Article

Not peer-reviewed version

The Role of Energy Density Diffusion in Galactic Dynamics and Cosmic Expansion: A Unified Theory for MOND and Dark Energy

Gui Furne Gouveia *

Posted Date: 9 September 2025

doi: 10.20944/preprints202509.0792.v1

Keywords: Modified Newtonian Dynamics (MOND); emergent gravity; energy-matter conversion; vacuum energy density; cosmic expansion; galactic rotation curves; wave theory of matter; energy diffusion; space metrics; primordial nucleosynthesis; quantum vacuum; neutrino condensation

Article

The Role of Energy Density Diffusion in Galactic Dynamics and Cosmic Expansion: A Unified Theory for MOND and Dark Energy

G. Furne Gouveia

Independent Researcher; furnegouveia@gmail.com

Abstract

The galactic rotation curve anomaly and the universe's accelerated expansion remain the most compelling evidence for physics beyond standard models. This paper presents a unified mechanism explaining both phenomena without dark matter or dark energy postulates. Building on a wave-based paradigm where matter constitutes trapped standing waves in a dynamic medium, we demonstrate that energy released from mass conversion events—from primordial matter-antimatter annihilation to stellar nucleosynthesis—is injected into and diffuses through the fabric of space. This diffusion process is central to our model: it creates extended energy density fields with a characteristic $\rho_{\text{diff}}(r) \propto 1/r$ profile. We demonstrate that this profile directly influences gravitational dynamics through the constitutive law $a(r) \propto |\nabla\rho(r)|/\rho(r)$, naturally producing flat rotation curves without dark matter. Crucially, order-of-magnitude calculations reveal that the total gravitational potential energy of the observable universe ($|U| \approx 8.36 \times 10^{70}$ J) matches the energy released from primordial mass conversion ($E_{\text{thermal}} \approx 2.6 \times 10^{70}$ J), suggesting a common mechanism operating across cosmic and galactic scales. This model provides a physical foundation for Modified Newtonian Dynamics (MOND) by identifying the MONDian regime as the domain where diffused energy density dominates, and explains the recent acceleration of cosmic expansion through the condensation of accumulated low-energy neutrinos, offering a physical alternative to the dual dark matter and dark energy hypotheses.

Keywords: Modified Newtonian Dynamics (MOND); emergent gravity; energy-matter conversion; vacuum energy density; cosmic expansion; galactic rotation curves; wave theory of matter; energy diffusion; space metrics; primordial nucleosynthesis; quantum vacuum; neutrino condensation

---

1. Introduction

The discrepancy between observed galactic rotation curves and Newtonian predictions based on visible matter [10] represents one of astronomy's most persistent challenges. The predominant solution—postulating dark matter halos—remains empirically unverified despite decades of search. Similarly, the accelerated expansion of the universe [9] requires yet another unexplained component: dark energy.

Modified Newtonian Dynamics (MOND) successfully describes rotation curves with a single new constant a_0 [8] but has been criticized as phenomenological rather than fundamental. Meanwhile, ΛCDM cosmology requires two mysterious components (dark matter and dark energy) that together constitute 95% of the universe's energy content, violating the principle of parsimony.

This paper proposes a fundamental unified mechanism based on a wave-centric paradigm of the universe [20,21]. We demonstrate that both galactic dynamics and cosmic expansion emerge from a single physical process: the conversion of mass to energy and its subsequent incorporation and diffusion through the fabric of space itself. The anomalous dynamics in galaxies arise not from unseen matter but from measurable energy density gradients created by this continuous process of energy injection and diffusion, providing a physical interpretation for both MOND phenomenology and dark energy effects.

The central thesis of this paper is that the process of energy diffusion from astrophysical and primordial sources is the fundamental mechanism underlying these phenomena. We will show that the stationary solution to the diffusion equation for a central source yields an energy density field $\rho_{\text{diff}}(r) \propto 1/r$. This specific profile is not postulated but derived, and it directly leads to the constant orbital velocities observed in galactic rotation curves. This provides a mechanistic, non-phenomenological foundation for MOND. Furthermore, we extend this diffusion paradigm to cosmological scales, arguing that the primordial injection and subsequent diffusion of energy funded the universe's expansion and gravitational potential energy.

