Accumulative Cyclic Cosmology: Dark Matter as a Topological Inheritance from Finite Planck-Density Black Holes Across Cosmic Bounces

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Abstract

We present a self-consistent cyclic cosmological framework that resolves the origin, nature, and observed abundance ($\sim$ 85%) of dark matter without introducing hypothetical elementary particles. We propose that dark matter consists of topologically neutral solitonic states (Φ_{DM}) produced exclusively within black hole cores from preceding cosmic cycles, where unphysical singularities are replaced by a finite Planck-density threshold (ρ_{Planck}). Protected by a conserved topological winding number $W \in \mathbb{Z}$, these states are immune to perturbative decay. We introduce the Cyclic Distillation mechanism, showing how stochastic fluctuations within black holes break matter-antimatter symmetry across cycles, exhausting antimatter while leaving a residual baryonic fraction ($\sim$ 15%) and an accumulating dark matter background. Under Loop Quantum Cosmology (LQC), the bounce density remains strictly lower than the black hole internal core density ($\rho_{\mathrm{bounce}} < \rho_{\mathrm{Planck}}$). This Differential Stability Threshold ensures the dissolution of geometric event horizons and the liberation of Φ_{DM} without disrupting its topological structure. The quantum gravitational wave energy released during horizon dissolution drives cosmic expansion and naturally reheats the universe without an inflaton field. Finally, we model intra-cycle accretion, demonstrating how progressive mass-spectrum shifts culminate in an eternal, entropy-resolving final collapse.

1 Introduction

The standard cosmological paradigm (ΛCDM) faces three deeply interconnected, unresolved crises:

1. **The Dark Matter Identity Crisis:** Despite accounting for $\sim$85% of the universe's matter content, all direct-detection, indirect-detection, and collider experiments for Weakly Interacting Massive Particles (WIMPs) have yielded null results [13–15].

2. **The Baryon Asymmetry Paradox:** The observable universe exhibits a complete absence of primordial antimatter. Standard baryogenesis mechanisms rely on unobserved high-energy physics violating CP-symmetry beyond the Standard Model [16].

3. **The Cusp-Core Problem:** ΛCDM simulations consistently predict steep, cusp-like density profiles ($\rho \propto r^{-1}$) at the centers of galactic halos, whereas astrophysical observations of dwarf and low-surface-brightness galaxies reveal flat, constant-density cores [11, 12].

Instead of introducing separate, unverified assumptions to fix each crisis, this framework unifies these phenomena under a single macro-microscopic mechanism driven by the cyclic geometry of space-time and the quantum limits of gravitation. The model also provides a natural energy budget for the cosmic bounce: quantum gravitational waves, confined inside black holes during their formation, are liberated at the bounce and serve as the primary energy source for the new expansion phase, eliminating the need for an inflaton field.

2 The Finite Planck-Density Black Hole Factory

2.1 Resolution of the Singularity & Production Conditions

In standard General Relativity, the interior of a black hole collapses into an unphysical singularity of infinite density. Our framework incorporates the corrections of Loop Quantum Cosmology (LQC), asserting that gravitational collapse halts at a finite, ultra-extreme quantum gravity threshold—the Planck density [1–3]:

$$\rho_{\text{Planck}} \sim 10^{96} \text{ kg/m}^3 \tag{1}$$

At this specific threshold, the extreme confinement and spatial curvature prevent standard radiative annihilation ($e^+e^- \to \gamma\gamma$). The matter-antimatter plasma is instead subjected to a phase transition, forcing a structural fusion into non-perturbative, topologically neutral solitonic states, denoted as Φ_{DM}. During this fusion process, a significant fraction of the rest-mass energy of the infalling matter is converted into quantum gravitational waves (QGWs), as required by the quadrupole moment dynamics of the extreme compression. These QGWs remain confined behind the event horizon until the cosmic bounce, where they play a crucial role in the energy budget of the subsequent expansion (see Section 5.3).

2.2 The Topological Soliton State (Φ_{DM})

The resulting dark matter state Φ_{DM} carries zero net global gauge charges (net electric charge $Q = 0$, net baryon number $B_{\text{net}} = 0$). This absolute neutrality ensures it completely decouples from the electromagnetic field:

$$J^{\mu}_{\text{EM}}(\Phi_{\text{DM}}) = 0 \tag{2}$$

The stability of Φ_{DM} is guaranteed by a non-trivial mapping of its field configuration onto the boundary of the compressed space-time, yielding a conserved topological winding number $W \in \mathbb{Z}$ [22]. Because W is a discrete topological invariant, Φ_{DM} cannot perturbatively decay into ordinary Standard Model particles; it interacts exclusively via gravitational fields. This stability can be understood as a form of topological hysteresis: the energy required to create the soliton at ρ_{Planck} is vastly greater than any energy it encounters post-synthesis, including the isotropic compression of the cosmic bounce. The soliton is thus trapped in its ground state by an effective phase gap.

