Updated Constraints and Future Prospects on Majoron Dark Matter

Based on [arXiv: 2304.04430] with Kensuke Akita(IBS)

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Neutrino mass: Dirac or Majorana?

- Dirac Neutrinos (Higgs Mechanism)

$$\mathscr{L} = -\frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D^T & 0\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix} + \mathrm{h.c.} \qquad m_i = m_D \sim 10^{-2}\,\mathrm{eV}$$

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

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M_R may be explained by the spontaneous Global U(1)L symmetry breaking

Majoron model

Singlet Majoron Model

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

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

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

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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

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

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

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

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

Singlet Majoron Model

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

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

$$m_D = \frac{\lambda_D v}{\sqrt{2}}$$

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

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

Since $f \gg v$,

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

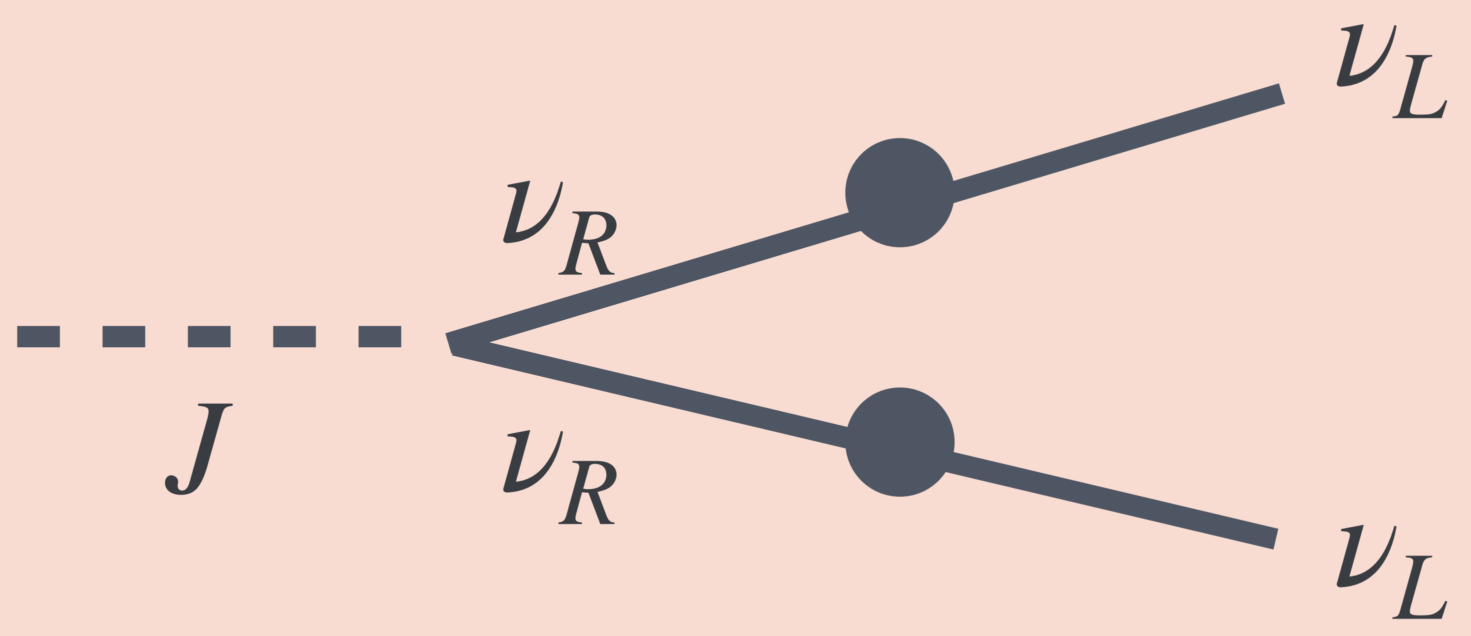
→Seesaw mechanism works!

Majoron as a pNG boson of U(1)L

Assume

$m_{1,2,3} \ll m_J \sim \mathcal{O}(\mathrm{MeV} - \mathrm{TeV}) \ll m_{4,5,6}$

in our work



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

- Stability
  - Interacts only with neutrinos at tree-level
  - Suppressed by $1/f$

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

- Least constrained since they couple only with neutrinos at tree-level.

