Updated Constraints and Future Prospects on Majoron Dark Matter

Based on JHEP 07 (2023) 132 [arXiv: 2304.04430]
In collaboration with with Kensuke Akita(IBS-CTPU)

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Introduction

Remark: Absolute value symbols may be gone in pdf format.

Neutrino mass: Dirac or Majorana?

- Dirac Neutrinos (Higgs Mechanism)

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

$$m_i = m_D \sim 10^{-2}\,\mathrm{eV}$$

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- Majorana Neutrinos (Seesaw Mechanism)

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$$m_i \sim m_D^2/M_R \sim 10^{-2}\,\mathrm{eV}$$

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

Neutrino mass: Dirac or Majorana?

- Dirac Neutrinos (Higgs Mechanism)

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

M_R may be explained by the spontaneous global Lepton # 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

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

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

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

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Singlet Majoron Model

U(1)$_L$ Lepton number symmetry

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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

Singlet Majoron Model

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

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

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

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

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

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

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

Since $f \gg v$,

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

→Seesaw mechanism works!

Singlet Majoron Model

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

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

Explicit Symmetry Breaking (ESB) term

Φ: SM Higgs

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

Σ: new singlet scalar

- Majorons are massive (p-NG boson) in our work

→ A good Dark Matter (DM) candidate!

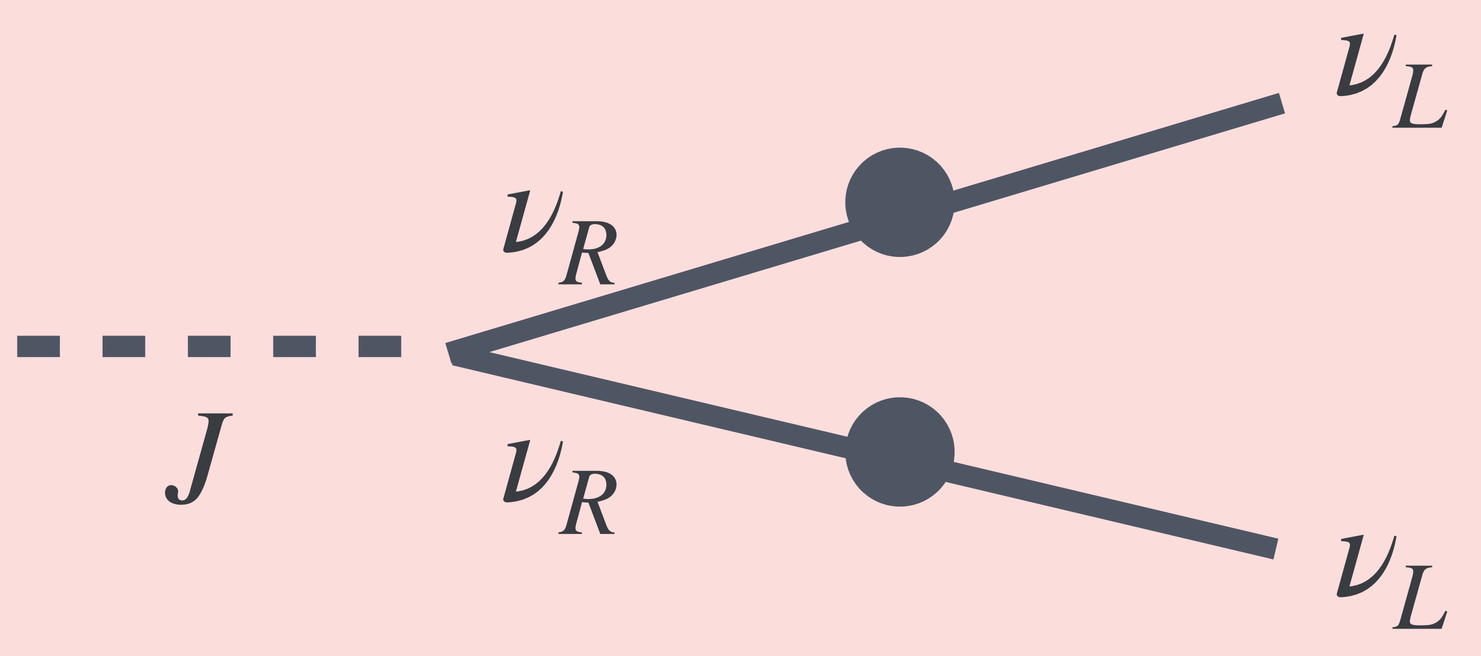
- Various ESB terms are discussed to explain DM production mechanism, mass mechanism....
- For general discussion, we do not specify ESB terms

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



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

- 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

Constraints from Majoron Decay into neutrinos

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

- Consider DM in Milky Way → Line-shaped signal

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

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

- Consider DM in Milky Way → Line-shaped signal $\frac{d\Phi}{dE} \propto \delta_D\left(E - \frac{m_J}{2}\right)$

- Decay rate in mass basis

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

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

$$\Gamma(J \to 2\nu_i) = \frac{m_J}{16\pi f^2} m_i^2 = 0 \ (\text{for } m_i = 0)$$

