Frontiers in Particle Physics - 2024

Probing New Physics with JWST observations of high redshift massive galaxies

Priyank Parashari

Based on P. Parashari & R. Laha, MNRAS: Letters, 526, L63–L69 (2023) arXiv: 2305.00999

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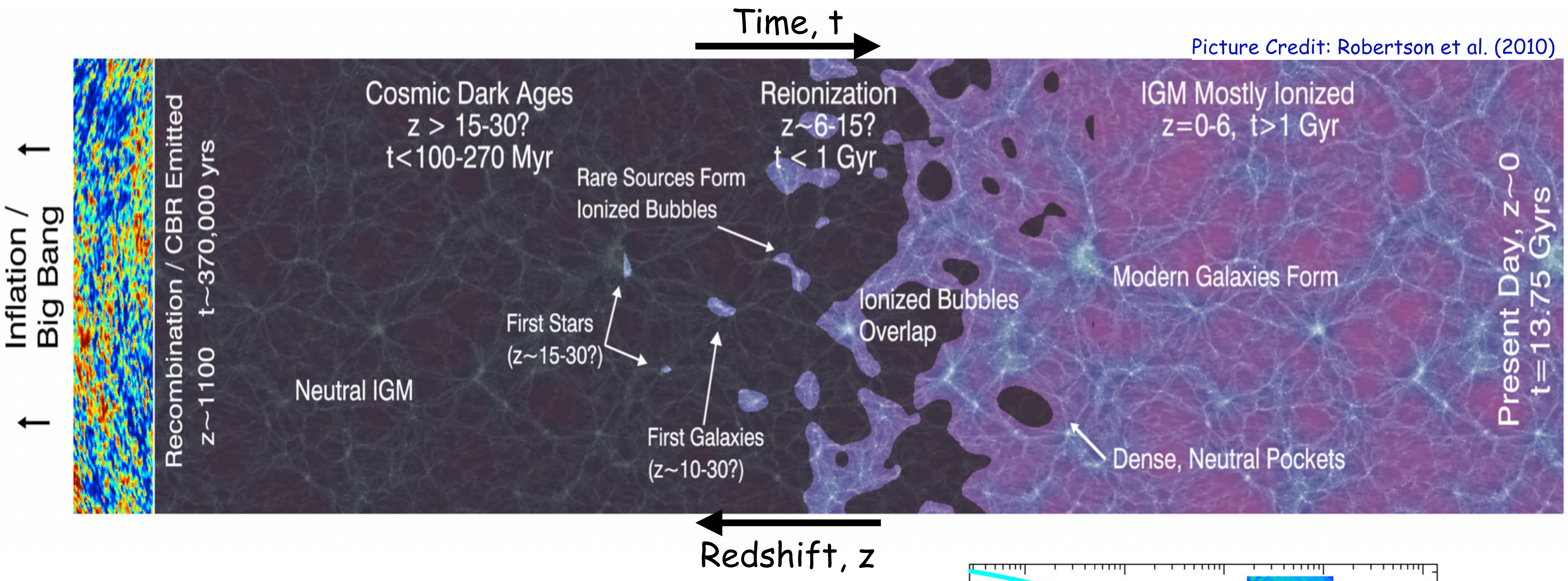
Centre for
High Energy Physics

Introduction



Picture Credit: Robertson et al. (2010)

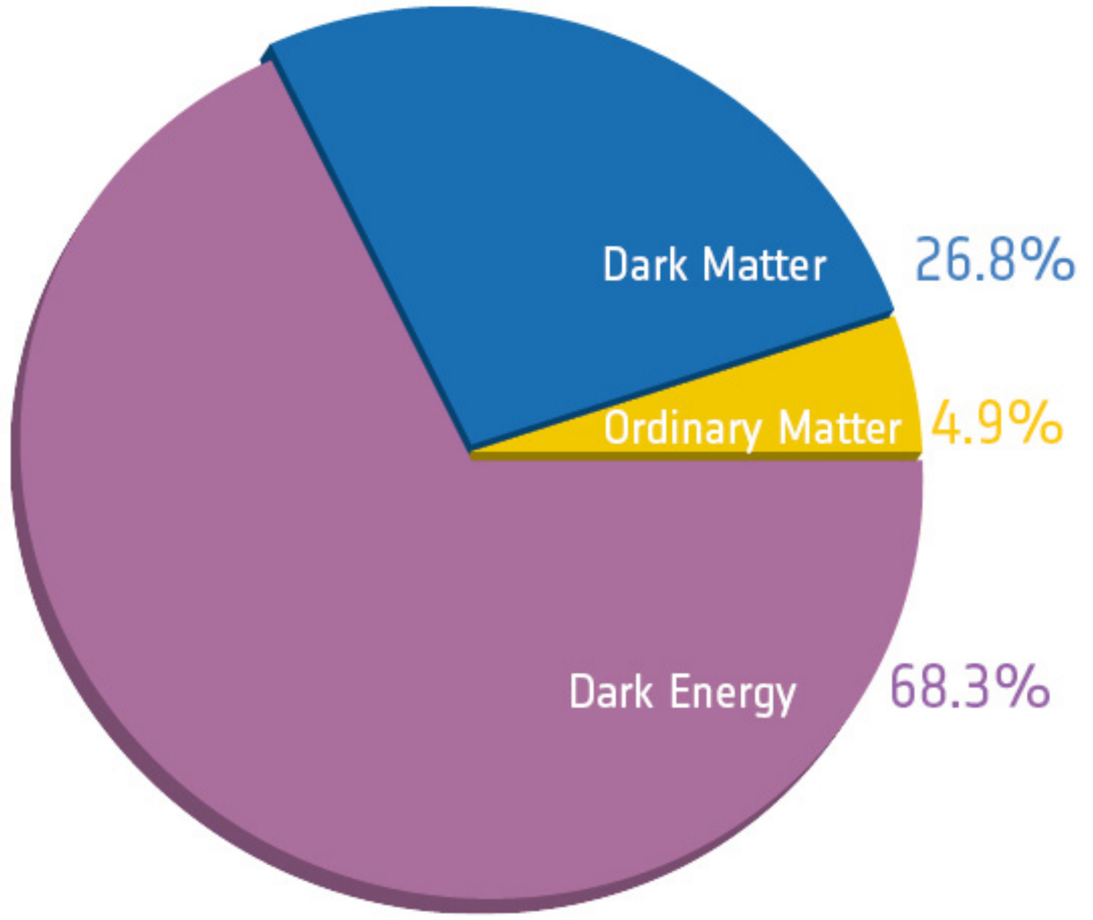
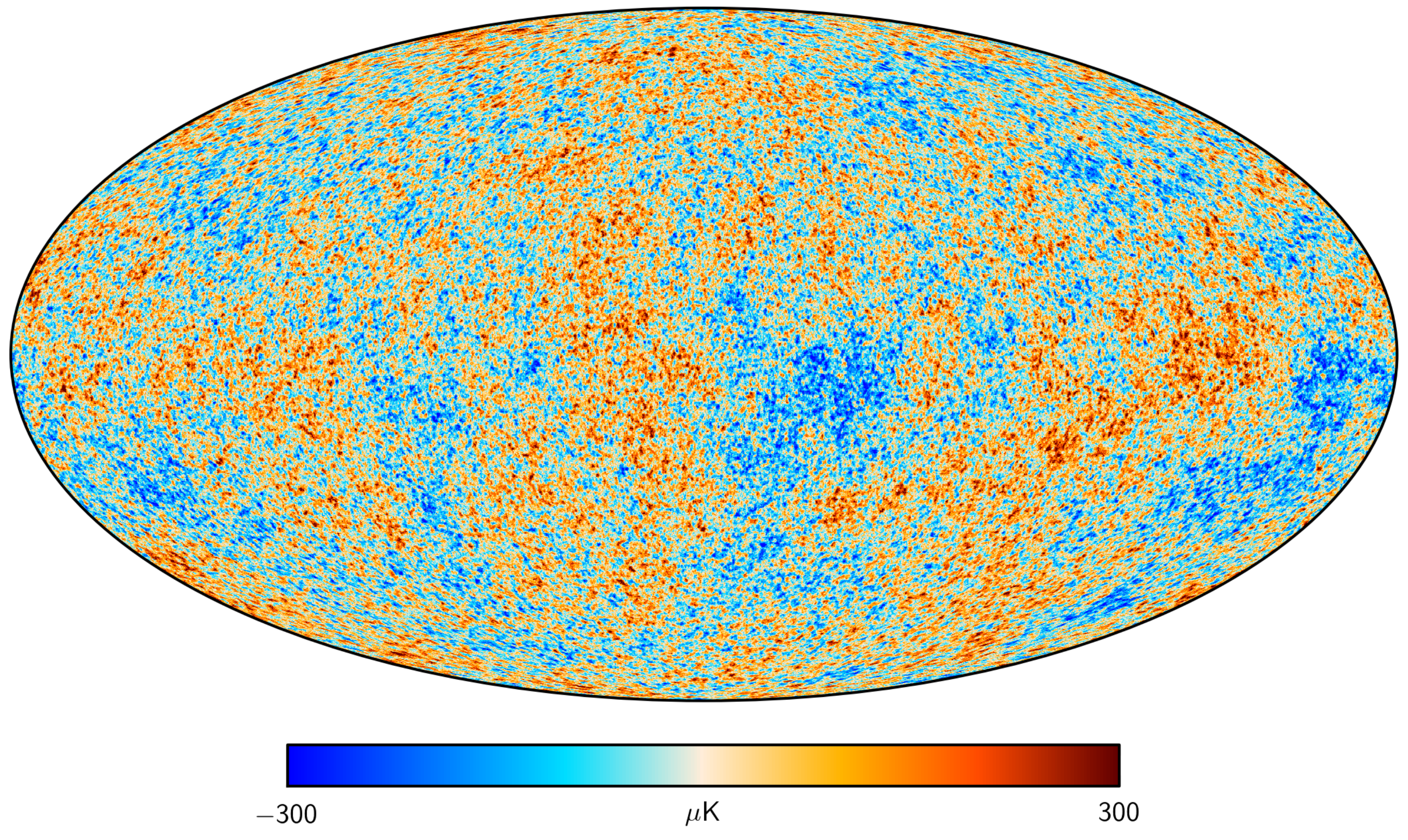
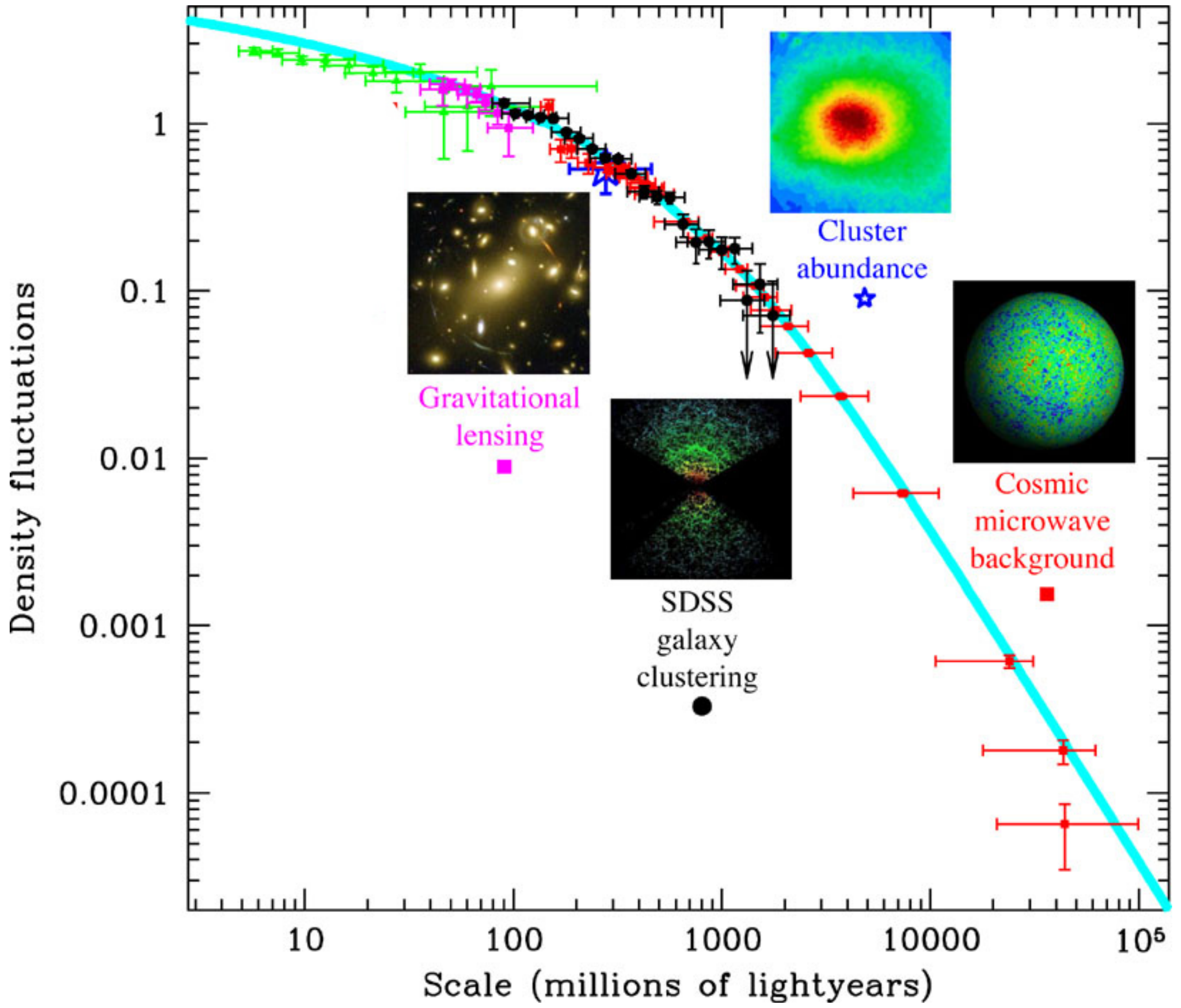


