

Minimal Majoron Dark Matter

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PPC@UNSW in Sydney 2026/9/3

Based on arXiv: 2605.12946 [hep-ph]

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Today's Topic

1. Introduction:

The Majoron model is a minimal extension of the seesaw model.

global $U(1)_{B-L}$

$$\mathcal{L} \supset i\bar{N}_i \not{\partial} N_i + |\partial_\mu \sigma|^2 - V(\sigma) - \left[\frac{1}{2} g_i \sigma \bar{N}_i^c N_i + y_{\alpha i} \bar{L}_\alpha \tilde{H} N_i + \text{h.c.} \right]$$

$$\text{For } T < f, \quad \sigma = \frac{1}{\sqrt{2}}(f + \rho + iJ), \quad \mathcal{L} \supset -\frac{1}{2} m_J^2 J^2$$

Majoron J : pNG boson

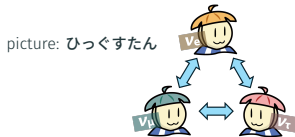
2. Majoron DM production: Freeze-in and Misalignment

3. Results: Viable parameters and Leptogenesis

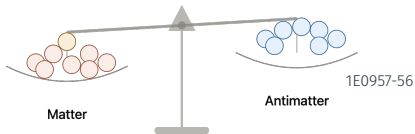
4. Summary and Conclusion

1. Introduction: Beyond Standard Model

- The Standard Model explains almost all particle physics.
- Many unsolved mysteries

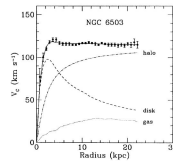


Neutrino Oscillation (mass)

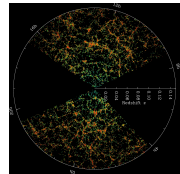


Baryon asymmetry

Dark Matter



galaxy, kpc

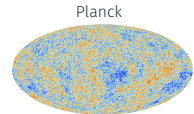


SDSS

LSS, 100 Mpc



galaxy cluster, Mpc



CMB, Gpc

and others...

1. Introduction: Type-I Seesaw (neutrino mass)

Type-I Seesaw Lagrangian

N_i : Right-handed neutrinos (RHNs)

$$\mathcal{L} \supset -y_{\alpha i} \bar{L}_\alpha \tilde{H} N_i - \frac{1}{2} M_i \bar{N}_i^c N_i + h.c.$$

[Minkowski, '77]

[Yanagida, '79]

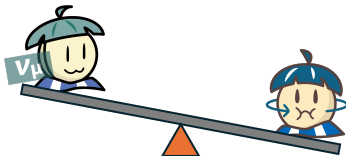
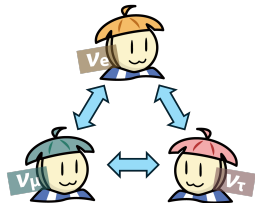
[Gell-Mann, Ramond, Slansky, '79]

• Seesaw mechanism

$$\begin{aligned} &\xrightarrow{\text{EWSB}} -m_D \bar{\nu} N - \frac{1}{2} M_i \bar{N}_i^c N_i \\ &= -\frac{1}{2} m_\nu \bar{\nu}^c \nu - \frac{1}{2} M_i \bar{N}_i^c N_i \end{aligned}$$

Neutrino mass

$$m_\nu = m_D M^{-1} m_D^T$$



1. Introduction: Type-I Seesaw (Leptogenesis)

Type-I Seesaw Lagrangian

N_i : Right-handed neutrinos (RHNs)

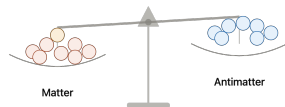
$$\mathcal{L} \supset -y_{\alpha i} \bar{L}_\alpha \tilde{H} N_i - \frac{1}{2} M_i \bar{N}_i^c N_i + h.c.$$

- Seesaw mechanism

- Leptogenesis

[Fukugita, Yanagida '86]

Breaks $B - L$



Leptogenesis

N decays produce lepton asymmetry.

