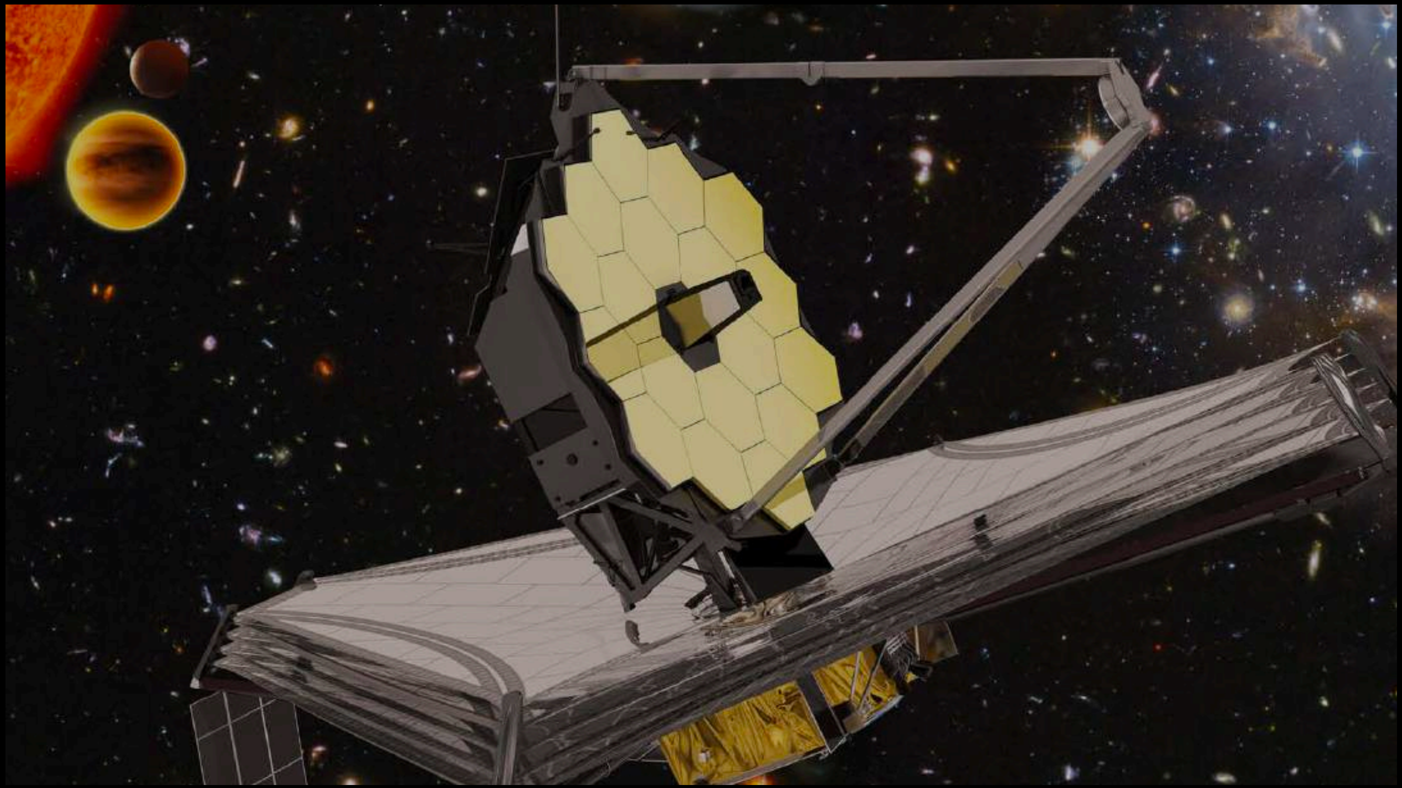
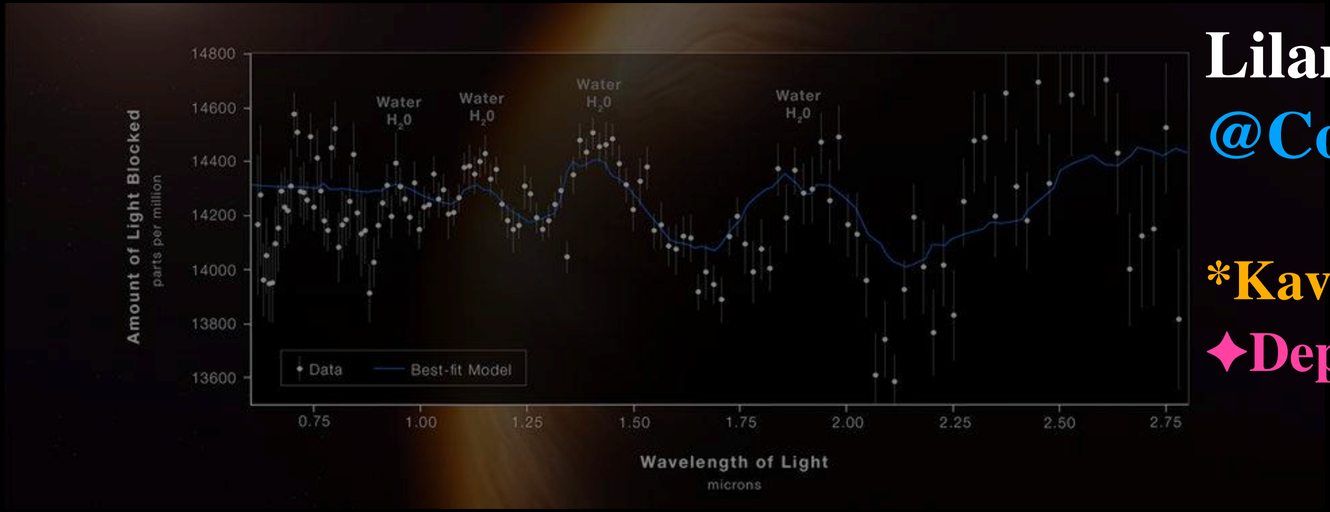
What Is JWST Telling Us about Early Galaxy Formation & Cosmology?





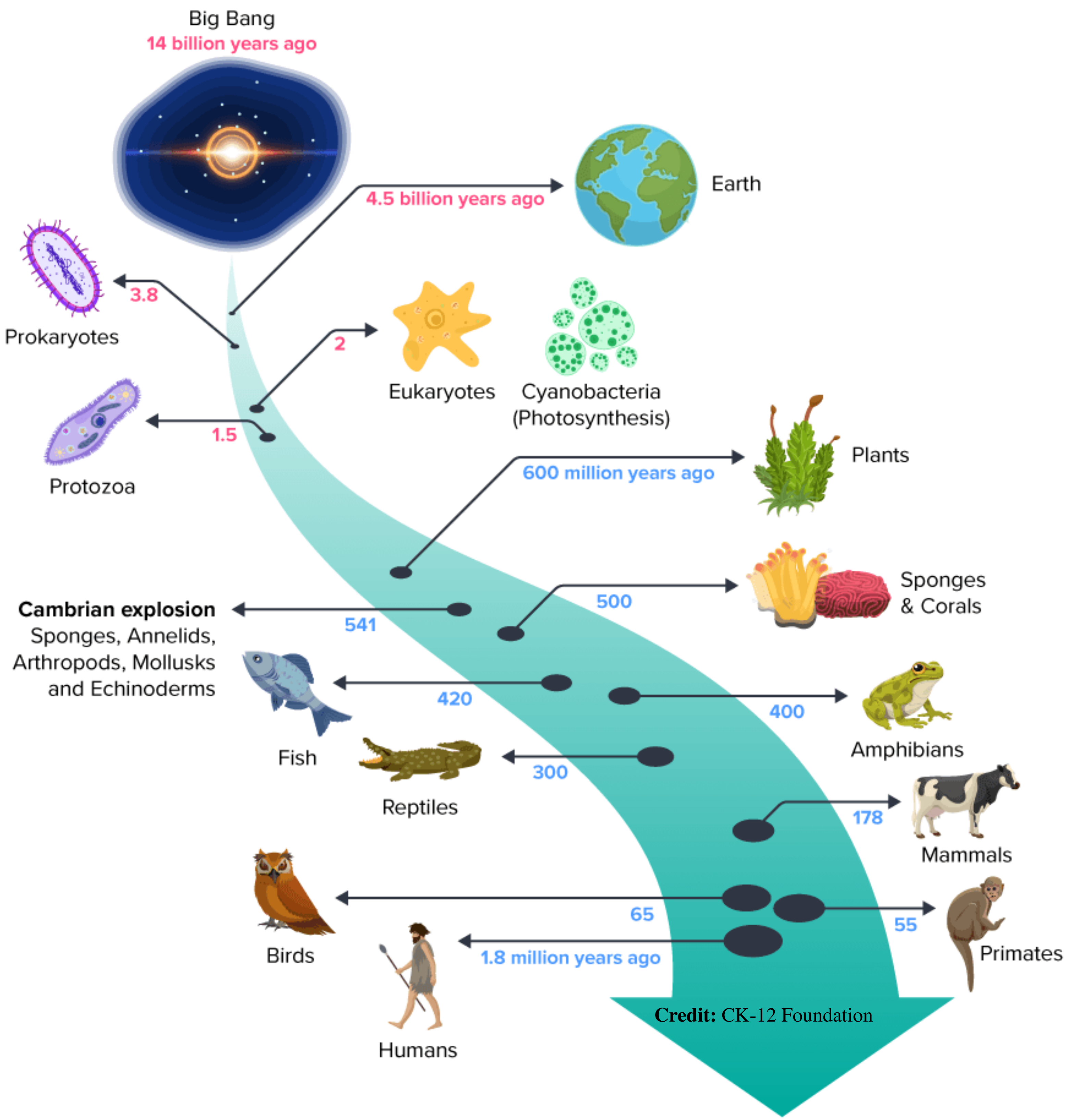
Lilan Yang* & Mike Boylan-Kolchin✦

@Cosmologyfromhome2023

***Kavli IPMU, the University of Tokyo**

✦Department of Astronomy, the University of Texas at Austin

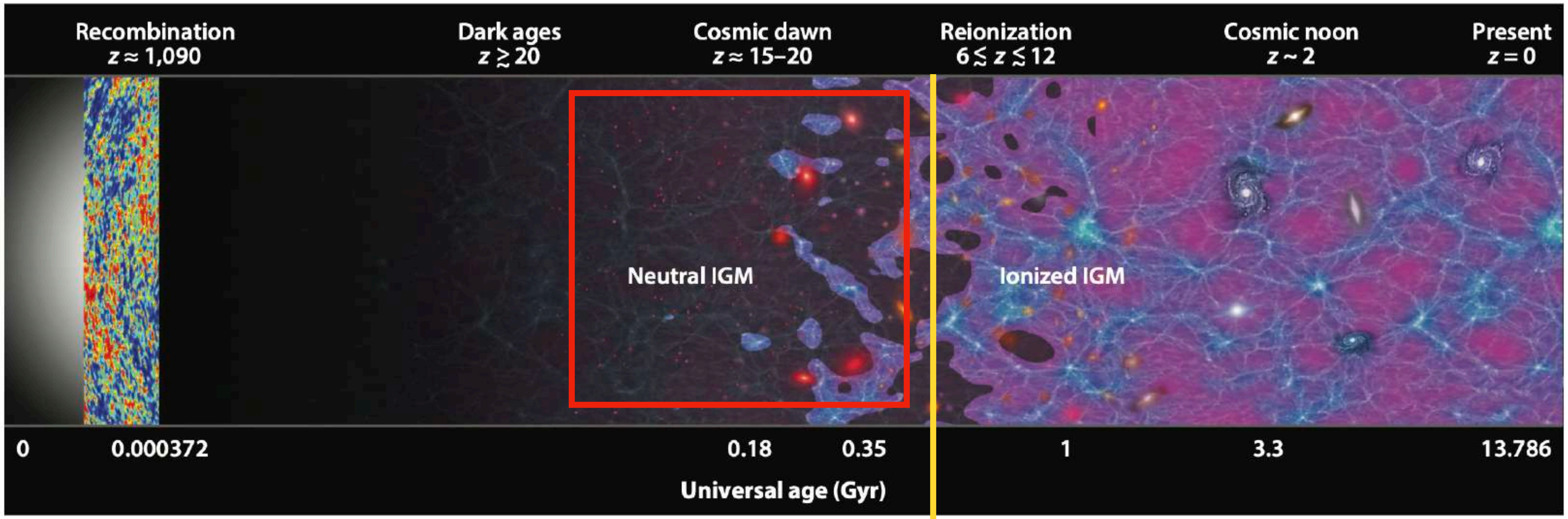
Timeline of the Life



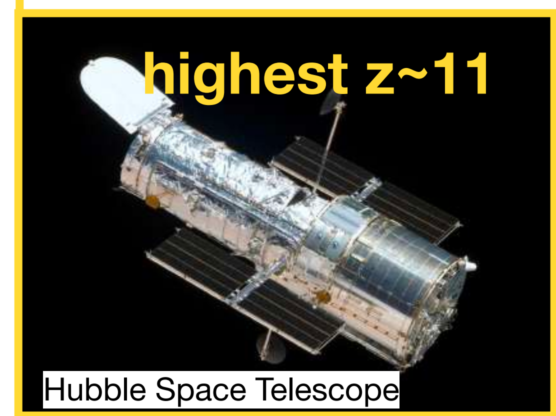
Credit: CK-12 Foundation

The diversity of life on Earth today is the result of **Universe evolution**

Timeline of the Universe



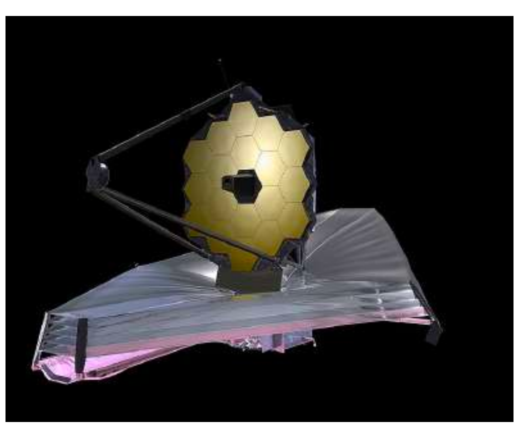
Robertson 2022



Key Questions

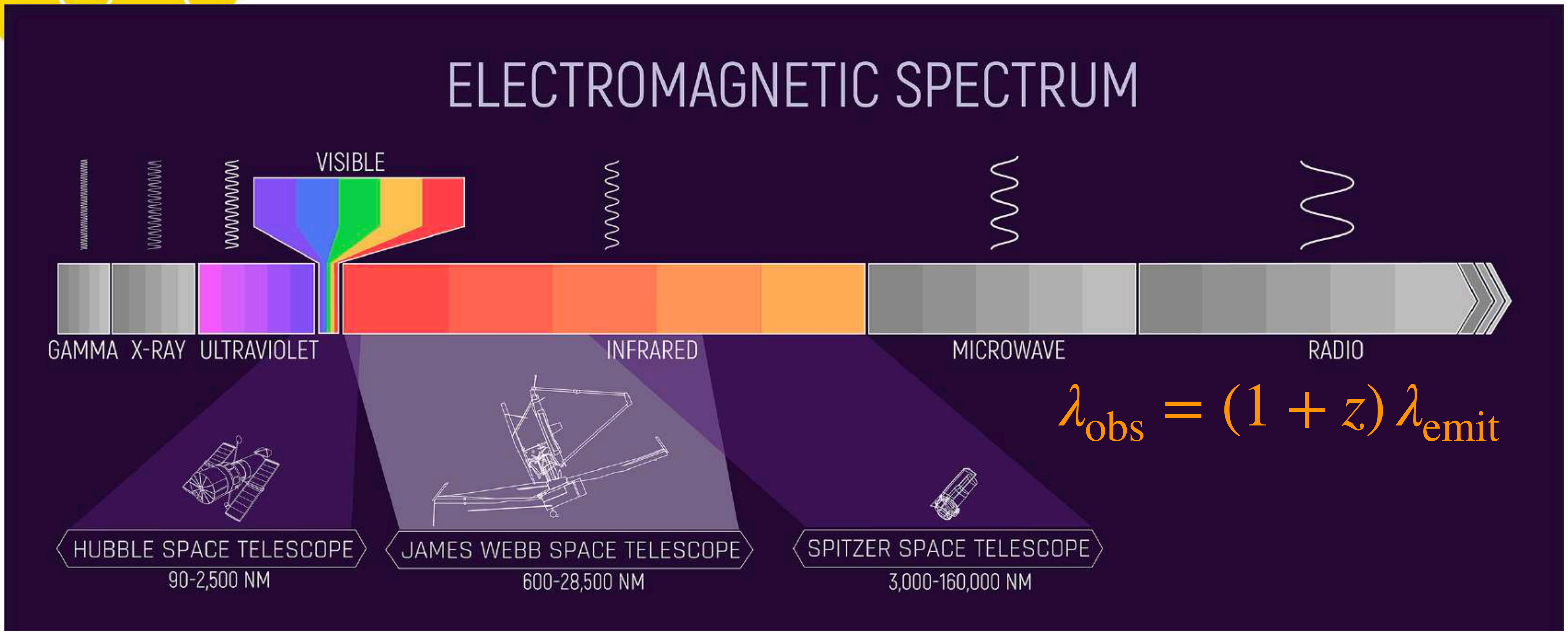
1. What are the first stars/galaxies?
2. How did reionization occur? and what caused it?

3. Observed structures consistent with initial conditions?
4. Physics beyond base ΛCDM?

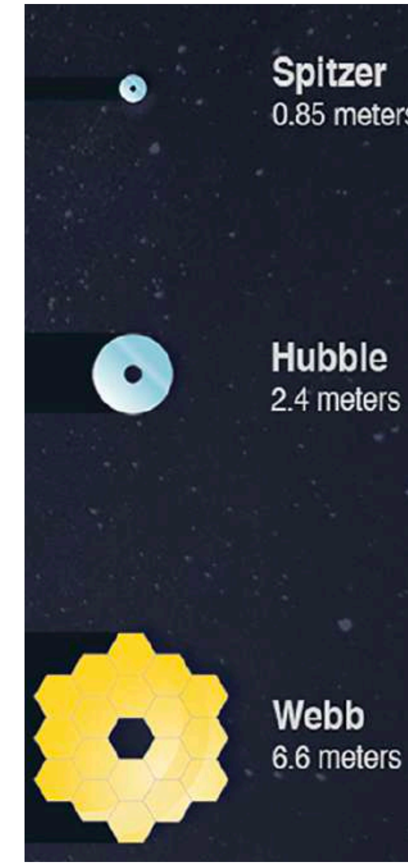


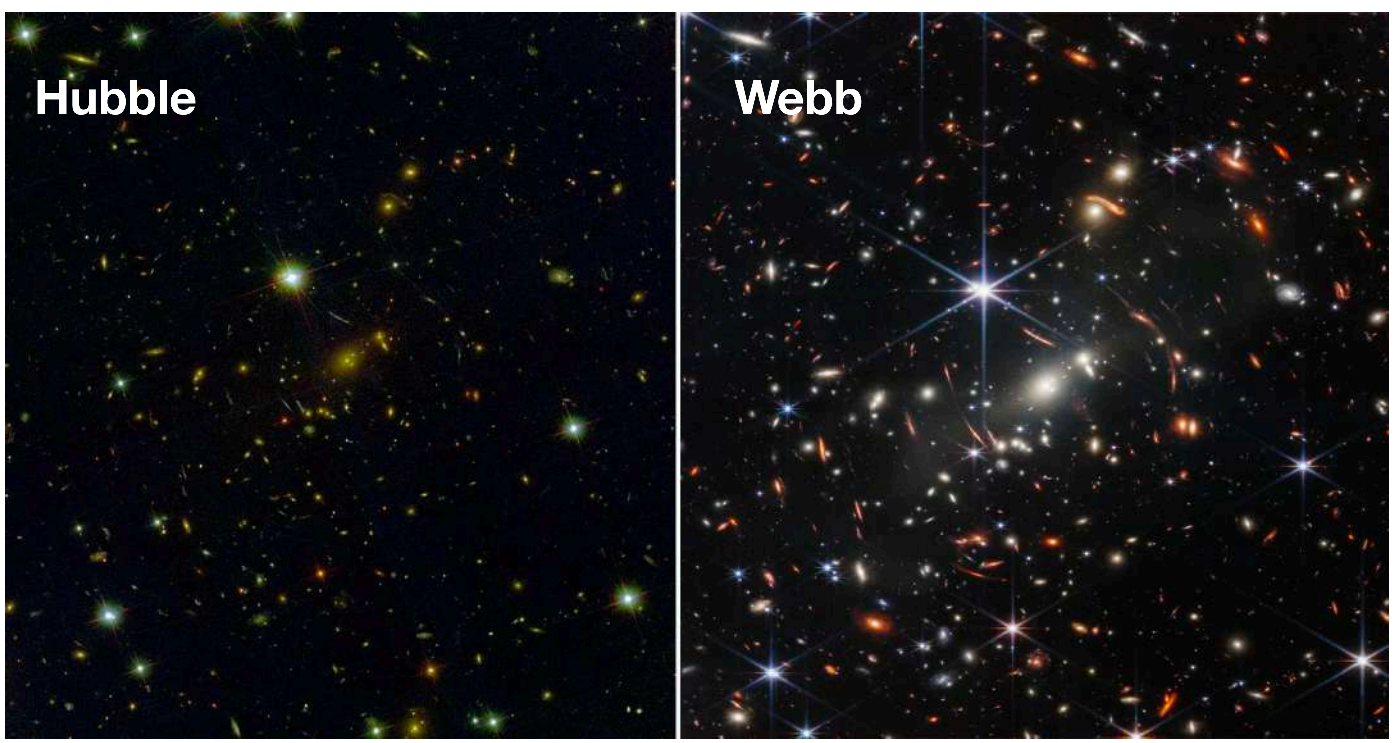
Why JWST

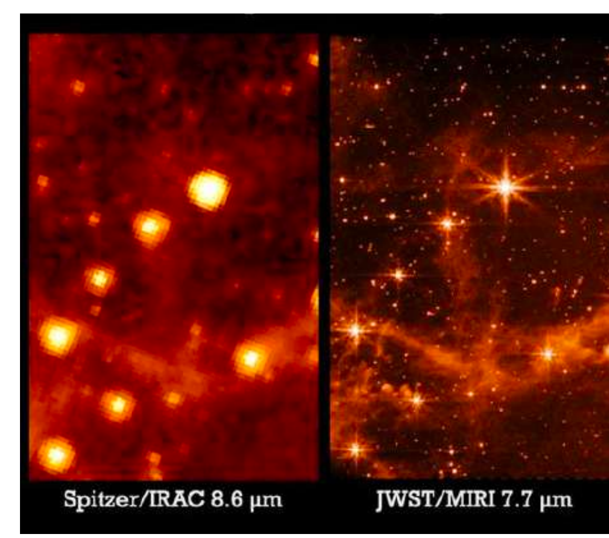
Telescope Primary Mirror Sizes



$$\lambda_{\rm obs} = (1+z)\,\lambda_{\rm emit}$$

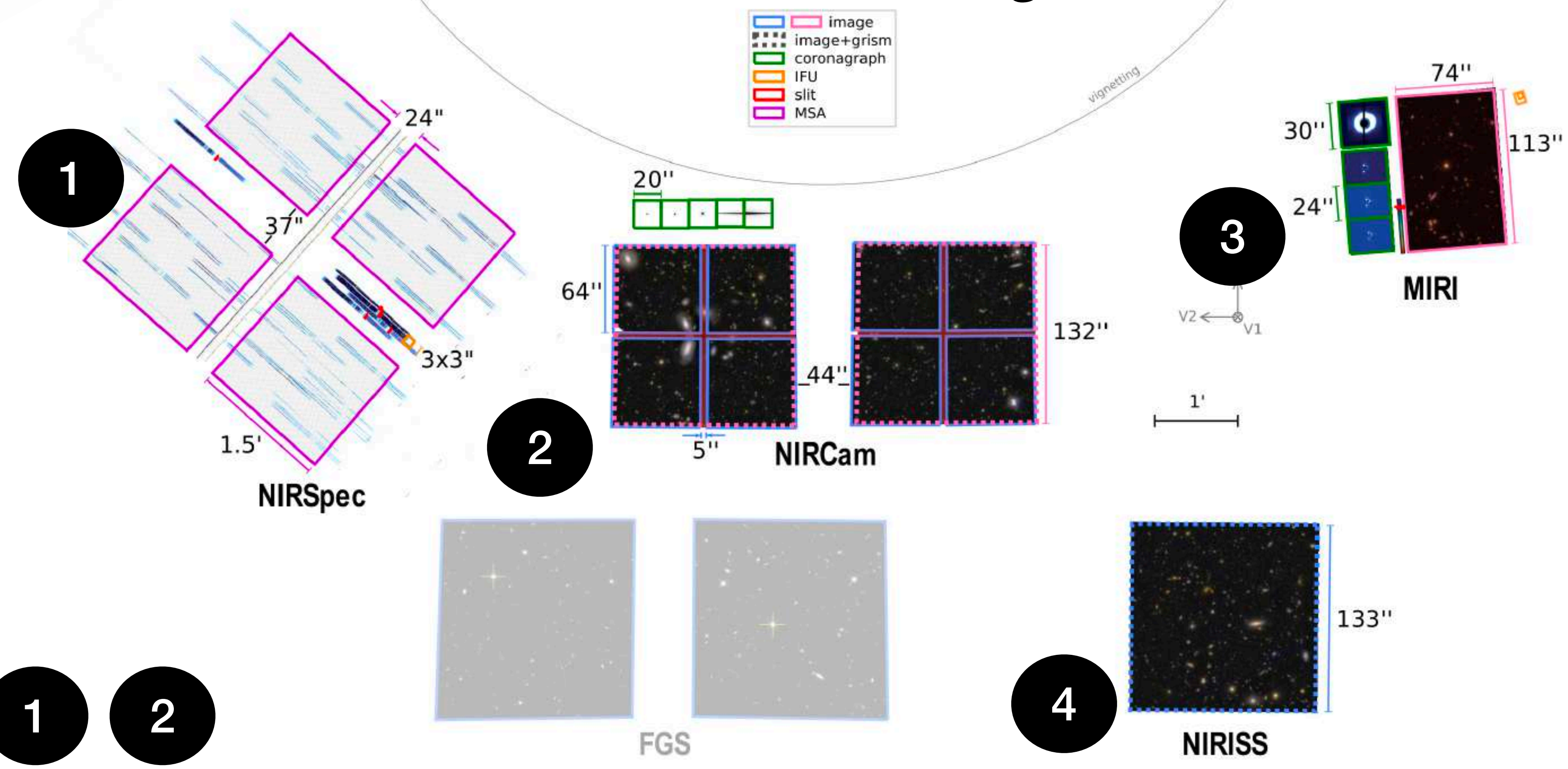






galaxy cluster SMACS 0723, known as Webb's ***First*** Deep Field unveiled July 11, 2022

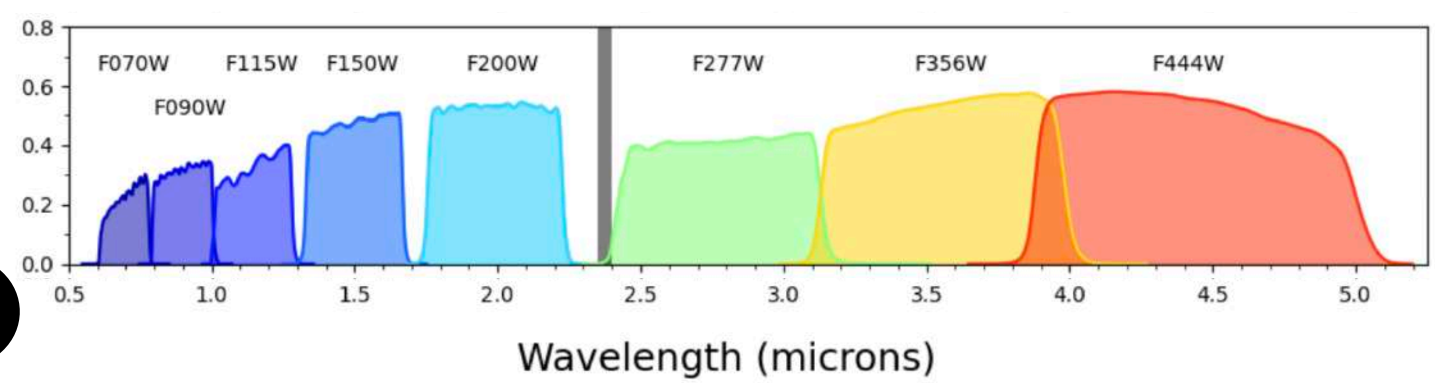
Overview of JWST



1 2

Near Infrared Spectrograph (NIRSpec): near-IR spectroscopy from 0.6–5.3 µm

Near Infrared Camera (NIRCam): offers imaging from 0.6–5.0 µm, coronagraphy, slitless spectroscopy



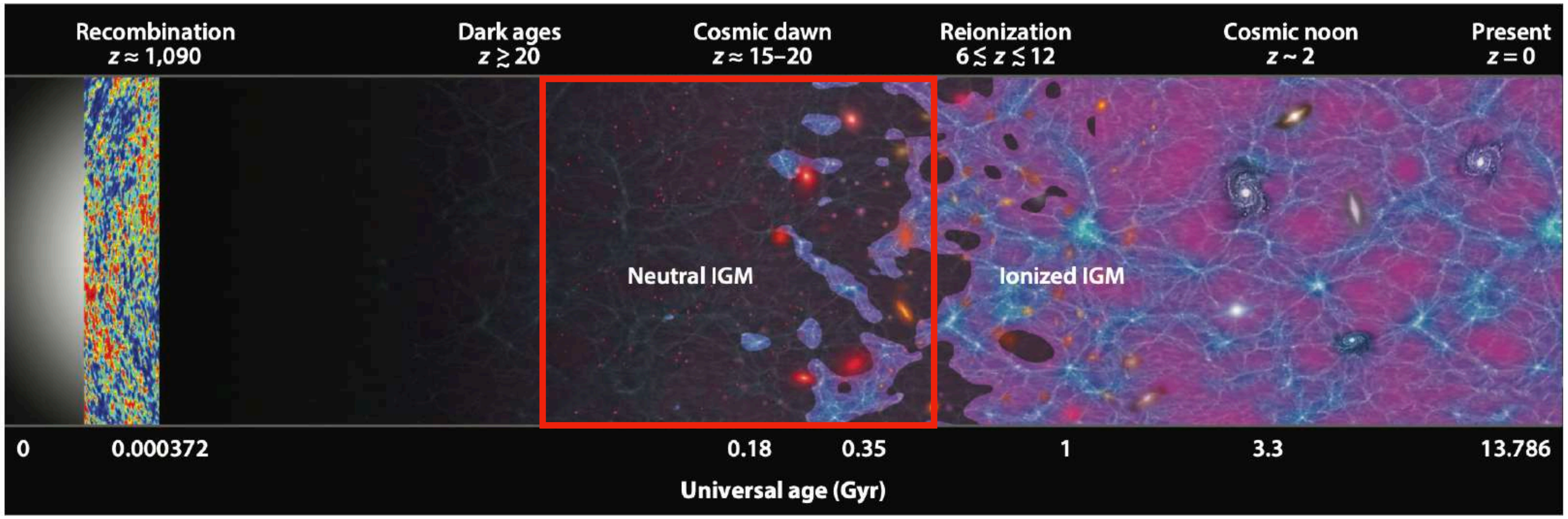
Example of NIRCam filters

3 4

Mid-Infrared Instrument (MIRI): imaging and spectroscopic from ~5 to 28µm

Near Infrared Imager and Slitless Spectrograph (NIRISS): slitless spectroscopy, and imaging

