Matter-Only Cosmology: A Unified Origin for Inflation and Dark Energy

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Abstract

The standard cosmological model, ΛCDM, successfully describes cosmic acceleration but posits dark energy as a mysterious, independent component of the universe. This paper demonstrates, instead, that dark energy is not a fundamental entity separate from matter, but rather arises as Gravitational Self-Energy (GSE) inherent to matter itself. This model, called Matter-Only Cosmology (MOC), shows that the observed matter density ($\Omega_m \approx 0.315$) naturally generates a dark energy density more than twice as large ($\Omega_\Lambda \approx 0.685$), driving late-time cosmic acceleration. This is made possible by the dynamic interplay of two competing GSE-induced terms: a negative self-energy component ($-\rho_{gs}$) and a positive interaction component (ρ_{m-gs}), all within standard gravity and without the need for fine-tuning or new fundamental fields. This unified framework elegantly resolves several of the deepest problems in physics. It not only provides a concrete physical origin for dark energy, but also predicts its entire life cycle, showing that it must have been attractive in the early universe, enhancing structure formation, before transitioning to a repulsive phase that drives cosmic acceleration. In doing so, it naturally explains the Hubble tension, the existence of massive galaxies in the early universe, recent indications of a weakening dark energy component, and resolves the cosmological constant coincidence problem. Moreover, MOC unifies the physics of primordial inflation and late-time acceleration as the same GSE dynamics, each with a natural, built-in end mechanism. Finally, by predicting stable, non-singular black hole interiors, MOC offers a resolution to the black hole information paradox. By expressing dark energy as an explicit function of the matter density ρ_m and the horizon scale R, the MOC framework transforms it from a phenomenological parameter into a predictive and falsifiable physical quantity.

Contents

1 Introduction

The discovery of the accelerated expansion of the universe [1,2] marked a monumental turning point in modern cosmology. To explain this cosmic repulsion, the standard cosmological model, ΛCDM, introduced a mysterious component known as dark energy [3,4]. With its positive energy density and negative pressure, the cosmological constant Λ, has been remarkably successful in describing the large-scale dynamics of the universe [5].

However, despite its observational successes, the ΛCDM model is plagued by profound and persistent foundational problems [6,7]. The very nature of dark energy remains unknown, suggesting that there is a fundamental piece of physics missing from our current understanding.

This paper argues that this missing piece does not lie in new particles or exotic fields, but in a fundamental misunderstanding of the total energy density that applies to all gravitating systems, the consequences of which become manifest in the Friedmann equation.

In standard cosmology, dark energy is hypothesized to have a positive energy density and exert negative pressure [3, 4], but this is an ad-hoc assumption (Λ's value, $w = -1$) to fit observations, not a prediction from first principles. The leading candidate for dark energy, vacuum energy, suffers from the cosmological constant problem, with a catastrophic discrepancy of 10^{60} to 10^{120} between theoretical predictions and observed values [7,8]. The model also faces the "coincidence problem" of why dark energy has become dominant only in the present epoch [9,10]. Furthermore, cracks have begun to appear in the observational facade of ΛCDM [11–14].

1) **The Hubble Tension:** The persistent discrepancy between the Hubble constant measured in the early universe (CMB) and the local universe suggests that the standard ΛCDM model may be incomplete, hinting at the possibility that dark energy is not a static cosmological constant, but rather a dynamic entity that evolves with cosmic time [11,15]. $H_0(CMB) \approx 67.4 km/s/Mpc$ vs. $H_0(local) \approx 74.0 km/s/Mpc$.

2) **Supernova data anomalies:** The most extensive supernova survey to date by the Dark Energy Survey (DES) team (2024), analyzing nearly 1500 supernovae, hinted that the simplest ΛCDM model is not the best fit, and that dark energy might be varying over time [13].

3) **Spectroscopic instrument findings:** The Dark Energy Spectroscopic Instrument (DESI) team (2024) also reported results where the best-fit model favors a time-varying dark energy, further questioning the cosmological constant hypothesis [12].

These mounting challenges compel us to consider whether a more fundamental re-interpretation is necessary. This paper proposes that the origin of these cosmological challenges lies in a long-standing omission within the standard formulation of gravity: the failure to rigorously account for the gravitational self-energy (GSE) as a source of gravity itself, a requirement mandated by the equivalence principle of General Relativity.

1.1 Components of total mass or equivalent mass in a gravitational system

In dealing with gravitational problems, we have long relied on the convenient use of equivalent energy and equivalent mass to simplify our calculations. Even without knowing the precise composition of the gravitational source's internal energy, we have assumed that the equivalent mass m already includes all unknown forms of energy. By doing so, we can perfectly account for the total energy possessed by the object and accurately solve problems involving its external gravitational interactions [16].

Because this equivalent energy–mass framework has been remarkably successful in solving gravitational problems without requiring a detailed understanding of the energies that constitute the object itself, we have long neglected the analysis of what actually composes this equivalent mass.

While this framework works excellently for analyzing external gravitational interactions, it becomes problematic when we attempt to investigate the internal energy composition of the equivalent mass itself.

The serious issues of dark matter and dark energy that have emerged in astronomy and cosmology arise precisely because physics has now reached a stage where we must go beyond analyzing the external gravitational effects of objects, and instead understand the internal energy structure and self-gravitating dynamics of the objects themselves. This is because the object to be analyzed is the interior of the universe, and matter and galaxies exist within the universe.

The total mass of any object, more precisely its total energy E_T, is given by the sum of the rest mass energy of its constituents ($M_{fr}c^2$) and the contributions from all potential energies, which include both (gravitational, electromagnetic, weak, strong) binding energies and interaction energies.

$$E_T = M_{fr}c^2 + \sum_i U_{BE,i} + \sum_{i>j} U_{int,ij} \tag{1}$$

Dividing by c^2 gives the total equivalent mass M_T.

1.2 A conceptual analogy: Binding energy in the hydrogen atom and a missing term in the Friedmann equation

A useful analogy for understanding the role of GSE in cosmology is provided by the hydrogen atom. A hydrogen atom is a composite system consisting of a proton and an electron bound together by electromagnetic interaction. Likewise, the universe is a composite gravitating system composed of many constituents such as matter, galaxies, and large-scale structures, interacting gravitationally.

The total energy of a hydrogen atom is given by

$$E_H = E_p + E_e + U_{\text{binding}} \tag{2}$$

where E_p and E_e are the rest-mass energies of the proton and electron in their free states, and $U_{\text{binding}} < 0$ is the electromagnetic binding energy. Because the binding energy is negative, the total energy (and hence the equivalent mass) of the hydrogen atom is smaller than the sum of the free state particle masses.

When a hydrogen atom acts as a gravitational source, its mass density must therefore be described as the **total equivalent mass density**

$$\rho_T = \rho_p + \rho_e + \rho_{\text{binding}} \tag{3}$$

rather than as a simple sum of free-particle mass densities. This treatment is standard in atomic, nuclear, and particle physics: binding energy is regarded as a localized contribution to the total mass-energy of a bound system.

Let us now examine what is effectively done in standard cosmology. Neglecting the curvature term for simple analysis, the Friedmann equation is written as

$$H^2 = \frac{8\pi G}{3}\rho_T = \frac{8\pi G}{3}\left(\rho_m + \rho_\Lambda\right) \tag{4}$$

where ρ_m denotes the matter density and ρ_Λ is introduced as a separate dark energy component [3,5].

In practice, ρ_m is constructed from the free-state mass densities of matter constituents (baryons and dark matter), analogous to using $\rho_p + \rho_e$ for the hydrogen atom. It is then found that this sum alone fails to reproduce the critical density required by the observed expansion rate, prompting the introduction of an additional energy density ρ_Λ [1,2,8].

We argue that this procedure reflects a conceptual oversight. From the standpoint of General Relativity, the source term entering the Friedmann equation should be the total equivalent mass density of the gravitating system [16–18]. In a cosmological context, this total density should include not only the free-state matter density but also the GSE arising from the mutual gravitational interaction of matter within the causal horizon.

In other words, the appropriate decomposition should be

$$\rho_T = \rho_{\text{free}} + \rho_{\text{GSE}} \tag{5}$$

where ρ_{GSE} represents the contribution of GSE. By omitting this term and using only free-state mass densities, standard cosmology is forced to reintroduce the missing energy in the form of an independent dark energy component.

It is important to note that gravitational binding energy is conventionally defined as the energy required to disassemble a bound system into free components and is therefore negative. However, as we will demonstrate in the following sections, GSE in a cosmological setting is not restricted to being negative; depending on the compactness and scale of the system, it can change sign and act as a repulsive contribution to the cosmic dynamics.

This observation suggests that what is conventionally identified as dark energy may instead be an intrinsic manifestation of GSE, consistently included in the total energy budget as required by the principles of General Relativity.

1.3 Gravitational field energy vs. gravitational self-energy

A frequent source of confusion in discussions of GSE arises from a failure to distinguish it from the energy of the gravitational field itself. In General Relativity, it is well known that the energy of the gravitational field cannot be localized in a coordinate-independent way [16, 18]. Because the gravitational field extends from the source to spatial infinity and depends on the choice of coordinates, no unique local energy density can be assigned to it. For this reason, gravitational field energy does not appear explicitly as a source term in the Einstein field equations, but is instead encoded implicitly in their nonlinear structure [17, 18].

Gravitational self-energy, however, is a fundamentally different physical quantity. It is not the energy of the gravitational field in empty space, but the gravitational potential energy arising from interactions among the constituents of a gravitating system itself [16]. As such, GSE is confined to the spatial extent of the system and its mass distribution. **Unlike gravitational field energy, it is therefore localized within the system and admits a well-defined contribution to the total energy budget** [16].

> *The mass–energy of a gravitating system includes the negative binding energy, such that the total gravitational mass is less than the sum of constituent rest masses.* [19]

This distinction is familiar in other areas of physics. In atomic physics, for example, the mass of a hydrogen atom is smaller than the sum of the rest masses of a free proton and electron. The difference is the (negative) electromagnetic binding energy, which is treated as a localized contribution to the atom's invariant mass [16, 18]. The bound system is regarded as a single object whose total mass already incorporates its internal binding energy.

There is no physical justification for treating gravity differently in this respect. While gravitational field energy cannot be localized, GSE, which is the energy of interactions between matter components, must be included in the effective energy density that is the source of the expansion of the universe. Ignoring these contributions is equivalent to using the free-state mass density instead of the equivalent mass density required by the principles of General Relativity, which is wrong in the sense of total energy accounting.

2 Gravitational Self-Energy as the Origin of Dark Energy

In a cosmological context, the binding energies from the strong, weak, and electromagnetic forces are confined to the constant, microscopic scales of particles and can be considered part of the unchanging free state mass M_{fr}. In stark contrast, a form of gravitational binding energy GSE, is a function of the macroscopic distribution of matter (M) and the universe's evolving scale (R). As the universe expands, the GSE is not constant; it is an active and dynamic participant in cosmic evolution. This leads to the central thesis of our work: the phenomenon labeled "dark energy" is not a new, exotic fluid, but is in fact the manifestation of the universe's own dynamic GSE.

2.1 The equivalent gravitational source

The calculation of Gravitational Potential Energy (GPE) involves integrating the potential energy of infinitesimally small mass shells dm as they are brought into a gravitational field generated by the interior mass $M'(r)$. The standard differential form is $dU_{gs} = -G\frac{M'(r)}{r}dm$. One of the fundamental principles of general relativity is that "all energy is a source of gravity [17,18]." Therefore, gravitational potential energy, or GSE, must also function as a source of gravity. The existing GSE equation omit this crucial element: the gravitational effect of GSE. In this calculation, the equivalent (or effective) mass should have been used as the internal mass; however, the free-state mass was incorrectly employed instead.

Our fundamental postulate is that the source term $M'(r)$ must be replaced by an **equivalent** source $M_{\text{eq}}(r)$, which includes not only the material mass but also the equivalent mass of its own GSE, $M'_{gs}(r)$.

$$M_{\text{eq}}(r) = M'(r) - M'_{gs}(r) \tag{6}$$

For a general mass distribution, we define the GPE of the inner sphere of radius r and mass $M'(r)$ using a structural parameter β. This parameter encapsulates the geometric distribution of mass and relativistic corrections, ranging from $\beta = 3/5$ for a uniform sphere in Newtonian mechanics to values in the range of $\beta \approx 1.0 \sim 2.0$ for various astrophysical configurations in General Relativity [20,21].

$$U_{gs}(r) = -\beta\frac{GM'(r)^2}{r} \tag{7}$$

The equivalent mass of this self-energy is therefore,

$$M'_{gs}(r) = \frac{|U_{gs}(r)|}{c^2} = \beta\frac{GM'(r)^2}{rc^2} \tag{8}$$

Substituting this back into the equivalent source equation yields [22].

$$M_{\text{eq}}(r) = M'(r)\left(1 - \beta\frac{GM'(r)}{rc^2}\right) \tag{9}$$

The **total GSE** U_{gs-T}, is the integral of the differential energy contributions from $r = 0$ to the final radius R.

$$U_{gs-T} = \int_0^R dU_{gs-T} = \int_0^R -G\frac{M_{\text{eq}}(r)}{r}dm \tag{10}$$

Assuming a uniform density ρ for analytical clarity, we have $M'(r) = \frac{4}{3}\pi r^3\rho$ and the differential mass shell is $dm = 4\pi r^2\rho\, dr$. Substituting these into the integral.

$$U_{gs-T} = \int_0^R -G\frac{1}{r}\left[M'(r)\left(1 - \beta\frac{GM'(r)}{rc^2}\right)\right](4\pi r^2\rho\, dr) \tag{11}$$

$$= -4\pi G\rho\int_0^R r\left[M'(r) - \frac{\beta G}{c^2}\frac{M'(r)^2}{r}\right]dr \tag{12}$$

We now substitute $M'(r) = \frac{4}{3}\pi r^3\rho$.

$$U_{gs-T} = -4\pi G\rho\int_0^R r\left[\left(\frac{4\pi}{3}\rho r^3\right) - \frac{\beta G}{c^2 r}\left(\frac{4\pi}{3}\rho r^3\right)^2\right]dr \tag{13}$$

$$= \int_0^R\left(-\frac{16\pi^2 G\rho^2}{3}r^4 + \frac{64\pi^3\beta G^2\rho^3}{9c^2}r^6\right)dr \tag{14}$$

$$\begin{aligned} U_{gs-T} &= \frac{3}{5}\left[\frac{5}{3}\left(-\frac{16\pi^2 G\rho^2 R^5}{15} + \frac{64\pi^3\beta G^2\rho^3 R^7}{63c^2}\right)\right] \\ &= \frac{3}{5}\left[-\frac{16\pi^2 G\rho^2 R^5}{9} + \frac{320\pi^3\beta G^2\rho^3 R^7}{189c^2}\right] \end{aligned} \tag{15}$$

To account for the relativistic contributions and the geometric distribution of mass in a general self-gravitating system, we generalize the Newtonian coefficient 3/5 to the structural parameter β.

$$U_{gs-T} = \beta\left[-\frac{16\pi^2 G\rho^2 R^5}{9} + \frac{320\pi^3 \beta G^2 \rho^3 R^7}{189c^2}\right] \tag{16}$$

Performing the definite integration yields the final expression for the generalized GSE or total GSE [22].

$$U_{gs-T} = -\beta\frac{GM^2}{R} + \frac{5}{7}\beta^2\frac{G^2M^3}{c^2R^2} = -\beta\frac{GM^2}{R}\left(1 - \frac{5\beta}{7}\frac{GM}{c^2R}\right) \tag{17}$$

This can also be written in a factored form to highlight the repulsive correction.

$$\boxed{U_{gs-T} = \beta\frac{GM^2}{R}\left(\frac{5\beta}{7}\frac{GM}{c^2R} - 1\right)} \tag{18}$$

2.2 Connection to post-Newtonian gravity: Validation and reinterpretation

It is crucial to note that the functional form of our derived self-energy correction, Eq. (18), is not an arbitrary ansatz but is structurally consistent with the rigorous results of General Relativity. In the post-Newtonian (PN) approximation, the total energy of a self-gravitating system includes relativistic corrections arising from the non-linearity of the Einstein field equations. Chandrasekhar [23] and Weinberg [18] derived that the gravitational potential energy of a static spherical distribution, to the first post-Newtonian order ($1/c^2$), takes the form.

$$U_{PN} \approx -\frac{3}{5}\frac{GM^2}{R}\left(1 - \kappa\frac{GM}{Rc^2}\right) \tag{19}$$

where κ is a coefficient of order unity (typically ~ 1) depending on the internal structure and pressure distribution.

The remarkable agreement between our non-perturbative GSE resummation (U_{gs-T}) and the formal post-Newtonian expansion (U_{PN}) serves two vital purposes.

1) **Validation:** It confirms that the intuitive principle that GSE acts as a negative equivalent mass accurately captures the essential nonlinear dynamics of general relativity without requiring the full complexity of tensor forms.

2) **Reinterpretation as dark energy:** While standard PN theory treats this term merely as a minute correction to binding energy in stellar structure, **we identify the total GSE term as the physical origin of dark energy.** In the cosmological context, where M represents the mass within the horizon, this total GSE term is not negligible; it grows to dominate the dynamics, driving the accelerated expansion.

By re-deriving this term from a fundamental physical principle rather than a mathematical approximation, GSE framework elevates the status of this "correction" to a central dynamical driver of the universe, providing a transparent mechanism for repulsive gravity that is obscured in the standard PN derivation.

1) **Approximation vs. Principle:** Chandrasekhar's result is derived from a perturbative expansion of Einstein's field equations, strictly valid only in the weak-field ($GM/Rc^2 \ll 1$) and slow-motion limits, inherently neglecting higher-order terms [23–25]. In contrast,

our derivation is non-perturbative and self-consistent, obtained from a closed-form resummation of GSE based on local energy conservation, rather than from a truncated weak-field expansion. This suggests potential validity even in regimes where standard PN approximations break down, such as the early universe or strong gravity environments.

2) **Static vs. Dynamic Applicability:** The PN derivation typically assumes a quasi-static equilibrium (e.g., virial or hydrostatic balance) suitable for stellar structure [23–25]. However, the core mechanism of the GSE framework, namely replacing bare mass with equivalent mass ($M \to M_{eq}$), relies on the principle of local energy conservation, which does not require the system to be in static equilibrium. Therefore, our approach is naturally applicable to dynamic cosmological scenarios, including the rapid expansion or contraction phases where the assumption of hydrostatic equilibrium would be invalid.

Therefore, our result should be viewed not merely as a reproduction of the PN approximation, but as a resummation or effective field generalization that captures the essential physics of self-repulsion in a closed, analytical form valid across diverse cosmic epochs.

2.3 The necessity of the GSE framework in cosmology

A frequent critique against semi-classical approaches is that they are not derived from the full formalism of General Relativity. This critique, however, fundamentally misunderstands the limitations of "complete GR" solutions in a cosmological context.

It is a mathematically established fact that no closed-form, analytic solution to the Einstein Field Equations exists for the interior of any gravitating system with non-zero density [24,25]. Numerical methods, such as solving the Tolman-Oppenheimer-Volkoff (TOV) equations, provide precise results for static, compact objects like neutron stars. However, these methods are both mathematically and physically inapplicable on cosmological scales, which are characterized by low density and dynamic expansion, not hydrostatic equilibrium.

Consequently, there is no analytical solution derived from "complete GR" for the total GSE of the universe [25].

The GSE framework, in stark contrast, provides the **first and currently only closed-form, analytic expression** for the effective energy density that includes GSE on a cosmological scale. By basing the derivation on the fundamental principle of source renormalization by self-energy, we bypass the complexity of the full field equations and derive a verifiable physical model. The GSE framework has been validated by its similarity to the first-order PN approximation performed by Chandrasekhar [23]. Furthermore, the GSE framework has some logical basis, as the Friedmann equation itself can be derived from the law of conservation of mechanical energy in Newtonian mechanics [16,26,27].

Therefore, at present, the GSE framework should be evaluated as the most advanced and only viable analytical theory capable of explaining the role of GSE in the evolution of the universe.

2.4 The two faces of Total Gravitational Self-Energy

The derivation in Eq. (18) is the cornerstone of our model. It reveals that the correctly calculated GSE is not a monolithic entity, but is composed of two distinct components with opposing signs. This provides the physical basis for the phenomenon of dark energy.

For clarity and official use throughout this paper, we shall designate these two components based on their physical origin.

1) **The negative (equivalent) mass component ($-\rho_{gs}$):** This term is the GSE term obtained from Newtonian mechanics, which was previously well known. The structural parameter β is applied to account for the structural evolution of the universe and the effects of general relativism.

$$-\rho_{gs} \equiv \frac{1}{Vc^2}\left(-\beta\frac{GM^2}{R}\right) < 0 \tag{20}$$

$$-\rho_{gs} = -\frac{3\beta}{4\pi}\frac{GM^2}{c^2R^4} = -\frac{4\pi\beta G}{3c^2}\rho_m^2 R^2 \tag{21}$$

2) **The positive (equivalent) mass component ($+\rho_{m-gs}$):** As can be seen from the integral equation, this term is the interaction term between the equivalent mass of GSE and the mass m. It is "Post-Newtonian" in spirit as it accounts for the energy of the gravitational field acting as its own source, a principle rooted in general relativity.

$$\rho_{m-gs} \equiv \frac{1}{Vc^2}\left(+\frac{5\beta^2}{7}\frac{G^2M^3}{c^2R^2}\right) > 0 \tag{22}$$

$$\rho_{m-gs} = +\frac{15\beta^2}{28\pi}\frac{G^2M^3}{c^4R^5} = +\frac{80\pi^2\beta^2G^2}{63c^4}\rho_m^3 R^4 \tag{23}$$

Thus, the total mass density of the universe ρ_T, is the sum of matter density and the effect of these two GSE components.[1]

$$\rho_T = \rho_m + \rho_{\Lambda_m} = \rho_m + \rho_{m-gs} - \rho_{gs} \tag{24}$$

We identify the Total GSE density as the Dark Energy density ρ_{Λ_m}.

$$\boxed{\rho_{\Lambda_m} = \rho_{m-gs} - \rho_{gs}} \tag{25}$$

$$\rho_{\Lambda_m} = \rho_{m-gs} - \rho_{gs} = \frac{3\beta}{4\pi}\frac{GM^2}{c^2R^4}\left(\frac{5\beta}{7}\frac{GM}{c^2R} - 1\right) \tag{26}$$

$$\rho_{\Lambda_m}(\rho_m, R) = \frac{4\pi\beta G\rho_m^2R^2}{3c^2}\left(\left(\frac{20\pi\beta G}{21c^2}\right)\rho_m R^2 - 1\right) \tag{27}$$

If defined as $\frac{4\pi G}{3c^2} \equiv c_1$ and $\frac{20\pi G}{21c^2} \equiv c_2$, $R_S = \frac{2GM}{c^2}$.

$$\boxed{\rho_{\Lambda_m}(\rho_m, R) = c_1\beta\rho_m^2R^2\left(c_2\beta\rho_m R^2 - 1\right)} \tag{28}$$

$$\boxed{\rho_{\Lambda_m}(M, R) = \frac{3\beta}{4\pi}\frac{GM^2}{c^2R^4}\left(\frac{5\beta}{14}\frac{R_S}{R} - 1\right)} \tag{29}$$

[1] In the appendix, we introduce an approach that explicitly expresses the total GSE term in terms of the GSE term and the interaction term between matter and GSE, and show that this approach can also account for dark energy in the same way.

