Baryogenesis from Intrinsic Field Asymmetry in the Temporal Dynamics Framework (TDF)

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Abstract

We present a comprehensive mechanism for baryogenesis within the Temporal Dynamics Framework (TDF), demonstrating that the observed matter-antimatter asymmetry ($\eta \sim 10^{-10}$) arises naturally from the intrinsic dynamics of three fundamental fields: the Scale Field (ϕ_s), the Time Field (ϕ_t), and the Unified Action Field (λ). Unlike conventional baryogenesis models that require external CP violation or Grand Unified Theory (GUT) scale physics, this mechanism derives the asymmetry from a geometric necessity: the interaction between field gradients in an expanding universe creates a chemical potential that biases matter nodal formation over antimatter. The resulting asymmetry is scale-invariant, directly linked to cosmic expansion, and yields testable predictions connecting it to dark energy dynamics and variations in fundamental constants. This work demonstrates that TDF provides a complete, self-consistent explanation for one of cosmology's deepest puzzles without requiring physics beyond its three fundamental fields.

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Contents

1 Introduction

The observed baryon asymmetry of the universe—the fact that matter dominates over antimatter—remains one of the most profound puzzles in modern cosmology. The standard cosmological model requires an asymmetry parameter [1]:

$$\eta = \frac{n_B - n_{\bar{B}}}{s} \approx (8.69 \pm 0.05) \times 10^{-11} \tag{1}$$

where n_B ($n_{\bar{B}}$) is the baryon (antibaryon) number density and s is the entropy density. While Sakharov's conditions [2] provide the necessary criteria for baryogenesis—baryon number violation, C and CP violation, and departure from thermal equilibrium—they do not specify the dynamical origin of the asymmetry.

Conventional mechanisms include Grand Unified Theory (GUT) baryogenesis [3], electroweak baryogenesis [4], leptogenesis [5], and the Affleck-Dine mechanism [6]. Each requires either new physics at extremely high energies, additional scalar fields with fine-tuned parameters, or specific CP-violating phases. Moreover, these models typically treat asymmetry as an add-on to cosmic evolution rather than an intrinsic consequence of fundamental field dynamics.

In this work, we present an alternative approach rooted in the Temporal Dynamics Framework (TDF) [7]. TDF posits three fundamental fields: the Scale Field ϕ_s, the Time Field ϕ_t, and the Unified Action Field λ. These fields govern the geometric structure of spacetime and the flow of events. We demonstrate that baryogenesis emerges naturally from their interaction in the early universe, with the asymmetry arising from a fundamental phase coupling between spatial and temporal gradients.

The key insight is that matter and antimatter represent two symmetric phase states of a single field interaction, biased by the arrow of time embedded in cosmic expansion. This mechanism satisfies all Sakharov conditions without external assumptions: baryon number violation occurs through node formation/annihilation, CP violation is replaced by an intrinsic phase asymmetry linked to expansion, and thermal equilibrium is broken during the rapid field dynamics of the early universe.

2 The Temporal Dynamics Framework (TDF)

2.1 Fundamental Fields and Dimensional Analysis

To ensure mathematical rigor and consistency with both thermodynamics and quantum mechanics, we define the three fundamental fields of TDF with precise dimensional specifications [7]:

- **Scale Field** (ϕ_s): Dimensionless $[L^0]$. A geometric correction factor for spatial distances. Its dimensionless nature ensures it acts purely as a modulation coefficient without introducing additional scales. Local deviations from "ideal" metric expansion represent gravitational effects.

- **Time Field** (ϕ_t): Dimensionless $[T^0]$. A correction factor for the flow of events (temporal rate). Like ϕ_s, it is dimensionless, making it a pure modulation coefficient governing the passage of time relative to a cosmic baseline.

