The cradles of Lyman photons in the first billion years

Pratika Dayal

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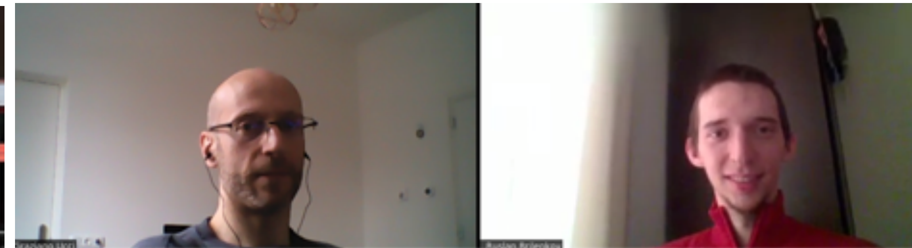
Key contributors



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

The golden age for understanding early galaxies

High-z Luminosity functions, stellar mass functions

The dust and metal enrichment of early galaxies

UV spectral slopes

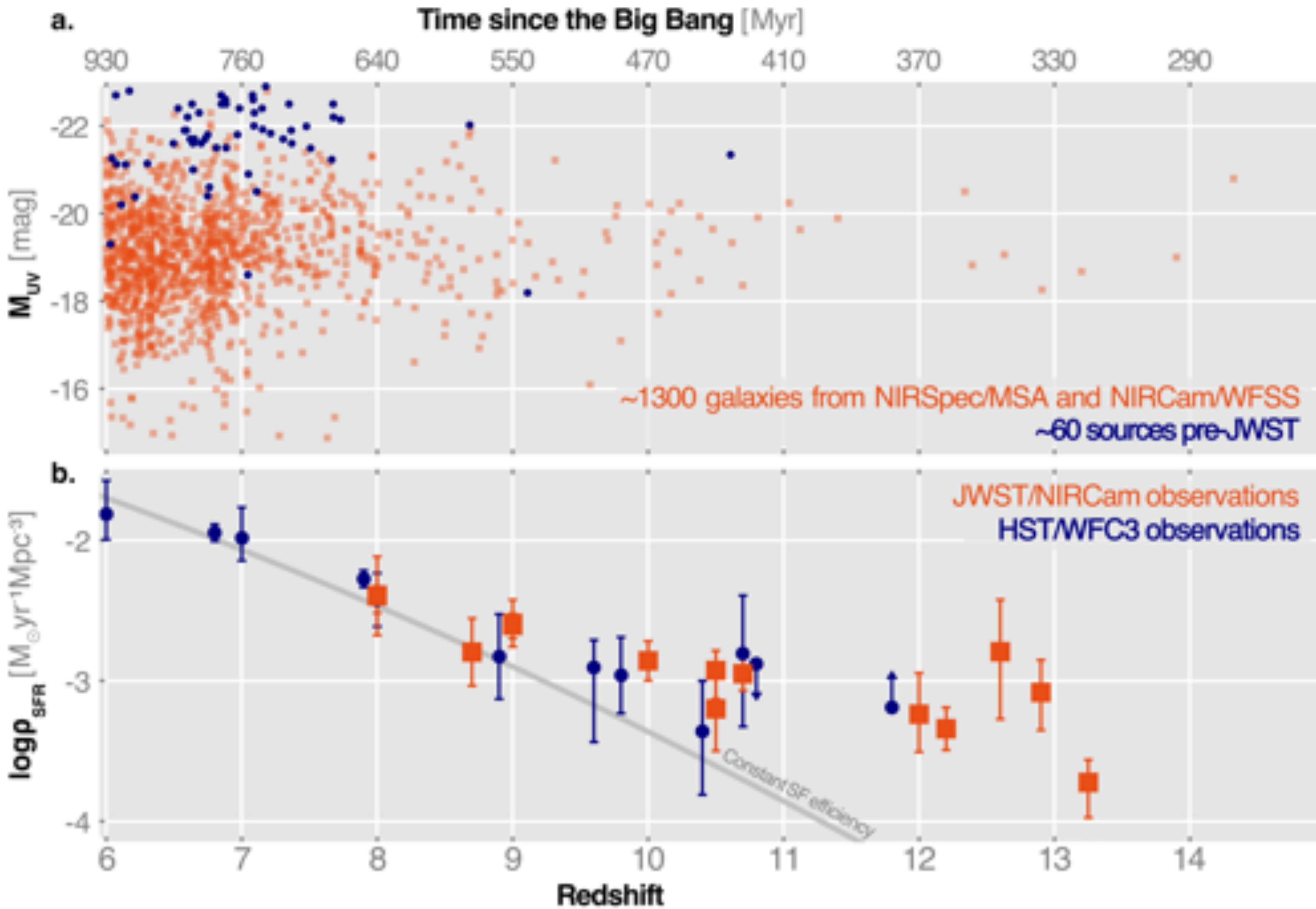
Ionizing photon production efficiency

Black hole masses and luminosities in early systems

Black hole-host galaxy relations

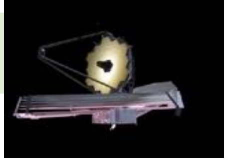
The emergence of galaxies and black holes in the first billion years

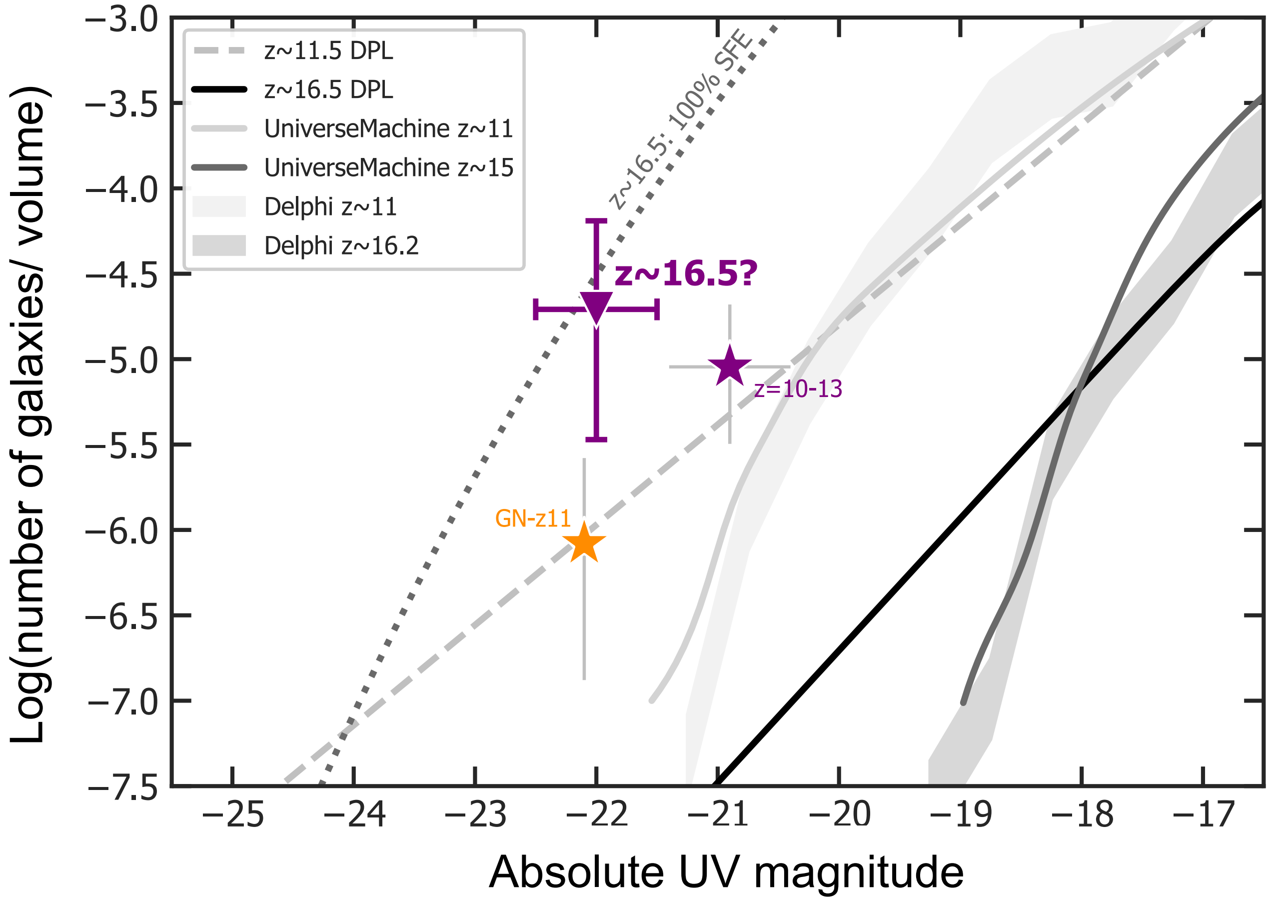
Extending the redshift frontier with the JWST



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

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





Naidu (incl. PD) et al. 2022,
Harikane et al. 2023,
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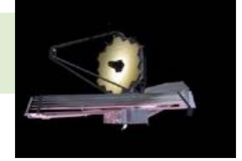

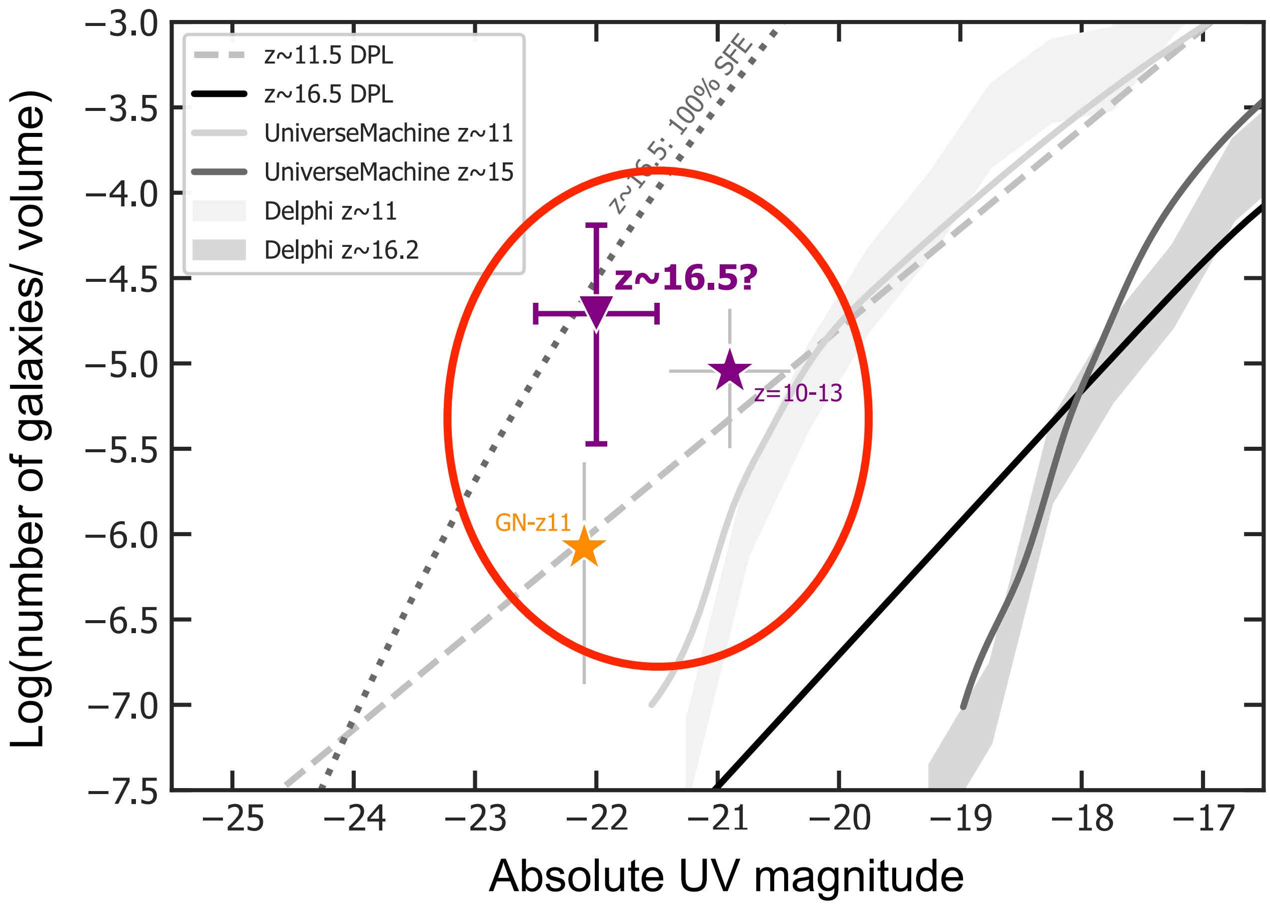

Naidu (incl. PD) et al. 2022,
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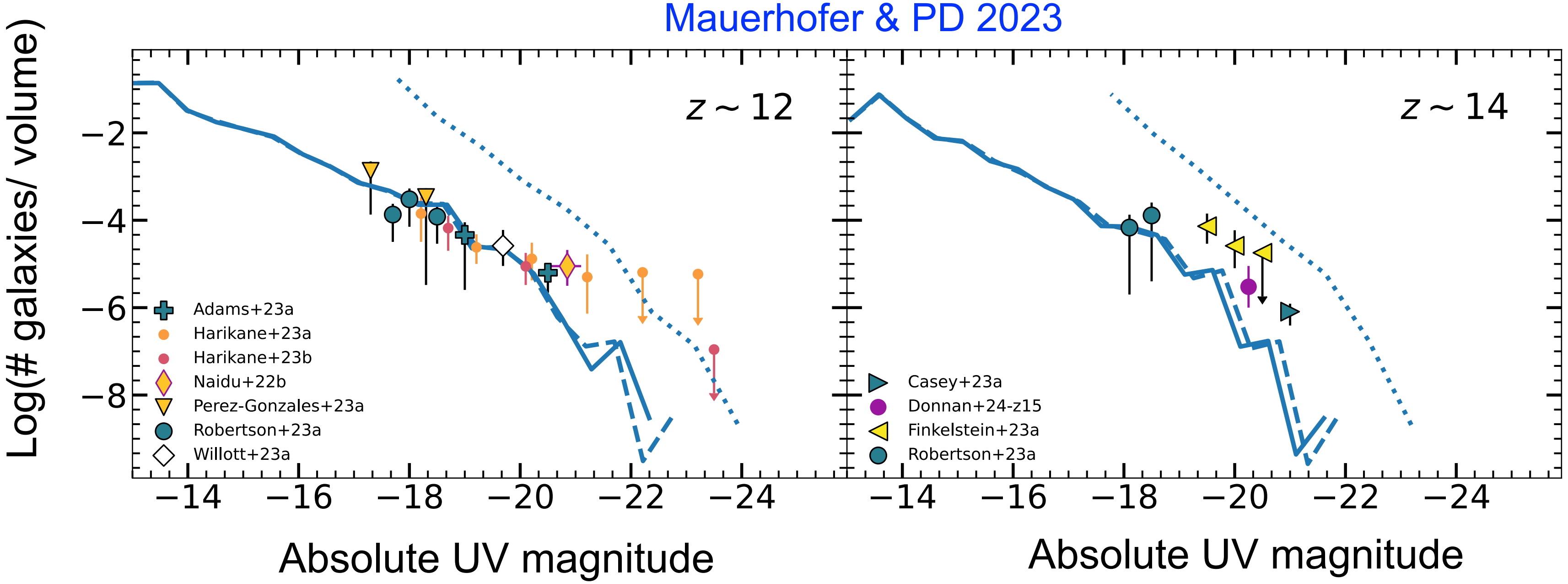
While in perfect agreement with theory at $z \leq 10$, early JWST observations showed an over-density of bright systems at $z \geq 11$. Caution: strong emission lines from z~5 object lead to a pathology yielding a photometric z~16 (Arrabal-Haro et al. 2023).

