

Estimating the Effective Age of the Universe under Time Dilation: ~45 Gyr

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Abstract

A new concept, relativistic time dilation adjusted Effective Age of the Universe (EAoU), is introduced and is estimated at ~45 Gyr in comparison to the widely accepted 13.79 Gyr based on the comoving observer framework. Conceptual ambiguities in the treatment of time and distance on cosmic scales, particularly in the application of General Theory of Relativity (GTR) to accelerated expansion, matter density, gravitational effects, and relativistic time dilation are discussed. We categorize the Age of Universe (AoU) into three types, *i.e.*, AoU—Type 1: cosmic time, Type 2: elapsed solar years, and Type 3: effective time corrected for relativistic effects. The EAoU framework reconciles some key observational paradoxes, particularly regarding the existence of high redshift massive galaxies such as MoM-z14. An equation derived from the FLRW equations (Equation 33) provides the EAoU as an observer-centric, relativistically adjusted time scale. Thermodynamic perspective to EAoU is also discussed. The revised view of the universe's timeline offers a plausible resolution to the rapid formation of massive early galaxies, without invoking exotic physics.

Keywords

Cosmology, Relativistic-Time-Dilation, FLRW-Metric, Observer-Centric Time, Effective-Age-of-the-Universe, High-Redshift-Galaxies, Cosmic-Expansion, Time-Elongation

1. Introduction

Cosmology is beset with many challenging questions and lacunae, which bring into question the standard model of cosmology (SMC) [1] [2] itself. Prominent amongst these challenges are the Hubble tension, dark matter and dark energy, inflation, accelerated expansion, and high red shift galaxies [3]. In addition, there

are the horizon and flatness problems [4], baryon asymmetry [5], singularity conditions, etc. Accelerated expansion of the universe [6] [7], often attributed—somewhat speculatively—to a repulsive dark energy component, further adds to the mounting number of unexplained phenomena. Recent observations of large high redshift galaxies by JWST have the scientific community wondering about the Big Bang and the evolutionary timeline of the universe.

In this paper, we adopt an observer-centric approach to study the evolutionary time line and age of the universe (AoU). This approach, different from the “co-moving galaxy” approach widely used, enables us to view space, time, age, and evolution of the universe in a new light and from the viewpoint of a “present day” observer on earth. This approach offers a reconciliation of the observational and theoretical lacunae with respect to the age and allowable evolutionary time for the observed high redshift galaxies.

JWST (NASA, 2025) [8], since its launch in 2021, while providing a wealth of cosmological data and revealing many new objects and phenomena in deep space, to some extent, seems to have further widened the gaps in our understanding of how the universe works, evolves or exists. A large number of high red shift galaxies at $z > 10$ observed [9]-[13] seem to defy the prevalent and widely accepted age and timeline of the universe. The latest JWST observed galaxy, MoM-z14, which is nearly 500 million light-years across (Naidu *et al.*, 2025) [13] with the highest confirmed redshift of 14.44, corresponding to an assessed epoch just 280 million years after the Big Bang, is surprisingly luminous for its epoch and challenges conventional models that predict fainter and smaller galaxies in that epoch. It is felt that such large galaxies will take much longer to evolve (Henriques *et al.*, 2014) [14]. According to the largely accepted cosmic timeline (**Figure 1** and **Figure 2**), the first stars appeared at around 200 million years after the Big Bang and the first galaxies after 400 million years [15]. High red shift galaxies such as MoM-z14 raise fundamental question about galaxy formation in a period of few hundred million years after the Big Bang. Either the largely accepted timeline of the universe (**Figure 1** and **Figure 2**) is somewhat misleading, or we are missing something in the physics of the universe and the Star Formation Rates (SFR) [14].

On the other hand, Hubble tension [15]-[17], which is the discrepancy in the assessed value of the Hubble constant by different methodologies, remains a bone of contention. Two of the most important studies in cosmology are the Planck Collaboration 2018 [16] using the Λ CDM with cosmic microwave background (CMB) [18] and the Cepheid Variable study [19]. CMB is believed to be the earliest relic of the universe, detected by us, from an estimated time of almost 380,000 years after the Big Bang. The two studies have come up with a significant 5σ tension in Hubble constant values.

Measurements arrived at through 42 local Type Ia supernovae (SNe Ia) calibrated by Cepheid variables [20] yielded $H_0 = 73.0 \pm 1.0$ km/s/Mpc, and the Planck observations of the CMB [16] [21] predicted $H_0 = 67.4 \pm 0.5$ km/s/Mpc [22]. Riess *et al.* (2023) [23], through JWST observations, revalidate the accuracy