A nice DM candidate to be tested through neutrino observations

Majoron Decay into neutrinos: $J \to 2\nu_i$

- Consider DM in Milky Way → Line-shaped signal

$$\frac{d\Phi}{dE} \propto \boxed{\delta_D\left(E - \frac{m_J}{2}\right)}$$

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- Decay rate in mass basis

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

1. Suppressed by vev f
2. Proportional to m_i^2

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

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- Extreme case: Quasi-Degenerate(QD) neutrino mass: $m_1 \sim m_2 \sim m_3$, $\sum m_i^2 \sim 0.1\,\mathrm{eV}^2$

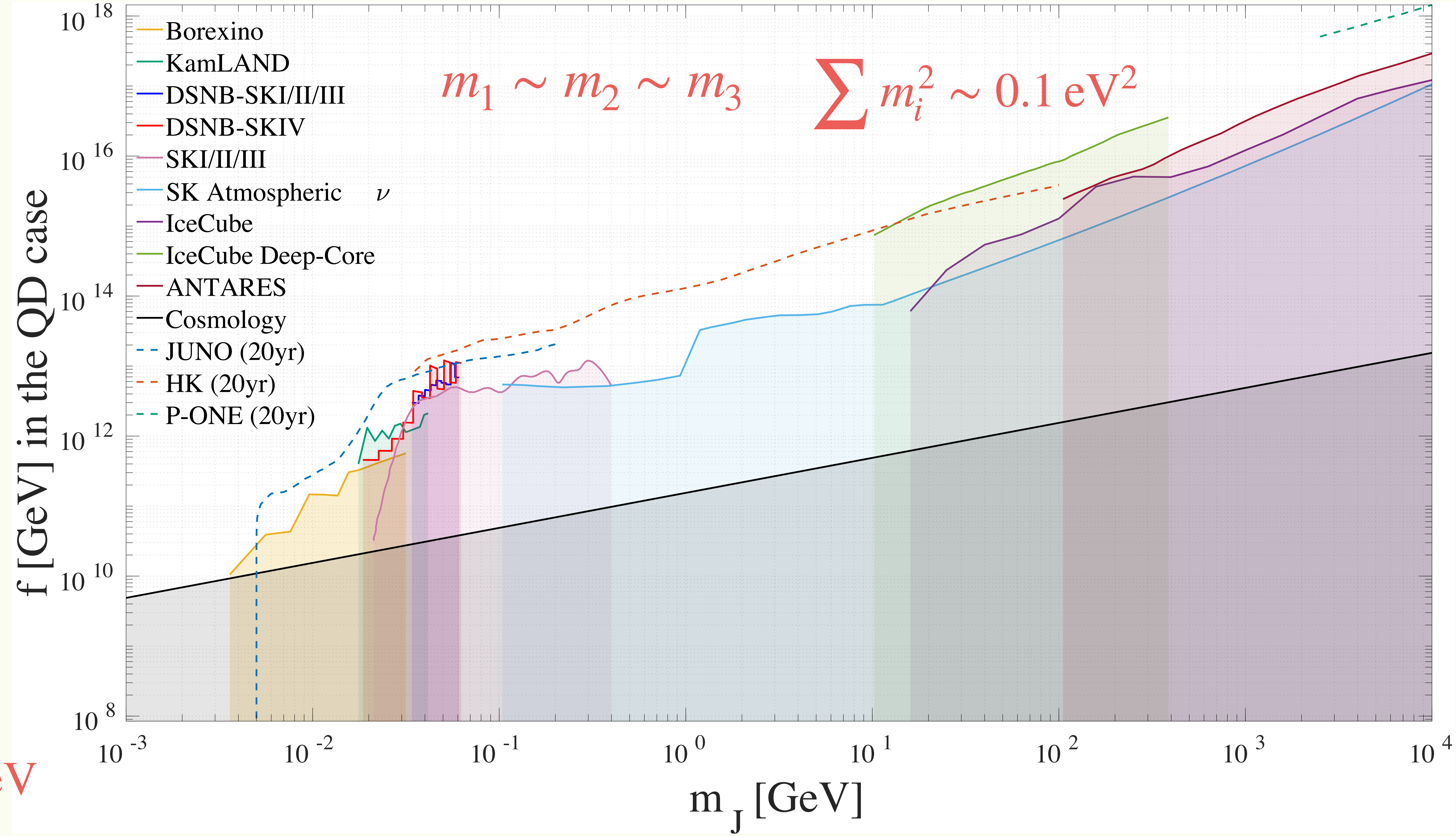
Constraint on Majoron Model(QD)

