Title: The puzzling emergence of galaxies and black holes in the first billion years

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Abstract:

Galaxy formation in the first billion years marks a time of great upheaval in our cosmic history: the first sources of light in the Universe, these galaxies ended the 'cosmic dark ages' and produced the first photons that could break apart the hydrogen atoms suffusing all of space starting the process of 'cosmic reionization'. The past few years have seen cutting-edge instruments such as the James Webb Space Telescope (JWST) provide tantalising glimpses of such galaxies assembling in an infant Universe. Puzzlingly, these observations are also yielding a sample of unexpectedly numerous and large black holes (up to a 100 million solar masses) within the first 600 million years, posing an enormous challenge for galaxy formation models. I will show how this data is providing an unprecedented opportunity to pin down the reionization state of the Universe in addition to providing an unrivalled resource for understanding the reionization topology in the forthcoming era of 21cm cosmology. I will also show how these early systems provide a powerful testbed for Dark Matter models beyond "Cold Dark Matter". Finally, I will try to give a flavour of the gravitational wave event rates expected from such early black holes in the Laser Interferometer Space Antenna Array (LISA) era.

The puzzling emergence of galaxies and black holes in the first billion years

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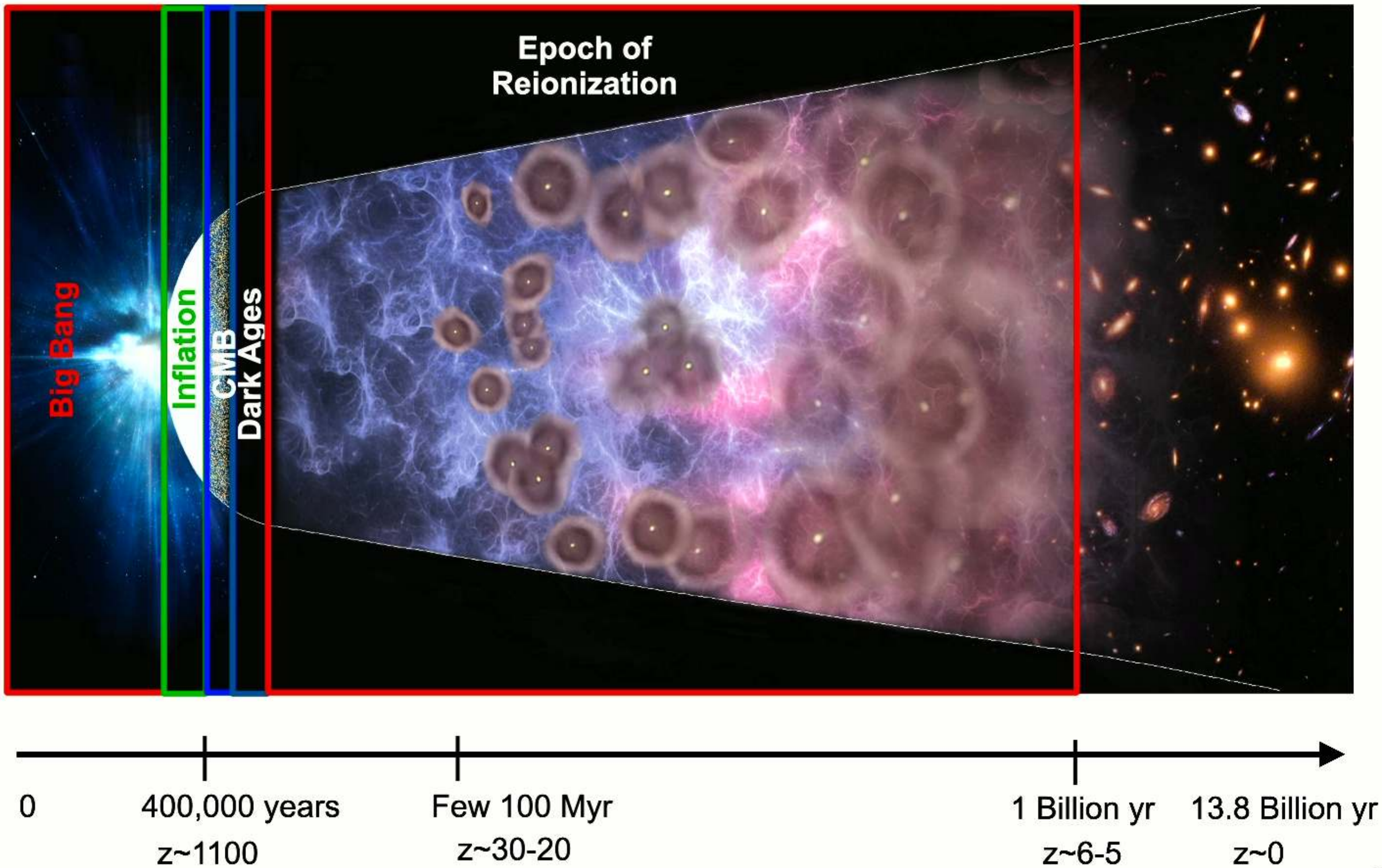
The cosmic timeline



2

The golden age for understanding early galaxies

When did the first galaxies form? What were their physical properties?

What were the key sources of reionization? Star formation? Black holes?

How did the patchy process of reionization proceed?

What was the role of black holes in early galaxy formation?

What was the merger rate of black holes at these early epochs?

What can signals from cosmic dawn tell us about cosmology (e.g. nature of dark matter)?

Key contributors

Nikki Arendse, Prishita Budhrani, Pelle van de Bor, Chris Boettner, Jonas Bremer, Paula Caceres, Maria Dziouba, Emma Giovinazzo, Anne Hutter, Marenthe Hopma, Laurent Legrand, Valentin Mauerhofer, Folkert Nobels, Giorgos Nikopoulos, Fabio Pacucci, Olmo Piana, Fernanda Pratama, Jill Straat, Maxime Trebitsch, Graziano Ucci..

