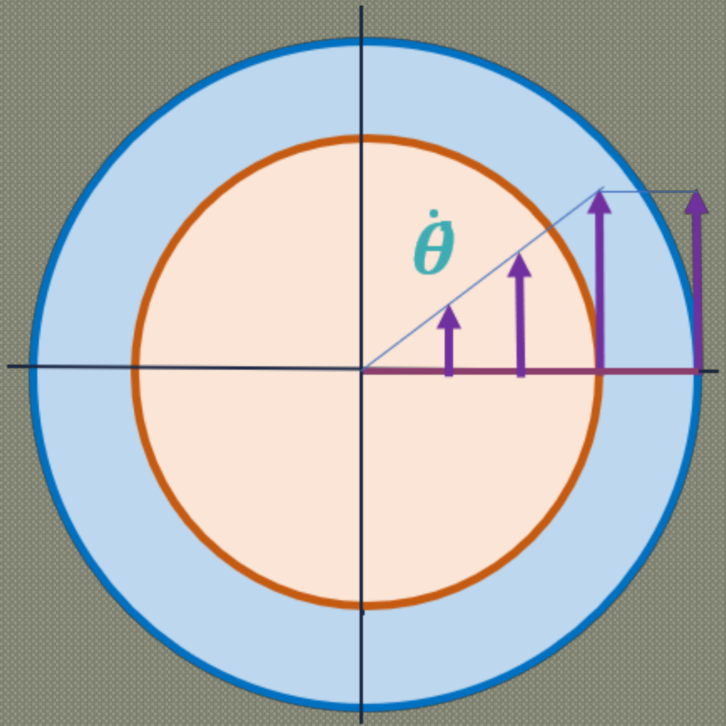
Spontaneous Leptogenesis in Type I Seesaw – Application to QCD axion models



Eung Jin Chun

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

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Content

- Cohen-Kaplan baryogenesis driven by pNGB
- Application to Type-I Seesaw with Majoron

  EJC, TH Jung 2311.09005
- Formulation of BE considering the role of Majoron both decay and inverse decay of RHN

  EJC, HM Lee, JH Song, 2512.06413
- Spontaneous cogenesis by QCD axion=majoron

  EJC, HM Lee, JH Song, 2512.12637

  EJC, 2601.09224

Spontaneous Baryogenesis

- Baryogenesis in a CPT violating background
- $\dot{\theta}$ acts as an effective chemical potential
- Seeding $\dot{\theta}$ in an equilibrium system when $U(1)$ violating interaction is effective
- Baryon asymmetry is generated.

Cohen, Kaplan, '87, '88

pNGB $\theta = \frac{a}{v_a}$ of spontaneously broken $U(1)$

$$\mathcal{L}_\theta = -x_\psi \, \partial_\mu \theta \, \bar{\psi} \gamma^\mu \psi$$

$$E_{\psi/\bar{\psi}} \to E_{\psi/\bar{\psi}} \pm x_\psi \dot{\theta} \Rightarrow \ \mu_\psi \to \mu_\psi - x_\psi \dot{\theta}$$

$$\text{Ex)} \ \psi_1 + \psi_2 \leftrightarrow \psi_3 + \psi_4$$

$$\mu_{\psi_1} + \mu_{\psi_2} - \mu_{\psi_3} - \mu_{\psi_4} = (x_{\psi_1} + x_{\psi_2} - x_{\psi_3} - x_{\psi_4})\dot{\theta}$$

$$n_B = \frac{1}{6} \mu_B T^2, \mu_B = \sum_\psi B_\psi \mu_\psi = c_B \dot{\theta} \Rightarrow Y_B \propto \frac{\dot{\theta}_*}{T_*}$$

Axiogenesis

- pNGB of $U(1)_{PQ}$ Co, Harigaya, 1910.02080 Domcke et.al., 2006.04138

$$\mathcal{L} = c_A \theta F_A \tilde{F}_A$$

- B+L is generated when WS (SS) is in equilibrium:

$$\text{WS:}\ N_g\left(3\mu_{q_L} + \mu_{l_L}\right) = c_W \dot{\theta}$$

$$\text{SS:}\ N_g\left(2\mu_{q_L} + \mu_{\bar{u}_R} + \mu_{\bar{d}_R}\right) = c_S \dot{\theta}$$

- Y_{B+L} frozen at $T_{B+L} = T_{EW}$

$$Y_B = \frac{\frac{1}{6} c_B \dot{\theta} T^2}{s} \approx 0.87 \times 10^{-10} \qquad m_a \approx \frac{m_\pi f_\pi}{v_a}$$

$$m_a Y_a = m_a \frac{v_a^2 \dot{\theta}}{s} \approx 200\text{eV} \left(\frac{v_a}{10^9 \text{GeV}}\right)$$

Majorogenesis

- pNGB of $U(1)_{B-L}$

$$\mathcal{L} = y_\nu LHN + \frac{1}{2} M_N NN + \dot{\theta} \sum_\psi x_\psi \bar{\psi} \gamma^0 \psi$$