Figure credit: Planck collaboration

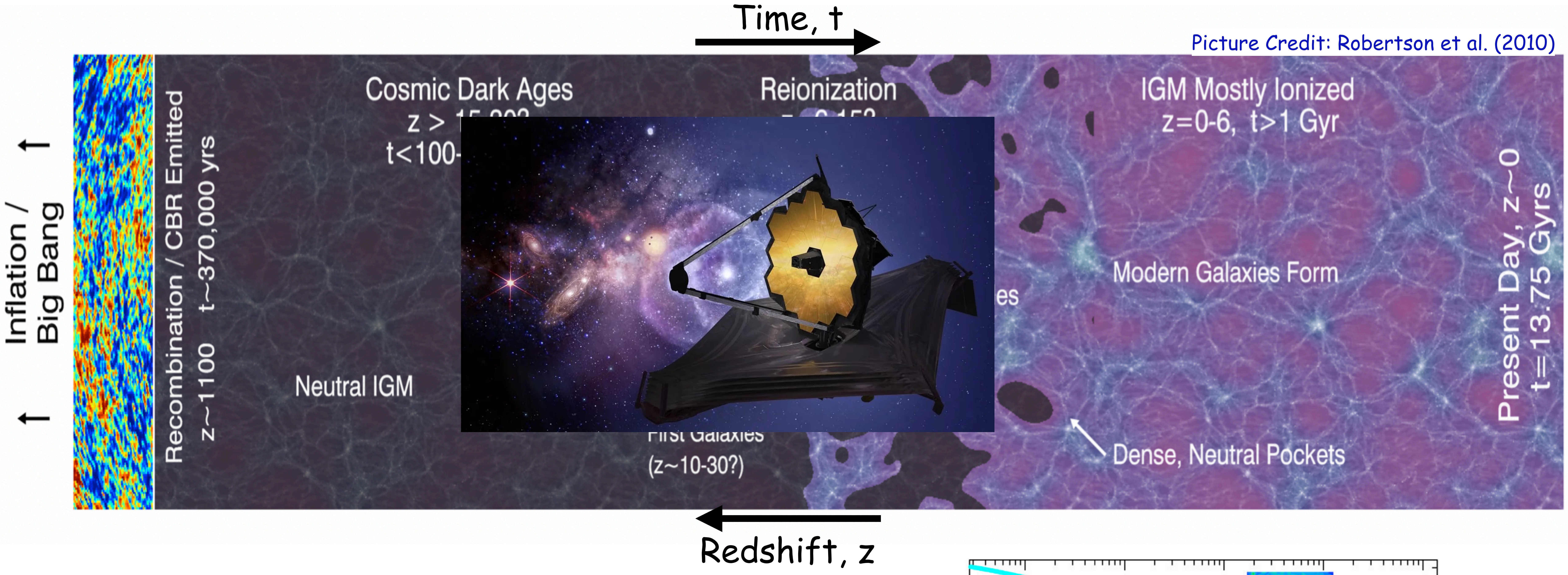




Standard ΛCDM Cosmology

- Six parameters model $(\omega_b, \omega_c, \tau_{\text{reio}}, \theta, A_s, n_s)$
- Fits the cosmological observations quite well.
- Some discrepancies? (H_0, σ_8)

Introduction



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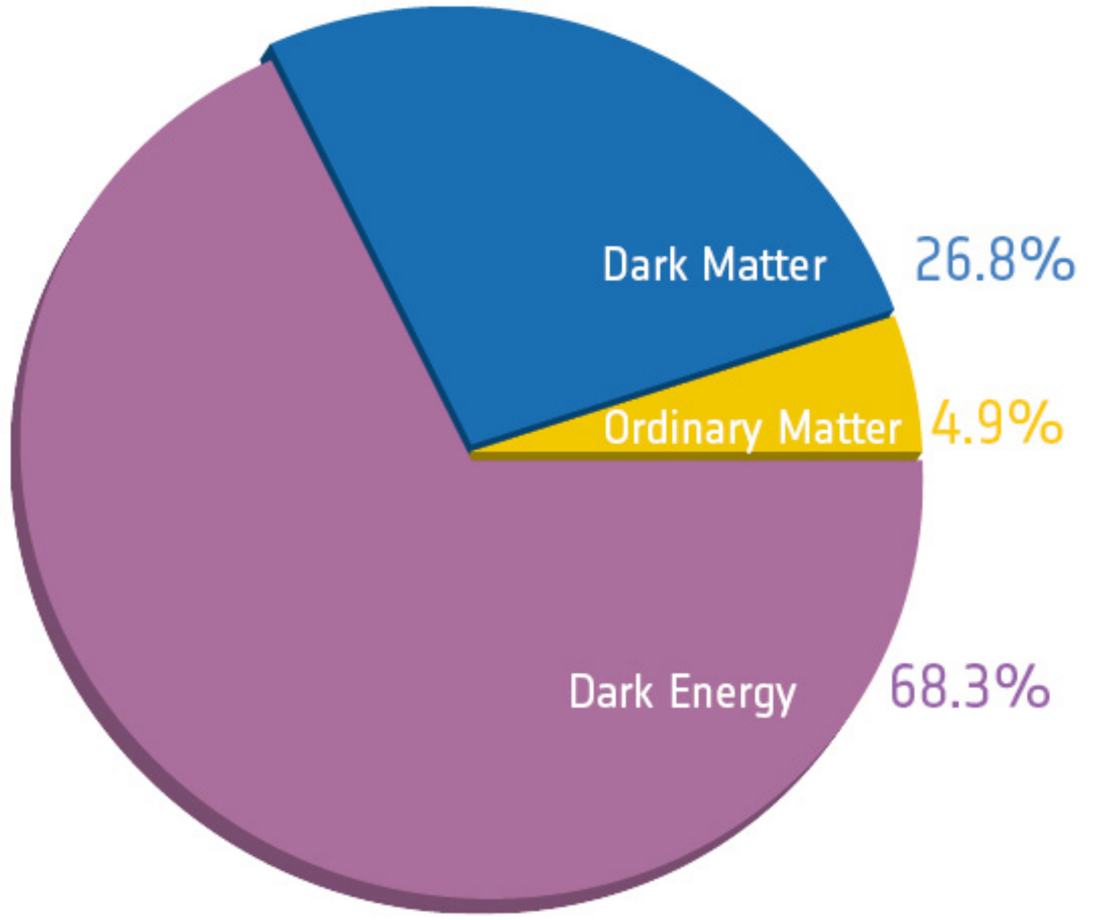

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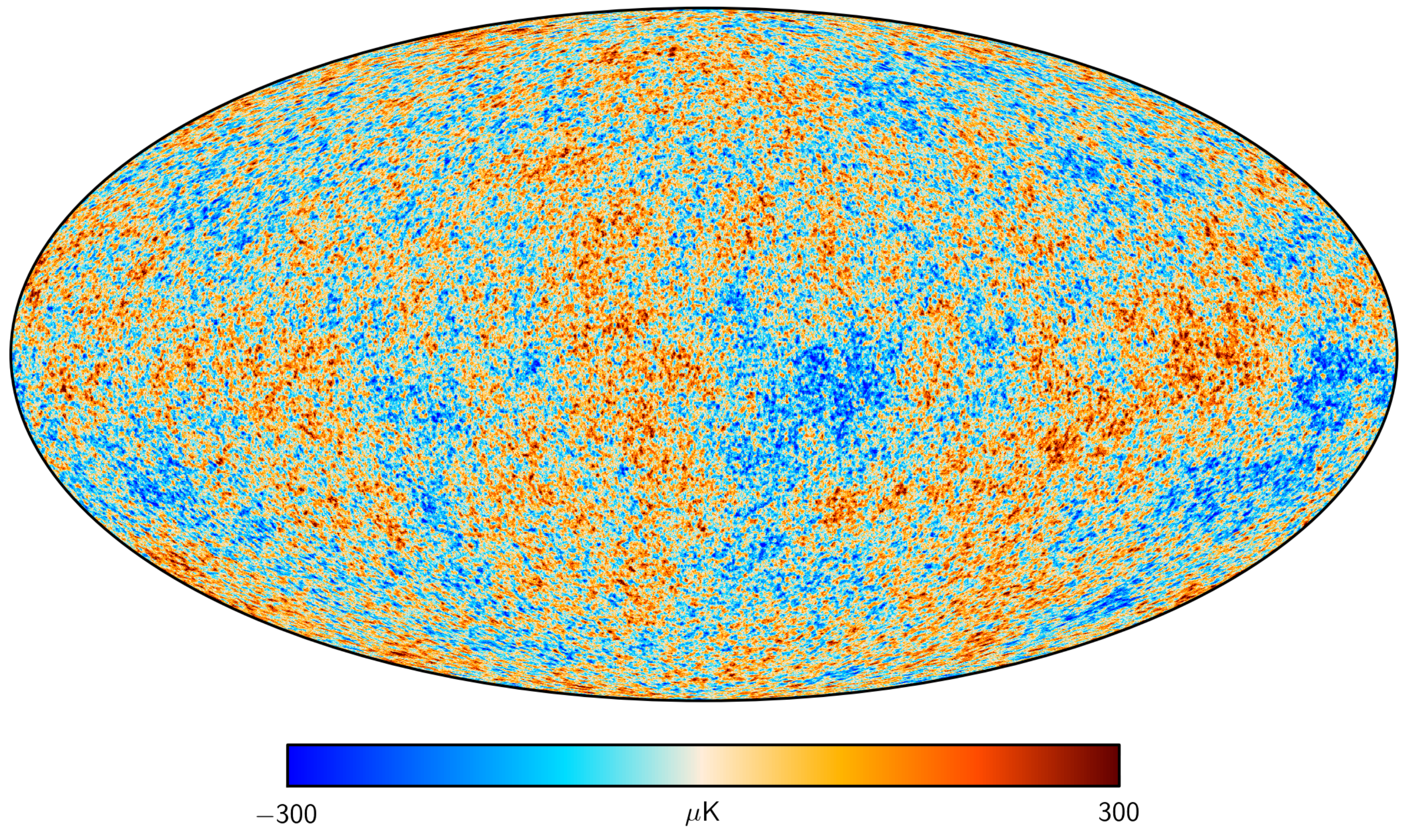

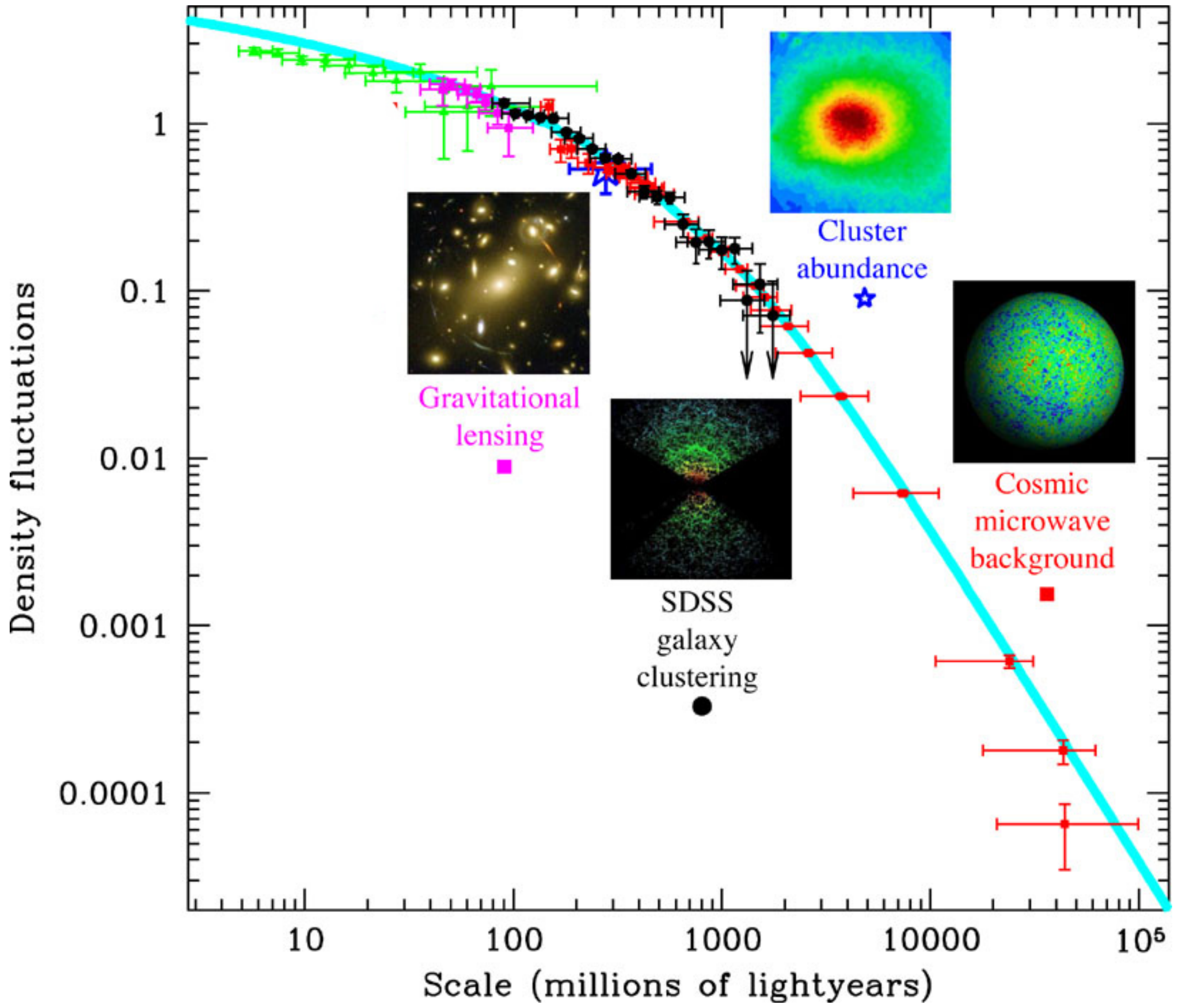

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James Webb Space Telescope (JWST)

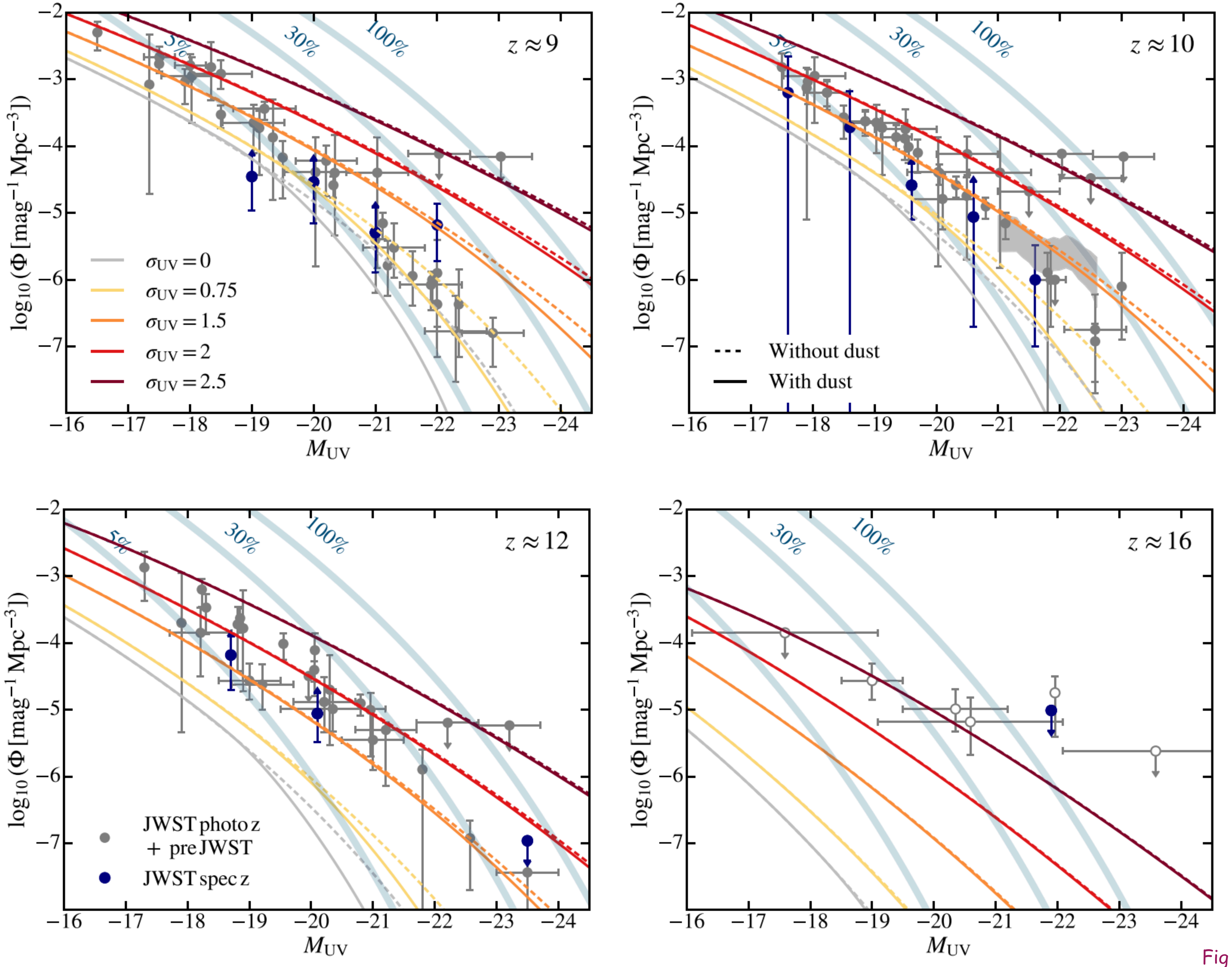
Figure credit: NASA webb

Launch date:
25 December 2021

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

- Young stars emits in UV range.
- JWST can observe the high redshift objects (higher than HST).