Observations continue to support over-abundance of bright systems

Mauerhofer & PD 2023



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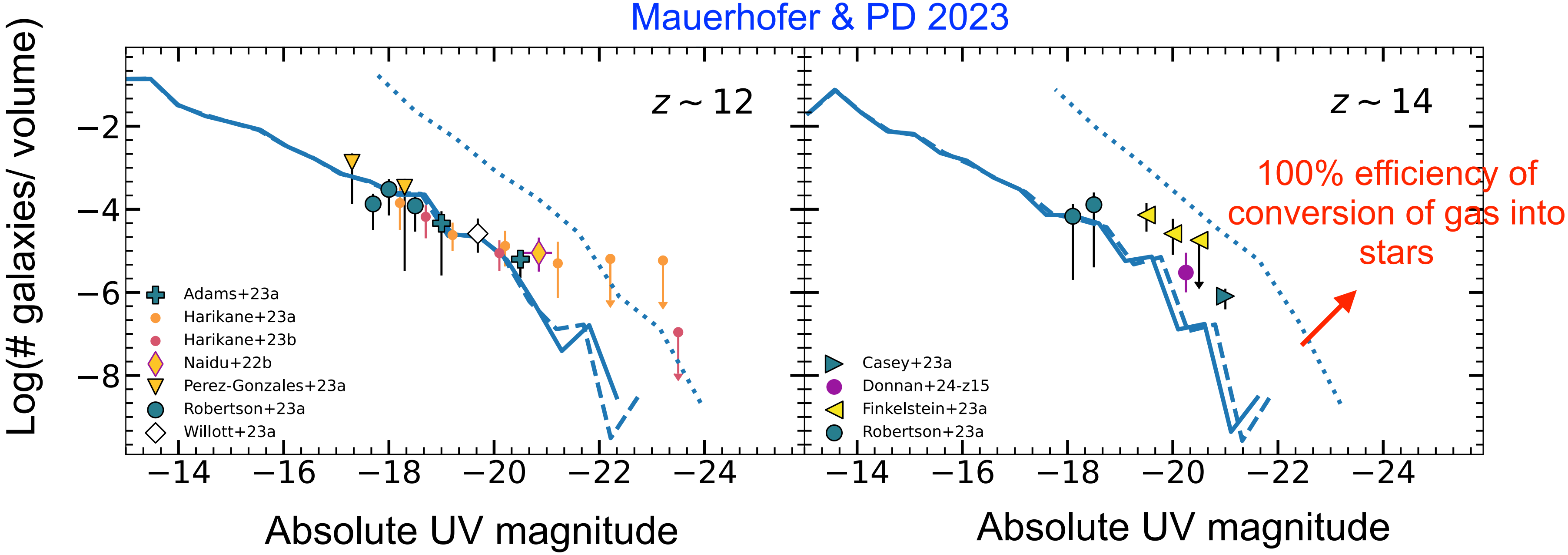

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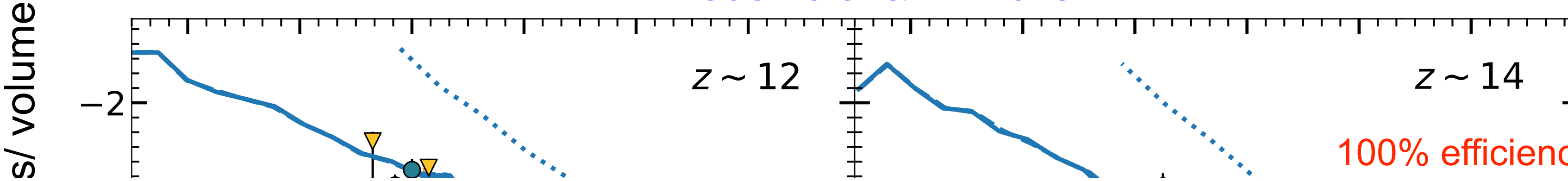
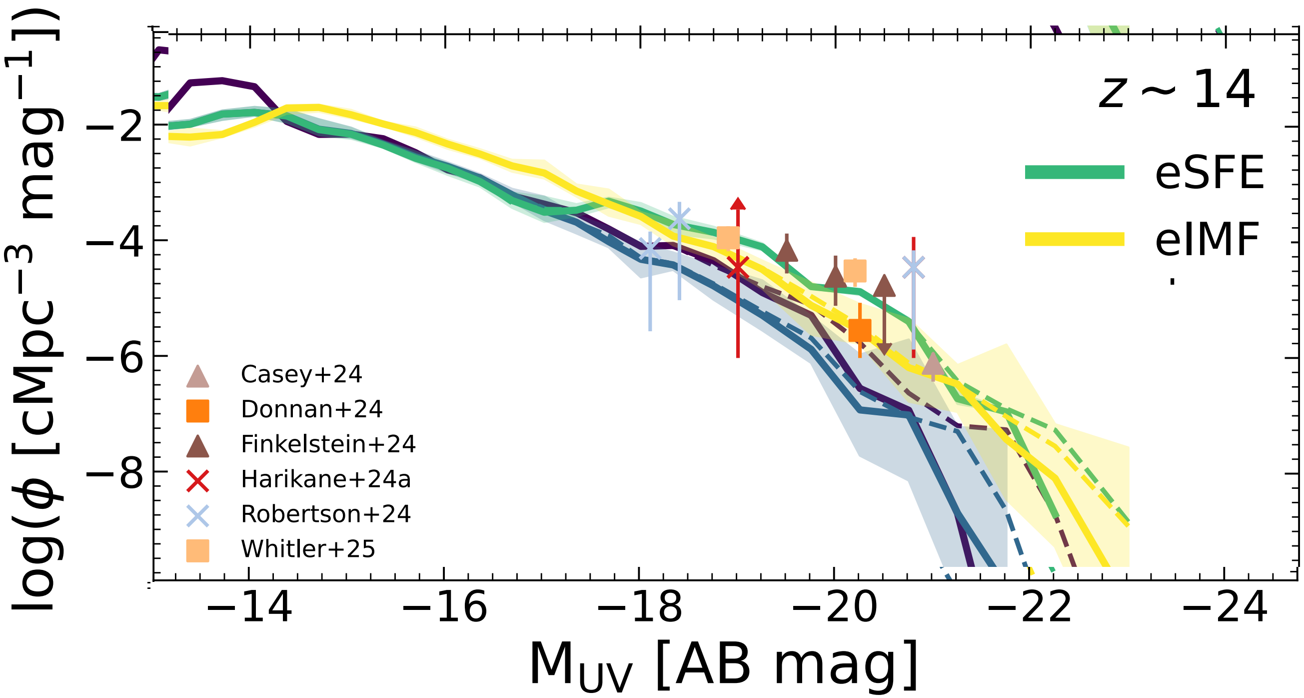
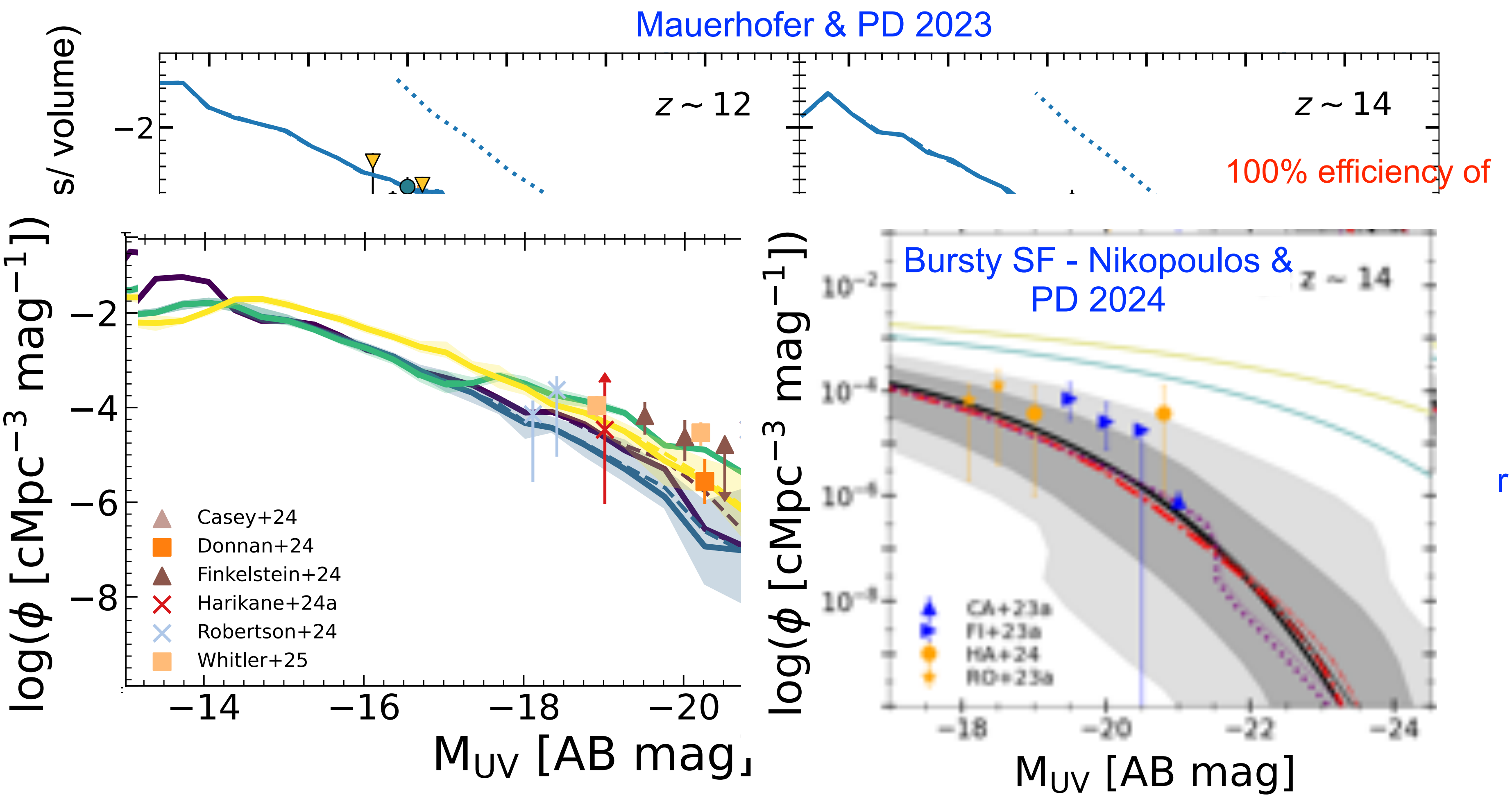




Increase in SF efficiency or an increasingly top-heavy IMF with z - Mauerhofer & PD 2025

