Future Constraints on Neutrino Lines from Dark Matter Based on ongoing work with Kensuke Akita (IBS, Korea)

Michiru NIIBO (Ochanomizu Univ., Tokyo Tech)

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Current detection strategies

(1) **Direct Detection**

Scatter DM particles with atoms (nuclei, electrons...)

(2) Optical Detection

Detect photons from DM or from standard model particles produced from DM

> Unfortunately, we have not detected any signals of DM and have imposed strong constraints on DM- standard model particle interactions.









Detection strategy (3) Neutrino observation

Complementary strengths of neutrino detection

- Detectable on the ground
- Less background than optical signals
- Electrically neutral -> stable, straight signal

Next-generation neutrino detectors

- JUNO (2023?-)
- Super Kamiokande (+ Gd)(2020 -)
- Hyper Kamiokande (2027 -)

Would undiscovered DM signals be finally found through neutrino observation?





How does dark matter interact with neutrinos?

Hint: Neutrino mass mechanism

Neutrino mass is the first deviation of SM

Majoron dark matter



 Motivated by the seesaw mechanism • The ratio of generations of produced neutrinos depends on their mass



Majoron DM model

- Majoron DM 1.
 - 1. Neutrino mass mechanism
 - 2. Majoron Model
 - 3. Majoron as the DM candidate

- 2. Neutrino signals from Majoron decay
 - Decay rate 1.
 - 2. (Anticipated) constraints on the model



Mass of neutrinos

• General spinors

 $\mathscr{L} = -\frac{1}{2} \begin{pmatrix} \overline{\psi_L} & \overline{\psi_R^c} \end{pmatrix} \begin{pmatrix} M_L & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \psi_L^c \\ \psi_R \end{pmatrix} + h.c.$



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 $\psi = (\psi_L, \psi_R)^T$

U(1) symmetry ($\psi \rightarrow e^{igQ}\psi$) is

- conserved by m_D ... Dirac spinors when ψ_I, ψ_R have same charge Q
- violated by M_L, M_R ... Majorana spinors



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Neutrinos

$$\mathscr{L} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} \mathbf{0} & \mathbf{m_D} \\ \mathbf{m_D^T} & \mathbf{M_R} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \mathbf{h} \cdot \mathbf{c} \, .$$

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- $m(\nu_I) \neq 0 \rightarrow M_I \neq 0 \text{ or } m_D \neq 0$
- ν_L has isospin: I=1/2 $\rightarrow M_L = 0, m_D \neq 0$ $\rightarrow \nu_R$ must exist!







Dirac or Majorana?

• Dirac Neutrinos

$$\mathscr{L} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$

- $m_i = m_D \sim 10^{-1} \,\mathrm{eV}$
- No natural reason to have such small m_D





Dirac or Majorana?

Dirac Neutrinos

$$\mathscr{L} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$

 Majorana Neutrinos $\mathscr{L} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$

•
$$m_i = m_D \sim 10^{-1} \,\mathrm{eV}$$

• No natural reason to have such small m_D

•
$$m_i \sim m_D^2 / M_R \sim 10^{-1} \, {\rm eV}$$
 for

$$M_R \gg m_D = \mathcal{O}(m_W)$$

- No principle to determine M_R
- Heavy ν_R effectively decouples from low energy physics
 - Consistent with experimental facts
- $\overline{\nu} = \nu$ violates U(1) (Lepton # conservation)





Dirac or Majorana?

Dirac Neutrinos

$$\mathscr{L} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

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> Assume that (1) the Seesaw mechanism, (2) Spontaneous U(1) Breaking **Majoron Model**

•
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 $\mathscr{L} = \mathscr{L}_{SM} + i\overline{\nu}_R\gamma_u\partial_u\nu_R - \lambda_D\Phi^*E_L\nu_R$

 $-\frac{\lambda_R}{2}\overline{\nu_R^c}\Sigma\nu_R - \lambda_{\Sigma}\left(\Sigma^{\dagger}\Sigma - \frac{f^2}{2}\right)^2 + \delta\Phi^{\dagger}\Phi\Sigma^{\dagger}\Sigma$

Φ: SM Higgs $E_L = (\nu_L, e_L)^T$: SU(2) doublet Σ: new singlet scalar



 $\mathscr{L} = \mathscr{L}_{\rm SM} + i\overline{\nu_R}\gamma_\mu\partial_\mu\nu_R - \lambda_D\Phi^*\overline{E_L}\nu_R$ $-\frac{\lambda_R}{2}\overline{\nu_R^c}\Sigma\nu_R - \lambda_{\Sigma}\left(\Sigma^{\dagger}\Sigma - \frac{f^2}{2}\right)^2 + \delta\Phi^{\dagger}\Phi\Sigma^{\dagger}\Sigma$