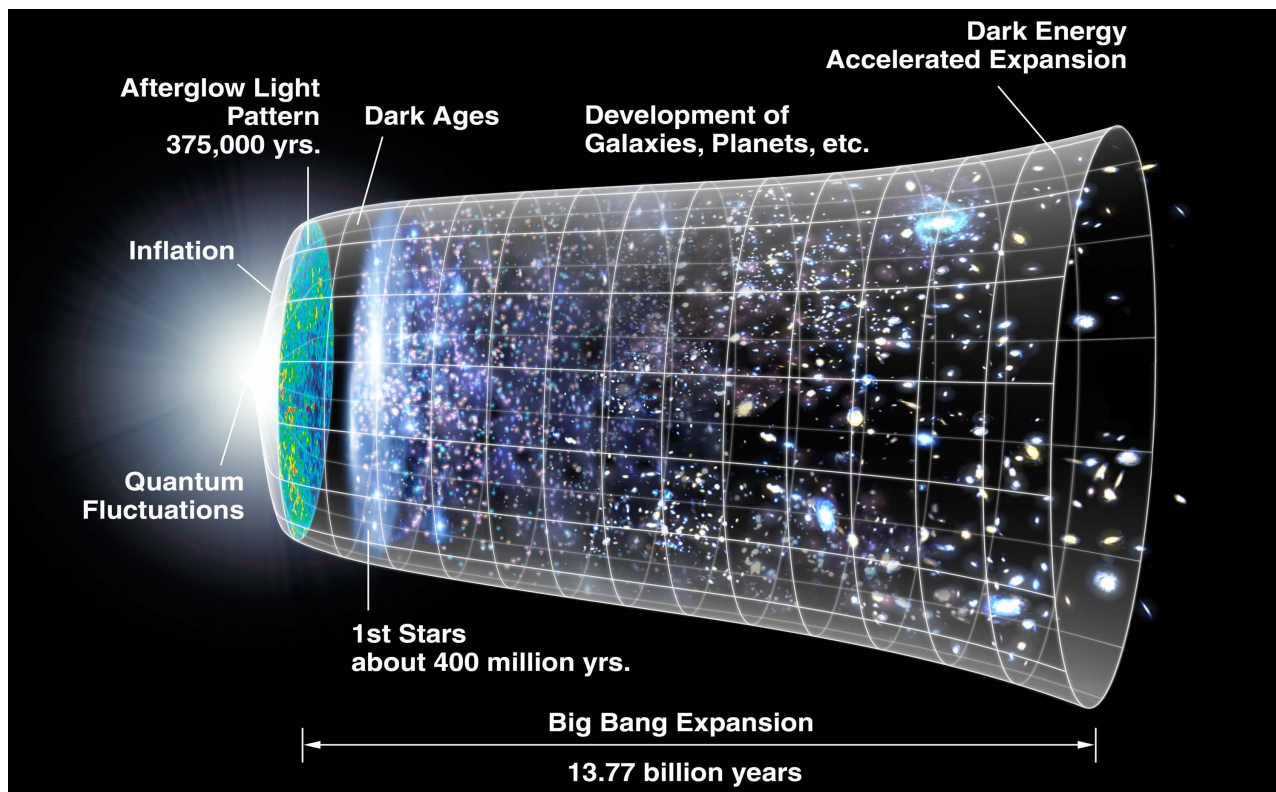


Figure 1. Timeline of the Universe based on Λ CDM Cosmology. **Credit:** Adapted from NASA/WMAP Science Team—Public Domain. <https://commons.wikimedia.org/w/index.php?curid=11885244>

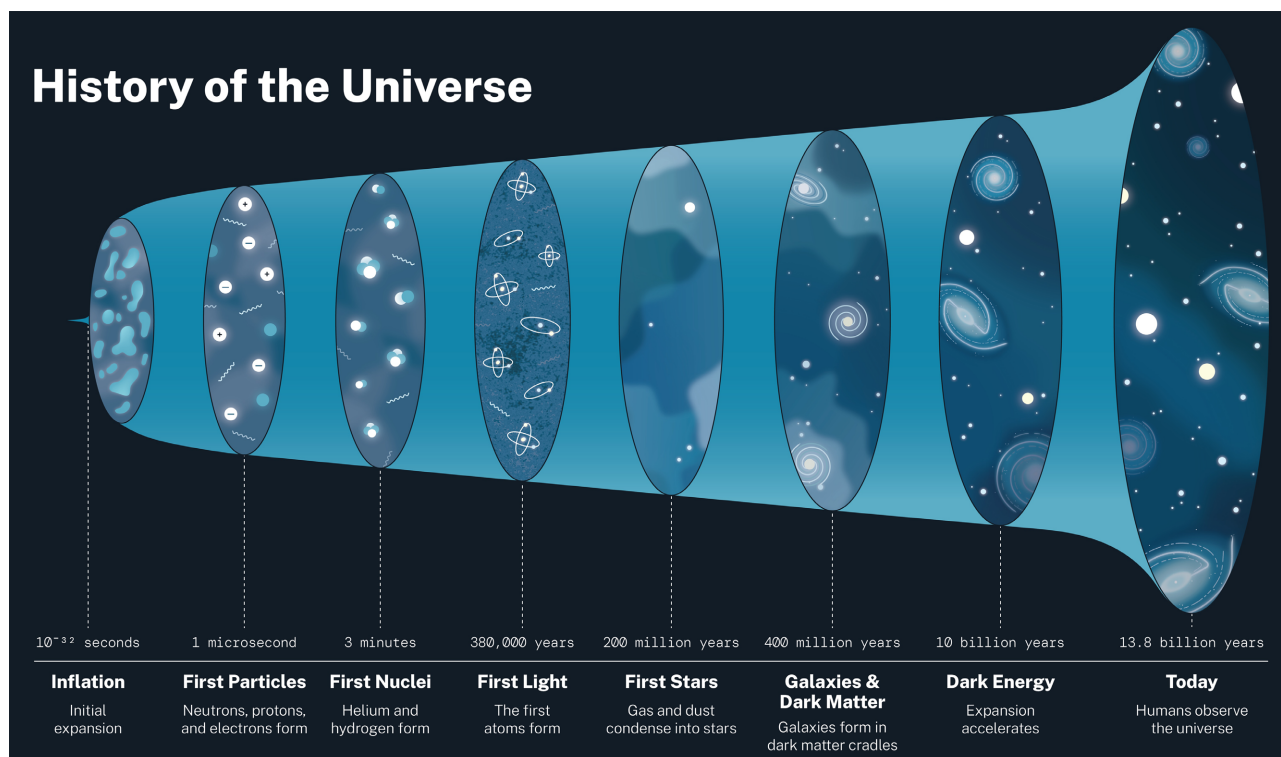


Figure 2. Cosmic Evolution from the Big Bang to the Present Epoch. **Credit:** Courtesy of NASA (<https://science.nasa.gov/resource/history-of-the-universe/>).

of H_0 derived earlier by them at 74.03 ± 1.42 km/s/Mpc [24]. Both studies estimate age of the universe at around 13.79 Gyrs and both appear to be the most comprehensive studies with little room for bridging the gap or tension, unless something very different is assumed at a fundamental level.

A fundamental underlying aspect of the cosmology, early universe dynamics, and the age of the universe (AoU) has to do with our understanding of the flow or passage of time as we assess age of stars and galaxies at 10+ Gyrs or examine near singularity conditions. If the passage of time is not properly understood and not treated well, there can be implications on SFRs or the Galaxy Formation Rates (GFR).

In this paper, we delve deeper into concepts of time and distance and examine if, in the context of General Theory of Relativity (GTR), these parameters have been treated correctly and appropriately from the perspective of an observer on earth.

2. Age of the Universe (AoU)

An important question in modern cosmology and the standard model (SMC) is the age of the universe (AoU). By most of the different methods, AoU has been assessed and reported at around 13.79 Gyr, as can be seen in **Table 1**. A fundamental question that arises with respect to the AoU is that given the relative nature of “time” in GTR, is it being treated in a manner that gives us the correct perspective on the AoU from the viewpoint of an observer on earth in the present time and if AoU, pegged at 13.79 Gyr, is the same “time” or the “proper time” that we perceive or is it something different?

