

Cogenesis by Majoron

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Outline

- Type I Seesaw & Baryon Asymmetry from RHN decay
- Kinetic motion of a pNGB leading to CDM population & Spontaneous Baryogenesis
- Type I seesaw with spontaneously broken $U(1)_{B-L}$ Majoron as a common origin of Baryon Asymmetry and Dark Matter

Seesaw and Baryogenesis

Seesaw & Leptogenesis

● Type I seesaw from Majorana singlet fermion

[Fukugita-Yanagita, 1986]

$$\mathcal{L} = y_\nu l H N + \frac{1}{2} M_N N N + h.c.$$

$$\Rightarrow m_\nu = y_\nu \frac{v_H^2}{M_N} y_\nu^T$$

$$(*) y_\nu \sim 0.5, M_N \sim 10^{12} \text{GeV} \Rightarrow m_\nu \sim 0.05 \text{eV}$$

- L violation (Majorana neutrinos) & B+L violation (EW sphaleron)
- C & CP violation: complex Yukawa coupling y_ν
- Out of equilibrium: N decay

$$\epsilon = \frac{\Gamma(N \rightarrow lH) - \Gamma(N \rightarrow \bar{l}\bar{H})}{\Gamma(N \rightarrow lH) + \Gamma(N \rightarrow \bar{l}\bar{H})} \neq 0$$

$$Y_B = c_B Y_{\Delta l} = c_B \kappa \epsilon \frac{n_N}{s}$$

Efficiency (washout)

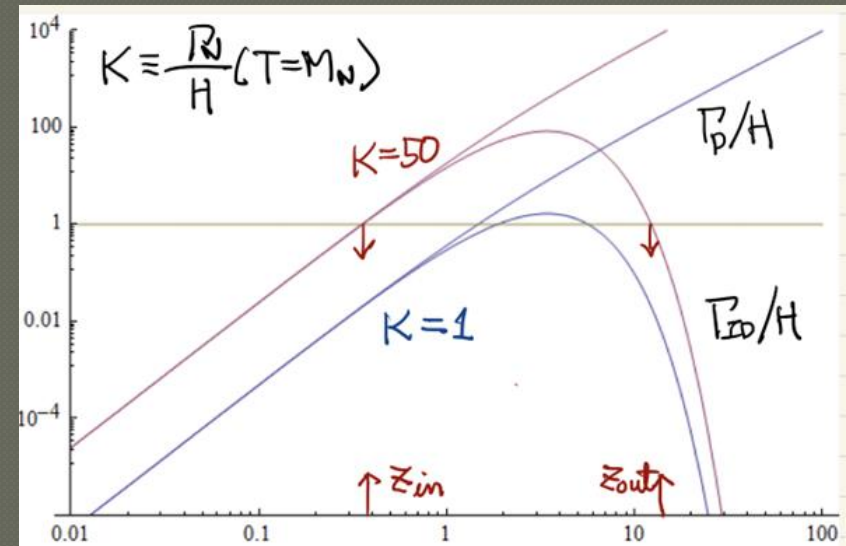
- Strength of decay/inverse-decay parameterized by

$$K \equiv \frac{\Gamma_N}{H(T = M_N)} \approx \frac{y_\nu^2 M_P}{8\pi M_N} \equiv \frac{\tilde{m}_\nu}{\text{meV}}$$

- $K \sim 1$: $lH \leftrightarrow N$ barely in equilibrium at $T \sim M_N$ (weak washout)
- $K \gg 1$: $lH \leftrightarrow N$ in equilibrium till late $T \ll M_N$ (strong washout)

- Efficiency factor: $\kappa \approx \frac{1}{K \ln K}$

(*) $\tilde{m}_\nu = 0.05\text{eV}$ ($K = 50$) $\Rightarrow \kappa \sim 10^{-2}$



(*) $lH \leftrightarrow N$ in equilibrium for $3M_N \gtrsim T \gtrsim 0.1M_N$ for $K = 50$