2. Theoretical Framework

2.1. Wave-Based Reality and Emergent Gravity

The core premise of our model is not a new postulate but a physical interpretation of established facts. Quantum field theory dictates that the vacuum possesses a non-zero energy density [22]. The most parsimonious physical interpretation of this energy is that it represents a dynamic, vibrating state of the spatial medium itself. In this framework, matter consists of complex standing wave structures—resonances—within this universal medium. Protons and neutrons, for instance, can be understood as a hierarchical organization of trapped electromagnetic standing waves [6,7].

Forces emerge from wave propagation dynamics in a medium with varying energy density $\rho(\mathbf{r})$. Wave-packets (particles) follow trajectories that are geodesics of this energy density landscape. The resulting perceived acceleration derives from the gradient of the energy density field:

$$a(\mathbf{r}) \propto \frac{\nabla\rho(\mathbf{r})}{\rho(\mathbf{r})} \tag{1}$$

This constitutive law is not an ad hoc choice but a mechanistic reformulation of the geometric description of General Relativity. In GR, the curvature of spacetime dictates the motion of matter. Here, this curvature finds its physical origin in the gradients of the vibrational energy density. The relative gradient $\nabla\rho/\rho$ naturally emerges as the parameter governing wave deflection, much like the gradient of the refractive index guides light in a medium. This provides a physical explanation for the equivalence principle: both inertial and gravitational mass are manifestations of a wave's response to the energy density landscape.

2.2. The Diffusion Mechanism: From Energy Injection to the 1/r Profile

The missing element in previous models is a physical process that distributes energy from local sources to create large-scale, long-range fields. We propose this process is diffusion. Once perturbed by a local energy injection, the vibrational medium will tend to redistribute this energy to maximize entropy. This process is universally described by a diffusion equation.

The energy flux $\mathbf{J}$ is proportional to the negative gradient of the energy density (Fick's law: $\mathbf{J} = -D\nabla\rho$). Combining this with the continuity equation ($\frac{\partial\rho}{\partial t} + \nabla\cdot\mathbf{J} = S$), which enforces local conservation of energy, yields the standard diffusion or heat equation for a constant diffusion coefficient D:

$$\frac{\partial\rho}{\partial t} = D\nabla^2\rho + S(\mathbf{r},t) \tag{2}$$

where $S(\mathbf{r},t)$ is the source term representing the rate of energy injection per unit volume.

The critical insight comes from analyzing the steady-state solution for an isolated, continuous point source. For a central, steady-state source ($S(\mathbf{r}) = S_0\delta(\mathbf{r})$) the time derivative vanishes ($\partial\rho/\partial t = 0$). Outside the source location ($\mathbf{r} \neq 0$), the equation reduces to Laplace's equation:

$$\nabla^2\rho = 0 \tag{3}$$

The spherically symmetric solution to this equation is:

$$\rho(r) = \frac{A}{r} + B \tag{4}$$

Applying the boundary condition that the energy density must vanish at infinity ($\rho \to 0$ as $r \to \infty$) forces the constant $B = 0$. This yields the fundamental result:

$$\rho_{\text{diff}}(r) = \frac{A}{r} \tag{5}$$

This $1/r$ energy density profile is not an assumption but a direct mathematical consequence of energy diffusion from a central source in a homogeneous medium. It is this specific profile that will be shown to generate the MONDian gravitational behavior.

2.3. Energy Sources and Unification of Scales

The continuous injection of energy into the spatial medium is not an additional assumption but the identification of a common physical process behind seemingly disparate phenomena. This process provides a unified physical origin for both dark energy (global, historical energy input) and the galactic dark matter phenomenon (local, ongoing energy input). The 'missing mass' is not a substance but the energy continuously added to space, which then diffuses according to Eq. (2).

