Cogenesis of DM & BAU by Majoron (=QCD axion)

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Outline

- Introduction to pNGB as DM and BAU generator.
  QCD axion vs. Majoron
- Cogenesis by Majoron — EJC, Jung, 2311.09005
- Cogenesis by QCD axion=Majoron — In preparation
- Large kinetic misalignment from AD mechanism
  or symmetry non-restoration
  EJC, Das, He, Jung, Sun, 2406.04180
- 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

$$y_Q \Phi Q Q^c \;\; \text{vs.} \;\; \frac{y_N}{2}\Phi N N$$

- Potential from (tiny) explicit breaking

$$V = m_a^2\, f_a^2 (1 - \cos\theta)$$

- Derivative and anomaly coupling

$$\mathcal{L}_\partial = x_\psi \partial_\mu \theta\; \bar{\psi}\bar{\sigma}^\mu \psi$$

$$\mathcal{L}_A = \frac{c_A}{32\pi^2}\,\theta F_A^{\mu\nu} F_{A\mu\nu}$$

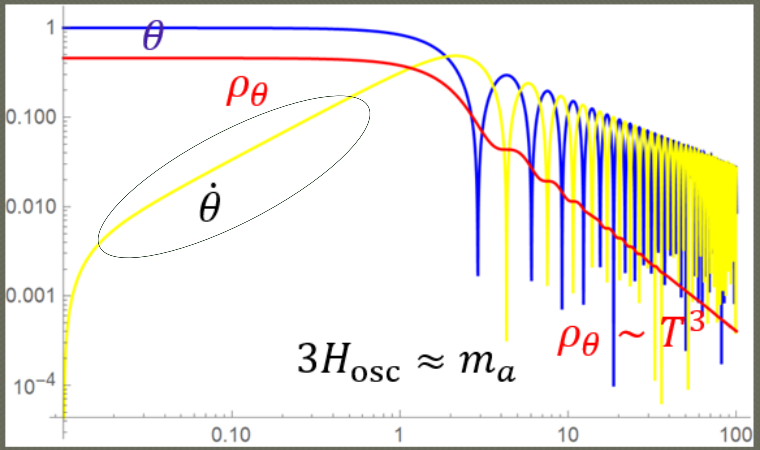
- Cosmic evolution

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

pNGB as CDM

- Conventional misalignment

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

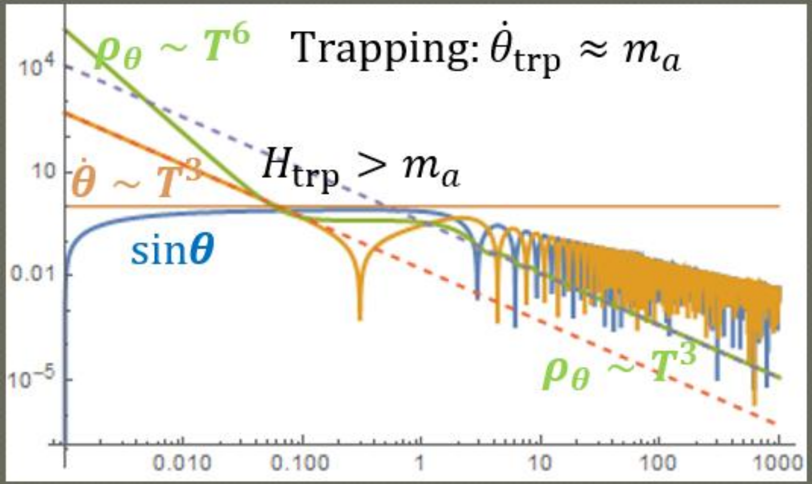


$$\rho_\theta = f_a^2\left(\frac{1}{2}\dot\theta^2 + m_a^2(1-\cos\theta)\right)$$

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

- Kinetic misalignment

Co, Hall, Harigaya, 1910.14152



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

pNGB generating BAU

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

- When B(L)NV interactions are in equilibrium, it can be fed into the internal chemical potential $\mu_\psi = c_\psi \dot{\theta}$ generating baryon asymmetry $\mu_B = c_B \dot{\theta}$.

