Learning the Deep Mysteries of Nature with Cosmology

Fiera di Primiero, 9 – 12 Sept 2025

ending the cosmic dark ages: the formation of the first stars and black holes

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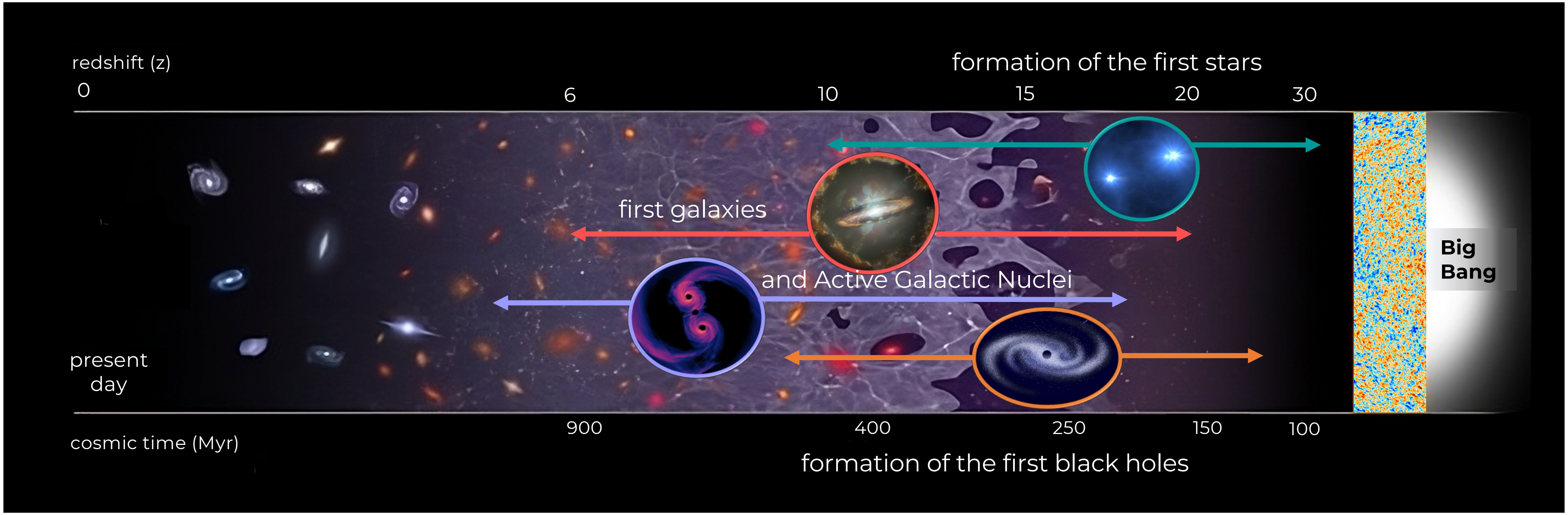
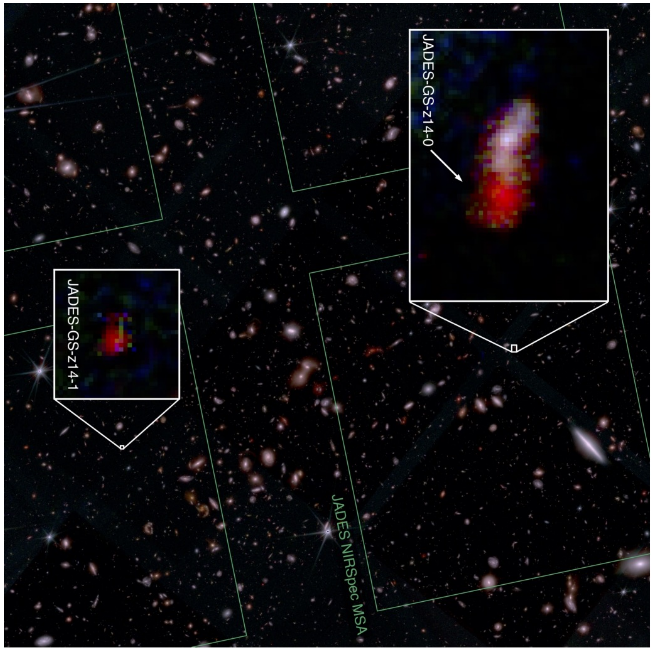
MUR Ministero dell'Università e della Ricerca

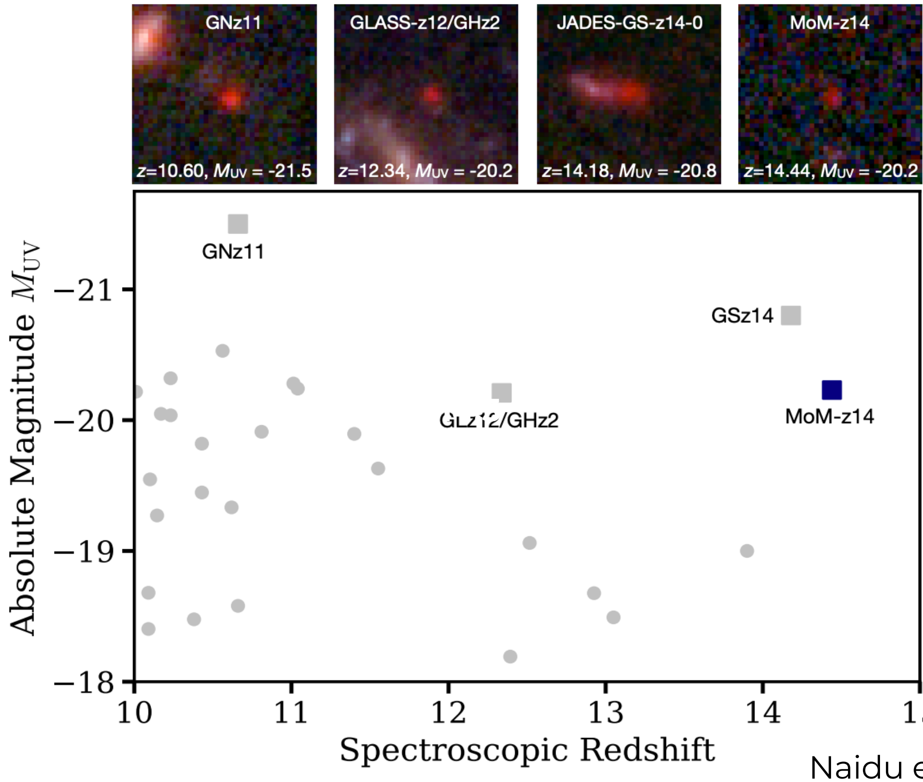
the transition from the cosmic dark ages into cosmic dawn



