The Newest from JWST: Does the Overabundance of UV-Bright Galaxies Imply a Change in Cosmology?

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Abstract

The Λ-*Cold Dark Matter* model is the current standard model of cosmology. The James Webb Space Telescope has detected an overabundance of UV-bright galaxies in the early universe which challenge predictions. UV-bright galaxies beyond $z \sim 9$ appear more numerous than predicted by current astrophysical models, posing a challenge to the ΛCDM model. In this paper we summarise numerous proposals to reconcile the JWST results. These proposals include astrophysical explanations such as lower dust attenuation, bursty star formation, top-heavy initial mass functions, and feedback-free starbursts, as well as exotic cosmological proposals of early dark energy and dynamical dark energy. We conclude that if future data shows overabundance continues past $z \sim 13$, it could suggest new cosmology beyond ΛCDM. Further JWST experiments as well as ground-based experiments such as CMBS-4 will be critical in understanding whether ΛCDM is sufficient to explain early galaxy formation or if new models will be required.

Word count: 2805 + 150 (captions) = 2955

Introduction

Modern cosmology is based on the cosmological principle (that the universe is spatially homogeneous and isotropic) and general relativity. The current *standard model of cosmology* is the Λ-Cold Dark Matter model (ΛCDM)[1], which combines the Big Bang model with cold dark matter and dark energy.

Most of our knowledge of the universe so far comes from the *Hubble Space Telescope*, *Spitzer*, and other ground-based telescopes [3]. The *James Webb Space Telescope* (JWST) has revolutionised the field. However, early observations have posed threats to our current understanding of galaxy formation and could require changes to cosmology.

The ΛCDM model provides our current understanding of galaxy formation. Following inflation, small clumps of dark matter formed haloes, which combine with other haloes to form galaxy formation sites[13]. In ΛCDM, the number of dark matter haloes per mass interval is given by the *halo mass function* (HMF).

However, the ΛCDM model faces problems such as the Hubble tension and the lack of detection of dark matter or dark energy [1]. The JWST has given the ΛCDM model its latest challenge.

Early JWST Results

The Near Infrared Camera (NIRCam) instrument on JWST provides deep imaging to $\lambda \simeq 5\,\mu\text{m}$, enabling detection of galaxies at $z \geq 10$ [10]. NIRCam has spectroscopically confirmed many galaxies found at $z \gtrsim 10$[14]. JWST has found many surprisingly bright galaxies that challenge current models of galaxy evolution.

The JWST has raised two key tensions about these galaxies: their unexpectedly large stellar masses and the overabundance of UV-bright galaxies. The second of these tensions is the focus of this review.

The abundance of UV-bright galaxies at $z \gtrsim 10$ surpasses theoretical, even after accounting for observational correction [12] [14]. Finkelstein et al. (2023) show that the observed galaxies at $z \sim 11$ are 1.8× more UV luminous than expected from HST results [12].

We now introduce the *UV luminosity function* (UVLF), which gives the abundance of stars for a given luminosity interval.

Limited area coverage and deep imaging availability led to uncertainty in early UVLF results at $z > 10$. Many early galaxy measurements relied on photometric redshifts (an estimate of the recession of a galaxy from photometry

[1] Cold refers to moving slowly with respect to the speed of light.

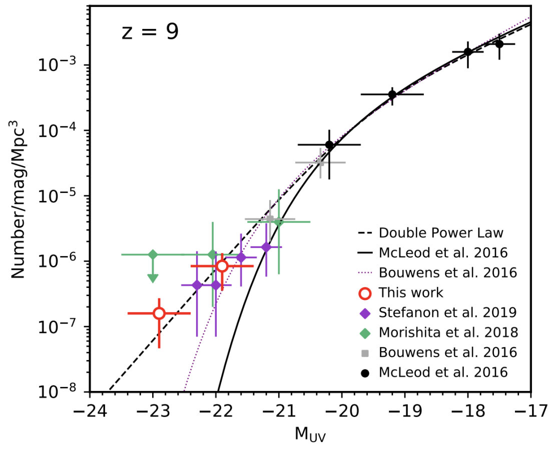


Figure 1: Rest-frame UVLF at $z = 9$ with Bowler et al. results (red points), DPL fit (dashed black), and Schechter fit (solid). [4, Figure 6]

