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HNLs and their Connection with $0\nu\beta\beta$: Theory Overview

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Dirac vs Majorana

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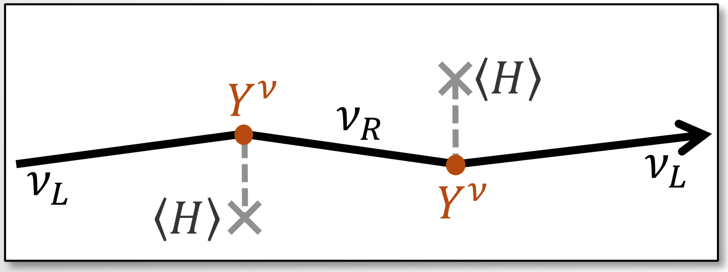
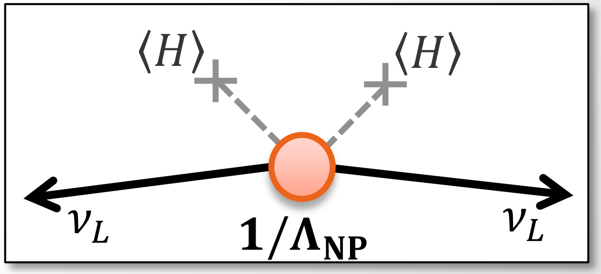
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs



Majorana mass, using only a left-handed neutrino
→ Lepton Number Violation



Beta Decays and Neutrinos

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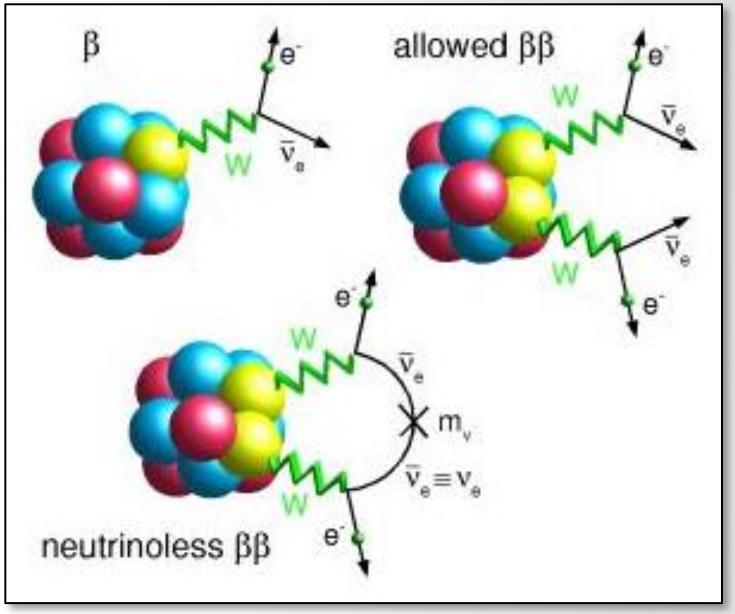
- Single beta decay
$$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$$
  - Kinematic neutrino mass measurement
- Allowed double beta ($\mathbf{2\nu\beta\beta}$) decay
$$(A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($\mathbf{0\nu\beta\beta}$) decay
$$(A,Z) \to (A,Z+2) + 2e^-$$
  - Violation of lepton number
  - Mediated by Majorana neutrinos
  - Alternatives:
    - $0\nu\beta^+\beta^+$: $(A,Z) \to (A,Z-2) + 2e^+$
    - $0\nu\beta^+\mathrm{EC}$: $(A,Z) + e^- \to (A,Z-2) + e^+$
    - $0\nu\mathrm{ECEC}$: $(A,Z) + 2e^- \to (A,Z-2)$



$0\nu\beta\beta$

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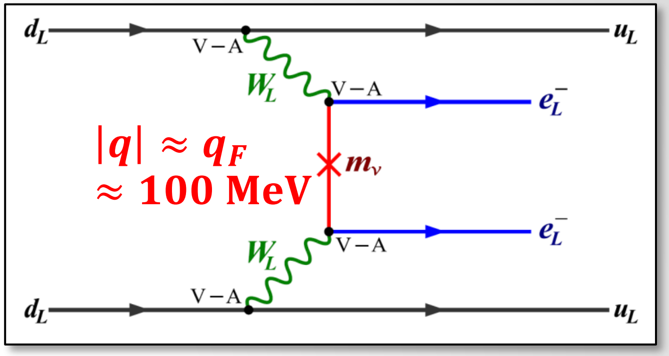
- Half-life

$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$$



- Particle Physics

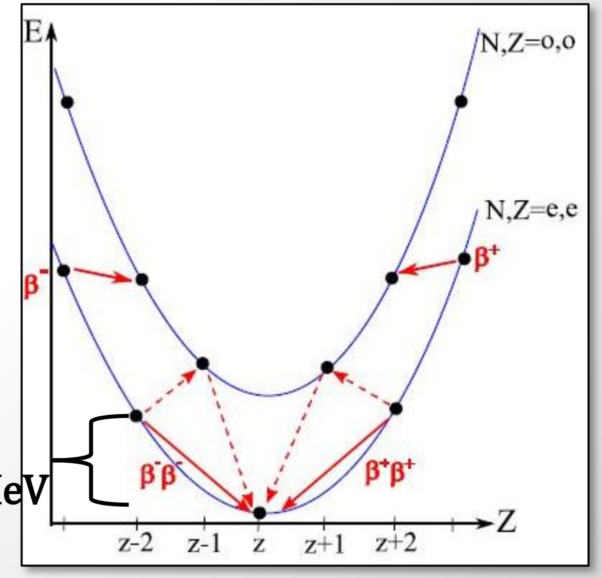
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu (1+\gamma_5)\gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu} \propto Q^5$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu} \approx 1$

$$T_{1/2}^{-1} \propto |m_{\beta\beta}|^2 q_F^2 G_F^4 Q^5$$

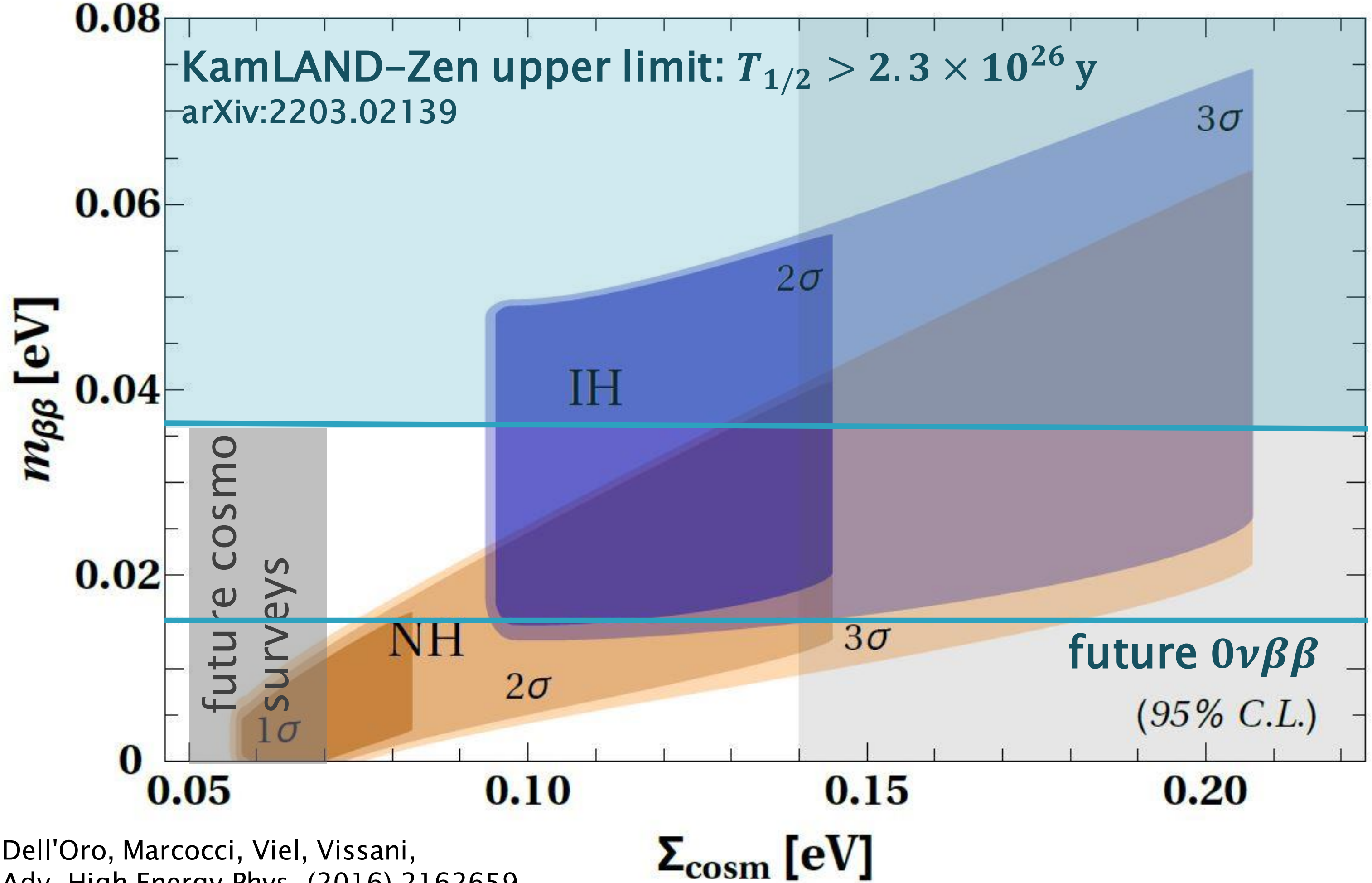
$$\frac{10^{25}\,\mathrm{y}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2$$

