Cogenesis by majoron

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Outline

Baryogenesis & DM from the same origin?

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

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

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

DM from coherent oscillation of $\theta, \dot{\theta}$

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

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

$$Y_B \sim \left(\frac{\dot{\theta}}{T}\right)_{T_B} \sim 10^{-10}$$

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

pNGB as a CDM candidate

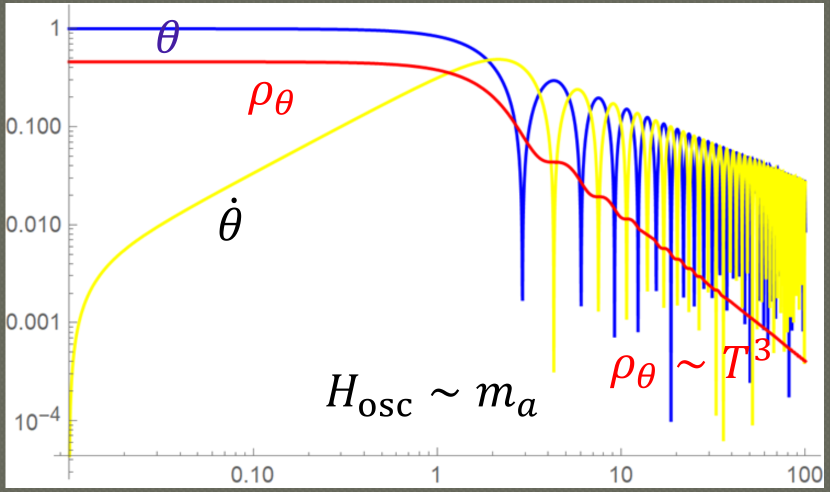
Coherent oscillation from misalignment

- 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:

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

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

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

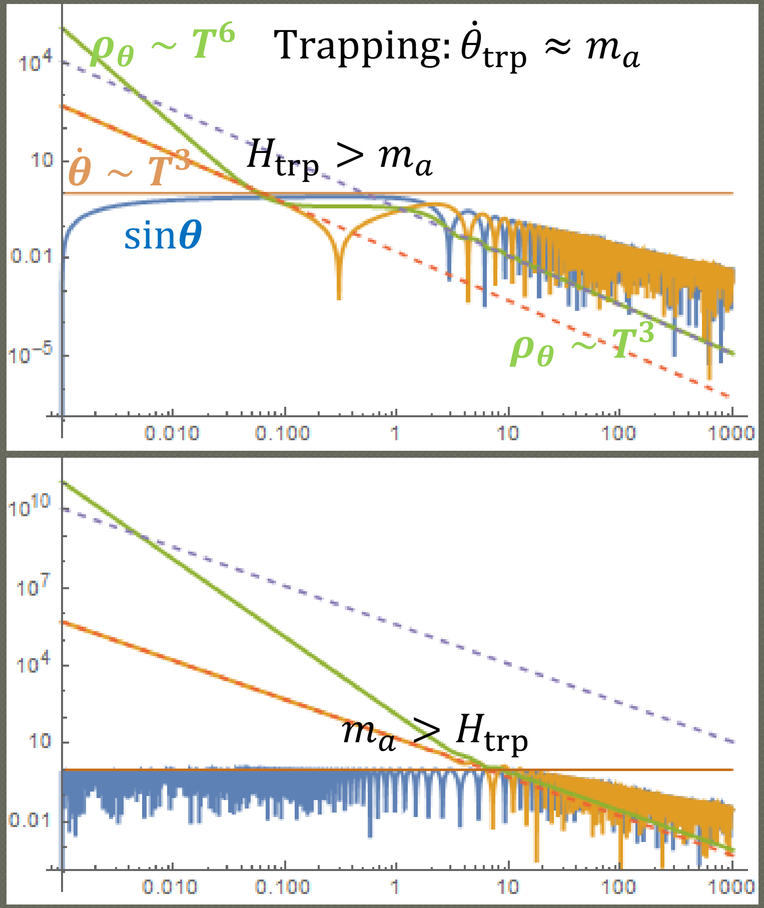
- With a kinetic motion $\dot{\theta}_i \neq 0$, it gets first trapped by the potential when KE=PE: $f_a^2\dot{\theta}^2 \approx m_a^2 f_a^2 \theta^2 \Rightarrow \dot{\theta}_{\rm trp} \approx m_a \theta_{\rm trp}$