JWST Observations: ΛCDM tension?



- Early data releases of JWST have revealed several high redshift galaxy candidates. (Castellano et al. 2022; Finkelstein et al. 2022; Naidu et al. 2022b; Adams et al. 2023b; Atek et al. 2023; Bouwens et al. 2023a; Donnan et al. 2023; Harikane et al. 2023b; Robertson et al. 2023; Yan et al. 2023))
- A large population of ultra-violet (UV)-bright galaxies at $z \gtrsim 10$. (Finkelstein et al. 2023; Harikane et al. 2023b).
- Possible tension with standard galaxy formation models??

Most of them are observed by photometry and many of them have been confirmed spectroscopically.

Fig credit: Shen et al. MNRAS 525, 3254–3261 (2023)

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Early data releases of JWST have revealed several high redshift surprisingly massive galaxy candidates.

- Labbé et al. 2023 have found 13 galaxy candidates $(6.5 \leq z \leq 9.1)$ using JWST data released within the Cosmic Evolution Early Release Science (CEERS) program.

- Six candidates found to have stellar mass $M_* > 10^{10} M_\odot$.

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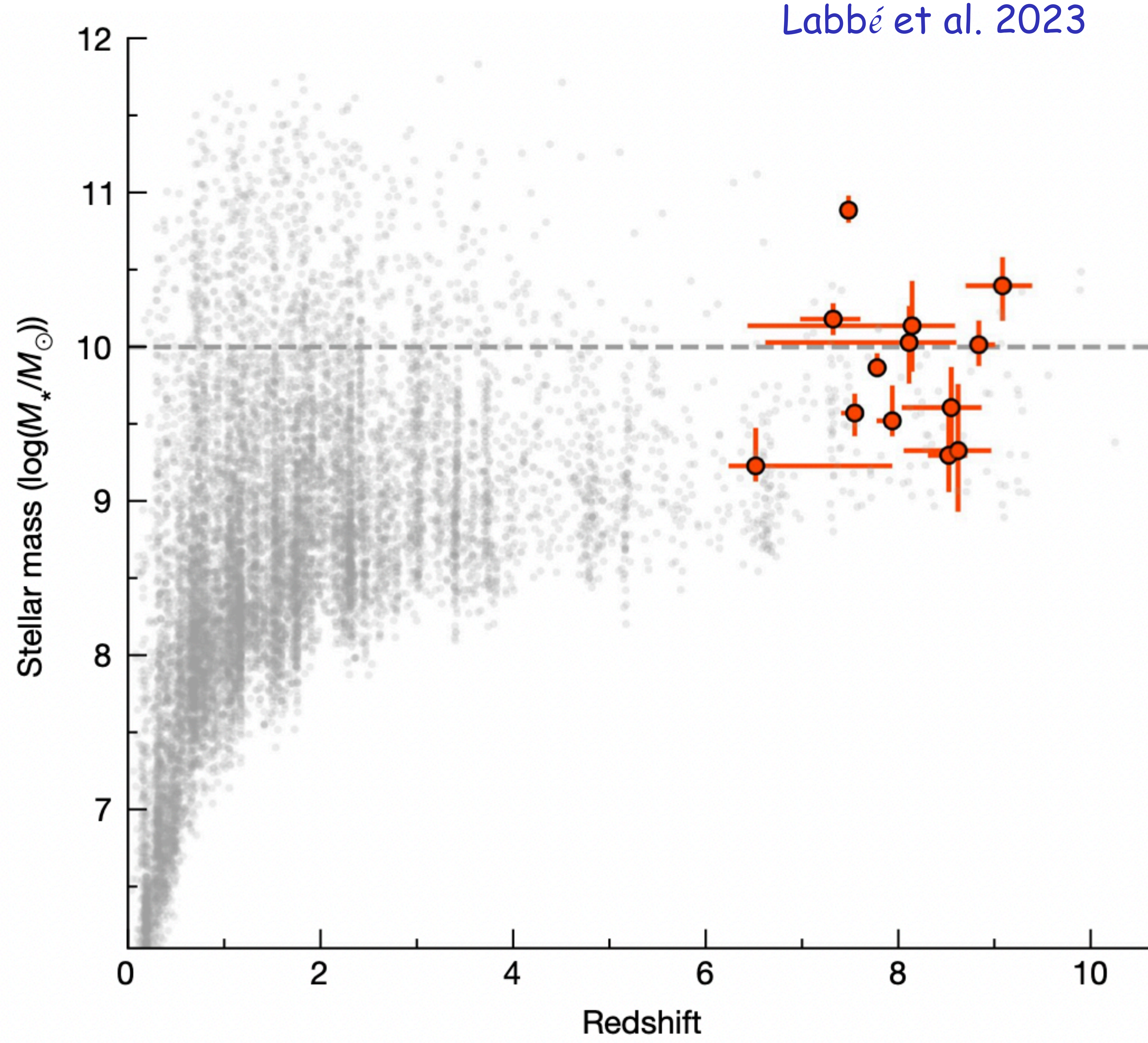
Labbé et al. 2023



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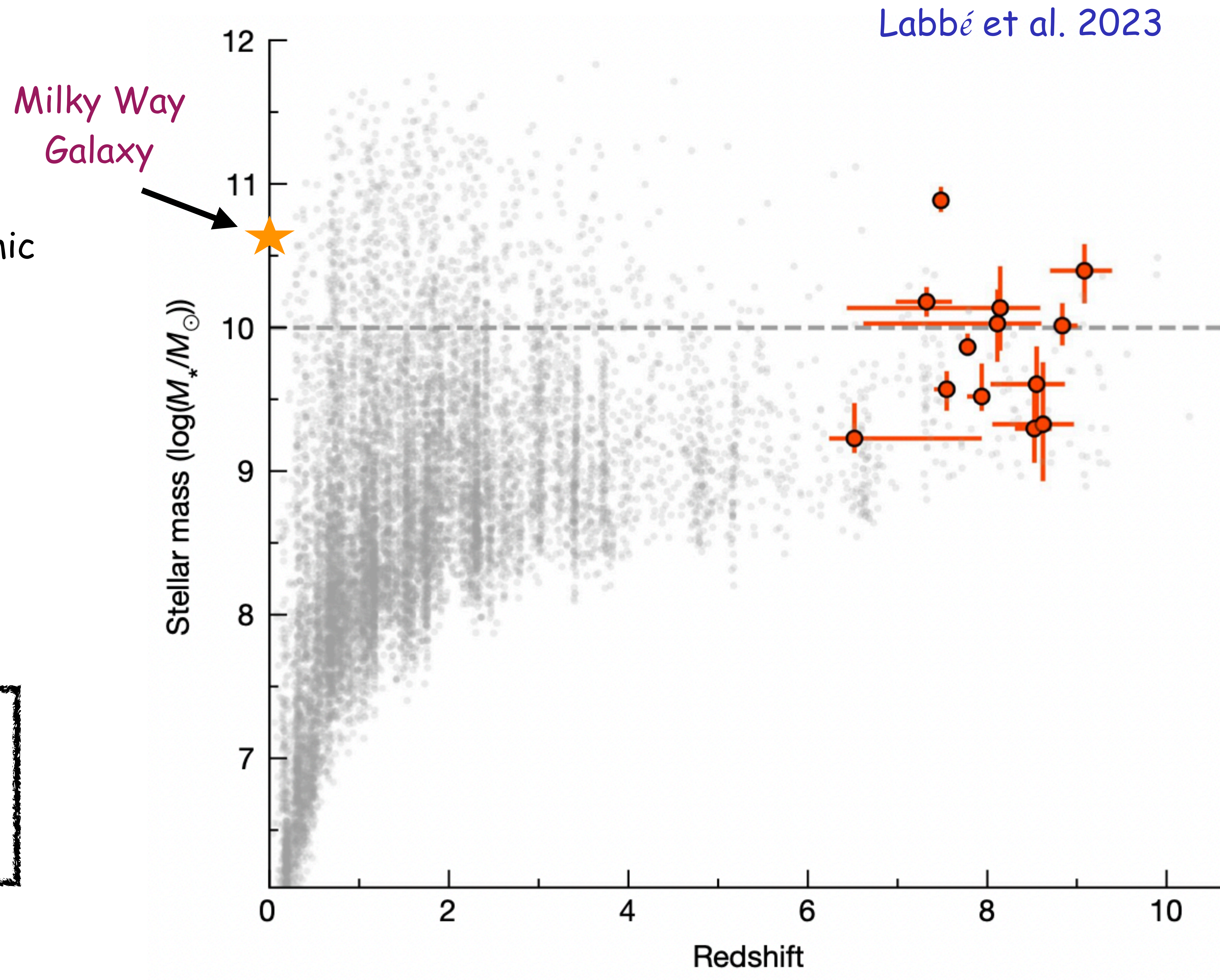
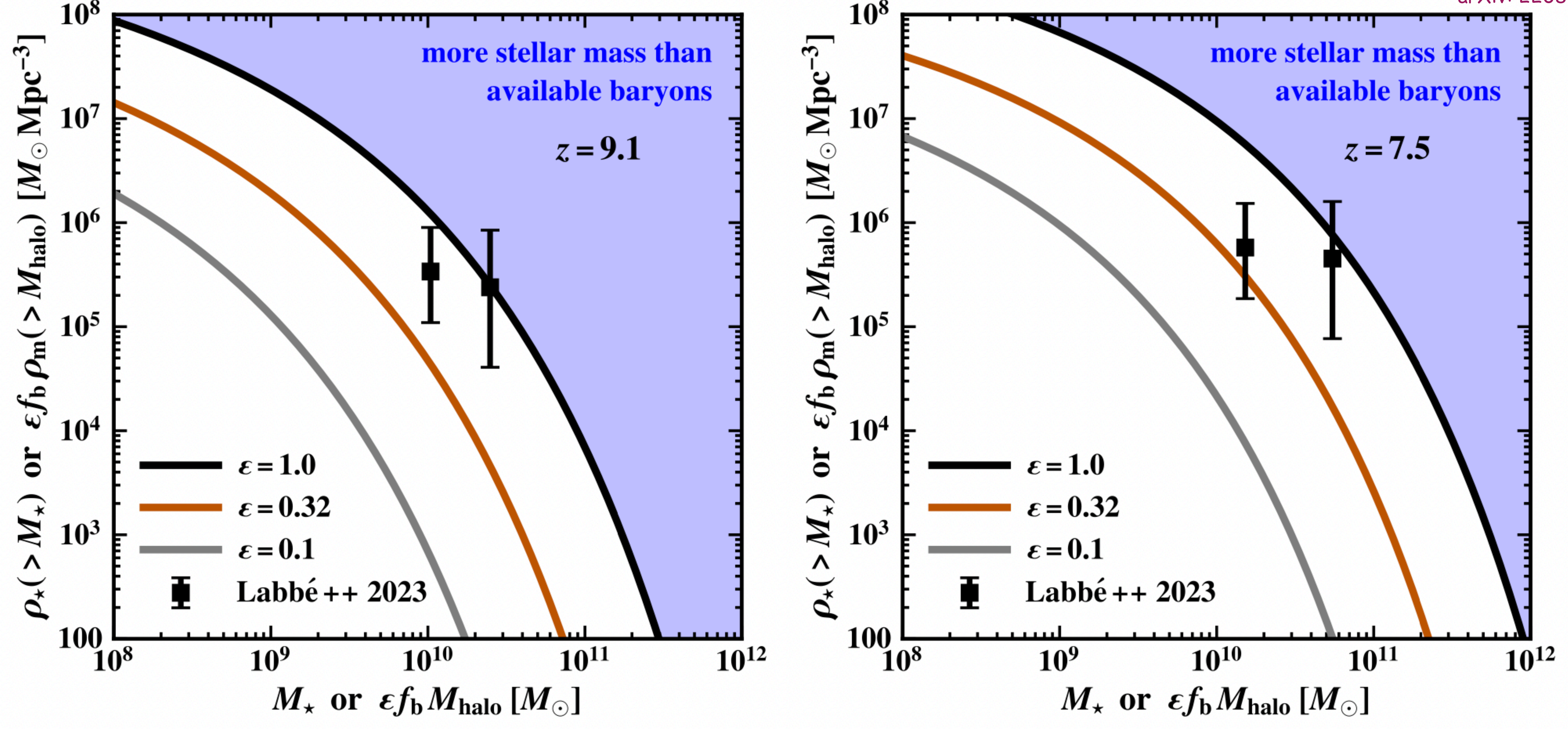


JWST Observations: ΛCDM tension?

These JWST observed massive galaxy candidates requires to have a very high star formation efficiency within standard cosmological model.

Boylan-Kolchin M., 2023, Nature Astronomy,
arXiv: 2208.01611



Actively debated in the literature and subject to systematic uncertainties (e.g. Larson et al. 2022; Chen, Mo & Wang 2023; Endsley et al. 2023; Prada et al. 2023; Steinhardt et al. 2023).

ΛCDM tension? → Hint for new physics?

Implications: Either the inferred galaxy properties are wrong (systematic or requires modification on the astrophysical side) or there is an issue with our successful standard cosmological model

- Various solutions involving modification on the astrophysical side or beyond standard cosmological model have been explored.