For a ray of light emitted at the dawn of the universe, reaching us through many epochs under accelerated expansion of the universe, varying matter density, time dilation, length contraction, and many other known and unknown effects such as gravitational lensing, quantum effects and entanglement, influences of dark matter, and dark energy—are we able to correctly assess the passage of time and the distances involved for this ray of light? In our opinion, there remains lack of conceptual clarity on “AoU” and treatment of “time” and “distance”, which we have dealt with in subsequent sections of this paper.

AoU time assessed at 13.79 Gyrs is not necessarily in the same unit of time that an observer assesses on earth now. The unit of measurement of AoU, also termed as “The Cosmic Time”, which in a homogeneous and isotropic universe, described by the Friedmann-Lemaître-Robertson-Walker (FLRW) metric, is the “proper time” experienced by a comoving observer who is at rest relative to the average motion of the cosmos. For such an observer, “cosmic time” and “proper time” coincide. In reality, however, no such observer exists; it remains only a theoretical construct.

When we look back from the current time, which is the “proper time” for an observer on earth, it is not necessarily equivalent to the “cosmic time.” There is also no mathematical proof establishing equivalence of “cosmic time” and the

Table 1. Different methods of AoU determination.

Method of Age Determination	Description of the Method	AoU (Gyr)	Reference	Assessment Type
FLRW Equations in Λ CDM	Uses the Friedmann equations to model the expansion of the universe based on observations of cosmic expansion.	~13.79	Planck (2018) [21]	Type 1
Cosmic Microwave Background (CMB)	Analyzes temperature fluctuations in the CMB to infer the universe's expansion history and age.	~13.79	Planck (2018) [21]	Type 1
Metallicity	Studies the chemical composition of the oldest stars to estimate their formation time relative to the Big Bang.	~13.79	Chaboyer <i>et al.</i> (1996)/(2021) [28] [29]	Type 2
Cepheid Variables	Measures the luminosity of Cepheid stars to determine distances and infer the Hubble constant.	~13.79	Riess <i>et al.</i> (1998) [7]	Type 2
Stellar Evolution Models	Estimates the age of the oldest star clusters using theoretical models of stellar life cycles.	~13.79	Harris (1996) [30] [31]	Type 2
White Dwarf Cooling	Models the cooling rates of white dwarfs to estimate their ages, providing a lower limit on the universe's age.	~11-14	Winget <i>et al.</i> (1987) [32] [33]	Type 2
Nucleocosmochronology	Studies the abundance of radioactive isotopes in stars to estimate the time since their formation.	~13.7	Timmes <i>et al.</i> (1996) [34] [35]	Type 2
Gravitational Wave Observations	Uses data from merging binary systems to estimate ages of their progenitors and cosmic timescales.	~10-14	Abbott <i>et al.</i> (2016) [36]	Type 2
Galaxy Evolution Models	Analyzes the formation and evolution of galaxies over cosmic time to infer the age of the universe.	~13.79	Behroozi <i>et al.</i> (2013) [37] [38]	Type 1
Type Ia Supernovae	Uses these supernovae as standard candles to measure distances and understand cosmic expansion.	~13.79	Perlmutter <i>et al.</i> (1999) [39]	Type 2
Baryon Acoustic Oscillations (BAO)	Study of BAO in the distribution of galaxies can enable measurement of the expansion history of the universe.	~13.79	Dawson, K. <i>et al.</i> (2013) [40]	Type 2

“proper time.” It is important to keep in mind that in order to perceive “time” and “distances”, in general in GTR, an observer is must and such an observer has to be in the present. The concept of the “existence of the observer” and what constitutes an observation is essential and fundamental aspect of physics [25] and theoretical constructs that by-pass observation and the observer can at best be termed as “speculative.” Therefore, because the AoU assessed at 13.79 Gyrs is based on comoving framework, it should be seen as a speculative number and should be critically examined under the GTR framework.

We, as the present observers on earth, can look at time lapse in AoU in three ways—AoU (type 1)—The “cosmic time” assessed at 13.79 Gyr, which is the prevailing concept and largely accepted; AoU (type 2)—In the units and measures of the time elapsed *i.e.*, in the “number” of solar years or solar Gyrs irrespective of the fact that these years in the past epochs would have been longer due to time elongation, and the Effective AoU (type 3)—In the units that are corrected to current proper time taking into account time elongation. We find that in literature, however, while referring or reporting AoU, no distinction is made amongst the different types and the AoU is assumed to be (type 1). In both type 1 AoU and

type 2 AoU, each unit of time considered is equal, be it at 1Gyr epoch or 12 Gyr epoch in the timeline. It is as if time is recorded on a counter and each value of the counter is same. With homogeneity and isotropy assumptions of the universe, type 1 and type 2 should be nearly equal and this is how type 1 AoU is justified.

Type 1 AoU is calculated using the scale factor in FLRW equations as described here.

3. Theoretical Background

Scale factor for comoving objects and observers is a part of SMC, also known as the Lambda-Cold Dark Matter (Λ CDM) model, which describes the evolution of the universe from the moment of Big Bang to its present state.

In SMC, Einstein’s General Theory of Relativity (GTR) [26] [27] forms the main underlying basis of the four-dimensional Λ CDM model given by:

$$G^{\mu\nu} + \Lambda g^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu} \tag{1}$$

where:

$G^{\mu\nu}$ is the Einstein Tensor, $T^{\mu\nu}$ is the Energy Momentum Stress Tensor, $g^{\mu\nu}$ is the metric tensor, and Λ is the cosmological constant.

The metric that satisfies both the cosmological principles of homogeneity and isotropy with time dependent scale factor $a(t)$ is given by the Robertson and Walker metric, as:

$$ds^2 = -c^2 dt^2 + a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2 d\omega^2 \right] \tag{2}$$

where,

$$d\omega^2 = d\theta^2 + \sin^2 \theta d\phi^2 \tag{3}$$

r , θ , and ϕ , are the spherical coordinates for the metric. The parameter $k = +1, 0, -1$ denotes closed, flat, and open geometries, respectively.

With Equations (1) and (2), the Friedmann equations are obtained:

$$\left(\frac{\dot{a}}{a}\right)^2 = \left(\frac{8\pi G}{3}\right)\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3} \tag{4}$$

and,

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3} \tag{5}$$

Equation (4) can be rewritten in terms of the Hubble’s parameter as:

$$H^2 = \frac{8\pi G}{3}(\rho + \rho_\Lambda) - \frac{kc^2}{a^2} \tag{6}$$

where, $\rho_\Lambda = \frac{\Lambda c^2}{8\pi G}$.