- 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



Majoron Decay into neutrinos: $J \to 2\nu_i$

- Consider DM in Milky Way → Line-shaped signal $\quad \dfrac{d\Phi}{dE} \propto \delta_D\left(E - \dfrac{m_J}{2}\right)$
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$$\mathscr{L}_{\text{int}} = -\frac{iM_R}{2f} J\overline{\nu_R^c}\nu_R + \text{h.c.} = \sum_{i,j=1}^{3} \frac{i\lambda_{ij}J}{2}\,\overline{n_i}\gamma_5 n_j, \quad \lambda_{ij} = \frac{m_i\delta_{ij}}{f}$$

1. Suppressed by vev f
2. Less decay into lighter neutrino

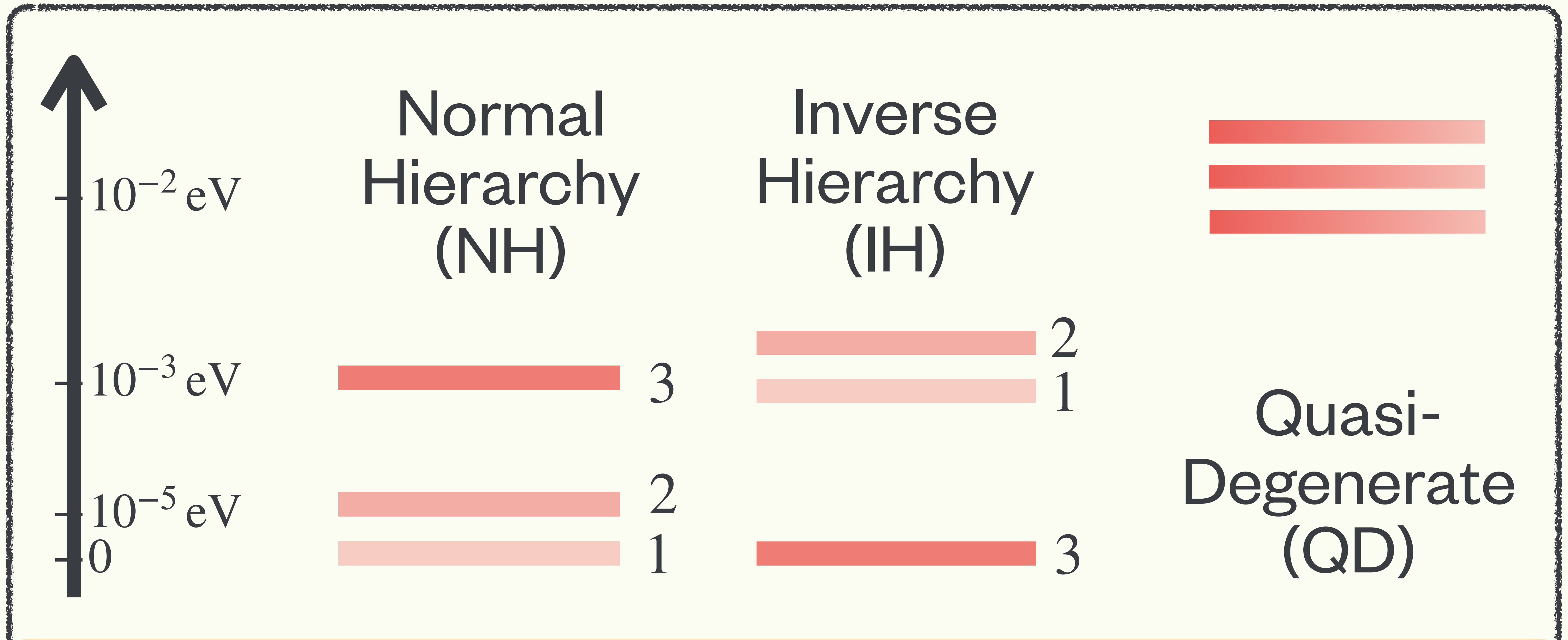
$$\Gamma(J \to 2\nu_i) = \frac{m_J}{16\pi f^2} m_i^2$$

