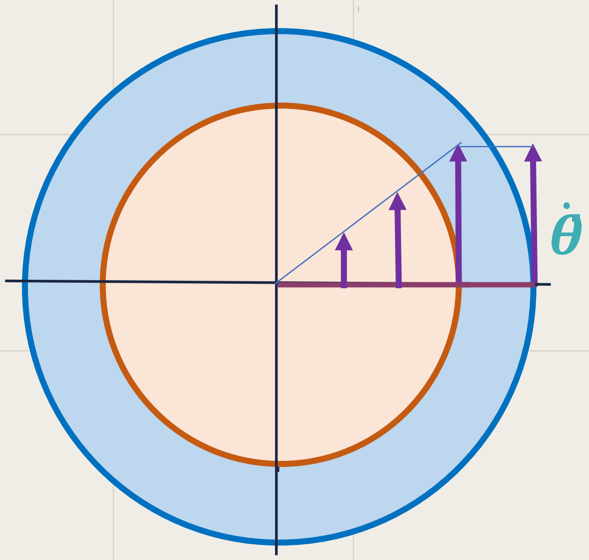

Spontaneous Cogenesis by QCD Axion in Type-I Seesaw

Unifying Dark Matter and Baryogenesis via Axion Kinetic Misalignment in DFSZ Framework augmented by Type-I seesaw

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Based on EJC (2601.09224); EJC, Lee & Song (2512.06413); with results from EJC, Das, He, Jung & Sun (2406.04180); EJC, Jung (2311.09005).

Four puzzles beyond Standard Model

1. Strong CP Problem

The fine-tuning of the QCD vacuum: $\theta < 10^{-10}$

$$\mathcal{L}_\theta = \frac{g_s^2}{32\pi^2}\theta G\tilde{G} \Rightarrow V(\theta) \sim -\Lambda_{QCD}^4 \cos(\theta)$$

2. Dark Matter

The missing cold mass of the universe.

$$\Omega_{CDM} h^2 = 0.12$$

3. Baryon Asymmetry

The observed matter-antimatter imbalance.

$$Y_B = 0.87 \times 10^{-10}$$

4. Neutrino Mass

The non-zero mass of active neutrinos requiring a high-scale mechanism beyond the SM.

$$m_\nu \lesssim 0.1 \text{ eV}$$

Synthesis Insight: Traditionally, cosmology requires separate frameworks to resolve these anomalies. The Spontaneous Cogenesis proposition demonstrates that a single scalar field's dynamics can solve all four simultaneously.

DFSZ Axion model augmented by Type-I seesaw

The Peccei-Quinn (PQ) scalar field (Charge $x_\Phi = 1$). Provides the symmetry breaking mechanism.

Heavy Majorana (right-handed) neutrino (Charge $x_N = -1/2$). Connects the PQ sector to lepton number violation.

$$-\mathcal{L}_{DFSZ} = y_H \Phi^2 H_u H_d + \frac{1}{2} y_N \Phi N N + y_\nu l N H_u + \text{h.c.}$$

Two Higgs doublets coupling to up-type and down-type fermions.

PQ charge assignment: $x_{(q,u^c,d^c,l,e^c,N;\, H_u,H_d)} = (\frac{1}{2},\frac{1}{2},\frac{1}{2},\frac{3}{2},-\frac{1}{2},-\frac{1}{2};\ -1,-1)$

Unified framework

Existence of a hypothetical pNGB
PQ symmetry breaking

$$\Phi = \frac{v_a}{\sqrt{2}} e^{i\frac{a}{v_a}} \qquad \theta \equiv \frac{a}{v_a}$$