$Q + 2m_e$
≈ 3–5 MeV



Three Active Neutrinos

- Effective $0\nu\beta\beta$ Mass



Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

Three Active Neutrinos

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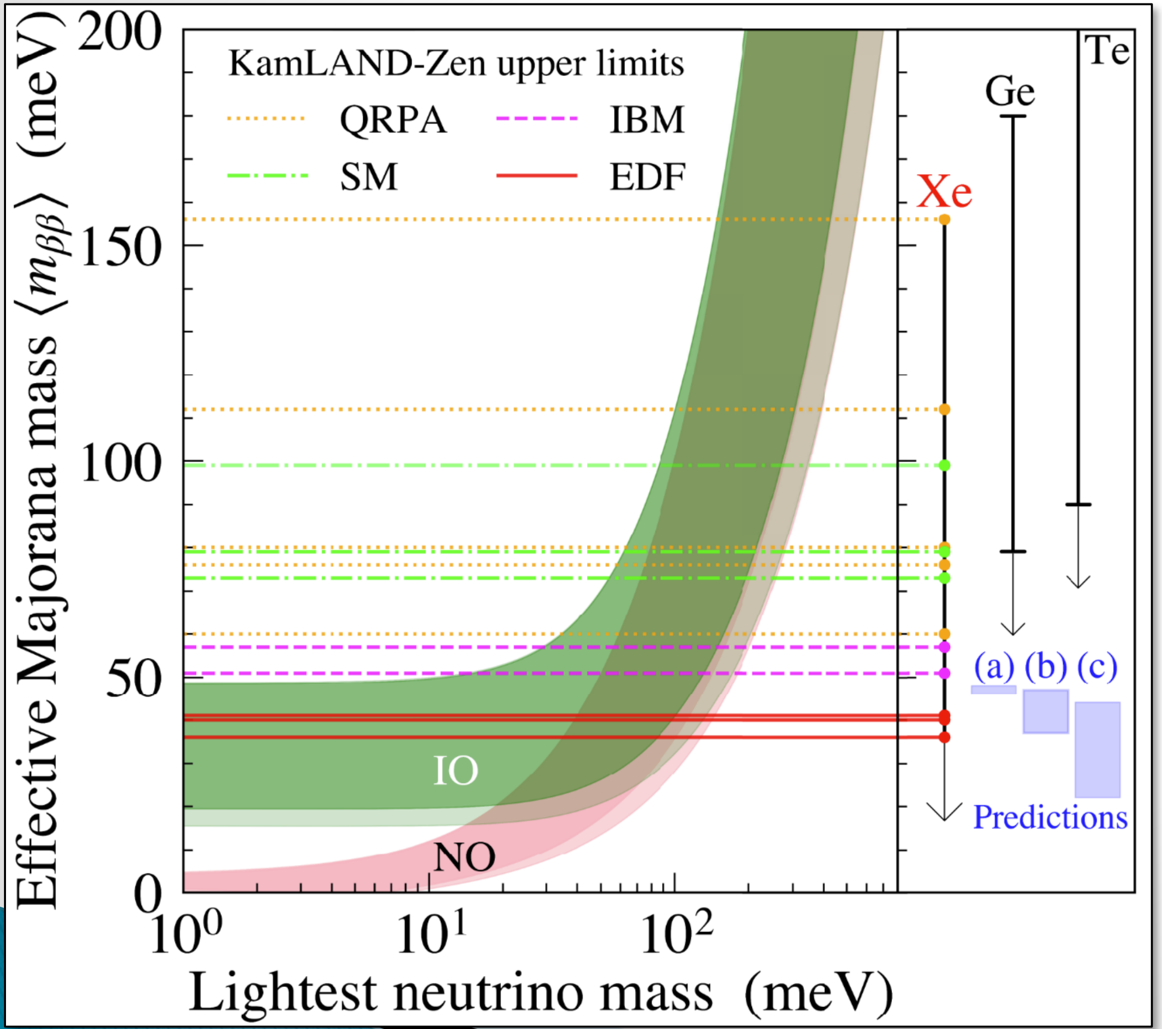
- Current Best Limit from KamLAND-Zen (arXiv:2203.02139)



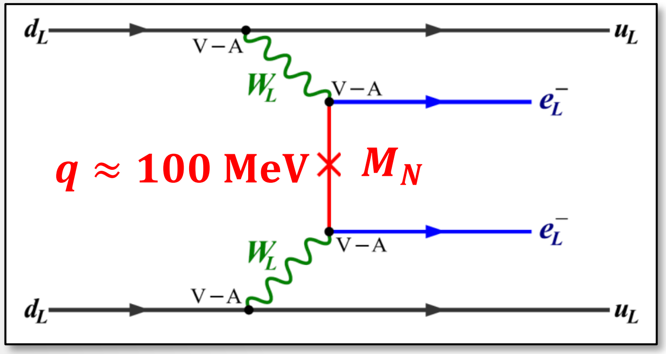
Theory Predictions:
(a) Minimal seesaw with texture zeros, Harigaya, Ibe, Yanagida, PRD 86 (2012) 013002
(b) Modular $A(4)$ in large volume limit, Asaka, Heo, Yoshida, PLB 811 (2020) 135956
(c) $U(1)_{L_e - L_\mu}, U(1)_{L_\mu - L_\tau}, U(1)_{B-L}$ gauge symmetries, Asai, EPJC 80 (2020) 76

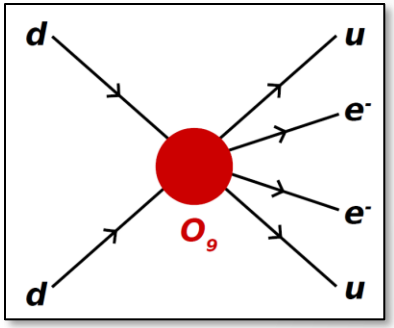
HNL in $0\nu\beta\beta$

- with masses larger than ≈ 100 MeV

$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{n} V_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\sum_{i=1}^{n}\frac{V_{ei}^2}{M_{N_i}} \rightarrow \left\langle \frac{1}{M_N} \right\rangle_{\beta\beta}$$