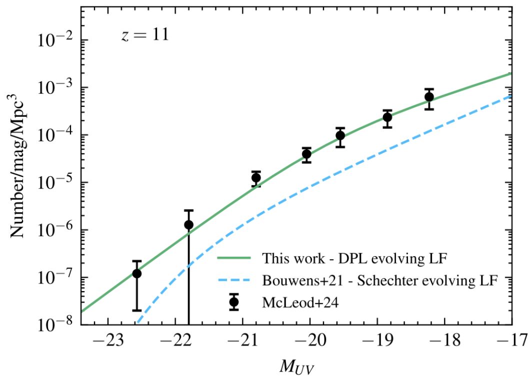


Figure 2: DPL parametrisation of Donnan et al. (2024) (solid green) vs evolving Schechter function of Bouwens et al. (2021) (dashed blue), with JWST data from McLeod et al. (2024). [10, Figure 2]

rather than spectroscopic measurements), possibly contaminated by low-redshift interlopers[2][20]. Therefore, it is important that results be spectroscopically confirmed[12]. Harikane et al. (2023) and Donnan et al. (2023) have spectroscopically confirmed many of the candidates at $z \gtrsim 10$ to be accurate high-redshift UV-bright galaxies [14][10]. The UV overabundance is therefore a real and important result.

The UVLFs were traditionally modelled by a Schechter function, which underpredicts bright galaxies beyond $z \sim 9$. Recent studies have now found a double power law (DPL) more accurately describes the data (see Figure 1). The DPL is now the standard for describing stellar populations at $z = 7 - 12$ [10].

The data from JWST beyond $z = 9$ continues to differ from Schechter function values. The number density of galaxies is found to evolve very little between $z = 9 - 12$ [14] and lacks the steeper decline expected from extrapolating the Schechter function (see Schechter (1976)) at lower redshifts [12][21][19]. As a result, the implied star formation rate (SFR) density declines slowly beyond $z \approx 10$, contrasting the rapid decline predicted by constant star-formation efficiency models [14]. This suggests higher than expected star formation in the early universe.

There have been many proposals to solve this discrepancy. We begin with the proposals of a *lower dust attenuation*[11] and *UV variability from bursty star formation*[21]; these proposals present minimal astrophysical changes. We then consider *feedback-free starbursts*[8] and a *top-heavy evolving initial mass function*[15], which challenge astrophysical processes more. Finally, we present the models of *early dark energy*[20] and *dynamical dark energy*[17], which propose major changes to cosmology. The remainder of this review focuses on the models aimed at understanding the JWST data.

The Donnan UVLF Model

Donnan et al. (2024) conduct a study of 2548 galaxies and determine the galaxy UVLF at $8.5 < z < 15.5$. They model the UVLF using an evolving Schechter function (detailed in Bouwens et al. (2021) [3]) for redshifts $z < 7$ and a DPL parametrisation for higher redshifts.

The model used is demonstrated in Figure 2. It is clear that the model fits well at $z \simeq 11$, and the extrapolated Schechter function underpredicts the JWST data [16]. The UV LF determined in Donnan et al. is then used to create a function of luminosity density ρ_{UV} and the star formation rate density ρ_{SFR}.

The findings of Donnan et al. affirm the findings of McLeod et al. (2024) that there is little evolution in the bright end of the UVLF to $z \simeq 12.5$. Donnan et al. argue that the results do not require novel astrophysical processes, nor threaten ΛCDM. It is shown that simple evolutions in the stellar population ages can explain the results. It is found that the ages required between $z \simeq 8 - 11$ are $\simeq 380 - 330$ Myr after the Big Bang. Donnan et al. note a steep drop-off in star formation rate density found beyond $z \approx 13$, which is consistent with signs of rapid evolution of the halo mass function and supported by early JWST data [10, Section 5.2].

[2] a misidentified galaxy that mimics higher redshift galaxy signals

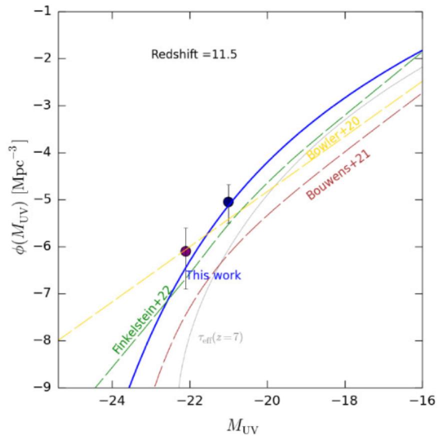


Figure 3: Comparison of Ferrara et al. (2022) UVLF (blue line) with GL-z11/GL-z13 (blue point) and GN-z11 galaxy (brown point). Also shown: Schechter (red line) [3], DPL (yellow/green lines) fits [4], and Ferrara model with dust attenuation (grey line)[11, Figure 3].

