Constraints on majoron dark matter from future neutrino experiments

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- Introduction: what Majoron is.
    - Why it is attractive as physics beyond the SM
- Majoron model setup
    - Why it is attractive as a dark matter candidate
- Current/ anticipated constraints on Majoron dark matter

Introduction(1) : Neutrinos mass mechanism

$$\mathscr{L} = -\frac{1}{2}\left(\overline{\nu_L} \quad \overline{\nu_R^c}\right)\begin{pmatrix} 0 & m_D \\ m_D^T & \boxed{M_R} \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \mathrm{h.c.} = -\frac{1}{2}\overline{n_R}\left(\mathrm{diag}(m_1 \cdots m_6)\right) n_R + \mathrm{h.c.}$$

Dirac

- $M_R = 0$
- $\bar{\nu} \neq \nu$ (Dirac)
- $m_i = m_D \sim 10^{-1}\,\mathrm{eV}$
- No principle to determine m_D

Majorana

- $M_R \neq 0$ (: arbitrary, since ν_R is singlet)
- $m_i \sim m_D^2/M_R \sim 10^{-1}\,\mathrm{eV}$
- No principle to determine M_R but consistent to the fact that ν_R has not observed yet.
- $\bar{\nu} = \nu$ ...Breaks Lepton # conservation

Introduction (2) : Lepton # symmetry

$$\mathscr{L} = \mathscr{L}_{\text{SM}}(\Phi, \nu_L, \cdots) + i\overline{\nu_R}\gamma_\mu\partial_\mu\nu_R - m_D\overline{\nu_L}\nu_R\left(1 + \frac{h}{v}\right) - \boxed{\frac{M_R}{2}\overline{\nu_R^c}\nu_R} + \text{h.c.}$$

Φ: SM Higgs
$= (v + h)/\sqrt{2}$

Lepton # Conservation: Global $\text{U}(1)_L$

$L(\text{leptons}) = 1, \quad L(\text{others}) = 0$

- $\psi \to e^{iL(\psi)}\psi, \quad \overline{\psi} \to e^{-iL(\psi)}\overline{\psi}, \quad \psi^c \to e^{-iL(\psi)}\psi^c,$
- Lagrangian is invariant under $U(1)_L$, except for $\overline{\nu_R^c}\nu_R$ term.

  → It would be a great hint of physics beyond the SM...

- Assume that $U(1)_L$ breaks spontaneously as well as other symmetries in SM.

Introduction (3): NG-boson with $\mathrm{U}(1)_L$... Majoron

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}}(\Phi, \nu_L, \cdots) + i\overline{\nu_R}\gamma_\mu \partial_\mu \nu_R - m_D \overline{\nu_L}\nu_R \left(1 + \frac{h}{v}\right) - \cancel{\frac{M_R}{2}\overline{\nu_R^c}\nu_R} + \mathrm{h.c.}$$

$$-\frac{\lambda_R}{2}\overline{\nu_R^c}\Sigma\nu_R - V(\Sigma, \Phi)$$

$$L(\Sigma) = -2$$

Spontaneous global $\mathrm{U}(1)_L$ breaking

$$V_{\Sigma,\Phi} = \lambda_\Sigma \left(\Sigma^\dagger\Sigma - \frac{f^2}{2}\right)^2 + \delta\Phi^\dagger\Phi\Sigma^\dagger\Sigma$$

$$\Sigma \to \frac{1}{\sqrt{2}}\big(f + \sigma(x) + iJ(x)\big),$$ J: massless NG-boson (Majoron)

Introduction (3): NG-boson with $\mathrm{U}(1)_L$... Majoron

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}}(\Phi, \nu_L, \cdots) + i\overline{\nu_R}\gamma_\mu\partial_\mu\nu_R - m_D\overline{\nu_L}\nu_R\left(1+\frac{h}{v}\right) - \frac{\lambda_R}{2}\overline{\nu_R^c}\Sigma\nu_R - V(\Sigma, \Phi)$$

- Majorana mass term of neutrinos...
  - explains neutrino tiny mass (seesaw mechanism)
  - is the first term which breaks $U(1)_{\mathrm{L}}$ (Lepton # symmetry)
- Majoron...
  - is NG boson associated with $U(1)_{\mathrm{L}}$ spontaneous breaking
  - explains Majorana mass term

⇨ Attractive physics beyond the Standard Model !