JWST revolution: an unprecedented leap forward



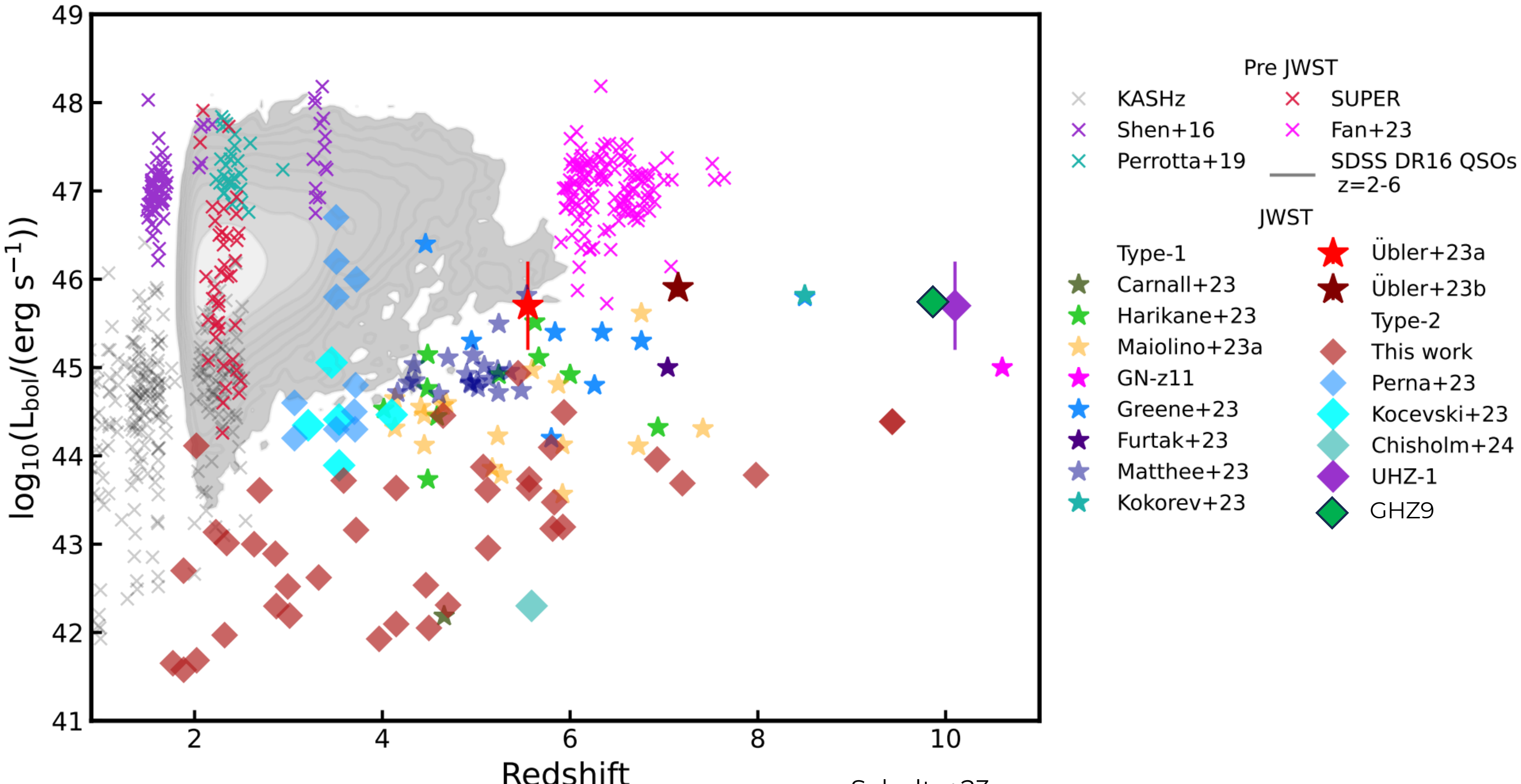
Carniani et al. 2024



Naidu et al. 2025

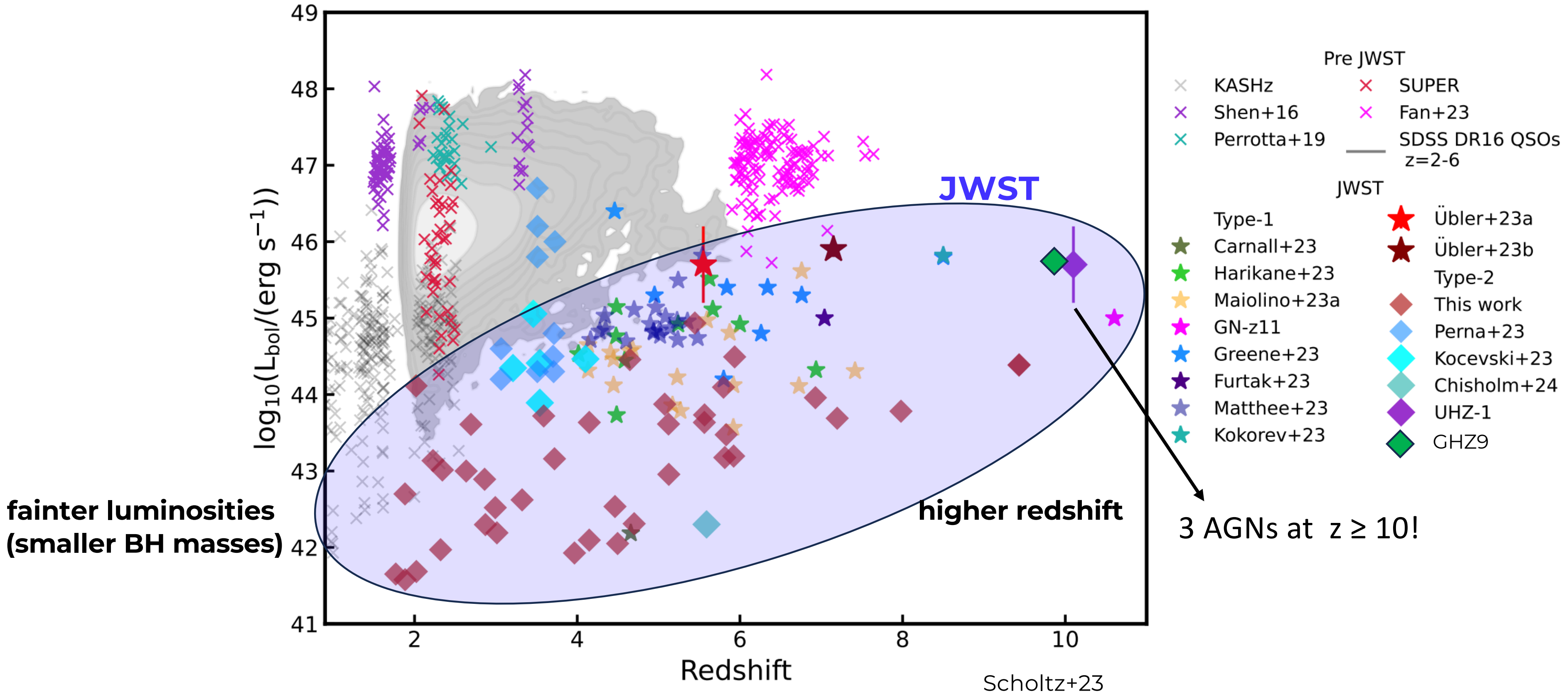
galaxies observed at z ≈ 14.5, a few hundred million years after the Big Bang

the new discovery space opened by JWST



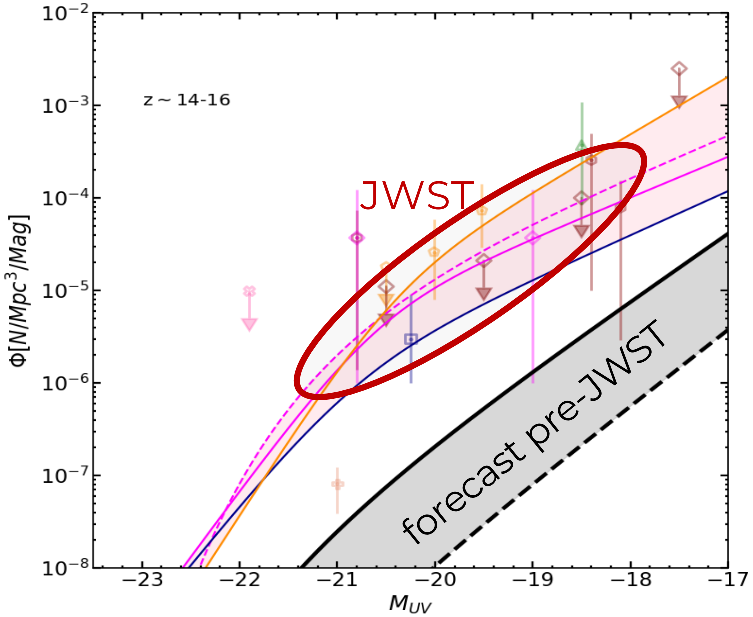
Scholtz+23

the new discovery space opened by JWST



new compelling questions

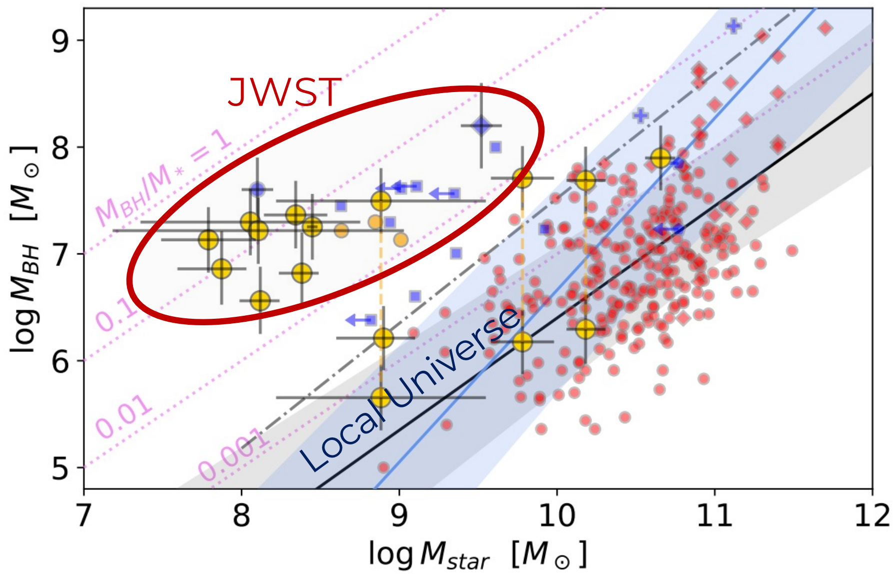
overabundace of UV luminous galaxies at z > 10



Castellano+2025

are stellar populations different at z > 10?

overmassive black holes in faint AGNs



Maiolino+2024

how do early black holes grow?

what kind of stellar populations inhabit z > 10 galaxies?

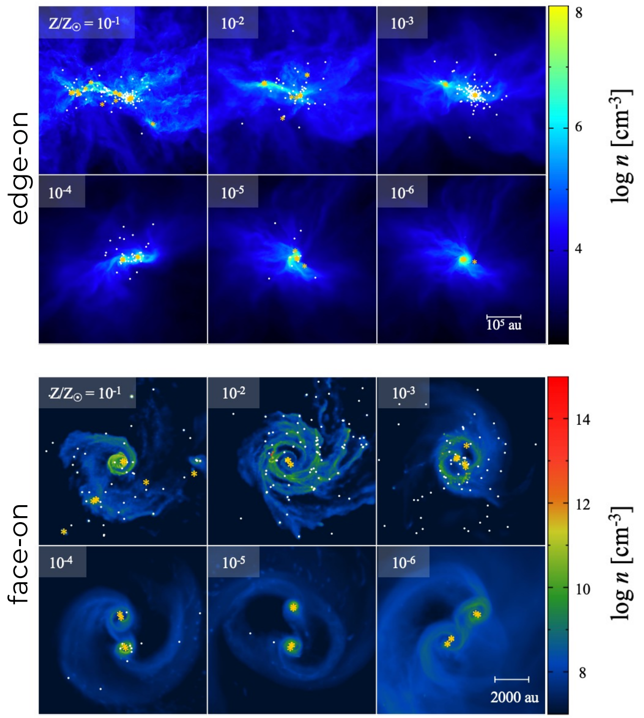
SED modeling – assuming a standard (Kroupa/Chabrier) IMF – suggests **$Z \approx 0.01 - 0.1\ Z_{sun}$** and young ages **$t_{age} < 10\text{-}15$ Myr**

what kind of stellar populations inhabit z > 10 galaxies?

SED modeling – assuming a standard (Kroupa/Chabrier) IMF – suggests **$Z \approx 0.01 - 0.1\ Z_{sun}$** and young ages **$t_{age} < 10\text{-}15$ Myr**

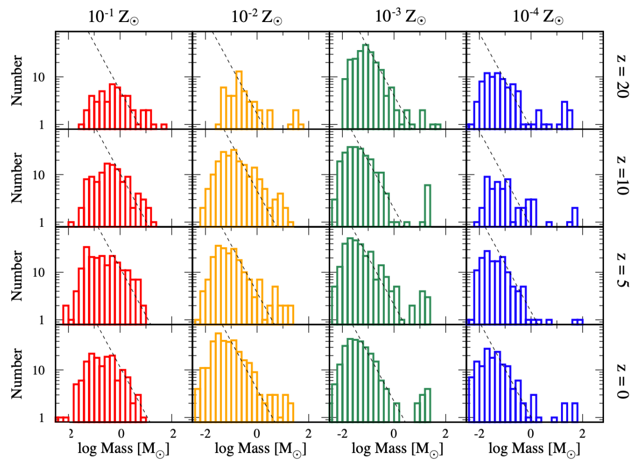
under these conditions there may be more massive stars than predicted by a «standard» IMF

projected gas density at $t_{end} = 10^4 - 10^5$ yr

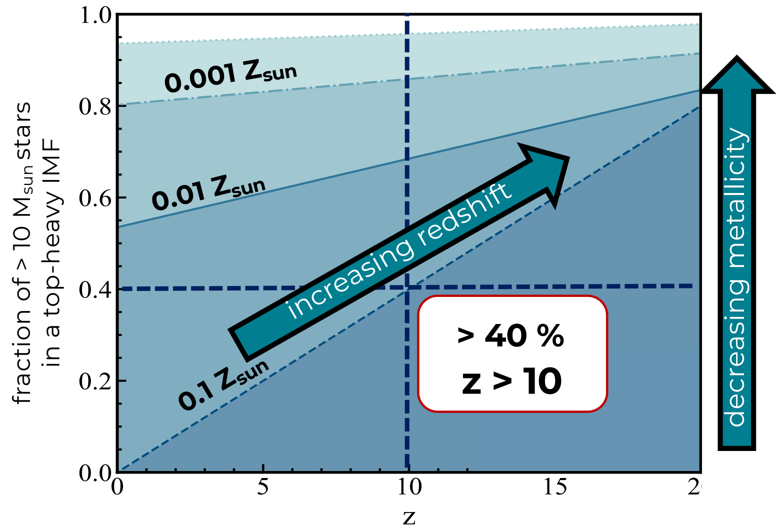


stars < 1 M_{sun} stars > 1 M_{sun}

combination of a Chabrier IMF at m < 10 M_{sun}
and a log-flat IMF at m ≥ 10 M_{sun}



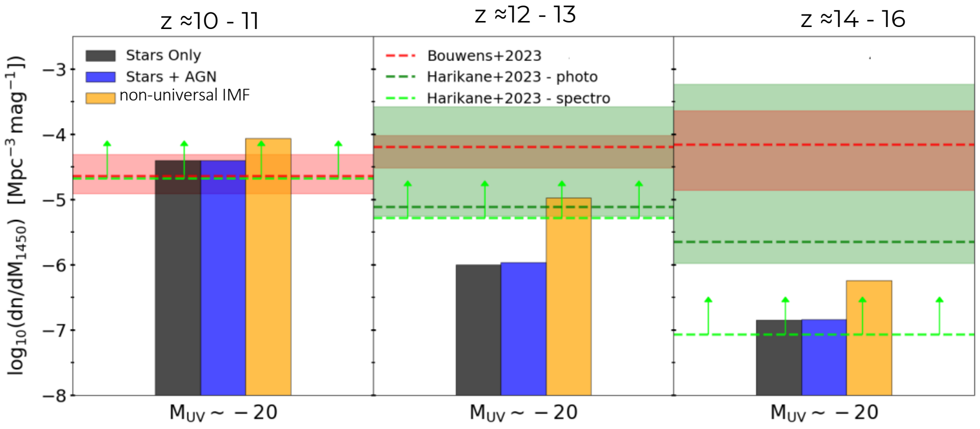
Chon+ (21, 22, 24)