- B-L is generated when LNV $N \leftrightarrow lH$ is in equilibrium

$$\text{LNV:}\ \mu_l + \mu_H = x_l \dot{\theta}$$

- Y_{B-L} frozen at $T_{B-L} \sim M_N$

$$m_a Y_a \approx 5 m_a \left(\frac{v_a}{10^9 \text{GeV}}\right)^2 \left(\frac{10^4 \text{GeV}}{M_N / z_N}\right)$$

EJC, TH Jung 2311.09005

Spontaneous Leptogenesis

- Type I seesaw with a spontaneously broken $U(1)_{B-L}$

$$\mathcal{L}_N = y_\nu \bar{l}_L \bar{H} N_R + \frac{1}{2}\Phi \bar{N}_L N_R + h.c.$$

$$\Phi = \frac{v_a}{\sqrt{2}}\, e^{i\theta}\,, \theta \equiv \frac{a}{v_a}; \quad x_S = 1,\ x_{N_R,\, l_L,\, e_R} = -\frac{1}{2},\ x_{q_{L,}u_R,\, d_R} = \frac{1}{6}$$

- Derivative couplings of a pNGB, Majoron: $\psi \to e^{i x_\psi \theta}\psi\,,$

$$\mathcal{L}_\theta = \sum_\psi \bar{\psi}\gamma^\mu\left(i\partial_\mu - x_\psi \theta_\mu\right)\psi \qquad \theta_\mu \equiv \partial_\mu \theta = (\dot{\theta}, \vec{0})$$

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix}, \quad \sigma^\mu = (1, \vec{\sigma})\,, \quad \bar{\sigma}^\mu = (1, -\vec{\sigma})\,, \quad \psi = \psi_L \text{ or } \psi_R$$

Full equilibrium solution

- Considering all the interactions, including $N \leftrightarrow lH$, are in equilibrium, and charge neutrality:

$$\mu_{q_L} + \mu_{\bar{u}_R} + \mu_H = 0 \qquad \mu_{l_L} + \mu_{\bar{e}_R} - \mu_H = 0$$

$$\mu_{q_L} + \mu_{\bar{d}_R} - \mu_H = 0 \qquad \mu_{l_L} + \mu_H = x_{l_L}\dot{\theta}$$

$$N_f(2\mu_{q_L} + \mu_{\bar{u}_R} + \mu_{\bar{d}_R}) = 0 \qquad N_f(3\mu_{q_L} + \mu_{l_L}) = 0$$

$$N_f\left(\mu_q - 2\mu_{\bar{u}_R} + \mu_{\bar{d}_R} - \mu_{l_L} + \mu_{\bar{e}_R}\right) + 2\mu_H = 0$$

$$\mu_{B-L} = \frac{79}{11}\frac{\dot{\theta}}{2} = \frac{79}{28}\mu_B$$

Spinors in the $\dot{\theta}$ background

- Dirac fermion: $\psi_L \neq {\psi_R}^c$

$$(p_\mu - x_\psi \theta_\mu)\bar{\sigma}^\mu u_L(p) = m_\psi u_R(p) \qquad (-p_\mu - x_\psi \theta_\mu)\bar{\sigma}^\mu v_L(p) = m_\psi v_R(p)$$

$$(p_\mu - x_\psi \theta_\mu)\sigma^\mu u_R(p) = m_\psi u_L(p) \qquad (-p_\mu - x_\psi \theta_\mu)\sigma^\mu v_R(p) = m_\psi v_L(p)$$

$$E = E_0 \pm x_\psi \dot{\theta}\,, \qquad E_0 = \sqrt{m_\psi^2 + |\vec{p}|^2}$$

Shift in energy of ψ, ψ^c

Effective chemical potential

$$u_L^r(p) = \sqrt{p_- \cdot \sigma}\,\xi^r \qquad v_L^r(p) = \sqrt{p_+ \cdot \sigma}\,r\xi^r$$

$$u_R^r(p) = \sqrt{p_- \cdot \bar{\sigma}}\,\xi^r \qquad v_R^r(p) = \sqrt{p_+ \cdot \bar{\sigma}}\,(-r)\xi^r$$

$r = \pm 1$ denotes spin states

$$p_{\mp,\mu} = p_\mu \mp x_\psi \theta_\mu = (E_0, \vec{p})$$

Same spinors as the standard form

Spinors in the $\dot{\theta}$ background

- Majorana fermion: $\psi_L = {\psi_R}^c$

$$(p_\mu - x_\psi \theta_\mu)\bar{\sigma}^\mu u_L(p) = m_\psi u_R(p) \qquad (-p_\mu - x_\psi \theta_\mu)\bar{\sigma}^\mu v_L(p) = m_\psi v_R(p)$$
$$(p_\mu + x_\psi \theta_\mu)\sigma^\mu u_R(p) = m_\psi u_L(p) \qquad (-p_\mu + x_\psi \theta_\mu)\sigma^\mu v_R(p) = m_\psi v_L(p)$$

$$E = \sqrt{m_\psi^2 + \left(|\vec{p}| - s x_\psi \dot{\theta}\right)^2} \Rightarrow E \approx E_0 - s\frac{|\vec{p}|}{E_0} x_\psi \dot{\theta}$$

