Cogenesis by majoron

Based on the work with Tae Hyun Jung, 2311.09005;
Suruj Jyoti Das, Minxi He, Tae Hyun Jung, Jin Sun, 2406.04180

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Baryogenesis and DM from a pNGB

Majoron $\theta \equiv \frac{a}{f_a}$ in Seesaw Model with $U\cancel{(1)}_{B-L}$

Connection to neutrino mass

$$\mathcal{L}_N = y_\nu lHN + \frac{1}{2}\Phi NN + \frac{\Phi^n}{\Lambda^{n-4}} + \text{h.c.} \;\Leftarrow\; \Phi = \frac{f_a}{\sqrt{2}}e^{i\theta}$$

$$V_n = \frac{1}{n^2}m_a^2 f_a^2\left(1 - \cos(n\theta)\right)$$

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

DM from a classical oscillation of $\theta, \dot{\theta}$

Spontaneous Baryogenesis in the background of $\dot{\theta} \neq 0$

Cohen-Kaplan, ’87, ’88

$$\frac{\rho_{\mathrm{DM}}}{s} = m_a\frac{n_a}{s} = m_a Y_\theta \approx 0.44\mathrm{eV}$$

$$Y_B = Y_{\dot{\theta}}\left(\frac{T_B}{f_a}\right)^2 \approx 10^{-10}$$

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

pNGB as a CDM candidate

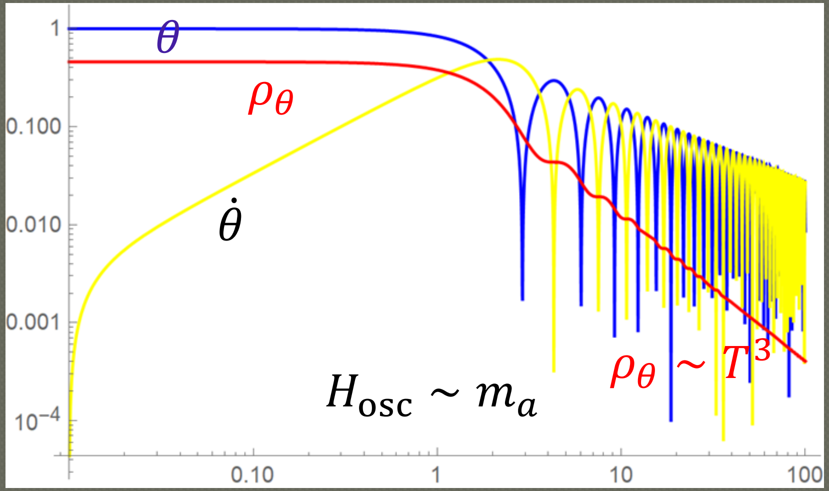
Coherent oscillation from misalignment

- 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 $H(T_{\rm osc}) \approx m_a$ and becomes coherent (wave) dark matter:

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

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

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

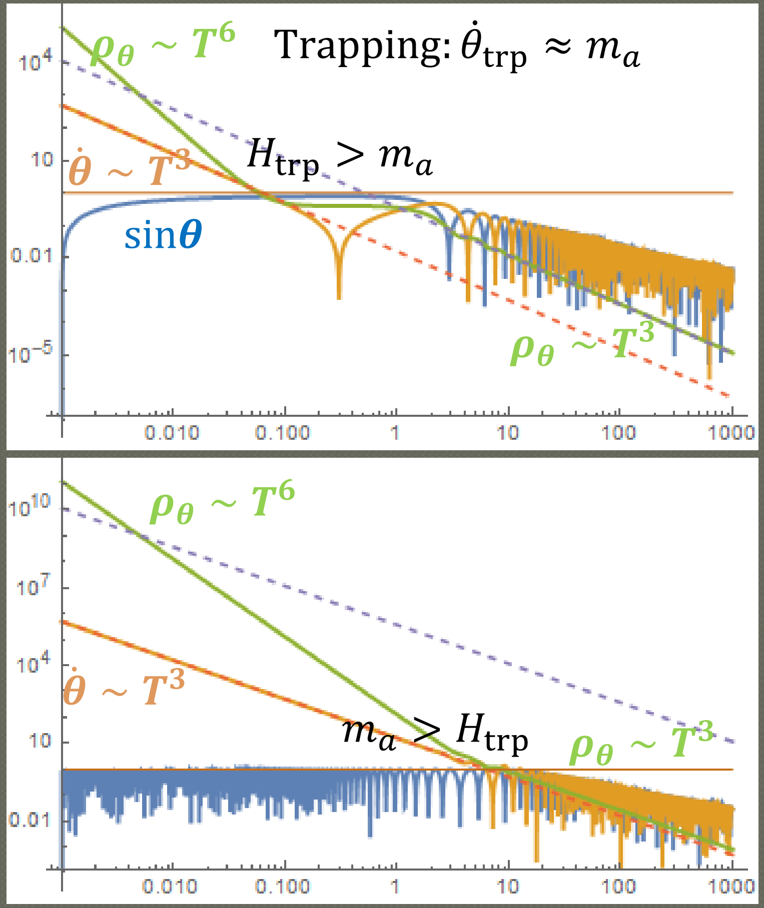
- With a kinetic motion $\dot{\theta}_i \neq 0$, it gets first trapped by the potential when KE=PE: $f_a^2\dot{\theta}^2 \approx m_a^2 f_a^2 \theta^2 \Rightarrow \dot{\theta}_{\rm trp} \approx m_a \theta_{\rm trp}$