**CDM & Baryogenesis
from
kinetic motion of pNGB**

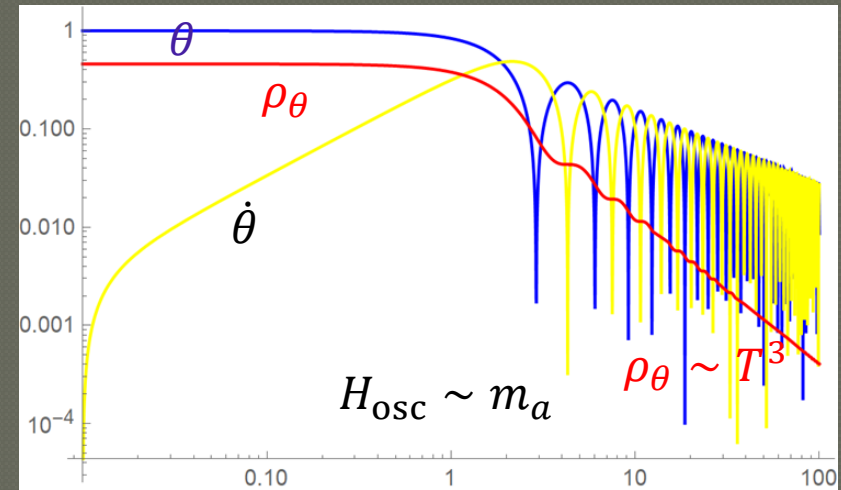
Coherent oscillation from misalignment

- When a boson field have an initial amplitude displaced from the vacuum value $\theta_i \equiv \frac{a_i}{f_a} \neq 0$, it starts to oscillate at $H(T_{\text{osc}}) \approx m_a$ and becomes coherent (wave) dark matter:

$$\frac{\rho_{\text{DM}}}{s} \approx \frac{m_a^2 f_a^2 \theta_i^2}{s(T_{\text{osc}})} \approx 0.44 \text{ eV}$$

$$\Rightarrow f_a \sim 5 \cdot 10^{11} \text{ GeV} \left(\frac{\text{eV}}{m_a} \right)^{\frac{1}{4}}$$

Preskill, Wise, Wilczek; Abbott, Sikivie; Dine, Fischler, 1983



$$\ddot{\theta} + 3H\dot{\theta} + m_a^2 \sin\theta = 0$$

$$\rho_\theta = f_a^2 \left(\frac{1}{2} \dot{\theta}^2 + m_a^2 (1 - \cos\theta) \right)$$

Coherent oscillation from kinetic motion

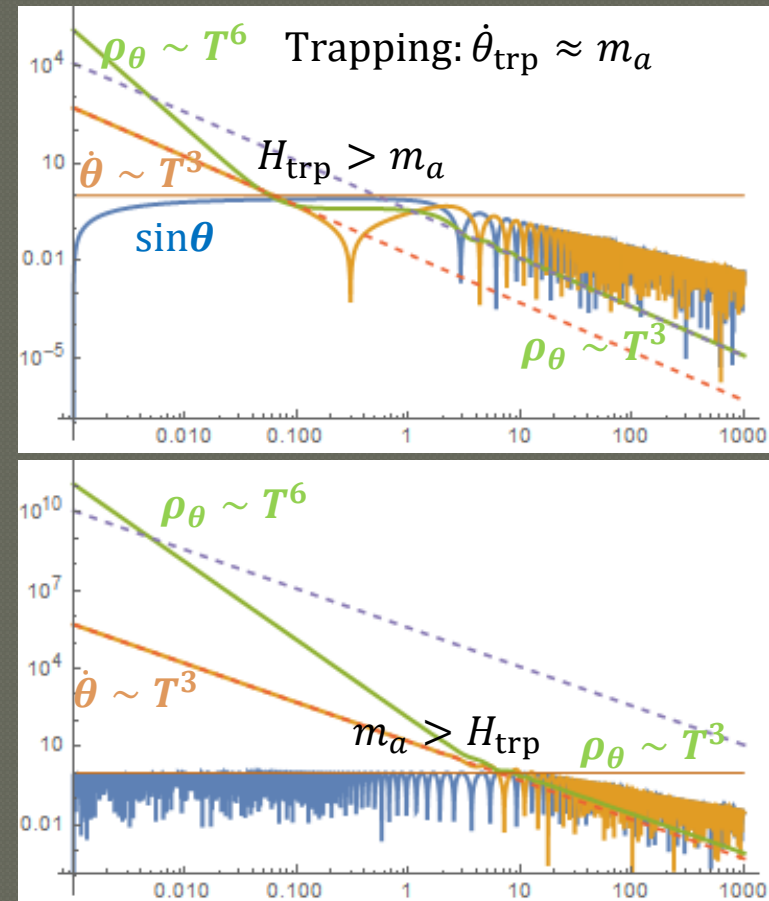
- With a kinetic motion $\dot{\theta}_i \neq 0$, it gets first trapped by the potential when KE=PE: $f_a^2 \dot{\theta}^2 \approx m_a^2 f_a^2 \theta^2 \Rightarrow \dot{\theta}_{\text{trp}} \approx m_a \theta_{\text{trp}}$