$$N \rightarrow LH \neq N \rightarrow \bar{L}\bar{H}$$

$$\Delta L \neq 0$$

Sphaleron process
 $T \gtrsim 200 \text{ GeV}$

$$\Delta B \neq 0$$

preserve $B - L$

1. Introduction: Majoron Model

Minimal extension of Type-I Seesaw Lagrangian

Seesaw $\mathcal{L} \supset - \left[y_{\alpha i} \bar{L}_{\alpha} \tilde{H} N_i + \boxed{\frac{1}{2} M_i \bar{N}_i^c N_i} + h.c. \right]$

SSB can be the origin of the RHN mass

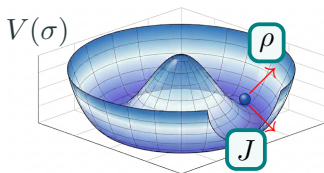
Global $U(1)_{B-L}$ $\mathcal{L} \supset - \left[y_{\alpha i} \bar{L}_{\alpha} \tilde{H} N_i + \boxed{\frac{1}{2} g_i \sigma \bar{N}_i^c N_i} + h.c. \right] - V(\sigma)$

σ : a complex scalar with $B - L$ charge $+2$

Spontaneous $U(1)_{B-L}$ breaking

$$\sigma = \frac{1}{\sqrt{2}}(f + \rho + iJ), \quad M_i = \frac{g_i f}{\sqrt{2}}$$

Majoron J : (p)NG boson



2. Majoron DM production: Minimal Majoron Model

2 RHNs (Minimality)

$$\mathcal{L} \supset - \left[y_{\alpha i} \bar{L}_{\alpha} \tilde{H} N_i + \frac{1}{2} g_i \sigma \bar{N}_i^c N_i + h.c. \right] - V(\sigma) \quad (i = 1, 2)$$

We assume $T_R < f$: $U(1)_{B-L}$ is always broken.

$$\sigma = \frac{1}{\sqrt{2}}(f + \rho + iJ), \quad M_i = \frac{g_i f}{\sqrt{2}}$$

Global $U(1)_{B-L}$ may be explicitly broken (e.g. quantum gravity)
→ Majoron has mass, but we keep agnostic about its origin.

$$\mathcal{L} \supset -\frac{1}{2} m_J^2 J^2$$

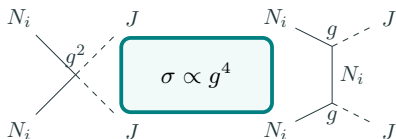


Majoron DM

2. Majoron DM production: Freeze-in

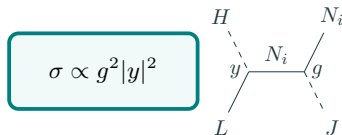
- H, L is in thermal, N is produced via $N \leftrightarrow HL$
- Majoron is produced via N

(1) $NN \rightarrow JJ$



(2) $HL \rightarrow NJ$

($NH \rightarrow JL, NL \rightarrow JH$)

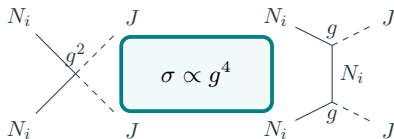


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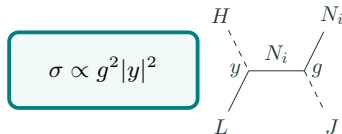
($M_1 = M_2 = M$, $T_R = 10M$ for simplicity)

(1) $NN \rightarrow JJ$



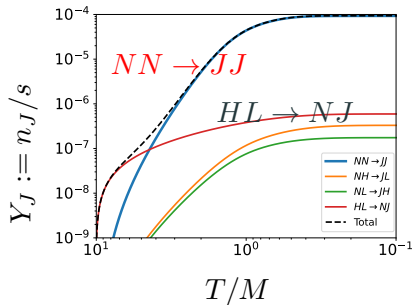
(2) $HL \rightarrow NJ$

($NH \rightarrow JL, NL \rightarrow JH$)



For a large g ,

(1) $NN \rightarrow JJ$ dominates.