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

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

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

Co, Hall, Harigaya, 1910.14152



pNGB for Baryogenesis

Spontaenous 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 $\dot{\theta} \equiv \dot{a}/f_a$.
- 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 $\mu_B \propto \dot{\theta}$ which freezes at $T = T_B$ when B violation decouples.

Axiogenesis

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

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

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

$$Y_B \sim 0.1 Y_\theta \left(\frac{T_{EW}}{f_a}\right)^2 \sim 10^{-10}$$

$$\frac{\rho_{\rm DM}}{s} \sim m_a Y_\theta \sim 0.44\text{eV}$$

$$\Rightarrow \; m_a \sim 10^{-9}\ \text{eV} \left(\frac{10^{11}\text{GeV}}{f_a}\right)^2$$

Seesaw & B-L (L) violation

- Seesaw mechanism explaining tiny Majorana neutrinos mass: $\mathcal{L} = y_\nu lNH + \frac{1}{2}MNN + h.c. \Rightarrow \mathcal{L}_W = \frac{m_\nu}{v_H^2} lHlH + h.c.$ $m_\nu = y_\nu^2 \frac{v_H^2}{M_N}$
- B-L violation by Weinberg operator $ll \leftrightarrow HH$ in equilibrium for $M_N \gtrsim T \gtrsim 10^{13}\text{GeV}$.

Co, et.al., 2006.05687

- B-L violation by decay & inverse-decay $N \leftrightarrow lH$ in equilibrium for $\frac{M_N}{z_{\text{in}}} \gtrsim T \gtrsim \frac{M_N}{z_{\text{out}}}$.

EJC, Jung, 2311.09005;
EJC, Das, He, Jung, Sun, 2406.04180
Barns, et.al., 2402.10263

Majorogenesis

$$\mathcal{L} = y_\nu lHN + \frac{1}{2} y_N \Phi NN + h.c. \text{ with } \Phi = \frac{f_a}{\sqrt{2}} e^{i\theta}$$

◆Anomaly-free B-L symmetry broken by $M_N = \frac{y_N}{\sqrt{2}} f_a$.

◆The pNGB (Majoron) coupling to the B-L current:

$$\dot{\theta} \sum_\psi x_\psi \bar{\psi} \gamma^0 \psi \text{ where } (x_\psi) = \left(\frac{1}{3}, -\frac{1}{3}, -1, 1, 1\right) \text{ for } \psi = (q, q^c, l, e^c, N).$$

◆N decay/inverse-decay in equilibrium → $\mu_{B-L} \propto \dot{\theta}$.

◆B (B-L) asymmetry freezes at $T_B \approx \frac{M_N}{z_{\rm out}}$ → $Y_B = \frac{c_B \dot{\theta}(T_B)\, T_B^2}{s(T_B)}$.