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

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

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

Co, Hall, Harigaya, 1910.14152



pNGB for Baryogenesis

Cohen-Kaplan, 1987, 88

Spontaenous Baryogenesis

- Consider $U(1)_B$ spontaneously broken at the scale f_a.
- Due to the pNGB coupling to the baryon current $\frac{1}{f_a}\partial_\mu a \sum_\psi x_\psi \bar{\psi}\gamma^\mu\psi$ the energy of $\psi/\bar{\psi}$ gets shifted by $E_{\psi/\bar{\psi}} = E_0 \mp x_\psi \dot{\theta}$ in the background of homogenous classical field, $\dot{\theta} \equiv \dot{a}/f$ (violating **C & CPT**).
- When **B violation is in thermal equilibrium**, the baryon asymmetry $Y_B \equiv \frac{\mu_B T^2}{s}$ is generated as $\mu_B = c_B\dot{\theta}$ through chemical equilibration, and freezes when B violation decouples at $T = T_B$.

(note) $n_\psi^{eq} - n_{\bar{\psi}}^{eq} \approx \frac{g_\psi}{6}(\mu_\psi - x_\psi\dot{\theta})T^2$

- In terms of the baryon number $Y_\theta = \frac{\dot{\theta} f_a^2}{s}$ stored in the kinetic motion of θ, the final baryon asymmetry is given by $Y_B = c_B Y_\theta \left(\frac{T_B}{f_a}\right)^2$.

Axiogenesis

- Application to 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 $T_B = T_{\rm EW}$
- Cogenesis?

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

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

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

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

Application to Majoron

Seesaw & B-L (L) violation

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

EJC, Jung, 2311.09005;
EJC, Das, He, Jung, Sun, 2406.04180

Efficient inverse-decay

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

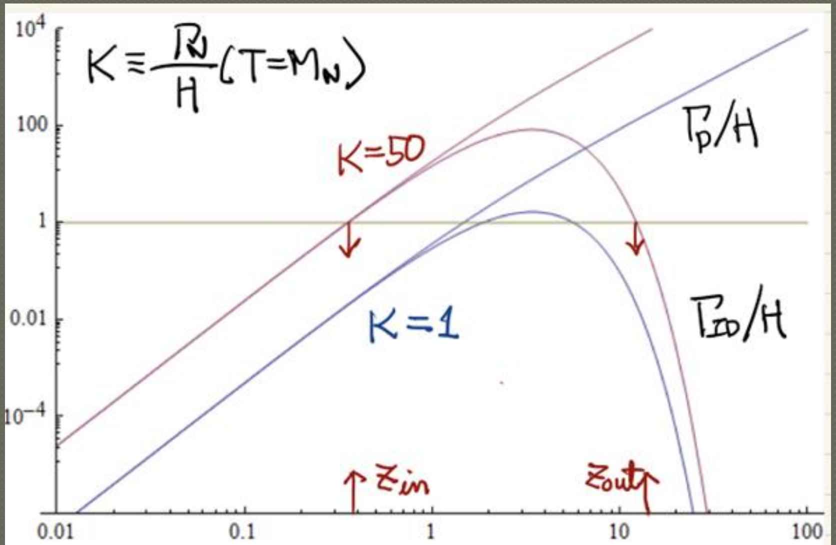
  $K \sim 1: lH \to N$ barely in equilibrium

  $K \gg 1: N \leftrightarrow lH$ in equilibrium during

  $$T = \left(\frac{M_N}{z_{\text{fi}}}, \frac{M_N}{z_{\text{fo}}}\right).$$

- Consider $\tilde{m}_\nu = 0.05\text{eV}$ leading to $K = 50$.

(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).