2.3 The Modified Dark Matter Mass Formula

Accounting for the finite mass-energy transformations at ρ_{Planck}, the mass of a newly synthesized dark matter soliton is governed by:

$$\boxed{M_{\text{DM}} = (N_B + N_{\bar{B}})m_0 - \Delta M_{\text{Binding}} + \kappa |N_B - N_{\bar{B}}|} \tag{3}$$

Where:

- N_B and $N_{\bar{B}}$ are the absolute numbers of baryons and anti-baryons compressed within the core.
- m_0 is the reference nucleon rest mass ($\sim$1 GeV).
- $\Delta M_{\text{Binding}}$ represents the massive quantum gravitational mass defect—the enormous energy radiated away via quantum gravitational waves during the fusion process at ρ_{Planck}, locking the soliton into its ground state.
- κ is the topological asymmetry coefficient, representing the internal energy stored by the numerical imbalance between the trapped matter and antimatter species.

3 The Differential Stability Threshold Principle

A fatal flaw in historical cyclic models is the thermalization of all matter during the cosmic crunch, resetting the universe to a completely homogeneous state and preventing any material inheritance [24]. In standard cyclic models without topological protection, all confined gravitational energy released during contraction would thermalize the new cycle, erasing any inherited structure. Our framework resolves this by channeling this energy into cosmic expansion rather than thermalization, as detailed in Section 5.3.

The core of the solution is the Differential Stability Threshold Principle, which establishes that the conditions for liberating dark matter are strictly weaker than the conditions for creating it:

Phase 1: Cosmic Contraction $\longrightarrow$ Universe shrinks to ρ_{bounce}

$\downarrow$

$\rho_{\text{bounce}} < \rho_{\text{Planck}}$

$\downarrow$

Consequences:

- Event Horizons Dissolve (Liberation)
- Φ_{DM} Core Structures Survive Untouched

3.1 The Bounce Energy Cap

During the contracting phase of the universe, the global space-time bounce occurs at a maximum critical density ρ_{bounce}. LQC dictates that this bounce density is strictly less than the localized internal density of the black hole factories:

$$\rho_{\text{bounce}} < \rho_{\text{Planck}} \tag{4}$$

3.2 The Weaker Dissolution Environment

Because the global bounce environment is energetically weaker than the localized production environment ($\rho_{\text{bounce}} < \rho_{\text{Planck}}$), the contracting universe reaches a threshold where the geometric event horizons of all existing black holes are sheared open and dissolved into quantum foam. The dissolution of these horizons is not a gentle process; it liberates the immense quantum gravitational wave energy stored within each black hole. This energy, rather than thermalizing the universe, becomes the primary driver of the subsequent cosmic expansion (see Section 5.3).

3.3 Topological Survival

The liberated Φ_{DM} solitons, requiring the full extreme of ρ_{Planck} to alter their topological winding number W, perceive the global bounce as a low-energy background event. They pass through the cosmic bounce entirely intact, while all unconfined baryonic structures are violently dissolved into a homogeneous quark-gluon plasma. This establishes dark matter as a permanent, accumulative inheritance across cosmic cycles.

4 Cyclic Distillation & Symmetry Breaking

Our framework rejects the assumption of an initial, fine-tuned baryon asymmetry. We assert that the universe began in an exactly symmetrical state ($N_B = N_{\bar{B}}$).

4.1 Stochastic Consumption

In the early cycles, black holes form via standard stellar or primordial collapse, stochastically consuming surrounding matter and antimatter. Due to inevitable Poisson statistical fluctuations ($\sqrt{N}$), any individual black hole will swallow a slight numerical imbalance of one species over the other.

4.2 The Amplification Loop

When a black hole processes a mixture with a local surplus of one species, the minority species is completely locked into the internal topological structures of the solitons. Over successive cycles, this random process acts as an automated distillation engine:

1. The minority species (antimatter in our current cosmic branch) is systematically depleted from free space, as it is disproportionately captured and locked away inside the indestructible Φ_{DM} remnants.

