Future Constraints on Neutrino Lines from Dark Matter

Based on ongoing work with Kensuke Akita (IBS, Korea)

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20/Feb/2023

INTERNATIONAL CONFERENCE ON HOLOGRAPHY, STRING THEORY AND SPACETIME IN DA NANG

Current detection strategies

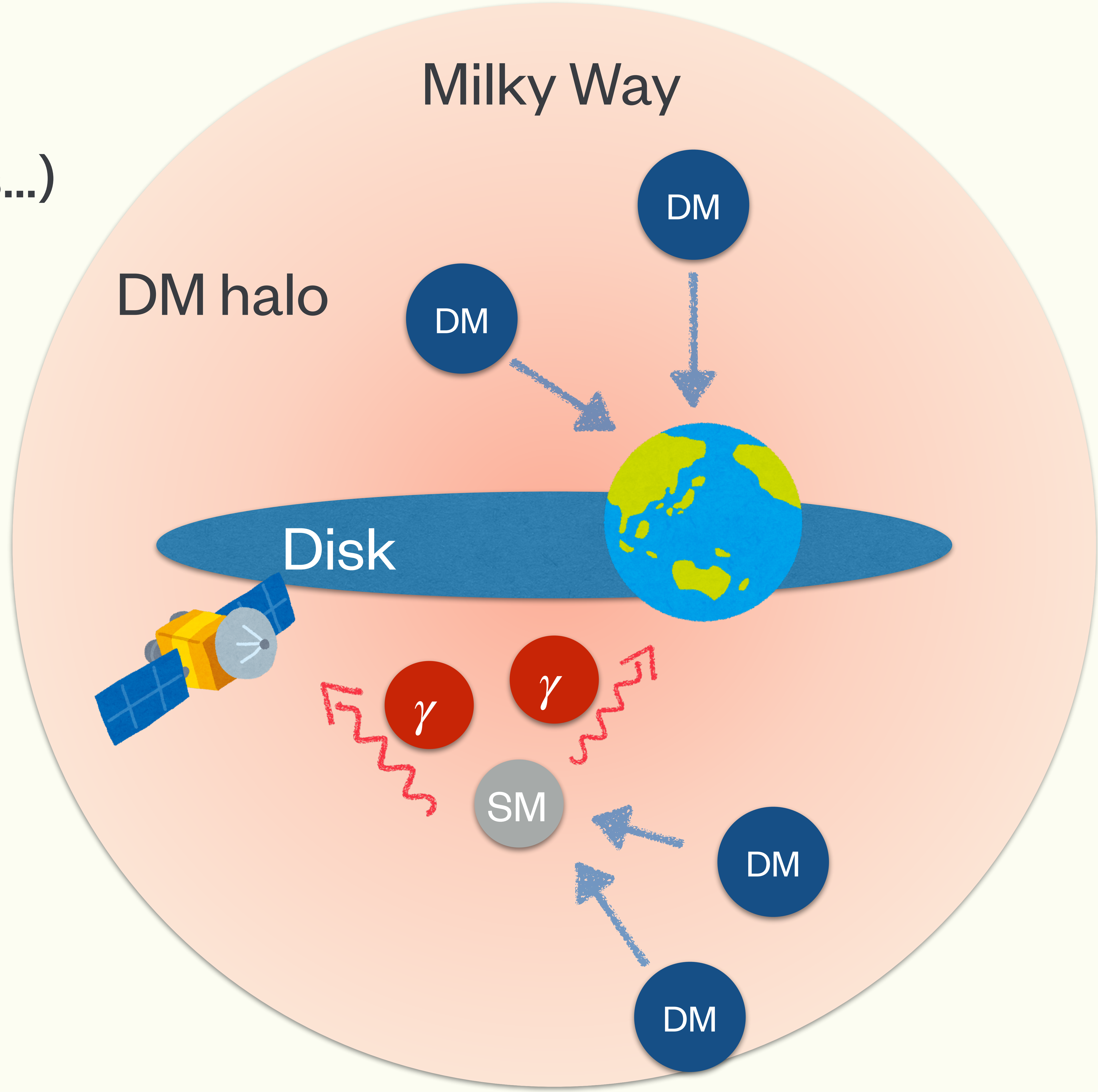
(1) Direct Detection

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

(2) Optical Detection

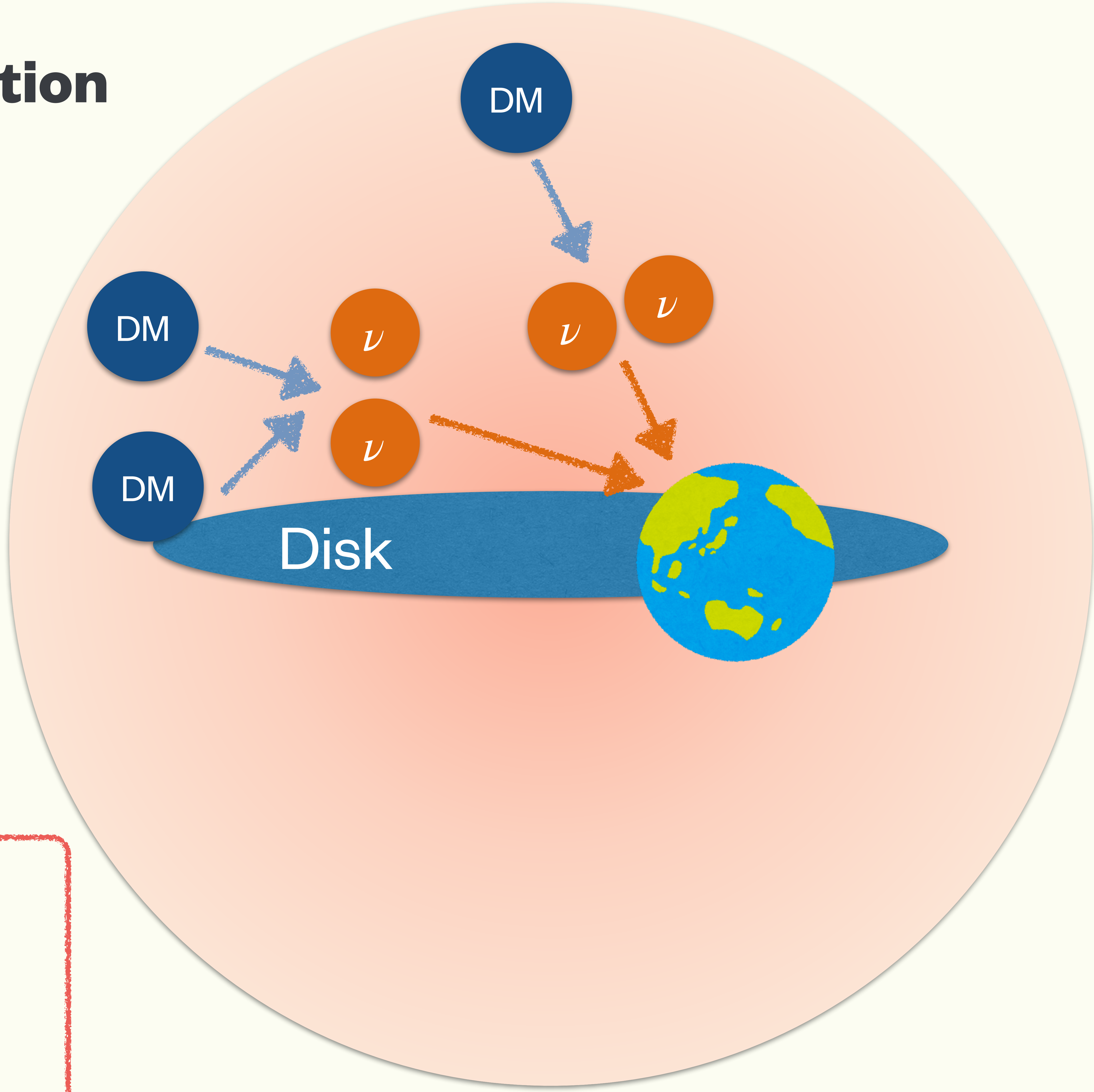
Detect photons from DM or from standard model particles produced from DM

⇨ 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 -)



