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Sterile Neutrinos in Neutrinoless Double Beta Decay

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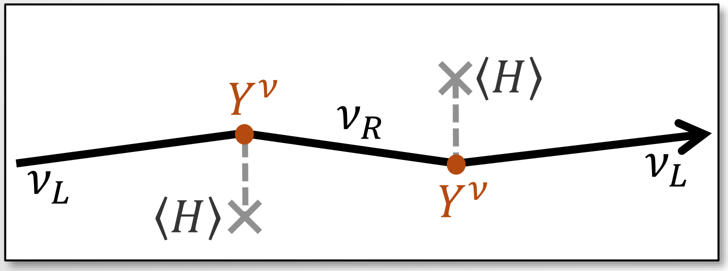
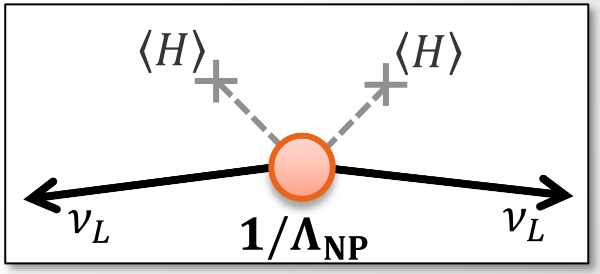
Dirac versus Majorana

- 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

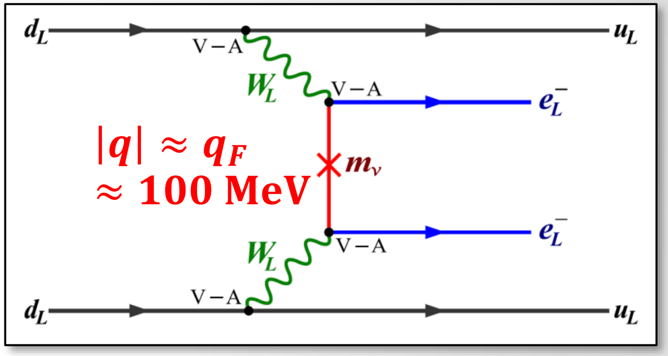




Neutrinoless Double β Decay

- Half-life

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



- Particle Physics

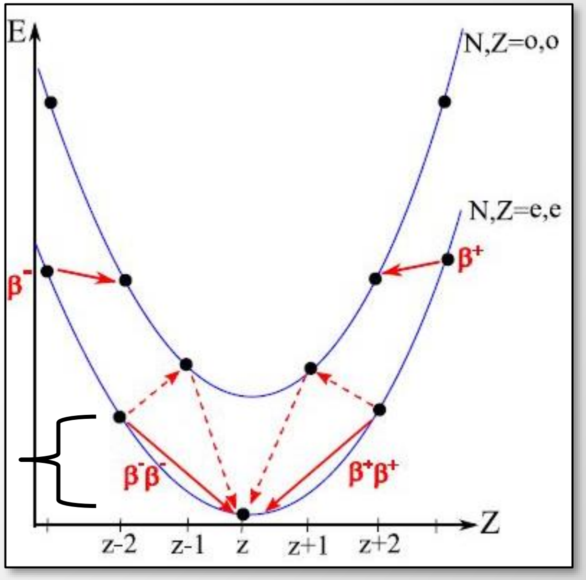
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{G_F^2}{4} \sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx G_F^2 \frac{\gamma_\mu (1+\gamma_5) \gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu} \propto Q^5$

$$\Gamma_{0\nu\beta\beta} \sim m_\nu^2 G_F^4 q_F^2 Q^5 \sim (m_\nu / 0.1\ \text{eV})^2 \left(10^{26}\ \text{yr}\right)^{-1}$$

- Nuclear Physics
  - Nuclear matrix element $M^{0\nu} \approx 1$ but large uncertainties

$Q + 2m_e \approx$ 3–5 MeV



Three Active Neutrinos

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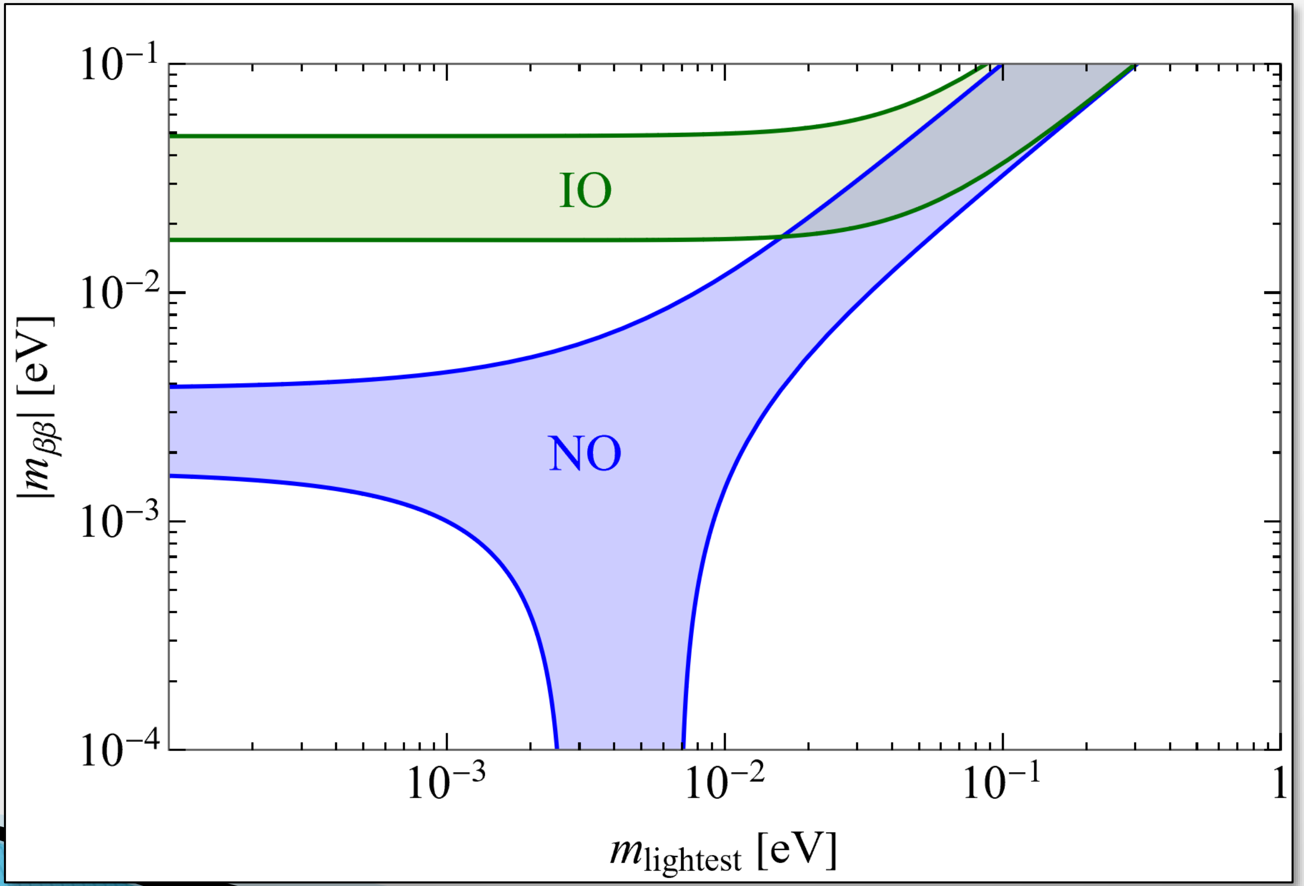
- Effective $0\nu\beta\beta$ Mass