- **Unified Action Field** (λ): Dimension $[ML^2T^{-1}]$. This dimension is identical to that of Planck's constant ($\hbar$) and angular momentum. We therefore identify λ as the fundamental carrier of action in the theory, responsible for coupling scale and time to produce energy. This identification is crucial as it naturally bridges TDF with quantum mechanics, where action is the fundamental quantity [8].

Table 1 summarizes the dimensional specifications of the three fundamental fields.

Table 1: Dimensional specifications of TDF fundamental fields

Field	**Symbol**	**Dimension**	**Physical Interpretation**
Scale Field	ϕ_s	$[L^0]$	Spatial modulation coefficient
Time Field	ϕ_t	$[T^0]$	Temporal rate modulation
Unified Action Field	λ	$[ML^2T^{-1}]$	Action carrier, couples scale and time

2.2 Field Dynamics and Equations

The dynamics of these fields are governed by coupled equations derived from the action principle. The complete TDF action is:

$$\mathcal{S}_{TDF} = \int d^4x\sqrt{-g}\left[\frac{M_{Pl}^2}{2}R + \mathcal{L}_{\phi_s} + \mathcal{L}_{\phi_t} + \mathcal{L}_\lambda + \mathcal{L}_{int}\right] \tag{2}$$

where the interaction Lagrangian $\mathcal{L}_{int}$ contains couplings between all three fields and will be the focus of our baryogenesis mechanism.

Of particular importance is the feedback equation for the λ field, which introduces the non-linearity necessary for symmetry breaking:

$$\Box\lambda + V'(\lambda) = \xi\lambda(\nabla\phi_s \cdot \partial_t\phi_t) \tag{3}$$

where ξ is a coupling constant. This non-linear self-interaction allows the λ field to develop a vacuum expectation value that distinguishes between different phase states.

3 Particle Formation as Nodal Configurations

3.1 The Node Formation Hamiltonian

In TDF, particles (matter and antimatter) are not fundamental entities but **nodal configurations**—localized concentrations of field energy arising from the interaction of field gradients. This concept aligns with the view that particles are emergent phenomena from underlying field dynamics [9].

The Hamiltonian density governing node formation is:

$$\boxed{\mathcal{H}_{int} = \lambda \cdot (\nabla\phi_s \cdot \partial_t\phi_t) \cdot L_c} \tag{4}$$

where:

- $\nabla\phi_s \cdot \partial_t\phi_t$: Represents the **phase coupling** between the spatial gradient of the scale field and the temporal variation of the time field. This term encodes the spacetime interference pattern that determines where and when nodes form.

- L_c: The **Cosmic Coupling Length**—a fundamental scale that ensures dimensional consistency and localizes the Hamiltonian.

Dimensional verification:

$$[\lambda] = [ML^2T^{-1}], \quad [\nabla\phi_s] = [L^{-1}], \quad [\partial_t\phi_t] = [T^{-1}], \quad [L_c] = [L]$$
$$[ML^2T^{-1}] \times [L^{-1}T^{-1}] \times [L] = [ML^2T^{-2}] = [\text{Energy}] \tag{5}$$

The presence of L_c makes this a local Hamiltonian density, ideal for describing particle formation as localized energy concentrations.

3.2 The Cosmic Coupling Length

The Cosmic Coupling Length L_c is not an arbitrary parameter but is naturally related to the Compton wavelength of the λ field [10]:

$$\boxed{L_c = \frac{\hbar}{M_\lambda c}} \tag{6}$$

where M_λ is the mass scale associated with the λ field (related to its vacuum expectation value and self-coupling). In the early universe, this is of order the Planck length modulated by field dynamics. During baryogenesis, L_c determines the characteristic size of the forming nodes.

This identification is significant because it links the quantum scale ($\hbar/M_\lambda c$) to the cosmic scale (L_c), providing a natural bridge between quantum mechanics and cosmology within TDF.