Majoron & Spontaneous Leptogenesis

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

- Anomaly-free B-L symmetry broken by $M_N = \frac{y_N}{\sqrt{2}} f_a$.
- The pNGB (Majoron) coupling to j^μ_{B-L}: $\partial_\mu \theta \sum_\psi x_\psi \bar{\psi} \gamma^\mu \psi$

  where $\left(x_q, x_{q^c}, x_l, x_{e^c}, x_N\right) = \left(\frac{1}{3}, -\frac{1}{3}, -1, 1, 1\right)$
- For a Majorana particle, $E = \sqrt{\mathrm{p}^2 + M_N^2 + \frac{1}{4}\dot{\theta}^2 - \mathcal{H}\dot{\theta}\mathrm{p}} \approx E_0 - \mathcal{H}\,\frac{\dot{\theta}}{2}\frac{\mathrm{p}}{E_0}$
- N decay/inverse-decay in equilibrium:

  $\langle N \leftrightarrow lH \rangle = \langle N \leftrightarrow \bar{l}\bar{H} \rangle = \langle \bar{N} \leftrightarrow \bar{l}\bar{H} \rangle = \langle \bar{N} \leftrightarrow lH \rangle \rightarrow \mu_l + \mu_H + \dot{\theta} = 0$
- B (B-L) asymmetry freezes at $T_B \approx M_N / z_{\mathrm{fo}}$ to generate $Y_B = c_B \frac{\dot{\theta}(T_B)\, T_B^2}{s(T_B)}$.

Chemical equilibration

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

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

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

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

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

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

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

$$\Rightarrow$$

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

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

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

Cogenesis by initial kinetic motion

- Simultaneous generation of Y_B & $\rho_{\rm DM}$:

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

- $T_B = \dfrac{M_N}{z_{\rm fo}}$ when $\dfrac{M_N}{z_{\rm fo}} > T_{EW}$:

Trapping condition

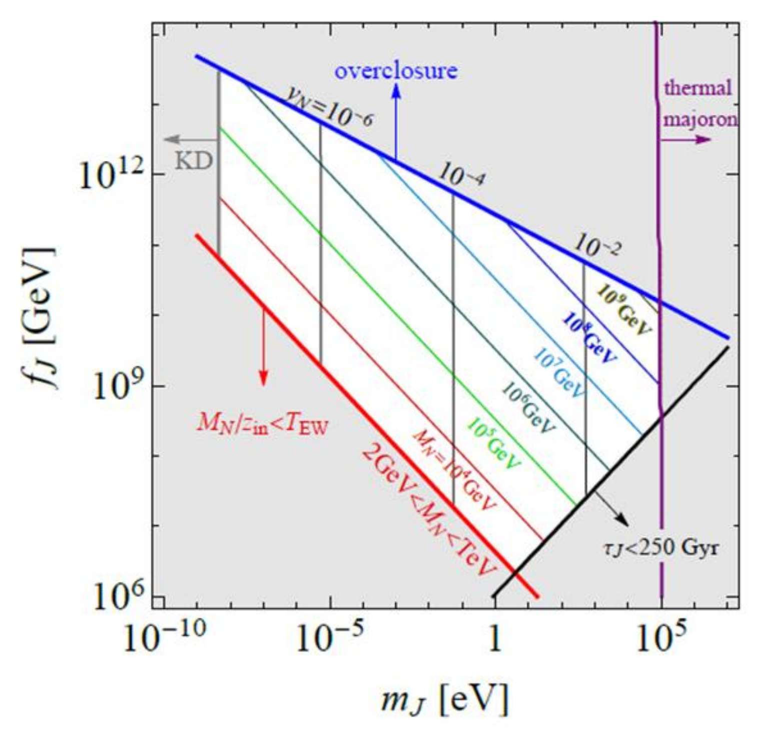
$$\dot\theta_{\rm trp} \sim m_a > H_{\rm trp}$$

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

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

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

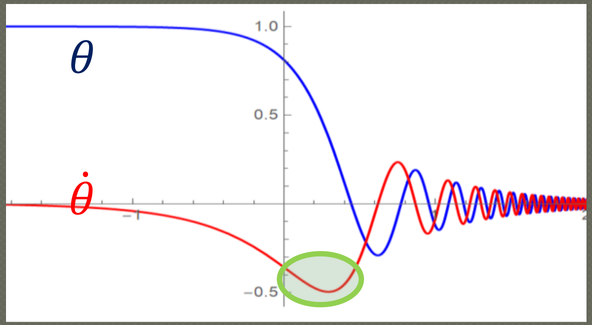
$$f_a \sim 2\cdot 10^6\text{GeV}\left(\frac{\text{eV}}{m_a}\right)^{1/2}$$