Low Dust Attenuation

Ferrara et al. (2023) present a dust-free model of the UV LF which can explain the observed galaxy abundance at $z = 10 - 14$ [11]. They argue that a *'conspiracy'* between a decreasing dust attenuation of galaxies and declining abundance of host halos explains the weak evolution from $z = 7 - 14$. Moreover, despite the reduced number of haloes, a lower dust attenuation compensates, making the galaxies brighter.

The report focuses on two very bright galaxies, GLASS-z13 and GLASS-z11. These galaxies are found to require host haloes of mass $M = 10^{11.33} M_\odot$ which are very rare at that redshift (4.8σ fluctuation). They also determine the UV luminosity as a function of M[3] which is then used to compare the predicted UVLF with the data. Two versions of the model with zero dust attenuation and dust attenuation increasing with galaxy star formation rate (specifically $\propto \mathrm{SFR}^{1.45}$) are tested against data at $z = 7$, both are found to be in agreement[11]. They show that declining dust attenuation reproduces the stable UVLF evolution and suggest that the GLASS galaxies were free of dust.

The zero dust attenuation model is tested at $z = 11.5$ and found to be in agreement with observed data (Figure 3). The function is also tested against data from Donnan et al. (2023) [9] at $z = 13.5$ and found to produce data within $\simeq 1\sigma$. This leads to their conclusion that the early massive galaxies are unaffected by dust attenuation. Proposed explanations for this include radiation leakage or the ejection of dust in the early evolutionary stages of galaxy buildup [11].

Bursty Star Formation

Shen et al. (2023) [21] propose that the JWST results can be explained by variability in the UVLF of galaxies at $z \geq 9$. They propose that physical processes such as bursty star formation (star formation in quick, intense bursts) can explain the variability, consistent with ΛCDM.

In their model, Shen et al. assume a linear relation between the star formation rate and the UV luminosity. They then introduce a *scatter* in the $M_{\rm UV} - M_{\rm halo}$ relation to simulate variability. They find a variability of $\sigma_{\rm UV} \approx 0.75$ mag matches constraints at $z \approx 9$ but a very large $\sigma_{\rm UV}$ is required at higher redshifts (reaching $\sigma_{\rm UV} \approx 2.00 \pm 0.25$ at $z \approx 12.0 \pm 1.6$). UV variability makes low-mass galaxies appear brighter, increasing the UVLF[21].

Spectroscopic measurements of emission lines can give an understanding of burstiness in star formation, and improved simulations may shed light on the origin of UV variability [21]. Shen et al. argue that the results from JWST can be shown to be consistent with ΛCDM cosmology paired with a standard galaxy formation model and UV luminosity variability.

The very large $\sigma_{\rm UV}$ required at high redshifts is a problem. This is addressed in Shen et al. (2024), where they find that at high redshift ($z \sim 16$), $\sigma_{\rm UV}$ in the ΛCDM framework becomes unphysical [20, Section 5].

Top-Heavy Initial Mass Function

The *initial mass function* (IMF) describes the initial distribution of stellar masses in a given mass interval. In 1955, Edwin E. Salpeter developed a power-law IMF function, $dN/dM \propto M^{-\alpha}$[18]. Data from the JWST has led to the suggestion that

[3]the function used is $M_{\rm UV} = -2.5 \log L_{1500} + 5.89 + 1.087\tau_{\rm eff}$. Where $\tau_{\rm eff}$ refers to the dust attenuation effects.

