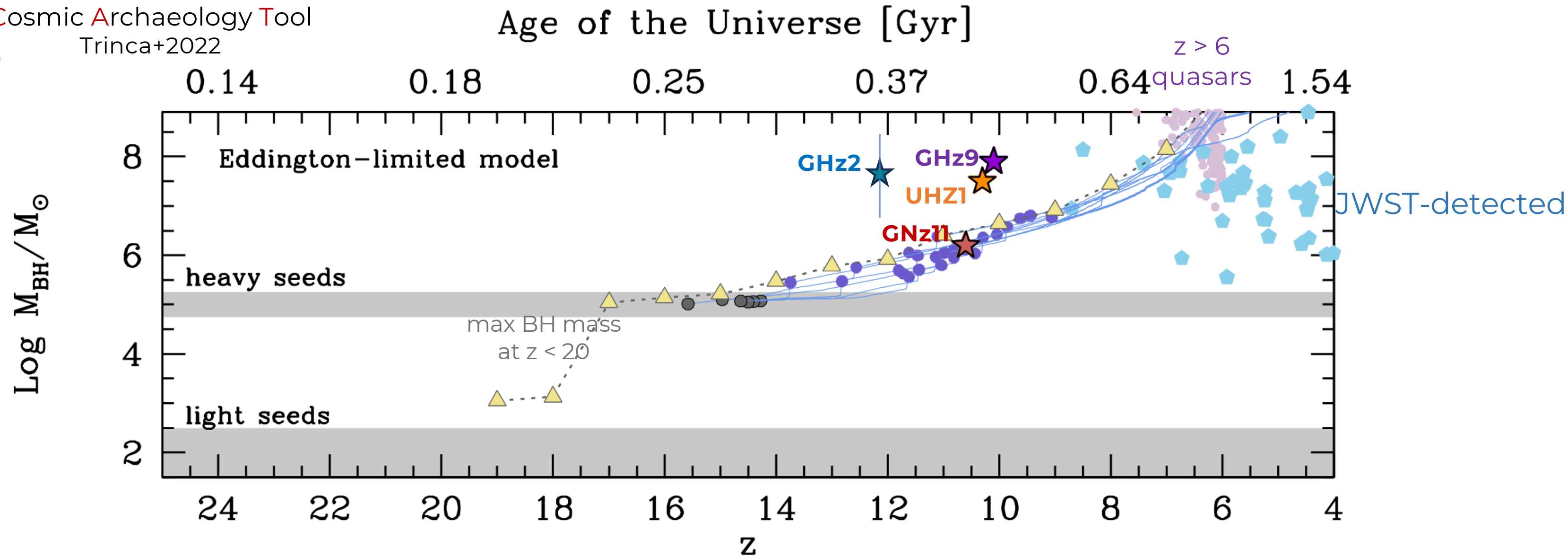


Schneider, Trinca+23

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

implications of JWST-detected BHs at z > 10

Cosmic Archaeology Tool
Trinca+2022



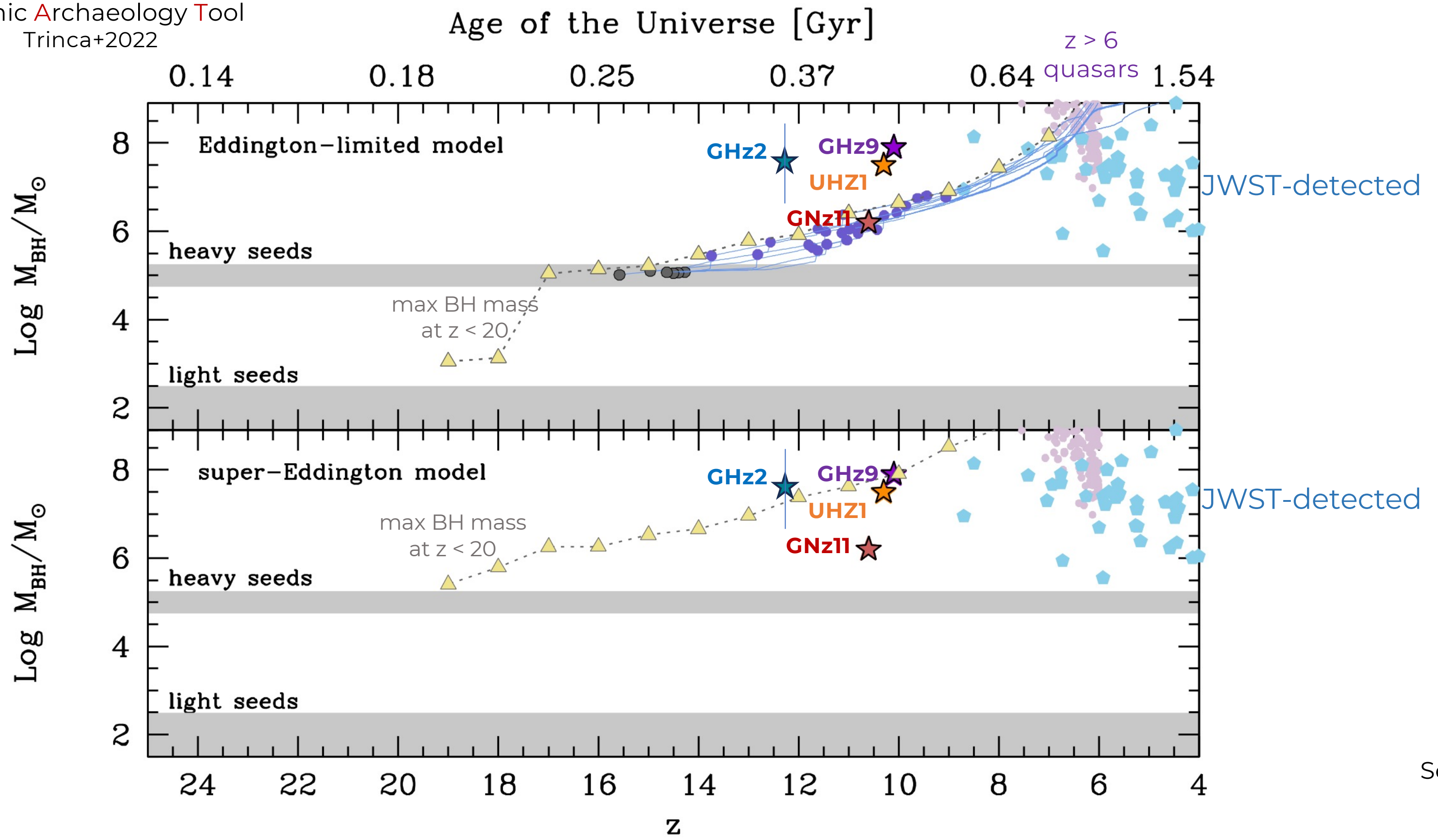
if BHs growth is Eddington-limited:
- GNz11 must originate from heavy BH seeds forming at z≈ 15
- estimated masses of UHZ1, GHZ9, and GHZ2 exceed the maximum BH mass at z ≈ 8 – 12.5