REBELS
Reionization Era Bright Emission Line Search

PANORAMIC

cosmic spring

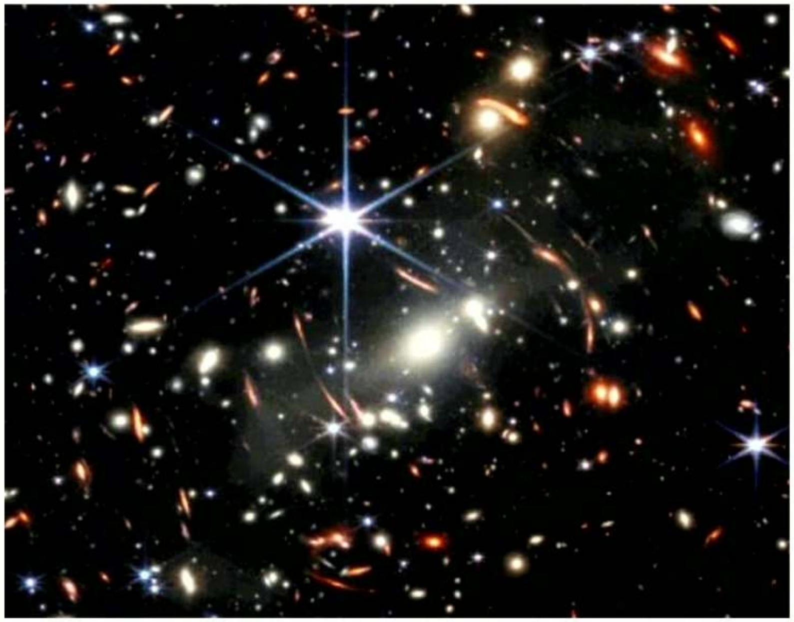
UNCOVER

MEDIUM BANDS: MEGASCIENCE

MIRAGE OR MIRACLE

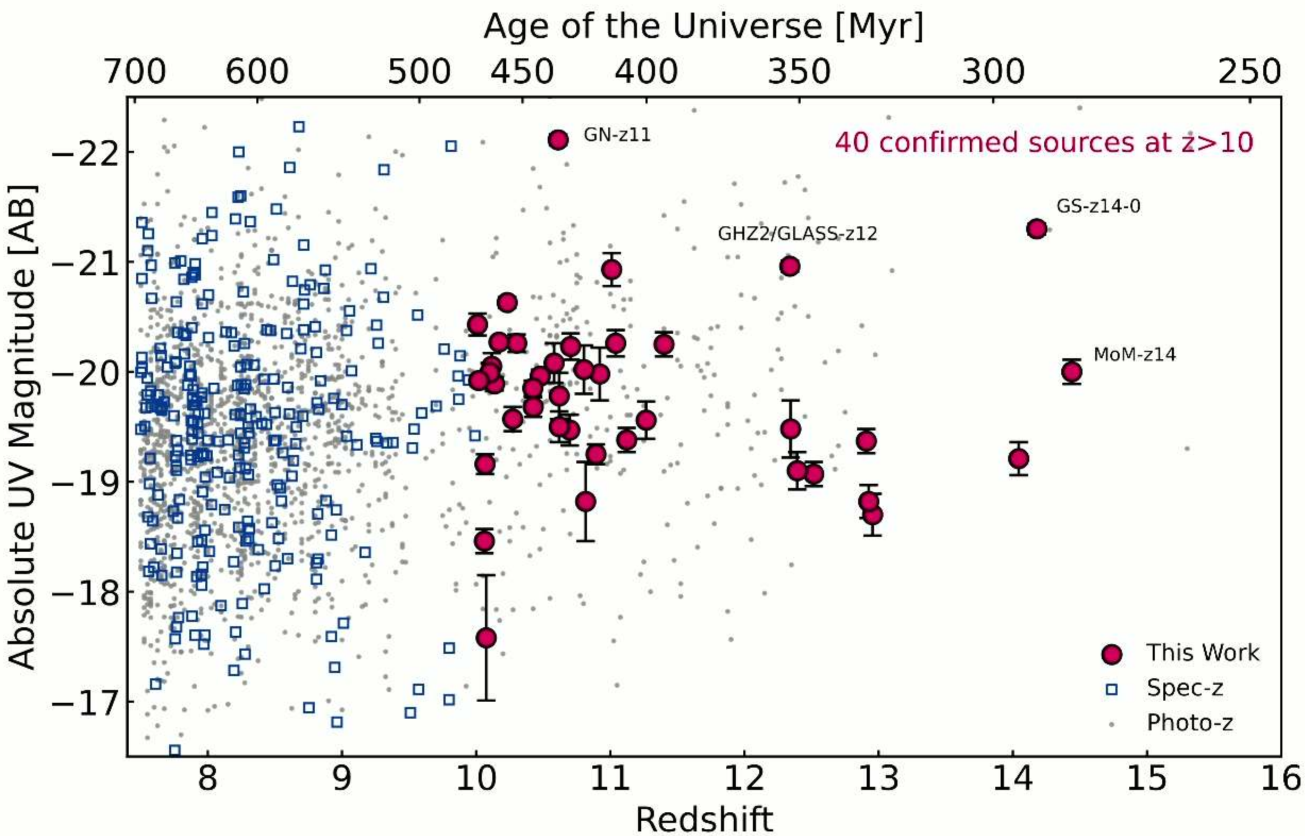
VENUS

The puzzling emergence of star forming galaxies in the first billion years



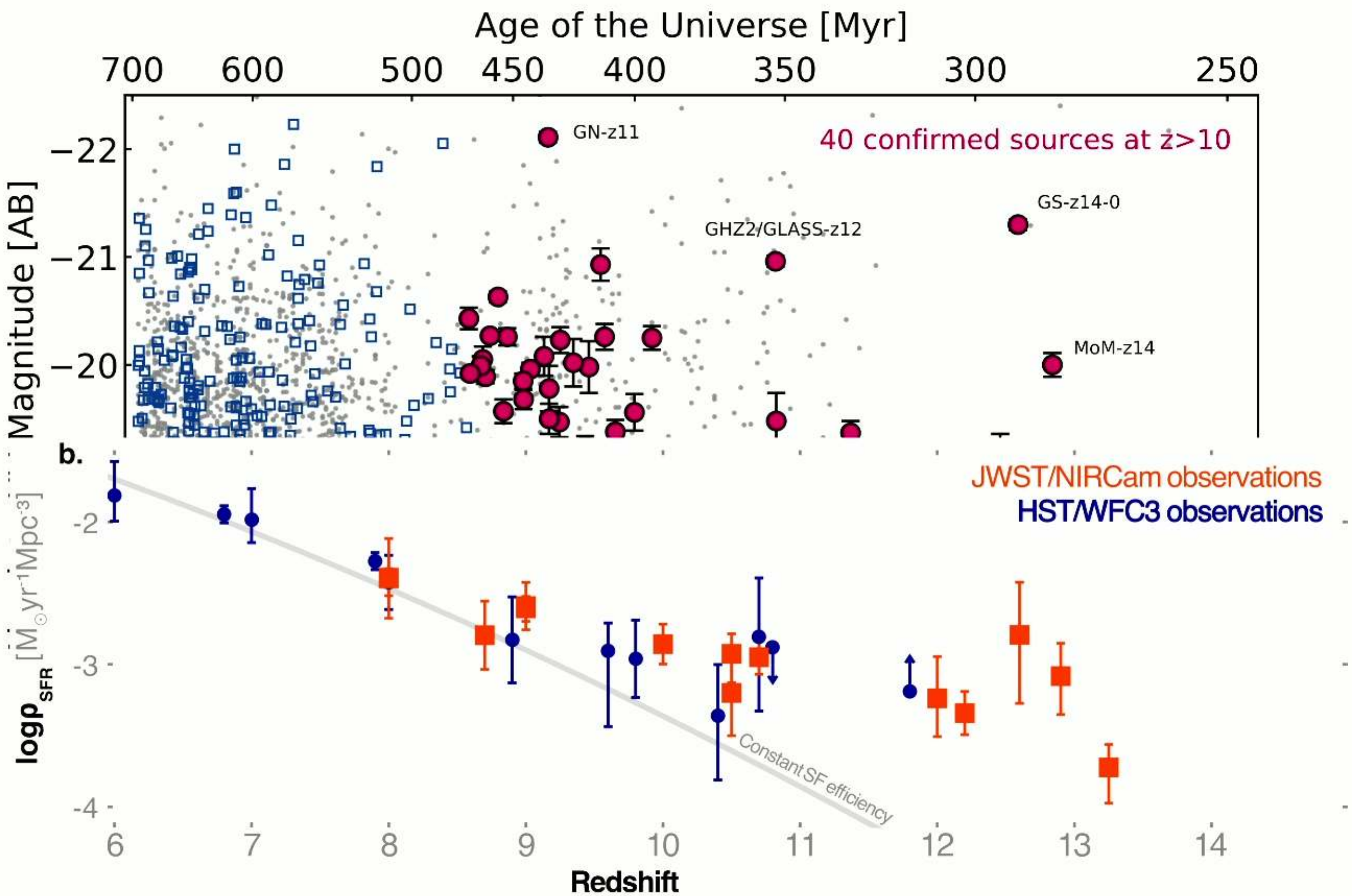
5

Increasing number of objects being spectroscopically confirmed



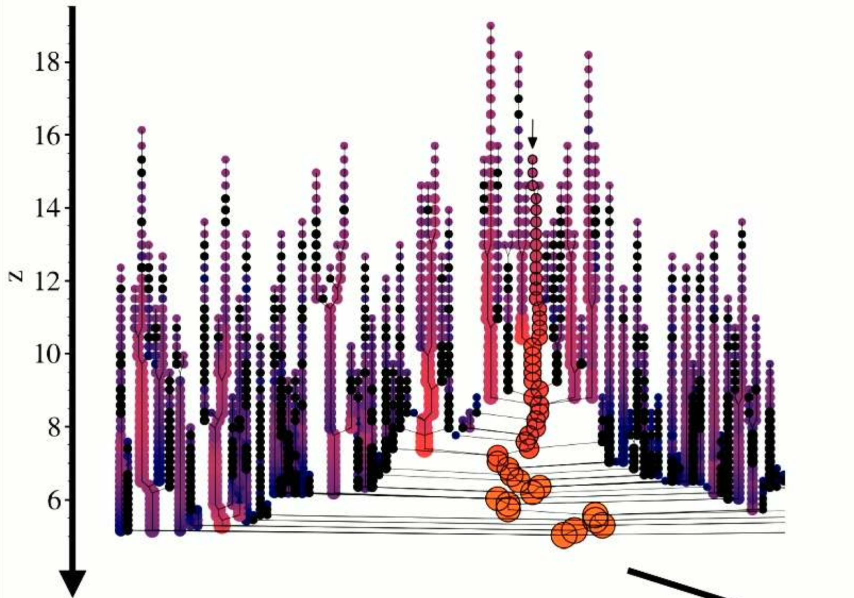
Roberts-Borsani (+ PD) et al. 2025

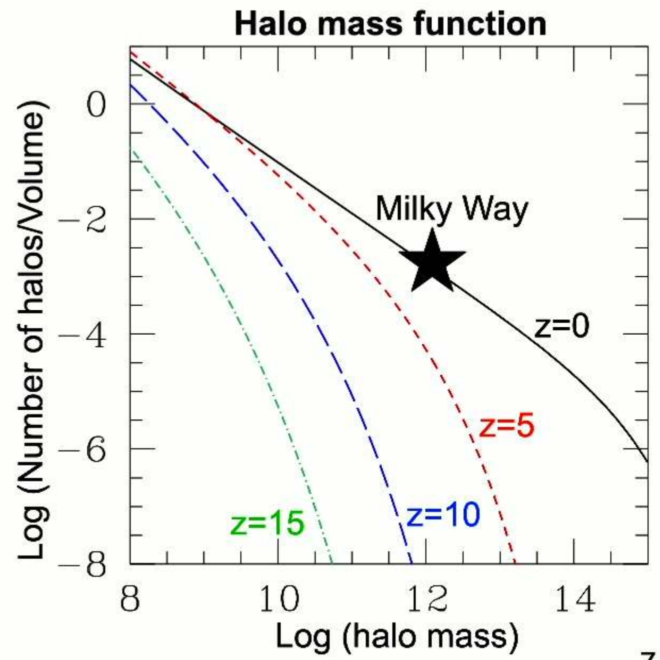
Increasing number of objects being spectroscopically confirmed



Adamo et al. 2024: review article written by the attendees of the 2024 ISSI breakthrough workshop "The first billion year of the Universe"

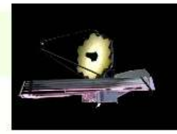
Structure formation in the cold dark matter paradigm