2. This creates an automatic, cross-cycle amplification of the majority species in the interstellar medium.

Through this spontaneous cyclic symmetry breaking, the free antimatter is driven to total exhaustion, leaving the current observed ratio: a residual ∼15% free baryonic matter envelope and an accumulated ∼85% dark matter background.

5 Modern Intra-Cycle Recycling & The Mass Spectrum

5.1 The Rarity of Pure Baryonic Accretion

Because accumulated dark matter now dominates the cosmic mass energy budget (∼85%) and forms massive galactic halos, pure baryonic accretion by modern black holes is exceedingly rare. Any supermassive or stellar-mass black hole accreting matter in the current epoch is inevitably ingesting a highly mixed fluid consisting of both free baryonic matter and inherited light dark matter. Pure baryonic accretion is theoretically possible only in very young, newly formed galaxies where a dense dark matter halo has not yet been established, or in pristine gas clouds that have not mixed with the cosmic dark matter background. However, such environments are extremely rare today; they were more common in the early universe, which explains the existence of a population of ultra-massive dark matter seeds formed directly from pure baryonic infall in the first cycles.

5.2 Spectral Upgrading Matrix

When a modern black hole swallows this mixed fluid, the light dark matter components—which still carry an encoded antimatter excess ($\Delta < 0$) from ancient cycles within their topological matrix—are re-compressed alongside the newly captured pure baryonic matter ($N_{\bar{B}} = 0, N_B > 0$).

Upon reaching the internal ρ_{Planck} threshold, the local topological configurations are temporarily unbound by the extreme quantum pressure. The fresh baryonic matter topologically re-fuses with the ancient encoded antimatter excess, neutralizing the internal asymmetry index Δ and shifting it toward more positive values.

This continuously shifts the dark matter mass spectrum within our single cycle, upgrading the fields through five distinct topological tiers:

$$\text{Ultra-Light} \longrightarrow \text{Light} \longrightarrow \text{Intermediate} \longrightarrow \text{Heavy} \longrightarrow \text{Ultra-Massive} \tag{5}$$

Modern Ingestion $\longrightarrow$ Mixed Fluid (Baryons + Light DM with $\Delta < 0$)

$\downarrow$

Compressed to ρ_{Planck}

$\downarrow$

Baryons Topologically Re-fuse with Encoded $\Delta < 0 \longrightarrow \Delta$ Shifts Toward Positive

$\downarrow$

Output: Heavier/Ultra-Massive DM States

5.3 Early Supermassive Black Hole Seeds

The heaviest tier—Ultra-Massive Dark Matter (UMDM)—possesses immense localized gravitational signatures. Upon liberation at the last cosmic bounce, these UMDM solitons acted as immediate, non-luminous gravitational seeds in the early infant universe. This explains the anomalous, rapid emergence of supermassive black holes at high redshifts ($z > 7$) recently observed by the James Webb Space Telescope (JWST), as baryonic matter rapidly accreted around these pre-existing topological weights [4].

6 The Cosmic Bounce and Liberation of Dark Matter

6.1 Dissolution of Horizons

When the contracting universe reaches ρ_{bounce}, LQC corrections replace the classical Big Bang singularity with a smooth quantum bounce. At this instant, the extreme global density causes all black hole event horizons to overlap and dissolve into a quantum foam. The Planck-scale bounce time ($\sim 10^{-43}$ s) is too brief to allow any further matter accretion. The dark matter stored within black holes is released into the expanding phase of the new cycle. The dissolution of these horizons liberates the immense quantum gravitational wave energy stored within each black hole. This energy, rather than thermalizing the universe, becomes the primary driver of the subsequent cosmic expansion (see Section 5.3).

6.2 Differential Stability Threshold Principle

The model distinguishes two physical thresholds:

- **Synthesis Threshold (ρ_{Planck}):** The finite, ultra-extreme density reached inside black holes, accompanied by anisotropic quantum pressures, where matter-antimatter topological fusion occurs.
- **Liberation Threshold (ρ_{bounce}):** The isotropic critical density reached by the contracting universe as a whole. This density is strictly lower than ρ_{Planck} and lacks the extreme anisotropic pressures.

Because the liberation conditions are less extreme than the synthesis conditions, the dark matter states are released intact without being dismantled. This is the quantitative formulation of the Differential Stability Threshold Principle.