Heavy Majorana RH neutrinos
$m_N = y_N v_a/\sqrt{2}$

The axion/majoron emerges
to resolve the strong CP problem

$$-\mathcal{L}_\theta = \sum_\psi x_\psi \partial_\mu \theta\, \bar{\psi}\gamma^\mu \psi + \frac{g_s^2}{32\pi^2} c_s \theta G\tilde{G} + \frac{g_w^2}{32\pi^2} c_w \theta W\widetilde{W}$$

$$f_a = \frac{v_a}{c_s}$$

Type-I Seesaw

$$m_\nu \sim \frac{y_\nu^2 v_{EW}^2}{m_N}$$

Baryogenesis

$$Y_{B-L} \sim \frac{\dot{\theta}_*}{T_*}, T_* \sim m_N$$

DM genesis

$$m_a \frac{n_a}{s} \sim 0.22\text{eV}$$

Cosmic $\dot{\theta}$ background

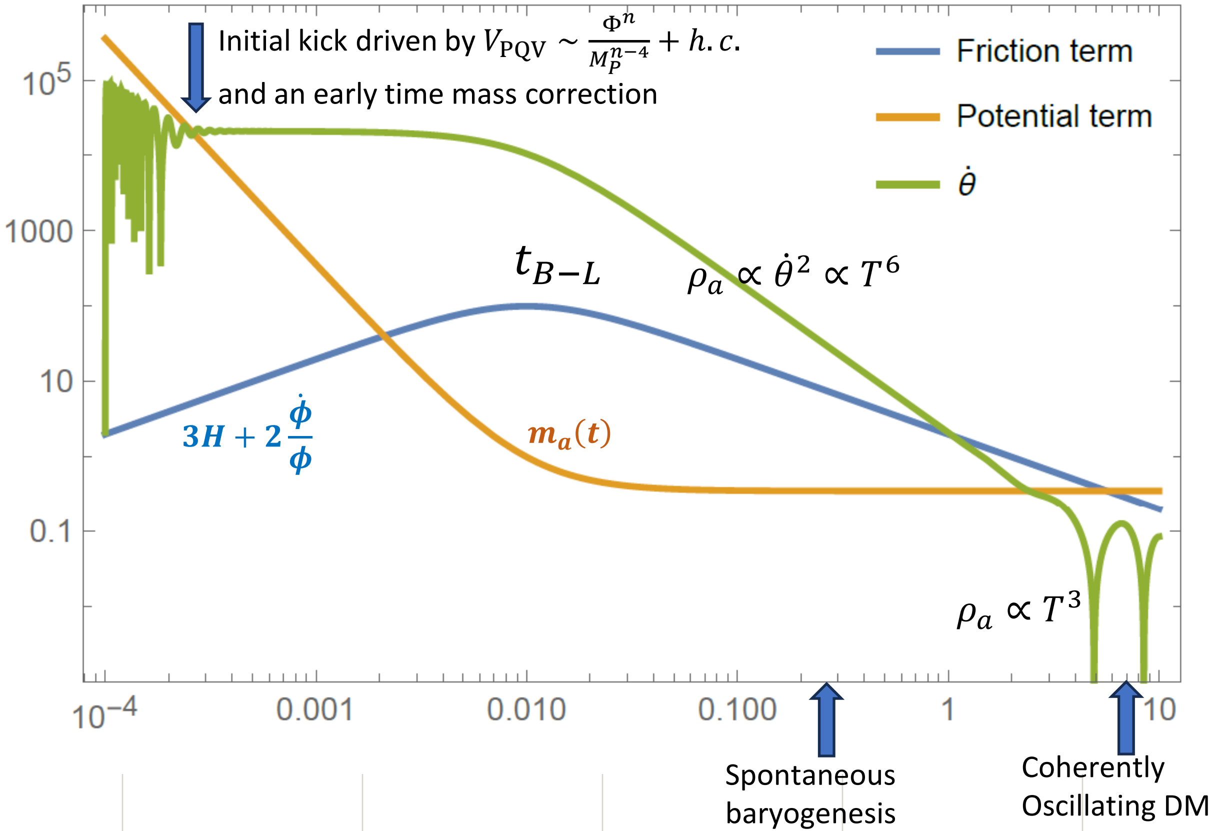
Affleck, Dine 1985

$\delta V \propto -H^2|\Phi|^2$

EJC, et.al., 2406.04180

$\delta V \propto -T^2|\Phi|^2$

$$\Phi(t) = \frac{\phi(t)}{\sqrt{2}} e^{i\theta(t)}$$



Cogensis condition for QCD axion

Baryon asymmetry

$$Y_B = \left.\frac{\frac{1}{6} d_B \dot{\theta} T^2}{s}\right|_{T=T_*} = 0.87 \times 10^{-10}$$