(note) $Y_\theta \equiv \frac{n_\theta}{s} = \frac{\dot{\theta} f_a^2}{s} = \text{conserved}$

- Then, oscillation starts after a while if $H(T_{\text{trp}}) > m_a$ (i); or immediately if $m_a > H(T_{\text{trp}})$ (ii):

$$\Rightarrow \frac{\rho_{\text{DM}}}{s} \approx \begin{cases} \frac{m_a^2 f_a^2 \theta_{\text{trp}}^2}{s(T_{\text{osc}})}, & (i) \\ \frac{\dot{\theta}_{\text{trp}}^2 f_a^2}{s(T_{\text{trp}})} \approx m_a Y_\theta, & (ii) \end{cases}$$

Co, Hall, Harigaya, 1910.14152



Spontaneous Baryogenesis

Cohen-Kaplan, 1987, 88

- Consider $U(1)_B$ spontaneously broken at the scale f_a .
- The pNGB coupling to the baryon current $\frac{1}{f_a} \partial_\mu a \sum_\psi x_\psi \bar{\psi} \gamma^\mu \psi$ shifts the energy of $\psi/\bar{\psi}$ by $E_{\psi/\bar{\psi}} = E_0 \mp x_\psi \dot{\theta}$ in the background of $\dot{\theta} \equiv \frac{\dot{a}}{f_a}$ (**CPT violation**).
- When **B violation is in thermal equilibrium**, the chemical potential of $\psi/\bar{\psi}$ is generated $\mu_\psi = c_\psi \dot{\theta}$ depending on the equilibration processes.
- This leads to the baryon asymmetry $Y_B \equiv \frac{\mu_B T^2}{s}$ with $\mu_B = c_B \dot{\theta}$ which freezes at $T = T_B$ when B violation decouples.

Axiogenesis

- Application to a chiral $U(1)_{PQ}$ symmetry.
- Anomaly interaction $aG\tilde{G}/aW\tilde{W}$ in equilibrium:
Strong sphaleron $\rightarrow 2\mu_q + \mu_{u^c} + \mu_{d^c} = c_S\dot{\theta}$
EW sphaleron $\rightarrow 3\mu_q + \mu_l = c_W\dot{\theta}$
- B (B-L) asymmetry is frozen at $T_B = T_{EW}$: $\mu_B = c_B\dot{\theta}$

Co-Harygaya, 1910.02080;
Domcke et.al., 2006.04138;
and others

Nb) Cogenesis from QCD axion? $m_a \sim \frac{m_\pi f_\pi}{f_a}$

$$Y_B \sim 0.1 Y_\theta \left(\frac{T_{EW}}{f_a} \right)^2 \sim 10^{-10} \quad \Rightarrow \quad m_a \sim 10 \text{ eV} \left(\frac{10^6 \text{ GeV}}{f_a} \right)^2$$
$$\frac{\rho_{DM}}{s} \sim m_a Y_\theta \sim 0.44 \text{ eV}$$

Type I seesaw with $U(\cancel{1})_L$

Majoron as the common origin of
baryon asymmetry and dark matter

Majorogenesis

$$\mathcal{L} = y_\nu l H N + \frac{1}{2} y_N \Phi N N + \frac{\Phi^n}{\Lambda^{n-4}} + \text{h.c.} \quad \text{with } \Phi = \frac{f_a}{\sqrt{2}} e^{i\theta}$$