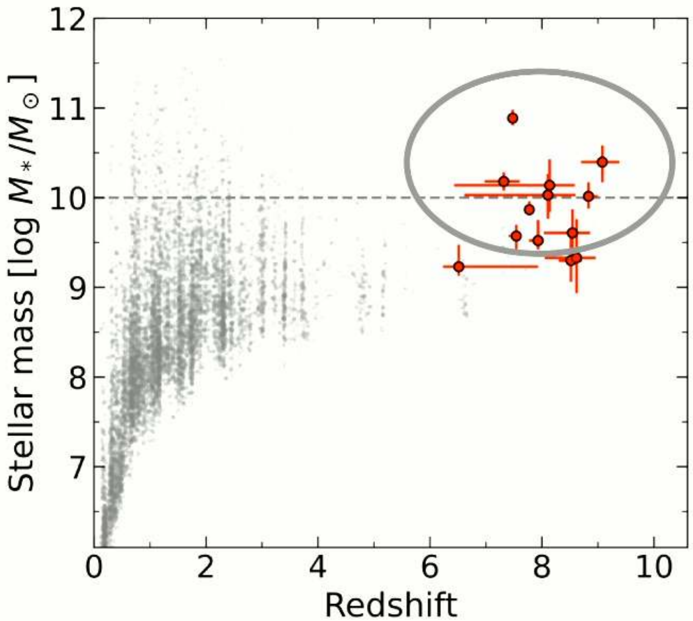


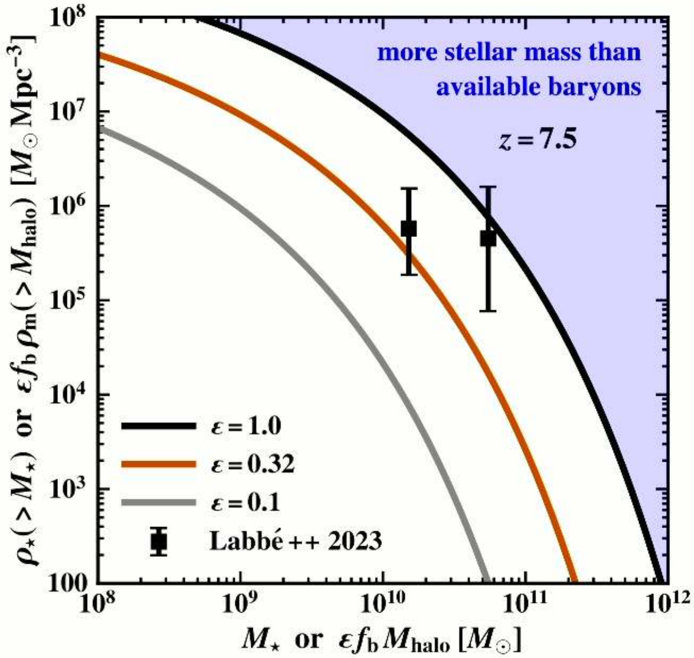


7

A puzzling over-abundance of massive systems

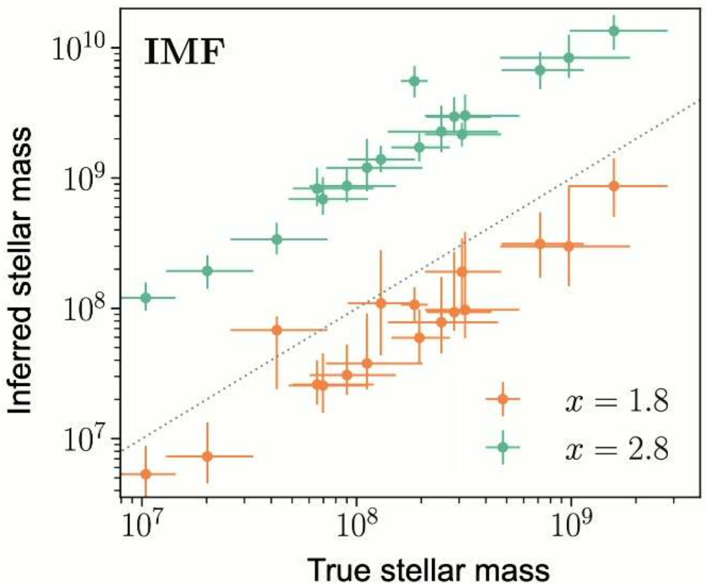






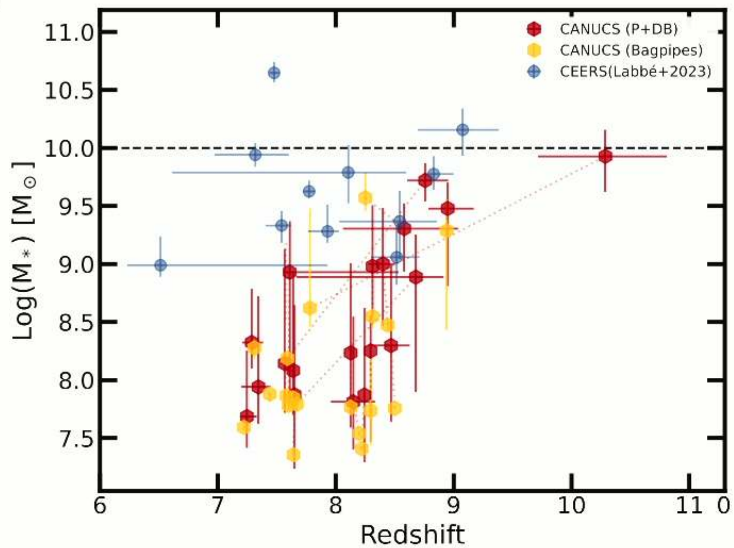
Early observations also seem to indicate an over-abundance of massive systems at all z>7 (Labbe et al. 2023). Explaining the stellar mass density at early epochs seems to require galaxies that can convert **ALL** of their baryons into stars (Boylan-Kolchin 2023). Or does a more prosaic solution lie in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

Caution: stellar mass estimates very intricate at these early epochs

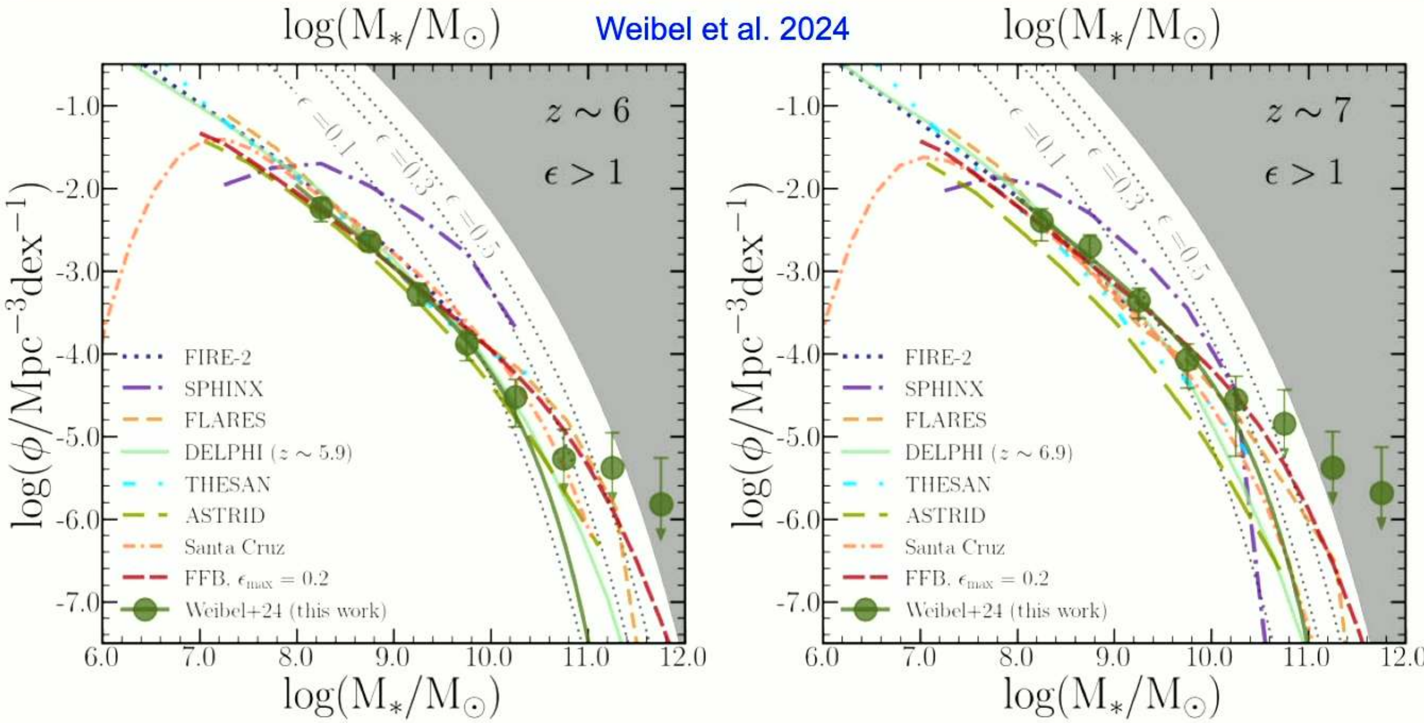


The mass distribution of stars in a newly formed stellar population (i.e. relative numbers of less/more massive stars) crucially determines the mass-to-light ratio (Wang incl. Dayal et al. 2024)

Field-to-field variance and exact history of star formation (which affects mass to light ratio) can lead to of stellar mass variations by factor 30 (Desprez et al. 2023)



