Primordial power spectrum in light of JWST observations of high redshift galaxies

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MNRAS: Letters, 526, L63-L69 (2023)

arXiv: 2305.00999

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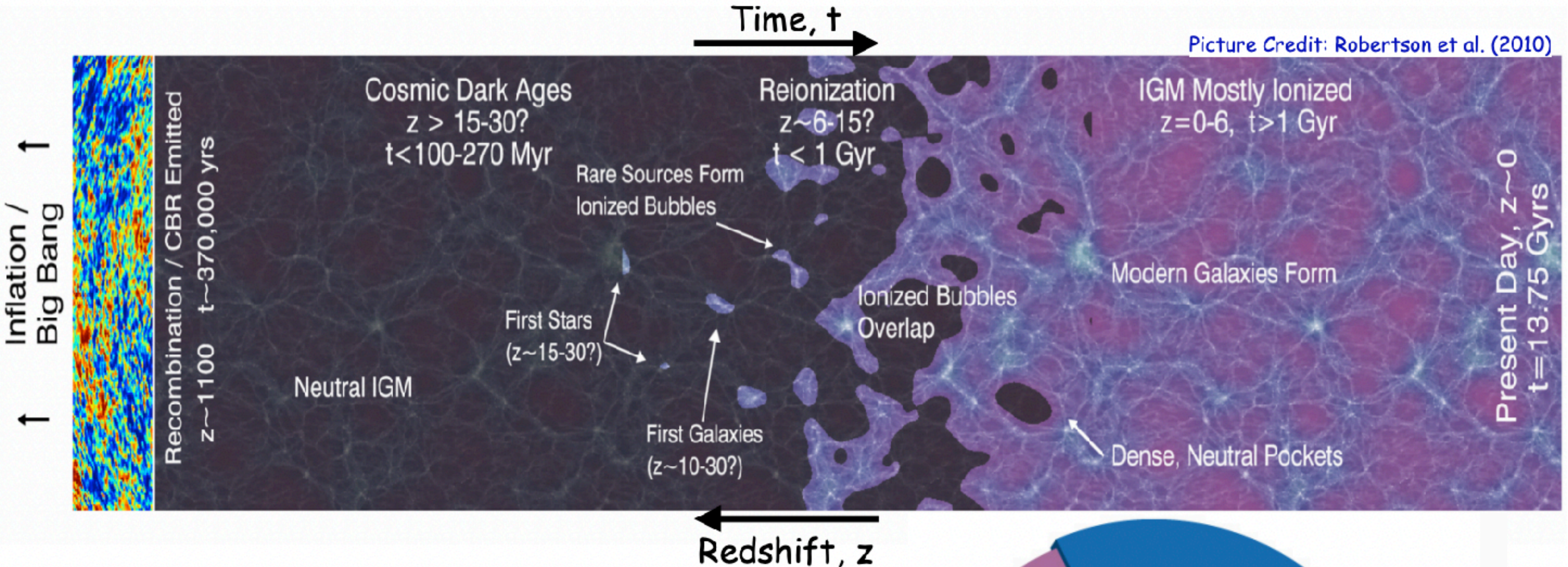
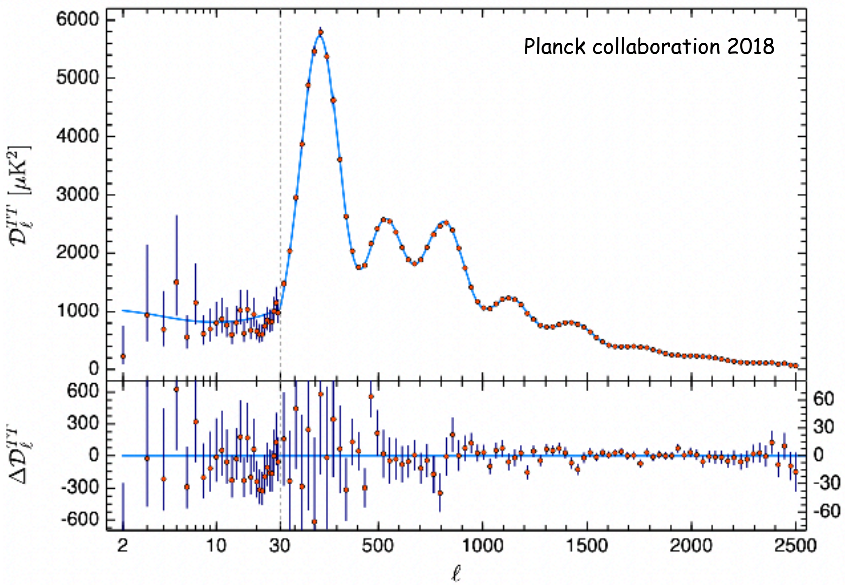
Cosmology and JWST

Cosmology





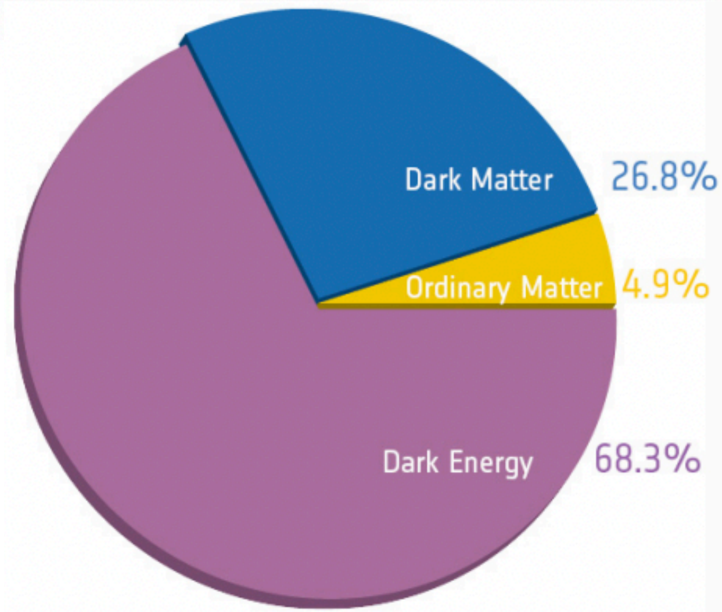


Figure credit: Planck collaboration

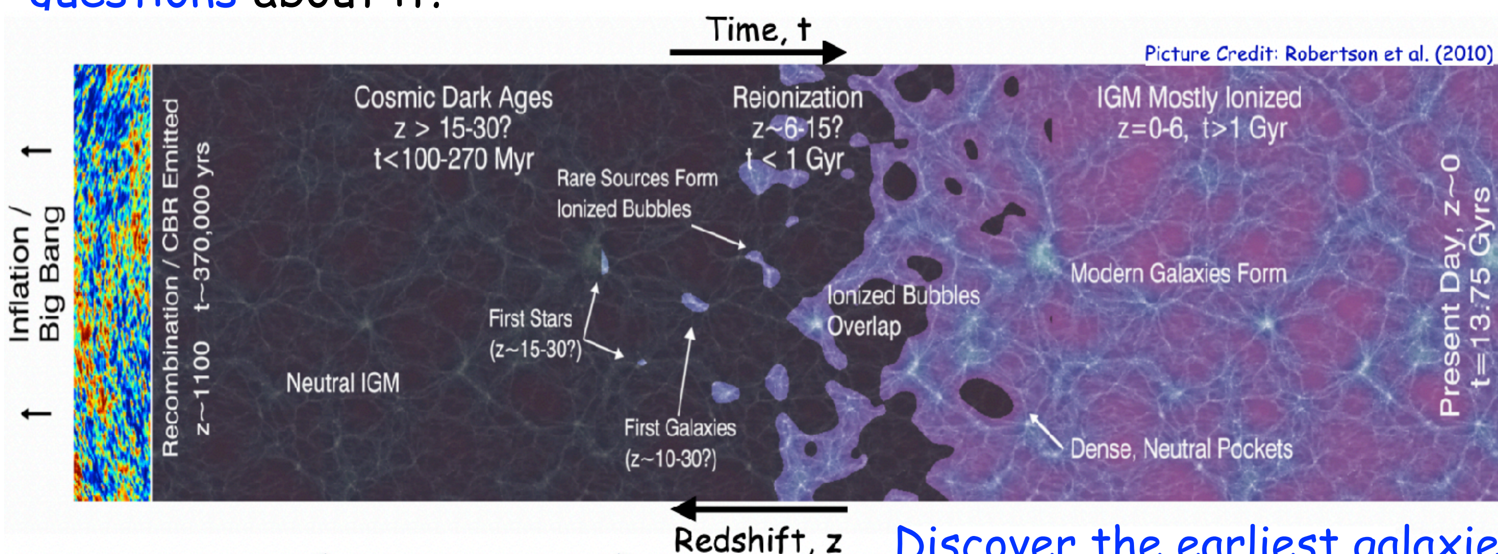
Cosmology

- - - *Planck* 2018 6-parameter fit to flat ΛCDM cosmology -

baryon density of the Universe	$\Omega_b = \rho_b/\rho_{crit}$	$^{\ddagger}0.02237(15)\,h^{-2} = {}^{\dagger}0.0493(6)$
cold dark matter density of the Universe	$\Omega_c = \rho_c/\rho_{crit}$	$^{\ddagger}0.1200(12)\,h^{-2} = {}^{\dagger}0.265(7)$
100 × approximation to r_*/D_A	$100 \times \theta_{MC}$	$^{\ddagger}1.04092(31)$
reionization optical depth	τ	$^{\ddagger}0.054(7)$
ln(power prim. curv. pert.) ($k_0 = 0.05\,\mathrm{Mpc}^{-1}$)	$\ln(10^{10}\Delta^2_{\mathcal{R}})$	$^{\ddagger}3.044(14)$
scalar spectral index	n_s	$^{\ddagger}0.965(4)$

PDG 2024

How do we probe ΛCDM more precisely or in newer regimes or answer outstanding questions about it?