Key Questions List



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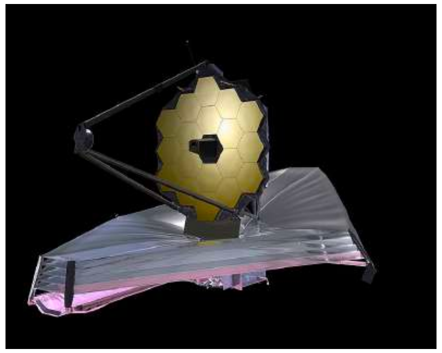
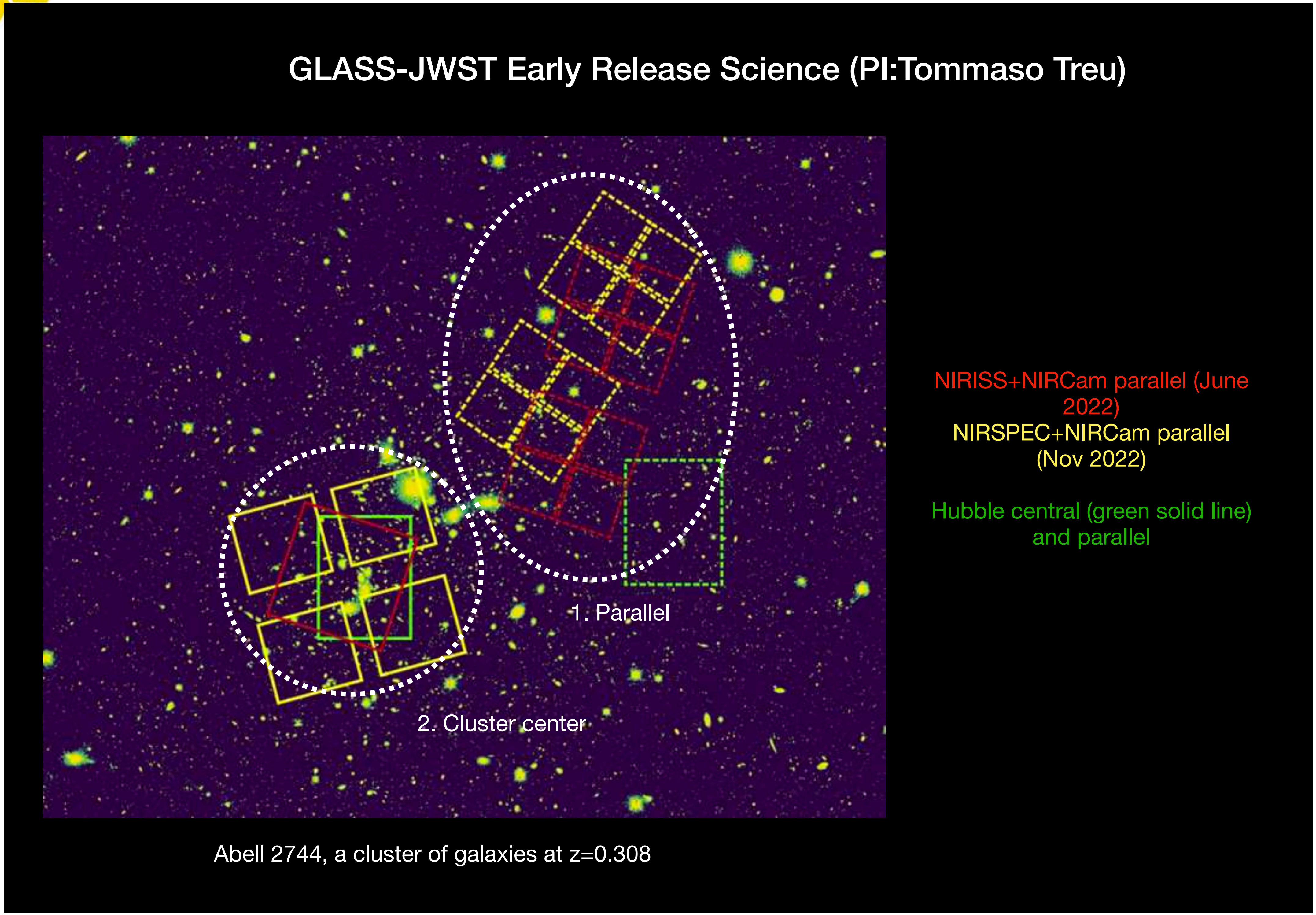


First look by Webb

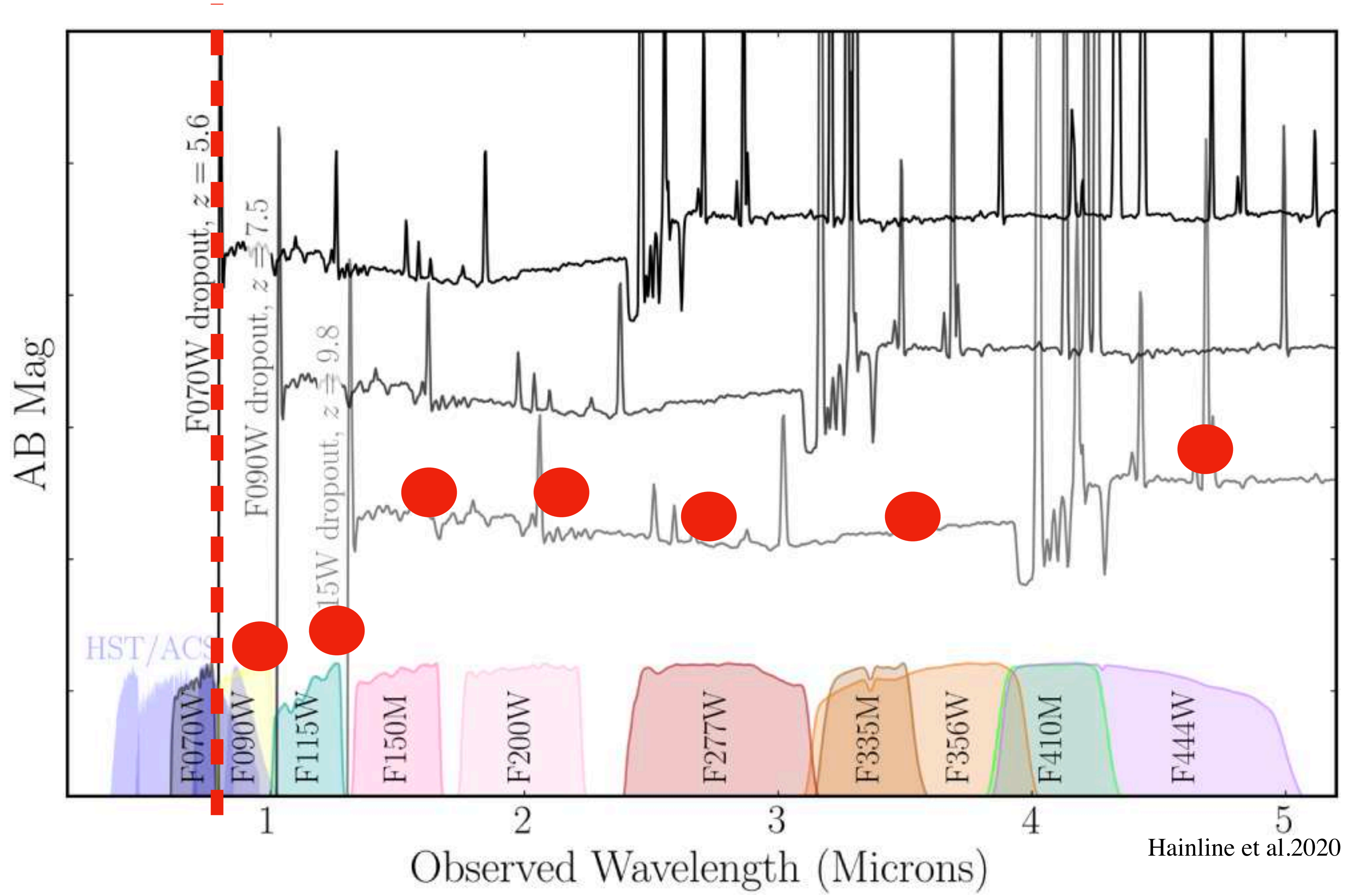


“In 2017, thirteen "Early Release Science" (ERS) Programs were selected with the goal of collecting as quickly as possible public datasets that would showcase the power of JWST while enabling a full characterization of its instrument suite.”

Treu …. Yang et al, 2022

Dropout technique & SED Fitting

searching for the high-z galaxies



Dropout technique:

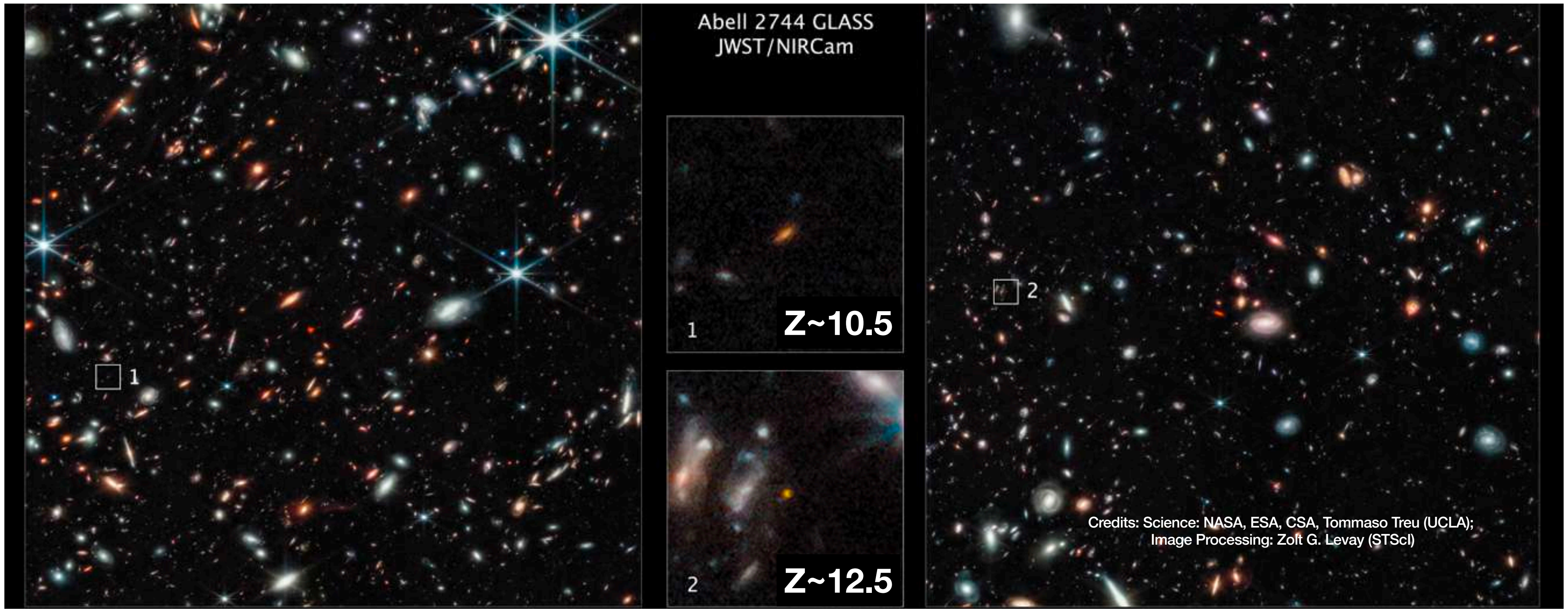
large break occurs at the **912-1216 Å** (Lyman limit-Lyman alpha) from **neutral hydrogen absorption** in the line-of-sight

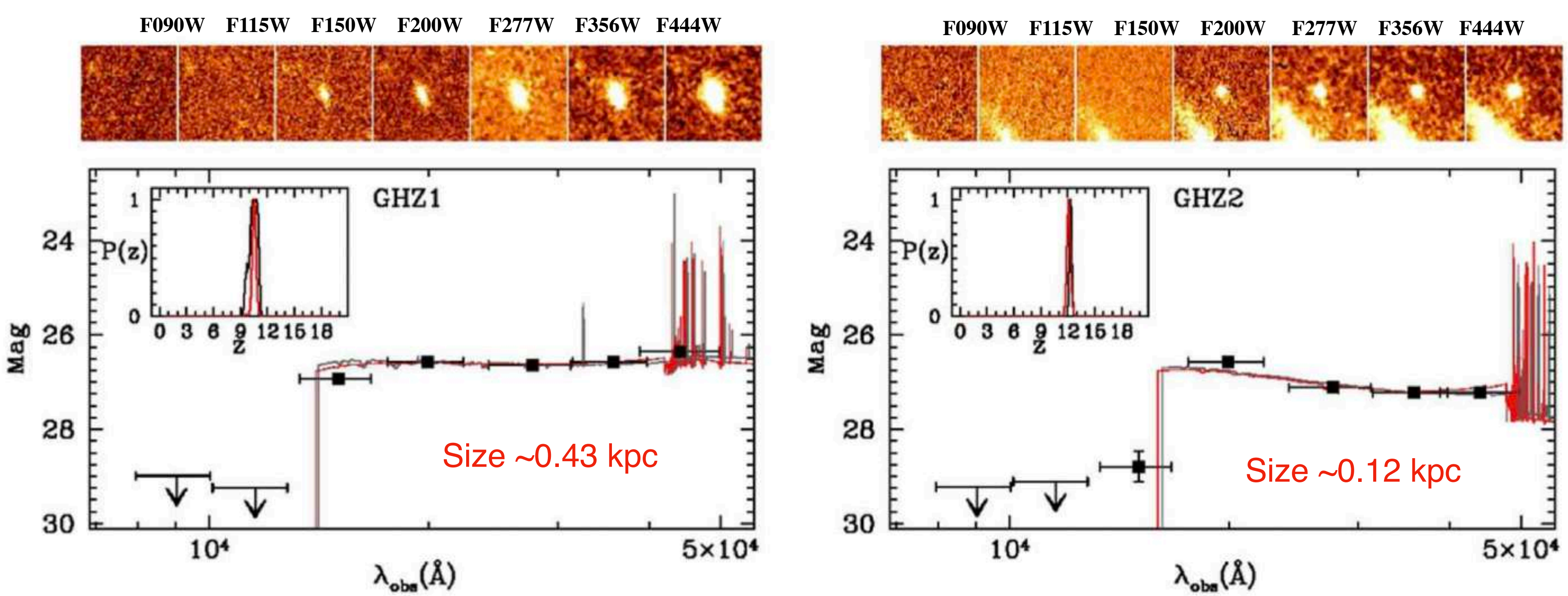
Spectral energy distributions (SED):

Estimating galaxies's properties, such as stellar mass, dust attenuation etc

Discovery 2 bright early galaxies

With just 4 days of analysis



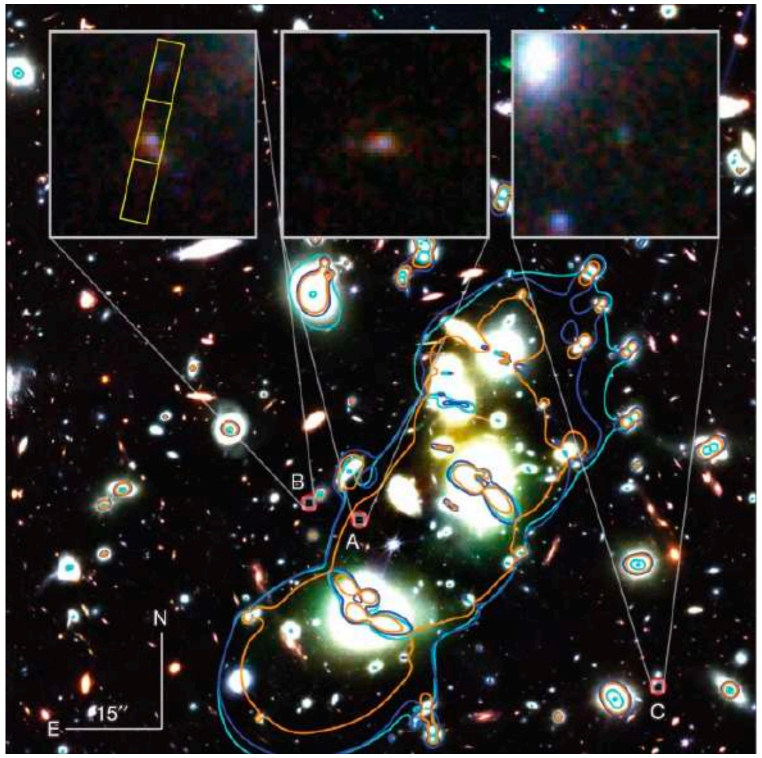


Milky Way: ~13 kpc, Magnitude ~ -21.3

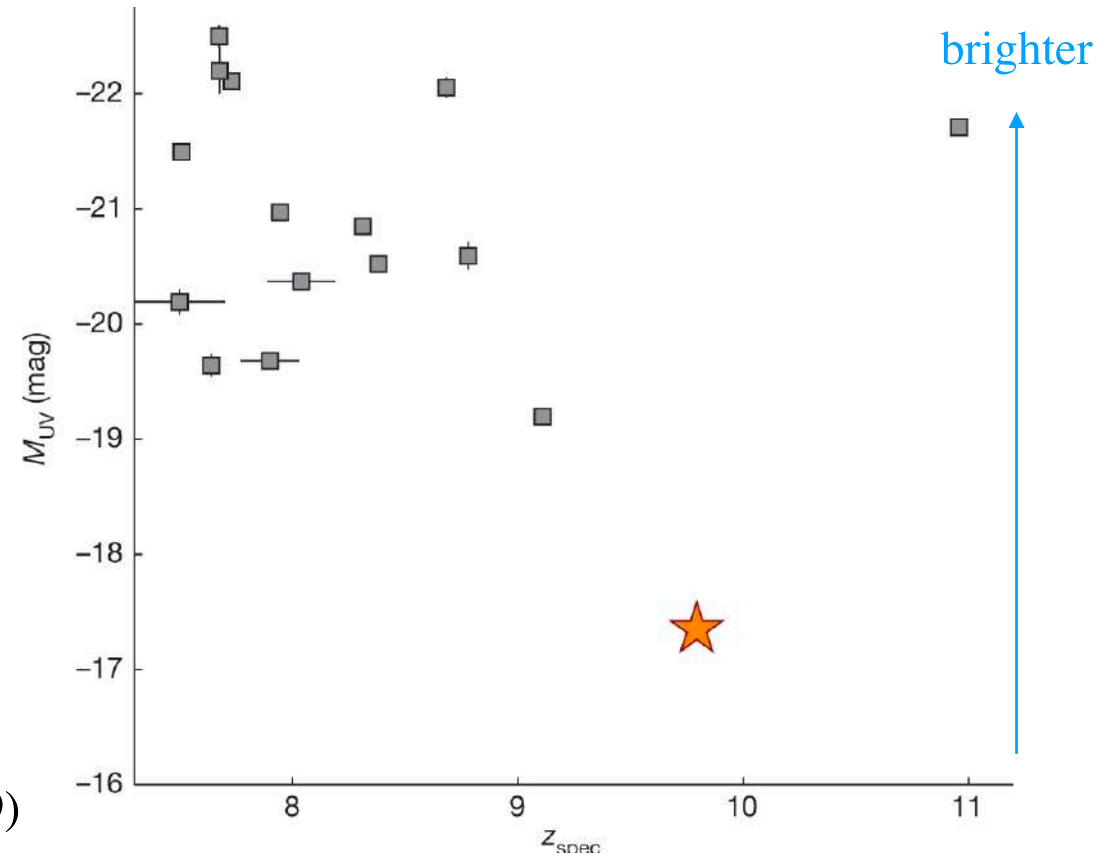
Castellano …, Yang, et al. 2022
Yang et al.2022

Discovery 1 ultra-faint early galaxy

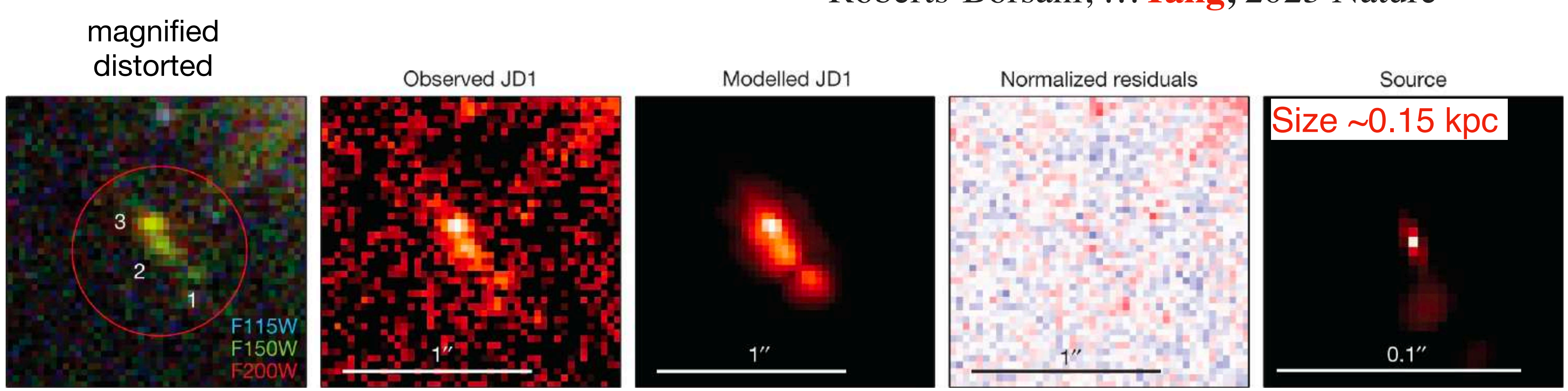
With gravitational lensing



ultra-faint galaxy (M_{UV} = −17.35, z=9.79)

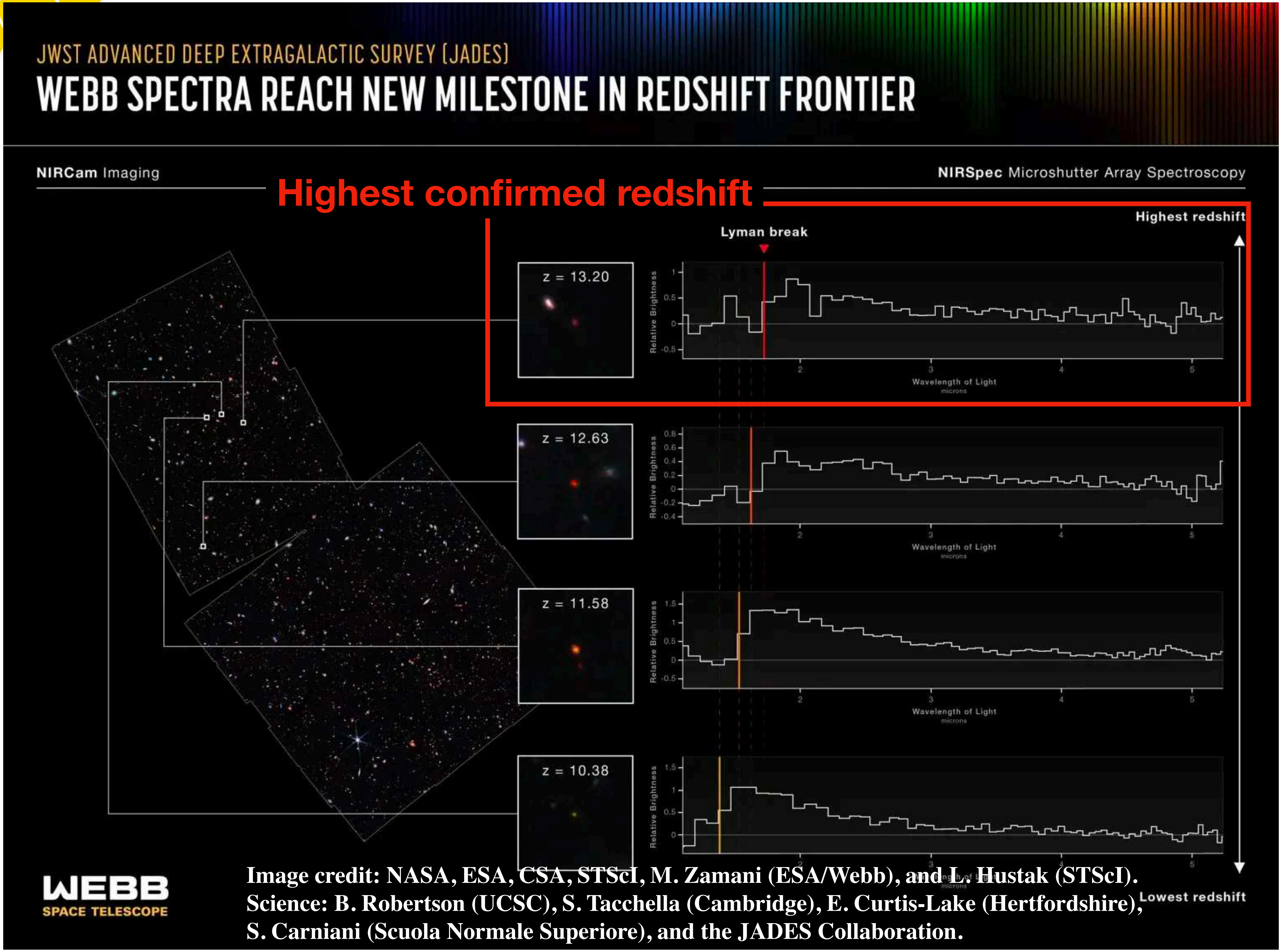


Roberts-Borsani, …**Yang,** 2023 Nature



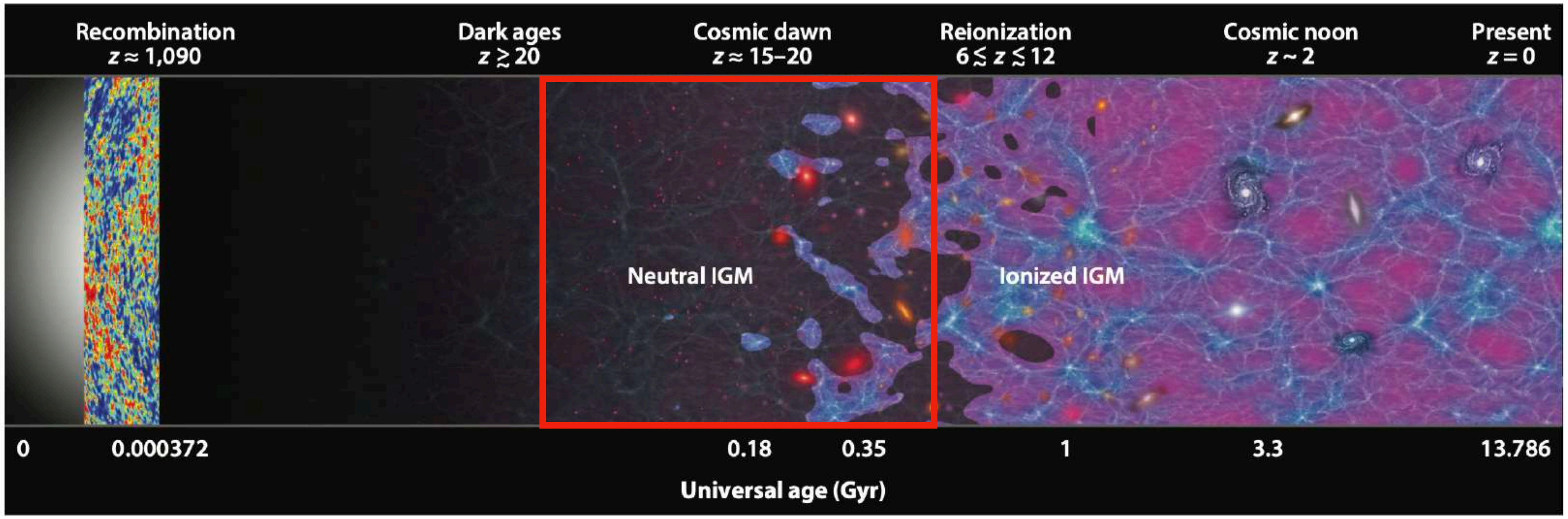
Lensed image is reconstructed by **Lenstruction**, **Yang et al 2020**

