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Evaluating ΛCDM Predictions for Early Galaxy Formation with Observations from JWST's SMACS 0723 Field

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ABSTRACT

This paper investigates whether the observed properties of GLASS-z12, a very high-redshift galaxy observed in the JWST SMACS 0723 field, align with predictions made by the Lambda-Cold Dark Matter (ΛCDM) model of cosmology. Using JWST NIRCam imaging products and a spectroscopic redshift of $z = 12.34$, I calculated a lookback time of $t_L = 13.439 \pm 0.13$ Gyr for GLASS-z12, where the quoted uncertainty reflects sensitivity to the Planck 2018 base-ΛCDM parameters H_0 and Ω_m (assuming spatial flatness). This implies that the observed light was emitted approximately 352 million years after the Big Bang. Combined with external estimates of its stellar mass (~ 10^9 M☉) and effective radius ~ 0.5 pkpc, the inferred early formation appears difficult to reconcile with naive expectations from standard hierarchical growth in ΛCDM. Taken together, these results motivate further observational and theoretical work to test whether the apparent tension can be resolved within ΛCDM through parameter choices and astrophysical systematics, or whether extensions such as Early Dark Energy provide a better description of early galaxy formation.

INTRODUCTION

As our ability to observe the universe deepens, discrepancies between theory and observation are becoming increasingly difficult to dismiss. Tensions between theory and experimentation have long existed within the fields of astrophysics and astronomy, but the last few years have seen those tensions rise in a way that potentially could jolt our understanding of the universe.

For the last few decades, a model known as Lambda-Cold Dark Matter (or ΛCDM) has served as the dominant cosmological framework used to describe the structure and evolution of the universe [1]. This model states that the universe is composed of dark energy, cold dark matter, and ordinary matter. It proposes that our Universe emerged from the Big Bang and has been expanding ever since, with its current accelerated expansion being driven by dark energy. Among other things, the model predicts a gradual formation of structure, where small density fluctuations in the early universe grew over large periods of time into stars, galaxies, and galaxy clusters through gravitational collapse [2]. This model has been used to successfully explain a wide range of cosmic observations and holds as our best understanding of the universe [3].

Crucially, according to this model, it should have taken hundreds of millions of years for small, primitive galaxies to form after the Big Bang, while massive galaxies with significant mass are expected to have appeared a full billion years after. However, this viewpoint clashes with recent data received from the James Webb Space Telescope (JWST). Launched in December 2021 as the most powerful space observatory ever built, JWST was built to see farther back in time than any telescope before it, using its advanced infrared instruments to look at some of the earliest galaxies that formed after the Big Bang [4]. Beginning with its primary release of images on July 12th, 2022, JWST's observations sparked a massive degree of contention [5].

The cause of this was that some of the galaxies it identified were both massive, mature, and endowed with extremely high redshifts, indicating that they must have appeared within the first 500 million years of the Universe's existence. A surprising amount of these galaxies were detected, more than 100 times what our best theories predicted [6]. To date, the furthest known galaxy that has ever been observed is known as MoM z14, detected by JWST in May of 2025 with a shockingly high spectroscopic redshift of $z = 14.44$ [7]. This indicates that it is aged only 290 million years after the Big Bang.

Observations such as this go fundamentally against what ΛCDM predicts about the timeline of massive galaxy formation. If these JWST observations are accurate, it would insinuate that there is something fundamentally wrong or potentially incomplete with our ΛCDM model and, in extension, our understanding of the Universe itself [4].

So, what happens when the most successful model in cosmology meets the most powerful telescope ever launched? The past three years have seen a surge in attempts to explain the growing tension between JWST observations and predictions from the ΛCDM model. Several leading hypotheses have emerged to account for the discrepancy. Initial reactions took a more pessimistic outlook on our model of cosmology; Menci et al (2022) argued that the unexpectedly large number of massive galaxies observed by JWST at redshifts around 10 cannot be explained by ΛCDM or most dark energy models without extreme assumptions, pointing to possible tensions with the standard cosmological framework [8]. Boylan-Kolchin (2023) echoed this result, proposing that most massive galaxy candidates observed by JWST at redshifts $z \approx 7\text{–}10$ nearly exhaust the baryonic limits allowed by ΛCDM [9]. If these galaxies' inferred masses are correct, either galaxy formation must have been implausibly efficient or the cosmological model needs revision.