$s = \pm 1$ denotes helicity

$$u_L^s(p) = \sqrt{p_+ \cdot \sigma}\,\xi^s \qquad v_L^s(p) = \sqrt{p_- \cdot \sigma}\, r \xi^s$$
$$u_R^s(p) = \sqrt{p_- \cdot \bar{\sigma}}\,\xi^s \qquad v_R^s(p) = \sqrt{p_+ \cdot \bar{\sigma}}\,(-r)\xi^s$$

Effective chemical potential in helicity

$$p_{\pm,\mu} = p_\mu \pm x_\psi \theta_\mu \approx \left(E_0 \pm x_\psi \dot{\theta}\left(1 \mp s\frac{|\vec{p}|}{E_0}\right), \vec{p}\right)$$

Modified spinor solutions

Asymmetric Decays at tree-level

Bossingham, et.al., 1712.03312

- $N_{Rs} \to l_L H,\ \overline{l_L}\overline{H}$ with $s = \pm 1$

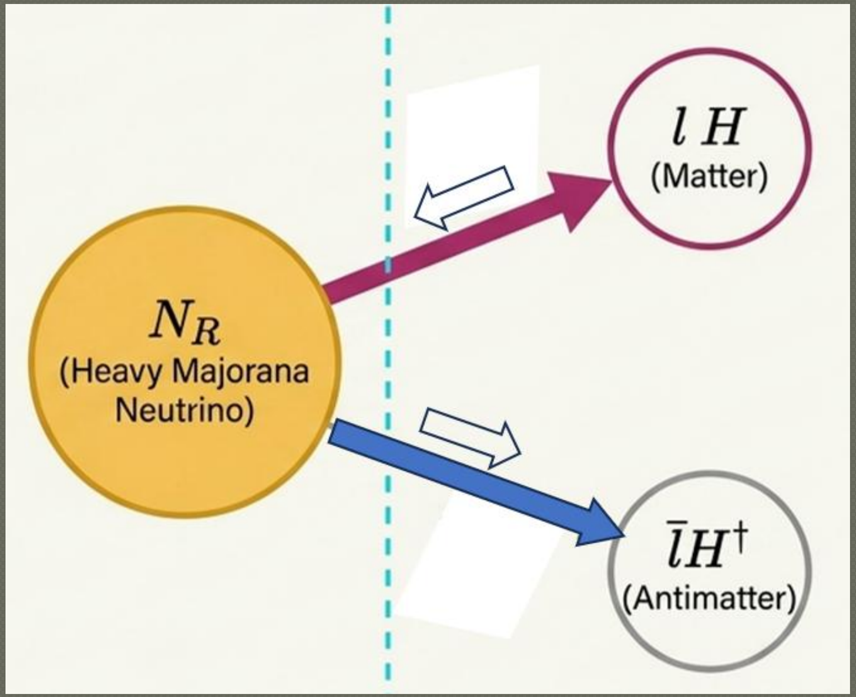
$$|\mathcal{M}|_s^2 = |y_\nu|^2\left(E_l^0 - s|\vec{p_l}|\cos\theta\right)\left(E_N^0 + s|\vec{p_N}| - \frac{\dot{\theta}}{2}\left(1 + s\frac{|\vec{p_N}|}{E_N^0}\right)\right) \qquad \cos\theta = \hat{p}_l \cdot \hat{p}_N$$

$$|\overline{\mathcal{M}}|_s^2 = |y_\nu|^2\left(E_l^0 + s|\vec{p_l}|\cos\theta\right)\left(E_N^0 - s|\vec{p_N}| + \frac{\dot{\theta}}{2}\left(1 - s\frac{|\vec{p_N}|}{E_N^0}\right)\right)$$

- In the relativistic limit, $|\vec{p}_N| \to E_N^0$: $N_{R+}(\vec{p}) \to l_L(-\vec{p});\ \ s = +1, \cos\theta = -1$

- In the static limit, $|\vec{p}_N| \to 0$: $\dfrac{\Gamma_N(l) - \Gamma_N(\bar{l})}{\Gamma_N(l) + \Gamma_N(\bar{l})} = -\dfrac{\dot{\theta}}{2m_N}$

$\dot{\theta}$ bais in decay & thermal equilibrium



It alters decay kinematics. Without conventional CPV from Yukawas couplings, decay 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

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

Boltzmann Equations

- Thermal averaging the decay & inverse decay biased by $\dot{\theta}$

$$\frac{dY_N}{dz} = -zK\gamma_D\left(Y_N - Y_N^{eq}\right) \qquad z \equiv \frac{m_N}{T}, K \equiv \frac{\Gamma_N}{H_1} = \frac{\frac{|y_\nu|^2}{8\pi} m_N}{H(z=1)}$$

$$Y \equiv \frac{n}{s}$$

$$Y_N = Y_{N_+} + Y_{N_-}$$

$$\frac{dY_{B-L}}{dz} = zK\gamma_M\varepsilon_1\left(Y_N - Y_N^{eq}\right) - zK\gamma_{ID}\left(Y_{B-L} + \frac{y_\theta \varepsilon_1}{z^2}\right)$$