- Detection in flavor basis Eg.) Inverse beta decay $\bar{\nu}_e + p \to n + e^+$ @ MeV:

1. PMNS matrix is taken into account

$$\boxed{\Gamma(\text{IBD}) = P(\nu_i \to \overline{\nu_e})\Gamma(J \to \nu\nu)} \simeq \frac{m_J}{16\pi f^2}\sum_{i=1}^{3}|U_{ei}|^2 m_i^2$$

Uncertainty: neutrino mass



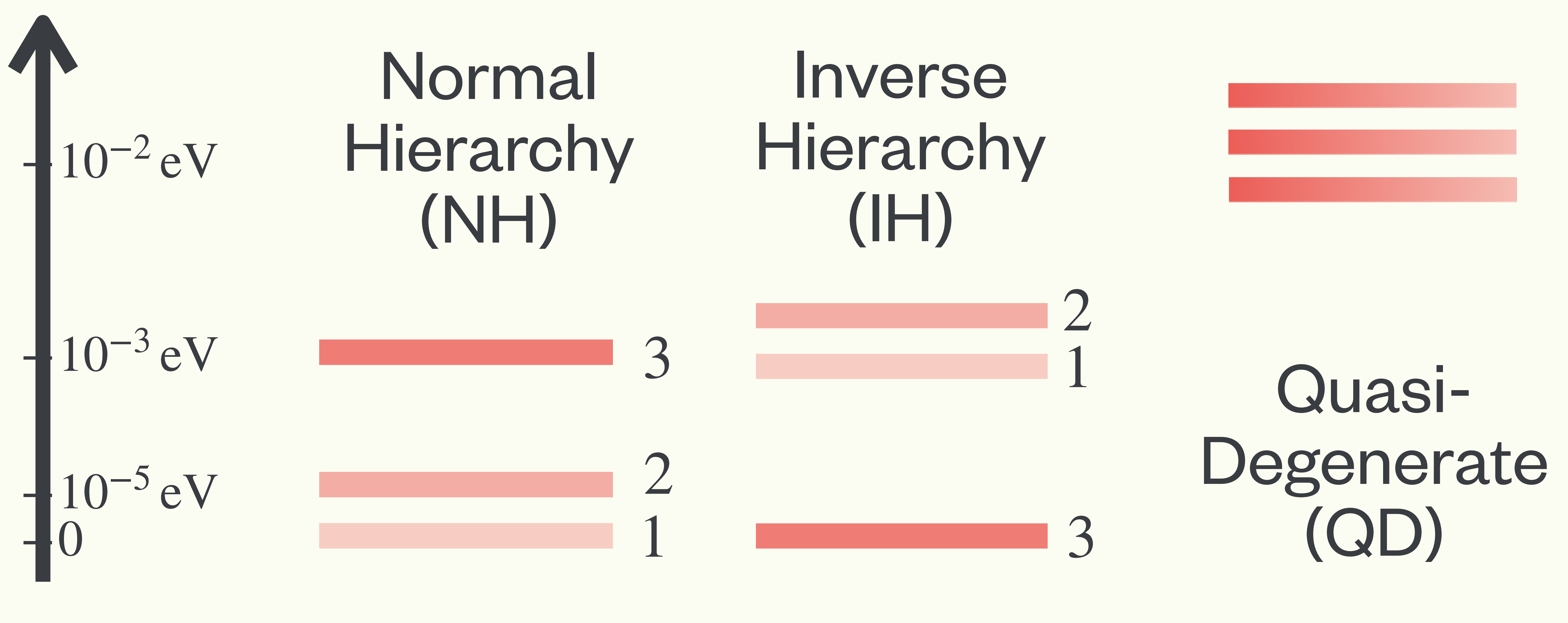
Σm_i^2 (eV^2)	2.6×10^{-3}	4.9×10^{-3}	0.10