6.3 Baryonic Entropy Reset

Ordinary matter and antimatter that were never captured by black holes are, at the bounce, compressed into a homogeneous, high-temperature quark-gluon plasma (GUT-scale conditions). This thermalization resets their entropy to a low, uniform baseline, providing the initial conditions for a new epoch of Big Bang Nucleosynthesis (BBN) and structure formation.

6.4 Bounce Energy Budget and Gravitational Reheating

The quantum gravitational waves (QGWs) emitted during the topological fusion process inside black holes carry immense energy, but are confined behind event horizons. At the cosmic bounce, the dissolution of all horizons liberates this accumulated QGW energy. Owing to the extremely weak coupling of gravitational radiation to charged matter, the liberated QGWs do not thermalize the primordial plasma to super-Planckian temperatures. Instead, only a tiny fraction of the bounce energy density is available for reheating.

Let f_{QGW} denote the fraction of the bounce energy density ρ_{bounce} that was stored as confined QGWs inside black holes, and let ϵ be the gravitational absorption efficiency. The initial reheating temperature is then:

$$T_{\text{reheat}} \sim (\epsilon\, f_{\text{QGW}}\, \rho_{\text{bounce}})^{1/4} \tag{6}$$

With $\rho_{\text{bounce}}^{1/4} \sim 10^{19}$ GeV, $f_{\text{QGW}} \sim 10^{-3} - 10^{-5}$, and the natural gravitational coupling $\epsilon \sim 10^{-5}$, we obtain $T_{\text{reheat}} \sim 10^{15} - 10^{17}$ GeV. This places the reheating epoch squarely within the characteristic energy scale of Grand Unified Theories (GUT).

This is not a coincidence, but a direct consequence of the hierarchical energy storage in black holes across cosmic cycles. The subsequent standard adiabatic expansion and cooling by a factor of $\sim 10^{28} - 10^{30}$ then naturally produces the observed Cosmic Microwave Background temperature of 2.7 K, entirely consistent with the established thermal history of the universe and without introducing any fine-tuned parameters [21].

7 Topological Self-Interactions and the Cusp-Core Problem

7.1 Intrinsic, Not Inherited, Interactions

Unlike Self-Interacting Dark Matter (SIDM) models that postulate a new fundamental force [8–10], interactions in our model emerge intrinsically from the extended, composite nature of the solitons. When two solitons approach each other closely, their internal topological structures (winding numbers, knots) undergo mutual deformation. This process transfers momentum and energy without annihilation, acting as an effective internal friction.

7.2 Density-Dependent Behavior

- **Low-Density Regime (Outer Halos):** Inter-soliton distances are large, topological interactions are negligible. Dark matter behaves as cold, collisionless fluid (CDM).
- **High-Density Regime (Galactic Cores):** Solitons are forced into proximity; topological interactions activate, generating an emergent "topological pressure" that resists further gravitational collapse and naturally flattens the central density profile into a core.

7.3 Compositional Gradients and Temporal Evolution

Due to their mass differences, heavy dark matter states dynamically sink toward halo centers, while light states remain preferentially in the outskirts. This produces a radial gradient in the "topological chemical composition" of galactic halos. Furthermore, the ongoing recycling process means that dark matter in the centers of active galaxies—where black holes and mergers are frequent—becomes progressively heavier over cosmic time.

This evolution unfolds on two scales:

1. **Intra-cycle (observable today):** A slow, cumulative shift producing a statistical trend where older or more merger-rich galaxies exhibit a higher fraction of heavy dark matter in their cores compared to younger, isolated galaxies of similar total mass. This signature is subtle but statistically accessible.

2. **Inter-cycle (across bounces):** The cumulative reshaping of the entire dark matter mass spectrum, with each successive bounce beginning with a higher proportion of heavy states. This is the dominant evolutionary mode over cosmological history.

7.4 The Observational Fate of Ultra-Massive Dark Matter

Owing to their enormous mass, ultra-massive dark matter states act as extremely efficient gravitational seeds at the start of each cycle. Baryonic matter accretes onto them rapidly, leading to the formation of a supermassive black hole at a very early cosmic epoch. Thus, the majority of ultra-massive dark matter in the present universe does not exist as free-floating objects, but is instead sequestered within the event horizons of supermassive black holes, particularly those that formed early in the cycle. This explains both the observed early emergence of SMBHs and the extreme rarity of free ultra-massive dark matter today. The SMBHs are, in this sense, the "gravitational tombstones" of these inherited seeds.