Spectroscopically redshift z=13.20



JADES-GS-z13-0 spectroscopically confirmed redshift 13.20

Key Questions List



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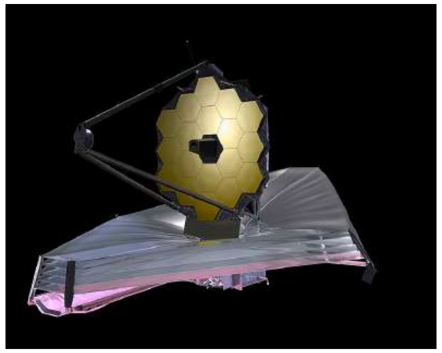
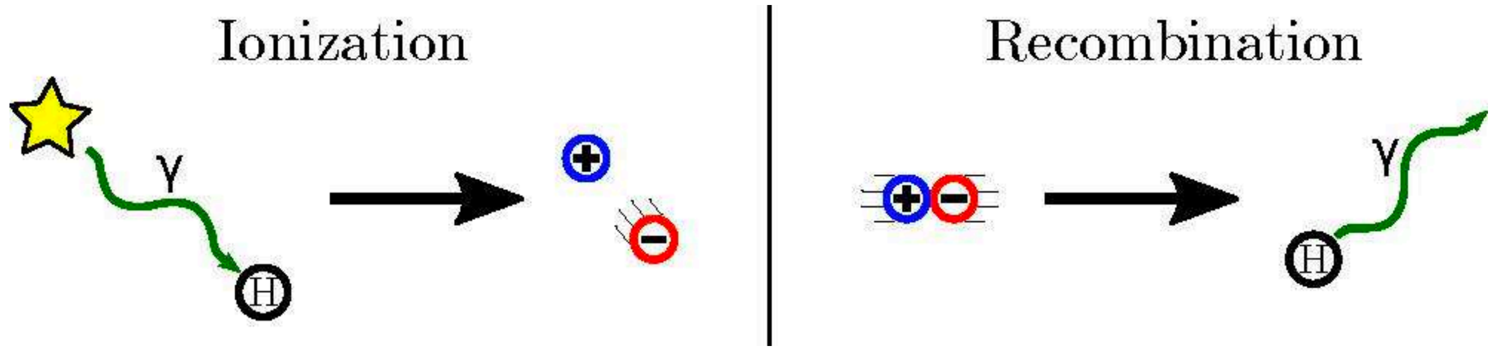
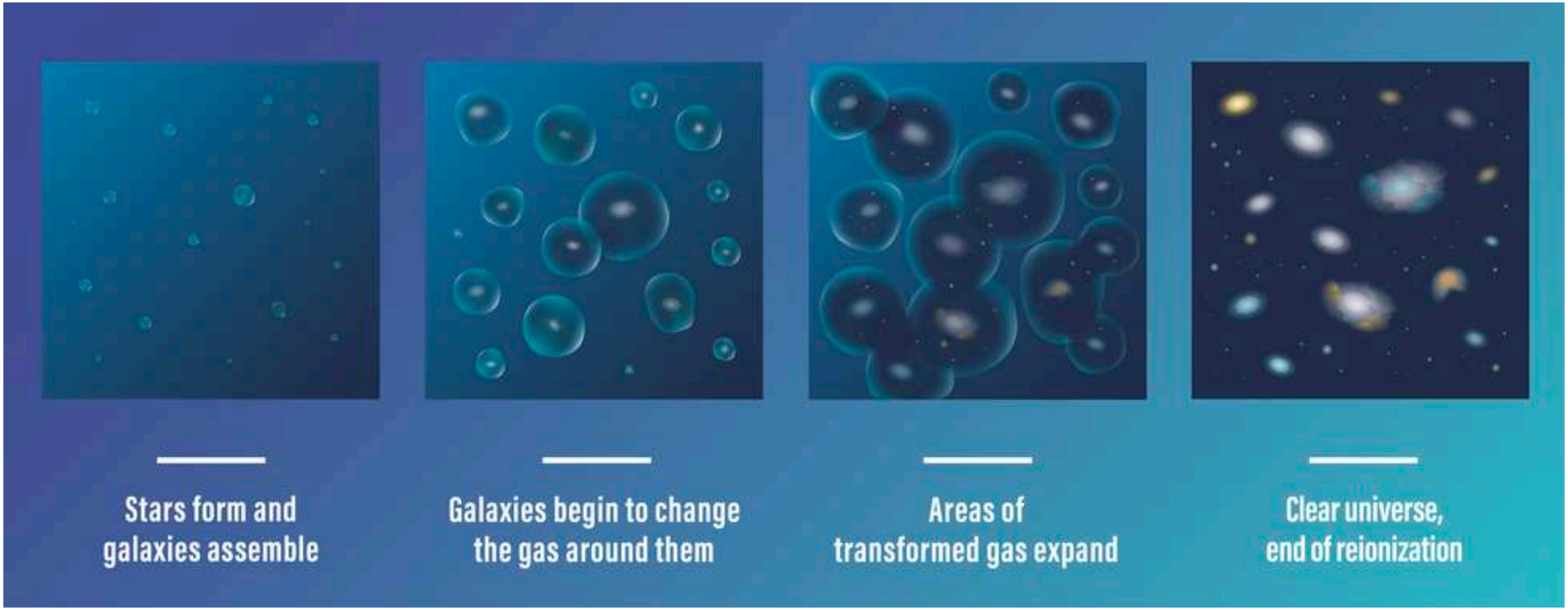


Galaxies Transformed the Early Universe

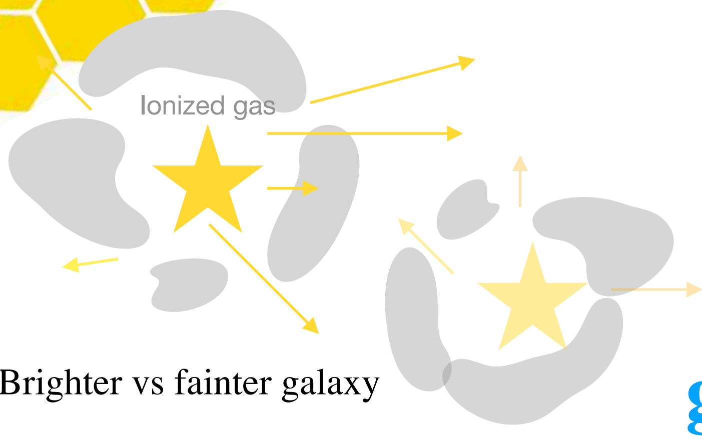


Wise 2019



Credits: NASA, ESA, CSA, Joyce Kang (STScI)

Production of ionizing photons



Brighter vs fainter galaxy

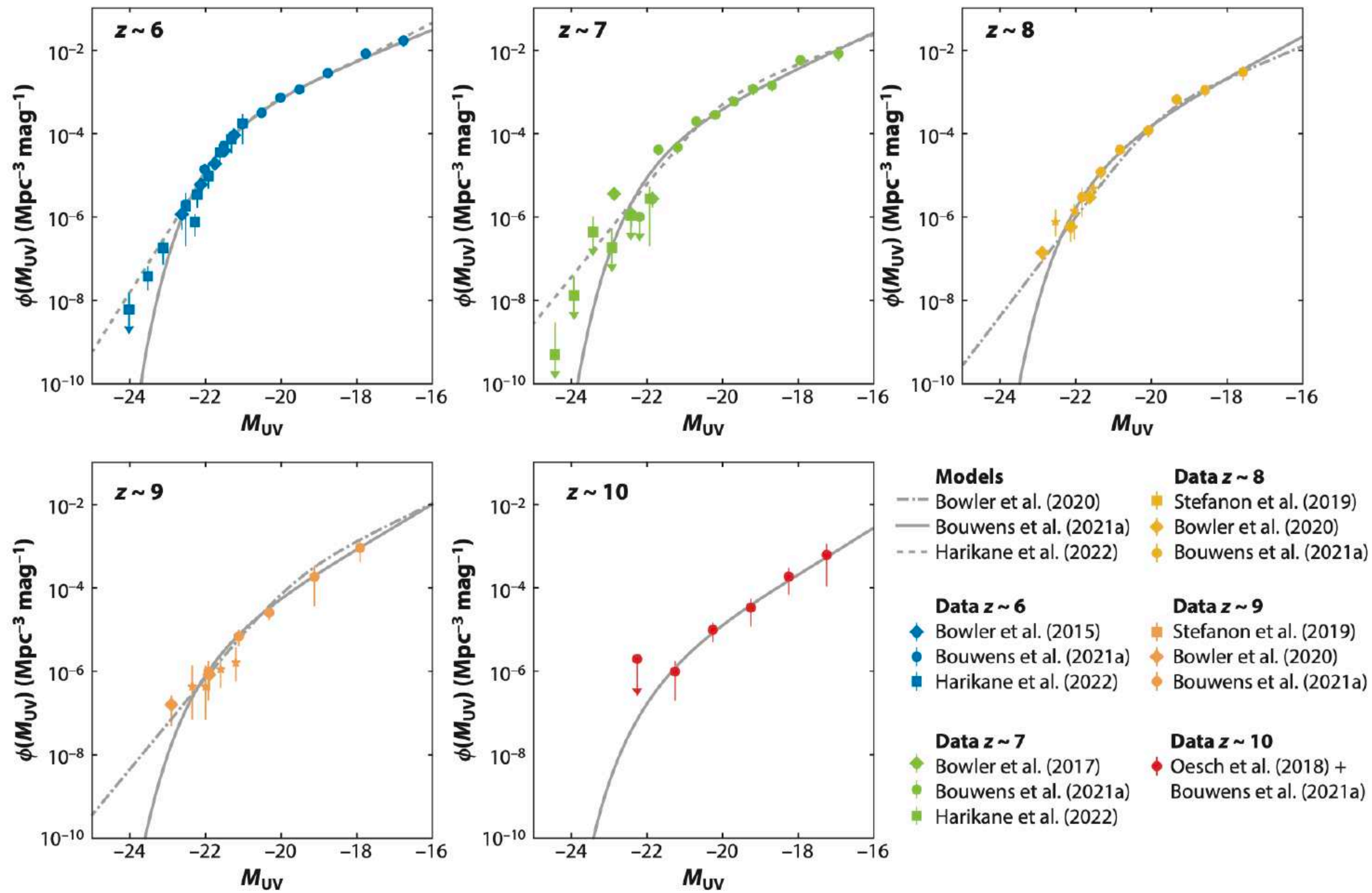
$$\dot{n}_{ion} = f_{esc}\, \xi_{ion}\, \rho_{UV}$$

total UV luminosity density

production efficiency

photons escaping rate

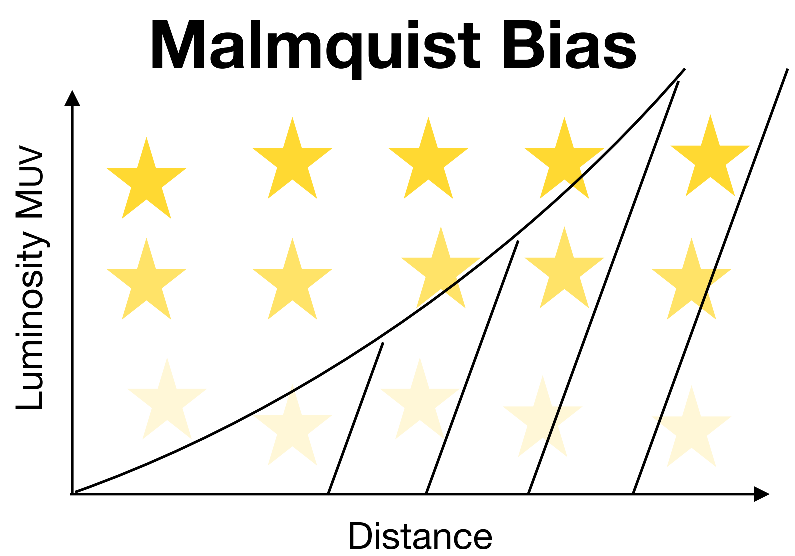
ground-based and Hubble UVLF



Robertson 2022

Determine the shape of UVLF

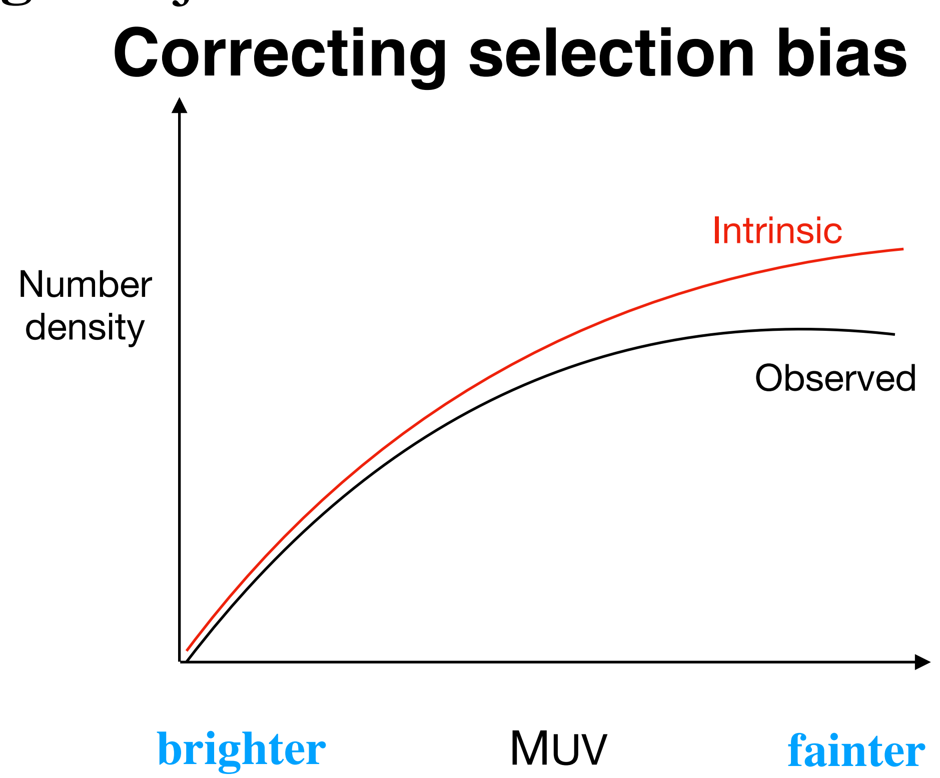
Correcting selection bias



preferential detection
of intrinsically **bright** objects

higher surface brightness

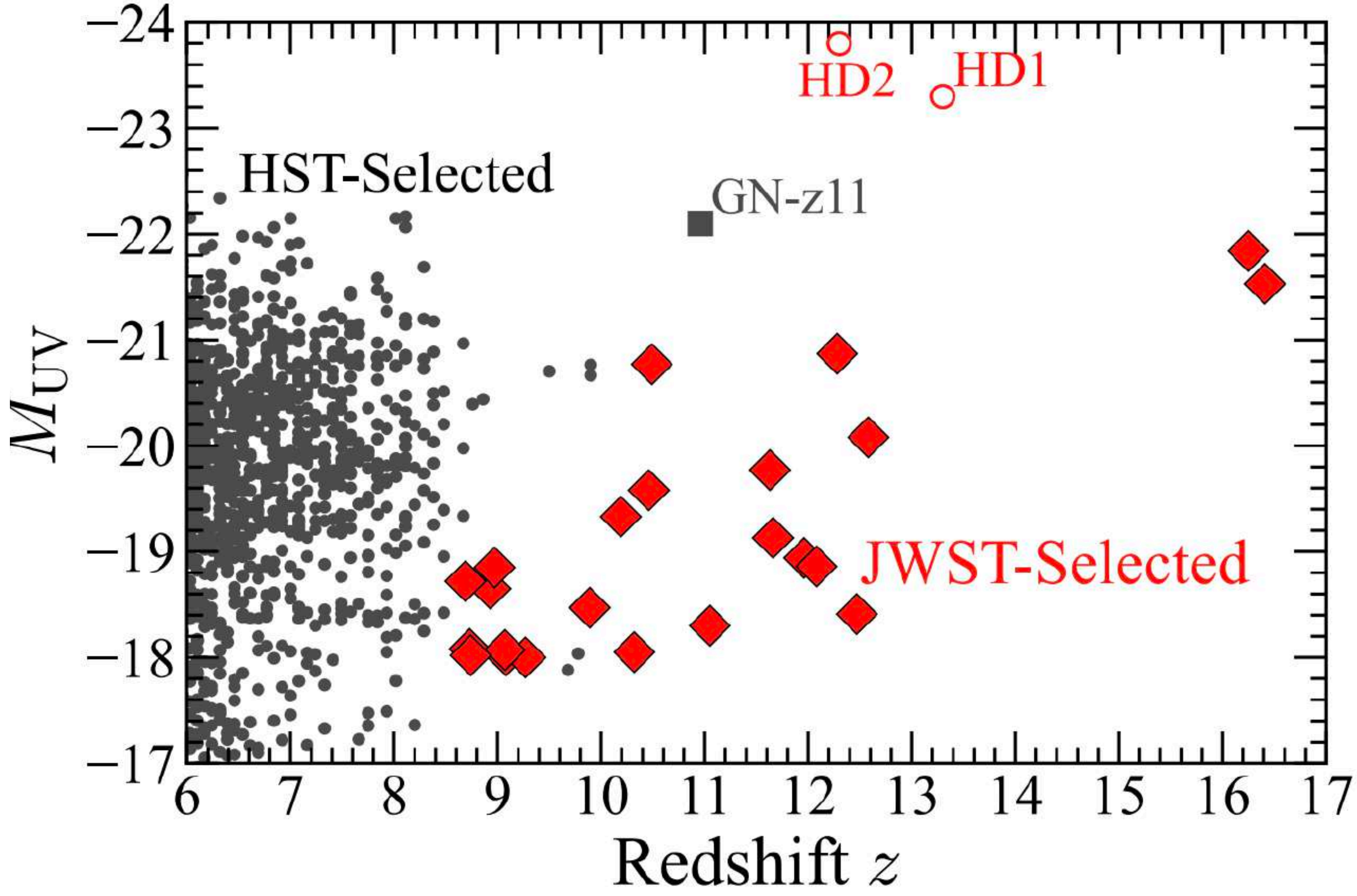
Given luminosity,
smaller size are easier to be observed



UVLF using JWST data

Updated of UVLF at bright-end

Field	F115W dropouts $z \sim 9$	F150W dropouts $z \sim 12$	F200W dropouts $z \sim 16$
SMACS J0723	⋯	1	0
GLASS	13	1	0
CEERS1	⋯	0	0
CEERS2	⋯	4	1
CEERS3	⋯	1	0
CEERS6	⋯	0	0
Stephan's Quintet	⋯	1	1
Total (z)	13	8	2
Total		23	



Harikane et al.2023

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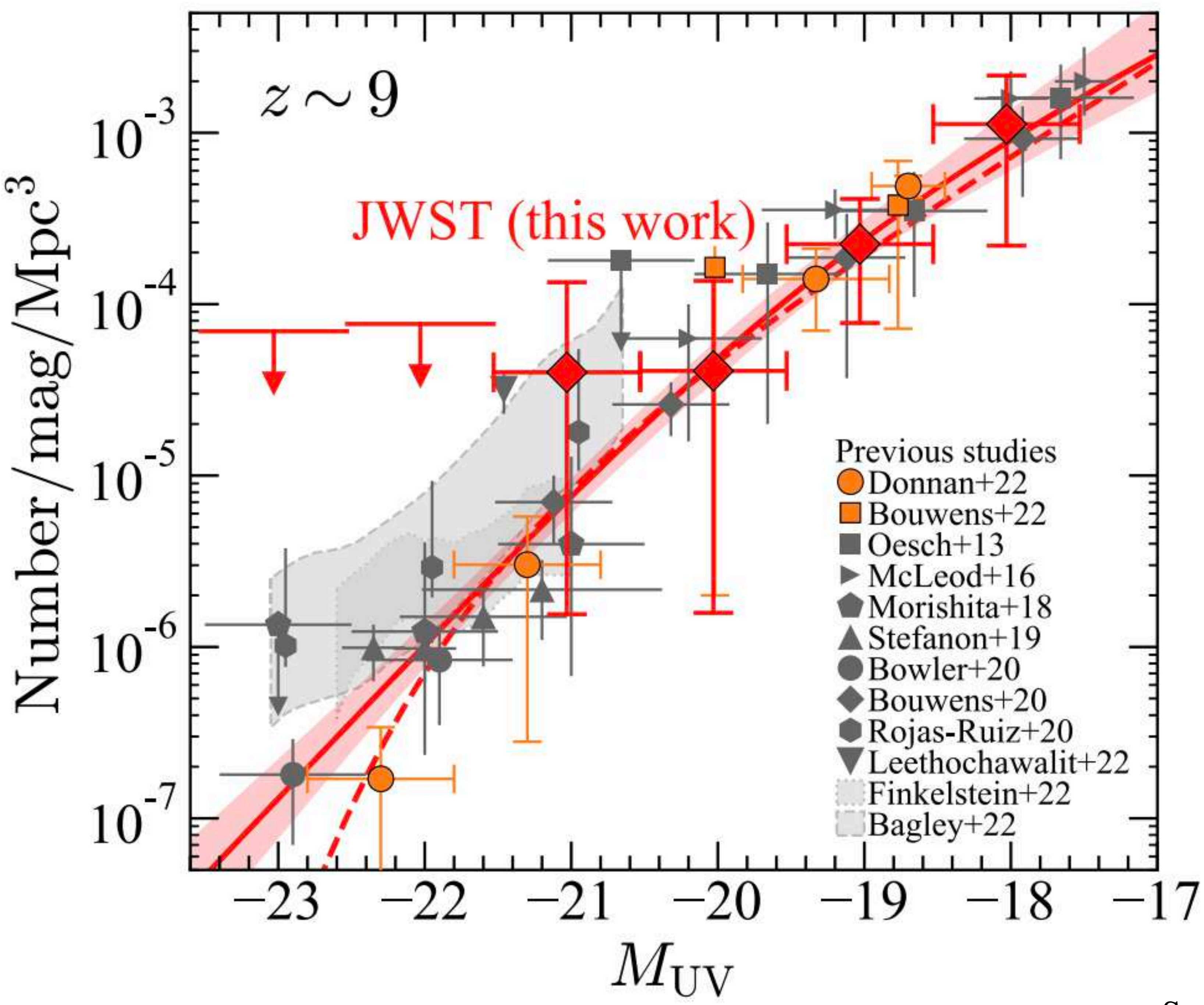
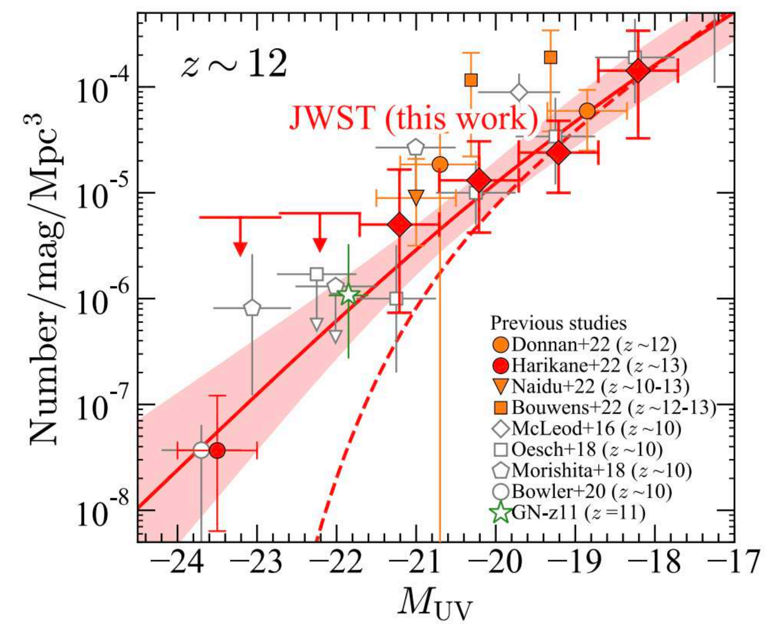
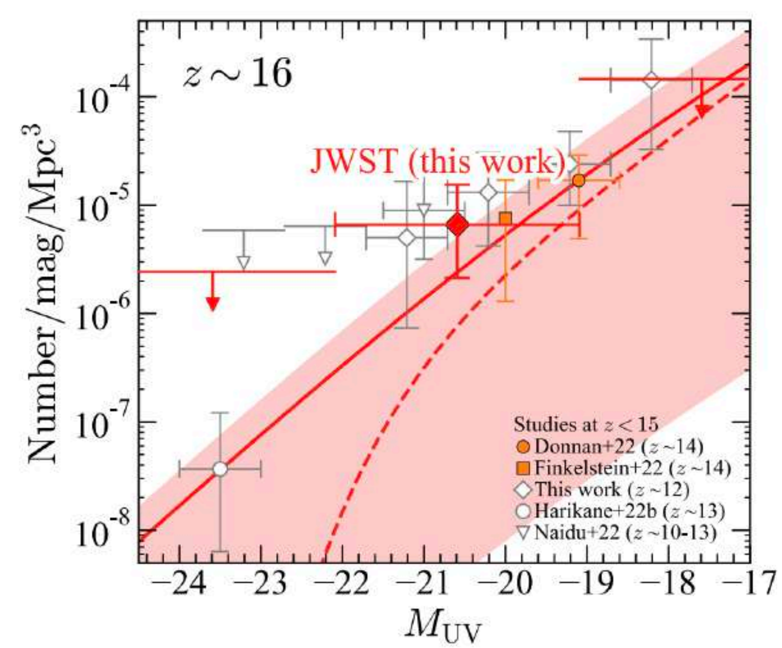


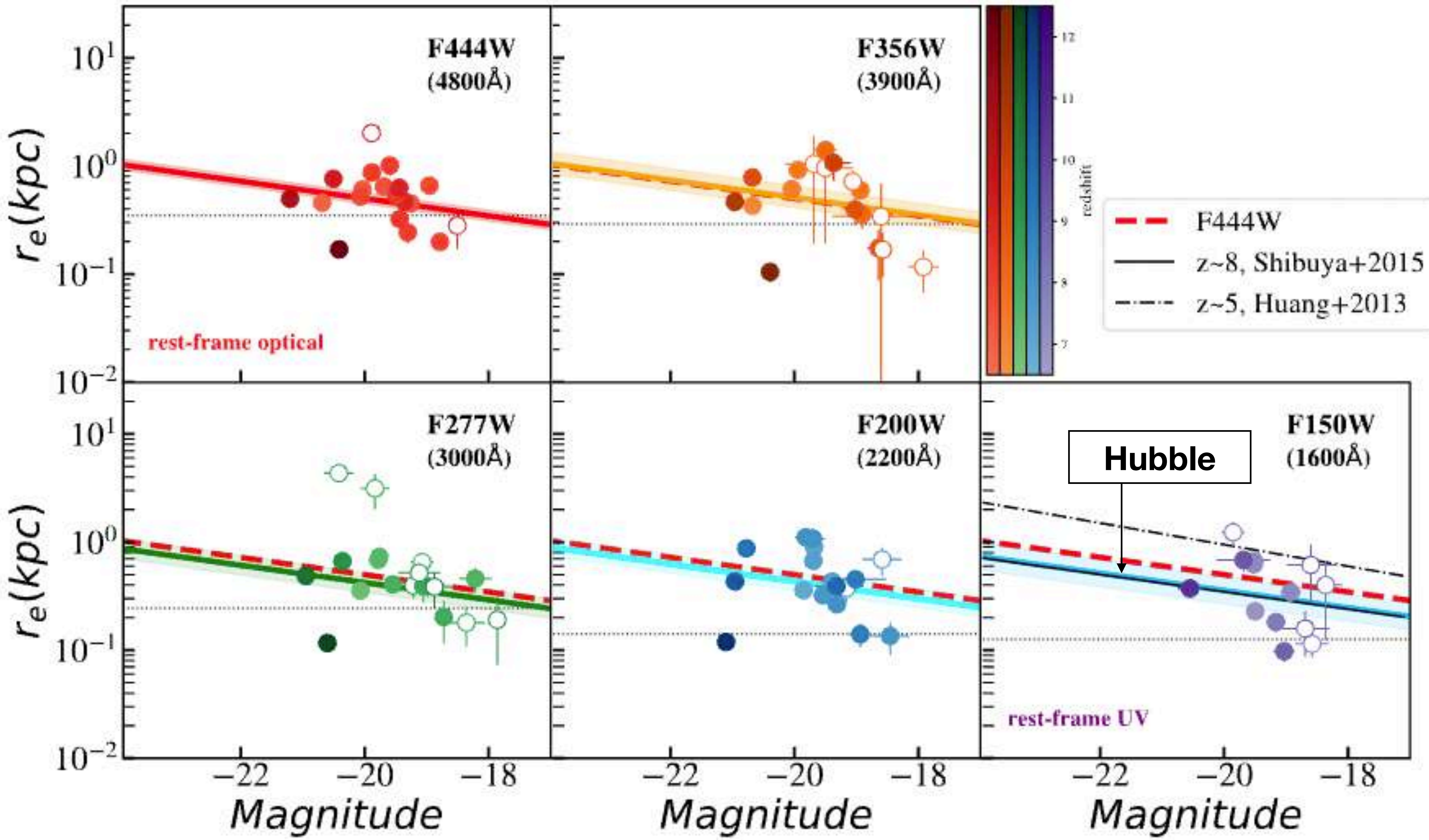




See also Bouwens et al. 2022; Donnan et al. 2023; Finkelstein et al. 2022; Naidu et al. 2022