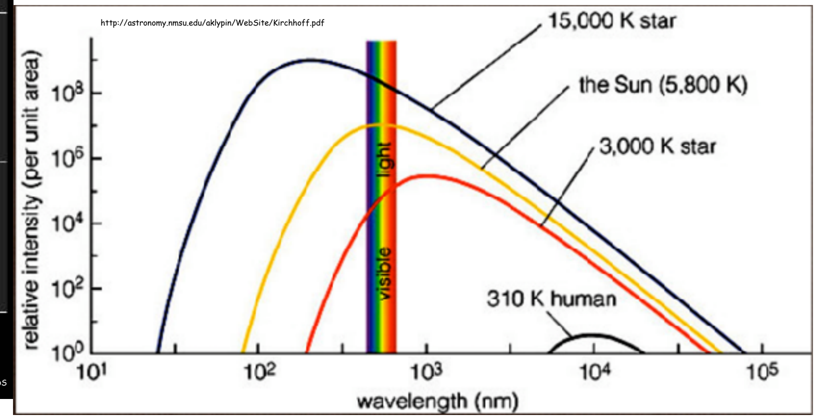


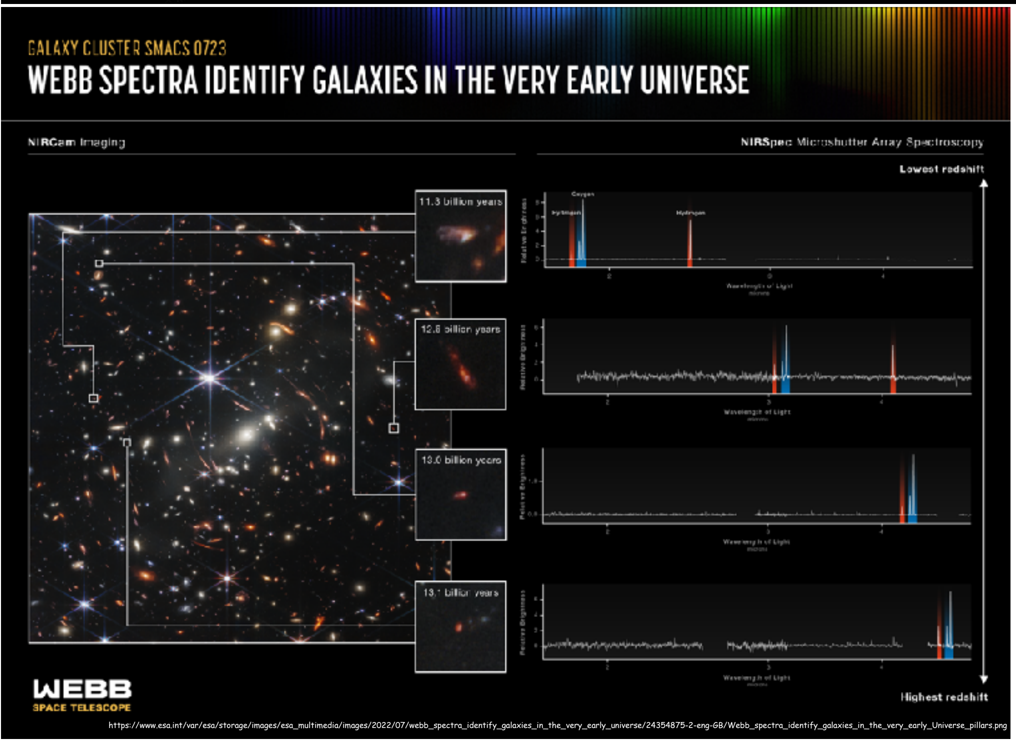
This region is not probed at all (before 2022)
Do we have new data regarding this region?

Discover the earliest galaxies observable and answer fundamental questions about particle physics and astrophysics/ cosmology

Earliest galaxies observed

Young (and thus hotter) stars emit mostly in the UV wavelengths



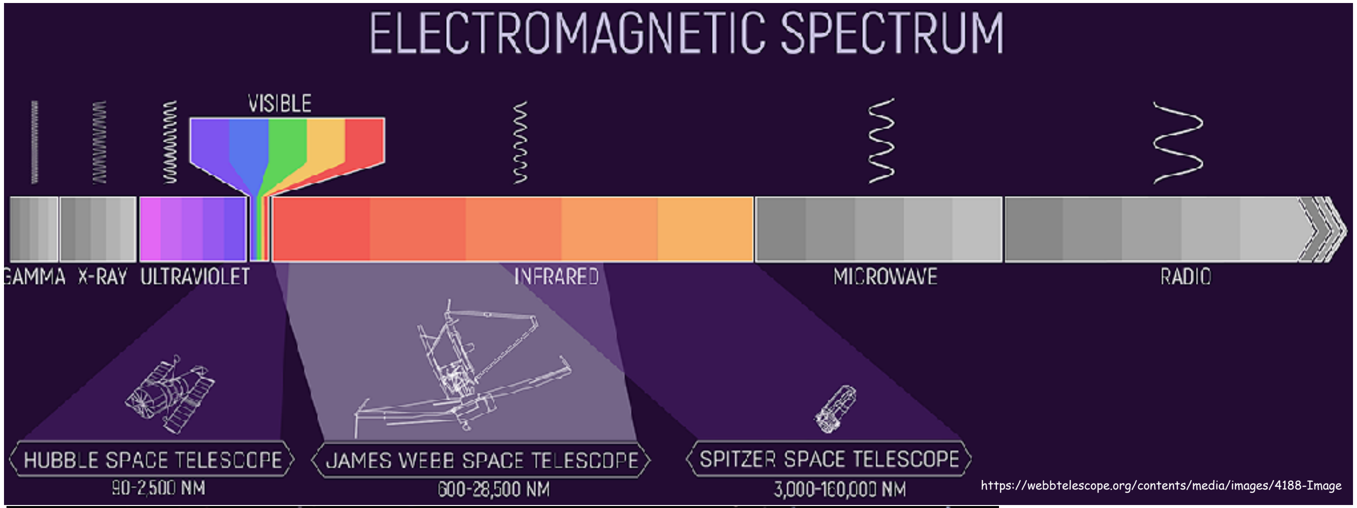


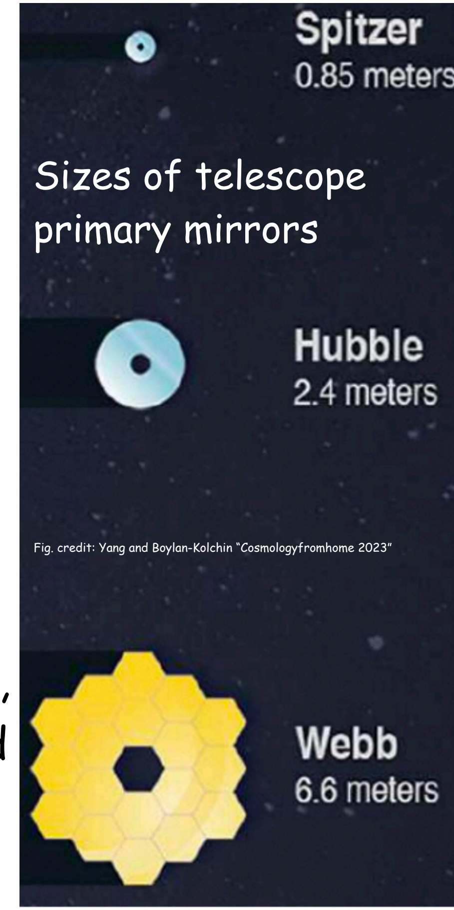
These UV emissions get redshifted to longer wavelengths (i.e., optical and IR)