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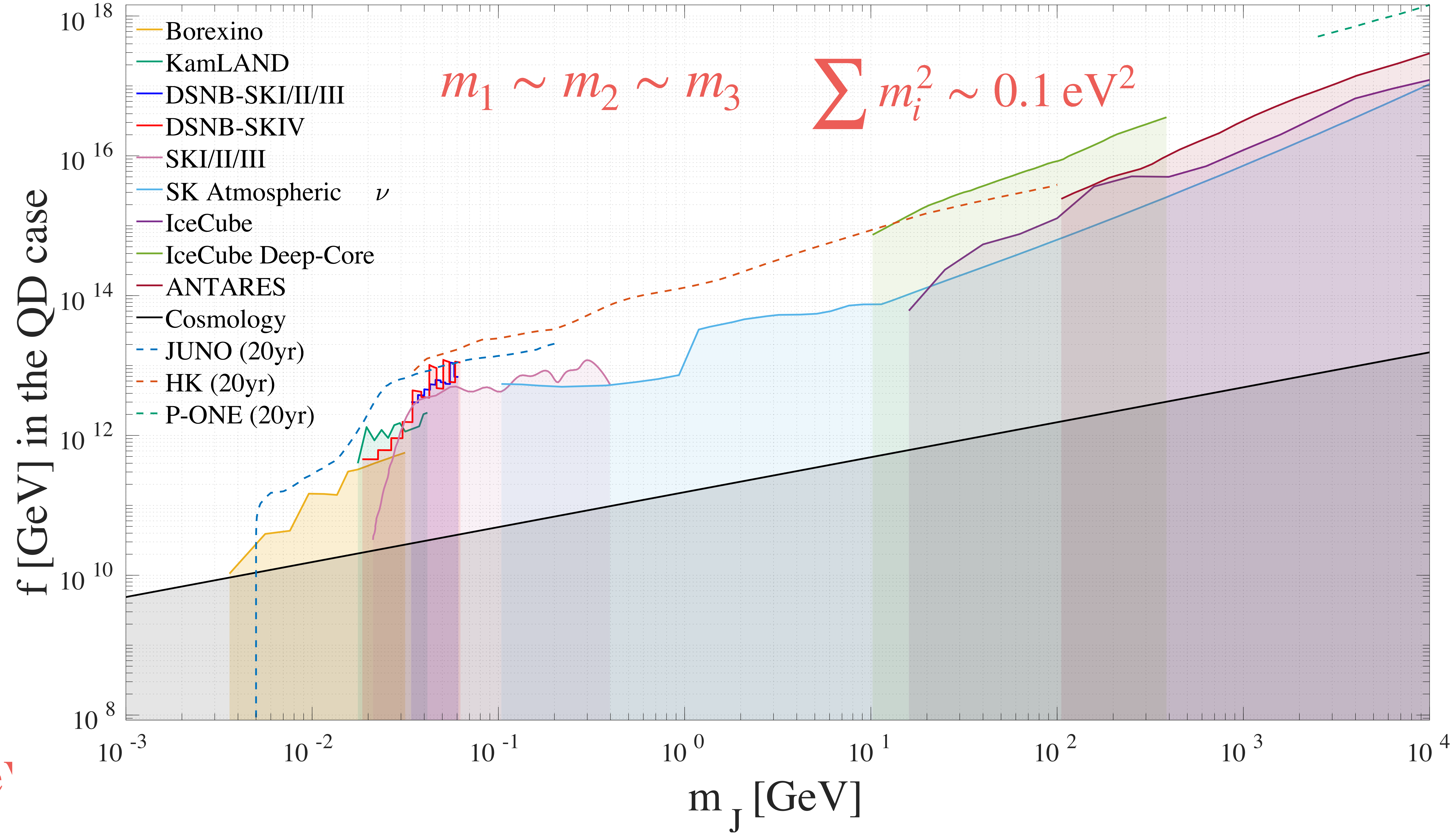
- Extreme case: Quasi-Degenerate(QD) neutrino mass: $m_1 \sim m_2 \sim m_3\,,\quad \sum m_i^2 \sim 0.1\,{\rm eV}^2$

Corresponding to $\sum m_i \sim 0.5\,{\rm eV}$

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 $\frac{d\Phi}{dE} \propto \delta_D\left(E - \frac{m_J}{2}\right)$
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1. Suppressed by f
2. Proportional to m_i^2

$$\Gamma(J \to 2\nu_i) = \frac{m_J}{16\pi f^2} m_i^2 \quad = 0 \;(\text{for } m_i = 0)$$

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

1. PMNS matrix is taken into account

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

Uncertainty: neutrino mass

	NH	IH	QD
set	$m_1 = 0$	$m_3 = 0$	$\Sigma m_i \sim 0.5\,\text{eV}$
Σm_i^2 (eV^2)	2.6×10^{-3}	4.9×10^{-3}	0.10

Uncertainty: neutrino mass

- Decay rate uncertainty

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

Constraints get weaker in the NH, IH case

	Normal Hierarchy (NH)	Inverse Hierarchy (IH)	Quasi-Degenerate (QD)
set	$m_1 = 0$	$m_3 = 0$	$\Sigma m_i \sim 0.5$ eV
Σm_i^2 (eV^2)	2.6×10^{-3}	4.9×10^{-3}	0.10

Uncertainty: neutrino mass

- Decay rate uncertainty

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

Constraints get weaker
in the NH, IH case

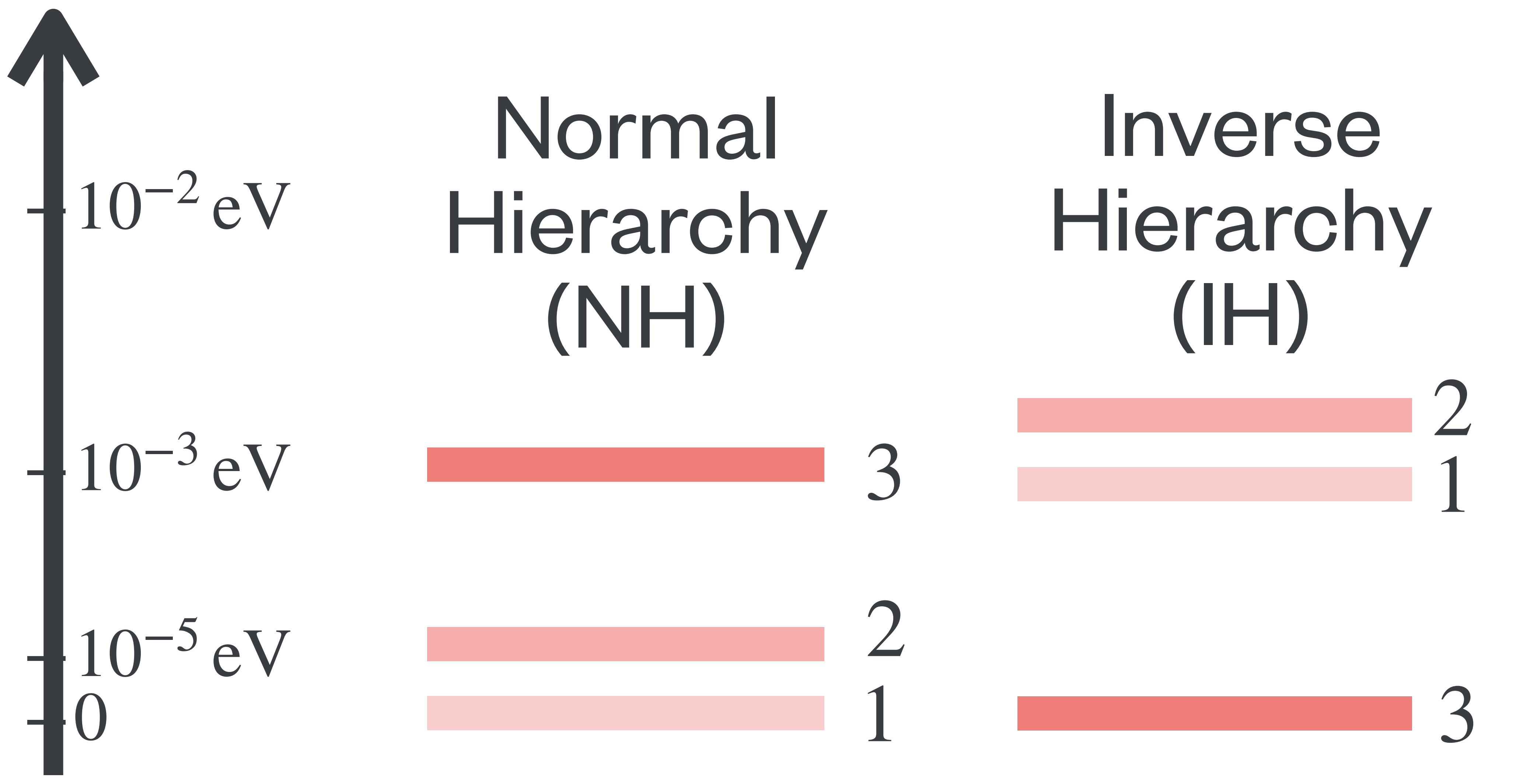
- NH vs IH (@MeV: $\bar{\nu}_e + p \to n + e^+$)