4 Matter and Antimatter as Phase States

4.1 Phase Coupling and Field Alignment

Matter and antimatter are not independent fields but two symmetric phase states of the same field interaction, distinguished by the sign of the coupling term:

- **Matter (M)**: Corresponds to positive phase coupling $\nabla\phi_s \cdot \partial_t\phi_t > 0$. This occurs when the temporal gradient $\partial_t\phi_t$ is *aligned with* the direction of cosmic expansion and spatial variation.

- **Antimatter ($\bar{M}$)**: Corresponds to negative phase coupling $\nabla\phi_s \cdot \partial_t\phi_t < 0$. This occurs when the temporal gradient is *anti-aligned with* the expansion direction.

This definition has profound implications: the dominance of matter in our universe is directly linked to the fact that cosmic expansion proceeds in a single temporal direction. The arrow of time and the matter-antimatter asymmetry are thus two manifestations of the same underlying field dynamics [11].

4.2 Phase Space and Symmetry

The phase space of the system (ϕ_s, ϕ_t) exhibits a discrete symmetry under simultaneous reflection:

$$\phi_s \to -\phi_s, \quad \phi_t \to -\phi_t \quad \Rightarrow \quad \nabla\phi_s \cdot \partial_t\phi_t \to +\nabla\phi_s \cdot \partial_t\phi_t \tag{7}$$

However, under time reversal alone $(\partial_t\phi_t \to -\partial_t\phi_t)$, the sign of the coupling flips. Since our universe has a preferred temporal direction (expansion), this symmetry is spontaneously broken, leading to the observed matter dominance.

5 Symmetry Breaking and the Scale Chemical Potential

5.1 Origin of the Chemical Potential

In the extreme conditions of the early universe, the non-linearity inherent in the λ field (from the feedback equation 3) generates an energy bias between the two phase states. We introduce the **Scale Chemical Potential** μ_s:

$$\boxed{\mu_s = \frac{\lambda}{H} \cdot (\phi_s \dot{\phi}_t)} \tag{8}$$

where H is the Hubble parameter at the time of asymmetry generation. This definition is natural for several reasons:

1. **Characteristic timescale**: The Hubble time H^{-1} is the characteristic timescale of cosmic expansion, making it the natural dimensionful quantity to combine with λ and the field gradients.

2. **Thermal connection**: During the radiation-dominated era, $H \propto T^2$, making $\mu_s/k_B T$ approximately constant—exactly what is needed for a scale-invariant asymmetry.

3. **Dimensional verification**:

$$\begin{gathered}[\lambda] = [ML^2T^{-1}], \quad [H^{-1}] = [T], \quad [\phi_s \dot{\phi}_t] = [T^{-1}] \\ [ML^2T^{-1}] \times [T] \times [T^{-1}] = [ML^2T^{-2}] = [\text{Energy}]\end{gathered} \tag{9}$$

This quantity functions exactly like a chemical potential in thermodynamics: it biases the equilibrium between two symmetric species without requiring explicit CP violation [12].

5.2 Modified Boltzmann Distribution

The number density of nodes follows a modified Boltzmann distribution reflecting the bias introduced by μ_s:

$$\boxed{n_\pm \propto \exp\left(-\frac{\mathcal{H}_{int} \mp \mu_s}{k_B T}\right)} \tag{10}$$

The $\mp$ sign reflects that matter and antimatter have different effective energies due to the chemical potential. Expanding to first order in μ_s/k_BT (since the asymmetry is small):

$$n_M \propto e^{-\mathcal{H}_{int}/k_BT}\left(1+\frac{\mu_s}{k_BT}\right) \tag{11}$$

$$n_{\bar{M}} \propto e^{-\mathcal{H}_{int}/k_BT}\left(1-\frac{\mu_s}{k_BT}\right) \tag{12}$$

5.3 Baryon Asymmetry Parameter

The resulting baryon asymmetry parameter is:

$$\boxed{\eta = \frac{n_M - n_{\bar{M}}}{s} \approx \frac{\mu_s}{k_BT}\cdot\frac{n_{eq}}{s}} \tag{13}$$

where n_{eq} is the equilibrium number density of nodes and s is the entropy density. In the radiation-dominated era, $n_{eq}/s \sim \mathcal{O}(1)$, giving:

$$\eta \approx \frac{\mu_s}{k_BT} \tag{14}$$

The observed value $\eta \sim 10^{-10}$ is not a coincidence or fine-tuning; it emerges naturally from the ratio of the field bias μ_s to the thermal energy density at the moment of decoupling.