- ◆ Anomaly-free B-L symmetry broken by $M_N = \frac{y_N}{\sqrt{2}} f_a$.
- ◆ The pNGB (Majoron) coupling: $\dot{\theta} \sum_\psi x_\psi \bar{\psi} \gamma^0 \psi$
where $x_\psi = \left(\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, -1, 1\right)$ for $\psi = (q, u^c, d^c, l, e^c)$
- ◆ N decay/inverse-decay in equilibrium to generate $\mu_{B(B-L)} \propto \dot{\theta}$,
which freezes at $T_B \approx \frac{M_N}{z_{\text{out}}} \rightarrow Y_B = \frac{c_B \dot{\theta}(T_B) T_B^2}{s(T_B)} = c_B Y_\theta \left(\frac{T_B}{f_a}\right)^2 \approx 10^{-10}$
- ◆ CDM population generated when $\dot{\theta}$ trapped by the potential
 $V_n = \frac{1}{n^2} m_a^2 f_a^2 (1 - \cos(n\theta)) \rightarrow \frac{\rho_{\text{DM}}}{s} = m_a Y_\theta \approx 0.44 \text{eV}$

Chemical equilibration

- Four Yukawas + EW Sphaleron + charge neutrality (simple case):

$$y_u q u^c H \Rightarrow \mu_q + \mu_{u^c} + \mu_H = 0$$

$$y_d q d^c \tilde{H} \Rightarrow \mu_q + \mu_{d^c} - \mu_H = 0$$

$$y_e l e^c \tilde{H} \Rightarrow \mu_l + \mu_{e^c} - \mu_H = 0$$

$$y_\nu l N H \Rightarrow \mu_l + \mu_H - \dot{\theta} = 0 \quad (\text{LNV: } \mu_N \equiv 0)$$

$$\mathcal{A}_{B+L}(W\tilde{W}) \Rightarrow 3(3\mu_q + \mu_l) = 0$$

$$Y = 0 \Rightarrow 3 \left(\frac{1}{6} 2 \cdot 3\mu_q - \frac{2}{3} 3\mu_{u^c} + \frac{1}{3} 3\mu_{d^c} - \frac{1}{2} 2\mu_l + \mu_{e^c} \right) - \frac{1}{2} 2 \cdot 2 \mu_H = 0$$



$$\mu_B = \frac{1}{3} 3 (2\mu_q - \mu_{u^c} - \mu_{d^c}) = \frac{28}{11} \dot{\theta}$$

$$\mu_L = \frac{1}{3} 3 (2\mu_l - \mu_{e^c}) = -\frac{51}{11} \dot{\theta}$$

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

Cogenesis from initial kinetic motion

- ❖ Simultaneous generation of Y_B & ρ_{DM} :

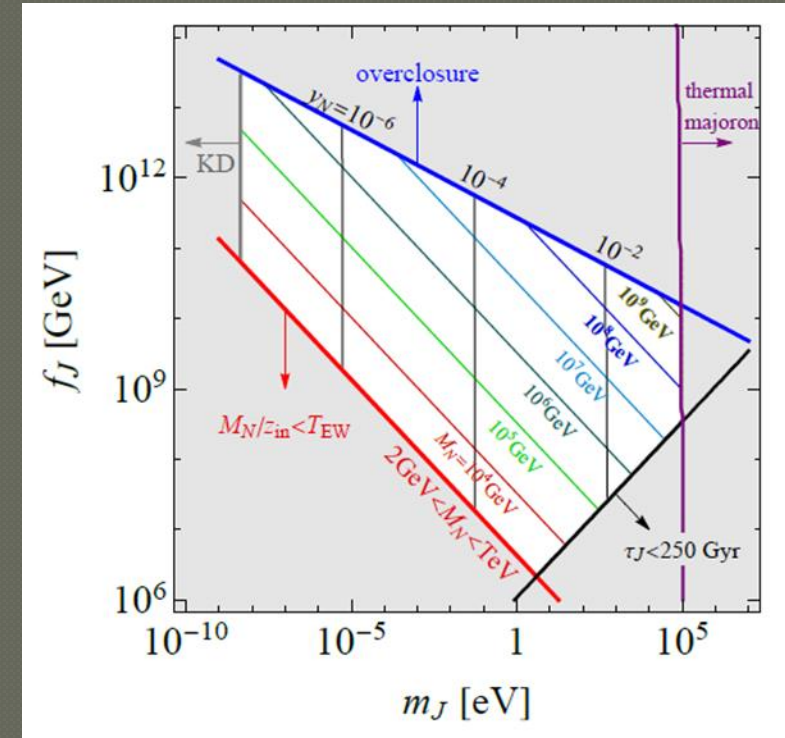
$$m_a Y_\theta = 0.44 \text{eV} \Rightarrow Y_B \approx 0.1 Y_\theta \left(\frac{T_B}{f_a} \right)^2 \approx 0.1 \frac{0.44 \text{eV}}{m_a} \left(\frac{T_B}{f_a} \right)^2$$

