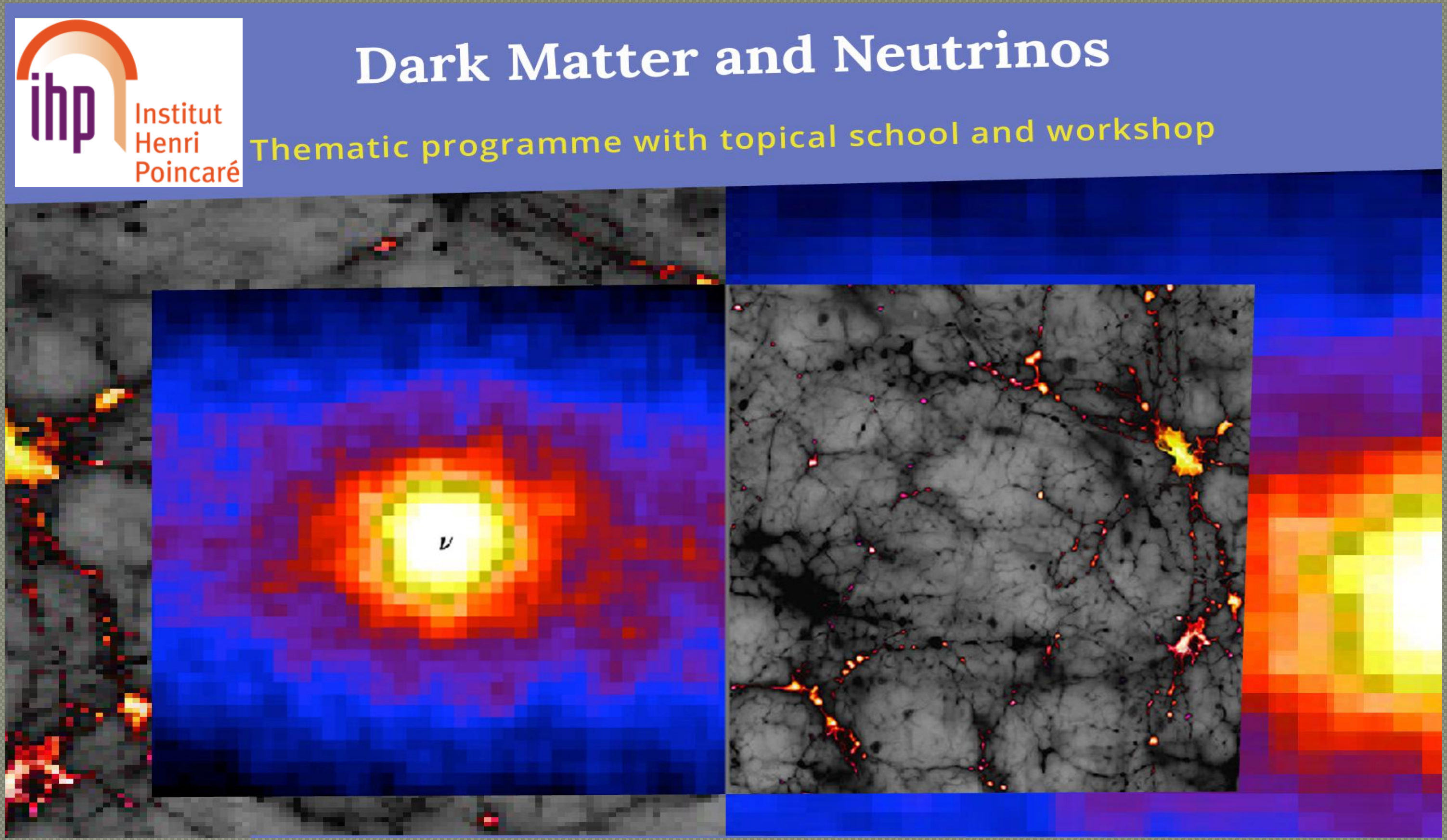
Cogenesis driven by Majoron



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Outline

- Introduction to pNGB as DM and BAU generator.
  QCD axion vs. Majoron
- Cogenesis of DM and BAU by Majoron EJC, Jung, 2311.09005
- Large kinetic misalignment in symmetry non-restoration
  EJC, Das, He, Jung, Sun, 2406.04180 (in revision)
- Conclusion