Schneider, Trinca+23

data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+24, Bogdan+23, Kokorev+24, Kovacs+24; Chavez Ortiz+25

implications of JWST-detected BHs at z > 10

Cosmic Archaeology Tool
Trinca+2022



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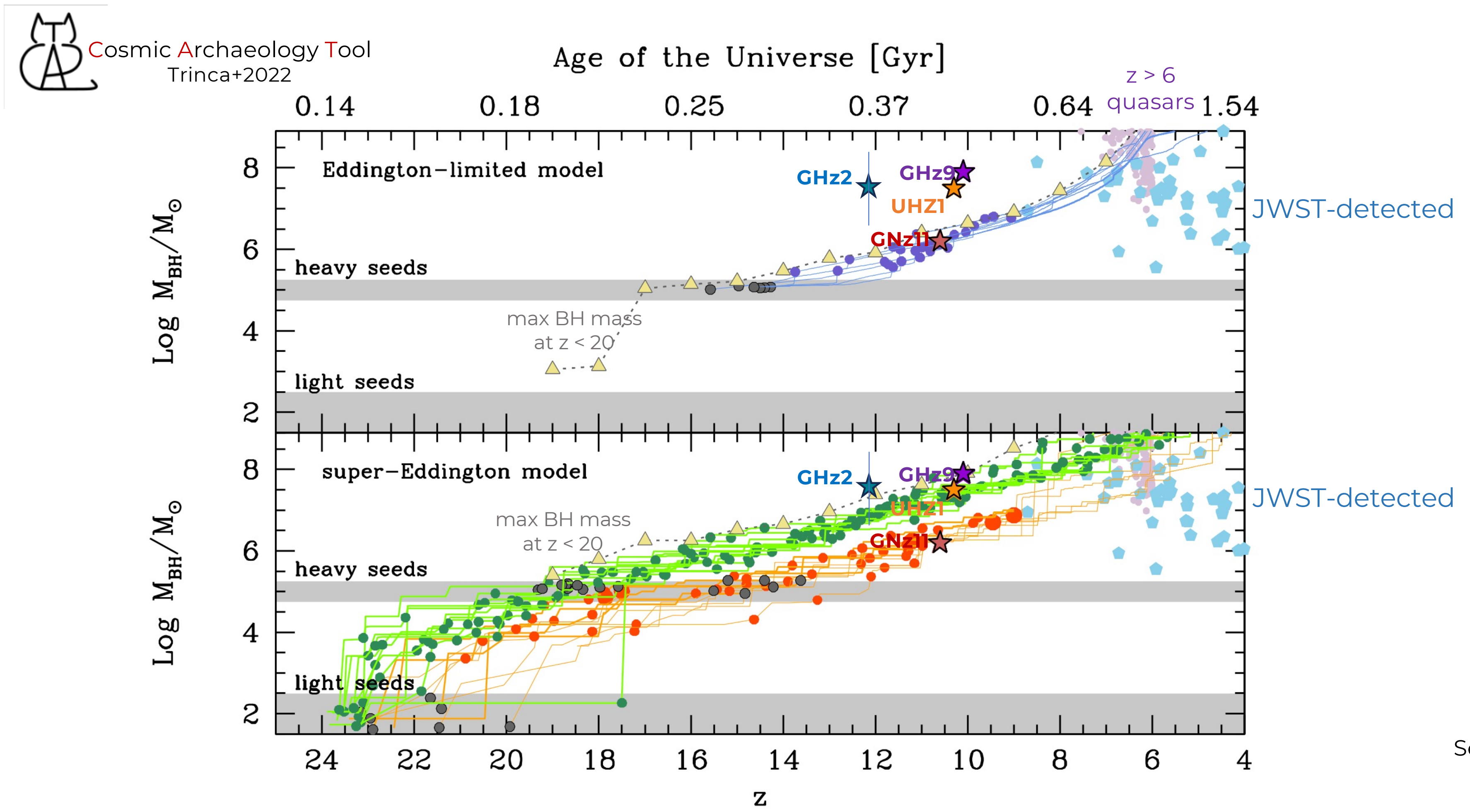
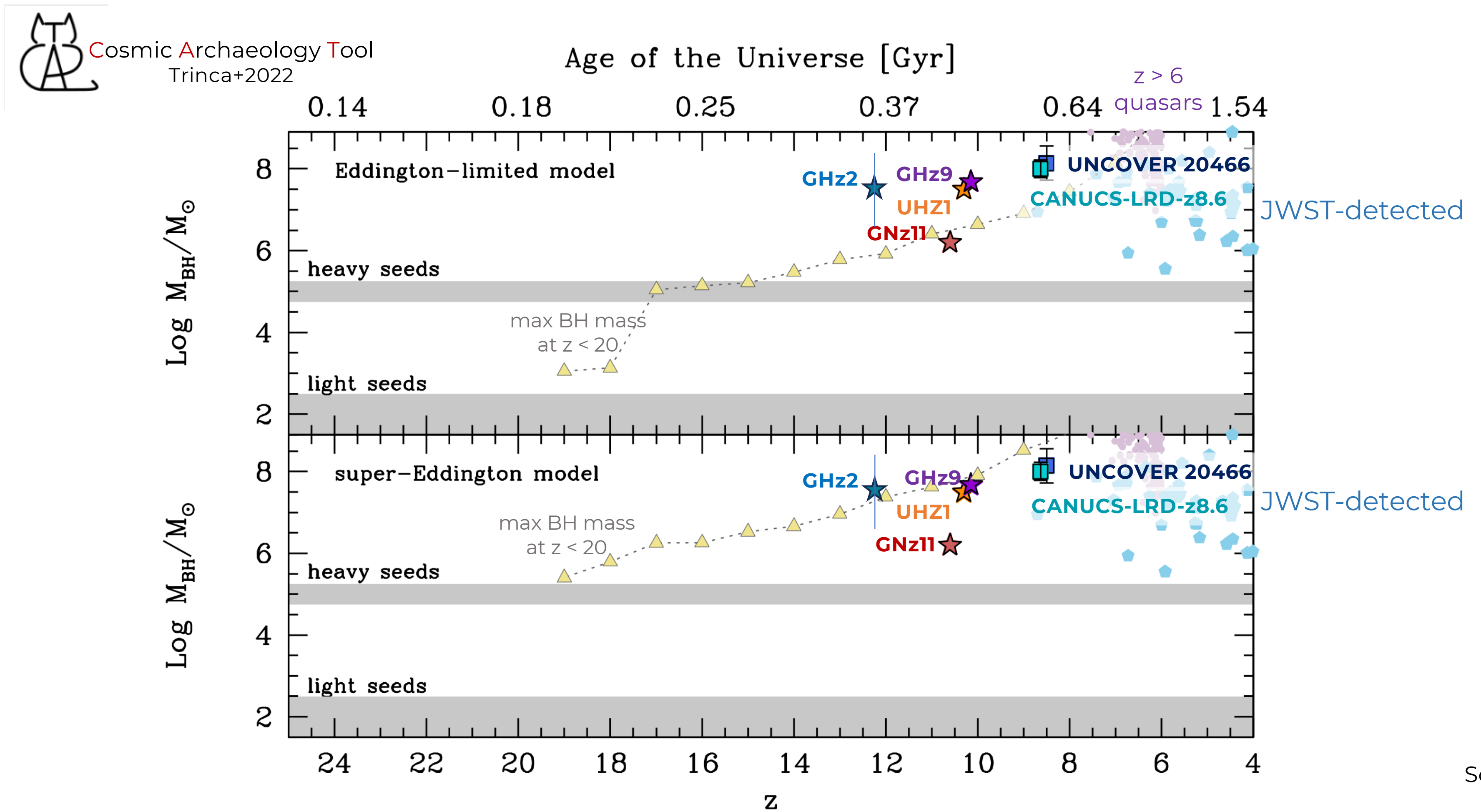


Schneider, Trinca+23

data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+24, Bogdan+23, Kokorev+24, Kovacs+24, Chavez Ortiz+25

two extreme objects at z ≈ 8



adapted from
Schneider, Trinca+23

data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+24, Bogdan+23, Kokorev+24, Kovacs+24; Chavez Ortiz+25, Napolitano+24; Tripodi+24

