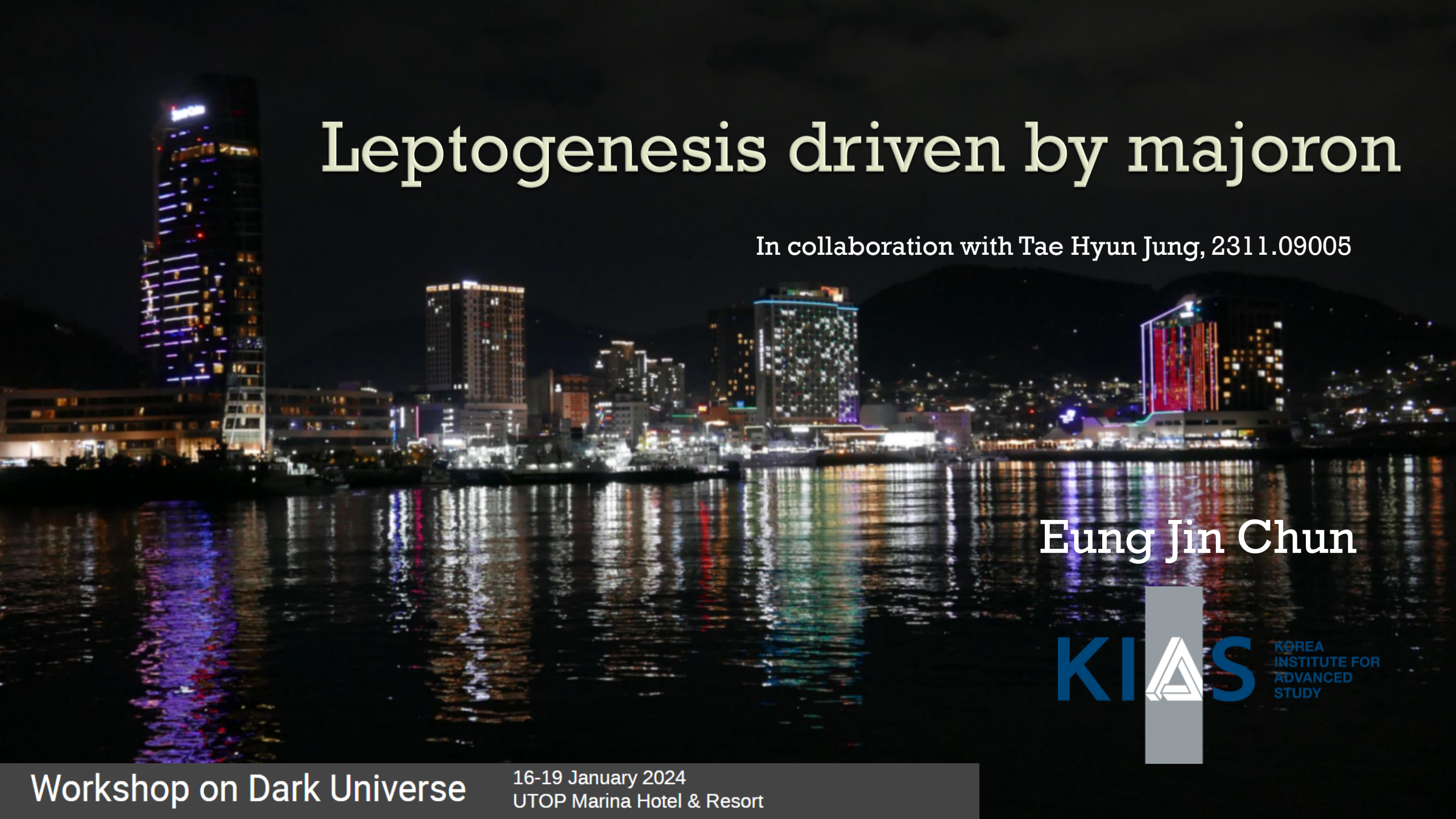

Leptogenesis driven by majoron

In collaboration with Tae Hyun Jung, 2311.09005

Eung Jin Chun

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Workshop on Dark Universe
16-19 January 2024
UTOP Marina Hotel & Resort


CONGRATULATIONS

Testing Higgs Triplet Model and Neutrino Mass Patterns

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Vacuum Stability, Perturbativity, EWPD and Higgs-to-diphoton rate in Type II Seesaw Models

Eung Jin Chun, Hyun Min Lee, and Pankaj Sharma

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CONGRATULATIONS

Rotating black holes at future colliders: Greybody factors for brane fields

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Dark matter and a new gauge boson through kinetic mixing