Majoron Model (1): Set up

$$\mathscr{L} = \mathscr{L}_{\rm SM}(\Phi, \nu_L, \cdots) + i\overline{\nu_R}\gamma_\mu\partial_\mu\nu_R - m_D\overline{\nu_L}\nu_R\left(1+\frac{h}{v}\right) - \frac{\lambda_R}{2}\overline{\nu_R^c}\Sigma\nu_R - V(\Sigma,\Phi)$$

(1) Potential

$$V = \underline{\lambda_\Sigma\left(\Sigma^\dagger\Sigma - \frac{f^2}{2}\right)^2} + \delta\Phi^\dagger\Phi\Sigma^\dagger\Sigma$$

$$= \frac{\lambda_\Sigma}{4}\left(2f\sigma + \sigma^2 + \underline{J^2}\right)^2 + \delta\Phi^\dagger\Phi\Sigma^\dagger\Sigma \qquad \left(\Sigma \to \frac{1}{\sqrt{2}}\left(f + \sigma(x) + iJ(x)\right)\right)$$

In the pure majoron model: massless (NG boson)

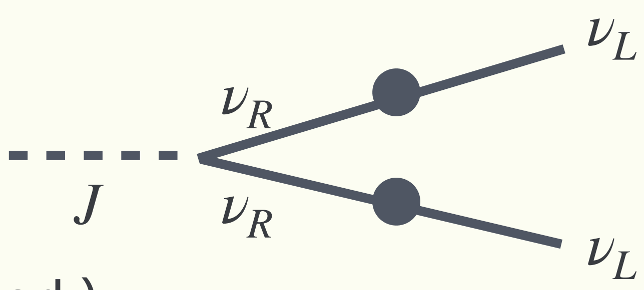
In reality: massive with the arbitrary mass (pNG boson)

Majoron Model (2): Dark Matter Candidate

- Majoron J $\quad \mathscr{L}_{\text{int}} = -\frac{iM_R}{2f} J \overline{\nu_R^c} \nu_R + \text{h.c.}$
  - pNG boson associated with $\mathrm{U}(1)_L$
  - Massive ($m_{1,2,3} \ll m_J \sim \mathcal{O}(\mathrm{MeV}) \ll m_{4,5,6}$ in our work)
  - Stable when $f \gg v$

$$\Gamma(J \to \nu\nu) \simeq \frac{m_J}{16\pi f^2} \sum m_i^2 \sim \frac{1}{3 \times 10^{19}\,\mathrm{sec}} \left(\frac{m_J}{1\,\mathrm{MeV}}\right) \left(\frac{10^9\,\mathrm{GeV}}{f}\right)^2 \left(\frac{\sum m_i^2}{10^{-3}\mathrm{eV}^2}\right)$$

  - Least constrained



Connected only with ν at tree level

Majoron J is an attractive dark matter candidate

Constraint on Majoron Model

- Interaction in mass basis

$$\mathscr{L}_{\text{int}} = -\frac{iM_R}{2f} J \overline{\nu_R^c} \nu_R + \text{h.c.} = \sum_{i,j=1}^{3} \frac{i\lambda_{ij} J}{2} \overline{n}_i \gamma_5 n_j, \quad \lambda_{ij} = \frac{m_i \delta_{ij}}{f}$$