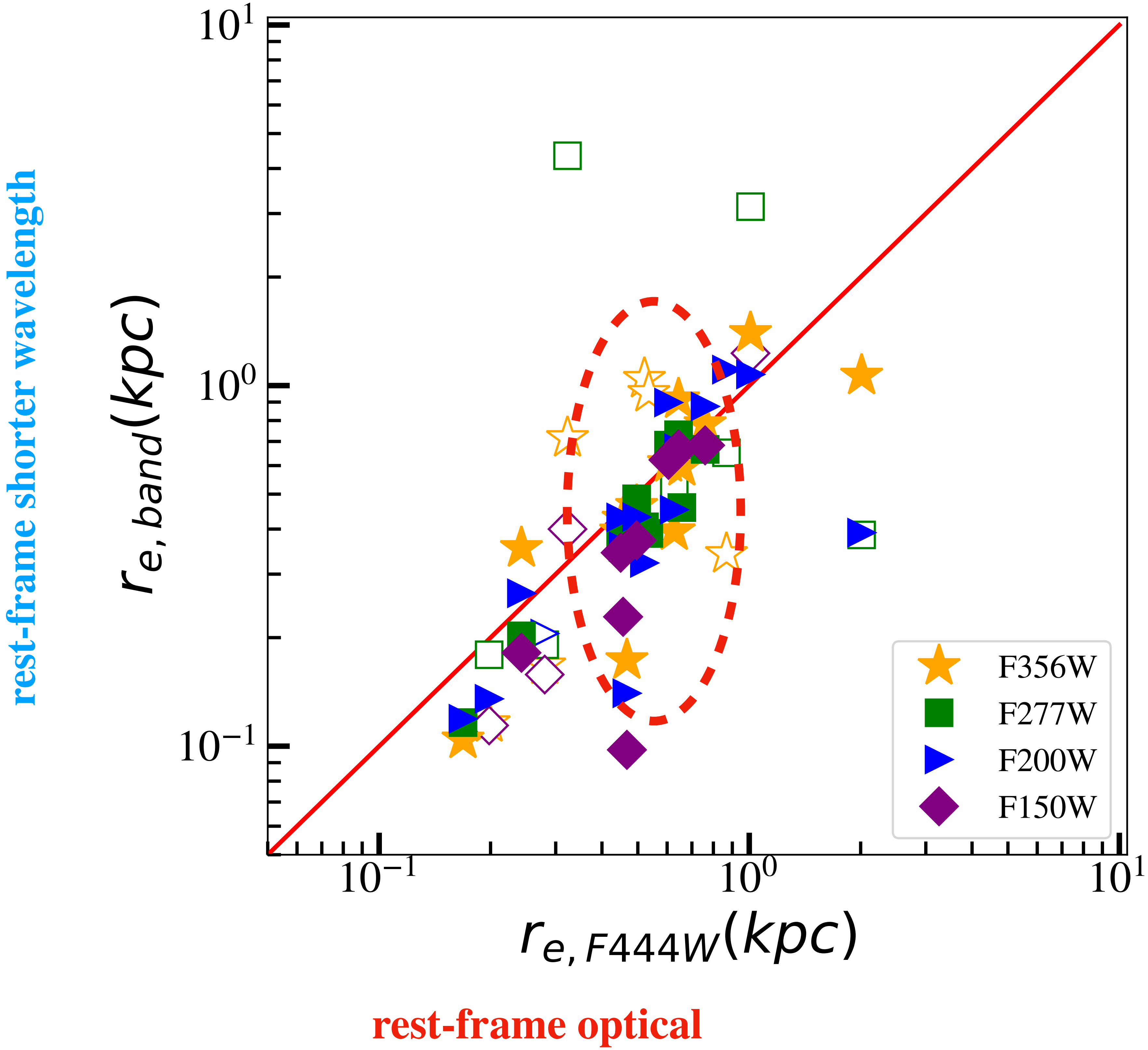
The first optical band Size-L relation

Updated of size-L at bright-end



Yang et al. 2022

Sizes of early galaxies z~7-13

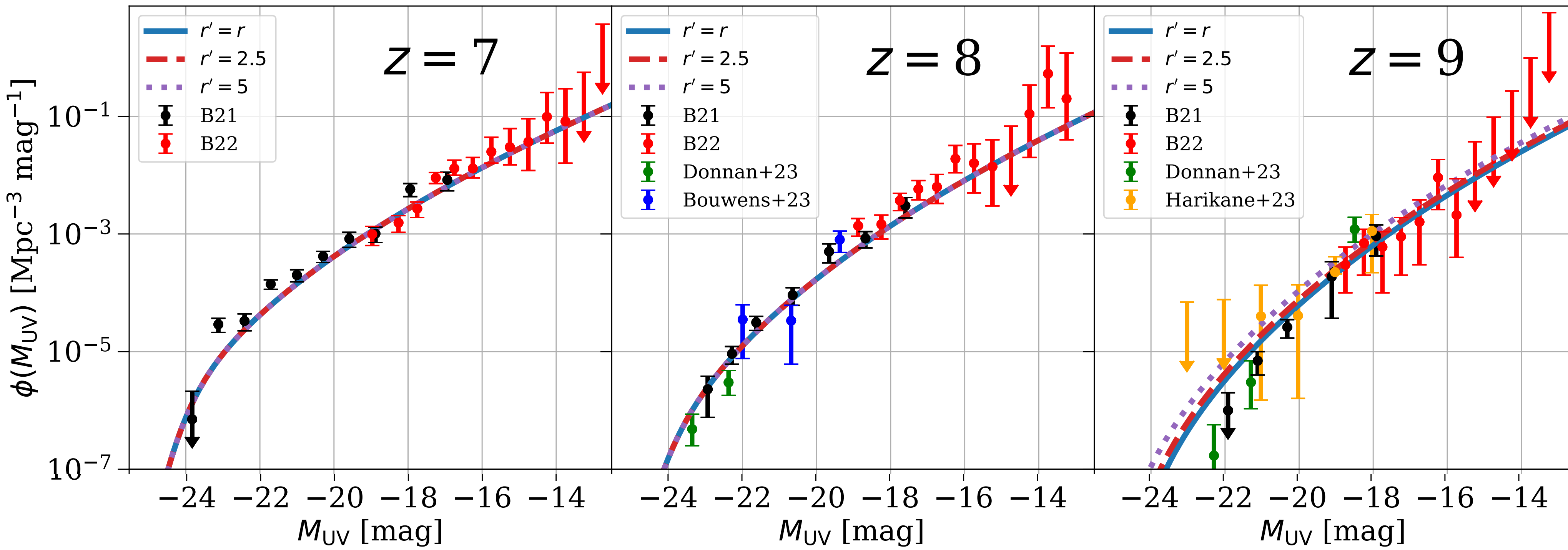


size is roughly
0.45-0.6 kpc
at the MUV=-21

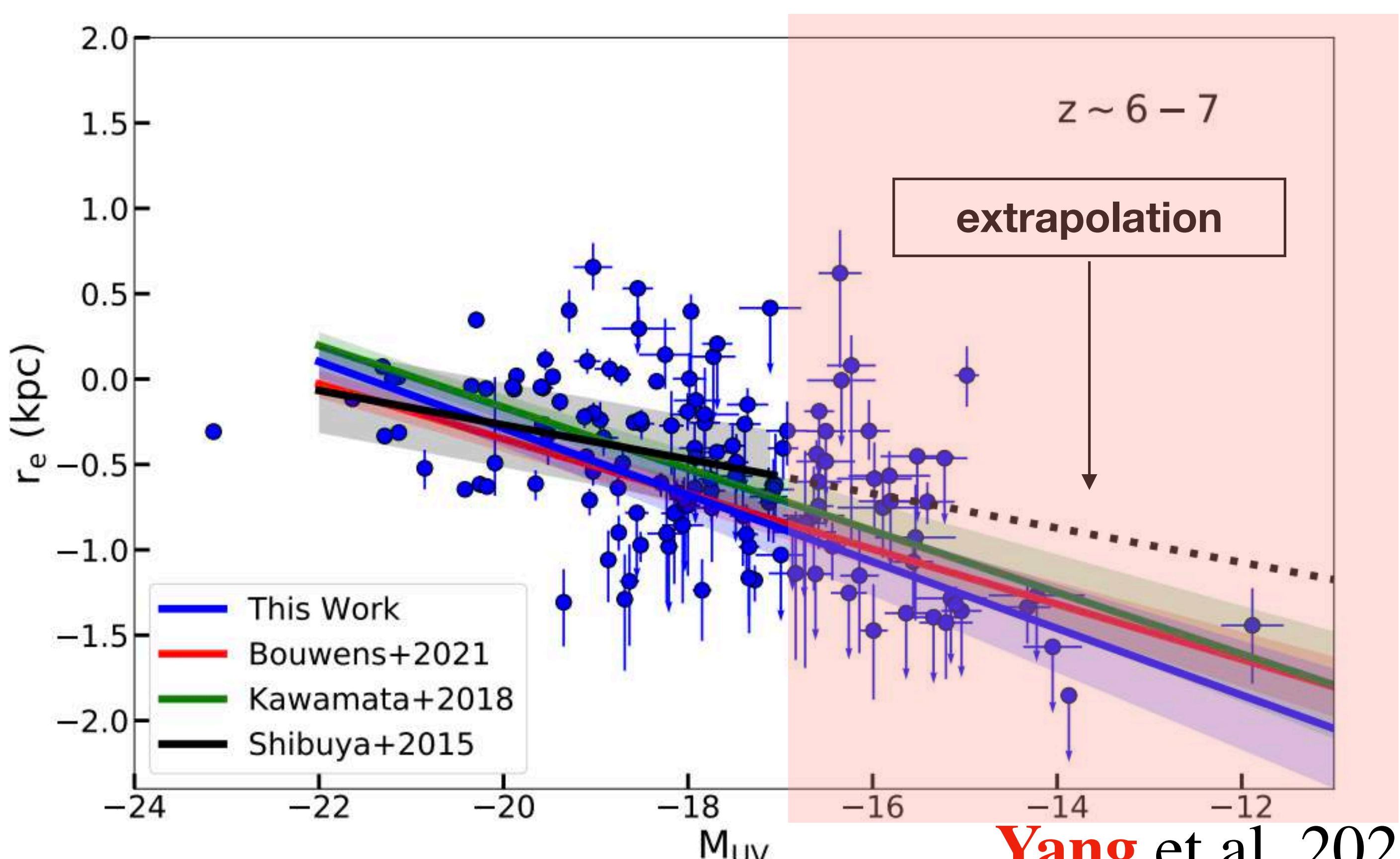
Yang et al. 2022

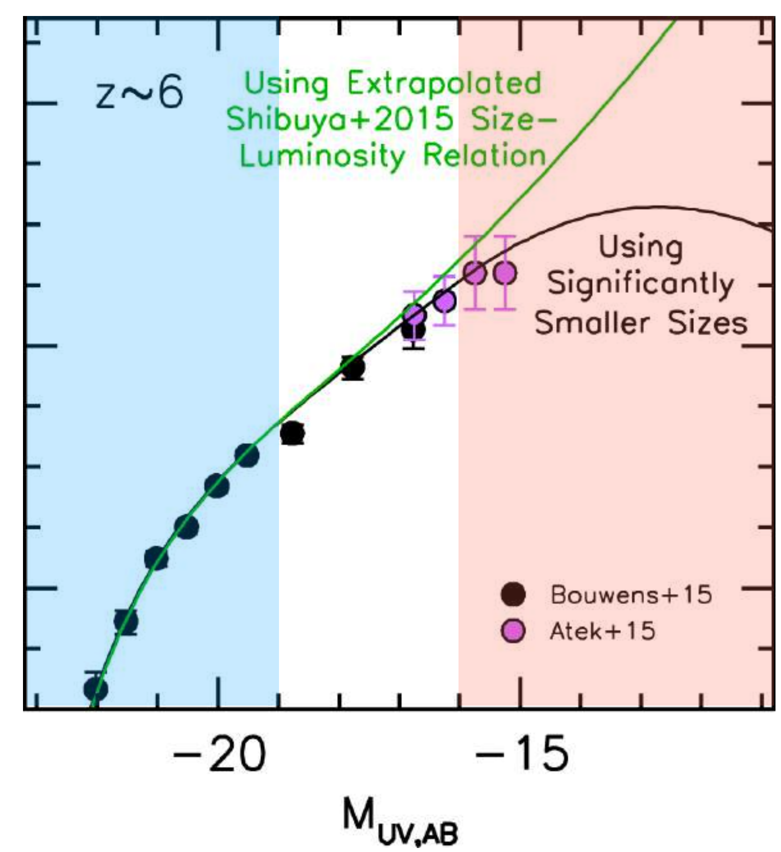
Faint galaxies observed via strong lensing

red points are Hubble lensed galaxies



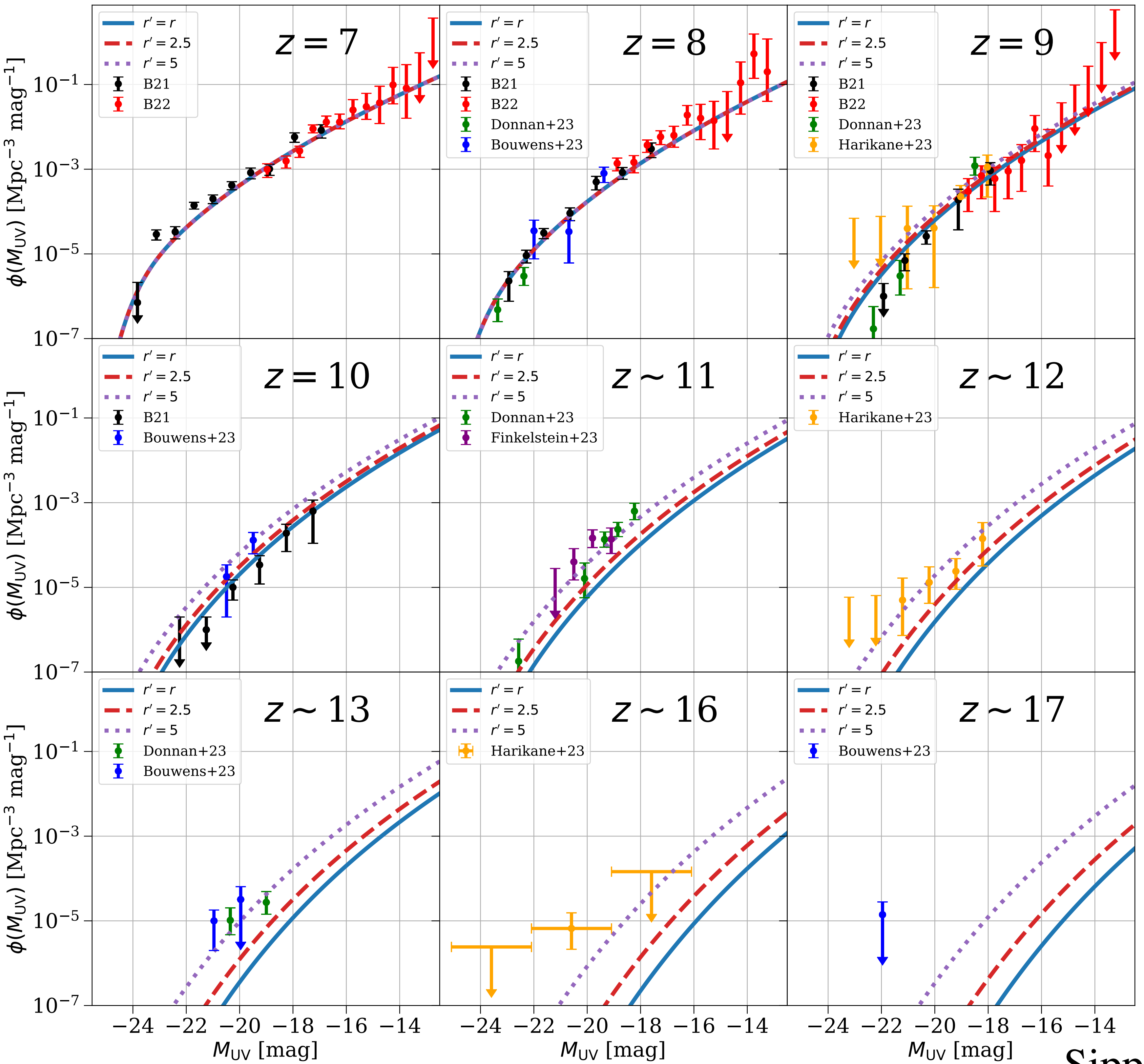
Bouwens et al. 2022
Sipple & Lidz, 2023





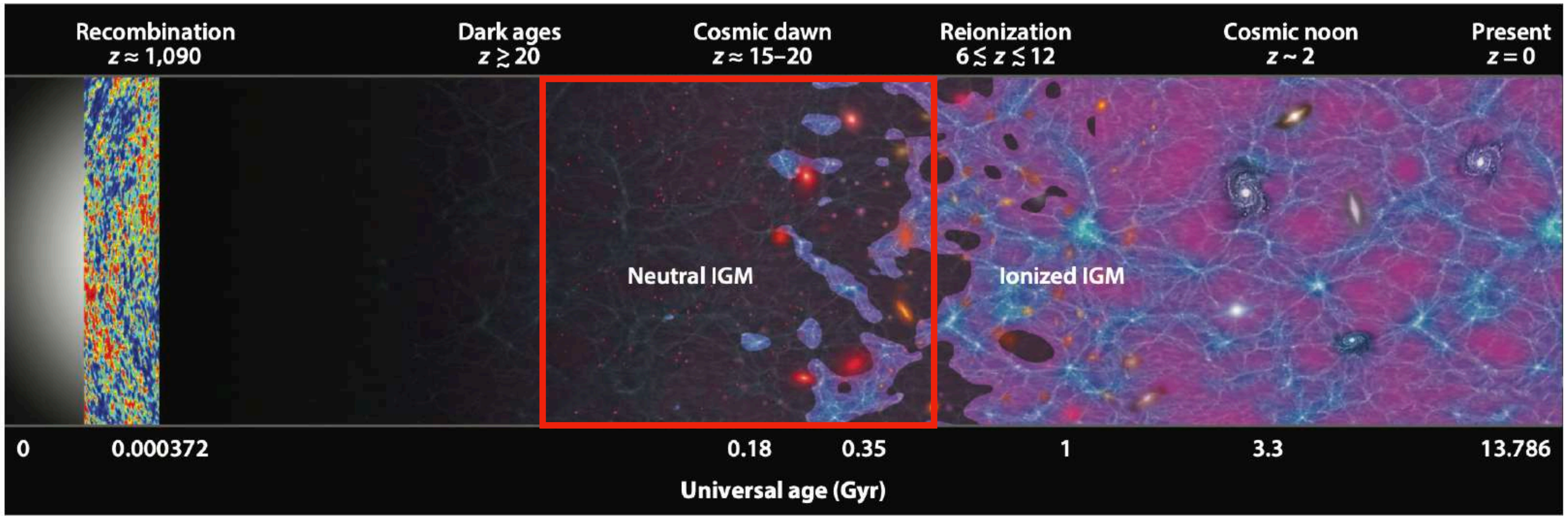
Yang et al. 2022

Overview of UV luminosity function



Sipple & Lidz, 2023

Key Questions List



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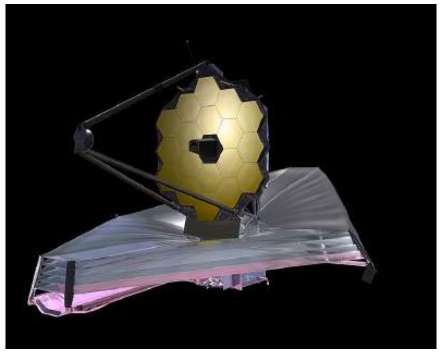
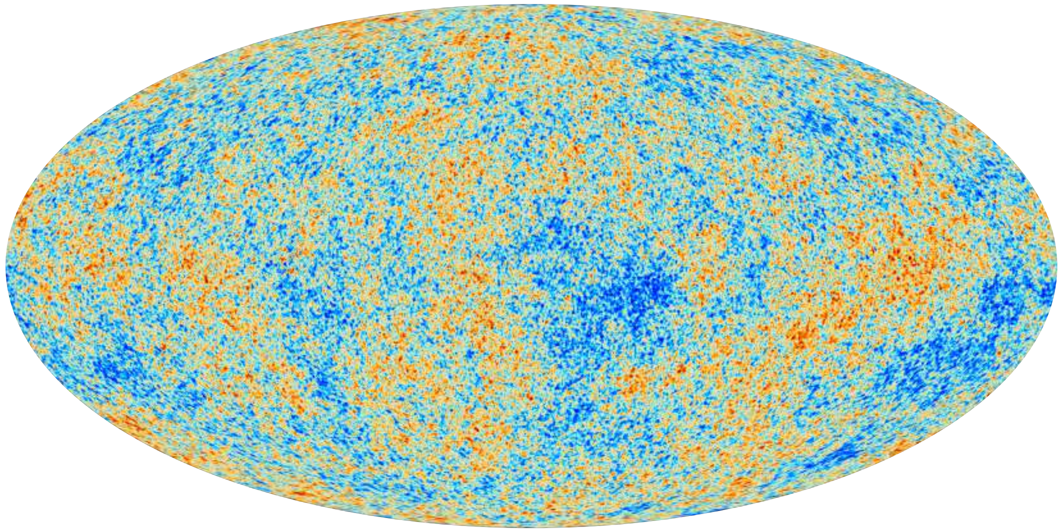
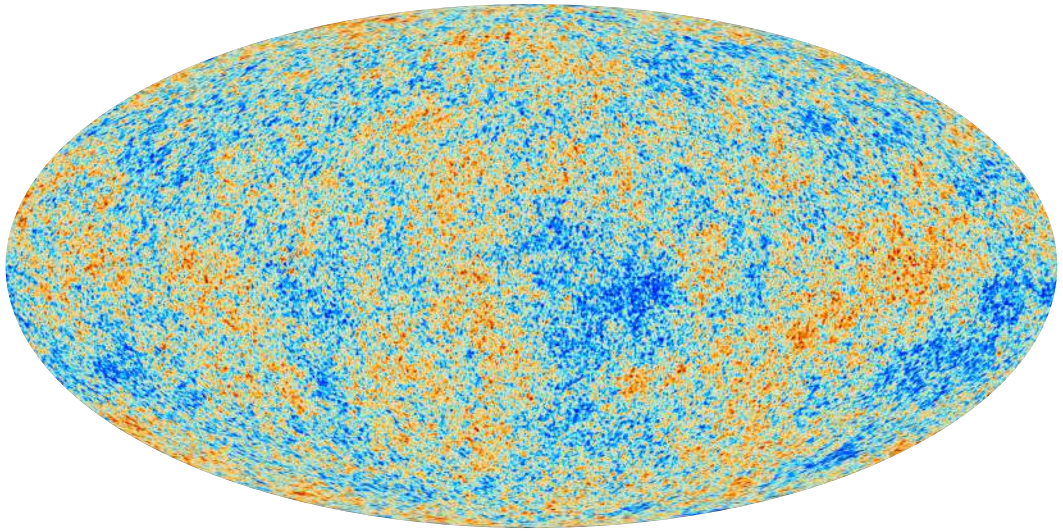




$$\langle \delta_{\rm T}^2 \rangle^{1/2} \sim 10^{-5}$$

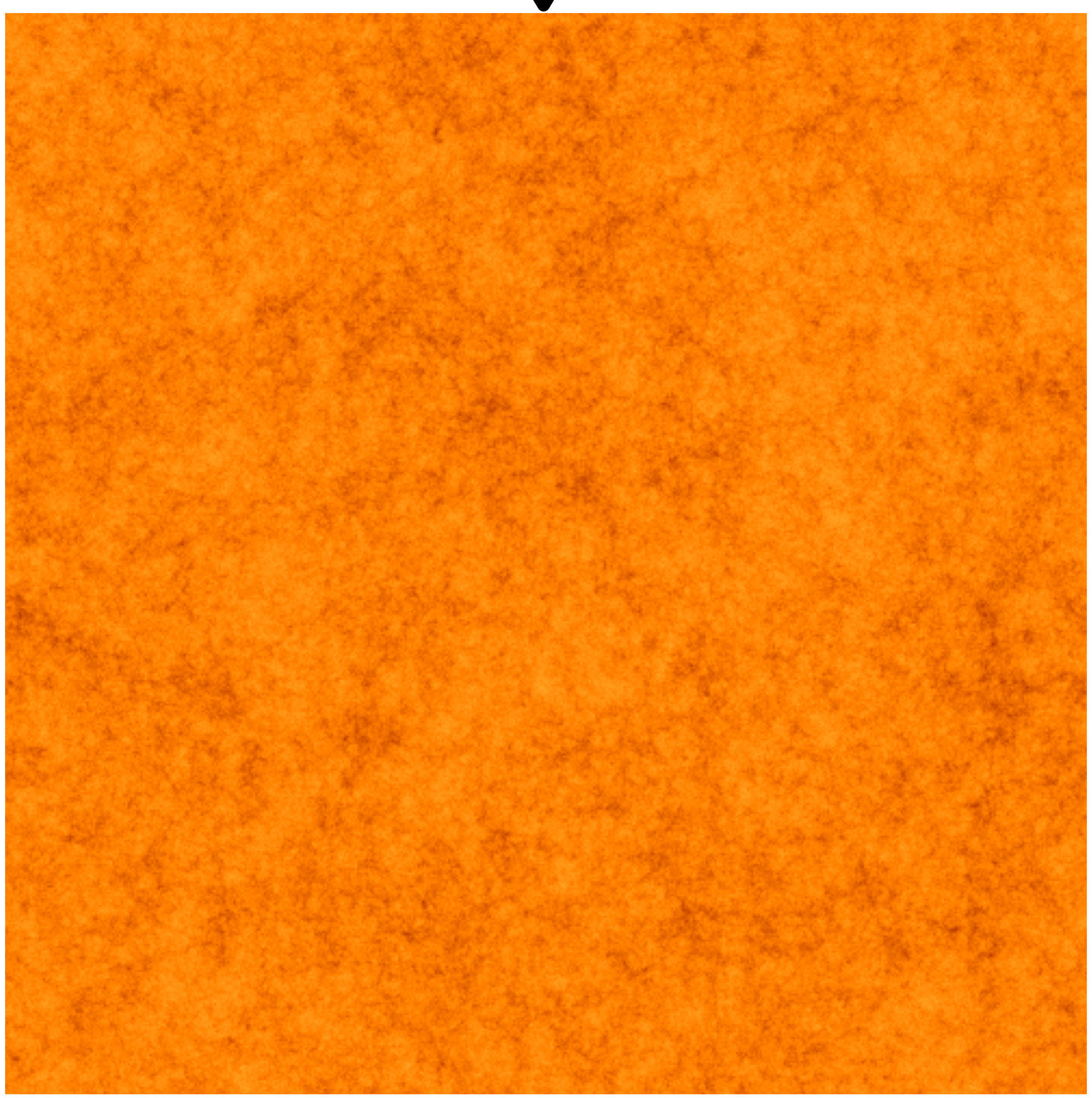
$\rho_{\rm b}, \rho_{\rm c}, n_{\rm s}, A_{\rm s}, \theta_\star, \tau$

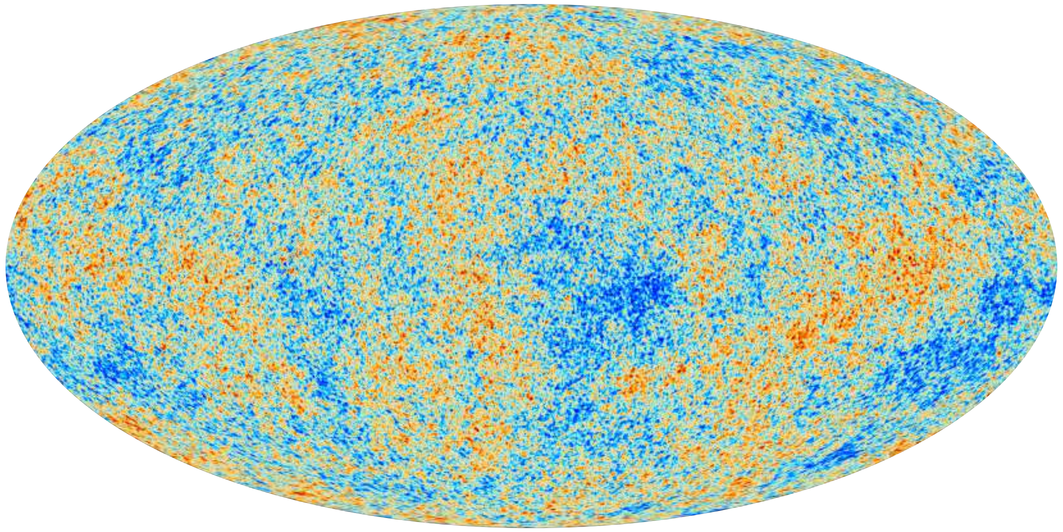


$$\langle \delta_{\mathrm{T}}^2 \rangle^{1/2} \sim 10^{-5}$$

$$\rho_{\mathrm{b}}, \rho_{\mathrm{c}}, n_{\mathrm{s}}, A_{\mathrm{s}}, \theta_{\star}, \tau$$

$z = 127$

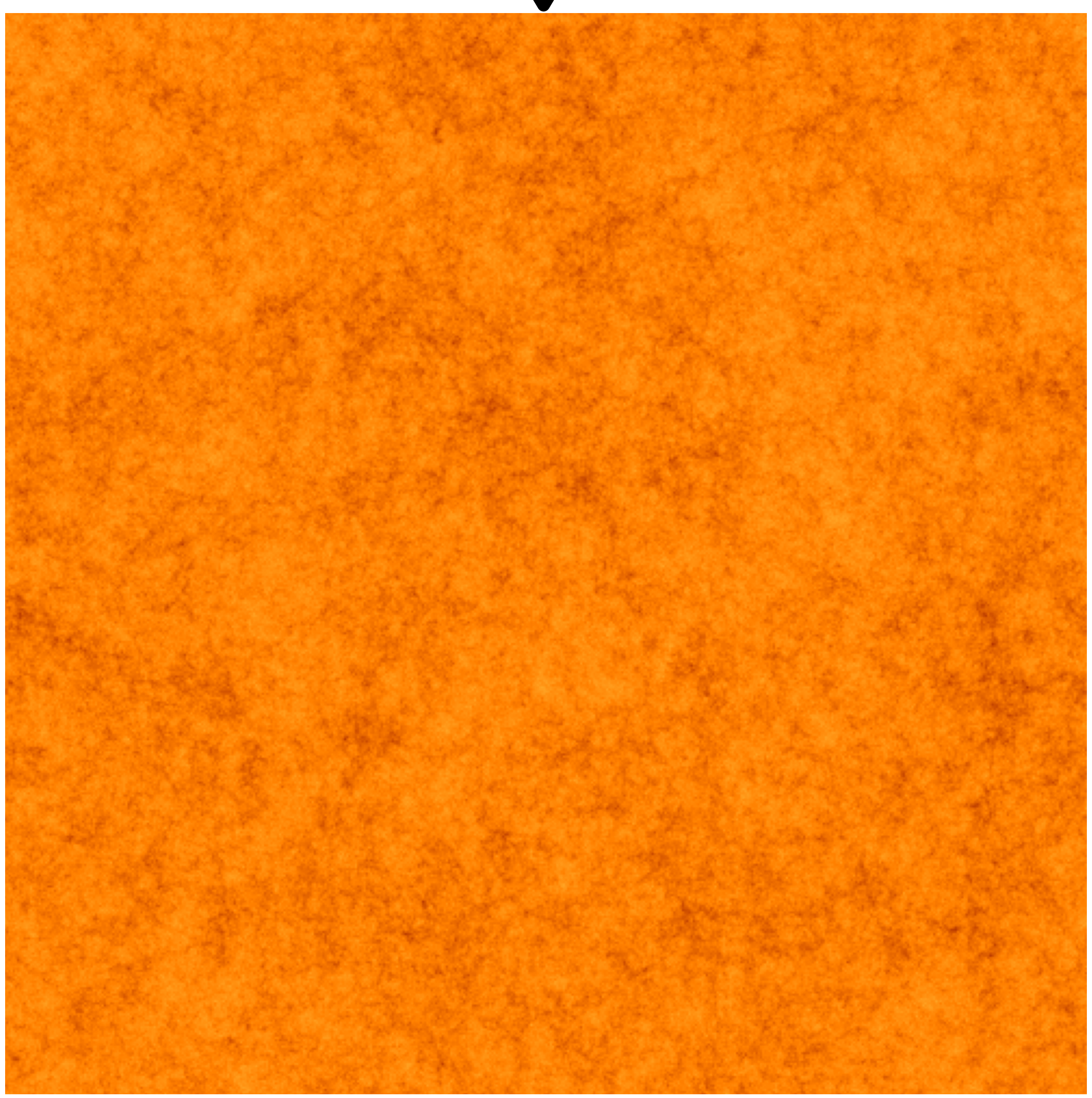




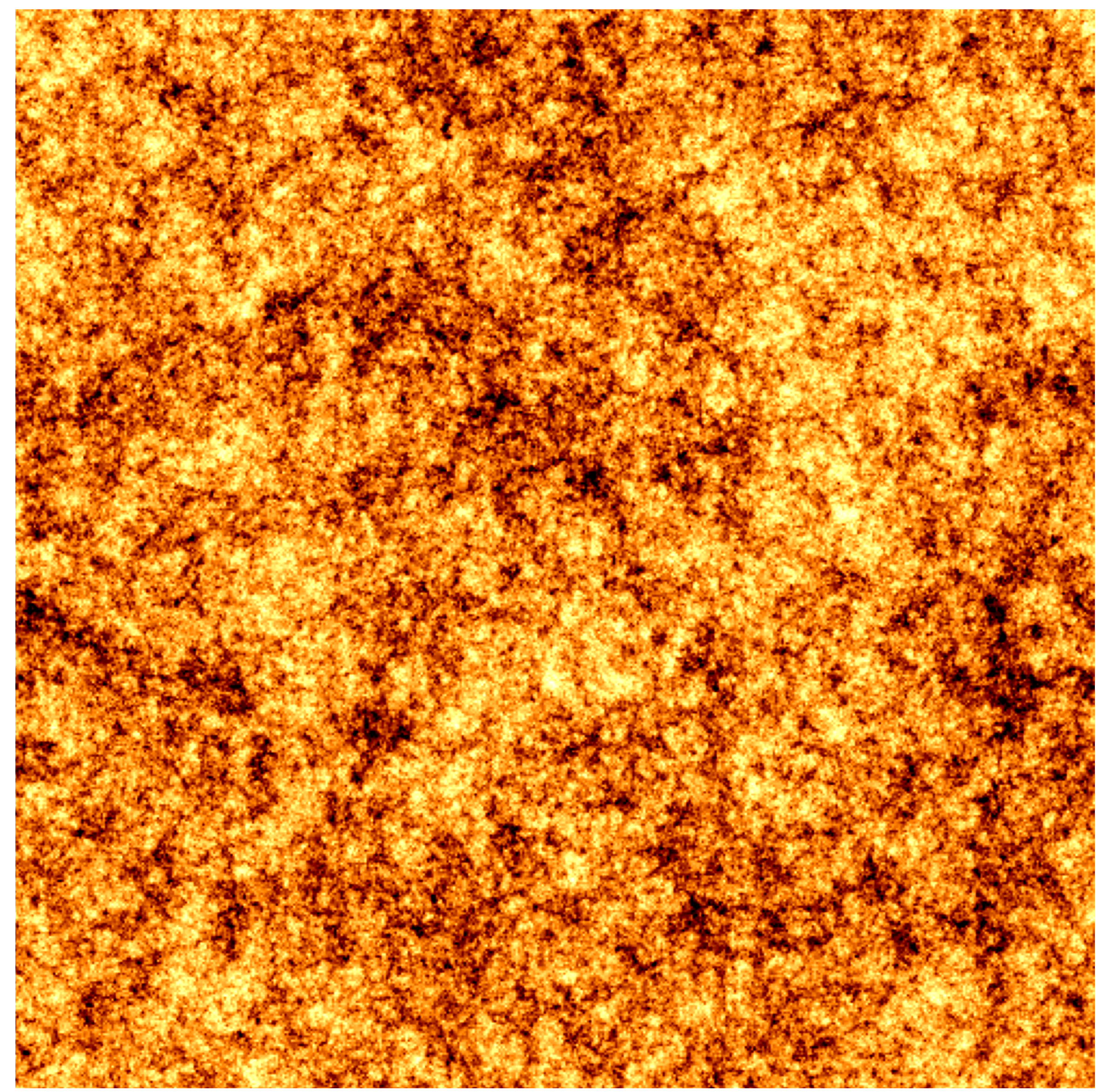
$$\langle \delta_T^2 \rangle^{1/2} \sim 10^{-5}$$