degenerate & $\theta_{13} \approx 0$

$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}| \approx m_\nu \sqrt{1 - \sin^2(2\theta_{12}) \sin^2(\phi_{12}/2)}$$



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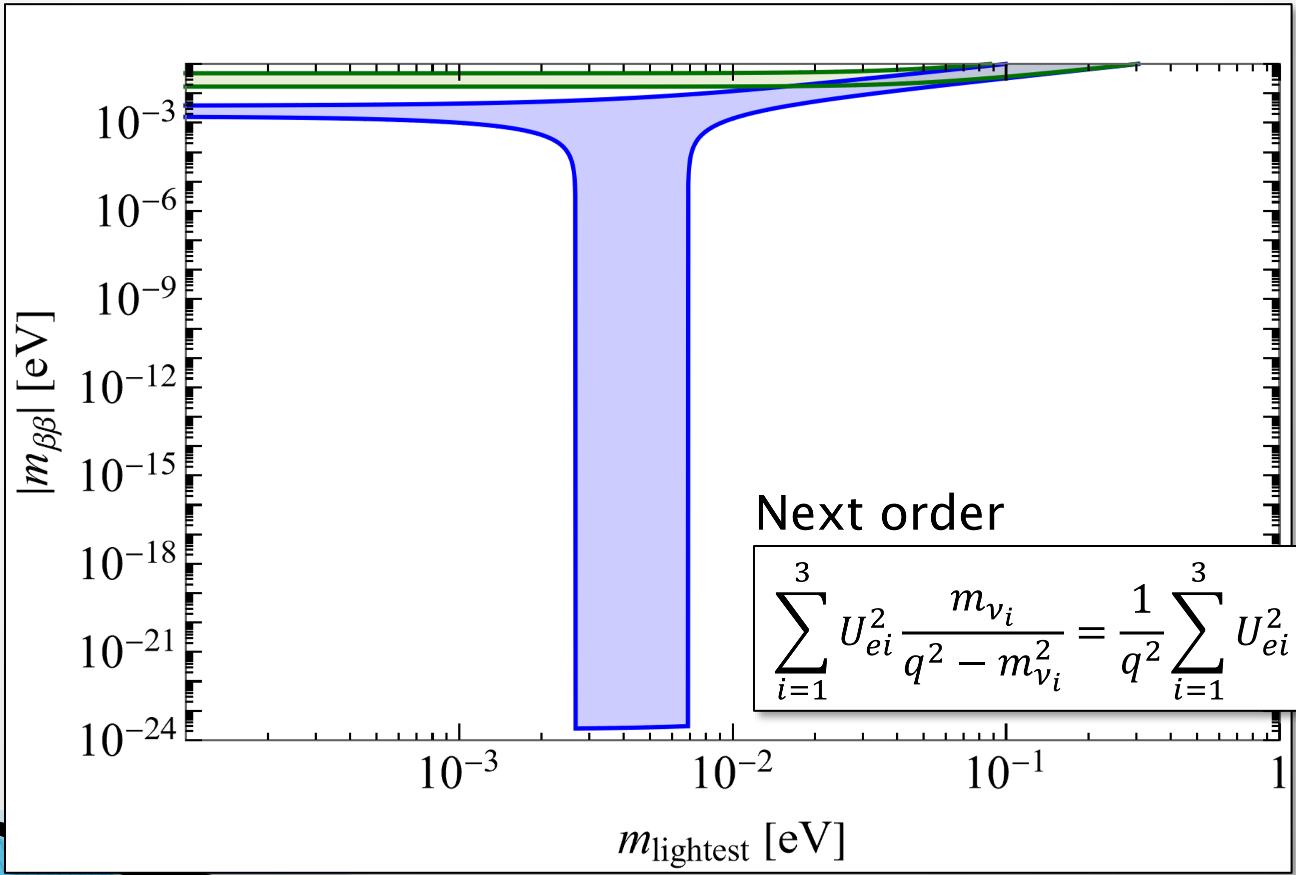

Next order

$$\sum_{i=1}^{3} U_{ei}^2 \frac{m_{\nu_i}}{q^2 - m_{\nu_i}^2} = \frac{1}{q^2} \sum_{i=1}^{3} U_{ei}^2 \left(m_{\nu_i} + \frac{m_{\nu_i}^3}{q^2} \right)$$