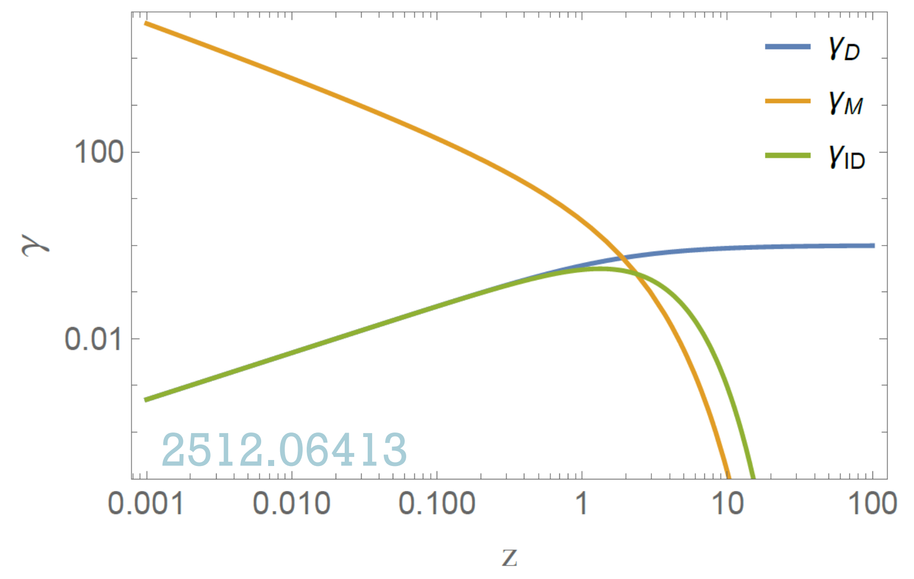
$$Y_{\Delta N} = Y_{N_+} - Y_{N_-}$$

decouples

$$\varepsilon_1 \equiv \frac{\dot{\theta}_1}{2m_N}; \quad y_\theta \equiv c_{B-L}\frac{1}{2}\frac{45}{2\pi^2}\frac{1}{g_*} \qquad c_{B-L} = \frac{79}{11}\ (\text{flavor} - \text{dependent})$$

B-L Asymmetry arises both from the decay at tree level
& equilibration by the inverse-decay (washout process).