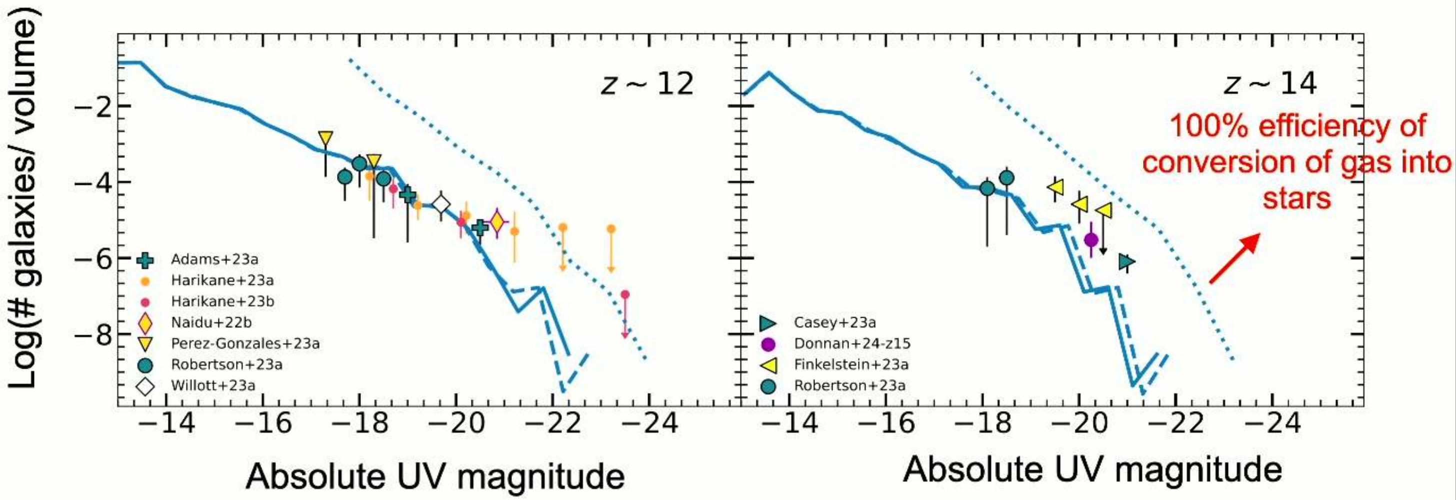
Stellar mass demographics at early epochs



- Star formation efficiency increases with stellar mass - star formation suppressed in low-mass systems possibly due to feedback
- At all z~6-9, observational upper limits hit against the upper theoretical ceiling of all baryons forming stars. If confirmed, these pose a serious challenge to galaxy formation models.

Also: Duncan+2014, Grazian+2015, Song+2016, Stefanon+2017, Bhatawdekar+2019, Kikuchihara+2020, Furtak+2021, Stefanon+2021, Weaver+2023, Navarro-Carrera+2024, Wang+2024, Harvey+2024

A puzzling over-abundance of bright systems at high-z

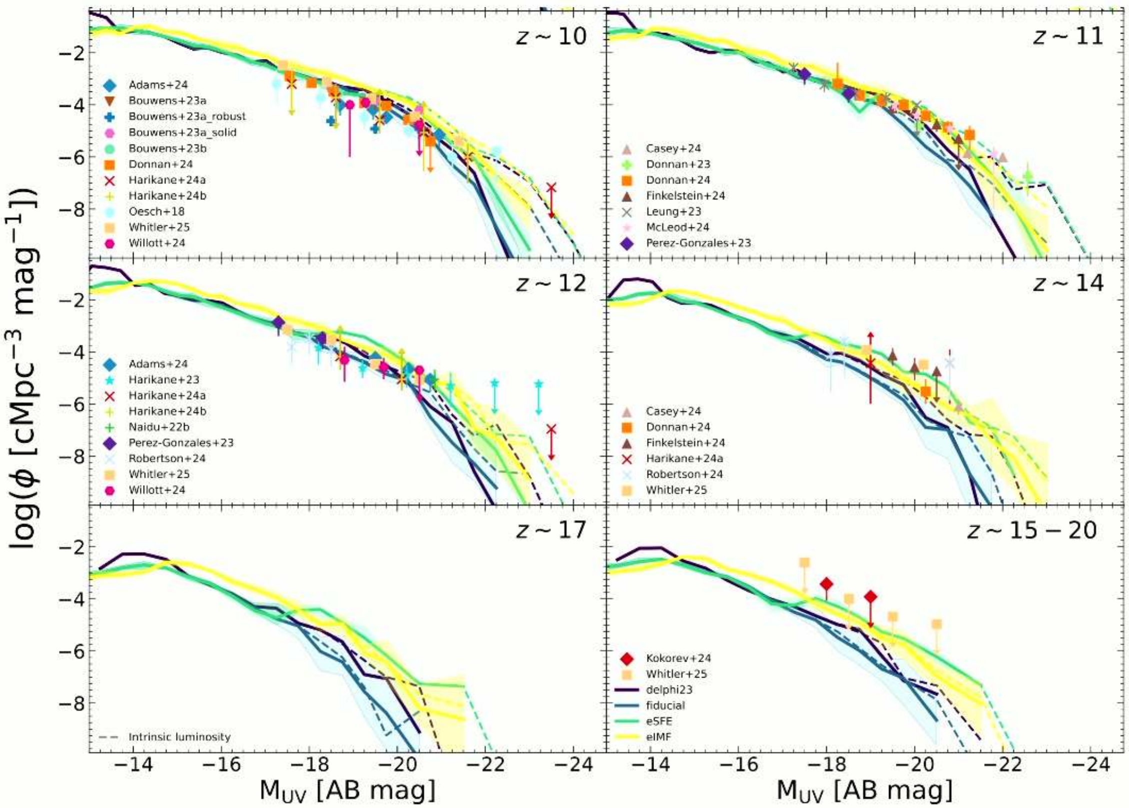


High-z galaxy candidates seem to hit against the upper limit allowed by theory - i.e. allowing all of the baryonic component of a halo turning into young stars that can produce copious amounts of UV light

Valentin Mauerhofer

Giorgos Nikopoulos

Explaining z>11 UV LFs and their redshift evolution



Our solutions:

- Increasingly top-heavy IMF with increasing redshift (Yung et al. 2023, Cueto, Hutter, PD et al. 2023, Trinca et al. 2024, Hutter, Cueto, PD et al. 2024)

- An increase in the normalisation of star formation efficiency (fraction of cold gas forming stars)

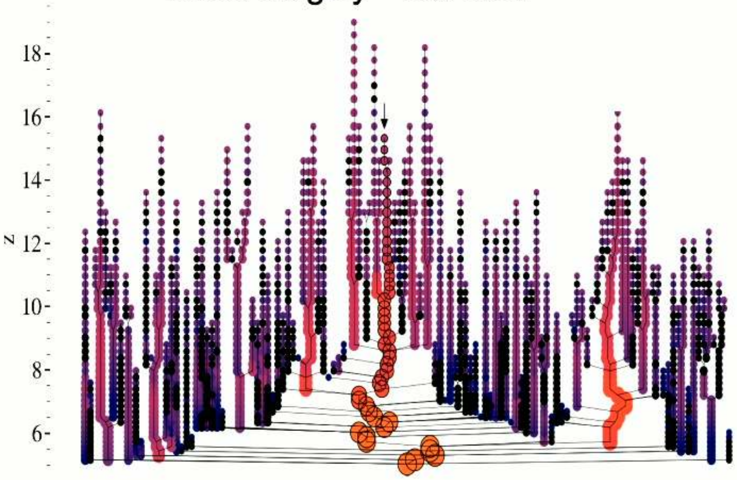
Mauerhofer, Dayal et al. 2025

Other possibilities include a *decreasing importance of dust attenuation with increasing redshift* (Ferrara, Pallottini, PD 2023, Mauerhofer & PD 2023, Ferrara24ab,25), *bursty star formation* (Mason et al. 2023, Mirocha & Furlanetto 2023, Sun et al. 2023, Nikopoulos & PD 2024), *black hole contribution* (Ono et al. 2018, Pacucci, PD et al. 2022), *feedback-free star formation* (Dekel et al. 2023).

