# The emergence of galaxies in the first billion years: implications for cosmology, reionization and gravitational wave astronomy

**Pratika Dayal**

rijksuniversiteit groningen

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# The theory team

On behalf of: the Atacama Large Millimetre Array ***(ALMA; REBELS)*** team, James Webb Space Telescope ***(JWST; UNCOVER, PANORAMIC, PRIMER and CosmicSpring)*** programs, the Square Kilometre Array ***(SKA) and Euclid*** reionization theory working groups

# The open questions

- What were the physical properties of early galaxies?
- How was early galaxy assembly dependent on the environment?
- What did early galaxies evolve into through cosmic time?
- When & how was the Universe reionized?
- What was the impact of reionization on early galaxy formation?
- What was the role of black holes in early galaxy formation & reionization?
- How many gravitational wave events do we expect from the early Universe?
- What can signals from cosmic dawn tell us about cosmology (e.g. nature of dark matter)?

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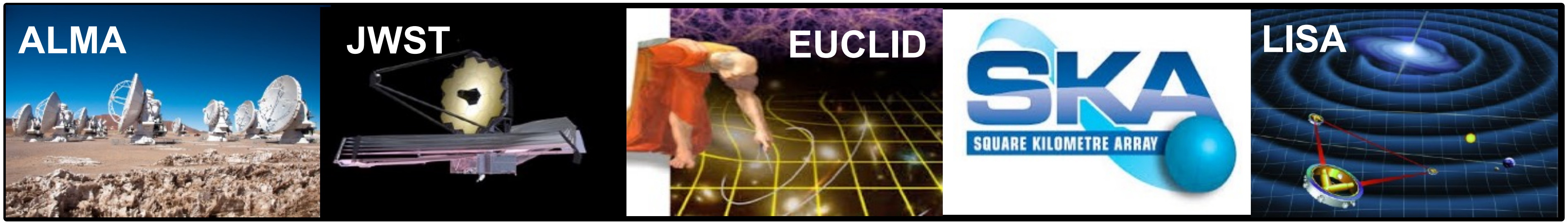
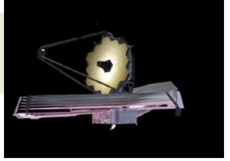
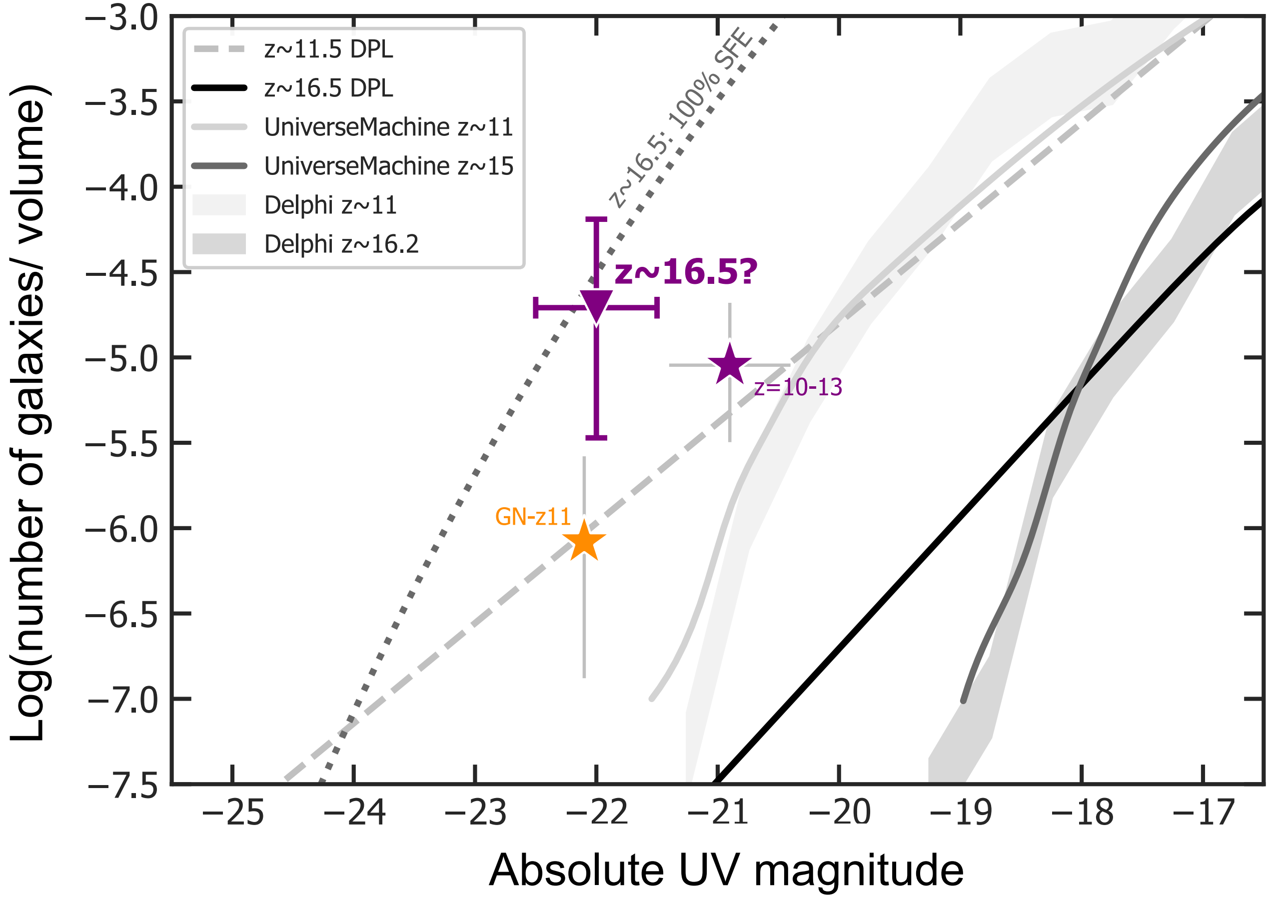


# The emergence of galaxies in the first billion years: implications for galaxy formation & cosmology

# An over-abundance of bright systems in the first billion years






Naidu, incl. Dayal et al. 2022,
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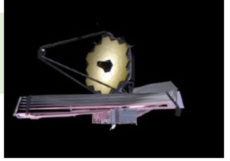

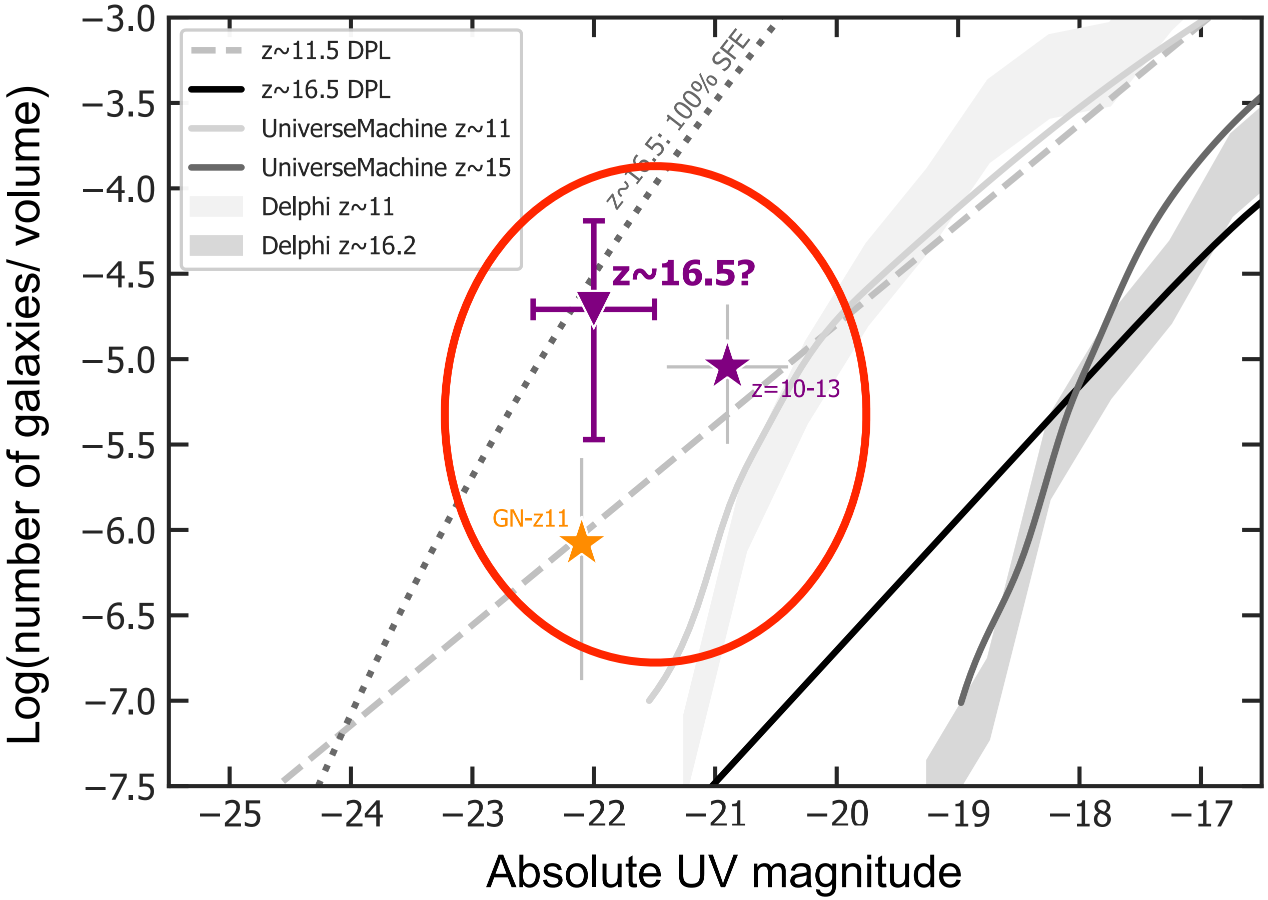


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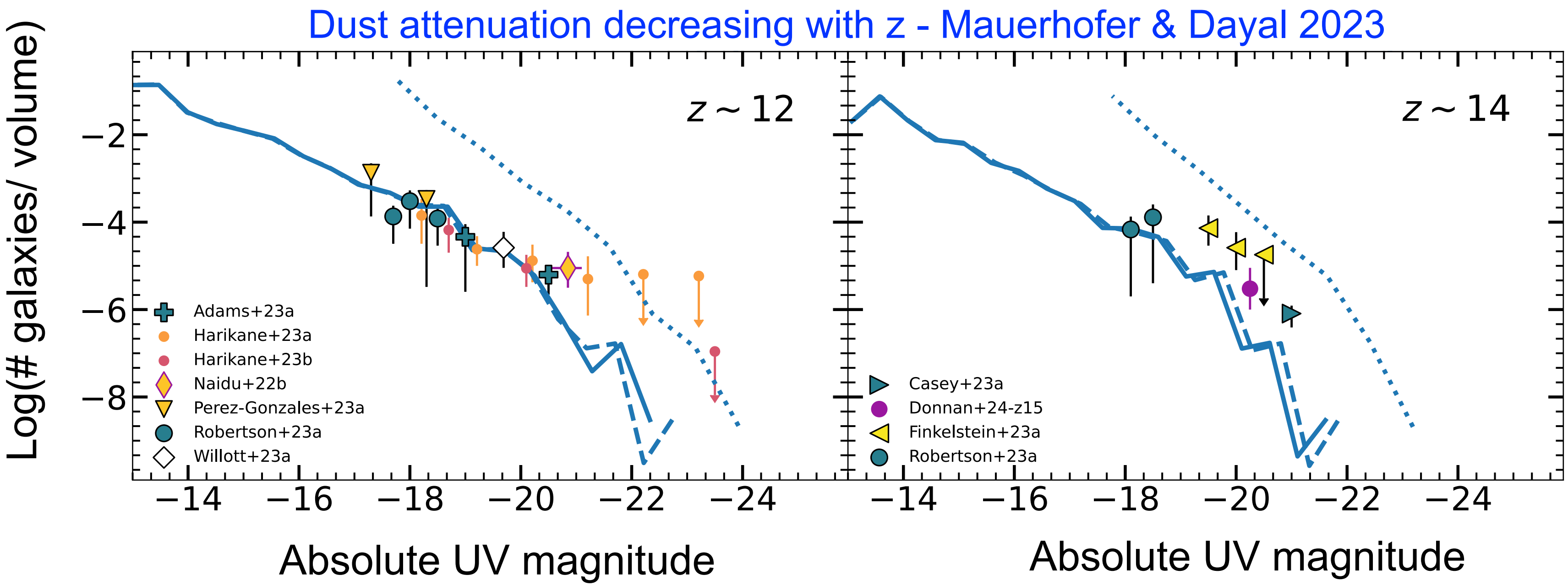
While in perfect agreement with theory at $z \leq 10$, early JWST observations showed an over-density of bright systems at $z \geq 11$. Strong emission lines from z~5 object lead to a pathology yielding a photometric z~16 (Arrabal-Haro et al. 2023).