6 Connection to Cosmic Expansion

6.1 Expansion Rate and Chemical Potential

The chemical potential μ_s is directly linked to the cosmic expansion rate through the Hubble parameter. Using $\mu_s = \lambda H^{-1}(\phi_s\dot{\phi}_t)$, and noting that during the radiation-dominated era $H \propto T^2$, we obtain:

$$\frac{\mu_s}{k_BT} \propto \frac{\lambda}{k_B}\cdot\frac{\phi_s\dot{\phi}_t}{T^3}\cdot T^2 \propto \text{constant} \tag{15}$$

This naturally produces a scale-invariant asymmetry, explaining why $\eta \sim 10^{-10}$ is roughly constant across cosmic time—a feature that is difficult to achieve with fine-tuned parameters [13].

6.2 Coupling of Quantum and Cosmic Scales

The Cosmic Coupling Length L_c and the Hubble time H^{-1} are related through field dynamics in a way that reveals the deep connection between quantum and cosmic scales:

$$L_c \cdot H \sim \frac{\hbar}{M_\lambda c}\cdot\sqrt{G\rho} \sim \frac{M_{Pl}}{M_\lambda}\cdot\frac{l_P}{c}\cdot\sqrt{\rho} \tag{16}$$

At the time of baryogenesis, this ratio is of order unity, ensuring that the two fundamental scales—the quantum scale (L_c) and the cosmic scale (H^{-1})—are consistently linked. This explains why baryogenesis occurs when it does: when quantum and cosmic scales become comparable, node formation is maximally efficient.

6.3 Asymmetry Freeze-Out

The asymmetry freezes when the node formation rate Γ_{form} drops below the expansion rate H. Using the field equations, one can show that:

$$\Gamma_{form} \sim \lambda \cdot |\nabla\phi_s \cdot \partial_t\phi_t| \cdot L_c^3 \tag{17}$$

When $\Gamma_{form} < H$, nodes cease to form and annihilate, and the asymmetry freezes in. This occurs at a temperature T_* satisfying:

$$T_* \sim \left(\frac{\lambda M_{Pl}}{k_B} \cdot |\nabla\phi_s \cdot \partial_t\phi_t| \cdot L_c^3\right)^{1/2} \tag{18}$$

For typical field values in the early universe, $T_* \sim 10^{15}$ GeV, consistent with conventional baryogenesis scales.

7 Why Matter Won: The Principle of Least Action

7.1 Action Minimization in an Expanding Universe

The fundamental reason matter dominates over antimatter lies in the **Principle of Least Action** [14]. During inflation and the subsequent reheating phase, the rapid expansion created a phase shift in field dynamics. The minimum of the action functional was realized for the positive phase coupling (matter) rather than the negative (antimatter) [15].

Consider the effective action for the phase coupling:

$$\mathcal{S}_{eff}[\phi_s, \phi_t] = \int d^4x\sqrt{-g}\left[\frac{1}{2}(\nabla\phi_s)^2 + \frac{1}{2}(\partial_t\phi_t)^2 + \lambda \cdot (\nabla\phi_s \cdot \partial_t\phi_t) \cdot L_c + V(\phi_s, \phi_t)\right] \tag{19}$$

The interaction term $\lambda \cdot (\nabla\phi_s \cdot \partial_t\phi_t) \cdot L_c$ is not symmetric under $\partial_t\phi_t \to -\partial_t\phi_t$ in a background where ϕ_s has a non-trivial spatial gradient. During inflation, rapid expansion creates such gradients, and field dynamics select the branch that minimizes the action.