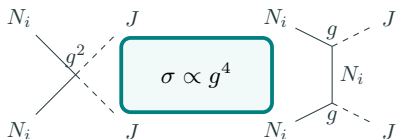
$g = 10^{-2}$, $M = 10^8$ GeV

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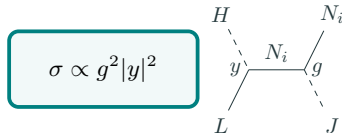
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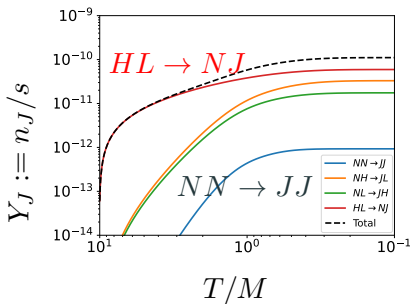
(2) $HL \rightarrow NJ$

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For a small g ,

(2) $HL \rightarrow NJ$ dominates.

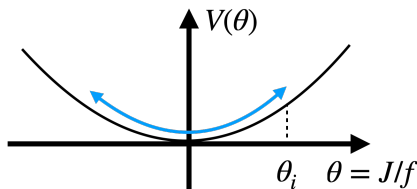


$g = 10^{-4}, M = 10^8 \text{ GeV}$

2. Majoron DM production: Misalignment

- Majoron field starts coherent oscillation when $H \simeq m_J$.
- Majoron energy density is $\rho^{\text{osc}} \simeq (1/2)m_J^2 f^2 \theta_i^2$
- θ_i is expected to be of $\mathcal{O}(1)$ without fine-tuning.

$$\Omega_J^{(\text{mis})} h^2 \simeq 0.12 \theta_i^2 \left(\frac{f}{4 \times 10^{10} \text{ GeV}} \right)^2 \left(\frac{m_J}{10 \text{ keV}} \right)^{1/2}$$

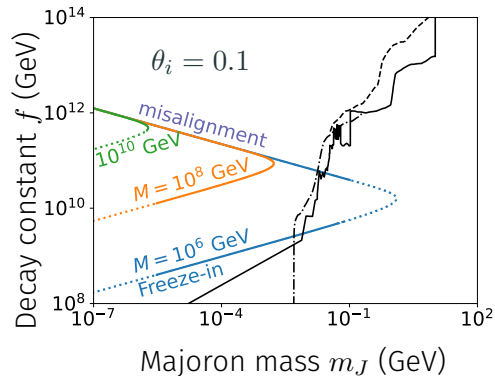


θ_i : initial misalignment angle during inflation

3. Results: Viable parameter space

arXiv: 2605.12946 [hep-ph]
KA, KH, HK and TY

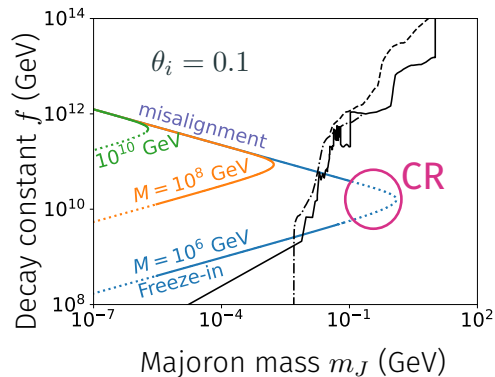
$$\text{DM abundance } (\Omega_J^{(\text{mis})} + \Omega_J^{(\text{FI})})h^2 \simeq 0.12$$



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Constraints

[Akita, Niibo '23]

- Gray : $J \rightarrow \nu\nu$ (tree)
- Dot: **Cosmic Ray**
($J \rightarrow l\bar{l}, q\bar{q}$, 1-loop)
($J \rightarrow \gamma\gamma$, 2-loop)