While these findings point toward potential shortcomings in the ΛCDM framework, an alternative view is that the model itself remains sound, but the value of some of its parameters, like those established by the Planck Collaboration in 2018, simply require revision [10]. The parameter under closest scrutiny is the cosmological constant (Λ), which represents the constant energy density of empty space. It corresponds to the simplest model of dark energy, in which this energy is uniform in space and unchanging over time. Many have proposed that alterations to this framework might be necessary, particularly how it changes over time [11]. After testing whether alternative dark energy models can explain JWST's observation of unusually massive high-redshift galaxies, Forconi et al (revised in 2024) concluded that Early Dark Energy (EDE) significantly improves the fit over ΛCDM [12]. This form of dark energy would have only made a brief appearance in the very early Universe, influencing its expansion for its first moments [13].

Beyond this, comprehensive analyses such as the Dark Energy Survey (DES-SN5YR) examine a wide array of cosmological models against diverse datasets. They find that while none of the non-standard cosmological models are strongly favored over ΛCDM, 11 out of 15 models are moderately preferred when when cross-checked against supernovae, CMB, and baryon acoustic oscillation data which suggests that the cosmological constant likely does not fully explain the dynamics of the universe's expansion [14].

Some researchers suggest truly grand alterations to the cosmological constant. One such study, examining JWST photometric and spectroscopic observations of high-redshift galaxies, shows that a dark energy model with both a negative cosmological constant and an evolving component can accommodate the JWST observations of massive galaxies at redshifts 5 to 11 with a high degree of consistency while remaining consistent with other cosmological data and potentially easing existing cosmological tensions [15]. While the implications of a negative cosmological constant seem to go against well-established results of a consistently accelerating expansion of the Universe, this model is motivated by string theory frameworks where anti-de Sitter (AdS) vacua, characterized by a negative cosmological constant, are common [16].

Despite these perspectives, it alternatively appears that there may not be issues with our cosmological model after all. More recent research has proposed that the tension between JWST observations and the standard cosmological model stems not from flaws in our theoretical understandings, but rather from challenges in interpreting our observations [17]. In August 2024, a study titled Evidence for a Shallow Evolution in the Volume Densities of Massive Galaxies at z = 4–8 from The Cosmic Evolution Early Release Science Survey (CEERS) found that out of the 261 early galaxies they studied, nine appeared significantly brighter and therefore more massive due to the influence of active black holes at their centers. Gas falling into these black holes emits intense radiation as it heats up from friction, artificially boosting the galaxies' apparent brightness and its presumed mass. After correcting for these black hole contributions, the remaining galaxy population aligns well with predictions from the standard cosmological model [18].