Sterile Neutrinos

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- SM + Sterile Neutrinos

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_{iR}\partial\!\!\!/ N_{iR} - (Y_\nu)_{\alpha i}\bar{L}_\alpha \tilde{H} N_{iR} - \frac{1}{2}(\mathcal{M}_S)_{ij}\bar{N}^c_{iR}N_{jR} + \text{h.c.}\,.$$

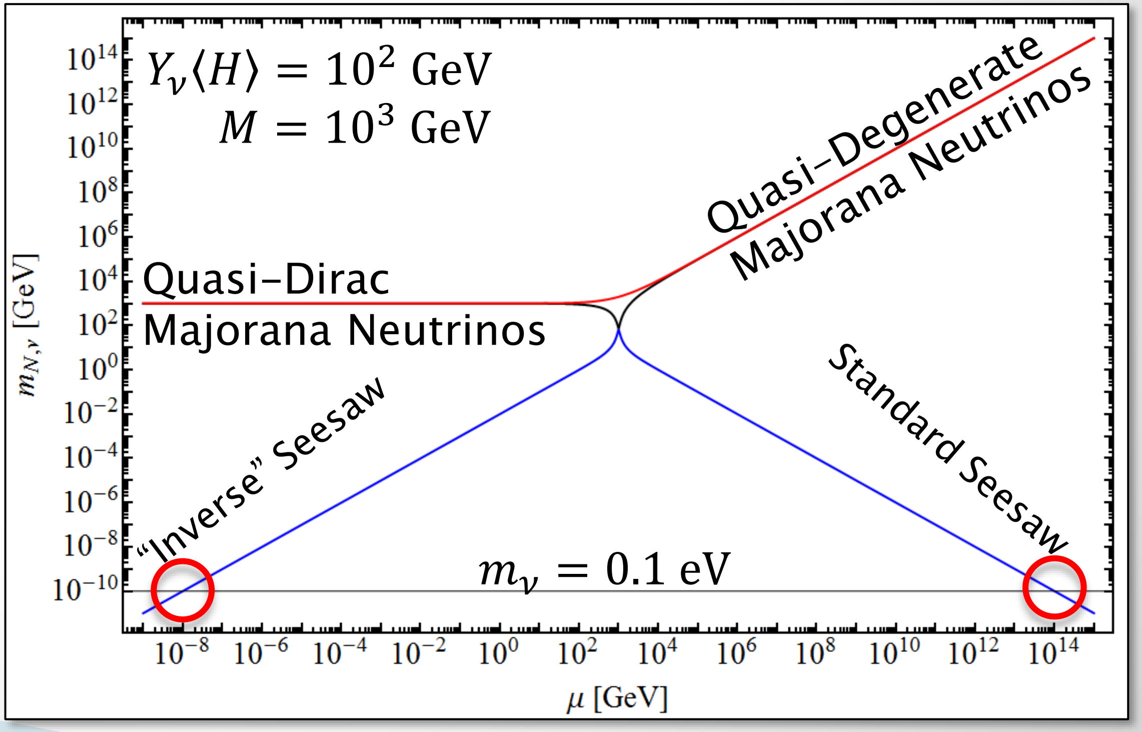
  - Seesaw Mechanism with TeV scale heavy neutrinos
    - Standard Seesaw with small Yukawa couplings

$$V^{\nu N} \approx Y_\nu \approx 10^{-6}\sqrt{M_N/\text{TeV}}$$

  - "Bent" Seesaw mechanisms
    - Decouple $\Lambda_{\rm LNV}$ from heavy neutrino mass

$$\begin{array}{cccc} & \nu & N_1 & N_2 \end{array}$$

$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$



$1\nu + 2N$: Pheno Parametrization

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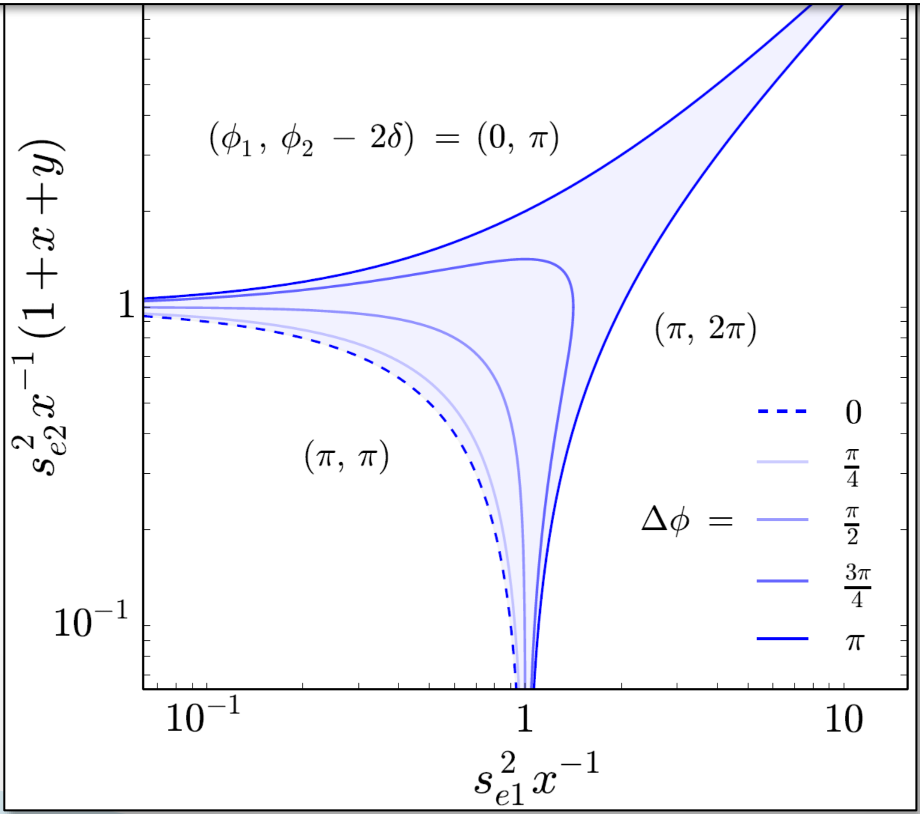
- Relation between active-sterile mixing angles (tree level)

$$(\mathcal{M}_\nu)_{\alpha\beta} = 0 \quad \Rightarrow \quad 0 = \sum_{i=1}^{\mathcal{N}_A} m_i U_{\alpha i} U_{\beta i} + \sum_{k=1}^{\mathcal{N}_S} m_{N_\kappa} U_{\alpha N_\kappa} U_{\beta N_\kappa}$$