- Short-distance on nuclear scale





- Light neutrino mass via seesaw

$$\begin{matrix} & & & \nu & N_1 & N_2 \end{matrix}$$

$$\mathrm{diag}(m_\nu, M_N, M_N + \Delta M_N) = V \cdot \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix} \cdot V^T$$

'Vanilla' seesaw $\mu_R \gg m_D$

$$\frac{m_\nu}{0.1\ \mathrm{eV}} = \frac{V_{eN}^2}{10^{-12}}\frac{M_N}{100\ \mathrm{GeV}}$$

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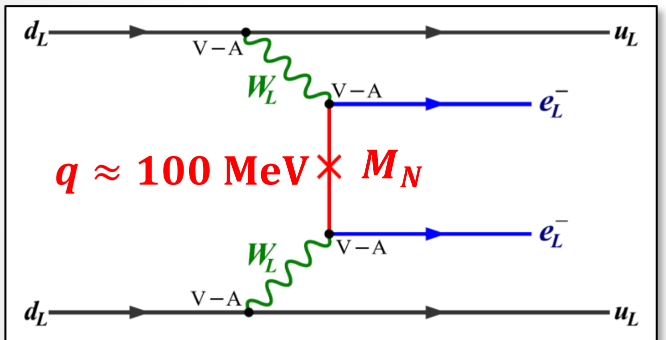
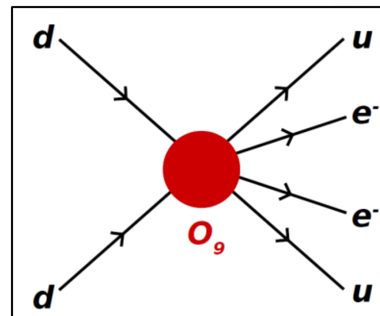
HNL in $0\nu\beta\beta$

- with masses larger than $\approx$ 100 MeV

$$\mathcal{A}^{lep}_{\mu\nu} = \frac{1}{4}\sum_{i=1}^{n} V_{ei}^2\, \gamma_\mu(1+\gamma_5)\frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2}\gamma_\nu(1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4}\sum_{i=1}^{n}\frac{V_{ei}^2}{M_{N_i}} \rightarrow \left\langle \frac{1}{M_N} \right\rangle_{\beta\beta}$$

- Short-distance on nuclear scale





- Light neutrino mass via seesaw

$$\begin{array}{c} \qquad\qquad\qquad\qquad\qquad\qquad\quad \nu \quad\; N_1 \quad\; N_2 \end{array}$$

$$\mathrm{diag}(m_\nu, M_N, M_N + \Delta M_N) = V \cdot \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix} \cdot V^T$$

Inverse seesaw

$M \gg \mu_S, \mu_R, m_D$

$$\frac{m_\nu}{0.1\ \mathrm{eV}} = \frac{V_{eN}^2}{10^{-4}}\frac{\mu_S}{\mathrm{keV}}$$

Quasi-Dirac N

Approximate L conservation

$1\nu + 2$HNL: Pheno Parametrization

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- Parametrization

$$\begin{array}{c} \\ \mathrm{diag}(m_\nu, M_N, M_N + \Delta M_N) = V \cdot \end{array} \begin{array}{c} \quad \nu \quad\;\; N_1 \quad N_2 \\ \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix} \end{array} \begin{array}{c} \\ \cdot V^T \end{array}$$

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{12} & \sin\theta_{12} \\ 0 & -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{e2} & 0 & \sin\theta_{e2} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{e2} e^{i\delta} & 0 & \cos\theta_{e2} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{e1} & \sin\theta_{e1} & 0 \\ -\sin\theta_{e1} & \cos\theta_{e1} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot D$$

- Contribution of heavy and light neutrinos to $0\nu\beta\beta$
  - See, e.g., Lopez-Pavon, Pascoli, Wong, Phys. Rev. D 87, 093007; Hernández, Jones-Pérez, Suarez-Navarro, Eur. Phys. J. C (2019) 79: 220
- Masses and observable active-sterile mixing as input
  - Large mass-splitting $\Delta m_N = m_{N_2} - m_{N_1}$ lead to large loop-contribution to light neutrino mass

$1\nu + 2$HNL: Pheno Parametrization

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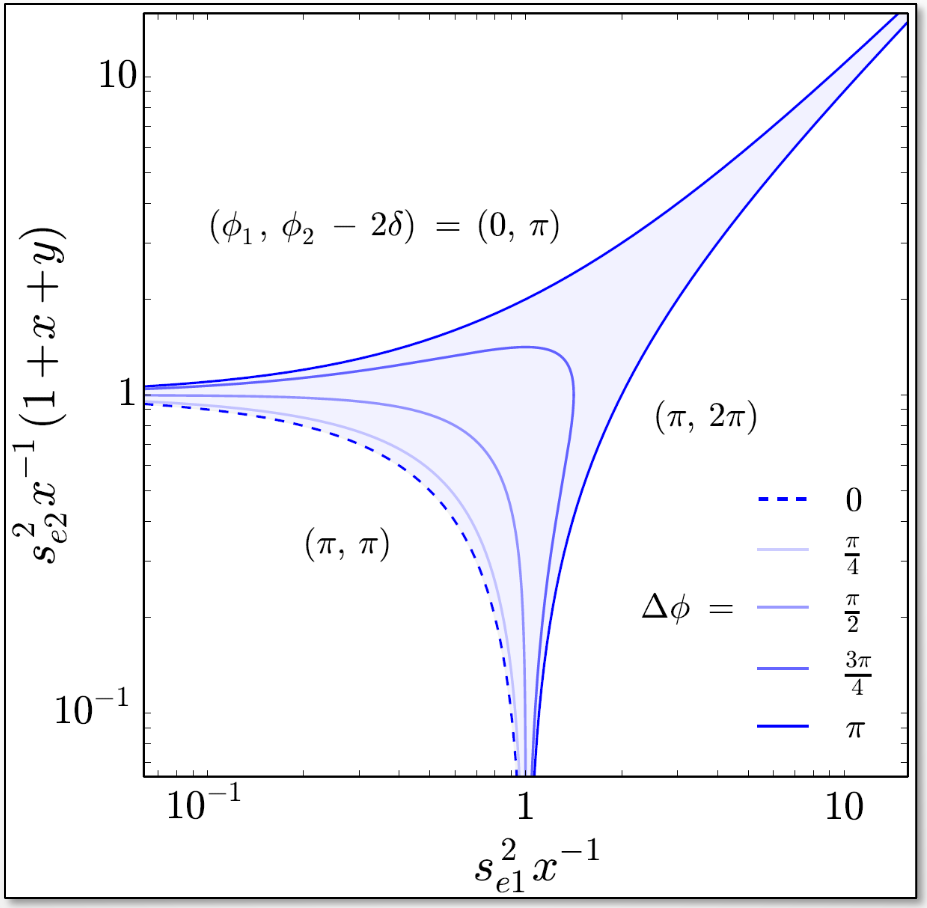
- Relation between active-sterile mixing angles (tree level)