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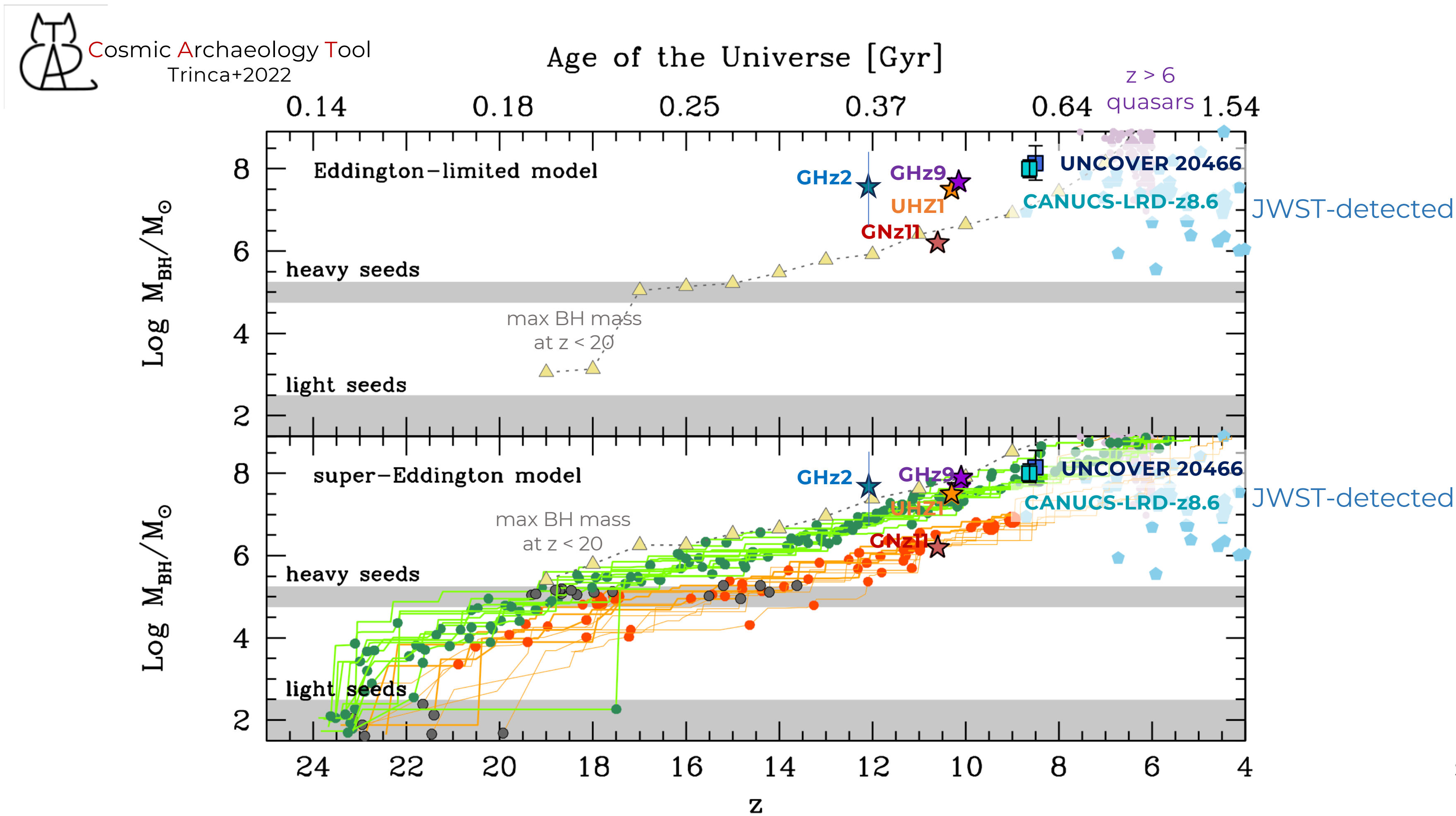

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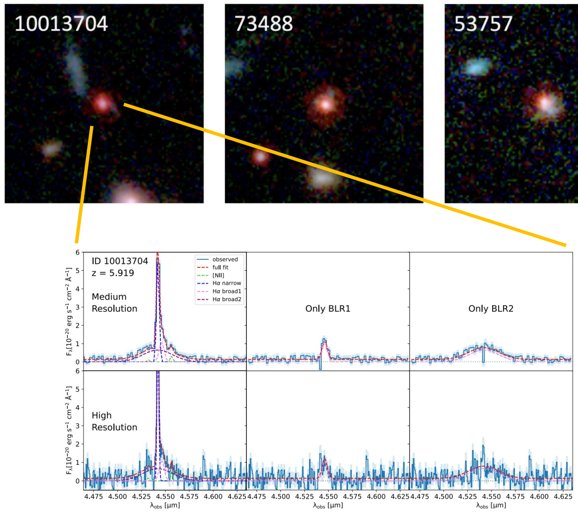
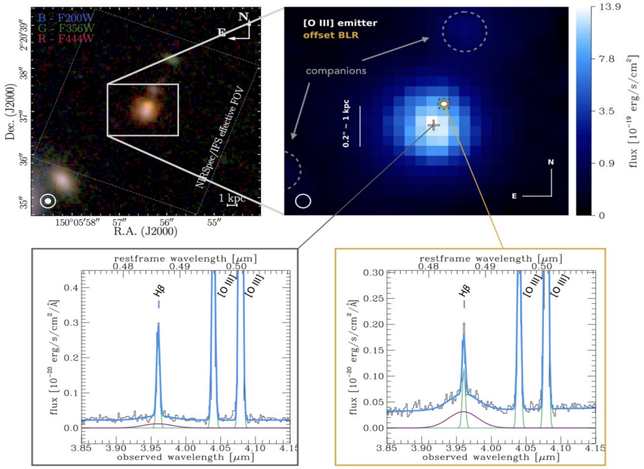
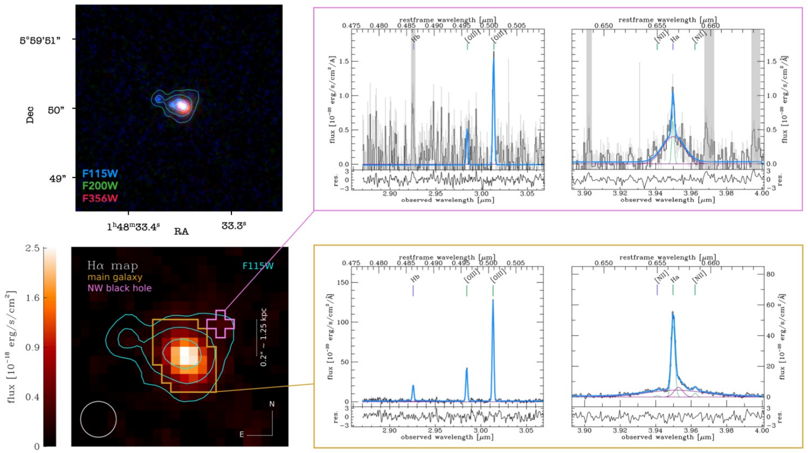
multiple massive BHs were common in the early Universe