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U(1) Lepton number symmetry

 $\psi \rightarrow e^{iL(\psi)}\psi,$

$L(\nu_R) = 1, \quad L(\Sigma) = -2$



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Spontaneous U(1) breaking

Φ: SM Higgs $E_L = (\nu_L, e_L)^T$:SU(2) doublet Σ : new singlet scalar

U(1) Lepton number symmetry

 $\psi \to e^{iL(\psi)}\psi,$

$$L(\nu_R) = 1, \quad L(\Sigma) = -2$$

$$\Sigma \to \frac{1}{\sqrt{2}} \left(f + \sigma(x) + iJ(x) \right)$$

(p)NG boson: J(x) |Majoron

Take $f \gg v \therefore m_{\sigma} \gg m_{h}$

 $\rightarrow \sigma(x)$ decouples from SM



 $\mathscr{L} = \mathscr{L}_{SM} + i\overline{\nu}_R\gamma_u\partial_u\nu_R - \lambda_D\Phi^*E_L\nu_R$

 $-\frac{\lambda_R}{2}\overline{\nu_R^c}\Sigma\nu_R - \lambda_{\Sigma}\left(\Sigma^{\dagger}\Sigma - \frac{f^2}{2}\right)^2 + \delta\Phi^{\dagger}\Phi\Sigma^{\dagger}\Sigma$

 $\Sigma \rightarrow \frac{1}{\sqrt{2}} \left(f + \sigma(x) + iJ(x) \right)$ $-\frac{1}{2}M_R\overline{\nu_R^c}\nu_R\left(1+\frac{\sigma(x)+iJ(x)}{f}\right), M_R=\frac{\lambda_R f}{\sqrt{2}}$



 $\mathscr{L} = \mathscr{L}_{\rm SM} + i\overline{\nu}_R\gamma_\mu\partial_\mu\nu_R - \lambda_D\Phi^*$

 $-\frac{\lambda_R}{2}\overline{\nu_R^c}\Sigma\nu_R - \lambda_{\Sigma}\left(\Sigma^{\dagger}\Sigma - \frac{f^2}{2}\right)^2 + \delta\Phi^{\dagger}\Phi\Sigma^{\dagger}\Sigma$

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$$\overline{E_L}\nu_R \qquad -m_D\overline{\nu_L}\nu_R \left(1 + \cdot\right)$$

$$\Phi^* \to (v + h(x), 0)^T / \sqrt{2}$$
$$-m_D \overline{\nu_L} \nu_R \left(1 + \frac{h(x)}{v} \right), \ m_D = \frac{\lambda_D v}{\sqrt{2}}$$

 $M_R \gg m_D(\mathcal{O}(\lambda) \sim 1)$

Since $f \gg v$,







Dark Matter Candidate?

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ive?
NG boson associated with U(1)L

$$_{1,2,3} \ll m_J \sim \mathcal{O}(\text{MeV}) \ll m_{4,5,6}$$
 in our work
e?
teracts only with neutrinos at tree-level
uppressed by $1/f$
 $\Gamma(J \rightarrow \nu\nu) \simeq \frac{m_J}{16\pi f^2} \sum m_i^2 \sim \frac{1}{3 \times 10^{19} \text{ sec}} \left(\frac{m_J}{1 \text{ MeV}}\right) \left(\frac{10^9 \text{ GeV}}{f}\right)^2 \left(\frac{\sum m_J}{10^{-3} \text{ eV}}\right)^2$

Least constrained since couple only with neutrinos:





Neutrino Line signal from Majoron DM

Interaction in mass basis

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

- Detected in flavor basis Eg.) Inverse beta decay (IBD) @ MeV: $\bar{\nu}_e + p \rightarrow n + e^+$
- Possibility

$$\Gamma(\text{IBD}) = \frac{P(i \to e)\Gamma(J \to \nu\nu)}{P(i \to e)\Gamma(J \to e)}$$

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





Uncertainty: neutrino mass

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

$$\Gamma(\text{IBD}) = \sum_i P(i \to e) \Gamma(J \to \nu\nu) = \alpha_e \Gamma(J \to \nu\nu)$$

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



| $) \propto \frac{\alpha_e}{\beta}$ | $\sum m_i^2$ | $\alpha_e = -$ | $\sum_{i=1}^{3} U_{ei} ^2 \sum_{i=1}^{3} m_i^2$ | <i>m</i> ² _{<i>i</i>} | |
|------------------------------------|--------------|-----------------------------------|--|---|------------|
| | | | NH | IH | QD |
| | | α_{e} | 0.03 | 0.48 | 1/3 |
| asi - nerate 2D) | | 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 × |
| | | | | < 5 | $\times 5$ |









Constraint on Majoron Model(QD)

- Colored regions:
 Current constraints
- Dashed curves:
 Future sensitivities

• Stronger constraints on larger m_J $\Gamma(J \rightarrow \nu\nu) = \frac{m_J}{16\pi f^2} \sum m_i^2$ • $f > 10^{13}$ GeV at $m_J \sim 1$ GeV