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

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

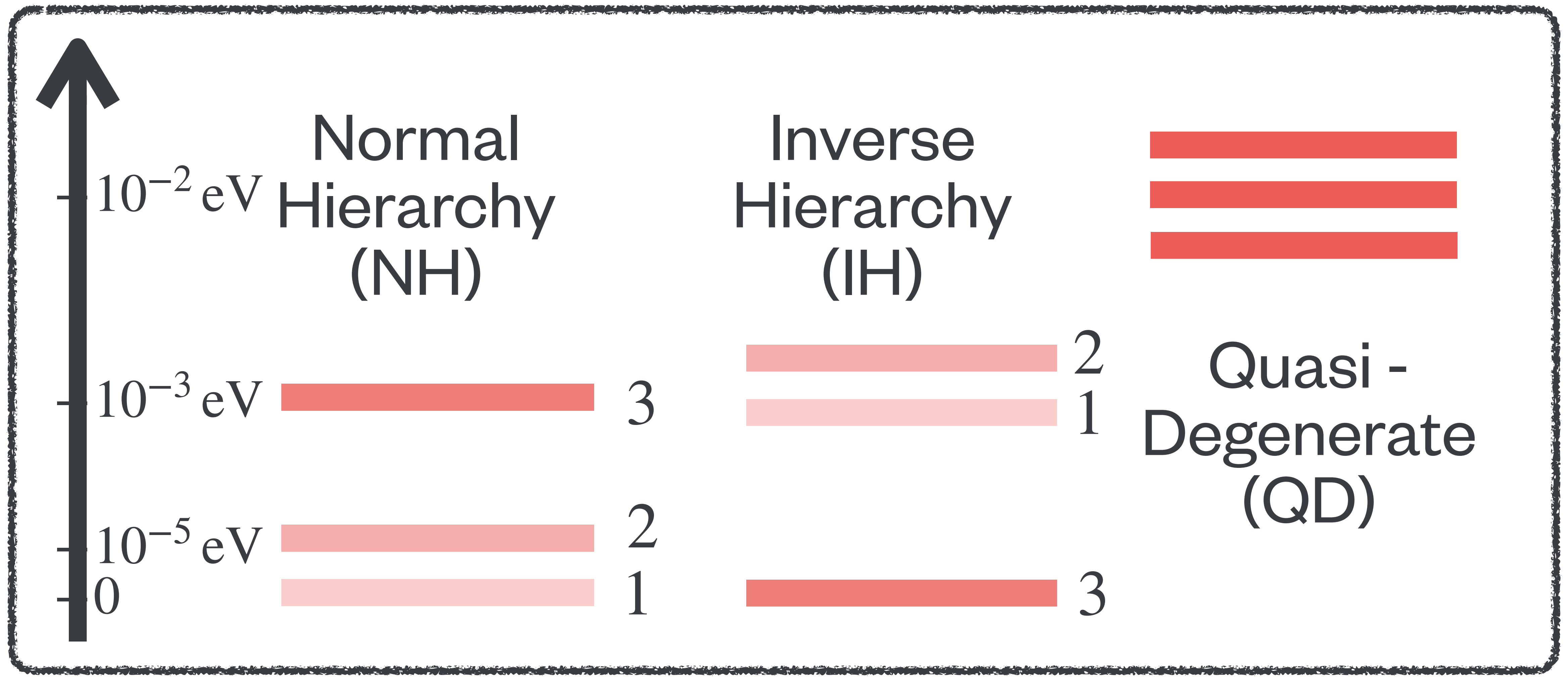
$$\alpha_e = \frac{\sum_{i=1}^{3} U_{ei}{}^2 m_i^2}{\sum_{i=1}^{3} m_i^2}$$

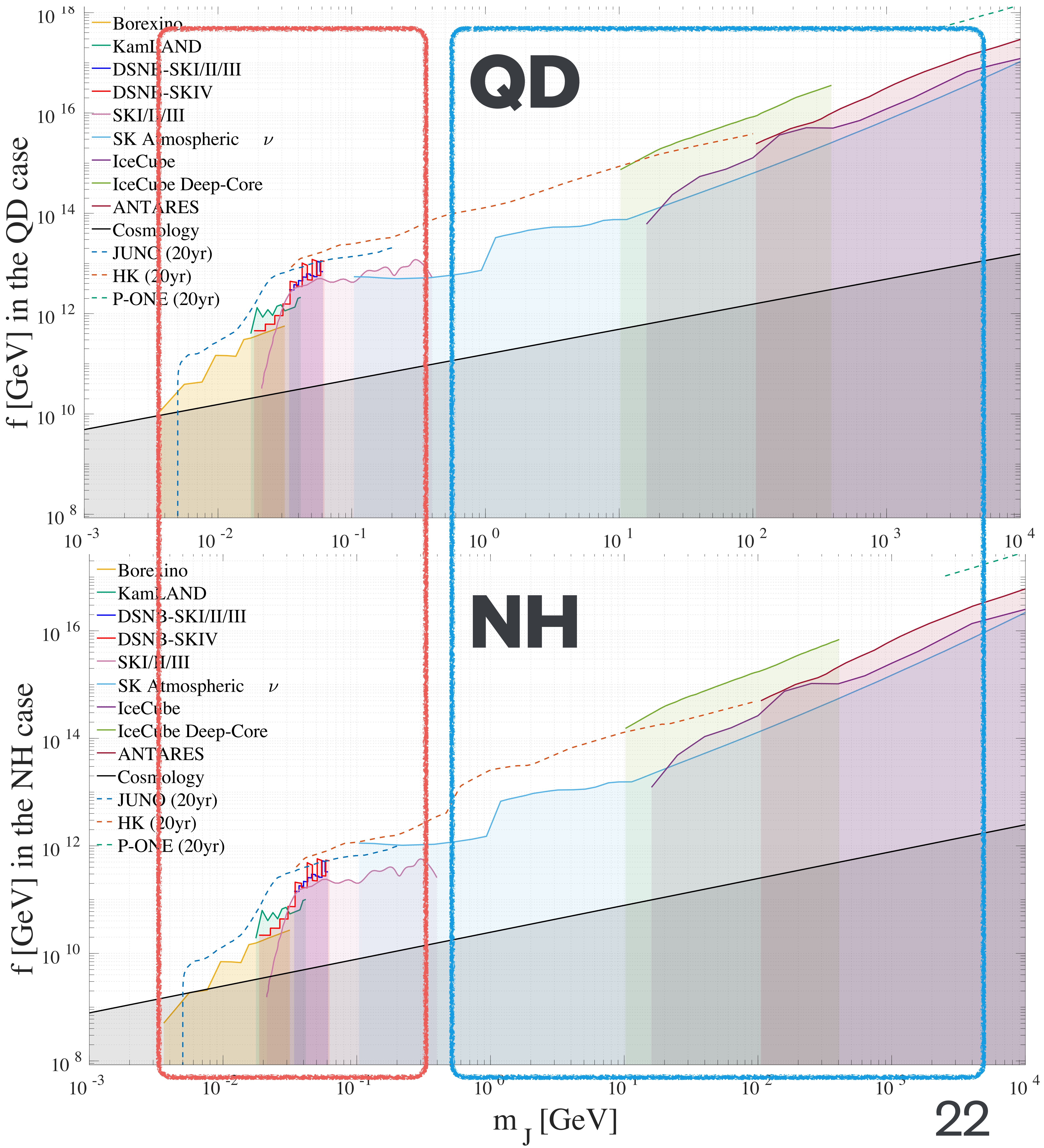
Constraints from IBD is
weak in the NH case