- ❖ $T_B = \frac{M_N}{z_{\text{out}}}$ when $\frac{M_N}{z_{\text{out}}} > T_{EW}$:

Trapping condition $m_a \sim 4 \cdot 10^6 \text{ eV } y_N^2$
 $\dot{\theta}_{\text{trp}} \sim m_a > H_{\text{trp}} \quad f_a \lesssim 10^8 y_N^{-1} \text{ GeV} \left(\frac{\text{eV}}{m_a} \right)^{1/4}$

- ❖ $T_B = T_{EW}$ when $M_N < T_{EW}$:

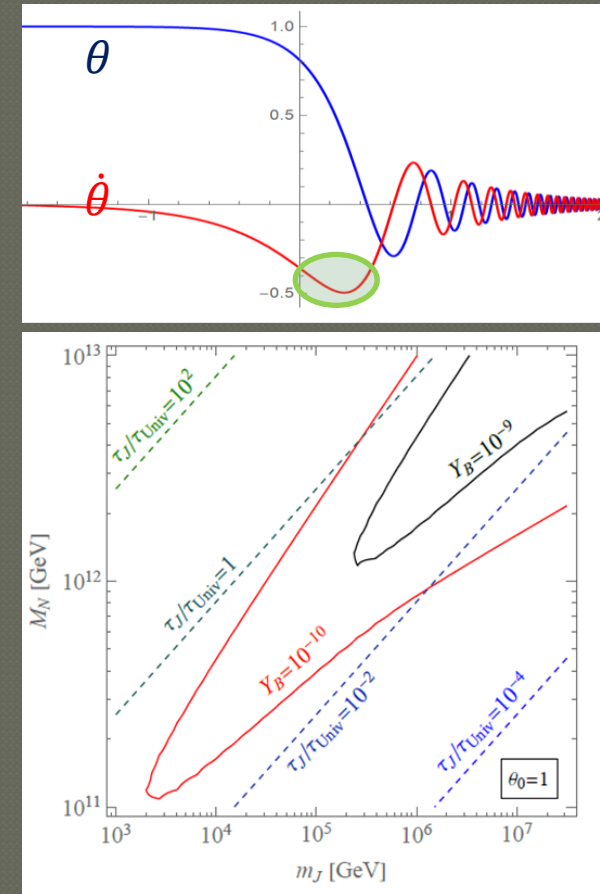
$$f_a \sim 2 \cdot 10^6 \text{ GeV} \left(\frac{\text{eV}}{m_a} \right)^{1/2}$$



$$Y_\theta \sim 10^{-7} \left(\frac{f_a}{M_N} \right)^2 \quad \tau_a^{-1} = \frac{m_\nu^2 m_a}{16\pi f_a^2}$$

Cogenesis from initial misalignment

- Starting from $\dot{\theta} = 0$, $\dot{\theta} \sim m_a$ arises at $T_{\text{osc}} \sim \sqrt{m_a M_P}$ around which Y_B is supposed to be generated.
- Considering $T_{\text{osc}} = T_B$, one finds $m_a \sim 10^3 \text{ GeV}$ and $T_B \sim \frac{M_N}{10} \sim 10^{10} \text{ GeV}$, and thus $\frac{\rho_a}{s} \sim \frac{m_a^2 f_a^2}{s(T_{\text{osc}})} \gg 0.44 \text{ eV}$.
- Way out: Early oscillation with $m_a(T) \gg m_a^0$ to separate out $T_B \gg T_{\text{osc}}$.