Sterile Neutrinos in $0\nu\beta\beta$

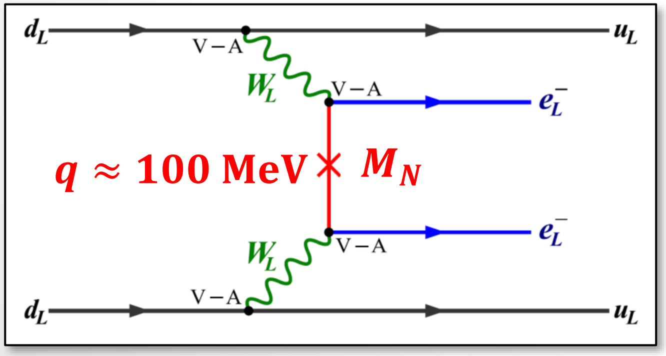
- Masses lighter than ≈ 100 MeV

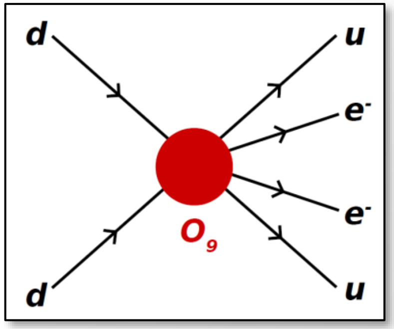
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}} + s_{14}^2 m_{\nu_4} e^{i\phi_{14}} + \cdots |$$

- Masses heavier than ≈ 100 MeV

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{-\gamma_\mu (1+\gamma_5)\gamma_\nu}{4} \sum_{i=1}^{3} \frac{V_{ei}^2}{M_{N_i}} \rightarrow \left\langle \frac{1}{M_N} \right\rangle_{\beta\beta}$$

- Short-distance on nuclear scale





HNL – Current Limits

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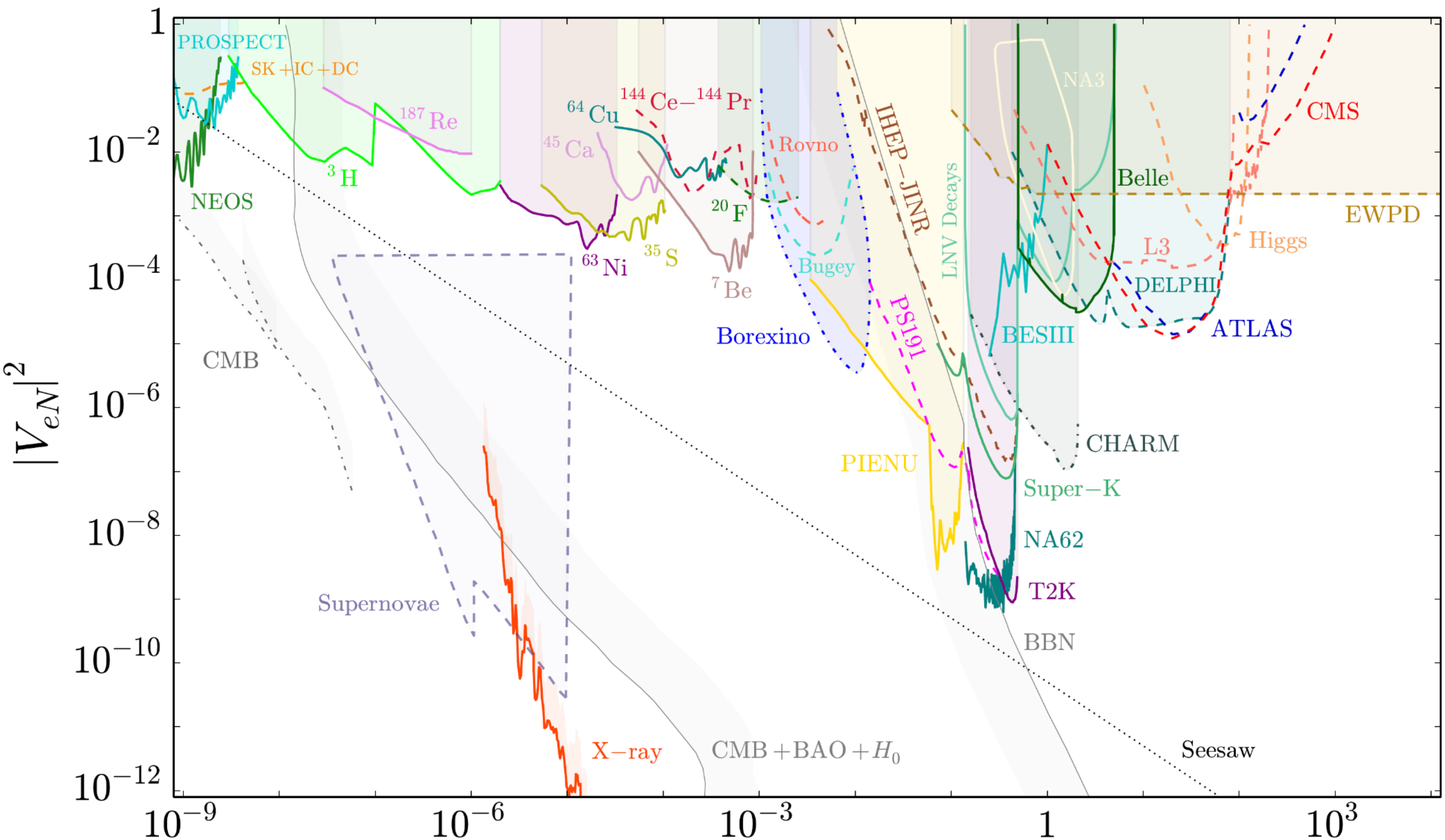

Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

HNL – Future Sensitivities

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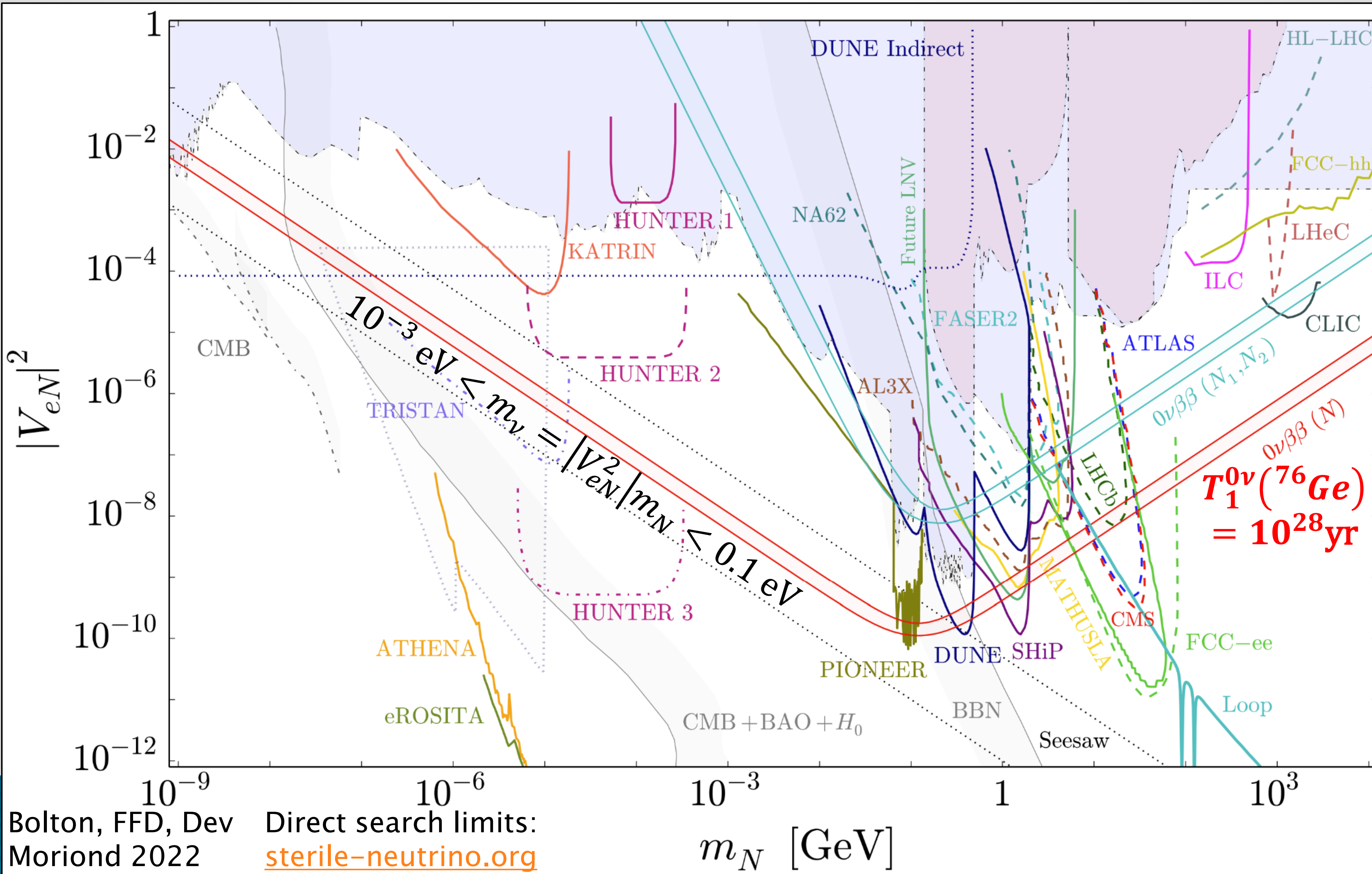