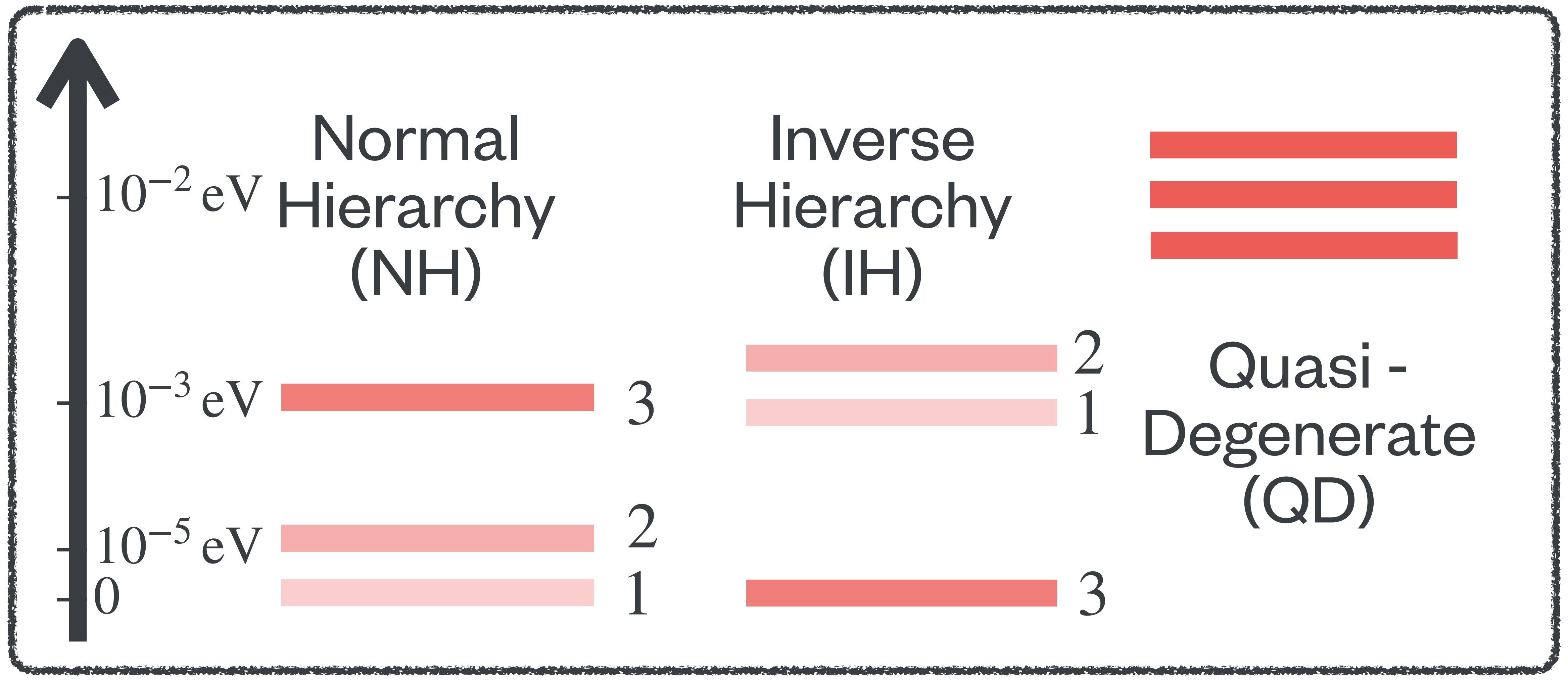
α_e	0.03	0.48
$\Sigma m_i^2 (\mathrm{eV}^2)$	2.6×10^{-3}	4.9×10^{-3}
$f \propto \sqrt{\alpha_e \Sigma m_i^2}$	8.8×10^{-3}	4.7×10^{-2}

