Majorogenesis

Eung Jin Chun
to appear in collaboration with Tae Hyun Jung

Baryogenesis

- Baryon number density of the Universe is well determined:

$$Y_B = \frac{n_B}{s} \approx 0.85 \times 10^{-10}$$

- If symmetric, $N\bar{N} \leftrightarrow \pi\pi$ freezes out at $T_f \sim m_N/43$ leading to $n_N/s \sim 10^{-18}$.
- Requires larger initial asymmetry explaining no antimatter today.

- Dynamic generation of baryon asymmetry [Sakharov]
  - Baryon number violation
  - C & CP violation
  - Out of equilibrium

Seesaw & Leptogenesis

- Heaviness of sterile RHN for lightness of active neutrinos:

$$\mathcal{L} = y_\nu \, \bar{l}_L \bar{H} N_R + \frac{1}{2} M \, \bar{N}_R^c N_R + h.c.$$

[Fukugita-Yanagita]

- Lepton number violation: $M \neq 0$
- C & CP violation: CP phase in y_ν
- Out of equilibrium: N decay

- RHN decay produces lepton asymmetry:

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

- L asymmetry converts to B asymmetry by EW spharelon process violating $B + L$:

$$Y_B \propto c_B \, \epsilon \, \frac{n_N}{s}$$

Spontaenous Baryogenesis

Cohen-Kaplan, '87,'88

- Consider a Baryon number spontaneously broken at the scale f.
- Its pseudo-Goldston boson ϕ couples to the Baryon current: $\frac{1}{\mathrm{f}}\partial_\mu\phi\, j_B^\mu$ where $j_B^\mu = \sum_\psi x_\psi \bar{\psi}\gamma^\mu\psi$ with x_ψ being the B number.
- In the background of homogenous classical field, $\dot{\theta} \equiv \dot{\phi}/f \neq 0$, ψ gets an "extra chemical potential" shifting the energy $E = E_0 \mp x_\psi\dot{\theta}$ of $\psi/\bar{\psi}$ (CP & T violation)
- When a B violating interaction involving ψ is in thermal equilibrium, the thermal chemical potential develops $\mu_\psi = x_\psi\dot{\theta}$ generating B asymmetry $\mu_B = c_B\dot{\theta}$ at T_B when B violation decouples.

Axiogenesis

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

- PQ symmetry breaking → axion ϕ
- Quark chiral symmetry broken by $G\tilde{G}$
- $G\tilde{G}$ in equilibrium → $\mu_{q_L} - \mu_{q_R} = c_A \dot{\theta}$
- B+ L violation in equilibrium by EW sphaleron → $3\mu_{q_L} + \mu_{l_L} = 0$
- B (B-L) asymmetry is frozen at $T_B = T_{\rm EW}$: $\mu_B = c_B \dot{\theta}$.

Spontaenous Leptogenesis

$$\mathcal{L} = y_\nu \bar{l}_L \bar{H} N_R + \frac{1}{2} y_N \Phi \overline{N_R^c} N_R + h.c. \text{ with } \Phi = \frac{f_J}{\sqrt{2}} e^{iJ}$$

- B-L (L) symmetry broken by $M_N = \frac{y_N}{\sqrt{2}} f_J$ & y_ν.
- Majoron couples to j^μ_{B-L}: $\dot{\theta} \sum_\psi x_\psi \bar{\psi} \gamma^\mu \psi$.
- N_R decay/inverse-decay & EW sphaleron are in equilibrium: $\langle N \leftrightarrow lH \rangle = \langle N \leftrightarrow \bar{l}\bar{H} \rangle = \langle \bar{N} \leftrightarrow \bar{l}\bar{H} \rangle = \langle \bar{N} \leftrightarrow lH \rangle \rightarrow \mu_l + \mu_H = x_l \dot{\theta}$ & $3\mu_q + \mu_l = 0$.
- B-L (B) asymmetry washed in at $T_B = T_{ID} \sim \frac{M_N}{10}$ or $T_B = T_{EW}$: $\mu_B = c_B \dot{\theta}(T_B)$.