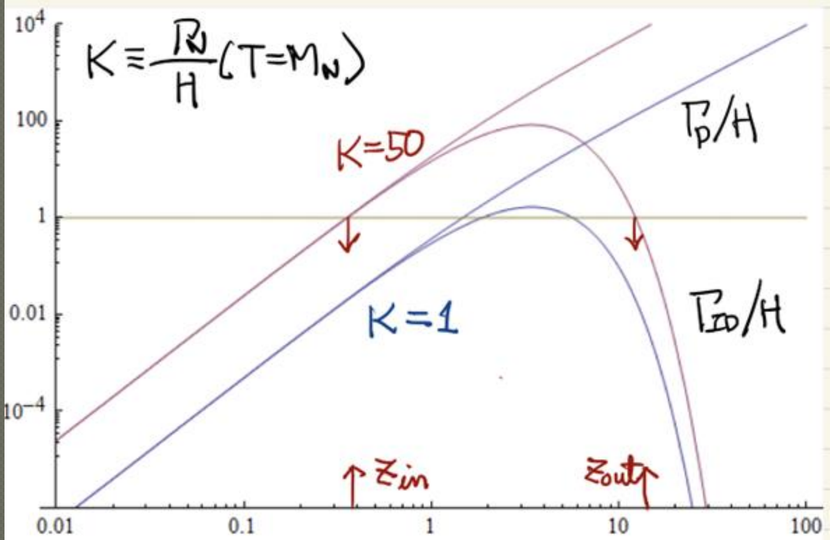
Efficient inverse-decay

- Define $K \equiv \left(\frac{\Gamma_N}{H}\right)_{T=M_N} \approx \frac{\widetilde{m}_\nu}{\text{meV}}$

  $K \sim 1: lH \leftrightarrow N$ barely in equilibrium at $T \sim M_N$

  $K \gg 1: N \leftrightarrow lH$ in equilibrium during $T = (\frac{M_N}{z_{\text{in}}}, \frac{M_N}{z_{\text{out}}})$.

- Consider $\widetilde{m}_\nu = 0.05\text{eV}\ (K = 50)$



(Note) In the standard thermal leptogenesis, the inverse-decay washes out the lepton asymmetry roughly by $\frac{1}{K\ln K} \sim 10^{-2}$ (strong washout).

Medium potential $\dot{\theta}$

DIRAC FERMION

$$p_+^\mu \gamma_\mu \psi_L = m\psi_R$$
$$p_+^\mu \gamma_\mu \psi_R = m\psi_L$$

$$p_\pm^\mu \equiv (E \pm x_\psi \dot{\theta}, \vec{p})$$

$$\Rightarrow E = E_0 - x_\psi \dot{\theta}$$

$$n_\psi - n_{\bar{\psi}} \propto \mu_\psi - x_\psi \dot{\theta}$$

Ex) Electron Yukawa
$Y_e l e^c \tilde{H}$ in equilibrium

$$\Rightarrow \mu_l + \mu_{e^c} - \mu_H = 0$$

MAJORANA FERMION

$$p_+^\mu \gamma_\mu \psi_L = M\psi_R$$
$$p_-^\mu \gamma_\mu \psi_R = M\psi_L$$

$$\mathcal{H} = \hat{p} \cdot \vec{\sigma} = \pm 1$$

$$\Rightarrow E = \sqrt{M^2 + \left(\mathrm{p} + \mathcal{H} x_\psi \dot{\theta}\right)^2} \approx E_0 + \mathcal{H} x_\psi \dot{\theta} \frac{\mathrm{p}}{E_0}$$

$$n_{N_+} - n_{N_-} \propto \mu_N - x_N \dot{\theta}(1+z)e^{-z} \qquad z \equiv \frac{M}{T}$$

Neutrino Yukawa $Y_\nu l N H$ in equilibrium

◆ Opposite helicity states $N_\pm$ have the same rates and thus μ_N decouples: $\langle N_+ \leftrightarrow lH \rangle = \langle N_- \leftrightarrow lH \rangle$; $\langle N_+ \leftrightarrow \bar{l}\bar{H} \rangle = \langle N_- \leftrightarrow \bar{l}\bar{H} \rangle \;\Rightarrow\; \mu_l + \mu_H + \dot{\theta} = 0$

Chemical equilibration

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

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

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

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

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

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

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

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

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

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

Cogenesis by initial kinetic motion

- Simultaneous generation of Y_B & ρ_{DM}:

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

- $T_B = \dfrac{M_N}{z_{\mathrm{out}}}$ when $\dfrac{M_N}{z_{\mathrm{out}}} > T_{EW}$:

Trapping condition

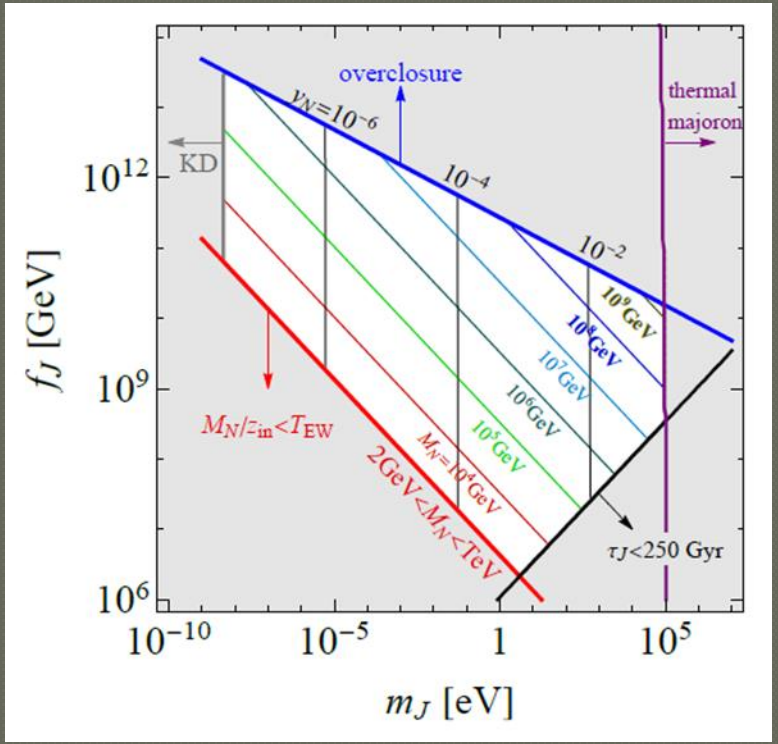
$$\dot{\theta}_{\mathrm{trp}} \sim m_a > H_{\mathrm{trp}}$$

$$m_a \sim 4 \cdot 10^6\, eV\, y_N^2$$

$$f_a \lesssim 10^8\, y_N^{-1} \mathrm{GeV} \left(\frac{\mathrm{eV}}{m_a}\right)^{1/4}$$

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

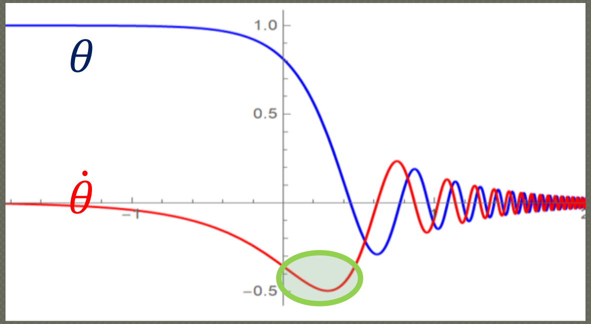
$$f_a \sim 2 \cdot 10^6 \mathrm{GeV} \left(\frac{\mathrm{eV}}{m_a}\right)^{1/2}$$

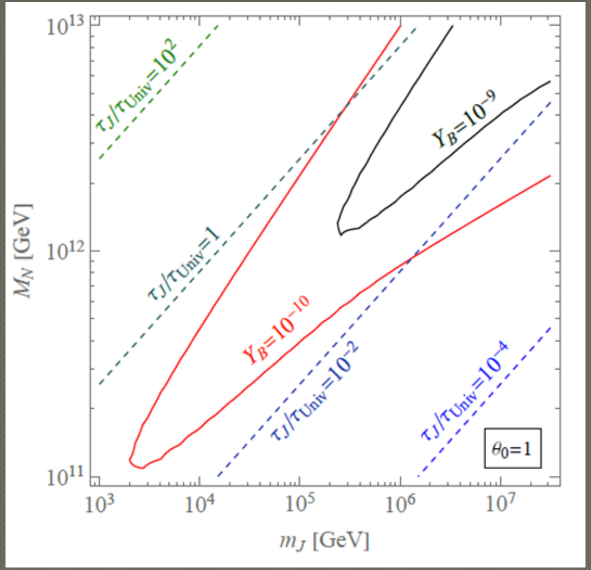


$$\tau_a^{-1} = \frac{m_\nu^2 m_a}{16\pi f_a^2}$$

Cogenesis by conventional misalignment

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





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:

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

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

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

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

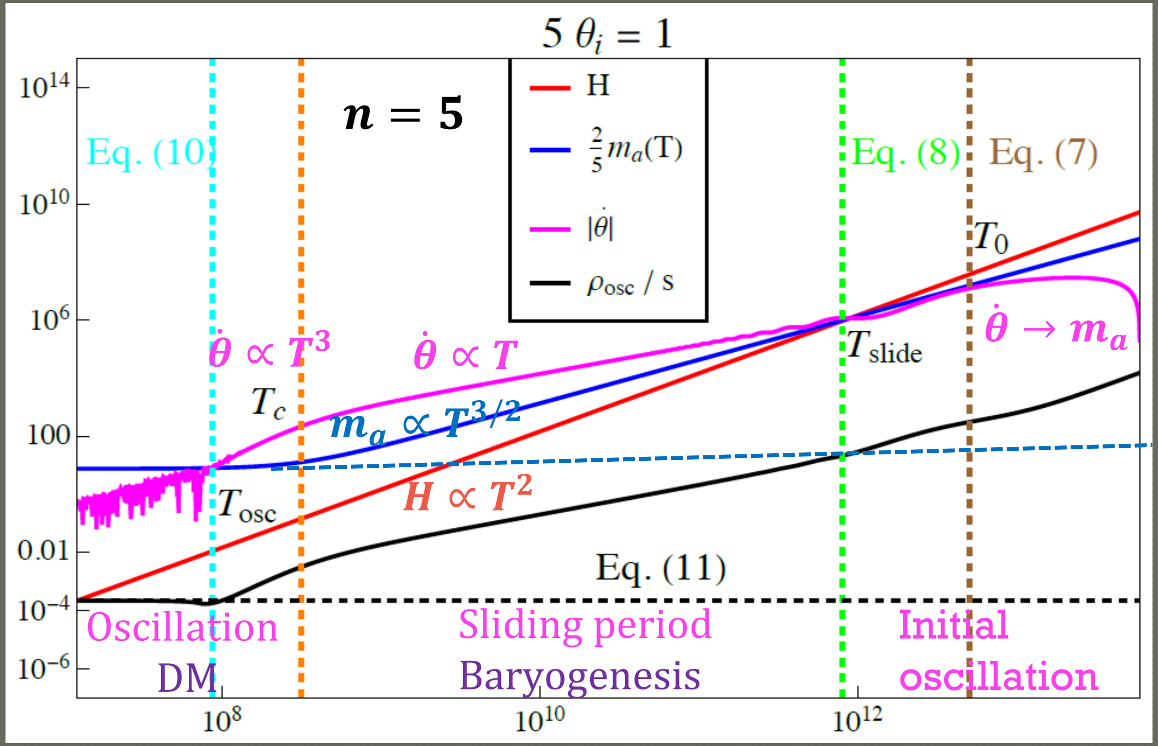
Dynamics of sliding pNGB

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

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

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

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



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

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 $H(T_0) \approx m_a(T_0)$

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

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

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

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 $\dot{\theta} \propto T^3$.

$$T_c \approx \sqrt{\frac{f_{a0}}{c_\lambda}} = 10^2\text{GeV}\left(\frac{f_{a0}}{10^6\text{GeV}}\right)^{\frac{1}{2}}\left(\frac{10^8}{c_\lambda}\right)^{\frac{1}{2}}$$

$T_c < T_B < T_{\text{slide}}$

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: $T_{\text{osc}} = T_{\text{trp}}$.

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

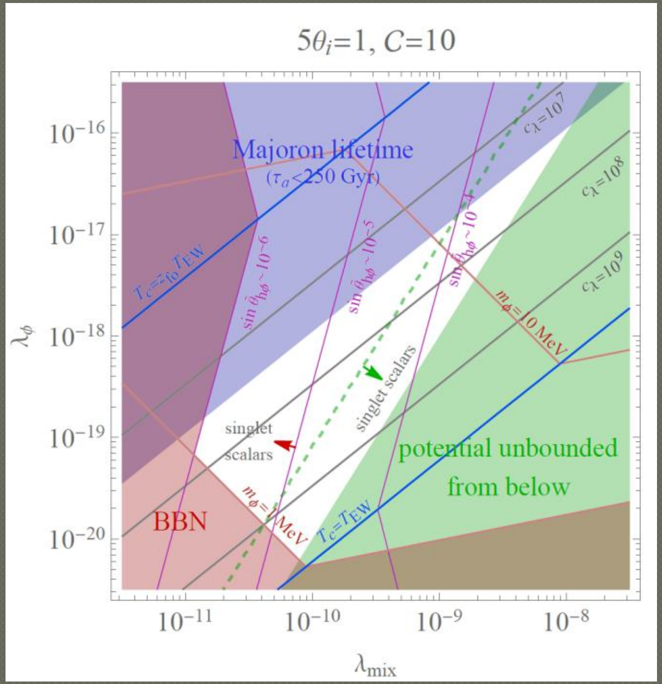
Era of DM

Cogenesis corner

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

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

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



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

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

Discussion

- 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 general study including the weak washout regime $(K \sim 1)$ and higher dimensional operators $(n > 5)$.
- Extendable to various seesaw models.