Dependence on the mass hierarchy

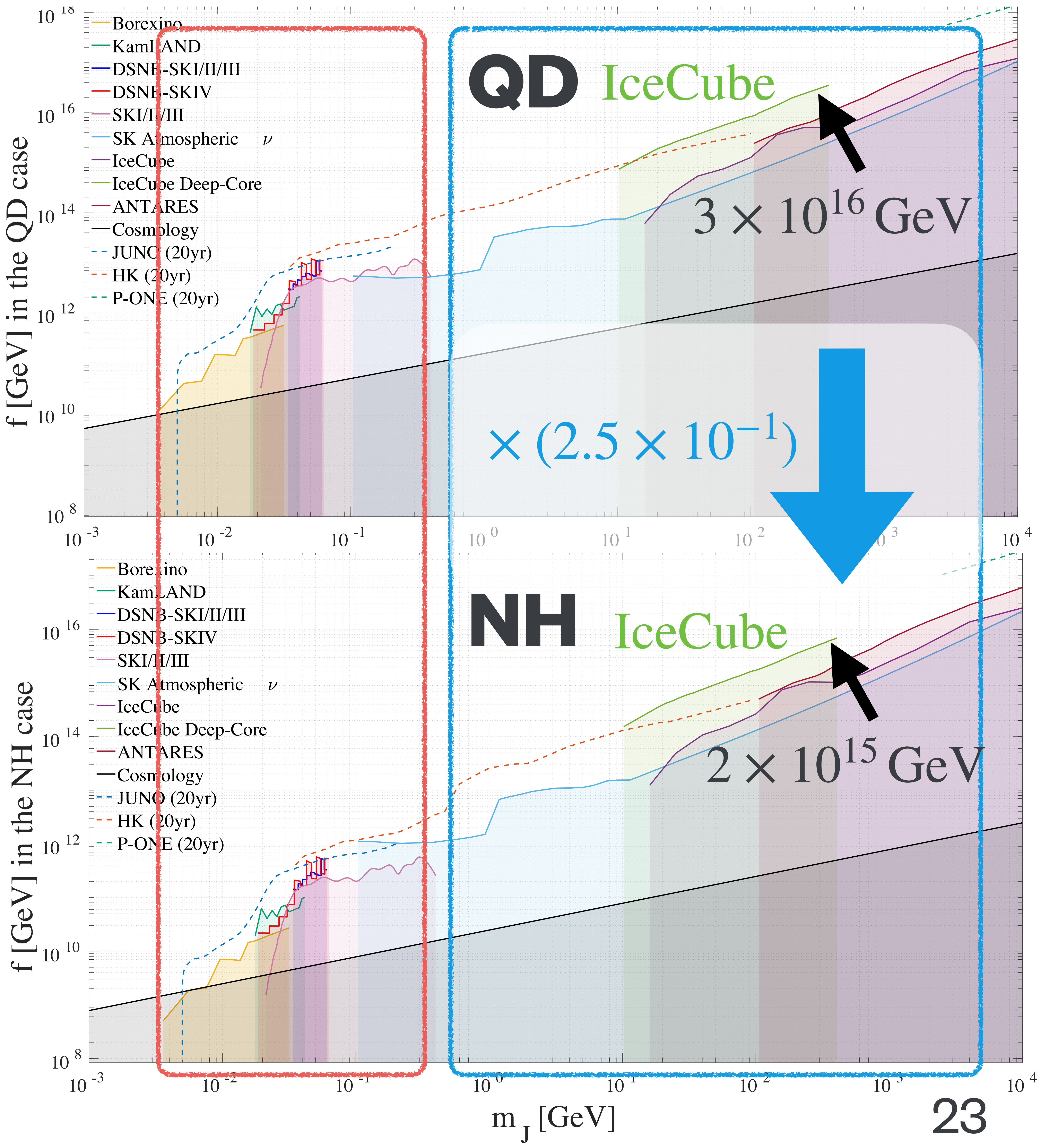




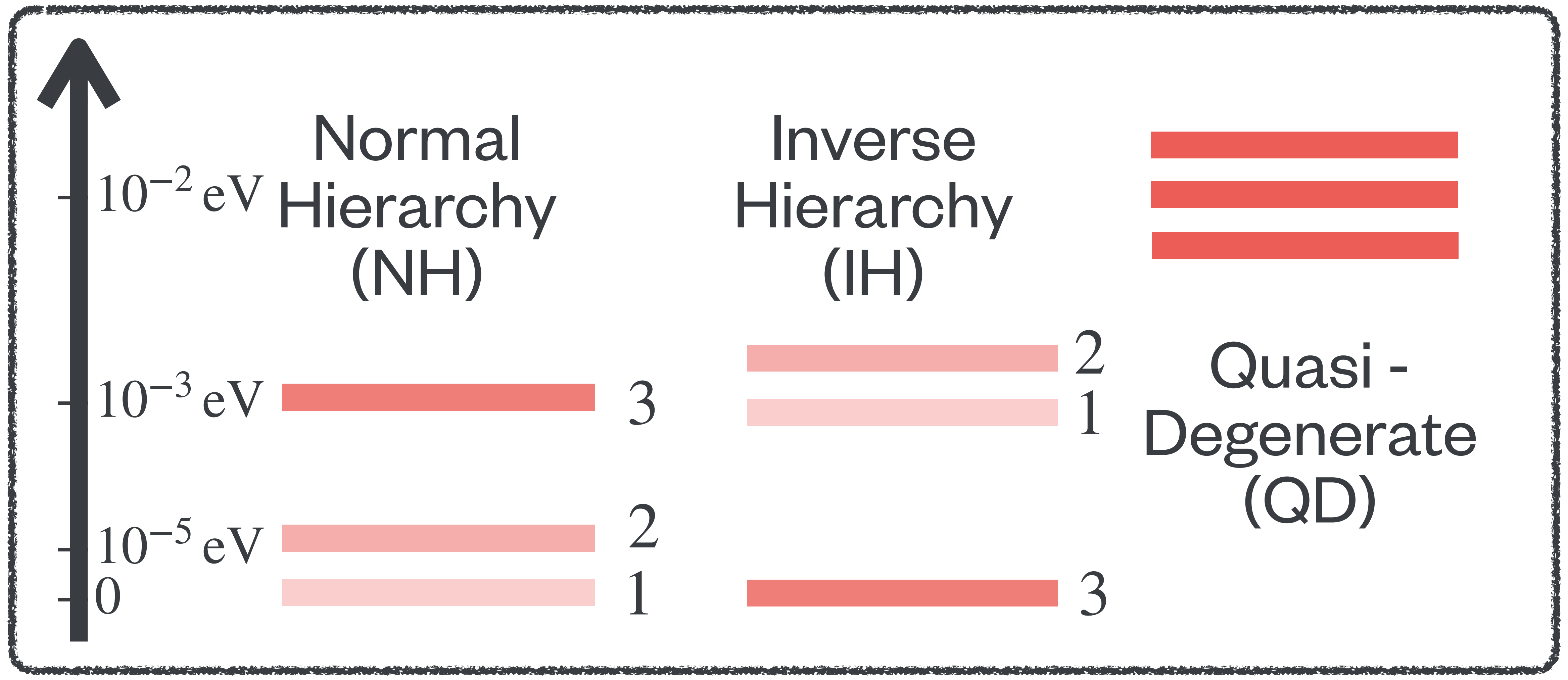
Dependence on the mass hierarchy



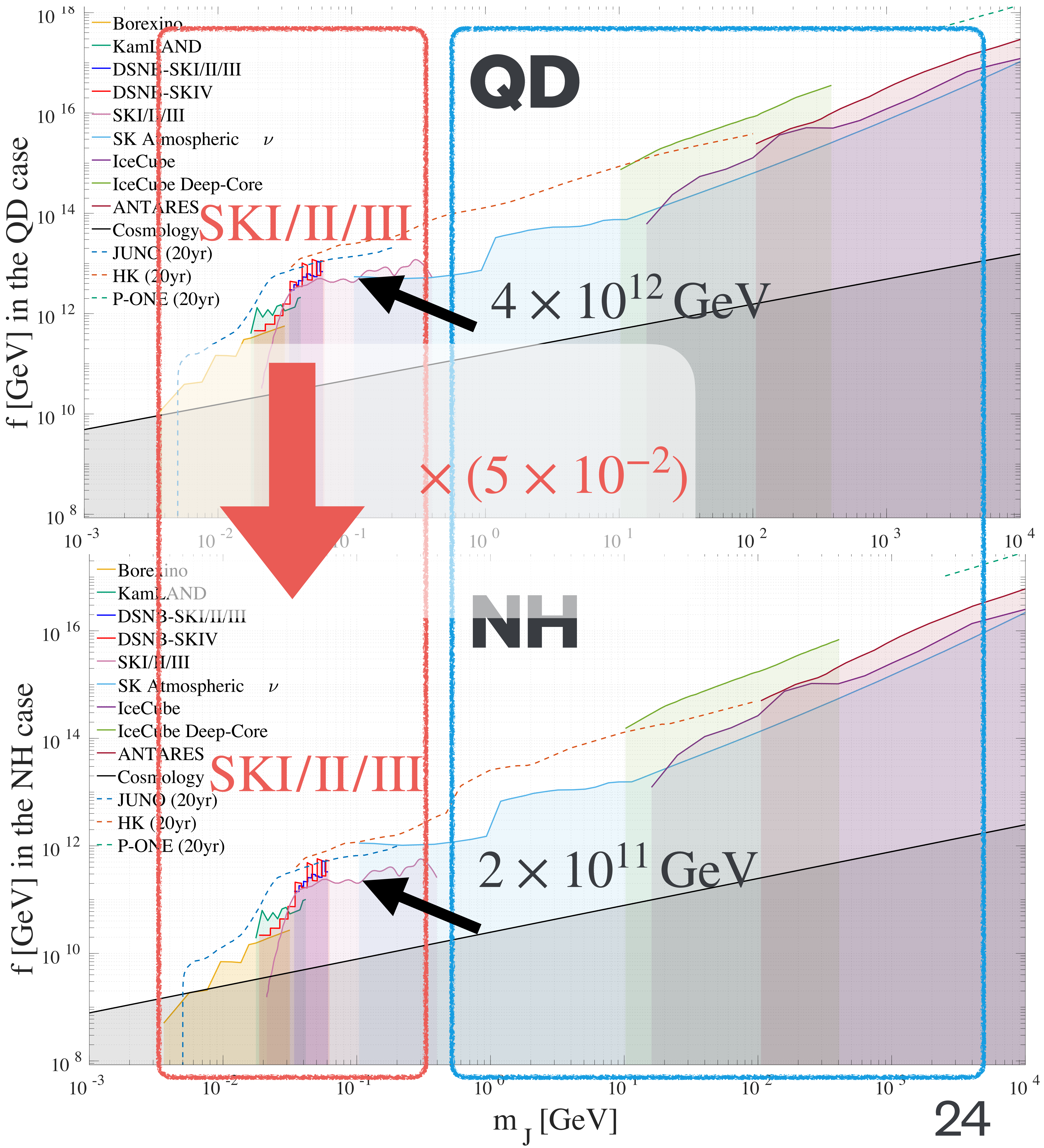
- $m_J \geq \mathcal{O}(1\,\mathrm{GeV})$: $\nu_\mu, \nu_\tau \to \times (2.5 \times 10^{-1})$