$\rho_b, \rho_c, n_s, A_s, \theta_\star, \tau$

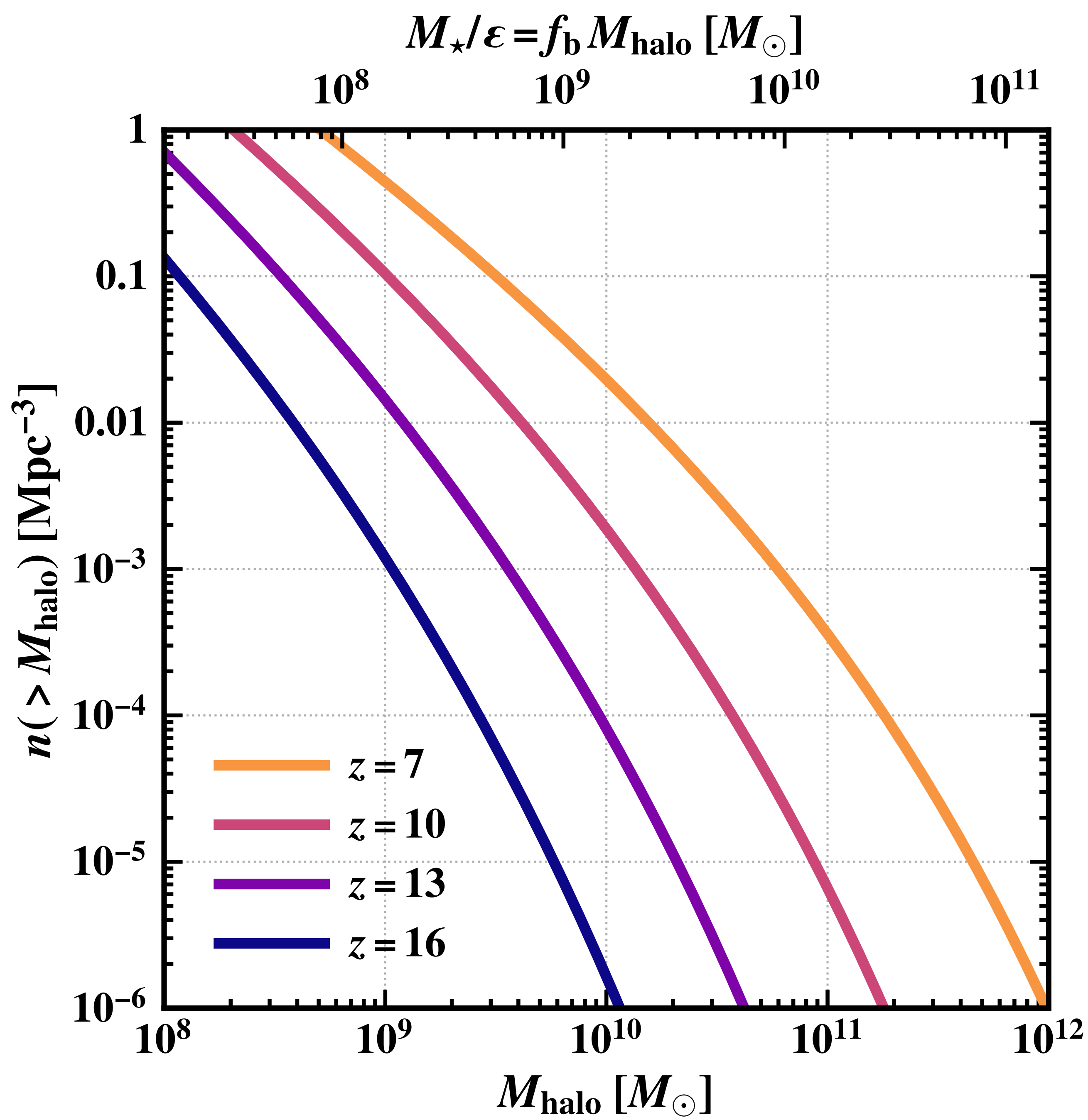
$z = 127$



$z = 0$



From density fluctuations to dark matter halos



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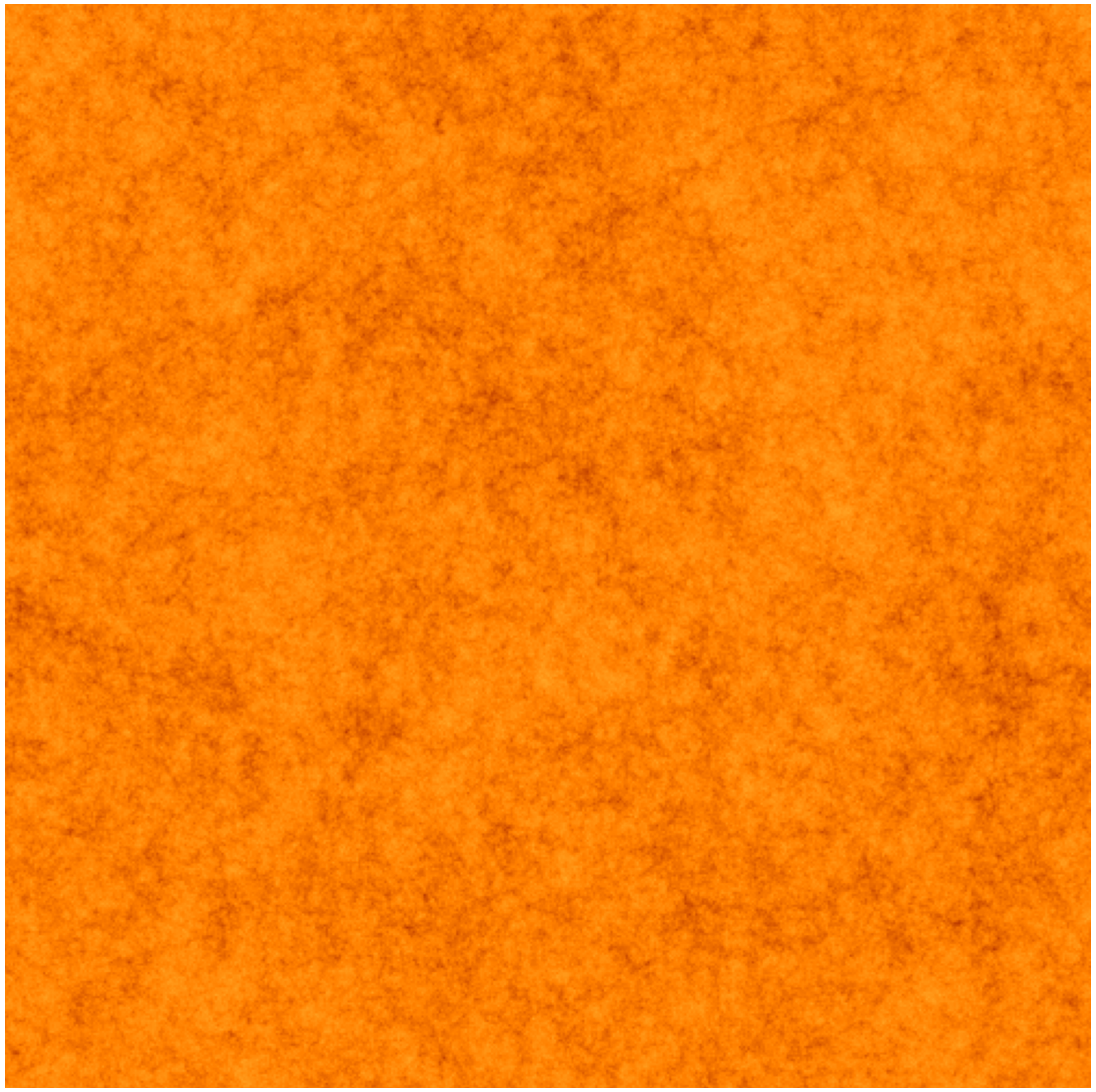
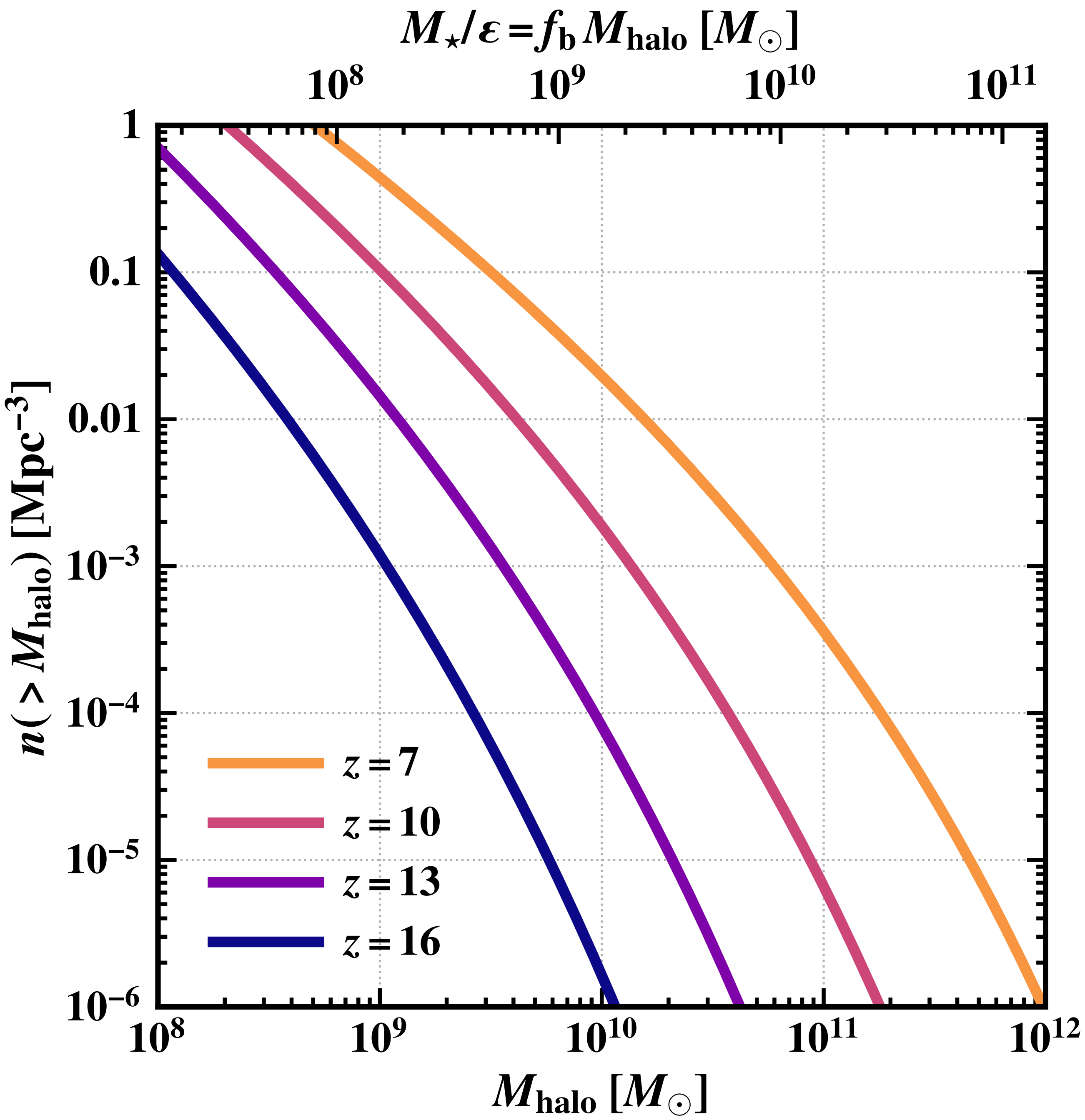
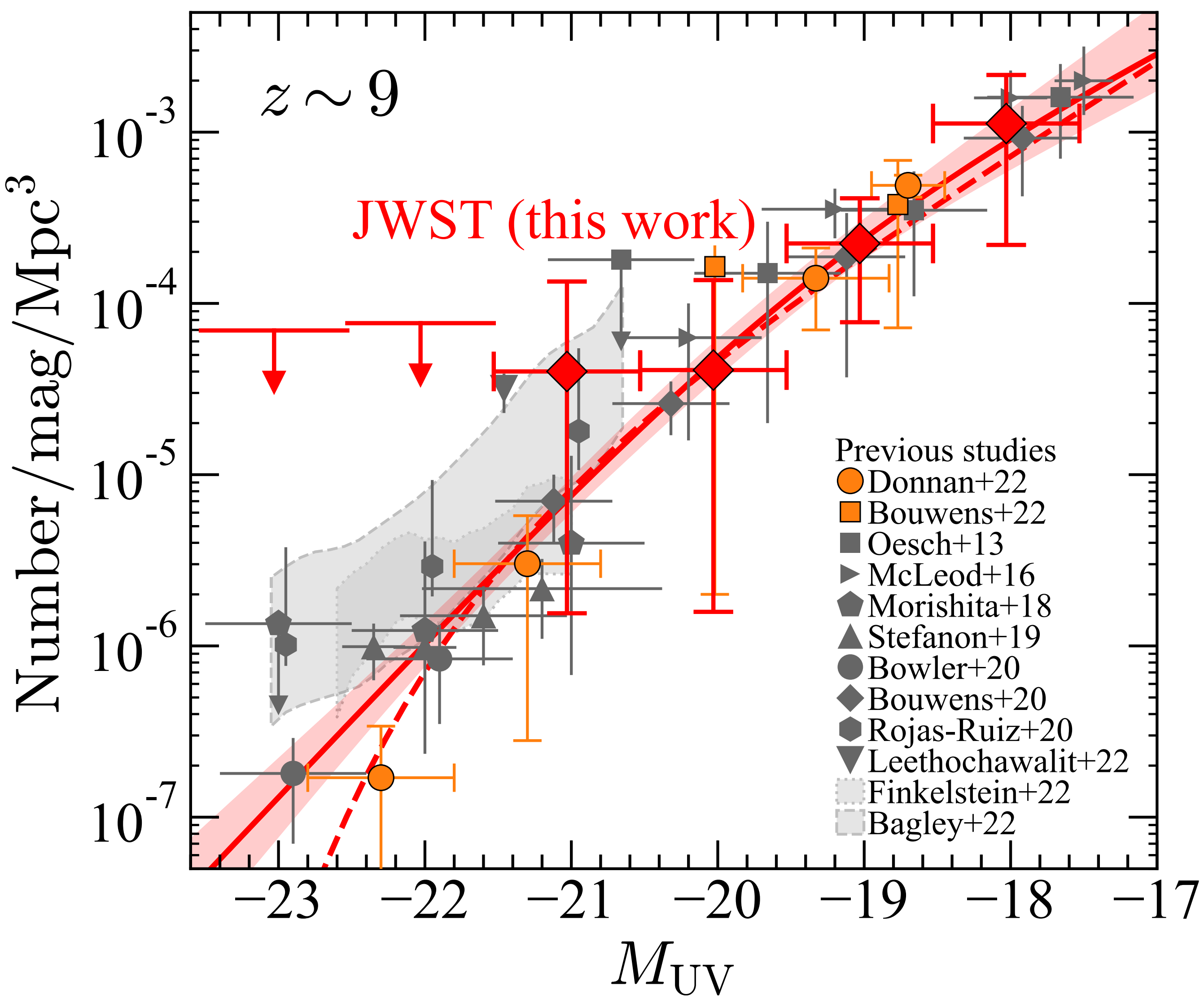


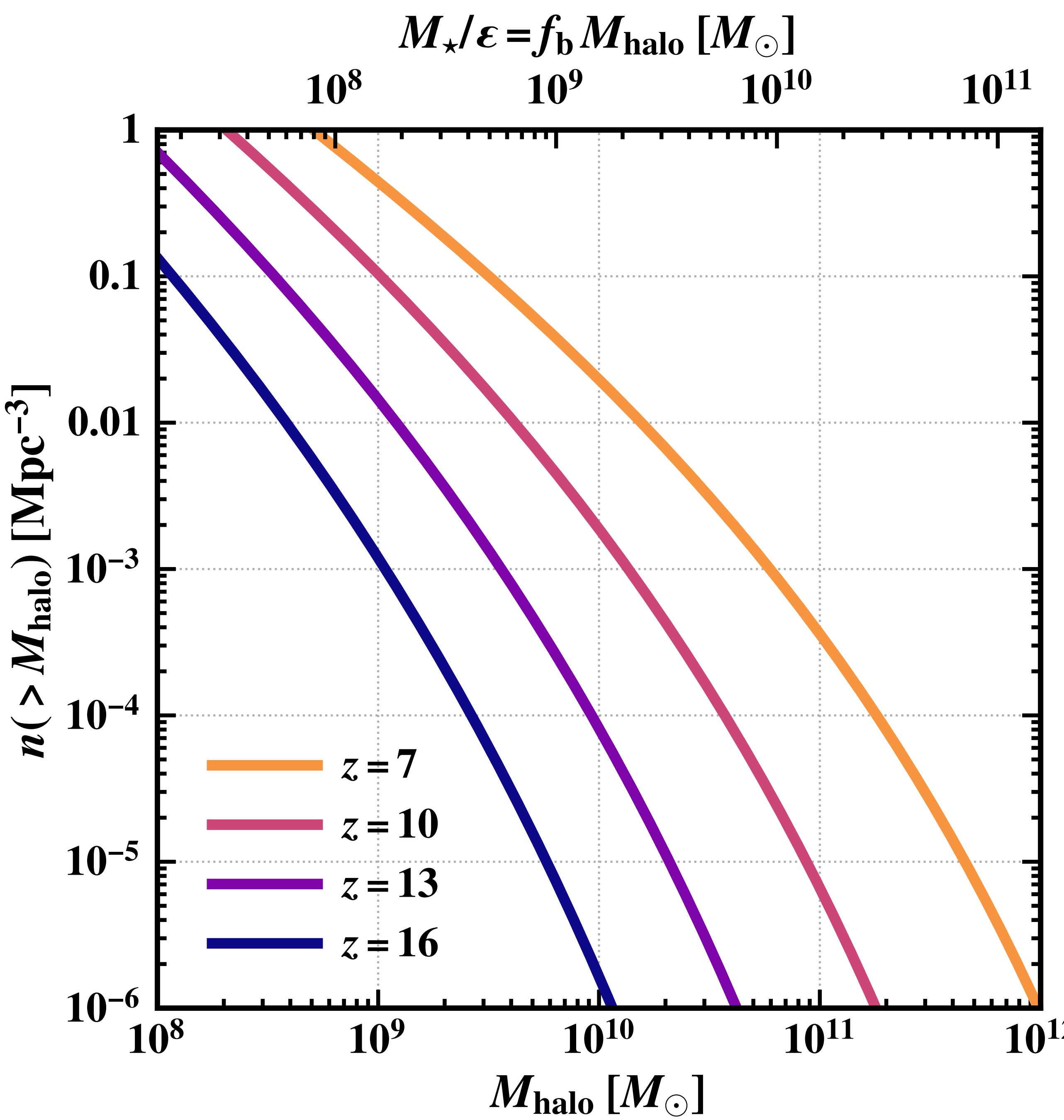


From dark matter halos to galaxies

Observations



Theory



From dark matter halos to galaxies

$$\phi_{\rm UV} \equiv \frac{{\rm d}n}{{\rm d}M_{\rm UV}} = \int {\rm d}M_{\rm h} \frac{{\rm d}n}{{\rm d}M_{\rm h}} P(M_{\rm UV}|M_{\rm h})$$

can do the same procedure for stellar mass functions as well using $P(M_\star \,|\, M_{\rm UV})$

From dark matter halos to galaxies

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UV luminosity function

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UV luminosity function

Halo mass function

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From dark matter halos to galaxies

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UV luminosity function

Halo mass function

galaxy formation physics

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From dark matter halos to galaxies

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UV luminosity function

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galaxy formation physics

$$\dot{M}_\star = f_\star(z, M_{\rm h}) f_{\rm b} \dot{M}_{\rm h}$$

From dark matter halos to galaxies

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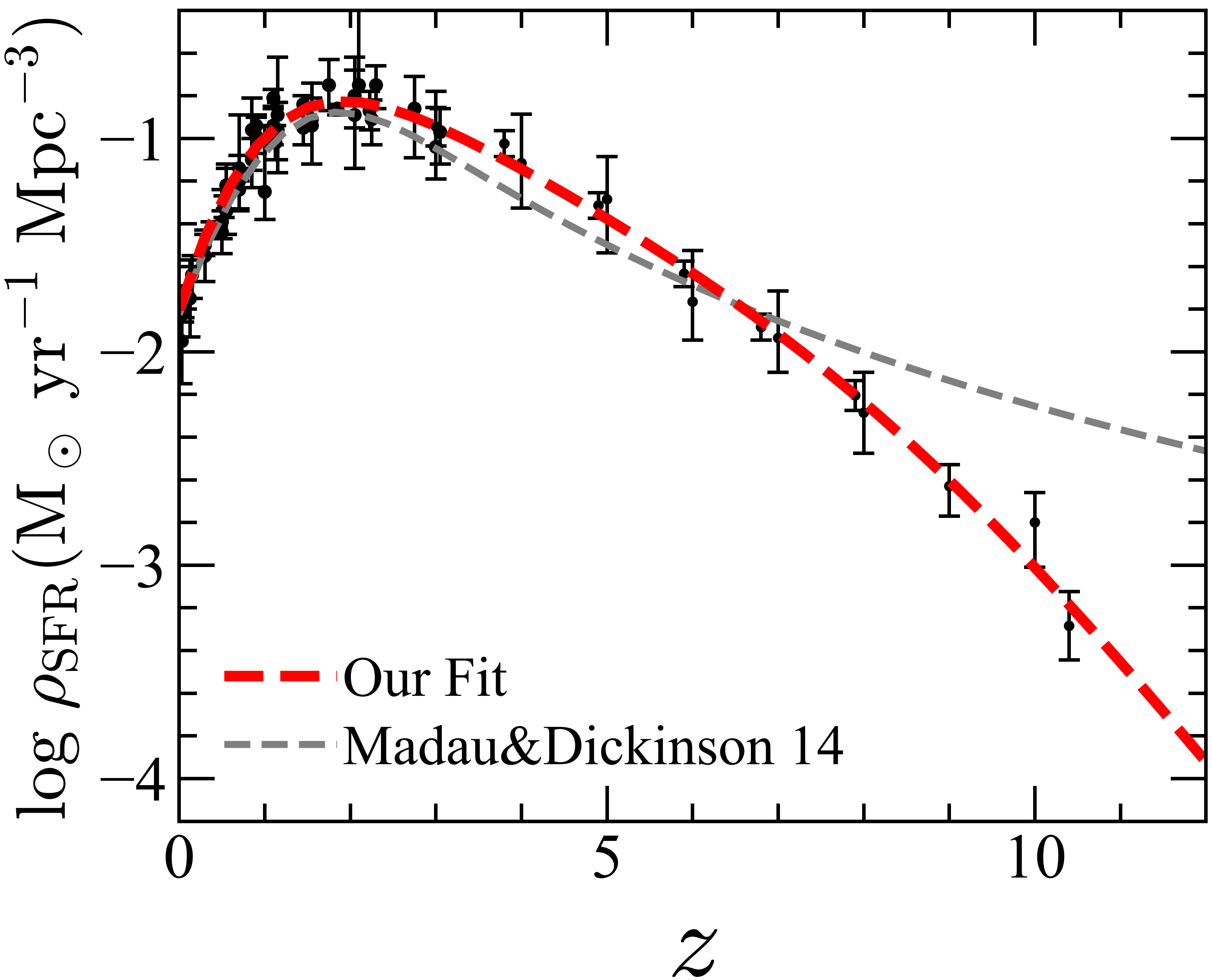
galaxy formation physics