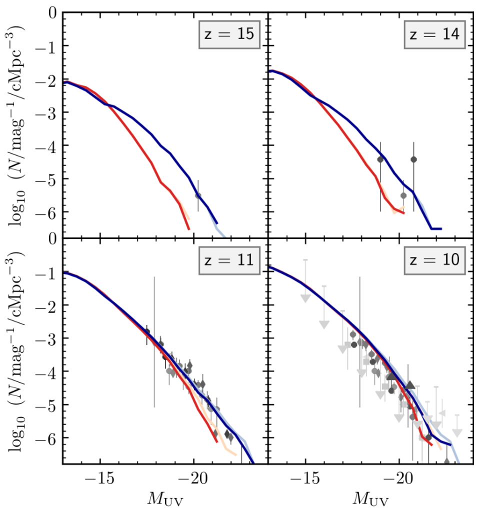


Figure 4: UVLFs for Salpeter (red) and Evolving (blue) IMF at $z = 10, 11, 14, 15$, with (dark lines) and without (light lines) dust attenuation. HST (light grey) and JWST (dark grey) data shown. [15, Figure 3]

the stellar populations in early galaxies formed with an IMF that was more top-heavy (produces more high-mass stars than low-mass stars) than the Salpeter IMF [15]. Hutter et al. find that a top-heavy IMF can enhance UV luminosities by $\Delta M_{\mathrm{UV}} \simeq 2.6$ in massive galaxies, whilst smaller galaxies, limited by feedback, only experience an enhancement of $M_{\mathrm{UV}} \simeq 1.3$.

In Cueto et al. (2024), they implemented an IMF with top-heaviness increasing with increasing redshift and decreasing gas-phase metallicity; however, they found that their IMF didn't fully reconcile with the JWST data since the heavier IMF is counteracted by stronger stellar feedback[7, Section 5].

Hutter et al. instead adopt an *evolving IMF* that is only top-heavy for some galaxies with particularly high star formation rates and dense gas environments [15]. They find it successfully reproduces the observed UV LFs at $z = 5 - 15$. In Figure 4, where the Salpeter IMF (red line) is compared to Hutter's Evolving IMF (blue line), we can see that the Evolving IMF fits the observed JWST data for higher redshifts much better than the Salpeter IMF. They also find that there is increased scattering in a top-heavy IMF, helping explain the range of UV luminosities found.

Interestingly, adopting the evolving IMF causes cosmic reionisation to start earlier by $\Delta z \simeq 2$ compared to the Salpeter IMF, since there are more ionising photons from top-heavy IMF galaxies. However, they find that reionisation completes by $z \simeq 5.6$ in both IMF models [15].

Feedback-Free Starbursts

The high UV luminosities at $z \gtrsim 10$ suggest a higher than usual star formation efficiency. Dekel et al. (2023) show that the JWST results can be explained by *feedback-free starbursts* (FFBs) in the brightest galaxies at $z \gtrsim 10$. Importantly this proposal does not require any changes to standard ΛCDM cosmology. FFBs refer to the rapid formation of stars *before* feedback (e.g., supernovae) can hinder their formation.

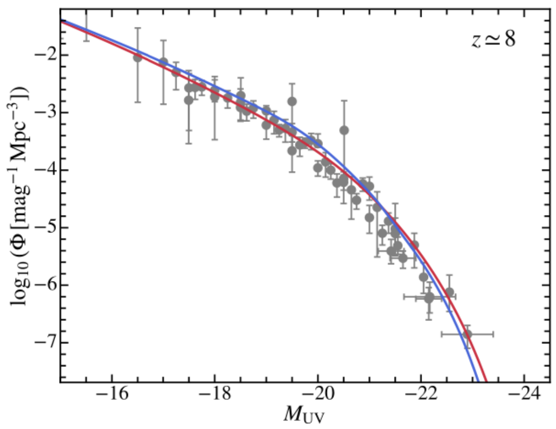
FFBs occur if the free-fall time (t_{ff}) (the time for a gas cloud to collapse under its own gravity) is shorter than the delay for feedback processes. At low metallicities, stellar winds and supernovae take $\gtrsim 1$ Myr to kick in, which gives time for stars to form unimpeded if $t_{\mathrm{ff}} < 1$ Myr. The free-fall time of a star-forming cloud is related to the gas number density by Equation 1 [8, Equation 4].

$$t_{\mathrm{ff}} = \left(\frac{3\pi}{32G\rho}\right) = 0.84\ \mathrm{Myr}\ \left(\frac{n}{10^{3.5}\mathrm{cm}^{-3}}\right)^{-\frac{1}{2}} \qquad (1)$$