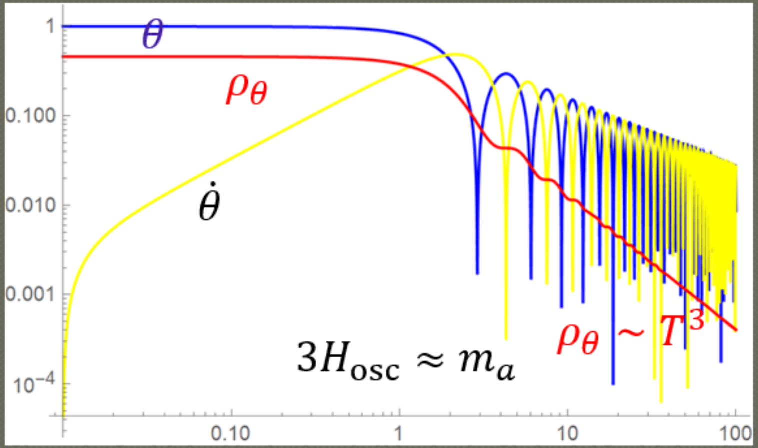
pNGB from U(1) Breaking

- A massless phase field from spontaneous breaking
  $$\Phi = \frac{f_a}{\sqrt{2}}\, e^{i\theta}\,; \;\; \theta \equiv \frac{a}{f_a}$$
- QCD axion (KSVZ) vs. Majoron
  $$y_Q \Phi Q Q^c \;\; \textbf{vs.} \;\; \frac{y_N}{2}\Phi N N$$
- Potential from (tiny) explicit breaking
  $$V = m_a^2\, f_a^2 (1 - \cos\theta)$$
- Derivative and anomaly coupling
  $$\mathcal{L}_\partial = x_\psi \partial_\mu \theta\, \bar{\psi}\bar{\sigma}^\mu \psi$$
  $$\mathcal{L}_A = \frac{c_A}{32\pi^2}\theta F_A^{\mu\nu} F_{A\mu\nu}$$
- Cosmic evolution of coherent (classical) field
  $$\ddot{\theta} + \left(3H + 2\frac{\dot{f}_a}{f_a}\right)\dot{\theta} + m_a^2 \sin\theta = 0$$

pNGB as CDM

- Conventional misalignment

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

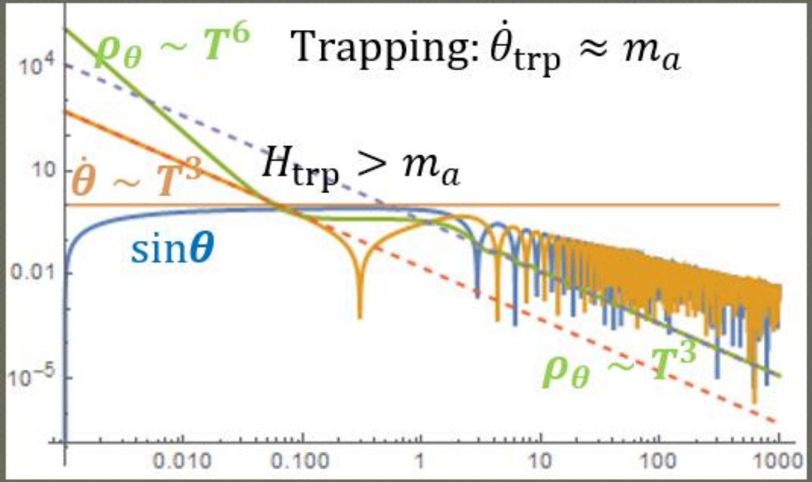


$$\rho_\theta = f_a^2\left(\frac{1}{2}\dot\theta^2 + m_a^2(1-\cos\theta)\right)$$

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

- Kinetic misalignment

Co, Hall, Harigaya, 1910.14152



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

pNGB as BAU generator

- In the background of $\dot{\theta} \neq 0$ violating C & CPT, a fermion ψ gets an "external chemical potential" $x_\psi \dot{\theta}$ $(E_\psi = E_0 \mp x_\psi \dot{\theta})$.