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Baryon asymmetry of the Universe

- Baryon number density of the Universe is well determined:

$$\frac{n_B}{s} \approx 0.85 \times 10^{-10}, \qquad \frac{n_{\bar{B}}}{s} \approx 0$$

- For symmetric components, $N\bar{N} \leftrightarrow \pi\pi$ freezes out at $T_f \sim m_N/43$ leading to $n_B/s \sim 10^{-18}$.
- Requires large initial asymmetry:

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

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

Beyond Standard Model

Seesaw & Leptogenesis

- Heaviness of sterile RHN for lightness of active neutrinos:

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

$$\Rightarrow m_\nu = y_\nu \frac{v_H^2}{M_N} y_\nu^T$$

[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 $B + L$:

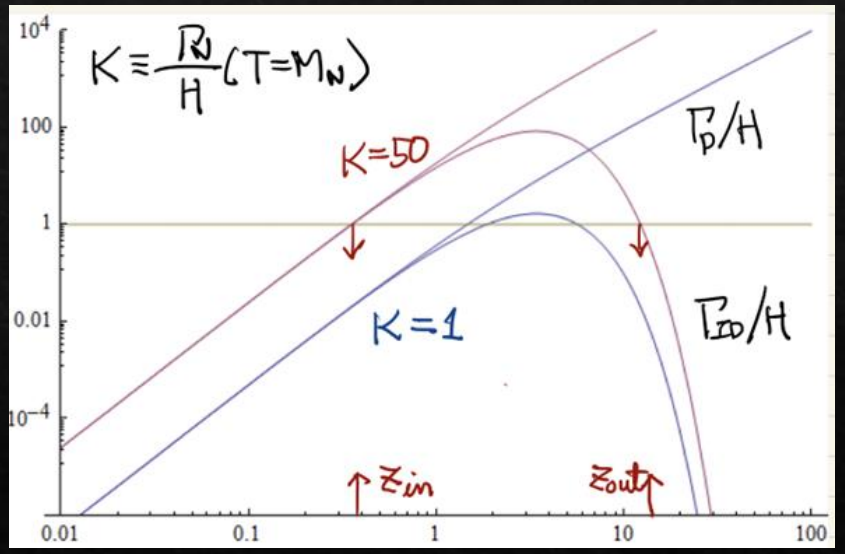
$$Y_B = c_B \kappa \, \epsilon \, \frac{n_N}{s}$$

Efficiency (washout)

- $K \equiv \frac{\Gamma_N}{H(T=M_N)} \approx \frac{y_\nu^2}{8\pi}\frac{M_P}{M_N} \approx \frac{\tilde{m}_\nu}{\text{meV}}$
- $K \sim 1: lH \to N$ barely in equilibrium

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

  $$T = (M_N/z_{in},\ M_N/z_{out}).$$
- Efficiency factor: $\kappa \approx \frac{1}{K \ln K}$
- $\tilde{m}_\nu = 0.05\text{eV}\ (K = 50) \Rightarrow \kappa \sim 10^{-2}$ (strong washout)



Spontaenous Baryogenesis

Cohen-Kaplan, '87,'88

- Consider $U(1)_B$ 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, $\dot{\theta} \equiv \dot{\phi}/f \neq 0$, $\psi/\bar{\psi}$ gets an "extra chemical potential" shifting the energy $E = E_0 \mp x_\psi\dot{\theta}$ (CP 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

- 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 $T_B = T_{\rm EW}$: $\mu_B = c_B\dot{\theta}$.
- Y_B& Y_{DM}?

Co-Harygaya, 1910.02080

....

Domcke et.al., 2006.04138

$$Y_B \sim \frac{\dot{\theta}}{T}(T_{EW}) \sim 10^{-10} \qquad m_a Y_a \sim \frac{f_a^2\dot{\theta}}{T^3}(T_{EW}) \sim 0.4\,\text{eV} \;\Rightarrow\; m_a \sim 1\,\text{eV}\left(\frac{10^7\,\text{GeV}}{f_a}\right)^2$$