Efficiency Functions



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

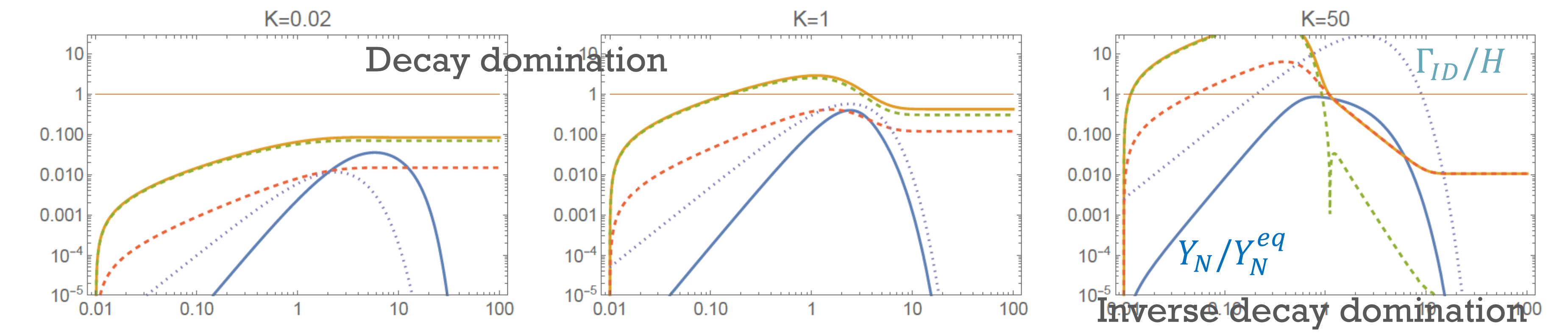
$e^{-\frac{m_N}{T}}$

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

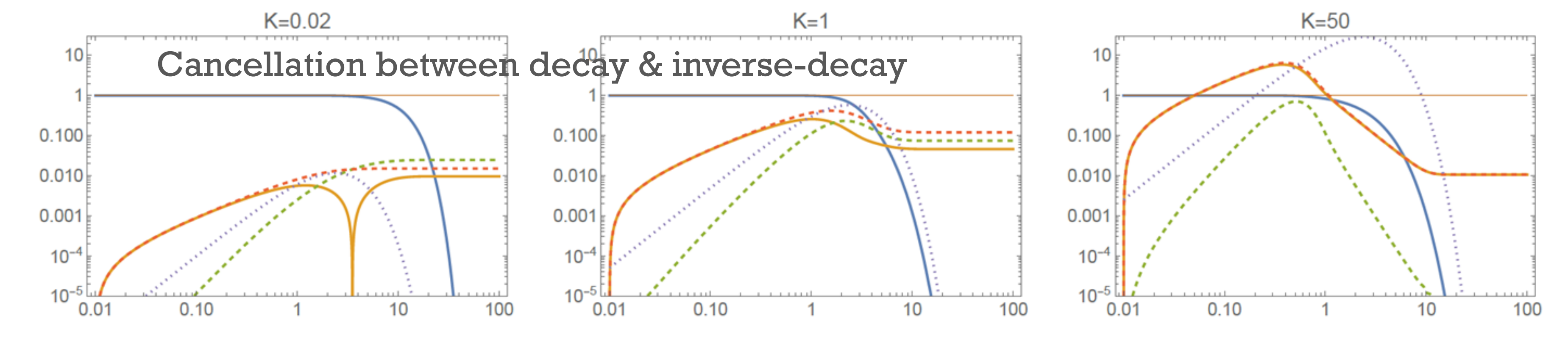
Evolution of Asymmetry

EJC, HM Lee, JH Song, 2512.06413

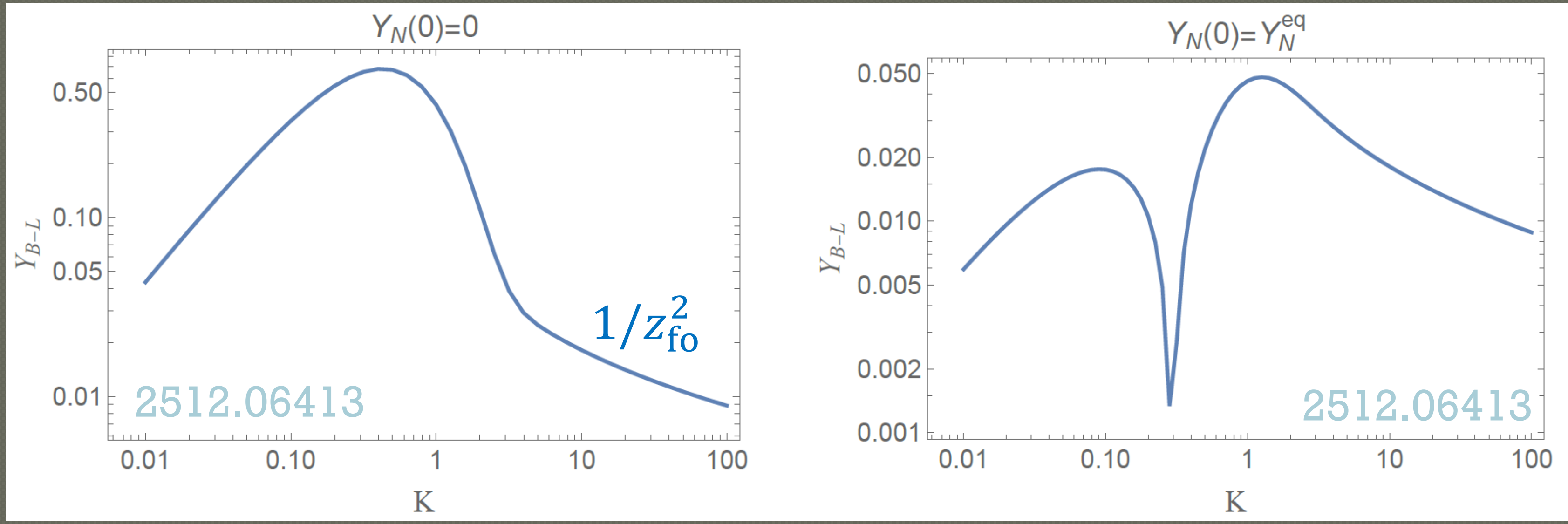
$Y_N(0) = 0$



$Y_N(0) = Y_N^{eq}$



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



For $K < 1$, the decay determines Y_{B-L}

Fine cancellation at $K \approx 0.3$

For $K > 4$, the inverse-decay determines Y_{B-L} for both cases

(Cohen-Kaplan regime of full equilibration: $\kappa = 1/z_{\rm fo}^2$)

Cogenesis driven by pNGB

- Successful baryogenesis requires an appropriate initial kinetic misalignment: $\boldsymbol{\varepsilon_1 \equiv \frac{\dot{\theta}_1}{2m_N} = \frac{Y_{B-L}}{y_\theta\, \kappa(K)}}$.

$$Y_B = \kappa(K)|c_B| \left(\frac{\frac{1}{6}\dot{\theta}T^2}{s}\right)_{T=m_N} = 0.87 \times 10^{-10}$$

- Can this turn into bosonic DM of a right amount?

$$m_a Y_a = m_a \left(\frac{\dot{\theta} v_a^2}{s}\right) = 0.22\mathrm{eV}$$

- What is the origin of such an initial condition?

Cogenesis by QCD Axion in Type-I Seesaw

Unifying Dark Matter and Baryogenesis in DFSZ Framework augmented by Type-I seesaw