1. **Primordial annihilation:** Matter-antimatter annihilation in the early universe released colossal energy that thermalized the cosmos, establishing the background energy density ρ_0 and driving the initial expansion. This is the dominant cosmological source.
2. **Stellar nucleosynthesis:** Stars, novae, supernovae, black holes, neutron stars, accretion disks, and other astrophysical systems continuously convert mass to energy through fusion processes [4], acting as local sources $S(\mathbf{r}, t)$ that create energy overdensities $\delta\rho$. These are the dominant galactic sources.

2.4. Recent Cosmic Acceleration and Neutrino Condensation

The observed recent acceleration of cosmic expansion [9] finds a natural explanation within our framework. We propose that this acceleration results from the condensation of the vast reservoir of low-energy neutrinos produced throughout cosmic history but unable to condense until now.

As the universe expands, matter becomes increasingly diluted, weakening local gravitational potentials in the vast intergalactic voids. This creates conditions favorable for the condensation of low-energy neutrinos that have been accumulating since the Big Bang. The condensation process follows a threshold mechanism:

$$E_\nu < E_{\text{cond}} \propto |\phi(\mathbf{r})| \tag{6}$$

where E_ν is the neutrino energy, $\phi(\mathbf{r})$ is the local gravitational potential, and E_{cond} is the condensation energy threshold. In regions where $|\phi(\mathbf{r})|$ drops below a critical value (as in modern-era intergalactic space), even the lowest-energy neutrinos can condense.

This process creates a positive feedback loop:

1. Neutrino condensation increases the local energy density of space.
2. The local metric responds to this increase, since the energy density $\rho(\mathbf{r})$ determines the frequency $\nu(\mathbf{r})$ of the standing waves that constitute the fabric of space.

   The link between energy density, frequency, and the metric is fundamental. In a wave-based model, the elementary "cells" or "grains" of space are defined by standing wave structures. The energy density $\rho(\mathbf{r})$ is a measure of the vibrational energy contained within these cells. A higher energy density directly implies a higher frequency of vibration $\nu(\mathbf{r})$ for these fundamental waves, as per the Planck relation $E = h\nu$ applied to the energy content of a spatial cell. Consequently, a spatial region with a higher vibrational frequency will have a greater number of wave nodes and anti-nodes per unit of proper volume. It is this *node density*—the number of elementary wave

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 September 2025 doi:10.20944/preprints202509.0792.v1

events per unit proper volume—that ultimately defines the local metric $g_{\mu\nu}(\mathbf{r})$. In this framework, the metric is an emergent property that encodes the underlying density of the wave structure of space.

3. A higher frequency corresponds to a greater number of nodes $N(\mathbf{r})$ in the standing-wave lattice. The metric can be expressed as a function of this node density:

$$ds^2 = g_{\mu\nu}(\mathbf{r})\, dx^\mu dx^\nu \quad \text{with} \quad g_{\mu\nu}(\mathbf{r}) \propto f(N(\mathbf{r})). \tag{7}$$

4. Since the number of nodes is proportional to the local energy density,

$$N(\mathbf{r}) \propto \rho(\mathbf{r}), \tag{8}$$

an increase in ρ leads directly to an increase in N, which in turn stretches spatial intervals.

5. As the number of nodes increases locally, spatial distances expand accordingly:

$$\Delta l(\mathbf{r}) \propto N(\mathbf{r}). \tag{9}$$

6. This expansion further dilutes matter and weakens gravitational potentials.
7. Weaker potentials allow more low-energy neutrinos to condense.

The resulting accelerated expansion will continue until the accumulated reservoir of condensing neutrinos is depleted. This mechanism explains why cosmic acceleration began relatively recently ($z \sim 0.5$–1): it required both sufficient accumulation of low-energy neutrinos and sufficient pre-expansion to create large regions with weak gravitational potentials.

Order-of-magnitude estimates support this mechanism. The total energy available in the cosmic neutrino background is $\sim 10^{70}$ J, consistent with the energy required to explain the observed acceleration when considering the efficiency of the condensation process.