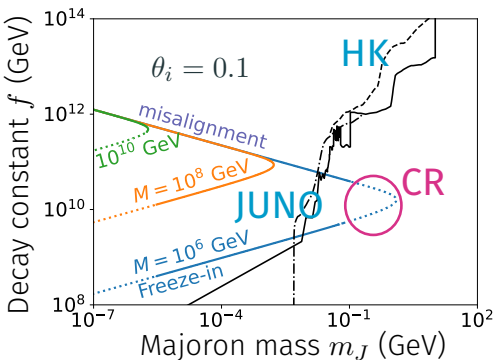
Only for Freeze-in,

- Warm DM: $m_J \gtrsim \mathcal{O}(1)$ keV

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$$\text{DM abundance } (\Omega_J^{(\text{mis})} + \Omega_J^{(\text{FI})})h^2 \simeq 0.12$$



Only for Misalignment,

- Isocurvature:

$$T_R \lesssim 10^{13} \text{ GeV}$$

(in case instantaneous reheating)

Irrelevant for $T_R = 10M$

Future sensitivity

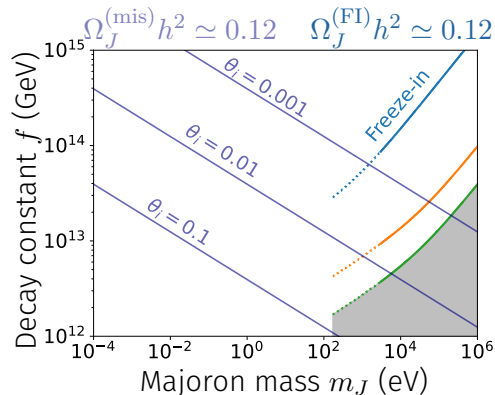
- **JUNO** and **HK**

- $m_J \lesssim \mathcal{O}(10) \text{ MeV}$ is consistent with current constraints.
- Freeze-in dominated region is reduced with a larger RHN mass.

3. Results: Consistency with Leptogenesis

arXiv: 2605.12946 [hep-ph]
KA, KH, HK and TY

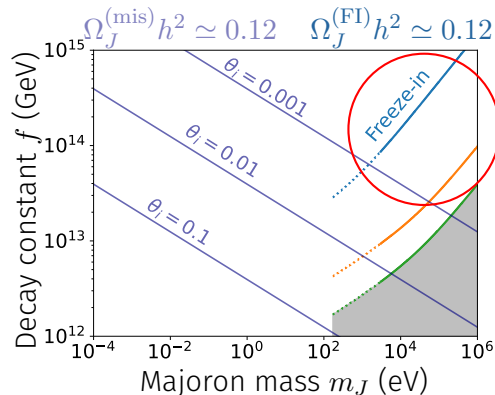
- Leptogenesis model points: $M_1 = 10^{12}, 10^{11}, 2.7 \times 10^{10}$ GeV
- $M_2 = T_R = 10M_1$ and Casas-Ibarra parameters are adjusted.



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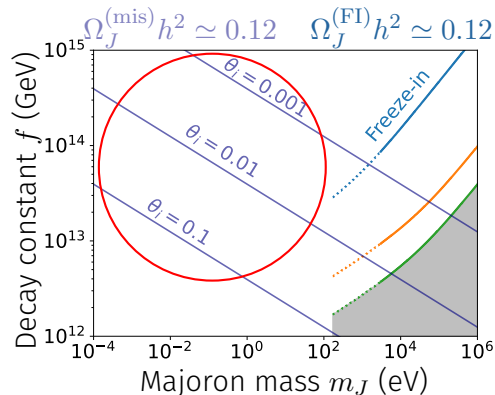
For Freeze-in constraints,

- Warm DM: $m_J \gtrsim \mathcal{O}(1)$ keV
- Misalignment: mild fine-tuning $\theta_i \lesssim \mathcal{O}(0.01)$