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

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

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

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

Cosmic evolution of $\dot{\theta}$

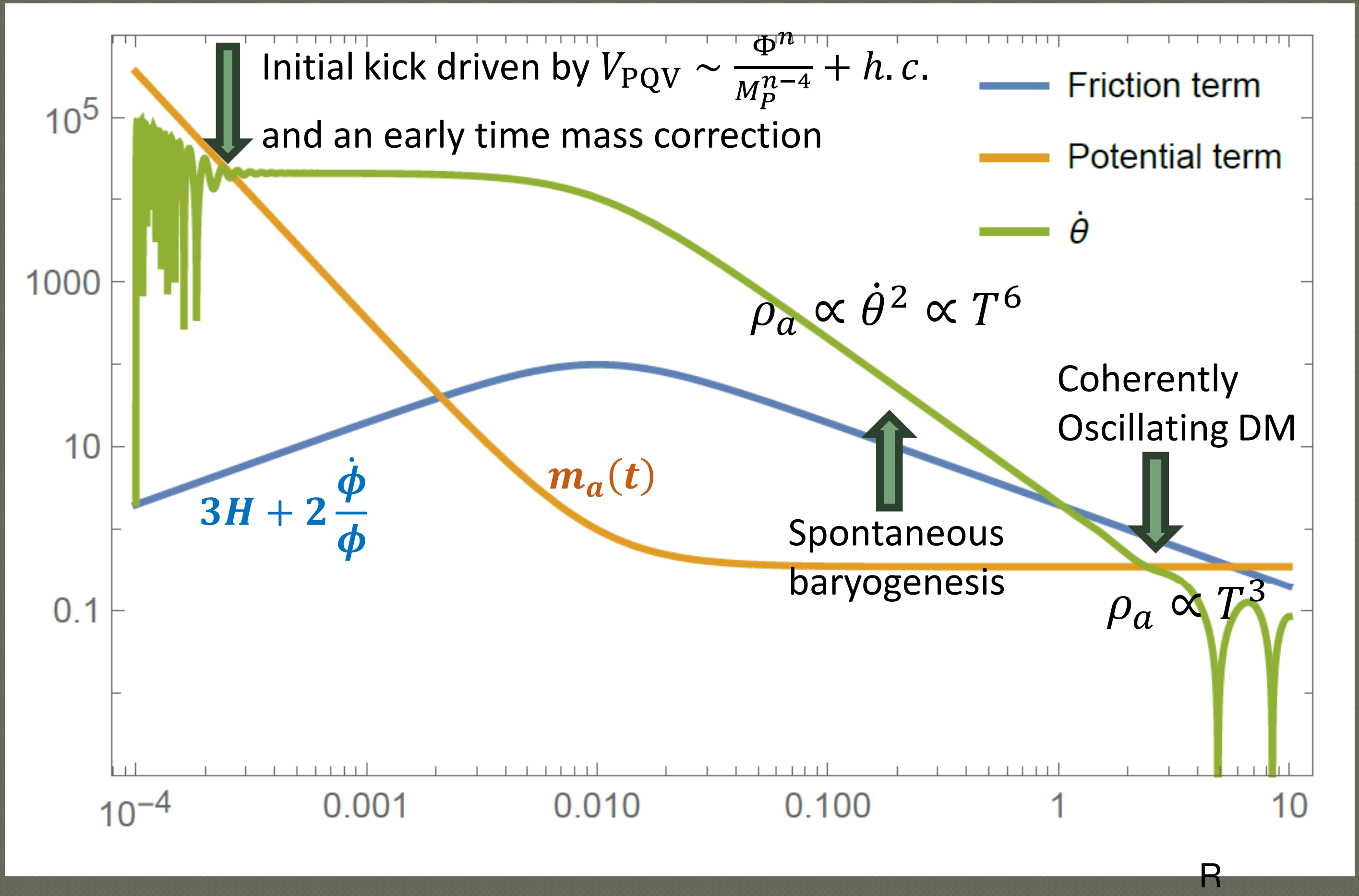
Affleck, Dine 1985

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

EJC, et.al., 2406.04180

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

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



DFSZ model augmented by Type-I seesaw

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

$U(1)_{\mathrm{PQ}} = U(1)_{B-L}$ $x_\Phi = 1$ Axion=Majoron

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

After symmetry breaking: $\psi \to e_\psi^{i x_\psi \theta} \psi$

$$-\mathcal{L}_{\mathrm{DFSZ}} = B_H H_u H_d + \frac{1}{2} m_N N N + y_\nu l N H_u + h.c.$$

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

Full equilibrium solution

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.

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

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

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

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

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

$$n_{B-L} = c_{B-L}\frac{1}{6}\,\dot{\theta}T^2 \text{ with } c_{B-L} = -\frac{13}{2} \qquad \boxed{c_s = 2N_f, c_w = 3N_f}$$

Boltzmann Equations

- Thermal averaging the decay & inverse decay biased by $\dot{\theta}$

$$\frac{dY_N}{dz} = -zK\gamma_D\left(Y_N - Y_N^{eq}\right) \qquad z \equiv \frac{m_N}{T}, K \equiv \frac{\Gamma_N}{H_1} = \frac{\frac{|y_\nu|^2}{8\pi} m_N}{H(z=1)}$$

$$Y \equiv \frac{n}{s}$$

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$$\frac{dY_{B-L}}{dz} = zK\gamma_M\varepsilon_1\left(Y_N - Y_N^{eq}\right) - zK\gamma_{ID}\left(Y_{B-L} + \frac{y_\theta \varepsilon_1}{z^2}\right)$$