Baryon asymmetry

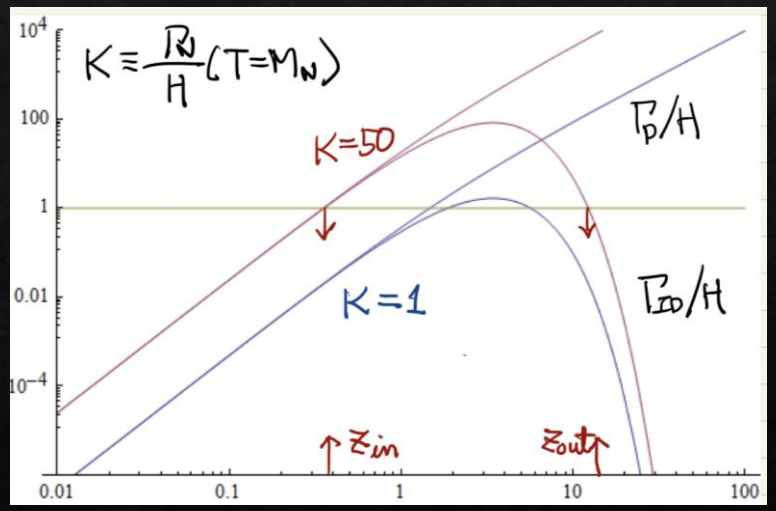
- When $M_N > T_{out} = \frac{M_N}{z_{out}} > T_{EW}$,

$$Y_B = \frac{28}{79}\, c_{B-L}\, Y_{B-L}^{eq}(T_B) = \frac{14}{237}\, c_{B-L} Y_\theta \left(\frac{M_N}{z_{out} f_J}\right)^2$$

- When $M_N < T_{EW} < T_{in} = \frac{M_N}{z_{in}}$,

$$Y_B = Y_B^{eq}(T_{EW}) = \frac{1}{6} c_B Y_\theta \left(\frac{T_{EW}}{f_J}\right)^2 \qquad Y_\theta \equiv \frac{n_\theta}{s} = \frac{f_J^2 \dot{\theta}^2}{s}$$

Requiring $M_N = z_{in} T_{in} \approx K^{-\frac{1}{3}} T_{in}$



Majoron DM

- Assuming soft-breaking of B-L by $\Phi^{n+4}/\Lambda^n + h.c.$:

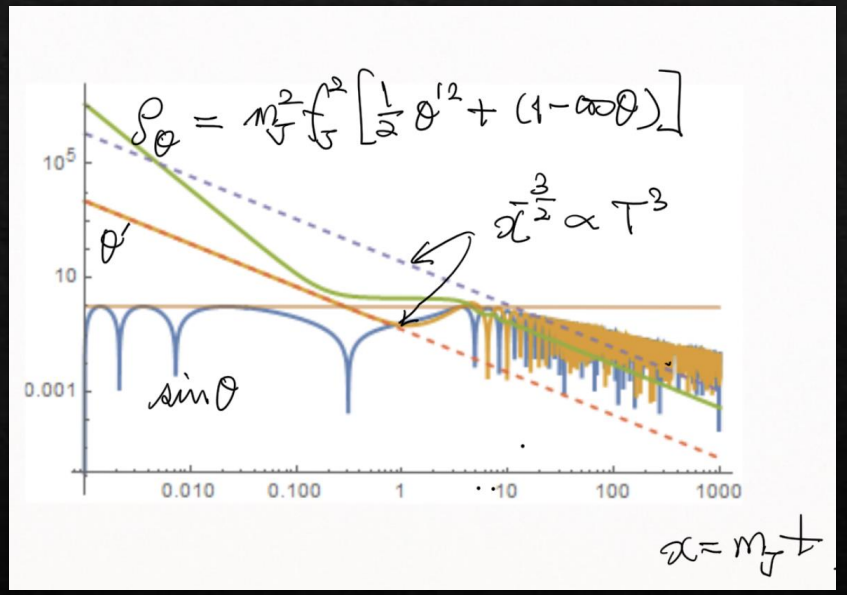
$$V(\theta) = m_J f_J^2 \left(\frac{1}{2}\dot{\theta}^2 + (1-\cos\theta)\right)$$