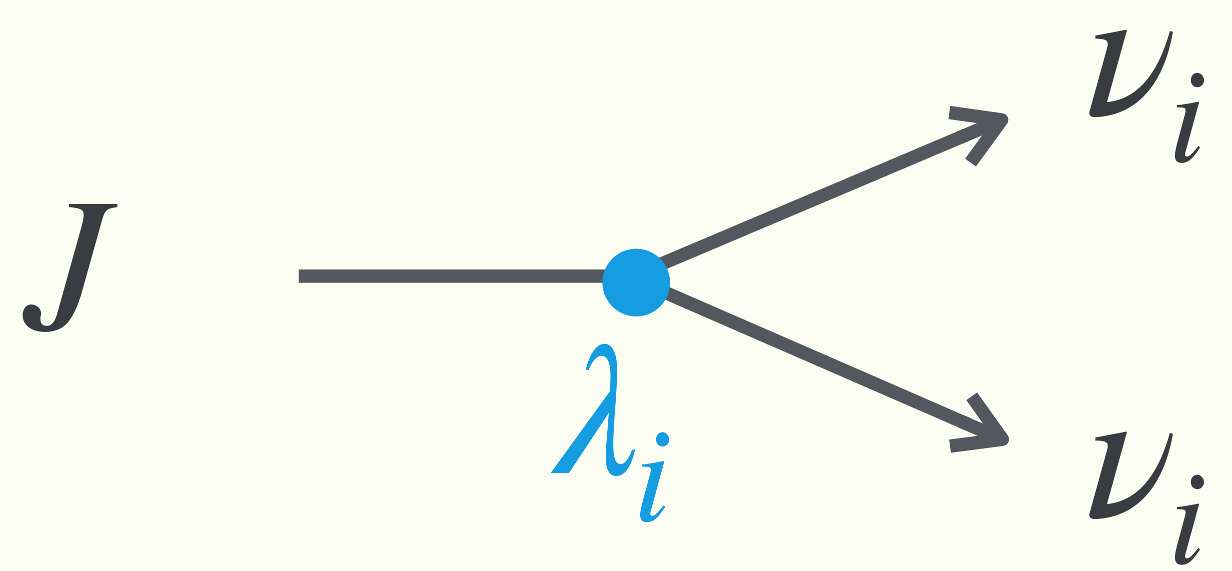
⇨ Would undiscovered DM signals be finally found through neutrino observation?

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

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

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

Mass of neutrinos

- General spinors

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

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

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

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

- conserved by m_D ... Dirac spinors

  when ψ_L, ψ_R have same charge Q

- violated by M_L, M_R ... Majorana spinors

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- Neutrinos

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

- $m(\nu_L) \neq 0 \to M_L \neq 0$ or $m_D \neq 0$
- ν_L has isospin: I=1/2 $\to M_L = 0, m_D \neq 0$
  $\to \nu_R$ must exist!

Dirac or Majorana?

- Dirac Neutrinos

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

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

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- $m_i \sim m_D^2/M_R \sim 10^{-1}\,\mathrm{eV}$ 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 $U(1)_L$ (Lepton # conservation)

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Assume that
(1) the Seesaw mechanism,
(2) Spontaneous U(1)L Breaking
⇨ Majoron Model

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Singlet Majoron Model

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

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

Φ: SM Higgs

$E_L = (\nu_L, e_L)^T$:SU(2) doublet

Σ: new singlet scalar

Singlet Majoron Model

U(1)L Lepton number symmetry

$$\psi \to e^{iL(\psi)}\psi,$$
$$L(\nu_R) = 1, \quad L(\Sigma) = -2$$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + i\overline{\nu_R}\gamma_\mu\partial_\mu\nu_R - \lambda_D\Phi^*\overline{E_L}\nu_R$$
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Spontaneous U(1)$_L$ breaking

Φ: SM Higgs

$E_L = (\nu_L, e_L)^T$:SU(2) doublet

Σ: new singlet scalar

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

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

Take $f \gg v \;\therefore\; m_\sigma \gg m_h$

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

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

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

Singlet Majoron Model

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

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

$$\Phi^* \to (v + h(x), 0)^T/\sqrt{2}$$

$$-m_D\overline{\nu_L}\nu_R\left(1 + \frac{h(x)}{v}\right), \quad m_D = \frac{\lambda_D v}{\sqrt{2}}$$