Symmetry non-restoration

- Consider a U(1) breaking field Φ coupling to the Higgs or any bosons S in thermal equilibrium:

$$V(\Phi, S) = \lambda_\phi |\Phi|^4 + \lambda_S |S|^4 - 2\lambda_{\text{mix}} |\Phi|^2 |S|^2 - \mu_\phi^2 |\Phi|^2 \pm \mu_S^2 |S|^2$$

$$\Phi = \frac{\phi}{\sqrt{2}} e^{ia/\langle\phi\rangle}$$

$$c_\lambda \approx \frac{\lambda_{\text{mix}}}{6\lambda_\phi} < \frac{\lambda_S}{6\lambda_{\text{mix}}}$$

$$\lambda_\phi \sim \lambda_{\text{mix}}^2 \Rightarrow c_\lambda \sim \frac{1}{\lambda_{\text{mix}}} \sim 10^8$$

- Temperature dependent VEV and mass:

$$V_T(\phi) = \frac{\lambda_\phi}{4} \phi^4 - (\mu_\phi^2 + \lambda_{\text{mix}} T^2) \phi^2 + \dots$$

$$V_a = \frac{\Phi^n}{\Lambda^{n-4}} + h.c. = \frac{1}{n^2} m_a^2(T) f_a^2(T) \left(1 - \cos \left(\frac{na}{f_a(T)} \right) \right)$$

$$\langle\phi\rangle_T = f_a(T) = \sqrt{f_{a0}^2 + c_\lambda T^2} \equiv f_{a0} \sqrt{1 + \frac{T^2}{T_c^2}}$$