Uncertainty: neutrino mass

- Decay rate uncertainty

$$\Gamma(J \to 2\nu) = \frac{m_J}{16\pi f^2} \boxed{\sum_{i=1}^{3} m_i^2}$$

Constraints get weaker in the NH, IH case



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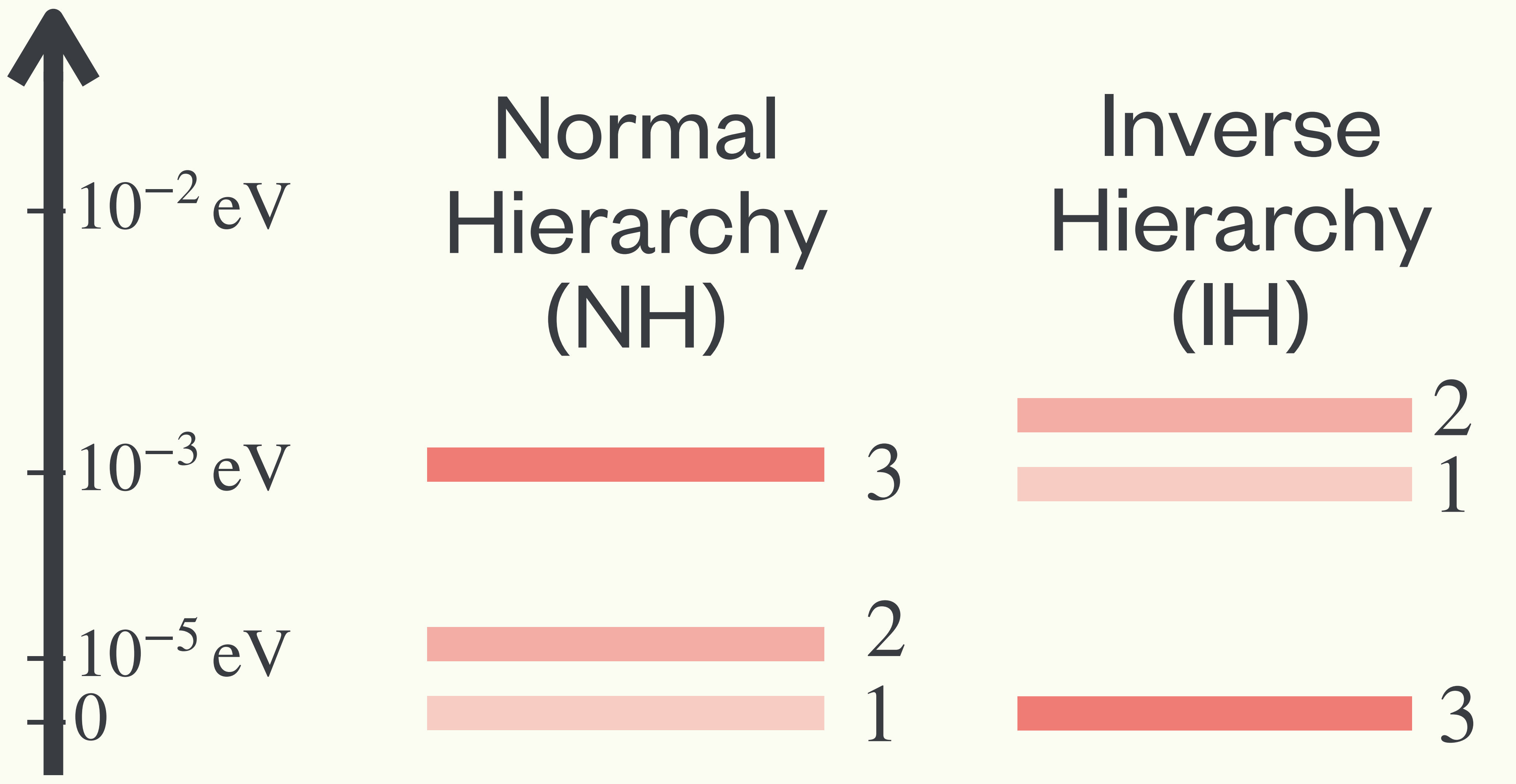
- NH vs IH (@MeV: $\bar{\nu}_e + p \to n + e^+$)

$$\Gamma(\text{IBD}) \simeq \frac{m_J}{16\pi f^2}\sum_{i=1}^{3} |U_{ei}|^2 m_i^2 \propto \frac{\boxed{\alpha_e \sum m_i^2}}{f^2}$$