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

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

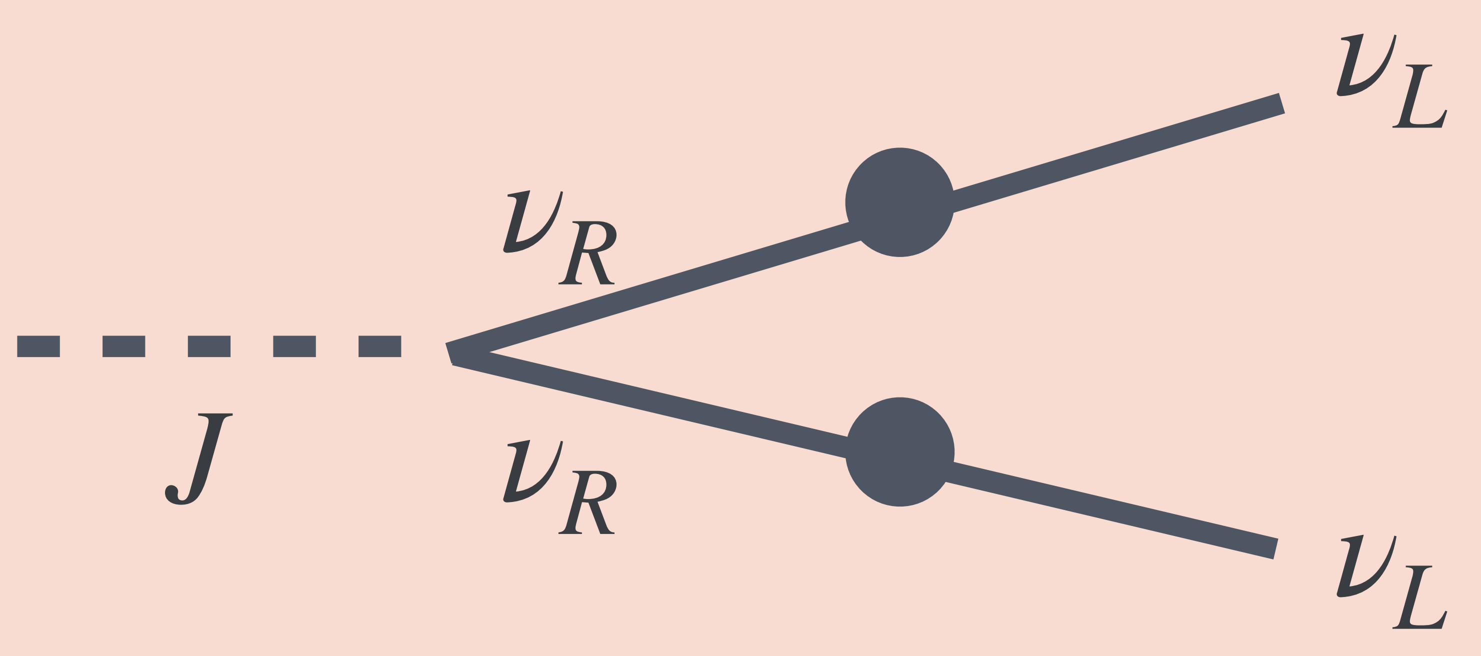
Since $f \gg v$,

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

→Seesaw mechanism works!

Dark Matter Candidate?

- Massive?
  - pNG boson associated with $U(1)_L$
  - $m_{1,2,3} \ll m_J \sim \mathcal{O}(\mathrm{MeV}) \ll m_{4,5,6}$ in our work
- Stable?
  - Interacts only with neutrinos at tree-level
  - Suppressed by $1/f$



$$\mathscr{L}_{\mathrm{int}} = -\frac{iM_R}{2f} J \overline{\nu_R^c} \nu_R + \mathrm{h.c.}$$

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

- Least constrained since couple only with neutrinos!