HNL – Future Sensitivities

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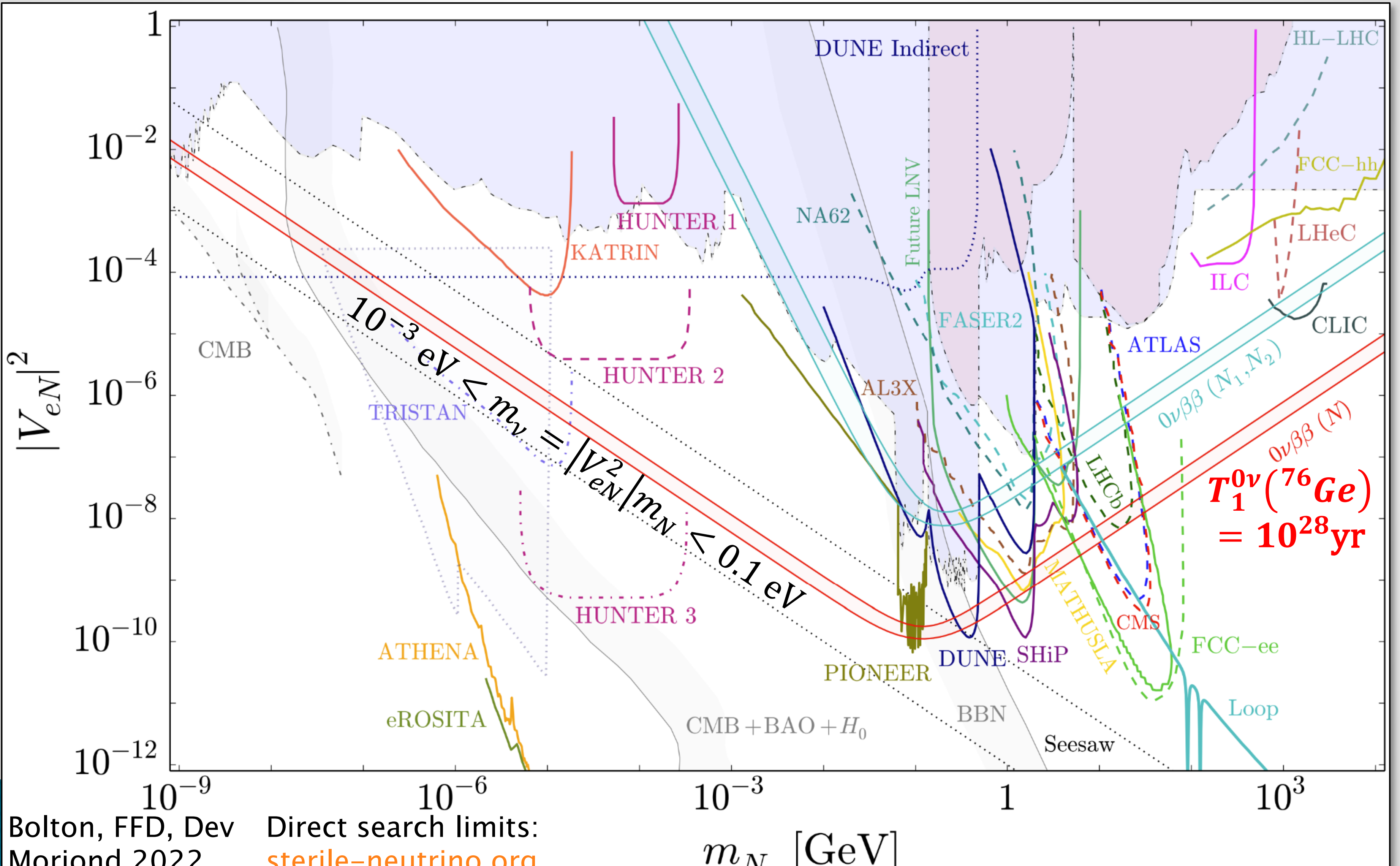

Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

HNL – Comparison with $0\nu\beta\beta$

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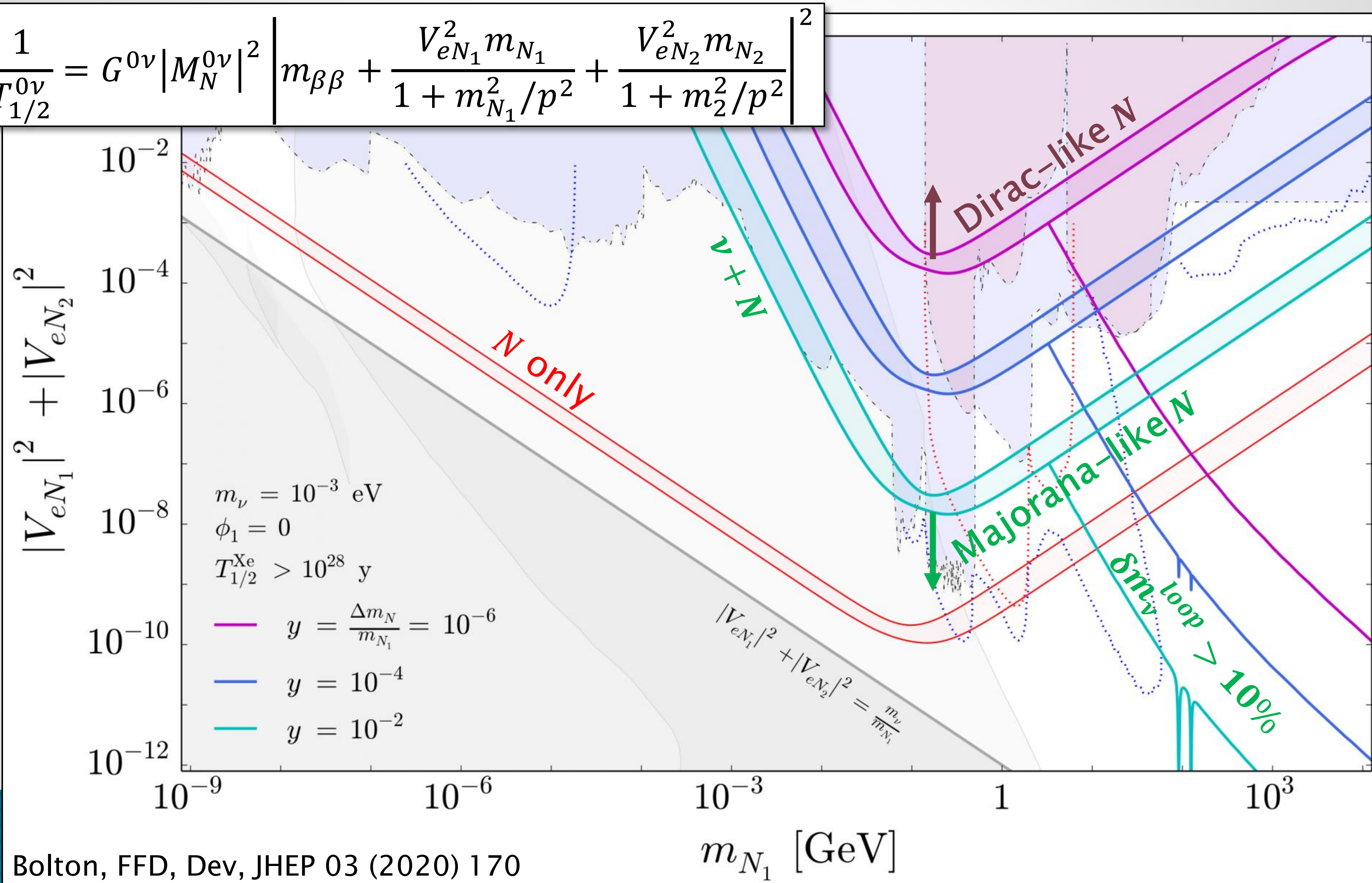
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}\left|M_N^{0\nu}\right|^2 \left| m_{\beta\beta} + \frac{V_{eN_1}^2 m_{N_1}}{1+m_{N_1}^2/p^2} + \frac{V_{eN_2}^2 m_{N_2}}{1+m_2^2/p^2}\right|^2$$