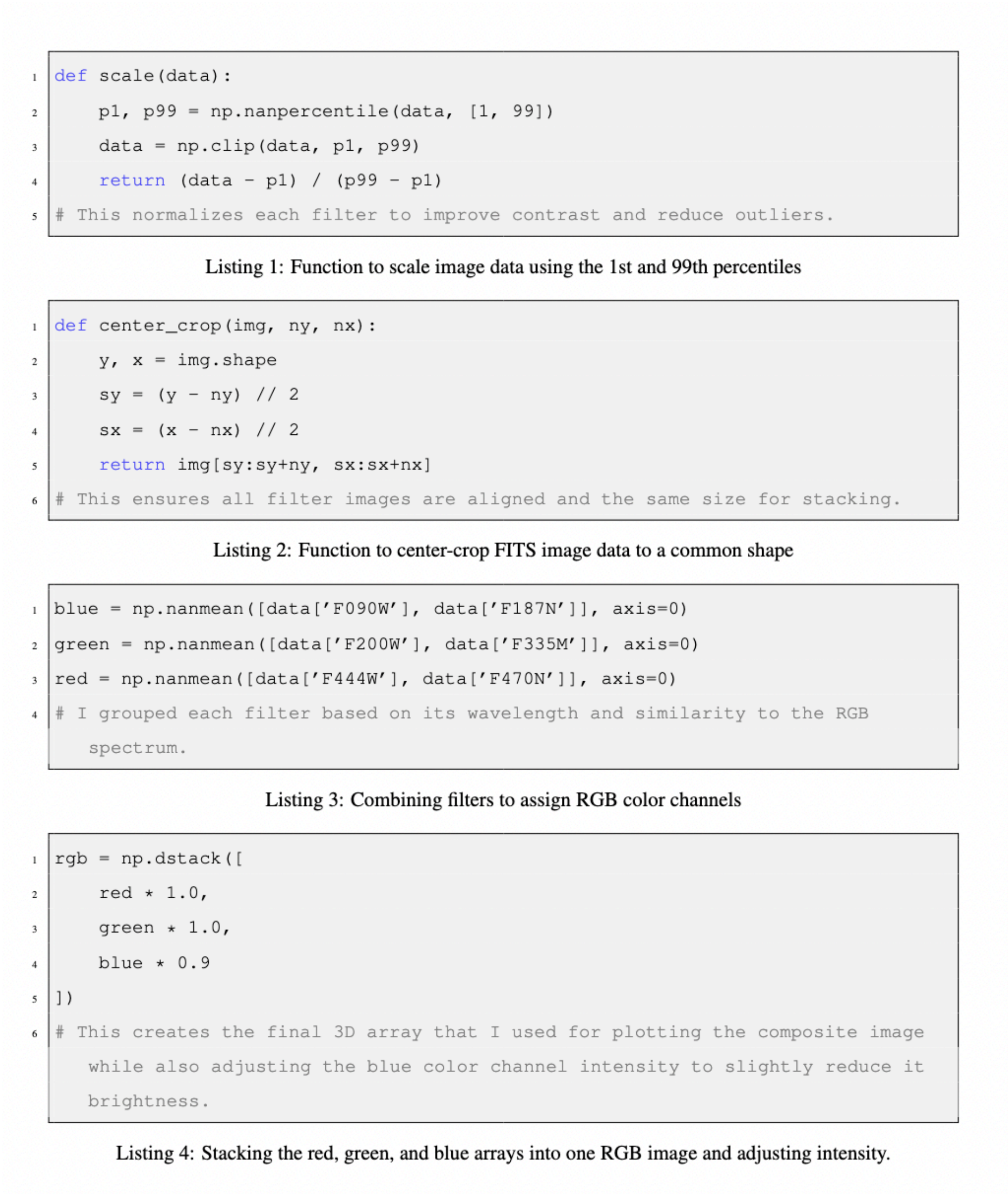
Some research has even proposed that no fundamental problem or so-called crisis in cosmology exists at all. A recent paper argued that even if all extreme-redshift galaxy candidates observed by JWST are confirmed, their existence is consistent with ΛCDM without requiring any exotic new physics at all [19].

METHODS

I have conducted a quantitative analysis using publicly available astronomical data from the James Webb Space Telescope (JWST), specifically from the Mikulski Archive for Space Telescopes (MAST) [20]. I focused on imaging data from JWST's Near Infrared Camera (NIRCam) as it operates as Webb's primary infrared imager and is optimized to detect galaxies with high-redshifts.

For this project I selected six NIRCAM/IMAGE filters from the SMACS J0723.3-7327 dataset: F090W, F200W, F335M, F444W, F187N, and F444W–F470N. (The results of two of these filters as loaded in VSCode can be seen in Figure 2.) I processed these FITS files by removing non-positive values, scaling using the 1st and 99th percentiles, and center-cropping to match each of their dimensions to one another. I then grouped the filters into RGB channels based on their wavelengths and combined them using numpy stacking. The following code excerpts show the most important steps of my image construction process for my first finalized image, generated with Python in VSCode: normalizing pixel intensities using percentile-based scaling, aligning image dimensions through center-cropping, grouping filters into RGB channels based on wavelength, and stacking the data into a three-channel image. I have also included a brief explanation with each excerpt on its functionality within the larger code.

As an added note, I originally wrote this code for creating images of the Pillars of Creation, a prominent star-forming region located within the Eagle Nebula (Messier 16 or M16). While it would not yield much of a discussion to compare observations within this image to the ΛCDM model because the Pillars are a local, small-scale structure within our own galaxy, far removed from the cosmological scales and early-universe conditions that ΛCDM describes, the exercise proved very helpful for developing the image processing techniques I later applied to the distant galaxies in the SMACS J0723.3-7327 Deep Field. I chose to include my work and resulting images of the Pillars of Creation to showcase my data reduction and image reconstruction techniques on a well scientifically significant region and so I could ensure the reliability of the methods before applying them to the less-explored and more challenging deep field observations of SMACS J0723.



```python
def scale(data):
    p1, p99 = np.nanpercentile(data, [1, 99])
    data = np.clip(data, p1, p99)
    return (data - p1) / (p99 - p1)
# This normalizes each filter to improve contrast and reduce outliers.
```