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| | | | | ,"这些我们,我们有不是,我们也不能不不不不能不能。""你不是你的,你们们就不是你,你不能不能不能不能。""你们,你不是你,你不能不能不能。""你们,你们就不能不能。" | | | | | """"""""""""""""""""""""""""""""""""""" | | | | 化过程 化过程 化过程 计过程 化化合金 化化合金 化合金 化合金 化合金 化合金 化合金 化合金 化合金 化 | | | | | | | | | |
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| | | | | ,"""""""""""""""""""""""""""""""""""""" | | | | | """"""""""""""""""""""""""""""""""""""" | | | | ""我们不是是不是不是不是不是不是不是我们就不是不是不是不是不是不是不是不是我们就不是不是不是不是不是不是不是你的?""你们就是我们就是你们的,你们就 | | | | | | | | | |
| | | | | ,"""""""""""""""""""""""""""""""""""""" | | | | | | | | | | | | | | | | | | |
| | | | | ,"""""""""""""""""""""""""""""""""""""" | | | | | """"""""""""""""""""""""""""""""""""""" | | | | ""是是是是是有什么?""你们,我们不是不是是不是不是不是,我们就不是不是不是不是不是不是不是,你们就不是你?""你们就是我们就是你们,我们也不能能。" | | | | | | | | | |
| | | | | 1、"""""""""""""""""""""""""""""""""""""" | | | | | """""""""""""""""""""""""""""""""""""" | | | | "是是是是是是有什么?""你是不是是不是是是是是是不是是不是是不是是不是是不是是是是是是是是是是是是是 | | | | | | | | | |
| | | | | 1、"""""""""""""""""""""""""""""""""""""" | | | | | """""""""""""""""""""""""""""""""""""" | | | | "是是是是是有什么?""你们不是不是,我们就是是不是不是不是不是不是,我们就不是不是不是不是不是不是不是不是不是我们就是我们就是这些,我们也不能不是不是 | | | | | | | | | |
| | | | | 2、"""""""""""""""""""""""""""""""""""""" | | | | | · · · · · · · · · · · · · · · · · · · | | | | | | | | | | | | | |
| | | | | 2、"""""""""""""""""""""""""""""""""""""" | | | | | · · · · · · · · · · · · · · · · · · · | | | | | | | | | | | | | |
| | | | | 2、"""""""""""""""""""""""""""""""""""""" | | | | | """"""""""""""""""""""""""""""""""""""" | | | | | | | | | | | | | |
| | | | | ,一种"中国"之外,有"中国","三、"中国","三、"中国","三、"中国","三、"中国","三、"三、"三、"三、"三、"、"三、"三、"、"二、"三、"、"三、"三、""一"、"""、"""、" | | | | | · · · · · · · · · · · · · · · · · · · | | | | | | | | | | | | | |
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| | | | | ,一种中午后,中午中,古时,大中,大中,大中,中午中,古,大中,大中,大中,大中,中午中,百年,五月,大中,大中,中午下,五月,五月,五月,十月,十月至至年五月,月 | | | | | 1、1、1、1、1、1、1、1、1、1、1、1、1、1、1、1、1、1、1、 | | | | | | | | | | | | | |
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| | | | | ,"""""""""""""""""""""""""""""""""""""" | | | | | "我不是是,我不能不是,我不能不是,我不能不是,你不能不是,不不能不能不是,你不能不能不是,你不能不能不是,你不能不能不是,你不不能不能不能不能不能。" | | | | | | | | | | | | | |
| | | | | ,"""""""""""""""""""""""""""""""""""""" | | | | | ····································· | | | | | | | | · · · · · · · · · · · · · · · · · · · | | | | | |





Dependence on the mass hierarchy



• $m_J \ge \mathcal{O}(1 \text{ GeV})$: $\nu_\mu, \nu_\tau \to \times (2.5 \times 10^{-1})$

• $\Gamma(J \rightarrow 2\nu) \propto \Sigma m_i^2$ gets smaller (NH)

• $m_J \lesssim \mathcal{O}(1 \,\text{GeV})$: $\nu_e \to \times (5 \times 10^{-2})$

• $\Gamma(J \rightarrow 2\nu_1) = 0$ in the NH case



Summary

- Neutrino is an attractive DM detection channel
 - Complementary strengths from direct and optical detections
 - Next-generation experiments
- Majoron is an attractive dark matter candidate
 - Majoron is pNG-boson associated with $U(1)_I$, which explains $M_R \neq 0$
 - Stable particle: $\Gamma \leq (10^{17} \text{ sec})^{-1}$ at $f \sim 10^9 \text{ GeV}$
- Anticipated constraints from future detectors
 - VEV of U(1)L breaking: $f > 10^{13} \text{ GeV}$ at $m_I \sim 100 \text{ MeV}$
 - Constraints depend on mass hierarchy and flavor sensitivity