Maiolino et al. 2024



Übler et al. 2024

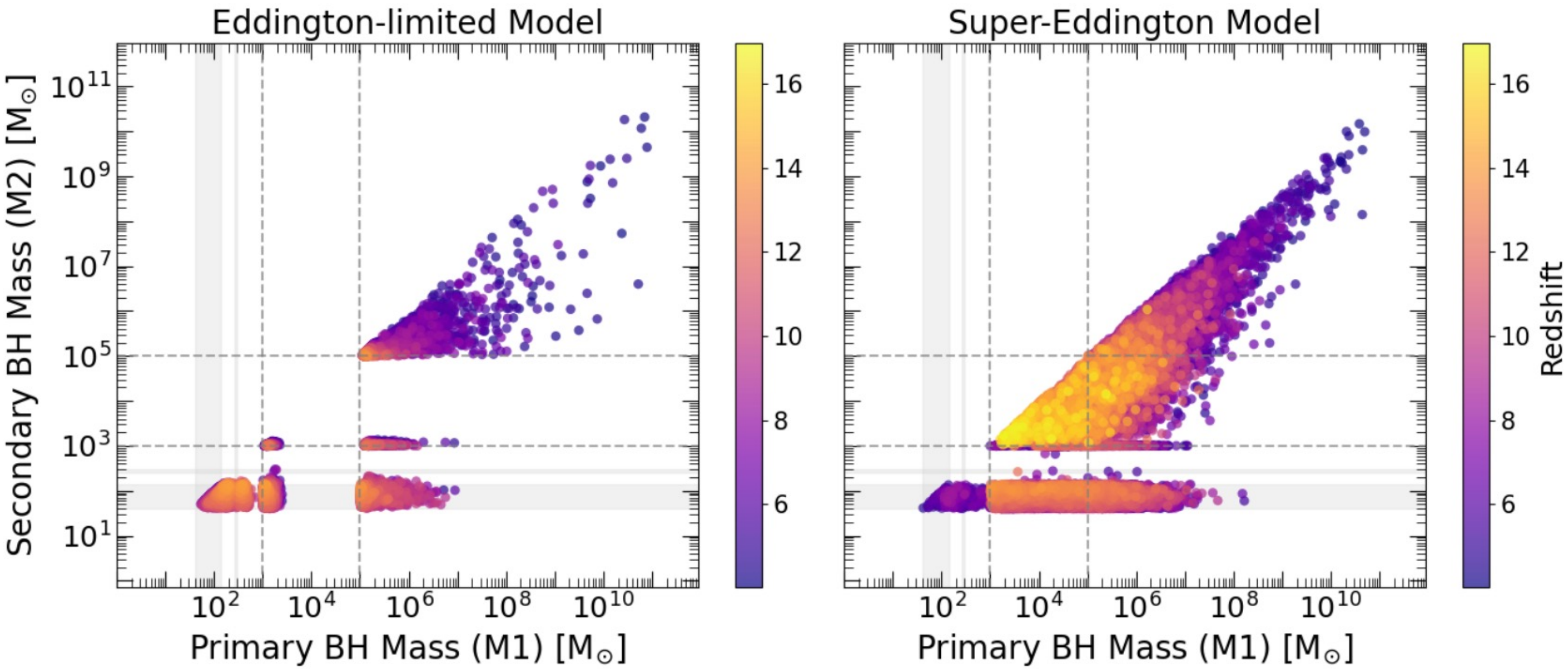


Übler et al. 2025

projected separations range between few kpc to few hundreds pc

see also Junkkarinen et al. 2001; Komossa et al. 2003; Comerford et al. 2009, 2013, 2015; Green et al. 2010; Husemann et al. 2018; Mannucci et al. 2022; Koss et al. 2023; Perna et al. 2023, 2025; Scialpi et al. 2024; Matsuoka et al. 2024; Zamora et al. 2024; Ulivi et al. 2025; Tanaka et al. 2024; Mérida et al. 2025

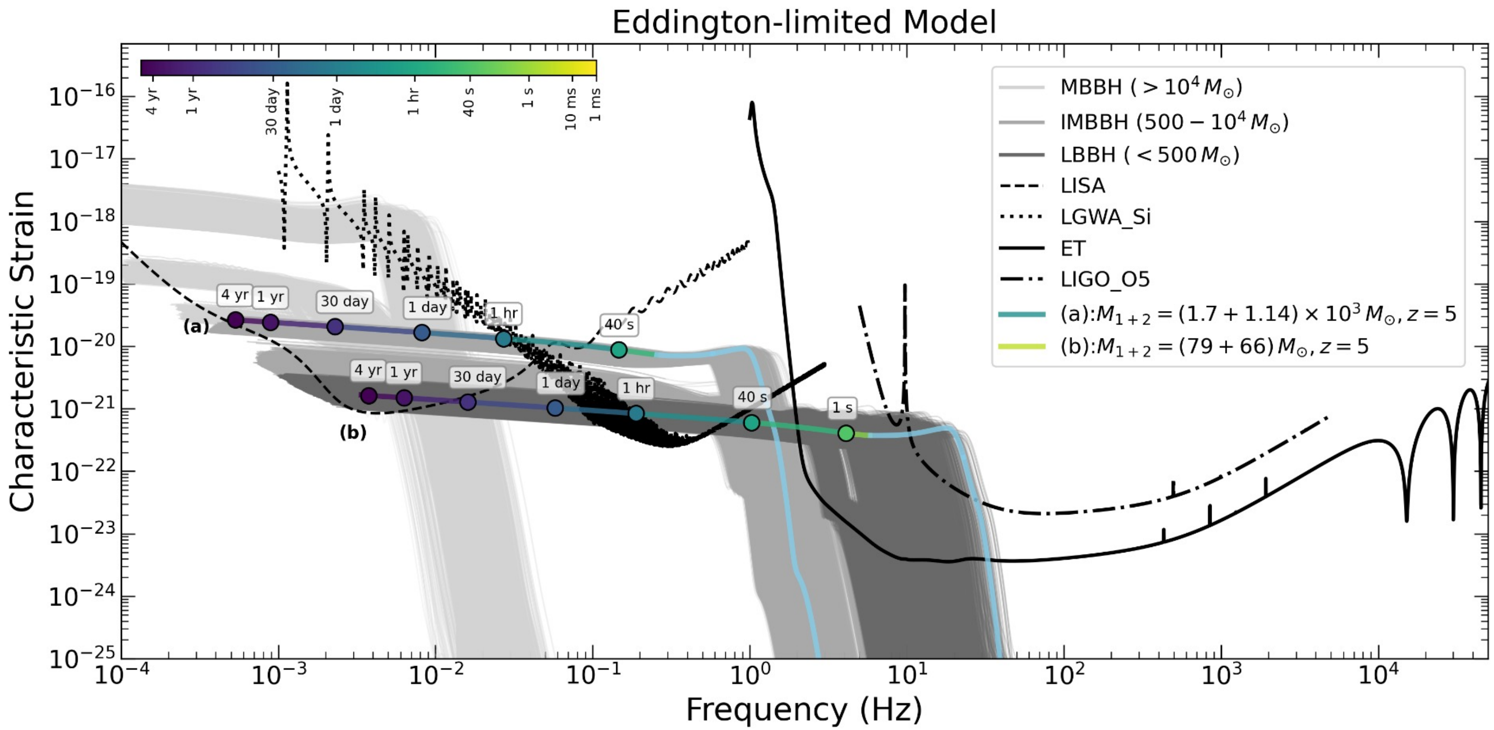
merging BHs across cosmic epochs



the different mass-redshift distributions reflect different growth modes of BH seeds

Davari, Valiante, Trinca, RS, et al. 2026

GW signals from growing BH seeds



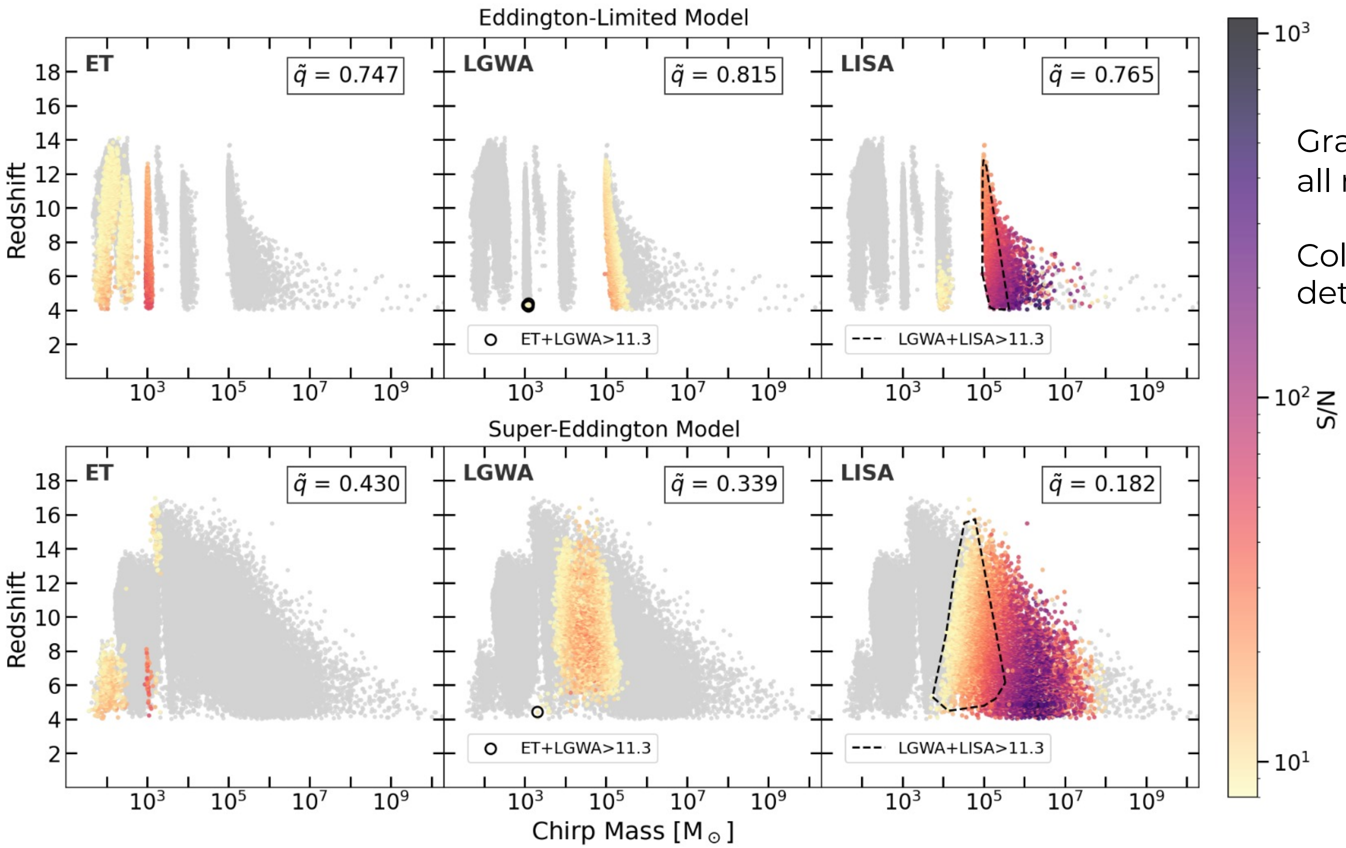
future GW telescopes on the ground and in space open up a new window to constrain the merging binary BH population across a broad mass/redshift range

