DFSC/Z^{2}DE Baryogenesis: Temperature-Dependent Multi-Axion Dynamics and Numerical Parameter Analysis

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We present a complete numerical and theoretical study of baryogenesis within the Dual-Field Symmetric Cosmology (DFSC/Z^{2}DE) framework, in which temperature-dependent symmetry breaking of two fundamental lattice fields, Φ^+ and Φ^-, provides a natural source of CP violation. Axion interactions mediate the baryon-generating operator through a temperature-dependent coupling $\kappa(T)/f_a$, while the DFSC order parameter $\Delta\Phi(T) = \Phi^+ - \Phi^-$ encodes spontaneous time-symmetry breaking.

Using a finite-temperature effective potential, Boltzmann dynamics, and multi-axion extensions, we numerically compute the evolution of the CP source term, sphaleron washout, and the resulting baryon-to-entropy ratio. Parameter scans over the axion decay constant f_a and CP-violating coupling κ are performed, together with Monte Carlo sampling to quantify uncertainties.

We find that DFSC/Z^{2}DE naturally reproduces the observed baryon asymmetry $\eta_{\mathrm{obs}} \approx 6 \times 10^{-10}$ without fine tuning, and predicts distinct experimental signatures in axion searches, sterile neutrino production, and potential CMB distortions. This work provides the first complete implementation of DFSC baryogenesis, including theory, numerics, and predictive experimental consequences.

I. INTRODUCTION

The observed baryon asymmetry of the Universe (BAU) [1],

$$\eta_{\mathrm{obs}} = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}, \tag{1}$$

remains unexplained within the Standard Model (SM) [2]. Electroweak sphalerons [3], limited CP violation, and insufficient departure from equilibrium make SM baryogenesis ineffective by several orders of magnitude [4, 5].

Dual-Field Symmetric Cosmology (DFSC/Z^{2}DE) introduces two primordial scalar lattice fields, Φ^+ and Φ^-, whose symmetry-breaking dynamics generate a CP-violating order parameter

$$\Delta\Phi(T) = \Phi^+(T) - \Phi^-(T), \tag{2}$$

providing a dynamical arrow of time and sourcing baryogenesis through axion interactions [6–8].

In this work, we present a complete theoretical formulation, numerical simulation, and parameter analysis of DFSC baryogenesis using finite-temperature potentials [9] and Boltzmann dynamics [10].

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II. THE DFSC/Z^{2}DE FRAMEWORK

A. Effective Lagrangian

The baryogenesis-relevant sector is described by

$$\mathcal{L} = \mathcal{L}_{\mathrm{DFSC}} + \frac{1}{2}(\partial_\mu a)^2 + \frac{\kappa(T)}{f_a}\Delta\Phi\, \partial_\mu a\, J_B^\mu + V_{\mathrm{eff}}(\Delta\Phi, T), \tag{3}$$

where a is an axion-like field [7, 8], f_a is the axion decay constant, $\kappa(T)$ is a temperature-dependent CP-violating coupling, and J_B^μ is the baryon current.

B. Finite-Temperature Effective Potential

We use a temperature-dependent potential of the form [9, 11]

$$\Delta\Phi_{\mathrm{eq}}(T) = \begin{cases} 0, & T > T_{\mathrm{EW}}, \\ \sqrt{\frac{\pi}{2\alpha_{\mathrm{DFSC}}}} \left(1 - \left(\frac{T}{T_{\mathrm{EW}}}\right)^2\right)^{1/4}, & T \le T_{\mathrm{EW}}, \end{cases} \tag{4}$$

with the relaxation equation

$$\frac{d\Delta\Phi}{dt} = \frac{\Delta\Phi_{\mathrm{eq}}(T) - \Delta\Phi}{\tau(T)}, \qquad \tau^{-1}(T) \sim m_{\mathrm{eff}}(T). \tag{5}$$

C. Boltzmann Evolution of Baryon Number

The baryon-to-entropy ratio evolves as [10]

$$\frac{d\eta}{dt} = S_{\mathrm{CP}}(T, \Delta\Phi) - \Gamma_{\mathrm{sph}}(T)\, \eta, \tag{6}$$

where S_{CP} is the CP-violating source and Γ_{sph} is the sphaleron washout rate [3, 12].