Neutrino Line signal from Majoron DM

- Interaction in mass basis

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

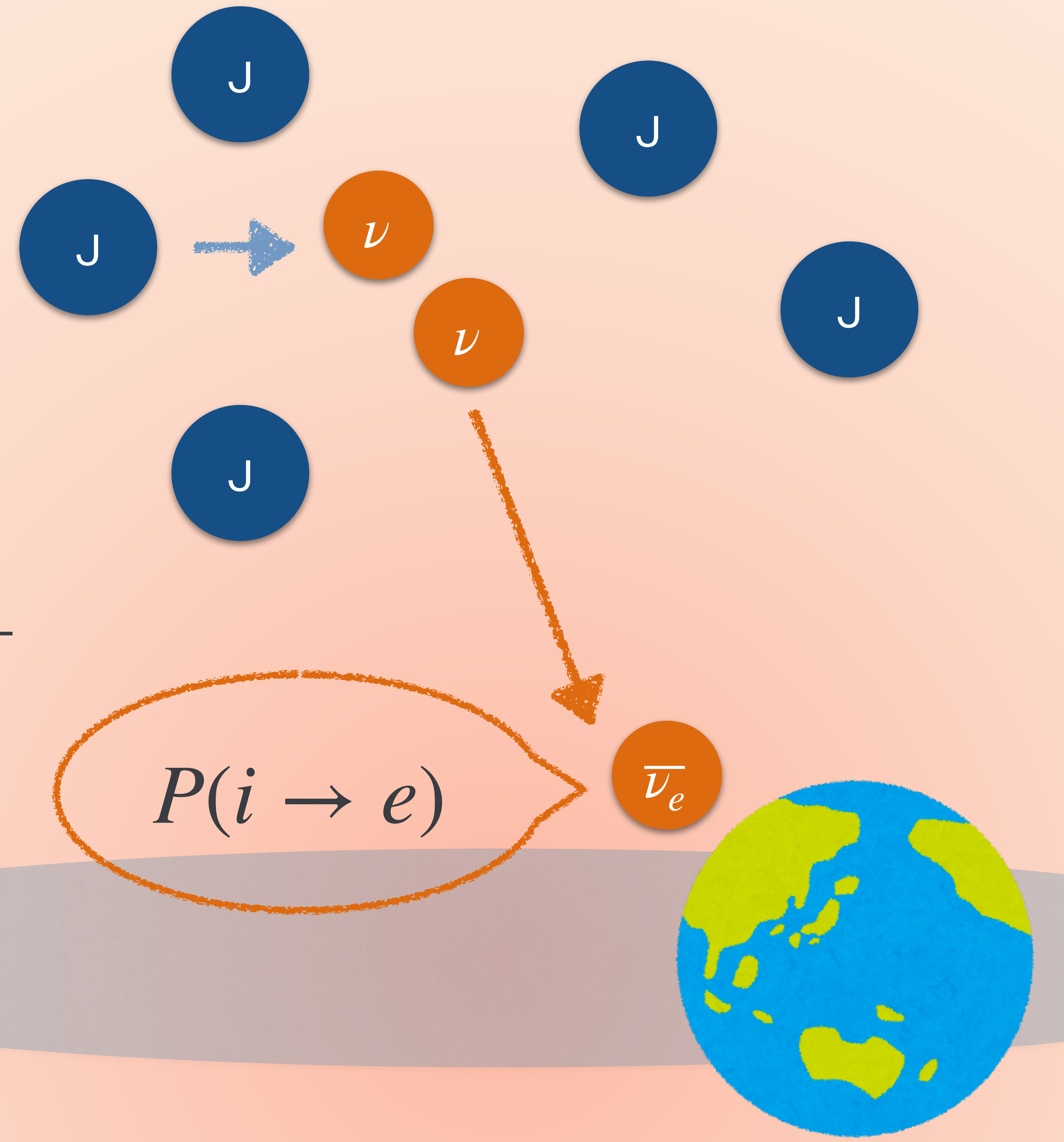
- Detected in flavor basis

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

- Possibility

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

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