Davari, Valiante, Trinca, RS, et al. 2026

imprints on GW signals of growth mode

EL model
nearly equal-mass binaries
(q ≈ 0.7 – 0.8)

SE model
more asymmetric mergers
(q ≈ 0.2 – 0.4)



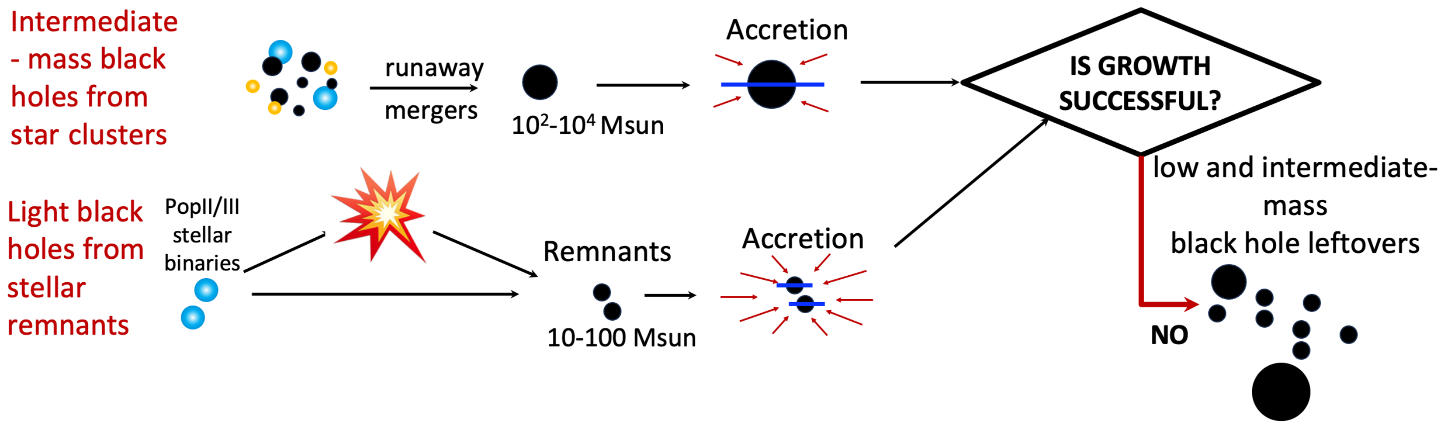
Gray:
all mergers

Colours:
detectable mergers

the mass and redshift range that would be accessible by 3G detectors depend on the accretion mode!

Davari, Valiante, Trinca, RS, et al. 2026

3. failed black hole seeds

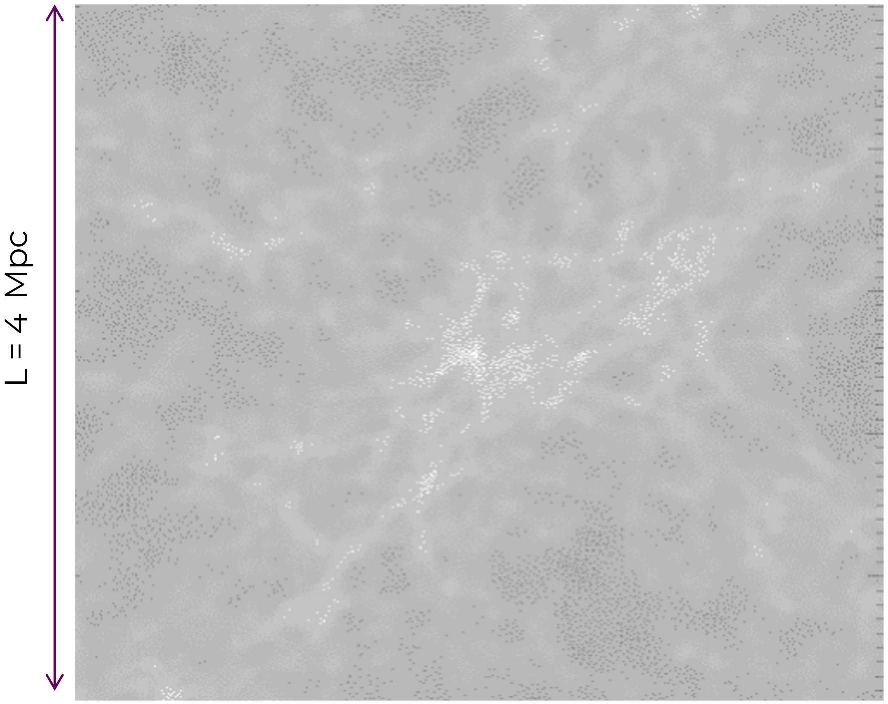


Credits: R. Maiolino, M. Mapelli, R. Schneider, M. Volonteri

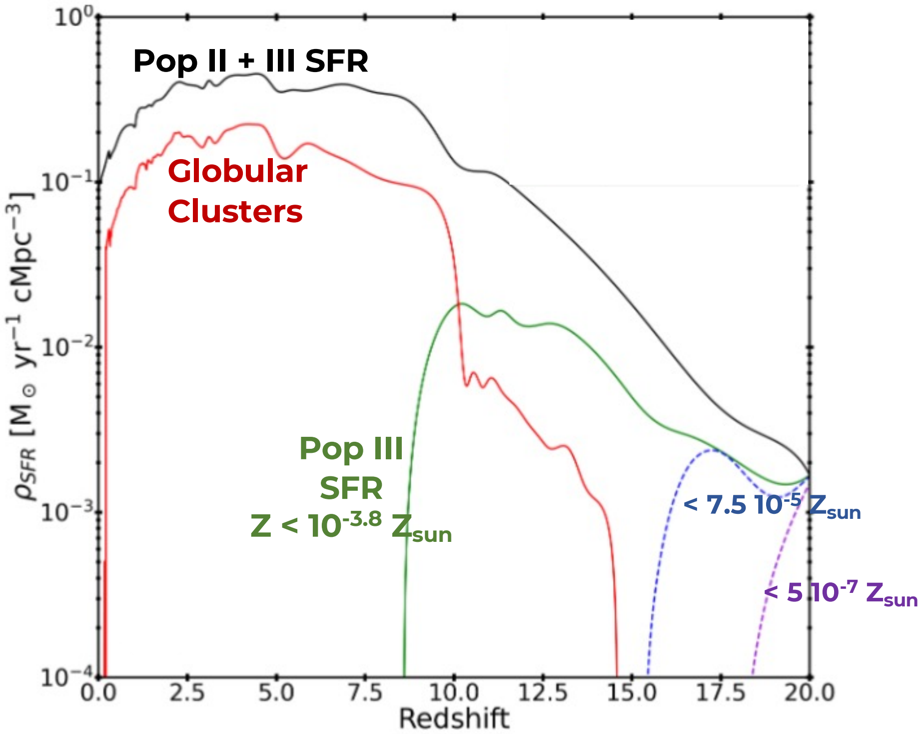
tracing stellar BBHs through cosmic times