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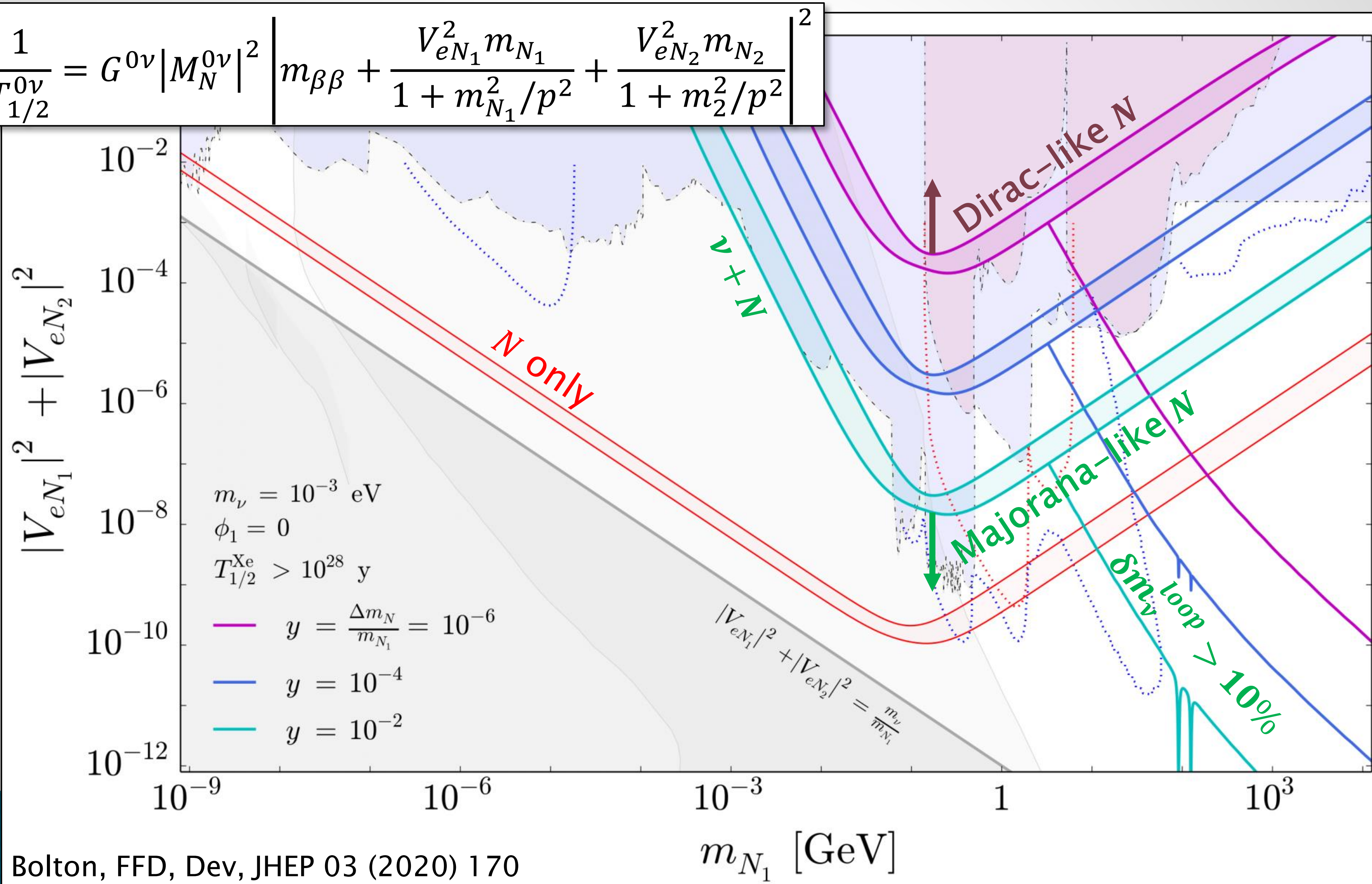
HNL – Comparison with $0\nu\beta\beta$

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



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

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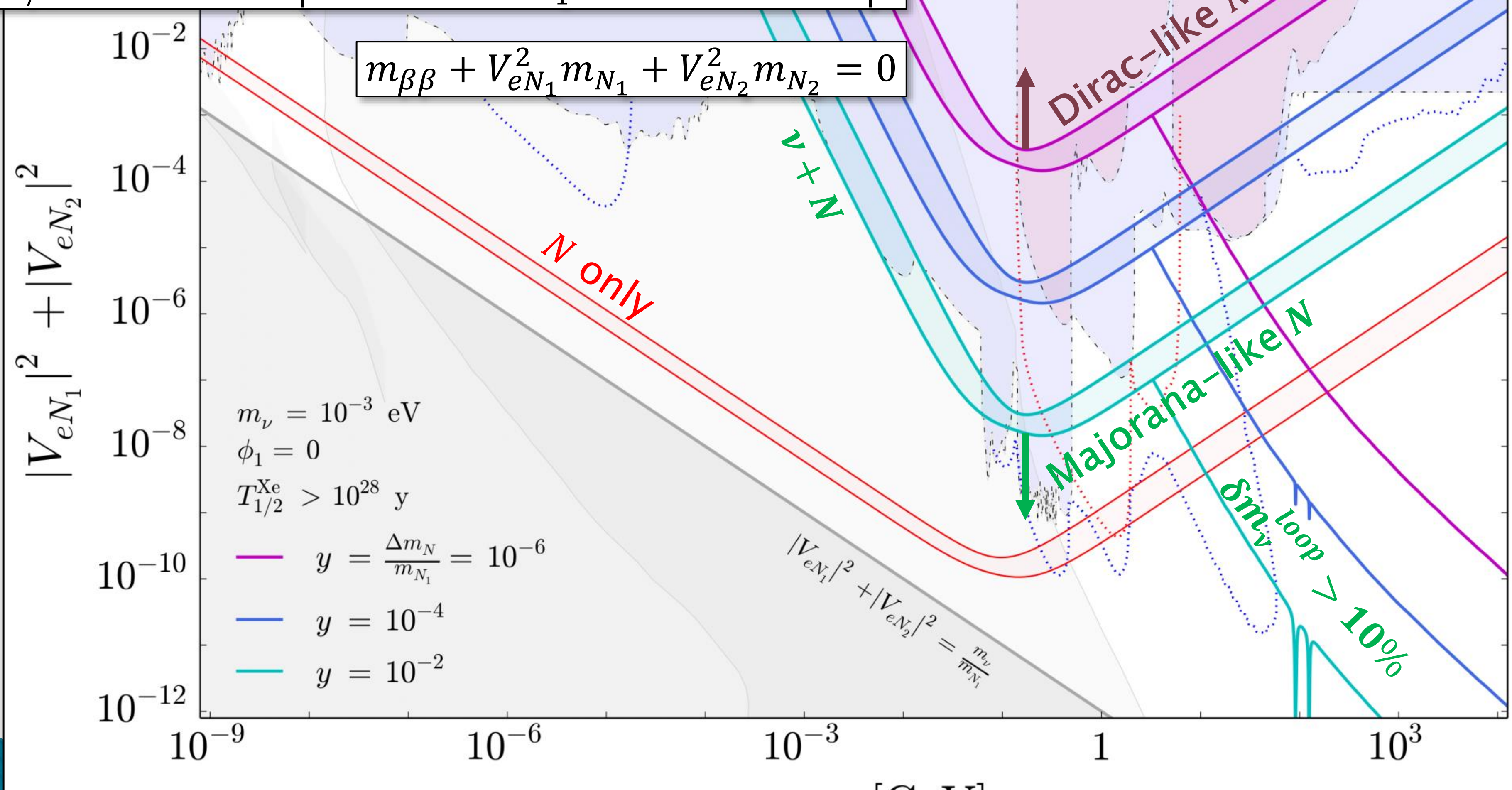
$$m_{\beta\beta} + V_{eN_1}^2 m_{N_1} + V_{eN_2}^2 m_{N_2} = 0$$