In terms of dimensionless densities, the Friedmann equations can be written as:

$$H^2 = H_0^2 \left(\frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{r,0}}{a^4} + \Omega_{\Lambda,0} + \frac{\Omega_{K,0}}{a^2} \right) \tag{7}$$

At present $a = 1$, therefore:

$$\Omega_{k,0} = 1 - \Omega_{m,0} - \Omega_{\Lambda,0} - \Omega_{r,0} \tag{8}$$

where,

H_0 is the Hubble’s constant at present time and Ω are the dimensionless densities corresponding to matter (baryonic + dark), radiation, and dark-energy as given below:

$$\Omega_m(a) = \frac{\rho_m(a)}{\rho_{crit}(a)} \tag{9}$$

$$\Omega_r(a) = \frac{\rho_r(a)}{\rho_{crit}(a)} \tag{10}$$

$$\Omega_\Lambda(a) = \frac{\rho_\Lambda(a)}{\rho_{crit}(a)} \tag{11}$$

$\Omega_{m,0}$, $\Omega_{r,0}$, and $\Omega_{\Lambda,0}$ are the present values and

$$\rho_m \propto a^{-3} \tag{12}$$

$$\rho_r \propto a^{-4} \tag{13}$$

The critical density of the universe, for it to be flat at any time t is given by:

$$\rho_{crit} = \frac{3H^2}{8\pi G} \tag{14}$$

If the actual density ρ is greater than ρ_{crit} , the universe is closed and will eventually stop expanding and re-collapse.

If ρ is equal to ρ_{crit} , the universe is flat and will continue to expand forever at a decreasing rate.

If ρ is less than ρ_{crit} , the universe is open and will expand forever at an increasing rate.

In a flat universe, The matter density ρ_m scales with the expansion of the universe as:

$$\rho_m = \rho_{m,0} (1+z)^3 \tag{15}$$

Assuming dark energy density as constant we have from Equation (7)

$$H^2 = H_0^2 \left(\Omega_{m,0} (1+z)^3 + \Omega_\Lambda \right) \tag{16}$$

The Hubble parameter can also be expressed in terms of the scale factor “ a ”:

$$H_{(a)} = \frac{\dot{a}}{a} \tag{17}$$

Now,

$$1+z = \frac{a_0}{a} \tag{18}$$

where a_0 is the scale factor at present, set at $a_0 = 1$. Therefore:

$$z = \frac{1}{a} - 1 \tag{19}$$

On substituting this into the Friedmann equation, we get:

$$H^2 = H_0^2 \left(\Omega_m \left(\frac{1}{a} \right)^3 + \Omega_\Lambda \right) \tag{20}$$

H is then given by:

$$H = H_0 \sqrt{\frac{\Omega_m}{a^3} + \Omega_\Lambda} \tag{21}$$

or

$$H = H_0 \sqrt{\left(\Omega_m (1+z)^3 + \Omega_\Lambda \right)} \tag{22}$$

AoU, “ t_0 ”, which is the age of the universe at present, can be calculated with the integral:

$$t_0 = \int_0^1 \frac{da}{aH(a)} \tag{23}$$

Using Equation (21) we have

$$t_0 = \int_0^1 \frac{da}{aH_0 \sqrt{\frac{\Omega_m}{a^3} + \Omega_\Lambda}} \tag{24}$$

On substituting “ a ” from Equation (17) we have:

$$da = - \frac{dz}{(1+z)^2} \tag{25}$$

Thus AoU in terms of z is given by:

$$t_0 = \frac{1}{H_0} \int_0^\infty \frac{dz}{(1+z) \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \tag{26}$$

Time elapsed from any epoch at z will be given by:

$$T(z) = \int_z^\infty \frac{1}{(1+z')H(z')} dz' \tag{27}$$

where z' is the integration variable.

The standard cosmological framework expresses the age of the universe at a given redshift z through the integral of the inverse Hubble parameter, weighted by $(1+z)^{-1}$, as shown in Equation (27). While this provides a proper time for a co-moving observer since the Big Bang, it does not account for the relativistic time dilation experienced by observers at different epochs. In particular, during earlier cosmic times, the universe expanded significantly faster, and physical processes (such as star formation, cooling, and gravitational collapse) occurred under sub-

stantially dilated time intervals when viewed from the present epoch.

Effective Age of Universe

The popular concept of the passage of time is based on our observations and experience from Earth in present times. Therefore, when we consider AoU, it is assumed that the unit of measurement is the same solar “years” that we have measured in present, going backwards many times till the beginning of the universe or the Big Bang in accordance with standard model. This would indeed be the case if Ω were constant, particularly Ω_m . In reality, however, something else must be happening in accordance with GTR. As we go backwards to Big Bang, time elongation happens due to increase in density, therefore every “year” is not the same, it becomes longer and longer when compared with a “year” today. Therefore, though AoU can be said to be 13.79 Gyrs, the first giga-year after the Big Bang is more elongated than the next giga-year and so on and so forth till the current giga-year when elongation or time dilation should be negligible.

Thus while the AoU is 13.79 Gyr, in relation to our proper time and our position as observer at present, there should also be, what we term as Effective AoU (EAoU), which can be approximately assessed by applying a time dilation factor to AoU in different epochs. Though, a straightforward conclusion from GTR, to the best of our knowledge, EAoU is not found in contemporary literature or research.

Linked to relativistic time elongation is the corresponding reinterpretation of spatial separation. In addition to time, spatial intervals too are influenced by spacetime curvature in the early universe. This motivates the introduction of a complementary concept—an Effective Distance of the Universe (EDoU)—defined in the observer’s frame and adjusted for relativistic effects across epochs. Although stellar parallax methods [41] [42] and standard candle-based cosmic ladder techniques are employed to estimate distances across different regimes, these methods ultimately rely on calibration standards anchored in the observer’s local spacetime.

In the dense, early universe, significantly higher matter-energy density leads to stronger spacetime curvature—even in a spatially flat universe—resulting in contracted effective intervals from the observer’s frame. Therefore, the inferred distances to high-redshift galaxies—when evaluated through the lens of present-frame measurements—are effectively shorter than what traditional metrics suggest. This observer-centric EDoU complements the Effective Age of the Universe (EAoU) and supports a relativistically coherent reinterpretation of both cosmic time and distance within a unified framework.