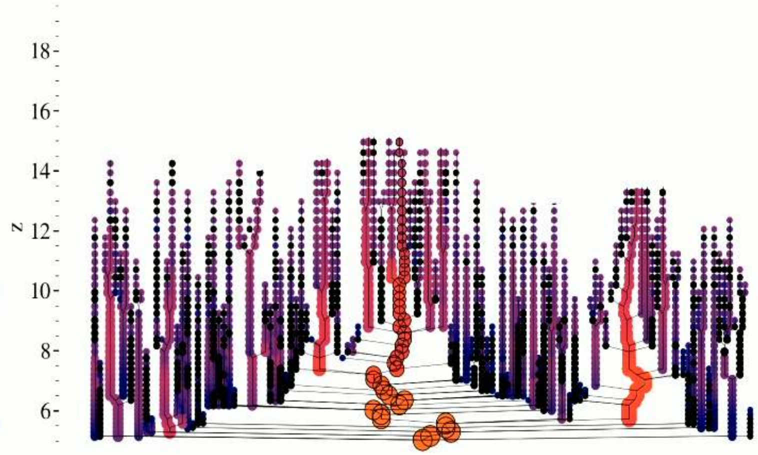
Signals from cosmic dawn: testing dark matter models

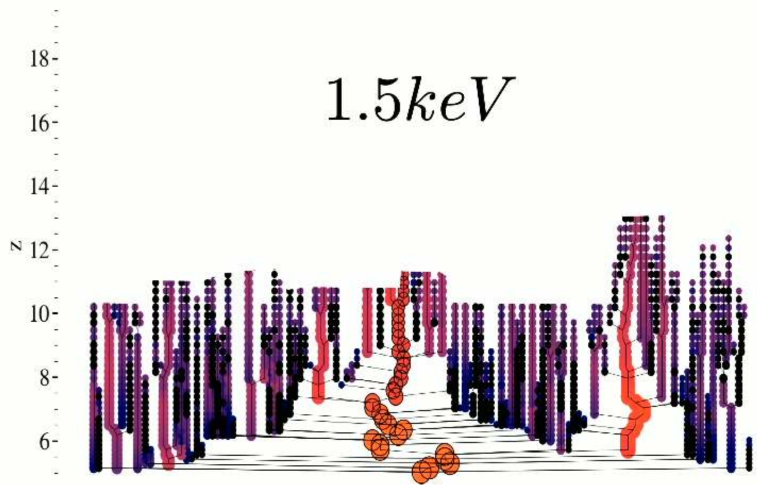
CDM

Mass roughly ~100 GeV



$3keV$

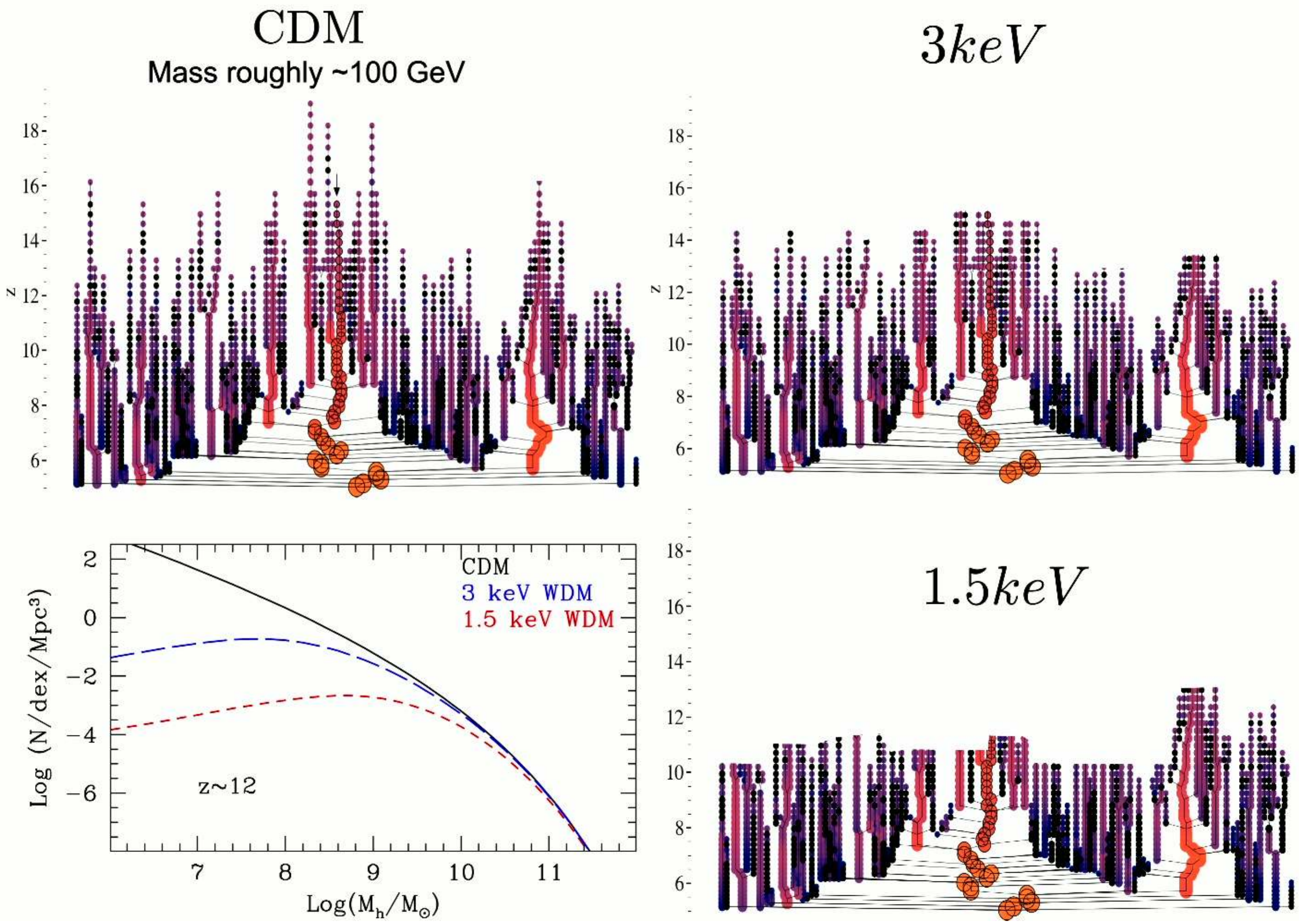




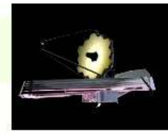
Maria
Dzoubia

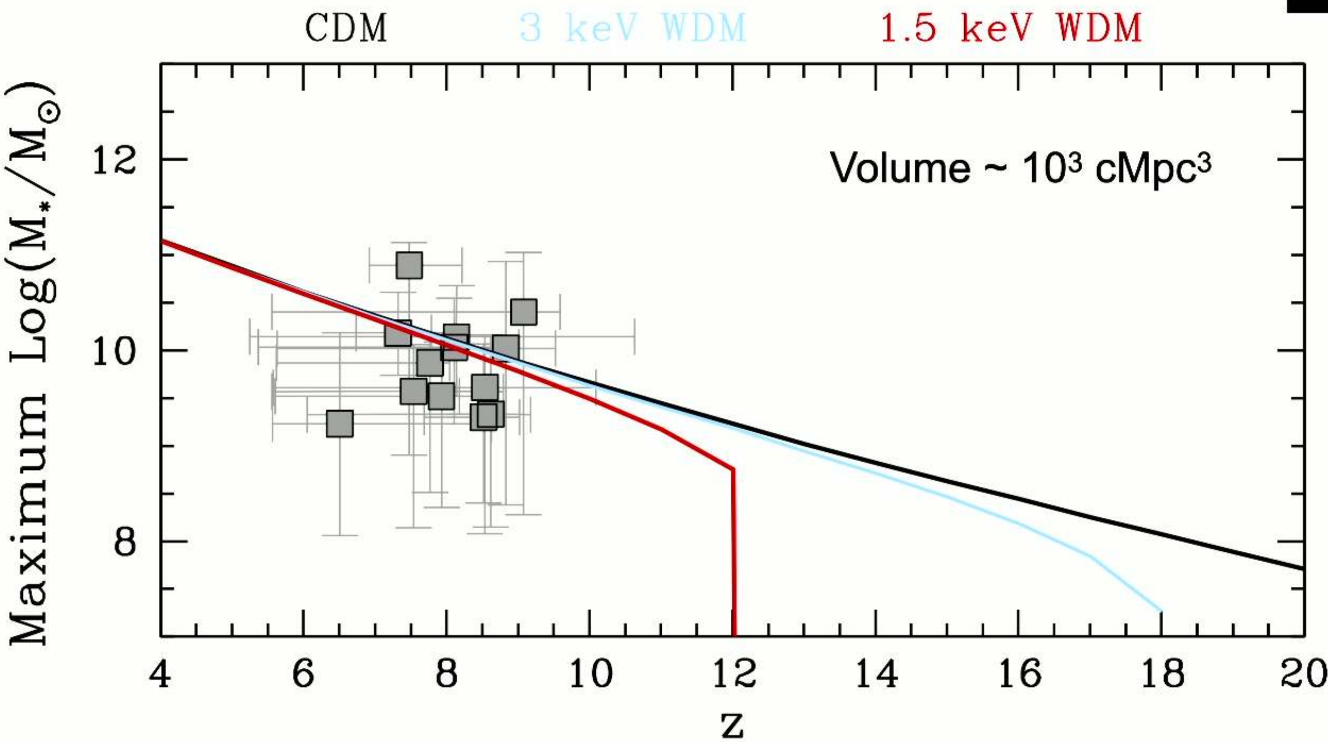
Jill
Straat

Signals from cosmic dawn: testing dark matter models



Testing the nature of (warm) dark matter with JWST





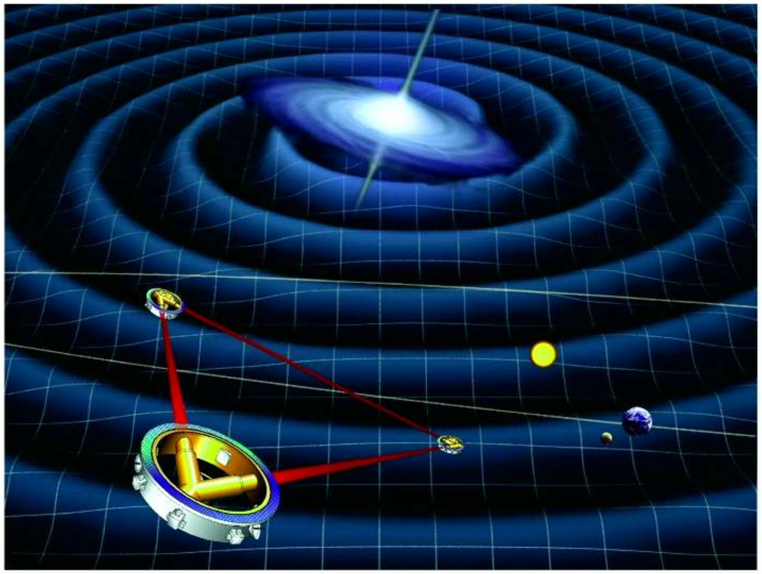
The detection of any galaxies existing in multiple JWST fields (~ 10^3 cMpc^3) can be used to rule out light (1.5 keV) WDM models. Crucial to derive warm dark matter mass constraints at an epoch inaccessible by any other means.