2.5 Cosmological interpretation: Attraction and repulsion

Having defined the fundamental components of GSE, we now turn to their cosmological interpretation. The role of an energy (or mass) component in cosmic expansion is determined by its influence in the Friedmann acceleration equation.

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i(\rho_i + 3P_i) = -\frac{4\pi G}{3}\sum_i \rho_i(1+3w_i) \tag{30}$$

For dark energy, the equation of state parameter is observed to be $w_{\Lambda_m} \approx -1$, implying it exerts a strong negative pressure. It is under this specific cosmological condition that the two components of GSE acquire their distinct roles as sources of attraction and repulsion.

- The **positive equivalent mass density**, ρ_{m-gs}, has a positive mass (or energy) density ($\rho > 0$). With negative pressure ($P \approx -\rho$), its contribution to the acceleration equation becomes $(\rho + 3P) \approx -2\rho$, which is negative. This results in a positive $\ddot{a}$, driving cosmic **repulsion** (acceleration).
- The **negative equivalent mass density**, $-\rho_{gs}$, has a negative equivalent mass (or energy) density ($\rho < 0$). With negative pressure ($P \approx -\rho$), its contribution becomes $(\rho + 3P) \approx -2\rho$, which is positive. This results in a negative $\ddot{a}$, acting as a source of cosmic **attraction** (deceleration).

Therefore, while $-\rho_{gs}$ and ρ_{m-gs} are the fundamental physical entities, it is their interplay within the dynamical environment of an expanding universe with negative pressure that allows them to function as the sources of cosmic attraction and repulsion, respectively. This framework demonstrates that dark energy is not an ad-hoc addition, but a necessary consequence of correctly accounting for the energy of gravity itself.

This framework, rooted in a rigorous application of established principles, is termed **Matter-Only Cosmology (MOC)**[2]. This designation reflects the model's core premise: that the phenomena of cosmic acceleration and dark energy arise from the GSE of matter itself and the energy of the interaction between GSE and mass energy, and do not use a heterogeneous, non-baryon energy fluid.

In the following sections, we will demonstrate how this single, first-principles correction to GSE not only provides a precise physical origin for dark energy but also naturally accounts for its observed density in the late universe, thereby offering a comprehensive and self-consistent solution to one of the greatest puzzles in modern science.

3 The Total Gravitational Self-Energy and the Structural Parameter β

As established in the previous section, the origin of dark energy in our framework is the total GSE of the universe, calculated in a self-consistent manner. That entire derivation was built upon a single, generalized expression for the GSE of a mass distribution, in which a structural parameter β compactly summarizes the effects of internal mass distribution and relativistic corrections, without introducing any new dynamical degrees of freedom beyond matter itself. This section provides a deeper analysis of this foundational component, $U_{gs} = -\beta GM^2/R$, and clarifies the physical interpretation and practical role of β.

[2] Here, "matter" includes both baryonic and dark matter (Ω_m). The "matter-only" name refers to the absence of an independent dark energy fluid, but the principle itself applies equally to radiation ($\rho_m \to \rho_r$).

3.1 From Newtonian binding energy to a relativistic framework

The existing GSE (U_{gs}) is the total gravitational potential energy inherent to a mass distribution, arising from the mutual attraction of its constituent parts. For any object of mass M, which can be conceptualized as a collection of infinitesimal masses ($M = \sum dm_i$), this energy represents the work done to assemble the object from infinity. It is a specific, fundamental type of **gravitational potential energy (GPE)**, often more commonly known as gravitational binding energy (with a negative sign), as it signifies the energy that must be supplied to disperse the system [28].

In the familiar context of Newtonian physics, the self-energy of a uniform sphere of mass M and radius R is given by the well-known formula (e.g., [29]).

$$U_{gs,\text{Newton}} = -\frac{3}{5}\frac{GM^2}{R} \tag{31}$$

This formula, while a useful approximation, is insufficient for cosmological applications where relativistic effects become significant. In the framework of general relativity (GR), the calculation of self-energy for a static, spherically symmetric object requires integrating over the volume, accounting for the curvature of spacetime. While a full GR derivation is complex, its results can be effectively parameterized into a generalized form that mirrors the Newtonian expression [30, 31].

$$U_{gs} = -\beta\frac{GM^2}{R} \tag{32}$$

The dimensionless coefficient β thus replaces the specific value of 3/5 and encapsulates, in an effective manner, the structural properties of the mass distribution and the relativistic nature of its gravity. Its value is not a universal constant and depends on the object's density profile and internal pressures.

3.2 The physical interpretation and structural evolution of β

The coefficient β serves as a structural descriptor in our model, connecting simplified analytical forms to the complex physical reality of the evolving cosmos. Its value is tightly constrained by well-established physical principles and reflects the average structural state of matter, rather than acting as an arbitrary tuning parameter.

3.2.1 Theoretical constraints and structural models

The theoretical range of β is bounded by the degree of mass concentration and relativistic effects.

- **Lower bound (Newtonian uniformity):** For a non-relativistic, completely uniform sphere, β is precisely $3/5 = 0.6$.
- **Upper bound (relativistic compactness):** For realistic, compact objects described by general relativity, such as neutron stars, numerical solutions to the Tolman-Oppenheimer-Volkoff (TOV) equations show that β ranges from approximately 1.0 up to 2.039 for highly centrally-condensed bodies [20, 21].

To understand how cosmic structure formation affects β, we performed a numerical integration of the gravitational potential energy for the Navarro-Frenk-White (NFW) profile [32], which describes the universal density distribution of dark matter halos. The results reveal a clear correlation between the concentration parameter c and the structural coefficient β [33].

- $c = 20$ (Highly dense cores / Early structures): $\beta \approx 1.62$
- $c = 15$ (Dense galaxies): $\beta \approx 1.45$
- $c = 10$ (Typical Milky Way-sized halos): $\beta \approx 1.25$
- $c = 5$ (Galaxy clusters / Late-time structures): $\beta \approx 1.02$

These benchmarks imply a specific evolutionary trajectory: a highly uniform, relativistic early universe (near the Schwarzschild limit) exhibits a high β value (approaching ~ 2.0), while the hierarchical formation of structures and subsequent virialization lowers β towards unity (~ 1.0). From a cosmological perspective, once galaxy-scale halos have formed and virialized (roughly $t \gtrsim 0.5$–$1\,\text{Gyr}$), the large-scale mass distribution evolves mainly through mergers and gentle rearrangements, so the effective, volume-averaged $\beta(t)$ is expected to change only slowly thereafter.

3.2.2 Phenomenological significance of $\beta(t)$

In this paper, we treat β as a dynamic, but slowly varying, parameter $\beta(t)$ that represents an effective, cosmologically averaged value. It accounts for complex large-scale phenomena.

- **Inhomogeneity and hierarchy:** The universe is hierarchically structured. As shown by our NFW analysis, the transition from dense, early structures (high c) to extended galaxy clusters (low c) drives the effective β to evolve.
- **Causality and retardation:** $\beta(t)$ implicitly parameterizes the retardation effects of gravitational interactions propagating at the speed of light, which are not captured in static Newtonian models.

Consequently, the value of $\beta \approx 1.0180$ (+30% model)–1.4949 (0% model) derived in this study is not an arbitrary figure. It aligns with the polytrope $n = 3$ model ($\beta = 3/2$), which describes marginally relativistic stellar structures [34], and quantitatively matches the NFW halo profile with a concentration of $c \approx 15$ ($\beta \approx 1.45$) [32]. Over the cosmological time window relevant for our simulations ($t \gtrsim 0.8\,\text{Gyr}$), all well-fitting MOC runs keep $\beta(t)$ within a narrow band of width $\Delta\beta \sim 0.1$, indicating that only mild evolution is required to reproduce the full dark energy phenomenology.

This agreement suggests that the β value required by the MOC model is a physical indicator, signaling that the universe is in a highly structured, virialized state consistent with established astrophysical models, and that the emergence of dark energy in MOC is driven primarily by the geometric scaling of total GSE rather than by any finely tuned time dependence of $\beta(t)$.

4 The Friedmann Equations in the MOC Framework

The standard ΛCDM model successfully describes cosmic evolution by introducing dark energy as an independent fluid with a negative pressure, $P_\Lambda = -\rho_\Lambda$ [3, 4, 8]. Our new cosmology, hereafter referred to as MOC, argues that the observed effects of dark energy are not due to a new substance or energy, but are an inherent manifestation of the GSE of matter itself and its associated interaction energy.This section reformulates the Friedmann equations within this new MOC paradigm.

4.1 A re-examination of the gravitational source term

The first Friedmann equation, a cornerstone of cosmology, can be derived from both general relativity and, more intuitively, from the Newtonian conservation of energy for a test particle at the edge of an expanding sphere (see e.g., [26, 27, 35], and Figure 1). This Newtonian derivation reveals a crucial insight: the energy density ρ in the equation $H^2 \propto \rho$ is sourced directly from the system's total energy, which must include GSE, not merely from the rest mass of its particles.

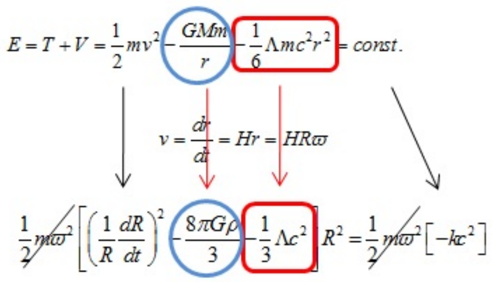

Figure 1: A schematic of the Friedmann equation's derivation from mechanical energy conservation ($E = K + U$). This approach highlights that the density term ρ originates from the total potential energy U of the system, not just its rest mass [36].

In the context of the Friedmann equations, all quantities denoted by ρ represent equivalent mass densities, defined as energy densities divided by c^2, and therefore act on equal footing as gravitational sources.

Standard cosmology has long operated on the implicit assumption that the rest-mass density of matter ρ_m, is the sole dynamical source of gravity on cosmological scales. This, we argue, is an incomplete picture. The total mass density ρ_T, which sources cosmic expansion in the Friedmann equations, must also include the equivalent mass density associated with the GSE of matter and its self-interaction.

The total effective mass density ρ_T that governs cosmic expansion is therefore composed of two fundamental contributions.

1) **Matter (ρ_m):** The standard, observable rest-mass density of baryonic and dark matter. It constitutes the primary material content of the universe and the origin of all gravitational interactions.

2) **Total GSE or Dark Energy (ρ_{Λ_m}):** The net equivalent mass density arising from matter's own GSE. It is not an independent fluid, but an emergent contribution generated by matter through its self-gravity. As demonstrated, it consists of two distinct components:

   - **Negative component ($-\rho_{gs}$):** The equivalent mass density associated with classical gravitational binding energy.
   - **Positive component (ρ_{m-gs}):** The equivalent mass density generated when GSE itself gravitates, in accordance with the general relativistic principle that all forms of energy act as sources of gravity.

The standard cosmological model, ΛCDM, treats matter and dark energy as separate, non-interacting fluids [3,4,8]. In contrast, Matter-Only Cosmology (MOC) argues that dark energy is an emergent property derived from the GSE of matter itself. Consequently, the total mass-energy density entering the Friedmann equation is the sum of the physical matter density (ρ_m)

and the dark energy density (ρ_{Λ_m}), which is composed of a negative classical binding energy component ($-\rho_{gs}$) and a positive relativistic interaction component (ρ_{m-gs}).

$$\rho_T = \rho_m + \rho_{\Lambda_m} = \rho_m + \rho_{m-gs} - \rho_{gs} \tag{33}$$

This is not a modification to the existing physics. It is simply a more precise way to write ρ_T or ρ_{eq}. Including the spatial curvature k explicitly, the first Friedmann equation in the MOC framework takes the physically complete form.

$$H^2 = \frac{8\pi G}{3}\rho_T - \frac{k}{a^2} = \frac{8\pi G}{3}(\rho_m + \rho_{m-gs} - \rho_{gs}) - \frac{k}{a^2} \tag{34}$$

Below, we derive the explicit forms of this equation for both an expanding cosmological space and a static, self-gravitating system.

4.2 Friedmann equations in an expanding universe

In a cosmological context, we must distinguish between the scale of gravitational interaction, set by the particle horizon (χ_p), and the scale of volumetric dilution, set by the physical radius of the horizon (R_{phys}).

4.2.1 Mass growth and matter density: physical meaning of χ_p versus R_{phys}

In the MOC framework, it is essential to distinguish between two conceptually different notions of "horizon size" that enter the self-energy calculation in different ways. The particle horizon defines a *causal interaction scale*, whereas the physical horizon defines a *dilution scale* for densities. Such a distinction is standard in relativistic cosmology, where causal structure and physical volume play fundamentally different roles [18, 37, 38]. We therefore introduce two radii.

$$\chi_p(t) = \int_0^t \frac{c}{a(t')}\,dt' \qquad \text{(comoving particle horizon)} \tag{35}$$

$$R_{\text{phys}}(t) = a(t)\,\chi_p(t) \qquad \text{(physical horizon radius)} \tag{36}$$

The comoving horizon χ_p measures the maximum comoving distance over which any signal propagating at speed c could have established causal contact since the Big Bang. Because gravitational influence is mediated by the spacetime metric and ultimately constrained by causality, $\chi_p(t)$ provides the appropriate scale for determining which mass elements have entered the causal network of mutual gravitational interaction by time t [17, 39, 40]. In this sense, $\chi_p(t)$ determines *which* mass elements have had the opportunity to contribute coherently to the accumulated gravitational potential energy.

This motivates our definition of the effective enclosed mass,

$$M(t) \equiv \text{mass inside the causal horizon} \;\propto\; \chi_p(t)^3 \tag{37}$$

leading to the comoving-volume scaling

$$M(t) = M(t_0, f)\left(\frac{\chi_p(t)}{\chi_p(t_0)}\right)^3 \tag{38}$$

Importantly, this construction does *not* imply that matter exists only within χ_p. Rather, matter exists on all scales, but only the portion within the particle horizon has been in causal contact and can therefore be treated as part of a single, gravitationally connected system at time t, consistent with standard discussions of horizon-limited dynamics in cosmology [35, 37].

By contrast, the matter density $\rho_m(t)$ is defined as a *local physical density* and therefore obeys ordinary cosmological dilution in physical space,

$$\rho_m(t) = \frac{\rho_m(t_0, f)}{a(t)^3} \tag{39}$$

This behavior follows directly from mass conservation in an expanding FRW background and is independent of the causal bookkeeping encoded by χ_p [4,18]. The key point is that $M(t)$ and $\rho_m(t)$ play distinct physical roles: $M(t)$ tracks the amount of mass that has become causally connected to the observer's worldline, while $\rho_m(t)$ characterizes how that mass is distributed per unit *physical* volume at time t.

4.2.2 Derivation of GSE densities: why interaction uses χ_p but dilution uses R_{phys}

The GSE depends on (i) the amount of mass participating in mutual gravitational interactions and (ii) the characteristic separation over which those interactions are established. In an expanding universe, both ingredients are constrained by causality. The particle horizon $\chi_p(t)$ therefore provides the natural interaction scale, as it represents the largest comoving separation over which gravitational information could have propagated since the initial singularity [39,40]. Accordingly, the formation of the binding energy is characterized by

$$U_{gs}(t) \sim -\beta(t)\,\frac{G\,M(t)^2}{\chi_p(t)} \tag{40}$$

This choice reflects the physical fact that gravity is an infinite-range interaction whose effective reach at finite cosmic time is limited not by instantaneous kinematic scales such as c/H, but by the integrated causal structure of spacetime [41,42]. Only mass elements that have been able to exchange gravitational influence can contribute coherently to the global potential energy.

Once the total self-energy is formed, however, its *density* must be defined by dividing by the *physical* volume occupied by the causally connected region at that epoch. This role is played by the physical horizon radius $R_{\text{phys}}(t) = a(t)\chi_p(t)$, which sets the actual size of the causal domain in physical units. The corresponding volume is

$$V_{\text{phys}}(t) = \frac{4\pi}{3} R_{\text{phys}}(t)^3 \tag{41}$$

Because energy densities in FRW cosmology are defined per unit physical volume, the conversion from a global energy U_{gs} to an equivalent mass density must involve V_{phys} [8,18]. This yields the generallized GSE density prescription.

$$-\rho_{gs}(t) = \frac{U_{gs}(t)}{V_{\text{phys}}(t)c^2} = -\frac{1}{\left(\frac{4\pi}{3}R^3_{\text{phys}}\right)c^2}\left(\beta(t)\frac{GM(t)^2}{\chi_p(t)}\right) \tag{42}$$

and similarly for the relativistic interaction component,

$$\rho_{m\text{-}gs}(t) = \frac{U_{m\text{-}gs}(t)}{V_{\text{phys}}(t)c^2} \tag{43}$$

with $U_{m\text{-}gs}$ evaluated using the same causal interaction scale $\chi_p(t)$ [22,23].

$$\boxed{-\rho_{gs}(t) = -\frac{3\beta(t)}{4\pi}\frac{GM(t)^2}{c^2\chi_p(t)R_{\text{phys}}(t)^3}} \tag{44}$$

$$\rho_{m-gs}(t) = +\frac{15\beta(t)^2}{28\pi}\frac{G^2M(t)^3}{c^4\chi_p(t)^2R_{\text{phys}}(t)^3} \tag{45}$$

Conceptually, the general prescription can be summarized as follows: the particle horizon $\chi_p(t)$ sets the scale over which gravitational binding energy is **generated** (causal interaction scale), while the physical horizon $R_{\text{phys}}(t)$ sets the scale over which that energy is **diluted** into a density (physical-volume scale). Using R_{phys} as the interaction length would incorrectly treat the binding energy as an instantaneous, local phenomenon, while using χ_p as the dilution scale would violate the standard FRW interpretation of ρ as a physical energy density [37,38]. The MOC framework therefore assigns χ_p and R_{phys} to distinct roles in a manner that is both causally consistent and fully compatible with relativistic cosmology.

4.2.3 General GSE Framework:The Friedmann equations in expanding space

Substituting the GSE densities and expressing them in terms of ρ_m gives the first Friedmann equation.

$$H^2 = \frac{8\pi G\rho_m}{3}\left[1 + c_1\beta\rho_m\frac{R^3_{\text{phys}}}{\chi_p}(c_2\beta\rho_m\frac{R^3_{\text{phys}}}{\chi_p} - 1)\right] - \frac{k}{a^2} \tag{46}$$

Here, the coefficients are $c_1 = \frac{4\pi G}{3c^2}$ and $c_2 = \frac{20\pi G}{21c^2}$. This form explicitly shows the non-trivial scaling with the dynamic variable R^3_{phys}/χ_p.

Adopting an equation of state $w_{\Lambda_m} \approx -1$ for the total GSE component, the acceleration equation becomes

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m - 2\rho_{\Lambda_m}) = -\frac{4\pi G}{3}\left[\rho_m - 2c_1\beta\rho_m^2\frac{R^3_{\text{phys}}}{\chi_p}(c_2\beta\rho_m\frac{R^3_{\text{phys}}}{\chi_p} - 1)\right] \tag{47}$$

This equation demonstrates that the sign of cosmic acceleration is determined by the evolving GSE term, allowing for a natural transition from early-time deceleration to late-time acceleration.

In essence, this reveals the central thesis of MOC: *the sole fundamental energy source is matter (ρ_m) itself. Dark energy is not an independent physical entity but a secondary, emergent property arising from matter's own gravitational field. Therefore, in principle, matter creates dark energy and accelerates the universe by itself.*

4.2.4 Static GSE Framework: The Friedmann equations in non-expanding space

The MOC framework can also be applied to non-expanding, static systems by setting the interaction and dilution scales to be identical, i.e., $\chi_p = R_{\text{phys}} = R$. This simplification makes the equations applicable to a wide range of physical problems beyond cosmology.

Substituting the explicit GSE–based expressions in terms of the matter density, the equation may be written as

$$H^2 = \frac{8\pi G}{3}\left(\rho_m + c_1\beta\rho_m^2R^2(c_2\beta\rho_mR^2 - 1)\right) - \frac{k}{a^2} \tag{48}$$

$$H^2 = \frac{8\pi G}{3}\rho_m\left(1 - c_1\beta\rho_mR^2 + c_1c_2\beta^2{\rho_m}^2R^4\right) - \frac{k}{a^2} \tag{49}$$

The curvature term enters in the standard way and plays the same geometric role as in ΛCDM. Importantly, its presence does not alter the physical interpretation of the energy budget: all nontrivial dynamical effects arise from the GSE of matter itself.

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + \rho_{\Lambda_m} + 3P_T) \approx -\frac{4\pi G}{3}(\rho_m + (1 + 3w_{\Lambda_m})\rho_{\Lambda_m}) \tag{50}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left[\rho_m + (1 + 3w_{\Lambda_m})c_1\rho_m^2 R^2(c_2\rho_m R^2 - 1)\right] \tag{51}$$

if, $w_{\Lambda_m} \approx -1$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left[\rho_m - 2c_1\rho_m^2 R^2(c_2\rho_m R^2 - 1)\right] \tag{52}$$

The MOC framework can also be applied to non-expanding, static systems by setting the interaction and dilution scales to be identical, i.e., $\chi_p = R_{\text{phys}} = R$. This simplification makes the equations applicable to a wide range of physical problems beyond cosmology.

In this static limit, the first Friedmann equation reduces to

$$\frac{8\pi G}{3}\left[\rho_m + c_1\beta\rho_m^2 R^2(c_2\beta\rho_m R^2 - 1)\right] - \frac{k}{R^2} = 0 \tag{53}$$

This equation describes the conditions for hydrostatic equilibrium in a self-gravitating sphere, where the repulsive GSE pressure can counteract gravitational collapse. The acceleration equation similarly simplifies

$$\ddot{a} \propto -\frac{4\pi G}{3}\left[\rho_m - 2c_1\beta\rho_m^2 R^2(c_2\beta\rho_m R^2 - 1)\right] \tag{54}$$

This static formulation provides a powerful analytical tool. For astrophysical objects like stars or black hole interiors, it offers a framework to model their internal energy-density structure, where repulsive GSE effects could potentially regulate the formation of singularities. For elementary particle physics, it provides a novel approach to the self-energy problem by treating a particle as a self-contained, gravitationally-bound system whose divergences are naturally regularized by its own GSE [20, 43].