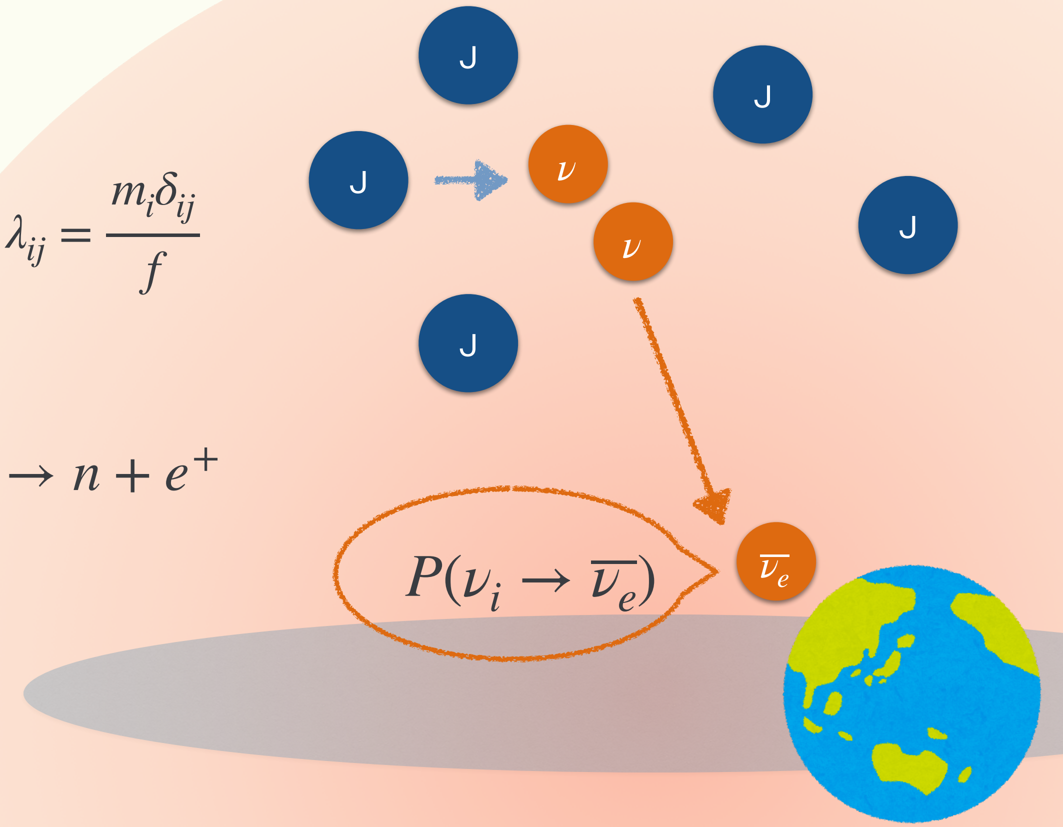
- Detected in flavor basis

Inverse beta decay (IBD) @ MeV: $\bar{\nu}_e + p \rightarrow n + e^+$

- Possibility

$$\Gamma(\text{IBD}) = P(\nu_i \rightarrow \overline{\nu_e}) \Gamma(J \rightarrow \nu\nu)$$

$$\simeq \frac{m_J}{16\pi f^2} \sum |U_{ei}|^2 m_i^2$$



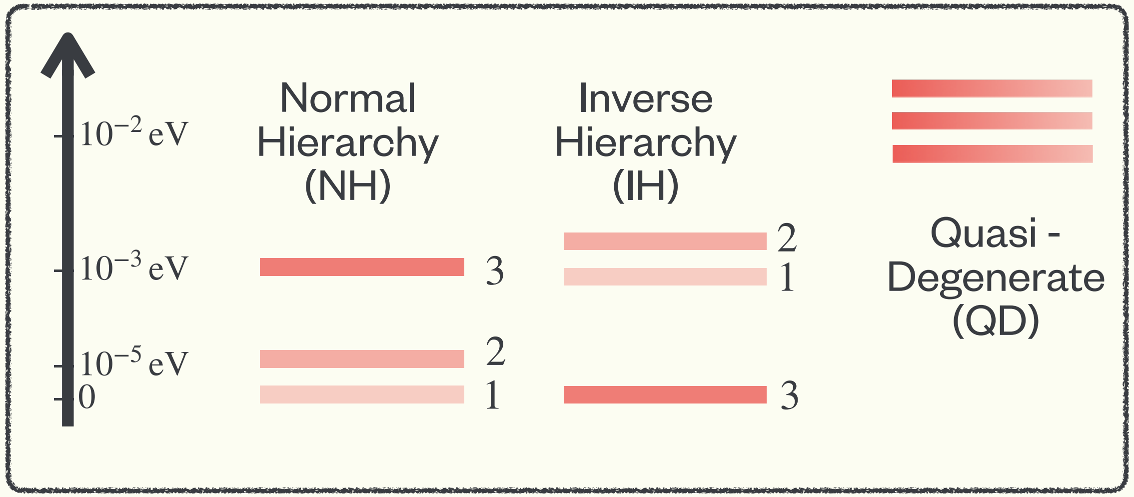
Constraint on Majoron Model: Depends on Mass Hierarchy

$$\Gamma(J \to \nu\nu) = \frac{m_J}{16\pi f^2} \sum m_i^2$$

$$\Gamma(\mathrm{IBD}) = \sum_i P(\nu_i \to \overline{\nu_e})\Gamma(J \to \nu\nu) = \alpha_e \Gamma(J \to \nu\nu) \propto \frac{\alpha_e \sum m_i^2}{f^2}$$

$$\alpha_e = \frac{\sum_{i=1}^3 |U_{ei}|^2 m_i^2}{\sum_{i=1}^3 m_i^2}$$

α_e and $\Sigma_i m_i^2$ depend on the mass hierarchy



	NH	IH	QD
α_e	0.03	0.48	1/3
Σm_i^2 (eV^2)	2.6×10^{-3}	4.9×10^{-3}	0.17
$\sqrt{\alpha_e \Sigma m_i^2}$	8.8×10^{-3}	4.7×10^{-2}	2.3×10^{-1}