Listing 1: Function to scale image data using the 1st and 99th percentiles

```python
def center_crop(img, ny, nx):
    y, x = img.shape
    sy = (y - ny) // 2
    sx = (x - nx) // 2
    return img[sy:sy+ny, sx:sx+nx]
# This ensures all filter images are aligned and the same size for stacking.
```

Listing 2: Function to center-crop FITS image data to a common shape

```python
blue = np.nanmean([data[’F090W’], data[’F187N’]], axis=0)
green = np.nanmean([data[’F200W’], data[’F335M’]], axis=0)
red = np.nanmean([data[’F444W’], data[’F470N’]], axis=0)
# I grouped each filter based on its wavelength and similarity to the RGB
   spectrum.
```

Listing 3: Combining filters to assign RGB color channels

```python
rgb = np.dstack([
    red * 1.0,
    green * 1.0,
    blue * 0.9
])
# This creates the final 3D array that I used for plotting the composite image
   while also adjusting the blue color channel intensity to slightly reduce it
   brightness.
```

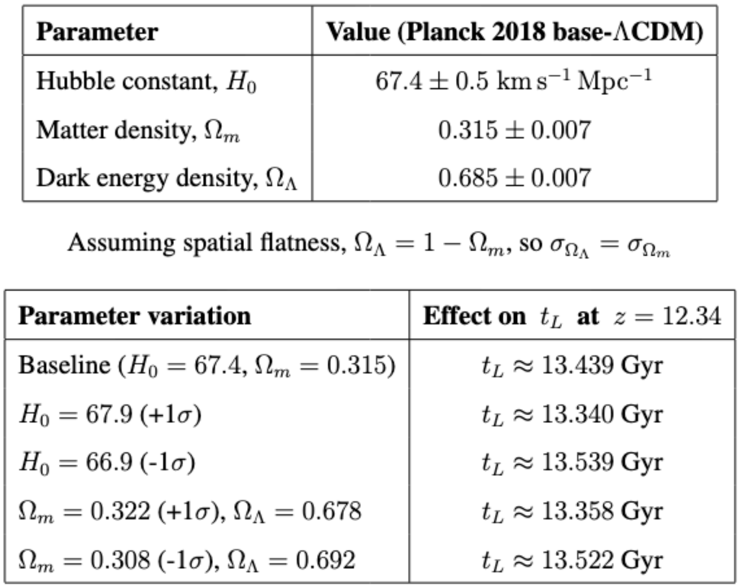
Listing 4: Stacking the red, green, and blue arrays into one RGB image and adjusting intensity.

Resulting from this code, my first RGB composite image of the Deep Field can be seen below in Figure 3.

When experimenting with the coloring in this first image, I learned that there were issues with adjusting the relative intensities of the red, green, and blue channels through linear channel scaling (see Listing 4; blue multiplied by 0.9). Linear scaling multiplies each pixel by a constant which uniformly adjusts all pixel intensities and doesn't account for both subtle details in faint regions, which can get washed out, or bright areas, which can get overemphasized. To solve this, I experimented with a program called Siril to adjust the brightness of each FITS file (each of six filters) along a curve with generalized hyperbolic stretch transformations. This involved a preliminary stretch intensity of 12.9 coupled with a stretch factor of 8 on dark regions of each image, and a subsequent stretch intensity of 3.9 coupled with a stretch factor of 1.8 on brighter regions. I then used an additional program called GIMP, or GNU image manipulation program to work with coloring my final images, which involved manually adjusting the logarithmic histogram of each filter. With these adjustments, my second RGB composite image of the Deep Field is shown below in Figure 4.

Methodological note: Figures 3 and 4 are qualitative visualization products of the image-processing workflow (cropping, scaling, and color mapping) and are included to demonstrate data handling and to visually locate high-redshift sources in the field. The cosmological inference presented below (lookback time and cosmic age at z) does not depend on the display-stretch or RGB choices; it is computed from the published spectroscopic redshift and the adopted CDM parameters.