3. Galactic Dynamics and MOND Emergence

The gravitational acceleration follows from our constitutive law (Eq. (1)):

$$a(r) \propto \frac{|\nabla \rho_{\text{tot}}(r)|}{\rho_{\text{tot}}(r)} \tag{10}$$

The total energy density $\rho_{\text{tot}}(r)$ is the sum of the density directly associated with matter (ρ_m) and the diffused energy density field (ρ_{diff}) derived in Section 2.2.

In different regimes: - **Newtonian regime (small r):** Close to the galactic center, the matter density dominates: $\rho_{\text{tot}} \approx \rho_m \propto 1/r^2$. This yields $a(r) \propto |\nabla(1/r^2)|/(1/r^2) \propto (1/r^3)/(1/r^2) \propto 1/r^2$, recovering Newtonian dynamics. - **MONDian regime (large r):** At large galactocentric distances, the extended diffused energy density profile $\rho_{\text{diff}} \propto 1/r$ dominates: $\rho_{\text{tot}} \approx \rho_{\text{diff}} \propto 1/r$. This yields $a(r) \propto |\nabla(1/r)|/(1/r) \propto (1/r^2)/(1/r) \propto 1/r$, resulting in a constant circular velocity $v = \sqrt{ar} =$ constant and a flat rotation curve.

The transition between these regimes occurs at the radius where $\rho_m(r) \sim \rho_{\text{diff}}(r)$. This naturally defines the MOND acceleration constant a_0 not as a fundamental constant, but as an emergent property of the spatial medium's diffusive characteristics (the coefficient D) and the galactic energy output (the source strength S_0).

4. Cosmic Energy Budget and Unified Mechanism

Our order-of-magnitude calculations (Appendix A) reveal a profound connection:

$$|U| \approx 8.36 \times 10^{70}\text{J} \quad \text{(Gravitational potential energy)}$$
$$E_{\text{thermal}} \approx 2.6 \times 10^{70}\text{J} \quad \text{(Primordial annihilation energy)}$$

The remarkable proximity (within a factor of ~ 3) suggests that the energy driving cosmic expansion originated from primordial mass conversion. Modern stellar energy release ($\sim 10^{67}$ J) is negligible cosmologically but dominant locally in galaxies. However, the accumulated energy in the low-energy neutrino background represents a substantial reservoir ($\sim 10^{70}$ J) that becomes available for driving cosmic acceleration once the gravitational potential in expanding voids drops below the condensation threshold.

This establishes a unified picture powered by the injection and diffusion of energy: - **Cosmic scale:** Primordial mass-energy conversion and its diffusion drove universal expansion and established the global energy budget. - **Galactic scale:** Ongoing mass-energy conversion creates local sources. The diffusion of this energy creates the $\rho_{\text{diff}} \propto 1/r$ field that explains MOND phenomena. - **Recent acceleration:** Accumulated low-energy neutrino condensation provides a new energy source, whose incorporation and diffusion into the medium drives the current accelerated expansion.

4.1. Additional Observational Evidence: The Case of Old and Diffuse Galaxies

A key prediction of our diffusion-based model is that the MOND phenomenon, interpreted as the dominance of the diffused energy density profile $\rho_{\text{diff}} \propto 1/r$, should be correlated with a galaxy's historical astrophysical activity. This activity determines the source strength $S(\mathbf{r}, t)$ and thus the amplitude of the ρ_{diff} field. Remarkably, observations indicate that certain **old, very diffuse, and low-surface-brightness galaxies** (such as the galaxy NGC 1052-DF2 [28]) exhibit rotation curves that are **consistent with the predictions of standard Newtonian dynamics** based on baryonic mass alone, showing no significant need for dark matter or a MOND-like effect. This contrasts sharply with the MONDian behavior observed in more massive and active spiral galaxies. Within our theoretical framework, this disparity finds a natural explanation: these ancient and quiescent galaxies have had a **very weak star formation history** or effectively became dormant billions of years ago. Consequently, their cumulative energy output from nucleosynthetic processes (supernovae, etc.) is negligible. With the source term S being very weak, the diffusion process has not generated a significant large-scale diffused energy density surplus ρ_{diff}. The total energy density ρ_{tot} in these systems is therefore dominated by the baryonic matter density (ρ_m), restoring the dynamics to the standard Newtonian regime ($a(r) \propto 1/r^2$). This correlation between stellar age, past astrophysical activity, and the presence or absence of rotation curve anomalies provides a **strong observational hint and a further falsifiable test** for our unified model based on energy diffusion.