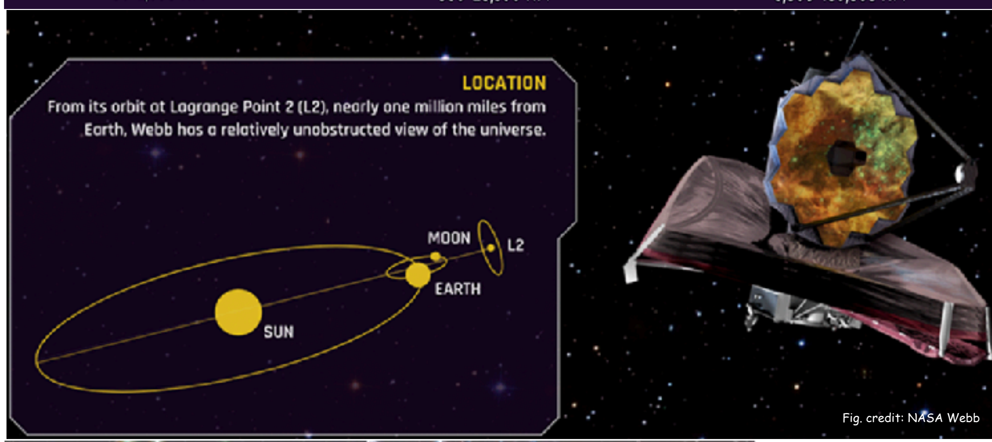
$$\lambda_{\rm obs} = (1+z)\lambda_{\rm emit}$$

We need IR telescopes to observe the earliest galaxies

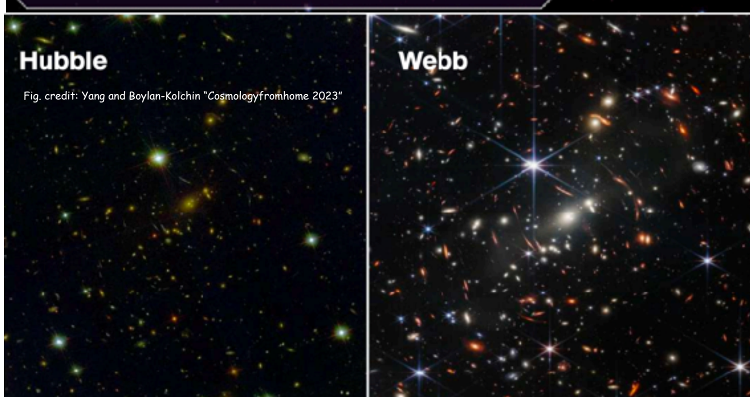
JWST (James Webb Space Telescope)

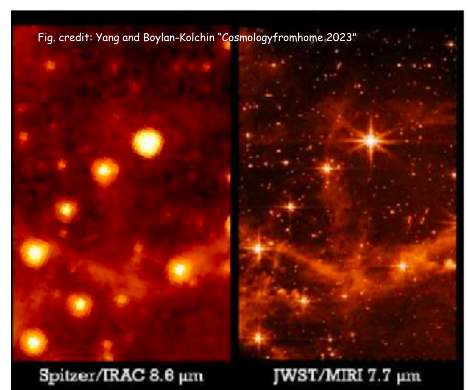






Four different instruments on-board: NIRSpec, NIRCam, MIRI, and NIRISS





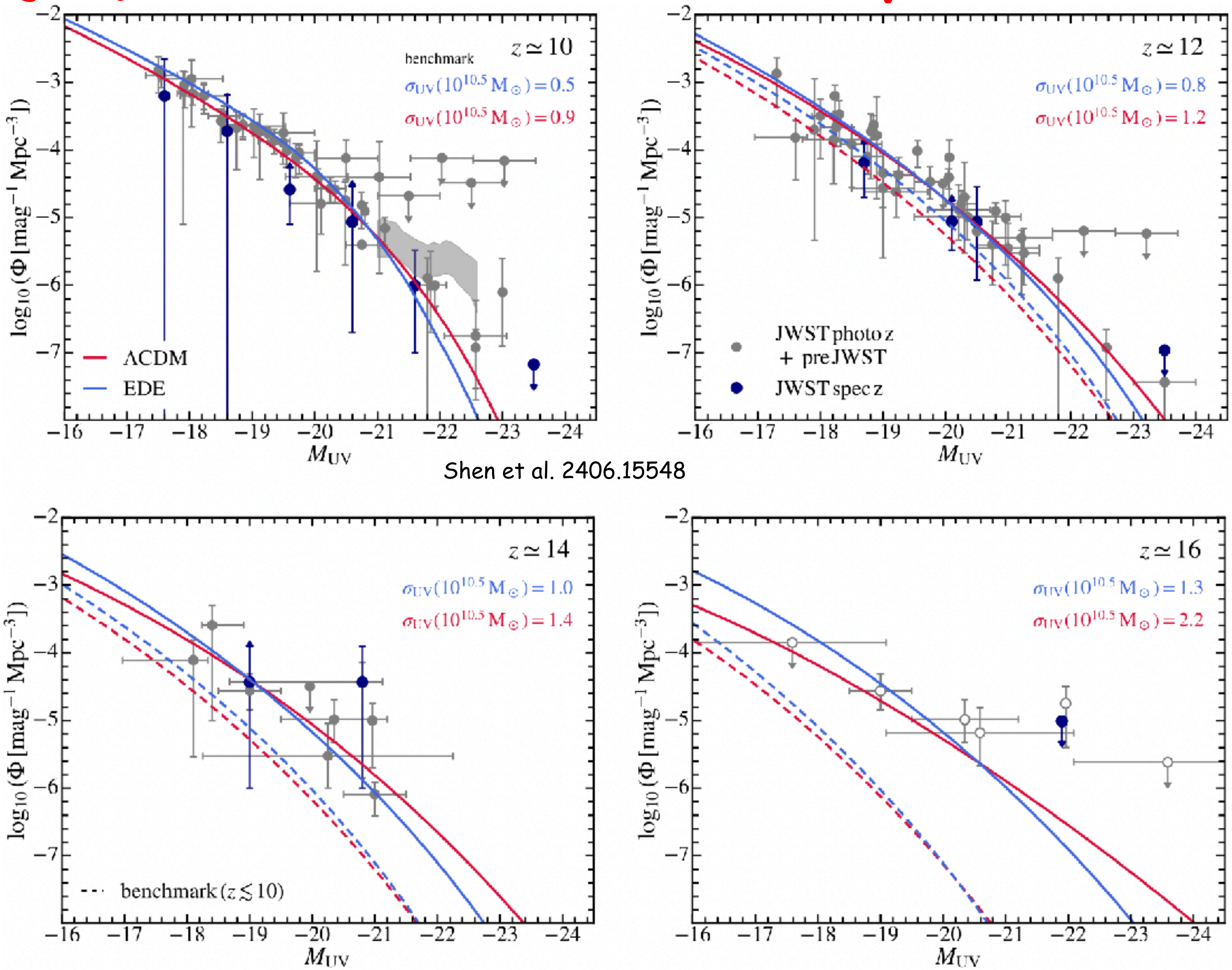
NIRSpec: Near InfraRed Spectrograph

NIRCam: Near InfraRed Camera

MIRI: Mid InfraRed Instrument

NIRISS: Near InfraRred Imager and Slitless Spectrograph

JWST observations of earliest galaxies



Shen et al. 2406.15548

Early data releases of JWST have revealed several high redshift galaxy candidates (Castellano et al. 2022; Finkelstein et al. 2022; Naidu et al. 2022; Adams et al. 2023; Atek et al. 2023; Bouwens et al. 2023; Donnan 2023; Harikane et al. 2023; Robertson et al. 2023; Yan et al. 2023 and many other recent papers)

Most of these galaxy candidates were identified photometrically, and later confirmed by spectroscopic observations

Brighter and more numerous than expected from prior observations at lower redshifts

See recent review by Tacchella 2410.04227; see Napolitano et al. 2410.10967 for latest observational results; see Driskell et al. 2410.11680 + Semenov et al. 2410.09205 + many others

Slide idea: Priyank Parashari

JWST observations as a test of ΛCDM cosmology

How do such massive galaxies form so early in the Universe (~ 300 Myr after the Big Bang)?

How do we test ΛCDM cosmology using such JWST data sets?

Galaxy formation involves understanding gravitational dynamics for N-body systems involving large cosmological simulations (with uncertain baryonic physics involved)

These are the first cosmological observations at these redshifts; thus availability of cosmological simulations were initially limited

Can we get test fundamental parameters of ΛCDM cosmology using semi-analytical arguments?