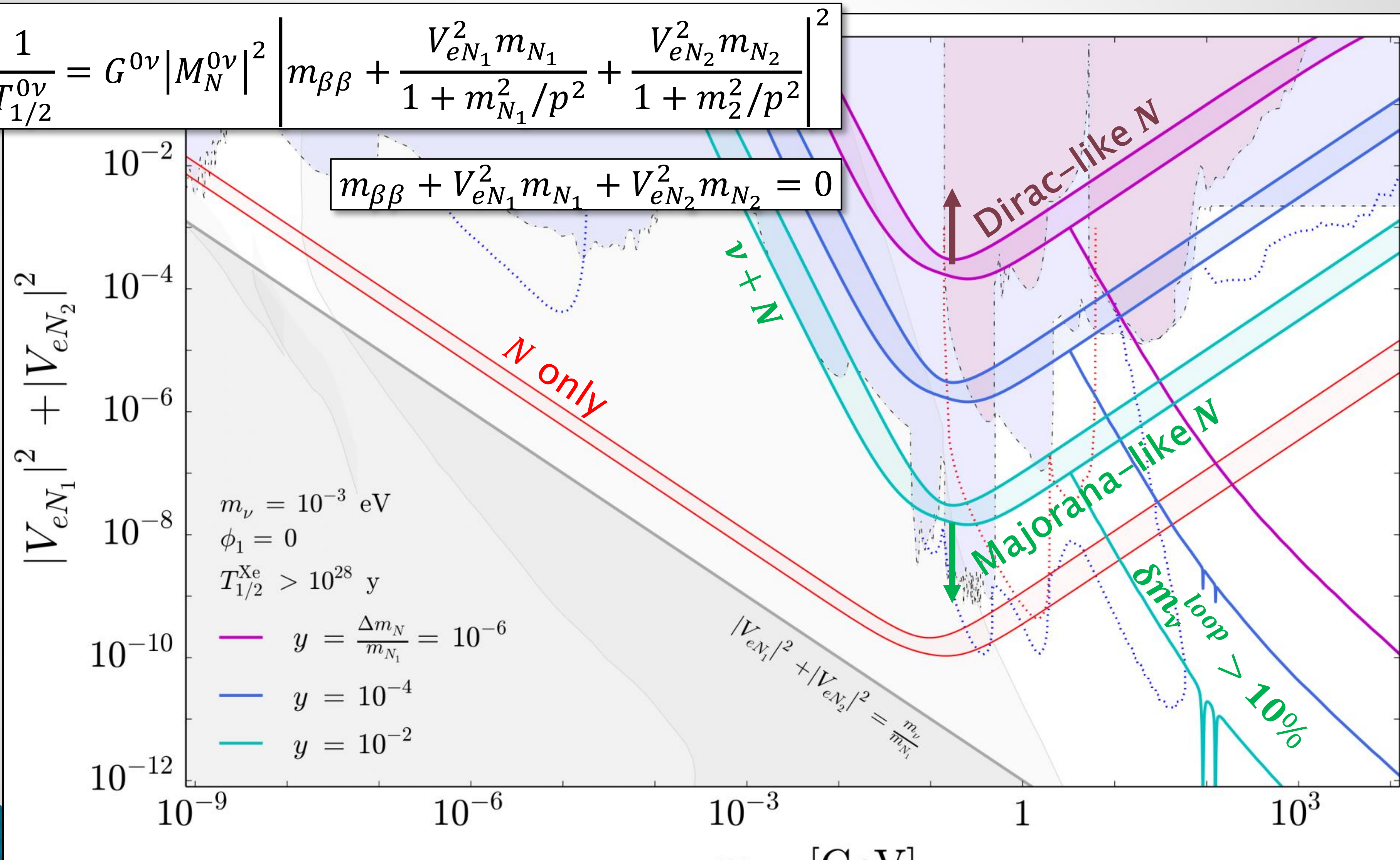


Bolton, FFD, Dev, JHEP 03 (2020) 170

HNL – Comparison with $0\nu\beta\beta$

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}\left|M_N^{0\nu}\right|^2 \left| m_{\beta\beta} + \frac{V_{eN_1}^2 m_{N_1}}{1 + m_{N_1}^2/p^2} + \frac{V_{eN_2}^2 m_{N_2}}{1 + m_2^2/p^2} \right|^2$$

$$m_{\beta\beta} + V_{eN_1}^2 m_{N_1} + V_{eN_2}^2 m_{N_2} = 0$$



Bolton, FFD, Dev, JHEP 03 (2020) 170

HNL – Comparison with $0\nu\beta\beta$

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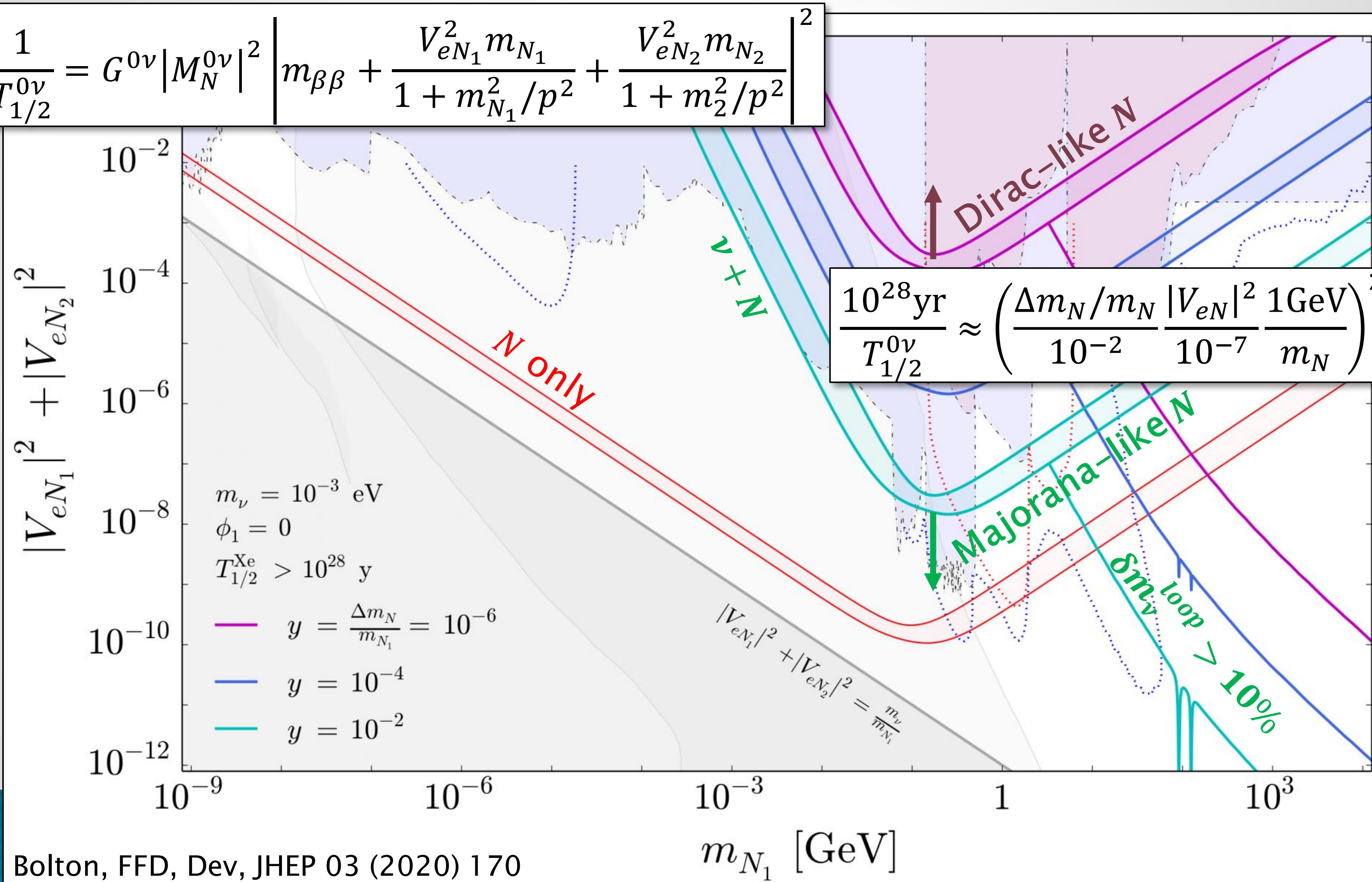
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}\left|M_N^{0\nu}\right|^2 \left| m_{\beta\beta} + \frac{V_{eN_1}^2 m_{N_1}}{1+m_{N_1}^2/p^2} + \frac{V_{eN_2}^2 m_{N_2}}{1+m_2^2/p^2}\right|^2$$

$$\frac{10^{28}\mathrm{yr}}{T_{1/2}^{0\nu}} \approx \left(\frac{\Delta m_N/m_N}{10^{-2}}\frac{|V_{eN}|^2}{10^{-7}}\frac{1\mathrm{GeV}}{m_N}\right)^2$$