We measure distance in lightyears but as we go into a distant past of 12 Gyr, each lightyear is also not same as the one we measure today in terms of present or proper kilometres.

Our understanding of “time” on a cosmic scale is linked to the speed and frequency of light and the rate at which the space-time is expanding. For a very distant cosmic object, it is assumed that if we know the distance of that object from

earth at the time light observed by us was emitted, we can figure out the time elapsed from the moment the light left the star and its observation by us on earth. The more distant an object, farther back in time it is. In an expanding universe, as we go back in time, distances and time separations are subject to general relativistic time dilation and length contraction effects. These effects may be miniscule till some epochs in the past, say 2 billion years from now. However, beyond a certain point in the past, these effects cannot be ignored.

It is important to factor in the behaviour of spacetime and the passage of a ray of light in an epoch, say 12 Gyr ago (12 Gyr epoch). In the 12 Gyr epoch, we will have time dilation and spatial contraction due to higher gravity and higher matter density in comparison with that in the present.

The Time Dilation Factor, D can be computed in terms of redshift z and $H(z)$ at an epoch z_1 by the integral derived from FLRW equations (Equation (27)) as follows:

$$D = \int_{z_1}^{z_0} \frac{dz}{H(z)(1+z)} \tag{28}$$

where,

z_1 is Redshift of the epoch in the past we are considering.

z_0 : Current redshift ~ 0 .

$H(z)$: Hubble parameter as a function of redshift.

In FLRW framework, $H(z)$ in terms of the cosmic density parameters is given by:

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_\Lambda} \tag{29}$$

Using Equations (28) and (29) for Planck 2020 parameters and Riess parameters given in **Table 2**, the time-dilation factor was evaluated by integrating the Friedmann equation from the Big-Bang limit ($a \rightarrow 0$) to the present cosmic time, t_0 , in each cosmology: $t_0 = 13.87$ Gyr for the Planck 2018 Λ CDM parameters (Planck Collaboration VI 2020) [16] and $t_0 \approx 12.6$ Gyr for the SH0ES $H_0 = 74 \text{ km}\cdot\text{s}^{-1}\cdot\text{Mpc}^{-1}$ solution (see Riess *et al.*, 2019 for the age— H_0 scaling) [24].

Table 2. Parameters for AoU and EAoU determination.

Parameter	Planck 2020	Riess
H0	67.36 km/s/mpc	74 km/s/mpc
Mass Density Ω_m	0.3153	0.315
Dark E Ω_Λ	0.6847	0.688
Curvature Density Ω_k	0	0
Baryon Density Ω_b	0.0486	0.0486
Spectral Index	0.965	0.965
Premordial Amplitude	2.1E-09	2.1E-09

To incorporate the relativistic effects of cosmological time dilation into the perception of evolutionary time across different epochs, we define the *Effective Age of the Universe (EAoU)* as a modified cumulative time. In this framework, each epoch contributes to the integral not merely by its duration in proper time (as measured by a co-moving observer and as shown in equation 28), but is weighted by the time dilation factor $1 + z'$, which reflects how much slower the passage of time would appear when viewed from the present epoch.

Physically, the factor $1 + z'$ arises because all causal processes experience stretching of time intervals in an expanding universe. At earlier epochs (high z), clocks appear to tick slower by a factor of $1/(1 + z')$ when viewed from today. Conversely, from our present-day perspective, each unit of time at high redshift contains effectively more proper-time capacity when scaled by $1 + z'$. This means that events unfolding at $z' = 10$ evolve over what appears, from our frame, to be a much longer duration than the same amount of co-moving time at $z' \sim 0$.

Figures 3(a)-(f) and **Figures 4(a)-(f)** illustrate the computed evolution of key cosmic parameters under the Planck and SHOES (Riess) scenarios, respectively. Under the Planck configuration, EAoU rises exponentially beyond 13 Gyr of Lookback time, reaching 44.06 Gyr at 13.87 Gyr. This behaviour, seen in **Figure 3(a)**, reflects a state of extreme time dilation in the early universe. The divergence between EAoU and the standard AoU becomes more pronounced with redshift, as highlighted in **Figure 3(b)**, where the gap grows to ~ 30 Gyr near the origin of the universe (13.78 Gyr Lookback). **Figure 3(c)** captures the steep increase in incremental time-dilated intervals, indicating that relativistic effects intensify closer to the Big Bang.

Other simulations show that by the time the Lookback reaches 13.87 Gyr, the universe had contracted to only 0.62% of its current size (**Figure 3(d)**), with redshift rising sharply to ~ 158 (**Figure 3(e)**). The relationship between Lookback time and the Time Dilation Factor is plotted in **Figure 3(f)**, reinforcing the exponential distortion in effective time near high redshifts.

For the SHOES scenario, the same parameters are plotted in **Figures 4(a)-(f)**. The trends are broadly similar, though the cutoff Lookback time is slightly earlier at 12.57 Gyr. EAoU in this case reaches approximately 40.6 Gyr, and the AoU-EAoU gap peaks near 28 Gyr. The corresponding minimum size of the universe is computed as 0.51% of its current scale. The differences between Planck and SHOES outcomes arise from their respective Hubble constant values, which affect the shape and slope of the derived functions.

According to GTR we will have gravitational time dilation in regions of high matter density. Since the early universe was significantly denser ($\rho(z) \propto (1 + z)^3$), clocks at higher redshifts ran slower from our present-day perspective. This gravitational dilation further supports the inclusion of a $1 + z'$ factor in our integral, reflecting the deeper gravitational wells experienced by early cosmic structures. Together with expansion-driven time dilation, this further forms the physical basis for defining the Effective Age of the Universe (EAoU).