JWST observations of massive galaxies at high redshifts

Semi-analytical method to calculate the number of dark matter halo per unit mass and per unit volume as a function of redshift (halo mass function)

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

This gives a way to statistically compare with the JWST data set

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

where n = number density of dark matter haloes

M = dark matter halo mass

ρ_0 = mean density of the Universe

σ = mass variance of smoothed linear matter density field in a sphere of radius R

$$M = \frac{4\pi}{3}\rho_0 R^3$$

see cosmology text books by Baumann or Dodelson + Schmidt

$f(\sigma)$ = fitting function obtained using Press - Schechter formalism and including corrections for ellipsoidal collapse, calibrated to numerical simulations

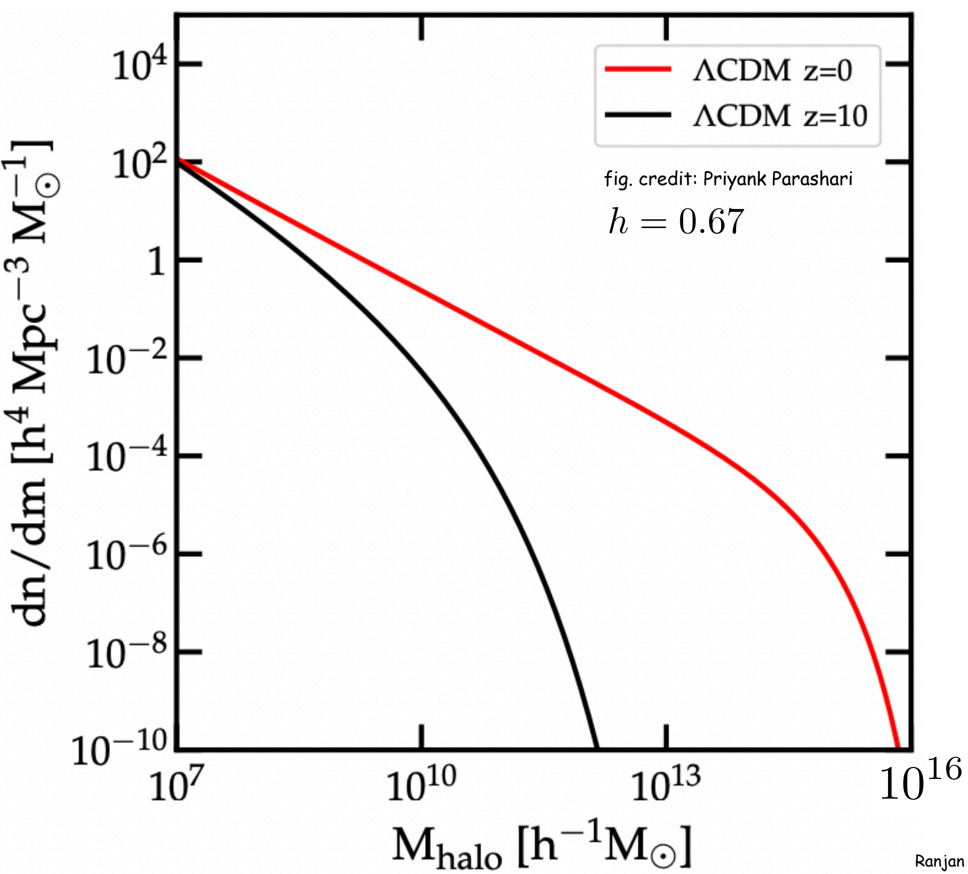
Halo mass function

The mass variance (σ) depends on the linear matter power spectrum, $P(k)$, as

$$\sigma^2(R) = \frac{1}{2\pi^2}\int_0^\infty k^2\, P(k)\, W^2(kR)\, dk$$

where k = wavenumber and $W(kR)$ is the filter function in Fourier space

$P(k) = P_{\rm prim}(k) T^2(k)$ where $P_{\rm prim}(k)$ is the primordial power spectrum, predicted in various very early Universe cosmological models and $T(k)$ = transfer function



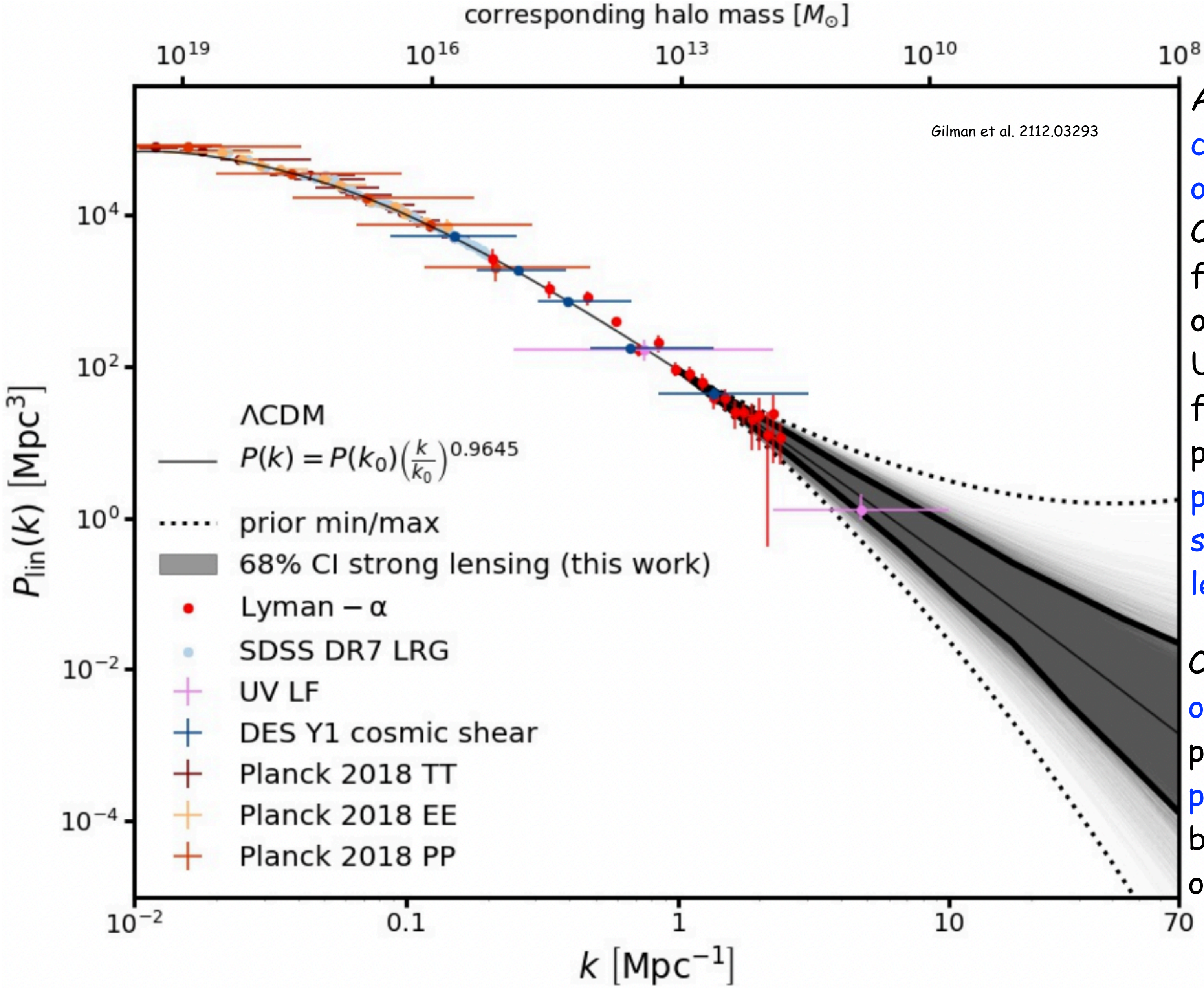
$$P_{\rm prim}(k) \propto k^{n_s}$$

where $n_s = 0.965 \pm 0.004$ is the scalar spectral index

Heavier dark matter haloes form later in the Universe in a bottom-up approach as observed

JWST is probing halo mass function at the highest redshifts: we must be able to probe the primordial power spectrum using this data-set

Primordial power spectrum



A variety of cosmological observables (using CMB, Lyman-alpha forest observations, UV luminosity functions, etc.) probe the primordial power spectrum at various length scales

Can we use JWST observations to probe the primordial power spectrum better than current observations?