Early dark energy component (Shen et al. 2023; Boylan-Kolchin 2023), presence of primordial black holes or axion miniclusters (Liu & Bromm 2022; Hütsi et al. 2023; Yuan et al. 2023; Dolgov 2023), fuzzy dark matter & warm dark matter (Gong et al. 2023; Bin Liu et al. 2024), primordial non-Gaussianity (Biagetti et al. 2023), cosmic strings (Jiao et al. 2023).

Halo Mass Function

Semi-analytical method: We utilise the extended Press–Schechter formalism to compute the statistics of non-linear density field from the linear power spectrum.

The halo mass function is defined as the number density of DM haloes per unit mass:

$$\frac{dn}{d\ln M} = M\frac{\rho_0}{M^2}f(\sigma)\left|\frac{d\ln\sigma}{d\ln M}\right|$$

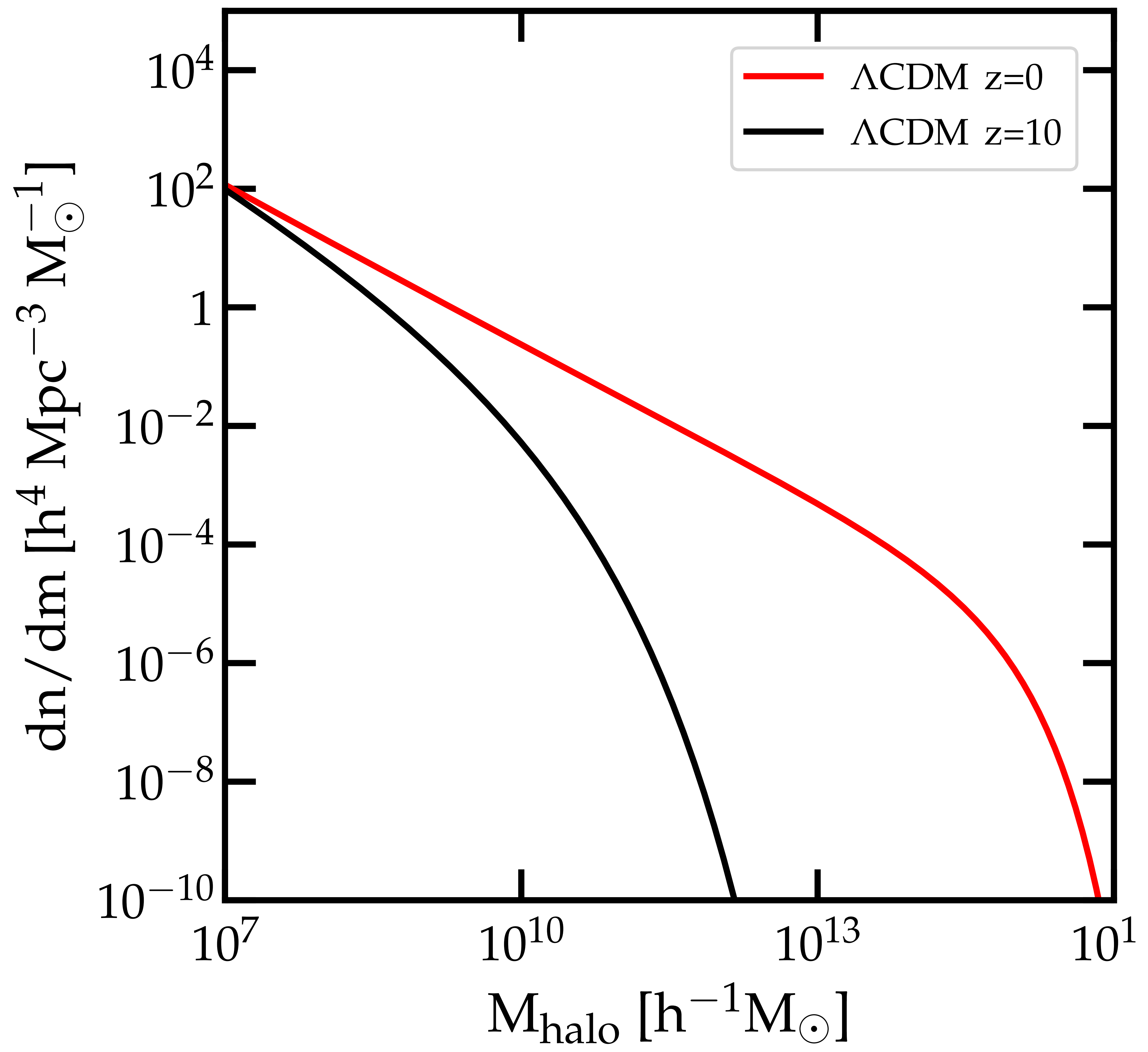
Where $\sigma^2(R) = \frac{1}{2\pi^2}\int_0^\infty k^2P(k)W^2(kR)dk$ and $M = \frac{4\pi\rho_0}{3}R^3$

For $f(\sigma)$, we use the Sheth-Tormen fitting function:

$$f(\sigma) = A\sqrt{\frac{2a}{\pi}}\left[1+\left(\frac{\sigma^2}{a\delta_c^2}\right)^p\right]\frac{\delta_c}{\sigma}\exp\left[-\frac{a\delta_c^2}{2\sigma^2}\right]$$

δ_c = critical overdensity for collapse, $A = 0.3222,\ a = 0.707,$ and $p = 0.3$

Computed using HMF code



Important quantities: Cumulative Comoving Number and Mass Densities & UV luminosity function

The cumulative comoving galaxy number density with stellar masses above some threshold

M_* as

$$n_*(>M_*, z) = \int_{M_{\rm halo}}^{\infty} dM \frac{dn(M,z)}{dM},$$

where $M_{\rm halo} = \dfrac{M_*}{\epsilon f_b}$ and $f_b = \Omega_b/\Omega_m$

and the corresponding cumulative comoving stellar mass density

$$\rho_*(>M_*, z) = \epsilon f_b \int_{M_{\rm halo}}^{\infty} dM\, M \frac{dn(M,z)}{dM}.$$

- ϵ is the star formation efficiency, and satisfies $\epsilon \leq 1$
- Exact value depends on star formation physics

UV Luminosity Function:

$$\Phi_{\rm UV} = \frac{dn}{dM}\frac{dM}{dM_{\rm UV}}$$

To compute UV Luminosity function, we need to know the $M_{\rm UV} - M_{\rm halo}$ relation.

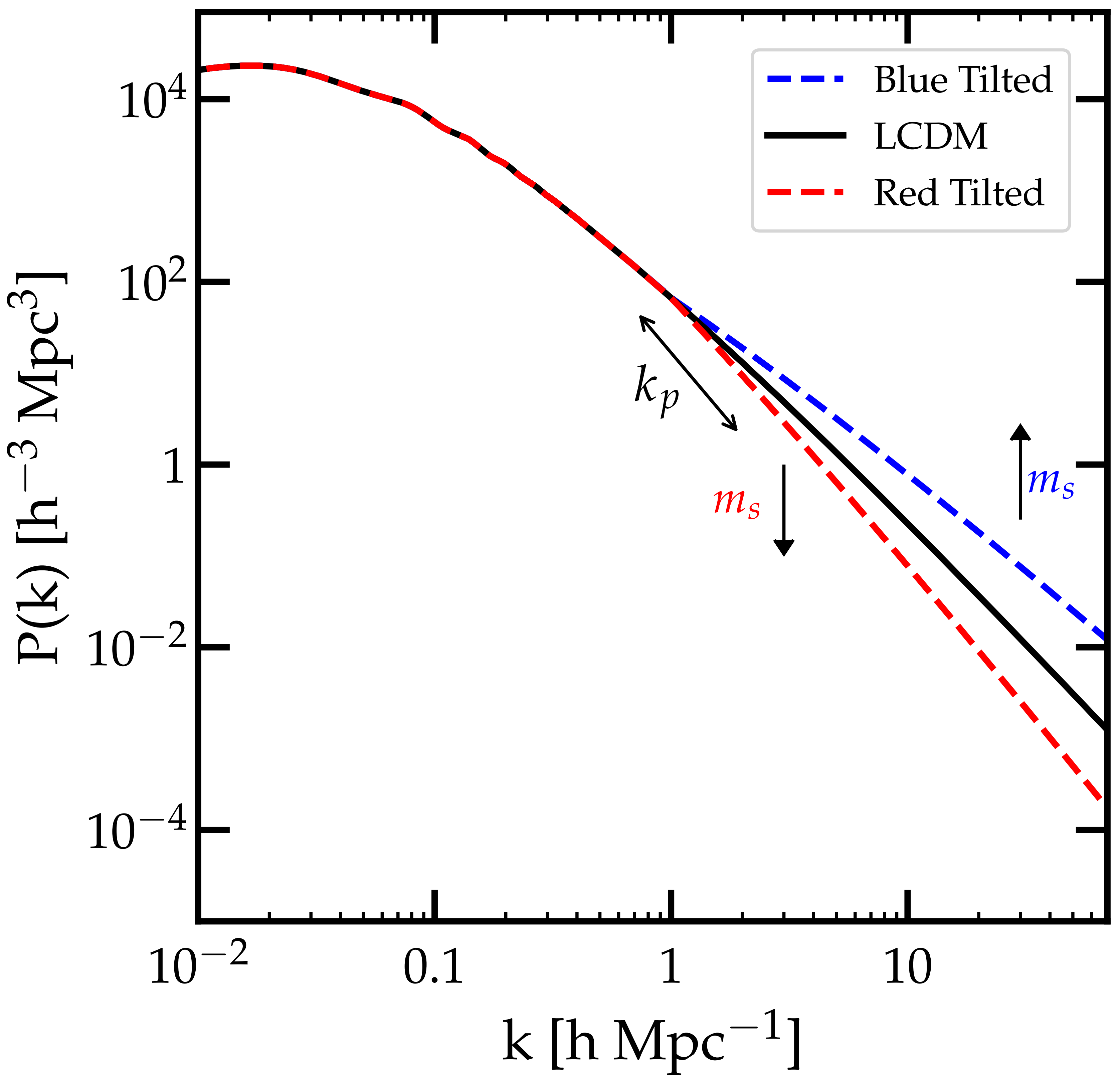
Modified Primordial Power Spectrum

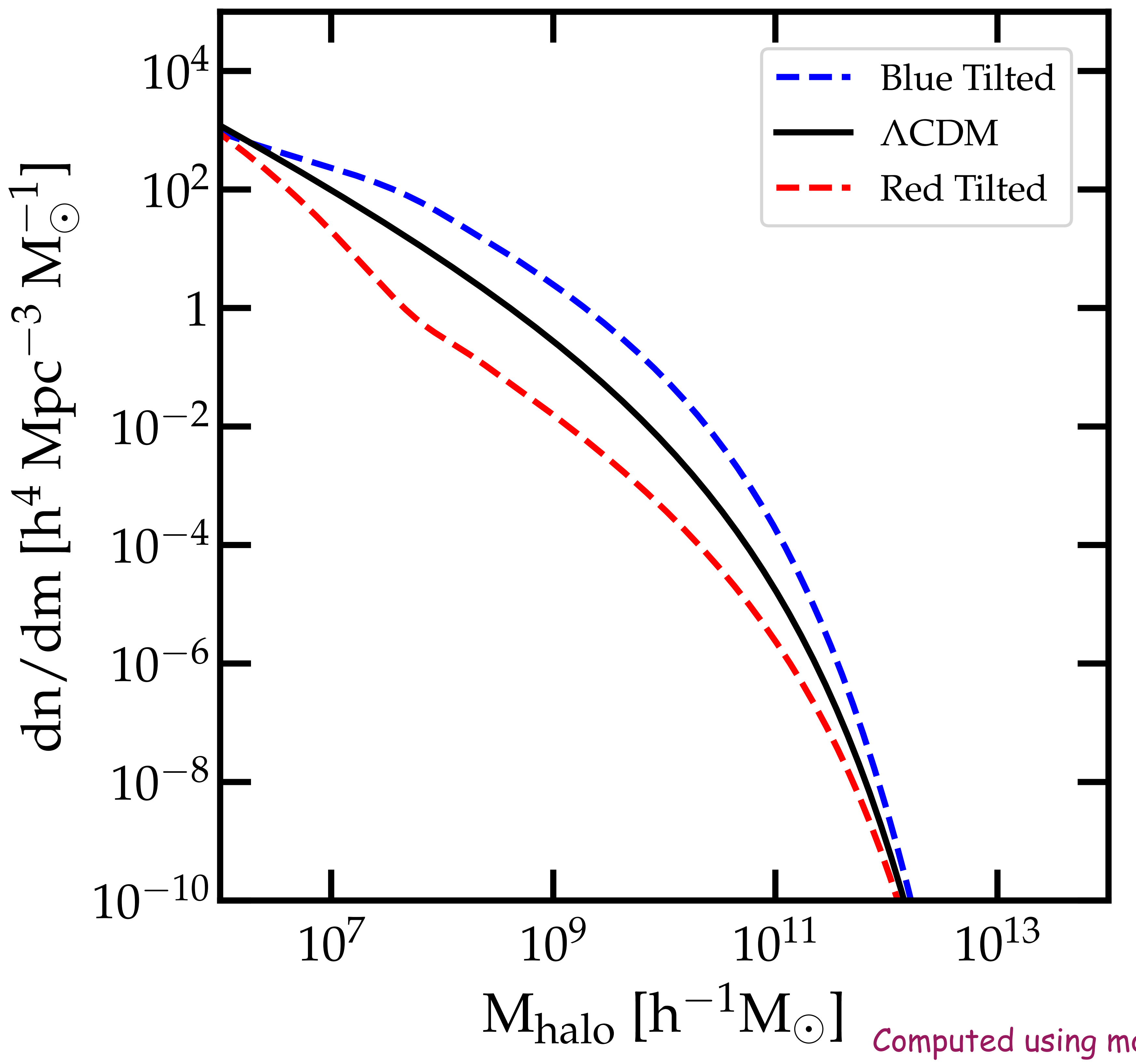
We study a modified primordial power spectrum where it deviates from the standard primordial power spectrum at small length scales with a model agnostic form:

P. Parashari & R. Laha, MNRAS: Letters, 526, L63–L69 (2023) arXiv: 2305.00999

$$P_{\rm prim}(k) \propto k^{n_s}, \qquad \text{for } k < k_p,$$
$$\propto k_p^{n_s - m_s} k^{m_s}, \qquad \text{for } k > k_p\,.$$

For $m_s > n_s$, the power spectrum will be blue tilted on scales $k > k_p$, and it is red tilted if $m_s < n_s$.