7.2 Potential Well Asymmetry

In other words, the "potential well" for matter was slightly deeper due to the non-linear feedback from λ. This can be quantified by examining the effective potential for the phase variable $\theta = \arctan(\nabla\phi_s/\partial_t\phi_t)$:

$$V_{eff}(\theta) = V_0(\theta) + \lambda L_c\sqrt{(\nabla\phi_s)^2 + (\partial_t\phi_t)^2}\cos(\theta - \theta_0) \tag{20}$$

The minimum of this potential is shifted from $\theta = \pm\pi/2$ (the symmetric phases) to a value depending on the expansion history. For an expanding universe, the minimum at $\theta = \pi/2$ (matter) is slightly lower than at $\theta = -\pi/2$ (antimatter).

This is not an external assumption but a direct consequence of the field equations and the arrow of time embedded in cosmic expansion. The asymmetry is thus geometric in origin, not dependent on specific particle physics parameters [16].

8 Self-Consistency and Testable Predictions

8.1 Internal Consistency of the Mechanism

This baryogenesis mechanism is fully self-consistent within TDF:

1. **Minimal field content**: It uses only the three fundamental fields (ϕ_s, ϕ_t, λ) already present in the theory for other purposes (dark energy, cosmic expansion, quantum-classical transition).

2. **Derived bias**: The chemical potential μ_s is derived from the same dynamics that govern dark energy—specifically, the evolution equations for ϕ_t link $\dot{\phi}_t$ to the Hubble parameter and the dark energy equation of state.

3. **Natural scale**: The observed $\eta \sim 10^{-10}$ emerges without fine-tuning. From $\eta \approx \mu_s/k_B T$ and $\mu_s \sim \lambda H^{-1}\dot{\phi}_t$, with $\lambda \sim M_{Pl}^2/H_0$ (from dark energy constraints) and $\dot{\phi}_t \sim H$, we obtain $\eta \sim H/M_{Pl} \sim 10^{-10}$ at baryogenesis temperatures.

8.2 Testable Predictions

The mechanism yields several distinctive predictions that can be tested with current and future observations:

1. **Correlation with dark energy dynamics**: Since $\mu_s \propto \dot{\phi}_t$ and $\dot{\phi}_t$ is linked to the dark energy equation of state $w(z)$, there should be a correlation between η and $w(z)$. Specifically, deviations from $w = -1$ imply a time-varying $\dot{\phi}_t$, which would affect the baryon asymmetry if measured at different redshifts. Future missions like Euclid and the Nancy Grace Roman Space Telescope can test this [17].

2. **Variation of fundamental constants**: The dynamics of ϕ_t imply a non-zero time variation of Newton's constant:

$$\frac{\dot{G}}{G} \sim 2\frac{\dot{\phi}_t}{\phi_t} \sim 10^{-13}\ \mathrm{yr}^{-1} \tag{21}$$

   at present, with larger values in the early universe. This is within reach of Lunar Laser Ranging experiments and upcoming atomic clock tests [18].

3. **Features in the matter power spectrum**: The scale-dependent chemical potential leaves specific imprints on the matter power spectrum. Since node formation was biased on scales corresponding to L_c at baryogenesis, this creates a characteristic feature in the power spectrum at comoving wavenumber:

$$k_* \sim \frac{a(T_*)}{L_c(T_*)} \tag{22}$$

   This corresponds to masses around $10^5 M_\odot$, potentially observable with 21 cm cosmology [19].

4. **Primordial gravitational waves**: The rapid field dynamics during baryogenesis would have produced a stochastic background of gravitational waves with a characteristic frequency today:
$$f_* \sim \frac{T_*}{M_{Pl}} \cdot \frac{T_0}{T_*} \cdot H_0 \sim 10^{-3} \text{ Hz} \tag{23}$$
within the range of LISA and DECIGO [20].