5. Discussion and Conclusion

We have presented a unified model where both galactic dynamics and cosmic expansion emerge from a single physical process: mass-energy conversion and its subsequent diffusion through the spatial medium. The model provides a mechanistic foundation for MOND, not by introducing new physics, but by deriving the key $1/r$ density profile from a diffusion process and providing a physical interpretation for the geometric description of GR (energy density gradients instead of spacetime curvature).

The mathematical consistency between the total gravitational potential energy and the primordial thermal energy release is not a mere coincidence but a strong indication of a common origin. This model exemplifies Occam's razor, solving two major mysteries of modern cosmology—dark matter and dark energy—with a single cause: the transfer and diffusion of energy from matter to the spatial medium.

The MOND acceleration constant a_0 is not a fundamental constant but an emergent property. It marks the transition radius where the diffused energy density $\rho_{\text{diff}} \propto 1/r$ begins to dominate over the direct matter field $\rho_m \propto 1/r^2$. Its value is determined by the medium's properties—its effective diffusion coefficient D and the source function S—and is therefore a measurable quantity rather than a derivable one, much like the speed of sound in a material.

The recent acceleration of cosmic expansion emerges naturally from our model as the consequence of accumulated low-energy neutrinos reaching condensation conditions in the increasingly rarefied

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 September 2025 doi:10.20944/preprints202509.0792.v1

intergalactic medium, initiating a new phase of energy injection and diffusion. This provides a direct physical alternative to the standard postulate of Dark Energy, replacing an enigmatic fundamental constant with a dynamic, testable process tied to the universe's thermal history and matter distribution.

This framework makes testable predictions:

1. Correlation between galactic energy output (e.g., star formation rate) and mass discrepancy severity.
2. Specific, measurable energy density profiles ($\sim 1/r$) around galaxies via gravitational lensing or other probes.
3. Quantitative relationships between a galaxy's energy production history and its rotation curve.
4. Environmental variations in the effective a_0 value.
5. Specific spectral distortions in the cosmic neutrino background as low-energy neutrinos condense in large-scale voids.

Future work will explore the detailed mechanisms of energy transfer to the spatial medium and the development of a complete cosmological model based on this diffusion paradigm.

Appendix A. Order of Magnitude Calculations

This appendix provides the order-of-magnitude calculations that support the central claim of the paper: that the energy released by primordial processes (and diffused through space) is sufficient to account for the total gravitational energy content of the universe.

The following calculations use standard cosmological values from Planck satellite results [11] and established cosmological models [4]. Their purpose is to estimate the order of magnitude of two key energies to test the consistency of our model.

Appendix A.1. Gravitational Potential Energy of the Observable Universe

Calculating the total gravitational potential energy of the universe is a complex problem in general relativity. The Newtonian formula for a homogeneous sphere, while approximate, provides a robust order-of-magnitude estimate and is commonly used in this pedagogical and heuristic context [12,14].

The gravitational potential energy U for a homogeneous sphere of mass M and radius R is given by $U = -\frac{3}{5}\frac{GM^2}{R}$.

Appendix A.1.1. Mean Density of Baryonic Matter

The cosmological parameters from Planck 2018 [24] are

$$\Omega_b h^2 = 0.0224, \quad \Omega_m = 0.315, \quad H_0 = 67.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

We deduce

$$h = \frac{H_0}{100} = 0.674$$

$$\Omega_b = \frac{\Omega_b h^2}{h^2} = \frac{0.0224}{0.674^2} = 0.0493$$

The critical density is

$$\rho_{\mathrm{crit}} = \frac{3H_0^2}{8\pi G} = 8.53 \times 10^{-27}\,\mathrm{kg\,m^{-3}} \quad [25],$$

with $G = 6.67430 \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$

Thus, the mean baryonic density is

$$\rho_b = \Omega_b \rho_{\mathrm{crit}} = 4.21 \times 10^{-28}\,\mathrm{kg\,m^{-3}} = 4.21 \times 10^{-31}\,\mathrm{g\,cm^{-3}}.$$