$|U_{e1}| > |U_{e2}| > |U_{e3}|$

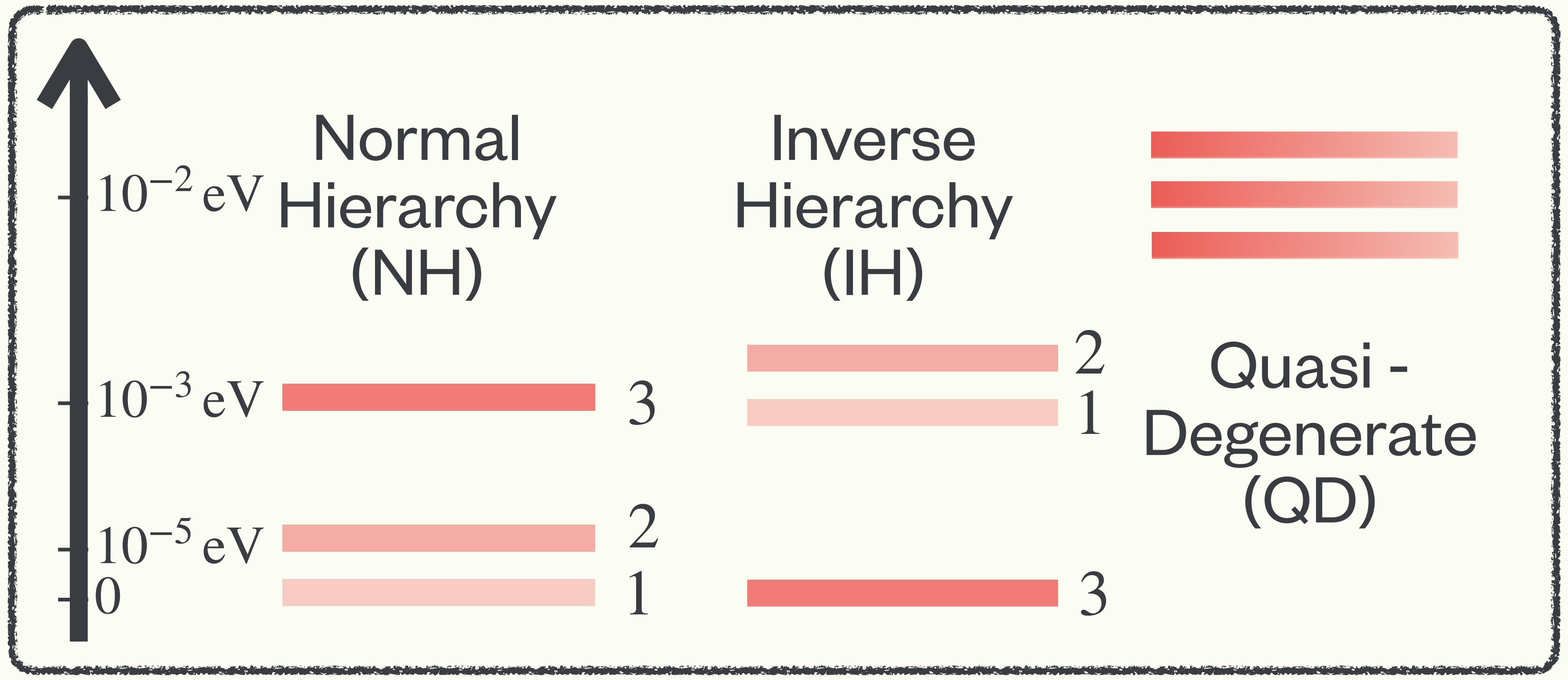
Constraints from IBD is
weak in the NH case