A model-independent modification to the primordial power spectrum

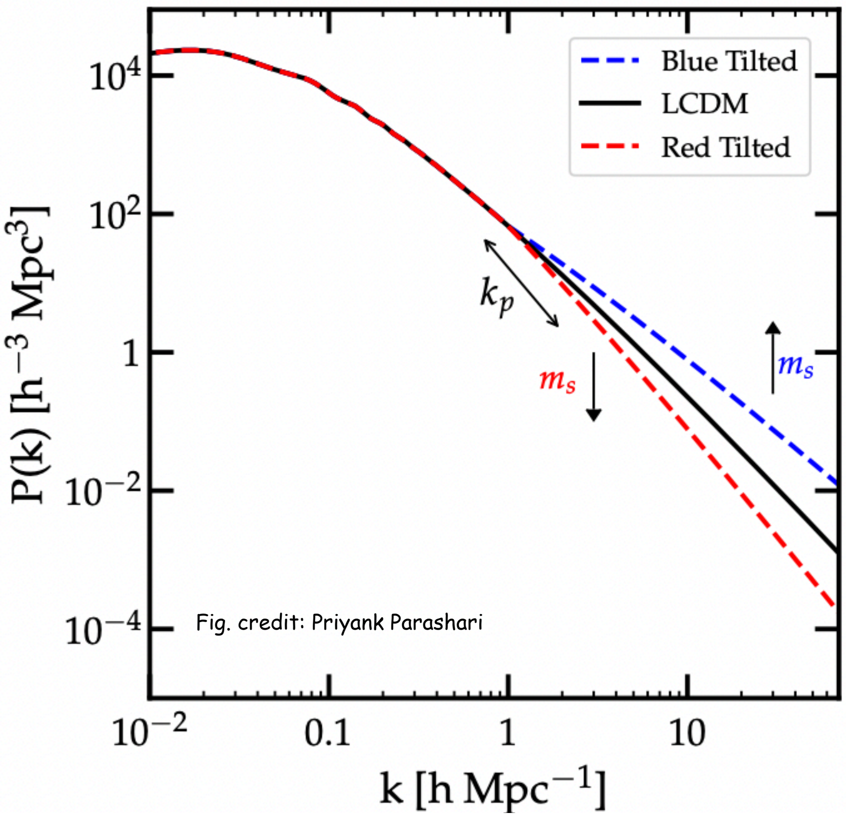
We parametrize a model-independent modification to the primordial power spectrum by two independent parameters:

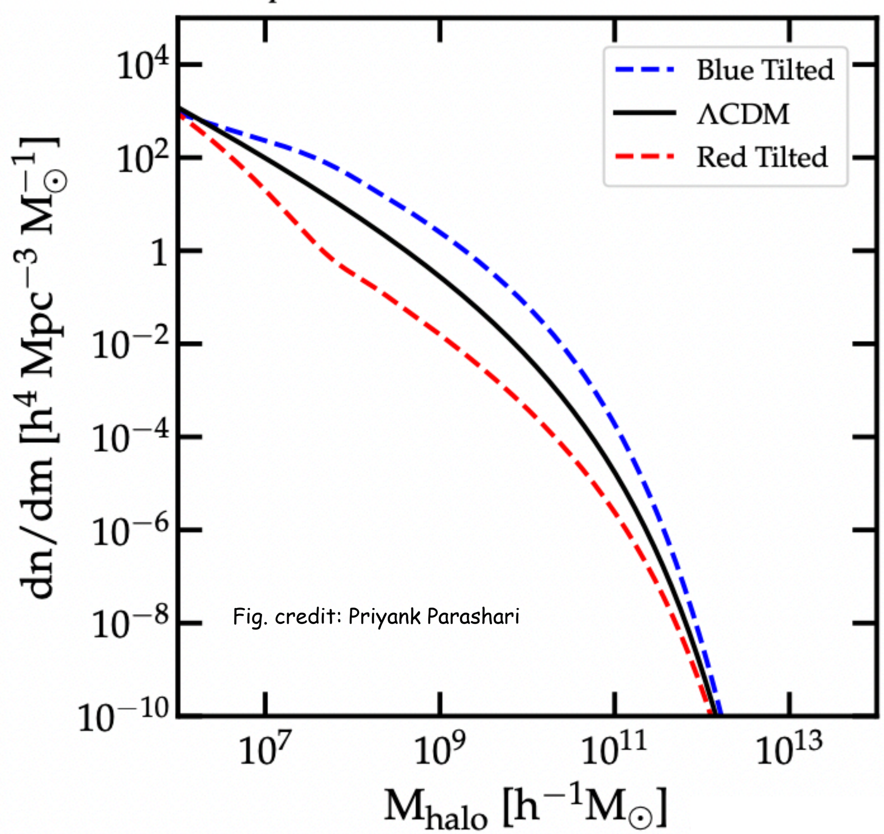
$$P_{\rm prim}(k) \propto k^{n_s}, \qquad \text{for } k < k_p,$$
$$\propto k_p^{n_s - m_s} k^{m_s}, \qquad \text{for } k > k_p$$

k_p = pivot scale

m_s = tilt index

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





How to convert dark matter halo mass to corresponding stellar mass?

JWST does not measure the dark matter halo mass directly, but measures the stellar light emitted by a galaxy: we need a prescription to convert the dark matter halo mass to stellar mass (JWST articles that we used specified the stellar mass rather than the UV luminosity)

Given a halo mass M, what is the stellar mass M_*?

Assuming a redshift z, the cosmic baryon fraction is $f_b = \frac{\Omega_b}{\Omega_m}$ where $\Omega_b = 0.0493$ and $\Omega_m = 0.3153$

Stellar mass inside a dark matter halo of mass M will be $M_* = \epsilon f_b M$ where $\epsilon \leq 1$ denotes the star formation efficiency (depends on star formation physics)

Cumulative co-moving number density of haloes with masses above some mass threshold is

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

Boylan-Kolchin 2208.01611

Cumulative co-moving mass density of haloes with masses above some mass threshold is

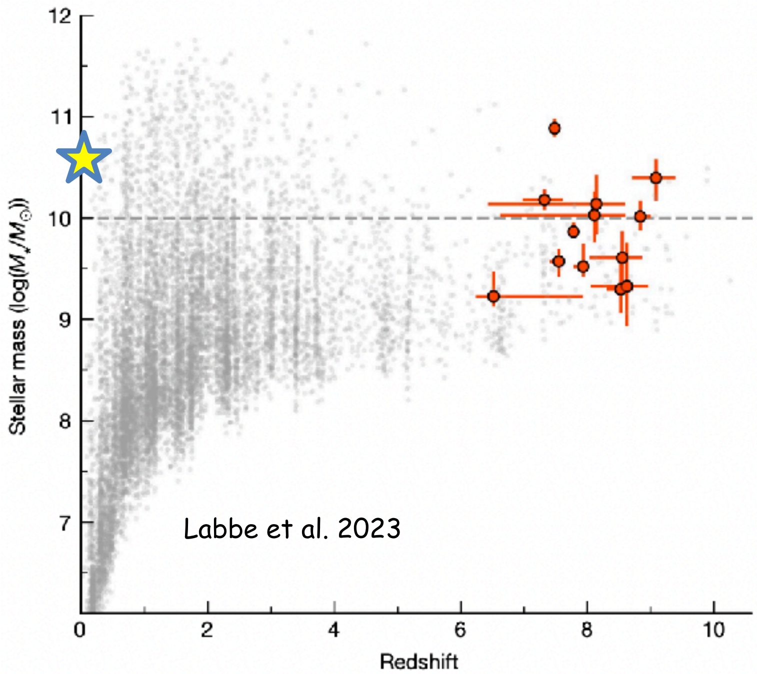
$$\rho(> M_{\rm halo}, z) = \int_{M_{\rm halo}}^{\infty} dM \, M \frac{dn(M, z)}{dM}$$

Cumulative co-moving galaxy number density (CCGND) is denoted by $n_*(> M_*, z)$

Cumulative co-moving stellar mass density (CCSMD) is $\rho_*(> M_*, z) = \epsilon f_b \, \rho(> M_{\rm halo}, z)$

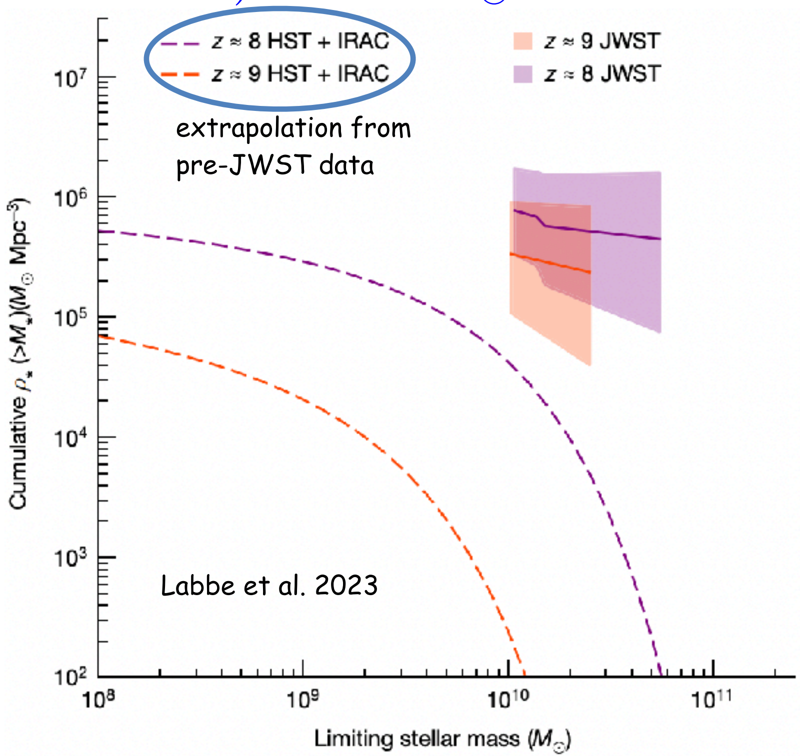
Interplay between star formation efficiency and blue tilt in the primordial power spectrum from CEERS observation