Observations continue to support over-abundance of bright systems

Mauerhofer & PD 2023



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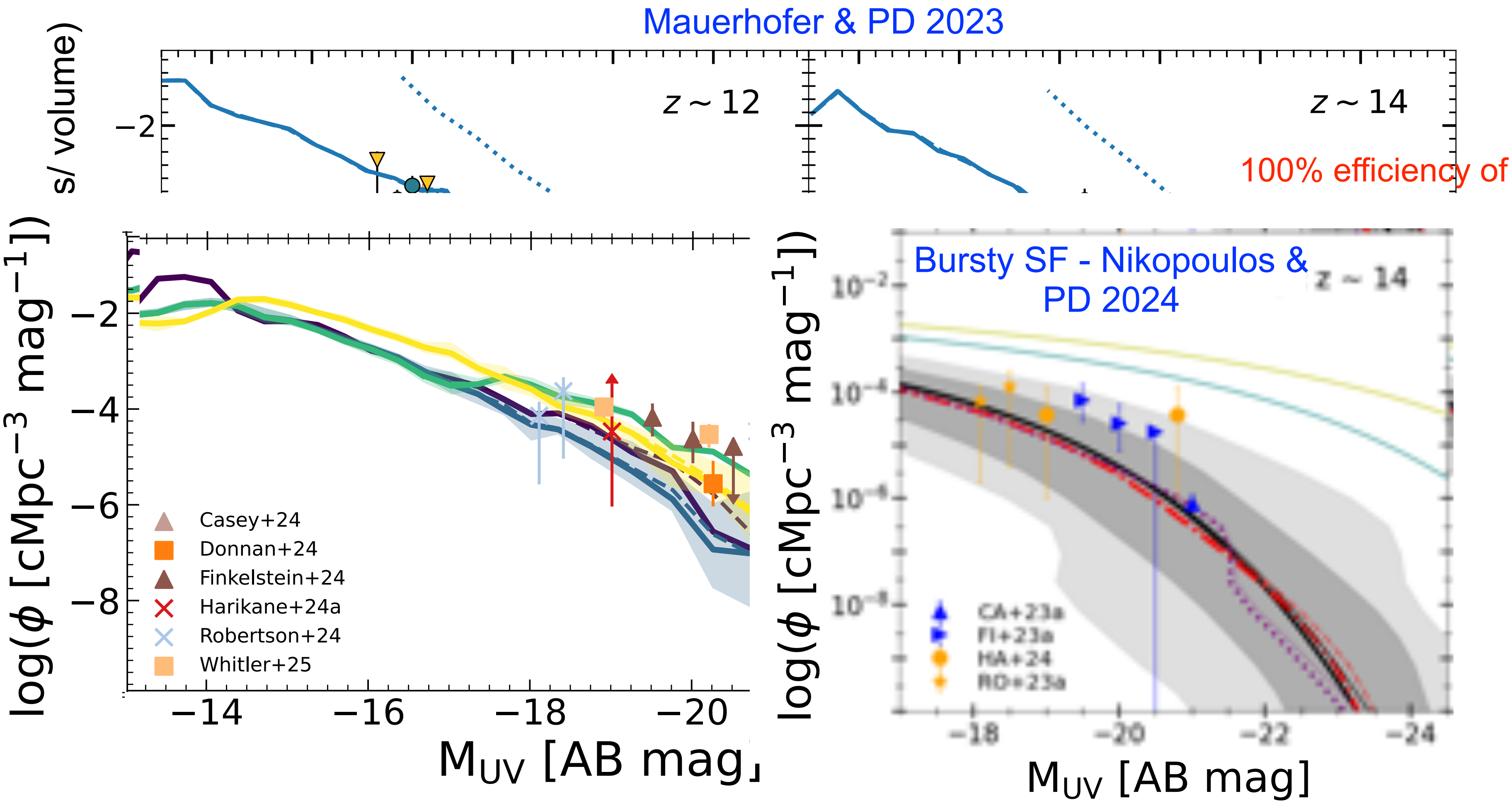
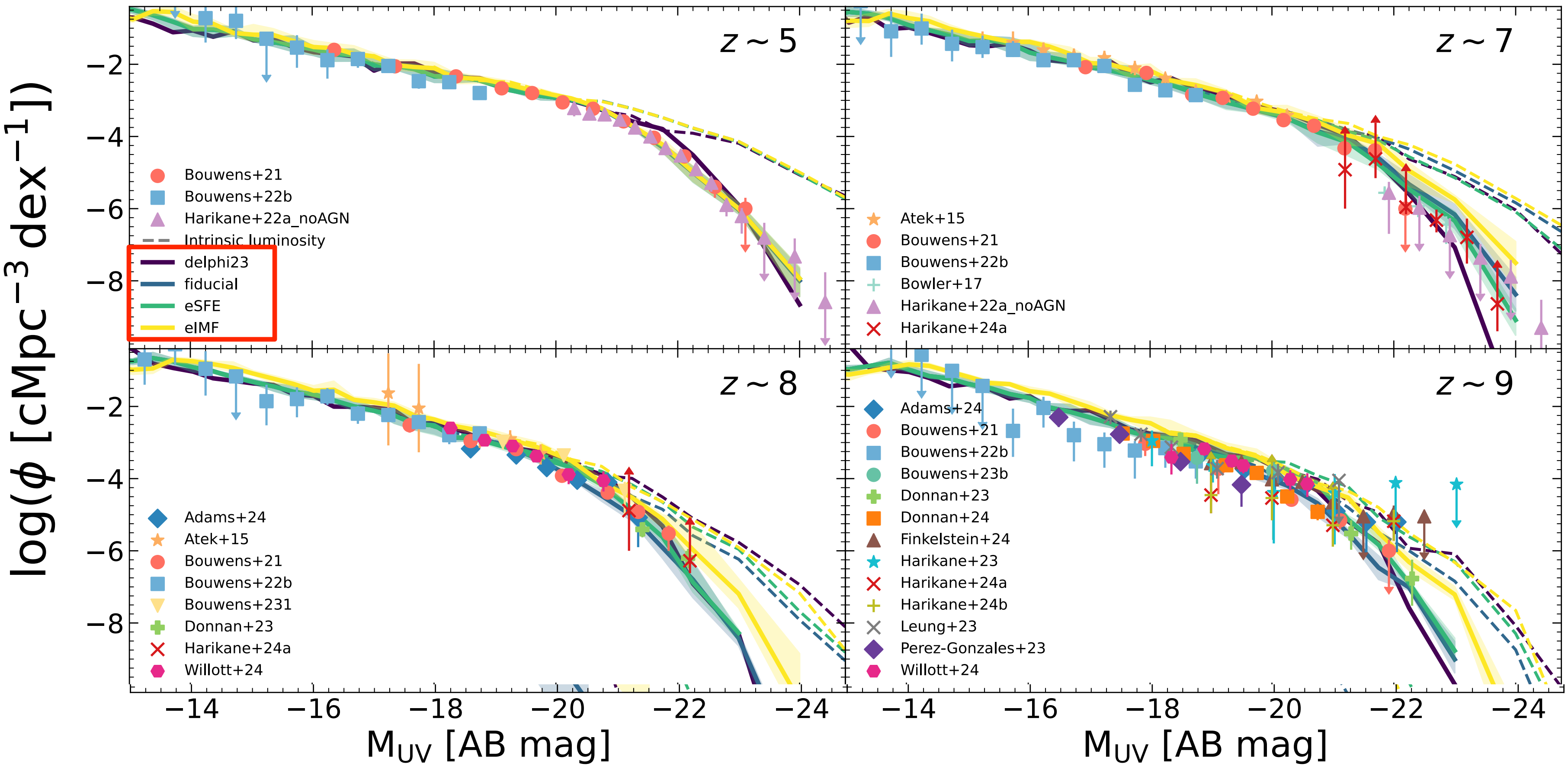


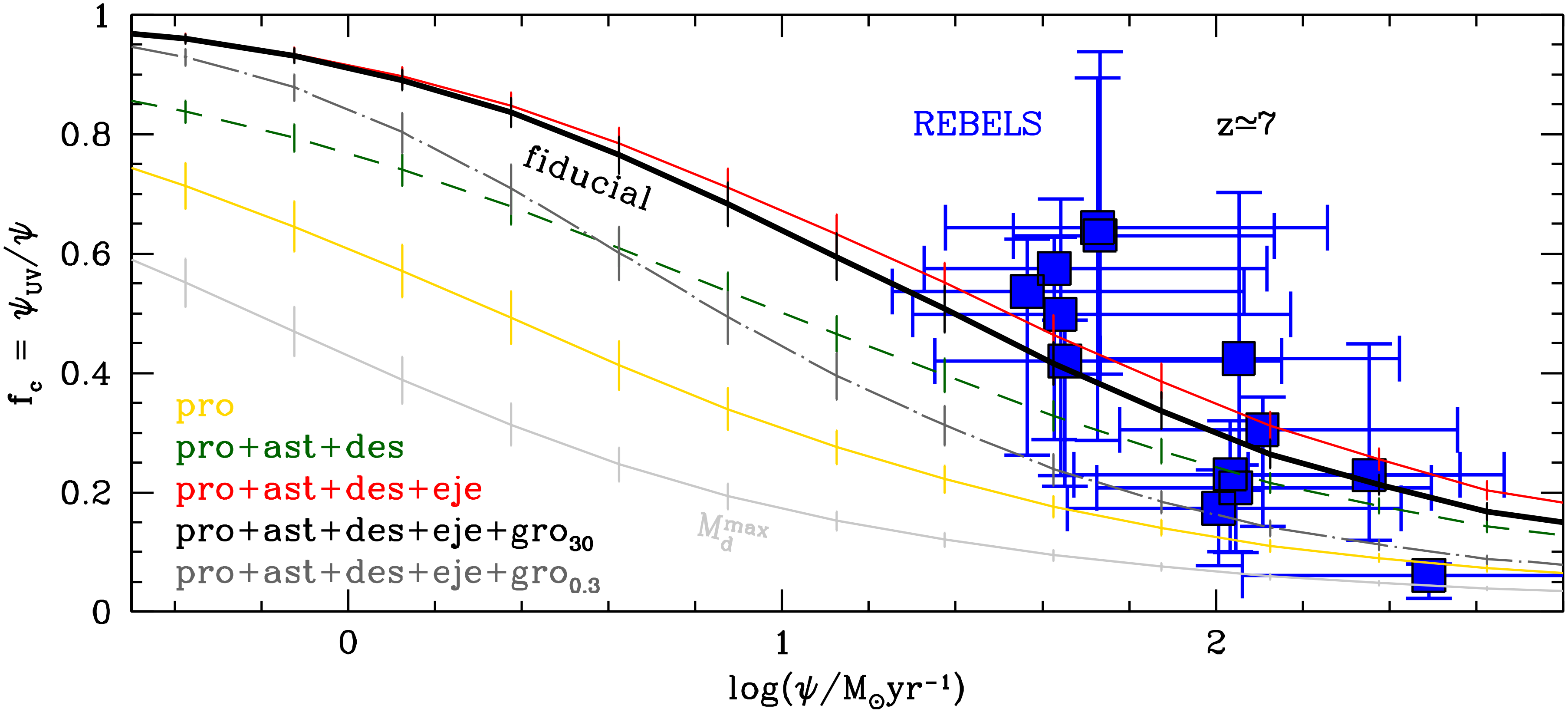
Possible solutions include a *decreasing importance of dust attenuation with increasing redshift* (Ferrara, Pallottini, PD 2023; Ferrara25 a,b), an *evolving initial mass function* (Yung et al. 2023, Cueto, Hutter & PD et al. 2023, Trinca et al. 2024, Mauerhofer & PD, 2025), *bursty star formation* (Mason et al. 2023, Mirocha & Furlanetto 2023, Sun et al. 2023, Shen et al. 2024, Nikopoulos & PD 2024), *black hole contribution* (Ono et al. 2018, Pacucci, PD et al. 2022) or *feedback-free star formation* (Dekel et al. 2023, 2025).

Dust determines the bright end of the UV LF at z<10



Impact of dust attenuation decreases with increasing redshift (Mauerhofer & PD, 2023, 2025; Ferrara+2023, 2025ab; Popping et al. 2017; Vijayan et al. 2019; Triani et al. 2020).

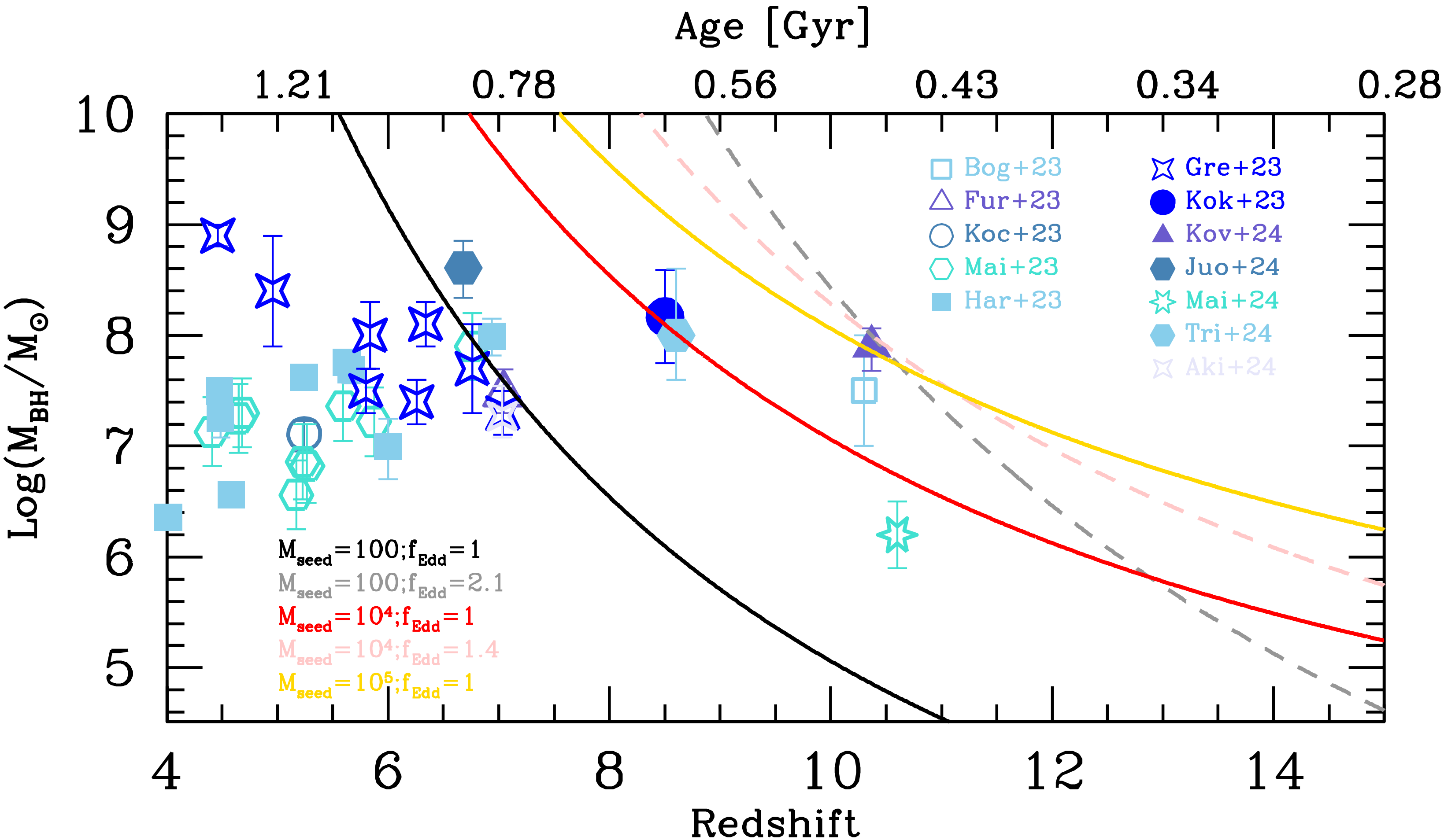
Dust obscuration of star formation



For observed galaxies at z~7, ratio of UV to total SFR implies an obscuration fraction of 45-90%.