4.3 The origin of cosmic acceleration and dark energy

The second Friedmann equation governs cosmic acceleration. In the MOC framework, dark energy is not an independent fluid but an effective quantity ρ_{Λ_m}, emerging from the dynamics of the universe's matter content. As such, its pressure properties are not assumed axiomatically but can be derived directly from the conservation of energy.

The total energy density of the universe is $\rho_T = \rho_m + \rho_{\Lambda_m}$. The conservation of this total energy is expressed by the fluid equation.

$$\dot{\rho}_T + 3H(\rho_T + P_T) = 0 \tag{55}$$

where $P_T = P_m + P_{\Lambda_m}$. Assuming matter is a pressureless fluid ($P_m = 0$), and knowing that matter is independently conserved ($\dot{\rho}_m + 3H\rho_m = 0$), the equation simplifies to describe the evolution of our dark energy component.

$$\dot{\rho}_{\Lambda_m} + 3H(\rho_{\Lambda_m} + P_{\Lambda_m}) = 0 \tag{56}$$

From this, we can solve for the effective pressure of the GSE-induced dark energy.

$$P_{\Lambda_m} = -\rho_{\Lambda_m} - \frac{\dot{\rho}_{\Lambda_m}}{3H} \tag{57}$$

This equation reveals a crucial insight: the pressure of our dark energy has two components. The first term $-\rho_{\Lambda_m}$, represents the 'vacuum-like' negative pressure that is characteristic of a cosmological constant. The second term, proportional to the time derivative of the dark energy density, represents the dynamic, evolutionary nature of our model.

To analyze cosmic acceleration within the MOC framework, we define the effective equation of state for the dynamic dark energy component as $w_{\Lambda_m}(t) \equiv P_{\Lambda_m}/\rho_{\Lambda_m}$. This is derived from the continuity equation for the dark energy component, $\dot{\rho}_{\Lambda_m} + 3H(\rho_{\Lambda_m} + P_{\Lambda_m}) = 0$, yielding

$$w_{\Lambda_m}(t) = -1 - \frac{\dot{\rho}_{\Lambda_m}}{3H\rho_{\Lambda_m}} \tag{58}$$

where the evolution of ρ_{Λ_m} is governed by the interplay of GSE terms in Eq. (29). Unlike the constant $w = -1$ of the cosmological constant in ΛCDM, w_{Λ_m} in MOC is inherently dynamic, reflecting the time-dependent balance between attractive and repulsive GSE contributions.

4.4 Applicability to the radiation era

Although the name "Matter-Only Cosmology" emphasizes that no fundamental dark energy fluid is introduced, the calculations of the fundamental physical mechanism, GSE, apply universally regardless of the type of energy source.

During the radiation-dominated epoch, the dominant energy component of the universe is not matter but radiation, whose energy density is ε_r. The gravitational source is therefore the equivalent mass of this radiation energy, $\rho_r \equiv \varepsilon_r/c^2$. Our framework applies directly by replacing the source term ρ_m with ρ_r. The total mass density equation thus retains its fundamental structure.

$$\rho_T = \rho_r + \rho_{\Lambda_m} = \rho_r + \rho_{m-gs}[\rho_r] - \rho_{gs}[\rho_r] \tag{59}$$

Here, the notation $\rho_{gs}[\rho_r]$ explicitly shows that the positive and negative components of the GSE are now sourced by the radiation density, ρ_r. The main difference is in the scaling behavior and pressure: the radiation density evolves as $\rho_r \propto a^{-4}$, in contrast to matter density which scales as $\rho_m \propto a^{-3}$. For radiation, $w = 1/3$, while for matter, $w \approx 0$.

Consequently, the MOC/GSE mechanism is formally valid and applicable throughout the entire history of the universe, from the end of inflation through the radiation- and matter-dominated eras, and into the late-time accelerated expansion. In this work, we primarily focus on quantifying the predictions for the post CMB epoch. The implications of this framework for the inflationary period itself will be explored in Section 10.

4.5 Theoretical consistency: Positive energy density and the origin of repulsion

A critical theoretical challenge for any alternative gravity or dark energy model is to generate repulsive effects without violating fundamental stability conditions. Models that invoke negative mass or phantom energy ($w < -1$) often suffer from vacuum instabilities, such as the "vacuum decay" or the presence of ghost modes, which render the theory physically pathological [44, 45].

In this section, we demonstrate that the MOC framework avoids these pathologies by strictly maintaining a positive total energy density, while generating repulsion solely through an effective pressure term derived from the total GSE.

4.5.1 Stability via positive total energy density

We analytically searched for the condition under which the total density becomes negative, i.e., $\rho_{\Lambda_m} < -\rho_m$. Substituting the derived expression for ρ_{Λ_m} from Eq. (29) and the matter density ρ_m, we obtain the inequality.

$$\frac{3\beta}{4\pi}\frac{GM^2}{c^2R^4}\left(\frac{5\beta}{14}\frac{R_S}{R}-1\right)<-\frac{3M}{4\pi R^3} \tag{60}$$

Simplifying this inequality by introducing the dimensionless variable $x = R_S/R$ leads to the quadratic condition.

$$\frac{5\beta^2}{28}x^2-\frac{\beta}{2}x+1<0 \tag{61}$$

Analysis of the discriminant (D) of this quadratic equation reveals a definitive result.

$$D=\left(-\frac{\beta}{2}\right)^2-4\left(\frac{5\beta^2}{28}\right)(1)=-\frac{13\beta^2}{28}<0 \tag{62}$$

Since the discriminant is always negative for any real structural parameter β, the quadratic expression is always positive. This implies that there is no physical radius R for which the total energy density becomes negative.

$$\rho_T(R)>0 \quad \text{for all } R>0 \tag{63}$$

In the case where ρ_{Λ_m} has a negative mass density (e.g., in binding energy dominant regimes), for physically feasible radii $R>0$, the magnitude of the negative mass density does not exceed the mass density of the substance. The result is the same even if we use the equation (44) and (45).

This result is crucial. It implies that the MOC universe satisfies the *Weak Energy Condition* (WEC) regarding the density component ($\rho \geq 0$) [39, 40]. Consequently, the vacuum state in MOC is stable against spontaneous decay, and the theory is free from the catastrophic instabilities associated with genuine negative mass fluids [46].

4.5.2 Repulsion from effective pressure

If the total mass-energy is positive, how does the model generate cosmic acceleration? The answer lies in the second Friedmann equation (acceleration equation), which depends on the active gravitational mass density $\rho + 3P/c^2$.

$$\frac{\ddot{a}}{a}=-\frac{4\pi G}{3}\left(\rho_T+\frac{3P_{\Lambda_m}}{c^2}\right) \tag{64}$$

While ρ_T remains positive, the total GSE introduces a significant negative effective pressure P_{Λ_m}. In general relativity, binding energy contributes to the pressure of the system [16]. For the specific configuration of GSE, this pressure contribution is negative and substantial.

Our derivation shows that the equation of state parameter $w_{\Lambda_m} = P_{\Lambda_m}/\rho_{\Lambda_m}$ effectively behaves as $w_{\Lambda_m} \approx -1$ on cosmological scales [20]. Since ρ_{Λ_m} appears as a negative density component in the binding energy context (though $\rho_T > 0$), the combination of terms in the acceleration equation results in a net repulsive force.

$$\rho_T+3P_{\Lambda_m}/c^2<0 \tag{65}$$

Thus, the MOC framework achieves a “safe” mechanism for antigravity.

- **Ontological stability:** The universe consists of positive energy ($\rho_T > 0$), ensuring stability consistent with standard energy conditions [39].
- **Dynamical repulsion:** The gravitational self-interaction generates negative pressure ($P_{\Lambda_m} < 0$), driving cosmic acceleration as observed [1, 2].

This decoupling of stability (density) and dynamics (pressure) allows MOC to explain Dark Energy and Inflation as purely gravitational phenomena without invoking exotic fields or violating quantum stability requirements.

4.6 Definition of the GSE framework

The Gravitational Self-Energy (GSE) framework argues that the total energy (or equivalent mass) of any physical system is the sum of its free-state energy and its GSE. Crucially, this framework extends the classical definition by including not only the standard self-energy term but also an interaction term arising from the coupling between the free state mass and the equivalent mass of the self-energy field. Since all physical entities possess energy and thus generate gravity, the GSE framework is a universal principle applicable to all matter distributions, from elementary particles to the universe at large.

[Classification: General vs. Static Model]

Depending on the dynamical state of the spacetime background, the framework is classified into two regimes.

- **The General GSE Model:** Applied to expanding space, where the scale of gravitational interaction (χ_p) evolves differently from the scale of spatial dilution (R_{phys}). This general form governs the dynamics of the universe, explaining cosmic inflation and dark energy as emergent phenomena driven by the evolving GSE density.
- **The Static GSE Model:** A limiting case applied to gravitationally bound systems where the spacetime metric is locally static and decoupled from cosmic expansion (e.g., black holes, stars, or elementary particles). In these systems, the dominance of self-gravity prevents spatial dilution, ensuring that the scale of gravitational interaction remains commensurate with the physical size of the object ($R_{\text{phys}} \approx \chi_p$). This allows for a simplified description of internal structure and stability, neglecting the negligible contributions from the evolving cosmic background.

5 Observational Validation and the Evolution of β

In the preceding sections, we established the foundational equation of MOC. This new paradigm argues that the universe's dark energy arises from the total GSE, which is calculated in a self-consistent manner.

$$\rho_{\Lambda_m} = \rho_{m-gs} - \rho_{gs} = \frac{3\beta GM^2}{4\pi c^2 R^4}\left(\frac{5\beta}{14}\frac{R_S}{R} - 1\right) \tag{66}$$

Here, β is a structural parameter that represents not only the relativistic correction for binding energy but also the structural evolution of the universe over time. However, since it changes very slowly after the formation of the galaxy structure, it can be treated as a constant.

The ultimate test of this framework is to confront it with empirical data. Can this GSE-driven mechanism reproduce the observed cosmic history? To answer this, we turn to the two primary anchors of modern cosmology: the early-universe constraints from the Cosmic Microwave Background (CMB) [5] and the late-universe measurements from local distance ladders (e.g., SH0ES) [15].

As a parameter that encodes the structural evolution of the universe, the value of β is not fixed by theory but must be constrained by observation. Our strategy is therefore to determine β by demanding consistency with the observations from both CMB and SH0ES data. We treat the total matter density parameter, Ω_m, not as a fixed input, but as a variable to be explored. For both the CMB baseline (H_0 = 67.4 km/s/Mpc) and the SH0ES baseline (H_0 = 73.04 km/s/Mpc), we calculate the value of β required to produce the observed present-day dark energy density, $\rho_{\Lambda_m} = (1-\Omega_m)\rho_c$. This procedure is repeated for a range of matter densities, representing scenarios where cosmic structure might be more significant than assumed in the standard ΛCDM model ($\Omega_m \approx 0.315$) [5].

The results of this analysis, summarized in Tables 1 and 2, reveal the required values of β across a spectrum of possible universes. By comparing these required β values to the physically plausible range derived from stellar structure theory ($\beta \approx 0.6-2.04$) and large-scale structure simulations [47, 48], we can assess the viability of the MOC framework.

Matter Incr. (%)	ρ_m ($\times 10^{-27}$ kg/m^3)	ρ_{Λ_m} (Target)	**Required β**	ρ_{m-gs} ($\times 10^{-27}$ kg/m^3)	$-\rho_{gs}$
-20	2.150	6.383	**2.2068**	12.522	-6.139
-10	2.418	6.115	**1.8597**	12.662	-6.547
0	2.687	5.846	**1.5952**	12.780	-6.934
10	2.956	5.577	**1.3879**	12.877	-7.300
20	3.224	5.309	**1.2219**	12.956	-7.648
30	3.493	5.040	**1.0863**	13.019	-7.979
40	3.762	4.771	**0.9737**	13.067	-8.296
50	4.030	4.502	**0.8791**	13.100	-8.598
60	4.299	4.234	**0.7986**	13.120	-8.886

Table 1: **Required Structural Parameter β for CMB Baseline (H_0 = 67.4 km/s/Mpc, $R = 46.5$ Gly, $\rho_c \approx 8.53 \times 10^{-27}$ kg/m^3)** The table lists the necessary β values to recover the precise CMB dark energy density for various matter density scenarios. The range from approximately -10% to +30% matter variation yields physically plausible β values ($1.0 \lesssim \beta \lesssim 2.0$) consistent with virialized structures. Specifically, the 0% ($\beta \approx 1.5952$) and +20% ($\beta \approx 1.2219$) models are particularly favored as they align well with standard astrophysical expectations.

An examination of Tables 1 and 2 reveals a critical new insight into the MOC framework. First and foremost, the results demonstrate that our model is highly robust: valid solutions for β exist across a broad range of matter densities, from scenarios where matter is scarcer than the standard ΛCDM estimate to those where it is more abundant.

Specifically, for the canonical density ($\Omega_m \approx 0.315$, 0% increase), the required structural parameters are $\beta \approx 1.5952$ (CMB) and $\beta \approx 1.4949$ (SH0ES). Crucially, these values are not arbitrary. They fall squarely within the physically predicted range for a universe that has undergone significant structure formation.

The late Universe is expected to be highly virialized and less uniform on cosmological scales, which naturally correlates with a region where β approaches 1. From this perspective, models in which $\beta \simeq 1.0 \sim 1.5$ (i.e., models corresponding to +10% to +20% matter enhancement scenarios) appear particularly well-motivated within the MOC framework.

While the standard ΛCDM model does not require such an increase in the matter density at the present epoch, the MOC framework allows for, and indeed predicts, this possibility as a consequence of properly accounting for GSE and large-scale structural evolution.

Matter Incr. (%)	ρ_m	ρ_{Λ_m} (Target)	Required β	ρ_{m-gs}	$-\rho_{gs}$
	($\times 10^{-27}$ kg/m^3)			($\times 10^{-27}$ kg/m^3)	
-20	2.525	7.496	**2.0681**	14.706	-7.210
-10	2.840	7.180	**1.7428**	14.870	-7.690
0	3.156	6.865	**1.4949**	15.008	-8.143
10	3.472	6.549	**1.3007**	15.122	-8.573
20	3.787	6.233	**1.1450**	15.215	-8.982
30	4.103	5.918	**1.0180**	15.289	-9.371
40	4.418	5.602	**0.9125**	15.345	-9.743
50	4.734	5.287	**0.8239**	15.384	-10.098
60	5.050	4.971	**0.7484**	15.408	-10.437

Table 2: **Required Structural Parameter β for SH0ES Baseline ($H_0 = 73.04$ km/s/Mpc, $\chi_p(t_0) = R = 43.337$ Gly,$\rho_c \approx 1.002 \times 10^{-26}$ kg/m^3).** The table lists the precise β values required to recover the observed SH0ES dark energy density across varying matter density scenarios. The range from -10% to $+30\%$ corresponds to physically viable structural parameters ($1.0 \lesssim \beta \lesssim 2.039$).

5.1 The Hubble Tension as a natural consequence of MOC

One of the most significant challenges in modern cosmology is the "Hubble tension"—the persistent discrepancy between the value of the Hubble constant (H_0) measured from the early universe and that from the local, late-time universe [11]. Measurements from the Cosmic Microwave Background (CMB) by the Planck satellite suggest $H_0 \approx 67.4$ km/s/Mpc [5], while local measurements using Type Ia supernovae from the SH0ES team indicate a higher value of $H_0 \approx 73.04$ km/s/Mpc [15]. In the standard ΛCDM model, where dark energy is an immutable constant, this disagreement presents a fundamental crisis [49–52].

However, within the MOC framework, this tension is not a crisis but a natural and predicted consequence of cosmic evolution. The key is our structural parameter, β, which is not a fundamental constant but an effective parameter reflecting the evolving structure of the universe's matter distribution.

5.1.1 The evolution of $\beta(t)$ as a record of cosmic structure formation

As the universe evolves, its structure changes little by little. In the early universe (the CMB era), matter was distributed almost uniformly. As time progressed, gravitational instability caused this matter to clump together, forming the complex cosmic web of galaxies, clusters, and vast voids we see today [37]. This process of structure formation directly impacts the total GSE of the universe and, consequently, must be reflected in the value of β. A more clustered, inhomogeneous, and virialized universe is expected to have a different effective β than a smooth, uniform one.

Our analysis of the two primary cosmological datasets confirms this picture with remarkable clarity. Instead of requiring a large, unobserved matter component, MOC successfully explains the data with matter densities very close to the canonical value. We highlight two key scenarios based on our updated calculations.

- **The 0% matter-increase scenario ($\Omega_m \approx 0.315$):** To explain the universe as seen in the CMB, our model requires $\beta_{\mathrm{CMB}} \approx 1.595$. For the local universe (SH0ES), it requires

$\beta_{\text{SH0ES}} \approx 1.495$. Both values are physically viable, yet they show a clear decreasing trend ($\Delta\beta \approx -0.100$) over cosmic time.

- **The 10% matter-increase scenario ($\Omega_m \approx 0.346$):** We are also interested in the +10% material growth model, considering the recent publication of the results of studies with 12.06% material growth claims ($\Omega_m \approx 0.352$) [53]. It requires $\beta_{\text{CMB}} \approx 1.388$ for the early universe and $\beta_{\text{SH0ES}} \approx 1.301$ for the present day.

In the MOC framework, the Hubble tension is re-framed not as a crisis, but as a powerful confirmation of our model. The discrepancy in the measured values of H_0 arises because cosmologists have attempted to describe two physically distinct cosmic epochs within a single, constant dark energy model (Λ). If the dark energy density is not constant, but changes with time, this is destined to fail.

The tension is the expected signal of a universe where the apparent "dark energy" is not a constant, but a dynamic entity whose properties evolve in response to the changing structure of the cosmos. It is governed by the internal dynamics of $\beta(t)$, $\rho_m(t)$, and the cosmic scale $R(t)$. This transforms the tension from a problematic anomaly into crucial evidence for a universe where matter alone dictates its own complex, evolving destiny. The fact that two different values of H_0 are measured is not a problem for MOC; it is a core prediction.

6 Cosmic History of the MOC

6.1 Preface on methodology and limitations

The currently accepted cosmological constants and datasets are predominantly derived from calculations based on the standard ΛCDM model. This model fundamentally assumes a constant dark energy density, represented by the cosmological constant, Λ [3, 4]. However, the MOC that we seek to build posits a significant departure from this paradigm; it features a dark energy density that evolves over time and exhibits different dynamics. A complete and rigorous formulation of MOC would therefore require the construction of a new dataset based entirely on its own axioms and principles.

At present, MOC is in its nascent stages, whereas the ΛCDM model is supported by a vast accumulation of data. Furthermore, as the author is not a specialist in cosmology, a proprietary dataset for MOC does not yet exist. Consequently, the primary objective of this paper is not to present a definitive, precision-tested model, but rather to introduce the core ideas of MOC to the wider academic community and to explore its potential through calculations based on simplified assumptions.

Given the absence of a dedicated observational dataset for MOC, the following analysis is necessarily reliant on the existing ΛCDM-based data. Therefore, the results should be interpreted not as a measure of the model's precision or accuracy, but as a preliminary investigation into the promise and potential of MOC. We ask readers to focus on the core logic and potential of the MOC framework, rather than focusing on the numerical discrepancies that may arise from these fundamental approximations.

6.2 Methods: General framework for MOC cosmic history simulations

6.2.1 Overview: Horizon-scale separation

This work develops a MOC framework in which the dark energy density $\rho_{\Lambda_m}(t)$ arises dynamically from the GSE of matter. Unlike standard ΛCDM, where ρ_Λ is constant, MOC treats dark energy as an emergent property of structure formation.

A critical innovation in this simulation is the adoption of a **horizon-scale separation framework** for calculating GSE densities. We distinguish between the scale of interaction and the scale of dilution.

1) **Energy Formation (Causal Scale):** The potential energy of the cosmic web is determined by gravitational interactions limited by the particle horizon. Since gravity is an infinite-range force limited only by causality, the binding energy U_{gs} scales with the **comoving particle horizon** (χ_p), which represents the fixed coordinate mesh of causally connected mass [38].

2) **Density Dilution (Physical Scale):** While the energy is generated over the comoving network, the resulting energy *density* exists within the expanding physical universe. Therefore, the volume dilution follows the **physical horizon** ($R_{\text{phys}} = a(t)\chi_p$), i.e. the proper radius of the observable region at each epoch [38].

This two–scale horizon formulation captures the competition between the growth of the gravitational network (increasing energy) and the rapid expansion of physical volume (decreasing density), and it provides the basis for all MOC simulations presented in this work.

6.2.2 Constants and horizon definitions

We adopt the following constants and present-day anchors based on SH0ES data.

- Hubble constant: $H_0 = 73.04\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.
- Critical density: $\rho_c = 3H_0^2/8\pi G \simeq 1.002 \times 10^{-26}\,\text{kg}\,\text{m}^{-3}$.
- Present age (SH0ES-based): $t_0 = 12.73\,\text{Gyr}$.

We define two distinct horizon scales.

$$\chi_p(t) = \int_0^t \frac{c}{a(t')}dt' \quad \text{(Comoving Horizon)} \tag{67}$$

$$R_{\text{phys}}(t) = a(t)\chi_p(t) \quad \text{(Physical Horizon)} \tag{68}$$

At the present epoch ($a = 1$), these two scales coincide: $\chi_p(t_0) = R_{\text{phys}}(t_0) \approx 43.337\,\text{Gly}$.

6.2.3 Mass growth and matter density

The effective gravitational mass $M(t)$ involved in the self-energy calculation is the mass enclosed within the causal horizon. This mass scales with the comoving volume, reflecting the increasing amount of matter entering the causal horizon over time.

$$M(t) = M(t_0, f)\left(\frac{\chi_p(t)}{\chi_p(t_0)}\right)^3 \tag{69}$$

Here, $M(t_0, f)$ is the present-day mass determined by the matter enhancement factor f relative to the standard $\Omega_m = 0.315$. Conversely, the matter density $\rho_m(t)$ follows standard cosmological dilution in physical space.

$$\rho_m(t) = \frac{M(t)}{V_{\text{phys}}(t)} = \frac{\rho_m(t_0, f)}{a(t)^3} \tag{70}$$

where $V_{\text{phys}}(t) = \frac{4\pi}{3}R_{\text{phys}}(t)^3$.