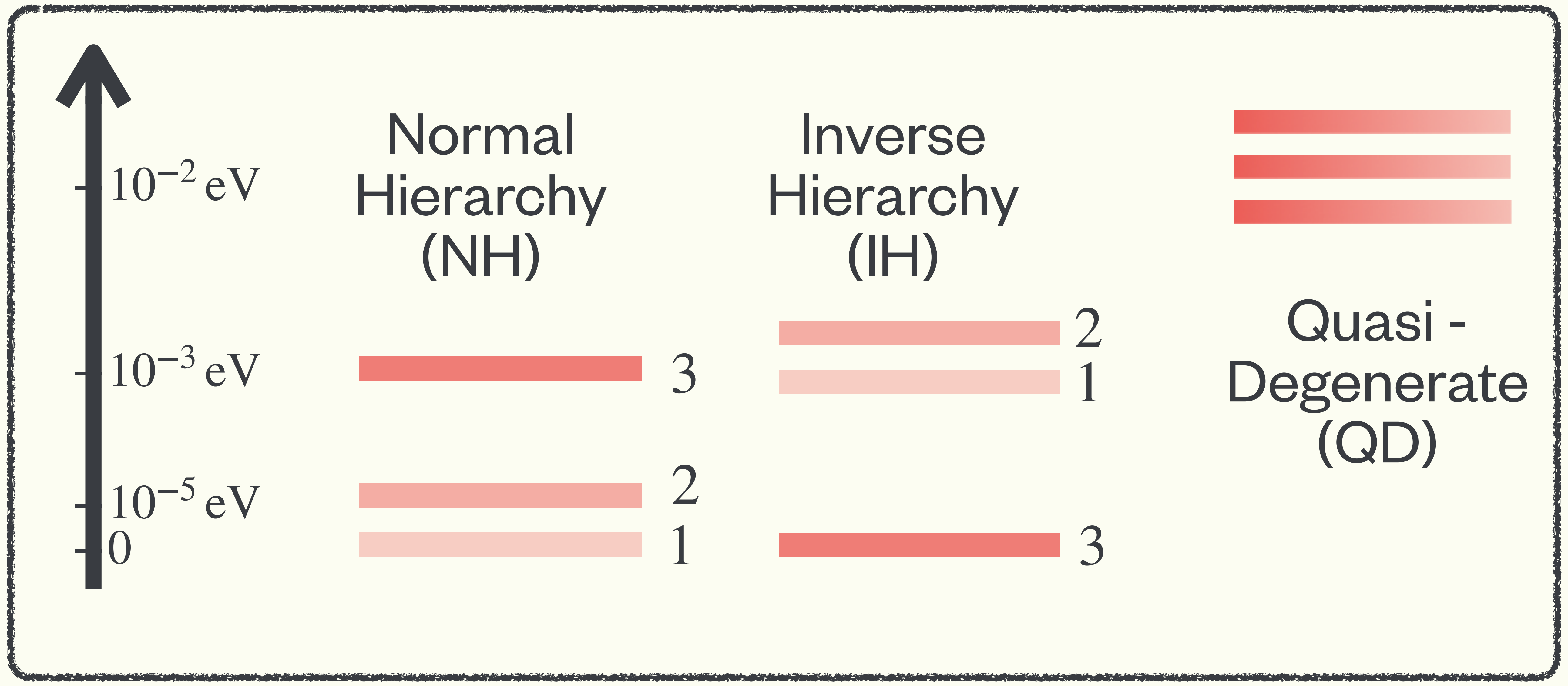
Uncertainty: neutrino mass

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

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

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

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}

$\times 5$ $\times 5$

Results

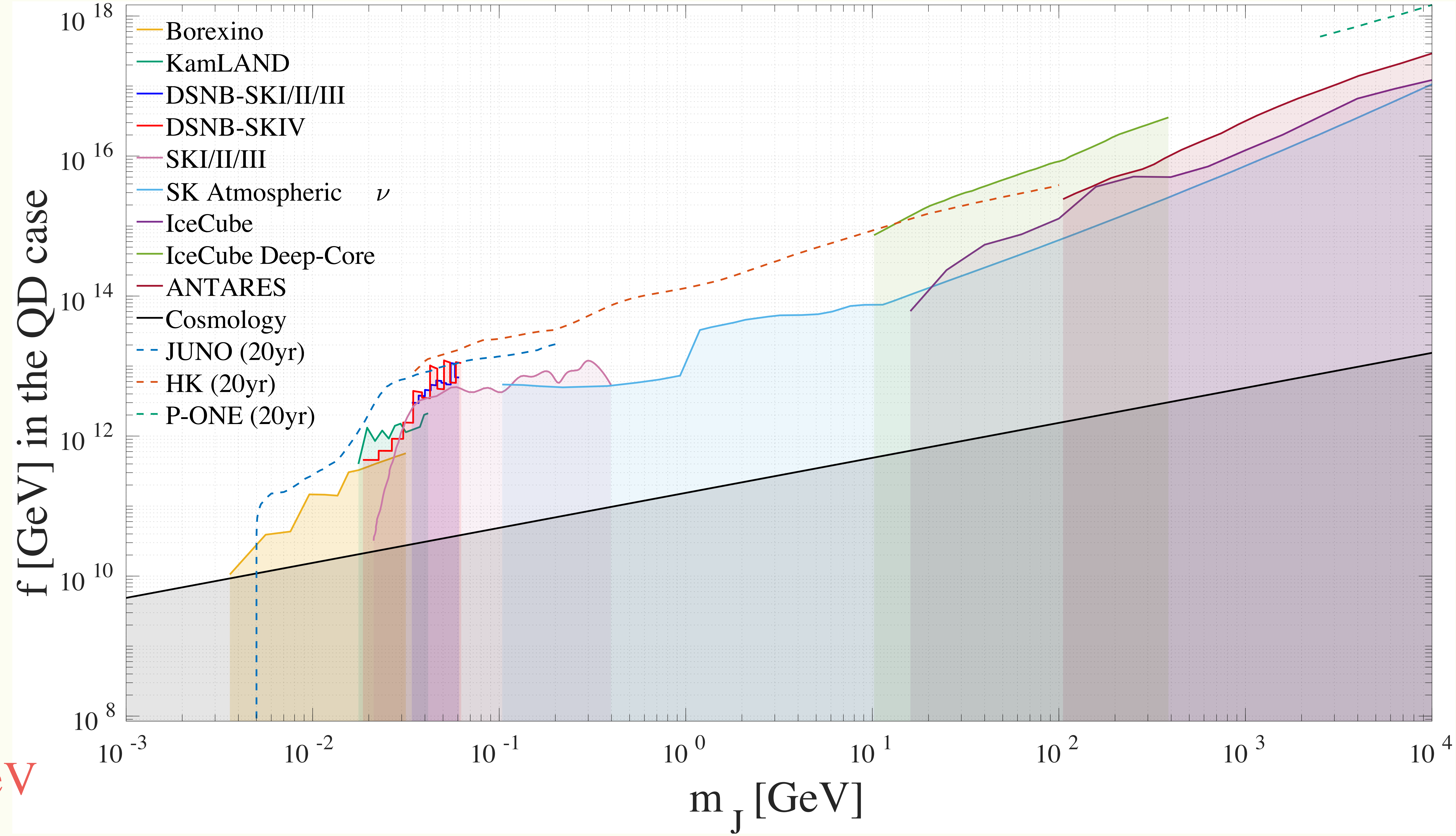
Constraint on Majoron Model(QD)