PD et al. 2022, Bouwens et al. 2021, Palla et al. 2024, Algera et al. 2023

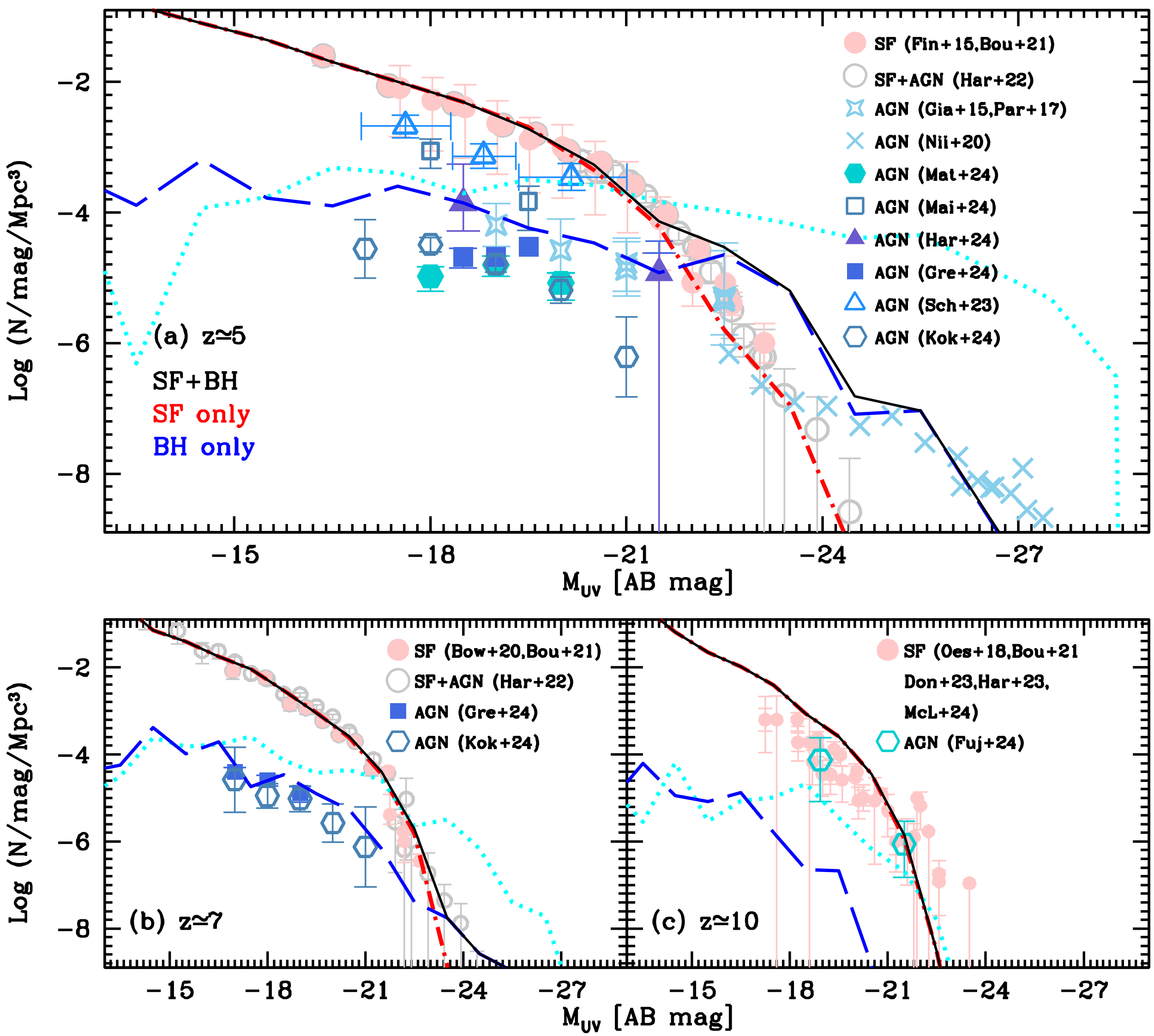
JWST shows an emergence of Obese black holes



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..

The “UV LF” post ALMA & JWST



Dayal & uncover team, 2024

Matthee+23, Maiolino+23, Harikane+23, Greene+23, Scholtz+23, Fujimoto+23, Kokorev+24, Kocevski+24, Akins+24

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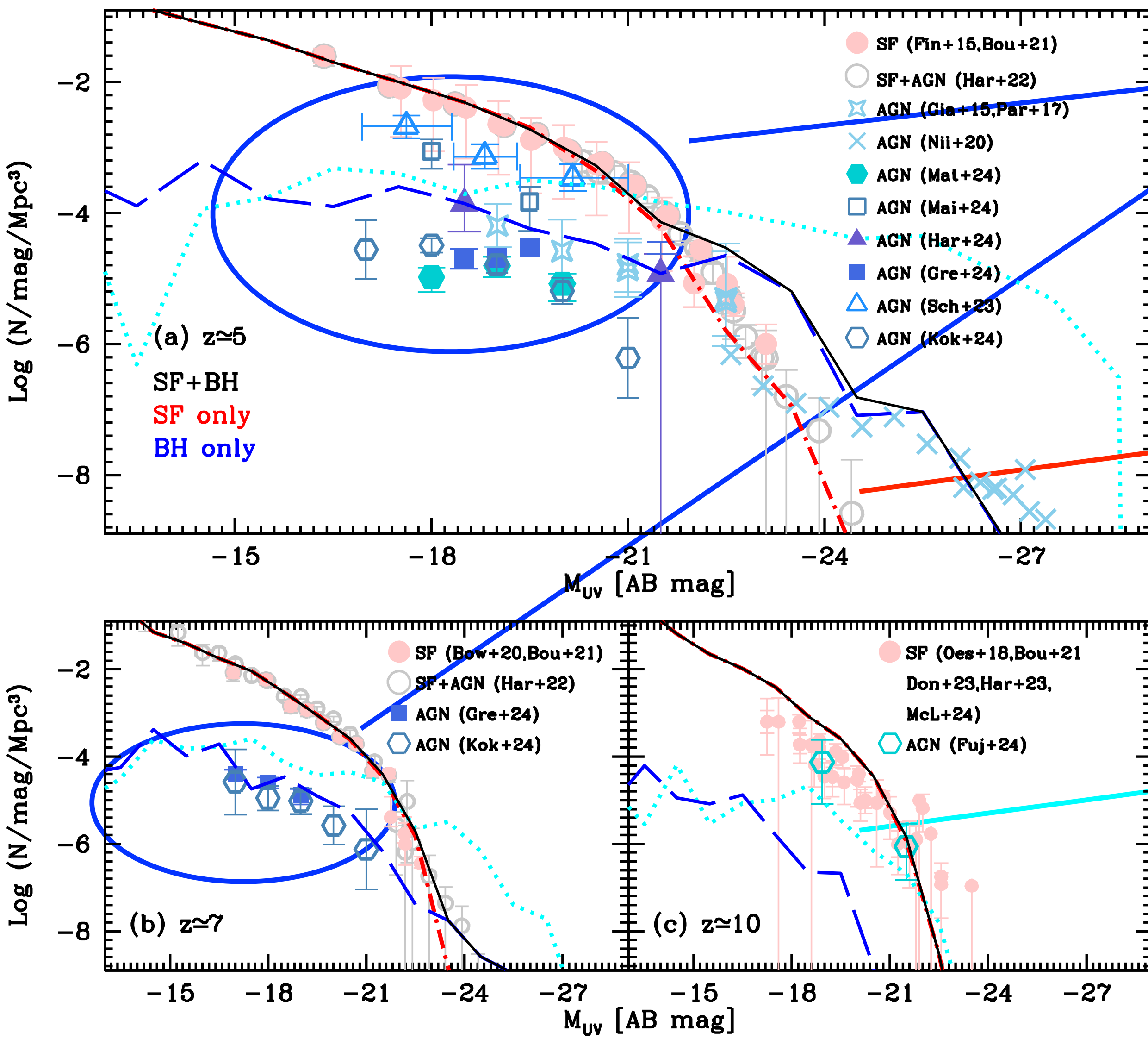


UV from both BH+stellar component - dust attenuated!

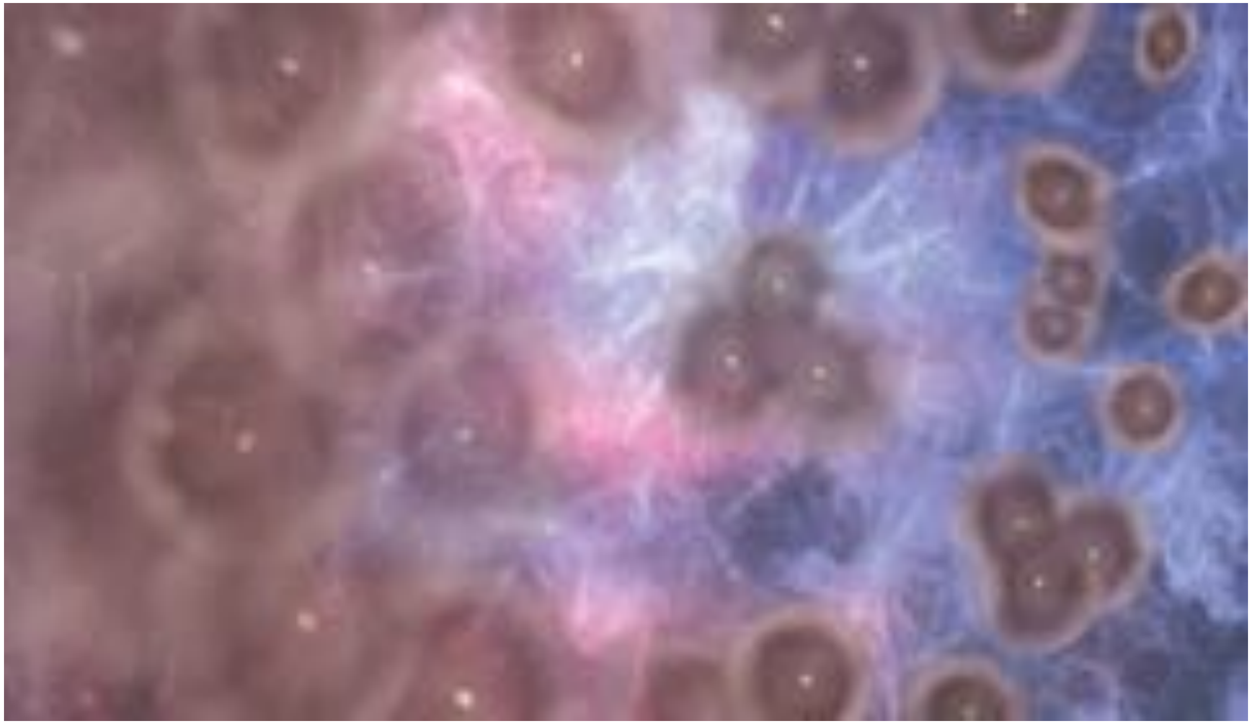
Dust-attenuated SF galaxy LF

Max BH UV LF

Dayal & uncover team, 2024

Matthee+23, Maiolino+23, Harikane+23, Greene+23, Scholtz+23, Fujimoto+23, Kokorev+24, Kocevski+24, Akins+24

The reionization implications of early systems



Modelling reionization: evolution of volume filling fraction of ionized hydrogen

Fractional volume filled with ionized hydrogen

Growth of ionized regions due to H ionizing photons

Decrease in ionized region sizes due to recombination

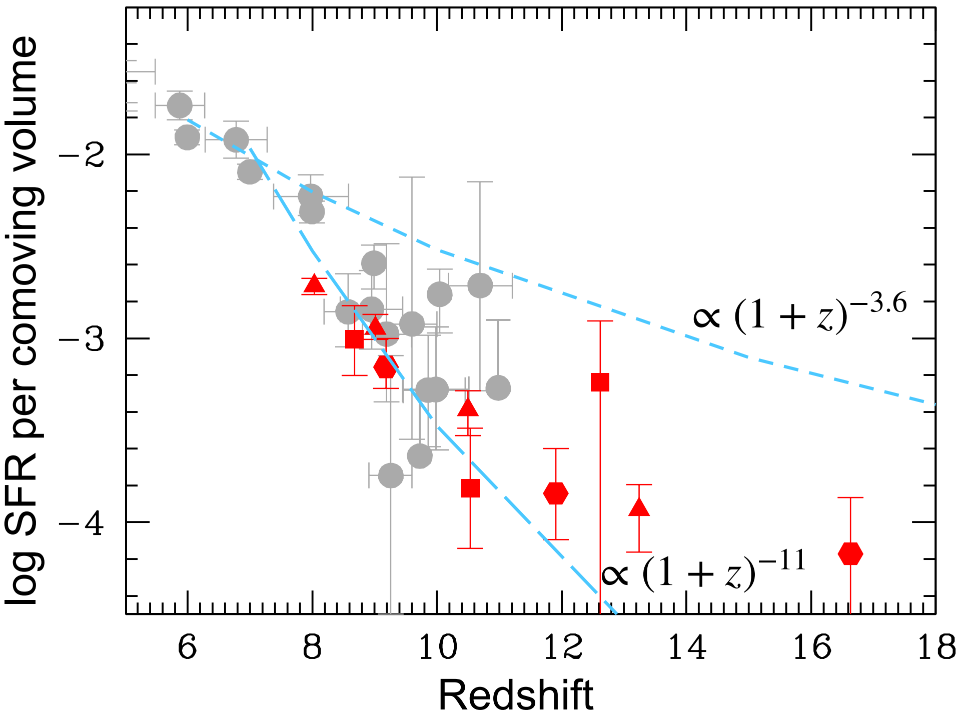
$$\frac{dQ_{II}}{dt} = \frac{dn_{int} f_{esc}}{dz} \frac{1}{n_H} - \frac{Q_{II}}{t_{rec}} \frac{dt}{dz}$$

$$t_{rec} = \frac{1}{\chi \, n_H \, (1+z)^3 \alpha_B \, C} \cdot$$

Measure of over-density as f(space,time)