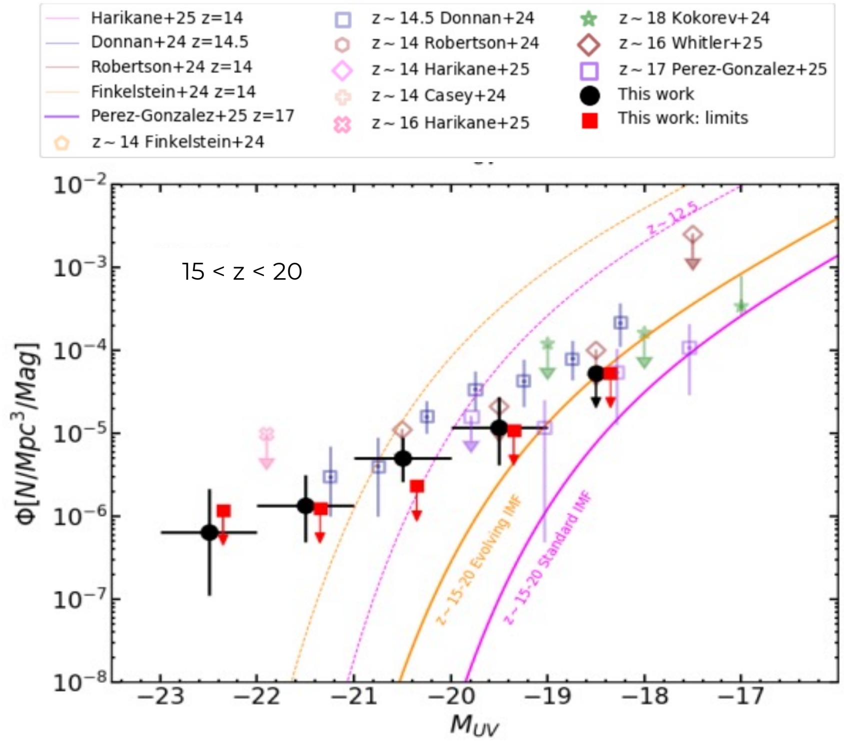
$$f_{\rm massive} = 1.07 * \left(1 - 2^x\right) + 0.04 \times 2.67^x \times z,$$
with $x = 1 + \log Z/Z_\odot$,

effects of a non-universal IMF on UV luminosities

number density of sources at Muv = -20



Trinca et al. 2024

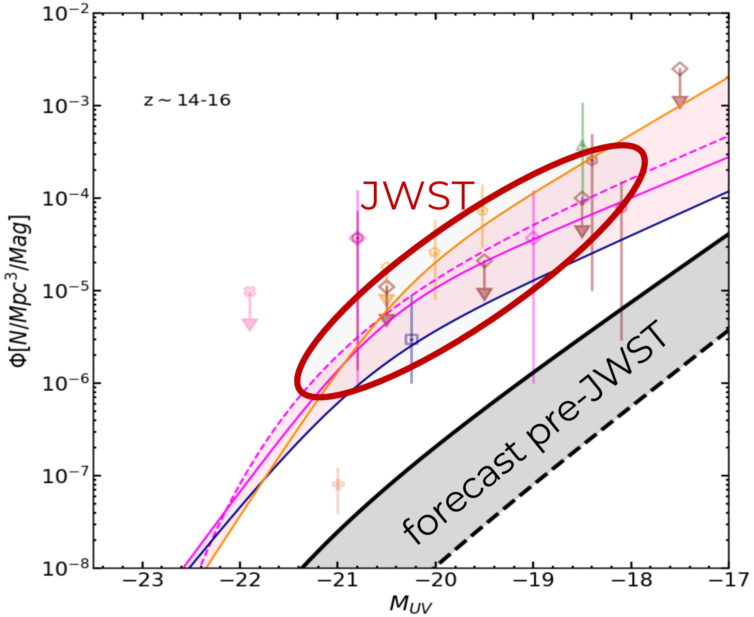


Castellano et al. 2025

- good agreement with the UV luminosity function @ z ≈ 12
- faster evolution than observed at z > 12, particularly at the bright end

new compelling questions

overabundace of UV luminous galaxies at z > 10

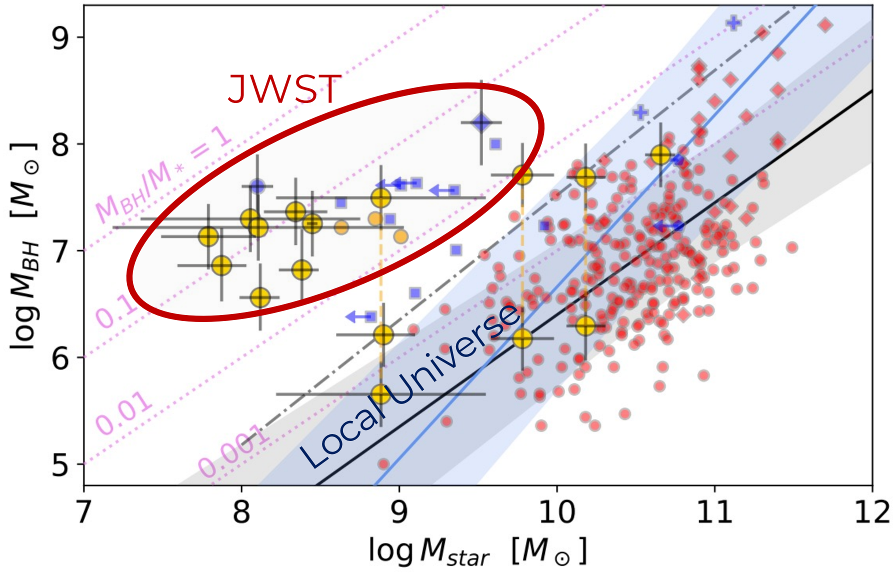


Castellano+2025

are stellar populations different at z > 10?

yes, but this is probably not enough

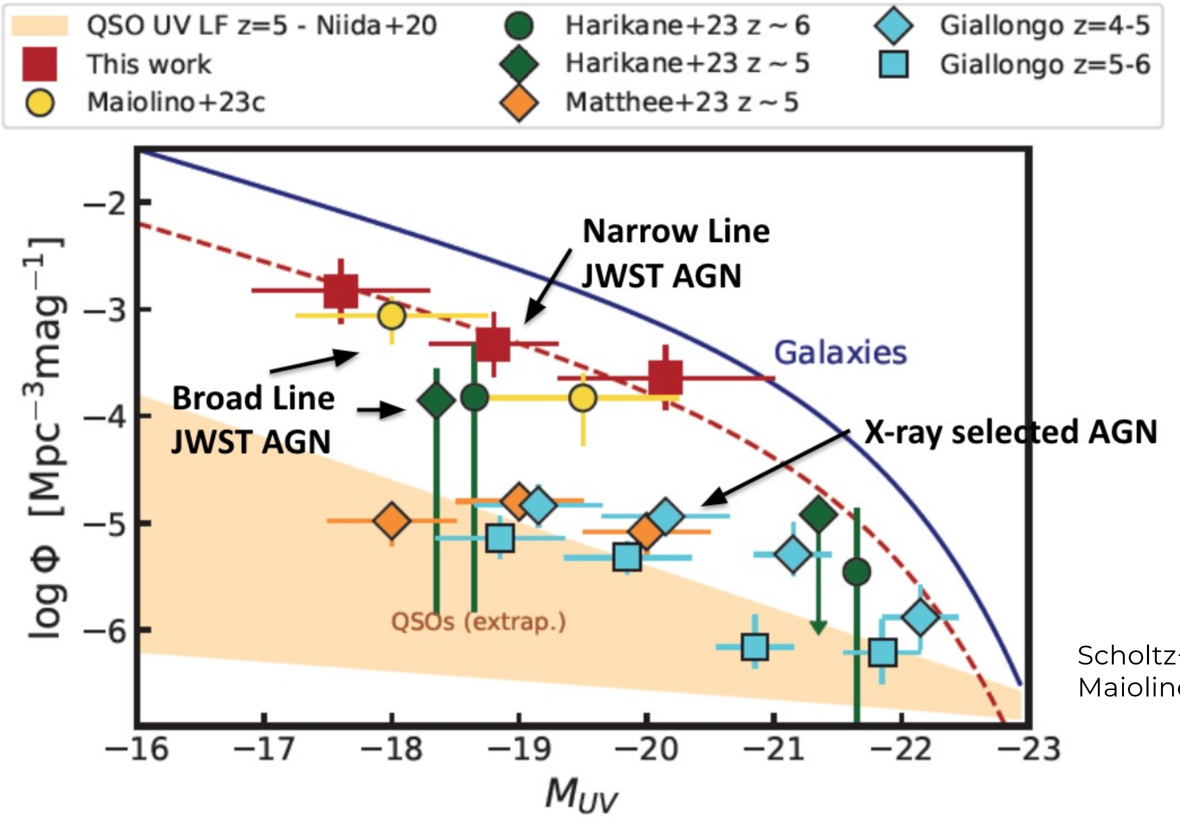
overmassive black holes in faint AGNs



Maiolino+2024

how do early black holes grow?

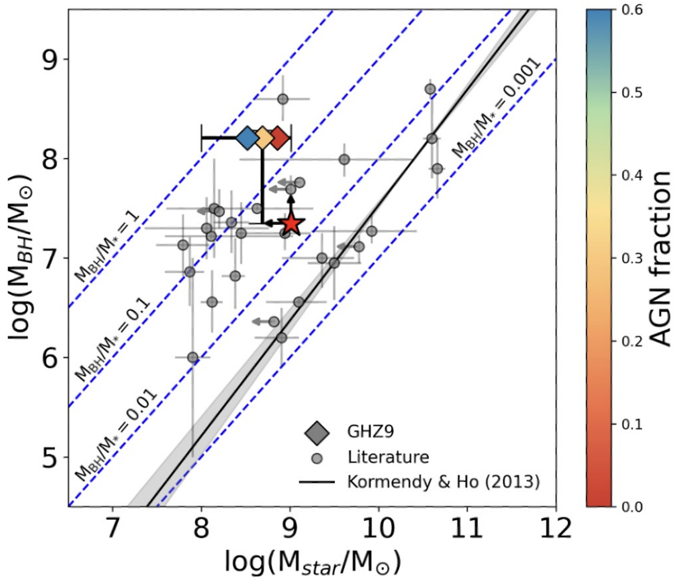
large number density of AGNs at z ≈ 4 - 6