$$m_a^2(T) = m_{a0}^2 \left(\frac{f_a(T)}{f_{a0}} \right)^{n-2}$$

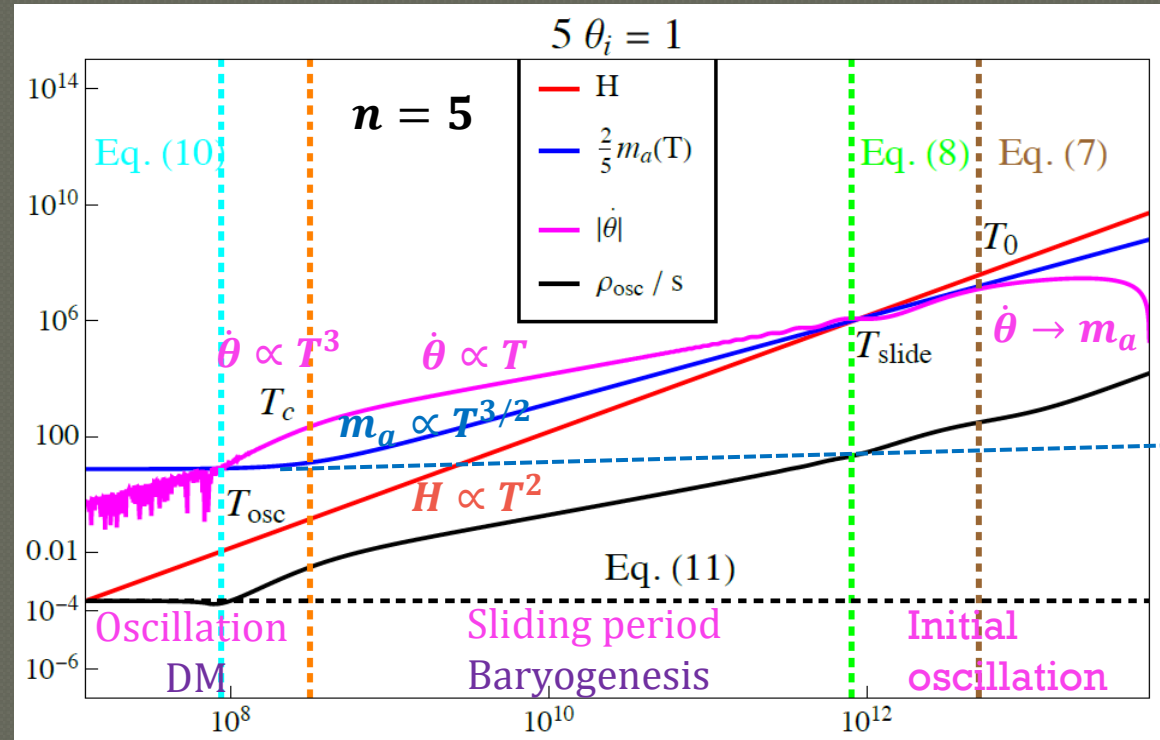
Dynamics of sliding pNGB

$$\ddot{\theta} + \left(3H + 2 \frac{\dot{f}_a(T)}{f_a(T)} \right) \dot{\theta} + \frac{1}{n} m_a^2(T) \sin(n\theta) = 0$$

$$\frac{\dot{f}_a(T)}{f_a(T)} = -H \frac{T^2}{T_c^2} \left(1 + \frac{T^2}{T_c^2} \right)^{-1} \approx -H \text{ for } T \gg T_c$$

$$m_a^2(T) = m_{a0}^2 \left(1 + \frac{T^2}{T_c^2} \right)^{\frac{n-2}{2}}$$

$$\ddot{\theta} + H\dot{\theta} + \frac{1}{n} m_a^2(T) \sin(n\theta) = 0$$



$$\ddot{\theta} + H\dot{\theta} = T \frac{d}{dt} \frac{\dot{\theta}}{T} \approx 0$$

$$\Rightarrow \dot{\theta} \approx T$$

First oscillates at high T

- Starting from the initial $\theta_i \neq 0$, the early oscillation starts to produce $\dot{\theta} \neq 0$ around T_0 when $H(T_0) \approx m_a(T_0)$

$$T_0 \approx 5 \cdot 10^{11} \text{GeV} \left(\frac{100}{g_*} \right) \left(\frac{c_\lambda}{10^8} \right)^{\frac{3}{2}} \left(\frac{m_{a0}}{\text{eV}} \right)^2 \left(\frac{10^6 \text{GeV}}{f_{a0}} \right)^3$$

- It escapes from oscillation at T_{slide} when the kinetic energy becomes larger than the potential energy.

$$\dot{\theta}(T_{\text{slide}}) \approx \frac{2}{5} m_a(T_{\text{slide}}) \Rightarrow T_{\text{slide}} \approx \frac{C}{16} (5\theta_i)^4 T_0$$

Slides and oscillate again

- It slides down as $\dot{\theta} \propto T$ from T_{slide} to T_c below which temperature dependence disappears and thus falls down as $\dot{\theta} \propto T^3$.

$$T_c \approx \sqrt{\frac{f_{a0}}{c_\lambda}} = 10^2 \text{GeV} \left(\frac{f_{a0}}{10^6 \text{GeV}} \right)^{\frac{1}{2}} \left(\frac{10^8}{c_\lambda} \right)^{\frac{1}{2}} \quad T_{c,EW} < T_B < T_{\text{slide}}$$

Era of Baryogenesis

- As the kinetic energy reduces as T^6 , it soon gets trapped in the potential and the second oscillation starts to produce dark matter density: $T_{\text{osc}} = T_{\text{trp}}$.