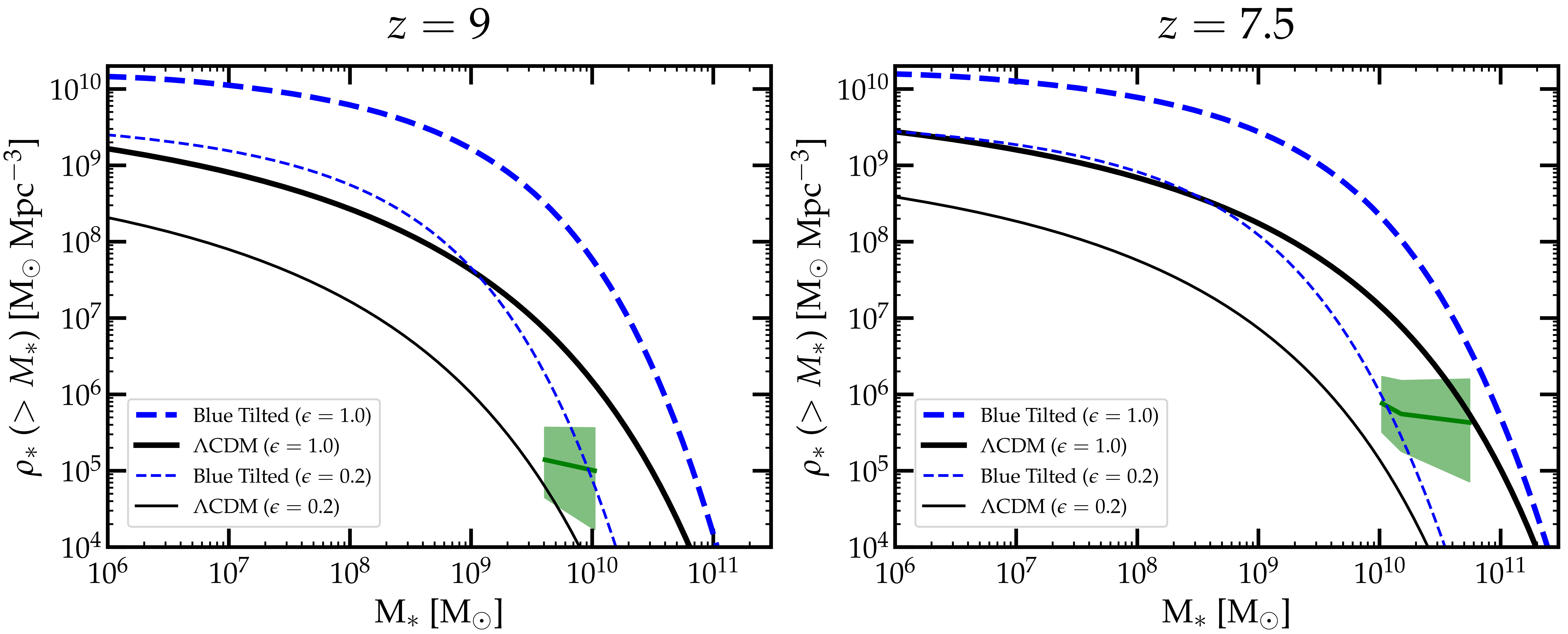


Computed using modified HMF code

JWST Observations and Modified Power Spectrum

P. Parashari & R. Laha, MNRAS: Letters, 526, L63–L69 (2023) arXiv: 2305.00999

- Blue-tilted primordial power spectrum can reduce the required star formation efficiency.



$m_s = 2.0$ and $k_p = 1\,h\,Mpc^{-1}$

Computed using modified HMF code

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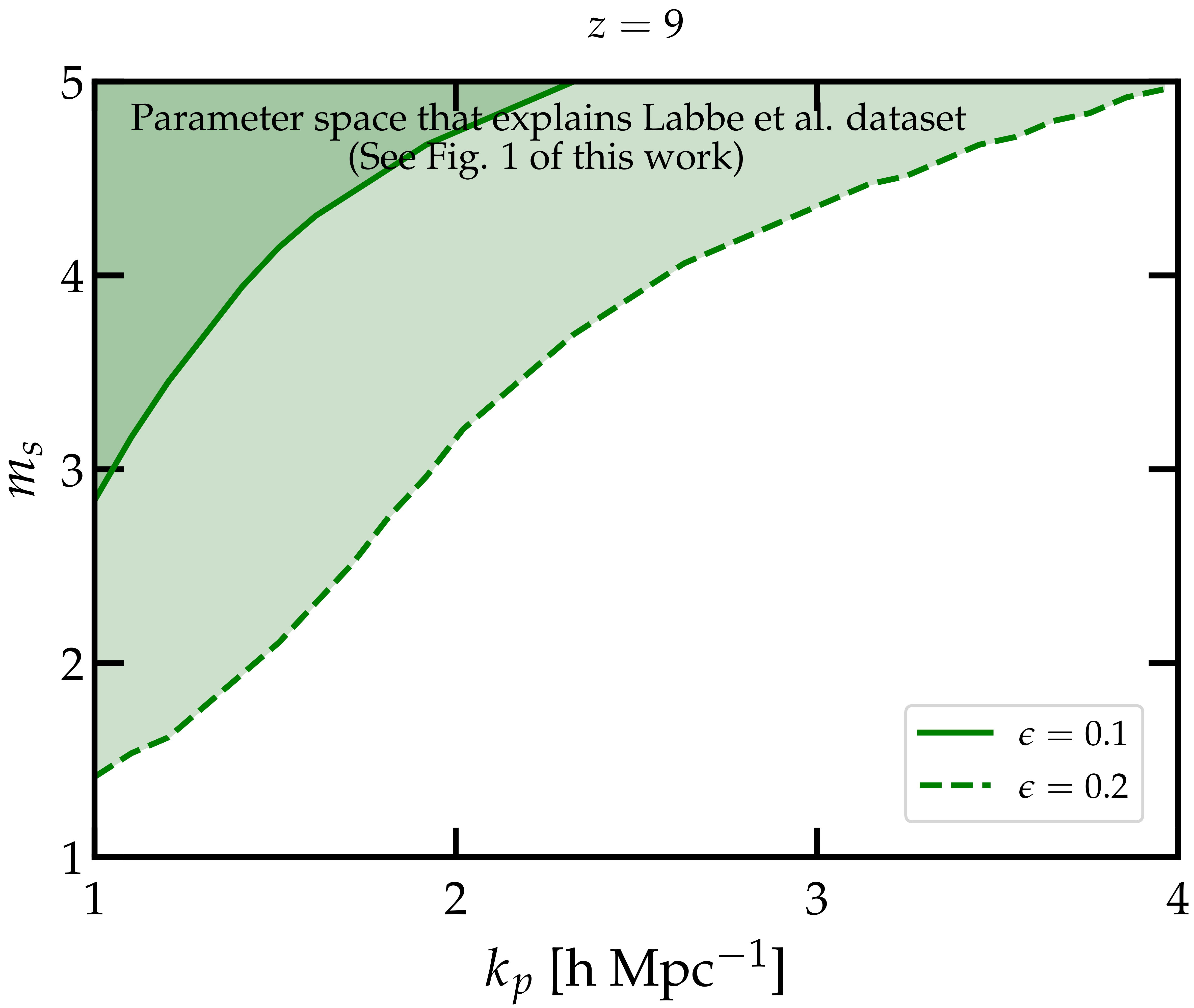

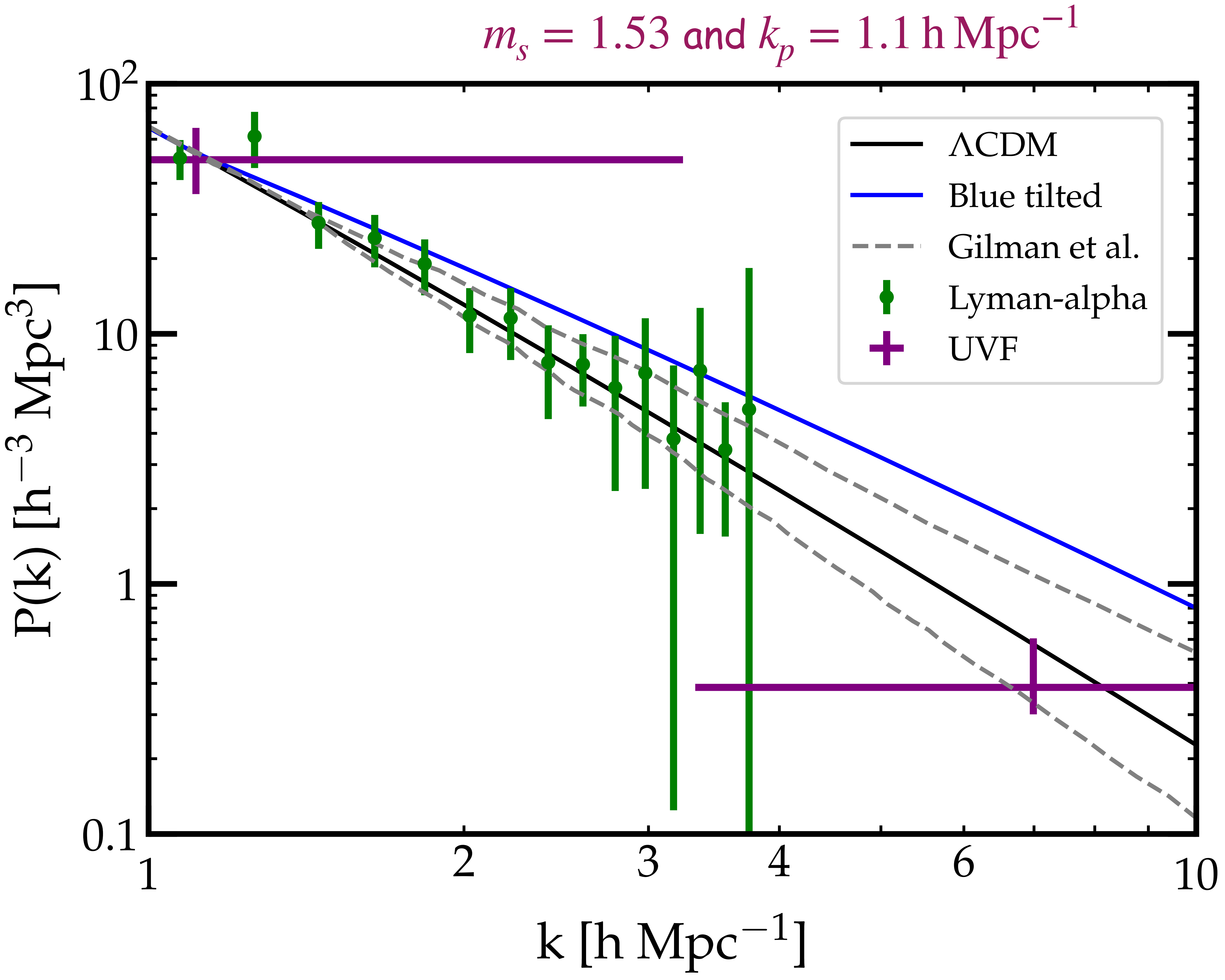

- Required parameter space to reduce this tension may be in conflict with earlier observations.

P. Parashari & R. Laha, MNRAS: Letters, 526, L63–L69 (2023) arXiv: 2305.00999

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Other Works with JWST Observations and Modified Power Spectrum

- After our work, Hirano & Yoshida (2023) did simulations with a blue-tilted power spectrum and **found their results consistent with our results**. (arXiv: 2306.11993). Padmanabhan H. & Loeb A. (2023) also found similar results arXiv:2306.04684.

- In another work, Sabti et al. (2023) performed an analysis by assuming a Gaussian enhancement in the power spectrum and found that the enhancement required to explain Labbé et al. (2023) observations will conflict with previous constraints on these scales by HST, **which is consistent with our result**. (arXiv: 2305.07049)

JWST observations from the JADES program (spectroscopically confirmed galaxies)

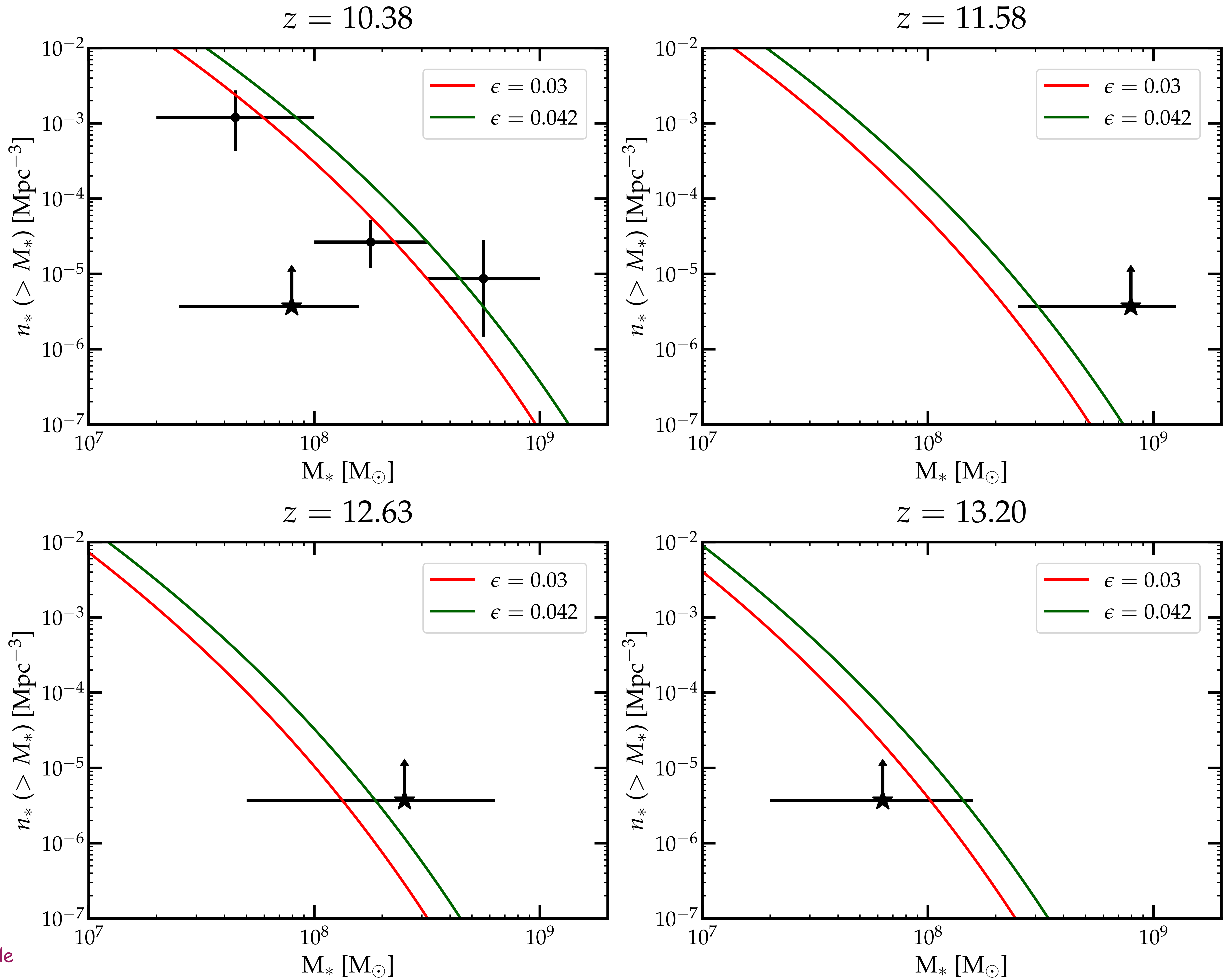
JWST Observations (JADES)

P. Parashari & R. Laha, MNRAS: Letters, 526, L63-L69 (2023) arXiv: 2305.00999

- Recently Curtis-Lake et al. (2022) and Robertson et al. (2023) have reported 4 galaxies from the JADES survey with spectroscopically confirmed redshifts ($z > 10$).