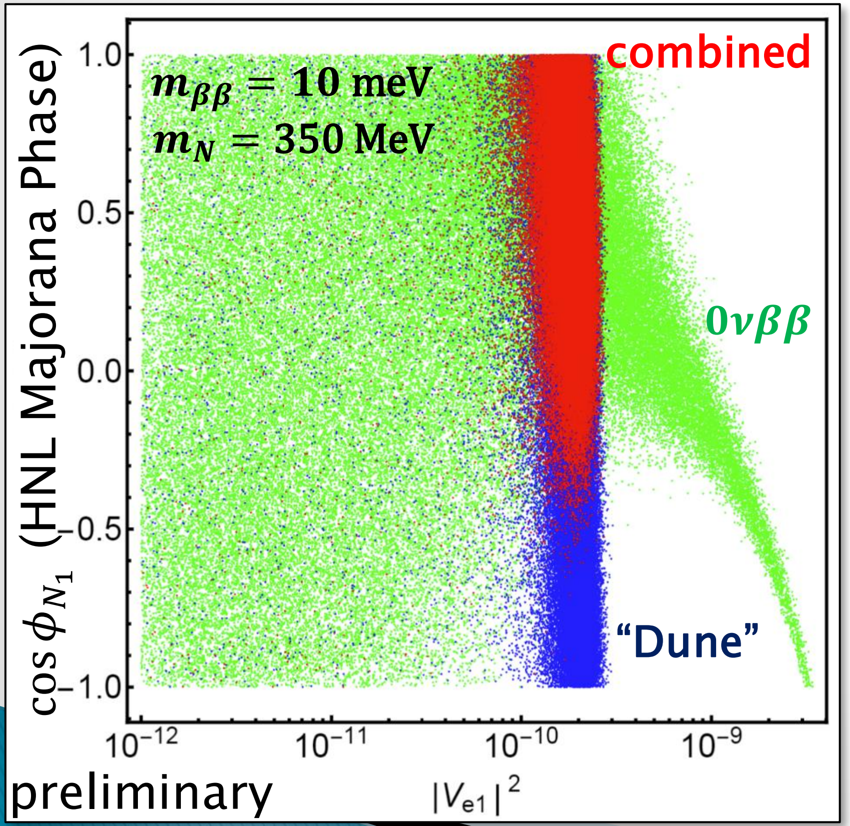


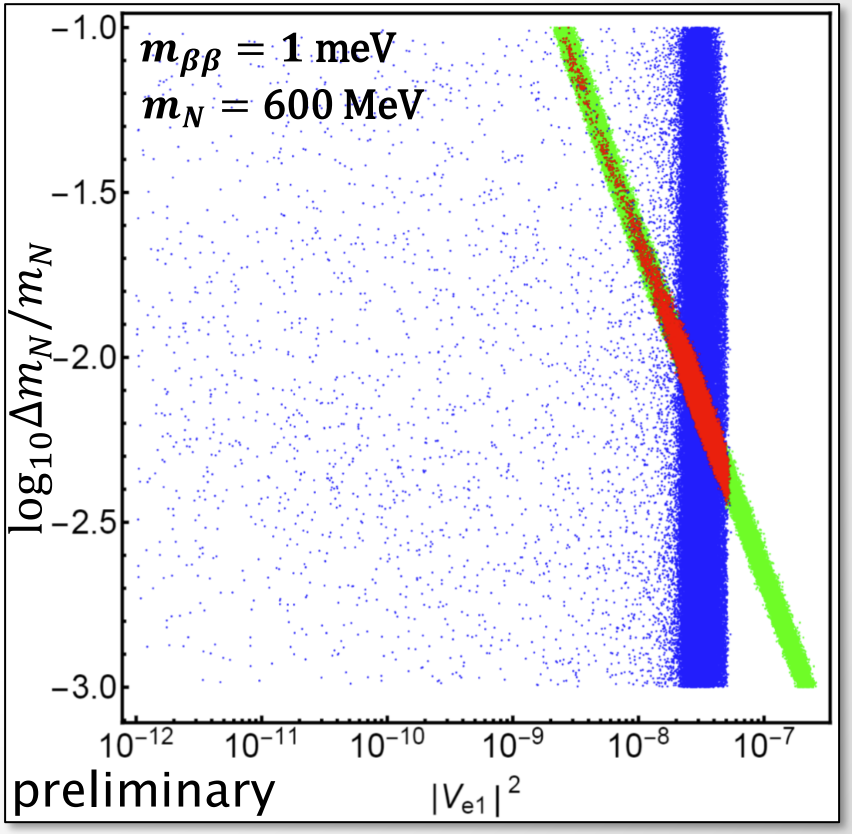
Bolton, FFD, Dev, JHEP 03 (2020) 170

Complementarity

Patrick Bolton, FFD, Mudit Rai, Zhong Zhang, Work in Progress

- Between direct searches and $0\nu\beta\beta$
  - Simulation of DUNE-like setup
  - Measurement of events at "DUNE" and $0\nu\beta\beta$ decay at LEGEND-1000 near expected sensitivity





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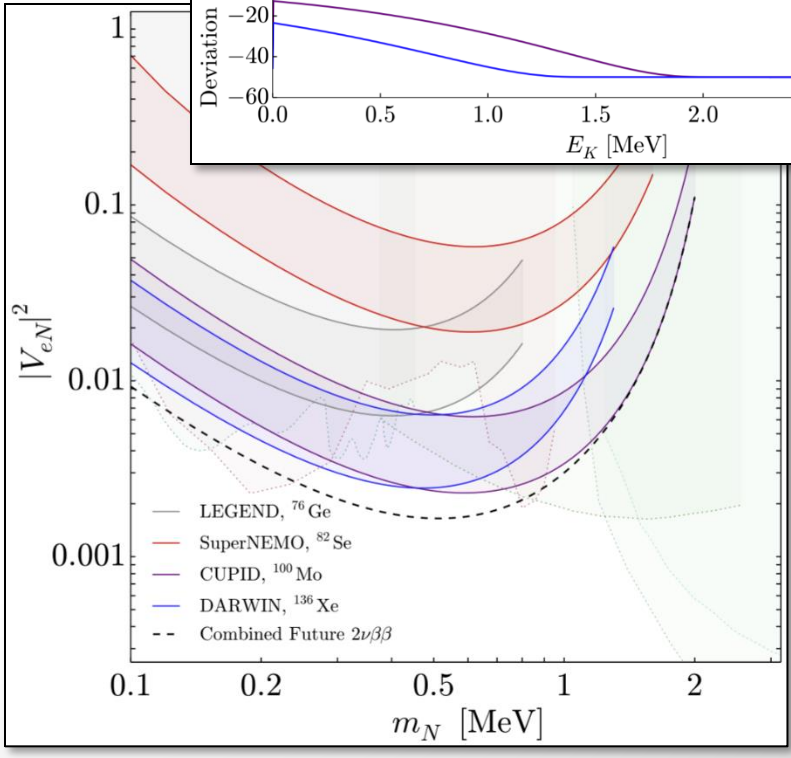
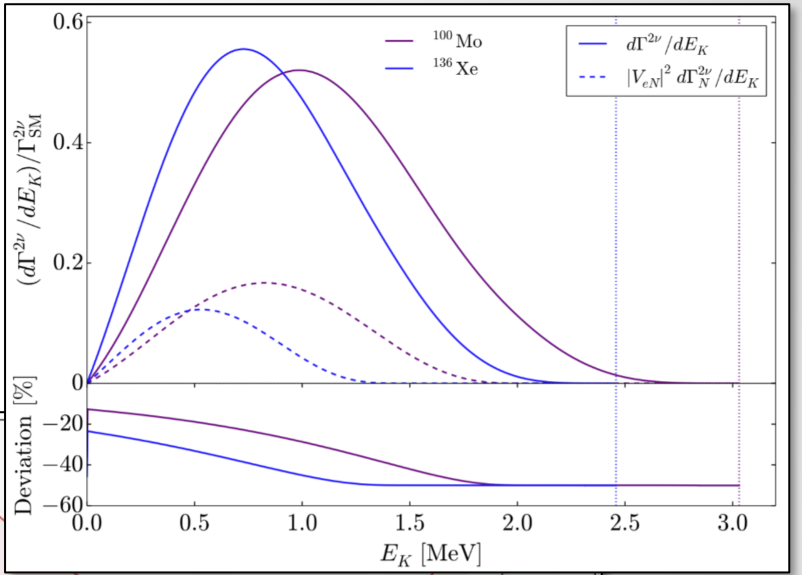
HNL in $2\nu\beta\beta$