$\times 5$ $\times 5$

Constraint on Majoron Model

$f\,[\mathrm{GeV}]$ in the case of QD

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α_e	0.03	0.48	$1/3$
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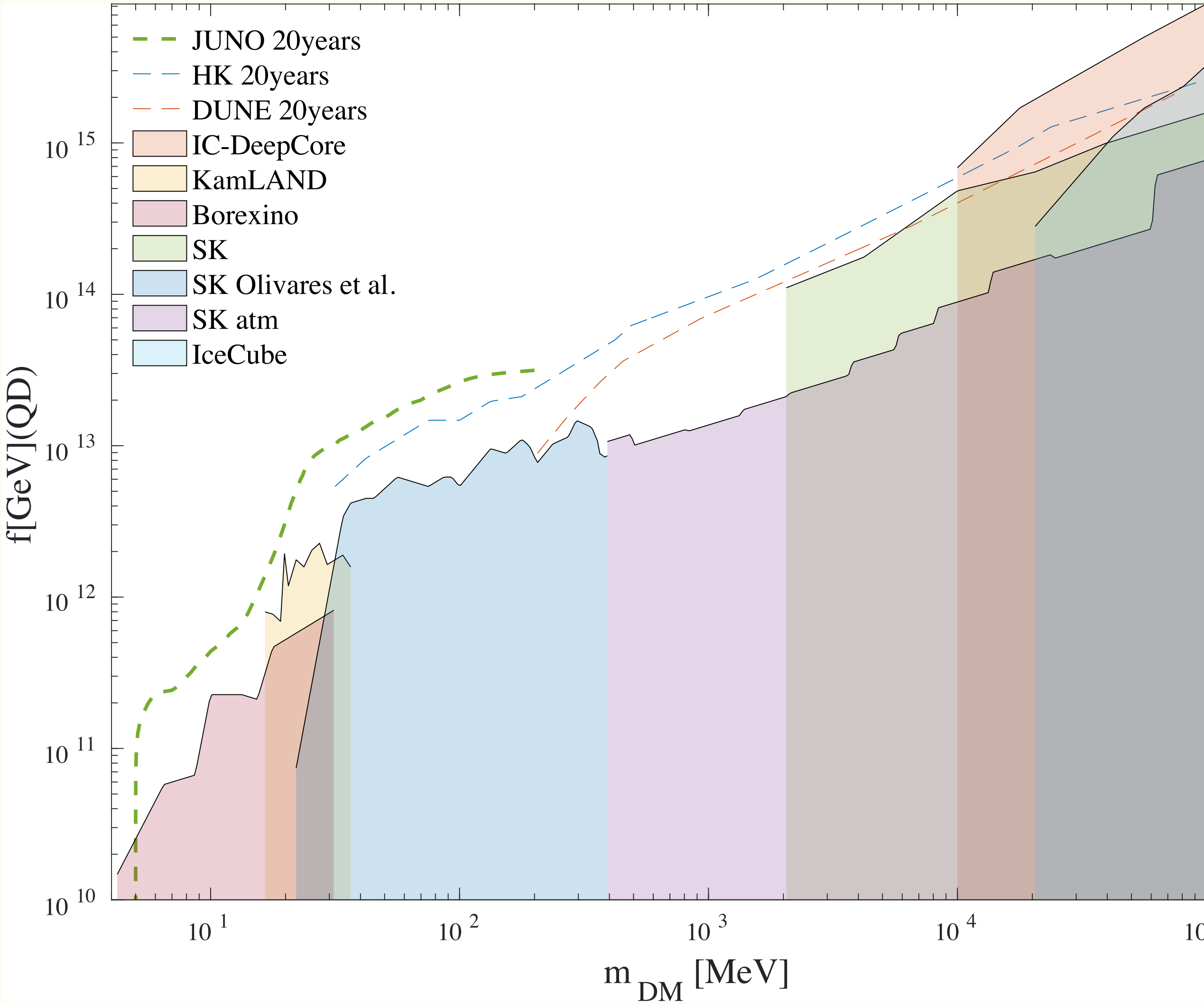
$$\Phi \propto \frac{\alpha_e \Sigma m_i^2}{f^2}$$: max in QD case