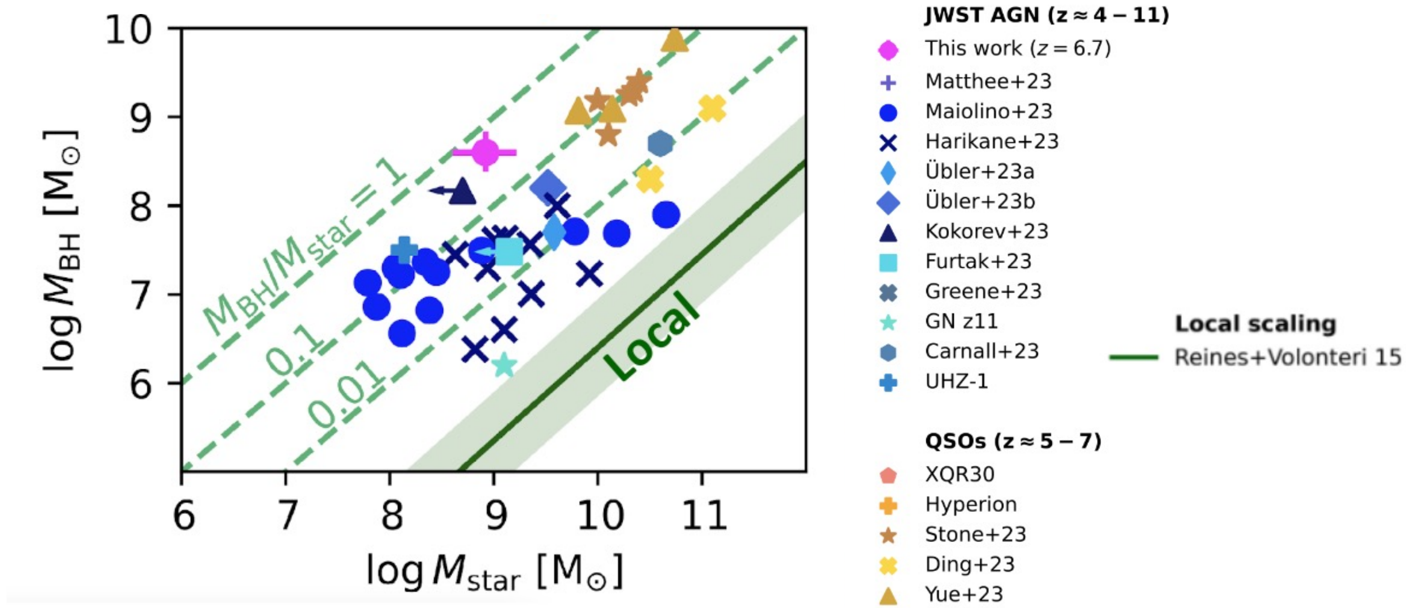
Scholtz+23
Maiolino+23, 24

≈ 20 % of galaxies at z ≈ 4 – 6 host AGNs

JWST-BHs are overmassive compared to their host galaxies



Kokorev+24, Napolitano+24

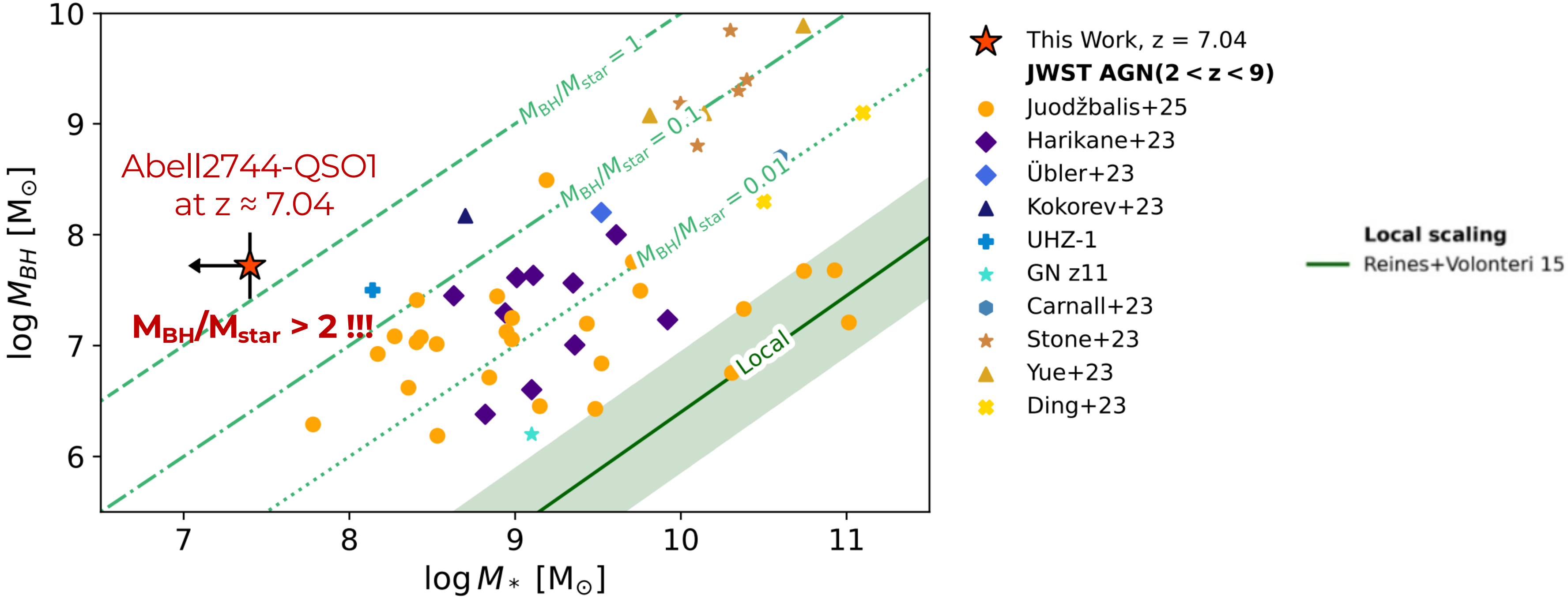


Maiolino+23, Juodzbalis+24

large offset (up to 3 dex) from the local M_{BH}-M_{star} relation

an almost «naked» black hole at z ≈ 7

the first direct, dynamical measurement of a BH mass at these redshifts!



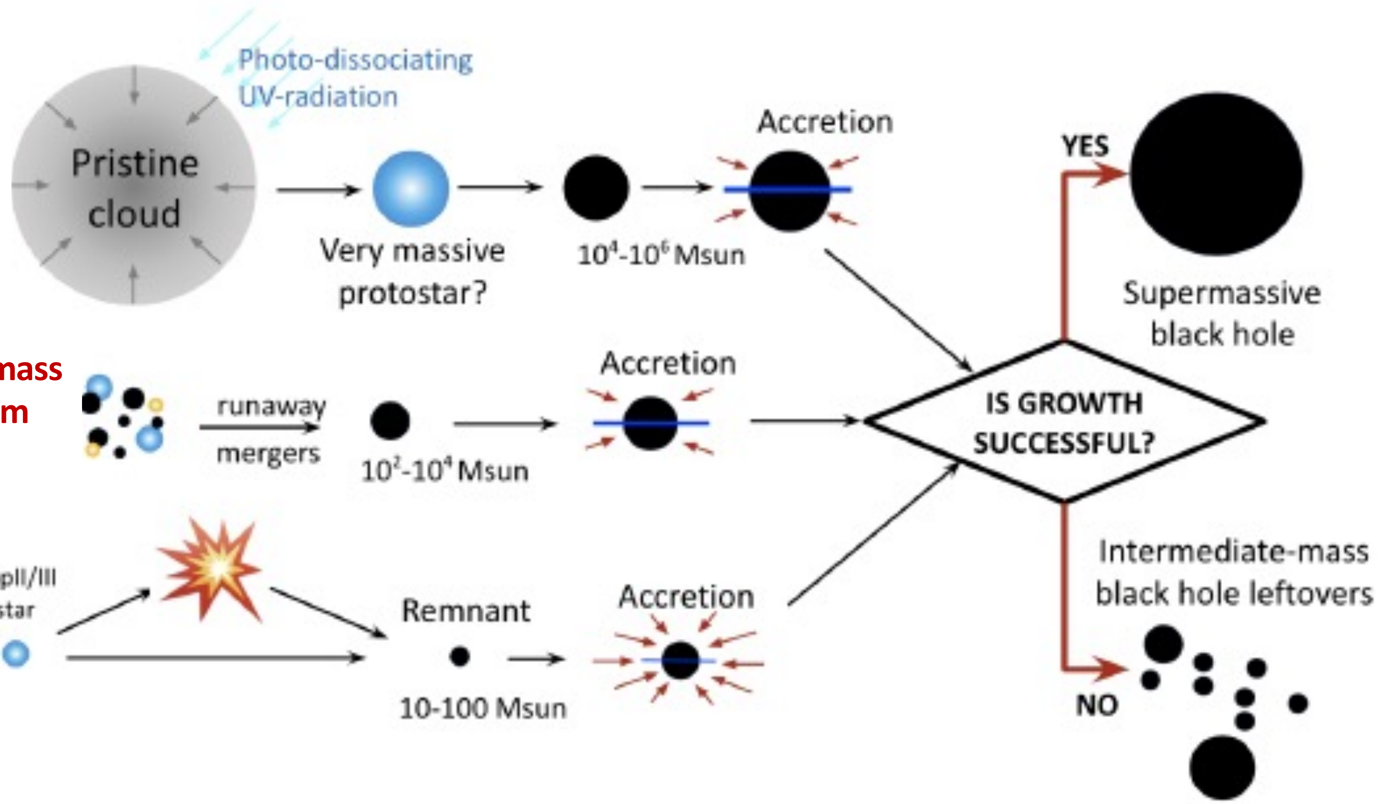
Juodzbalis et al. 2025

theoretical scenarios for black hole seed formation

Heavy black holes from supermassive stars

Intermediate-mass black holes from star clusters

Light black holes from stellar remnants



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)

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

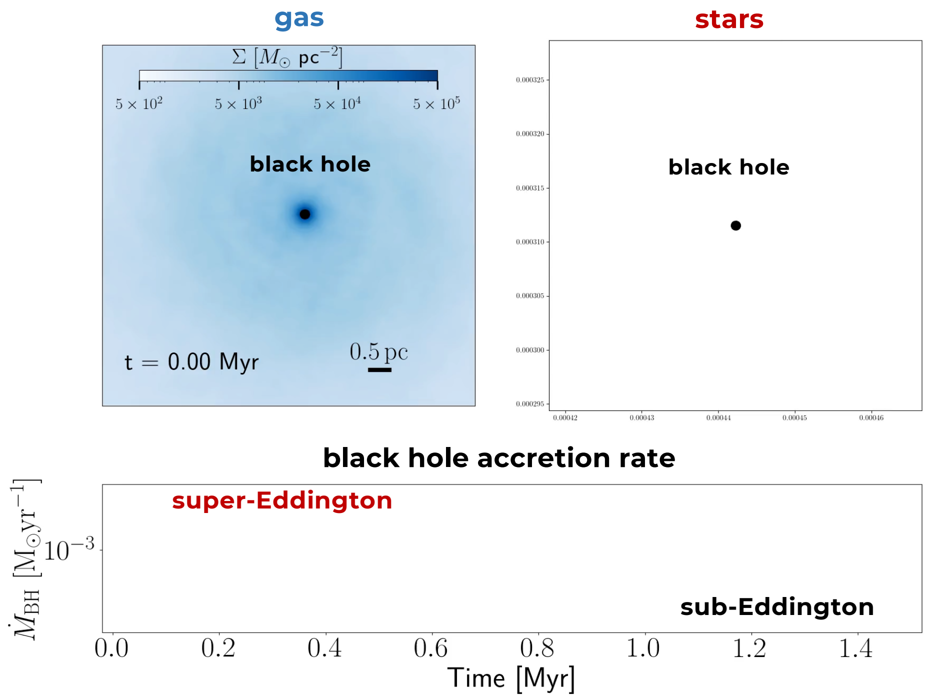
super-Eddington accretion in protogalactic cores