6.2.4 Derivation of GSE densities

The core ansatz of the General GSE Framework implies that the total GSE U_{gs-T} is a function of the mass $M(t)$ and the characteristic interaction scale $\chi_p(t)$.

$$U_{gs-T} \sim -\frac{GM(t)^2}{\chi_p(t)} \tag{71}$$

However, the equivalent mass density ρ_{Λ_m} is this energy divided by the physical volume $V_{\text{phys}}c^2$.

1) The negative energy component ($-\rho_{gs}$): Representing the classical binding energy, generalized by $\beta(t)$.

$$-\rho_{gs}(t) = \frac{U_{gs}}{V_{\text{phys}}(t)c^2} = -\frac{1}{\frac{4\pi}{3}R_{\text{phys}}^3 c^2}\left(\beta(t)\frac{GM(t)^2}{\chi_p(t)}\right) \tag{72}$$

Simplifying with $R_{\text{phys}} = a\chi_p$.

$$-\rho_{gs}(t) = -\frac{3\beta(t)}{4\pi}\frac{GM(t)^2}{c^2\chi_p(t)R_{\text{phys}}(t)^3} \tag{73}$$

2) The positive energy component (ρ_{m-gs}): The interaction term arises from the general relativistic correction. Following the same generalized logic (interaction scale χ_p, dilution scale R_{phys}).

$$\rho_{m-gs}(t) = +\frac{15\beta(t)^2}{28\pi}\frac{G^2M(t)^3}{c^4\chi_p(t)^2R_{\text{phys}}(t)^3} \tag{74}$$

3) Total dark energy density: The dark energy density is the sum of these components.

$$\rho_{\Lambda_m}(t) = \rho_{m-gs}(t) - \rho_{gs}(t) \tag{75}$$

This formulation naturally leads to a dynamic evolution where the energy source grows slowly (linked to χ_p), but the volume expands rapidly (linked to R_{phys}^3), ensuring that ρ_{Λ_m} dominates in the specific epoch where the causal connection is maximized relative to spatial dilution.

6.2.5 Structural parameter evolution $\beta(t)$

The structural parameter $\beta(t)$ evolves linearly to connect the early universe and the present.

$$\beta(t) = \beta_{t_0} + (\beta_{\text{CMB}} - \beta_{t_0})\frac{t_{\text{step}}}{12} \tag{76}$$

The present-day value β_{t_0} is derived iteratively for each matter fraction f to satisfy the boundary condition.

$$\rho_m(t_0, f) + \rho_{\Lambda_m}(t_0, f) = \rho_c \tag{77}$$

$\rho_m(t_0, f) + \rho_{\Lambda_m}(t_0, f) = \rho_c$ This ensures that the simulation reproduces the observed SH0ES critical density exactly at $z = 0$, while predicting the cosmic history backward in time.

6.3 MOC cosmic history simulation datas

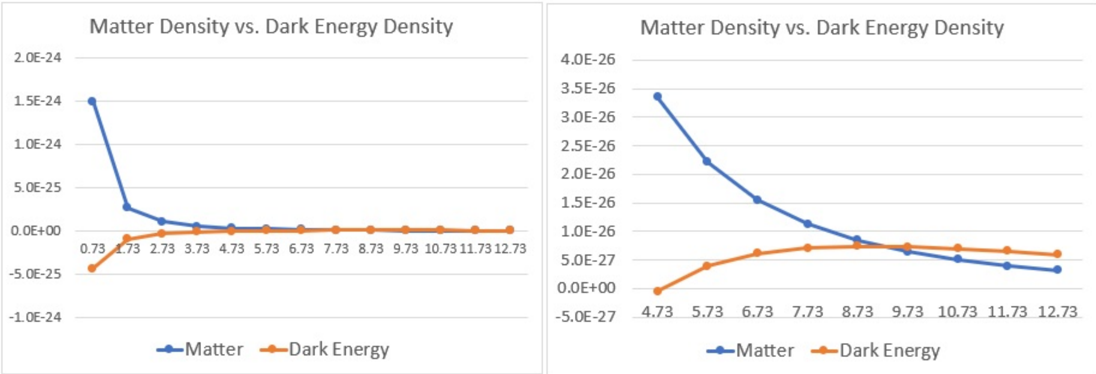

Figure 2: MOC Cosmic History Simulation (SH0ES baseline, 0% Matter Enhancement): Matter Density vs. Dark Energy Density. Dark energy density becomes negative at t< ∼ 4.73 Gyr, promotes the formation of galaxy structures, then accelerates the expansion of the universe from approximately t ∼7 Gyr, peaks around t=8.73 Gyr, and then monotonically decreases.

Age (Gyr)	Scale $a(t)$	Evolving $\beta(t)$	Comoving Ho. $\chi_p(t)$ (Gly)	Physical Ho. $R_{\text{phys}}(t)$ (Gly)	**Matter** $\rho_m(t)$	Repulsive $\rho_{m-gs}(t)$	Attractive $-\rho_{gs}(t)$	**Dark Energy** $\rho_{\Lambda_m}(t)$
					(10^{-27} kg m^{-3})			
0.73	0.1283	1.5952	17.080	2.191	1495.70	178.939	-612.111	**-433.172**
1.73	0.2285	1.5868	22.764	5.202	264.769	98.902	-191.466	**-92.564**
2.73	0.3111	1.5785	26.487	8.240	104.912	71.075	-102.170	**-31.096**
3.73	0.3854	1.5701	29.365	11.317	55.181	55.880	-65.702	**-9.822**
4.73	0.4552	1.5618	31.748	14.452	33.490	45.845	-46.362	**-0.517**
5.73	0.5224	1.5534	33.797	17.656	22.157	38.537	-34.574	3.963
6.73	0.5883	1.5451	35.599	20.943	15.514	32.858	-26.714	6.144
7.73	0.6540	1.5367	37.211	24.336	11.293	28.244	-21.131	7.113
8.73	0.7200	1.5283	38.668	27.841	8.463	24.415	-17.008	7.407
9.73	0.7871	1.5200	39.996	31.481	6.478	21.157	-13.852	7.305
10.73	0.8559	1.5116	41.214	35.275	5.038	18.348	-11.376	6.973
11.73	0.9266	1.5033	42.337	39.229	3.971	15.925	-9.408	6.516
12.73	1.0000	1.4949	43.337	43.337	3.159	13.755	-7.799	5.956

Table 3: **MOC Cosmic History Simulation (SH0ES +0% Matter Enhancement):** The structural parameter evolves linearly from $\beta(0.73) = 1.5952$ to $\beta(12.73) = 1.4949$. In the early universe ($t \lesssim 4.73$ Gyr), the dark energy density $\rho_{\Lambda_m}(t)$ is negative, enhancing deceleration and promoting the rapid formation of massive galactic structures. During the intermediate epoch, $\rho_{\Lambda_m}(t)$ transitions to positive values and drives the universe into an accelerated expansion phase around $t \approx 7$ Gyr, reaches a maximum near $t \approx 8.73$ Gyr, and subsequently decreases monotonically. This single, self-consistent equation for $\rho_{\Lambda_m}(t)$ simultaneously accounts for the existence of early massive galaxies, the onset of late-time acceleration, the quasi-constant behavior of dark energy, and recent indications of a mild decline in the dark energy density.

Age (Gyr)	Scale $a(t)$	Evolving $\beta(t)$	Comoving Ho. $\chi_p(t)$ (Gly)	Physical Ho. $R_{\text{phys}}(t)$ (Gly)	**Matter** $\rho_m(t)$	Repulsive $\rho_{m-gs}(t)$	Attractive $-\rho_{gs}(t)$	**Dark Energy** $\rho_{\Lambda_m}(t)$
					$(10^{-27}\ \text{kg}\,\text{m}^{-3})$			
0.73	0.1283	1.3879	17.080	2.191	1645.27	180.289	-644.405	**-464.116**
1.73	0.2285	1.3806	22.764	5.202	291.245	99.649	-201.568	**-101.919**
2.73	0.3111	1.3734	26.487	8.240	115.403	71.612	-107.562	**-35.950**
3.73	0.3854	1.3661	29.365	11.317	60.699	56.303	-69.169	**-12.866**
4.73	0.4552	1.3588	31.748	14.452	36.839	46.193	-48.809	**-2.616**
5.73	0.5224	1.3516	33.797	17.656	24.373	38.829	-36.399	2.430
6.73	0.5883	1.3443	35.599	20.943	17.066	33.108	-28.124	4.983
7.73	0.6540	1.3370	37.211	24.336	12.422	28.459	-22.246	**6.213**
8.73	0.7200	1.3298	38.668	27.841	9.309	24.600	-17.905	6.695
9.73	0.7871	1.3225	39.996	31.481	7.126	21.318	-14.583	6.735
10.73	0.8559	1.3152	41.214	35.275	5.542	18.488	-11.976	6.512
11.73	0.9266	1.3080	42.337	39.229	4.368	16.046	-9.905	6.141
12.73	1.0000	1.3007	43.337	43.337	3.475	13.860	-8.211	5.649

Table 4: **MOC Cosmic History Simulation (SH0ES +10% Matter Enhancement)**: The structural parameter $\beta(t)$ evolves linearly from 1.3879 to 1.3007. In the early universe ($t \lesssim 5\,\text{Gyr}$), the dark energy density $\rho_{\Lambda_m}(t)$ is negative, enhancing deceleration and promoting the formation of galactic structures. During the intermediate epoch, $\rho_{\Lambda_m}(t)$ transitions to positive values; it drives the universe into an accelerated expansion phase around $t \approx 7.73\,\text{Gyr}$, reaches a maximum near $t \approx 8.73\,\text{Gyr}$, and then decreases monotonically toward the present.

Age (Gyr)	Scale $a(t)$	Evolving $\beta(t)$	Comoving Ho. $\chi_p(t)$ (Gly)	Physical Ho. $R_{\text{phys}}(t)$ (Gly)	**Matter** $\rho_m(t)$	Repulsive $\rho_{m-gs}(t)$	Attractive $-\rho_{gs}(t)$	**Dark Energy** $\rho_{\Lambda_m}(t)$
					$(10^{-27}\ \text{kg}\,\text{m}^{-3})$			
0.8	0.1295	1.3879	17.744	2.298	1360.95	125.700	-489.386	**-363.686**
1.8	0.2226	1.3812	23.496	5.230	267.964	75.358	-168.138	**-92.780**
2.8	0.2998	1.3745	27.340	8.197	109.688	56.002	-92.735	**-36.733**
3.8	0.3694	1.3678	30.335	11.206	58.636	44.930	-60.731	**-15.801**
4.8	0.4346	1.3611	32.827	14.267	36.007	37.466	-43.458	**-5.992**
5.8	0.4972	1.3544	34.975	17.390	24.047	31.925	-32.784	**-0.859**
6.8	0.5584	1.3477	36.872	20.589	16.975	27.563	-25.594	1.969
7.8	0.6190	1.3409	38.572	23.876	12.462	23.992	-20.459	3.533
8.8	0.6796	1.3342	40.113	27.261	9.417	20.993	-16.636	4.357
9.8	0.7408	1.3275	41.522	30.759	7.270	18.421	-13.693	**4.728**
10.8	0.8031	1.3208	42.818	34.387	5.706	16.185	-11.371	4.814
11.8	0.8668	1.3141	44.017	38.154	4.538	14.230	-9.509	4.722
12.8	0.9323	1.3074	45.129	42.074	3.647	12.508	-7.992	4.516
13.8	1.0000	1.3007	46.165	46.165	2.956	10.990	-6.742	4.244

Table 5: **MOC Cosmic History Simulation (CMB +10% Matter Enhancement)**: GSE density evolution computed on a CMB–based background ($H_0 = 67.4$) with a +10% matter enhancement and the same $\beta(t)$ profile derived from the SH0ES analysis. Unlike the SH0ES–anchored runs, here we *do not enforce* the flatness condition $\rho_m(t_0) + \rho_{\Lambda_m}(t_0) = \rho_c(H_0^{\text{CMB}})$. We intentionally retain the small mismatch between the MOC-predicted total density ($\rho_{\text{tot}} \approx 7.20$) and the standard CMB critical density ($\rho_c \approx 8.53$) as a diagnostic of how the GSE contribution compares to the canonical ΛCDM budget without ad-hoc renormalization.Dark energy is negative at t<6 Gyr, and the accelerating expansion of the universe occurs at t 9.3 Gyr.

Age (Gyr)	Scale $a(t)$	Evolving $\beta(t)$	Comoving Ho. $\chi_p(t)$ (Gly)	Physical Ho. $R_{\text{phys}}(t)$ (Gly)	**Matter** $\rho_m(t)$	Repulsive $\rho_{m-gs}(t)$	Attractive $-\rho_{gs}(t)$	**Dark Energy** $\rho_{\Lambda_m}(t)$
					(10^{-27} kg m^{-3})			
0.73	0.1283	1.2219	17.080	2.191	1794.84	181.422	-675.170	**-493.749**
1.73	0.2285	1.2155	22.764	5.202	317.722	100.274	-211.190	**-110.920**
2.73	0.3111	1.2091	26.487	8.240	125.894	72.059	-112.695	**-40.635**
3.73	0.3854	1.2027	29.365	11.317	66.217	56.654	-72.469	**-15.816**
4.73	0.4552	1.1963	31.748	14.452	40.188	46.479	-51.137	**-4.658**
5.73	0.5224	1.1899	33.797	17.656	26.589	39.070	-38.135	0.935
6.73	0.5883	1.1835	35.599	20.943	18.617	33.312	-29.465	3.847
7.73	0.6540	1.1770	37.211	24.336	13.551	28.634	-23.307	5.327
8.73	0.7200	1.1706	38.668	27.841	10.156	24.751	-18.759	5.992
9.73	0.7871	1.1642	39.996	31.481	7.773	21.449	-15.278	6.171
10.73	0.8559	1.1578	41.214	35.275	6.046	18.601	-12.547	6.054
11.73	0.9266	1.1514	42.337	39.229	4.765	16.144	-10.377	5.767
12.73	1.0000	1.1450	43.337	43.337	3.791	13.944	-8.602	5.342

Table 6: **MOC Cosmic History Simulation (SH0ES +20% Matter Enhancement)**: The structural parameter $\beta(t)$ evolves from 1.2219 to 1.1450. In the early universe ($t \lesssim 5.5$ Gyr), the dark energy density $\rho_{\Lambda_m}(t)$ is negative, enhancing deceleration and promoting the formation of galactic structures. During the intermediate epoch, $\rho_{\Lambda_m}(t)$ transitions to positive values; it drives the universe into an accelerated expansion phase around $t \approx 8.4$ Gyr, reaches a maximum near $t \approx 9.73$ Gyr, and then decreases monotonically toward the present. A single dark energy equation consistently explains the enhanced structure formation in the early universe, the subsequent accelerated expansion, and the recent decline in dark energy density.

Age (Gyr)	Scale $a(t)$	Evolving $\beta(t)$	Comoving Ho. $\chi_p(t)$ (Gly)	Physical Ho. $R_{\text{phys}}(t)$ (Gly)	**Matter** $\rho_m(t)$	Repulsive $\rho_{m-gs}(t)$	Attractive $-\rho_{gs}(t)$	**Dark Energy** $\rho_{\Lambda_m}(t)$
					(10^{-27} kg m^{-3})			
0.73	0.1283	1.8597	17.080	2.191	1346.13	177.291	-578.020	**-400.729**
1.73	0.2285	1.8500	22.764	5.202	238.292	97.992	-180.803	**-82.811**
2.73	0.3111	1.8402	26.487	8.240	94.421	70.421	-96.480	**-26.060**
3.73	0.3854	1.8305	29.365	11.317	49.663	55.366	-62.043	**-6.677**
4.73	0.4552	1.8207	31.748	14.452	30.141	45.424	-43.780	1.644
5.73	0.5224	1.8110	33.797	17.656	19.942	38.183	-32.649	5.534
6.73	0.5883	1.8013	35.599	20.943	13.963	32.556	-25.227	7.330
7.73	0.6540	1.7915	37.211	24.336	10.163	27.985	-19.954	8.031
8.73	0.7200	1.7818	38.668	27.841	7.617	24.190	-16.061	8.130
9.73	0.7871	1.7720	39.996	31.481	5.830	20.963	-13.080	7.882
10.73	0.8559	1.7623	41.214	35.275	4.534	18.180	-10.742	7.438
11.73	0.9266	1.7525	42.337	39.229	3.573	15.779	-8.885	6.894
12.73	1.0000	1.7428	43.337	43.337	2.843	13.629	-7.365	6.264

Table 7: **MOC Cosmic History Simulation (SH0ES -10% Matter Enhancement)**: The structural parameter $\beta(t)$ evolves from 1.8597 to 1.7428. In the early universe ($t \lesssim 4.5$ Gyr), the dark energy density $\rho_{\Lambda_m}(t)$ is negative, enhancing deceleration and promoting the formation of galactic structures. During the intermediate epoch, $\rho_{\Lambda_m}(t)$ transitions to positive values; it drives the universe into an accelerated expansion phase around $t \approx 6.6$ Gyr, reaches a maximum near $t \approx 8.73$ Gyr, and then decreases monotonically toward the present.

7 Analysis of the Cosmic History using MOC

Here we analyze key simulation results derived from the MOC framework, ranging from a SH0ES–anchored matter density close to the standard ΛCDM value ($\Omega_m \approx 0.315$) to modified scenarios with matter enhancements of $\{-10\%, 0\%, +10\%, +20\%\}$ relative to this baseline (Tables 7–6).

Before proceeding to a physical interpretation of the dynamical behavior of $\rho_{\Lambda_m}(t)$, it is important to clarify the meaning of the cosmic age used in the present analysis. The often-quoted present age $t_0 \simeq 12.73$ Gyr is not a direct observable, but rather a derived quantity obtained by adopting the SH0ES value of the Hubble constant ($H_0 = 73.04\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) within the standard ΛCDM framework. As such, this value is intrinsically model dependent.

In the MOC framework, the Hubble parameter is not treated as a fixed external input, and the dark energy density $\rho_{\Lambda_m}(t)$ is generated dynamically by the GSE of matter. In particular, $\rho_{\Lambda_m}(t)$ becomes negative in the early universe, contributing an additional attractive component that enhances the overall deceleration relative to ΛCDM. Consequently, for a given late-time value of H_0, a longer cosmic time is naturally required to reach the present expansion state.

Therefore, while the SH0ES-based ΛCDM model yields $t_0 \simeq 12.73$ Gyr, the physically relevant age of the universe in the MOC framework is expected to be larger. A conservative expectation is that the true cosmic age lies between the SH0ES ΛCDM value and the Planck-based estimate of $t_0 \simeq 13.8$ Gyr.

A coherent picture emerges across all simulated cases. In contrast to the standard ΛCDM scenario, where dark energy is a static cosmological constant, the MOC framework predicts a dynamical matter–induced dark energy density $\rho_{\Lambda_m}(t)$ with a characteristic *three–phase* evolution.

1) an early phase with **negative** $\rho_{\Lambda_m}(t)$, acting as an additional attractive component that enhances structure formation;

2) an intermediate phase in which $\rho_{\Lambda_m}(t)$ transitions through zero and becomes positive, eventually dominating the acceleration;

3) a late phase in which positive $\rho_{\Lambda_m}(t)$ varies only mildly and behaves quasi–constantly on Gyr timescales.

Below we quantify this behavior and connect it to current cosmological tensions and anomalies.

7.1 The competition of two GSE components

The central dynamical mechanism of the MOC framework is the competition between two distinct GSE contributions: the attractive self–energy density ($-\rho_{gs}$) and the repulsive interaction energy density ρ_{m-gs}. The dark energy density is defined as

$$\rho_{\Lambda_m}(t) = \rho_{m-gs}(t) - \rho_{gs}(t) \tag{78}$$

and its sign determines its gravitational role. A positive ρ_{Λ_m} carries negative effective pressure and drives accelerated expansion, whereas a negative ρ_{Λ_m} acts as an additional attractive component, effectively strengthening gravity.

The relative importance of these two GSE terms evolves over cosmic time. While $-\rho_{gs}$ scales primarily with the square of the matter density and dominates in dense, early time configurations, the interaction term ρ_{m-gs} becomes increasingly important as the horizon grows and the cosmic matter distribution evolves. The time dependence of the structural parameter

$\beta(t)$ further modulates this balance, encoding the transition from a nearly homogeneous early universe to a highly structured late–time cosmic web.

As a consequence, the MOC framework generically predicts a sign change in $\rho_{\Lambda_m}(t)$ during cosmic evolution, providing a natural transition from an early gravity–enhanced phase to a late time repulsive regime. The physical implications of this transition for early structure formation and late time cosmic acceleration are discussed in the following subsection.

7.2 The emergence of quasi-constant and weakening dark energy

A key quantitative outcome of the MOC simulations is the emergence of a positive dark energy density at late times with only mild evolution on multi-Gyr timescales. Across all four matter scenarios, once ρ_{Λ_m} becomes positive it grows to a maximum in the range $t \simeq 8$–10 Gyr and then decreases slowly thereafter. This is precisely the type of behavior required by recent indications of dynamical dark energy [12, 13, 53]: the dark energy is not strictly constant, but its variation is modest and occurs over long timescales.

[Quantitative late-time behavior]

In the baseline ($f = 0\%$) case (Table 3), ρ_{Λ_m} becomes positive between $t = 4.73$ and 5.73 Gyr, reaches its maximum.

$$\rho_{\Lambda_m}^{\max} \simeq 7.41 \times 10^{-27}\,\mathrm{kg\,m^{-3}}$$

at $t \simeq 8.73$ Gyr, and then declines to

$$\rho_{\Lambda_m}(t_0) \simeq 5.96 \times 10^{-27}\,\mathrm{kg\,m^{-3}}$$

at $t = 12.73$ Gyr.

The same qualitative pattern holds in every matter-enhancement scenario (all values below are in units of $10^{-27}\,\mathrm{kg\,m^{-3}}$).

- $f = -10\%$ (Table 7): peak $\rho_{\Lambda_m} \simeq 8.13$ at $t = 8.73$ Gyr, decreasing to 6.26 at $t = 12.73$ Gyr
- $f = +10\%$ (Table 4): peak $\rho_{\Lambda_m} \simeq 6.74$ at $t = 9.73$ Gyr, decreasing to 5.65 at $t = 12.73$ Gyr
- $f = +20\%$ (Table 6): peak $\rho_{\Lambda_m} \simeq 6.17$ at $t = 9.73$ Gyr, decreasing to 5.34 at $t = 12.73$ Gyr

In all four cases, once the peak is reached, the subsequent decline over the last $\sim$ 4–5 Gyr is only at the $\mathcal{O}(10\%)$ level, illustrating the quasi-constant but gently weakening character of dark energy in the late universe within MOC.