Using the RGB composite only as a visual reference to identify GLASS-z12 in the field, I then focused on a cosmological analysis based on its spectroscopically confirmed redshift of z=12.34 [21]. I was able to calculate the lookback time of the galaxy–the time between the emission of its light and the present day–using calculations that numerically integrate a key integral derived from the Friedmann equations using the input cosmological parameters [22]. This approach allows for a precise determination of the galaxy's age relative to the Big Bang, providing a quantitative basis to compare with theoretical predictions. By establishing its age and combining this with its stellar mass and radius, I can assess how GLASS-z12 fits within the expected timeline of early galaxy formation, offering a concrete test of ΛCDM predictions. Based on the values set by the 2018 Planck Collaboration [23], the value of certain cosmological parameters that I used in my calculation are as follows:



Parameter	**Value (Planck 2018 base-ΛCDM)**
Hubble constant, H_0	$67.4 \pm 0.5\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$
Matter density, Ω_m	0.315 ± 0.007
Dark energy density, Ω_Λ	0.685 ± 0.007

Assuming spatial flatness, $\Omega_\Lambda = 1 - \Omega_m$, so $\sigma_{\Omega_\Lambda} = \sigma_{\Omega_m}$

Parameter variation	**Effect on** t_L **at** $z = 12.34$
Baseline ($H_0 = 67.4$, $\Omega_m = 0.315$)	$t_L \approx 13.439$ Gyr
$H_0 = 67.9$ (+1σ)	$t_L \approx 13.340$ Gyr
$H_0 = 66.9$ (-1σ)	$t_L \approx 13.539$ Gyr
$\Omega_m = 0.322$ (+1σ), $\Omega_\Lambda = 0.678$	$t_L \approx 13.358$ Gyr
$\Omega_m = 0.308$ (-1σ), $\Omega_\Lambda = 0.692$	$t_L \approx 13.522$ Gyr

RESULTS

Image-processing results (visualization)

Figure 1: My RGB composite image of the Pillars of Creation.