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 $5 \times 10^3\ M_{sun}$

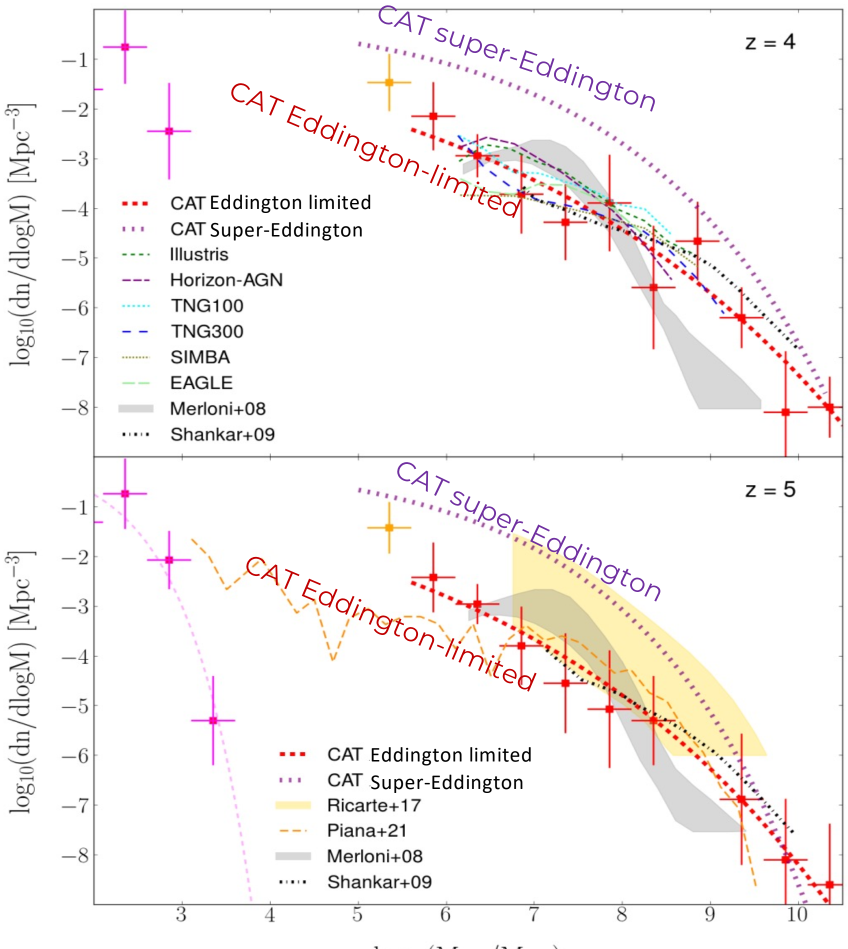


even the smallest initial seeds grow to $\approx 10^4\ M_{sun}$ - $10^5\ M_{sun}$ in < 1 Myr!

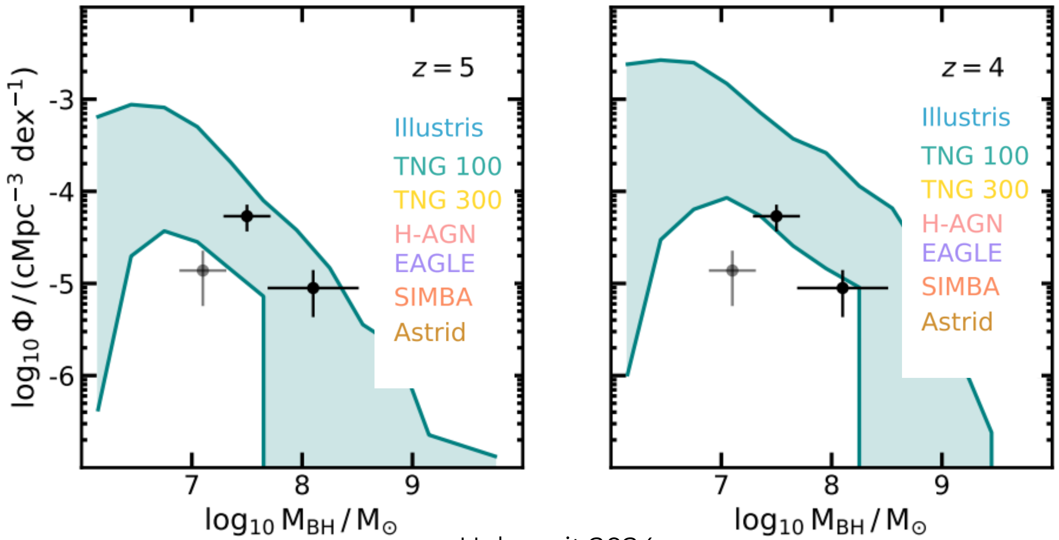
how can we test these scenarios?