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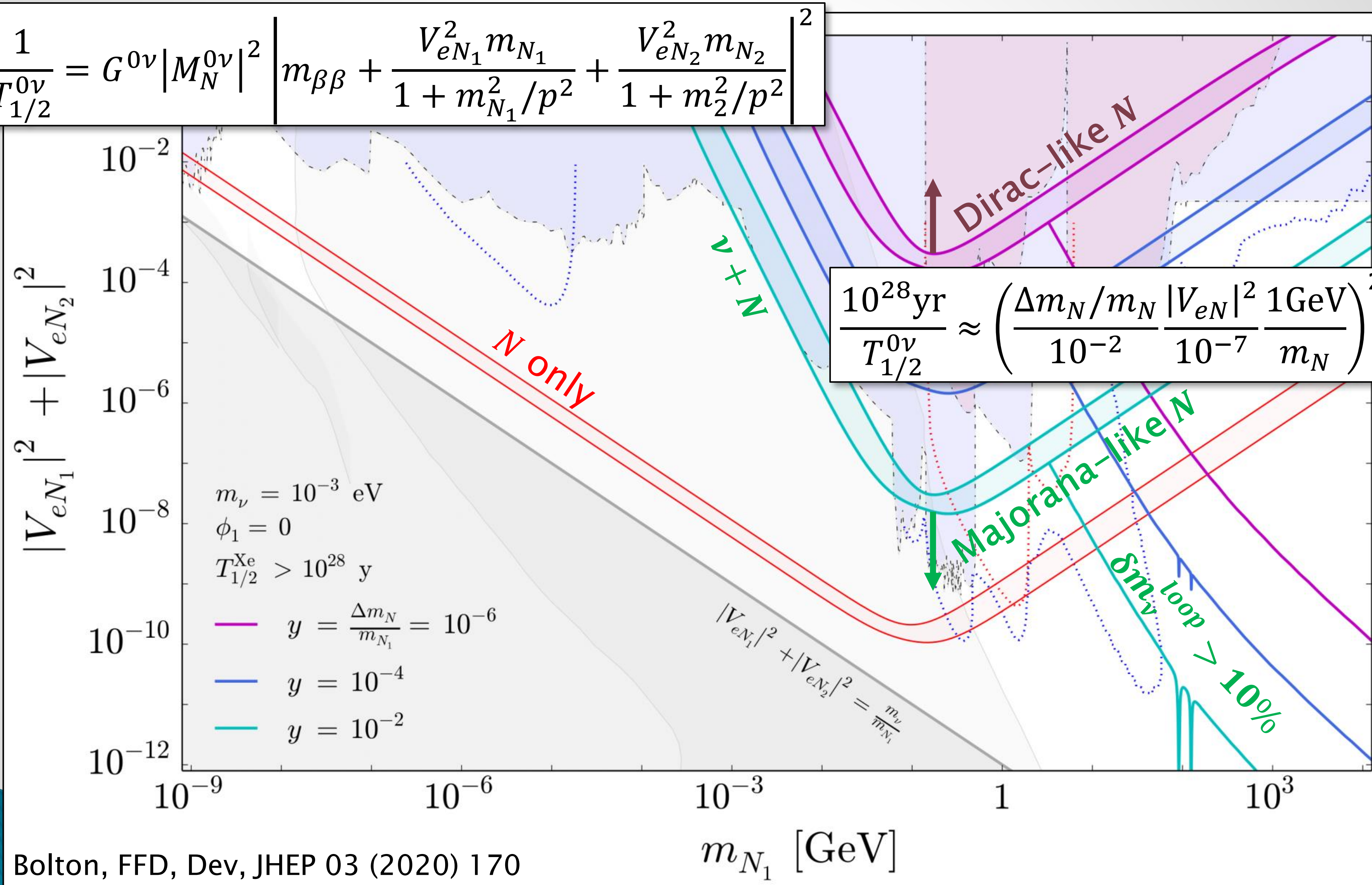
$$\frac{10^{28}\mathrm{yr}}{T_{1/2}^{0\nu}} \approx \left(\frac{\Delta m_N/m_N}{10^{-2}} \frac{|V_{eN}|^2}{10^{-7}} \frac{1\mathrm{GeV}}{m_N} \right)^2$$



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Sterile Neutrinos in χEFT

Dekens, de Vries, Mereghetti, Menéndez, Soriano, Zhou, Phys.Rev.C 108 (2023) 4, 045501

- Improved calculation based on chiral EFT
  - Enhanced contributions from soft and hard neutrino exchange
  - Inclusion of excited intermediate nucleus states
  - Smaller suppression of Seesaw cancellation term