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 $N \leftrightarrow lH$ in equilibrium

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

EJC, Jung 2311.09005

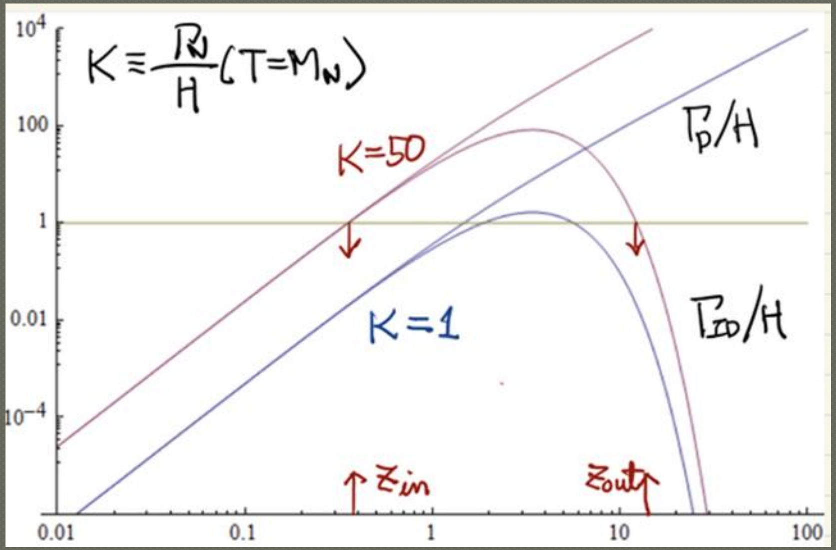
Seesaw & B-L violation

- Seesaw mechanism explaining tiny Majorana neutrinos mass:

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

- 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 $\tilde{m}_\nu = 0.05\text{eV}, i.e., K = 50.$)



Cogenesis of BAU & DM by pNGB

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

  i.e., $Y_B = c_B Y_\theta \left(\frac{T_B}{f_a}\right)^2$.

- Combining with DM condition $m_a Y_\theta = 0.44\text{eV}$,

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

- QCD axion:

  $T_B = T_{EW}$ & $m_a f_a = m_\pi f_\pi$

  → $f_a \approx 10^7 c_B \text{GeV}$ (ruled out).

- Majoron:

  $T_B = M_N / z_{\text{fo}}$

  → $M_N \approx \frac{z_{\text{fo}}}{\sqrt{c_B}} \frac{f_a}{10^9\text{GeV}} \sqrt{\frac{m_a}{6\text{meV}}}$.

Equilibrium solution with Majoron

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

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

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

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

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

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

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

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

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

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

Cogenesis region

- Simultaneous generation of BAU & DM:

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

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

Trapping condition

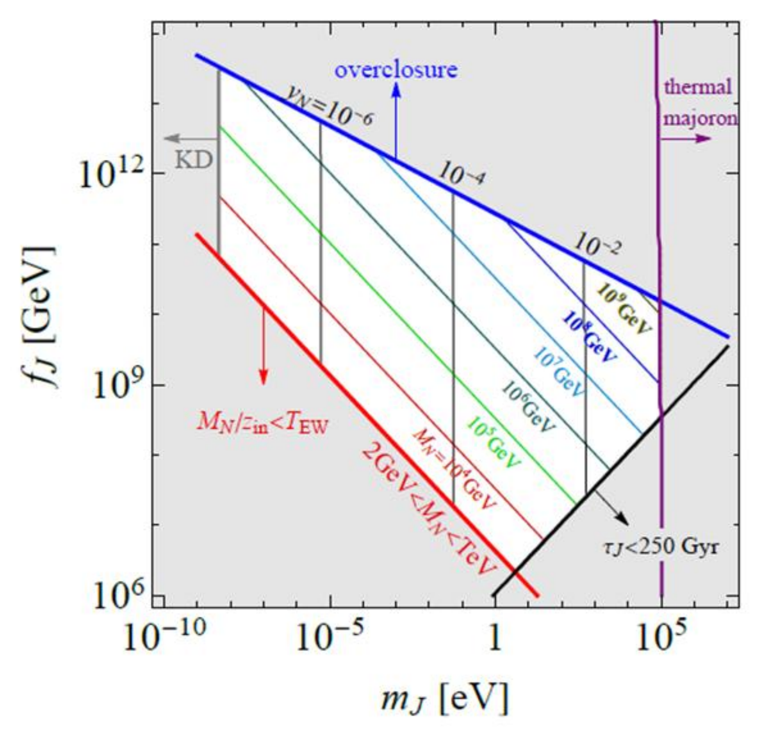
$$\dot{\theta}_{\rm trp} \sim m_a > H_{\rm trp}$$

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

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

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

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



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

Cogenesis by QCD axion=Majoron

- **KSVZ+Seesaw**
- Chemical equilibrium conditions to be met by separating out the first generation quark Yukawas

- $\mathcal{L}_{\rm PQ} = y_Q \Phi Q Q^c + \frac{1}{2} y_N \Phi N N + h.c.$

  PQ charges: $x_Q = x_Q^c = x_N = -x_l = x_e^c = -\frac{1}{2}.$

- $\dot{n}_{q_i} = \dot{n}_{u_i^c} = \dot{n}_{d_i^c} = \dot{n}_{l_i} = \dot{n}_{e_i^c} = 0$

  (Yukawas+SS+WS) & charge neutrality.

$$\mu_B = \frac{28}{79}\frac{1}{33}\left(28\, c_W - \frac{57\, m_u^2 - 15 m_d^2}{m_u^2 + m_d^2} c_S - 153 x_l\right)\dot{\theta} = c_B \dot{\theta}$$

$c_B = -2.2$ for $c_W = 0$ & $c_S = N_Q = 1$

Cogenesis achieved for $Y_B = c_B \left(\frac{0.44\text{eV}}{m_a}\right)\left(\frac{T_B}{f_a}\right)^2 \Rightarrow \; M_N \sim 10\text{TeV} \sqrt{\frac{f_a}{10^9\text{GeV}}}$

Large $\dot{\theta}$ via AD mechanism

- PQV operator of good quality to generate $Y_\theta = \frac{0.22\mathrm{eV}}{m_a} \approx 400 \left(\frac{f_a}{10^{10}\mathrm{GeV}}\right)$