the low-mass end of the black hole mass function

very sensitive to BH seeding and to the growth mode

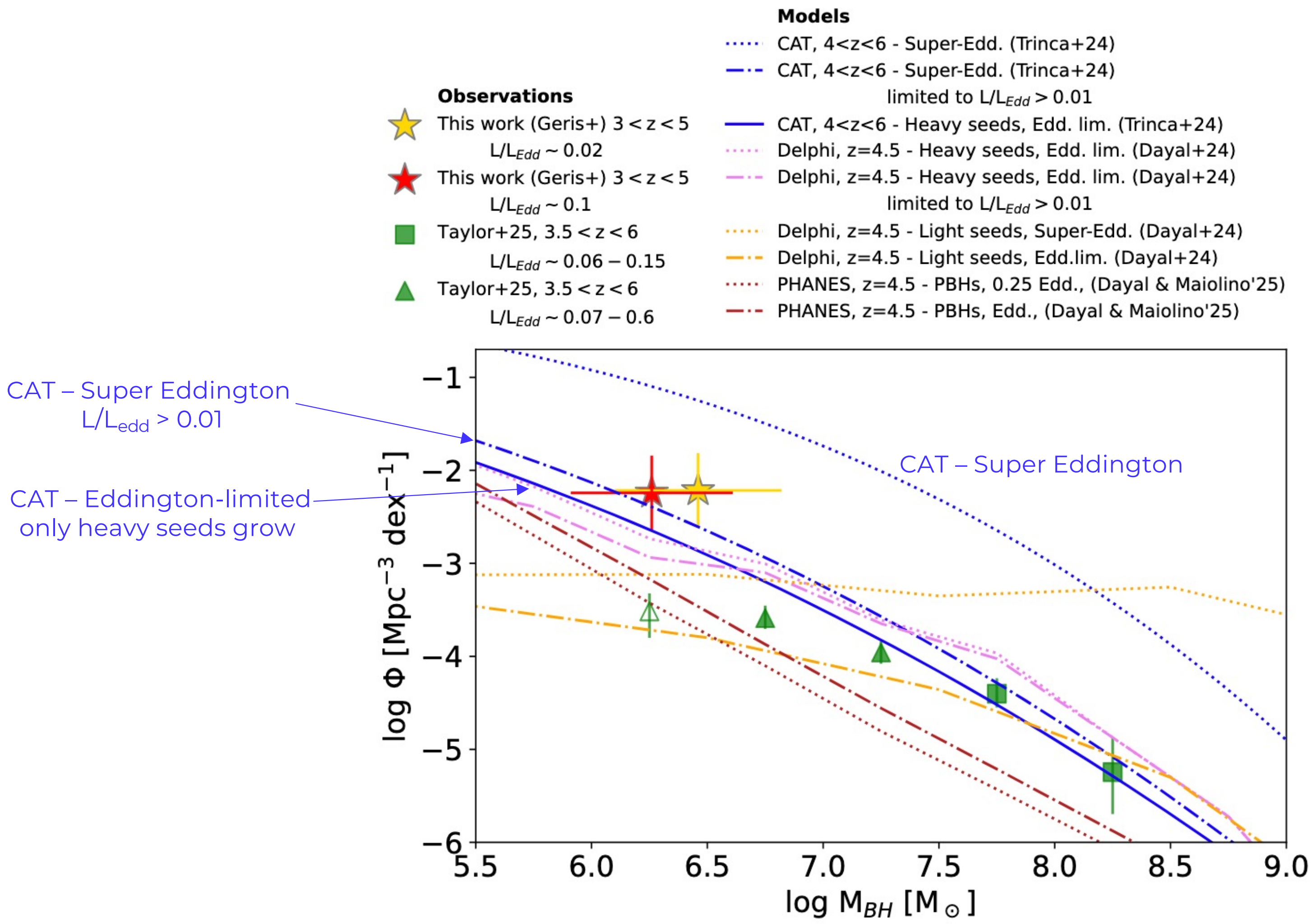


Trinca+2022



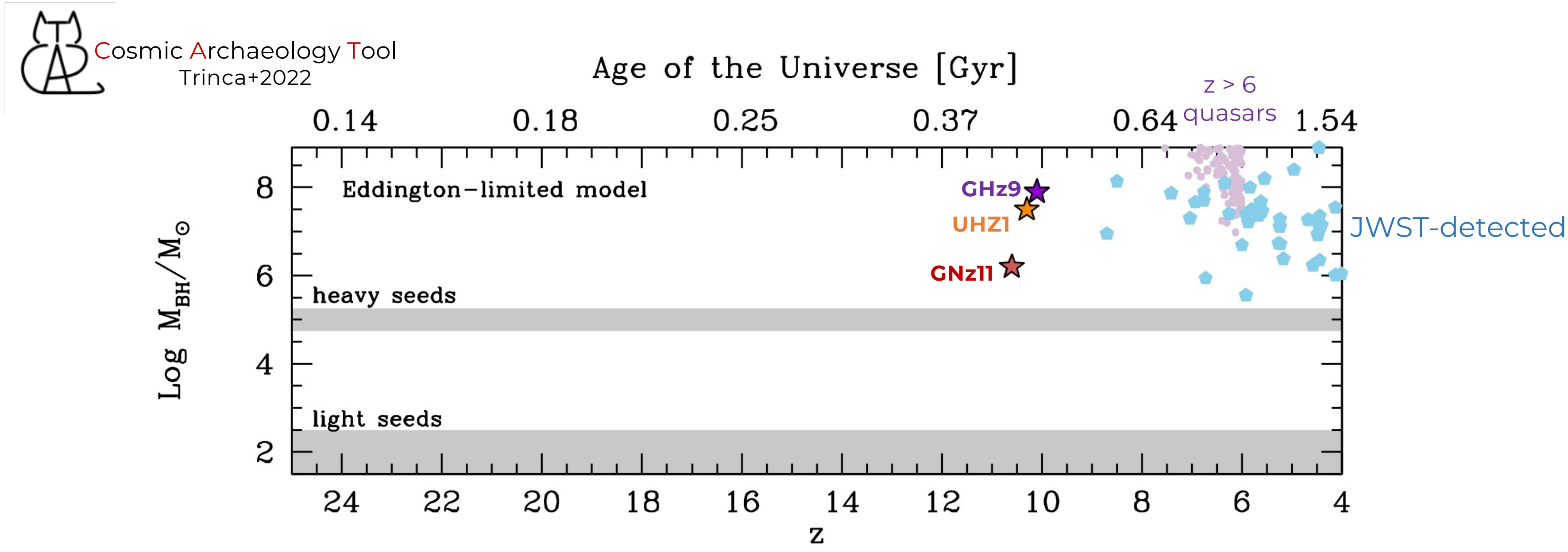
Habouzit 2024

probing the low-mass end with JWST



Geris et al. 2025

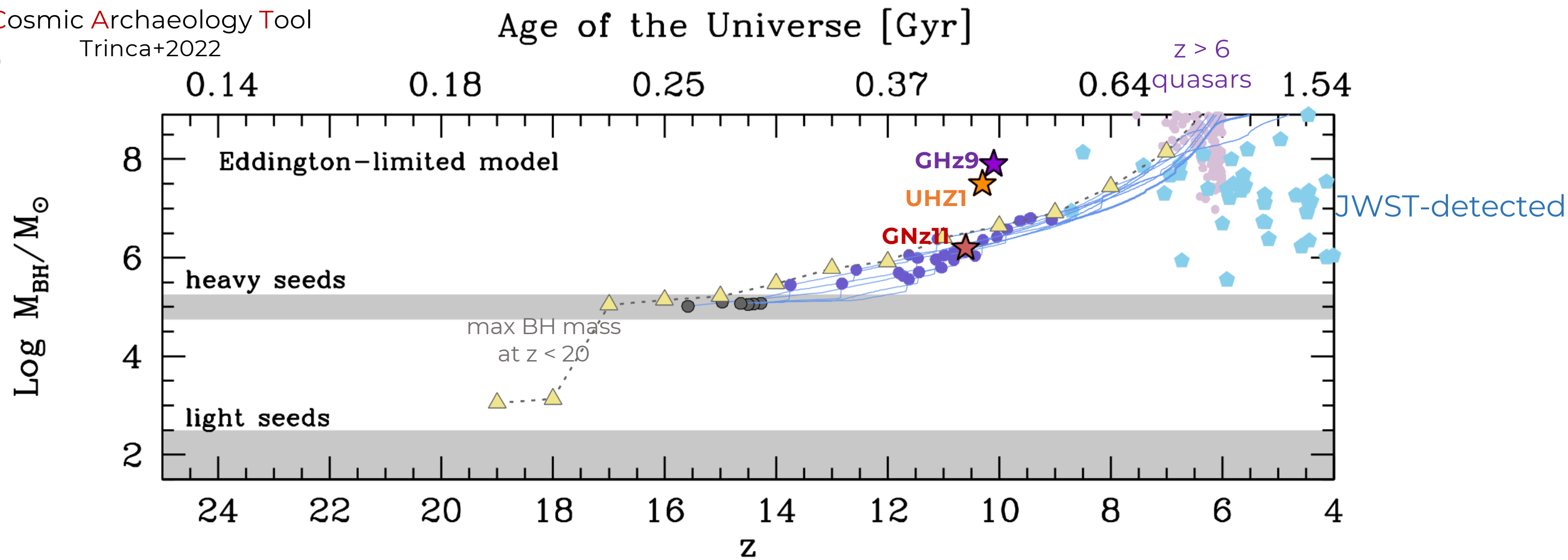
implications of JWST-detected BHs at z > 10



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



if BHs growth is Eddington-limited:

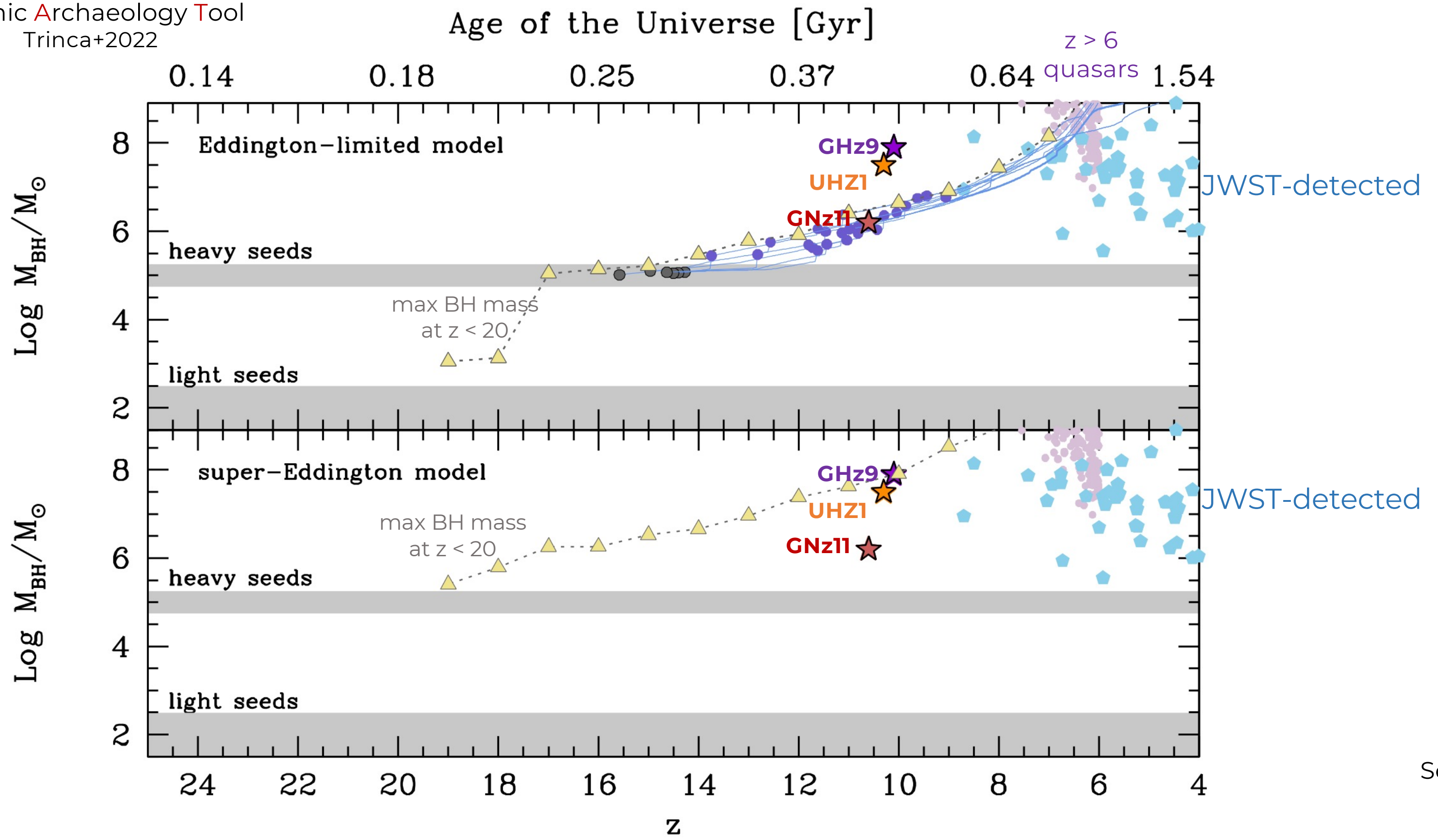
- GNz11 must originate from heavy BH seeds forming at z≈ 15
- estimated masses of UHZ1, GHZ9 exceed the maximum BH mass at z ≈ 8 - 10

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



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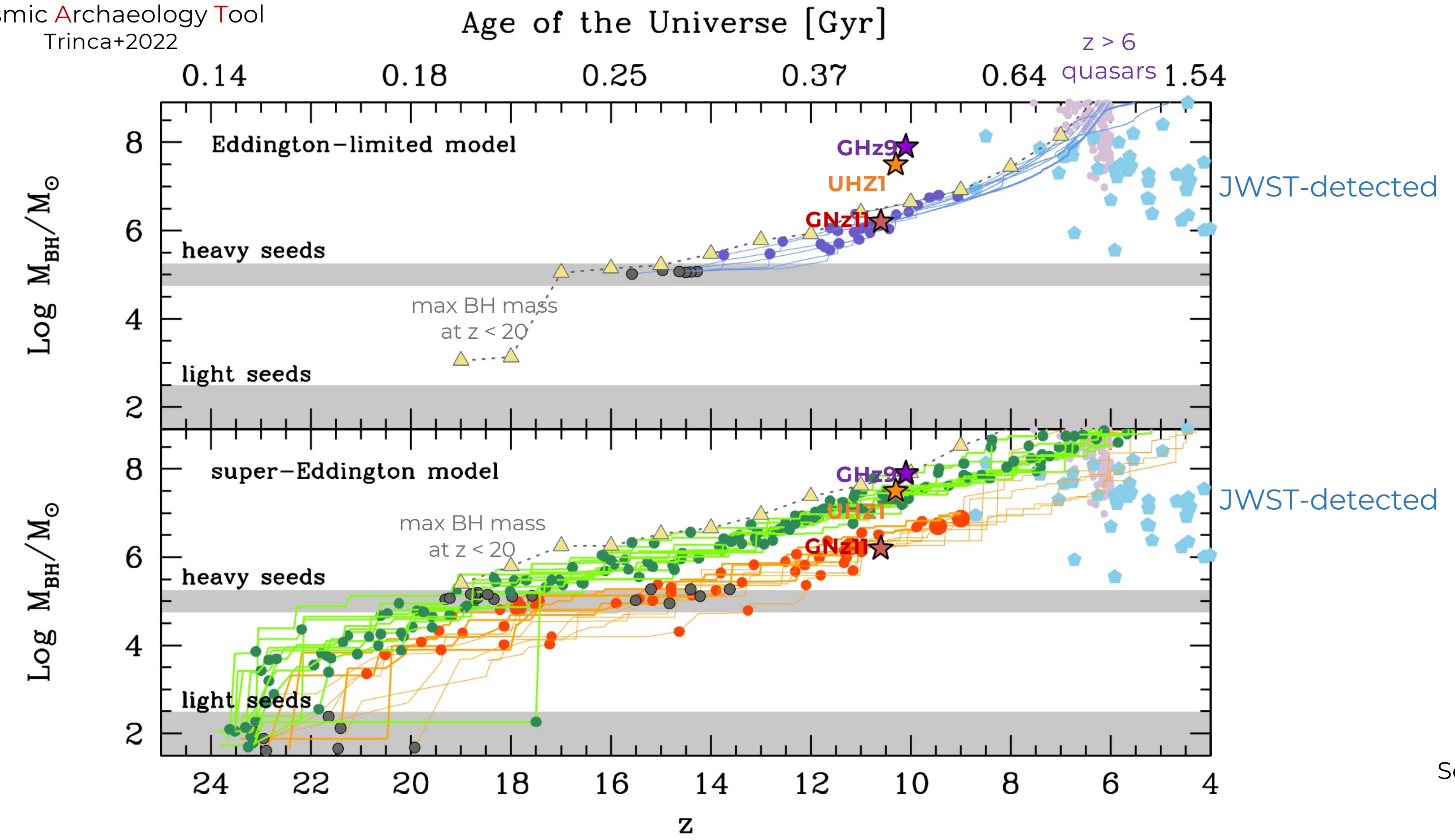
implications of JWST-detected BHs at z > 10