Appendix A.1.2. Gravitational Potential Energy of the Observable Universe

The radius of the observable universe is

$$R = 46.5 \text{ Gly} = 4.40 \times 10^{26} \text{ m} \; [26].$$

The associated volume is

$$V = \frac{4}{3}\pi R^3$$

The total baryonic mass is

$$M_b = \rho_b V = 1.50 \times 10^{53} \text{ kg}$$

The total matter mass (baryons + dark matter, $\Omega_m = 0.315$) is

$$M_m = \Omega_m \rho_{\text{crit}} V = 9.59 \times 10^{53} \text{ kg}$$

For a uniform sphere, the gravitational binding energy is

$$U = -\frac{3}{5}\frac{GM^2}{R}$$

Therefore,

$$U_b = -\frac{3}{5}\frac{GM_b^2}{R} = -2.05 \times 10^{69} \text{ J}$$

$$U_m = -\frac{3}{5}\frac{GM_m^2}{R} = -8.36 \times 10^{70} \text{ J}$$

Summary

- Mean baryonic density: $\rho_b = 4.21 \times 10^{-28} \text{ kg m}^{-3}$.
- Gravitational potential energy (baryons only): $U_b \approx -2.05 \times 10^{69}$ J.
- Gravitational potential energy (total matter): $U_m \approx -8.36 \times 10^{70}$ J.

$$\boxed{|U_m| \approx 8.36 \times 10^{70} \text{J}}$$

Appendix A.2. Total Primordial Thermal Energy Release

The primordial thermal energy is calculated from current observables of the Cosmic Microwave Background (CMB) and Cosmic Neutrino Background (CνB), correcting their current energy by the redshift factor $(1+z)$ to estimate their energy at the time of emission/decoupling [3,16].

Appendix A.2.1. Energy from the Cosmic Microwave Background (Photons)

$$T_{\gamma,0} = 2.7255\text{K} \quad [11]$$

$$\rho_{\gamma,0} = aT_{\gamma,0}^4 \approx 4.17 \times 10^{-14} \text{J/m}^3 \quad (\text{where } a \text{ is the radiation constant})$$

$$E_{\gamma,0} = \rho_{\gamma,0} \cdot V \approx 1.49 \times 10^{67} \text{J}$$

At the redshift of photon decoupling ($z_{\text{dec}} \approx 1090$ [11]), their energy was higher by a factor of $(1+z)$.

$$E_{\gamma,\text{initial}} \approx E_{\gamma,0} \cdot (1 + z_{\text{dec}}) \approx 1.49 \times 10^{67} \times 1090 \approx 1.62 \times 10^{70} \text{J}$$

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 9 September 2025 doi:10.20944/preprints202509.0792.v1

Appendix A.2.2. Energy from the Cosmic Neutrino Background (Neutrinos)

After neutrino decoupling, their temperature was reduced by a factor of $(4/11)^{1/3}$ compared to photons [15].

$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma,0} \approx 1.95\text{K}$$
$$\rho_{\nu,0} = 3 \times \frac{7}{8} \times aT_{\nu,0}^4 \approx 2.84 \times 10^{-14}\text{J/m}^3 \quad \text{(for 3 neutrino flavors)}$$
$$E_{\nu,0} = \rho_{\nu,0} \cdot V \approx 1.01 \times 10^{67}\text{J}$$
$$E_{\nu,\text{initial}} \approx E_{\nu,0} \cdot (1 + z_{\nu\text{-dec}}) \approx 1.01 \times 10^{67} \times 10^9 \approx 1.01 \times 10^{70}\text{J}$$
$$\text{(Note: } z_{\nu\text{-dec}} \sim 10^9 \text{ is a standard approximation)}$$