# Observations continue to support over-abundance of bright systems



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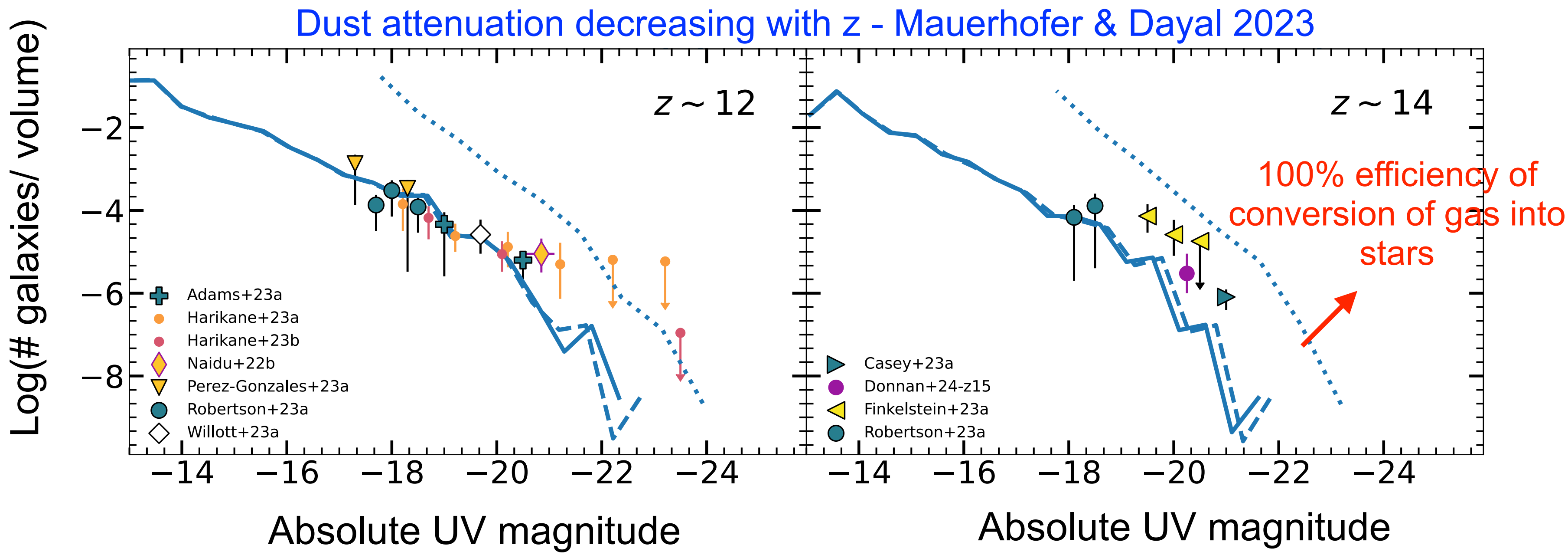

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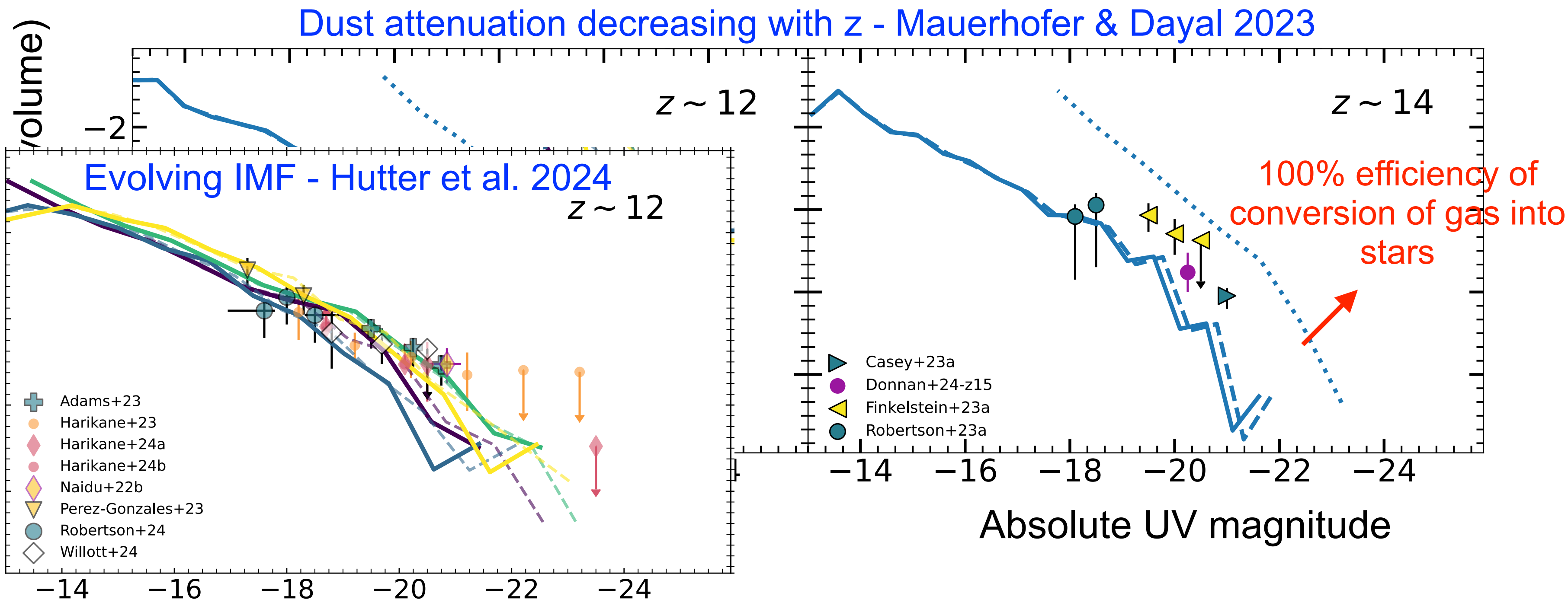

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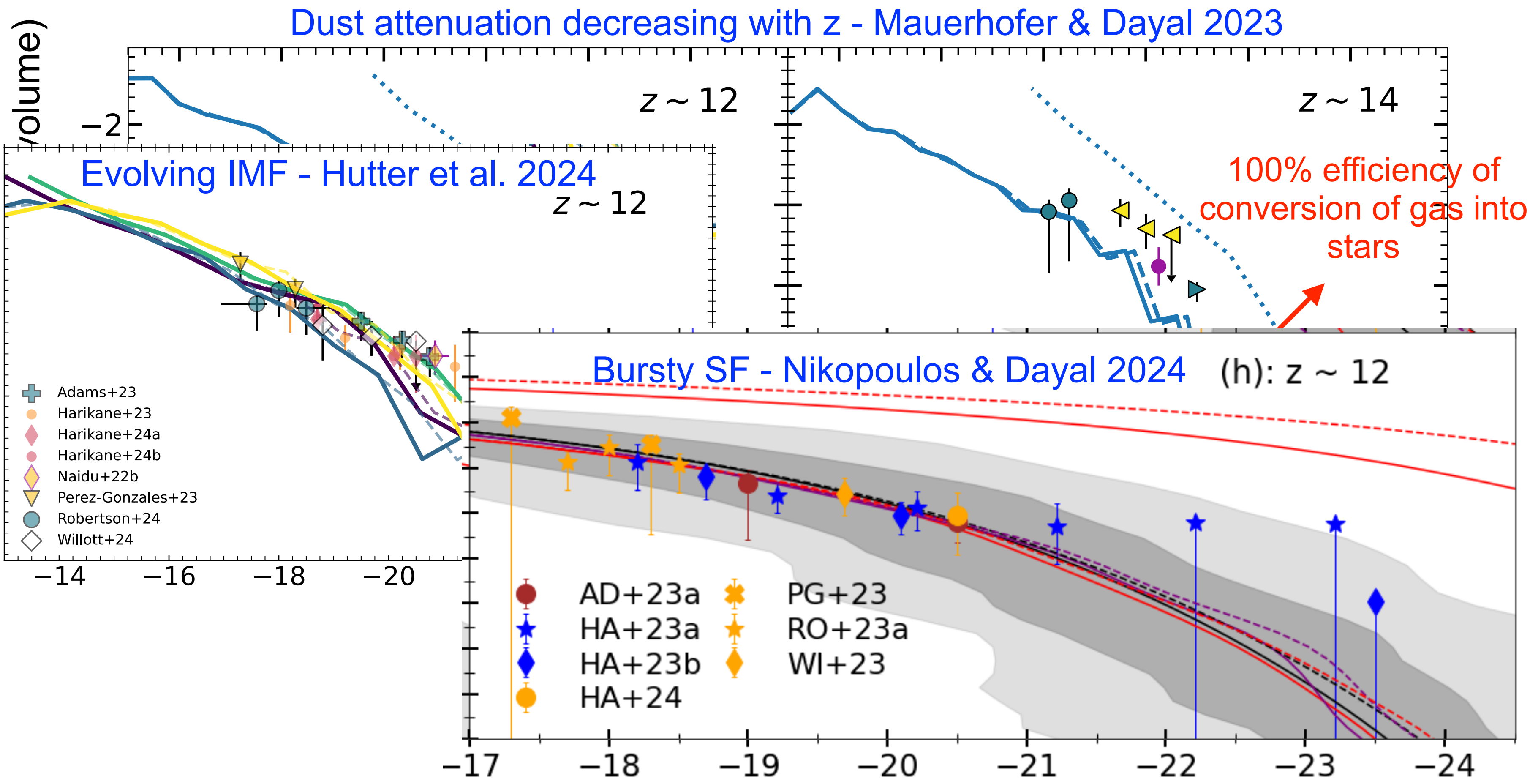

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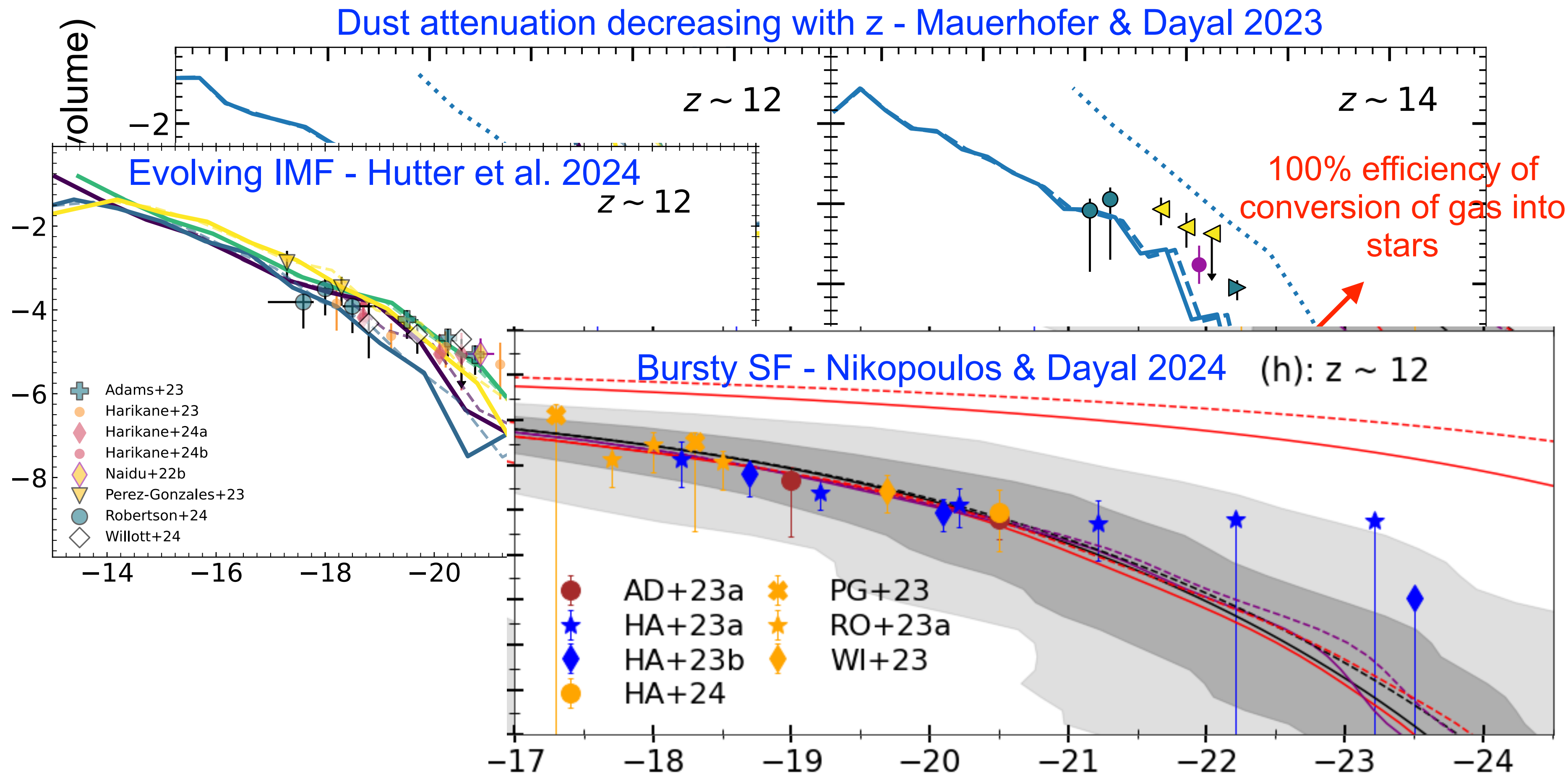
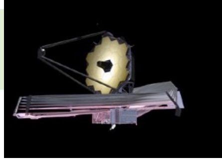
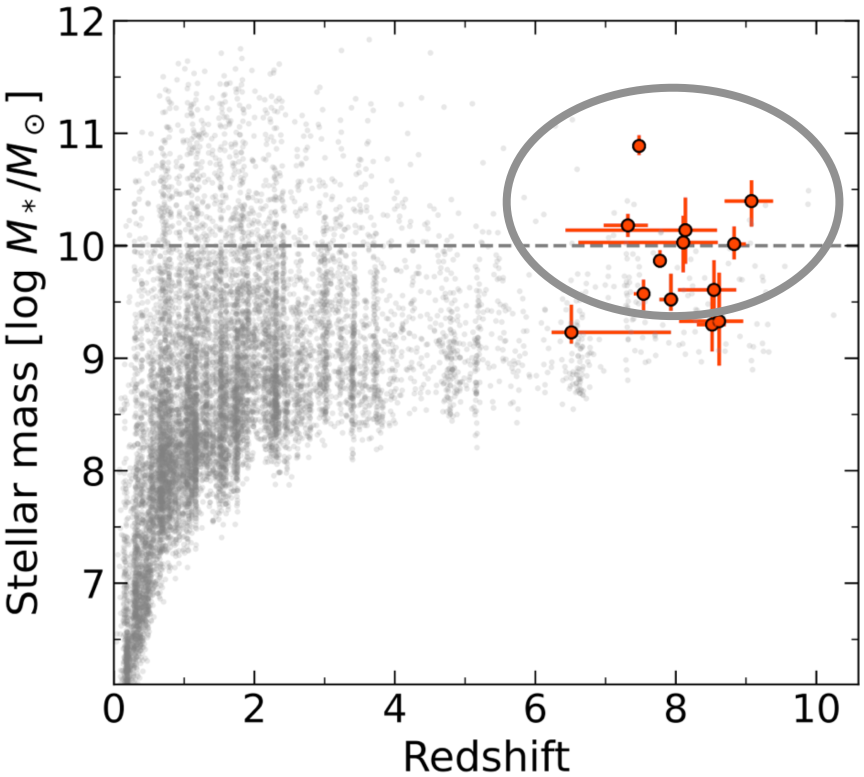