See also Mestichelli+25, Arca Sedda+26

GAMESH: high-res simulation of a Local Group-like volume



Graziani et al. 2015, 2017

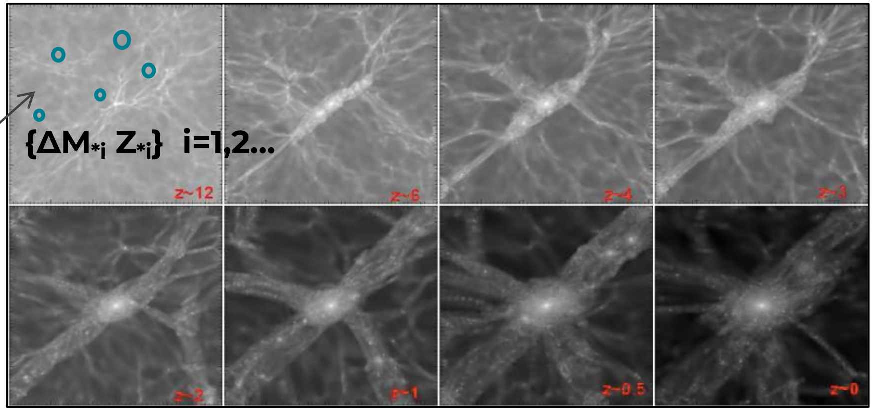


Angeloni+2026a

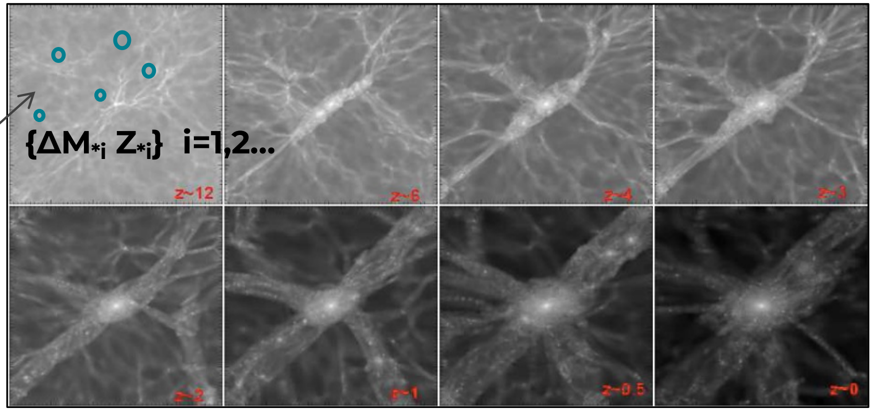
Schneider+17, Marassi+19, Graziani+2020

formation and coalescence sites of isolated BBHs

Binary Population Synthesis models



formation and coalescence sites of isolated BBHs

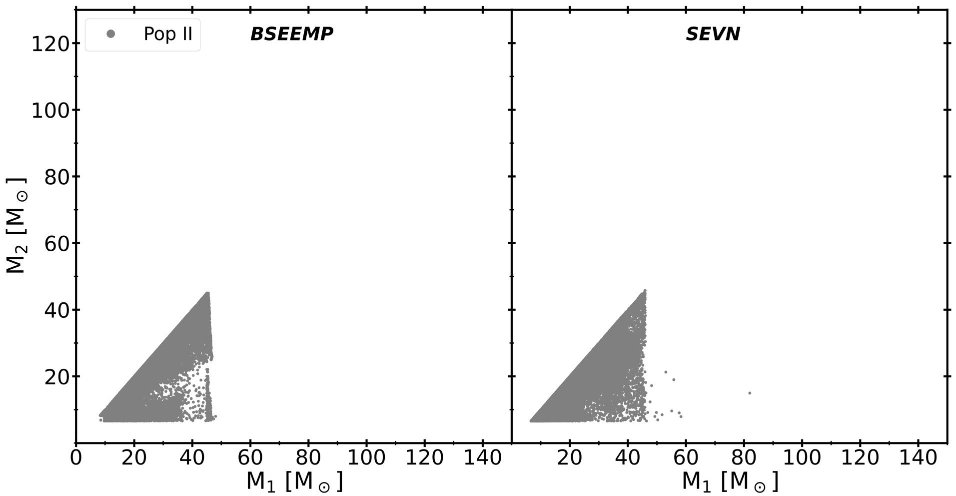


Binary Population Synthesis models

BSEEMP (Tanikawa+21)

SEVN (Iorio+23)

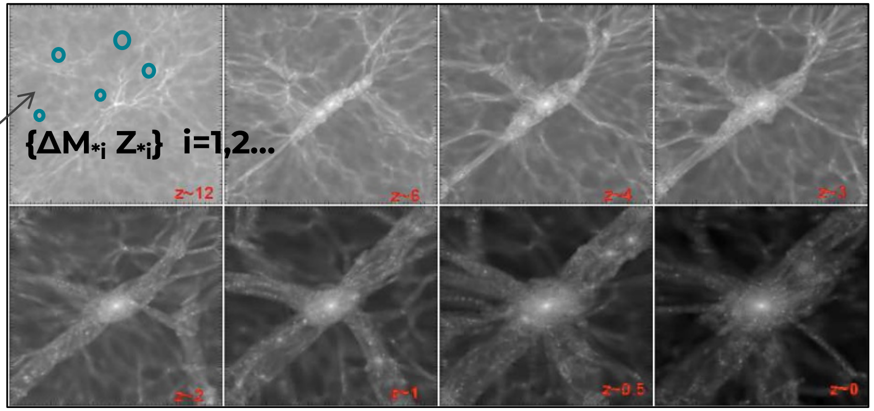
Similar Pop II BBHs mass distributions in the two models



Angeloni+ in prep

formation and coalescence sites of isolated BBHs

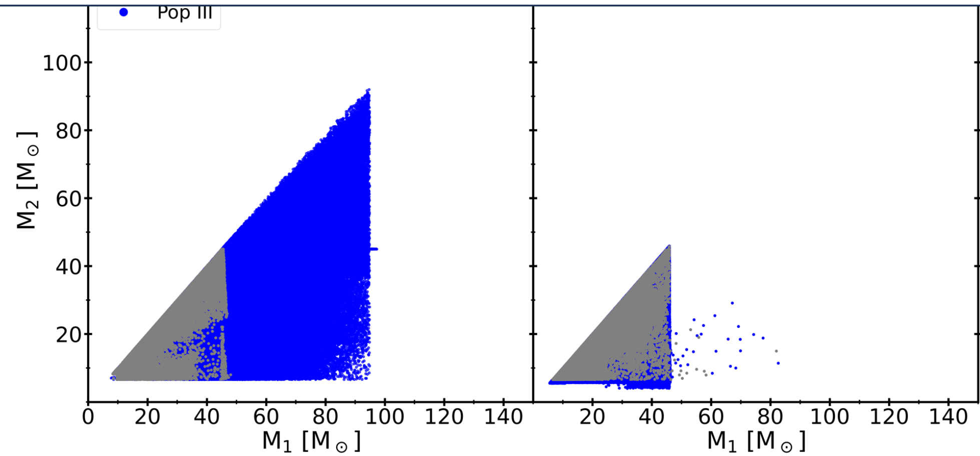
Binary Population Synthesis models



BSEEMP (Tanikawa+21) SEVN (Iorio+23)

differences due to treatment of convective overshooting is critical for massive Pop III stellar remnants!