[Onset of accelerated expansion]

The onset of accelerated expansion can be approximately identified by the condition

$$\rho_m(t) - 2\rho_{\Lambda_m}(t) < 0 \tag{79}$$

which follows directly from the standard Friedmann acceleration equation in ΛCDM, assuming a pressureless matter component ($w_m = 0$) and an effective dark energy component with equation of state close to $w \simeq -1$ once ρ_{Λ_m} becomes positive. In this sense, the above criterion provides a useful and physically well-motivated diagnostic for the onset of cosmic acceleration, even though $\rho_{\Lambda_m}(t)$ is dynamically generated rather than strictly constant in the MOC framework.

Applying this diagnostic to the four SH0ES-based simulations yields a consistent picture.

- $f = -10\%$: the condition $\rho_m \lesssim 2\rho_{\Lambda_m}$ is first satisfied between $t = 6.0$ and $6.7\,\mathrm{Gyr}$, corresponding to $t_{\mathrm{acc}} \approx 6.6\,\mathrm{Gyr}$
- $f = 0\%$: acceleration begins between $t = 6.73$ and $7.73\,\mathrm{Gyr}$, giving $t_{\mathrm{acc}} \approx 7.3\,\mathrm{Gyr}$
- $f = +10\%$: the onset occurs very close to $t = 7.73\,\mathrm{Gyr}$, where $\rho_{\Lambda_m} \approx \frac{1}{2}\rho_m$
- $f = +20\%$: the threshold is crossed between $t = 7.73$ and $8.73\,\mathrm{Gyr}$, giving $t_{\mathrm{acc}} \approx 8.4\,\mathrm{Gyr}$

Thus, while the exact onset time shifts with the assumed matter content, all four simulations exhibit accelerated expansion beginning within a relatively narrow window of $t_{\mathrm{acc}} \sim 6.5$ –8.5 Gyr. This demonstrates that the acceleration epoch is not a fragile or finely tuned feature of a particular parameter choice, but a robust consequence of the GSE dynamics under the MOC model: as the matter density increases, the onset of acceleration is systematically delayed to later cosmic times.

7.3 Resolving early–universe anomalies (JWST and Euclid)

One of the most striking features of the MOC simulations is the presence of **negative** dark energy density in the early universe. This regime provides a plausible explanation for several early structure anomalies, such as the "impossibly early" massive galaxies reported by JWST [54, 55] and the tensions in structure growth indicated by Euclid, KiDS, and related surveys [56, 57].

In all four SH0ES–based scenarios, the early–time values of ρ_{Λ_m} (at $t = 0.73\,\mathrm{Gyr}$) are significantly negative.

$$\begin{aligned} f = -10\%: &\quad \rho_{\Lambda_m} \simeq -4.01 \times 10^{-25}\,\mathrm{kg\,m^{-3}} \\ f = 0\%: &\quad \rho_{\Lambda_m} \simeq -4.33 \times 10^{-25}\,\mathrm{kg\,m^{-3}} \\ f = +10\%: &\quad \rho_{\Lambda_m} \simeq -4.64 \times 10^{-25}\,\mathrm{kg\,m^{-3}} \\ f = +20\%: &\quad \rho_{\Lambda_m} \simeq -4.94 \times 10^{-25}\,\mathrm{kg\,m^{-3}} \end{aligned}$$

These values represent a non–negligible attractive contribution in addition to the standard matter density. Physically, this phase of negative dark energy deepens gravitational potential wells and **accelerates the formation of massive bound structures.**

As a result, the MOC model allows for the efficient early assembly of large galaxies and supermassive black holes, even at high redshift, without invoking exotic new matter components or finely tuned early dark energy sectors. At the same time, the subsequent sign change and late–time positive ρ_{Λ_m} naturally supply the repulsive component required for present–day cosmic acceleration. Thus, within a single GSE–based framework, the MOC scenario provides a unified mechanism that can both enhance early structure growth and reproduce the observed late–time acceleration, turning several apparent crises of ΛCDM into potential evidence for matter–induced dark energy.

7.4 The cosmological constant coincidence problem

A long–standing conceptual puzzle in the standard ΛCDM framework is the **Cosmological Constant Coincidence Problem** (CCCP) [3, 4, 8]: why is the dark energy density observed today of the same order of magnitude as the matter density, despite their fundamentally different origins and vastly different redshift scalings? In ΛCDM, this near equality occurs only within a narrow temporal window, requiring either fine tuned initial conditions or anthropic arguments.

In the MOC framework, this coincidence is not a problem to be explained, but a natural and inevitable consequence of the model. The dark energy density $\rho_{\Lambda_m}(t)$ does not represent an independent vacuum component, but arises dynamically from the GSE of matter itself. As a result, $\rho_{\Lambda_m}(t)$ is intrinsically linked to the matter density $\rho_m(t)$ and to the growth of the particle horizon, rather than being a fixed external constant.

Because both ρ_m and ρ_{Λ_m} originate from the same underlying matter distribution, their magnitudes remain comparable over a substantial fraction of cosmic history. This behavior is explicitly demonstrated in the SH0ES–anchored simulations (Fig. 2), where the matter density and the dark energy density track each other closely throughout the late universe, crossing and diverging only mildly as the universe transitions into and out of its accelerated phase.

From this perspective, the apparent coincidence $\rho_m \sim \rho_{\Lambda_m}$ at the present epoch is not accidental. Instead, it constitutes one of the strongest empirical signatures of a matter–induced dark energy scenario. What appears as an unnatural coincidence in ΛCDM emerges naturally in the MOC framework as a direct consequence of GSE dynamics, providing a compelling resolution of the cosmological constant coincidence problem without invoking fine tuning or anthropic reasoning.

7.5 Describes the dynamics of the universe without new free parameters or fields

The MOC framework explains the observed dark energy phenomenology without introducing any additional free parameters or exotic components. The dark energy density arises uniquely from the GSE of matter and its structural evolution, making cosmic acceleration an emergent consequence rather than an imposed assumption.

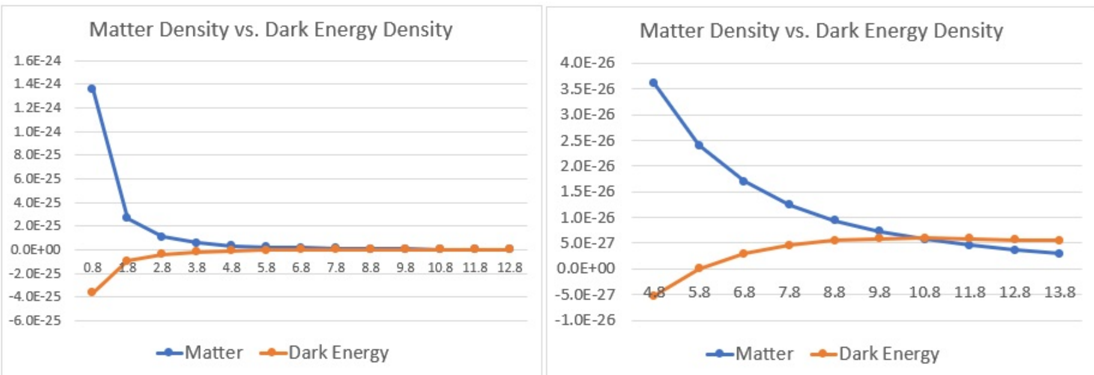

Figure 3: **MOC Cosmic History Simulation (Planck 2018 Baseline + 10% Matter Enhancement, β=1.3907 = const.):** Matter Density vs. Dark Energy Density. Dark energy density becomes negative at t< ∼ 5.8Gyr, promotes the formation of galaxy structures, then accelerates the expansion of the universe from approximately t ∼8.3 Gyr, peaks around t=10.8 Gyr, and then monotonically decreases.

The temporal variation of the structural parameter β remains modest, at the level of $\mathcal{O}(0.1)$ over the entire evolutionary history considered. **In fact, even when β is fixed to a constant value, the dark energy density exhibits the same qualitative behavior**: it is negative in the early universe, undergoes a sign transition at intermediate epochs, drives accelerated expansion in the late universe, reaches a finite maximum, and subsequently decreases monotonically.

This demonstrates that, within the MOC framework, the dark energy phenomenology is not sensitively dependent on the detailed evolution of structural parameters, but instead arises robustly from the geometric scaling of GSE.

Age (Gyr)	Scale $a(t)$	Structural β	Comoving Ho. $\chi_p(t)$ (Gly)	Physical Ho. $R_{\text{phys}}(t)$ (Gly)	**Matter** $\rho_m(t)$	Repulsive $\rho_{m-gs}(t)$	Attractive $-\rho_{gs}(t)$	**Dark Energy** $\rho_{\Lambda_m}(t)$
					(10^{-27} kg m^{-3})			
0.8	0.1295	1.3907	17.744	2.298	1360.95	126.208	-490.373	**-364.165**
1.8	0.2226	1.3907	23.496	5.230	267.964	76.399	-169.296	**-92.896**
2.8	0.2998	1.3907	27.340	8.197	109.688	57.331	-93.829	**-36.498**
3.8	0.3694	1.3907	30.335	11.206	58.636	46.449	-61.749	**-15.300**
4.8	0.4346	1.3907	32.827	14.267	36.007	39.115	-44.404	**-5.289**
5.8	0.4972	1.3907	34.975	17.390	24.047	33.661	-33.663	**-0.002**
6.8	0.5584	1.3907	36.872	20.589	16.975	29.352	-26.411	2.941
7.8	0.6190	1.3907	38.572	23.876	12.462	25.805	-21.218	4.587
8.8	0.6796	1.3907	40.113	27.261	9.417	22.807	-17.340	5.467
9.8	0.7408	1.3907	41.522	30.759	7.270	20.216	-14.345	5.872
10.8	0.8031	1.3907	42.818	34.387	5.706	17.943	-11.972	5.970
11.8	0.8668	1.3907	44.017	38.154	4.538	15.937	-10.060	5.875
12.8	0.9323	1.3907	45.129	42.074	3.647	14.153	-8.501	5.652
13.8	1.0000	1.3907	46.450	46.450	2.956	12.870	-7.298	5.574

Table 8: **MOC Cosmic History Simulation (Planck 2018 Baseline + 10% Matter Enhancement).** This table presents the cosmic evolution of energy densities under the MOC framework, assuming a 10% increase in matter density ($\Omega_m \approx 0.346$) relative to the standard Planck value. We adopt the Planck 2018 critical density ($\rho_c \approx 8.53 \times 10^{-27}$ kg/m^3) and assume that the current particle horizon matches the standard ΛCDM prediction ($p_0 = 46.45$ Gly). Under these conditions, a constant structural parameter $\beta = 1.3907$ is sufficient to satisfy the flatness condition ($\Omega_{tot} \approx 1$) and reproduce the observed dark energy density at the present epoch. The transition from deceleration to acceleration ($\rho_{\Lambda_m} > \rho_m/2$) occurs around $t \approx 7.8$–8.8 Gyr. Notably, the dark energy density peaks at $t \approx 10.8$ Gyr and subsequently declines, consistent with recent observational indications of weakening dark energy (e.g., DESI results). Finally, this simulation demonstrates the robustness of the MOC framework: even with a constant β (since structural evolution is slow after galaxy formation), this model successfully reproduces key qualitative features such as early negative energy, sign transition, and late decay without any fine-tuning.

This implies that β is not the driver of cosmic dynamics but simply the coefficient inherent to the GSE formulation, bringing the theory significantly closer to a parameter-free description of dark energy.

8 Effective Equation of State $w_{\Lambda_m}(t)$ and Key Transition Points in the MOC

8.1 Effective equation of state $w_{\Lambda_m}(t)$

In the MOC framework, the effective equation of state of matter–induced dark energy is not fixed at $w = -1$ but evolves dynamically with cosmic time. Using the updated SH0ES baseline simulation (+0% matter enhancement; Table 3), we evaluate the effective equation of state using the finite–difference estimation

$$w_{\Lambda_m}(t_i) \approx -1 - \frac{1}{3}\frac{\ln[\rho_{\Lambda_m}(t_{i+1})/\rho_{\Lambda_m}(t_i)]}{\ln[a(t_{i+1})/a(t_i)]} \tag{80}$$

Since $\rho_{\Lambda_m} < 0$ before the sign crossover, the equation of state is undefined for $t \lesssim 4.8\,$Gyr.

After the transition to positive values, $w_{\Lambda_m}(t)$ becomes meaningful and can be tracked through the subsequent evolution.

Cosmic Age (Gyr)	Estimated $w_{\Lambda_m}(t)$
5.73	≈ -2.2 (strongly phantom–like; rapid growth)
6.73	≈ -1.5
7.73	≈ -1.1
8.73	≈ -1.1
9.73	≈ -0.95
10.73	≈ -0.82
11.73	≈ -0.72
12.73	≈ -0.61

Table 9: Estimated $w_{\Lambda_m}(t)$ for the SH0ES baseline (+0% matter) model. Shortly after becoming positive at $t \approx 4.8$–5 Gyr, the dark energy density grows with a phantom–like equation of state ($w < -1$), then gradually approaches and crosses the cosmological–constant boundary ($w = -1$), and finally evolves into a quintessence–like phase ($w > -1$) in the late universe.

As summarized in Table 9, the effective equation of state is highly dynamic. Immediately after the sign change, the dark energy density increases rapidly between $t \approx 5.7$ and 7.7 Gyr, corresponding to a clearly phantom–like regime ($w < -1$). Around the epoch where $\rho_{\Lambda_m}(t)$ reaches its maximum ($t \approx 8.7$ Gyr), w_{Λ_m} remains close to, but still below, -1. Subsequently, as $\rho_{\Lambda_m}(t)$ begins to decline, the equation of state crosses the cosmological–constant boundary and moves into the quintessence regime, reaching $w \approx -0.6$ by $t = 12.73$ Gyr.

This late–time behavior naturally implies a weakening repulsive force, suggesting that the universe may be gradually exiting its phase of accelerated expansion. Such a trend is consistent with recent observational analyses indicating a possible decrease in dark energy strength [53].

8.2 Key transition points in the MOC model

Using the updated SH0ES baseline simulation, we identify two fundamental transition epochs. Transition times are obtained via linear interpolation between discrete simulation points. Importantly, the emergence of repulsive dark energy does not immediately lead to cosmic acceleration.

Transition	Definition	Interval	t (Gyr)	z	Notes
Sign Crossover	$\rho_{\Lambda_m} = 0$	4.73→5.73	≈ 4.85	≈ 1.2	Dark energy changes sign from attractive to repulsive.
Acceleration Onset	$\rho_{\Lambda_m} \approx \frac{1}{2}\rho_m$	6.73→7.73	≈ 7.25	≈ 0.6	Repulsive dark energy becomes strong enough to dominate over matter and trigger global acceleration.

Table 10: Key transition epochs for the SH0ES baseline (**+0% matter enhancement**). A characteristic feature of the MOC model is the delay between the onset of repulsive dark energy ($z \approx 1.2$) and the onset of accelerated expansion ($z \approx 0.6$). The resulting transition redshift lies within the broad range of model–independent observational estimates for the onset of cosmic acceleration.

The early negative phase ($t \lesssim 4.8$ Gyr) enhances structure formation by providing an additional gravitationally attractive contribution to the cosmic energy budget. However, the mere

Transition	Definition	Interval	t (Gyr)	z	Notes
Sign Crossover	$\rho_{\Lambda_m} = 0$	4.73→5.73	≈ 5.25	≈ 1.0	Dark energy changes sign from attractive to repulsive.
Acceleration Onset	$\rho_{\Lambda_m} \approx \frac{1}{2}\rho_m$	6.73→7.73	≈ 7.73	≈ 0.53	Repulsive dark energy becomes strong enough to compete with matter and trigger global acceleration.

Table 11: Key transition epochs for the SH0ES baseline (**+10% matter enhancement**). Compared to the baseline case, both the sign change of ρ_{Λ_m} and the onset of acceleration are shifted to slightly later times ($t \approx 5.25$ Gyr and $t \approx 7.73$ Gyr, respectively), illustrating how an increased matter content delays the onset of dark energy driven acceleration.

appearance of positive dark energy does not immediately induce cosmic acceleration. Only after the condition $\rho_{\Lambda_m} \gtrsim 0.5\rho_m$ is met at $t \approx 7.25$ Gyr does the universe transition into an accelerating phase. In the updated simulation, the dark energy density increases up to a maximum at $t \approx 8.7$ Gyr and then slowly declines, exhibiting a gradual flattening that is consistent with a slowly varying dark energy component rather than a strict cosmological constant.

The same qualitative pattern appears in the other SH0ES–based scenarios. For +10% and +20% matter enhancements, the sign crossover of ρ_{Λ_m} occurs slightly later ($t \approx 5.0$ and 5.5 Gyr, respectively), and the acceleration onset is shifted to $t \sim 7.7$–8.4 Gyr, while the peak dark energy density moves toward $t \approx 9$–9.7 Gyr (Tables 4, 6). In the −10% matter case, both the sign crossover and acceleration onset occur earlier (around $t \approx 4.5$ Gyr and $t \approx 6.6$ Gyr, respectively; Table 7), and the peak of ρ_{Λ_m} is reached near $t \approx 8.7$ Gyr. Despite these shifts, all cases exhibit the same three-phase sequence of (negative) attraction, growth to a positive maximum, and a slowly declining repulsive phase in the late universe.

9 The Future of the Universe in the MOC: Toward a Decelerating Phase and Damped Oscillatory Dynamics

In the MOC framework, the long-term fate of the universe is governed not by a fixed vacuum energy, but by the dynamical structure of the generalized GSE. Unlike ΛCDM, where dark energy is introduced as an independent constant, the MOC model treats the dark energy density as an emergent quantity determined by the interplay between physical dilution and causal structure [3,4,8]. In particular, the dark energy density depends explicitly on both the physical dilution scale R_{phys} and the causal interaction scale χ_p,

$$\rho_{\Lambda_m}(\rho_m, R_{\text{phys}}, \chi_p) = c_1 \beta \rho_m^2 \frac{R_{\text{phys}}^3}{\chi_p} \left(c_2 \beta \rho_m \frac{R_{\text{phys}}^3}{\chi_p} - 1 \right) \tag{81}$$

which follows directly from the generalized horizon formulation of the GSE densities.

The sign of cosmic acceleration is therefore determined entirely by the single combination $\rho_m(R_{\text{phys}}^3/\chi_p)$. While the matter density scales as $\rho_m \propto a^{-3}$ in an expanding FRW universe [18, 38], the physical horizon grows as $R_{\text{phys}} \propto a(t)$, whereas the particle horizon evolves more slowly, approximately as $\chi_p \propto \int da/(a^2 H)$ [35, 37]. During late-time acceleration, the Hubble parameter H approaches a slowly varying value, causing $\chi_p(t)$ to grow more slowly than $a(t)$. As a result, the combination $\rho_m(R_{\text{phys}}^3/\chi_p)$ decreases monotonically in the future, guaranteeing that the repulsive phase ($\rho_{\Lambda_m} > 0$) cannot persist indefinitely. A future transition back to $\rho_{\Lambda_m} < 0$ is therefore unavoidable.

Quantitatively, the SH0ES–anchored simulations indicate that the current repulsive phase is already past its maximum strength. Across all four matter realizations (−10%, 0%, +10%, +20%), the dark energy density $\rho_{\Lambda_m}(t)$ increases after its sign transition, reaches a broad maximum in the interval $t \simeq 8.7$–$9.7\,\mathrm{Gyr}$, and then decreases monotonically toward the present epoch ($t_0 = 12.73\,\mathrm{Gyr}$). At $z = 0$, the predicted values converge to $\rho_{\Lambda_m}(t_0) \simeq (5.3$–$6.3) \times 10^{-27}\,\mathrm{kg\,m^{-3}}$, with only weak dependence on the assumed matter enhancement, consistent with the expectation that the late-time dynamics is insensitive to detailed microphysical parameters [3, 4].

Although the present simulation window does not yet show a full turnover to negative ρ_{Λ_m}, the post-peak decline is clearly visible in all cases. This behavior implies that the effective equation of state has already crossed into the quintessence regime ($w > -1$) and is evolving away from the de Sitter limit [8]. The slowing and subsequent decrease of ρ_{Λ_m} therefore provides strong physical motivation for a near-future deceleration transition.

9.1 Self-regulation of cosmic expansion: A natural feedback cycle

A key structural feature of the MOC framework is the feedback between the expansion history and the GSE term itself, mediated by the distinct evolution of the physical horizon R_{phys} and the particle horizon χ_p. Such feedback mechanisms are generic in nonlinear gravitational systems [37, 38].

- During **accelerated expansion**, the physical horizon $R_{\mathrm{phys}}(t)$ grows rapidly, while the growth of the causal horizon $\chi_p(t)$ slows. This suppresses the factor $\rho_m(R^3_{\mathrm{phys}}/\chi_p)$ and weakens the repulsive GSE contribution. In the simulations, this behavior appears as a flattening and eventual decline of $\rho_{\Lambda_m}(t)$ following its maximum.
- During **decelerated expansion**, the growth of $R_{\mathrm{phys}}(t)$ is slower. Consequently, the quantity $\rho_m(R^3_{\mathrm{phys}}/\chi_p)$ decreases less rapidly, allowing the repulsive GSE component to re-strengthen relative to the attractive matter density and pushing ρ_{Λ_m} back toward positive values.

This feedback loop has the same qualitative structure as a **damped oscillator**: the system overshoots the neutral point ($\rho_{\Lambda_m} = 0$), but the amplitude of each excursion decreases over time as the overall energy scale continues to dilute [3, 38].

9.2 Entry into a decelerating phase in the near future

The MOC framework links the sign of cosmic acceleration directly to the factor $(c_2\beta\rho_m(R^3_{\mathrm{phys}}/\chi_p) - 1)$. As the universe accelerates, the growth of R_{phys} outpaces that of χ_p, causing this factor to decrease and the repulsive contribution to weaken. The simulations indicate that the sign transition $\rho_{\Lambda_m} = 0$ occurred in the past, at $t \simeq 4.5$–$8.7\,\mathrm{Gyr}$ depending on the matter content, and that all models subsequently exhibit a finite maximum of ρ_{Λ_m} followed by a gradual decline.

We therefore predict that the universe is likely to enter a new decelerating expansion phase within the next few billion years, as $\rho_{\Lambda_m}(t)$ continues to decrease from its post-peak values.

This prediction is reinforced by the inevitable decline of the quantity $\rho_m(R^3_{\mathrm{phys}}/\chi_p)$ and by the intrinsic feedback between the expansion history and the GSE term, which drives the system toward another dynamical transition [18, 37].