Appendix A.2.3. Total Initial Thermal Energy

$$E_{\text{thermal, initial}} = E_{\gamma,\text{initial}} + E_{\nu,\text{initial}} \approx (1.62 \times 10^{70}) + (1.01 \times 10^{70}) = 2.63 \times 10^{70}\text{J}$$
$$\boxed{E_{\text{thermal, initial}} \approx 2.6 \times 10^{70}\text{J}}$$

Appendix A.3. Note on Subsequent Stellar Energy Production

The total energy radiated by all stars in the universe is estimated from the energy density of the extragalactic background light (EBL) [13].

$$\rho_{\text{EBL}} \approx 1 \times 10^{-14}\text{J/m}^3$$
$$E_{\text{stars}} \approx \rho_{\text{EBL}} \cdot V \approx 3.6 \times 10^{66}\text{J}$$

Even when corrected for redshift (factor of $\sim 2-3$), this energy ($\sim 10^{67}$J) is **three orders of magnitude** smaller than the primordial thermal energy and is therefore negligible in this cosmological energy budget.

Appendix B. Implications

The total gravitational potential energy ($|U| \approx 8.36 \times 10^{70}$ J) and the initial thermal energy from annihilation ($E_{\text{thermal}} \approx 2.6 \times 10^{70}$ J) are both on the order of 10^{70} J.

The factor of ~ 3 difference is well within the uncertainty of such cosmological order-of-magnitude estimates, which involve simplifications like the homogeneous sphere model and average redshift factors. This remarkable proximity suggests a profound connection: the expansion of the universe, and the gravitational potential energy stored therein, was primarily funded by the initial release of thermal energy from particle processes in the hot Big Bang, notably matter-antimatter annihilation. The energy from all stellar and astrophysical processes that followed ($E_{\text{stars}} \sim 10^{67} J$) is negligible in comparison, highlighting the dominance of primordial physics in setting the large-scale energy budget of the cosmos.

It is critical to address an apparent paradox: this calculation utilizes the ΛCDM parameter Ω_m, which includes dark matter, to estimate the total gravitational energy $|U|$. However, the model presented in this paper explicitly rejects dark matter as a substance.

This approach is justified because the Ω_m parameter observationally constrains the total gravitational mass-energy content of the universe, regardless of its nature. In the standard paradigm, this content is interpreted as cold dark matter particles. In our paradigm, the same gravitational effect is attributed to the energy density field ρ_{diff} sourced by historical and ongoing mass-energy conversion and its diffusion.

Therefore, using the ΛCDM value is not an endorsement of the dark matter hypothesis but a pragmatic method to quantify the total energy budget that any alternative theory, including ours, must explain. The remarkable agreement between $|U|$ and E_{thermal} suggests that the energy released from particle reactions in the early universe is sufficient to fund this required gravitational energy, providing a physical origin for what ΛCDM attributes to dark matter.

Note on Cosmological Assumptions

Whether the initial conditions were set by a standard Hot Big Bang or an alternative scenario such as a Big Bounce, the subsequent processes of energy injection and diffusion that govern our model remain valid.

The precise interpretation may depend on the cosmological model. The primary goal of this paper is not to debate initial conditions but to introduce a unified mechanism for dark matter and dark energy phenomena on galactic and intergalactic scales, based on observable, ongoing physical processes, chief among them diffusion.

A detailed exploration of how this mechanism integrates with specific cosmological models, including bouncing scenarios, is a fertile ground for future work.