Possible solutions include a *decreasing importance of dust attenuation with increasing redshift* (Mauerhofer & Dayal, 2023; Ferrara, Pallottini, Dayal 2023), an *evolving initial mass function* (Yung et al. 2023, Cueto, Hutter & Dayal et al. 2023, Trinca et al. 2024), *bursty star formation* (Mason et al. 2023, Mirocha & Furlanetto 2023, Sun et al. 2023, Nikopoulos & Dayal 2024), *black hole contribution* (Ono et al. 2018, Pacucci, Dayal et al. 2022), *feedback-free star formation* (Dekel et al. 2023) or *low-redshift interlopers* (Arrabal-Haro et al. 2023).

# An over-abundance of massive systems - CDM implications





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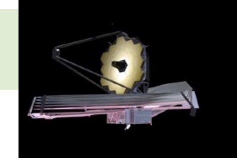
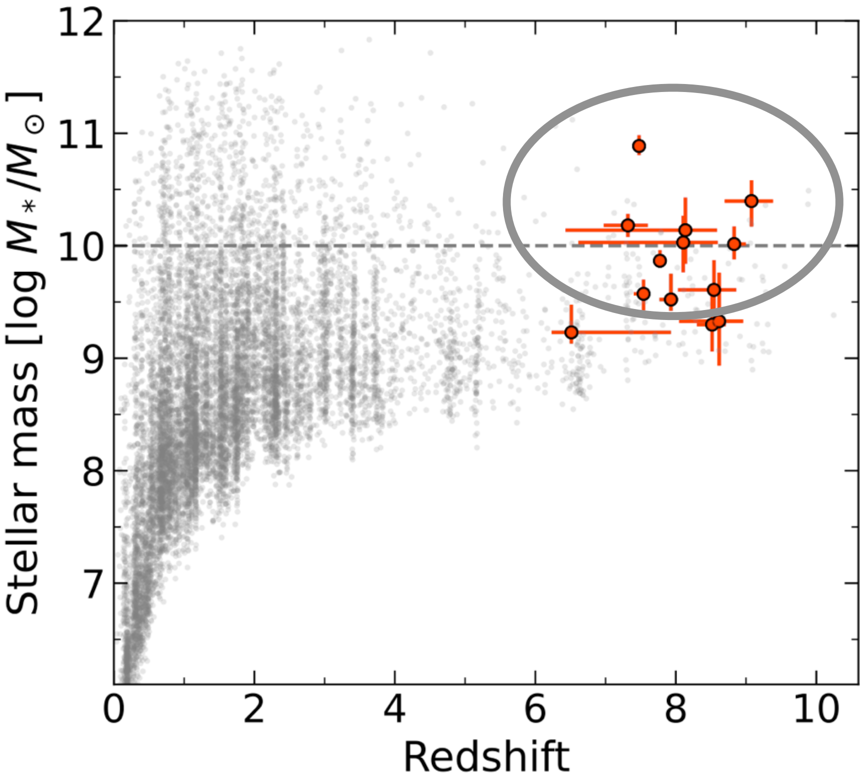
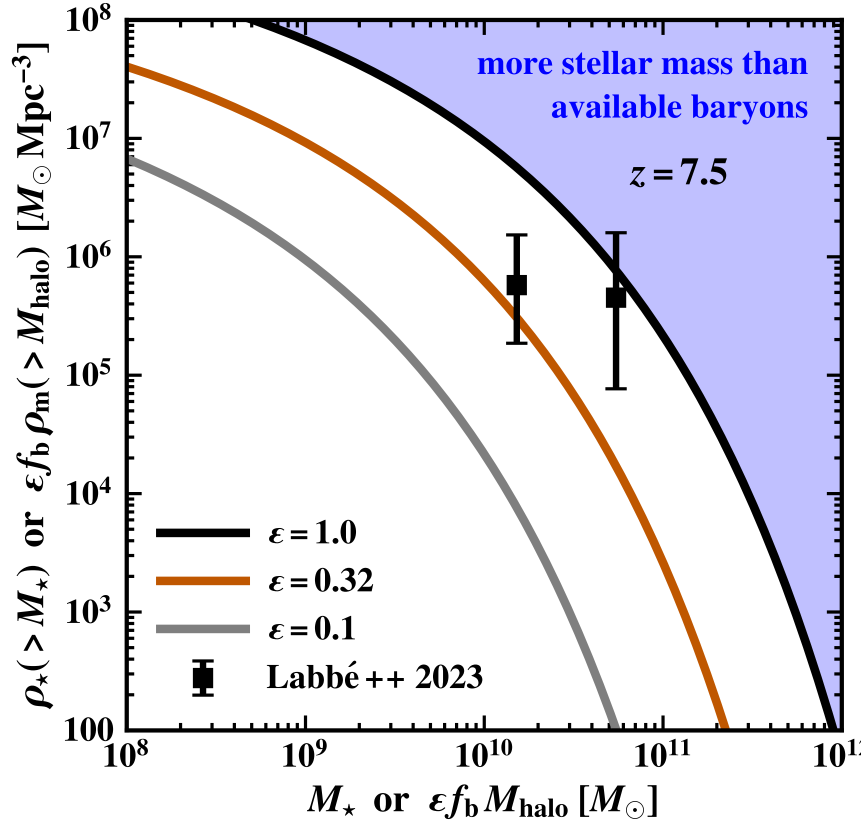
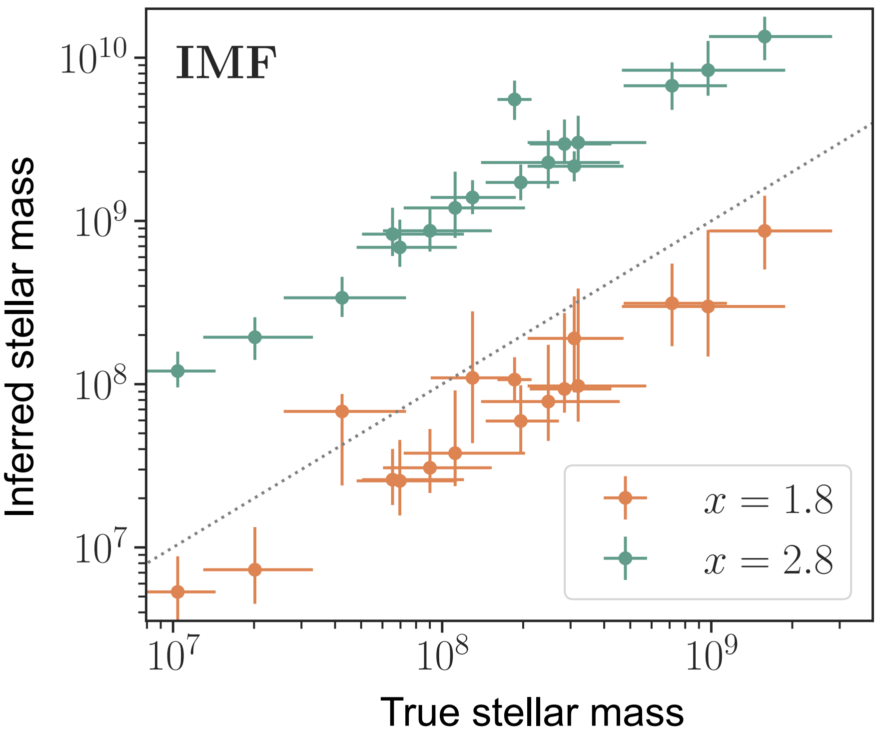





Early observations also seem to indicate an over-abundance of massive systems at all z>7 (Labbe et al. 2023). Explaining the stellar mass density at early epochs seems to require galaxies that can convert **ALL** of their baryons into stars (Boylan-Kolchin 2023). Or does a more prosaic solution lie in evolving mass-to-light ratios at high-redshifts?

# Stellar mass estimates very intricate at these early epochs




The initial mass function (mass distribution of stars in a newly formed stellar population) crucially determines the mass-to-light ratio (Wang incl. Dayal et al. 2024)

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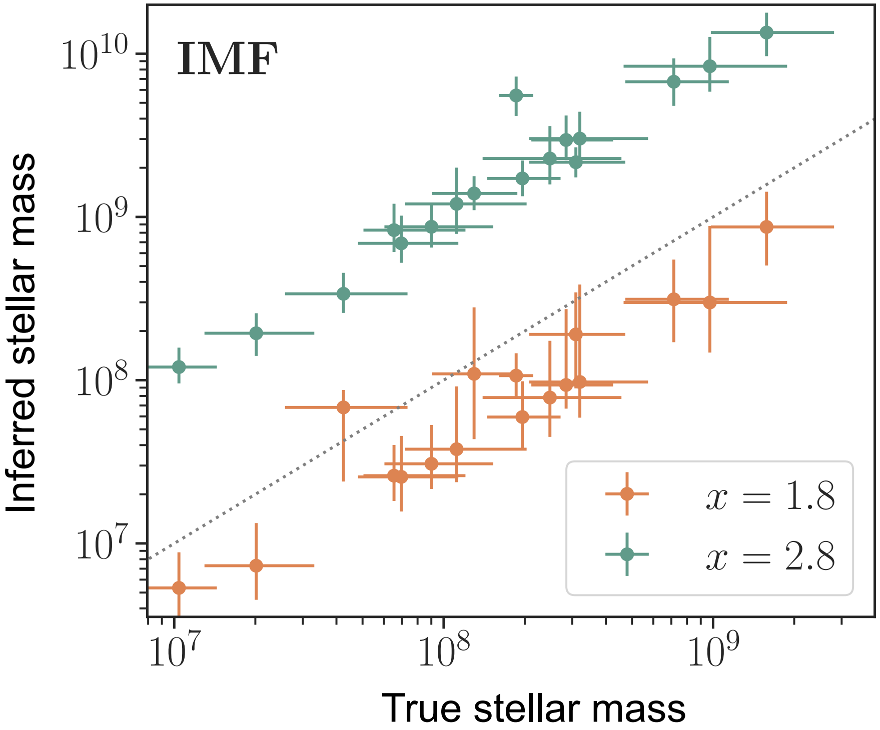