Shapiro & Giroux 1987; Madau et al. 1999

Modelling reionization: the source term post-JWST



Star formation rate density (used to model reionization) *extremely uncertain at z>8*. **Post-JWST** data from Bouwens et al. 2022, Donnan et al. 2023, Harikane et al. 2023

PD & Ferrara, 2018, Physics Reports

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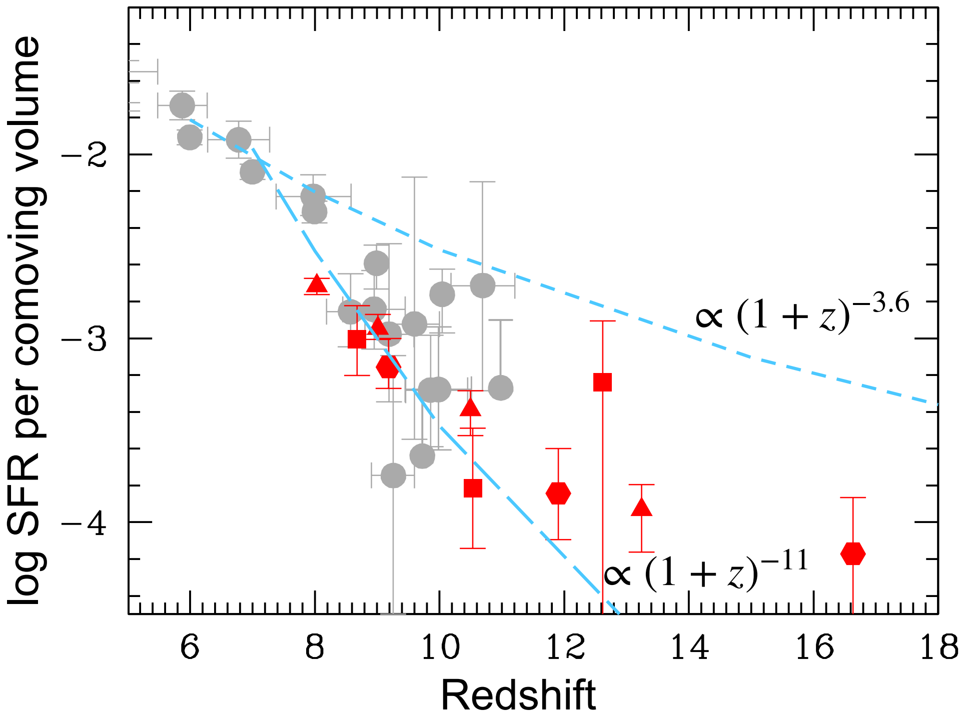

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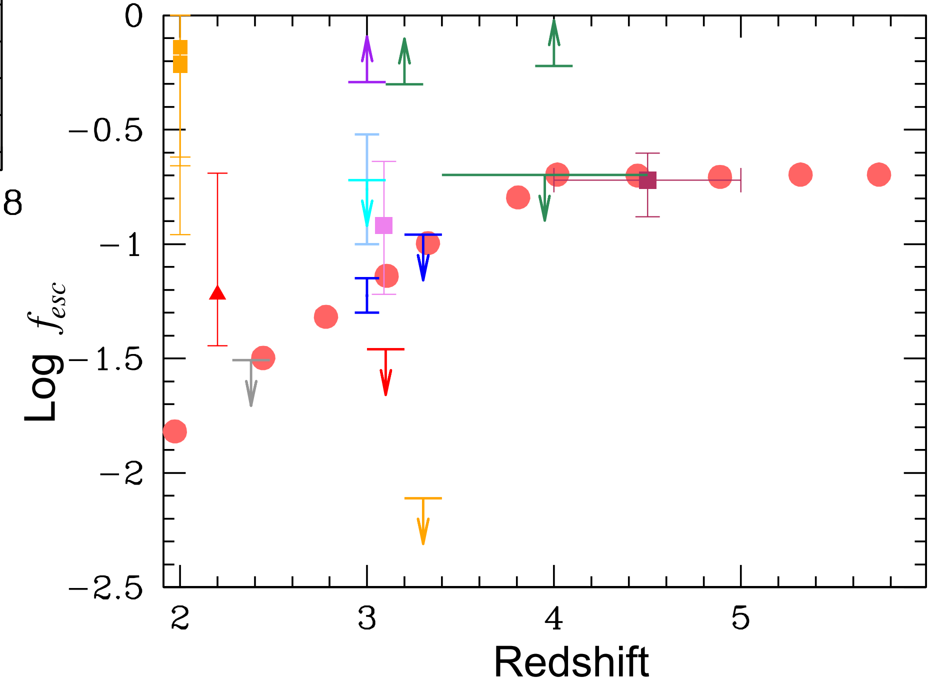
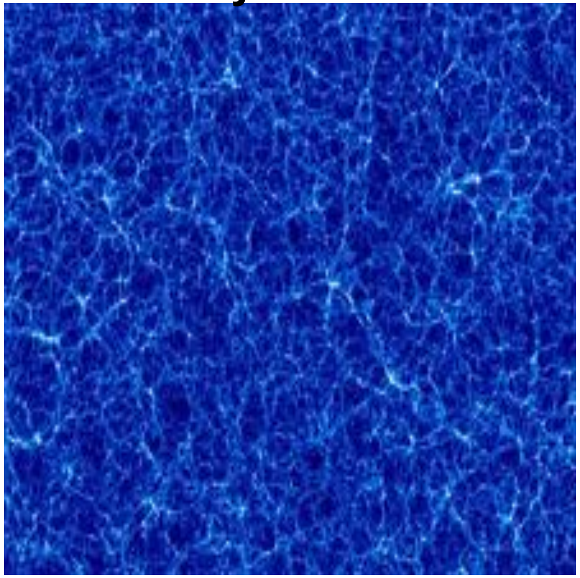


Trend of escape fraction of ionizing photons with redshift unclear.

PD & Ferrara, 2018, Physics Reports

Astraeus framework: coupling galaxy formation and reionization

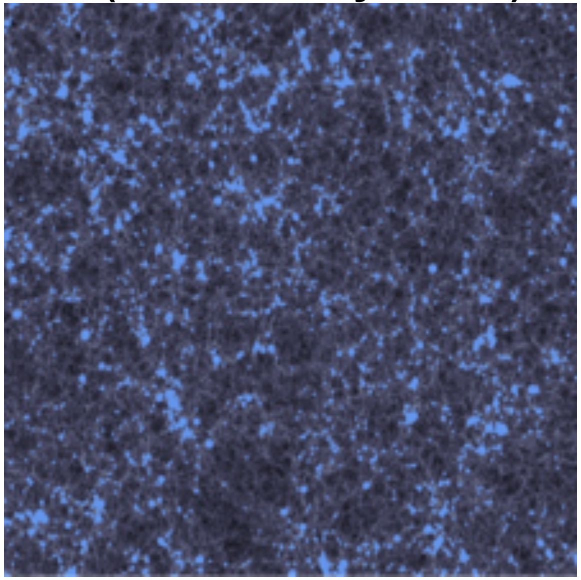
N-body simulation



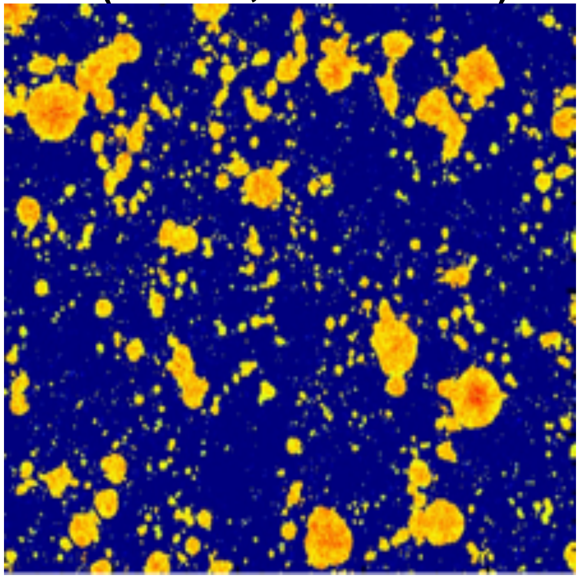
230 cMpc; 3840^3

Astraeus: semi-numerical rAdiative tranSfer coupling of galaxy formaTion and Reionization in N-body dArk mattEr simUlationS (**PI: Dayal)**

Galaxy formation (DELPHI; Dayal et al)



Reionization (CIFOG; Hutter et al)



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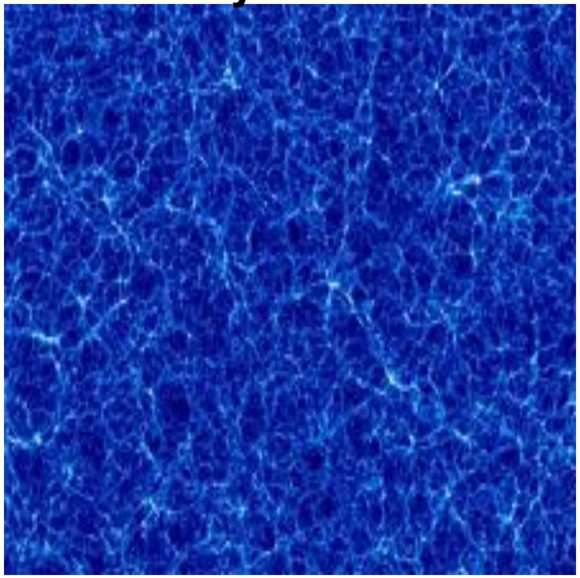

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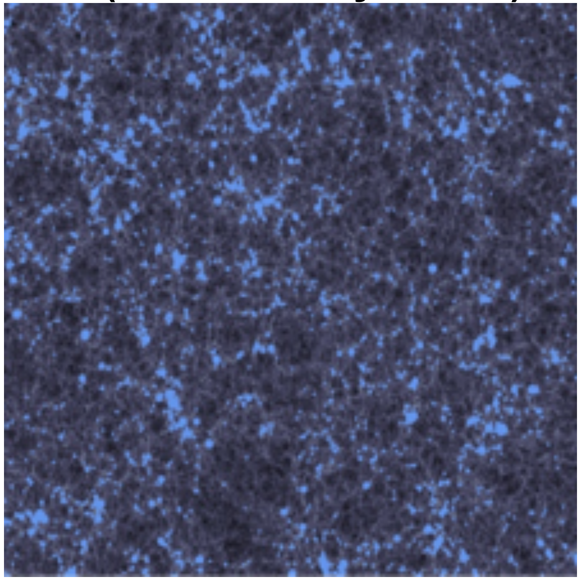

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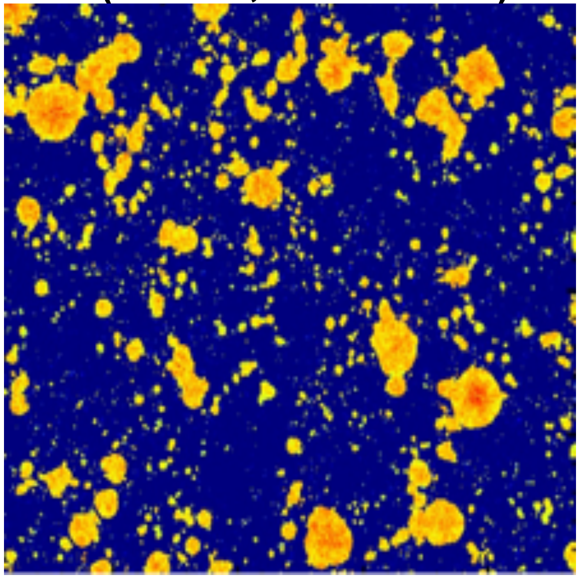
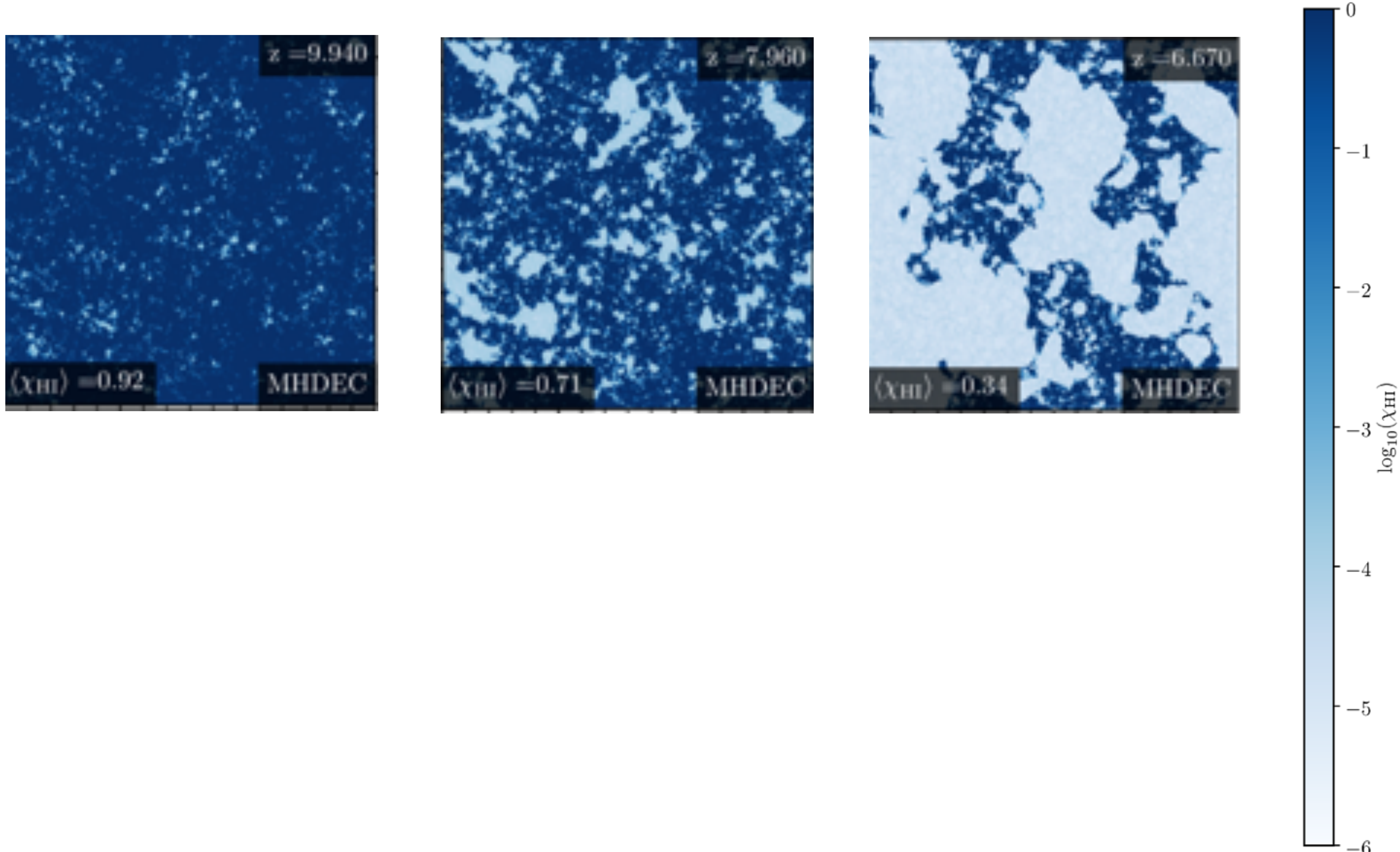


Key framework used for interpreting data from **JWST** observations (UNCOVER, PANORAMIC, PRIMER). **Forms training data-set for interpreting forthcoming SKA observations.**

Impact of the Lyman Continuum escape fraction on reionization topology



f_{esc} decreasing with increasing mass i.e. 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; f_{esc} increasing with increasing mass) drive the process (Astraeus VIII: Hutter, Trebitsch, Dayal et al. 2023).