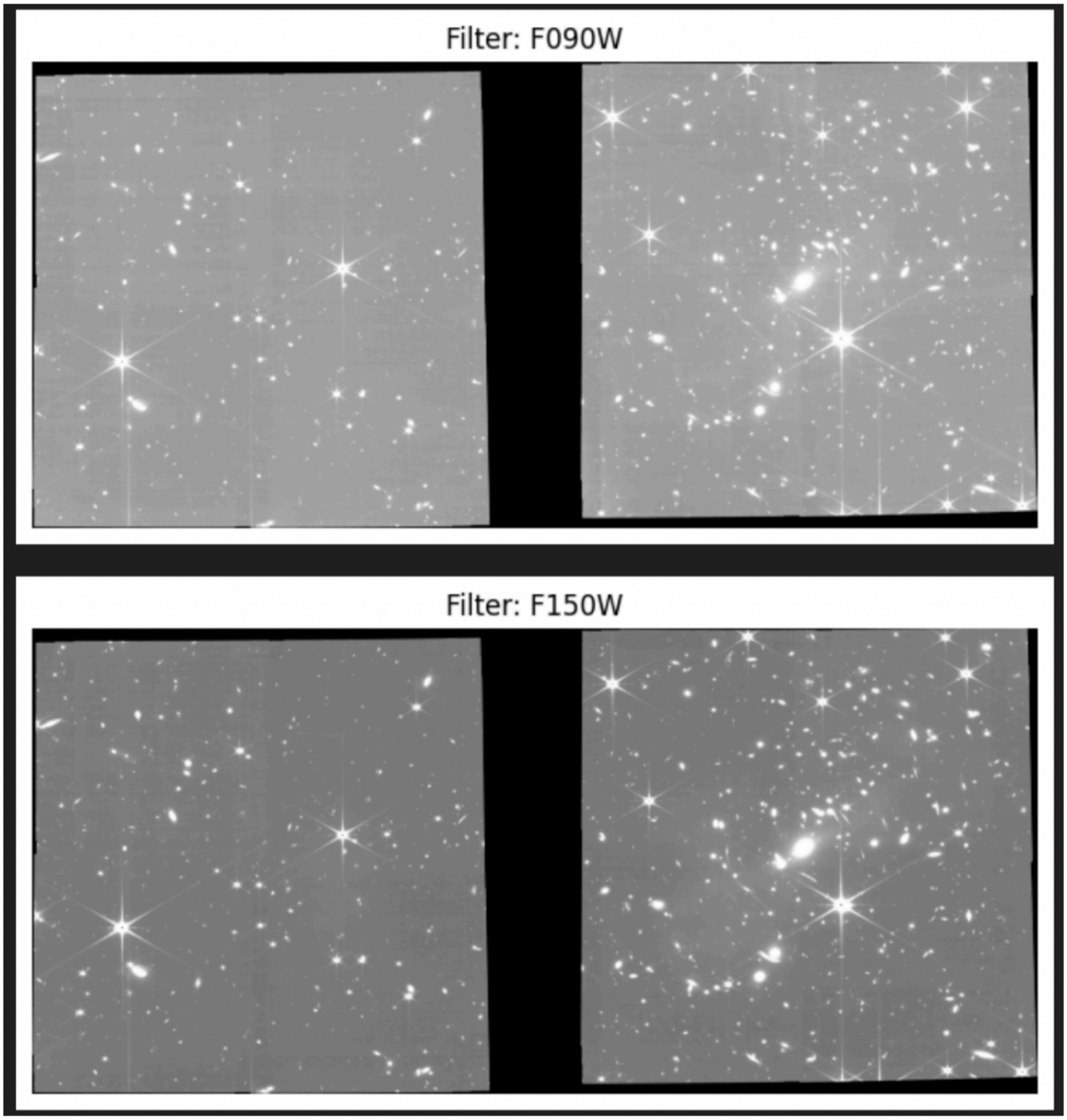


Figure 2: Filters F090W and F150W, two filters used in my larger RGB composite of the JWST SMACS0723 Deep Field