Bolton, FFD, Graf, Simkovic, PRD 103 (2021)

- Sterile neutrino search through energy endpoint (also Agostini, Bossio, Ibarra, Marcano, PLB 815 (2021))
  - Emission of one sterile neutrino in double beta decay: $\nu N\beta\beta$
  - Same principle as endpoint searches in single β decays
  - Observed limit at GERDA: $|V_{eN}|^2 < 0.013$ for $m_N \approx 500$ keV (arXiv:2209.01671)

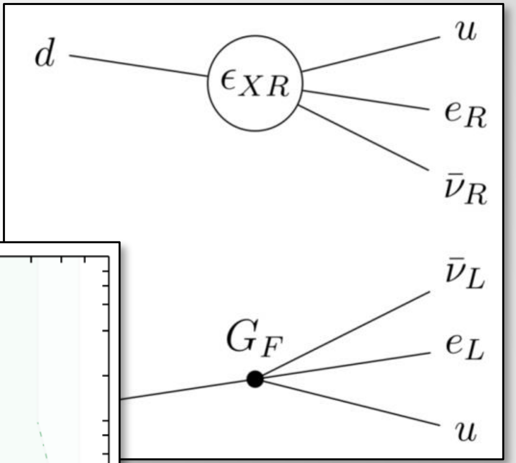


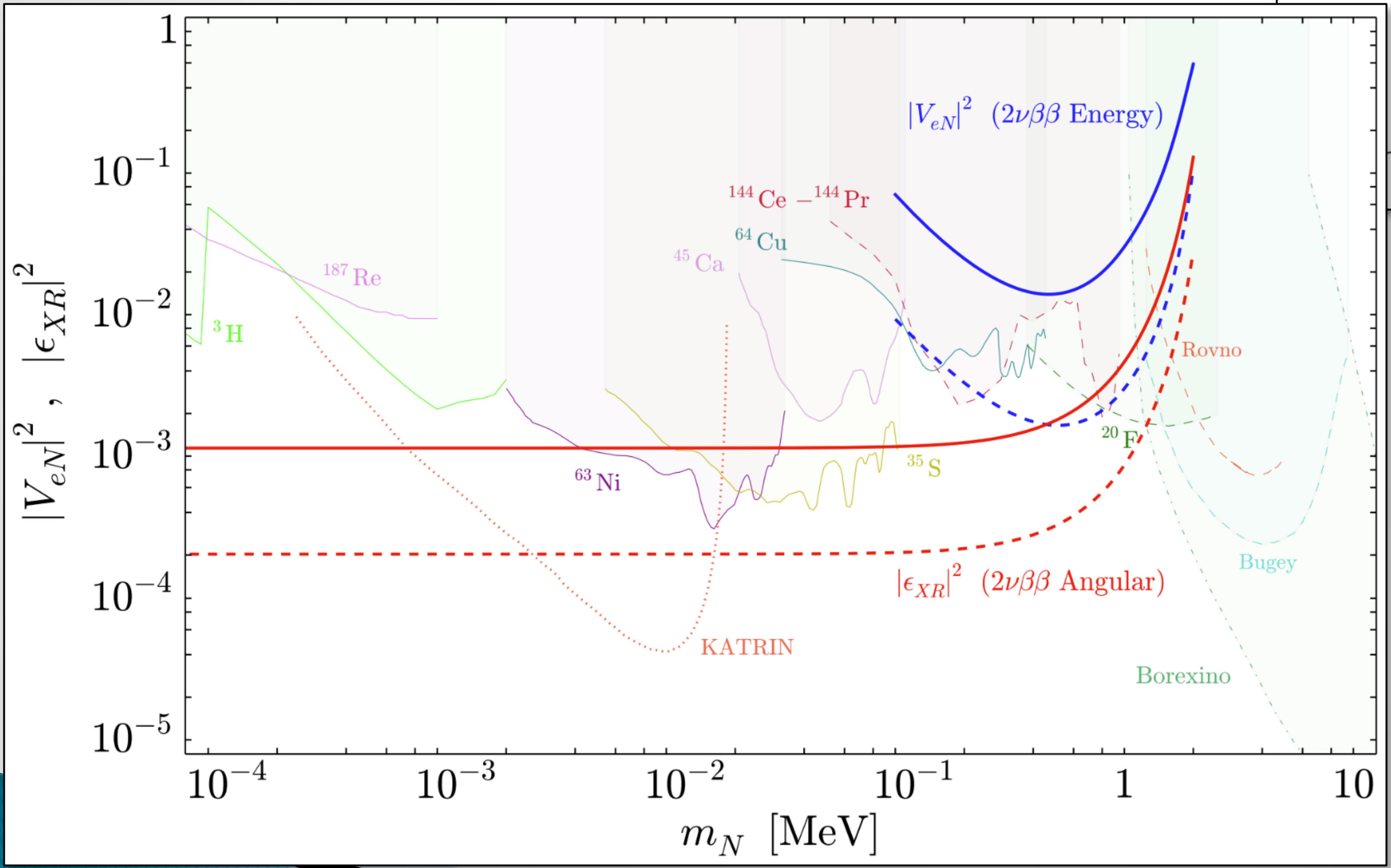


HNL in $2\nu\beta\beta$

FFD, Graf, Simkovic, PRL 125 (2020)

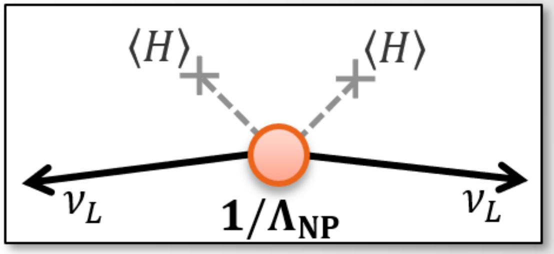
- Lepton-number conserving right-handed currents





Conclusion

- **Neutrinos much lighter than other fermions**
  - Mechanism of mass generation
  - Dirac or Majorana?
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Effective $0\nu\beta\beta$ mass $m_{\beta\beta} \approx 10 - 100\text{ meV}$ probes New Physics near GUT scale
  - Sensitive to Majorana HNL for $0.1\text{ eV} < m_N < 10\text{ TeV}$
  - Reduced sensitivity to Quasi-Dirac HNL in realistic seesaw scenarios
    - Complementarity with direct searches for $m_N \approx 1 - 10\text{ GeV}$
  - Sensitive to extended, "non-sterile" HNL scenarios, e.g.,
    - Eff. HNL Operators, Left-Right Symmetry, Composite HNL



$$\frac{T_{1/2}^{0\nu\beta\beta}}{10^{28}\text{ y}} \approx \left(\frac{\Lambda_{\text{NP}}}{10^{15}\text{ GeV}}\right)^2$$

$$\frac{10^{28}\text{yr}}{T_{1/2}^{0\nu}} \approx \left(\frac{\Delta m_N/m_N}{10^{-2}}\,\frac{|V_{eN}|^2}{10^{-7}}\,\frac{1\text{ GeV}}{m_N}\right)^2$$