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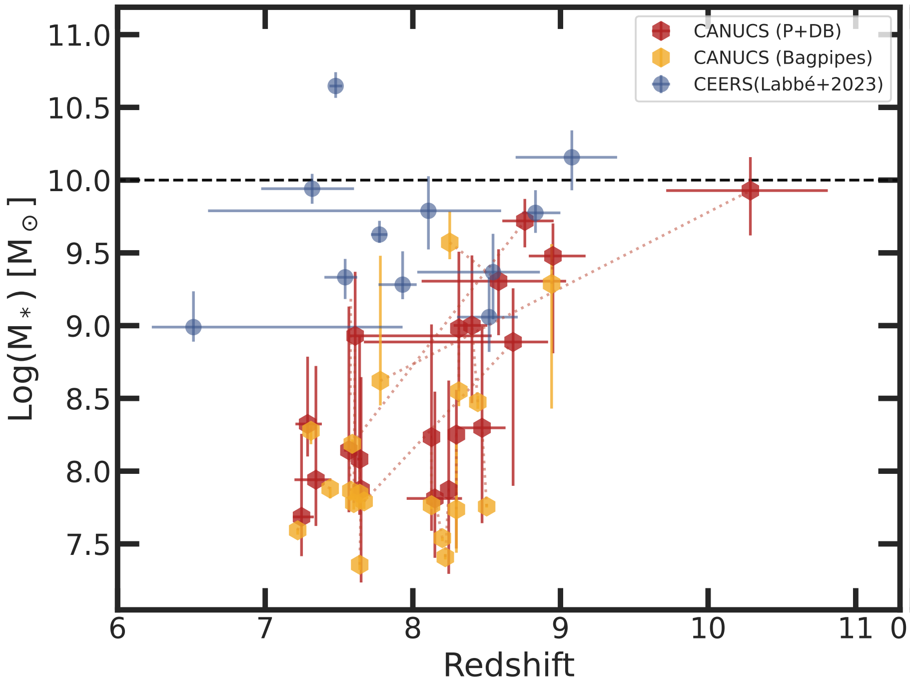
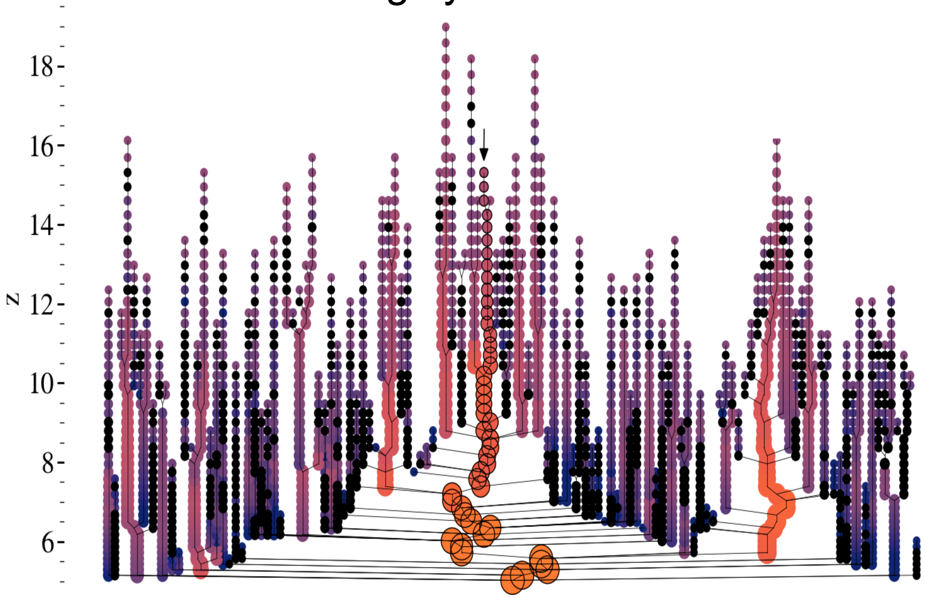
Field-to-field variance of stellar mass can be as large as a factor 30 - do not find stellar masses as high as Labbe (Desprez et al. 2023)



# Signals from cosmic dawn: implications for dark matter

CDM

Mass roughly ~100 GeV

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Dzoubia

Jill
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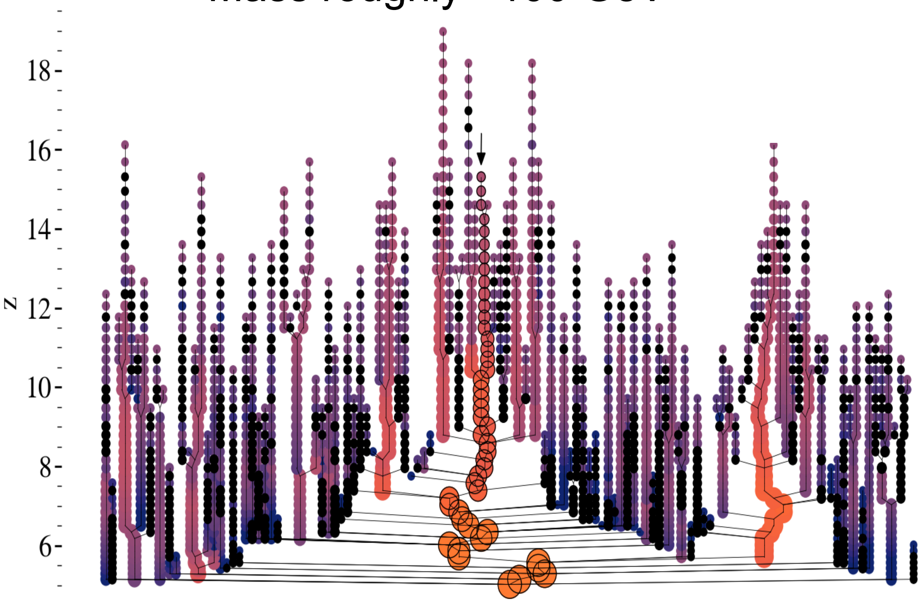
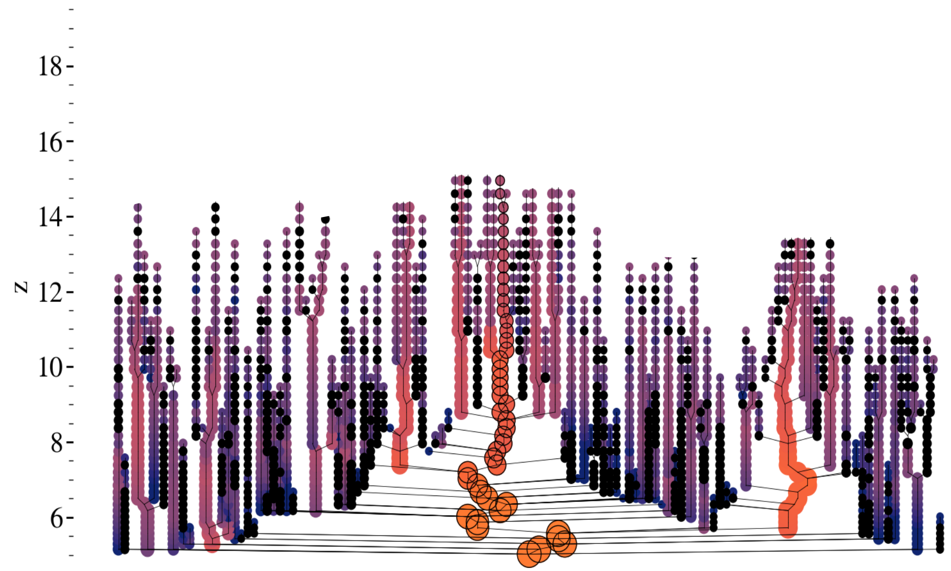



$3keV$

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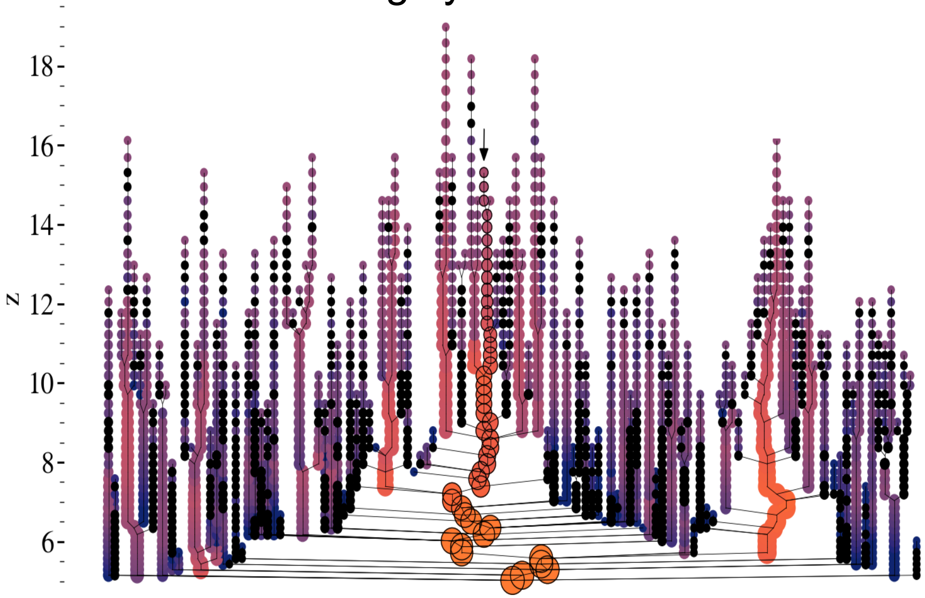


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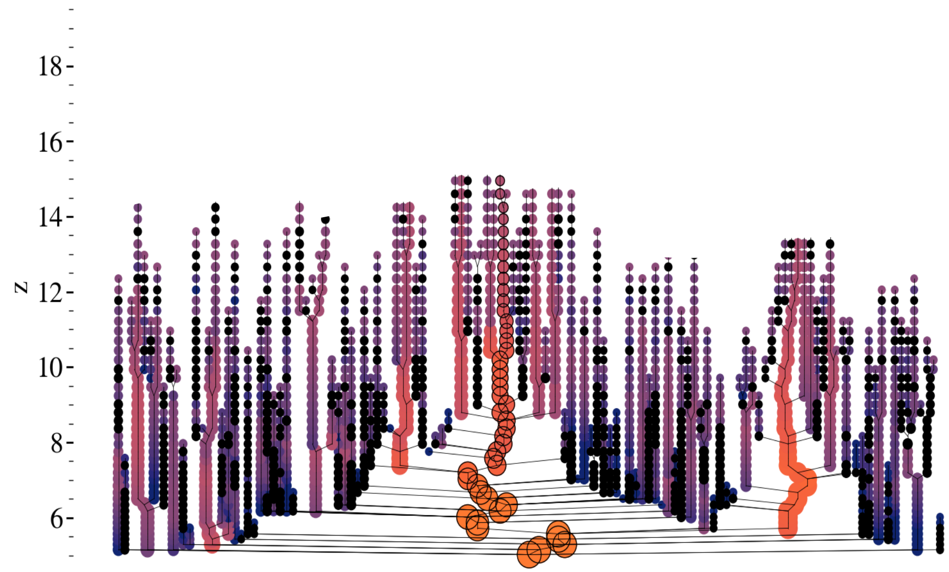
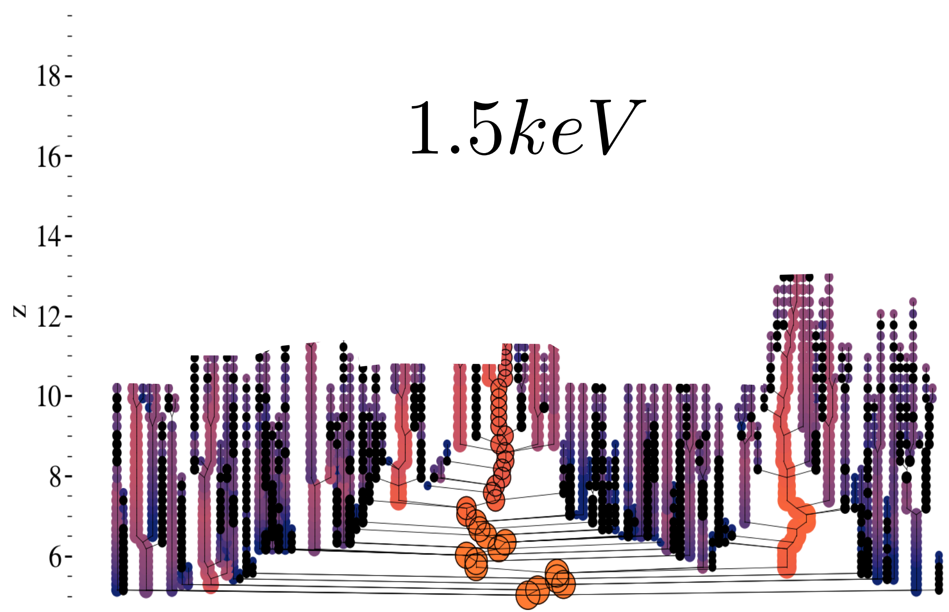