Cosmic Archaeology Tool
Trinca+2022

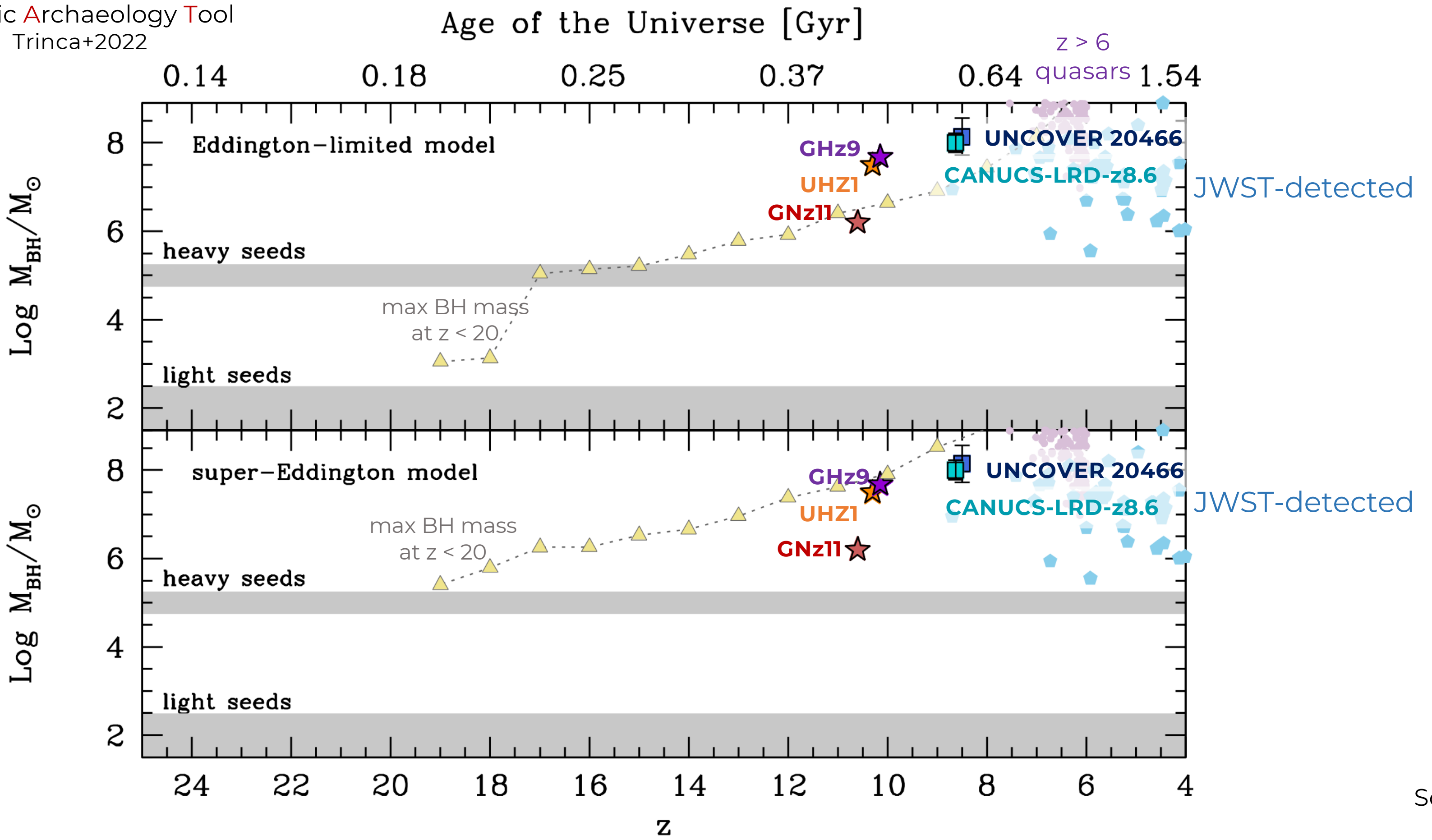


Schneider, Trinca+23

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

two extreme objects at z ≈ 8

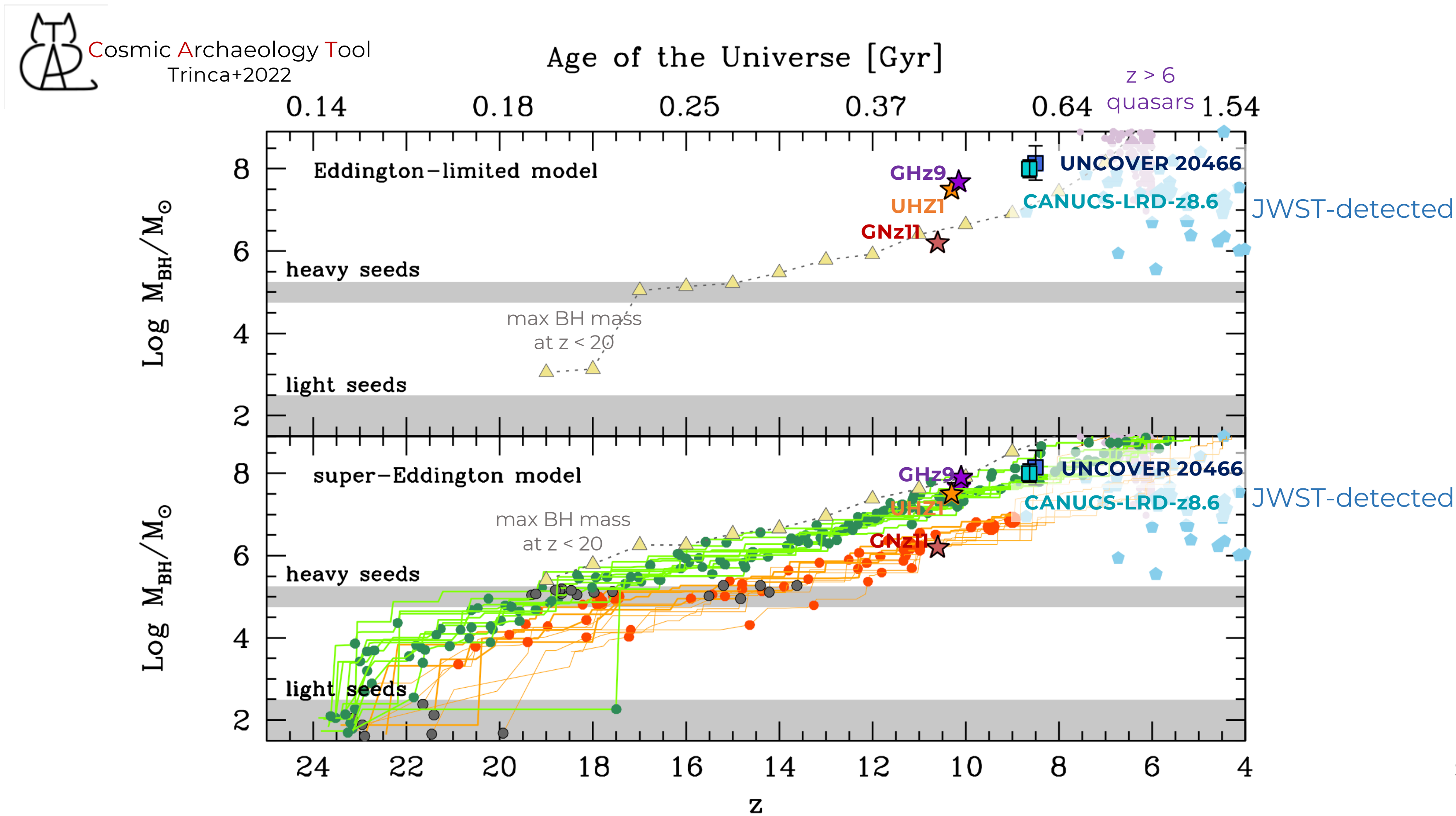
Cosmic Archaeology Tool
Trinca+2022



adapted from
Schneider, Trinca+23

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

two extreme objects at z ≈ 8



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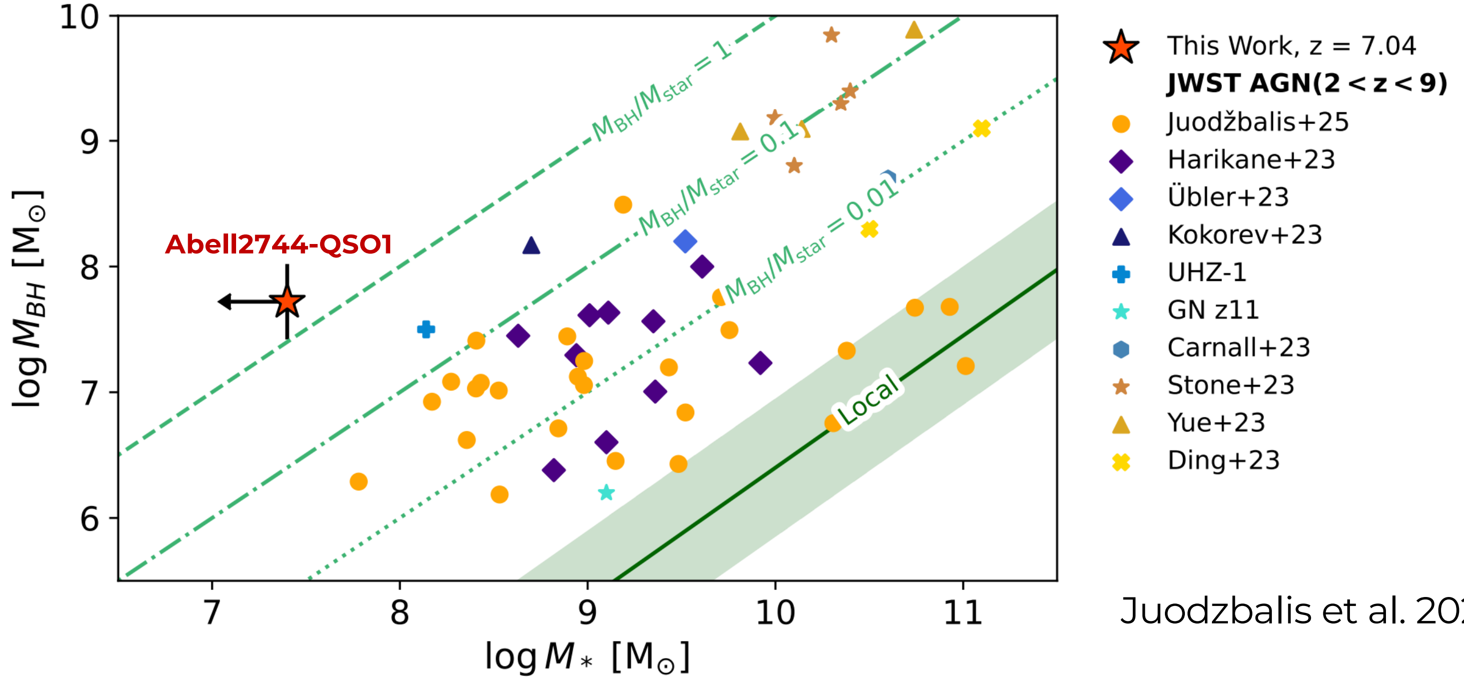
data from: Kocevski+23, Ubler+23, Harikane+23, Larson+23, Maiolino+24, Bogdan+23, Kokorev+24, Kovacs+24; Napolitano+24; Tripodi+24

connecting black holes with their host galaxies

the «overmassive» nature of AGNs discovered by JWST



Juodzbalis et al. 2025

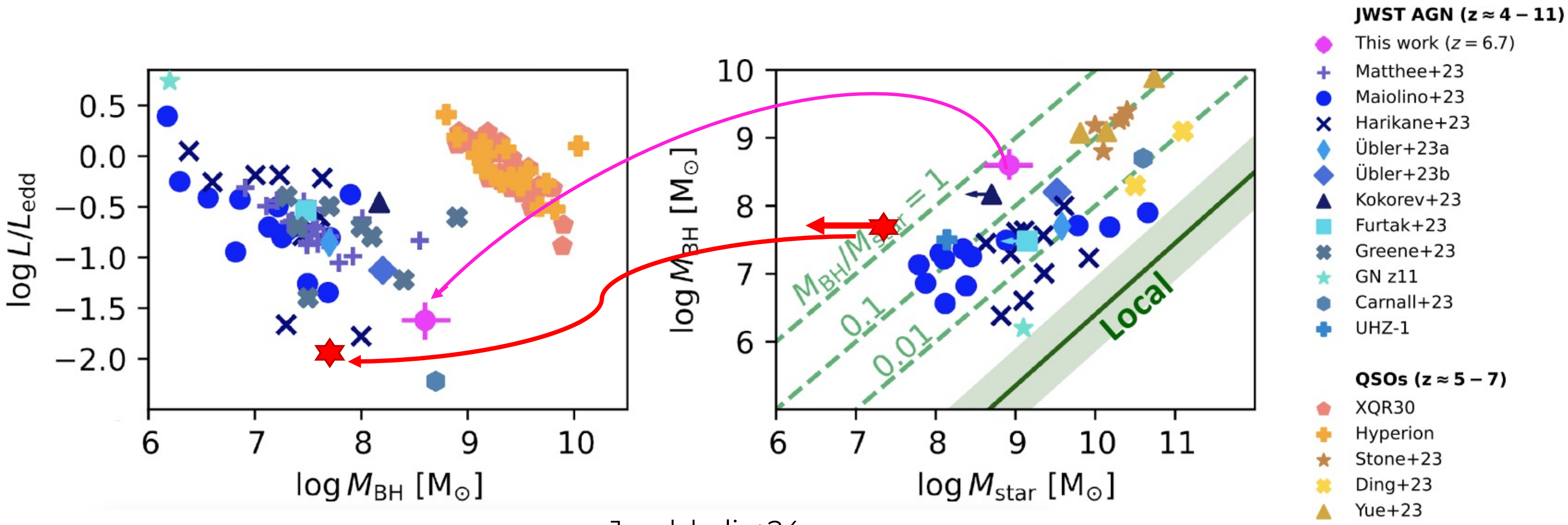
is this an evidence for heavy black hole seed formation? is this reflecting accelerated super-Edd growth?