HNL – Current Limits

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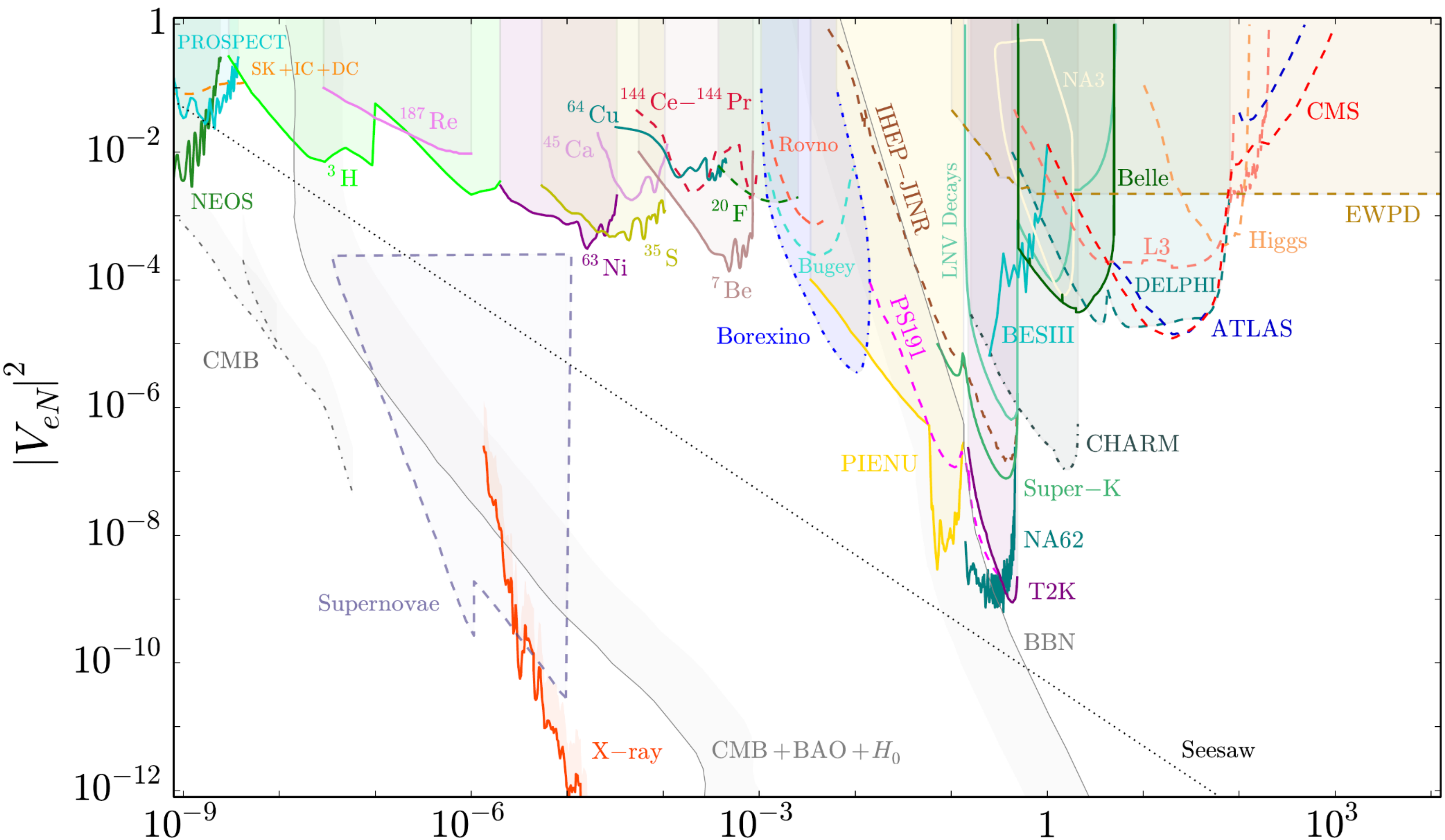

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HNL – Comparison with $0\nu\beta\beta$

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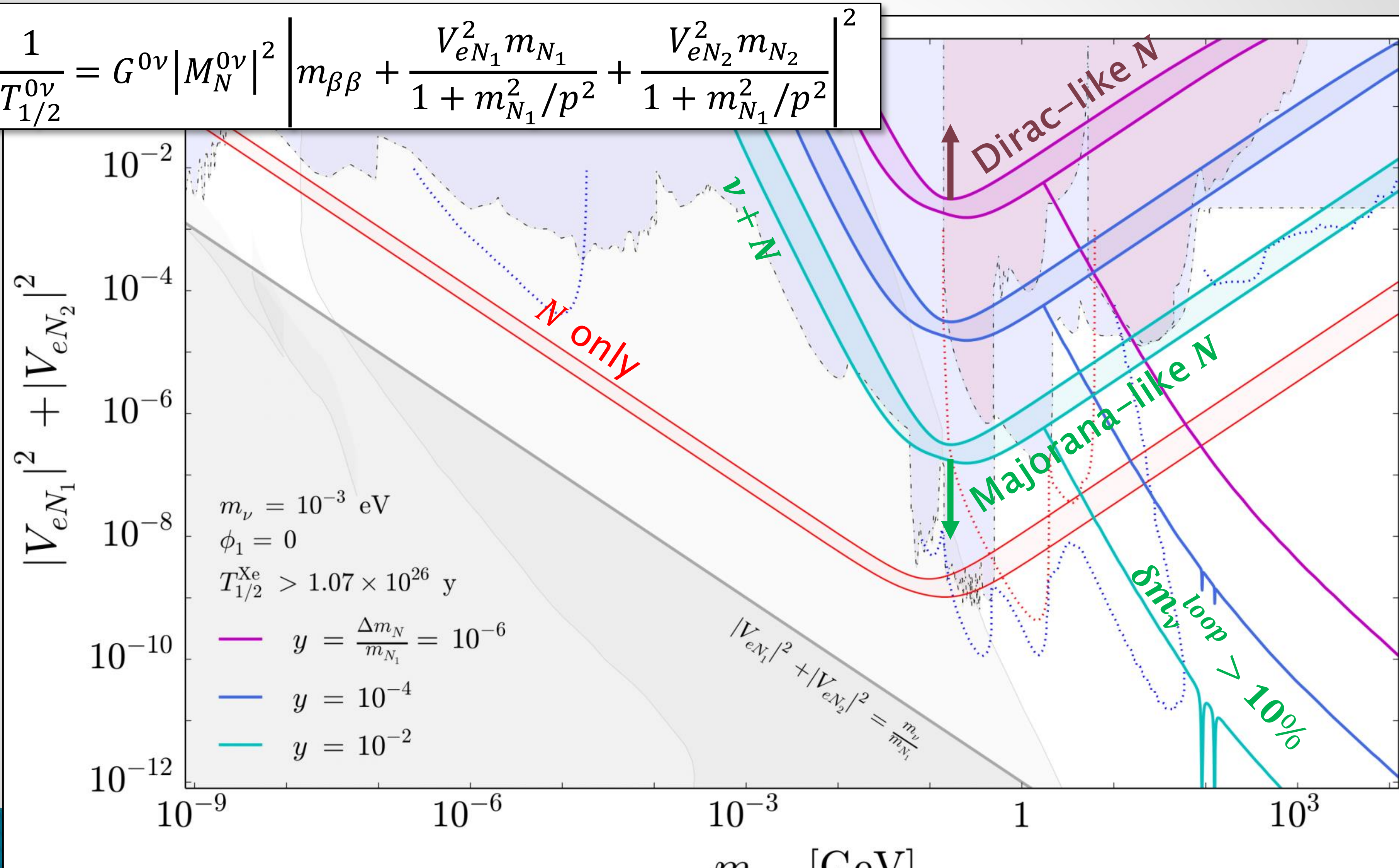

Bolton, FFD, Dev, JHEP 03 (2020) 170