We have from (27),

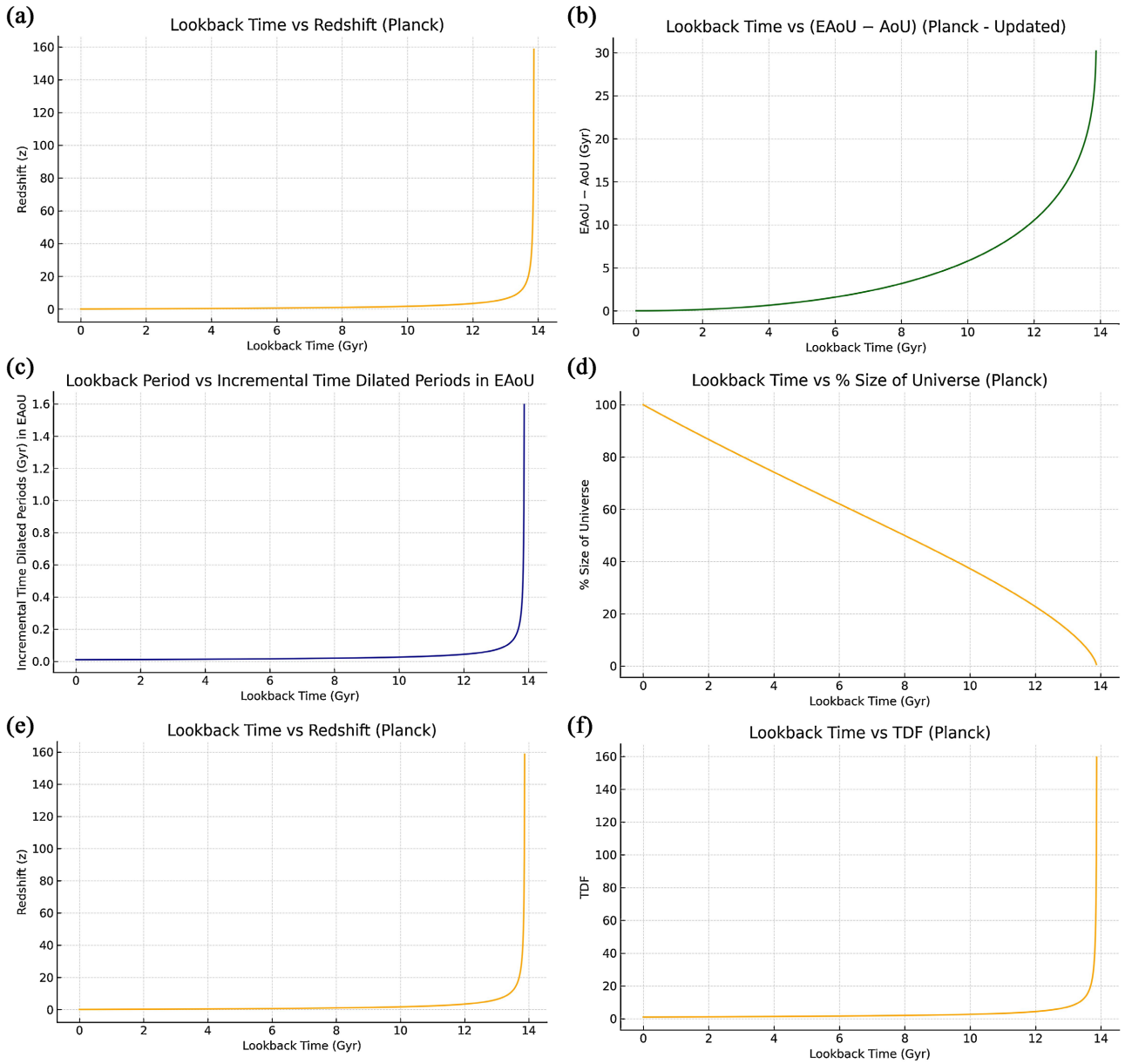


Figure 3. (a) Lookback Time v/s EAoU (Planck); (b) Lookback Time v/s (EAoU-AoU) (Planck); (c) Lookback Time v/s % Incremental Time Dilated Periods in EAoU (Planck); (d) Lookback Time v/s % Size of Universe (Planck); (e) Lookback Time v/s Redshift (Planck); (f) Lookback Time v/s TDF (Planck).

$$dt = \frac{dz'}{(1+z')H(z')} \tag{30}$$

Weighting by gravitational time dilation,

$$dt_{\text{effective}} = (1+z')dt \tag{31}$$

From (30), we substitute the differential form of proper time, into Equation (31), yielding a cancellation of the dilation factor and leading to equation (32) and then the integral in Equation (33).