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

Alternative probes of (W)DM offered by the high-z Universe

- Ultra-deep (Menci+2016) or Ultra-high z UV LF (Pacucci+2013)
- High-z GRBs (de Souza+2013)
- 21cm statistics (Sitwell+2014; Safrazadeh+2018; Chatterjee+2019)
- Later persistence of Direct collapse black holes (PD+17)
- Delayed IGM metallicity enrichment (Bremer+18)
- ???

The puzzling emergence of black holes in the first billion years

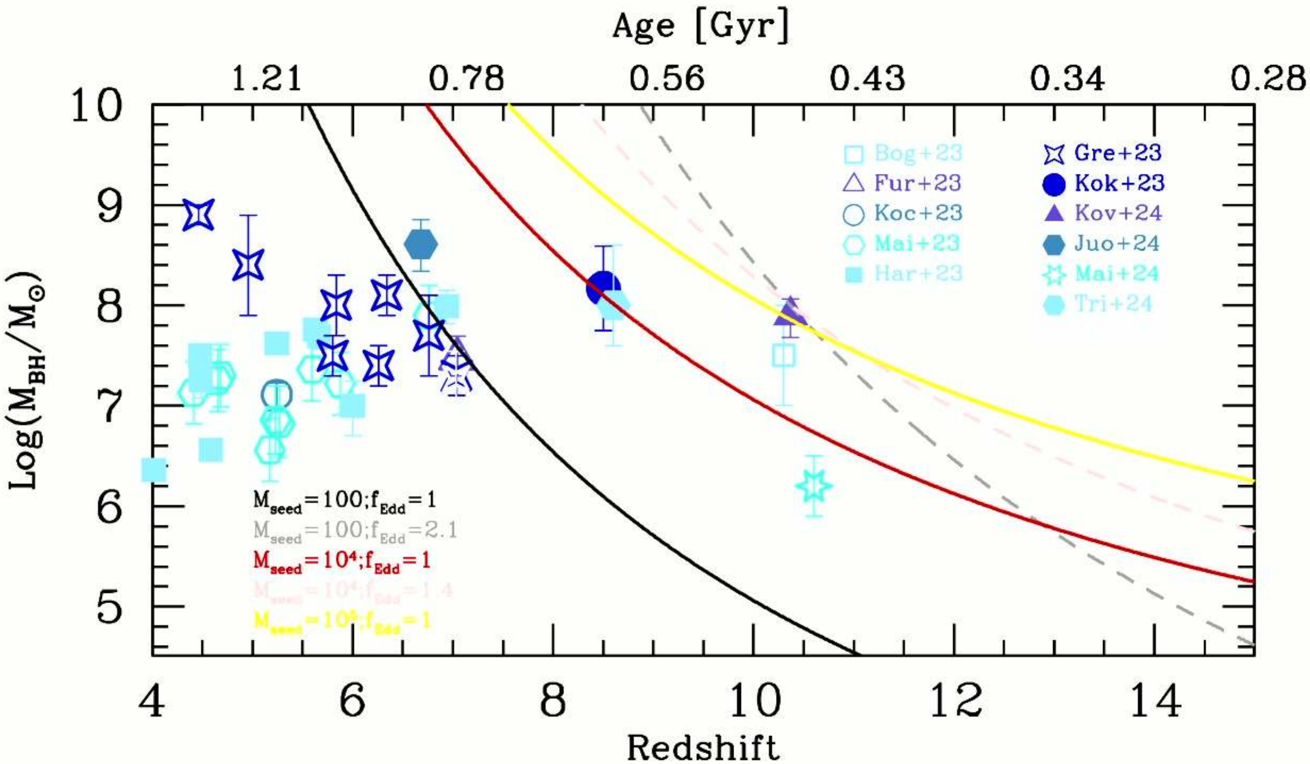


All interested Canadian researchers are welcome to join LISA!

16

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

UNCOVER



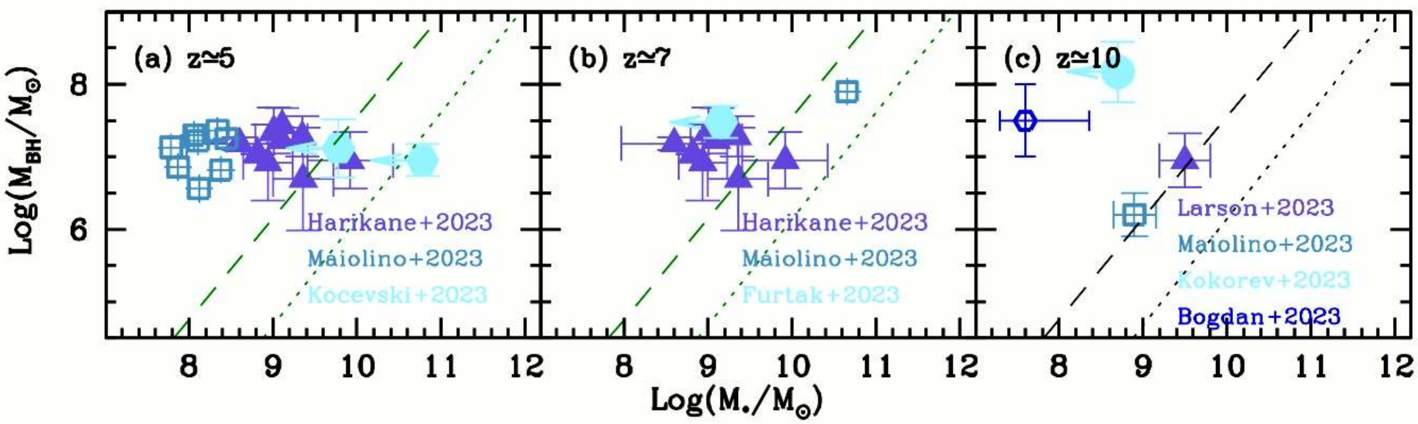
Explaining the supermassive black holes being observed by JWST require explanations such as super-Eddington accretion onto low-intermediate mass seeds or Eddington accretion onto massive ($10^5\ M_\odot$) seeds that formed at $z \sim 25$ posing a challenge for theoretical models.

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; Tripodi et al. 2024, Kocevski et al. 2024..