Constraint on Majoron Model

Mass hierarchy dependence

	NH	IH	QD
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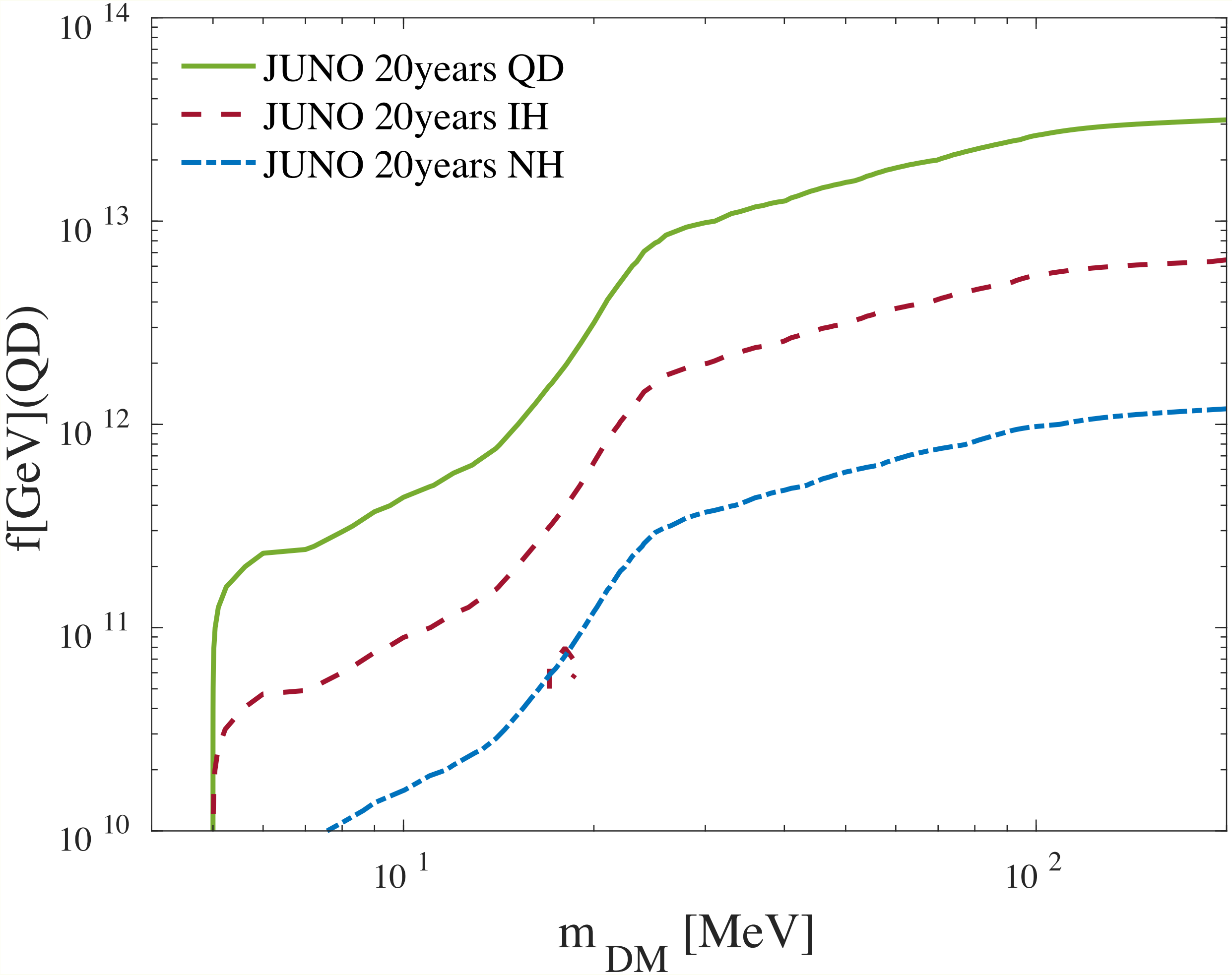
Constraint strongly depends on mass hierarchy ($\times$ 5)



Summary

- Majoron is an attractive physics beyond the SM
    - If neutrinos are Majorana with $M_R \neq 0$, neutrinos break global $\mathrm{U}(1)_L$
    - Majoron is pNG-boson associated with $\mathrm{U}(1)_L$, which explains $M_R \neq 0$

- Majoron is an attractive dark matter candidate
    - Set VEV $f \gg v \sim 10^2\,\mathrm{GeV}$ to be consistent with experiments
    - Majoron: stable ($\Gamma \leq (10^{17}\,\mathrm{sec})^{-1}$ at $f \sim 10^{19}\,\mathrm{GeV}$

- Constraints depend on mass hierarchy: QD > IH > NH