## $1.5keV$

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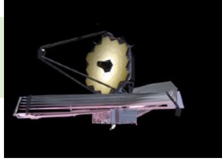
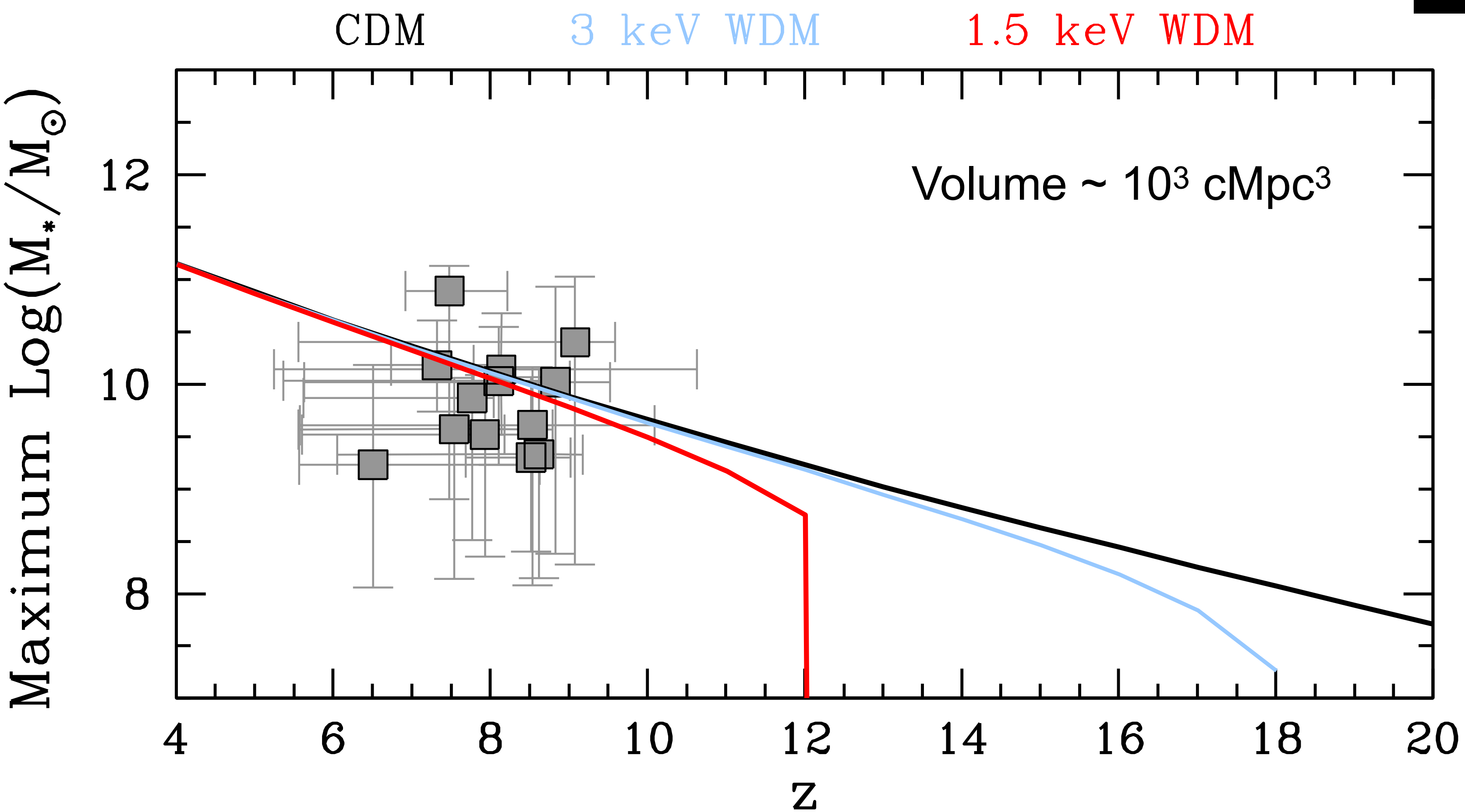
# Testing the nature of (warm) dark matter with JWST

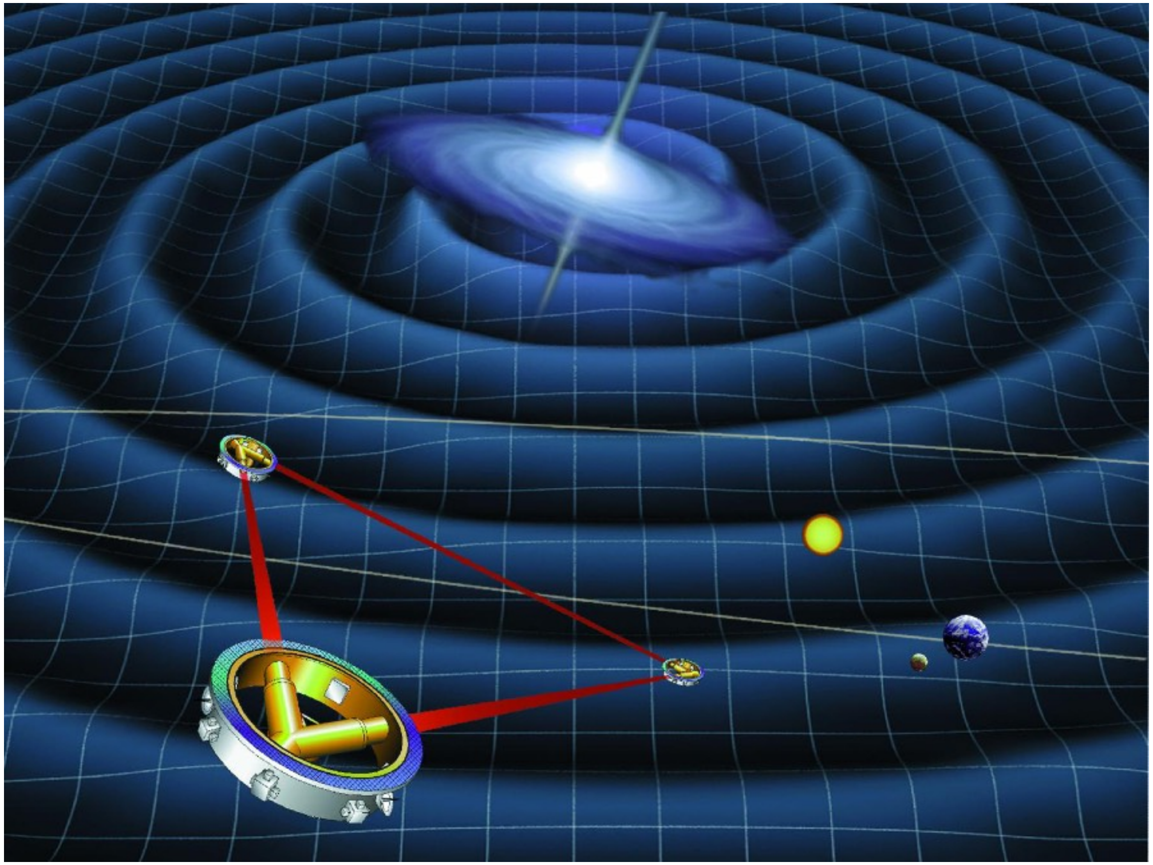




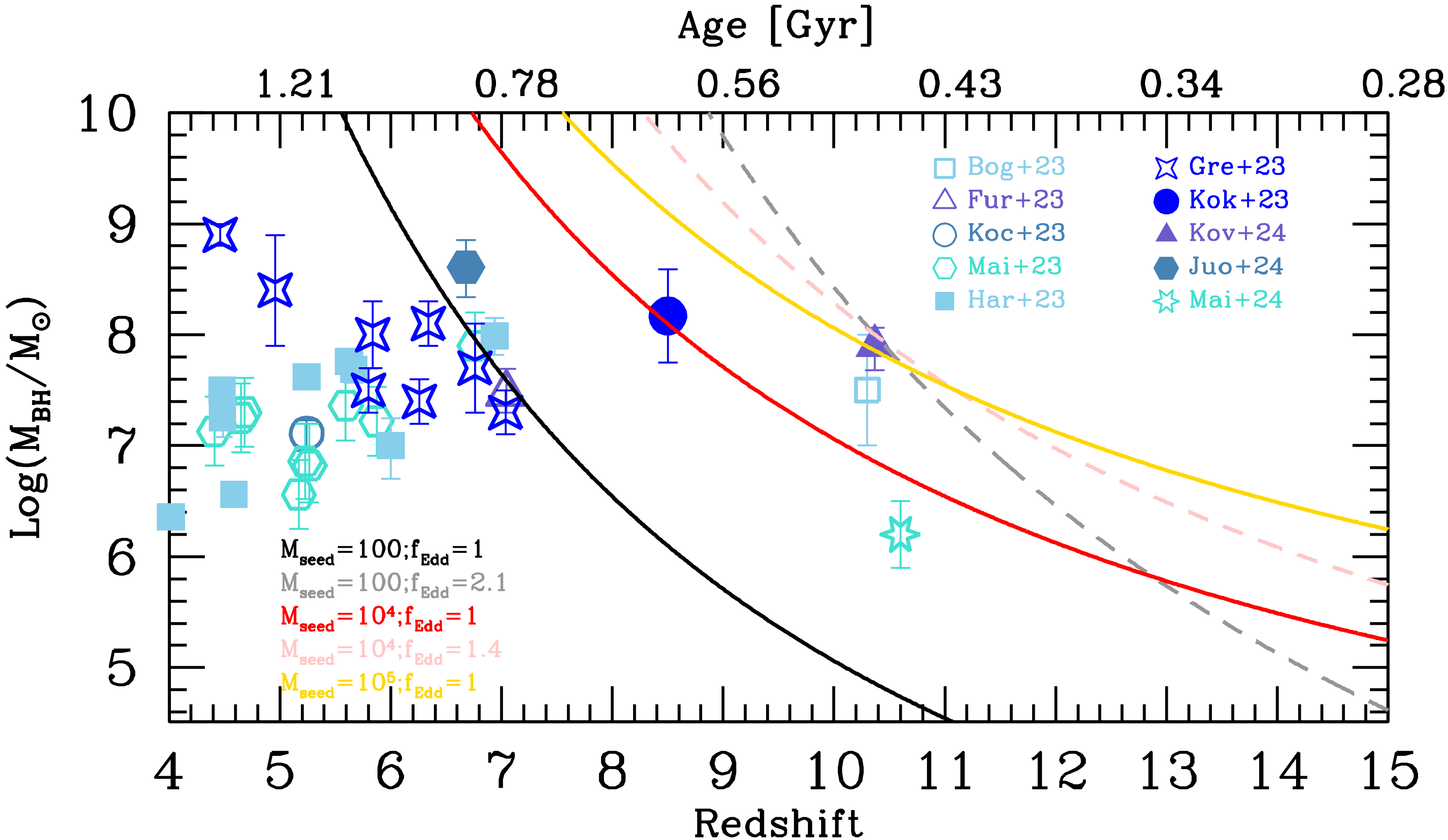

The detection of any galaxies existing in multiple JWST fields (~ $10^3$ cMpc$^3$) can be used to rule out light (1.5 keV) WDM models. Crucial to derive warm dark matter mass constraints at an epoch inaccessible by any other means.

Dayal & Giri, 2023, Dayal et al 2015, 2017, Maio & Viel 2023

# Black holes in the first billion years: implications for the era of gravitational wave astronomy



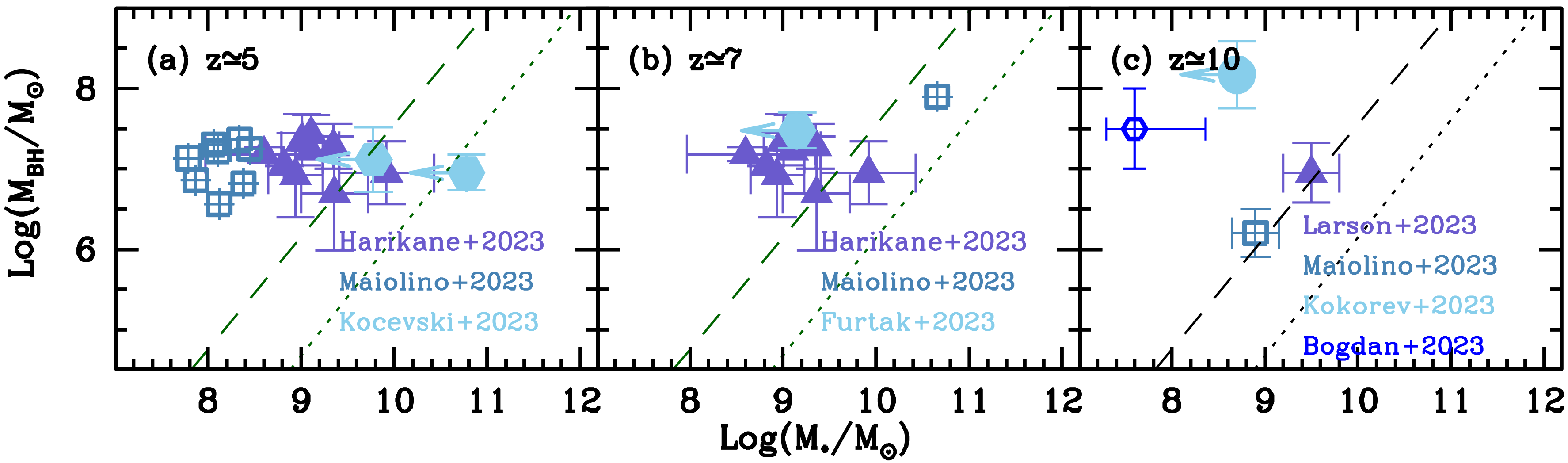
# Obese black holes in the first billion years in the JWST era




Explaining the supermassive black holes being observed by JWST require explanations such as super-Eddington accretion onto low-intermediate mass seeds or Eddington accretion onto massive ($10^5$ $M_\odot$) seeds that formed at $z \sim 25$ posing a challenge for theoretical models.