JWST-CEERS observations of massive galaxies at high redshifts



Using the first observations of JWST Cosmic Evolution Early Release Science (CEERS) program, Labbe et al. identified 6 galaxy candidates with stellar masses $\gtrsim 10^{10}\,\mathrm{M}_\odot$ with $7.4 \leq z \leq 9.1$

☆ displays Milky Way stellar mass = $(6.08 \pm 1.14) \times 10^{10}\,\mathrm{M}_\odot$ Licquia and Newman 1407.1078

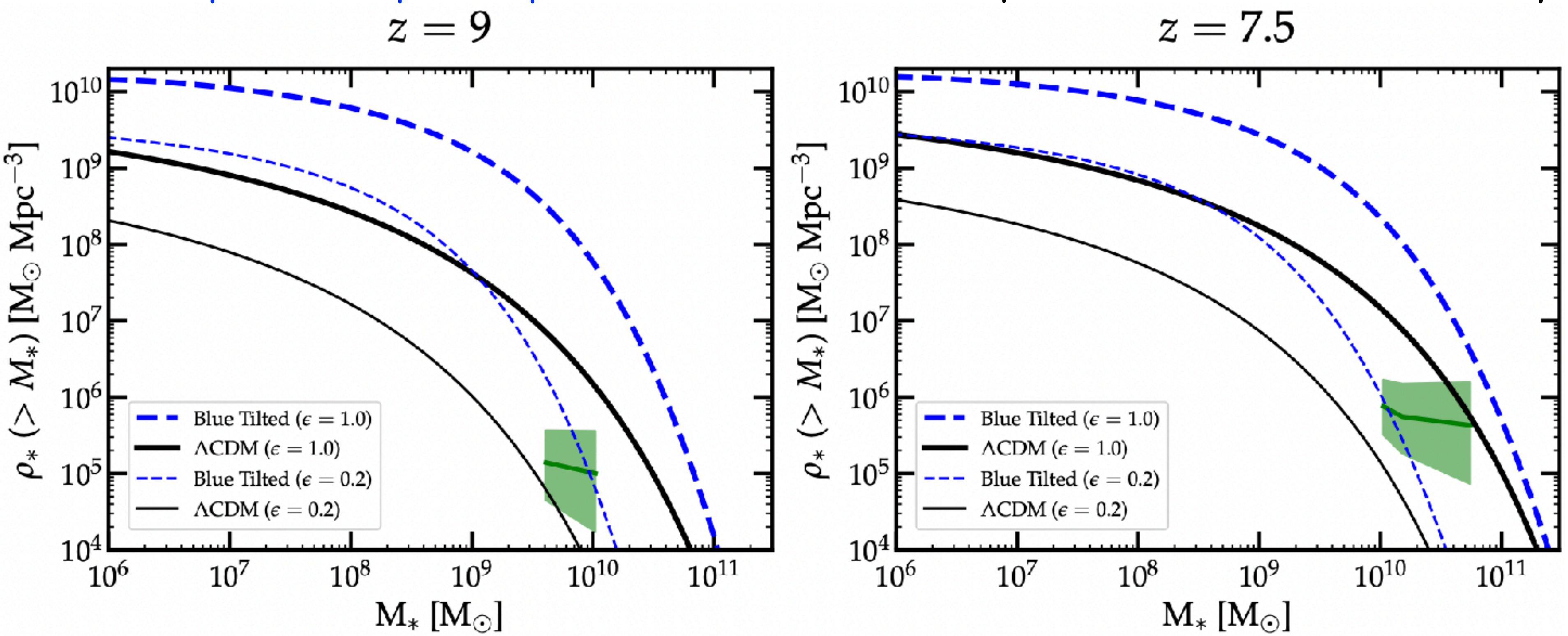


How do such massive galaxies form so early in the Universe (~ 600 Myr after the Big Bang)?

Why do they have such a high number density?

JWST-CEERS observations of massive galaxies at high redshifts

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

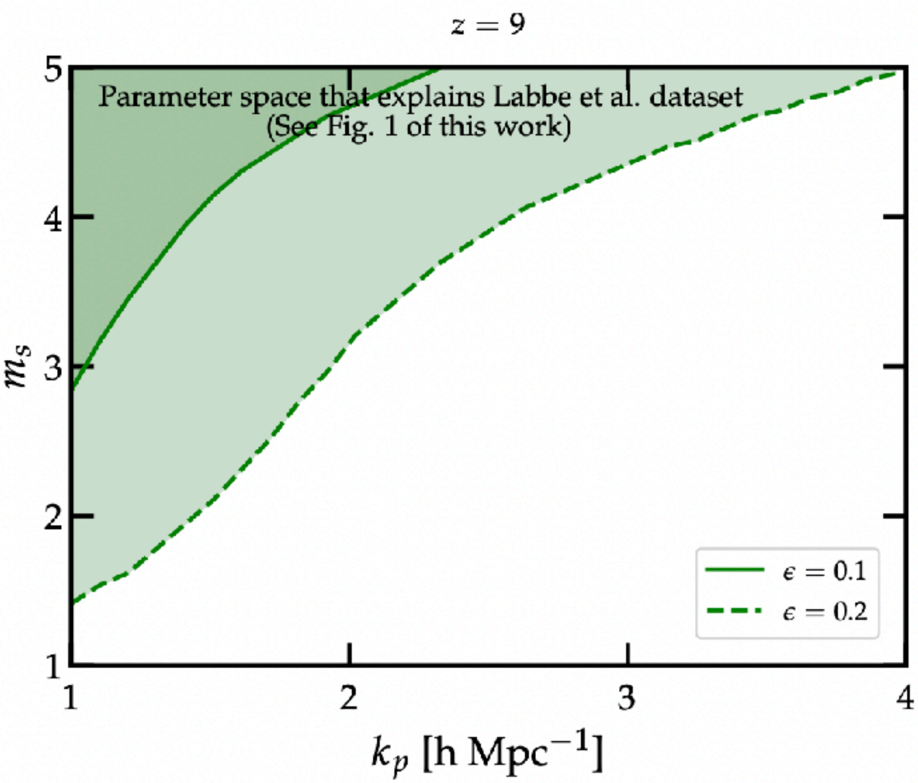


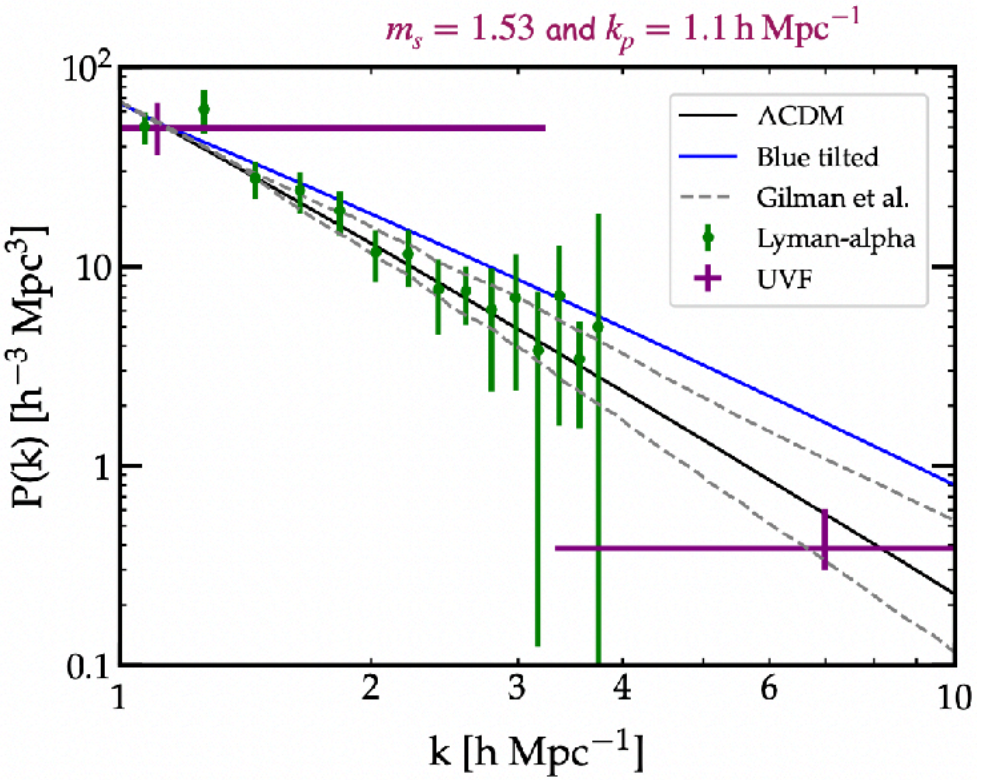
$m_s = 2.0$ and $k_p = 1\,\mathrm{h\,Mpc^{-1}}$