  - $\Gamma(J \to 2\nu) \propto \Sigma m_i^2$ gets smaller (NH)



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



NH-IH determination (in MeV-GeV)

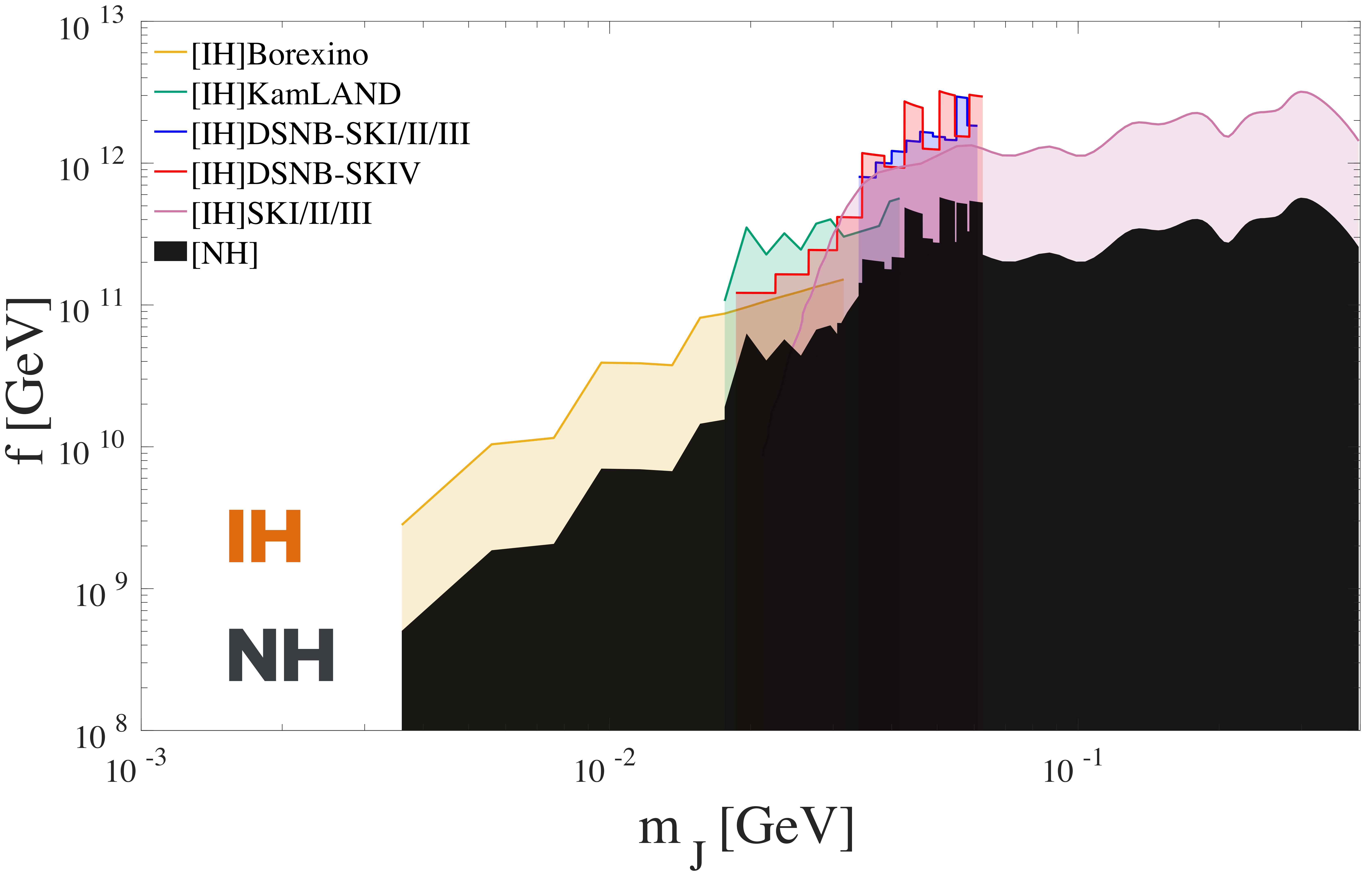
- DM mass is determined by the peak position