9.3 Long-term behavior: Damped oscillatory evolution

Because ρ_{Λ_m} depends on the monotonically decreasing quantity $\rho_m(R_{\rm phys}^3/\chi_p)$, future sign changes of the GSE term are unavoidable, leading naturally to alternating phases of acceleration and deceleration. As the matter density continues to dilute, each successive cycle exhibits decreasing amplitude and increasing period, characteristic of a damped dynamical system [3,38]. The universe therefore evolves toward a **damped, slowly varying expansion**, rather than eternal acceleration or ultimate recollapse. Future high-precision measurements of $w(a)$ and its time dependence (e.g., LSST, DESI, Euclid) will provide direct observational tests of the predicted near-future deceleration and the broader oscillatory behavior implied by the GSE dynamics.

10 A Unified Physical Origin for Cosmic Acceleration

The standard ΛCDM model treats primordial inflation and late-time acceleration as disconnected phenomena, typically driven by independent scalar fields [58–62]. The GSE framework in MOC unifies both via a single, intuitive principle. The dark energy density arises from the total GSE of the contents of the causal horizon, expressed elegantly in terms of its compactness ratio.

$$\rho_{\Lambda_m} = \rho_{m-gs} - \rho_{gs} \sim \frac{3\beta}{4\pi}\frac{GM^2}{c^2\chi_p R_{\rm phys}^3}\left(\frac{5\beta}{14}\frac{R_S}{\chi_p} - 1\right) \tag{82}$$

where M is the mass within the causal patch. In the general GSE framework, this single equation reveals a fundamental **Density-Scale Duality**: repulsive gravity ($\rho_{\Lambda_m} > 0$) is driven by extreme density at small scales (inflation) and by extreme scale geometric factors at low densities (dark energy).

10.1 Inflation: Acceleration at extreme density

We quantify the dark energy density at the Planck epoch. In the radiation-dominated early universe, the causal scale χ_p and the physical scale $R_{\rm phys}$ are tightly coupled and comparable ($R_{\rm phys} \approx \chi_p \approx l_{\rm pl}$). The MOC expression reads.

$$\rho_{\Lambda_m} = \frac{3\beta}{4\pi}\frac{GM^2}{c^2R^4}\left(\frac{5\beta}{14}\frac{R_S}{R} - 1\right), \qquad M = \frac{4}{3}\pi R^3\rho_r, \quad R_S = \frac{2GM}{c^2}. \tag{83}$$

We take $\rho_r \simeq \rho_{\rm pl}$, $R \simeq l_{\rm pl}$. Since the early universe is expected to be extremely dense and highly structured in terms of quantum fluctuations, we assume a structural parameter close to its upper bound, $\beta \simeq 2$.

The mass-density relation gives

$$\frac{GM^2}{c^2R^4} = \frac{16\pi^2}{9}\rho_{\rm pl} \approx 17.55\,\rho_{\rm pl} \tag{84}$$

Using the compactness ratio at the Planck scale.

$$\frac{R_S}{R} = \frac{8\pi G\rho_{\rm pl}l_{\rm pl}^2}{3c^2} = \frac{8\pi}{3} \approx 8.38 \tag{85}$$

Therefore, substituting these into the MOC expression.

$$\rho_{\Lambda_m} \approx \frac{3\beta}{4\pi}(17.55\rho_{pl})\left(\frac{5\beta}{14}\frac{8\pi}{3} - 1\right) \tag{86}$$

With $\beta \simeq 2$, the term in the parentheses becomes roughly 5.28, yielding

$$\rho_{\Lambda_m} \approx \frac{3(2)}{4\pi}(17.55\rho_{pl})(5.28) \approx 41.8\rho_{pl} \tag{87}$$

Assuming an equation of state $w \approx -1$ for this dark energy component, the acceleration equation becomes

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_r - 2\rho_{\Lambda_m}) \approx -\frac{4\pi G}{3}(\rho_{pl} - 83.6\rho_{pl}) > 0 \tag{88}$$

This strongly negative effective density results in a powerful accelerated expansion, solving the horizon and flatness problems naturally.

Energy Density & Hierarchy With $\rho_{\text{pl}} \simeq 5.16 \times 10^{96}\,\text{kg/m}^3$, the calculated dark energy density is

$$\rho_{\Lambda_m} \approx 2.16 \times 10^{98}\,\text{kg/m}^3 \tag{89}$$

$$E_{\Lambda_m} = \rho_{\Lambda_m} c^2 \approx 1.94 \times 10^{115}\,\text{J/m}^3 \tag{90}$$

$$E_{\Lambda_m}^{(\text{Planck})} \sim 10^{115}\ \text{J/m}^3 \tag{91}$$

which naturally matches the canonical "Planck vacuum" magnitude required for inflation.

Using the observed late-time dark energy density $\rho_{\Lambda\text{-obs}} \simeq 7 \times 10^{-27}\,\text{kg/m}^3$ (i.e., $E_{\Lambda\text{-obs}} \simeq 6 \times 10^{-10}\,\text{J/m}^3$),

$$\frac{\rho_{\Lambda_m}^{(\text{Planck})}}{\rho_{\Lambda\text{-obs}}} \approx \frac{2.16 \times 10^{98}}{7 \times 10^{-27}} \simeq 3 \times 10^{124} \tag{92}$$

Equivalently $E_{\Lambda_m}^{(\text{Planck})}/E_{\Lambda\text{-obs}} \sim 10^{124}$. Thus, MOC naturally attains the colossal inflationary scale while explaining the late-time tiny value through the same density–size GSE mechanism, without fine-tuning or new fields.

10.2 The self-terminating mechanism of MOC inflation

One of the persistent challenges in standard inflationary cosmology is the "reheating problem [63, 64]." In the standard scenario, the universe undergoes an exponential expansion of at least 10^{26} (often much larger, e.g., e^{60}), causing the temperature to plummet to near absolute zero ($T \propto 1/a$). To recover the hot Big Bang conditions required for nucleosynthesis, an ad-hoc mechanism is introduced where the inflaton field decays into standard model particles, "reheating" the universe. This process involves complex microphysics and fine-tuning that remains poorly understood.

The MOC framework offers a fundamental resolution to this issue. In MOC, the inflationary phase is not driven by an external scalar field but by the total GSE of the matter itself. Consequently, the end of inflation is not a triggered decay event but a natural, built-in consequence of the expansion dynamics.

The mechanism for this graceful exit is embedded within the term that determines the sign of the matter-induced dark energy density. Let us re-examine the core term from Eq. (29).

$$\Gamma(R) \equiv \left(\frac{5\beta}{14}\frac{R_S}{R} - 1\right) = \left(\frac{5\beta}{14}\frac{2GM}{c^2 R} - 1\right) \tag{93}$$

Substituting the mass-density relation $M = \frac{4}{3}\pi R^3 \rho$, this term reveals its explicit dependence on the scale R and density ρ.

$$\Gamma(R) = \left(\frac{5\beta}{14}\frac{8\pi G\rho R^2}{3c^2} - 1\right) \approx \left(\frac{20\pi\beta G\rho R^2}{21c^2} - 1\right) \tag{94}$$

Inflation begins at the Planck epoch when extreme density makes this term positive and large ($\Gamma > 0$), generating a powerful repulsive force. During this initial phase, the universe is radiation-dominated, meaning its energy density scales with the size of the causal patch R as $\rho \propto R^{-4}$. Substituting this scaling relation $\rho(R) = \rho_P (R_P/R)^4$ into the equation reveals the inherent evolution of the acceleration driver.

$$\Gamma(R) \approx \left(\frac{20\pi\beta G}{21c^2} \left(\rho_P R_P^4\right) \frac{1}{R^2} - 1 \right) = \left(\frac{C}{R^2} - 1 \right) \tag{95}$$

where C is a positive constant determined by initial conditions.

This result is profound. It demonstrates that the very act of inflationary expansion, which causes R to grow, is precisely what drives the universe toward the end of inflation. As R increases, the term proportional to R^{-2} inevitably plummets. It will inexorably cross the critical point where the term equals 1, causing the entire expression to become zero. An infinitesimal moment later, it becomes negative.

This flips the sign of ρ_{Λ_m} from positive (repulsive) to negative (attractive), automatically terminating the inflationary epoch.

10.3 A solution to the Reheating Problem

Because MOC inflation terminates automatically via this geometric mechanism, there is no need for a separate reheating phase. Standard inflation cools the universe to $T \sim 0$ K because the expansion factor is excessive (often $> 10^{50}$) to solve the horizon and flatness problems [59, 60]. To recover the standard Big Bang conditions, an ad-hoc reheating phase is required, where the inflaton energy decays into standard model particles [63, 64].

In contrast, MOC inflation is a power-law expansion driven by ρ_{Λ_m}, which naturally bridges the gap between the Planck scale and the Big Bang Nucleosynthesis (BBN) scale without over-expansion. The MOC framework posits that the universe begins in a hot, dense state ($T \approx T_P$) within a causal patch and expands adiabatically.

A simple adiabatic estimate confirms that the natural cooling from the Planck epoch aligns with the requirements for BBN. To transition from the Planck temperature ($T_P \sim 10^{32}$ K) to the BBN temperature ($T_{BBN} \sim 10^9$ K), the universe must expand by a factor of roughly $T_P/T_{BBN} \approx 10^{23}$.

$$\frac{T_P}{T_{BBN}} \approx 10^{23} \quad \Longrightarrow \quad \frac{\rho_P}{\rho_{BBN}} \approx \left(\frac{T_P}{T_{BBN}} \right)^4 \approx (10^{23})^4 = 10^{92} \tag{96}$$

This matches the density drop from the Planck density ($\sim 10^{96}$ kg/m^3) to the BBN density ($\sim 10^5$ kg/m^3).

In MOC, the universe expands adiabatically from the Planck epoch. The "inflation" is simply the early, rapid phase of this single, continuous expansion history. The universe remains hot throughout the process, cooling naturally from 10^{32} K to 10^9 K. Thus, the "hot Big Bang" is not a result of reheating; it is the direct continuation of the hot initial state [65]. The MOC model's core equations contain both the accelerator and the brake, inextricably linked, ensuring a seamless transition from the quantum gravity era to the standard radiation-dominated universe.

10.4 Dark Energy: Acceleration at extreme scale

In the late matter-dominated era, the same unified equation governs the dynamics, but the physics is now driven by extreme scale rather than extreme density. In the general GSE framework, the critical ratio's dependency becomes

$$\frac{5\beta}{14}\frac{R_S(t)}{\chi_p(t)} \propto \beta(t)\rho_m(t)\frac{R_{\text{phys}}(t)^3}{\chi_p(t)} \tag{97}$$

Here, a fascinating competition unfolds. The matter density $\rho_m(t)$ decays as $a(t)^{-3}$, while the duallscale factor R^3_{phys}/χ_p grows. Our simulations confirm that after an initial period of attraction, the growth of the scale factor eventually overwhelms the density decay, pushing the effective compactness term past the threshold. This transition marks the birth of late-time cosmic acceleration. The observed quasi-constant value of dark energy is thus interpreted as a dynamic equilibrium where the product $\beta\rho_m(R^3_{\text{phys}}/\chi_p)$ evolves to maintain a small positive net repulsion.

10.5 Two accelerations, one physical origin

The GSE framework unifies primordial inflation (high-density repulsion at $R \sim l_{\text{pl}}$) and late-time dark energy (large-scale repulsion at $R \sim 43$ Gly) through a single physical principle expressed in one equation. This density-scale duality naturally explains the observed 10^{124} hierarchy between the Planck-scale and present-day dark energy densities without fine-tuning. The colossal energy of the early vacuum and the minuscule energy of the present vacuum are simply two different manifestations of total GSE, evaluated at the two extreme ends of cosmic history. Unlike other unified models [66], MOC requires no new fields or modifications to gravity, providing a falsifiable, matter-only solution grounded in General Relativity.

10.6 Cyclic dynamics of dark energy: Beyond a single transition

In the standard ΛCDM model, the universe undergoes a single transition from deceleration to acceleration at $z \approx 0.6$. However, the MOC framework suggests a more complex and dynamic evolutionary history. The sign and magnitude of the dark energy density ρ_{Λ_m} are determined by the competition between the gravitational binding energy (attractive) and the repulsive self-interaction, governed by the critical term.

$$\Gamma(t) \propto \beta(t)\rho_m(t)\frac{R_{\text{phys}}(t)^3}{\chi_p(t)} - 1 \tag{98}$$

Here, ρ_m decays while the geometric term grows. This interplay suggests that $\Gamma(t)$ exhibits oscillatory behavior, similar to a damped oscillator.

Specifically, our model allows for the possibility that the universe has experienced multiple phases of acceleration and deceleration, rather than a single late-time transition. This "ringing" of the total GSE field implies that the cosmic expansion history might be characterized by a series of damped acceleration-deceleration cycles, **with the duration of each phase naturally increasing as the universe expands and the cosmic density dilutes.**

Such a scenario implies that the rapid oscillation in the high-density early universe corresponds to the brief inflationary epoch, while the lengthened cycle in the low-density late universe corresponds to the current prolonged era of cosmic acceleration. This dynamic evolution could leave distinct imprints on the primordial power spectrum or the distribution of large-scale structures, offering a potential resolution to current tensions in cosmological data (e.g., H_0 and S_8 tensions) through a non-monotonic expansion history [67].

Future work will focus on performing detailed numerical simulations to constrain the parameters of this oscillatory behavior and testing these predictions against high-precision data from upcoming surveys like DESI and Euclid.

11 Resolution of the Black Hole Singularity in MOC

One of the most profound challenges in modern physics is the singularity predicted to exist at the heart of a black hole [41, 42, 68]. MOC offers a novel and consistent resolution to this problem. Here, we extend the GSE framework from the cosmos to the core of a collapsing star, demonstrating that the same physical principle that drives cosmic acceleration naturally averts the formation of a singularity.

11.1 Gravitational dynamics in a collapsing object

While the Tolman-Oppenheimer-Volkoff (TOV) equation describes static stellar structures [30, 31], the dynamic collapse within a black hole's event horizon is more fundamentally described by the Friedmann equations. Unlike the TOV framework, which assumes hydrostatic equilibrium, the Friedmann equations govern general dynamical systems of expanding or contracting mass distributions without requiring static stability. Indeed, the seminal work by Oppenheimer and Snyder demonstrated that the interior of a collapsing sphere is mathematically equivalent to a time-reversed Friedmann universe [31]. Therefore, we adopt the Friedmann acceleration equation as the primary tool to analyze the collapse dynamics, determining whether the infalling matter accelerates toward a singularity or decelerates into a stable core.

Unlike the expanding universe where the effective mass depends on the evolving particle horizon, a collapsing star is a localized system residing well within the cosmic causal limit ($R \ll \chi_p$). In this compact regime, the entire mass of the object is causally connected and fully participates in the gravitational self-interaction. Consequently, the distinction between the interaction scale and the dilution scale that was essential on cosmological scales becomes irrelevant here: both are effectively set by the local radius R of the collapsing object.

$$\rho_T + 3P_T \approx \rho_m - 2\rho_{\Lambda_m} \tag{99}$$

The sign of this term dictates the net gravitational force. To analyze it, we use the GSE-derived expression for ρ_{Λ_m} specialized to a compact object of radius R,

$$\rho_{\Lambda_m}(M,R) = \frac{3\beta}{4\pi}\frac{GM^2}{c^2R^4}\left(\frac{5\beta}{14}\frac{R_S}{R} - 1\right) \tag{100}$$

11.2 The critical threshold and the emergence of repulsion

Equation (100) reveals a critical threshold in the dynamics of gravitational collapse, determined by the ratio of the object's radius R to its Schwarzschild radius R_S. The crossover point occurs when the term in the parentheses vanishes.

$$\frac{5\beta}{14}\frac{R_S}{R} - 1 = 0 \quad \Rightarrow \quad R_{critical} = \frac{5\beta}{14}R_S \tag{101}$$

Given that a collapsing core is a high-density environment similar to the early universe, we adopt a structural parameter value of $\beta \approx 1.5$. This value is consistent with our cosmological simulations for high-density epochs (e.g., CMB epoch). In this regime, the critical radius becomes $R_{critical} \approx \frac{7.5}{14}R_S \approx 0.54R_S$.

- **Phase 1: Accelerated collapse ($R > R_{critical}$)**
  For a collapsing object with $R > R_{critical}$, the bracketed term is negative, making $\rho_{\Lambda_m} < 0$. This means the dark energy acts as an attractive force, enhancing gravity. Thus, in the MOC framework, the initial stages of black hole formation are more rapid and violent than predicted by standard gravity.

- **Phase 2: The repulsive transition** ($R = R_{critical}$)
  At the specific radius $R \approx 0.54 R_S$ (assuming $\beta \approx 1.5$), the dark energy density vanishes. This marks the boundary between the attractive exterior and the repulsive interior.

- **Phase 3: The repulsive core** ($R < R_{critical}$)
  As the collapse proceeds past this critical radius, ρ_{Λ_m} flips sign and becomes positive. The active gravitational source term now contains a powerful repulsive component. The repulsive force, scaling as R^{-5} (dominated by the R_S/R term), grows catastrophically faster than the attractive force of matter (R^{-3}). This mismatch ensures that no matter how massive the collapsing object is, the repulsion will inevitably overwhelm the attraction at a small but finite radius. A singularity, which requires attraction to dominate down to $R = 0$, is therefore fundamentally forbidden in this framework. The collapse halts, forming a stable, **non-singular black hole core** within the horizon, thereby resolving the information loss paradox and preventing the breakdown of spacetime physics.

11.3 The equilibrium point: A singularity averted

The collapse is halted when the net gravitational force on the collapsing matter becomes zero. For simplicity, we can approximate the equilibrium condition using the general relativistic constraint for accelerated expansion, $\rho_m + \rho_{\Lambda_m} + 3P_{\Lambda_m} = 0$. Using the approximation $w_{\Lambda_m} \approx -1$ for the GSE component, this simplifies to $\rho_m \approx 2\rho_{\Lambda_m}$.

We can now solve for the equilibrium radius, R_{eq}. Substituting the expressions for ρ_m and our GSE-derived ρ_{Λ_m} (Eq. 100), we derive a quadratic equation for the dimensionless variable $X = R_S/R$.

$$\frac{5\beta^2}{14} X^2 - \beta X - 1 = 0 \tag{102}$$

Solving for the positive root gives the equilibrium ratio.

$$\frac{R_S}{R_{\text{eq}}} = \frac{14\beta + \sqrt{196\beta^2 + 280\beta^2}}{10\beta^2} = \frac{7 + \sqrt{119}}{5\beta} \tag{103}$$

Therefore, the equilibrium radius is

$$R_{\text{eq}} = \left(\frac{5\beta}{7 + \sqrt{119}} \right) R_S \approx 0.28 \beta R_S \tag{104}$$

Assuming $\beta \approx 1.5$ for the high-density core environment, we find

$$R_{\text{eq}} \approx 0.42 R_S \tag{105}$$

The collapse is thus stabilized at a finite radius of approximately $0.42 R_S$, well inside the event horizon but long before the Planck scale. For a stellar black hole of 3 solar masses ($R_S \approx 9$ km), our model predicts its core would stabilize at a macroscopic equilibrium radius of $R_{\text{eq}} \approx 3.8$ km. **This demonstrates that the singularity is resolved not at the mysterious Planck scale, but at a concrete, astrophysical scale through classical GSE dynamics alone.**

11.4 Observational validation: The cosmic connection

Crucially, the existence of the repulsive force required to prevent a singularity is contingent upon the condition $w_{\Lambda_m} < -1/3$. This condition is identical to the requirement for dark energy to drive cosmic acceleration in the second Friedmann equation [1, 2, 53, 62].

The fact that our universe is currently undergoing accelerated expansion is an established observational reality [1,2]. This observation serves as empirical proof that the dominant energy component of the universe (identified in the MOC framework as GSE) satisfies the condition $w_{\Lambda_m} < -1/3$. Furthermore, current cosmological constraints suggest $w \approx -1$, which provides an even stronger repulsive effect than the minimum requirement [62].

Because the physics of total GSE is scale-invariant in our framework, the same equation of state that governs the cosmos must also govern the interior of black holes. Therefore, the observational confirmation of cosmic acceleration directly implies that the interior of a black hole possesses the necessary physical properties to generate a repulsive core. In MOC, the accelerating universe and the non-singular black hole are two sides of the same coin, unified by the physics of total GSE.

11.5 A singularity-free core and the Information Paradox

The MOC framework naturally resolves the black hole singularity. Instead of a point of infinite density, the model predicts a dynamically stabilized core of finite, macroscopic size at the heart of the black hole. As matter collapses past the critical repulsive transition radius ($R \approx 0.54R_S$), the powerful repulsive force generated by the positive ρ_{Λ_m} grows until it precisely counterbalances the attractive force of matter at $R_{eq} \approx 0.42R_S$, creating a stable equilibrium structure.

By replacing the singularity with a stable, physical structure, this model offers a compelling resolution to the black hole information paradox [68–70]. The paradox arises because the destruction of information at a singularity violates the fundamental principle of unitarity in quantum mechanics. In our model, this conflict is entirely avoided. Information falling into the black hole is not destroyed; it is encoded in the physical state of this **non-singular black hole core**.

Because causality is preserved within this finite, macroscopic structure, the principles of quantum mechanics remain intact throughout the black hole's life and eventual evaporation. The information can, in principle, be returned to the universe as the black hole radiates away its mass via Hawking radiation, ensuring that the process is unitary. MOC thus provides a classical, matter-only mechanism that removes one of the deepest paradoxes in modern physics, offering a complete and self-consistent picture of a black hole from its event horizon to its very core.

12 Observational Tests and Falsifiability of MOC

12.1 Test 1: The sign-switch of dark energy

Prediction. A universal prediction of the MOC framework is that the dark energy was negative (attractive) in the early universe. Using the updated SH0ES-based simulations (Tables 7–6), the transition to positive values occurs in the range

$$t_{\text{crit}} \approx 4.5\text{–}5.5\ \text{Gyr}, \qquad z_{\text{crit}} \approx 1.0\text{–}1.2,$$

depending on the assumed matter enhancement scenario. This contrasts sharply with the ΛCDM expectation of a strictly positive and constant ρ_Λ at all redshifts.

Test. This prediction can be tested through model-independent reconstructions of $H(z)$ and $\rho_{\text{DE}}(z)$ using supernovae (Pantheon+), BAO, and cosmic chronometers [12,71,72]. MOC would be falsified if future data from DESI, Euclid, or LSST show with high confidence that $\rho_{\text{DE}}(z)$ has been strictly positive for all epochs $z \lesssim 1.5$ (corresponding to cosmic times $t \gtrsim 4$ Gyr), with no indication of an earlier attractive phase.

12.2 Test 2: Enhanced early structure growth

Prediction. Because ρ_{Λ_m} is negative for all $t \lesssim 4.5$–5.5 Gyr (i.e., $z \gtrsim 1.0$), the early universe experiences an additional attractive contribution to the energy budget. This should enhance the growth of density perturbations and produce a measurably larger value of the growth-rate observable $f\sigma_8(z)$ at intermediate and high redshifts relative to ΛCDM.