see e.g. Natarajan et al. 2024

see e.g.Trinca et al. 2024

a combination of the two?

overmassive and dormant black holes



Juodzbalis+24

,

JADES GN 1146115 at z ≈ 6.67

$\log M_{\rm BH}/M_{\odot}$ $8.61^{+0.38}_{-0.37}$

$\lambda_{\rm EDD}$ $0.024^{+0.011}_{-0.008}$

$M_{BH}/M_{star} \approx 0.4$!

Abell2744-QSO1 at z ≈ 7.04

$\log M_{\rm BH}/M_{\odot} = 7.7 \pm 0.3$

$L/L_{\rm Edd} \sim 0.01 - 0.02$

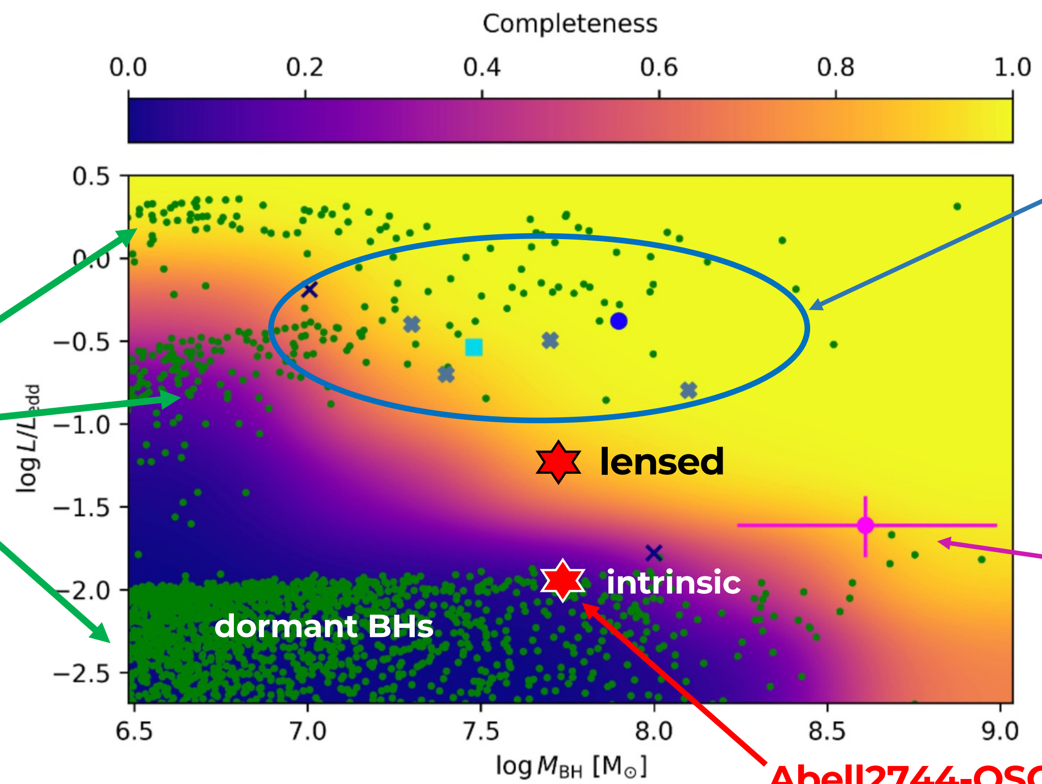
Juodzbalis+25

$M_{BH}/M_{star} > 2$!!!

is this a signature of super-Eddington accretion?

the short super-Eddington bursts make the black hole reach high masses
while allowing it to be dormant for long periods

BHs in the super-Eddington model



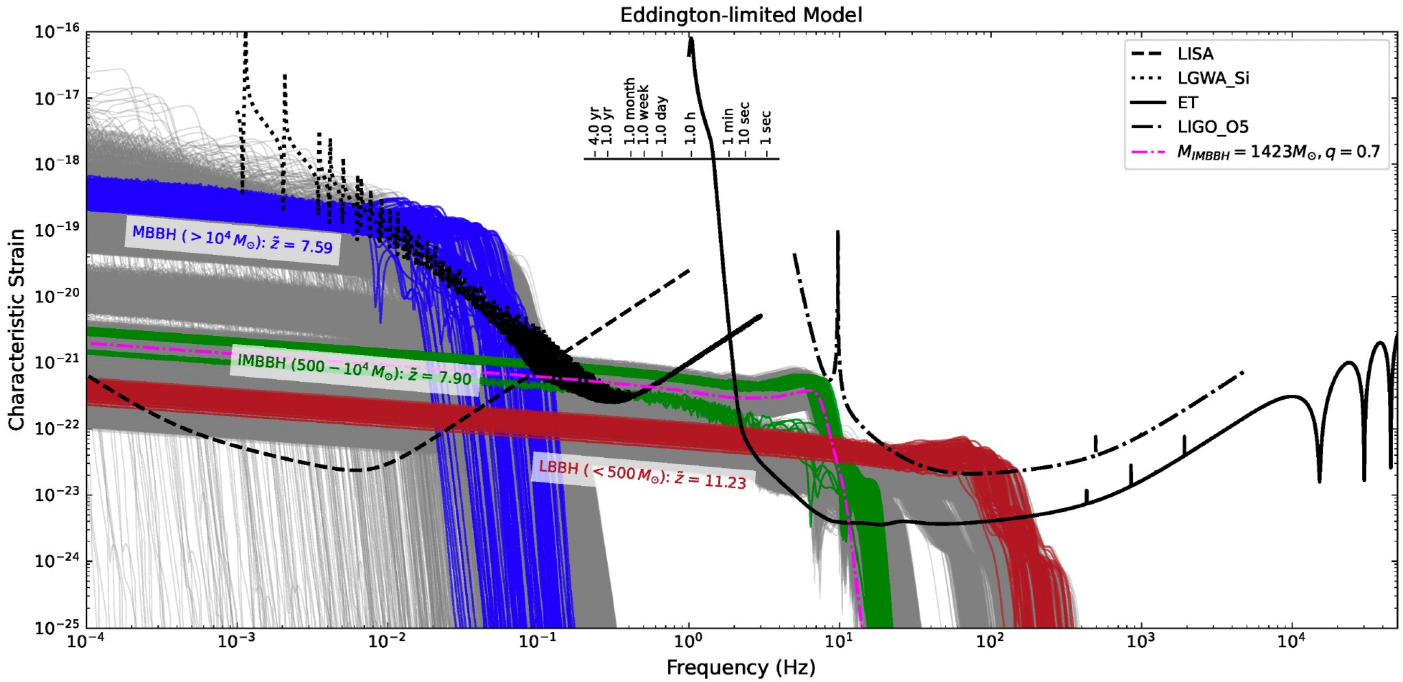
JWST AGNs at z ≈ 6 - 8
are preferentially selected
while actively accreting

JADES GN 1146115
overlaps with the high-mass tail of
dormant BHs

Abell2744-QSO1
is visible because
it is strongly lensed

Juodzbalis+24

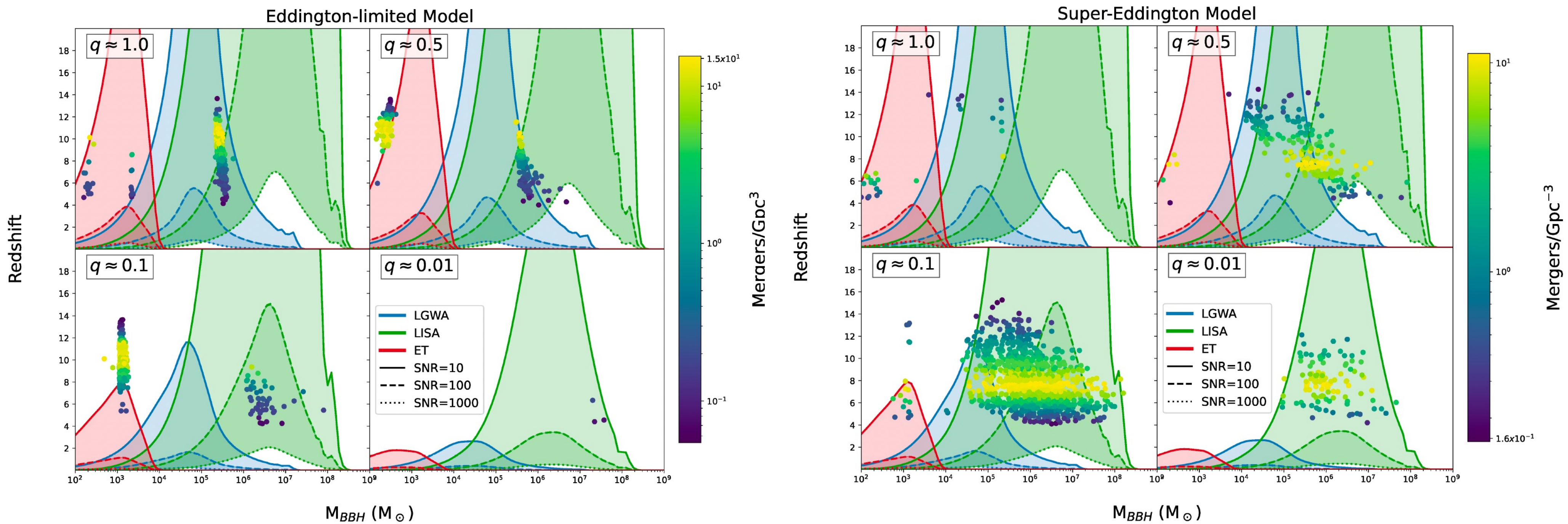
imprints on gravitational waves of seeds



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

Devari, Valiante, Trinca, RS, et al. In prep

imprints on gravitational waves of growth mode



different merger rates and black hole mass ratios are expected for different growth modes!

Devari, Valiante, Trinca, RS, et al. In prep

Conclusions

JWST observations have ignited a revolution in the exploration of cosmic dawn,
opening new compelling questions

- the UV luminosities of JWST detected galaxies at $z > 12$ are hard to explain, even when accounting for the varying properties of their stellar populations

- growing super-massive 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

the future is bright!