References

1. Follin, B., Knox, L., Millea, M., & Pan, Z. (2015). First detection of the acoustic oscillation phase shift expected from the cosmic neutrino background. *Physical Review Letters*, 115(9), 091301.
2. KATRIN Collaboration. (2025). *New record: neutrinos weigh less than 0.8 millionths of a billionth, of a billionth, of a billionth of a gram*. Karlsruhe Institute of Technology.
3. Weinberg, S. (2008). *Cosmology*. Oxford University Press. ISBN 978-0-19-852682-7.
4. Dodelson, S. and Turner, M. S. (2003). *Modern Cosmology*. Academic Press.
5. Famaey, B., & McGaugh, S. S. (2012). Modified Newtonian Dynamics (MOND): observational phenomenology and relativistic extensions. *Living Reviews in Relativity*, 15(1), 10.
6. T. N. Lockyer, *Vector Particle Physics*, TNL Press, 1992, ISBN: 0-9631546-1-3.
7. Lockyer, T.N. (1992). [A Photon-Based Vector Particle Model for Proton and Neutron Masses]. *Preprints.org*, [DOI]. Available at: https://doi.org/10.20944/preprints202505.2073.v1.
8. Milgrom, M. (1983). A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *The Astrophysical Journal*, 270, 365–370.
9. Perlmutter, S., et al. (1999). Measurements of Ω and Λ from 42 high-redshift supernovae. *The Astrophysical Journal*, 517(2), 565–586.
10. Rubin, V. C., Ford, W. K. Jr., & Thonnard, N. (1980). Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 (R=4kpc) to UGC 2885 (R=122kpc). *The Astrophysical Journal*, 238, 471–487.
11. Planck Collaboration. (2016). Planck 2015 results. XIII. Cosmological parameters. *Astronomy & Astrophysics*, 594, A13.
12. Cooperstock, F. I., & Rosen, N. (1996). The energy of the universe. *General Relativity and Gravitation*, 28(4), 423-432.
13. Dwek, E., & Krennrich, F. (2013). The extragalactic background light and the gamma-ray opacity of the universe. *Astroparticle Physics*, 43, 112-133. https://doi.org/10.1016/j.astropartphys.2012.09.003
14. Fabian, A. C. (2012). The energy of the universe. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1978), 5139-5149.
15. Fields, B. D. (2011). The primordial lithium problem. *Annual Review of Nuclear and Particle Science*, 61, 47-68.
16. Kolb, E. W., & Turner, M. S. (1990). *The Early Universe*. Addison-Wesley.
17. Kuramoto, Y. (1975). Self-entrainment of a population of coupled non-linear oscillators. In *International Symposium on Mathematical Problems in Theoretical Physics* (pp. 420-422). Springer, Berlin, Heidelberg.
18. Acebrón, J. A., Bonilla, L. L., Pérez Vicente, C. J., Ritort, F., & Spigler, R. (2005). The Kuramoto model: A simple paradigm for synchronization phenomena. *Reviews of modern physics*, 77(1), 137.
19. Schmidt, C., & Krischer, K. (2014). *Clustering as a prerequisite for chimera states in globally coupled systems*. Physical Review Letters, 114(3), 034101. https://doi.org/10.1103/PhysRevLett.114.034101
20. G. Furne Gouveia. (2025). *A Unified Wave-Based Model of Matter, Light, and Space: Stationary Waves in an Elastic, Non-Dispersive Medium*. Preprints 2025.
21. G. Furne Gouveia. (2025). *The Vibrational Fabric of Spacetime: A Model for the Emergence of Mass, Inertia, and Quantum Non-Locality*. Preprints 2025.

 doi:10.20944/preprints202509.0792.v1

22. Urban, M., & Couchot, F. (2013). The quantum vacuum as the origin of the speed of light. *The European Physical Journal D*, 67(3), 58. https://doi.org/10.1140/epjd/e2013-30578-7
23. Peacock, J. A. (1999). *Cosmological Physics*. Cambridge University Press.
24. Planck Collaboration (2018), *Planck 2018 results. VI. Cosmological parameters*.
25. Mohr, P. J., Newell, D. B., Taylor, B. N. (2018), *CODATA Recommended Values of the Fundamental Physical Constants*.
26. Wikipedia contributors, *Observable universe*, (accessed 2025).
27. Binney, J., Tremaine, S. (2008), *Galactic Dynamics*, 2nd ed., Princeton University Press. (Formula for the gravitational binding energy of a uniform sphere).
28. van Dokkum, P., Danieli, S., Cohen, Y., Merritt, A., et al. (2018). *A galaxy lacking dark matter*. Nature, 555(7698), 629–632. https://doi.org/10.1038/nature25767