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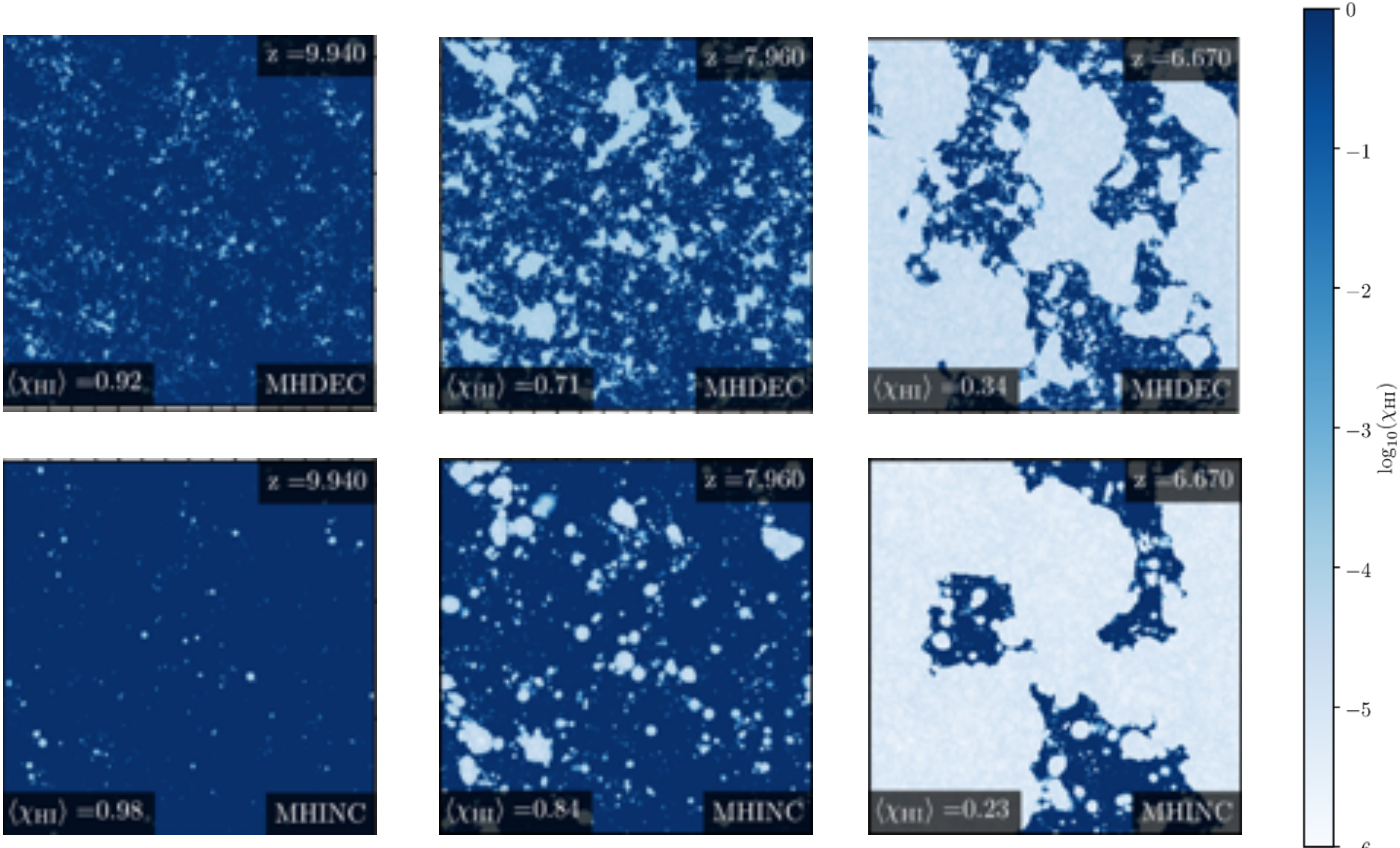

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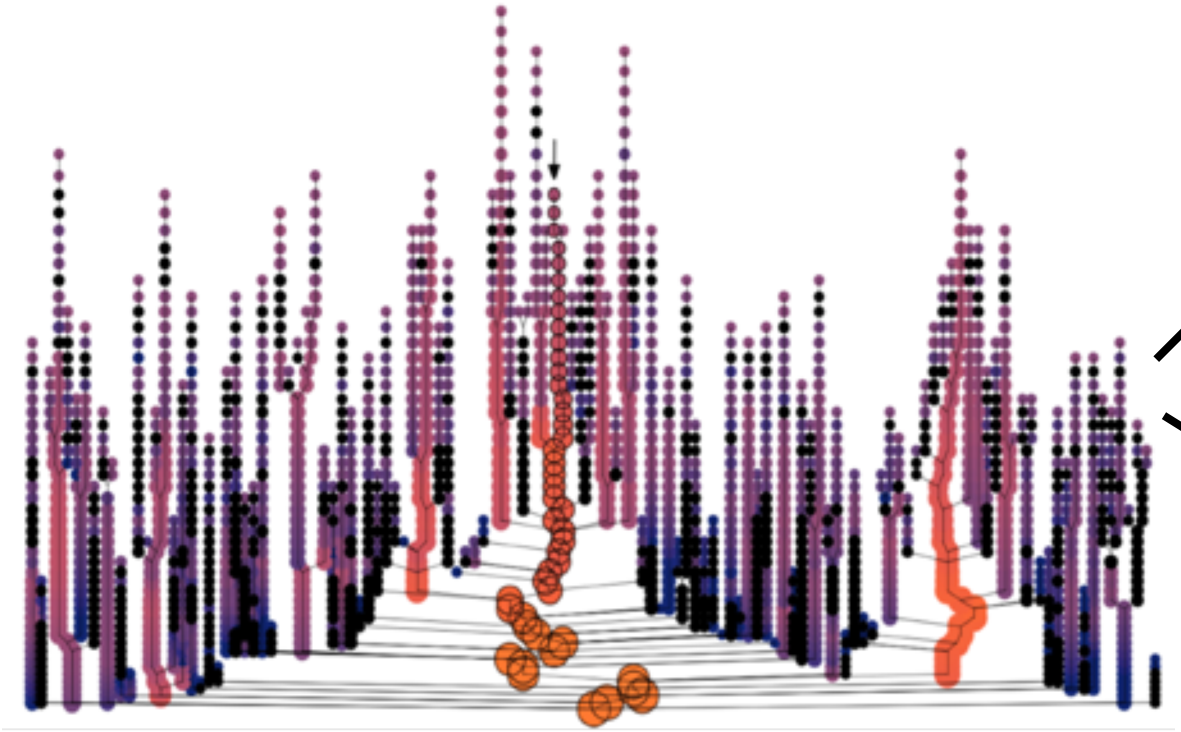
Escape fractions from galaxies and AGN

From the LzLCS, Chisholm et al. (2022) derive a relation between f_{esc} and the UV spectral slope:

$$f_{\rm esc} = (1.3 \pm 0.6) \times 10^{-4} \times 10^{(-1.22 \pm 0.1)\beta}.$$

The UV spectral slope becomes bluer the lower the dust attenuation (e.g. Bouwens et al. 2014; Cullen et al. 2023). I.e. larger f_{esc} values for low-mass, blue galaxies.

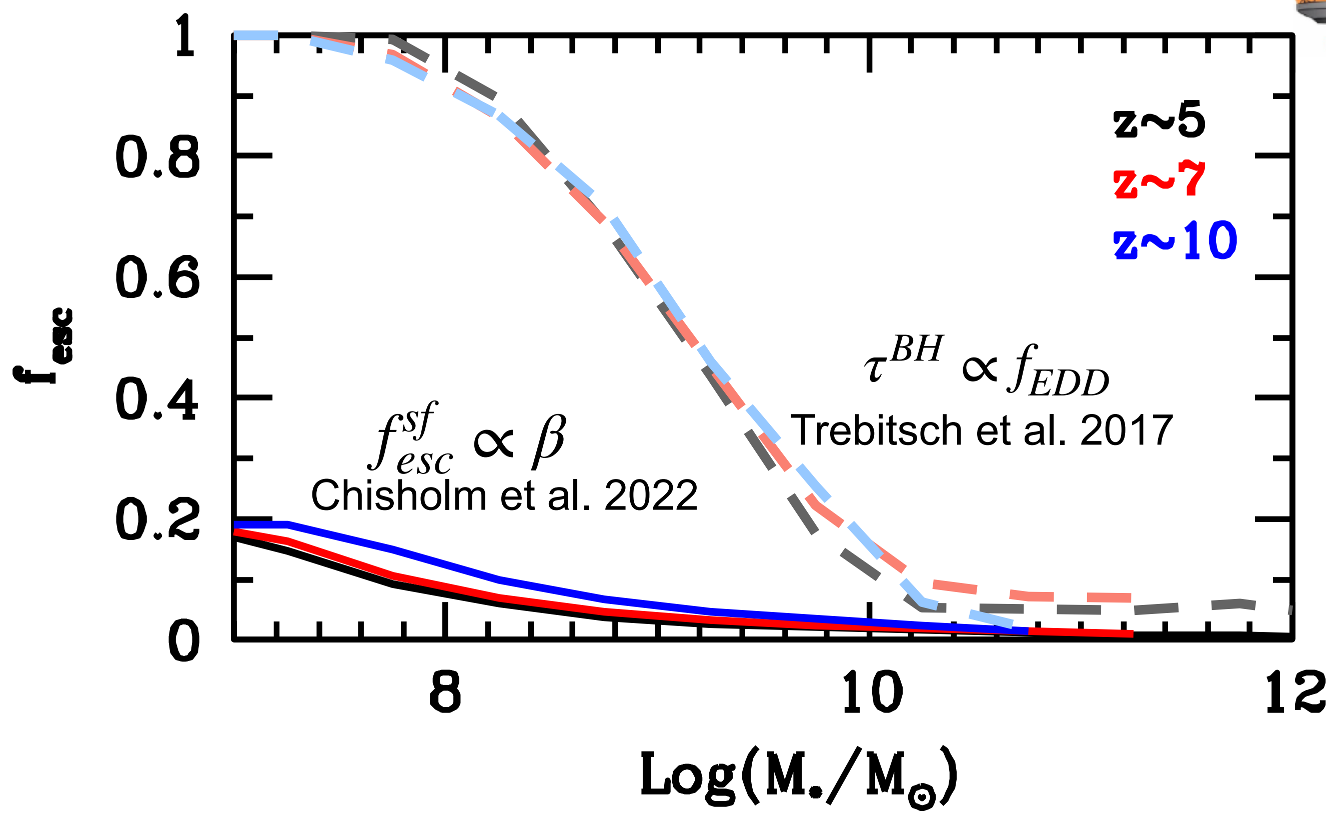


Galaxy properties tracked through time with dust masses baselined against ALMA ALPINE + REBELS data. Used to assign f_{esc}^{sf}.