- Keller et al. (2023) reported the lower limit on cumulative comoving galaxy number density inferred from these observations (Black stars).

> Since a red-tilted primordial power spectrum predicts a smaller cumulative comoving galaxy number density, we can use this observational data to constrain the red-tilt for a given ϵ.



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Constraints on Power Spectrum

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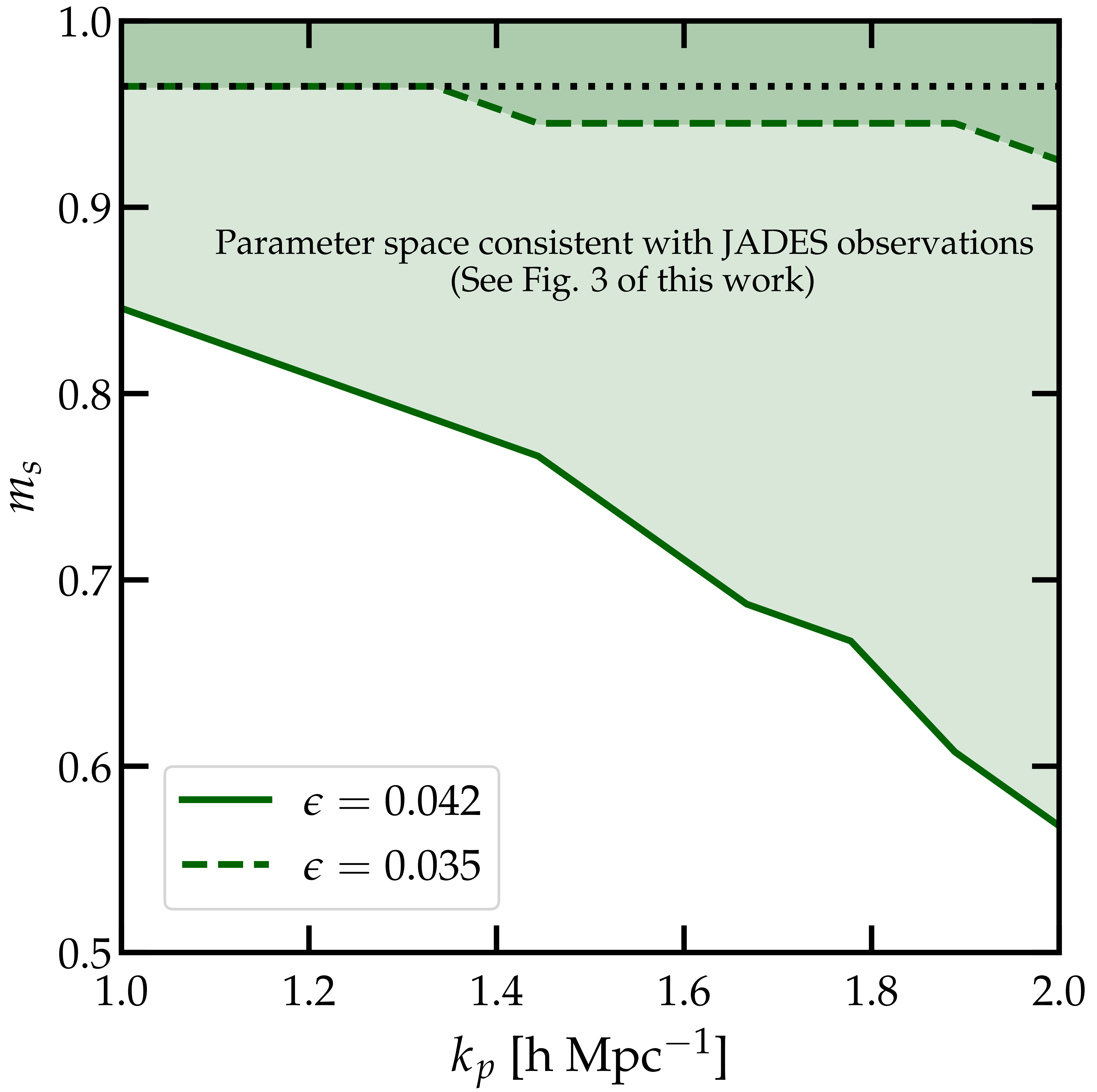

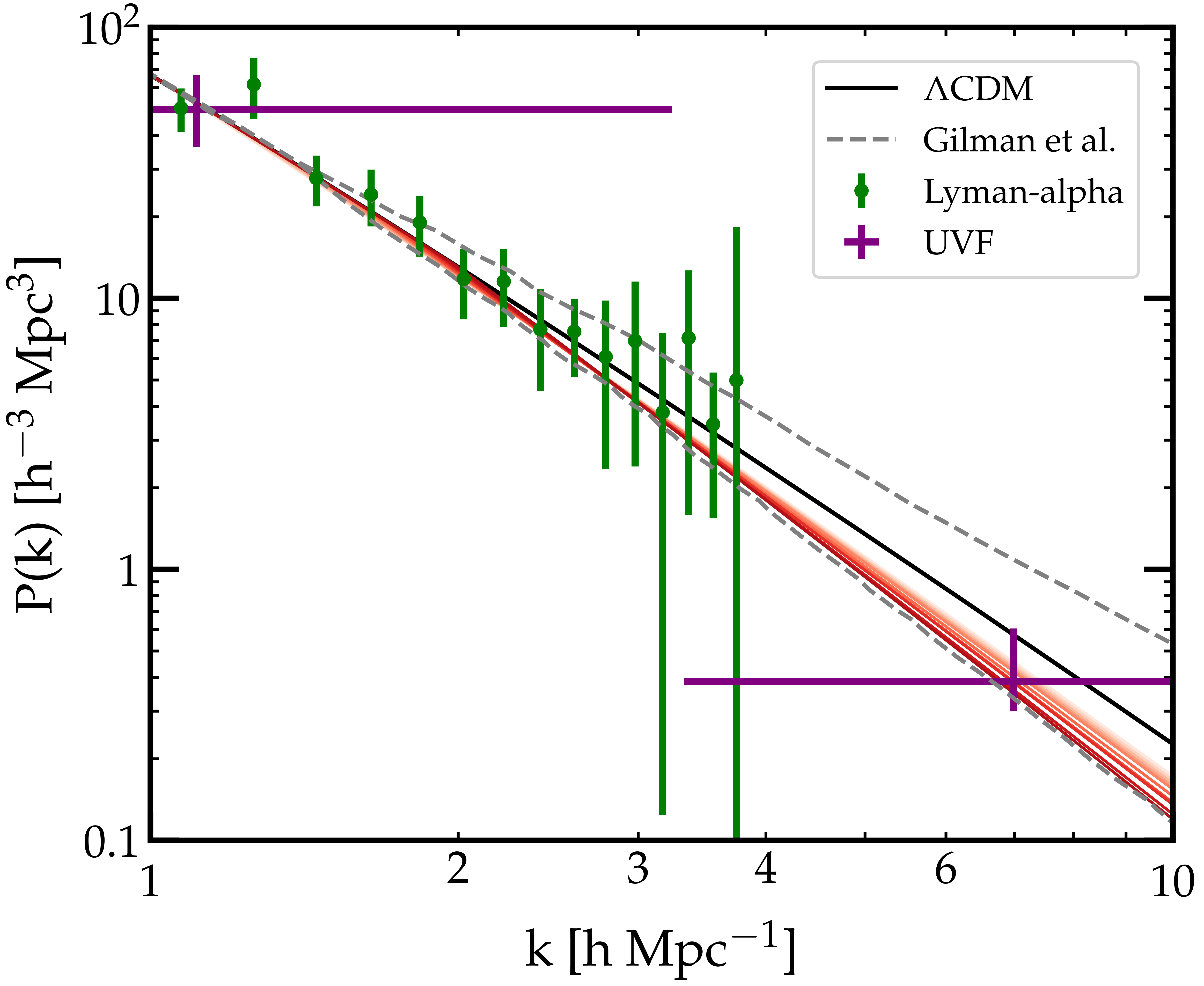

Computed using modified HMF code

we find the most stringent constraint on the matter power spectrum at scales $k \sim 2 - 7\,\mathrm{h\ Mpc^{-1}}$.

Summary

- JWST has opened up a new window to probe our Universe.
- JWST has already provided exciting and surprising results by observing several surprisingly UV-bright and massive galaxy candidates at high red shifts.
- High star formation efficiency is required to explain these galaxies within standard cosmology.
- A blue-tiled power spectrum can reduce this tension. However, the required parameter space will conflict with other observations.
- JWST has also reported a few spectroscopically confirmed galaxies. These galaxies can put the stringent constraints on matter power spectrum over scales $k \sim 2 - 7\,\mathrm{h\ Mpc^{-1}}$.
- We show the significance of JWST observations as a potential power spectrum probe.

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Thank you!

Outline

- Introduction to standard cosmological model
- Matter power spectrum and halo mass function
- JWST observations of high redshift galaxies
- Modified primordial power spectrum and JWST observations
- Summary

Standard Cosmological Model

Standard Cosmology: Inflation + ΛCDM

- Six parameters model $(\omega_b, \omega_c, \tau_{\rm reio}, \theta, A_s, n_s)$
- Fits the cosmological observations

Parameters related to inflation

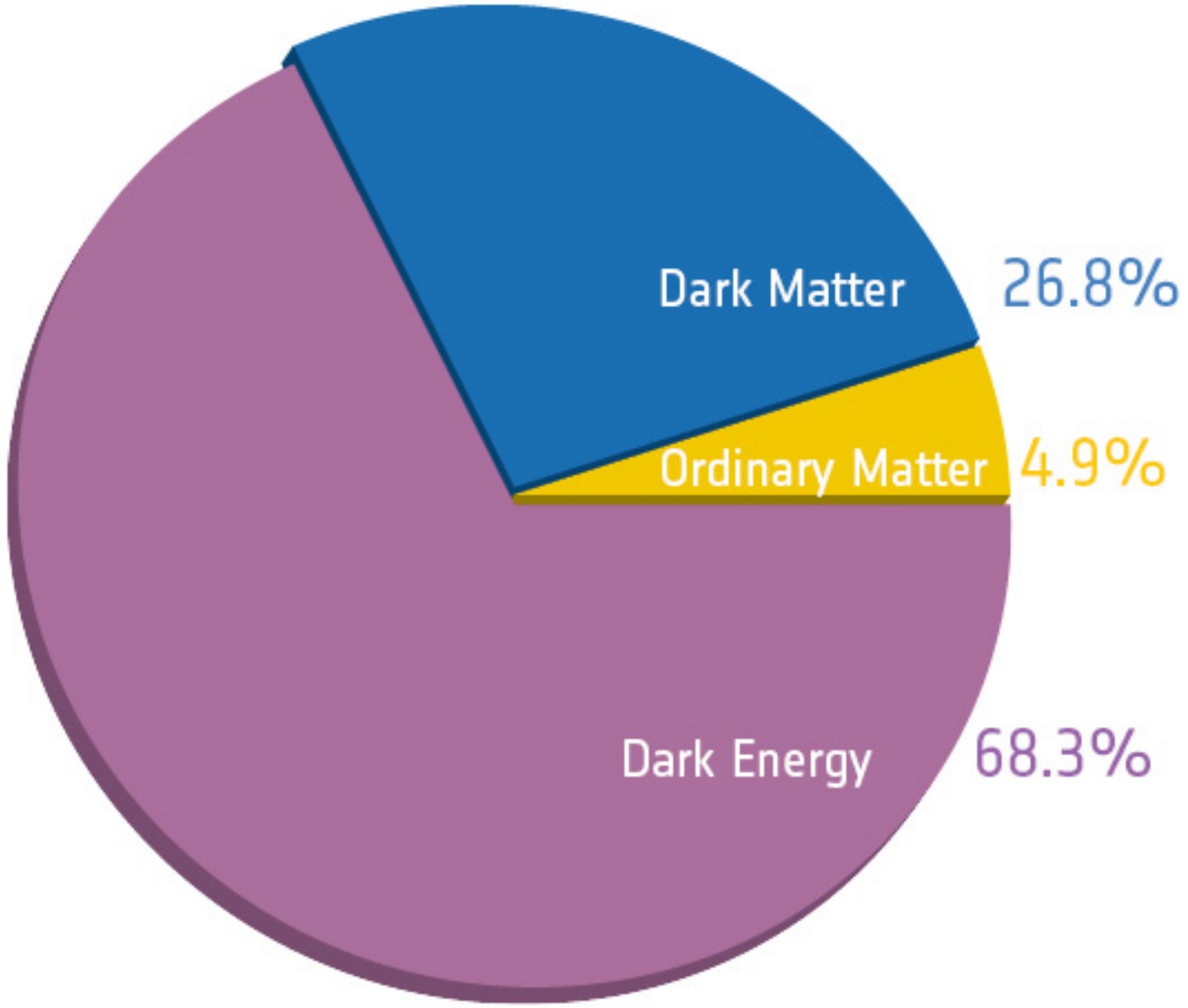

Figure credit: Planck collaboration

- Inflation sets the initial condition for the structure formation.
- The minimal single field inflation models predict a scale invariant primordial power spectrum.