- When BNV (LNV) operators are in equilibrium, it can be fed into the internal chemical potential μ_ψ generating charge asymmetry $n_\psi \propto \dot{\theta}$ and thus $n_B = c_B \dot{\theta} T^2$.

Cohen-Kaplan, 1987, 88

- QCD axion:

(B+L)NV by weak spharelon in equilibrium

$$\sum_{\psi \in A} \mu_\psi = c_A \dot{\theta}$$

Co-Harygaya, 1910.02080
Domcke et.al., 2006.04138

- Majoron:

(B-L)NV by neutrino Yukawa coupling lNH in equilibrium

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

EJC, Jung 2311.09005

Cogenesis of BAU & DM by pNGB

- The final baryon asymmetry is fixed at T_B when BNV interactions go out of equilibrium: $Y_B \equiv \frac{n_B}{s} = \frac{c_B \dot{\theta} T^2}{s}$,

  that is, $Y_B = c_B Y_\theta \left(\frac{T_B}{f_a}\right)^2$.
- Combining with DM condition $m_a Y_\theta = 0.44\mathrm{eV}$, we get

$$Y_B = c_B \left(\frac{0.44\mathrm{eV}}{m_a}\right)\left(\frac{T_B}{f_a}\right)^2 \approx 10^{-10}$$

- QCD axion:

  $T_B = T_{EW}$ & $m_a f_a = m_\pi f_\pi$ require $f_a \approx 10^7 c_B \mathrm{GeV}$ (ruled out).

- Majoron:

  $T_B = c_N M_N$ requires

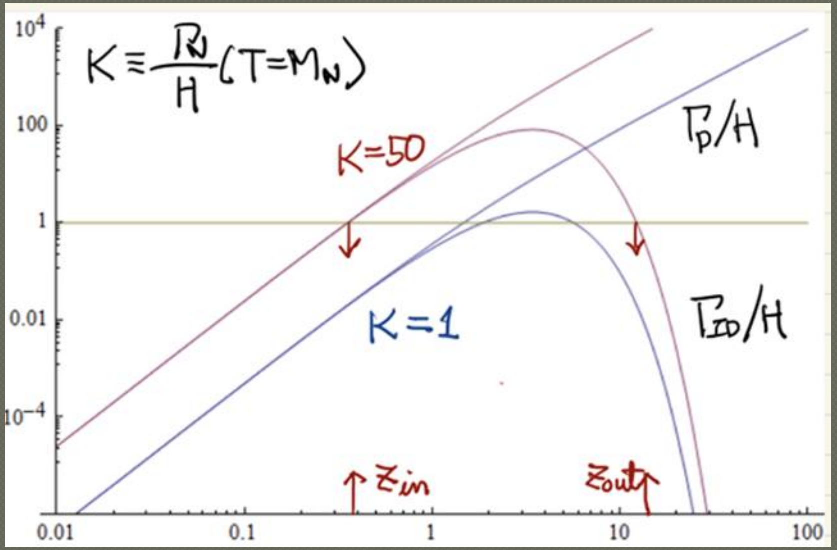
$$M_N \approx \frac{\mathrm{TeV}}{c_N\sqrt{c_B}} \frac{f_a}{10^9\mathrm{GeV}} \sqrt{\frac{m_a}{6\mathrm{meV}}}.$$

Seesaw & B-L (L) violation

- Seesaw mechanism explaining tiny Majorana neutrinos mass:

$$\mathcal{L} = y_\nu l N H + \frac{1}{2} M_N N N + h.c. \Rightarrow \quad m_\nu = y_\nu \frac{v_H^2}{M_N} y_\nu^T$$

- Define $K \equiv \left(\frac{\Gamma_N}{H}\right)_{T=M_N} \equiv \frac{\tilde{m}_\nu}{\text{meV}}$
- B-L violation by decay/inverse-decay $N \leftrightarrow lH$ is in equilibrium around $T{\sim}M_N$ for $K > 1$.
- Consider $\tilde{m}_\nu = 0.05\text{eV}$, i.e., $K = 50$.