Dayal 2024; also Bogdan et al. 2023, Furtak et al. 2023; Goulding et al. 2023; Greene et al. 2024; Kokorev et al. 2023; Maiolino et al. 2023, 24; Joudzbalis et al. 24

# Problematic black hole to stellar mass ratios at high-z



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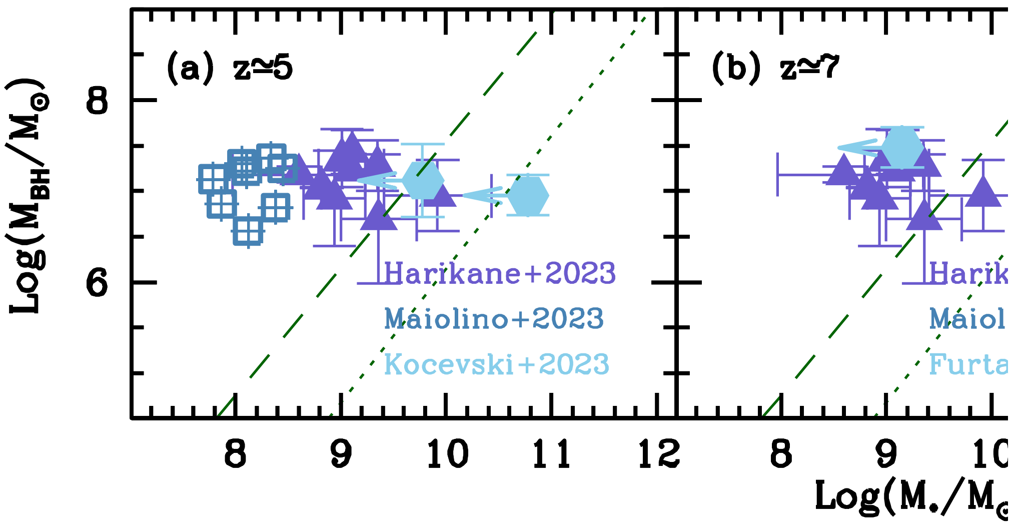


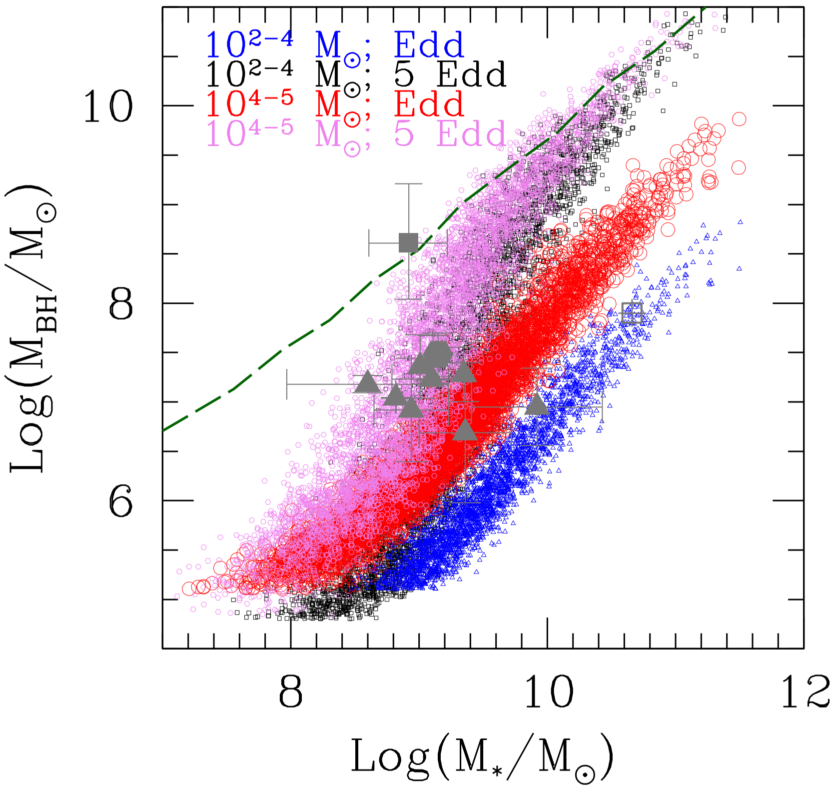

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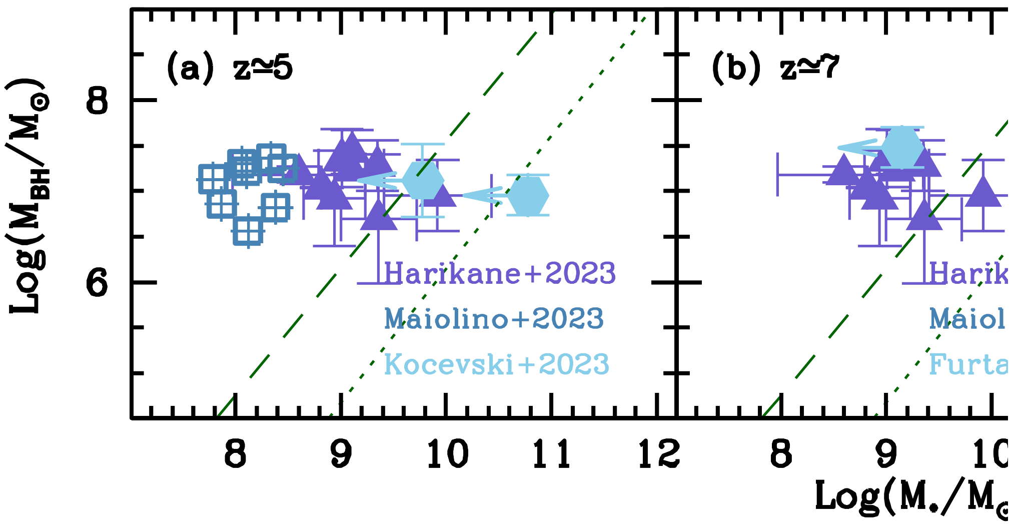
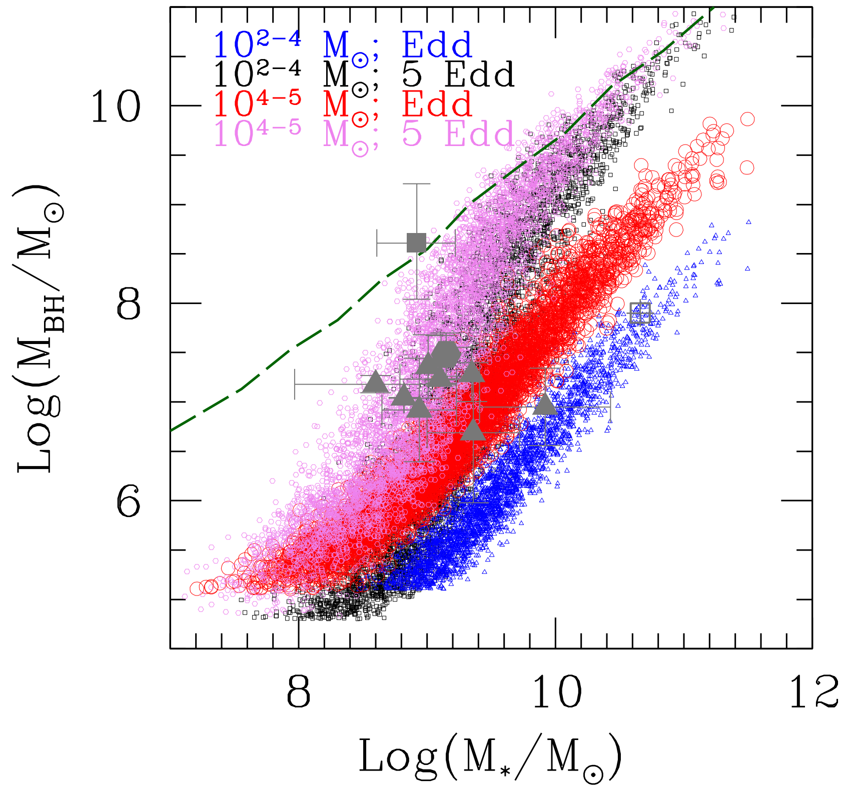
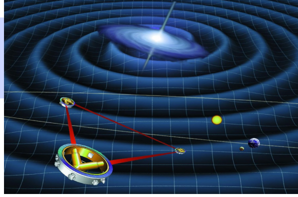


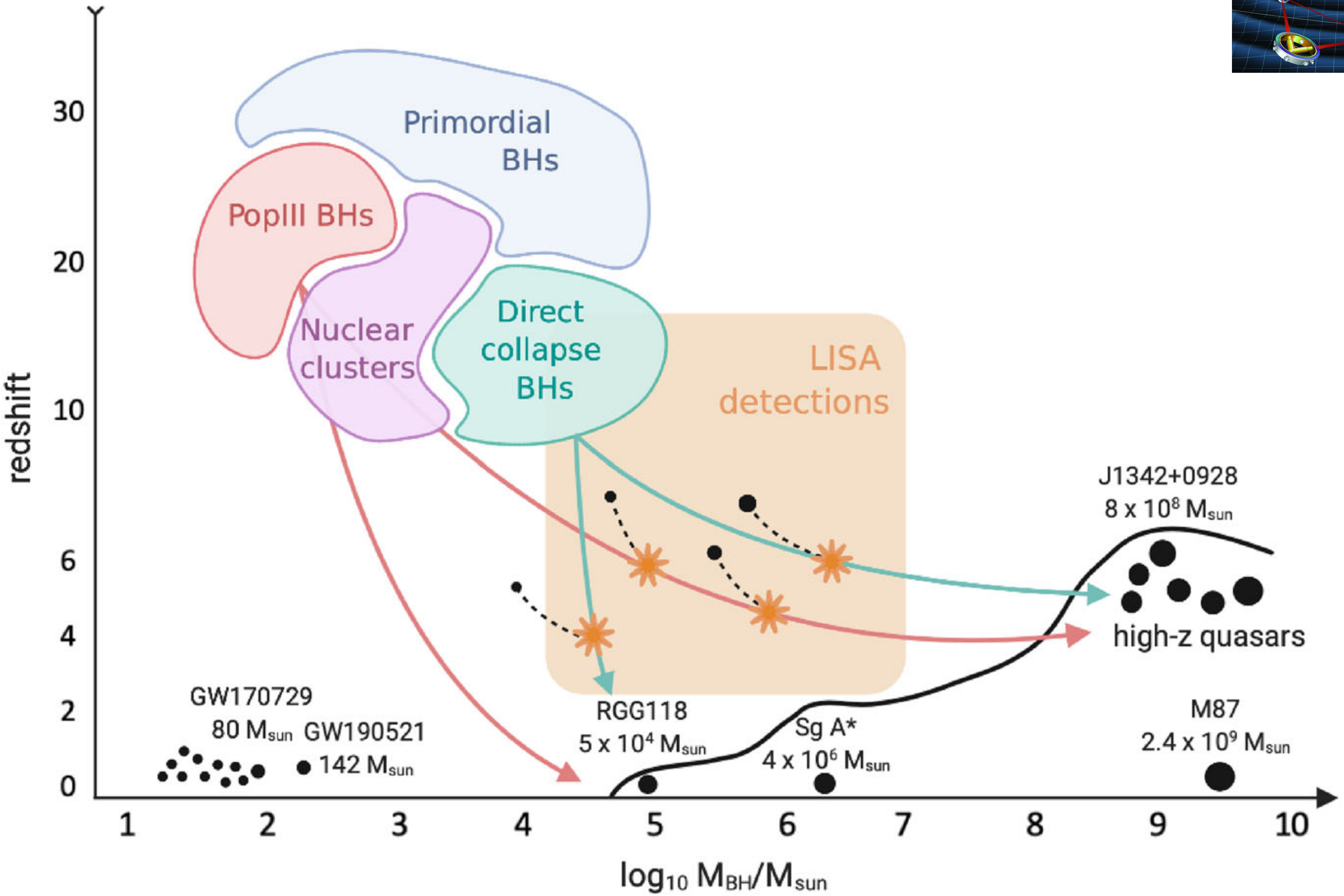




*JWST observations seem to indicate implausibly high BH to stellar mass ratios of 30-50% (Harikane et al. 23, Maiolino et al. 2023, 2024, Kocevski et al. 2023, Furtak (incl. Dayal) et al. 2023, Larson et al. 2023, Kokorev (incl. Dayal) et al. 2023, 2024, Bogdan et al. 2023)*. Solutions:

- Super-Eddington accretion onto low- or heavy-mass seeds (Schneider et al. 2023, Maiolino et al. 2024, Furtak et al. 2024, Dayal et al. 2024)
- Initial phases in the growth of heavy seeds (Natarajan et al. 2024)
- Stellar mass hidden due to dust/low surface brightness
- Baryons exist in right amount, but were not able to form stars (Maiolino et al. 2024)
- Black hole masses over-estimated (King 2024; Lupi et al. 2024)

# A need to revisit pathways for black hole seeding and growth





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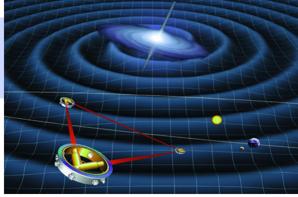
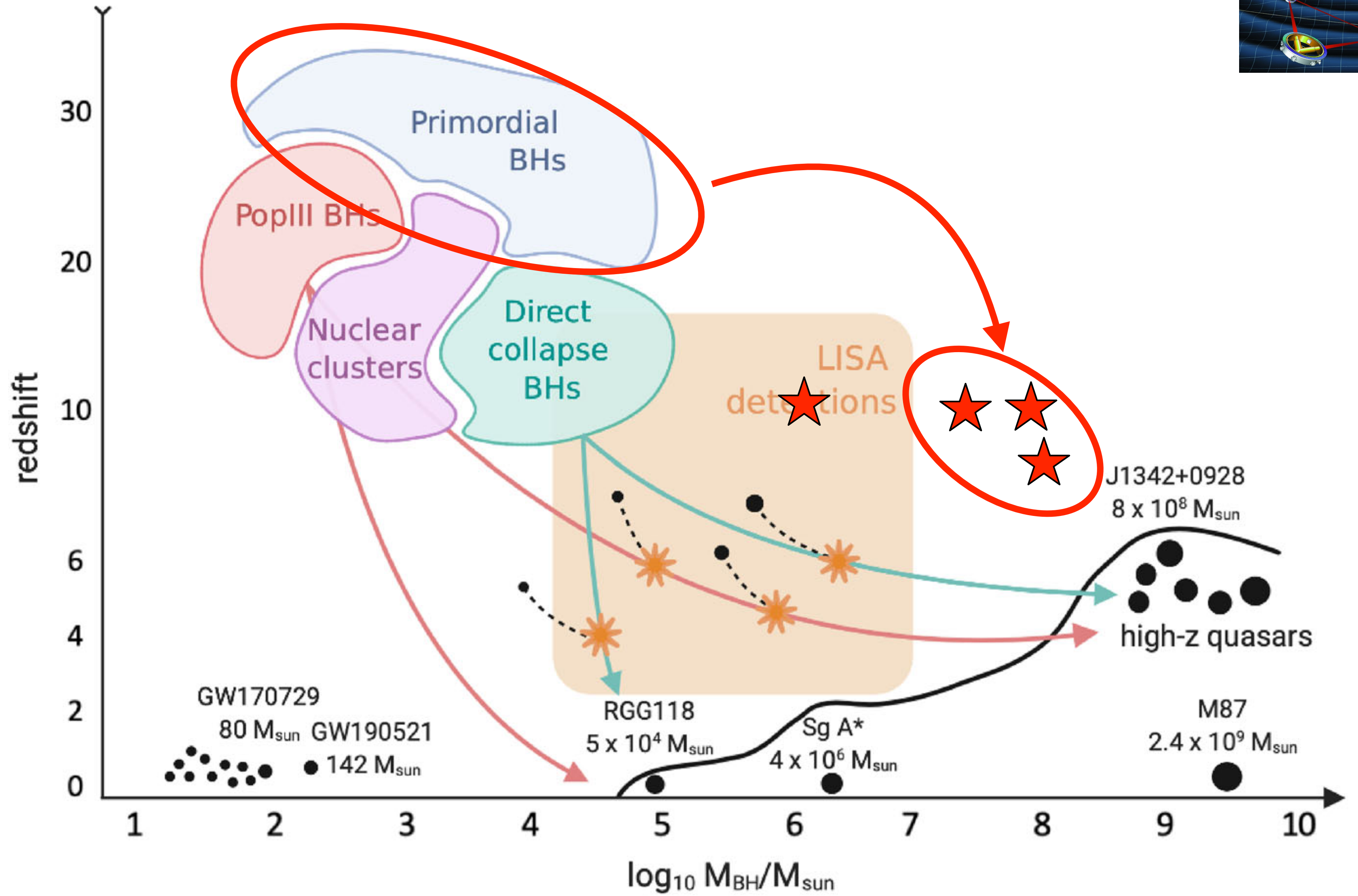
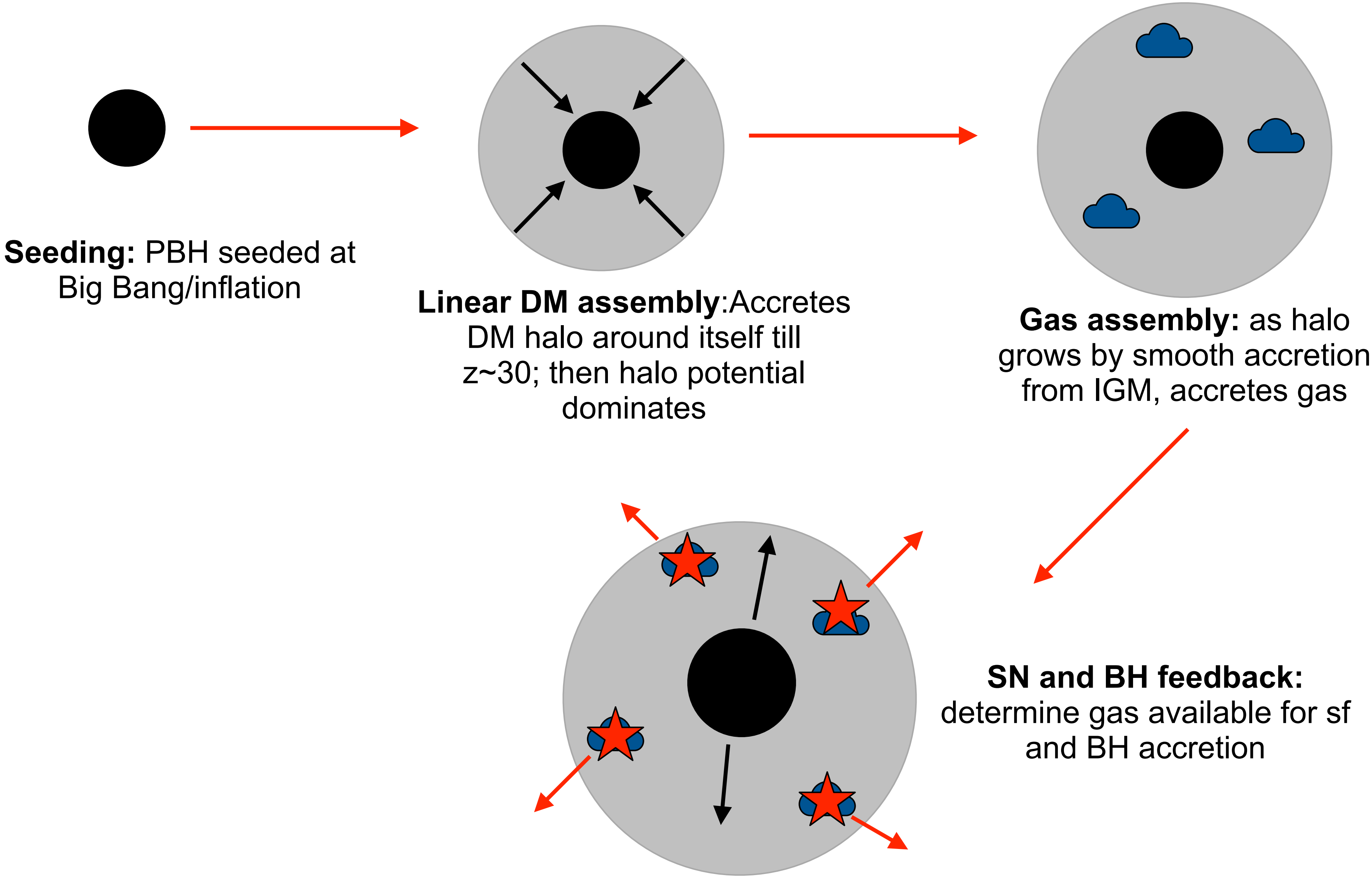




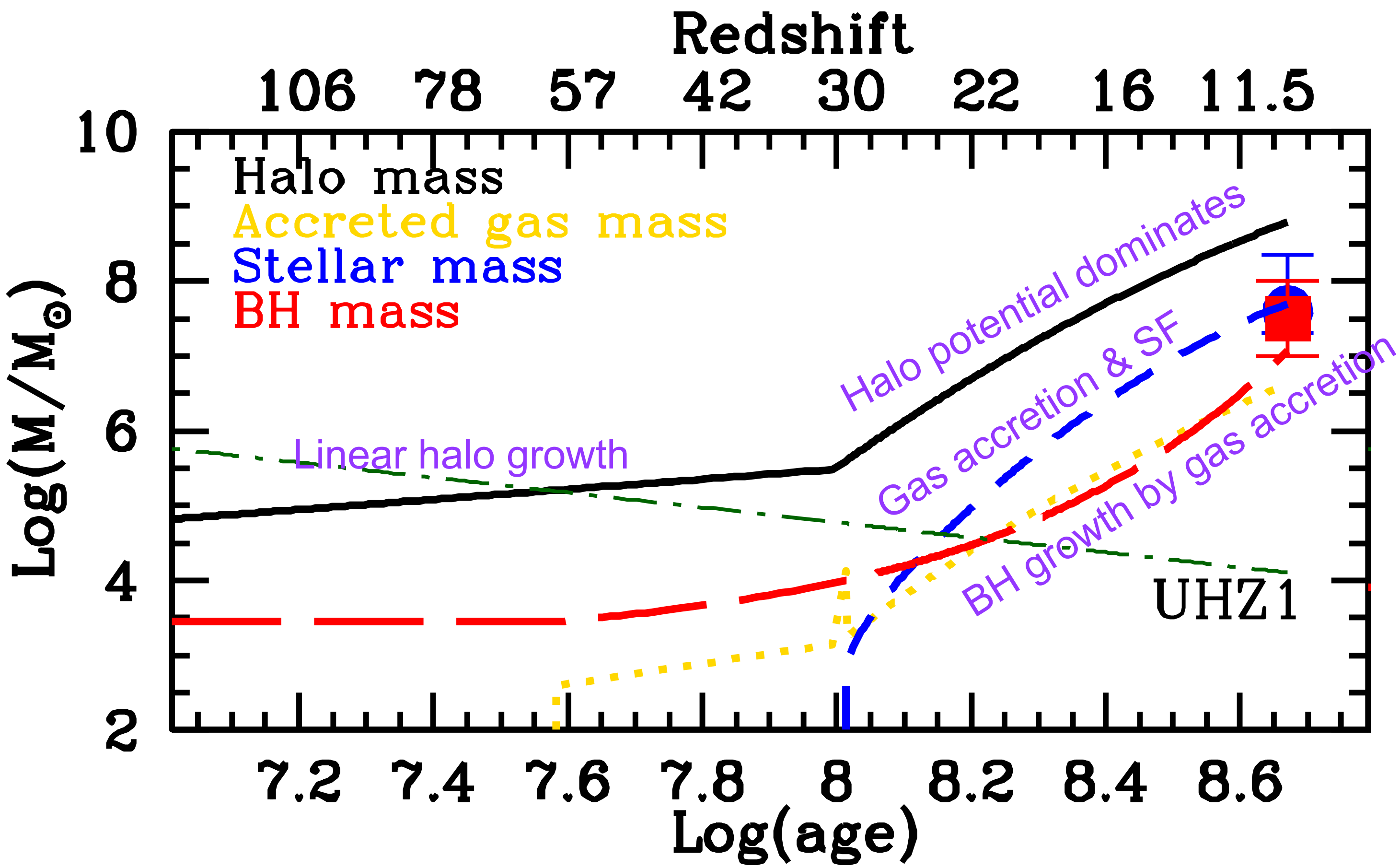

Given the different treatments of seeding, growth and merger timescales, *different models predict the detection of anywhere between 1-100 events per year with LISA (“Astrophysics with LISA” white paper, 2023, LRR).* Obese black holes uncovered by the JWST require revisiting black hole seeding and growth pathways e.g. primordial BHs (Dayal 2024).