$$\dot{M}_\star = f_\star(z, M_{\rm h}) f_{\rm b} \dot{M}_{\rm h}$$

Pre-JWST expectations

Steep fall-off in star formation toward higher redshift

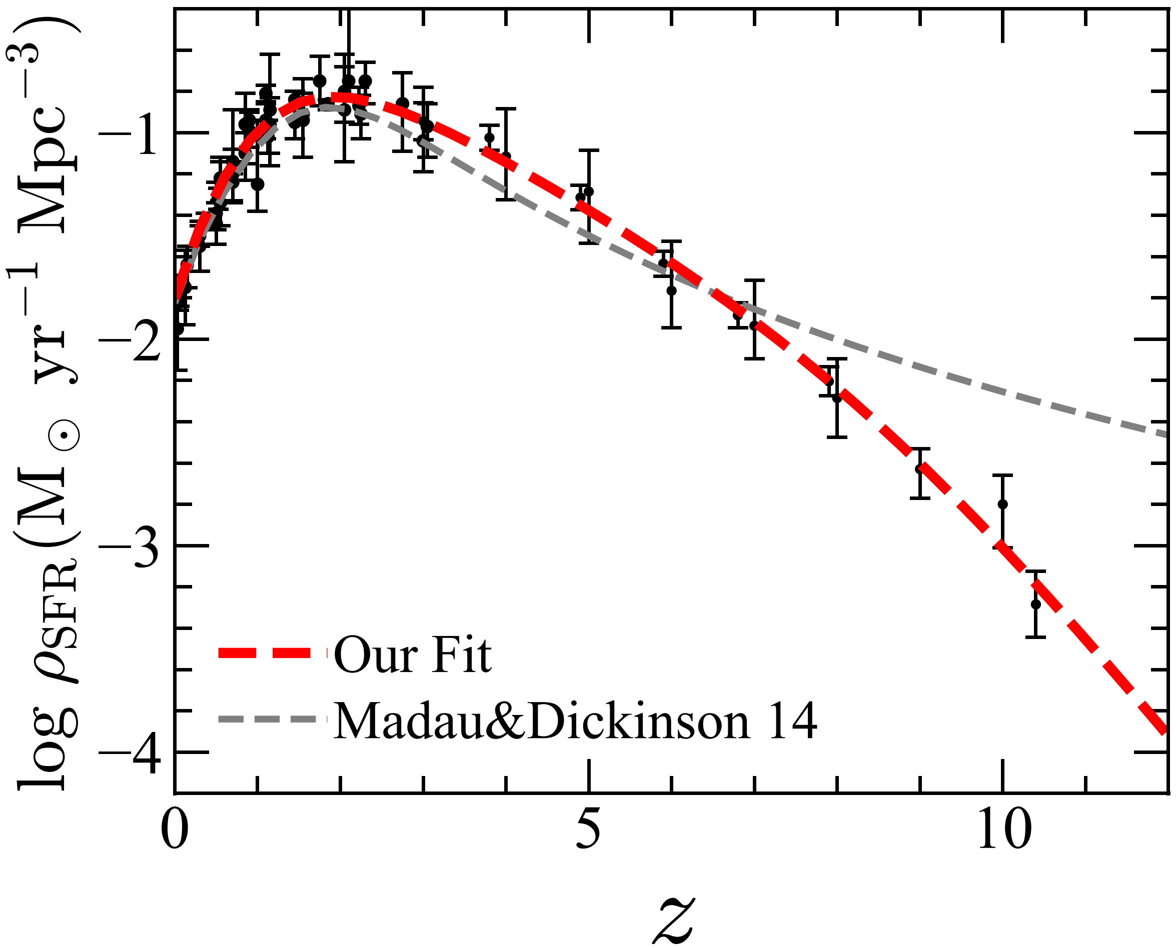


Constant star formation efficiency

Harikane et al. 2022

JWST: surprising levels of high-redshift star formation

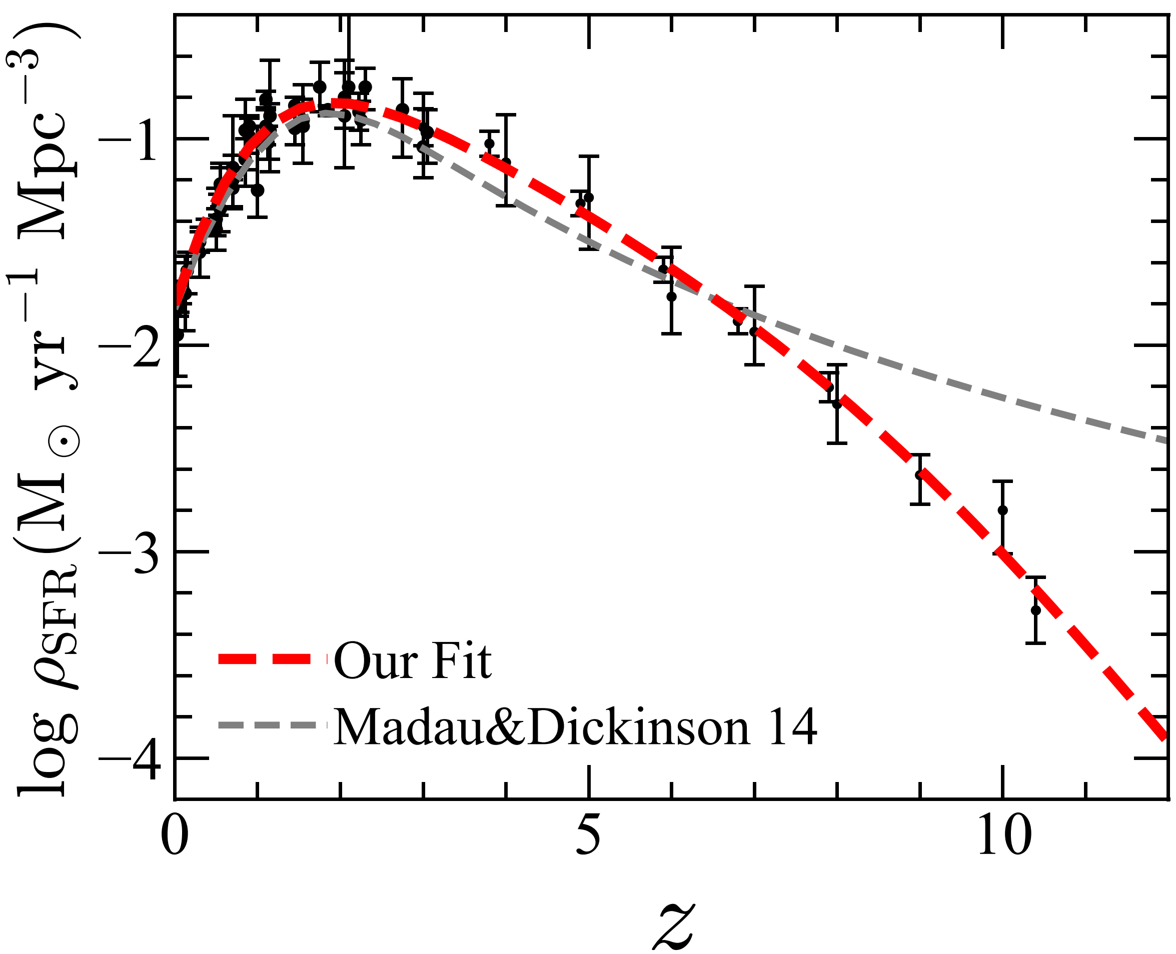
Pre-JWST expectations



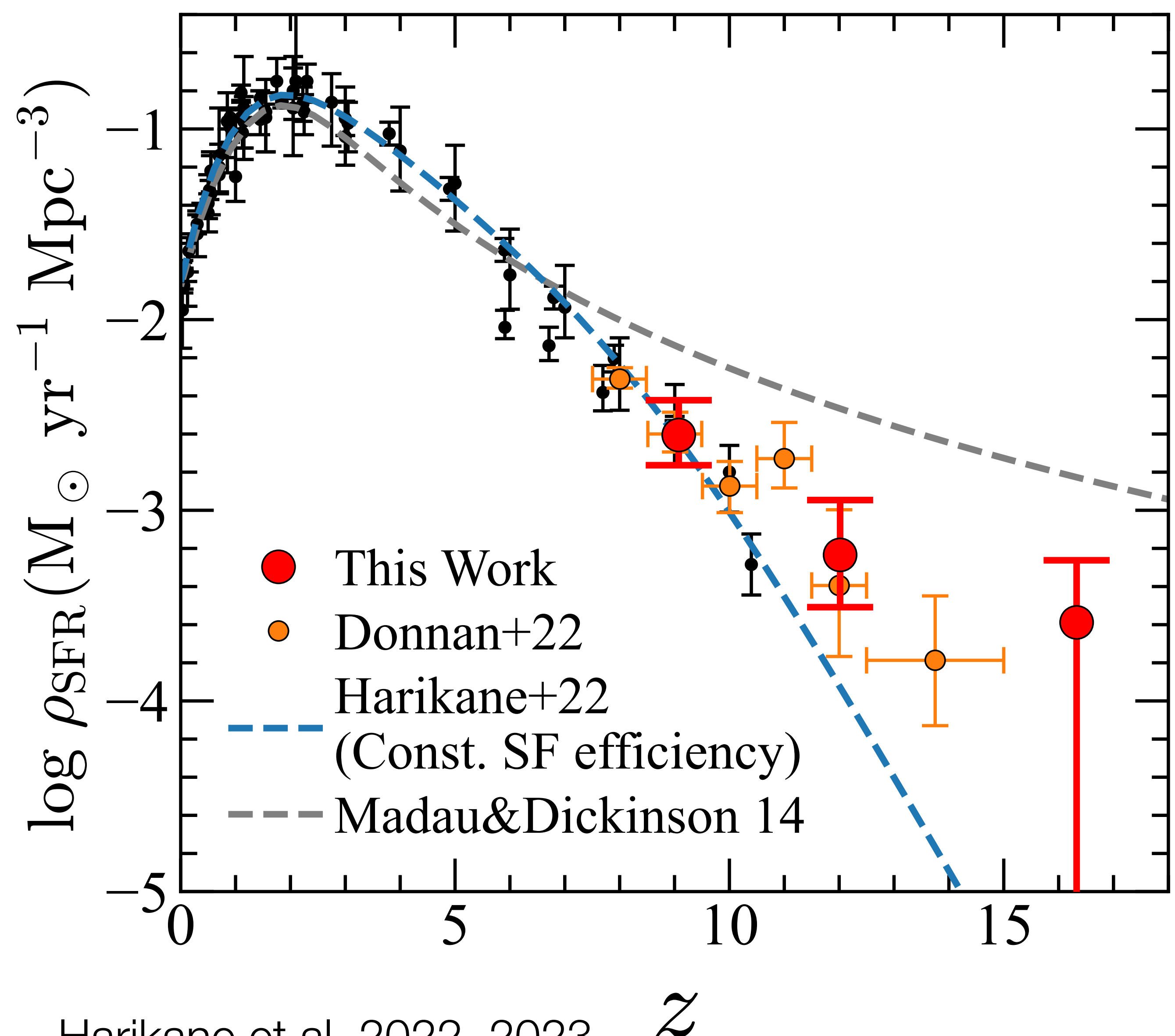
Harikane et al. 2022, 2023

JWST: surprising levels of high-redshift star formation

Pre-JWST expectations

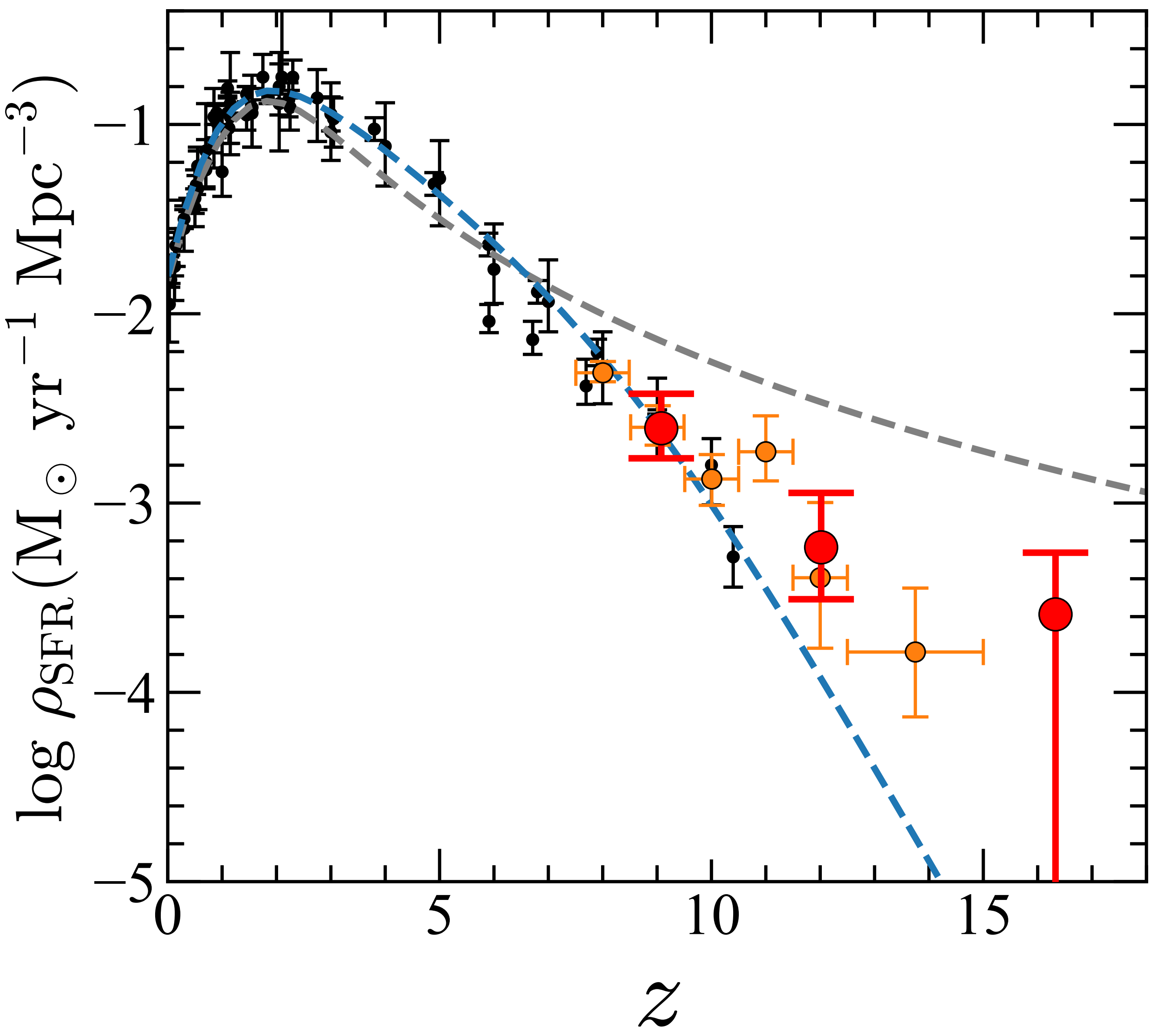


JWST results



Harikane et al. 2022, 2023

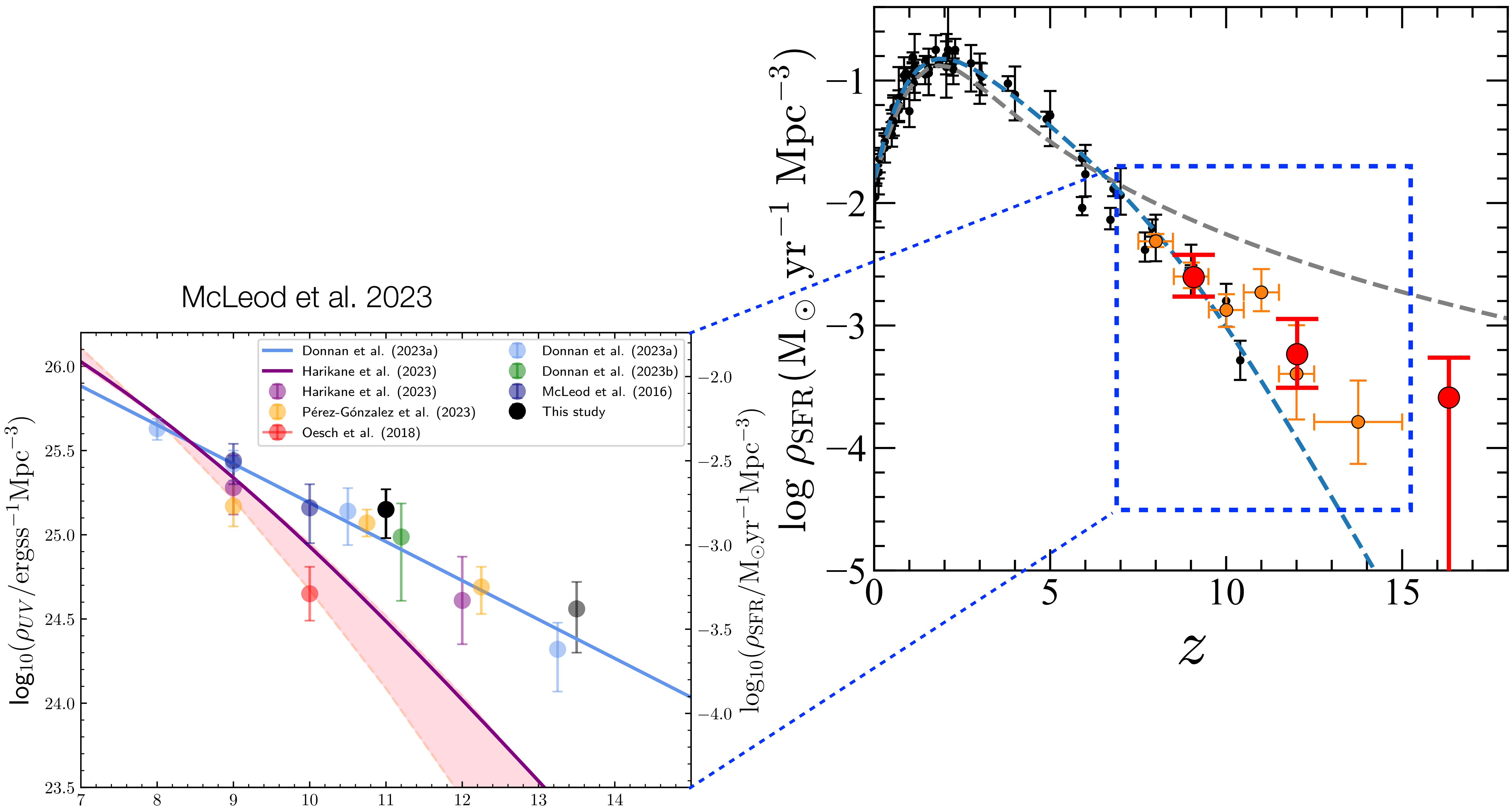
JWST: surprising levels of high-redshift star formation



Harikane et al. 2023

JWST: surprising levels of high-redshift star formation

McLeod et al. 2023

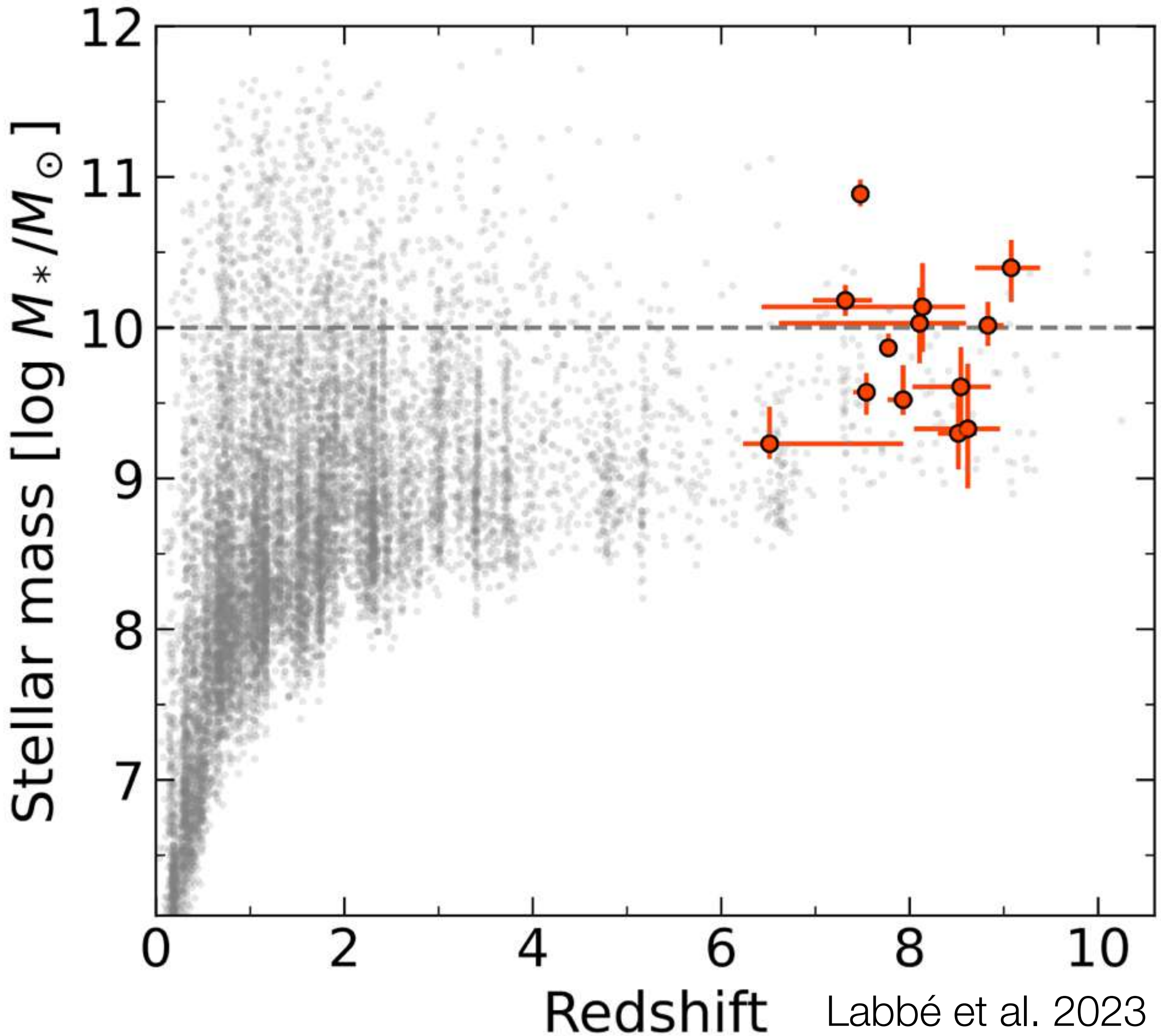


constant star formation efficiency

Harikane et al. 2023

First results from *JWST*: massive early galaxies

Galaxy candidates with $M_\star \approx 10^{10-11}\, M_\odot$ at $z \sim 8 - 10$ from CEERS



Labbé et al. 2023

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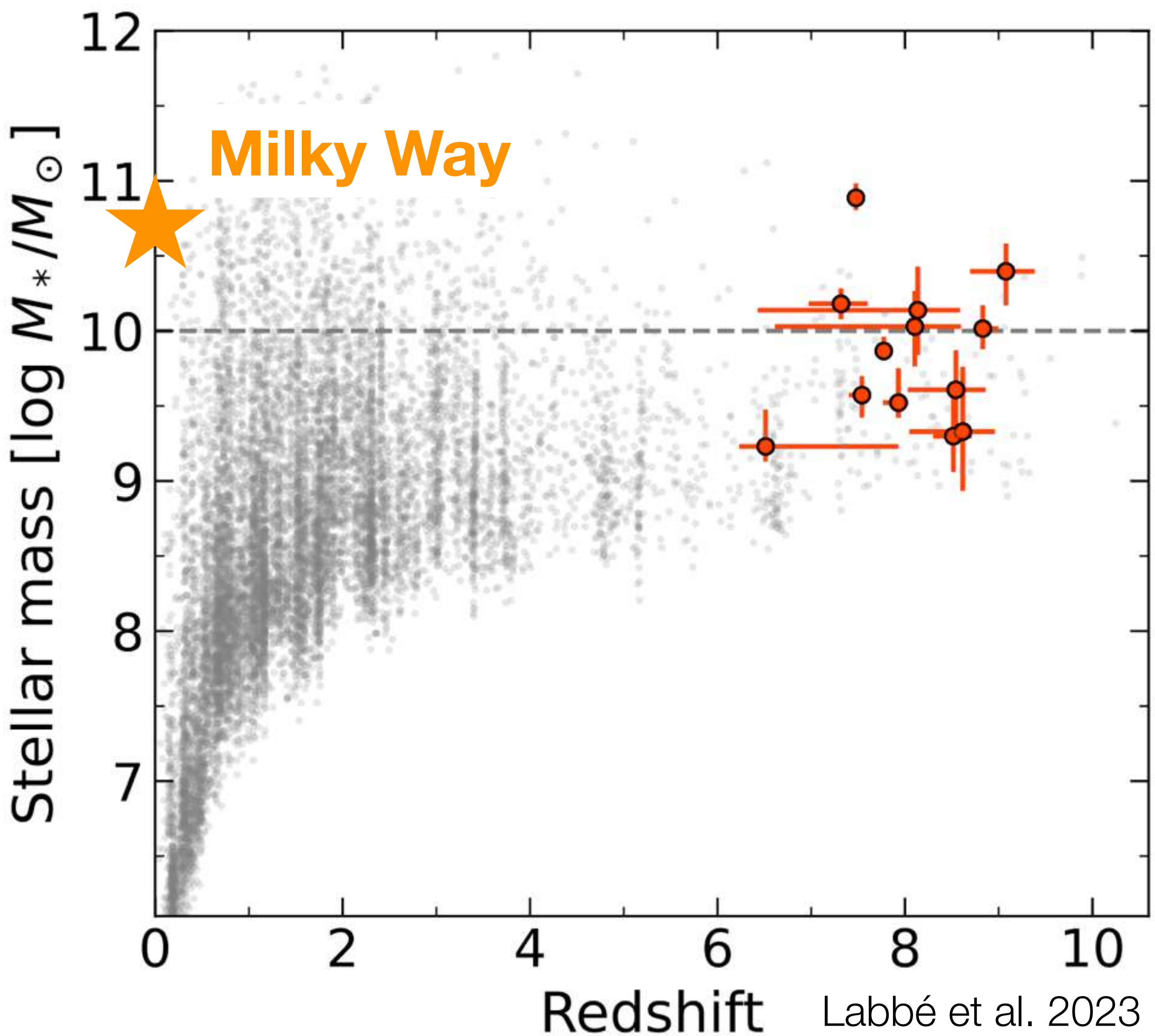

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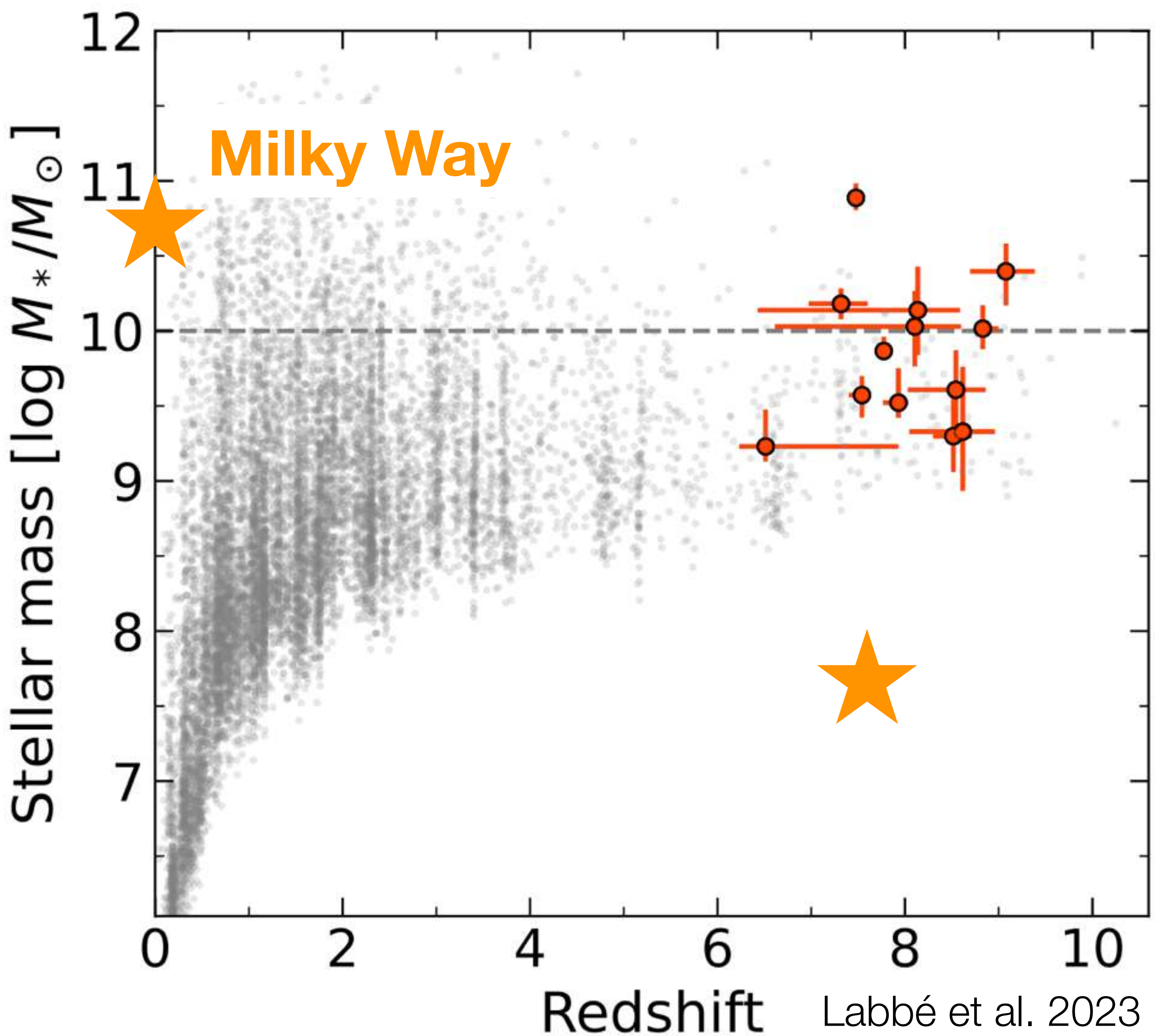
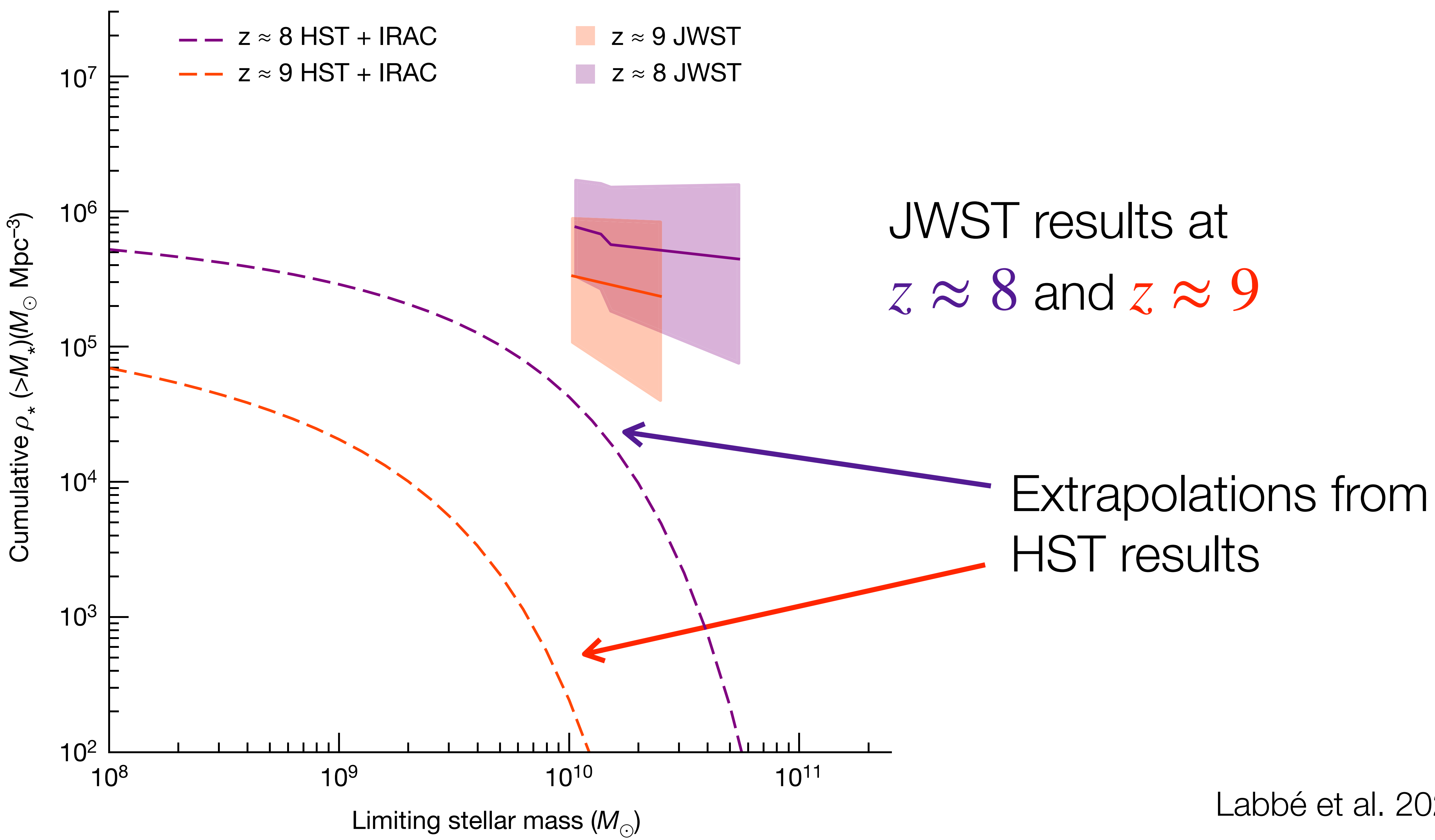