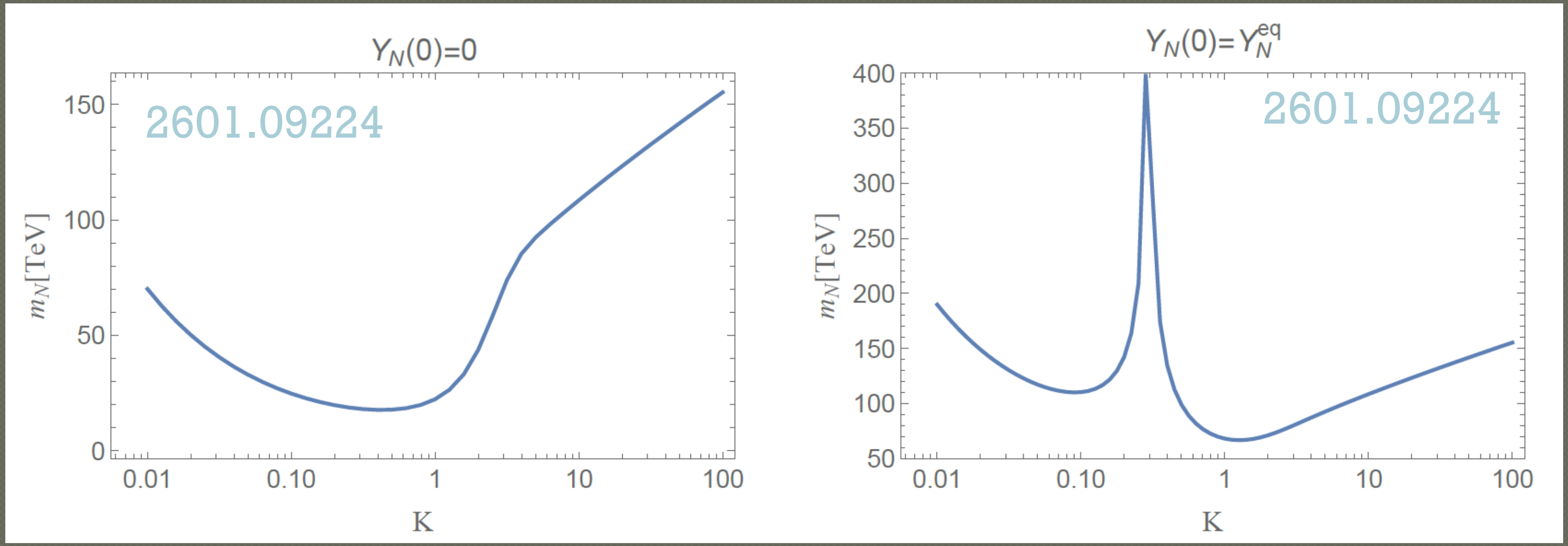
$$Y_{\Delta N} = Y_{N_+} - Y_{N_-}$$

decouples

$$\varepsilon_1 \equiv \frac{\dot{\theta}_1}{2m_N}; \quad y_\theta \equiv c_{B-L}\frac{1}{2}\frac{45}{2\pi^2}\frac{1}{g_*} \qquad c_{B-L} = -\frac{13}{2}\,(\text{flavor} - \text{dependent})$$

B-L Asymmetry arises both from the decay at tree level & equilibration by the inverse-decay (washout process).

Required RHN mass



$f_a = 10^9\text{GeV}$: $N_{DW} = 6$ $|c_B| = 2.3$ $(\boldsymbol{m_N \propto f_a})$

Hubble-induced $\dot{\theta}$ during inflation

- Origin of the initial kinetic misalignment?

Assume Hubble-induced mass-squared during the inflationary era and PQ violating potential a la Affleck-Dine.

$$V_{PQC} = -(\mu_S^2 + a_H H^2)|S|^2 + \lambda_S |S|^4$$

$$V_{PQV} = \lambda_n \frac{S^n}{M_P^{n-4}} + h.c. = \frac{|\lambda_n|}{2^{\frac{n}{2}}} \frac{\phi^n}{M_P^{n-4}} 2\cos(n\theta + \delta_n)$$

$$S = \frac{\phi}{\sqrt{2}} e^{i\theta} \quad \text{with} \quad \phi = v_a \sqrt{1 + \frac{H^2}{H_c^2}} \quad \text{where} \quad v_a = \frac{\mu_S}{\sqrt{\lambda_S}} \quad \text{and} \quad H_c = v_a \sqrt{\frac{\lambda_S}{a_H}}$$

Evolution of $\dot{\theta}$

- Slowly decreasing between t_0 (H_0) and t_c (H_c)