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

- Energy scale f is determined by the flux

$$\Phi \propto \Gamma(m_J, f)$$

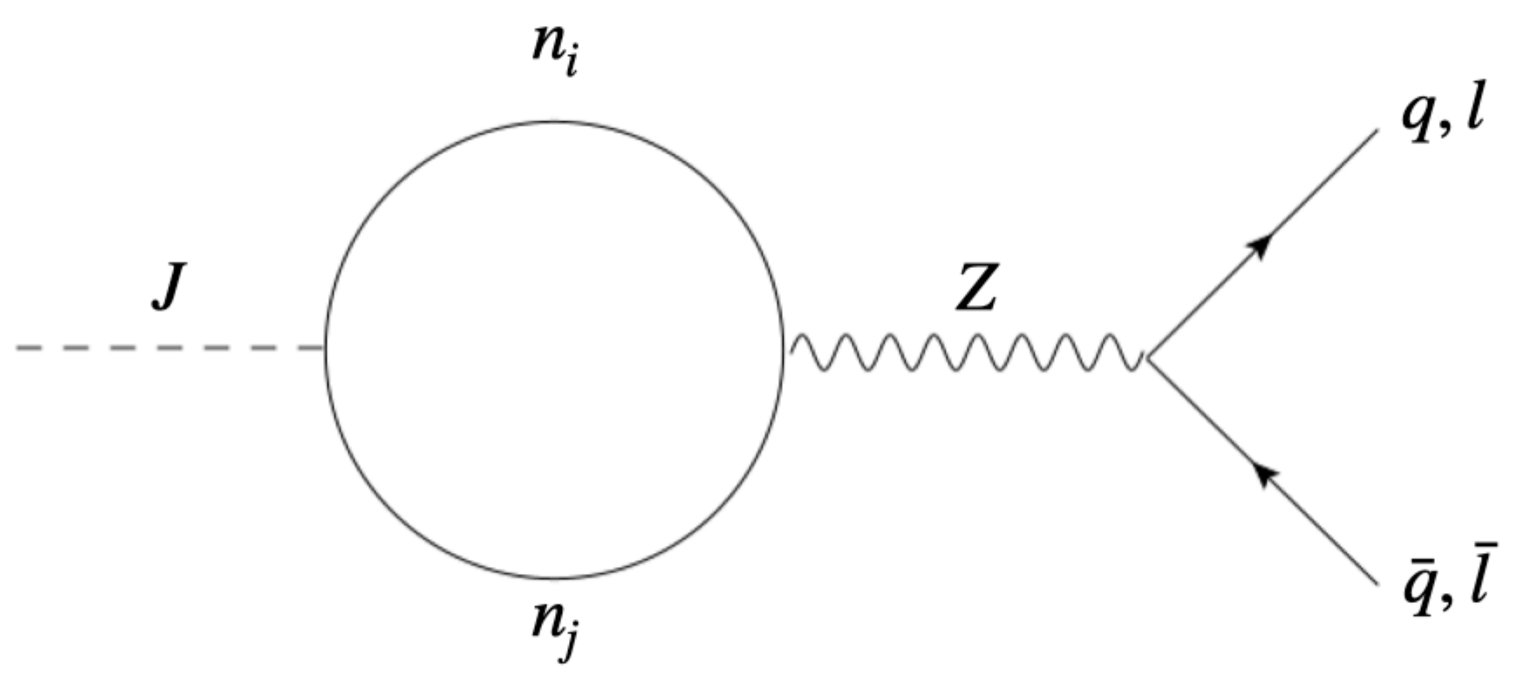
Once we detect a signal in IH region, NH with $m_1 = 0$ is ruled out!

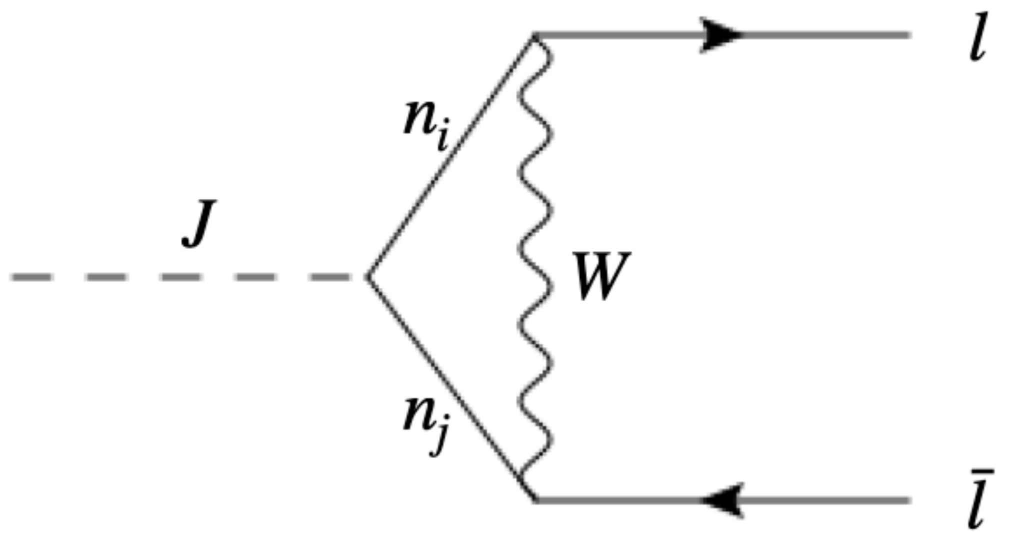


Constraints from Majoron Decay into Visible signals

Visible signals from Majoron DM

- Decay channels into charged fermions (one-loop)





Note that
$m_i \sim \frac{m_D^2}{M_R} = \frac{\lambda_D^2 v^2}{\lambda_R f}$
cannot determine m_D

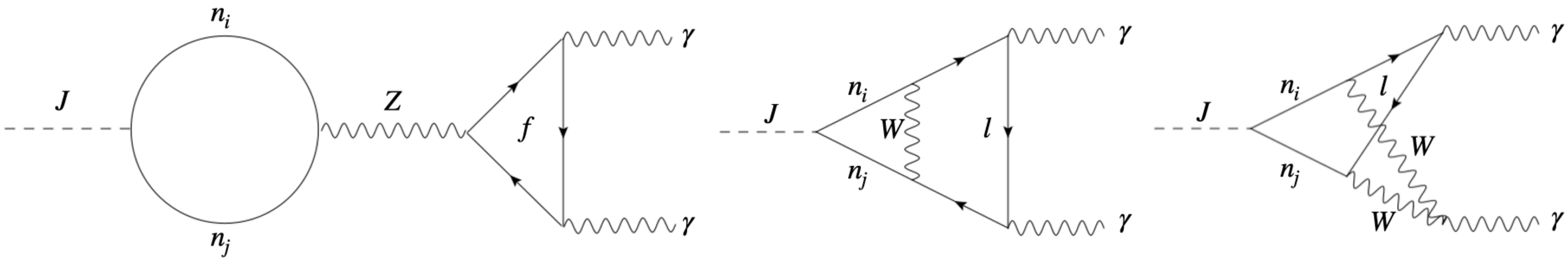
$$\Gamma(J \to q\bar{q}) \simeq \frac{3m_J}{8\pi}\left|\frac{m_q}{8\pi^2 v}T_3^q \mathrm{tr}K\right|^2$$

$$K = \frac{m_D m_D^\dagger}{vf} = \lambda_D \lambda_D^\dagger \frac{v}{f}$$

$$\Gamma(J \to l\bar{l}') \simeq \frac{m_J}{8\pi}\left(\left|\frac{m_l + m_{l'}}{16\pi^2 v}(\delta_{ll'}T_3^l \mathrm{tr}K + K_{ll'})\right|^2 + \left|\frac{m_l - m_{l'}}{16\pi^2 v}K_{ll'}\right|^2\right)$$