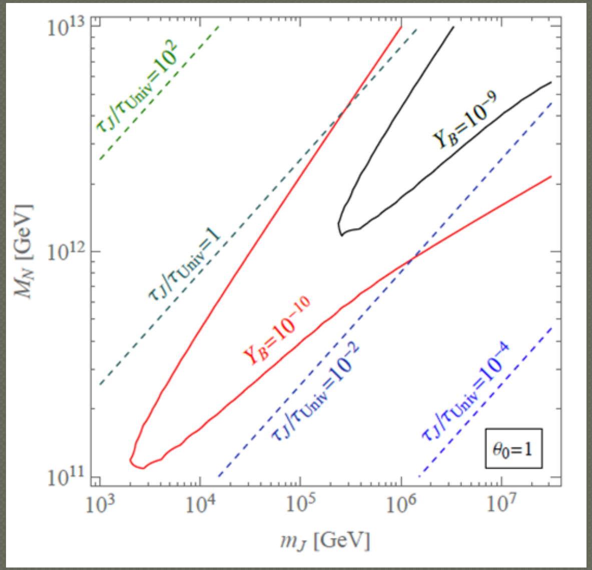


$$\tau_a^{-1} = \frac{m_\nu^2 m_a}{16\pi f_a^2}$$

Cogenesis by conventional misalignment

- Starting from $\dot{\theta} = 0$, $\dot{\theta} \sim m_a$ arises at around $T_{\rm osc} \sim \sqrt{m_a M_P}$ around which Y_B is supposed to be generated.
- Considering $T_{\rm osc} = T_B$, one finds $m_a \sim 10^3\,{\rm GeV}$ 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 which has to disappear before BBN.
- 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:

$$V(\Phi,S)=\lambda_\phi|\Phi|^4+\lambda_s|S|^4-2\lambda_{\rm mix}|\Phi|^2|S|^2-\mu_\phi^2|\Phi|^2\pm\mu_s^2|S|^2$$

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

$$c_\lambda\approx\frac{\lambda_{\rm mix}}{6\lambda_\phi}<\frac{\lambda_s}{6\lambda_{\rm mix}}$$

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

- Temperature dependent VEV and mass:

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

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

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

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

Dynamics of sliding pNGB

- Starting from the initial $\theta_0 \neq 0$, the early oscillation starts to produc e $\dot{\theta} \neq 0$ 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 immediately or after a while when the ki netic energy becomes larger than the potential energy.

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

Dynamics of sliding pNGB

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

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

- 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: $T_{\mathrm{osc}} = T_{\mathrm{trp}}$.