5. **CMB spectral distortions**: The dissipation of node density fluctuations on small scales would have produced μ-type spectral distortions in the CMB, potentially detectable by future missions like PIXIE [21].

9 Comparison with Conventional Baryogenesis Mechanisms

9.1 GUT Baryogenesis

Conventional GUT baryogenesis [3] relies on out-of-equilibrium decays of heavy gauge or Higgs bosons with CP-violating phases. This requires:

- New physics at 10^{16} GeV scales
- Complex CP phases fine-tuned to produce the observed asymmetry
- Specific branching ratios for baryon-number-violating decays

In contrast, TDF baryogenesis requires no new particle physics beyond the three fields already present, and the asymmetry arises from geometry rather than fine-tuned phases.

9.2 Electroweak Baryogenesis

Electroweak baryogenesis [4] uses the electroweak phase transition, requiring:

- A strong first-order phase transition (requiring new scalar fields)
- Sufficient CP violation (beyond the Standard Model)
- Specific bubble wall dynamics with particular properties

TDF baryogenesis operates at higher temperatures, avoiding the need for a strong first-order phase transition and its associated new physics.

9.3 Leptogenesis

Leptogenesis [5] generates an asymmetry in the lepton sector, which is then converted to a baryon asymmetry via sphalerons. This requires:

- Heavy right-handed neutrinos ($M_N \gtrsim 10^9$ GeV)
- CP-violating decays with specific branching ratios
- Carefully controlled washout processes

TDF baryogenesis is simpler, generating the asymmetry directly in the baryon-forming stage without requiring lepton number violation.

9.4 Affleck-Dine Mechanism

The Affleck-Dine mechanism [6] uses scalar field condensates in SUSY theories, requiring:

- Flat directions in the potential
- Specific initial conditions for the condensate
- A-term CP violation

TDF baryogenesis resembles this in using scalar fields (ϕ_s, ϕ_t) but requires no SUSY and derives the asymmetry from expansion dynamics rather than initial conditions.

Table 2 summarizes the comparison between TDF baryogenesis and conventional mechanisms.

Table 2: Comparison of baryogenesis mechanisms

Mechanism	**Energy Scale**	**Required New Physics**	**CP Violation**	**Free Parameters**
GUT Baryogenesis	10^{16} GeV	GUT gauge bosons, Higgs	Complex phases in couplings	Many
Electroweak	10^2 GeV	New scalars, extended Higgs	Complex phases	Many
Leptogenesis	$10^9 - 10^{12}$ GeV	Right-handed neutrinos	Complex Yukawa couplings	Several
Affleck-Dine	10^{2-16} GeV	SUSY, flat directions	A-terms	Initial conditions
TDF (this work)	10^{15} GeV	**None (uses existing TDF fields)**	**Geometric (from expansion)**	**0 (derived)**

10 Discussion and Open Questions

10.1 The Role of the λ Field

The Unified Action Field λ plays a dual role in TDF: it couples to field gradients to produce energy (as in $\mathcal{H}_{int}$) and provides the non-linearity necessary for symmetry breaking (through the feedback equation). This dual role is reminiscent of the inflaton's role in cosmic inflation [22], but λ continues to operate throughout cosmic history, also influencing dark energy.

A deeper understanding of the quantum nature of λ is needed. Since its dimension matches $\hbar$, it may be that λ represents a spacetime-dependent dynamical Planck constant—a stunning possibility that would unify quantum mechanics and gravity [16].

10.2 Initial Conditions and Eternal Inflation

The mechanism assumes that the early universe had non-zero gradients $\nabla\phi_s$ and $\partial_t\phi_t$. In the context of eternal inflation [23], such gradients are naturally generated by quantum fluctuations stretched to superhorizon scales. Thus, the required initial conditions are not fine-tuned but typical in inflationary cosmology.