Heavy BH seeds $(10^{3-5} M_{\odot})$, BH growth and feedback coupled baryons, Eddington fraction used to infer f_{esc}^{bh}

Dayal, Volonteri, Greene+UNCOVER team, 2024

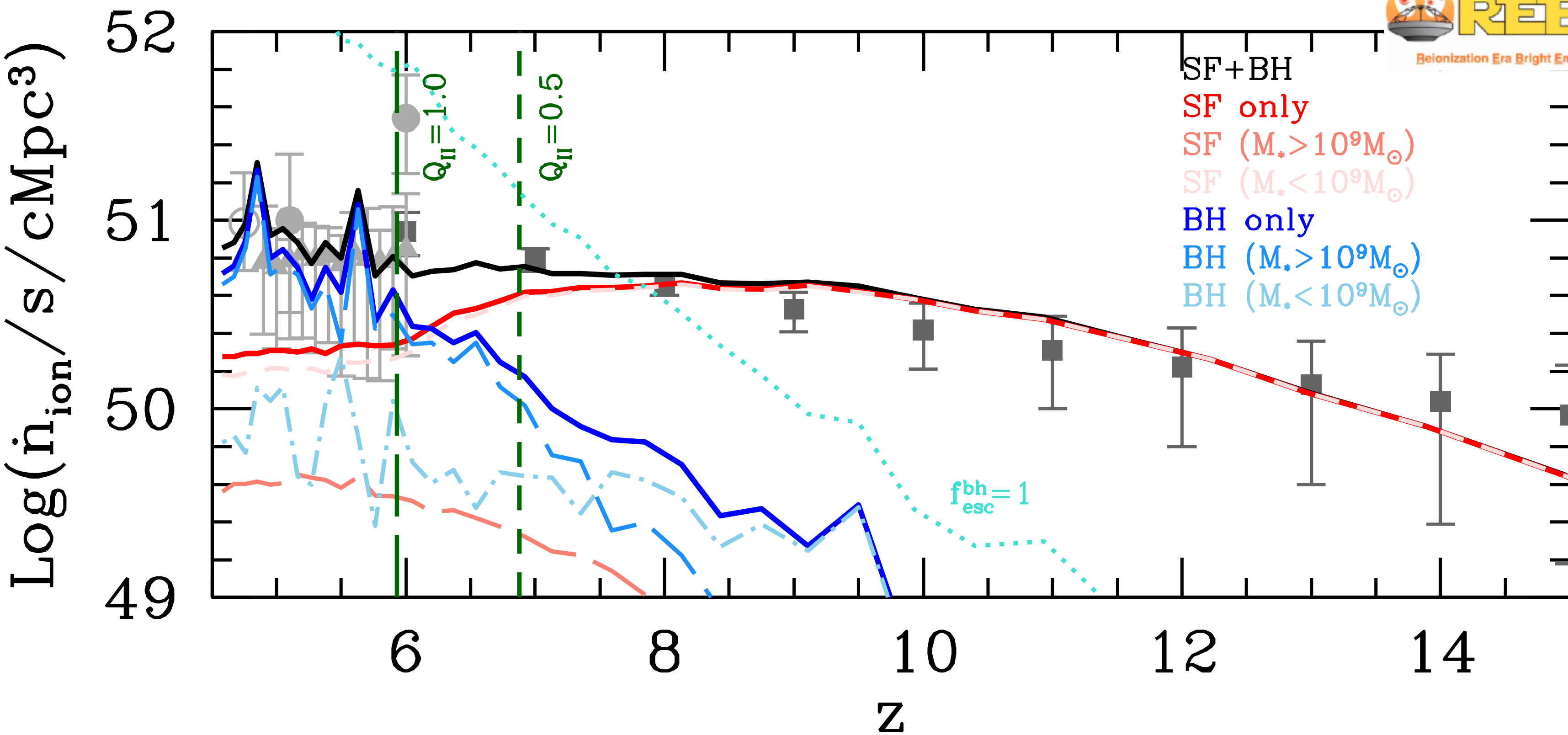
Escape fractions post ALMA & JWST



Escape fractions of ionizing photons decrease with increasing mass for both str forming galaxies and black holes. While f_{esc}^{sf} typically shows values less than 20%, f_{esc}^{bh} can have values as high as a 100% for low-mass systems, decreasing to about 20% for stellar masses larger than $10^{10} M_{\odot}$.

Dayal, Volonteri, Greene+UNCOVER team, 2024

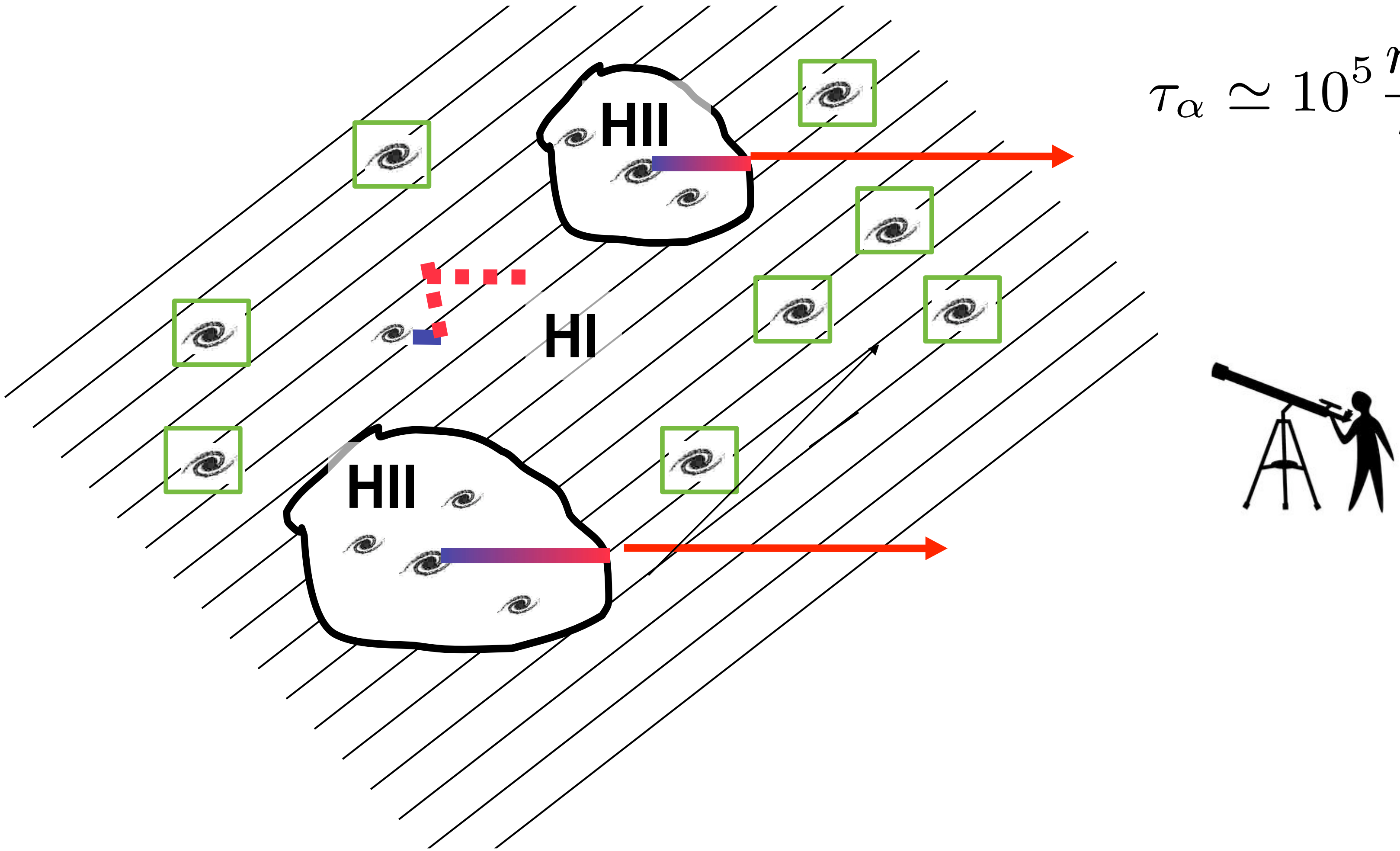
Key reionization sources post ALMA & JWST



- 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+UNCOVER team, 2024; Atek (incl. PD) et al. 2024; also e.g. Finlator et al. 2011, Gnedin 2014, Wise et al. 2014, Robertson et al. 2015, Madau 2017, Trebitsch et al. 2022; although see Giallongo et al. 2015, 2019, Madau & Haardt 2015, Chardin et al. 2015, Madau et al. 2024

Inferring the patchiness of reionization using Lyman Alpha Emitters



$$\tau_\alpha \simeq 10^5 \frac{n_{HI}}{n_H}$$

Implies a larger probability for clustered galaxies to be preferentially visible in Lyman Alpha (e.g. Castellano, PD et al. 2016; Endsley & Stark 2021; Leonova et al. 2021; Castellano et al. 2022; Tilvi et al. 2022). A larger number of "field" LAEs appear as reionization proceeds.

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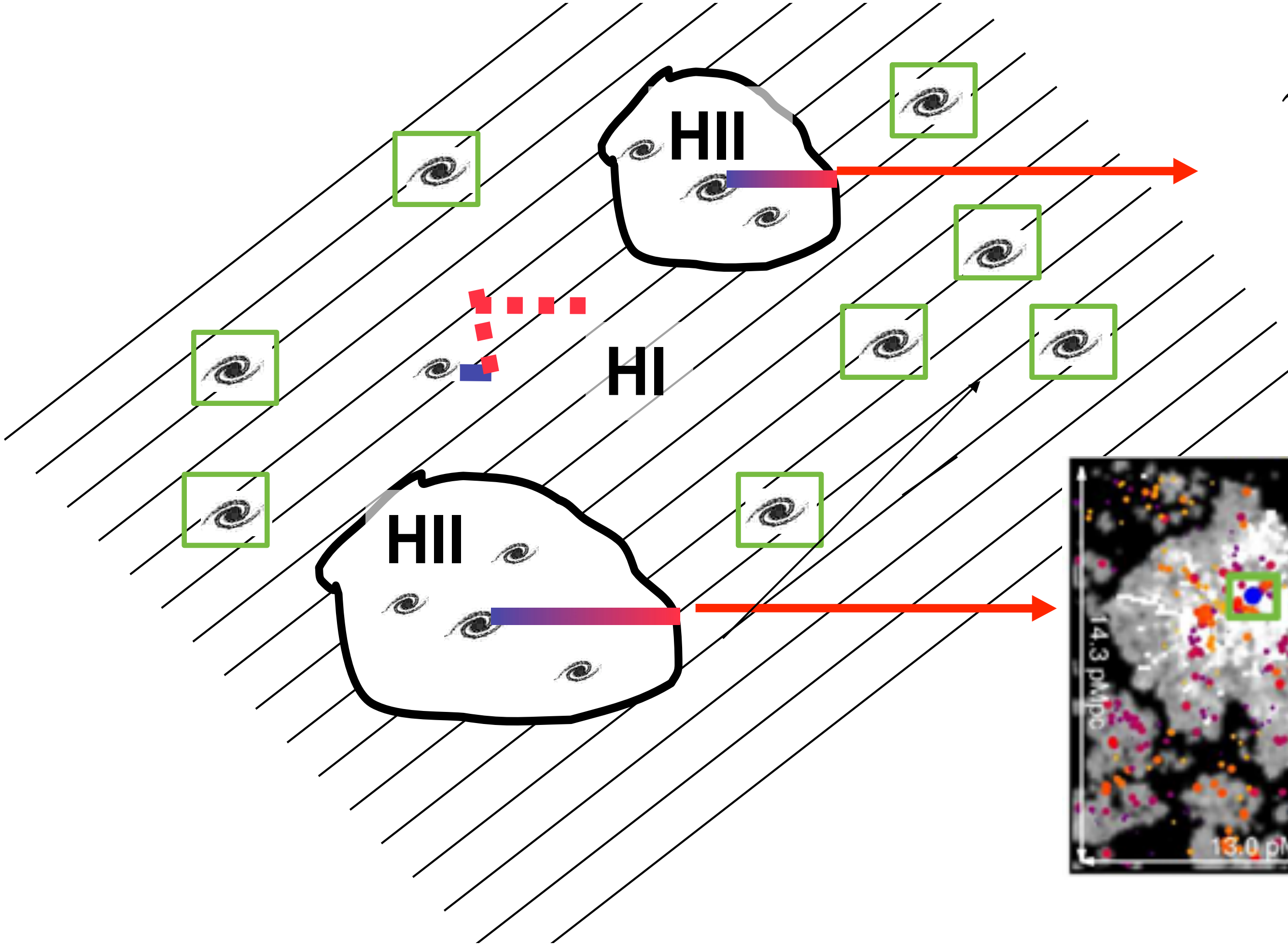

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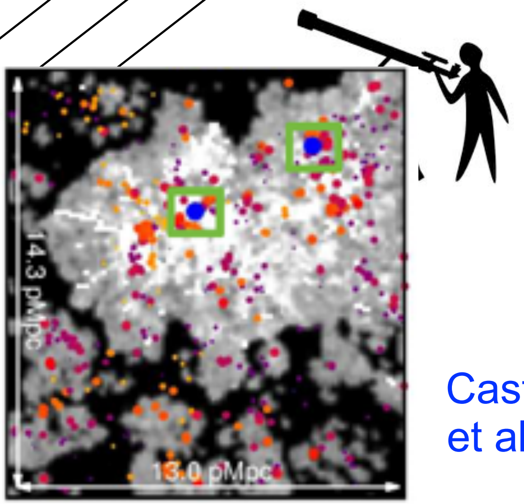