17

Problematic black hole to stellar mass ratios at high-z

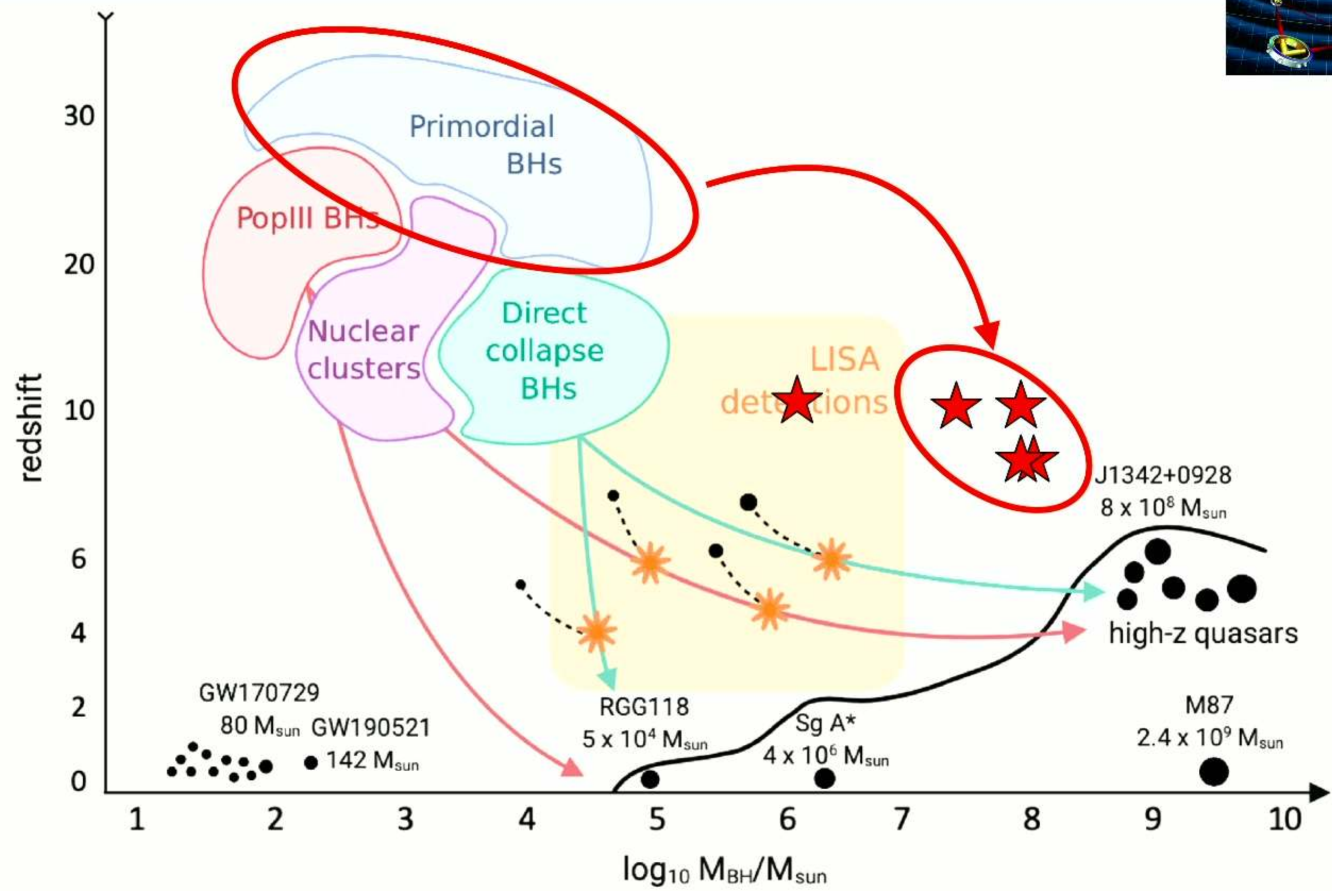
UNCOVER

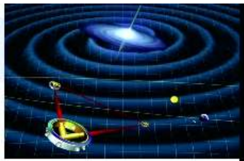


JWST observations seem to indicate implausibly high BH to stellar mass ratios of 30-50% (Harikane et al. 23, Maiolino et al. 2023, 2024, Kocevski et al. 2023, Furtak (incl. Dayal) et al. 2023, Larson et al. 2023, Kokorev (incl. Dayal) et al. 2023, 2024, Bogdan et al. 2023). Solutions:

- 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, Lupi et al. 2024)
- Initial phases in the growth of heavy seeds (Natarajan et al. 2024)
- Stellar mass hidden due to dust/low surface brightness (although Fujimoto et al. 2024)
- Baryons exist in right amount, but were not able to form stars (Maiolino et al. 2024)
- over-massive black holes outshining their hosts preferentially detected by the JWST (Volonteri et al. 2023)
- Black hole masses over-estimated (King 2024; Lupi et al. 2024)

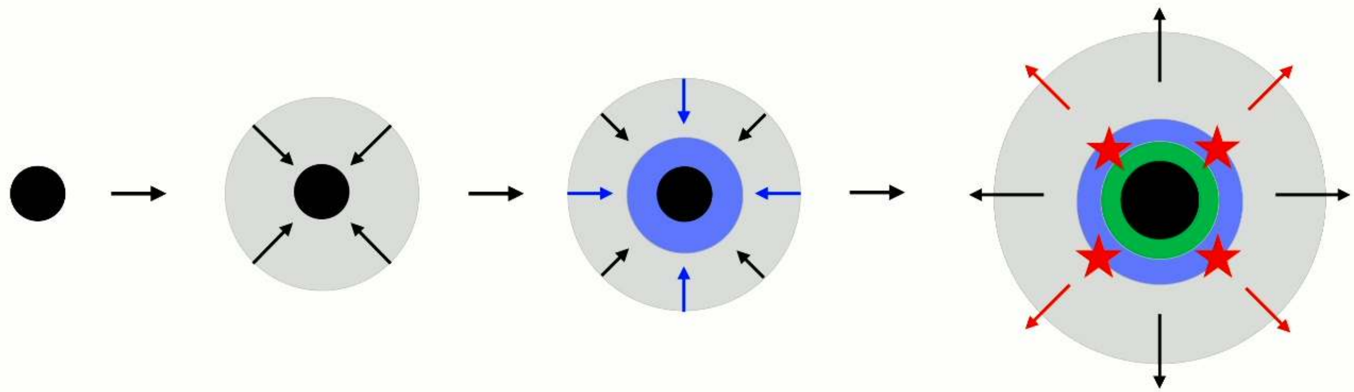
What comes first: stars or black holes?





Obese black holes uncovered by the JWST require revisiting black hole seeding and growth pathways e.g. primordial BHs.

Primordial black holes as seeds of structure formation



(a) Seeding: PBH seeded at Big Bang/inflation following a mass spectrum

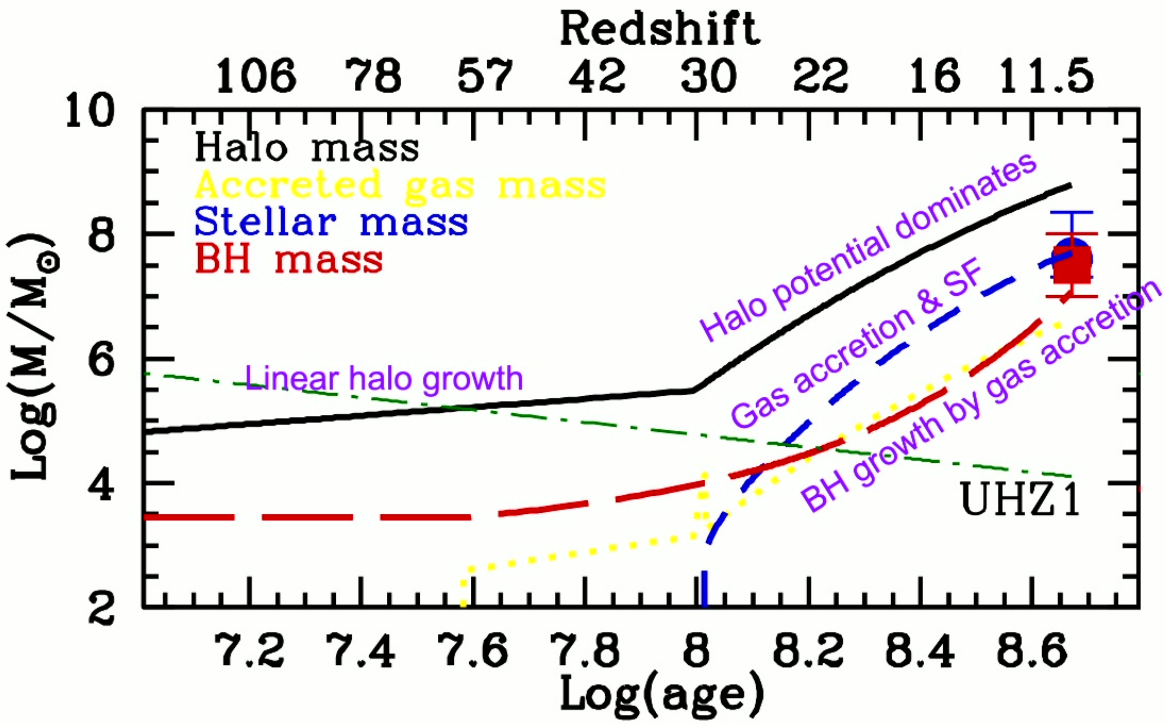
(b) DM assembly: PBH linearly accretes DM halo (gray) around itself down to z~34; growth by IGM smooth accretion at z<34

(c) Gas accretion: once halo massive enough to support baryonic over-density of 200, gas accretion (blue) allowed

(d) Black hole accretion, Star formation, feedback and metals: gas can accrete onto the black hole, and form stars (red); feedback from both. Supernovae drive metal enrichment (green).

Hawking 1971, Carr & hawking 1974, Carr 2005, Dayal 2024, Dayal & Maiolino 2025

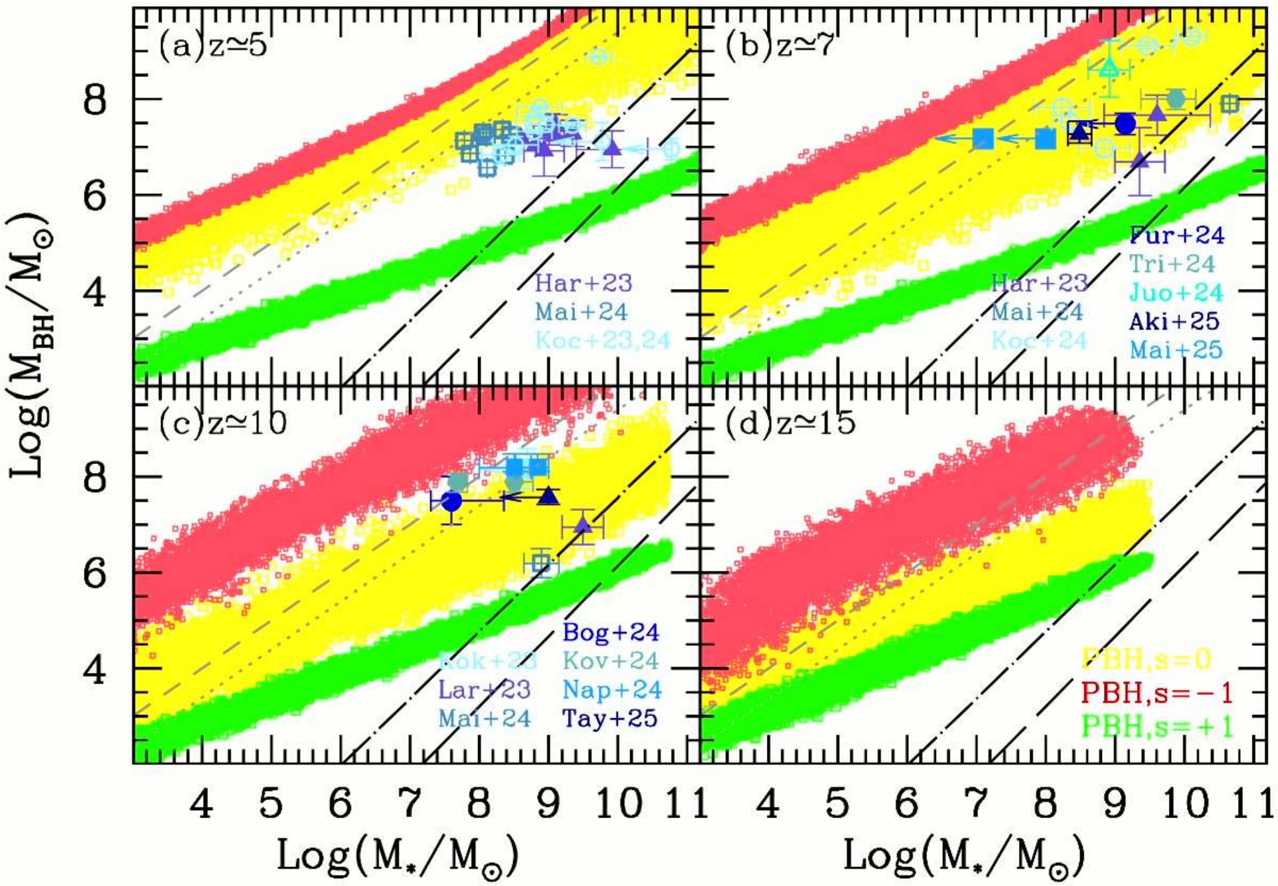
A primordial origin for early black holes