Cohen, Kaplan, 1987

Domcke, et.al., 2006.03148

DM abundance

$$m_a \frac{v_a^2 \dot{\theta}}{s} = 0.22\text{eV}$$

Co, Hall, Harigaya, 1910.14152

Axion mass relation

$$m_a = 6.7 \times 10^{-3} \left(\frac{10^9\text{GeV}}{f_a}\right) \text{eV}$$

$$\Rightarrow T_* \sim 2\, c_s \sqrt{\frac{f_a}{10^9\text{GeV}} \frac{10^{-2}}{d_B}}\, \text{TeV}$$

Co, Harigaya, 1910.02080
Axiogenesis

$$T_* = T_{B+L} \sim 130\text{GeV}$$

EJC, Jung, 2311.09005
Majoron in Type-I seesaw

$$T_* = T_{B-L} \sim m_N$$

Kinetic background as a chemical potential

The axion/majoron with a derivative coupling $x_\psi \partial_\mu \theta \, \bar{\psi} \gamma^\mu \psi$
→ The kinetic background $\dot{\theta}$ acts as a chemical potential, shifting the energy state of particle/antiparticle

Dirac fermion

$$\gamma^\mu (i\partial_\mu + x_\psi \theta_\mu) \psi_L = m\psi_R$$
$$\gamma^\mu (i\partial_\mu + x_\psi \theta_\mu) \psi_R = m\psi_L$$

Majorana fermion ($\psi_L = \psi_R^c$)

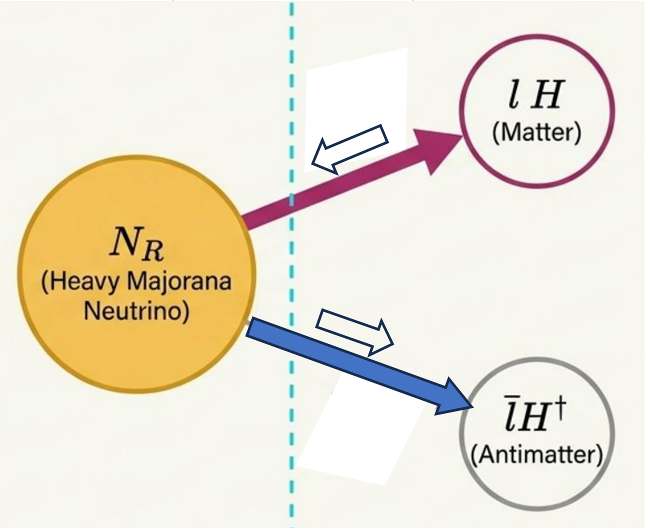
$$\gamma^\mu (i\partial_\mu + x_\psi \theta_\mu) \psi_L = m\psi_R$$
$$\gamma^\mu (i\partial_\mu - x_\psi \theta_\mu) \psi_R = m\psi_L$$

$$E_{\psi,\psi^c} = \sqrt{m^2 + \boldsymbol{p}^2} \pm x_\psi \dot{\theta}$$

$$E_{h=\pm} = \sqrt{m^2 + \left(h\,\boldsymbol{p} + x_\psi \dot{\theta}\right)^2} \approx E_0 + h \frac{\boldsymbol{p}}{E_0} x_\psi \dot{\theta}$$