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

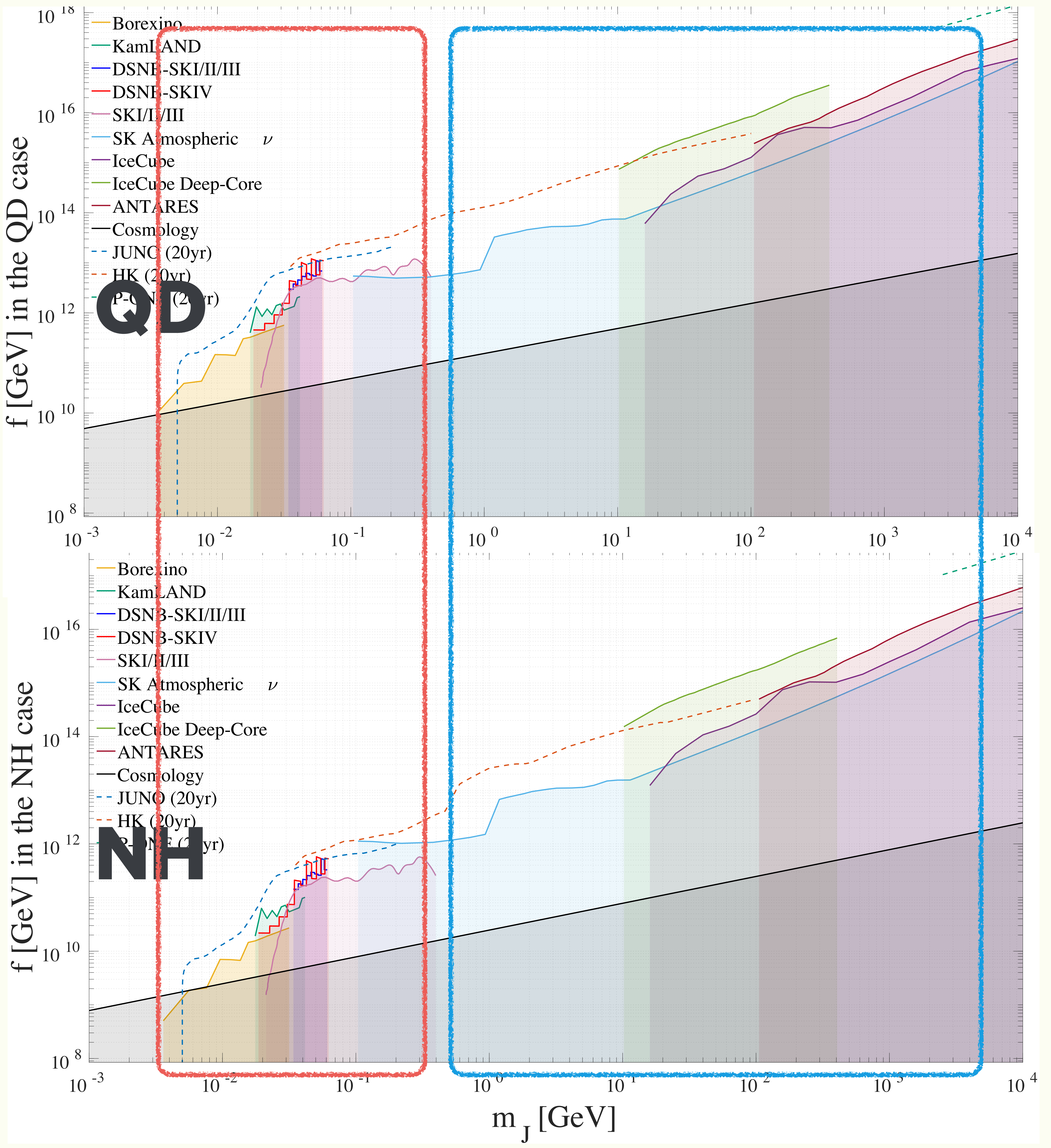


	NH	IH
α_e	0.03	0.48
$\Sigma m_i^2 (\text{eV}^2)$	2.6×10^{-3}	4.9×10^{-3}
$f \propto \sqrt{\alpha_e \Sigma m_i^2}$	8.8×10^{-3}	4.7×10^{-2}