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

Black hole to stellar mass ratios naturally high in PBH models



Dayal & Maiolino 2025

The emerging picture..

- Star forming galaxies: too many bright and massive objects too early on.

- Multiple field studies with the JWST can be used to rule out *light WDM models* simply using the observed stellar masses. Other probes from the era of cosmic dawn include 21cm signal.

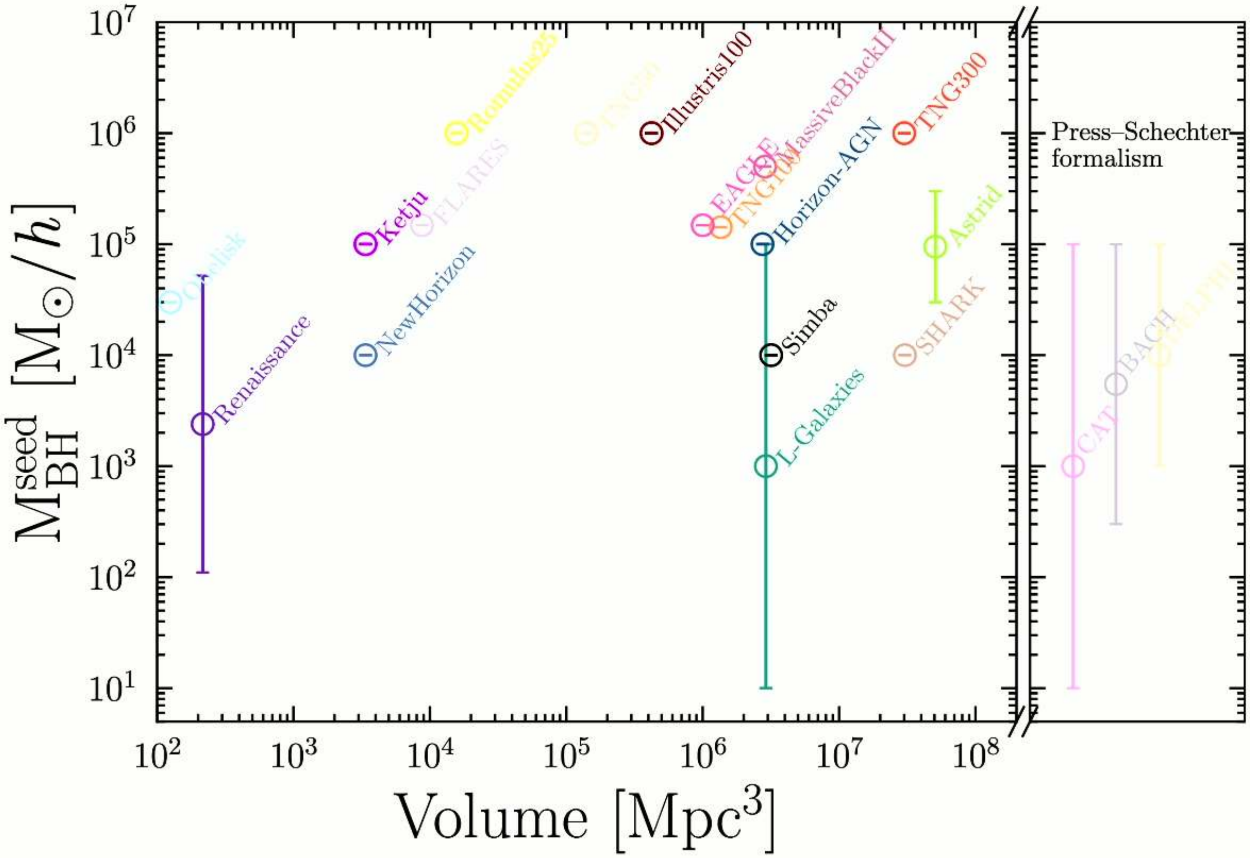
- JWST yielding a sample of *numerous and obese black holes as early as z~10* with black hole to stellar mass ratios as high as 50% requiring extremely efficient black hole growth - crucial implications for LISA.

- Primordial black holes that assemble their halos and baryons around themselves naturally result in high black hole to stellar mass ratios, offer a tantalising solution to the numerous and obese BHs being detected by the JWST as early as z~10.

- *Low-mass star forming galaxies ($< 10^9 M_\odot$ 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.

32

Astrophysical black hole mergers with LISA



Melanie Hobouzit

David Izquierdo-Villalba

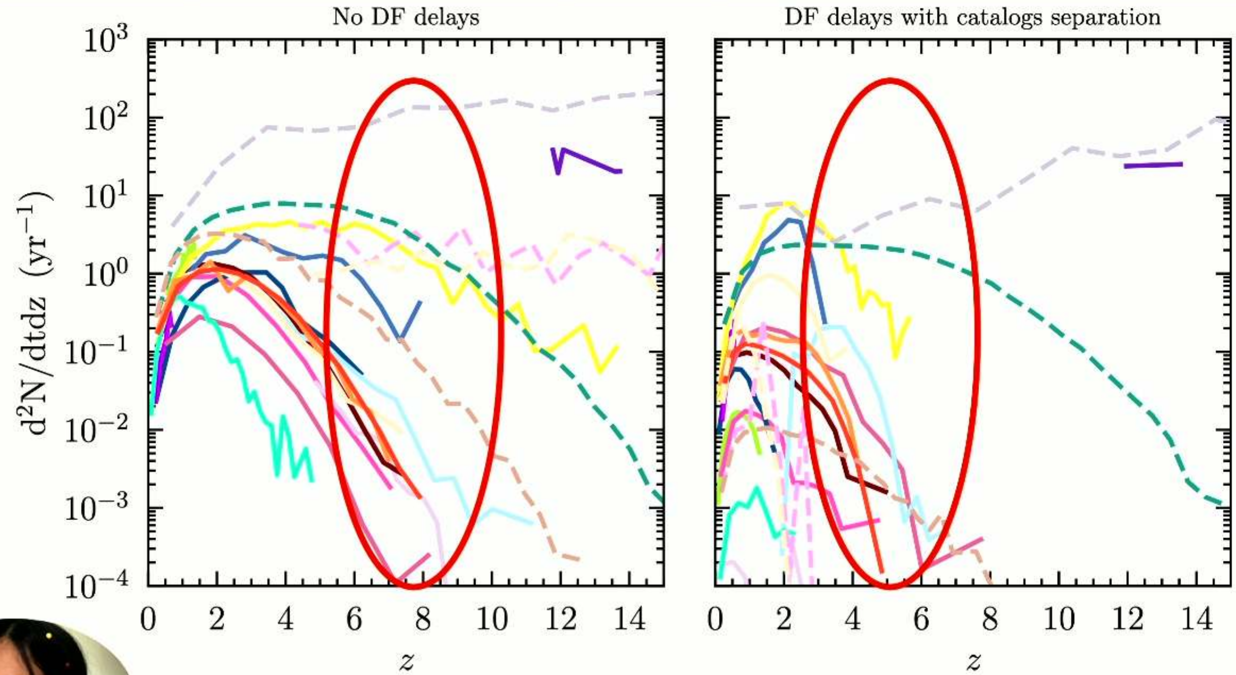
Matteo Bonetti

Silvia Bonoli

LISA Astrophysics working group: code comparison project

23

Gravitational wave events from astrophysical black holes



Paula Caceres-Burgos

The events rates expected from LISA crucially depend on the model resolution, treatments of seeding, growth and merger timescales, and implemented delays. Shape of event rate seems to be converging although huge dispersion (5 orders of magnitude) in numbers expected (LISA Astrophysics WG code comparison project and *"Astrophysics with LISA" white paper, 2023, LRR).*