New contribution to Boltzmann equations

$\dot{\theta}$ biasing the decay & thermal equilibrium



It alters decay kinematics. Without conventional CPV from Yukawas couplings, decays rates into leptons and antileptons inherently differ.

$$\frac{\Gamma(l)-\Gamma(\bar{l})}{\Gamma(l)+\Gamma(\bar{l})} = -\frac{\dot{\theta}}{2m_N}$$

inducing CP asymmetry at tree level

Cesar, Mavromatos & Sarkar, 1412.7077

It puts a bias in the equilibrium system during equilibration process of $N \leftrightarrow l\,H$.

$$\mu_l + \mu_H = x_l\dot{\theta}$$

acting as a source of B-L asymmetry

Full chemical equilibrium

Consider full equilibrium of all the Yukawa couplings, the bilinear term $H_u H_d$, and the strong/weak sphaleron Interactions under the condition of charge neutrality.

$$\mu_q + \mu_{u^c} + \mu_{H_u} = 0 \qquad \mu_q + \mu_{e^c} + \mu_{H_d} = 0$$

$$\mu_q + \mu_{d^c} + \mu_{H_d} = 0 \qquad \mu_l + \mu_{H_u} = (x_l + x_{H_u})\dot{\theta}$$

$$\mu_{H_u} + \mu_{H_d} = (x_{H_u} + x_{H_d})\dot{\theta}$$

$$N_f(2\mu_q + \mu_{u^c} + \mu_{d^c}) = c_s\dot{\theta} \qquad N_f(3\mu_q + \mu_l) = c_w\dot{\theta}$$

$$N_f(\mu_q - 2\mu_{u^c} + \mu_{d^c} - \mu_l + \mu_e^c) + 2\mu_{H_u} - 2\mu_{H_d} = 0$$

$$n_{B-L} = c_{B-L}\frac{1}{6}\,\dot{\theta}T^2 \;\text{ with }\; c_{B-L} = -\frac{13}{2}$$

$$c_s = 2N_f, c_w = 3N_f$$

Boltzmann equations

$$\frac{dY_N}{dz} = -zK\gamma_D(Y_N - Y_N^{eq})$$

$$z \equiv \frac{m_N}{T}$$

$$\frac{dY_{B-L}}{dz} = zK\gamma_M\varepsilon_1(Y_N - Y_N^{eq}) - zK\gamma_{ID}(Y_{B-L} + y_\theta\varepsilon_1)$$

Anatomy of the Equation

Standard decay rate.

$$K \equiv \frac{\Gamma_N}{H_1} = \frac{\frac{|y_\nu|^2}{8\pi} m_N}{H(z=1)}$$

The new decay efficiency term driven by the Majoron helicity chemical potential. Dominant at $T > m_N$.

Inverse-decay washout term. Uniquely couples to the CP-violating source y_θ in this model.