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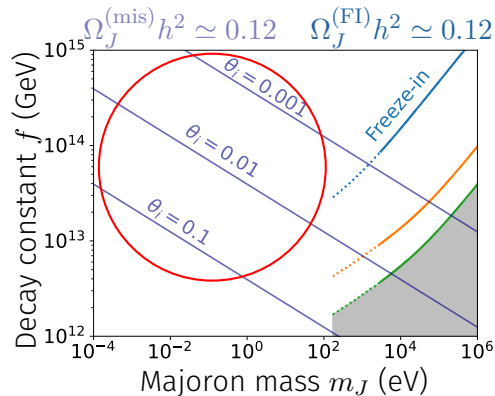
For misalignment constraints,

- Freeze-in: $m_J \lesssim \mathcal{O}(100)$ eV (Never produced thermally)
- Isocurvature: $T_R \lesssim 10^{13}$ GeV (instantaneous reheating)

3. Results: Consistency with Leptogenesis

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- Leptogenesis model points: $M_1 = 10^{12}, 10^{11}, 2.7 \times 10^{10}$ GeV
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For Freeze-in constraints,

- Warm DM: $m_J \gtrsim \mathcal{O}(1)$ keV
- Misalignment: mild fine-tuning $\theta_i \lesssim \mathcal{O}(0.01)$

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Favorable scenario

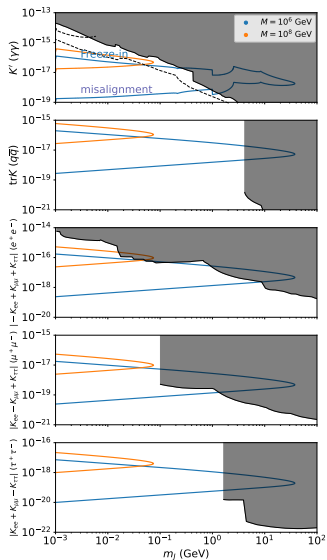
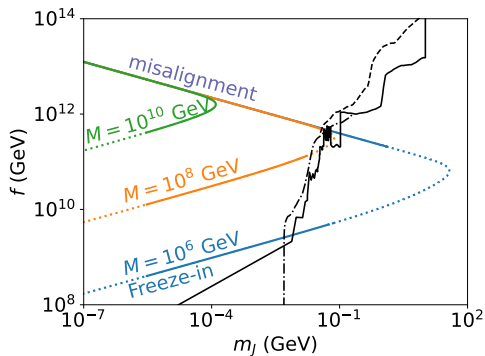
4. Summary and Conclusion

- We considered Majoron DM in its minimal setup.
- Production : Freeze-in and Misalignment
- $m_J \lesssim \mathcal{O}(10)$ MeV is consistent with current constraints.
- JUNO and HK can probe our model.
- Leptogenesis favors misalignment production for Majoron DM with $m_J \lesssim \mathcal{O}(100)$ eV.

Backup Slide

$\theta_i = 0.01$ case

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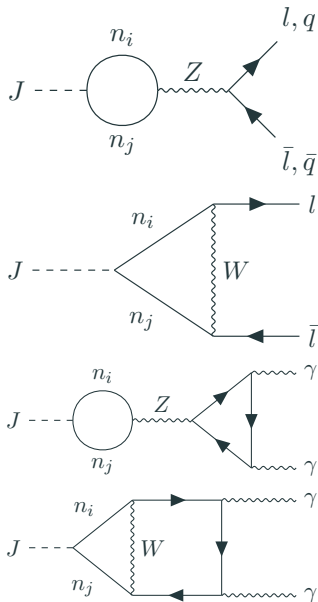
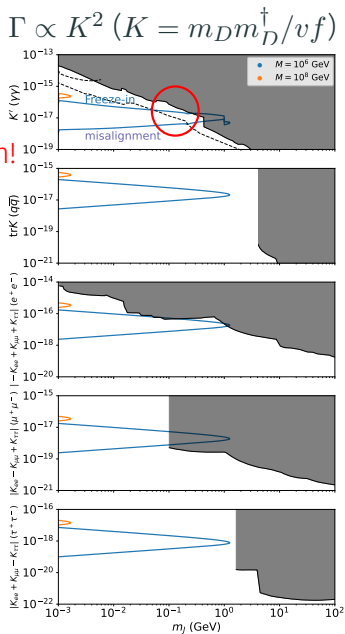


Constraints from K :

arXiv: 2605.12946 [hep-ph]

KA, KH, HK and TY

$\gamma\gamma$
Future
Observation!