Majoron 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 $M_N = \frac{y_N}{\sqrt{2}} f_a$.
- Majoron coupling: $x_\psi \partial_\mu \theta \bar{\psi} \bar{\sigma}^\mu \psi$ for $\psi = q, u^c d^c, l, e^c, N$ with $x_\psi = (B-L)_\psi$.
- For a Majorana particle, $E = \sqrt{(\mathrm{p} - \frac{1}{2}\mathcal{H}\dot{\theta})^2 + M_N^2} \approx E_0 - \mathcal{H}\,\frac{\dot{\theta}}{2}\frac{\mathrm{p}}{E_0}$
- N decay/inverse-decay in equilibrium:

$$\langle N_\uparrow \leftrightarrow lH \rangle - \langle N_\uparrow \leftrightarrow \bar{l}\bar{H} \rangle = \langle N_\downarrow \leftrightarrow lH \rangle - \langle N_\downarrow \leftrightarrow \bar{l}\bar{H} \rangle \rightarrow \mu_l + \mu_H = \dot{\theta}$$

- B (B-L) asymmetry freezes at $T_B \approx M_N / z_{\mathrm{fo}}$ to yield $Y_B = c_B \frac{\dot{\theta}(T_B)\, T_B^2}{s(T_B)} = c_B Y_\theta \left(\frac{T_B}{f_a}\right)^2$.

Chemical equilibration

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

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

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

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

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

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

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

$$\Rightarrow$$

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

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

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

Cogenesis

- Simultaneous generation of BAU & DM:

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

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

Trapping condition

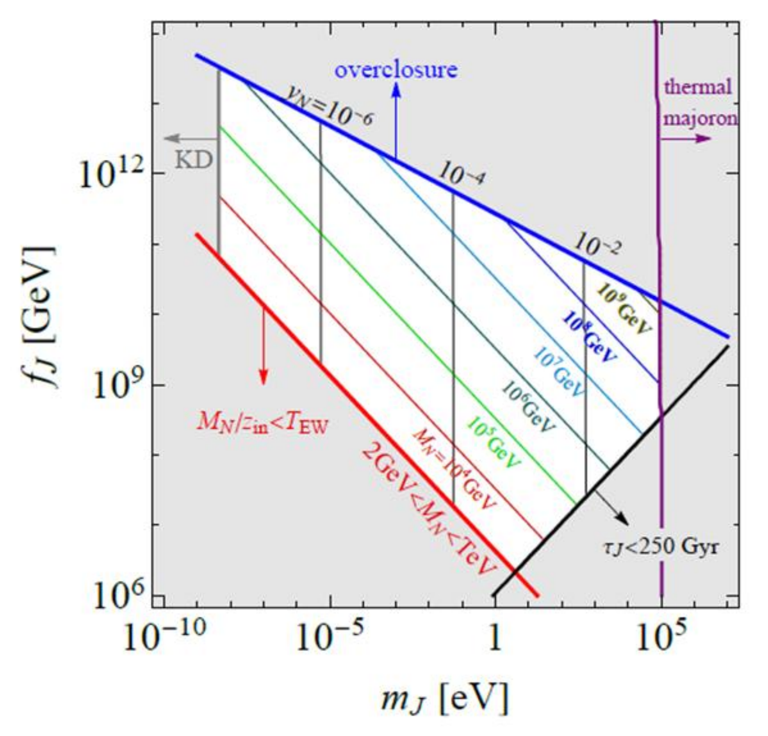
$\dot{\theta}_{\text{trp}} \sim m_a > H_{\text{trp}}$

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

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

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

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



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

Large $\dot{\theta}$ from 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:

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

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

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

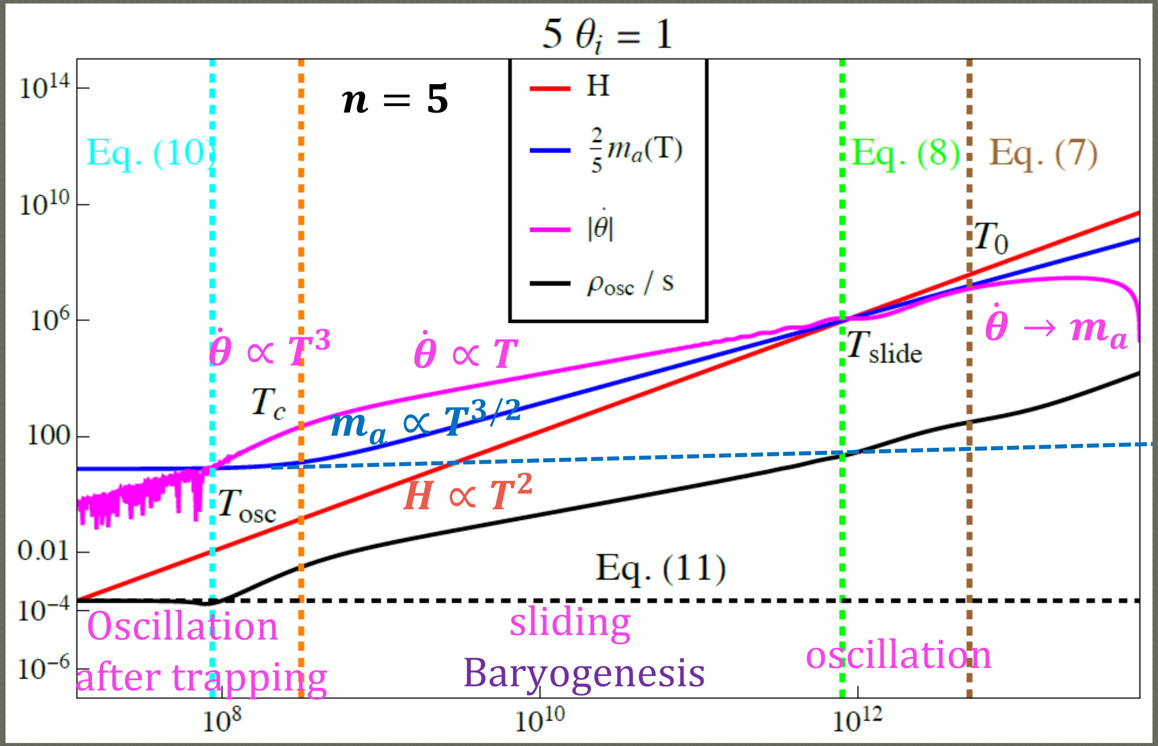
$$m_a^2(T) = m_{a0}^2\left(\frac{f_a(T)}{f_{a0}}\right)^{n-2}$$

Dynamics of sliding pNGB

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

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

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



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

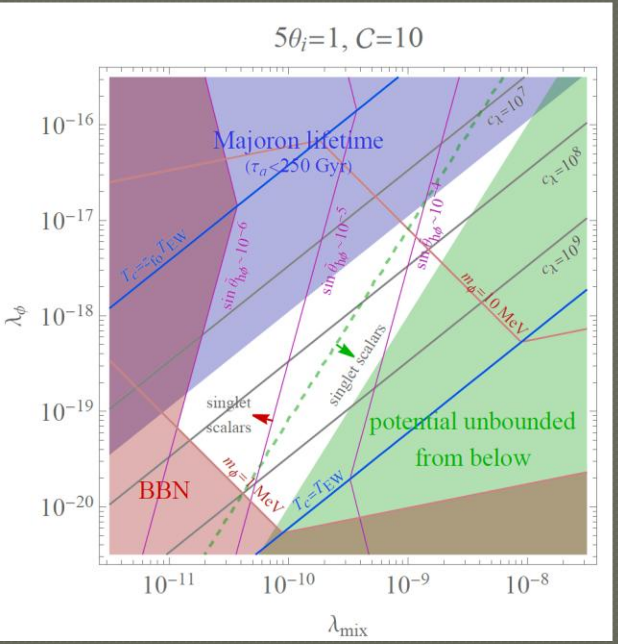
$$\ddot{\theta} + H\dot{\theta} + \frac{1}{5}m_a^2(T)\sin(5\theta_i) \approx 0$$
$$\Rightarrow \dot{\theta} \approx \sqrt{5}\sin(5\theta_i)\,T\log\frac{T^2}{T_i^2}$$

Cogenesis corner

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

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

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



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

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

Conclusion

- Type-I seesaw model with majoron provides an affordable framework for the cogenesis of baryon asymmetry and dark matter constraining the parameter space (m_a, f_a, M_N).
- Symmetry non-restoration from thermal effect can be an origin of large Y_θ.
- Extendable to any seesaw models.
- Application to the QCD axion?