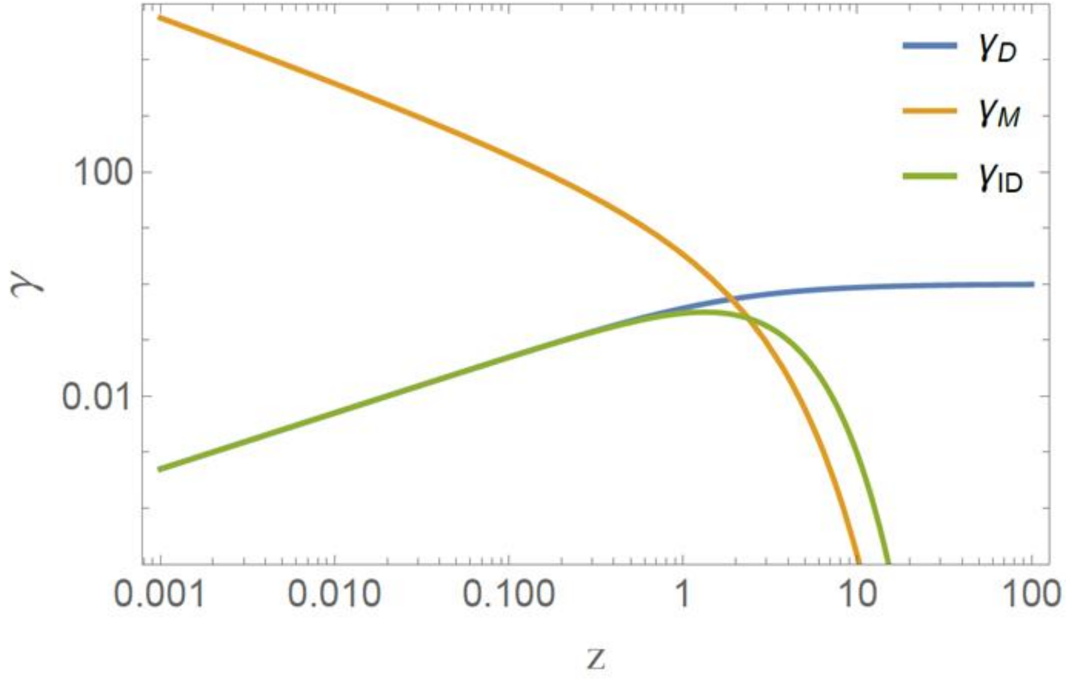
$$\varepsilon_1 \equiv c_l \frac{\dot\theta_1}{2m_N}, \quad c_l = -\frac{13}{2}$$

$$Y_{ext} \equiv c_l \frac{\frac{1}{6}\dot\theta T^2}{s} \equiv y_\theta\, \varepsilon_1$$

$$y_\theta \equiv \frac{1}{2}\frac{45}{2\pi^2}\frac{1}{g_*}\frac{1}{z^2}$$

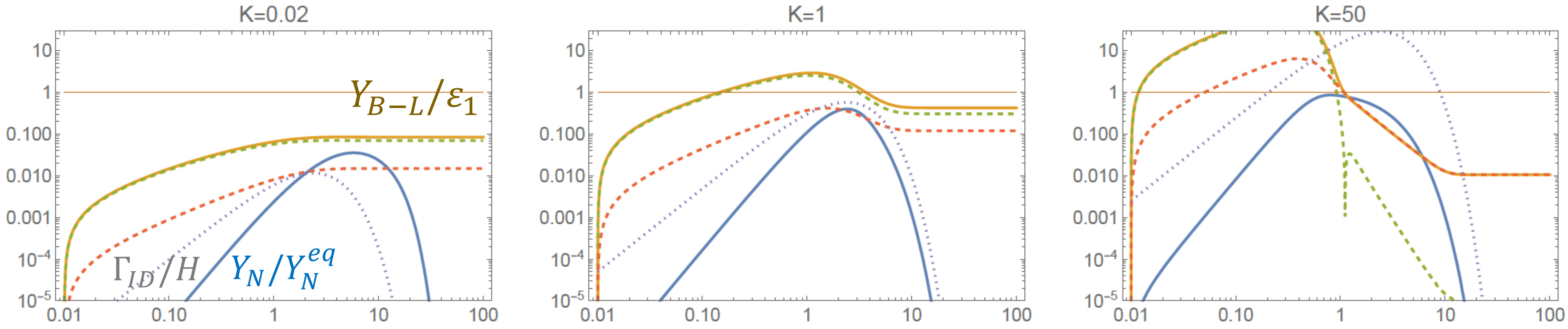
Thermal functions

$$\gamma_D = \frac{z^2 K_1(z)}{z^2 K_2(z)}, \qquad \gamma_{ID} = \frac{1}{2} z^2 K_2(z), \;\; \gamma_M = \frac{G_M(z)}{z^2 K_2(z)}, \qquad G_M(z) \equiv \int d|\vec{p}_N| e^{-\frac{E_N^0}{T}} \frac{2|\vec{p}_N|}{E_N^0} \ln\left(\frac{E_N^0 + |\vec{p}_N|}{E_N^0 - |\vec{p}_N|}\right)^2$$