In the Normal Ordering case,

$$m_D = iU\sqrt{m_\nu}R\sqrt{M}$$
$$R = \begin{pmatrix} 0 & \cos z & \sin z \\ 0 & -\sin z & \cos z \end{pmatrix}, \quad z \in \mathbb{C}$$

Leptogenesis parameters are

- $M_1 = 10^{12} \text{ GeV}, M_2 = 10M_1, a = 1.6, b = \pi/4$
- $M_1 = 10^{11} \text{ GeV}, M_2 = 10M_1, a = 1.9, b = \pi/8$
- $M_1 = 2.7 \times 10^{10} \text{ GeV}, M_2 = 10M_1, a = 2.8, b = 0.28$
- Majorana phase $\alpha = 0$ for all cases

Majoron decay to photons (expression of K')

$$K' = \text{tr } K \sum_{f=q,l} N_c^f T_3^f Q_f^2 h\left(\frac{m_J^2}{4m_f^2}\right) + \sum_l K_{ll} h\left(\frac{m_J^2}{4m_l^2}\right)$$

$$h(x) = -\frac{1}{4x} \left(\log\left(1 - 2x + 2\sqrt{x(x-1)}\right) \right)^2 - 1$$

- $m_J \lesssim \Lambda_{\text{QCD}}$: light quark should be replaced by hadron contribution.
- For simplicity, we keep only the lepton loops for $m_J < 1 \text{ GeV}$

Isocurvature

From Planck observation,

$$\beta_{\text{iso}} = \left(1 + \frac{8\pi^3 A_s f^2 \theta_i^2}{H_{\text{inf}}^2} \right)^{-1} \simeq \frac{H_{\text{inf}}^2}{8\pi^3 A_s f^2 \theta_i^2} < 0.038$$

This gives upper bound on H_{inf} ,

$$\begin{aligned} H_{\text{inf}} &\lesssim 1.4 \times 10^7 \left(\frac{f}{10^{12} \text{ GeV}} \right) \left(\frac{\theta_i}{0.1} \right) \text{ GeV} \\ &\simeq 6 \times 10^7 \left(\frac{\Omega_J h^2}{0.12} \right)^{1/2} \left(\frac{m_J}{1 \text{ eV}} \right)^{-1/4} \text{ GeV}. \end{aligned}$$

For instantaneous reheating,

$$T_R = \left(\frac{90}{\pi^2 g_*} \right)^{1/4} \sqrt{H_{\text{inf}} M_{\text{Pl}}} \lesssim 6 \times 10^{12} \left(\frac{m_J}{1 \text{ eV}} \right)^{-1/8} \text{ GeV}.$$

UV model

An exact discrete gauge symmetry $Z_N \subset U(1)_{B-L}$

($N = 5, 7, 11, 13$)

[Fujisawa, Liang, Matsumoto, Uwabo-Niibo, Yanagida '26]

=

approximate global $U(1)_{B-L}$ (as an accidental symmetry)

$$\mathcal{L} \supset i\bar{N}_i \not{\partial} N_i + |\partial_\mu \sigma|^2 - V(\sigma) - \left[\frac{1}{2} g_i \sigma \bar{N}_i^c N_i + y_{\alpha i} \bar{L}_\alpha \tilde{H} N_i + \text{h.c.} \right]$$

+

Planck-suppressed operators (it gives the Majoron mass)

$$\begin{aligned} \mathcal{L} &\supset \frac{\sigma^n}{M_{\text{Pl}}^{n-4}} \\ &\rightarrow -\frac{1}{2} m_J^2 J^2, \quad m_J^2 \sim \frac{f^{n-2}}{M_{\text{Pl}}^{n-4}} \end{aligned}$$