Test. Measurements of $f\sigma_8(z)$ from RSD [51, 52] and weak-lensing surveys provide a direct probe of this prediction [73]. If high-redshift data ($z \gtrsim 1.0$) from DESI or Euclid find a growth history fully consistent with, or weaker than, the ΛCDM expectation [56], the MOC prediction of an early attractive phase would be strongly disfavored.

12.3 Test 3: The post–crossover evolution of ρ_{Λ_m}

Prediction. In all updated SH0ES-based simulations, $\rho_{\Lambda_m}(t)$ exhibits a rapid increase immediately after the sign-switch, reaches a peak in the range $t \approx 8$–10 Gyr (depending on the matter enhancement scenario), and subsequently shows a gradual decline toward the present epoch. This "rise-and-fall" behavior is a direct consequence of the General GSE form,

$$\rho_{\Lambda_m} \propto c_1\beta(t)\rho_m(t)^2\frac{R_{\text{phys}}(t)^3}{\chi_p(t)}\left(c_2\beta(t)\rho_m(t)\frac{R_{\text{phys}}(t)^3}{\chi_p(t)} - 1\right)$$

which naturally produces a maximum when the accelerated growth of the physical volume $R_{\text{phys}}(t)^3$ is eventually counterbalanced by the combined effects of matter dilution $\rho_m(t)$ and the slower growth of the causal horizon $\chi_p(t)$. Thus MOC predicts a *dynamic dark energy density*, distinct from the constant ρ_Λ of ΛCDM or the simple monotonic models of quintessence [3, 62].

Test. Reconstruction of $\rho_{\text{DE}}(z)$ using SNe, BAO, and cosmic chronometers can reveal whether dark energy flattens or begins to weaken at late times ($z \lesssim 0.5$) [72]. MOC would be falsified if the reconstructed $\rho_{\text{DE}}(z)$ shows a strictly monotonic increase for all $z \lesssim 1.0$ with no sign of flattening or turnover, or if it remains exactly constant to high precision across the entire redshift range. Conversely, any detected late-time evolution of dark energy density (i.e., $w > -1$ at low z), as tentatively suggested by recent Dark Energy Survey (DES) [13] and Dark Energy Spectroscopic Instrument (DESI) analyses [12], would strongly support the MOC scenario.

12.4 Test 4: Infinite falsifiability from explicit functional origin

The Prediction: Unlike phenomenological dark energy models, MOC provides a fully explicit functional origin for the dark energy density ρ_{Λ_m}, specifying its dependence on cosmic variables (e.g., ρ_m, R, β) in analytic form. This functional transparency makes the model, in principle, infinitely falsifiable: any discrepancy in the detailed time/redshift evolution, scale dependence, or internal parameter relationships can serve as a direct test of the theory.

The Test: The analytical form of $\rho_{\Lambda_m}(t)$ is known, enabling comprehensive comparisons with high-precision observations for all detailed properties of functional evolution, as well as global features (sign conversion, peak, decline). Future advances in reconstructing the cosmic expansion history, horizon scale, and matter density (from DESI, Euclid, JWST, SKA, and beyond) will allow an unlimited number of new, specific tests of the model. This falsifiability, made possible by MOC's explicit predictive formalism, sets it apart from existing approaches and provides a transparent link between theory and observation.

13 Discussion

In this work, we have presented a mechanism where the GSE of the matter mimics the effects of dark energy. While our primary analysis focused on the β-normalized model (where the interaction term scales with β^2), it is crucial to examine the robustness of this result against alternative choices of interaction coefficients and to address current observational uncertainties.

13.1 Role of the structural parameter β and model robustness

In deriving the interaction energy between the matter distribution and the equivalen negative mass of GSE, we introduced the structural parameter β not as a dynamic driver, but as a necessary geometric coefficient to describe the physical state of matter. Since the cosmic matter distribution is neither perfectly uniform nor static, the calculation of the GSE within any given shell inherently depends on this structural descriptor, defined via $U_{gs}(r) = -\beta GM(r)^2/r$. This single parameter naturally encompasses the geometric distribution of mass, from $\beta \approx 2.0$ for uniform spheres to lower values ($\beta \approx 1.0$) for virialized cluster structures.

Our simulations demonstrate that once galaxy-scale structures have formed ($t \gtrsim 1\,\mathrm{Gyr}$), the evolution of β becomes very slow, effectively acting as a quasi-constant coefficient for the remainder of cosmic history. This implies that the specific time-evolution of $\beta(t)$ is not critical for the emergence of cosmic acceleration; rather, β primarily sets the overall normalization of the GSE interaction strength.

Consequently, the choice of how the interaction term scales with β (e.g., linear β vs. quadratic β^2) becomes a question of matching the effective coupling strength to the assumed background matter density. In our β^2–scaled formulation, which propagates the structural information consistently, the SH0ES–based MOC solutions with matter enhancements of $\{-10\%, 0\%, +10\%, +20\%\}$ yield present-epoch coefficients in the range

$$\beta(t_0) \simeq 1.145\ (+20\%\ \text{model}),\ 1.301\ (+10\%\ \text{model}),\ 1.495\ (0\%\ \text{model}),\ 1.743\ (-10\%\ \text{model}),$$

all comfortably within the theoretically motivated range for virialized cosmic structures ($\beta \approx 1.0$–2.0).

By contrast, adopting a linear scaling (replacing β^2 with β) would require a much larger coefficient, $\beta \simeq 7.37$, to reproduce the observed acceleration given the current SH0ES baseline ($\Omega_m = 0.315$). This suggests that the linear model would only be viable if the true cosmic matter density were significantly higher ($\Omega_m \gtrsim 0.35$), in which case the required β would fall back into the physically standard range ($\beta \sim 1$–2). Therefore, if future observations become more precise and demonstrate a significant increase in the cosmic matter density, the linear model may also be considered as a viable alternative.

13.2 Observational uncertainties and future constraints

First, there is a significant tension in the value of Ω_m across different dataset combinations. As highlighted in recent analyses [53], the inferred matter density can vary substantially, from $\Omega_m \approx 0.21$ to $\Omega_m \approx 0.36$, depending on whether SN Ia age-bias corrections are applied and which probes (CMB, BAO, SNe) are combined. Because the structural parameter β is defined through the matter distribution, this observational scatter in Ω_m directly propagates into an uncertainty range for β. The four SH0ES–anchored MOC simulations with matter modifications of $\{-10\%, 0\%, +10\%, +20\%\}$ demonstrate the resulting values of $\beta(t_0)$ as Ω_m varies. In all of these scenarios, however, $\beta(t)$ remains quasi-constant after the epoch of early structure formation, and the MOC model continues to reproduce the observed expansion history even under substantial matter-enhancement variations.

Second, and perhaps more fundamentally, nearly all existing cosmological datasets are reduced and calibrated under the assumption of the standard ΛCDM model. There is currently no comprehensive dataset processed specifically within the context of the MOC. Since the MOC model fundamentally reinterprets the source of cosmic acceleration as a GSE effect rather than a vacuum energy, it may require a re-analysis of raw observational data to be fully self-consistent.

As the MOC framework is in its initial stage, we anticipate that future studies, building dedicated datasets and likelihoods grounded in this alternative paradigm, will be able to break these degeneracies. Once such datasets are established, the MOC framework can be subjected to more stringent observational tests, allowing its viability as an alternative to ΛCDM to be assessed more conclusively.

14 Conclusion: A Unified Cosmology from Total Gravitational Self-Energy

The standard cosmology model treats inflation and late-time acceleration as disconnected phenomena, typically driven by independent scalar fields [58–62]. The Gravitational Self-Energy (GSE) framework in Matter-Only Cosmology (MOC) unifies both via a single, intuitive principle. The matter-induced dark energy density arises from the total GSE of the contents of the causal horizon. In the general General GSE framework, this is expressed as:

$$\rho_{\Lambda_m} = \frac{3\beta}{4\pi} \frac{GM^2}{c^2 \chi_p R_{\text{phys}}^3} \left(\frac{5\beta}{14} \frac{R_S}{\chi_p} - 1 \right) \tag{106}$$

where R_{phys} is the physical radius of dilution and χ_p is the causal interaction scale. This single equation reveals a fundamental **Density-Scale Duality**: repulsive gravity ($\rho_{\Lambda_m} > 0$) is driven by extreme density at small scales (inflation) and by the extreme growth of the physical scale relative to the causal horizon at low densities (dark energy).

In essence, the dynamical interactions governed by this single GSE principle determine the entire history of cosmic expansion, from the ignition and graceful escape of inflation, to the long epoch of deceleration, to the acceleration phase we observe today, and potentially to a future era of damped oscillatory stability.

By rigorously accounting for the **GSE of matter and its contribution to the source of gravity**, MOC offers a more complete, self-consistent, and physically motivated description of our universe. It replaces a series of disconnected puzzles with a unified framework and provides a rich set of falsifiable predictions. The road ahead is clear: to put this model to the test against the wealth of forthcoming observational data. The journey into the dark sector may not require new particles or new forces, but a return to a deeper understanding of the gravity we thought we knew so well.

Finally, the universality of the GSE principle suggests implications beyond cosmology. Furthermore, the validity of this self-energy principle is not confined to the macroscopic cosmos. When applied to the microscopic realm, the source renormalization mechanism ($M \to M_{eq}$) inherently suppresses the gravitational interaction strength near the Planck scale. This suggests that the same framework resolving cosmic singularity may also eliminate ultraviolet divergences (UV completion), offering a unified pathway toward the long-sought and definitive "**Completion of Quantum Gravity**" [43,74].

Puzzle	MOC's Resolution	Key Prediction / Feature
Dark Energy	Replaced the static Λ with a dynamic $\rho_{\Lambda_m}(t)$ born from the GSE of matter.	Predicts a dynamic life cycle: **early negative energy (attractive)**, current positive energy (repulsive), and a future return to deceleration due to the evolving horizon ratio.
Hubble Tension	Reframed as a measurement of the evolving cosmic structure, encapsulated in a time-varying structural parameter, $\beta(t)$.	Naturally explains why CMB ($z \sim 1100$) and local ($z \sim 0$) measurements of H_0 differ, as they probe different epochs with different β values.
Unification of Inflation & Dark Energy	The same GSE mechanism drives both **inflation (high-density repulsion)** and **late-time acceleration (large-scale repulsion)**.	Naturally explains the 10^{124} energy scale hierarchy between the two epochs via the evolution of $\rho_m(R^3_{\text{phys}}/\chi_p)$.
Cosmic Fate	**Dynamics governed by the competition between matter dilution and horizon growth.**	Predicts a **damped oscillatory evolution**, preventing eternal acceleration and leading to a stabilized, slowly varying expansion.

Table 12: Summary of cosmological puzzles resolved by MOC. The simulations demonstrate the robustness of these predictions, including the inevitable transition to a future decelerating phase.

A Appendix A: A Re-examination of the Energy Components of a Gravitating System

Theoretical motivation

In this paper, we have developed a cosmological model based on a fundamental principle of General Relativity: *all forms of energy, including gravitational potential energy itself, must act as sources of gravity [17, 18].* Standard cosmological models typically treat the mass density ρ_m as the sole source of gravity, implicitly assuming that the self-energy of the system is negligible or already incorporated. However, on cosmological scales, the GSE of the universe becomes significant and cannot be ignored.

We argue that the process of assembling mass M naturally induces a negative GSE component ($-M_{gs}$) and, consequently, a mutual interaction energy ($+M_{m-gs}$) between the mass and its own field. This appendix introduces an approach that explicitly demonstrates that the ρ_{m-gs} term derived from the GSE mechanism is an interaction term between the matter and equivalent mass of GSE.

$$\rho_{\Lambda_m} = \rho_{m-gs} - \rho_{gs} = \frac{3\beta}{4\pi}\frac{GM^2}{c^2R^4}\left(\frac{5\beta}{14}\frac{R_S}{R} - 1\right) \tag{107}$$

Here, the term $-\rho_{gs}$ represents the traditional negative GSE density, while ρ_{m-gs} represents the positive gravitational energy density arising from the coupling between the matter M and the equivalent mass of its self-energy, $-M_{gs}$. This decomposition reveals that what we observe as "dark energy" is not an exotic addition, but an intrinsic property of a self-gravitating system.

A.1 In a gravitational system, the total energy components of the system

In conventional energy accounting of a physical system, it is typically assumed that all forms of energy are implicitly incorporated into an equivalent-mass representation. However, a more careful examination reveals that a dynamical system composed of mass distribution is not a simple single-body system. Instead, it is effectively a composite system that includes an additional negative equivalent mass, $-M_{gs}$, arising from the system's own gravitational potential energy.

A crucial physical effect arises here: when two distinct energy components coexist, there necessarily appears a mutual gravitational interaction term U_{m-gs}.

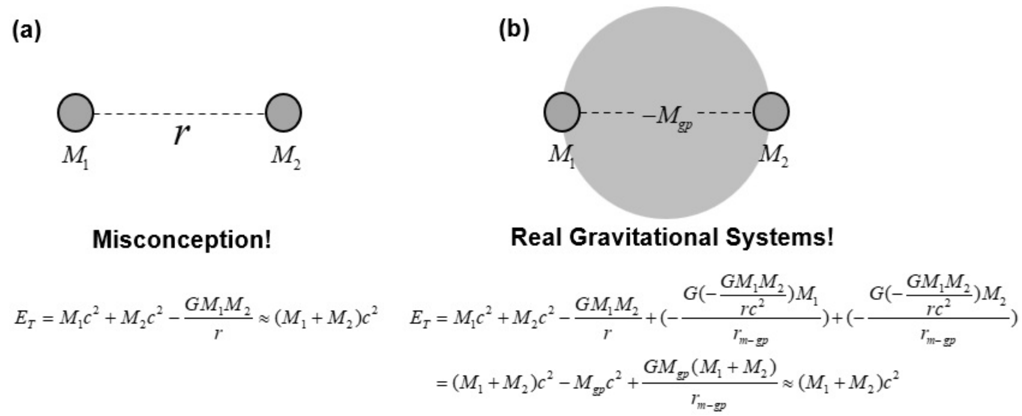

Figure 4: Conceptual diagram illustrating the composite nature of a gravitating system. The system consists of the free mass M_{fr} and the negative equivalent mass of its GSE, $-M_{gs}$. This configuration necessitates an interaction energy term U_{m-gs}, which manifests as a positive energy density.

The total mass-energy of the system is thus

$$M_T \approx M_{fr} + \frac{U_{gs}}{c^2} + \frac{U_{m-gs}}{c^2} = M_{fr} + (-M_{gs}) + M_{m-gs} \tag{108}$$

where $-M_{gs}$ and $+M_{m-gs}$ are the equivalent masses of the GSE and the interaction energy (GPE), respectively.

Since the gravitational potential energy (GPE) between a positive mass ($+M_{fr}$) and a negative equivalent mass ($-M_{gs}$) takes a positive form (repulsive interaction), the interaction energy is given by

$$U_{m-gs} = -\frac{G(+M_{fr})(-M_{gs})}{r} = +\frac{GM_{fr}M_{gs}}{r} > 0 \tag{109}$$

Consequently, the equivalent mass density obtained by dividing this interaction energy by volume, $+\rho_{m-gs}$, carries a positive energy density. The total mass density of the object is therefore

$$\rho_{Total} = \rho_{fr} + \rho_{m-gs} - \rho_{gs} \approx \rho_m + \rho_{m-gs} - \rho_{gs} \tag{110}$$

1) **Matter (ρ_m):** Strictly speaking, ρ_m is a net result of the free-state mass density (ρ_{fr} minus its GSE term ($-\rho_{gs}$) and interaction term($+\rho_{m-gs}$). Thus, $\rho_m = \rho_{fr} - (\rho_{m-gs} - \rho_{gp})$. In a weak field, $(\rho_{m-gs} - \rho_{gs})$ is negligible, thus $\rho_m \approx \rho_{fr}$. This matter distribution is the ultimate source of all subsequent gravitational effects.

2) **GSE ($-\rho_{gs}$):** The mass-equivalent of the system's own negative binding energy (U_{gs}). In relation to the expansion of the universe, the positive dark energy term is linked

to negative pressure, and the negative dark energy density plays an attractive role. In cosmology, rather than interpreting the $-\rho_{gs}$ term alone, it is thought more appropriate to understand the characteristics based on $\rho_{\Lambda_m} = \rho_{m-gs} - \rho_{gs}$.

3) **Interaction energy ($+\rho_{m-gs}$):** The mass-equivalent of the positive GPE that arises from the interaction between the matter field (M) and its own negative GSE field ($-M_{gs}$). In relation to the expansion of the universe, the positive dark energy term is connected to negative pressure, and since the positive dark energy density plays a repulsive role. In cosmology, rather than interpreting the ρ_{m-gs} term alone, it is thought more appropriate to define the characteristics based on $\rho_{\Lambda_m} = \rho_{m-gs} - \rho_{gs}$.

In standard astrophysical contexts, the term $(\rho_{m-gs} - \rho_{gs})$ is negligible compared to ρ_m, justifying the approximation $\rho_{Total} \approx \rho_m$. However, on the cosmological scale, these terms are no longer negligible. The net contribution of the GPE terms, $\rho_{\Lambda_m} = \rho_{m-gs} - \rho_{gs}$, becomes the dominant component driving cosmic acceleration.

$$\rho_{\Lambda_m} = \rho_{m-gs} - \rho_{gs} \tag{111}$$

A.2 Derivation of the matter-induced dark energy density

Having established the conceptual basis of MOC and the General GSE Framework, we now derive the explicit form of the dark energy density, ρ_{Λ_m}. The derivation leverages a physical model where gravitational potential energy is generated over the causal scale (the comoving horizon χ_p), while its density is diluted over the physical volume (V_{phys}) [18, 37, 38].

The total energy density in the Friedmann equation is given by $\rho_T = \rho_m + \rho_{m-gs} - \rho_{gs}$. The latter two terms, arising purely from gravitational interactions, constitute the matter-induced dark energy density.

The entire derivation originates from the GSE of the total mass $M(t)$ contained within the causal horizon. While the classical form scales as $1/R$, in our General GSE framework, the characteristic interaction length scale is the comoving horizon $\chi_p(t)$.

$$U_{gs,\text{General}} = -\beta(t)\frac{GM(t)^2}{\chi_p(t)} \tag{112}$$

Here, $\beta(t)$ encapsulates the necessary relativistic and structural corrections, evolving as the universe transitions from homogeneity to a structured state.

A.2.1 The negative-energy component: $-\rho_{gs}$

The first component $-\rho_{gs}$, represents the equivalent mass-density of the system's own gravitational binding energy. This binding energy corresponds to a mass defect, effectively creating a negative mass component, $-M_{gs}$, within the total energy budget [17, 39, 40].

$$-M_{gs} = \frac{U_{gs,\text{Gener}}}{c^2} = -\frac{\beta GM(t)^2}{c^2\chi_p(t)} \tag{113}$$

Distributing this negative mass over the physical volume $V_{\text{phys}}(t) = \frac{4\pi}{3}R_{\text{phys}}(t)^3$ yields the negative energy density component.

$$-\rho_{gs}(t) = \frac{-M_{gs}}{V_{\text{phys}}(t)} = -\frac{3\beta(t)}{4\pi}\frac{GM(t)^2}{c^2\chi_p(t)R_{\text{phys}}(t)^3} \tag{114}$$

A.2.2 The positive-energy component: $+\rho_{m-gs}$

The existence of the negative effective mass component ($-M_{gs}$), within the space containing the positive mass M, necessitates an interaction term. The interaction energy U_{m-gs} arises from the gravitational coupling between the matter distribution M and the effective mass ($-M_{gs}$) distribution. Here, we make a critical choice for the interaction coefficient.

A.2.3 A Note on the Interaction Coefficient

In Newtonian mechanics, the GSE of a uniform sphere is $U_{self} = -(3/5)GM^2/R$. However, in General Relativity, this is modified to $U_{self} = -\beta GM^2/R$, where β encapsulates relativistic effects. A parallel question arises for the interaction energy between two overlapping distributions. The general relativistic form of the interaction energy is complex and model-dependent. It might be characterized by a new coefficient β_2, not necessarily equal to β.

Faced with this ambiguity, we adopt $\beta_2 = 1$ as our working assumption in this specific derivation. This choice is motivated by physical reasoning: it is the natural value for stable, virialized systems and is consistent with the fact that the primary relativistic correction is already encapsulated within the M_{gs} term (which includes β). And, since the form containing β^2 was covered in the main text, there is also a need to analyze the case where the interaction coefficient is unity.

With this assumption, the interaction energy in the General GSE framework becomes

$$U_{m-gs} \approx -(1)\frac{GM(t)(-M_{gs})}{\chi_p(t)} = +\frac{GM(t)M_{gs}}{\chi_p(t)} \tag{115}$$

Substituting our definition of $M_{gs} = \beta GM^2/(c^2\chi_p)$, we obtain

$$U_{m-gs} = +\beta\frac{G^2M(t)^3}{c^2\chi_p(t)^2} \tag{116}$$

This leads to the positive equivalent mass-density.

$$\rho_{m-gs}(t) = \frac{U_{m-gs}}{V_{\text{phys}}(t)c^2} = \frac{3\beta(t)}{4\pi}\frac{G^2M(t)^3}{c^4\chi_p(t)^2R_{\text{phys}}(t)^3} \tag{117}$$

A.3 The complete expression for ρ_{Λ_m}

Combining the positive and negative energy density components, we arrive at the final expression for the dark energy density in this specific model ($\beta_2 = 1$).

$$\rho_{\Lambda_m}(t) = \rho_{m-gs}(t) - \rho_{gs}(t) = \frac{3\beta}{4\pi}\frac{G^2M^3}{c^4\chi_p^2R_{\text{phys}}^3} - \frac{3\beta}{4\pi}\frac{GM^2}{c^2\chi_pR_{\text{phys}}^3} \tag{118}$$

To reveal its physical significance, we can factor this equation. Expressing the term in the parenthesis using the Schwarzschild radius of the total causal mass, $R_S(t) = 2GM(t)/c^2$.

$$\rho_{\Lambda_m}(t) = \frac{3\beta(t)}{4\pi}\frac{GM(t)^2}{c^2\chi_p(t)R_{\text{phys}}(t)^3}\left(\frac{GM(t)}{c^2\chi_p(t)} - 1\right) \tag{119}$$

$$\rho_{\Lambda_m}(t) = \frac{3\beta(t)}{4\pi}\frac{GM(t)^2}{c^2\chi_p(t)R_{\text{phys}}(t)^3}\left(\frac{R_S(t)}{2\chi_p(t)} - 1\right) \tag{120}$$

This result demonstrates that under the assumption of a unity interaction coefficient ($\beta_2 = 1$), the condition for cosmic acceleration is governed purely by the ratio of the Schwarzschild radius to the comoving horizon, $\frac{R_S}{2\chi_p} > 1$, without an additional β factor inside the parenthesis. This provides a simpler, more fundamental criterion for the transition to dark energy dominance.