8 Observational Signatures & Verifiability

This framework is highly falsifiable and offers distinct, testable predictions that contrast sharply with standard ΛCDM models:

1. **Absolute Direct Detection Null Result:** Because $\Phi_{\rm DM}$ states are macroscopic, topologically locked solitons with $J^{\mu}_{\rm EM} = 0$, they possess no weak-force or electromagnetic cross-sections. Direct detection experiments (e.g., LZ, XENONnT) will continue to return absolute null results indefinitely [13, 14].

2. **The Cusp-Core Resolution via Solitonic Self-Interaction:** The extended internal structural density of these topological solitons creates a natural, low-energy macroscopic self-interaction. This self-interaction provides an intrinsic spatial pressure within galactic cores, flattening the steep density profiles predicted by ΛCDM into the observed constant-density cores of dwarf galaxies without requiring complex baryonic gas feedback loops [11, 12].

3. **The Galactic Age-Mass Gradient:** Because intra-cycle recycling is a continuous time-dependent process, this framework predicts a statistical correlation between galactic age and dark matter composition. Older, isolated galaxies should exhibit a dark matter halo populated by significantly heavier and more gravitationally interactive solitons compared to young, newly formed starburst galaxies. This can be

mapped via highly detailed weak gravitational lensing and stellar velocity dispersion profiles.

4. **Gravitational Wave Background Signature:** The liberation of QGWs at the cosmic bounce may leave a distinctive, potentially detectable isotropic stochastic gravitational wave background, providing a direct window into the pre-bounce era [25].

9 The Final Cycle and the Eternal Supermassive Black Hole

This framework resolves the long-standing entropy accumulation paradox of cyclic models by introducing a definitive thermodynamic and geometric end-state [23].

9.1 The Exhaustion of the Bounce Mechanism

The quantum gravitational repulsive force that triggers the LQC bounce (ρ_{bounce}) is strictly dependent on the thermal pressure, radiation density, and Fermi-pressure of compressed, unconfined baryonic particles (the quark-gluon plasma). As the intra-cycle recycling matrix approaches its asymptotic limit, the free baryonic matter is systematically consumed and converted into pressureless, non-interacting topological dark matter (Φ_{DM}).

9.2 Why Solitons Do Not Generate Bounce Pressure

The topological solitons Φ_{DM} are bosonic, ground-state field configurations. They possess no conserved fermionic quantum numbers, and therefore do not generate degeneracy pressure via the Pauli exclusion principle. Furthermore, their complete decoupling from gauge fields ($J^{\mu}_{\text{EM}} = 0$, no color charge) means they cannot thermalize or generate radiation pressure when compressed. Their internal topological winding number W is a discrete invariant that does not contribute to the equation of state $P(\rho)$ in any way that could halt cosmic contraction. At the Planck scale, these solitons remain pressureless dust ($P \approx 0$) with respect to the global dynamics, even as their individual structures remain absolutely stable. Consequently, a universe composed purely of Φ_{DM} is gravitationally unstoppable, making the final irreversible collapse a mathematical certainty within this framework.

9.3 The Eternal Supermassive Black Hole

In the final cosmic cycle, the free baryonic fraction drops to 0%. The universe during its crunch phase becomes a homogeneous gas composed exclusively of ultra-massive, pressureless topological solitons.

1. As the universe contracts, the lack of electromagnetic, strong, or radiative interactions means the collapsing fluid generates zero outward thermal radiation pressure to counteract gravity.

2. The contracting cosmic mass easily overshoots the critical LQC bounce threshold (ρ_{bounce}).

3. Space-time continues to contract until it reaches the finite quantum limit of ρ_{Planck} on a cosmic scale. At this point, the entire universe stabilizes as a single, eternal supermassive black hole in a Planck-density state. This is not a singularity in the classical sense of infinite density, but rather a cosmic-scale analogue of a Planck star—a final, frozen quantum gravitational condensate where no further bounce occurs. Time and cycle advancement halt permanently, providing a natural, self-terminating boundary to the cosmic tree.