Blue-tilted primordial power spectrum produces heavier dark matter halos at the same redshift, and heavier dark matter halos can host a larger amount of baryons + stars

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

JWST-CEERS observations of massive galaxies at high redshifts





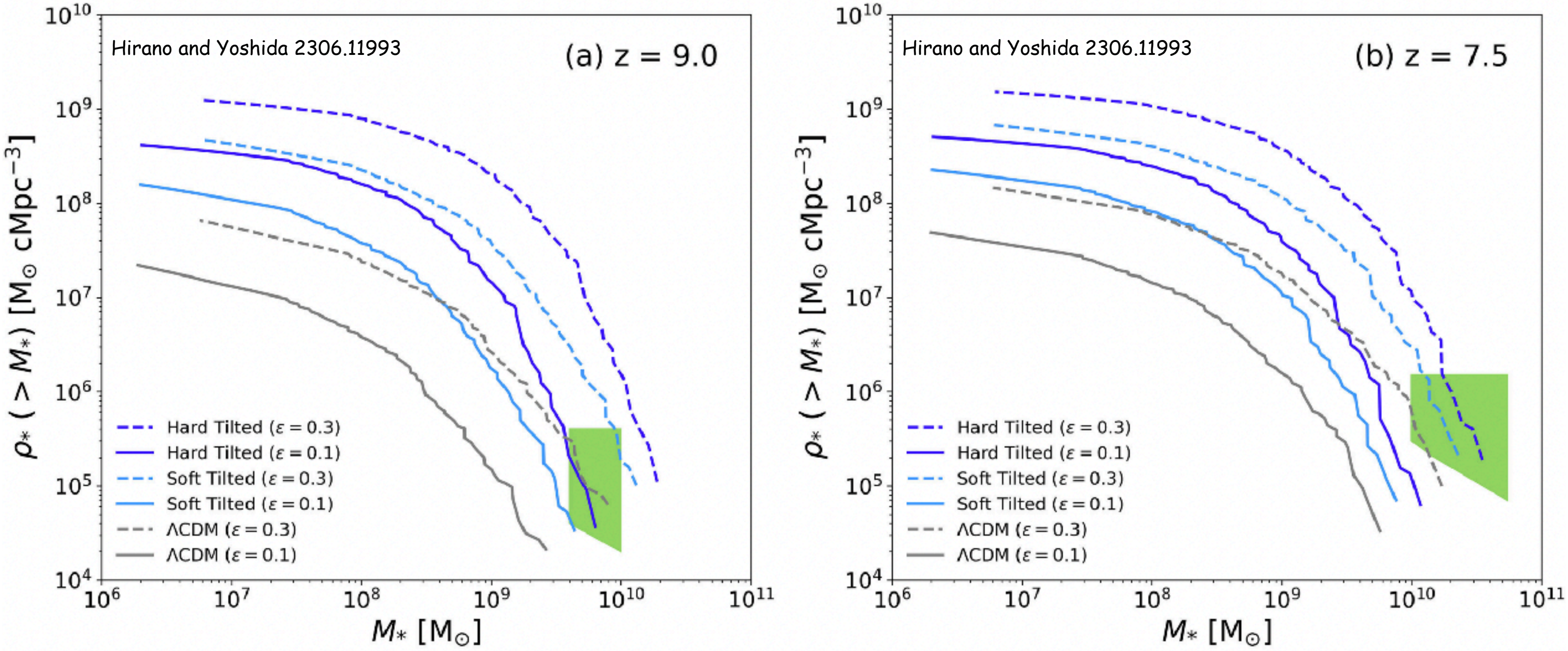
Parameter space that can explain the Labbe et al results while having a low star formation efficiency without taking into account constraints from other observables

Parameter space may be in conflict with various other observables especially with Milky Way dwarf galaxies (see Dekker and Kravtsov 2407.04198)

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

JWST-CEERS observations of massive galaxies at high redshifts

Hirano & Yoshida (arXiv: 2306.11993) did numerical simulations with a blue-tilted power spectrum and found their results consistent with our results



Sabti, Munoz, and Kamionkowski (arXiv: 2305.07049) performed an analysis by assuming a Gaussian enhancement in the power spectrum and found that the enhancement required to explain Labbe et al. (2023) observations will conflict with previous constraints on these scales by Hubble Space Telescope, which is consistent with our results

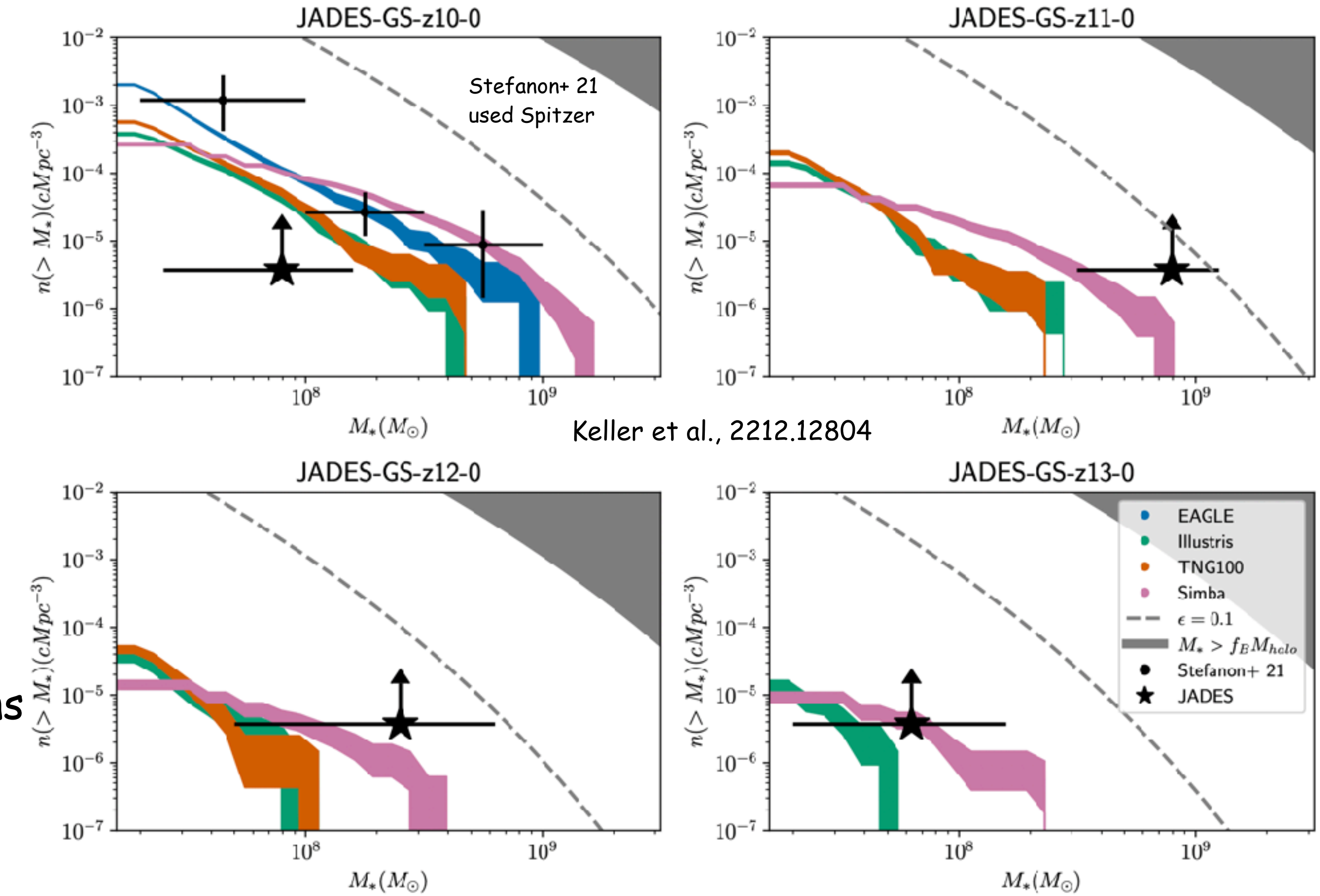
P. Parashari & R. Laha, MNRAS: Letters, 526, L63–L69 (2023) arXiv: 2305.00999

Constraints on the red tilt of the primordial power spectrum using galaxies observed in the JADES program

JADES observations of massive galaxies at high redshifts

Using some of the early observations of JWST Advanced Deep Extragalactic Survey (JADES) program, Curtis-Lake et al. and Robertson et al. discovered four galaxies spectroscopically

Keller et al. 2212.12804 compared these observations with numerical simulations and found that they are consistent with theoretical expectations; they also displayed lower limits on the cumulative number density of galaxies above a given stellar mass