A.4 Observational validation and the evolution of β

In the MOC model, β is the structural parameter, encoding not only the relativistic corrections to the binding energy but also the structural evolution of the cosmos over time.

The ultimate test of this framework is to confront it with empirical data. Can this GPE-driven mechanism reproduce the observed cosmic history? To answer this, we turn to the two primary anchors of modern cosmology: the early-universe constraints from the Cosmic Microwave Background (CMB) [5] and the late-universe measurements from local distance ladders (e.g., SH0ES) [15].

As a parameter that encodes the structural evolution of the universe, the value of β is not fixed by theory but must be constrained by observation. Our strategy is therefore to determine β by demanding consistency with the observations from both CMB and SH0ES data. We treat the total matter density parameter, Ω_m, not as a fixed input, but as a variable to be explored. For both the CMB baseline ($H_0 = 67.4$ km/s/Mpc) [5] and the SH0ES baseline ($H_0 = 73.04$ km/s/Mpc) [15], we calculate the value of β required to produce the observed present-day dark energy density, $\rho_{\Lambda\text{-eff}} = (1-\Omega_m)\rho_c$. This procedure is repeated for a range of matter densities, representing scenarios where cosmic structure might be more significant than assumed in the standard ΛCDM model ($\Omega_m \approx 0.315$).

The results of this analysis, summarized in Tables 13 and 14, reveal the required values of β across a spectrum of possible universes. By comparing these required β values to the physically plausible range derived from stellar structure theory ($\beta \approx 0.6-2$), we can assess the viability of the MOC framework and gain insight into the structural evolution of our universe.

Matter Incr. (%)	ρ_m ($\times 10^{-27}$ kg/m^3)	ρ_{Λ_m}	**Required β**	$\rho_{m\text{-}gs}$ ($\times 10^{-27}$ kg/m^3)	$-\rho_{gs}$
-20	2.150	6.383	**10.2792**	35.186	-28.803
-10	2.419	6.114	**4.6990**	24.264	-18.150
+0	2.688	5.845	**2.6295**	18.573	-12.728
+10	2.957	5.576	**1.6388**	15.001	-9.425
+20	3.225	5.308	**1.0824**	12.520	-7.212
+30	3.494	5.039	**0.7445**	10.684	-5.645
+40	3.763	4.770	**0.5269**	9.262	-4.492
+50	4.032	4.501	**0.3808**	8.132	-3.631

Table 13: CMB baseline ($H_0 = 67.4$ km/s/Mpc, $R = 46.5$ Gly). Required β and GSE components computed from $\rho_{\Lambda_m} = \beta\left(\frac{4\pi G}{3c^2}\rho_m^2 R^2\right)\left(\frac{4\pi G}{3c^2}\rho_m R^2 - 1\right)$.

A.5 Computer simulation data

Matter Incr. (%)	ρ_m (×10^{-27} kg/m^3)	ρ_{Λ_m}	Required β	$\rho_{m\text{-}gs}$ (×10^{-27} kg/m^3)	$-\rho_{gs}$
-20	2.525	7.495	**7.0184**	30.893	-23.398
-10	2.841	7.178	**3.5026**	21.961	-14.783
+0	3.156	6.864	**2.0267**	17.419	-10.555
+10	3.472	6.548	**1.2738**	14.577	-8.029
+20	3.788	6.232	**0.8469**	12.586	-6.354
+30	4.103	5.917	**0.5868**	11.083	-5.166
+40	4.419	5.601	**0.4185**	9.874	-4.273
+50	4.734	5.286	**0.3057**	8.869	-3.583

Table 14: SH0ES baseline ($H_0 = 73.04$ km/s/Mpc, $R = 43.337$ Gly). Required β and GSE components computed form $\rho_{\Lambda_m} = \beta\left(\frac{4\pi G}{3c^2}\rho_m^2 R^2\right)\left(\frac{4\pi G}{3c^2}\rho_m R^2 - 1\right)$.

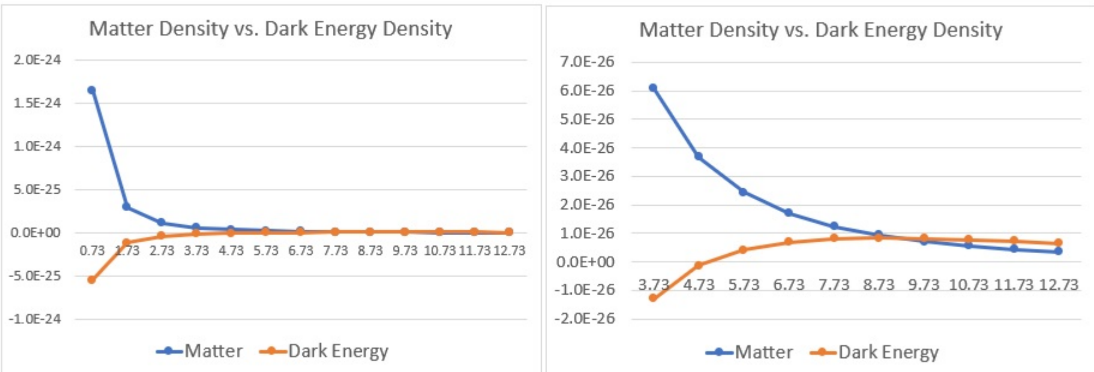

Figure 5: MOC Cosmic History Simulation (SH0ES baseline, Model-2, 10% Matter Enhancement): Matter Density vs. Dark Energy Density. In the early universe, dark energy was negative and promoted structure formation. It transitioned to positive around 4 Gyr, contributing to the accelerated expansion of the universe. At approximately t=7.5 Gyr, matter density and dark energy density became equal, and dark energy density peaked at approximately 8 Gyr and then gradually decreased.

Age (Gyr)	Scale $a(t)$	Evolving $\beta(t)$	Comoving Ho. $\chi_p(t)$ (Gly)	Physical Ho. $R_{\text{phys}}(t)$ (Gly)	**Matter** $\rho_m(t)$	Repulsive $\rho_{m-gs}(t)$	Attractive $-\rho_{gs}(t)$	**Dark Energy** $\rho_{\Lambda_m}(t)$
					(10^{-27} kg m^{-3})			
0.73	0.1283	1.6388	17.080	2.191	1645.27	214.737	-760.898	**-546.161**
1.73	0.2285	1.6084	22.764	5.202	291.245	117.716	-234.819	**-117.103**
2.73	0.3111	1.5780	26.487	8.240	115.403	83.876	-123.586	**-39.710**
3.73	0.3854	1.5476	29.365	11.317	60.699	65.364	-78.356	**-12.992**
4.73	0.4552	1.5171	31.748	14.452	36.839	53.136	-54.495	**-1.359**
5.73	0.5224	1.4867	33.797	17.656	24.373	44.243	-40.039	4.204
6.73	0.5883	1.4563	35.599	20.943	17.066	37.352	-30.467	6.885
7.73	0.6540	1.4259	37.211	24.336	12.422	31.779	-23.725	8.054
8.73	0.7200	1.3955	38.668	27.841	9.309	27.179	-18.790	8.389
9.73	0.7871	1.3651	39.996	31.481	7.126	23.293	-15.052	8.241
10.73	0.8559	1.3346	41.214	35.275	5.542	19.970	-12.153	7.817
11.73	0.9266	1.3042	42.337	39.229	4.368	17.126	-9.877	7.249
12.73	1.0000	1.2738	43.337	43.337	3.475	14.610	-8.041	6.569

Table 15: **MOC Cosmic History Simulation (SH0ES baseline, Model-2, +10% Matter Enhancement)**. Results using the alternative interaction coefficient assumption ($\beta_2 = 1$) discussed in the Appendix. The structural parameter evolves linearly from $\beta(0.73\,\text{Gyr}) = 1.6388$ to $\beta(12.73\,\text{Gyr}) = 1.2738$. Even with the reduced magnitude of the repulsive term (proportional to β^1 rather than β^2), the model successfully reproduces the transition from negative to positive dark energy at $t \approx 5.0$ Gyr, demonstrating the robustness of the GSE-driven acceleration mechanism.

Age (Gyr)	Scale $a(t)$	Evolving $\beta(t)$	Comoving Ho. $\chi_p(t)$ (Gly)	Physical Ho. $R_{\text{phys}}(t)$ (Gly)	**Matter** $\rho_m(t)$	Repulsive $\rho_{m-gs}(t)$	Attractive $-\rho_{gs}(t)$	**Dark Energy** $\rho_{\Lambda_m}(t)$
					(10^{-27} kg m^{-3})			
0.73	0.1283	1.0824	17.080	2.191	1794.84	184.134	-598.089	**-413.955**
1.73	0.2285	1.0628	22.764	5.202	317.722	100.984	-184.655	**-83.672**
2.73	0.3111	1.0432	26.487	8.240	125.894	71.987	-97.229	**-25.242**
3.73	0.3854	1.0235	29.365	11.317	66.217	56.125	-61.674	**-5.549**
4.73	0.4552	1.0039	31.748	14.452	40.188	45.648	-42.914	2.734
5.73	0.5224	0.9843	33.797	17.656	26.589	38.027	-31.546	6.481
6.73	0.5883	0.9647	35.599	20.943	18.617	32.122	-24.018	8.104
7.73	0.6540	0.9450	37.211	24.336	13.551	27.345	-18.713	8.632
8.73	0.7200	0.9254	38.668	27.841	10.156	23.400	-14.829	8.571
9.73	0.7871	0.9058	39.996	31.481	7.773	20.066	-11.886	8.180
10.73	0.8559	0.8862	41.214	35.275	6.046	17.214	-9.603	7.611
11.73	0.9266	0.8665	42.337	39.229	4.765	14.773	-7.810	6.963
12.73	1.0000	0.8469	43.337	43.337	3.791	12.611	-6.363	6.248

Table 16: **MOC Cosmic History Simulation (SH0ES baseline, Model-2, +20% Matter Enhancement)**. Results using the Model-2 assumption ($\beta_2 = 1$). The structural parameter evolves linearly from $\beta(0.73) = 1.0824$ to $\beta(12.73) = 0.8469$. This model exhibits an early transition to accelerated expansion at $t \approx 4.0$ Gyr, driven by the enhanced matter density. The dark energy density peaks around $t \approx 8$ Gyr and then slowly decreases, consistent with the dynamic nature of the GSE mechanism.

References

[1] A. G. Riess et al. (Supernova Search Team), "Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant," Astron. J. **116**, 1009 (1998).

[2] S. Perlmutter et al. (Supernova Cosmology Project), "Measurements of Omega and Lambda from 42 High-Redshift Supernovae," Astrophys. J. **517**, 565 (1999).

[3] P. J. E. Peebles and B. Ratra, "The cosmological constant and dark energy," Rev. Mod. Phys. **75**, 559 (2003).

[4] S. Dodelson, "Modern Cosmology," 2nd ed. (Academic Press, 2020).

[5] N. Aghanim et al. (Planck Collaboration), "Planck 2018 results. VI. Cosmological parameters," Astron. Astrophys. **641**, A6 (2020).

[6] P. Bull et al., "Beyond ΛCDM: Problems, solutions, and the road ahead," Phys. Dark Universe **12**, 56 (2016).

[7] S. Weinberg, "The cosmological constant problem," Rev. Mod. Phys. **61**, 1 (1989).

[8] S. M. Carroll, "The cosmological constant," Living Rev. Rel. **4**, 1 (2001).

[9] I. Zlatev, L. M. Wang, and P. J. Steinhardt, "Quintessence, Cosmic Coincidence, and the Cosmological Constant," Phys. Rev. Lett. **82**, 896 (1999).

[10] P. J. Steinhardt, "A quintessential introduction to dark energy," Phil. Trans. R. Soc. Lond. A **361**, 2497 (2003).

[11] E. Di Valentino et al., "In the realm of the Hubble tension—a review of solutions," Class. Quantum Grav. **38**, 153001 (2021).

[12] The DESI Collaboration, "First Cosmology Results from the Dark Energy Spectroscopic Instrument (DESI)," (2024) [arXiv:2404.03400].

[13] T. M. C. Abbott et al. (DES Collaboration), "Dark Energy Survey Year 3 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing," Phys. Rev. D **109**, 042001 (2024).

[14] The Dark Energy Survey Collaboration, "First Cosmology Results using Type Ia Supernovae from the Dark Energy Survey: A ΛCDM-Optimized Analysis," (2024) [arXiv:2401.02929].

[15] Riess, A. G., Casertano, S., Yuan, W., Macri, L. M., & Scolnic, D. Large Magellanic Cloud Cepheid standards for a 1% determination of the Hubble constant. *The Astrophysical Journal*, 876(1), 85. (2019).

[16] Misner, C.W., Thorne, K.S., & Wheeler, J.A., *Gravitation*, *W.H. Freeman*, (1973).

[17] Einstein, A. The Foundation of the General Theory of Relativity. *Annalen der Physik*, 354(7), 769-822. (1916).

[18] Weinberg, S., *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity*, *John Wiley & Sons*, (1972).

[19] Hans C. Ohanian and Remo Ruffini, *Gravitation and Spacetime*, *Cambridge University Press*, (2010).

[20] Hyoyoung, Choi, Sphere Theory: Completing Quantum Gravity through Gravitational Self-Energy (2025). Available at: https://www.researchgate.net/publication/388995044

[21] Lattimer, J. M., & Prakash, M. The Equation of State of Matter at High Density and its Implications for Neutron Stars. *The Astrophysical Journal*, 550(1), 426-442. (2001).

[22] Hyoyoung, Choi, Dark Energy is Gravitational Potential Energy or Energy of the Gravitational Field. (2022). Available at: https://www.researchgate.net/publication/360096238.

[23] S. Chandrasekhar, "The Post-Newtonian Equations of Hydrodynamics in General Relativity," *Astrophys. J.* **142**, 1488 (1965).

[24] H. A. Buchdahl, "General Relativistic Fluid Spheres," *Phys. Rev.* **116**, 1027 (1959).

[25] M. S. R. Delgaty and K. Lake, "Physical Acceptability of Isolated, Static, Spherically Symmetric, Perfect Fluid Solutions of Einstein's Equations," *Comput. Phys. Commun.* **115**, 395 (1998).

[26] E. A. Milne, "A Newtonian Gravitational Universe," *Q. J. Math.* **5**, 64 (1934).

[27] W. H. McCrea and E. A. Milne, "Newtonian Universes and the Curvature of Space," *Q. J. Math.* **5**, 73 (1934).

[28] Shapiro, S. L., & Teukolsky, S. A., *Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects*, *Wiley-VCH*, (1983).

[29] Binney, J., & Tremaine, S., *Galactic Dynamics (2nd ed.)*, *Princeton University Press*, (2008).

[30] Tolman, R. C. Static Solutions of Einstein's Field Equations for Spheres of Fluid. *Physical Review*, 55(4), 364-373. (1939).

[31] Oppenheimer, J. R., & Volkoff, G. M. On Massive Neutron Cores. *Physical Review*, 55(4), 374-381. (1939).

[32] Navarro, J. F., Frenk, C. S., & White, S. D. M. A Universal Density Profile from Hierarchical Clustering. *The Astrophysical Journal*, 490(2), 493-508. (1997).

[33] Dutton, A. A., & Macciò, A. V. Cold dark matter haloes in the Planck era: evolution of structural parameters. *Monthly Notices of the Royal Astronomical Society*, 441(4), 3359-3374. (2014).

[34] S. Chandrasekhar, *An Introduction to the Study of Stellar Structure*, *University of Chicago Press*, (1939).

[35] Ryden, B., *Introduction to Cosmology*, *Addison-Wesley*, (2003).

[36] Hyoyoung, Choi, On Problems and Solutions of General Relativity (Commemoration of the 100th Anniversary of General Relativity). (2015). Available at: https://www.researchgate.net/publication/286935998.

[37] Peebles, P. J. E., *Principles of Physical Cosmology*, *Princeton University Press*, (1993).

[38] V. F. Mukhanov, *Physical Foundations of Cosmology* (Cambridge University Press, Cambridge, 2005).

[39] S. W. Hawking and G. F. R. Ellis, *The Large Scale Structure of Space-Time*, Cambridge University Press (1973).

[40] R. M. Wald, *General Relativity*, University of Chicago Press (1984).

[41] Penrose, R. Gravitational Collapse and Space-Time Singularities. *Physical Review Letters*, 14(3), 57-59. (1965).

[42] Hawking, S. W., & Penrose, R. The Singularities of Gravitational Collapse and Cosmology. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 314(1519), 529-548. (1970).

[43] Hyoyoung, Choi, The Klein-Gordon-Choi Equation: A Unified Resolution of the Divergences in Quantum Gravity and QED. (2025). Available at: https://www.researchgate.net/publication/398285103.

[44] S. M. Carroll, M. Hoffman, and M. Trodden, "Can the dark energy be a phantom?," *Phys. Rev. D* **68**, 023509 (2003).

[45] J. M. Cline, S. Jeon, and G. D. Moore, "The Phantom menaced: Constraints on phantom dark energy from particle physics," *Phys. Rev. D* **70**, 043543 (2004).

[46] R. V. Buniy and S. D. H. Hsu, "Instabilities and the null energy condition," *Phys. Lett. B* **632**, 543 (2006).

[47] Boylan-Kolchin, M., Springel, V., White, S. D. M., Jenkins, A., & Lemson, G., Resolving cosmic structure formation with the Millennium-II Simulation, *Monthly Notices of the Royal Astronomical Society*, **398**(3), 1150-1164, (2009).

[48] Pillepich, A., et al., First results from the IllustrisTNG simulations: the stellar mass content of groups and clusters of galaxies, *Monthly Notices of the Royal Astronomical Society*, **475**(1), 648-675, (2018).

[49] Adame, J., et al. "Implications of the DESI 2024 BAO measurements on the Hubble and S_8 tensions". The Astrophysical Journal Letters. (or similar recent analysis citing DESI results), (2024).

[50] Abdalla, E., et al. "Cosmology intertwined: A review of the particle physics, astrophysics, and cosmology associated with the cosmological tensions and anomalies". Journal of High Energy Astrophysics, 34, 49-211. (2022).

[51] Amon, A., et al. (DES Collaboration). "Dark Energy Survey Year 3 results: Cosmology from cosmic shear and robustness to modeling uncertainty". Physical Review D, 105(2), 023514. (2022).

[52] Nunes, R. C., & Vagnozzi, S. "Arbitrating the S_8 tension with the Hubble tension". Monthly Notices of the Royal Astronomical Society, 505(4), 5427-5437. (2021).

[53] Y.-W. Lee et al., "A revised local matter density from Type Ia supernovae and its implication for the Hubble tension," Mon. Not. R. Astron. Soc. **546**, L1-L5 (2025).

[54] I. Labbe et al., "A population of red candidate massive galaxies at $z > 10$," Nature **616**, 266-269 (2023).

[55] M. Boylan-Kolchin, "Stress Testing ΛCDM with High-redshift Galaxy Candidates," Nat. Astron. **7**, 731-735 (2023).

[56] Euclid Collaboration, "Euclid: First constraints on cosmology from the Surface Brightness Fluctuation analysis of the Fornax cluster," Astron. Astrophys. **686**, A1 (2024).

[57] A. Amon et al. (KiDS-1000 Collaboration), "KiDS-1000 cosmology: Constraints from density split statistics," Astron. Astrophys. **646**, A152 (2021).

[58] A. A. Starobinsky, "A new type of isotropic cosmological models without singularity," Phys. Lett. B **91**, 99 (1980).

[59] Guth, A. H. Inflationary universe: A possible solution to the horizon and flatness problems. *Physical Review D*, 23(2), 347-356. (1981).

[60] Linde, A. D. A new inflationary universe scenario: A possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems. *Physics Letters B*, 108(6), 389-393. (1982).

[61] Albrecht, A., & Steinhardt, P. J. Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking. *Physical Review Letters*, 48(17), 1220-1223. (1982).

[62] Frieman, J. A., Turner, M. S., & Huterer, D. Dark Energy and the Accelerating Universe. *Annual Review of Astronomy and Astrophysics*, 46, 385-432. (2008).

[63] L. Kofman, A. D. Linde, and A. A. Starobinsky, "Reheating after inflation," *Phys. Rev. Lett.* **73**, 3195 (1994).

[64] B. A. Bassett, S. Tsujikawa, and D. Wands, "Inflation dynamics and reheating," *Rev. Mod. Phys.* **78**, 537 (2006).

[65] R. Allahverdi, R. Brandenberger, F.-Y. Cyr-Racine, and A. Mazumdar, "Reheating in Inflationary Cosmology: Theory and Applications," *Ann. Rev. Nucl. Part. Sci.* **60**, 27 (2010).

[66] Nojiri, S., & Odintsov, S. D. Unifying phantom inflation with late-time acceleration: Scalar phantom-non-phantom transition phase and generalized holographic dark energy. *General Relativity and Gravitation*, 38, 1285-1304. (2006). [arXiv:hep-th/0506212].

[67] A. Salehi and S. Aftabi, "New Hubble parameter data and possibility of more than one transition," *Eur. Phys. J. C* **82**, 1165 (2022).

[68] Hawking, S. W. Breakdown of predictability in gravitational collapse. *Physical Review D*, 14(10), 2460-2473. (1976).

[69] J. Preskill, "Do black holes destroy information?," In Proceedings of the International Symposium on Black Holes, Membranes, Wormholes, and Superstrings, World Scientific (1992), [arXiv:hep-th/9209058].

[70] L. Susskind, L. Thorlacius, and J. Uglum, "The Stretched Horizon and Black Hole Complementarity," Phys. Rev. D **48**, 3743 (1993), [arXiv:hep-th/9306069].

[71] D. Scolnic et al. (Pantheon+), "The Pantheon+ Analysis: The Full Dataset of Type Ia Supernovae and its Cosmological Constraints," Astrophys. J. **938**, 113 (2022).

[72] R. Jimenez and A. Loeb, "Constraining Cosmological Parameters with the Age of Old Galaxies," Astrophys. J. **573**, 37 (2002).

[73] N. Kaiser, "Clustering in real space and in redshift space," Mon. Not. R. Astron. Soc. **227**, 1 (1987).

[74] Hyoyoung, Choi, The Physical Origin of the Planck Scale Cutoff and Completion of Perturbative Quantum Gravity. (2025). Available at: https://www.researchgate.net/publication/397952460.