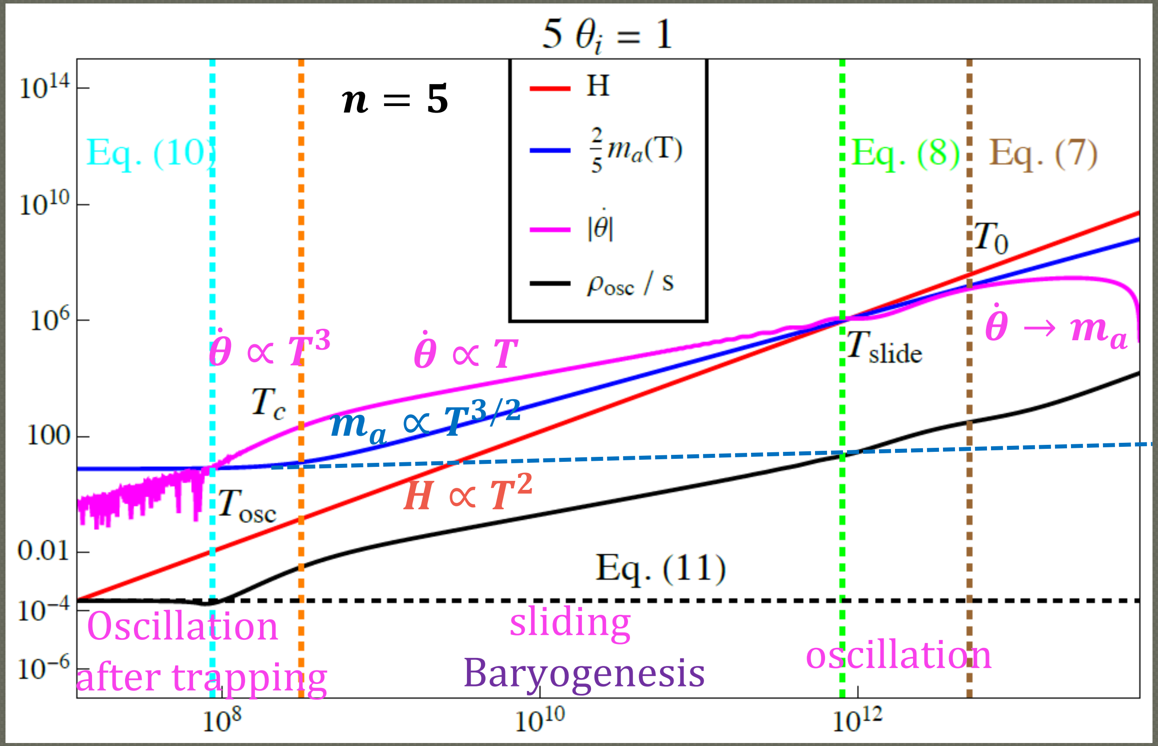
$$T_{\mathrm{osc}} \approx \frac{4\mathrm{GeV}}{C^{\frac{1}{5}}(5\theta_i)^{\frac{2}{3}}}\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\left(\frac{10^8}{c_\lambda}\right)^{\frac{5}{6}}\left(\frac{\mathrm{eV}}{m_{a0}}\right)^{\frac{1}{3}}\left(\frac{f_{a0}}{10^6\mathrm{GeV}}\right)^{\frac{5}{3}}$$

Dynamics of sliding pNGB

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

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

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



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

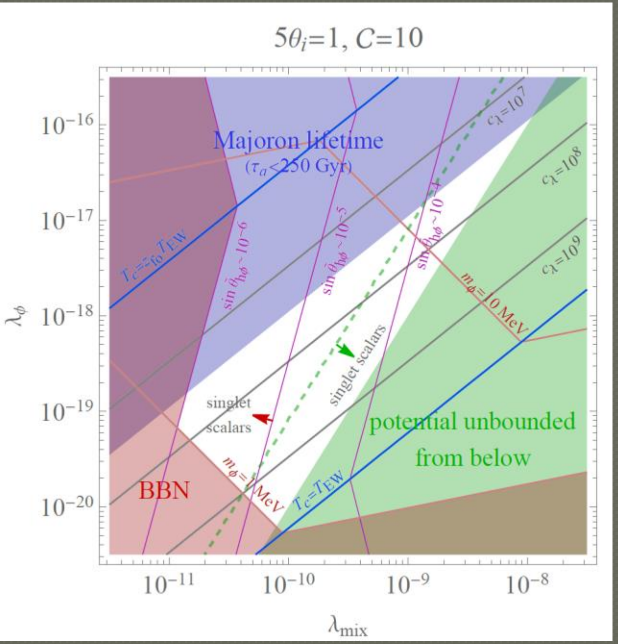
$$\ddot{\theta} + H\dot{\theta} + \frac{1}{5}m_a^2(T)\sin(5\theta_i) \approx 0$$
$$\Rightarrow \dot{\theta} \approx \sqrt{5}\sin(5\theta_i)\, T \log\frac{T^2}{T_i^2}$$

Cogenesis corner

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

$$Y_B = \frac{45}{2\pi^2}\frac{c_B}{g_*}\left(\frac{\dot{\theta}}{T}\right)_{\text{slide}} \begin{cases} 1 & \text{for } T_c < T_{EW} \text{ or } \dfrac{M_{N0}}{z_{\text{fo}}} \\ \left(\dfrac{T_{EW}}{T_c}\right)^2 & \text{for } \dfrac{M_{N0}}{z_{\text{fo}}} < T_{EW} < T_c \\ \left(\dfrac{M_{N0}}{z_{\text{fo}} T_c}\right)^2 & \text{for } T_{EW} < \dfrac{M_{N0}}{z_{\text{fo}}} < T_c \end{cases}$$

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



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

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

Outlook

- 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).

- Trivial extension to any seesaw models?

- PQ Symmetry non-restoration for cogenesis?