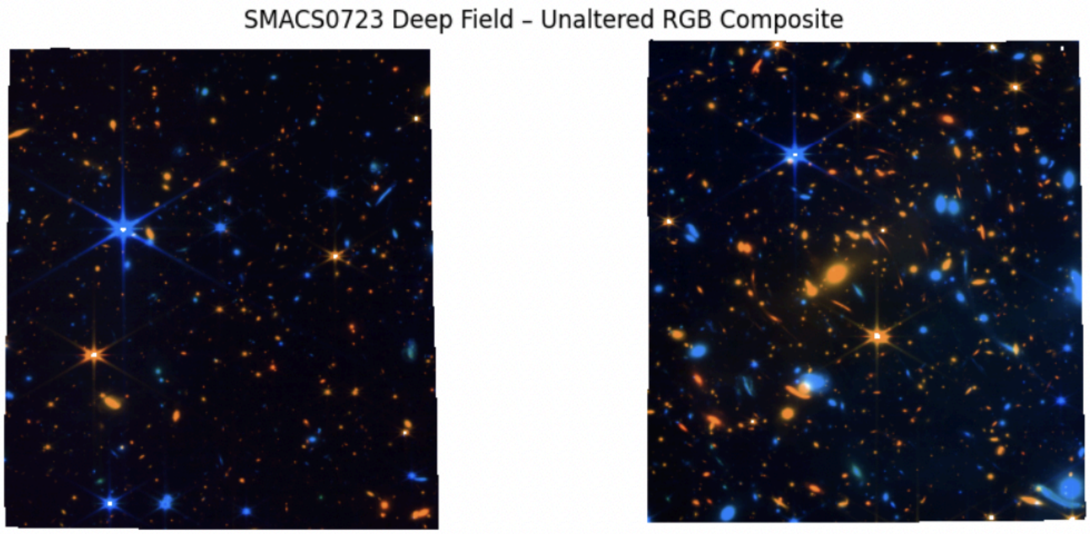


Figure 3: My first RGB composite image of the SMACS J0723.3-7330 galaxy cluster

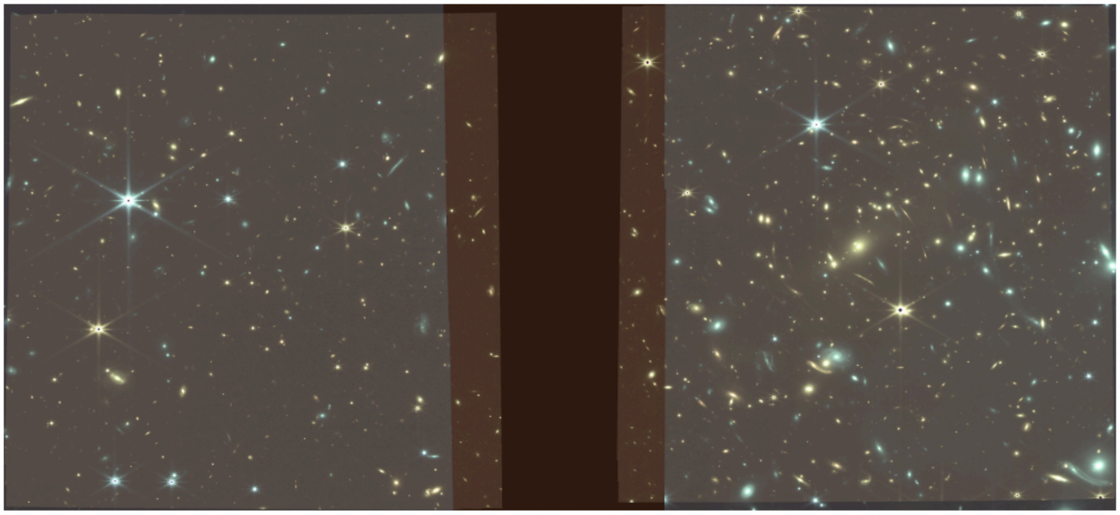


Figure 4: My second RGB composite image of the SMACS J0723.3-7330 galaxy cluster, using Siril and GIMP

Cosmological inference (from published redshift and adopted parameters)

After calculating the lookback time of GLASS-z12 from the Planck 2018 base-ΛCDM parameters and its spectroscopic redshift using Ned Wright's cosmology calculator [22], I obtained:
$t_L(z = 12.34) = 13.439$ Gyr.

Varying H_0 and Ω_m within their quoted 1σ uncertainties (and assuming spatial flatness so $\Omega_\Lambda = 1 - \Omega_m$) changes the inferred lookback time by ~0.10 Gyr and ~0.08 Gyr, respectively, giving a combined parameter sensitivity of $\sigma_{t_L} \approx 0.13$ Gyr; therefore, I report:

$t_L(z = 12.34) = 13.439 \pm 0.13$ Gyr.

In a universe of age 13.791 Gyr, this implies the observed light was emitted ≈ 352 million years after the Big Bang.

DISCUSSION

My findings suggest that GLASS-z12, a galaxy observed in the JWST SMACS 0723 Deep Field, may present challenges to the standard ΛCDM cosmological model. Using its spectroscopic redshift of z = 12.34 [21] and Planck 2018 base-ΛCDM parameters, I find a lookback time of
$t_L(z = 12.34) = 13.439 \pm 0.13$ Gyr
where the uncertainty reflects sensitivity to H_0 and Ω_m within their 1σ uncertainties (assuming spatial flatness) [22]. In a 13.791 billion year old universe, this places the emission time at ≈ 352 million years after the Big Bang. This early formation is already notable, but the most interesting result comes from combining this redshift with estimates of the galaxy's stellar mass and effective radius.

GLASS-z12 has a stellar mass of $\sim 10^9$ M⊙ and an effective radius around 0.5 pkpc [24]. To compare these imported values quantitatively to ΛCDM halo-growth expectations, I translate the stellar mass into an implied host halo mass scale. In the most optimistic case where all available baryons are converted into stars, $M_* \approx 10^9\, M\odot$ requires a halo mass of at least $M_h \geq M_*/f_b \approx 6 \times 10^9\, M\odot$, using $f_b = \Omega_b/\Omega_m \approx 0.155$ from Planck [23]. More realistic high-redshift stellar–halo mass relations instead associate $M_* \approx 10^9\, M\odot$ with haloes of order $M_h \sim 10^{11}$M⊙ (order-of-magnitude) [25]. For $M_h \sim 10^{11}$ M⊙ at z ≈ 12.34, the corresponding virial radius is of order $R_{200} \sim 10$ pkpc, and the empirical size–virial scaling $r_{1/2} \approx 0.015\, R_{200}$ predicts a characteristic stellar scale of ~0.1–0.2 pkpc [26]. Thus, the adopted $R_{eff} \sim 0.5$ pkpc is larger by a factor of a few than this simple ΛCDM-motivated benchmark, and achieving $M_* \approx 10^9\, M\odot$ by ≈352 Myr after the Big Bang requires very rapid early assembly [1].