Visible signals from Majoron DM

- Decay channels into photons (two-loop)



$$\Gamma(J \to 2\gamma) \simeq \frac{\alpha^2}{4096\pi^7}\frac{m_J^3}{v^2}\ K'^{\ 2}$$

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

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

Branching Ratio: (Visible)/(Neutrino)

- Neutrino signals: determined by f, m_J, m_ν

$$\Gamma(J \to 2\nu) \sim 10^{-21}\,\mathrm{GeV}^3 \frac{1}{f^2}\left(\frac{m_J}{1\,\mathrm{GeV}}\right)\left(\frac{m_\nu^2}{0.1\,\mathrm{eV}^2}\right)$$

- Visible signals: determined by $f, m_J\ \lambda_D$

$$\Gamma(J \to 2\gamma) \sim 10^{-24}\,\mathrm{GeV}^3 \frac{1}{f^2}\left(\frac{\lambda_D}{10^{-4}}\right)^4\left(\frac{m_J}{1\,\mathrm{GeV}}\right)^3$$

$$\Gamma(J \to 2q, 2l) \sim 10^{-22}\,\mathrm{GeV}^3 \frac{1}{f^2}\left(\frac{\lambda_D}{10^{-4}}\right)^4\left(\frac{m_J}{1\,\mathrm{GeV}}\right)\left(\frac{m_{q,l}}{1\,\mathrm{GeV}}\right)^2$$

- Neutrino mass: $$m_i = \frac{\lambda_D^2 v^2}{\lambda_R f} \sim 10^{-4}\,\mathrm{eV}\left(\frac{\lambda_D}{10^{-4}}\right)^2\left(\frac{10^{-4}}{\lambda_R}\right)\left(\frac{10^{13}\,\mathrm{GeV}}{f}\right)$$

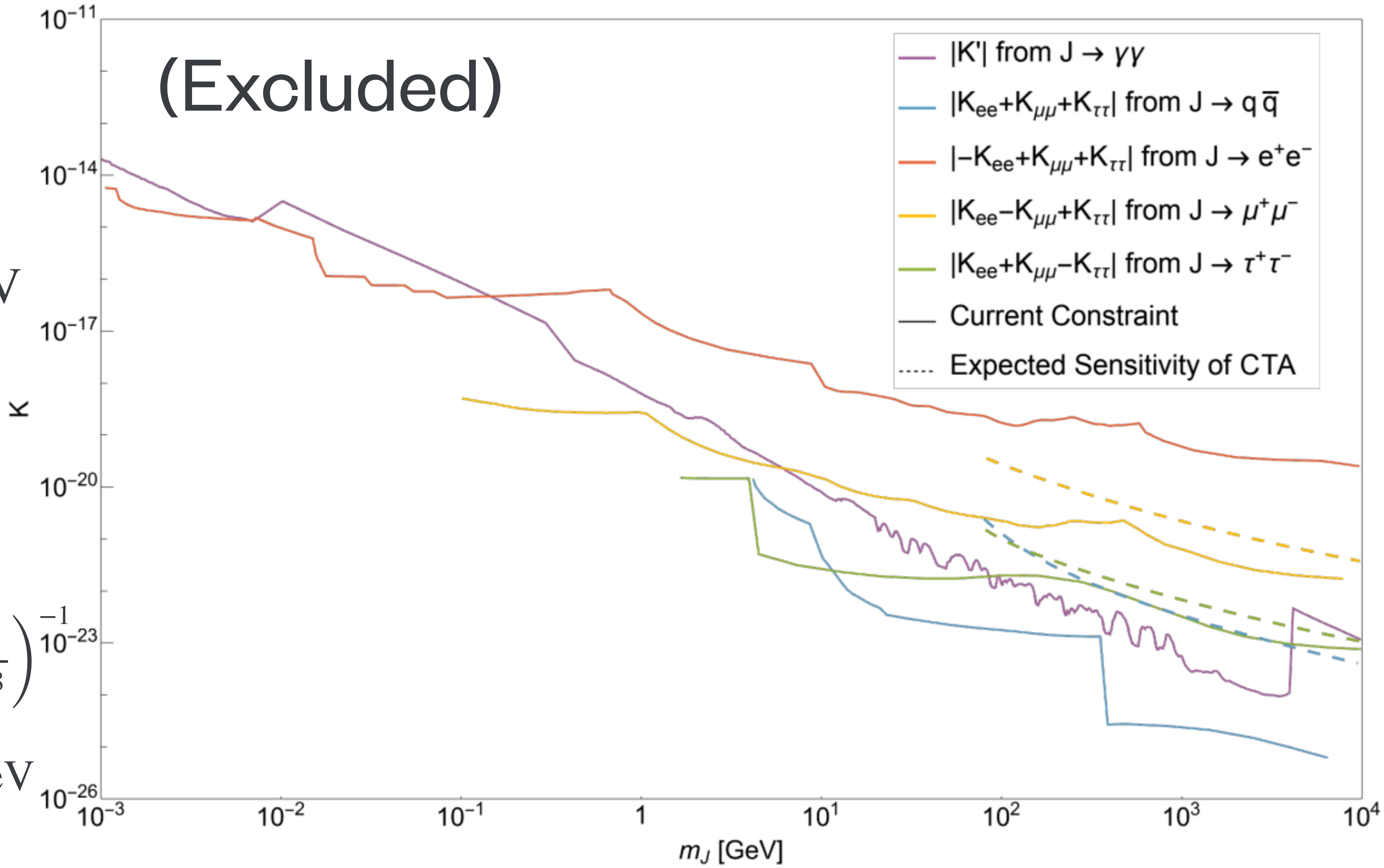
Constraint on Majoron Model

- Stronger constraints for larger m_J: $\Gamma \propto \frac{m_J}{K_{ll'}}$
- $K_{ll'} < 10^{-18}$ at $m_J \sim 1\,\mathrm{GeV}$
- Comparison

$$f = v\frac{(\lambda_D\lambda_D^\dagger)_{ll'}}{K_{ll'}}$$

$$\gtrsim 10^{12}\,\mathrm{GeV}\left(\frac{\lambda_D}{10^{-4}}\right)^2\left(\frac{K}{10^{-18}}\right)^{-1}$$

cf) $f > 10^{13}\,\mathrm{GeV}$ at $m_J \sim 1\,\mathrm{GeV}$



Summary

1. Majorana mass term of right-handed neutrino may arise from the spontaneous Lepton # symmetry breaking.
2. pNG boson associated with the Lepton # symmetry, Majoron, can be a DM candidate depending on the symmetry breaking energy scale f
3. Neutrino signals from Majoron DM
    1. $f > 10^{13}\,\mathrm{GeV}$ at $m_J \sim 1\,\mathrm{GeV}$
    2. Constraints depend on the mass hierarchy: weak in the NH case.
4. Visible signals
    1. $K_{ll'} \sim (\lambda_D^\dagger \lambda_D)_{ll'} v/f < 10^{-18}$ at $m_J \sim 1\,\mathrm{GeV}$
    2. Decay rate depend on not only f but also λ_D