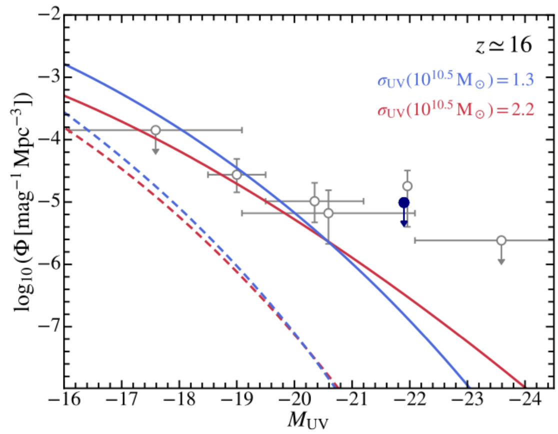
Hence, if the density of the star-forming gas is above a critical threshold of $n_{\mathrm{fbk}} = 2.23 \times 10^{3}\ \mathrm{cm}^{-3}$, star formation proceeds before feedback can intervene[8]. They further show that the threshold of a halo to allow FFBs is $M_v \gtrsim 10^{10.8} M_{\odot}$ at $z \sim 10$. Below these thresholds feedback occurs, lowering SFE. At $z \gtrsim 10$ the characteristic density permitting FFBs emerges naturally [8].

This density also means that the gas cloud surface density is such that radiative feedback suppression is also ineffective. Furthermore, clouds of $\mathrm{M} > 10^{4}\ \mathrm{M}_{\odot}$ are shielded against winds and radiation.

Dekel et al. also give some observable predictions of FFBs. Since FFBs proceed with almost 100% efficiency and have stellar densities of $n \sim 3 \times 10^{3}\ \mathrm{cm}^{-3}$, this implies stellar masses of $\mathrm{M}_{\mathrm{S}} \sim 10^{10}\mathrm{M}_{\odot}$ and SFRs of $\sim 65\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$ inside



(a) $z \simeq 8$



(b) $z \simeq 16$

Figure 5: Rest-frame UVLFs of ΛCDM (red) and EDE (blue) models vs. observation (grey dots). Dashed lines show benchmark model (from $z \lesssim 10$) predictions, solid lines include UV variability tuning [20, Figure 5d and 6d].

galactic radii of $R_e \lesssim 1$ kpc. Furthermore, the morphology of the stars can be expected to be compact, clumpy discs for massive galaxies and smoother discs or non-discs for lower-mass galaxies. We also know that the metallicities are required to be below $Z \sim 0.2 Z_\odot$, and dust attenuation is expected to be weak[4].

FFBs can have long-lasting implications. Firstly, the possibility that star clusters from FFBs could survive and could be observed today in the brightest cluster galaxies. Secondly, clusters formed from FFBs could form massive black holes, potentially explaining the formation of some supermassive black holes. Finally, they suggest that radiation from FFBs could contribute to cosmic reionisation (hydrogen ionisation in the early universe).

The FFB proposal does not require changes in standard ΛCDM cosmology; instead, the JWST results are explained via star formation at very high efficiencies beyond $z \sim 10$. The FFB phenomenon is yet to be verified and quantified through proper simulations that can capture the processes involved.

Early Dark Energy

The proposals mentioned up to now can be explained within standard ΛCDM cosmology. These proposals usually require strong adjustments to standard models of galaxy formation (such as high UV variability or high star formation efficiency). We focus now on exotic proposals that lie outside of standard cosmology.

One such proposal is the existence of *early dark energy* (EDE), which was originally proposed to solve the *Hubble tension*. The Hubble tension refers to the difference in measured values of the universe expansion rate from Planck satellite measurements of the CMB and from local expansion measurements of supernovae. In particular there is a 5σ disagreement between Planck CMB data ($H_0 = 67.27 \pm 0.60\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) and the latest supernovae data ($H_0 = 73.04 \pm 1.04\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) [1].

EDE allows for an increased expansion in the early universe before recombination[5] ($z \simeq 1000$). Shen et al. (2024) propose a model in which a scalar field model of EDE contributes $\sim 10\%$ of the critical density pre-recombination [20]. The primary influence of this is altering cosmological parameters to enhance the halo and galaxy abundance at high redshifts, alleviating the UV tension from JWST. The paper investigates the potential of EDE as a unified solution to the Hubble tensions and the UV tension.

They show that the cosmological model amplifies the Hubble constant determined from the CMB to $\sim 74\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, in agreement with local data. They also show that the number densities of haloes are amplified at higher redshifts for EDE compared to ΛCDM (see Fig. 1 in Shen et al. (2024) [20]), and that at $z = 0$ the HMFs are indistinguishable.