γ_M from the helicity chemical potential drops quickly due to additional helicity suppression $\frac{T}{m_N}$

Evolution of B-L asymmetry

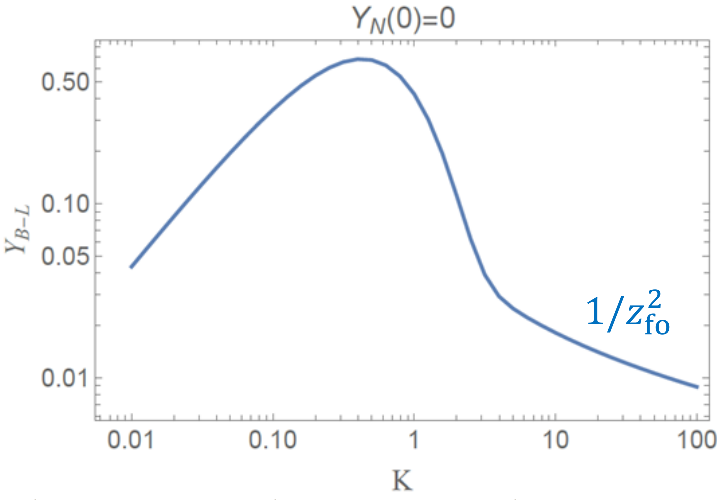


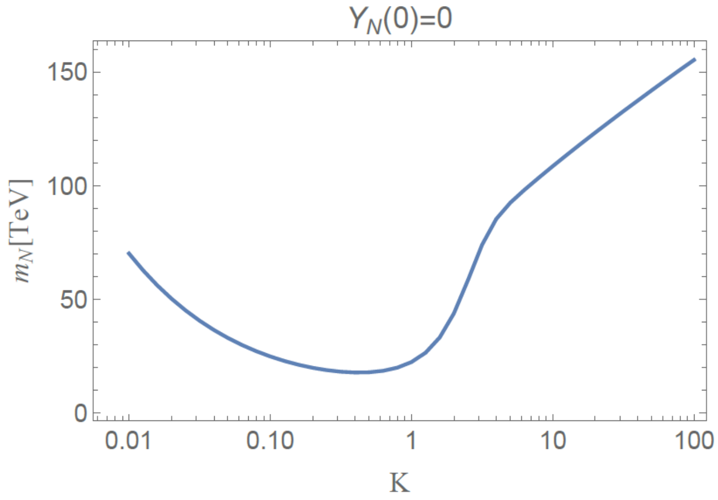
$Y_N(0) = 0$

Decay domination

Inverse decay domination

Efficiency $\kappa(K) = \frac{Y_{B-L}}{y_\theta \varepsilon_1}$, & required m_N





$$m_N \propto \left(\frac{f_a}{10^9\,\mathrm{GeV}}\right)^{1/2}$$

Initial kick driven by inflationary dynamics

Two engines: Hubble-induced mass & PQ violating potential

$$V_{\mathrm{PQC}}(\phi) = -(\mu_\Phi^2 + a_H H^2)|\Phi|\hat{}2 + \lambda_\Phi |\Phi|\hat{}4 \qquad V_{\mathrm{PQV}}(\phi,\theta) = -\lambda_n \frac{\Phi^n}{M_P^{n-4}} + h.c.$$

$$\Phi = \frac{\phi}{\sqrt{2}} e^{i\theta} \qquad \theta = \frac{a}{\phi} \qquad \phi = v_a \sqrt{1 + \frac{H^2}{H_c^2}} \qquad v_a = \frac{\mu_\Phi}{\sqrt{\lambda_\Phi}}, H_c = v_a \sqrt{\frac{\lambda_\Phi}{a_H}}$$