$$P_{\rm prim} = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

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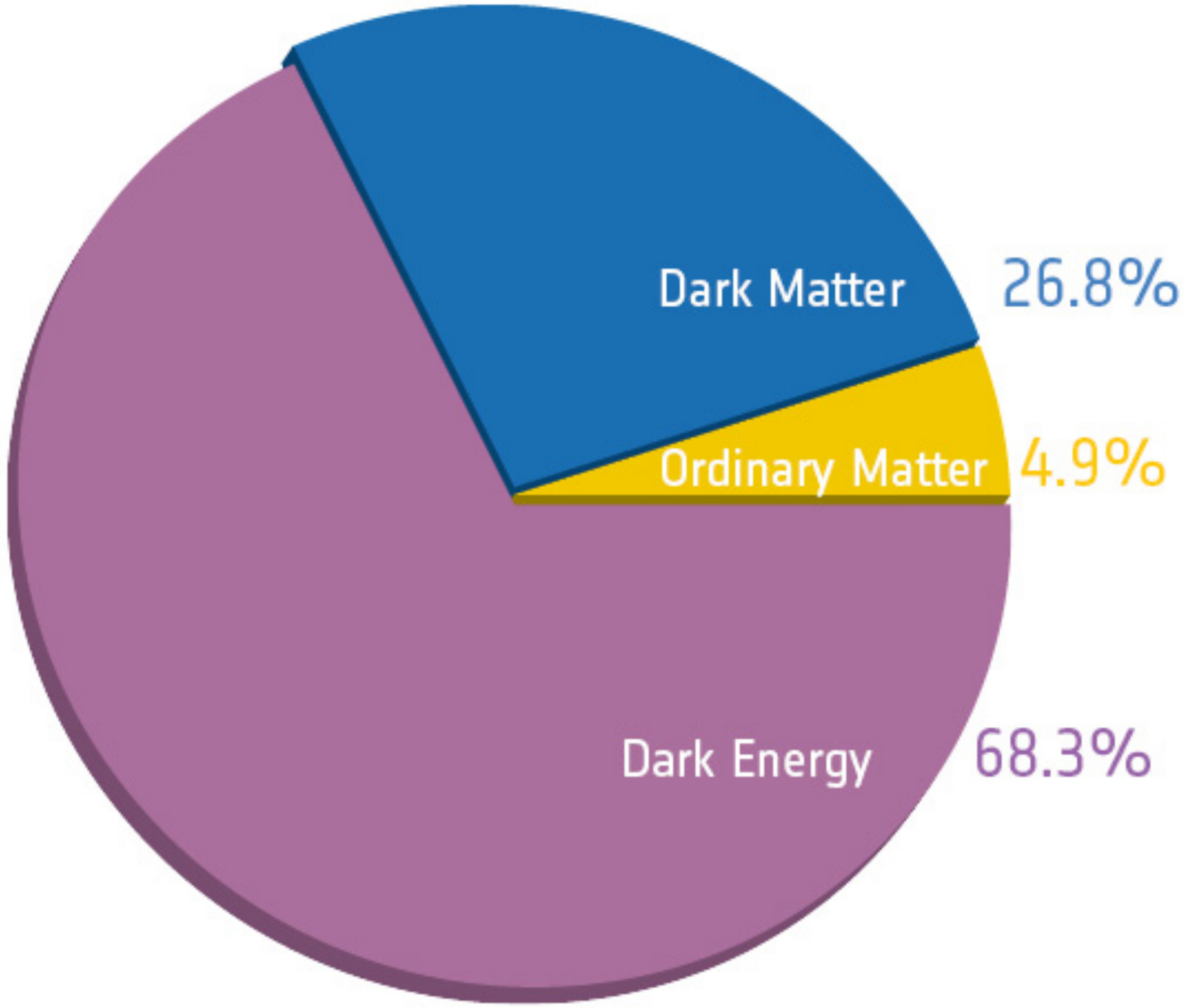

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Planck CMB 2018 contraints:

$n_s = 0.9649 \pm 0.0042$

$A_S = (2.099 \pm 0.102) \times 10^{-9}$

- CMB does not probe all the scales.
- Other observations at different scales is needed to probe power spectrum at all scales.

Matter Power Spectrum

- Tiny fluctuations generated during inflation evolves and form the structures that we observe at present.
- The matter power spectrum: defined as the two point correlation function of the density perturbations.

$$P(k) = P_{\rm prim}(k)T^2(k)$$

where $P_{\rm prim}(k)$ is the primordial power spectrum (depends on inflation model) and $T(k)$ is the transfer function.

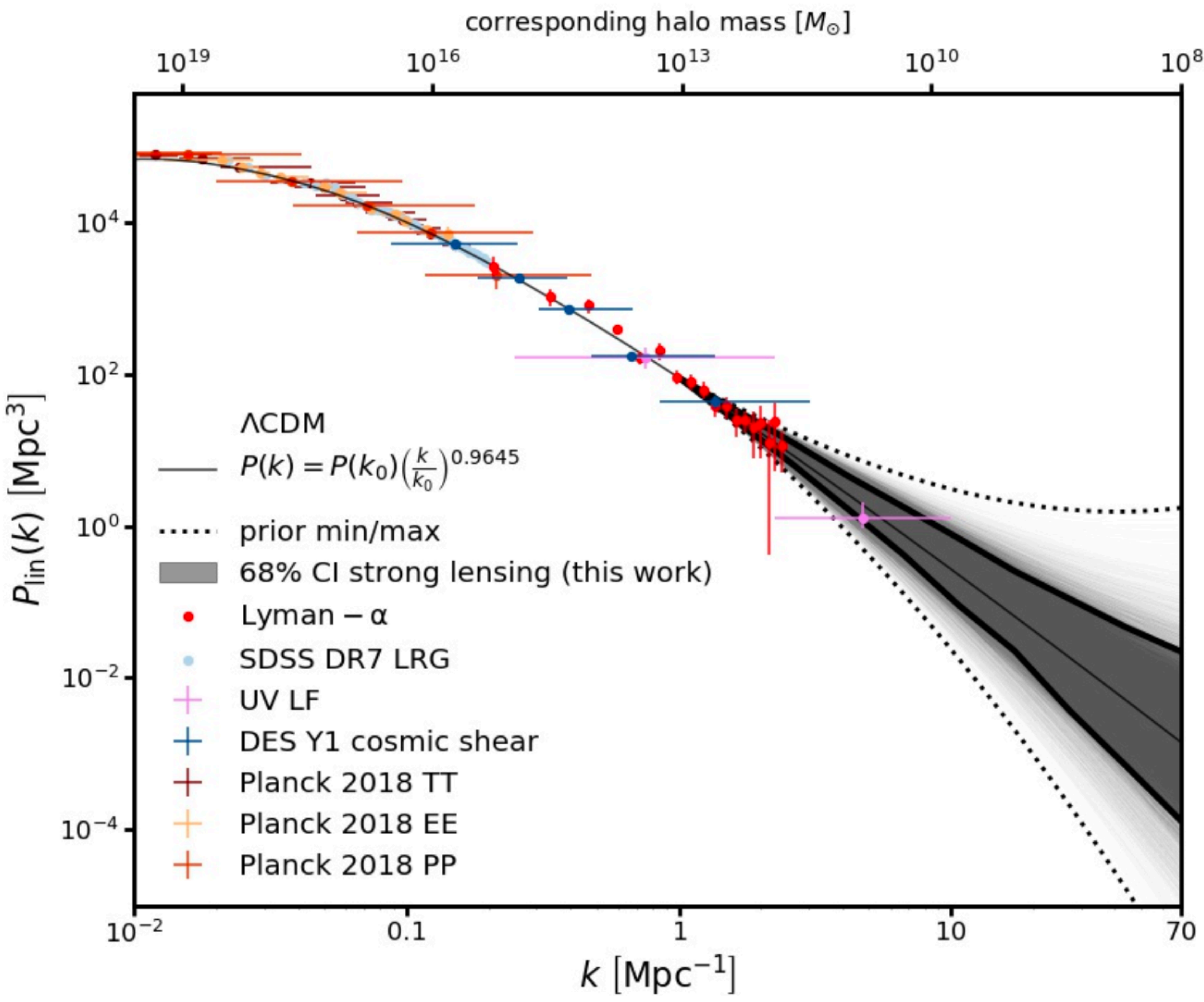
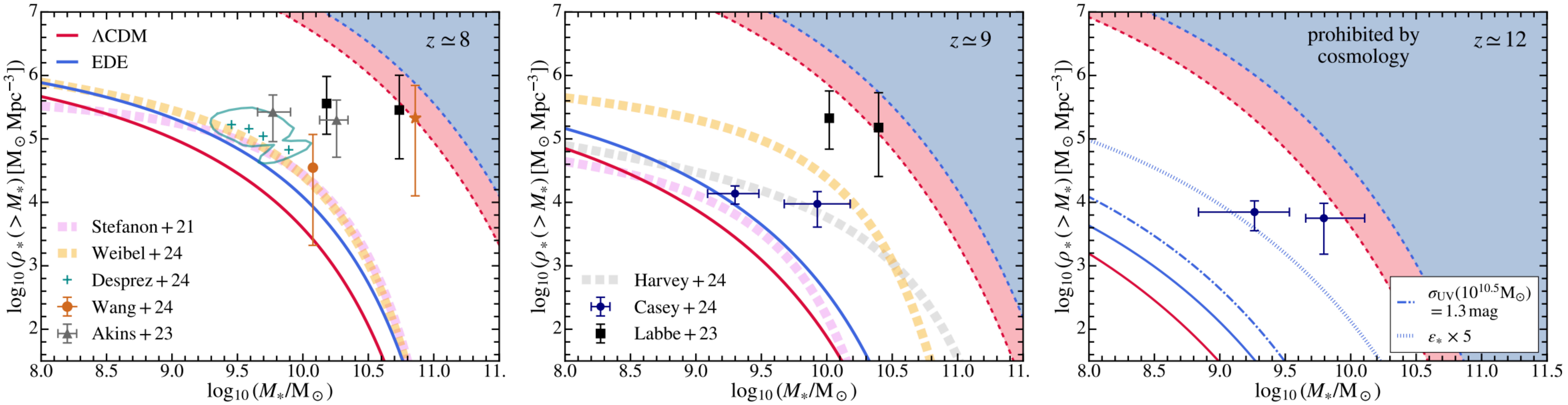


Figure credit: D. Gilman et al. (2022) arXiv:2112.03293



ΛCDM
EDE
z ≃ 8
Stefanon + 21
Weibel + 24
Despréz + 24
Wang + 24
Akins + 23
z ≃ 9
Harvey + 24
Casey + 24
Labbe + 23
z ≃ 12
prohibited by cosmology
$\sigma_{UV}(10^{10.5} M_\odot) = 1.3$ mag
$\varepsilon_* \times 5$
$\log_{10}(\rho_*(>M_*))\,[M_\odot\,Mpc^{-3}]$
$\log_{10}(M_*/M_\odot)$

Universe Timeline

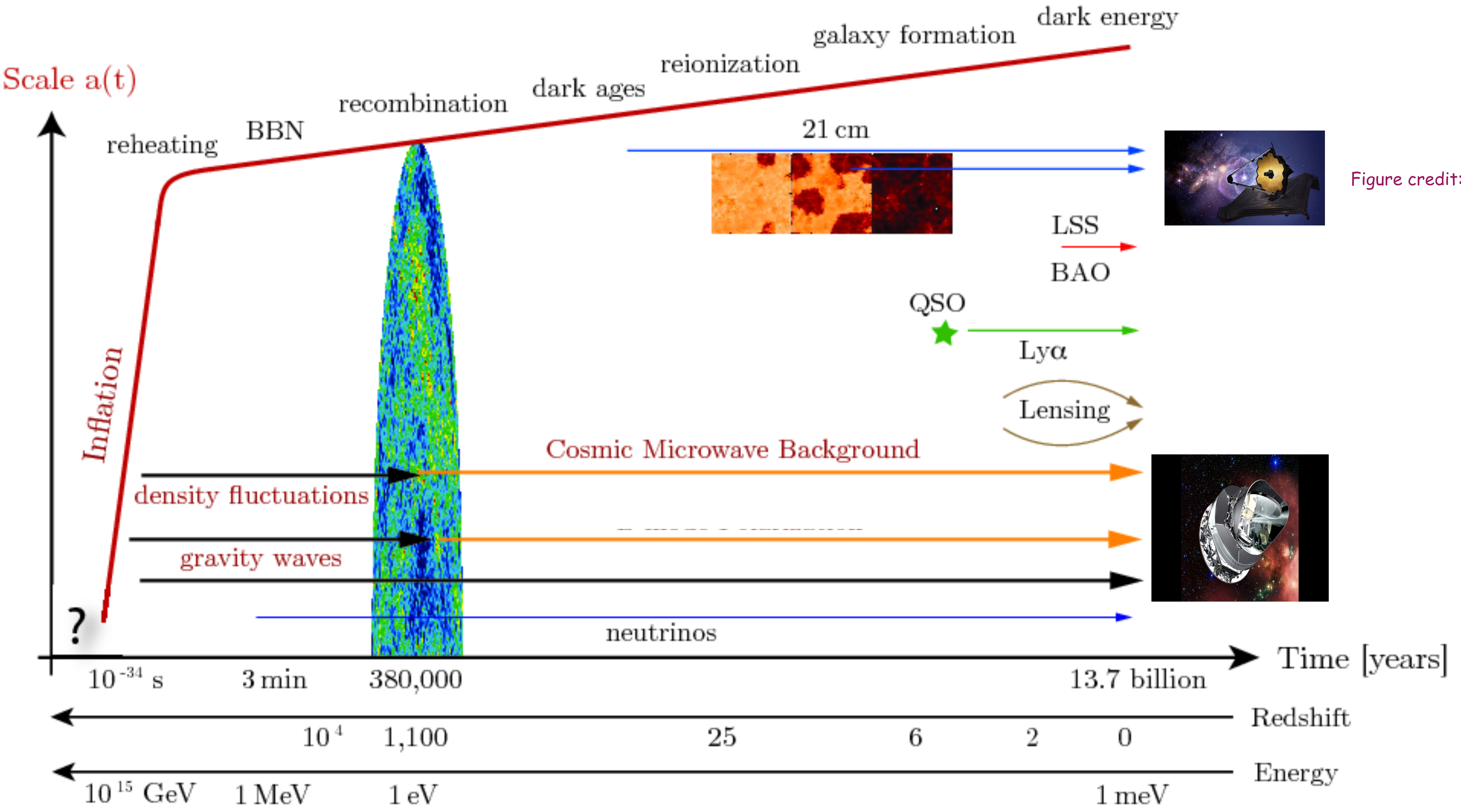


Figure credit: NASA webb

Figure credit: C09-06-01.3, p.523-686 Proceedings TASI-2009, arXiv:0907.5424

Cumulative Comoving Number and Mass Densities

Let me define the cumulative comoving number density of haloes with masses above

some threshold $M_{\rm halo}$ as

$$n(>M_{\rm halo}, z) = \int_{M_{\rm halo}}^{\infty} dM \frac{dn(M,z)}{dM}\,,$$

and the corresponding cumulative comoving mass density of haloes

$$\rho(>M_{\rm halo}, z) = \int_{M_{\rm halo}}^{\infty} dM\, M \frac{dn(M,z)}{dM}\,.$$

Cumulative comoving galaxy number density:

$$n_*(>M_*, z) = n(>M_{\rm halo}, z)$$

and cumulative comoving stellar mass density:

$$\rho_*(>M_*, z) = \epsilon f_b\, \rho(>M_{\rm halo}, z)$$

where stellar mass $M_* = \epsilon f_b M_{\rm halo}$
and $f_b = \Omega_b/\Omega_m$

- The star formation efficiency, $\epsilon \leq 1$
- Exact value depends on star formation physics