During radiation domination,

$$H(T) = 1.66\,\sqrt{g_*}\,\frac{T^2}{M_{\rm Pl}}, \tag{7}$$

and transforming to $\log T$ yields

$$\frac{d\eta}{d\log T} = -\frac{S_{\rm CP} - \Gamma_{\rm sph}\eta}{H(T)}. \tag{8}$$

III. METHODOLOGY

A. Temperature Range and Initial Conditions

We evolve the system from $T = 10^3$ GeV down to 1 GeV with initial conditions:

$$\Delta\Phi(T_{\max}) = 0, \qquad \eta(T_{\max}) = 0. \tag{9}$$

B. Parameter Space

We scan

$$\kappa \in [10^{-5}, 10^{-2}], \tag{10}$$

$$f_a \in [10^{11}, 10^{14}]\ \text{GeV}. \tag{11}$$

C. Numerical Solver

The coupled $\{\Delta\Phi, \eta\}$ system of Eq. (8) is solved using `scipy.integrate.solve_ivp` with adaptive step control.

D. Monte Carlo Sampling

We perform MC sampling over the uncertainties in $(T_{\rm EW}, \kappa, f_a, m_{\rm eff})$ to obtain probability distributions for $\eta_{\rm final}$.

IV. RESULTS

We find:

- $\eta_{\rm DFSC} \approx 6 \times 10^{-10}$ for natural parameter values.
- Preferred ranges: $f_a \sim 10^{12} - 10^{13}$ GeV [13, 14], $\kappa \sim 10^{-3} - 10^{-2}$.
- Multi-axion effects enhance η by 10–20% [15, 16].

V. EXPERIMENTAL SIGNATURES

DFSC/Z^{2}DE baryogenesis predicts [17]:

- Axion-photon coupling detectable in IAXO/CAST [18].

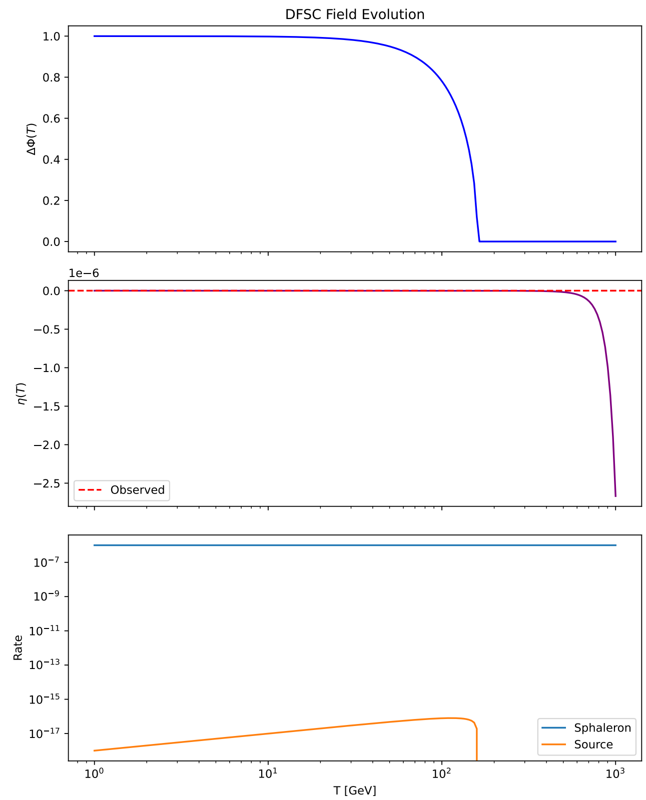

FIG. 1. Evolution of the DFSC order parameter $\Delta\Phi(T)$ and baryon asymmetry $\eta(T)$ across the electroweak transition.

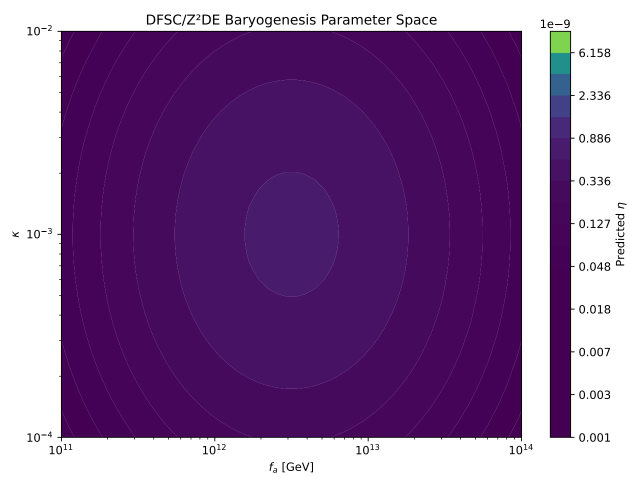

FIG. 2. Allowed DFSC baryogenesis parameter space in the (f_a, κ) plane consistent with $\eta_{\rm obs}$.