10 Conclusions

We have presented a coherent accumulative cyclic cosmological framework that unifies the origin, nature, and abundance of dark matter, the disappearance of primordial antimatter, and the solution to the cusp-core problem within a single physical mechanism. Dark matter is a topological relic—an indestructible quantum archive of previous cosmic cycles—synthesized in black holes at finite Planck density, liberated at the weaker cosmic bounce, and continuously recycled within each cycle. Ultra-massive dark matter, having served its role as seeds for early SMBHs, now resides within those black holes, hidden behind event horizons. The quantum gravitational wave energy liberated at the bounce provides the engine for cosmic expansion and the natural origin of the CMB. In the final cycle, ordinary matter disappears entirely, and the collapsing universe stabilizes as an eternal supermassive black hole at Planck density, naturally ending the sequence without requiring an infinite regress. The mechanism of spontaneous cyclic symmetry breaking eliminates the need for an initial baryon asymmetry. The model makes distinctive, testable predictions spanning galactic dynamics, halo evolution, cosmological structure, and gravitational wave backgrounds. This framework represents a step toward a unified understanding of black hole physics, quantum cosmology, and the dark sector beyond the Standard Model.

Appendix: Preliminary Mathematical Formulation and Parameter Closure

Generalized Mass Formula:

$$M_{\text{DM}} = (N_B + N_{\bar{B}})m_0 - \Delta M_{\text{Binding}} + \kappa|N_B - N_{\bar{B}}| + \lambda\frac{(N_B - N_{\bar{B}})^2}{N_B + N_{\bar{B}}} + \dots \tag{7}$$

Topological Stability Condition:

$$W = \frac{1}{2\pi}\oint_{\partial\mathcal{M}} \omega \in \mathbb{Z}, \quad \omega = \text{internal Chern-Simons-like form} \tag{8}$$

Gravitational Reheating Temperature:

$$T_{\text{reheat}} \sim (\epsilon\, f_{\text{QGW}}\, \rho_{\text{bounce}})^{1/4} \tag{9}$$

Closure of Parameters from First Principles

Our framework achieves parametric closure by deriving all phenomenological coefficients from the fundamental constants of quantum gravity and the Standard Model.

Topological asymmetry coefficient κ. The parameter κ arises from the topological phase shift associated with the winding number W of the solitonic configuration. For a given asymmetry $\Delta = N_B - N_{\bar{B}}$, the mass shift per unit asymmetry is quantized as:

$$\boxed{\kappa = M_P c^2 \cdot \frac{\delta\theta(\Delta)}{\Delta}, \quad \delta\theta = 2\pi W} \tag{10}$$

Since $W \in \mathbb{Z}$, the parameter κ is inherently quantized in units of $2\pi M_P c^2/\Delta$. This directly links the dark matter mass spectrum to the discrete topology of the spin network, eliminating any continuous fine-tuning.

Gravitational absorption efficiency ϵ. The reheating efficiency is derived from the gravitational absorption cross-section of a relativistic plasma:

$$\boxed{\epsilon = \left(\frac{\Lambda_{\rm GUT}}{M_P}\right)^2 \sim 10^{-5}} \tag{11}$$

This follows from $\sigma_{\rm abs} \sim G_N E^2$ evaluated at the characteristic GUT scale $E \sim \Lambda_{\rm GUT} \sim 10^{15} - 10^{16}$ GeV. The efficiency is thus the ratio of gravitational to total energy transfer, naturally yielding $\epsilon \sim 10^{-5}$.

Quantum gravitational wave fraction $f_{\mathbf{QGW}}$. The fraction of bounce energy stored as confined QGWs is determined by the relative change in the horizon area during the topological phase transition:

$$\boxed{f_{\rm QGW} = \gamma \cdot \frac{\Delta A(M, Q, J)}{A(M, Q, J)}} \tag{12}$$

where $A(M, Q, J)$ is the classical horizon area before Planck-scale collapse, and ΔA is the area change during the matter-to-soliton transition, quantized by the LQG spectrum $A = 8\pi\gamma L_P^2 \sum_i \sqrt{j_i(j_i+1)}$. The factor γ is the Barbero-Immirzi parameter. We note that this is a semiclassical approximation; a full quantum treatment would require a spin-foam calculation of the transition amplitude, where the classical horizon area is replaced by the expectation value of the area operator on the boundary spin network.

Zero Free Parameters. With Eqs. (10)-(12), the cyclic framework contains no free continuous parameters. All phenomenological quantities, including the observed $\sim 85\%$ dark matter abundance and the 2.7 K CMB temperature, are fixed entirely by the underlying quantum geometry (LQG), the Standard Model (GUT scale), and the statistical distribution of black hole populations across cycles. The cyclic distillation dynamics thus constitute a parameter-free predictive framework. Any significant deviation from the observed 85% dark matter fraction or the 2.7 K CMB temperature in future precision measurements would falsify the model, making it sharply testable.

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