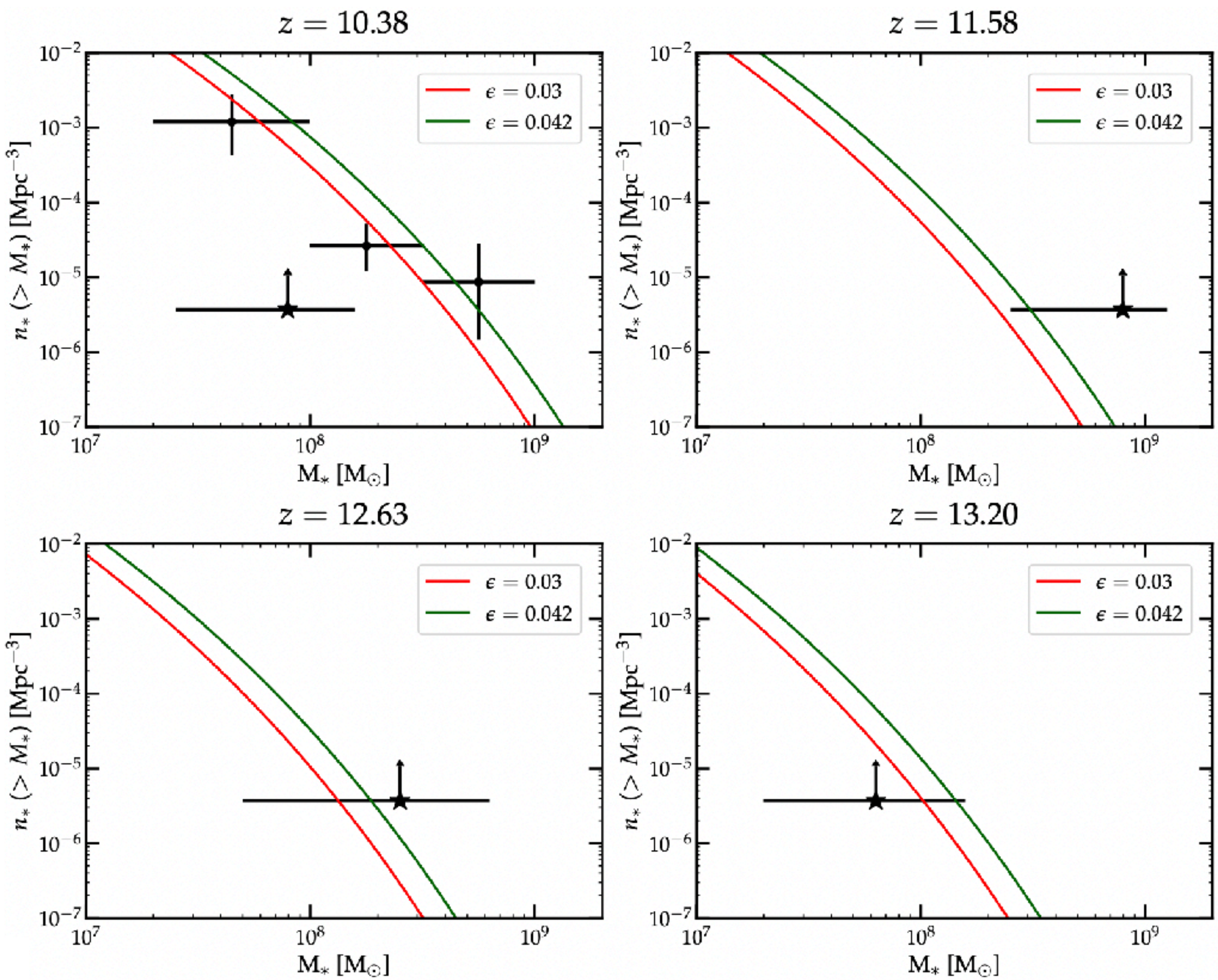


Four of the earliest galaxies by JADES: JADES-GS-z10-0 at $z = 10.38^{+0.07}_{-0.06}$, JADES-GS-z11-0 at $z = 11.58^{+0.05}_{-0.05}$, JADES-GS-z12-0 at $z = 12.63^{+0.24}_{-0.08}$, and JADES-GS-z13-0 at $z = 13.2^{+0.04}_{-0.07}$.

JADES observations of massive galaxies at high redshifts

Red-tilted primordial power spectrum produces lesser number of heavier dark matter halos at the same redshift

These observations give a lower limit on the cumulative number density of galaxies above a given stellar mass; thus the underlying power spectrum cannot be too red-tilted, implying a constraint on red-tilt of the primordial power spectrum



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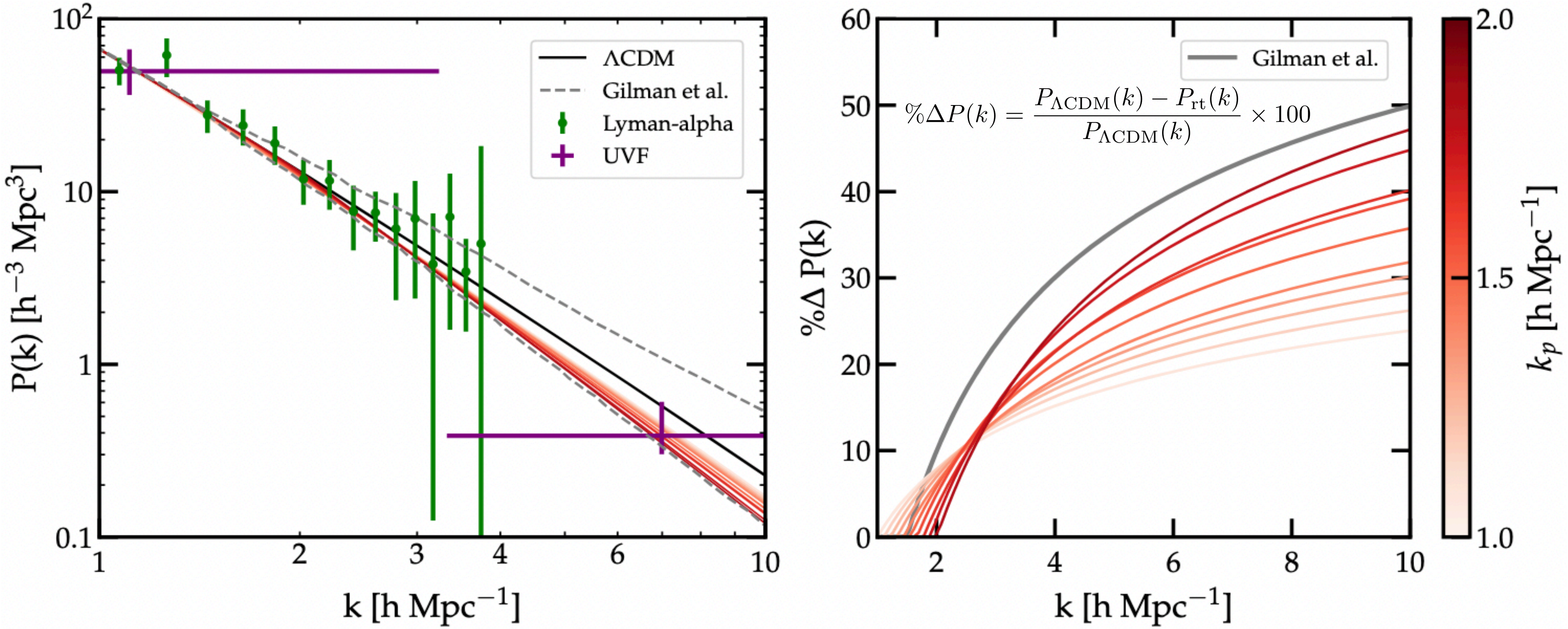
JADES observations of massive galaxies at high redshifts



Assuming $\epsilon = 0.042$, we show the maximum value of the red tilt that is allowed by the data. The red tilt allowed depends on the pivot scale $k_p \in [1, 2]\,\mathrm{h\,Mpc^{-1}}$

In the range $k \approx 2\,\mathrm{h\,Mpc^{-1}} - 7\,\mathrm{h\,Mpc^{-1}}$, we obtained the most stringent constraint on the red tilt in the primordial power spectrum

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

Conclusions

JWST has opened up a new window to probe our high-redshift Universe

JWST has discovered a number of massive galaxies at very high redshifts

We show that a blue tilted primordial power spectrum can lead to an enhanced formation of massive galaxies at high redshifts

Such a blue tilt may be in conflict with other measurements, especially using gravitational lensing and Hubble Space Telescope observations

We also used some spectroscopically confirmed galaxies in JADES program to derive the most stringent bound on the red tilt of the primordial power spectrum at scales $k \approx 2\,\mathrm{h\,Mpc^{-1}} - 7\,\mathrm{h\,Mpc^{-1}}$

We demonstrated the power of JWST to probe the primordial power spectrum: near future data-set may lead to an even more stringent constraint or a discovery!

Questions & comments: ranjanlaha@iisc.ac.in