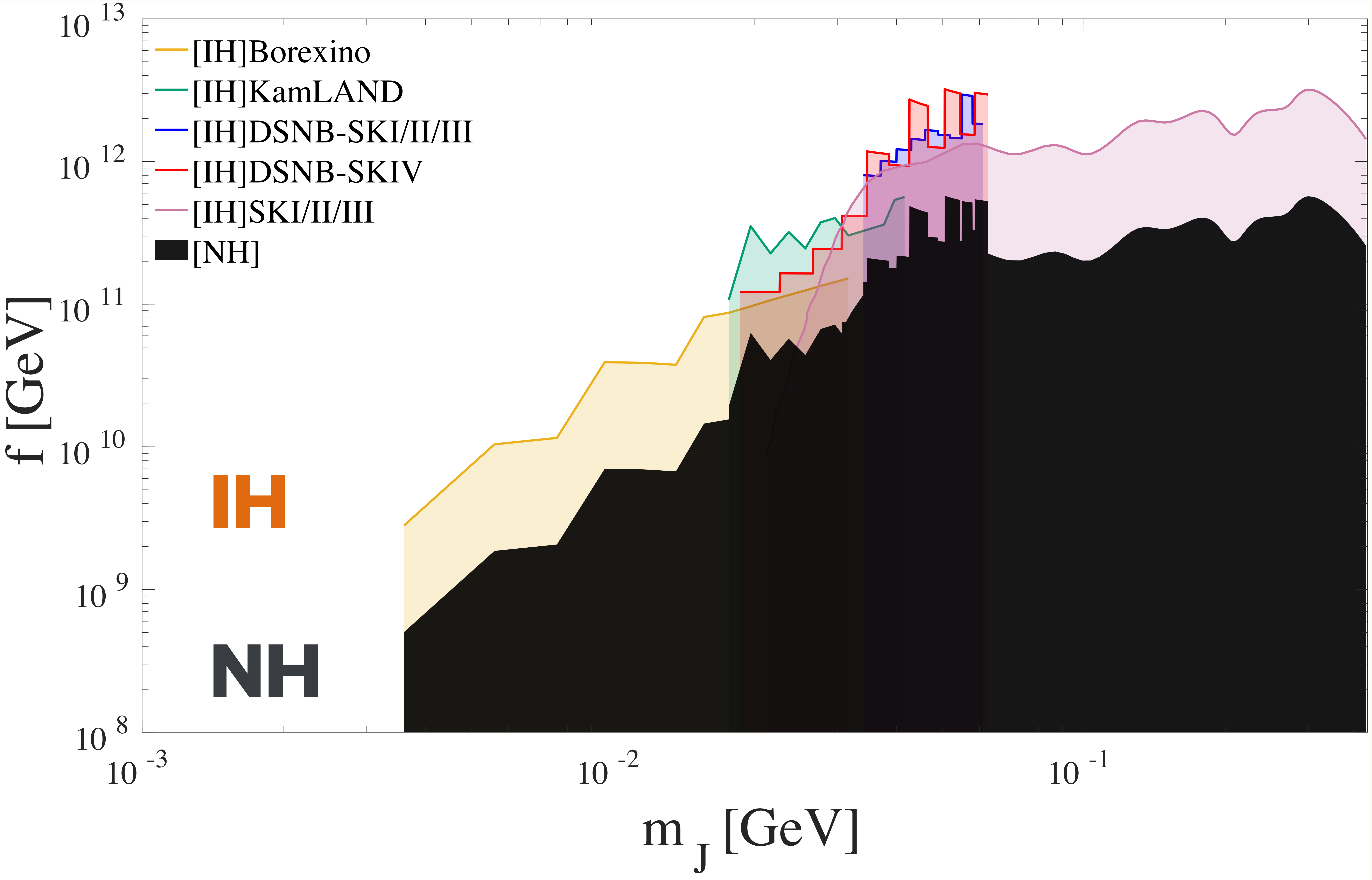
Dependence on the mass hierarchy



- $m_J \geq \mathcal{O}(1\,\mathrm{GeV})$: $\nu_\mu, \nu_\tau \to \times (2.5 \times 10^{-1})$
  - $\Gamma(J \to 2\nu) \propto \Sigma m_i^2$ gets smaller (NH)
- $m_J \lesssim \mathcal{O}(1\,\mathrm{GeV})$: $\nu_e \to \times (5 \times 10^{-2})$
  - $\Gamma(J \to 2\nu_1) = 0$ in the NH case



NH-IH determination (in MeV-GeV)



Summary

1. Majorana mass term of right-handed neutrino may arise from the spontaneous U(1)L breaking.
2. pNG boson associated with U(1)L, Majoron, can be a DM candidate depending on the symmetry breaking energy scale f
3. Neutrino signals from Majoron DM
    1. $f > 10^{12}\,\mathrm{GeV}$ at $m_J \sim 1\,\mathrm{GeV}$ (NH)
    2. Constraints strongly depend on the mass hierarchy