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

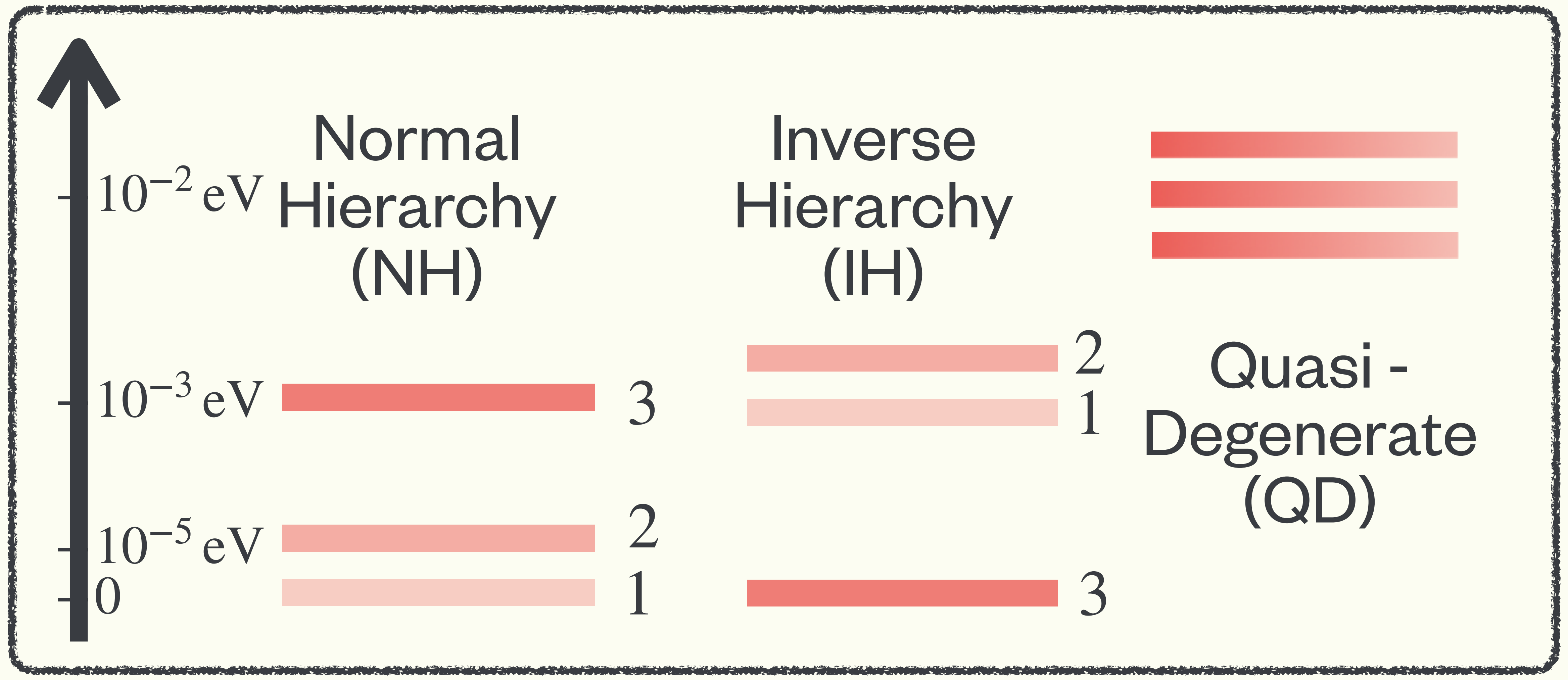
- Stronger constraints
  on larger m_J

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

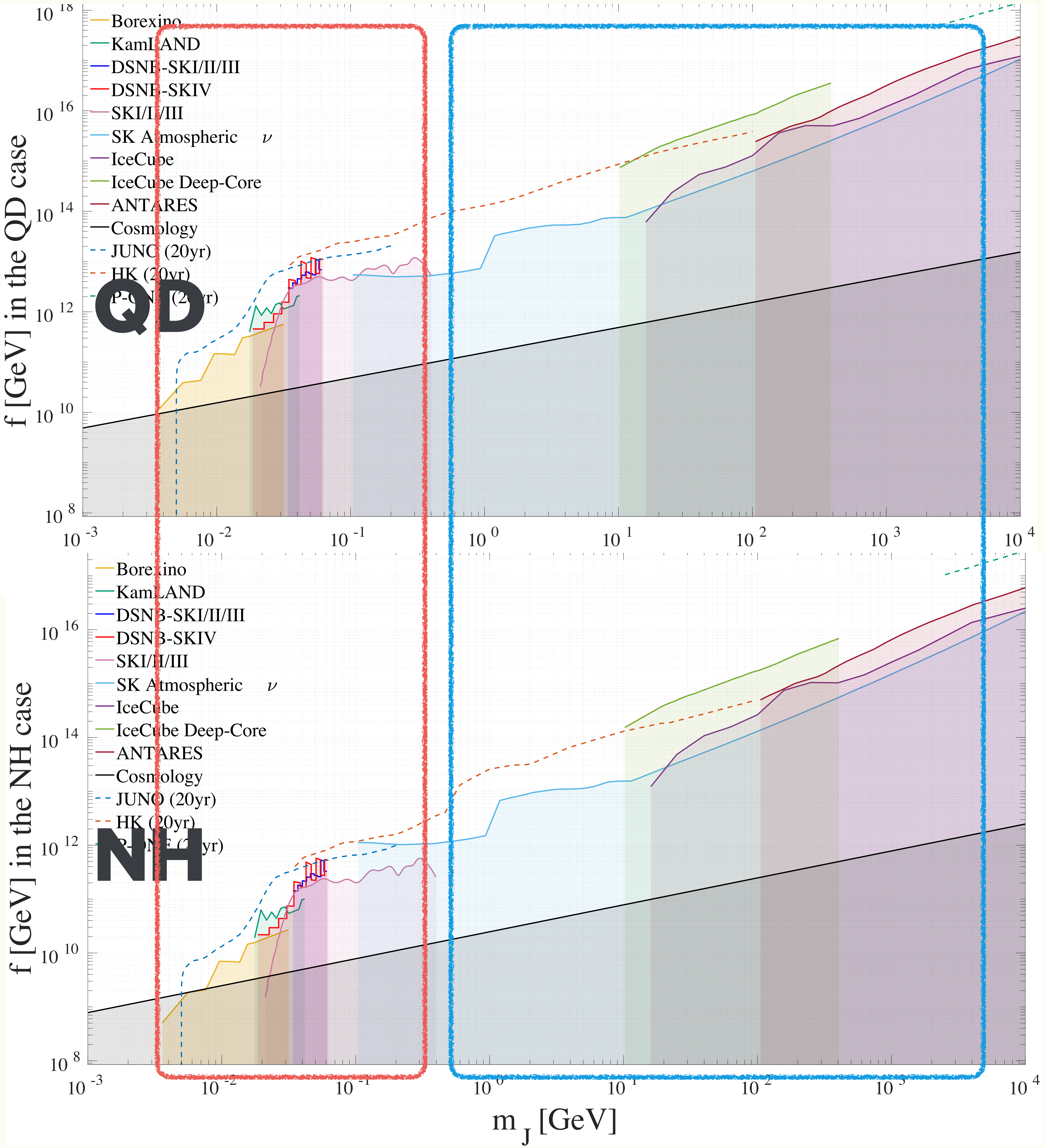
- $f > 10^{13}$ GeV at $m_J \sim 1$ GeV



Dependence on the mass hierarchy



- $m_J \geq \mathcal{O}(1\,\mathrm{GeV})$: $\nu_\mu, \nu_\tau \rightarrow \times (2.5 \times 10^{-1})$
  - $\Gamma(J \rightarrow 2\nu) \propto \Sigma m_i^2$ gets smaller (NH)
- $m_J \lesssim \mathcal{O}(1\,\mathrm{GeV})$: $\nu_e \rightarrow \times (5 \times 10^{-2})$
  - $\Gamma(J \rightarrow 2\nu_1) = 0$ 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 $\mathrm{U}(1)_L$, which explains $M_R \neq 0$
  - Stable particle: $\Gamma \leq (10^{17}\,\mathrm{sec})^{-1} \quad \mathrm{at} \quad f \sim 10^9\,\mathrm{GeV}$
- Anticipated constraints from future detectors
  - VEV of U(1)L breaking: $f > 10^{13}\,\mathrm{GeV}$ at $m_J \sim 100\,\mathrm{MeV}$
  - Constraints depend on mass hierarchy and flavor sensitivity