Labbé et al. 2023

First results from *JWST*: massive early galaxies

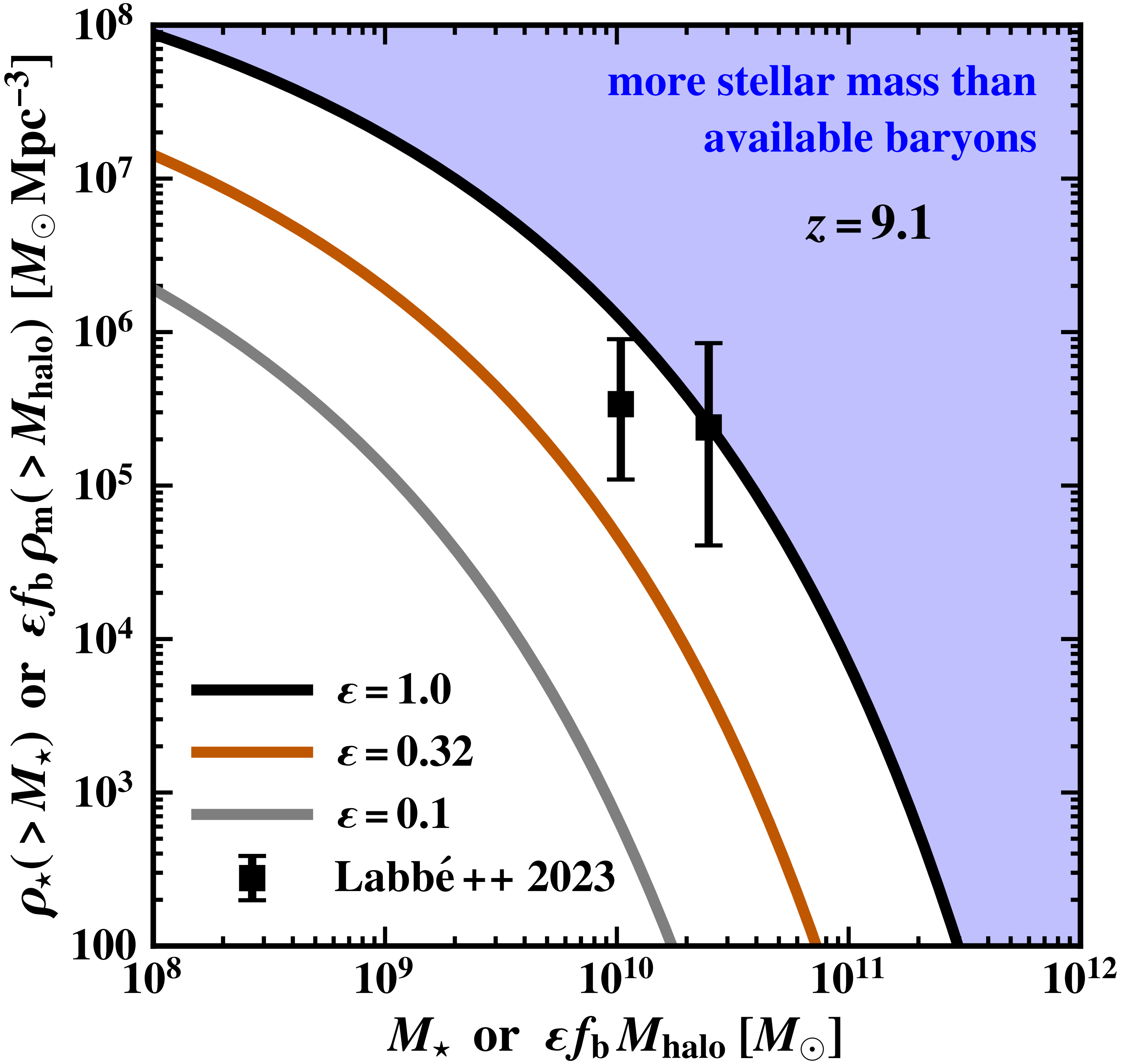
Galaxies with $M_\star \approx 10^{10-11}\, M_\odot$ at $z \sim 8 - 10$ imply *thousands* of times more stars per unit volume than expected based on *HST* results



Labbé et al. 2023

Massive early galaxies: in tension with ΛCDM

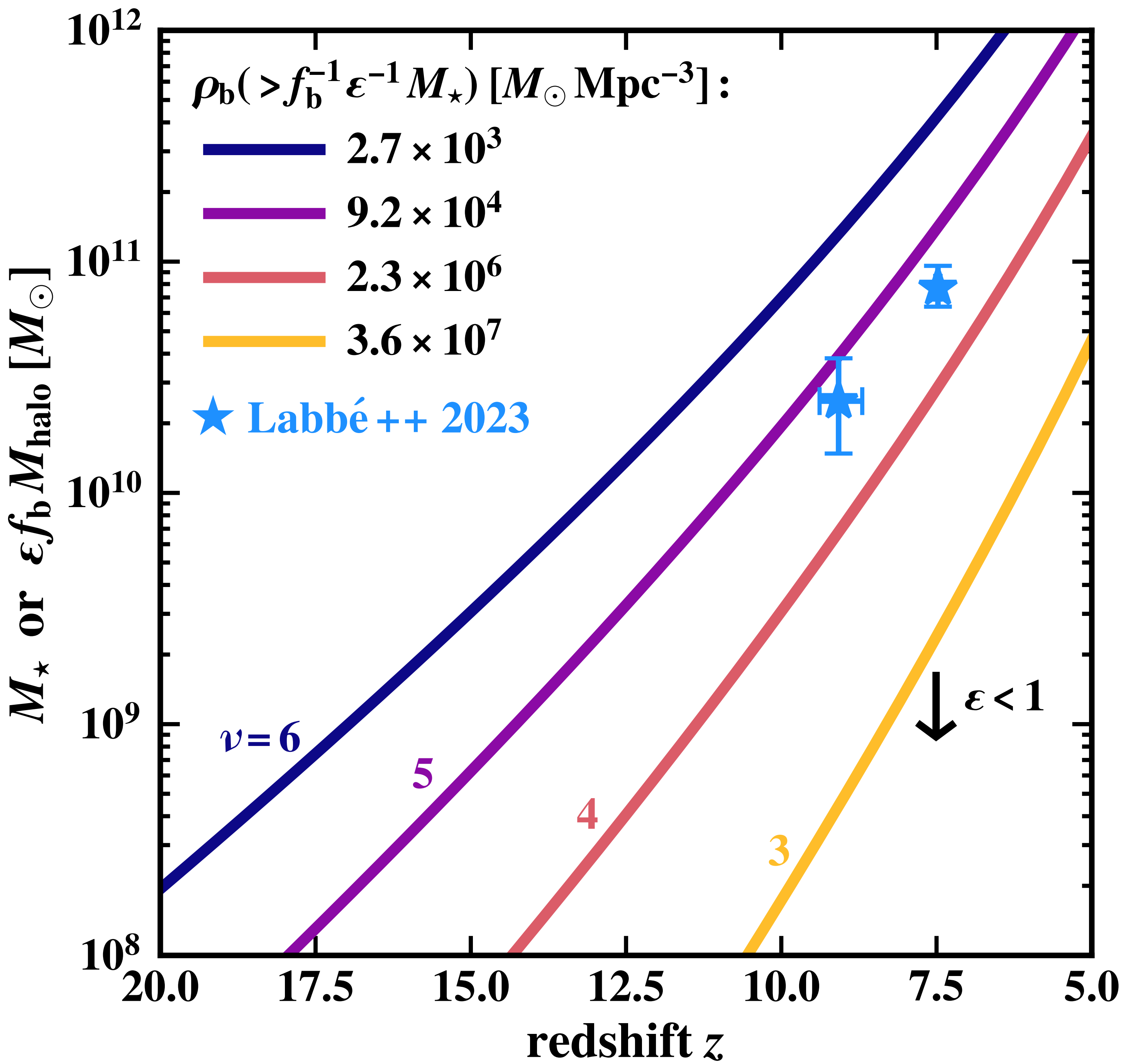
Uh oh: require *all* available baryons in the halo to be converted into stars in ΛCDM (i.e., $\epsilon_\star \approx 1$). *Note*: at $z = 0, \langle \epsilon_\star \rangle \lesssim 0.2$ at all halo masses



similar result at $z \approx 7.5$

Boylan-Kolchin 2023
arXiv:2208.01611

The implied dark matter hosts are *very* rare



Find implied peak heights of

$\nu \approx 4.5 \quad (\epsilon = 1)$,
$\nu \approx 5.4 \quad (\epsilon = 0.32)$, or
$\nu \approx 6.4 \quad (\epsilon = 0.1)$

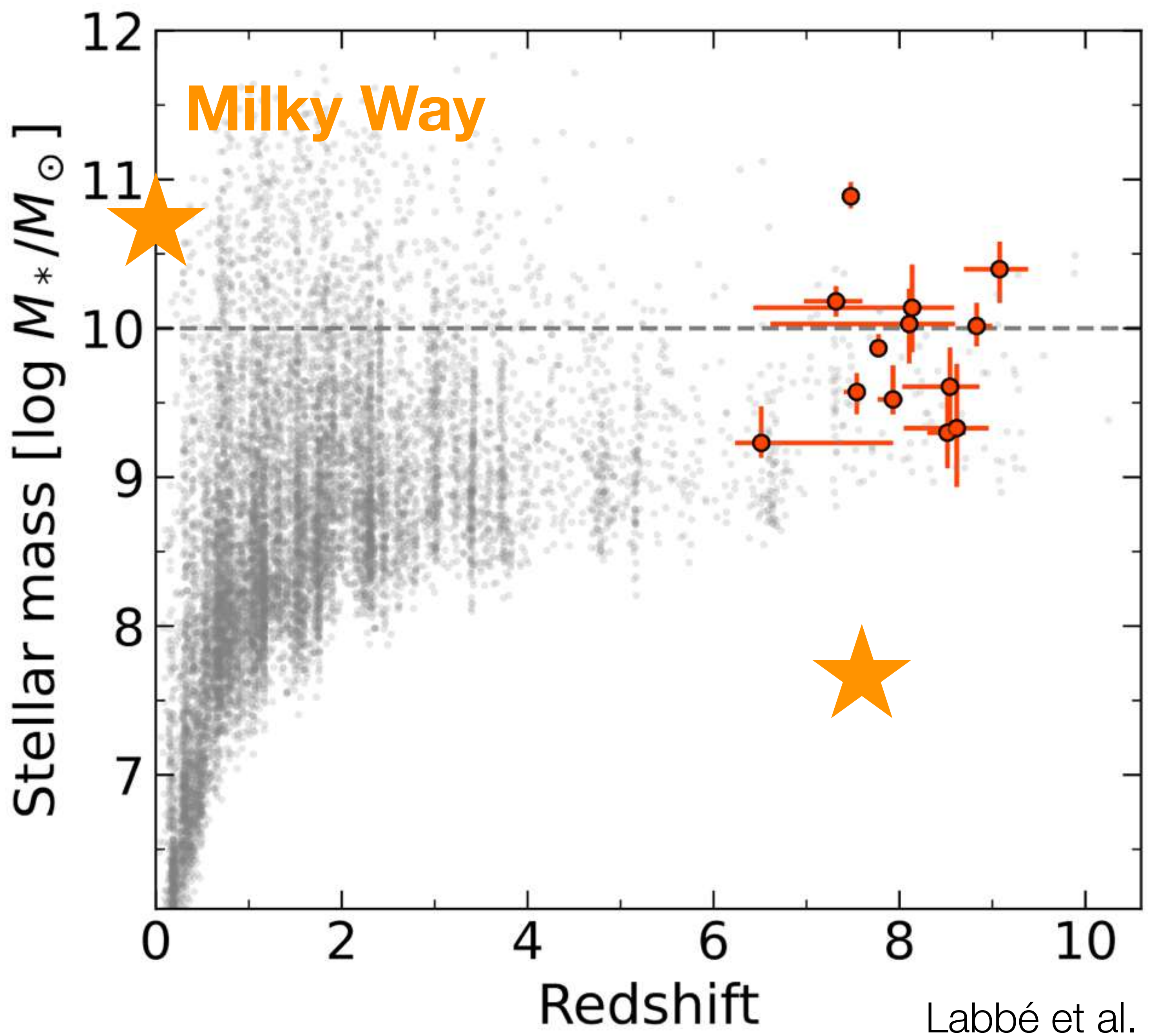
$$\nu \approx 4.5 \longleftrightarrow M_{halo}(z=0) \approx 5\times10^{15}\,M_\odot$$

Survey volume:
38 arcmin^2 $\approx 10^5\,\mathrm{Mpc}^3$

Boylan-Kolchin 2023
arXiv:2208.01611

JWST: massive early galaxies at early cosmic times

Galaxy candidates with $M_\star \approx 10^{10.5-11}\, M_\odot$ at $z \sim 8-10$ from CEERS



Labbé et al. 2023

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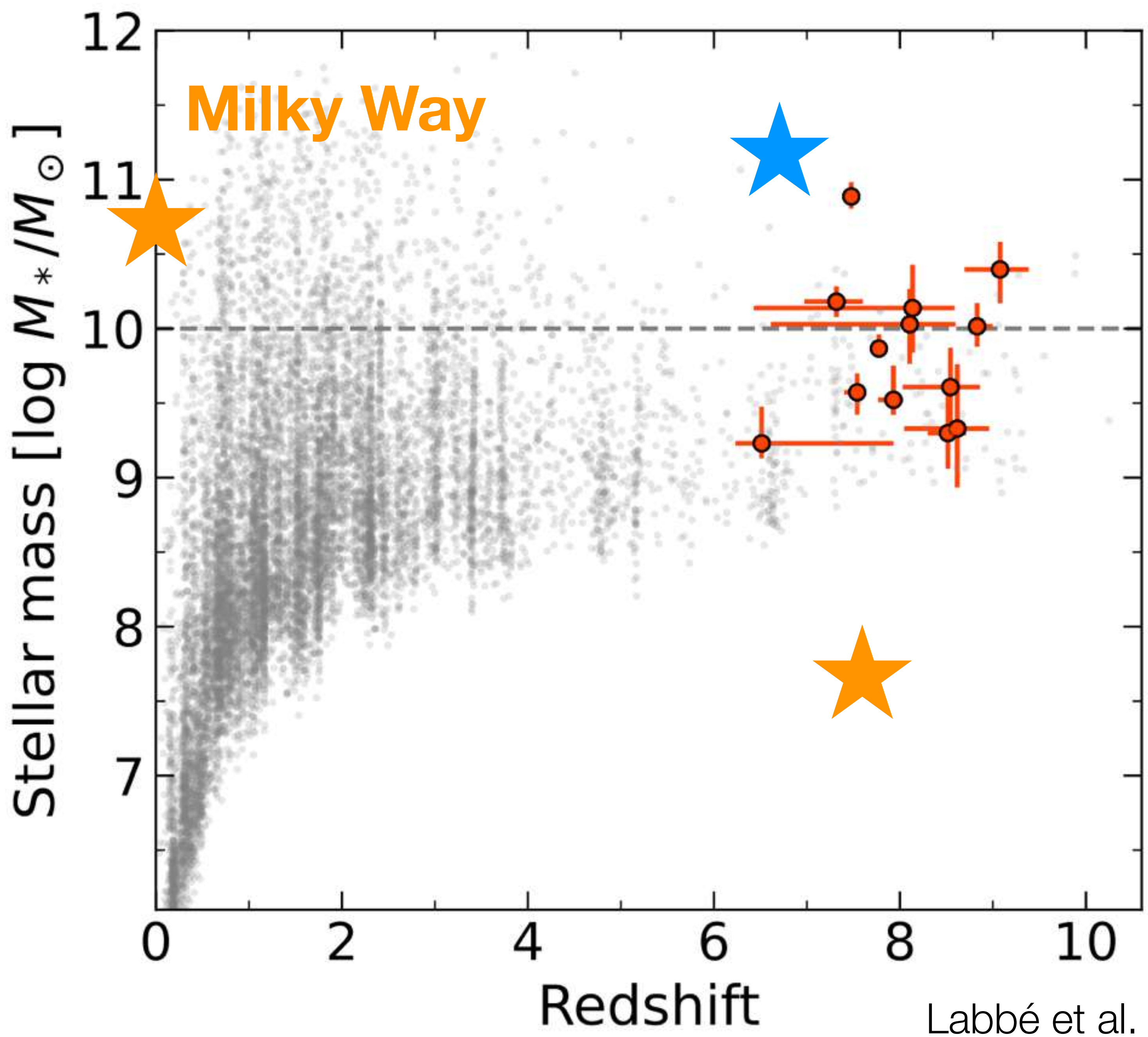


Labbé et al. 2023

HST+ALMA-detected galaxy at z=6.83 with:

$M_\star = 1.7 \times 10^{11}\,M_\odot$

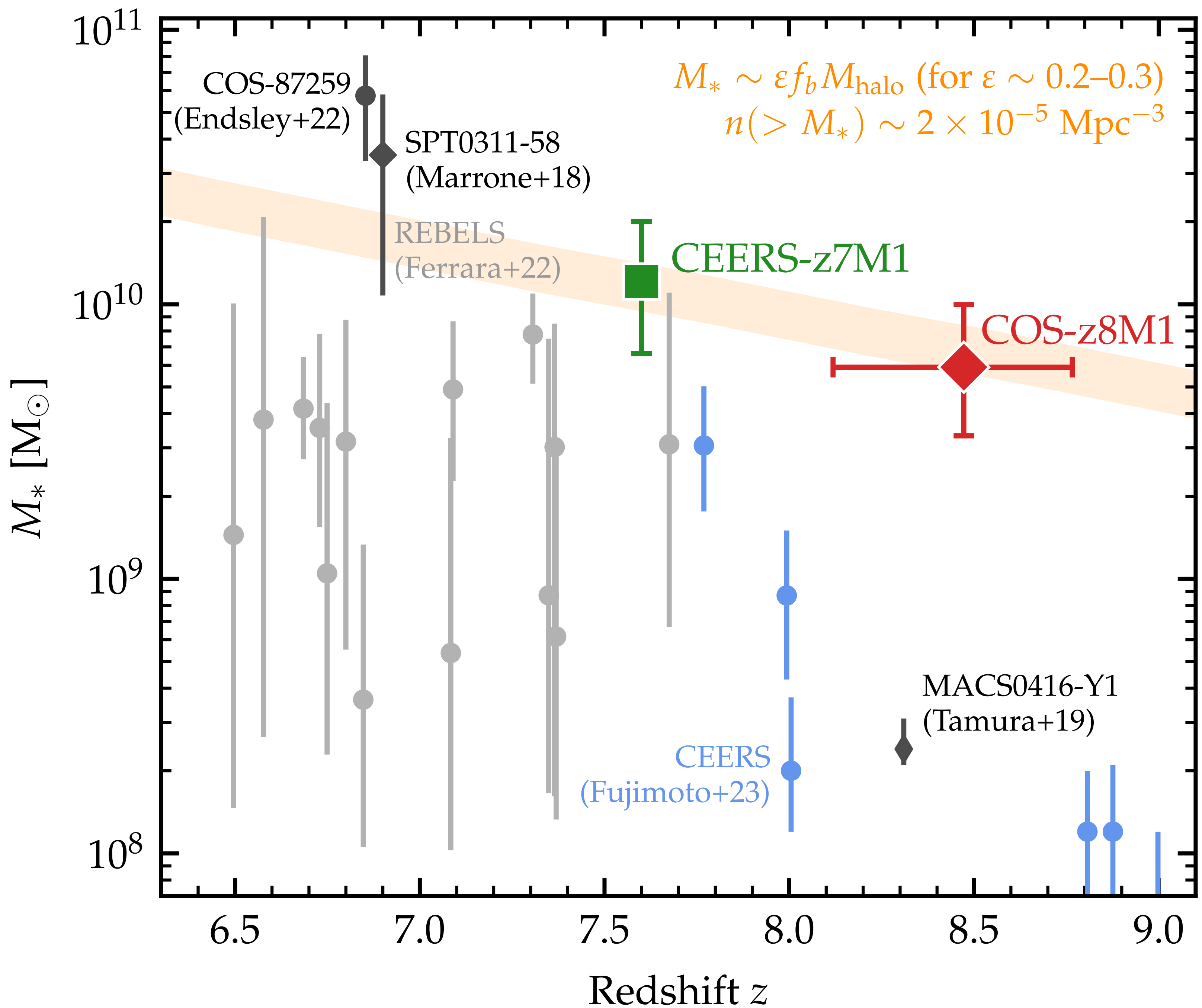
$M_{\rm BH} \approx 1.5 \times 10^{9}\,M_\odot$

$\dot{M}_\star \approx 1300\,M_\odot\,{\rm yr}^{-1}$

Endsley et al. 2023

JWST: massive early galaxies at early cosmic times

Massive dust-obscured galaxies (with ALMA detections)?



Akins et al. 2023

What could be going on ?

Many possible explanations within standard ΛCDM, including incorrect mapping from observed light to underlying stellar mass (AGN, star formation histories, ….) and sample variance

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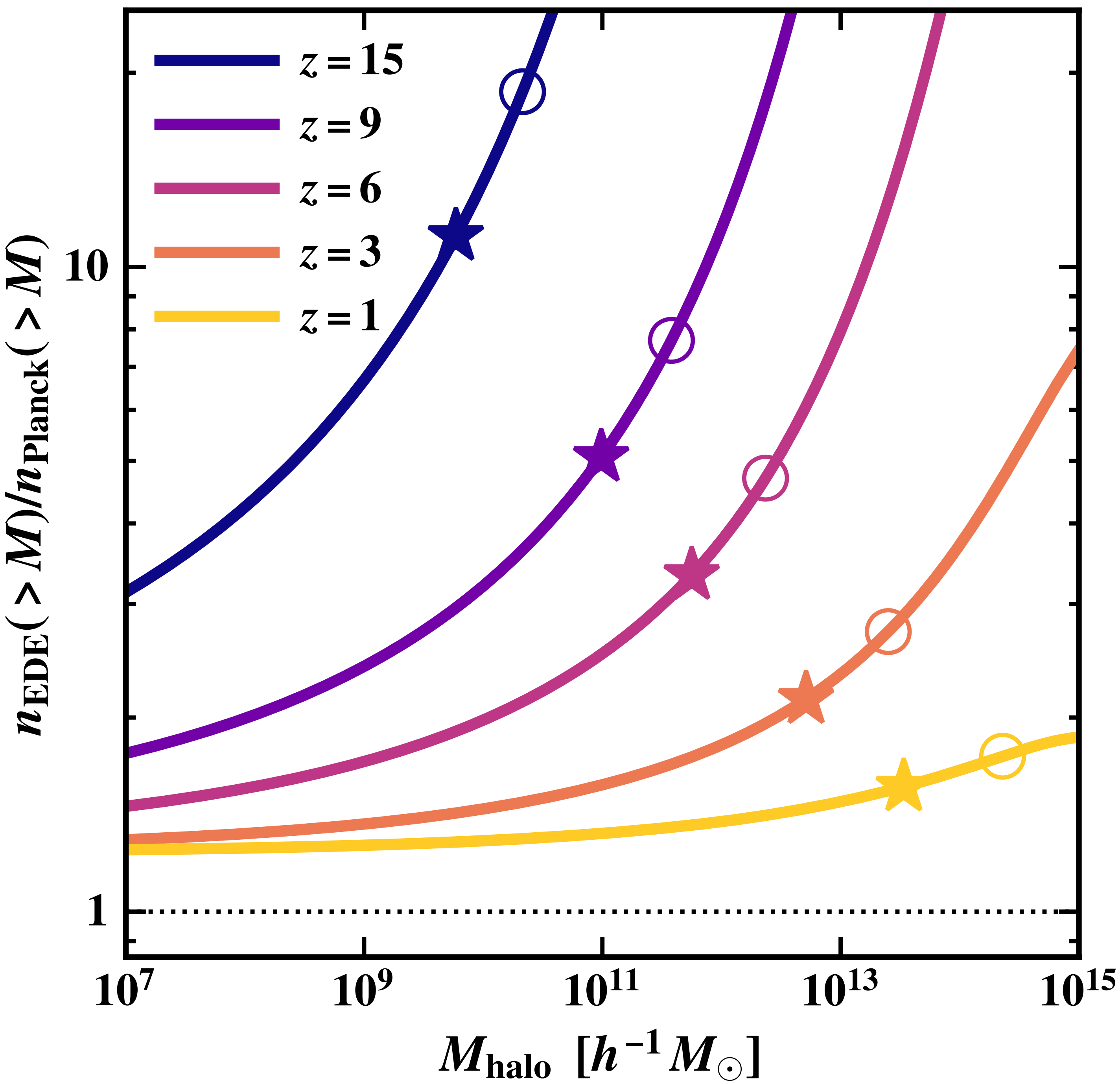
Many possible explanations within standard ΛCDM, including incorrect mapping from observed light to underlying stellar mass (AGN, star formation histories, ….) and sample variance

If the issue is cosmological: need more (faster) formation of cosmological structure at early times. **No wiggle room in base ΛCDM** — all parameters are known to $\lesssim 1\,\%$ precision — but extensions with additional parameters might work

- need higher $\rho_\mathrm{m}, \sigma_8, \text{and/or } n_\mathrm{s}$
- a small(ish) possible modification: a short period of **early dark energy** with $\Omega_\mathrm{EDE} \sim 0.1$ at $z \sim 3500$
  (Karwal++ 2016; Poulin++ 2018, 2019; Smith++ 2020, Riess & Kamionkowski 2022)

EDE leads to enhanced high-z structure formation

higher ρ_m, σ_8, & n_s than base Planck model: **more high-z galaxies**
(Klypin et al. 2021)

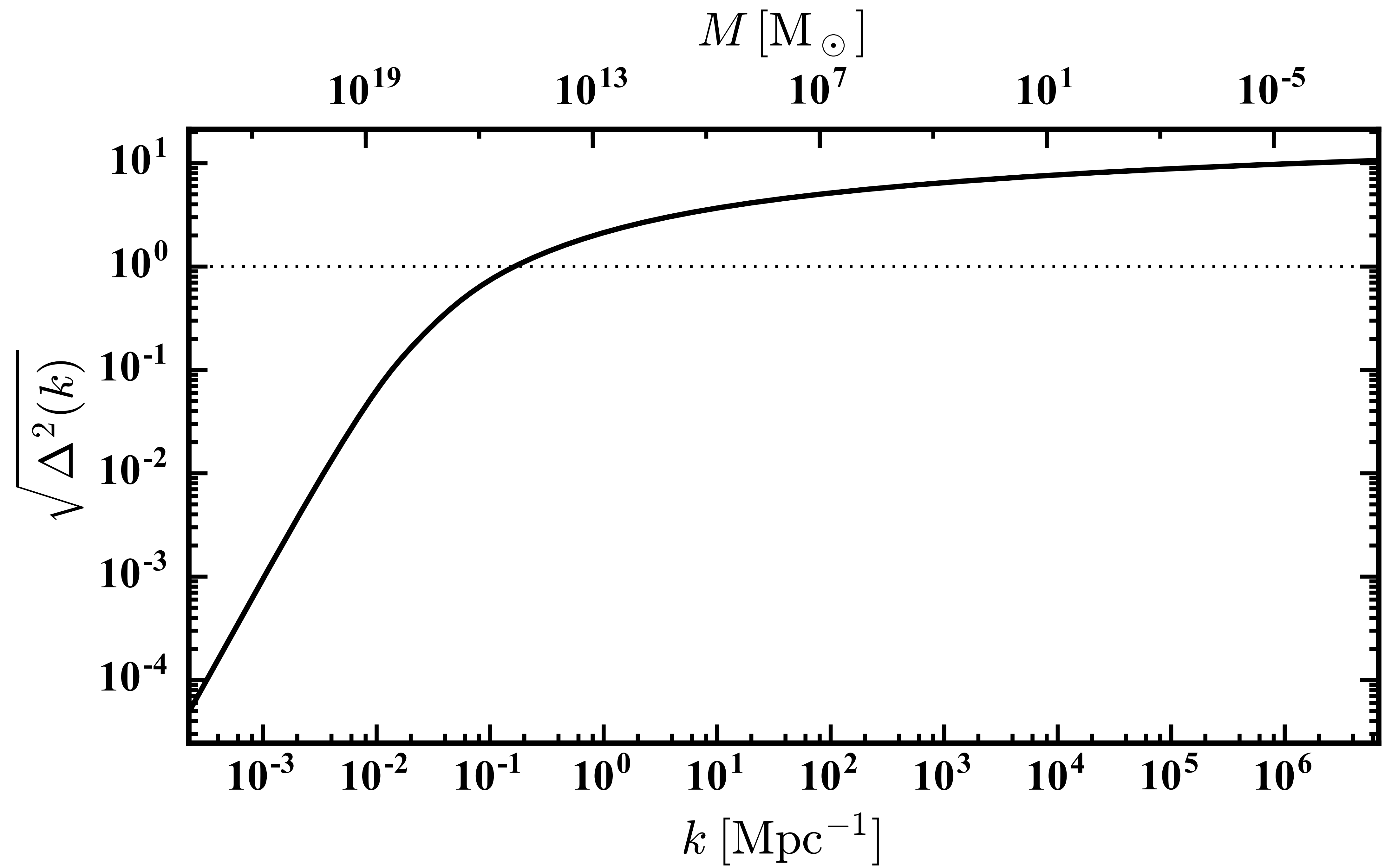


○: $n_{Planck}(>M; z) = 10^{-7}\,\mathrm{Mpc}^{-3}$
(COSMOS-Web)

★: $n_{Planck}(>M; z) = 10^{-5}\,\mathrm{Mpc}^{-3}$
(CEERS)

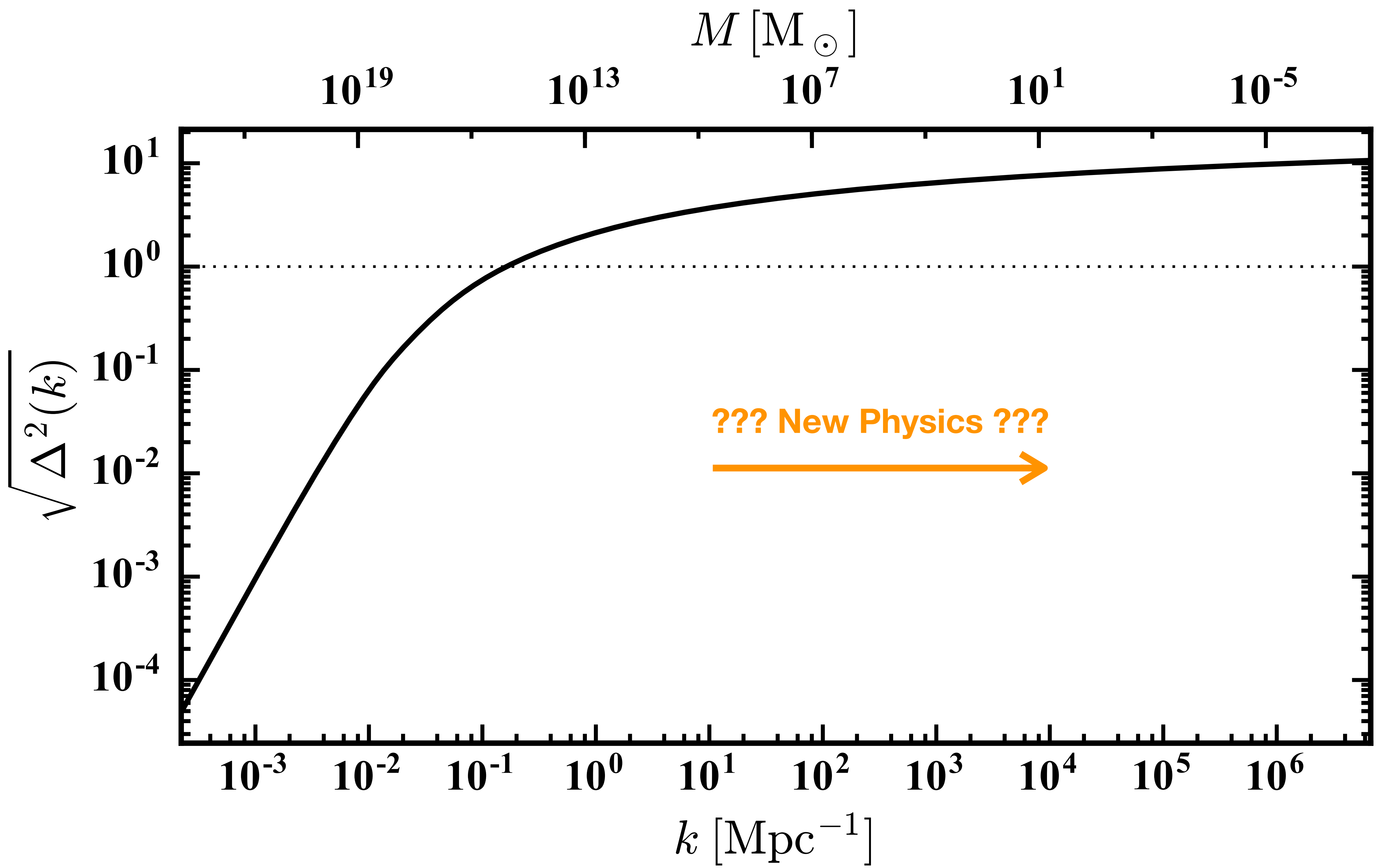
Differences are magnified at **higher redshifts** — but requires going to **lower** $M_\star$ and M_{halo}