The paper introduces UV variability and variable star formation efficiency in their model to allow it to be tuned to the data. Figure 5a plots the UVLFs at $z \simeq 8$ for the ΛCDM and EDE models, showing that the EDE and ΛCDM models agree and match observations. Figure 5b plots the same thing at $z \simeq 16$ with additional tuning of

[4] Here, Z is the mass fraction of all metals except hydrogen and helium

[5] recombination refers to the period of time when the universe had sufficiently cooled to allow electrons and protons to combine and form hydrogen atoms (≈ 380,000 years after the Big Bang).

the UV variability to fit the measured data; this is done across multiple redshifts (see Figs. 5, 6, and 7 in Shen et al. (2024)). It is found that at high redshifts, tuning of $\sigma_{\mathrm{UV}} \sim 1.4 - 2.2$ mag is required for the ΛCDM model. This level of UV variability is unphysical and exceeds predictions from simulations. However, in EDE, agreement is achieved with $\sigma_{\mathrm{UV}} \sim 0.8 - 1.3$ mag. Hence, EDE alleviates the tensions with sensible adjustments to galaxy physics compared to ΛCDM.

Shen et al. show that EDE simultaneously resolves the JWST tension and the Hubble tension whilst reducing reliance on extreme UV variability. Future work is required to confirm EDE, and forthcoming CMB experiments have the potential to strongly detect or exclude EDE.

Dynamical Dark Energy

A further exotic proposal that suggests a change in cosmology is Menci et al.'s proposal that the JWST observations can be explained by a dynamical model of dark energy with a negative cosmological constant Λ and a time-evolving dark energy field [17]. The motivation for a negative cosmological constant lies within complex string theory (specifically Anti-de Sitter ground states [17, Section 2]), but is also supported by independent measurements from the CMB and from DESI (Dark Energy Spectroscopic Instrument)[2]. As a consequence, structures in the early universe can form earlier and grow larger. This naturally explains the abundance of UV-bright galaxies without requiring modifications to galaxy physics. Further data beyond $z \simeq 15$ are required to verify or exclude the model.

Implications for Cosmology

The above proposals to account for the observed overabundance of UV-bright galaxies present consequences for both astrophysics and cosmology.

Donnan et al. (2024) find JWST data agrees with ΛCDM up to $z \simeq 12$, with a drop-off at $z = 13$. If later data shows continued abundance beyond $z = 13$, a different model may be required.

Ferrara et al. (2023) show that decreasing dust attenuation reproduces the UVLFs up to $z \simeq 14$. Shen et al. (2023) find that low levels of UV variability explain data from $z \simeq 9$, requiring very high variability for $z \simeq 12$. These require only small astrophysical changes, within ΛCDM.

Hutter et al. (2025) show an evolving top-heavy stellar initial mass function reproduces UVLFs at $z = 5 - 15$. Their proposal results in an earlier onset of reionisation. Dekel et al. (2023) propose that early universe feedback-free starbursts with $\sim 100\%$ efficient star formation can explain the UVLFs. These need larger astrophysical changes, but still remain within ΛCDM

Shen et al. propose an early dark energy model with additional dark energy pre-recombination through altering the ΛCDM model parameters. EDE uses UV variability to help explain the observed UVLFs but requires significantly less variability than in ΛCDM. The model also proposes a solution of the Hubble tension. Menci et al. use a string theory-motivated model of dynamical dark matter with a negative cosmological constant. Allowing for structures to form earlier and grow larger in the early universe, reproducing the abundance of UV-bright galaxies without modifying galaxy physics.

Future JWST studies

Upcoming JWST projects are of strong relevance to this review, in particular, observations beyond $z \sim 13$. If the level of bright galaxies declines beyond $z \sim 13$, then this supports astrophysical explanations (such as Donnan et al.'s UVLF). However, if the abundance continues to be large, then this supports dark energy models and poses a challenge to ΛCDM. The current furthest galaxy detected spectroscopically is JADES-GS-z14-0, confirmed at a redshift of $z = 14.32^{+0.08}_{-0.20}$ [5].

Furthermore, non-JWST experiments may also prove useful in our understanding of cosmology. The ground-based CMB Stage-4 experiment, which aims to map the CMB in more detail, aims to investigate the nature of dark energy and dark matter and may aid in testing early and dynamical dark energy models [6].

Upcoming experiments will be critical in determining whether ΛCDM is sufficient to explain early galaxy formation or if a new standard model of cosmology (perhaps incorporating EDE) is required.

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