# A primordial solution for early black holes




Carr 2005, Mack et al, 2007, Carr & Silk 2018, Dayal 2024

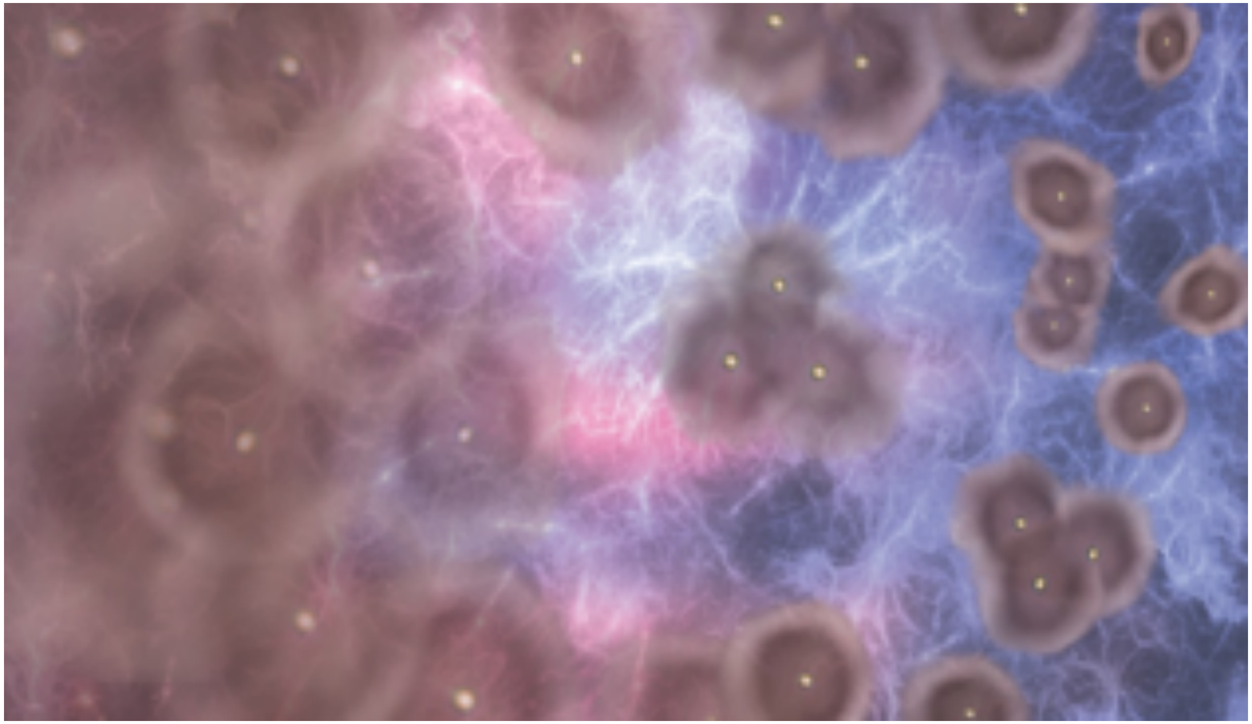
# A primordial origin for early black holes



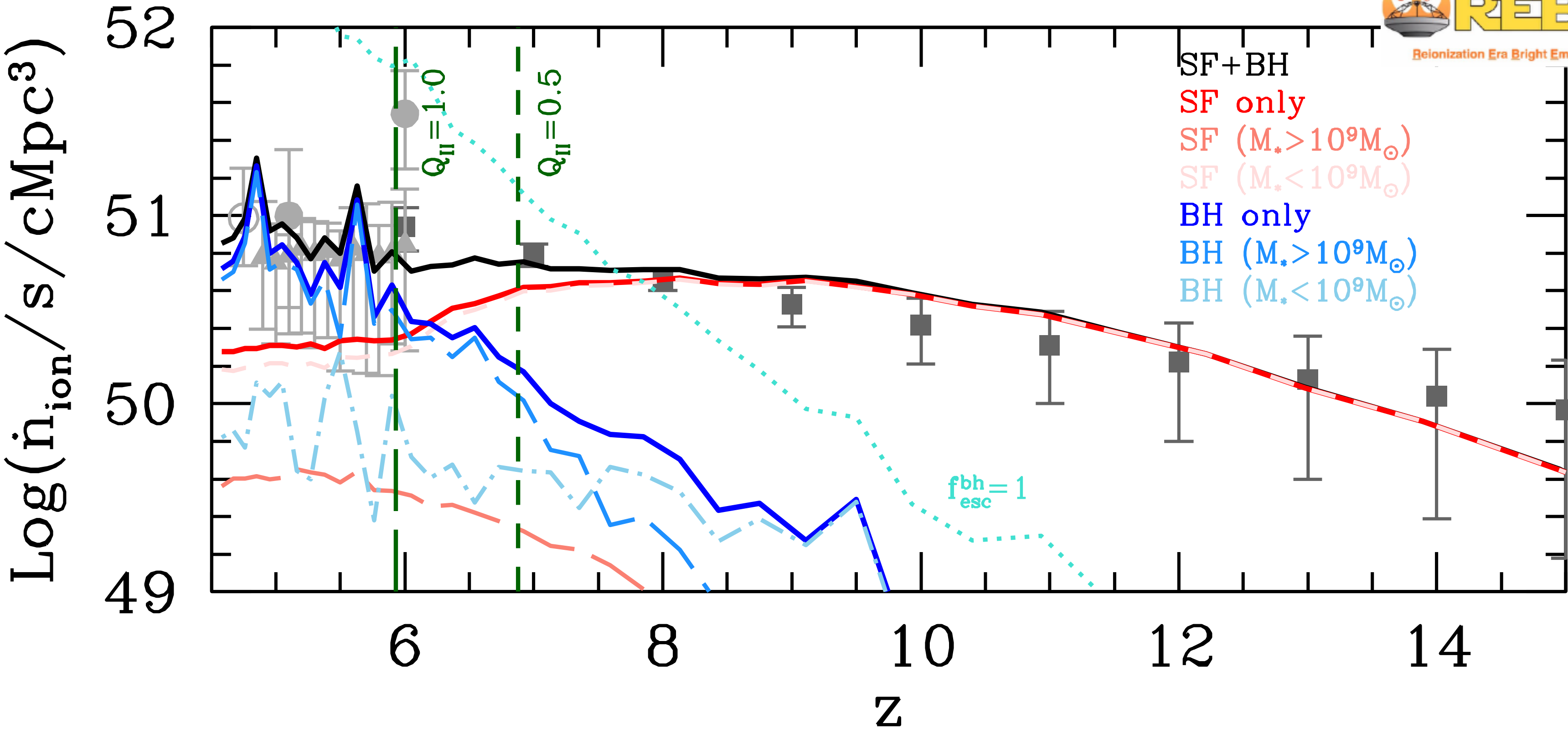

Primordial black holes that assemble their halos (and hence their baryons) around themselves naturally yield extremely high black hole to stellar mass ratios (~0.1-1.86) i.e. in some cases, the black hole grows to be more massive than the stellar mass of its host halo, presenting an attractive alternative to seeding these puzzling early systems.

Dayal 2024

# Early galaxies: implications for reionization in the era of 21cm cosmology



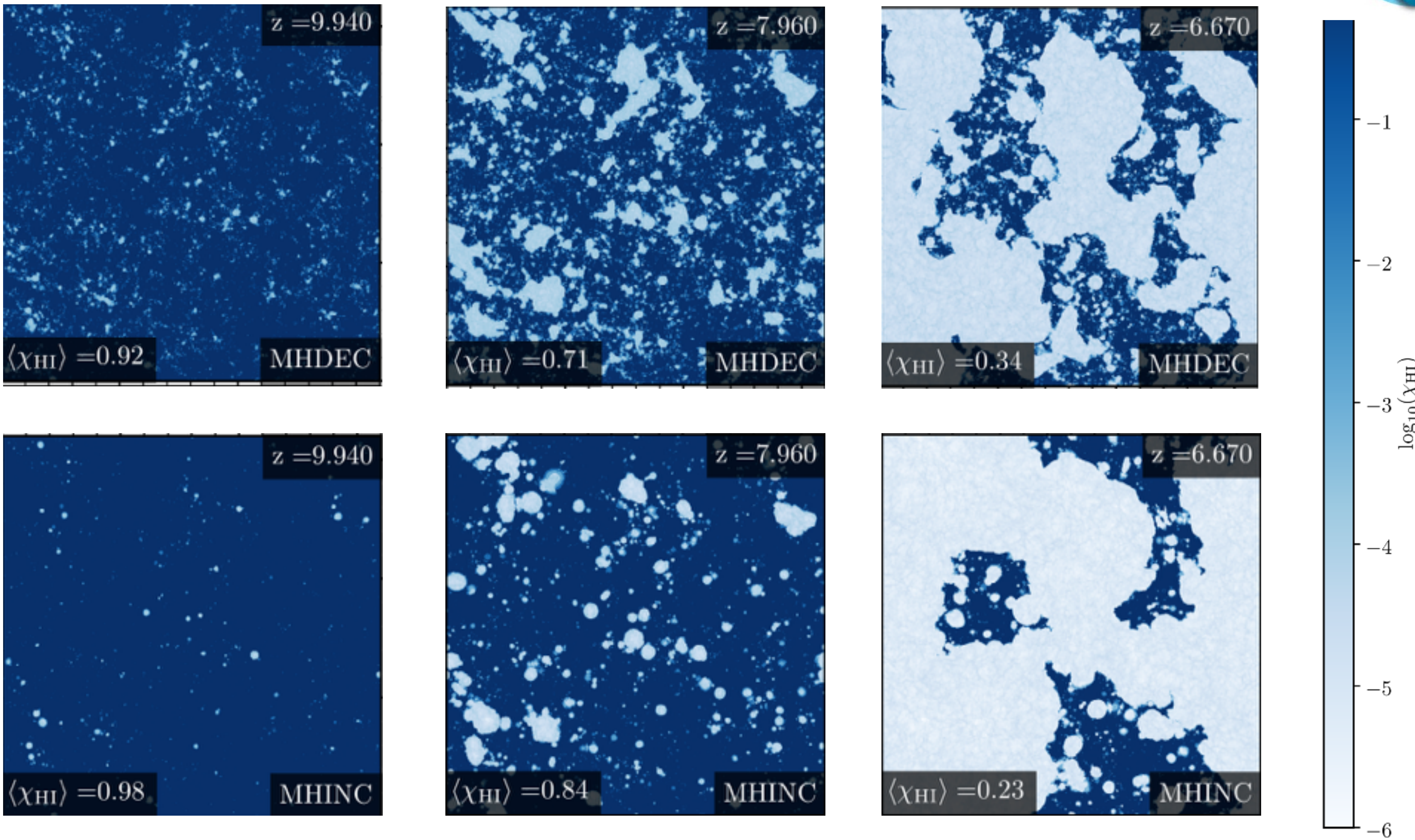
# The key reionization sources post-JWST




- Escaping emissivity dominated by low-mass ( $M_* \leq 10^9 M_\odot$) star forming galaxies down to z~7.
- AGN overtake the contribution from star formation at z~6.2 when reionization is 80% complete.
- AGN contribute at most 25% to the entire reionization process.

Dayal et al. 2024; Atek (incl. PD) et al. 2024

# Probing key reionization sources through its topology




Low-mass galaxies driving reionization (top panel) results in a more homogeneous distribution of ionized regions as compared to a more biased distribution if high-mass galaxies (bottom panel) drive the process (Astraeus VIII: Hutter, Trebitsch, Dayal et al. 2023).

# The emerging picture..

- Recent JWST observations indicate an over-abundance of *luminous systems* at z>10 - could be explained by bursty/extremely efficient SF, decreasing effects of dust, evolving IMF, interlopers..

- JWST detections of *exceptionally massive systems in terms of stellar mass* could be explained by varying IMFs, cosmic variance - no breaking of LCDM as of now.

- Multiple field studies with the JWST can be used to rule out *light (<3keV) WDM models* simply using the observed stellar masses.

- JWST yielding a sample of *numerous and obese black holes as early as z~10* with black hole to stellar mass ratios as high as 50% - solutions include extremely efficient black hole growth, inefficient stellar growth or extremely early origins of BH seeds. The presence of such black holes also has important connotations for the *GW event rates expected from LISA*.

- *Low-mass star forming galaxies ( $< 10^9 \mathrm{M}_\odot$ in stellar mass) are indicated to be the key reionization drivers. Galaxy-21cm correlations* will be crucial in shedding light on the patchy topology of reionization and constraining the average neutral fraction.