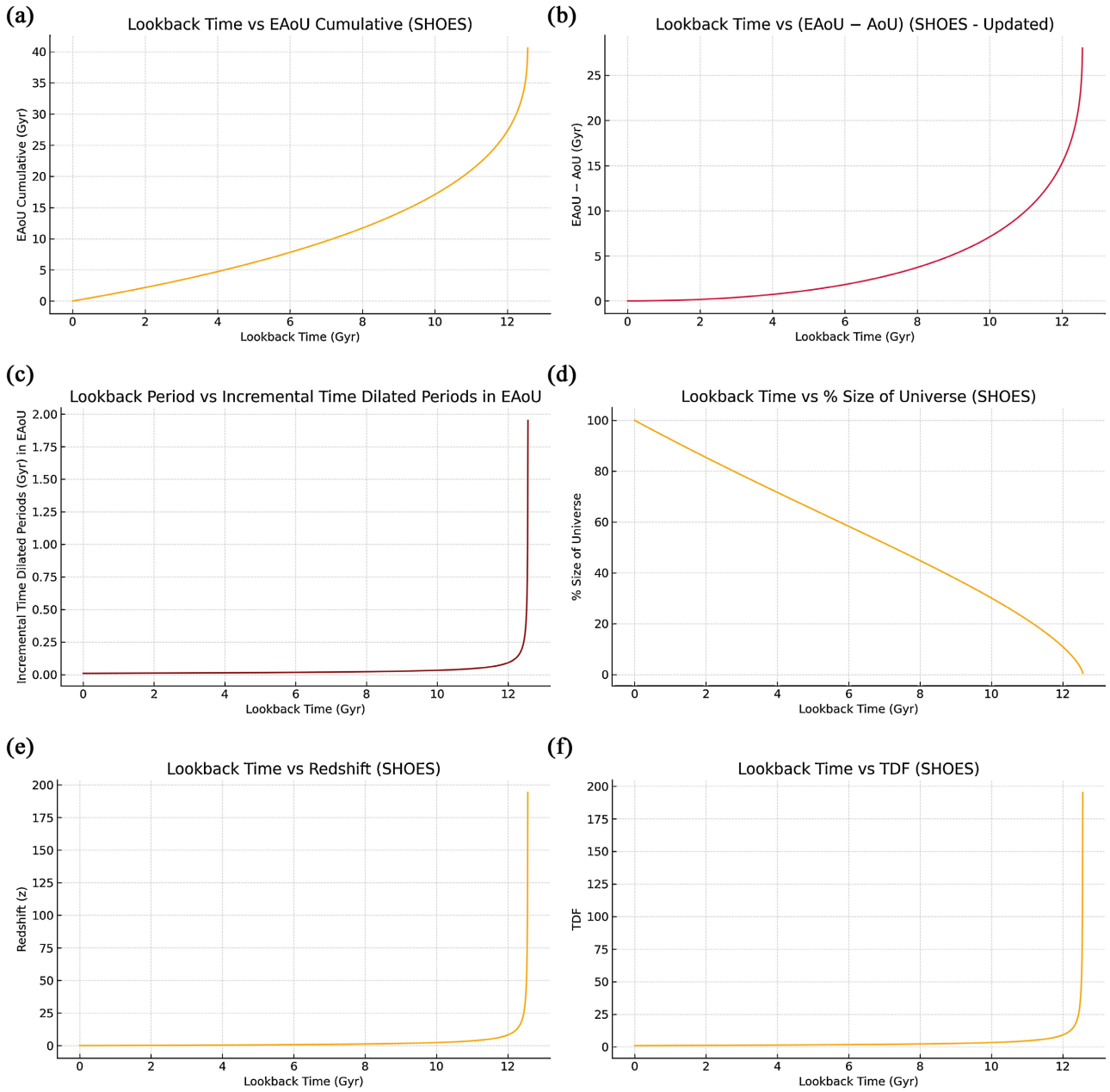


Figure 4. (a) Lookback Time v/s EAoU (SHOES); (b) Lookback Time v/s (EAoU-AoU) (SHOES); (c) Lookback Time v/s % Incremental Time Dilated Periods in EAoU (SHOES); (d) Lookback Time v/s % Size of Universe (SHOES); (e) Lookback Time v/s Redshift (SHOES); (f) Lookback Time v/s TDF (SHOES).

$$dt_{\text{effective}} = (1 + z') \frac{dz'}{(1 + z')H(z')} = \frac{1}{H(z')} dz' \tag{32}$$

Now integrating Equation (32), we have EAoU

$$EAoU(z) = \int_z^\infty \frac{1}{H(z')} dz' \tag{33}$$

where $H(z)$ is the redshift-dependent Hubble parameter. This formulation effectively rescales the cosmic timeline, amplifying early epochs in proportion to their

cosmological dilation, and thereby provides a more physically meaningful measure of the time available for processes like early galaxy formation. While analytic approximations exist in the high-redshift limit (neglecting dark energy), we retain the full form of $H(z)$ to preserve accuracy across all epochs.

While the standard Age of the Universe (AoU) is computed using the integrand $1/(1+z)H(z)$, which accounts for redshift and time dilation from the perspective of a comoving observer, in the derivation of the Effective Age of the Universe (EAoU) factor $(1+z)$ is eliminated and instead $1/H(z)$ is used in the integrand. This modification leads to significantly larger values of EAoU at high redshifts, reflecting a different physical interpretation: EAoU represents an intrinsic or “structure-effective” time scale. Thus, EAoU serves as a more appropriate metric for assessing how early galaxies and massive structures could plausibly have evolved so rapidly in the early universe, particularly in the context of observations by JWST.

An examination of metallicity route to AoU assessment [43] shows that here also time elongation correction is not applied and thus it is Type 2 AoU and approximately Type 1 AoU.

4. EAoU implication on High Redshift Galaxies

Identifying 10 spectroscopically confirmed and robustly identified high- z galaxies ($z \approx 10 - 20$), we mapped their redshifts to EAoU times, spanning approximately 9 to 14.5 Gyr (See [Table 3](#) and [Table 4](#)). For comparison, standard cosmic ages at these redshifts are merely 0.3 - 0.5 Gyr post-Big Bang. The EAoU framework thus provides significantly extended evolutionary clock time, supporting the assembly of $\sim 10^9 M_{\odot}$ stellar masses and vigorous SFRs ($\approx 20 - 100 M_{\odot}/\text{yr}$). Notably, HD1 and HD2 ($z \approx 13$) emerge at EAoU ≈ -11.5 Gyr, a window consistent with sustained star formation rates needed to build $\sim 10^9 M_{\odot}$ in stellar mass.

Table 3. List of high redshift galaxies.

Galaxy	z	Stellar Mass (M_{\odot})	SFR (M_{\odot}/yr)	Reference(s)
GN-z11	10.603	$\sim 1 \times 10^9$	$\sim 20 - 24$	Bunker <i>et al.</i> , 2023 [44]
UDFj-39546284	11.58	$\sim 1 \times 10^9$	—	Robertson <i>et al.</i> , 2023 [45]
CEERS2-588	11.04	$\sim 10^8$	~ 30	CEERS2-588 [46]
HD1	13.27	$\sim 5 \times 10^8 - 10^9$	110	Harikane 2022 [47]
HD2	12.7	$\sim 5 \times 10^8 - 10^9$	170	Harikane 2022 [47]
UHZ1	10.1	$\sim 4 \times 10^7$	—	Natarajan <i>et al.</i> , 2024 [48]
F200DB-045	20.4	—	—	Adams <i>et al.</i> , 2022 [49]
JADES GS-z14	14.18	—	≤ 120	Schouws <i>et al.</i> , 2025 [50]
GLASS-z11	11.1	$\sim 1 \times 10^9$	$\sim 20 - 60$	Chakraborty <i>et al.</i> [51]
GHZ1	10.6	$\log M_{\star} = 9.1 \pm 0.3$	36 ($-26/+54$)	Schouws <i>et al.</i> , 2025 [50]

Table 4. Assessed EAoU for high redshift galaxies.