Taken at face value, these properties place GLASS-z12 within the perspective that either early star formation and mass assembly were implausibly efficient, or some of the assumptions of ΛCDM may need revision [8, 9]. At the same time, this apparent tension can also be interpreted through the lens of parameter sensitivity within ΛCDM. The calculated lookback time depends on cosmological parameters, particularly Ω_m, Ω_Λ, and H_0; small shifts within observationally allowed ranges could modestly change the inferred cosmic age at z ~ 12, altering the resulting tension. In this sense, GLASS-z12 could be consistent with ΛCDM if minor adjustments to the cosmological constant or other parameters account for faster-than-expected early growth. This connects to proposals for modifications to the early expansion history, such as EDE. If galaxies like GLASS-z12 are typical at high redshifts, brief early adjustments to expansion or altered matter clustering could provide a natural mechanism for accelerating structure formation [12, 13]. In these cases, GLASSz12 would not outright falsify ΛCDM but instead could highlight areas where different models better explain our observations.

Despite all of this, an argument could still be offered that my data can be situated within the "no crisis" perspective. GLASS-z12 could potentially represent a rare but statistically permissible outlier, similar to other cases [18, 19]. With this perspective, the important question shifts from whether ΛCDM is wrong to how representative GLASS-z12 is of the broader population of early galaxies. This emphasizes the need for a broader study of these massive high-redshifted galaxies.

As JWST continues to deliver new data, ongoing comparison between observations and theoretical models remains crucial. This process will continue to allow cosmologists to identify genuine discrepancies and investigate whether they arise from observational biases or deeper theoretical challenges. Whether this marks the beginning of a shift in physics or simply an error in our understanding remains one of the most pressing questions in modern cosmology.

Limitations

There are certain limitations to my research. In particular, my analysis was constrained by limited computational resources and access to only public imaging tools and data, which restricted the depth of what I was able to do. Another limitation concerns the dependence of the lookback-time estimate on the adopted cosmological parameters (H_0, Ω_m and Ω_Λ). However, rather than treating this qualitatively, I quantified this effect by varying H_0 and Ω_m within their quoted 1σ Planck 2018 base-ΛCDM uncertainties (assuming spatial flatness so $\Omega_\Lambda = 1 - \Omega_m$) and found a combined sensitivity of $\sigma_{t_L} \approx 0.13$ Gyr at $z = 12.34$. This parameter sensitivity adds uncertainty to the inferred emission time and complicates comparisons between observations and ΛCDM predictions at very early epochs. Finally, my interpretation also depends on external estimates of GLASS-z12's stellar mass and effective radius, which can carry additional systematic uncertainties (e.g., assumptions in SED fitting, lensing magnification, and stellar-population modeling) that are not re-derived in this work.

CONCLUSION

In this study, I examined the properties of GLASS-z12, a high-redshift galaxy observed in the JWST SMACS 0723 Deep Field, to evaluate their consistency with the ΛCDM cosmological model. Using spectroscopic data, I calculated a lookback time of:

$t_L(z = 12.34) = 13.439 \pm 0.13$ Gyr ,

indicating that the observed light was emitted approximately 352 million years after the Big Bang, where the quoted uncertainty reflects sensitivity to the adopted Planck 2018 base-ΛCDM parameters (assuming spatial flatness). When combined with external estimates of its stellar mass and effective radius, these inferred properties appear unusually large for such an early epoch; in halo-based ΛCDM scalings, the adopted size is a factor of a few above the characteristic scale expected for the implied host halo.

These results suggest that either early galaxy formation and mass assembly were more efficient than typically assumed, or that refinements to the ΛCDM model, such as adjustments to its parameters or extensions like Early Dark Energy, may be required to fully account for observed high-redshift galaxies. While GLASS-z12 could represent a rare statistical outlier, its existence underscores the importance of careful comparison between observational data and theoretical expectations. Overall, this analysis contributes to the ongoing discussion about the completeness of ΛCDM and the mechanisms driving early cosmic structure formation.

Future Research

Future research could expand this analysis to include multiple galaxies in the SMACS 0723 Deep Field as well as other JWST deep field datasets, providing a broader statistical context for evaluating early galaxy formation. I also suspect that continued refinement of structure formation simulations under ΛCDM, EDE/IDE, and other models will be necessary to assess whether galaxies like GLASS-z12 represent true anomalies, rare statistical outliers, or underlying limitations in our cosmological understanding. In particular, combining these observations with updated high-redshift galaxy surveys and more precise cosmological parameter constraints may help clarify the extent of any tension between theory and observation. As more JWST data become available, this tension may become important for the next generation of cosmological theories.

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