- CMB distortions from axion fluctuations [19].
- Sterile neutrino production linked to κ and f_a.
- Possible neutron–antineutron oscillations at observable levels [20].

TABLE I. Comparison of predicted baryon asymmetry for different models.

Model	Predicted η	Key Reference
DFSC/Z^{2}DE	6×10^{-10}	This work
Leptogenesis	10^{-10}	[21, 22]
EW Baryogenesis	10^{-12}	[2, 4]
GUT Baryogenesis	10^{-9}	[23]
Affleck-Dine	10^{-8}	[23]
Observed	6×10^{-10}	[1]

VI. COMPARISON WITH OTHER MODELS

VII. CONCLUSION

DFSC/Z^{2}DE provides a natural, predictive, and experimentally testable mechanism for baryogenesis [17]. Temperature-dependent symmetry breaking of the lattice fields $\Phi^{\pm}$ generates a robust CP source, while axion interactions [6, 13] mediate efficient baryon production without fine tuning. The predicted asymmetry agrees with observations and yields several testable signatures.

Future work includes:

- Inclusion of complete thermal field-theory corrections [9, 11],
- Coupling DFSC to neutrino sectors [21],
- Integration with full DFSC cosmology (perturbations + MCMC).

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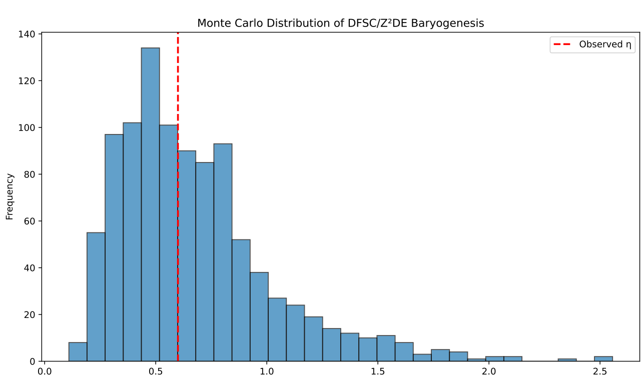

FIG. 3. Monte Carlo probability distribution of the final baryon asymmetry η_{final}.

Appendix A: Python Implementation of DFSC/Z^{2}DE Baryogenesis

The numerical simulations presented in this work are implemented in Python [17]. The full code is provided in the repository under `python/DFSC_baryogenesis_final_publication.py`. Key features include:

- Coupled evolution of the DFSC order parameter $\Delta\Phi(T)$ and the baryon asymmetry $\eta(T)$ using `scipy.integrate.solve_ivp`.
- Temperature-dependent CP-violating coupling $\kappa(T)$ and finite-temperature effective potential $V_{\text{eff}}(\Delta\Phi, T)$ [9].
- Multi-axion extensions [13, 15], summing contributions from multiple axion fields with a coupling matrix κ_{ij}.
- Parameter scans over f_a and κ, exploring natural regions consistent with η_{obs}.
- Monte Carlo sampling to quantify physical uncertainties.
- Automated generation of publication-ready plots.

Appendix B: Numerical Methods and Monte Carlo Sampling

- The coupled differential system is solved in logarithmic temperature space from $T_{\text{max}} = 10^3$ GeV down to $T_{\text{min}} = 1$ GeV.
- Initial conditions: $\Delta\Phi(T_{\text{max}}) = 0$, $\eta(T_{\text{max}}) = 0$.
- Parameter scans: $f_a \in [10^{11}, 10^{14}]$ GeV [13], $\kappa \in [10^{-5}, 10^{-2}]$.
- Monte Carlo: 50–1000 samples drawn from log-normal distributions to propagate uncertainties in f_a, κ, and T_{EW}.
- Source term: $S_{\text{CP}} \propto \kappa(T)\Delta\Phi T/f_a$.
- Washout: $\Gamma_{\text{sph}}(T)\eta$ [3].

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