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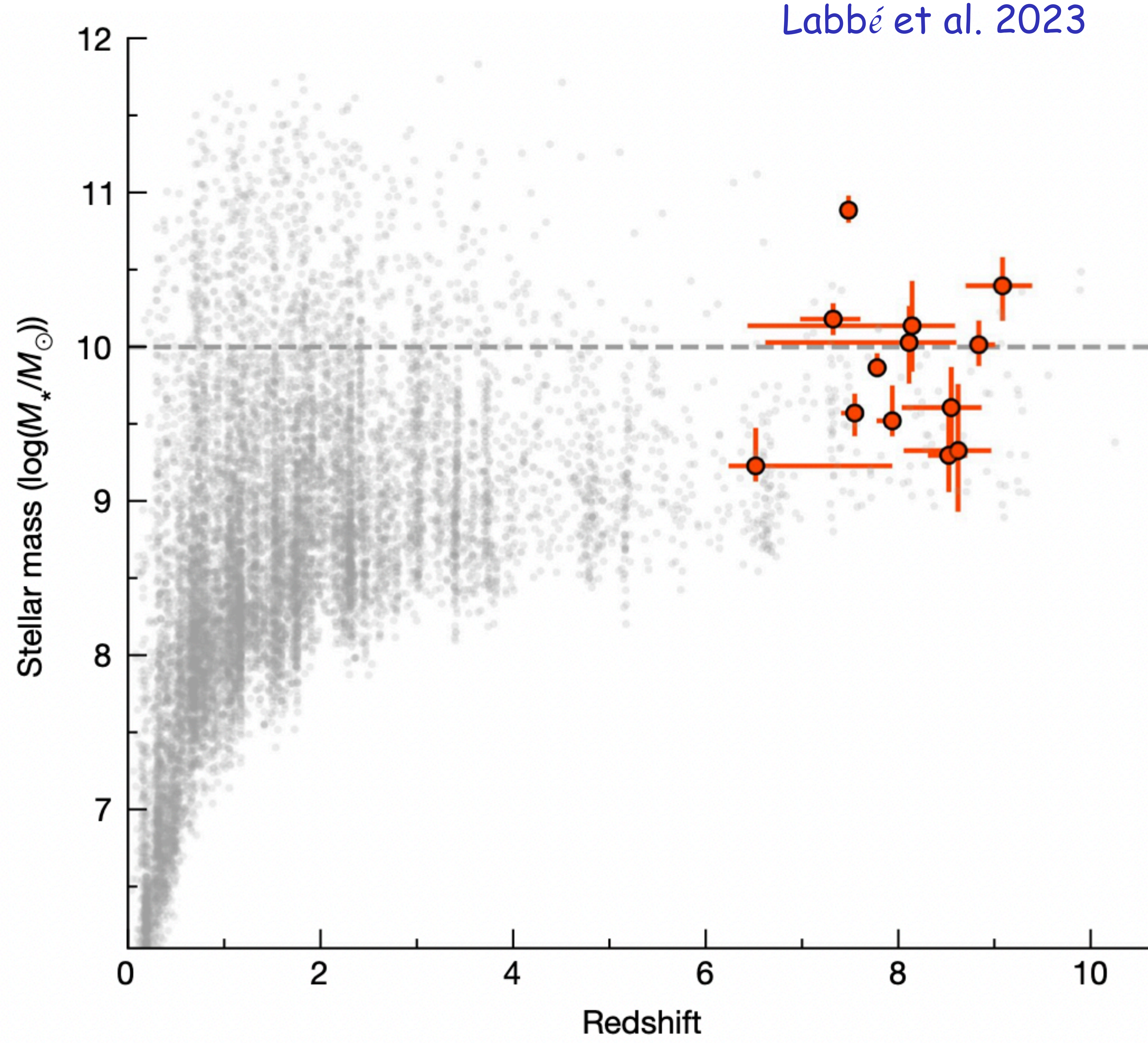
Early data releases of JWST have revealed several high redshift massive galaxy candidates.

- Labbé et al. 2023 have found 13 galaxy candidates $(6.5 \leq z \leq 9.1)$ using JWST data released within the Cosmic Evolution Early Release Science (CEERS) program.
- They identified these candidates by observing two redshifted breaks in their spectral energy distributions (SEDs): 1. Lyman break (1216 Å) and 2. Balmer break (3600 Å).
- Six candidates found to have stellar mass $M_* > 10^{10} M_\odot$.

Labbé et al. 2023



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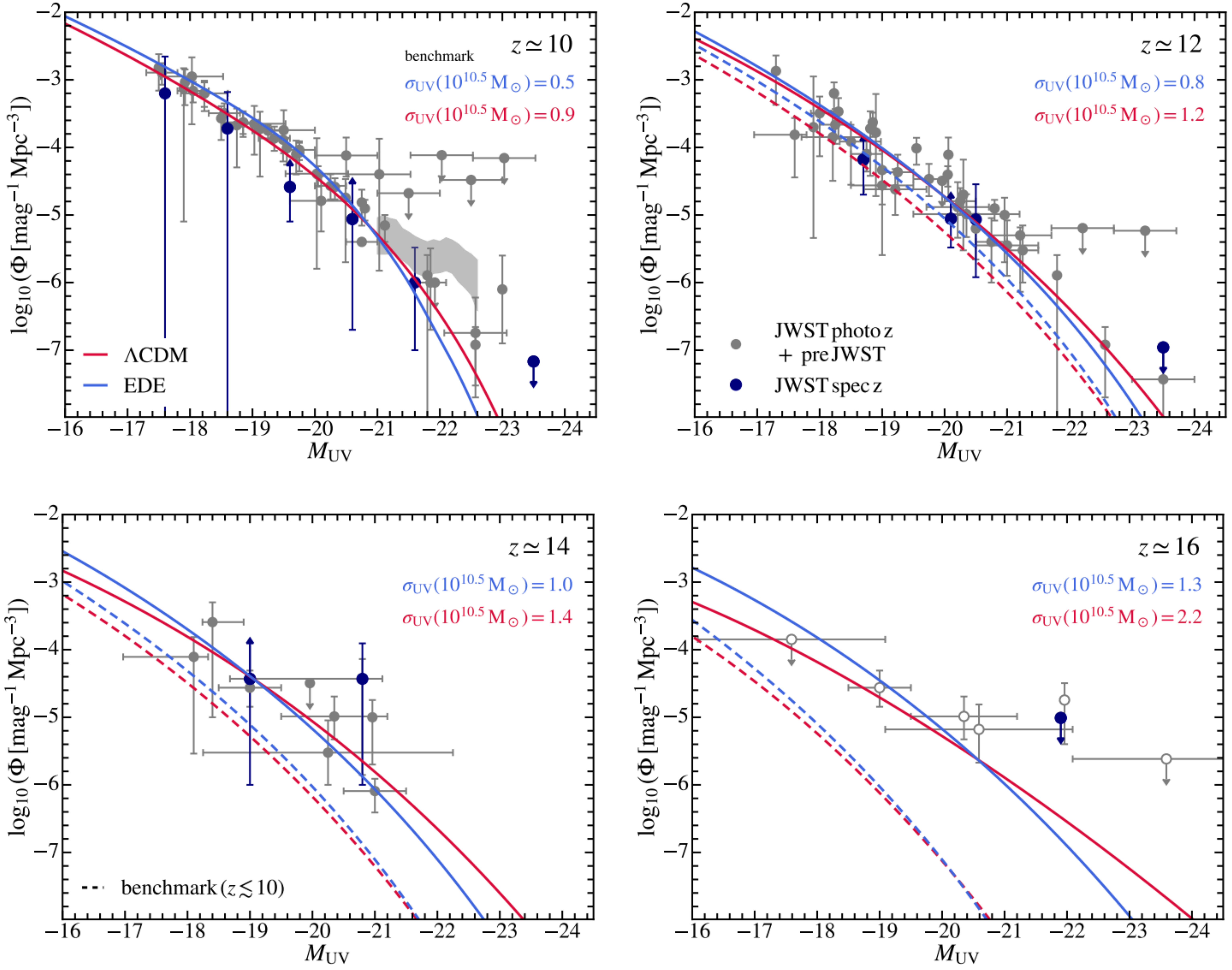

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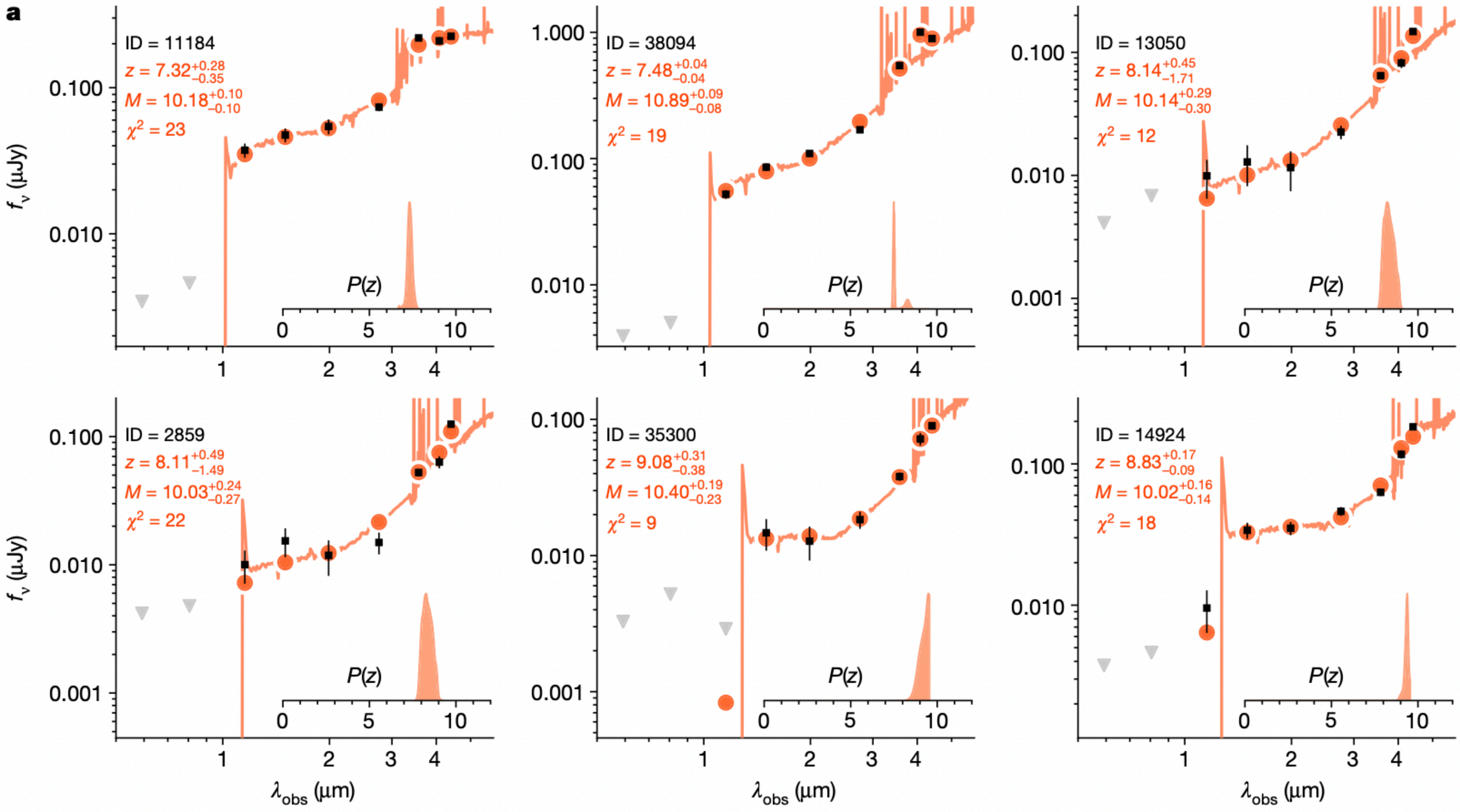

a
ID = 11184
z = 7.32 +0.28 −0.35
M = 10.18 +0.10 −0.10
χ2 = 23
ID = 38094
z = 7.48 +0.04 −0.04
M = 10.89 +0.09 −0.08
χ2 = 19
ID = 13050
z = 8.14 +0.45 −1.71
M = 10.14 +0.29 −0.30
χ2 = 12
ID = 2859
z = 8.11 +0.49 −1.49
M = 10.03 +0.24 −0.27
χ2 = 22
ID = 35300
z = 9.08 +0.31 −0.38
M = 10.40 +0.19 −0.23
χ2 = 9
ID = 14924
z = 8.83 +0.17 −0.09
M = 10.02 +0.16 −0.14
χ2 = 18
P(z)
fν (μJy)
λobs (μm)

JWST observations and modified power spectrum

Priyank Parashari & Ranjan Laha, MNRAS: Letters, 526, L63–L69 (2023)

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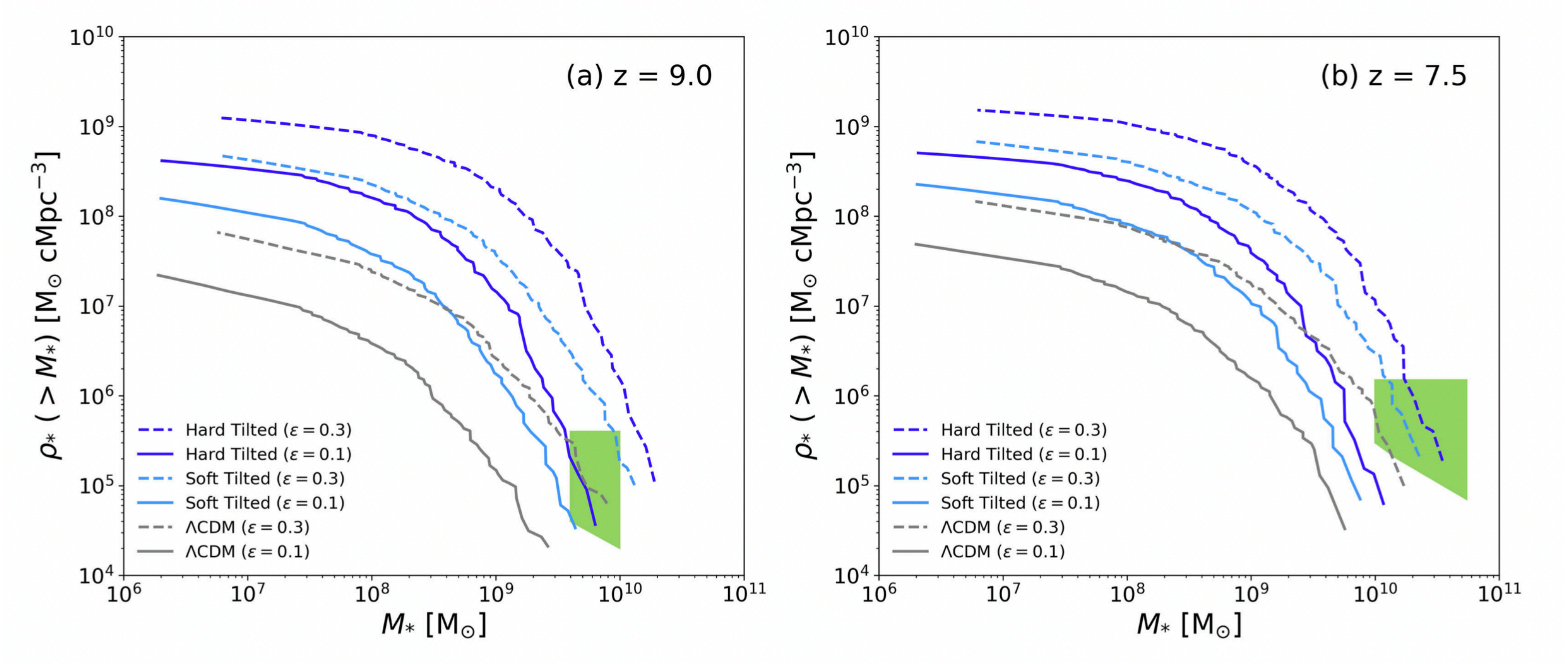

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