JWST observations: constraining the ΛCDM power spectrum



Bullock & Boylan-Kolchin 2017

JWST observations: constraining the ΛCDM power spectrum



Bullock & Boylan-Kolchin 2017

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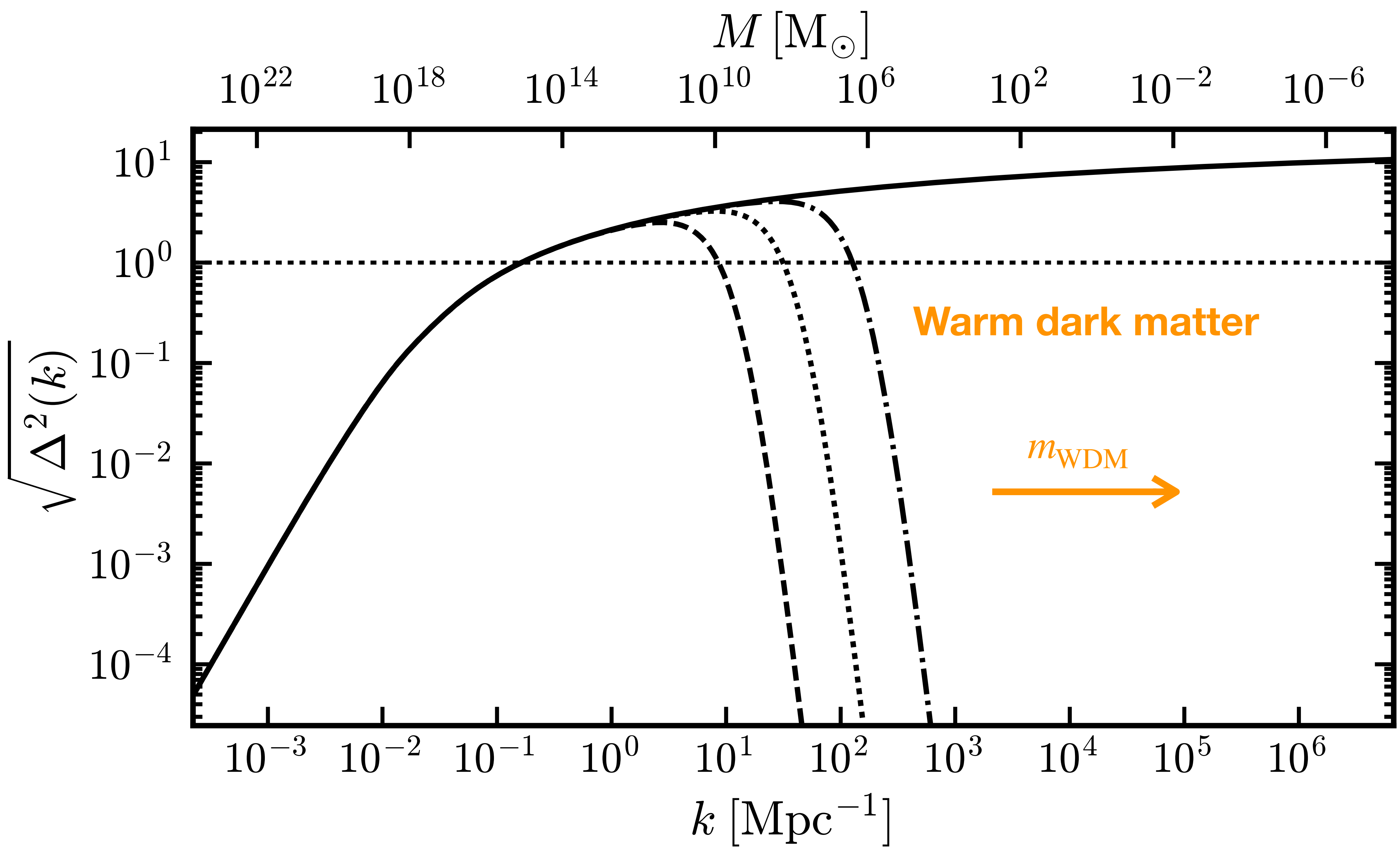
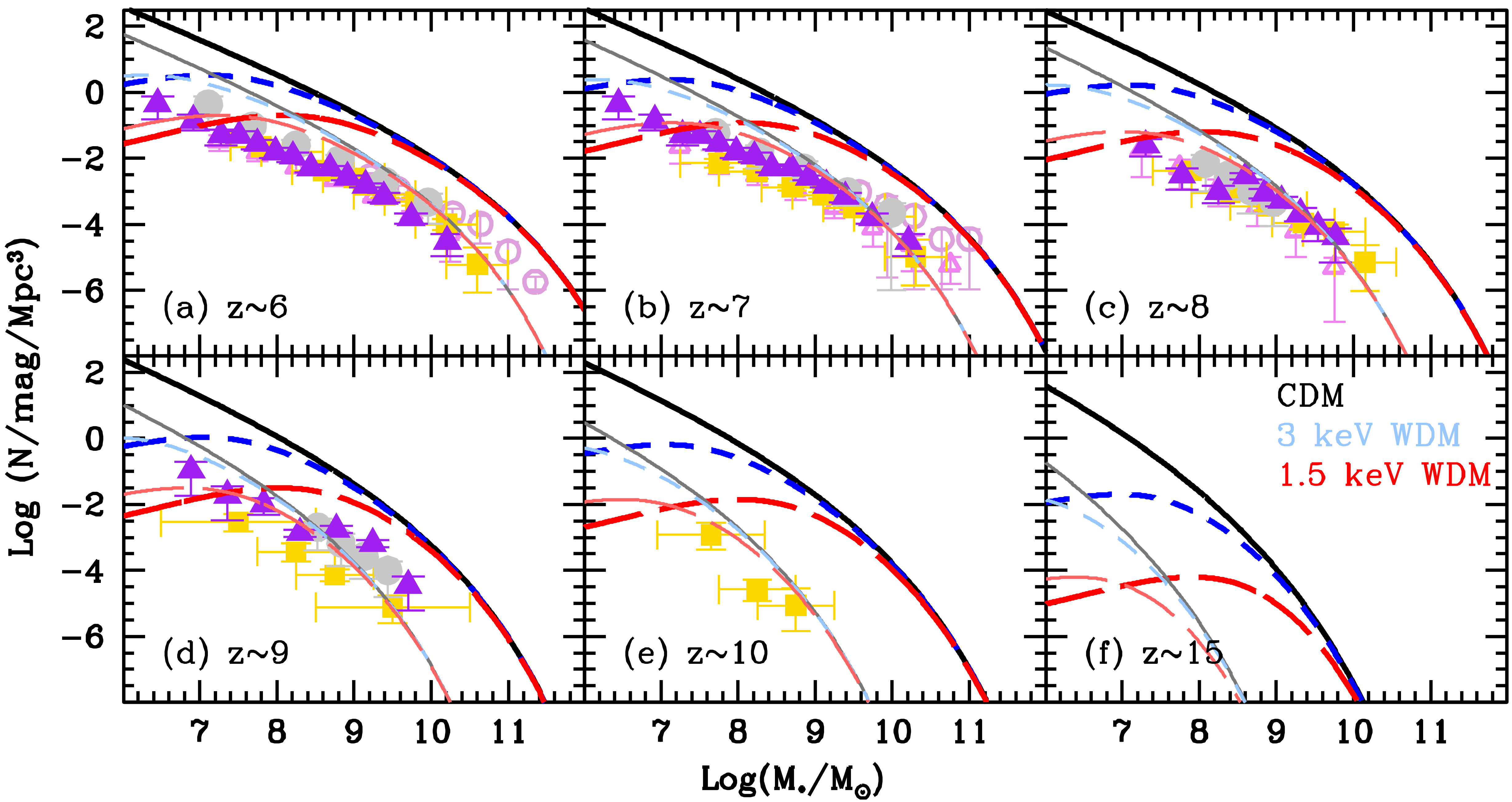


Bullock & Boylan-Kolchin 2017

JWST observations: constraining the ΛCDM power spectrum

Differences are largest at **highest redshifts**, **lowest masses**



Dayal & Giri 2023

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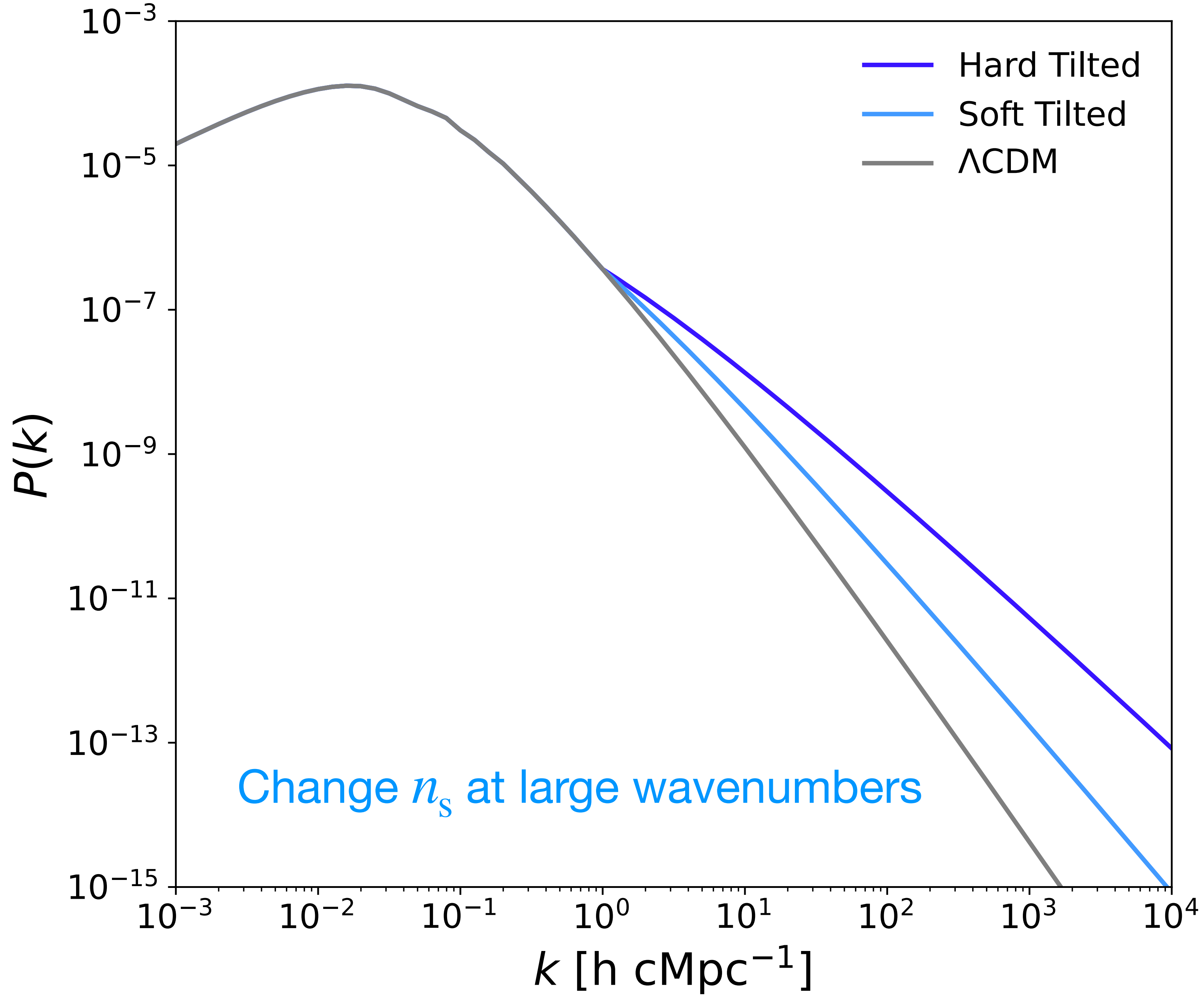

Hirano & Yoshida 2023

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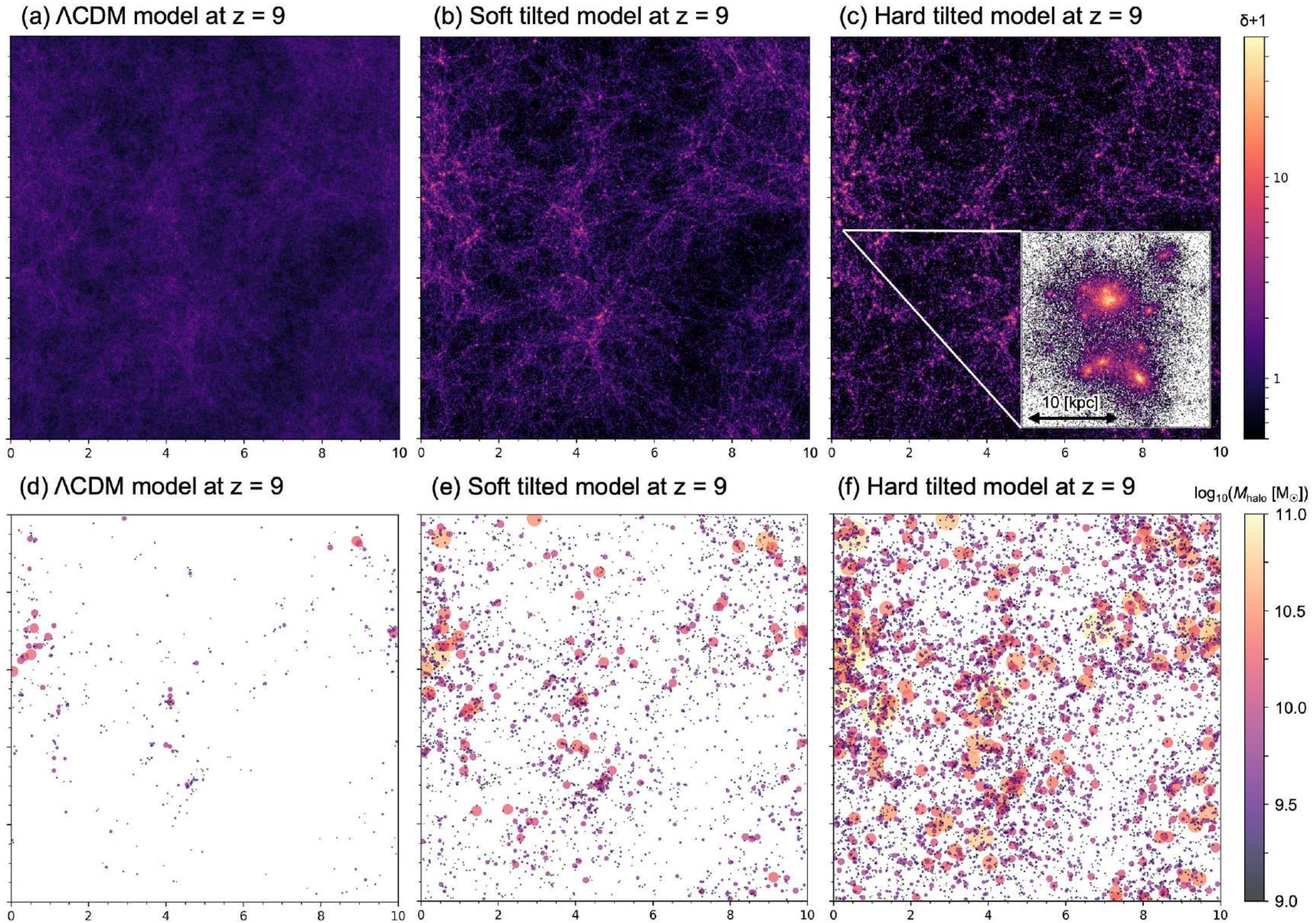

Hirano & Yoshida 2023

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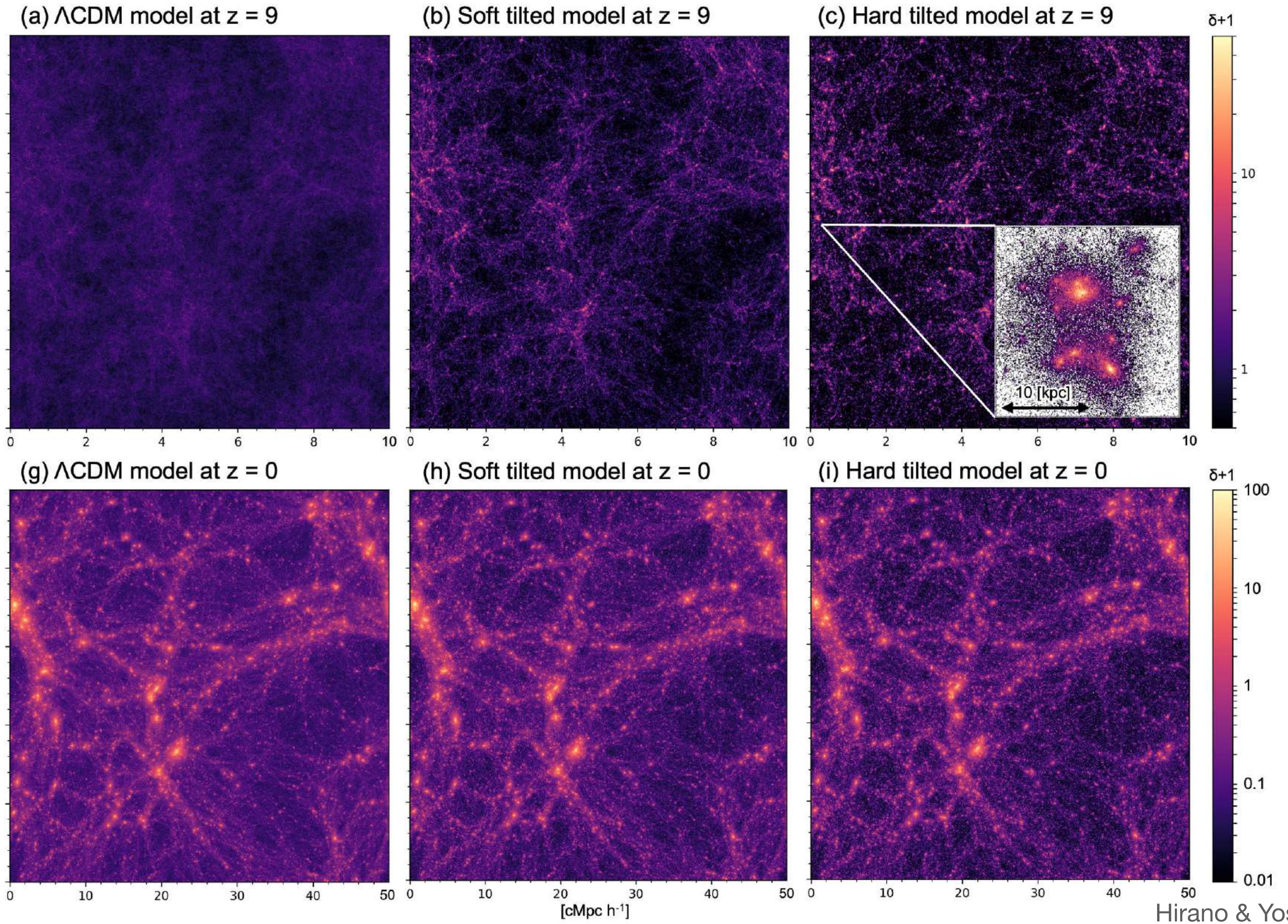
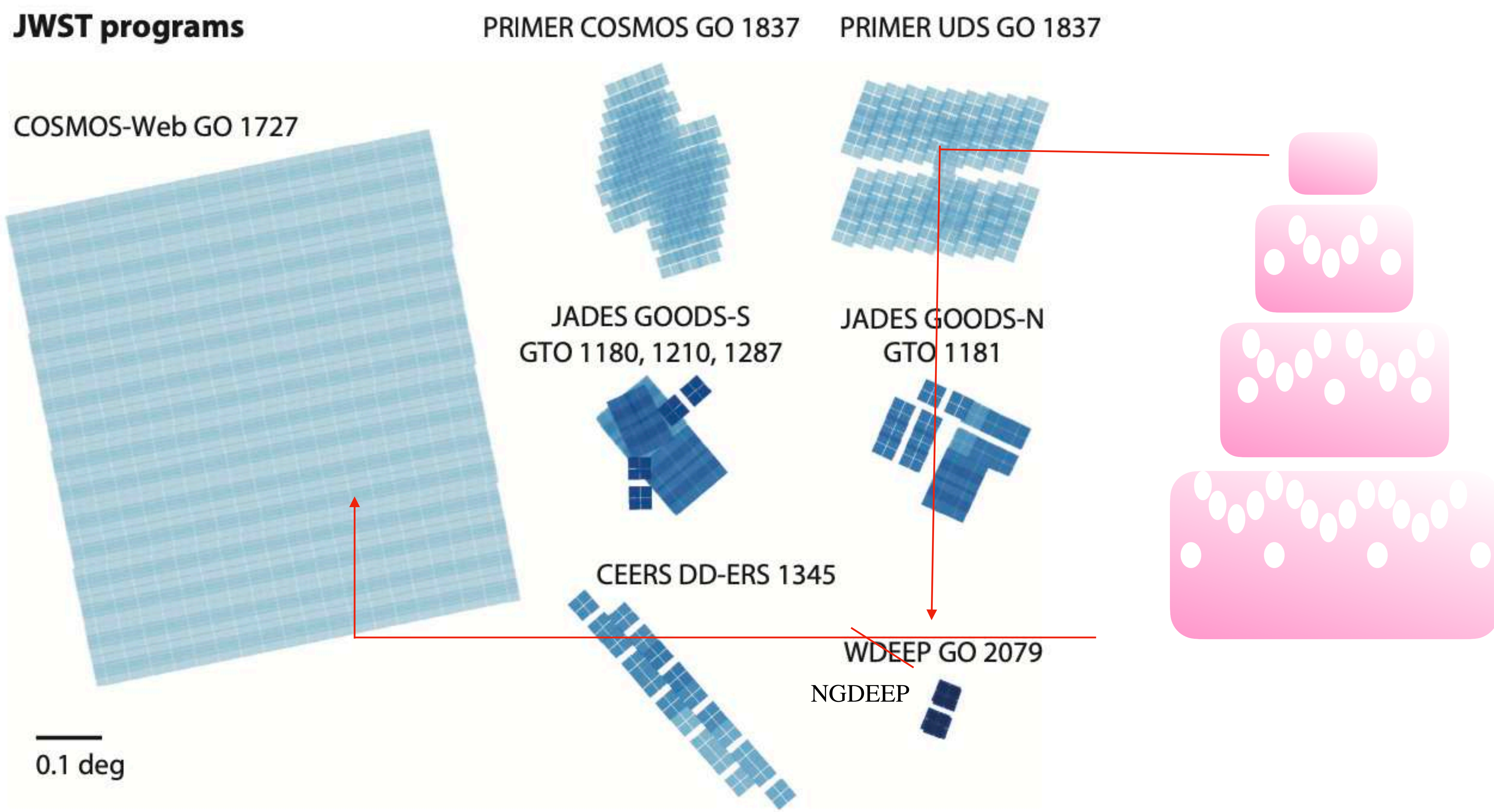


Hirano & Yoshida 2023

Programs relevant for galaxies and cosmology

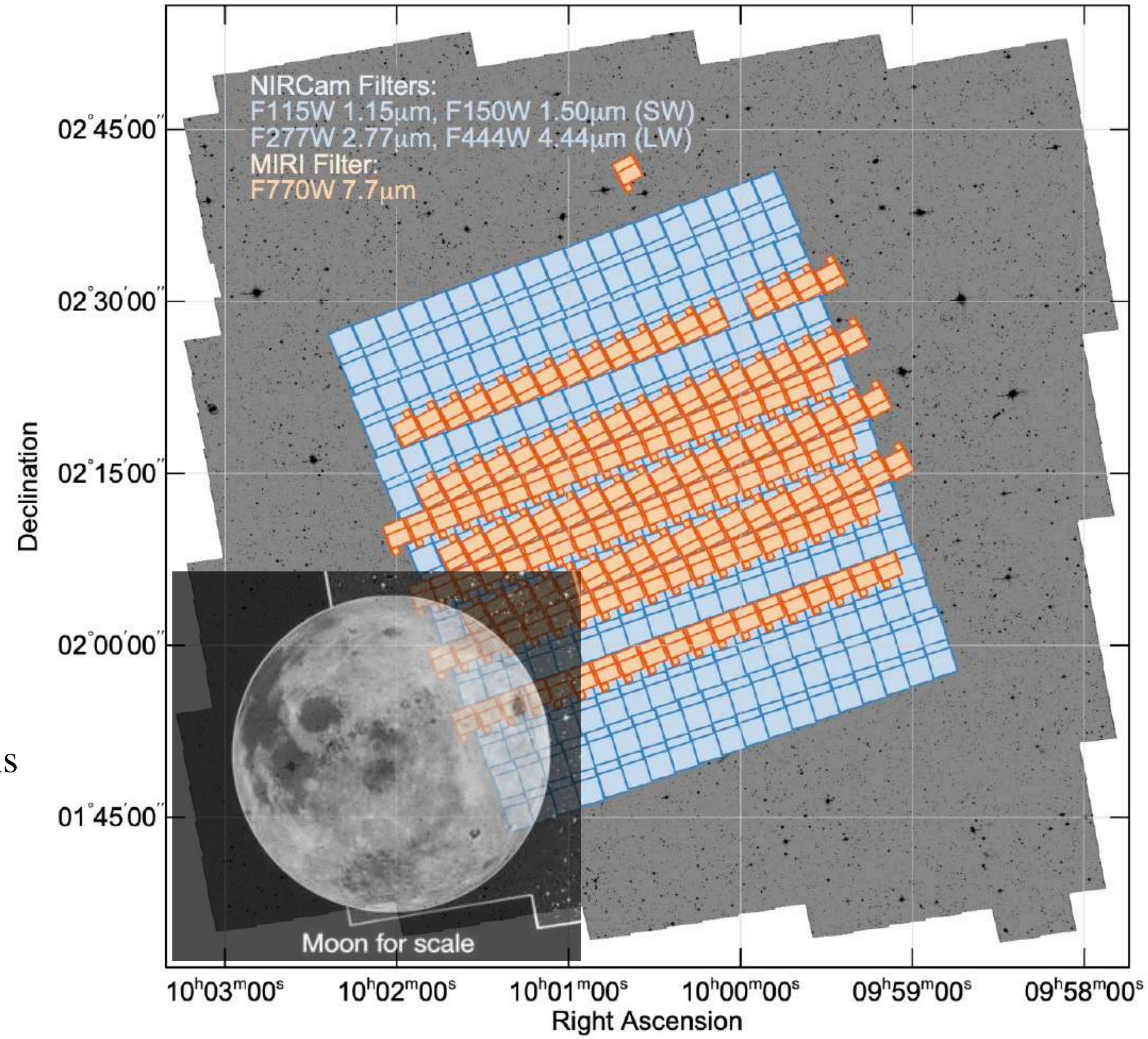


Robertson 2022

The COSMOS-Web survey

the biggest survey

roughly the size
of three full moons

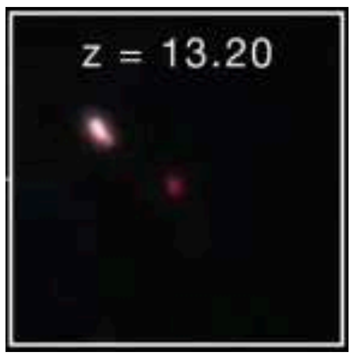


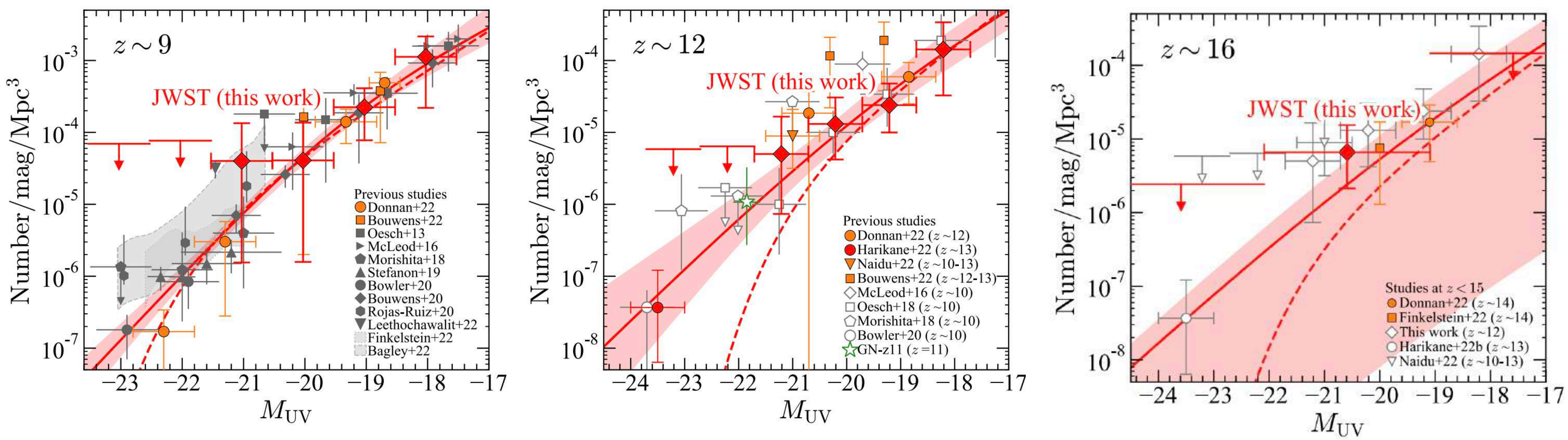
discover **thousands** of galaxies in the Epoch of Reionization

Casey …. **Yang**, et al. 2022

Summary

1. What are the first stars/galaxies?
2. How did reionization occur? and what caused it?





3. Are observed structures consistent with initial conditions?
4. Physics beyond base ΛCDM?