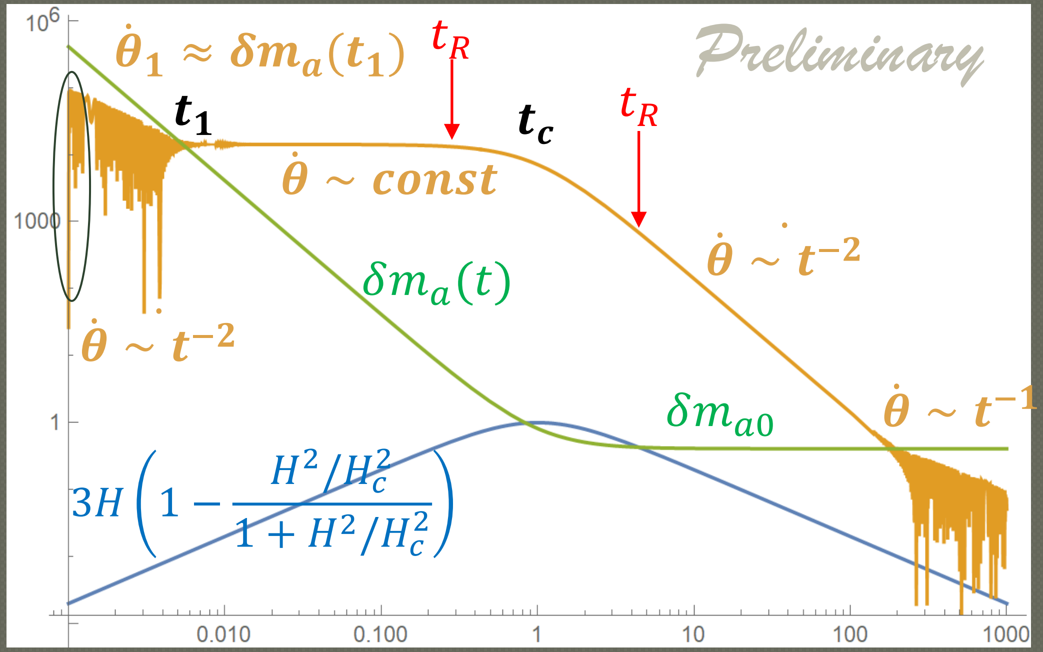
$$V = -\frac{1}{2}(\mu_0^2 + c_H H^2)\phi^2 + \frac{\lambda_0}{4}\phi^4 - \frac{\lambda_n}{\sqrt{2^n}}\frac{\phi^n}{M_P^{n-4}} 2\cos(n\theta) \qquad \Phi = \frac{\phi}{\sqrt{2}}e^{i\theta}$$

$$\phi = \sqrt{\frac{\mu_0^2 + c_H H^2}{\lambda_0}} \equiv f_a \sqrt{1 + \frac{H^2}{H_c^2}} \text{ with } H_c \equiv \frac{\mu_0}{\sqrt{c_H}} \qquad \delta m_{a0}^2 = 2n^2 \frac{\lambda_n}{\sqrt{2^n}}\frac{f_a^n}{M_P^{n-4}} \ll m_a^2$$

During inflation ($H = H_I$) & matter domination ($H = \frac{2}{3t}$)

$$\ddot{\theta} + \frac{2}{t}\left(1 - \frac{t_c^2/t^2}{1 + t_c^2/t^2}\right)\dot{\theta} + \frac{\delta m_{a0}^2}{n}\left(1 + \frac{t_c^2}{t^2}\right)^{\frac{n-2}{2}} \sin(n\theta) = 0$$

Cosmic evolution



- $Y_\theta = \dfrac{\dot\theta f_a^2}{s(T_R)} \approx$

$$\frac{1}{3}\left(\frac{\delta m_{a0}}{H_c}\right)\left(\frac{H_1}{H_c}\right)^{\frac{n-2}{2}}\left(\frac{f_a}{H_c}\right)^2\left(\frac{H_c}{M_P}\right)^{\frac{3}{2}}\begin{cases}\left(\dfrac{H_c}{H_R}\right)^{\frac{3}{2}} & t_R < t_c \\ \left(\dfrac{H_R}{H_c}\right)^{\frac{1}{2}} & t_R > t_c\end{cases}$$

- $Y_{\rm max} \approx 30\left(\dfrac{\delta m_{a0}}{\mu\mathrm{eV}}\right)\left(\dfrac{H_1}{10^{13}\mathrm{GeV}}\right)^4\left(\dfrac{10^5\mathrm{GeV}}{H_c}\right)^{\frac{11}{2}}$

for $n = 10$ & $f_a = 10^{10}$GeV.

Summary

- Type-I seesaw model with majoron provides an affordable framework for the cogenesis of BAU and DM enjoying the freedom in (m_a, f_a, M_N).

- Combining PQ and Seesaw, QCD axion can drive cogenesis for the RHN mass around 10~100 TeV.

- Large kinetic misalignment can arise by early dynamics setting $\dot{\theta} = m_a(t) \gg m_a(0)$.