Evolution of θ during matter domination after inflation

$$\ddot{\theta} + \frac{2}{t}\left(1 - \frac{t_c^2/t^2}{1 + t_c^2/t^2}\right)\dot{\theta} + \frac{1}{n}\delta m_a^2(t)\sin(n\theta + \delta_n) = 0$$

$$\delta m_a^2(t) = \delta m_{a0}^2 (1 + t_c^2/t^2)^{n-2} \qquad \delta m_{a0}^2 = 2n^2 \frac{|\lambda_n|}{\sqrt{2^n}} \frac{v_a^{n-2}}{M_P^{n-4}}$$

Initial condition set at t_0: $n_a(t_0) = \dot{\theta}_0 \phi_0^2$ with $\dot{\theta}_0 = \delta m_a(t_0)$ & $\phi_0^2 = v_a^2(1 + H_0^2)$

Parameter choice

Parameters restricted by

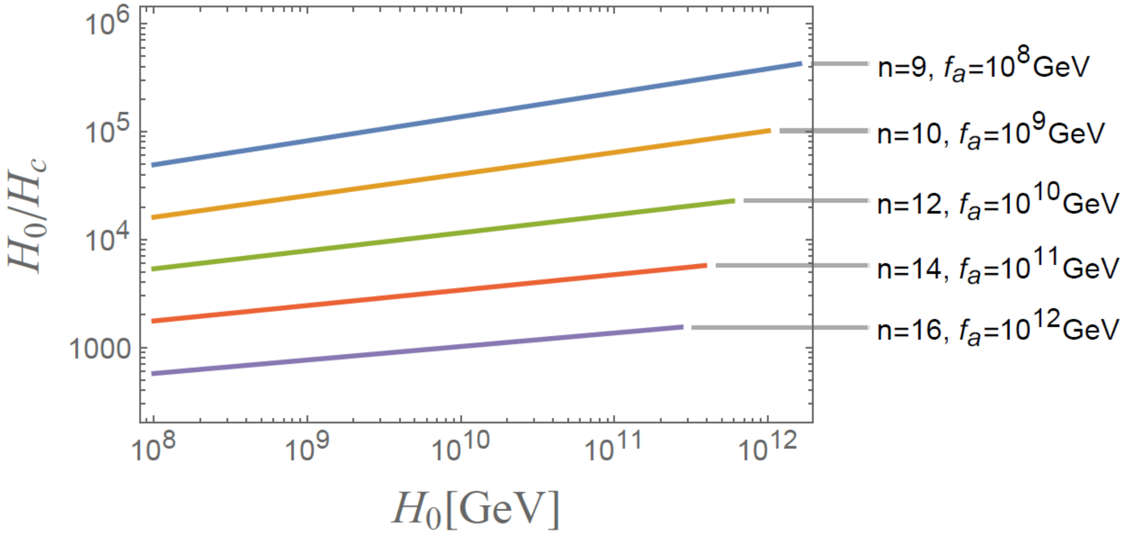
$H_0 < H_I \;\&\; H_c < f_a$

Axion quality

$\delta m_{a0}^2 < 10^{-10} m_a^2$

Isocurvature perturbation

$$\left(\frac{H_I}{2\pi\phi_I}\right)^2 \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{7/6} < 2.2\ \times 10^{-11}$$



Spontaneous Cogenesis by QCD Axion in Type I Seesaw

A single PQ symmetry breaking event and its kinetic axion background naturally and simultaneously explains:

- ✓ Strong CP Problem
- ✓ Neutrino Masses (Type-I Seesaw)
- ✓ Dark Matter Abundance
- ✓ Baryon Asymmetry

Key Results

Generalized Boltzmann equation

Apply to various neutrino mass models

m_N prediction in Type I seesaw

$$O(10)\text{–}O(100) \times \left(\frac{f_a}{10^9 GeV}\right)^{1/2} \text{TeV}$$

Viable initial kick in AD framework

Constrained model parameters

Papers

arXiv:2601.09224
arXiv:2512.06413