Galaxy	z	EAoU (Gyr)	Stellar Mass ($\times 10^9 M_{\odot}$)	SFR (M_{\odot}/yr)
GN-z11	10.6	-9	~ 1.0	$\sim 20 - 24$
UDFj-39546284	11.58	-9.5	~ 1.0	—
CEERS2-588	11.04	-9.2	—	—
HD1	13.27	-11.5	0.5 - 1.0	≥ 100
HD2	13	-11.5	0.5 - 1.0	≥ 100
UHZ1	10.1	-8.8	—	—
F200DB-045	20.4	-14.5	—	—
GS-z14	14.18	-12.5	—	≤ 120
GLASS-z11	11.1	-9.3	~ 1.0	~ 40
GHZ1	10.6	-9	≈ 1.3	$\sim 36 (\pm 30)$

These 10 representative high-redshift galaxies, spanning $z \approx 9 - 16$, exhibit star formation rates (SFRs) from $\sim 20 M_{\odot}/\text{yr}$ up to $\sim 120 M_{\odot}/\text{yr}$ and stellar masses of $\sim 10^9 M_{\odot}$ —remarkably high given their young cosmic ages under standard cosmology ($\approx 300 - 500$ Myr post-Big Bang). Interpreting their timelines within the EAoU framework (with $\text{EAoU}_0 \approx 45$ Gyr) yields effective ages of $\sim 36 - 44$ Gyr, significantly extending their effective growth time. This extended timescale alleviates the tension between observed high SFRs/stellar masses and limited cosmic time in Λ CDM. For instance, GN-z11 ($z = 10.60$, $\text{SFR} \approx 24 M_{\odot}/\text{yr}$, $M \approx 10^9 M_{\odot}$) has an EAoU-derived age of ~ 38 Gyr, as opposed to only ~ 430 Myr in conventional terms. Similarly, HD1 and GS-z14-0—at $z \approx 13 - 14$ and boasting SFRs of $\sim 100 - 120 M_{\odot}/\text{yr}$ —attain EAoU ages of $\sim 42 - 43$ Gyr, offering a plausible evolutionary window for their observed properties. These findings directly support our thesis that an EAoU ~ 45 Gyr can naturally accommodate the early assembly of massive, star-forming galaxies without invoking exotic astrophysics.

4.1. Thermodynamic Interpretation of EAoU

Recent developments in gravitational thermodynamics suggest that the large-scale evolution of the universe may be understood not just geometrically, but also as a manifestation of thermodynamic principles [52] [53]. The concept of Effective Age of the Universe (EAoU), as introduced in this paper, can be extended or supported by considering the thermodynamic arrow of time, entropy generation, and horizon thermodynamics.

4.1.1. Entropy and the Temporal Flow

According to the second law of thermodynamics, the entropy of a closed system increases over time. In cosmology, entropy is dominated by contributions from: (i) the cosmic microwave background (CMB), (ii) relic neutrinos, (iii) supermassive black holes, and (iv) large-scale structure formation [54] [55]. This progres-

sive entropy increase is believed to define a natural arrow of time, and its integral over cosmic history provides a form of entropic timekeeping. If cosmic epochs are compared not by coordinate time but by entropy generation in a comoving frame, we find that early epochs were entropically compressed—somewhat mirroring the relativistic time dilation described in EAoU.

4.1.2. Emergent Gravity and Thermodynamic Expansion

Building on Jacobson’s interpretation of Einstein’s field equations as an emergent thermodynamic identity ($\delta Q = TdS$) [56], several researchers have proposed that cosmic expansion itself may be viewed as a thermodynamic process [57]. Within this perspective: (a) the Hubble expansion rate, $H(z)$, can be interpreted as a macroscopic manifestation of thermodynamic flux, and (b) the flow of time emerges as a byproduct of entropy increase and the dynamical unfolding of spacetime. This view reinforces the EAoU framework, wherein early cosmic epochs—characterized by high time dilation—are perceived from our present frame as being effectively older. Furthermore, it follows logically that in such highly time-dilated epochs, the rate of entropy change would also be suppressed, implying lower entropy generation per unit proper time and consistent with the lower entropy states hypothesized for the early universe.

4.1.3. Toward an Effective Thermodynamic Age

A further development of EAoU could involve defining an Effective Thermodynamic Age of the Universe (ETAoU), by integrating entropy change over redshift:

$$\text{ETAoU}(z) = \int_z^\infty \frac{dS(z')}{T(z')} \quad (34)$$

where dS is entropy growth in a comoving volume and $T(z)$ is a temperature function (e.g., of the CMB). While this remains speculative and model-dependent, it opens a path toward embedding EAoU in a thermodynamic framework.

5. Conclusions and Discussions

We have categorized and redefined the Age of the Universe (AoU) under three distinct types:

- AoU (Type 1)—The standard *cosmic time* framework, widely accepted and measured at 13.79 Gyr;
- AoU (Type 2)—The *elapsed time* in terms of the number of solar years, without correction for relativistic time elongation in earlier epochs;
- AoU (Type 3)—The *Effective Age of the Universe (EAoU)*, adjusted to current proper time by incorporating relativistic time dilation.

Using Friedmann-Lemaître-Robertson-Walker (FLRW) equations, we estimate the EAoU to lie in the range of $\sim 40 - 45$ Gyr, depending on the chosen cosmological scenario. These estimates correspond to epochs when the scale factor was only 0.005 - 0.0062 (about 0.5% - 0.62% of its present value), implying that the universe’s linear dimensions were smaller by a factor of roughly 160 - 200.

The revised understanding of AoU directly impacts our interpretation of cosmic evolution, particularly the rates of star and galaxy formation (SFR/GFR). While the EAoU framework does not challenge the foundations of the Λ CDM model, it augments it with a relativistically consistent temporal metric, offering an alternative perspective more aligned with observational anomalies such as high-redshift, evolved galaxies seen in JWST and Hubble data.

This paper does not dispute any existing cosmological theory but introduces EAoU as a supplementary parameter, potentially resolving the paradox of early massive galaxy formation without invoking exotic physics.

Viewed through a thermodynamic lens, the EAoU framework links cosmic time to the irreversible growth of entropy and the scaling of temperature with expansion. While speculative, this perspective suggests a deeper connection between spacetime evolution and the second law of thermodynamics, pointing to an entropic foundation for cosmic chronology.

That said, a certain level of uncertainty remains—especially regarding the rate of natural processes under extreme time dilation. For example, it is unclear whether 1 Gyr at a Time Dilation Factor (TDF) of 50 is functionally equivalent to 1 Gyr at $TDF = 1$ in terms of entropy progression, star formation, or structure growth. This has broader implications not only for the early universe but also for environments near black holes and other regions of intense gravitational curvature.

No empirical studies have yet addressed how process rates vary under extreme relativistic conditions, and such experimentation is inherently difficult. Nonetheless, this is an open domain of inquiry deserving serious theoretical and conceptual attention.

A related preprint elaborating the observational consequences of EAoU is available at *Hossain, J. (2025) [58]. Effective Age of the Universe: Application of Relativistic Time Dilation. ResearchGate.*

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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