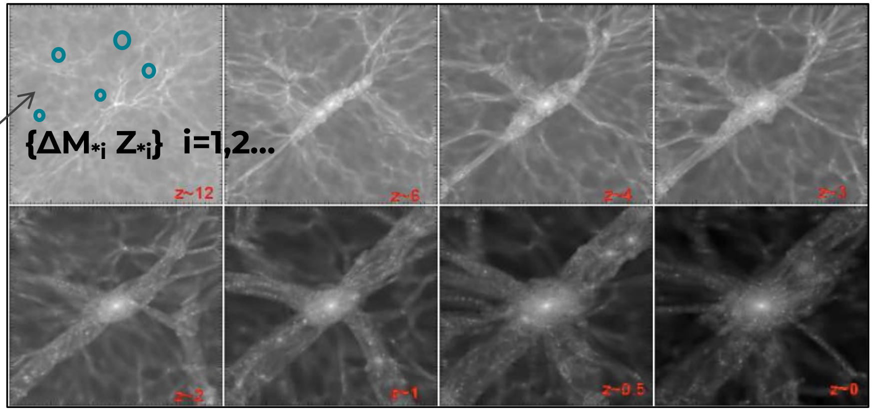
BBHs formed from Pop III binaries can reach component masses ≈ 90 M_{sun}



BBHs formed from Pop III binaries have component masses < 50 M_{sun}

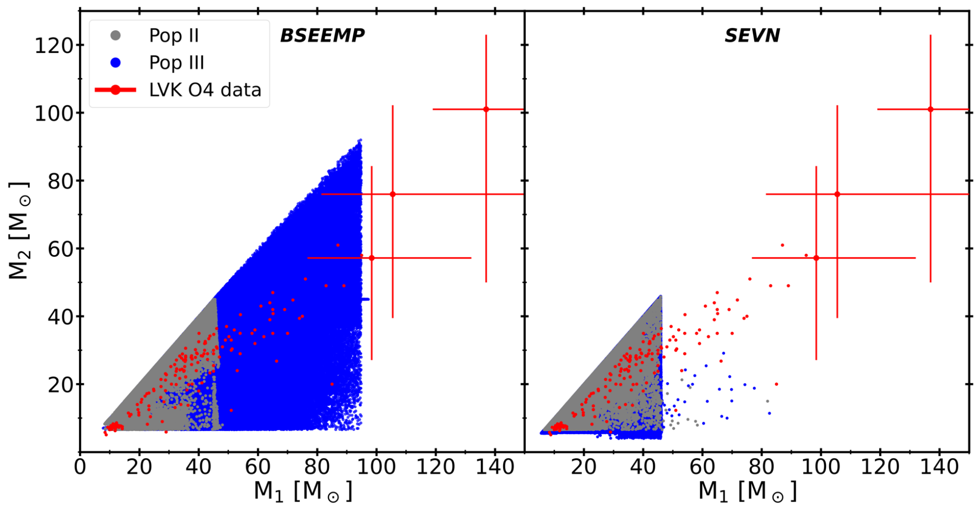
Angeloni+ in prep

formation and coalescence sites of isolated BBHs



Binary Population Synthesis models

BSEEMP (Tanikawa+21) SEVN (Iorio+23)



BBHs formed from Pop III binaries can reach component masses ≈ 90 M_{sun}

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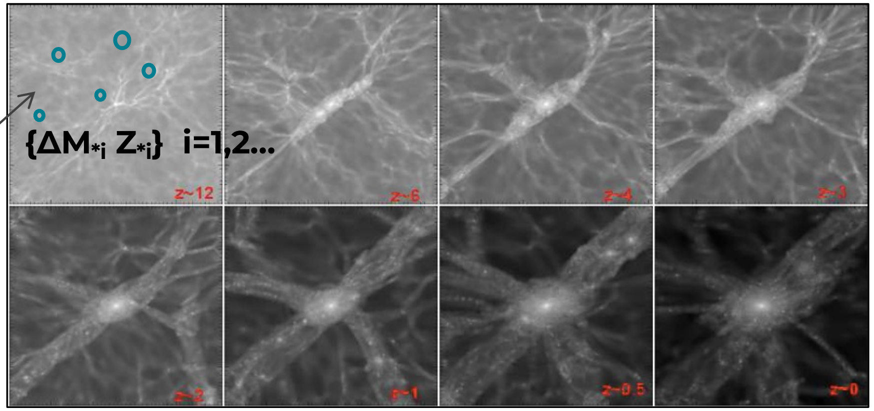
Angeloni+ in prep

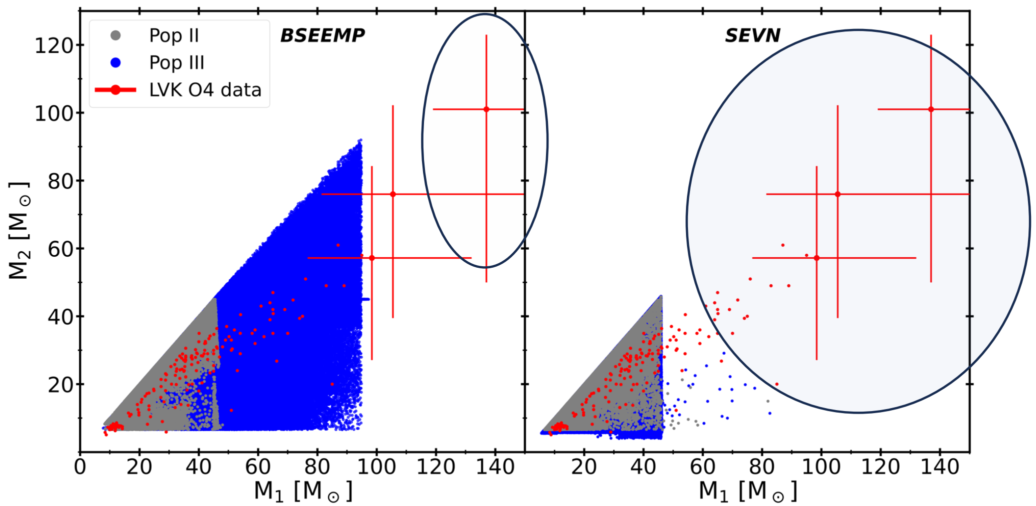
formation and coalescence sites of isolated BBHs



Binary Population Synthesis models

BSEEMP (Tanikawa+21)

SEVN (Iorio+23)

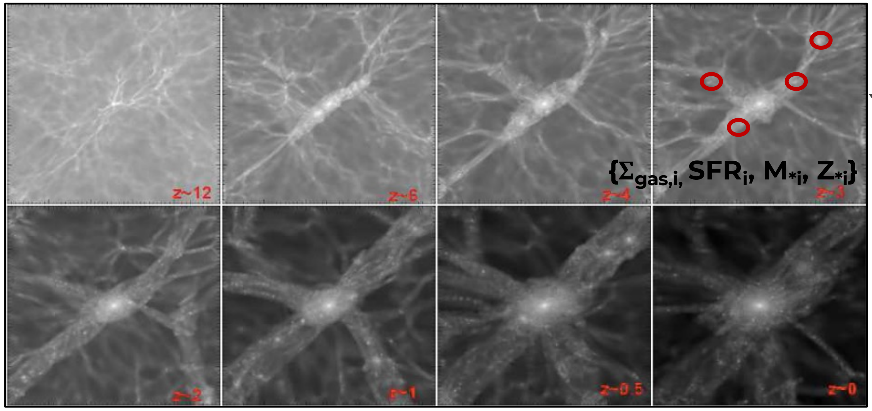


BBHs formed from Pop III binaries can reach component masses ≈ 90 M_{sun}

BBHs formed from Pop III binaries have component masses < 50 M_{sun}

Angeloni+ in prep

formation sites of globular clusters and dynamically formed BBHs



$\{\Sigma_{gas,i}, SFR_i, M_{*i}, Z_{*i}\}$ i=1,2...

globular clusters

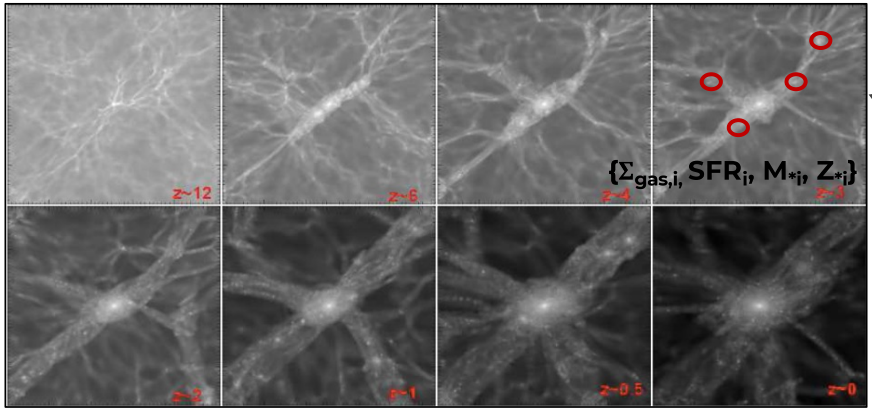
Cluster Population Synthesis models

FASTCLUSTER
(Mapelli et al. 2021; Torniamenti et al. 2024)