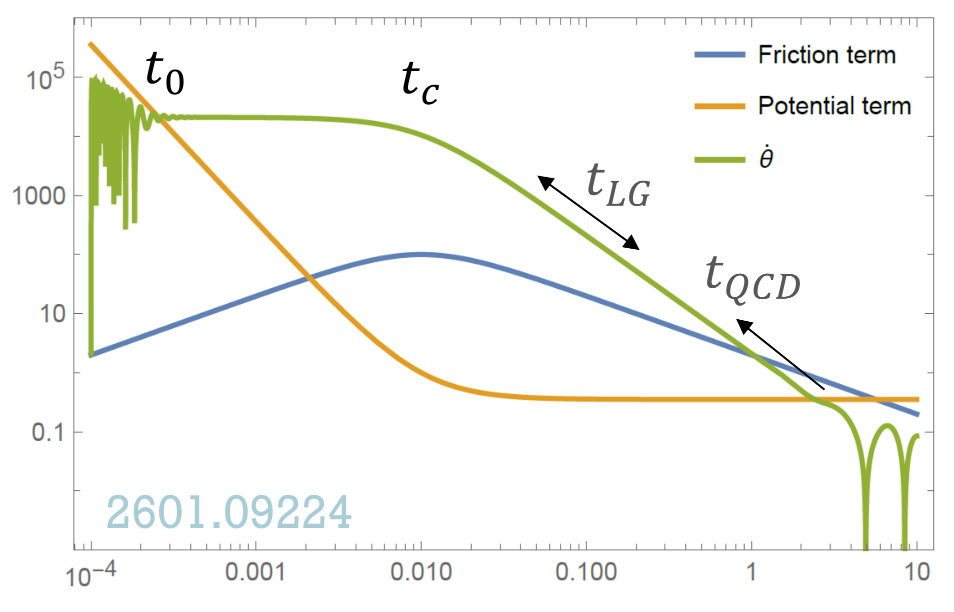
$$\ddot{\theta} + \left(3H + 2\frac{\dot{\phi}}{\phi}\right)\dot{\theta} + \frac{1}{\phi^2}\frac{\partial V_{PQV}}{\partial \theta} = 0$$

$$\frac{2}{t}\left(1 - \frac{t_c^2/t^2}{1 + t_c^2/t^2}\right)$$

Modified friction vanishes at t→0.

$$\delta m_a^2(t_U) < 10^{-10} m_a^2$$

Mass correction by V_{PQV}

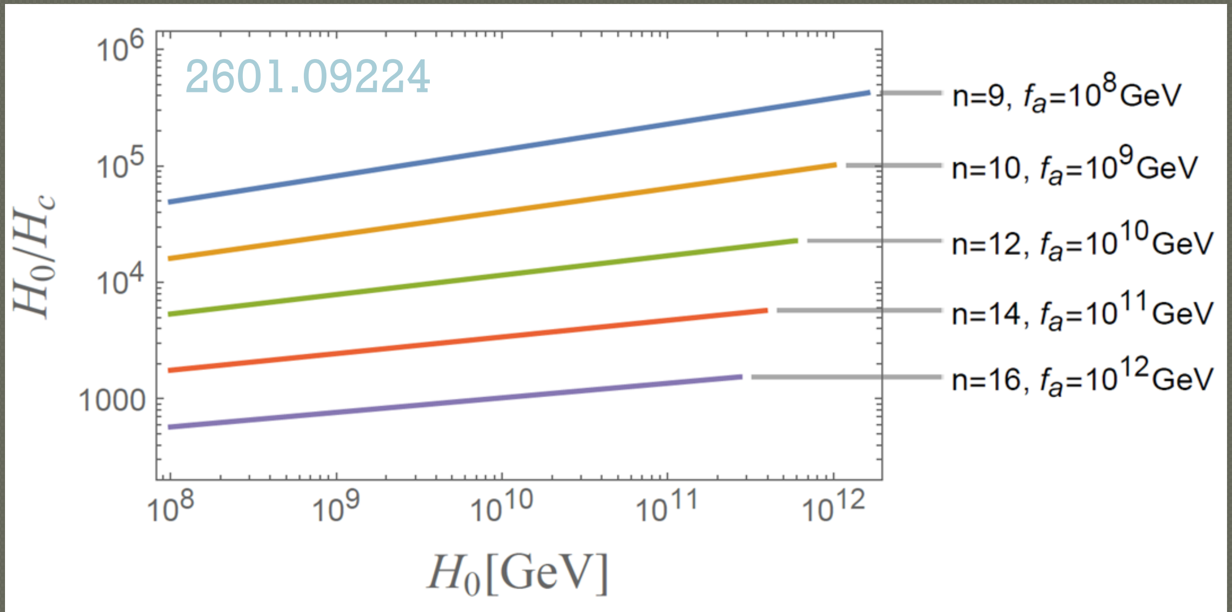


Parameter selection

- Axion quality: PQV by n>9 operator.
- PQ symmetry broken from the beginning → Constraint from isocurvature perturbation.

$$\left(\frac{H_I}{2\pi\phi_I}\right)^2\left(\frac{f_a}{10^{12}\text{GeV}}\right)^{7/2} < 2.2\times10^{-11}$$

$$\phi_I = v_a\, H_I/H_c$$



Conclusion

- Type I seesaw with a spontaneously broken $U(1)_{B-L}$ provides a natural framework for leptogenesis driven by Majoron.
- Majorana RHNs carry "helicity chemical potential", and their decays produce CP asymmetry at tree-level.
- Full Boltzmann equation are formulated and analyzed consistently coorporating the decay and inverse decay effects.
- QCD axion models extended with Type-I seesaw can realize cogenesis of DM and baryon asymmetry if $m_N \gtrsim 10\ \mathrm{TeV}\left(\frac{f_a}{10^9\mathrm{GeV}}\right)^{1/2}$.
- The results can be applicable to a wide class of neutrino mass models.