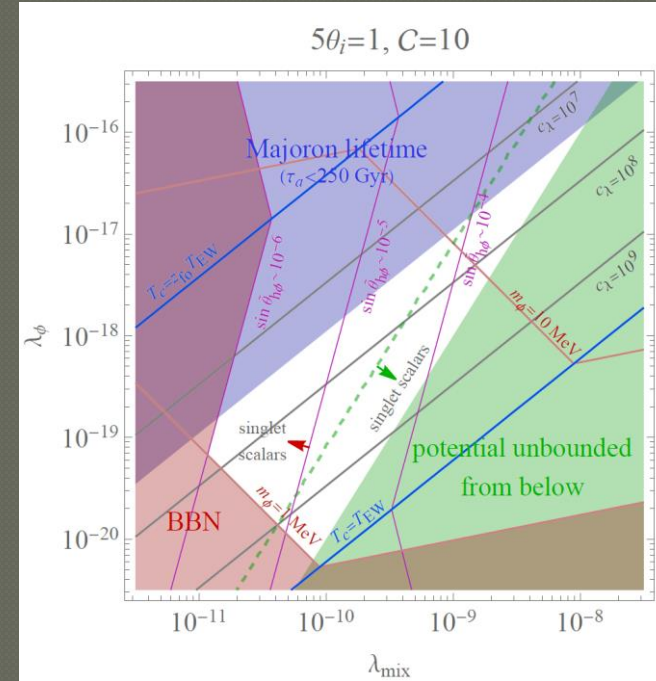
$$T_{\text{osc}} \approx \frac{4 \text{GeV}}{C^{\frac{1}{5}} (5\theta_0)^{\frac{2}{3}}} \left(\frac{g_*}{100} \right)^{\frac{1}{6}} \left(\frac{10^8}{c_\lambda} \right)^{\frac{5}{6}} \left(\frac{\text{eV}}{m_{a0}} \right)^{\frac{1}{3}} \left(\frac{f_{a0}}{10^6 \text{GeV}} \right)^{\frac{5}{3}} \quad \text{Era of DM}$$

Cogenesis corner

$$\left(\frac{\dot{\theta}}{T}\right)_{\text{slide}} \approx 10^{-7} C^{\frac{1}{2}} (5\theta_i)^2 \left(\frac{100}{g_*}\right) \left(\frac{c_\lambda}{10^8}\right)^{\frac{3}{2}} \left(\frac{m_{a0}}{\text{eV}}\right)^2 \left(\frac{10^6 \text{GeV}}{f_{a0}}\right)^3$$

$$Y_B = \frac{45}{2\pi^2} \frac{c_B}{g_*} \left(\frac{\dot{\theta}}{T}\right)_{\text{slide}} \begin{cases} 1 & \text{for } T_c < T_{EW} \text{ or } \frac{M_N}{z_{\text{out}}} \\ \left(\frac{T_{EW}}{T_c}\right)^2 & \text{for } \frac{M_N}{z_{\text{out}}} < T_{EW} < T_c \\ \left(\frac{M_N}{z_{\text{out}} T_c}\right)^2 & \text{for } T_{EW} < \frac{M_N}{z_{\text{out}}} < T_c \end{cases}$$

$$\frac{\rho_{\text{DM}}}{s} \approx 0.07 \text{eV} C^{\frac{1}{2}} (5\theta_i)^2 \left(\frac{100}{g_*}\right)^{\frac{3}{2}} \left(\frac{c_\lambda}{10^8}\right)^{\frac{5}{2}} \left(\frac{m_{a0}}{\text{eV}}\right)^3 \left(\frac{10^6 \text{GeV}}{f_{a0}}\right)^3$$



$$m_{a0} = \frac{5 \text{eV}}{C^{\frac{1}{9}} (5\theta_i)^{\frac{4}{9}}} \left(\frac{g_*}{100}\right)^{\frac{1}{3}} \left(\frac{10^8}{c_\lambda}\right)^{\frac{5}{9}}$$

$$f_{a0} = 3 \cdot 10^6 \text{GeV} C^{\frac{1}{18}} (5\theta_i)^{\frac{2}{9}} \left(\frac{100}{g_*}\right)^{\frac{1}{9}} \left(\frac{c_\lambda}{10^8}\right)^{\frac{5}{18}}$$

Summary

- Type-I seesaw model with majoron provides an affordable framework for the simultaneous generation of baryon asymmetry and dark matter enjoying freedom with the parameters (m_a, f_a, M_N) .
- Needs a comprehensive study for general K and $n > 5$.
- Simply(?) extendable to various seesaw models.
- Way to realize cogeneration with QCD axion?
- Origin of Y_θ : T-dependence, AD mechanism, Inflation, ...