RAPSTER
(Kritos et al. 2023, 2024)

Angeloni+2026a

formation sites of globular clusters and dynamically formed BBHs



$\{\Sigma_{gas,i}, SFR_i, M_{*i}, Z_{*i}\}$ i=1,2...

globular clusters

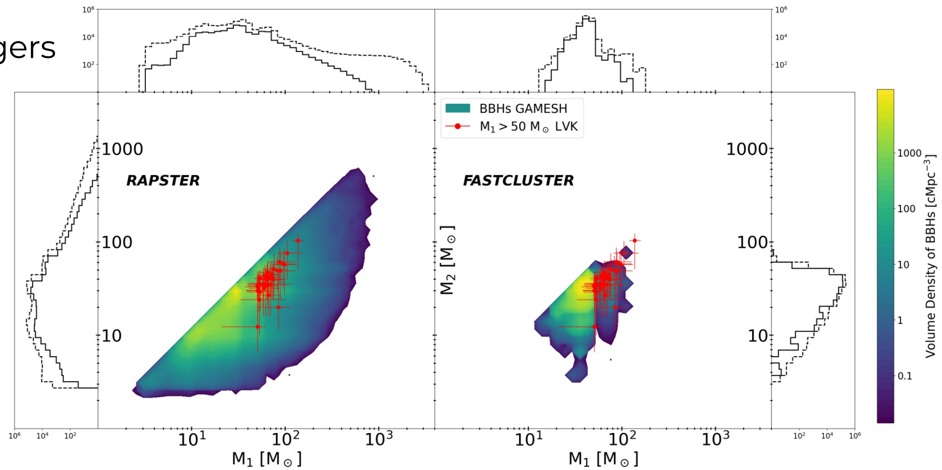
Cluster Population Synthesis models

FASTCLUSTER
(Mapelli et al. 2021; Torniamenti et al. 2024)

RAPSTER
(Kritos et al. 2023, 2024)

GWFISH

detectable BBH mergers with S/N>8



4 M_{sun} < M_{BH} < 4000 M_{sun}

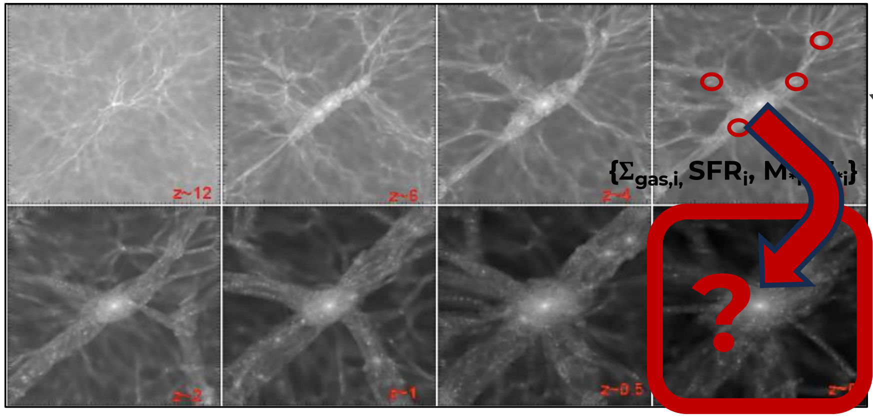
$R_{BBH} \approx 21.2$ Gpc^{-3} yr^{-1}

15 M_{sun} < M_{BH} < 200 M_{sun}

$R_{BBH} \approx 12.9$ Gpc^{-3} yr^{-1}

Angeloni+2026a

formation sites of globular clusters and dynamically formed BBHs



globular clusters

Cluster Population Synthesis models

FASTCLUSTER
(Mapelli et al. 2021; Torniamenti et al. 2024)

RAPSTER
(Kritos et al. 2023, 2024)

- ≈ 90% of observable IMBHs (with masses > 1000 M_{sun}) are formed in MW-progenitors
- ≈ 5% (238) are predicted to reside in the MW disk/center
- 4 IMBHs are predicted to reside in MW halo GCs

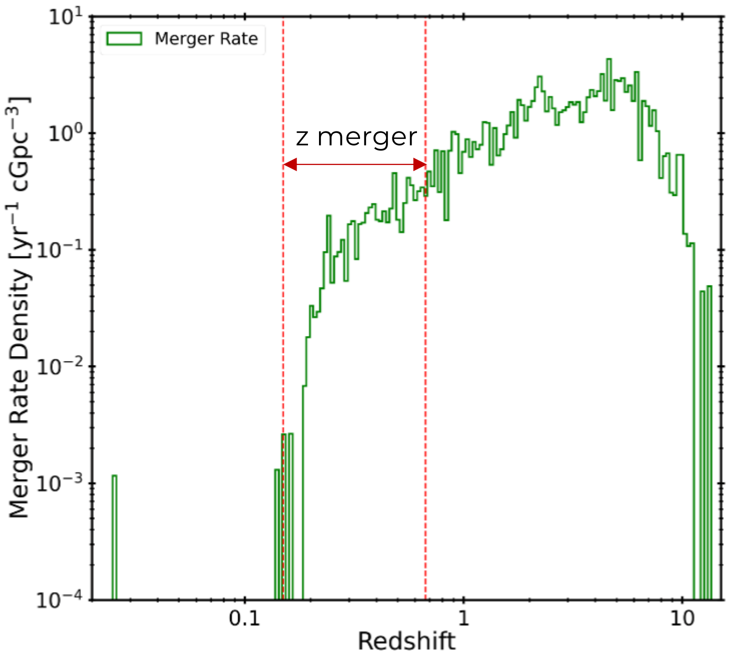
Angeloni+2026a

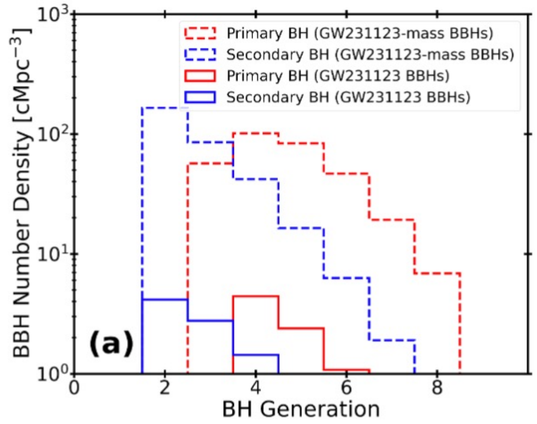
investigating the formation channel of GW231123: Population III stars or hierarchical mergers?

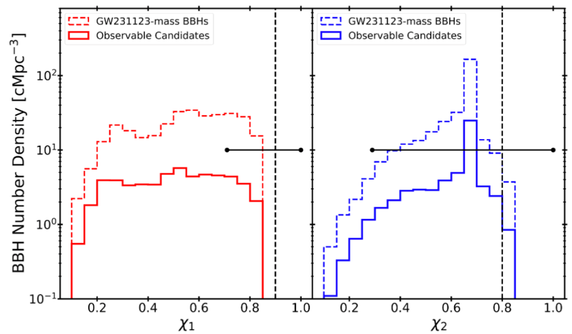
See also Paiella+25

GW231123: $M_1 \approx 137\ M_{sun}$ $M_2 \approx 103\ M_{sun}$ $z \approx 0.39$ $\chi_1 \approx 0.9$, $\chi_2 \approx 0.8$ (Abac+25)

dynamically formed BBH







Angeloni+26b

Conclusions

❖ paradigm shifts in black hole seed classification:
light-to-intermediate-to-heavy black hole seeds reflect the varying environmental conditions present throughout galaxy evolution and can form within the same host galaxy

❖ growing black hole seeds is challenging:
models show it may require favourable conditions but nature seems to have overcome the challenge!

❖ despite the enormous progresses, it is hard to derive tight constraints from data:
seeds must form early – before significant SF occurs in their host galaxy - and grow fast, perhaps in short super-Eddington bursts

❖ GW telescopes have the potential to constrain these scenarios
towards a unifying picture of black holes across scales and times!