Castellano et al. 2016

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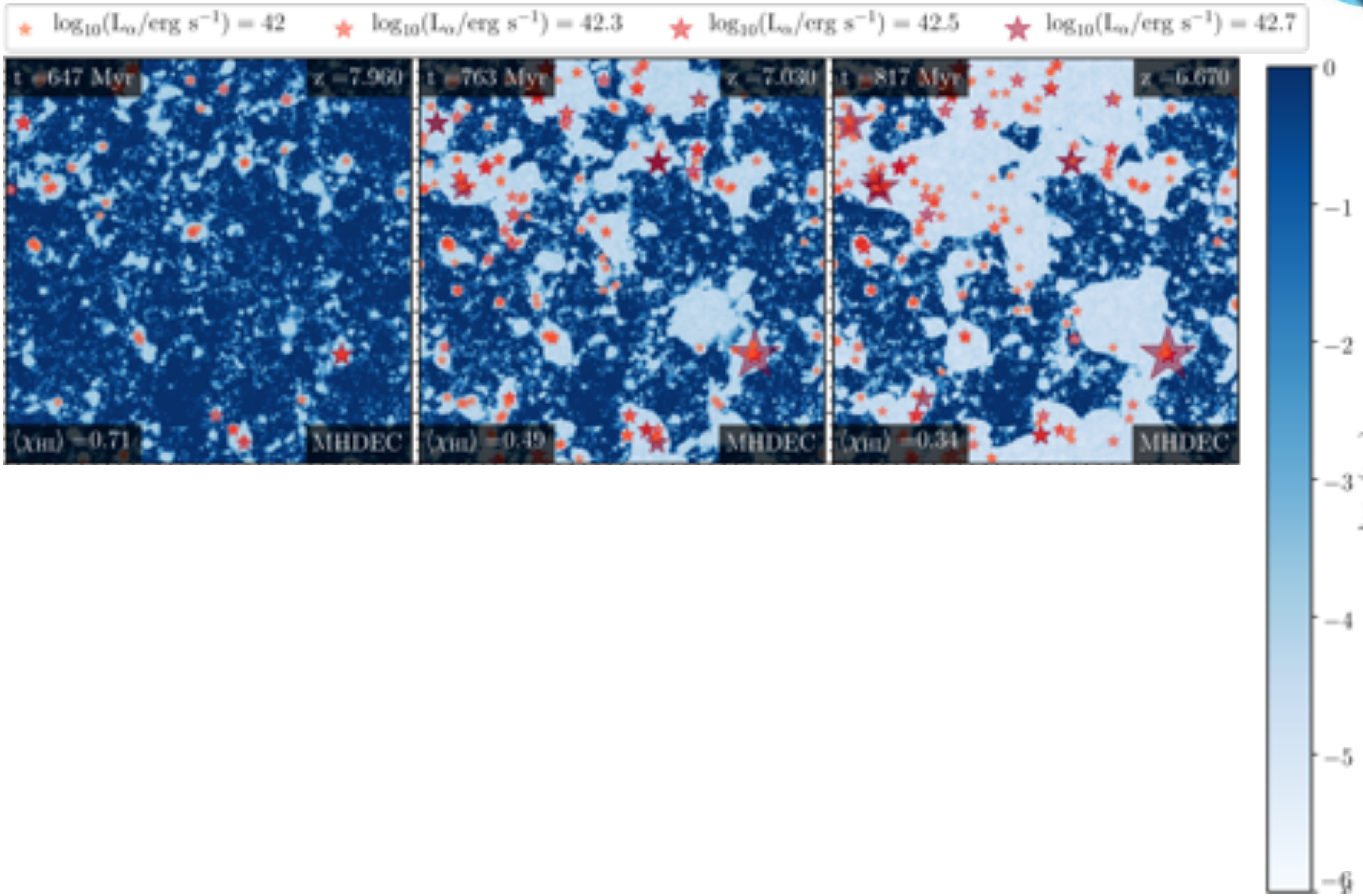
The visibility of galaxies as LAEs



The visibility and luminosity of Lyman Alpha Emitting galaxies crucially depends on f_{esc} (that determines reionization topology and impact of reionization feedback).

Astraeus VIII: Hutter, Trebitsch, Dayal et al., 2023

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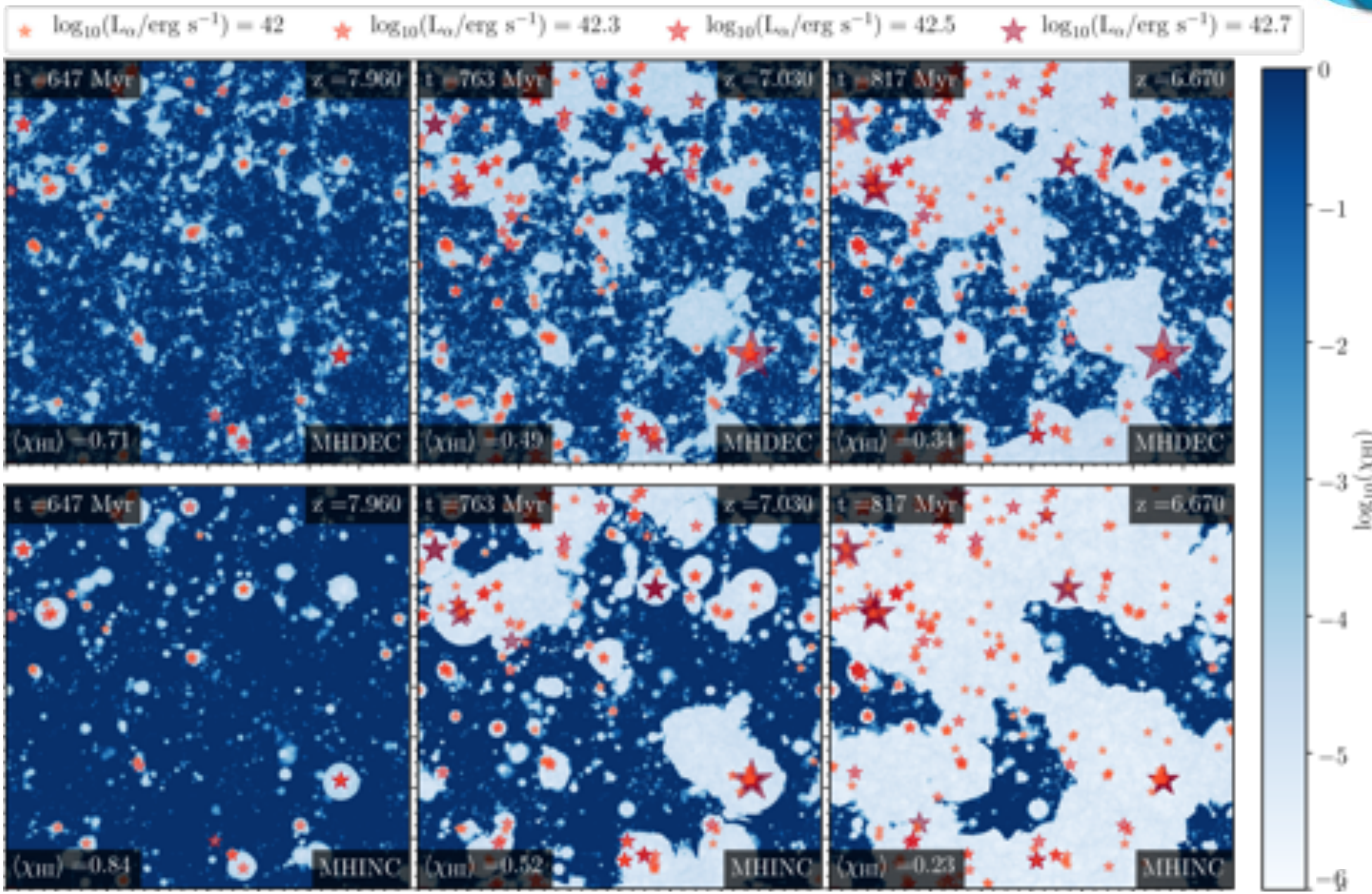

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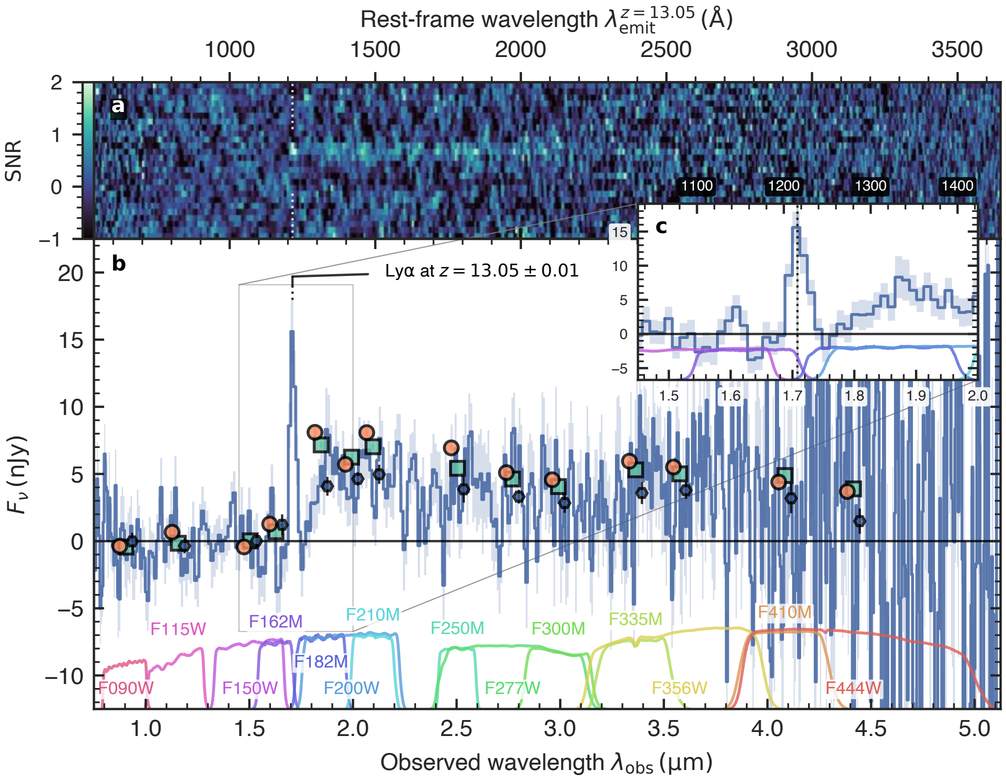
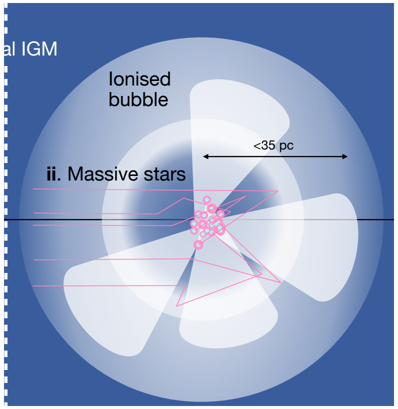
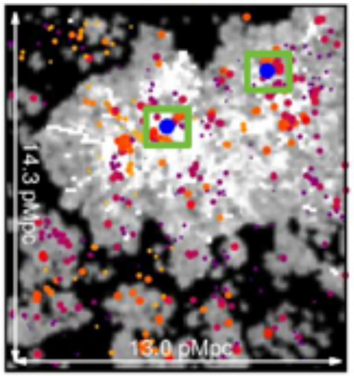
Witnessing the onset of reionization via Lyα emission at z~13



Lyα detected at z~13 using JWST (Witstok et al. 2024).

Explanations include massive, hot stars or an AGN

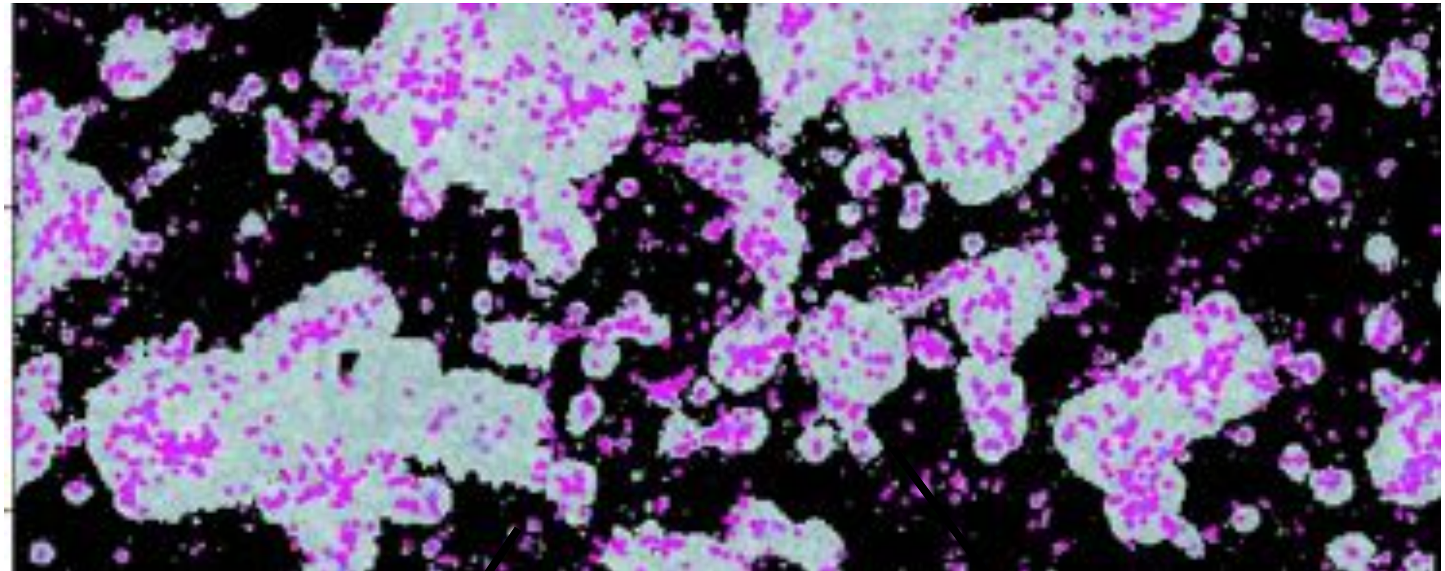




Could also hint at early over-density

also Jones et al. 2023; Jung et al. 2023; Nakane et al. 2023; Napolitano et al. 2024; Saxena et al. 2023b,a; Tang et al. 2023; Witten et al. 2023

The future: correlating 21cm and galaxies to constrain reionization



SKA EoR Synergy group

Euclid EoR group

21cm emission from neutral hydrogen

Galaxy populations
Subaru, JWST,
NGRST, EUCLID

Cross-correlating 21cm data with (Lyman Alpha emitting and black hole) galaxy data will yield information on reionization state & topology.

The emerging picture

- JWST is finding an over-abundance of bright systems at z>11. Multiple explanations including evolution in dust, IMF, star formation efficiency, (perhaps evolution of HMF, Dark Energy, Primordial Magnetic Fields..)

- Dust determines the bright end of the star forming galaxies UV LF for galaxies brighter than $M_{UV} \sim -21$ z<10. Impact of dust decreases with increasing redshift.

- JWST is yielding a sample of numerous and obese BHs as early as z~10 that pose a challenge for theoretical models.

- For reionization, emerging picture is one where low-mass galaxies ($< 10^9 M_\odot$ in stellar mass) are key reionization drivers, providing ~75% of the total photon budget.

- AGN only important in the end stages of reionziation (z<6) and can provide at most 25% of the total ionizing photons by z~4.

- LAEs are a critical probe of the patchiness and progress of reionization. JWST unveiling LAEs at redshifts as high as z~13, shedding light on earliest reionization stages.