- Evolution of the classical field θ:

$$\ddot{\theta} + \frac{1}{2x}\dot{\theta} + \sin\theta = 0$$

$$\text{where } \dot{\theta} \equiv \frac{d\theta}{dx} \text{ with } x \equiv m_J t$$

- Solution with initial kinetic misalignment: $\theta_0 = 0, \dot{\theta}_0 \neq 0$



Co-Hall-Harygaya, 1910.14152

Co-genesis of Y_B & Y_{DM}

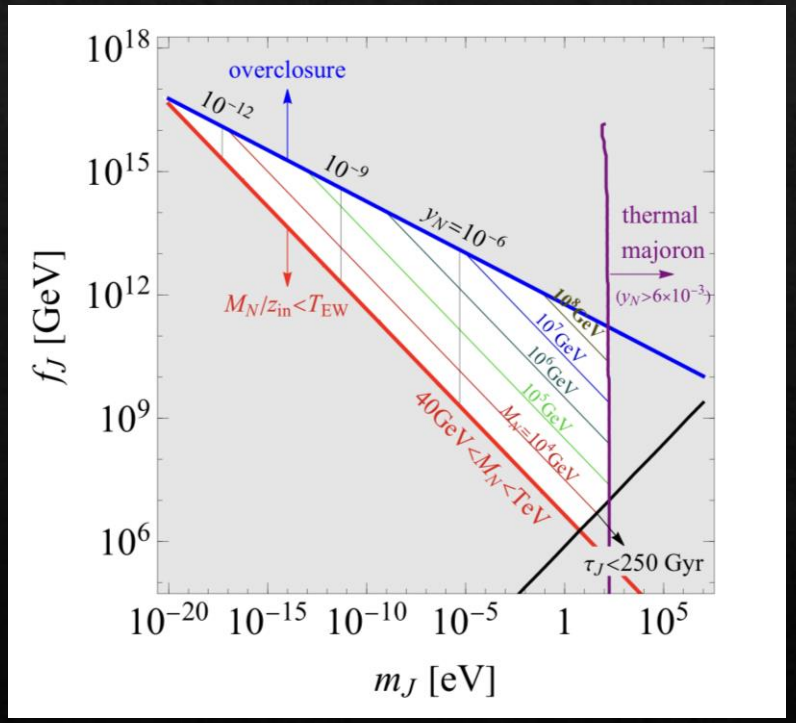
- Baryon density:

$$Y_B = \frac{n_B}{s} = \frac{45}{2\pi^2 g_*} c_B \frac{\dot{\theta}}{T}(T_B) \approx 10^{-10}$$

- DM density: $Y_\theta = \frac{n_\theta}{s} = \frac{f_J^2 \dot{\theta}^2}{s}$

$$m_J Y_\theta = \frac{45}{2\pi^2 g_*} \frac{f_J^2 \dot{\theta}}{T^3}(T_B) \approx 0.4\text{eV}$$

$$\Rightarrow m_J \frac{f_J^2}{T_B^2} \frac{Y_B}{c_B} \approx 0.4\text{eV} \ \left(T_B = \frac{M_N}{10}\right)$$



Summary

- In the seesaw model with spontaneous L number breaking, leptogenesis can be driven by the CP violation provided by the kinetic motion of majoron.
- It relies on the Majorona property of a RHN and the equilibriation of its decay and inverse-decay.
- It works for $\mathbf{10 < M_N/GeV < 10^9}$ and $m_J < \mathbf{keV}$.
- It requires a large majoron number $Y_\theta > 1$ for $M_N < 10^{-4} f_J$, and thus a huge initial kick $t_0\dot{\theta}_0$.