Majoron & Leptogenesis

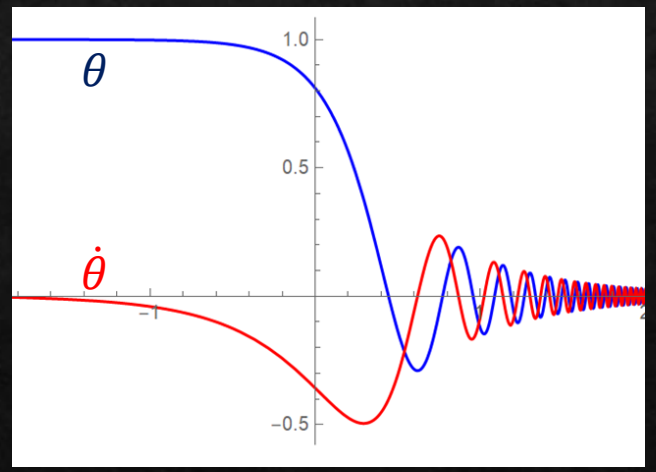
$$\mathcal{L} = y_\nu \bar{l}_L \bar{H} N_R + \frac{1}{2} y_N \Phi \overline{N_R^c} N_R + h.c. \text{ with } \Phi = \frac{f_J}{\sqrt{2}} e^{iJ}$$

- 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 $T_B = T_{EW}$: $\mu_B = c_B \dot{\theta}(T_B)$.

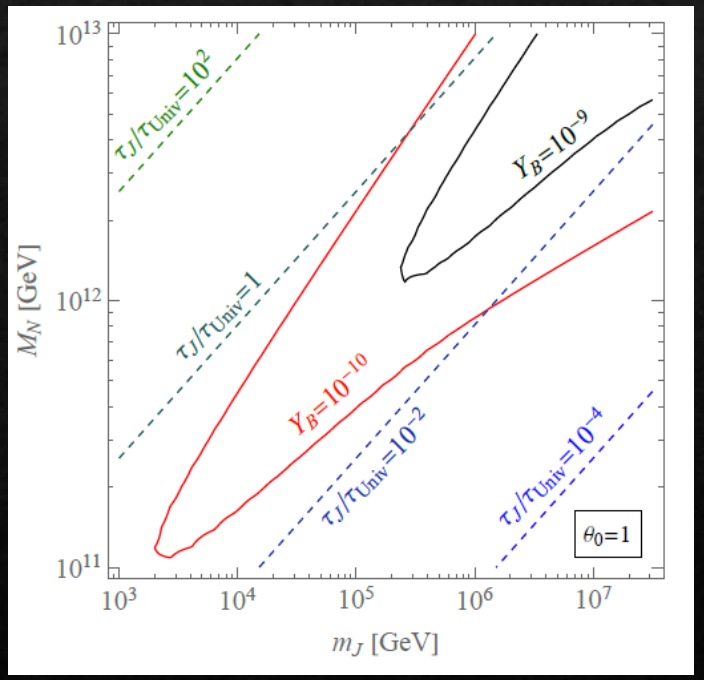
i) $\dot{\theta} \neq 0$ from conventional misalignment

- $\theta_0 \neq 0 \;\&\; \dot{\theta}_0 = 0.$
- Assuming soft-breaking of B-L by $\frac{\Phi^{n+4}}{\Lambda^n} + h.c.$:

$$V(\theta) = m_J^2 f_J^2 (1 - \cos(\theta))$$



$$\tau_J^{-1} = \frac{m_\nu^3}{8\pi f_J^2}$$



ii) $\dot{\theta} \neq 0$ from initial kinetic motion

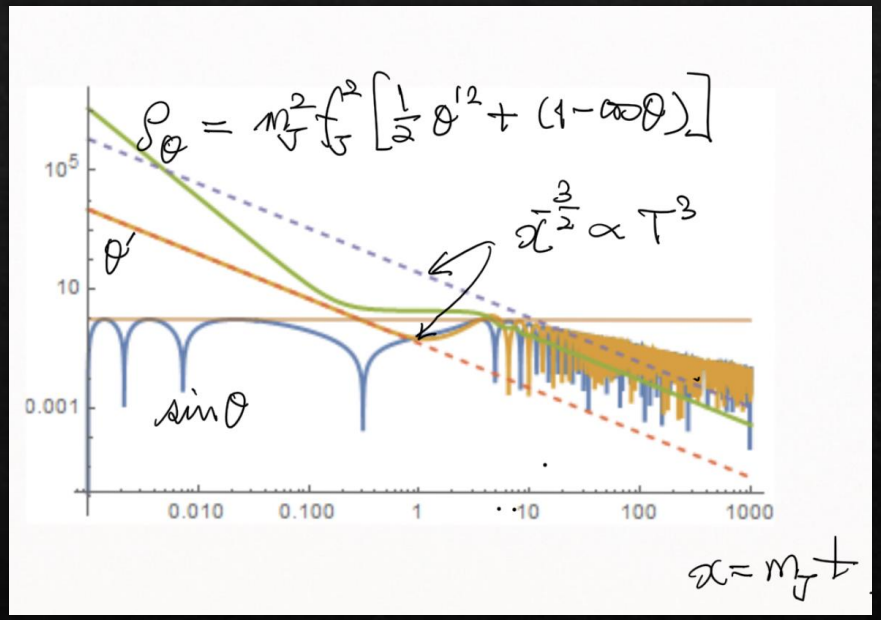
- $\theta_0 = 0$ & $\dot{\theta}_0 \neq 0$:

$$Y_\theta = Y_\theta^0 = f_J^2 \dot{\theta}_0 / s(T_0)$$

- Evolution of the classical field θ:

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

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



Majoron DM: $\rho_J = \rho_{DM}$?

Y_B from initial kinetic motion

- Shut down LNV when $M_N > T_{out} = \frac{M_N}{z_{out}} > T_{EW}$,

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

- Shut down Sphaleron when $M_N < T_{EW} < T_{in} = \frac{M_N}{z_{in}}$,

$$Y_B = Y_B^{eq}(T_{EW}) = \frac{1}{6} c_B Y_\theta \left(\frac{T_{EW}}{f_J}\right)^2 \qquad \text{Requiring } M_N = z_{in} T_{in} \approx K^{-\frac{1}{3}} T_{in}$$

Co-genesis of Y_B & Y_{DM}

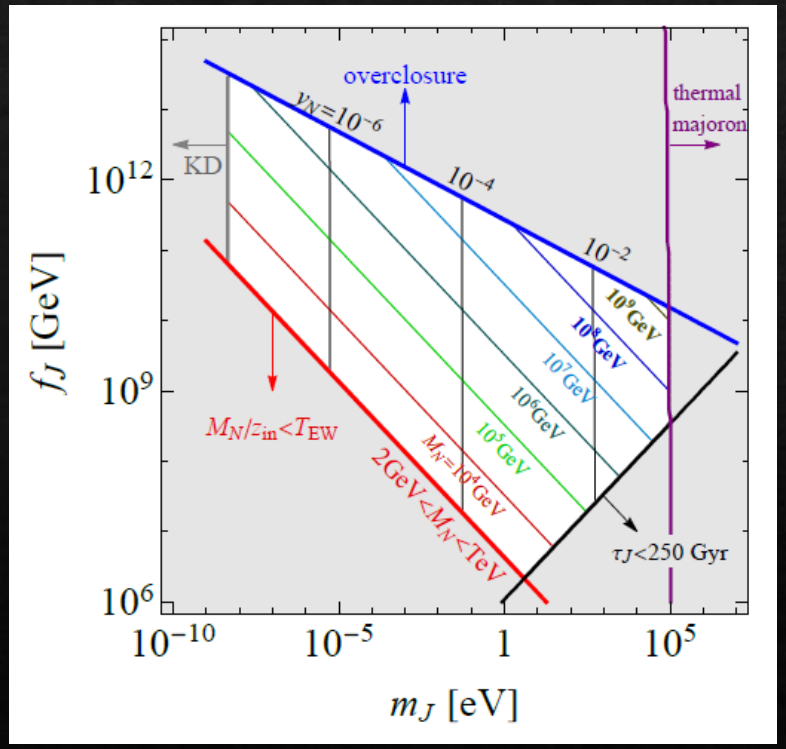
- Baryon density:

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

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

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

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



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 $10 < M_N/\mathrm{GeV} < 10^9$ and $m_J < \mathrm{keV}$.
- It requires a large majoron number $Y_\theta \gg 1$ for $M_N < 10^{-4} f_J$, and thus a huge initial kick $t_0\dot{\theta}_0$.

Thank you!

Back-up

- External chemical potential of Majorana fermion carries opposite sign according to its helicity:

$$E = \sqrt{\mathrm{p}^2 + M^2 + \frac{1}{4}\dot{\theta}^2 - \mathcal{H}\dot{\theta}\mathrm{p}} \approx E_0 - \mathcal{H}\,\frac{\dot{\theta}}{2}\frac{\mathrm{p}}{E_0}$$

- Opposite helicity states have the same decay rates and thus the chemical potentials cancel out:

$$\Gamma(N_+ \to lH) = \Gamma(N_- \to lH)$$
$$\Gamma(N_+ \to \bar{l}\bar{H}) = \Gamma(N_- \to \bar{l}\bar{H}) \quad \Rightarrow n_N = n_{N+} + n_{N-}$$