10.3 Isocurvature Constraints

Multi-field models often generate isocurvature perturbations that can conflict with CMB observations [24]. In TDF, the fields ϕ_s and ϕ_t are coupled to the metric such that their perturbations become adiabatic on superhorizon scales, naturally satisfying isocurvature constraints. A detailed calculation of the perturbation spectrum is in progress.

10.4 Baryon Number Violation and Stability

The mechanism requires baryon number violation to generate the asymmetry, but proton decay must be sufficiently suppressed today. In TDF, baryon number is conserved in the low-energy effective theory because node formation/annihilation ceases at late times. The vacuum expectation value of λ today suppresses baryon-number-violating operators by factors of $(L_c H_0)^2 \sim 10^{-120}$, ensuring proton stability [25].

11 Conclusion

We have presented a comprehensive baryogenesis mechanism within the Temporal Dynamics Framework that satisfies all Sakharov conditions while requiring no external assumptions beyond the three fundamental fields already present in the theory. The key elements are:

1. Matter and antimatter as phase states of the same field interaction, distinguished by the sign of $\nabla\phi_s \cdot \partial_t\phi_t$
2. A chemical potential $\mu_s = \lambda H^{-1}(\phi_s\dot{\phi}_t)$ arising from the non-linear dynamics of the λ field
3. Natural asymmetry generation $\eta \approx \mu_s/k_B T \sim 10^{-10}$ without fine-tuning
4. Direct cosmological connection linking η to the expansion rate and dark energy dynamics

This demonstrates that baryogenesis in TDF is not an add-on but a **geometric necessity** arising from the interaction of three fields in a high-tension, expanding background. The observed matter-antimatter asymmetry is directly linked to the arrow of time and cosmic expansion, eliminating the need for arbitrary CP violation or GUT-scale physics.

The mechanism is elegant, self-consistent, and provides clear, testable predictions ranging from dark energy correlations to gravitational wave signatures. If observationally confirmed, this would provide strong evidence for the Temporal Dynamics Framework and reveal the deep connection between matter asymmetry, the arrow of time, and the expansion of the universe.

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A Summary of Dimensional Analysis

Table 3: Dimensional analysis summary

Quantity	Symbol	Dimension	Physical Interpretation
Scale Field	ϕ_s	$[L^0]$	Spatial modulation coefficient
Time Field	ϕ_t	$[T^0]$	Temporal rate modulation
Unified Action Field	λ	$[ML^2T^{-1}]$	Action carrier, couples to gradients
Hamiltonian Density	$\mathcal{H}_{int}$	$[ML^{-1}T^{-2}]$	Node formation energy density
Cosmic Coupling Length	L_c	$[L]$	Quantum scale of λ field
Scale Chemical Potential	μ_s	$[ML^2T^{-2}]$	Energy bias between phases
Baryon Asymmetry	η	$[1]$	Dimensionless asymmetry parameter

B Summary of Key Equations

$$\mathcal{H}_{int} = \lambda \cdot (\nabla\phi_s \cdot \partial_t\phi_t) \cdot L_c, \quad L_c = \frac{\hbar}{M_\lambda c} \tag{24}$$

$$\mu_s = \frac{\lambda}{H} \cdot (\phi_s \dot{\phi}_t) \tag{25}$$

$$n_\pm \propto \exp\left(-\frac{\mathcal{H}_{int} \mp \mu_s}{k_B T}\right) \tag{26}$$

$$\eta = \frac{n_M - n_{\bar{M}}}{s} \approx \frac{\mu_s}{k_B T} \tag{27}$$

$$L_c \cdot H \sim \frac{\hbar}{M_\lambda c} \cdot \sqrt{G\rho} \sim \frac{M_{Pl}}{M_\lambda} \cdot \frac{l_P}{c} \cdot \sqrt{\rho} \tag{28}$$

$$T_* \sim \left(\frac{\lambda M_{Pl}}{k_B} \cdot |\nabla\phi_s \cdot \partial_t\phi_t| \cdot L_c^3\right)^{1/2} \tag{29}$$