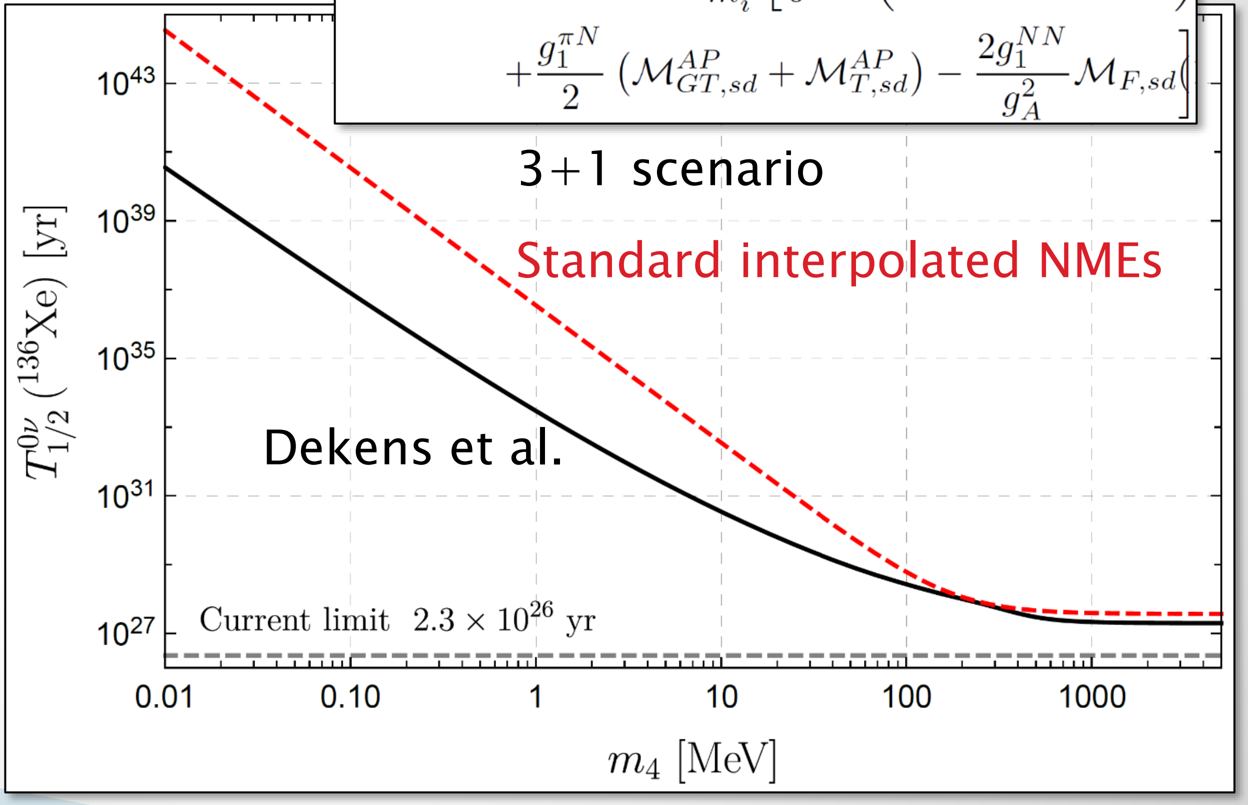
    $\frac{m_N^2}{k_F^2}$

    instead of

    $\frac{m_N^4}{k_F^4}$

    for $m_N \ll k_F$
  - Does not apply to bare sterile neutrino contrib.

$$A_\nu^{(9)} = -2\eta(\mu_0, m_i)\frac{m_\pi^2}{m_i^2}\Bigg[\frac{5}{6}g_1^{\pi\pi}\left(\mathcal{M}^{PP}_{GT,sd} + \mathcal{M}^{PP}_{T,sd}\right) + \frac{g_1^{\pi N}}{2}\left(\mathcal{M}^{AP}_{GT,sd} + \mathcal{M}^{AP}_{T,sd}\right) - \frac{2g_1^{NN}}{g_A^2}\mathcal{M}_{F,sd}\Bigg]$$



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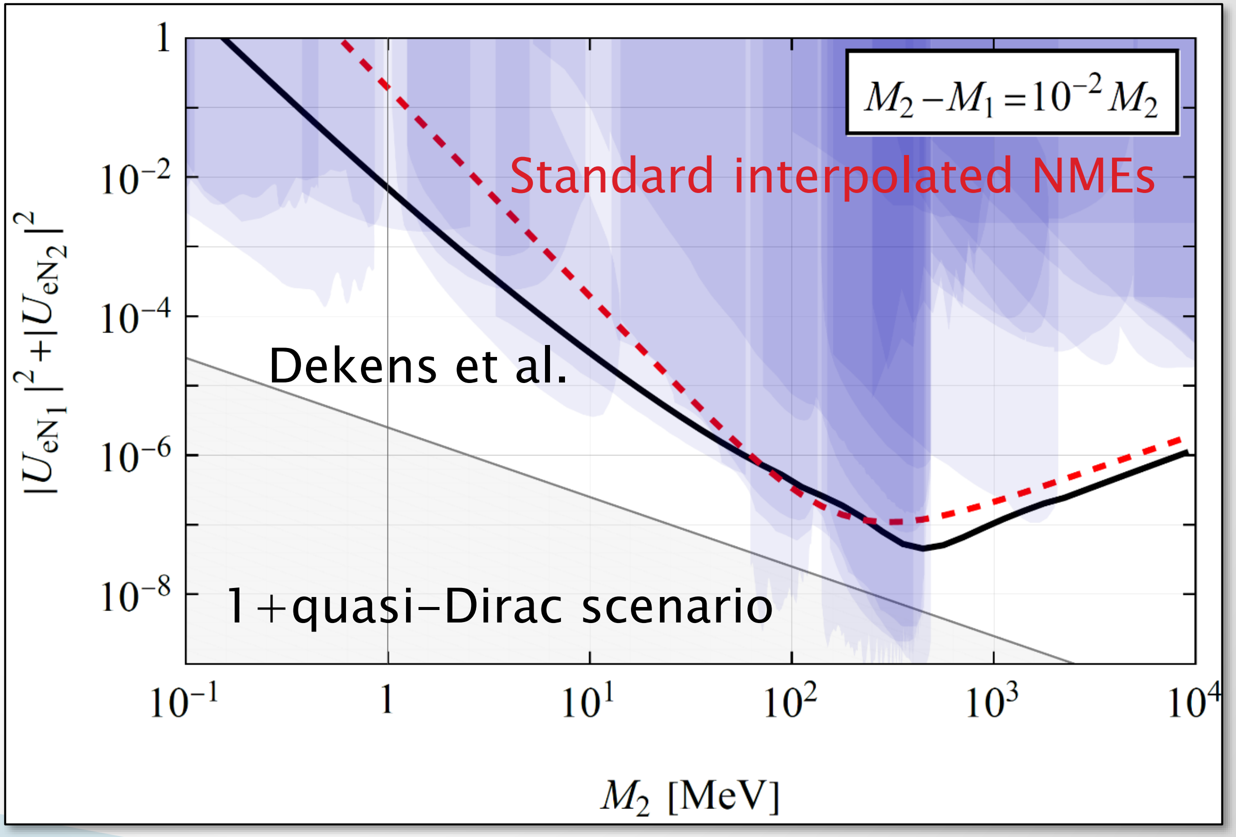

Complementarity with Direct Searches

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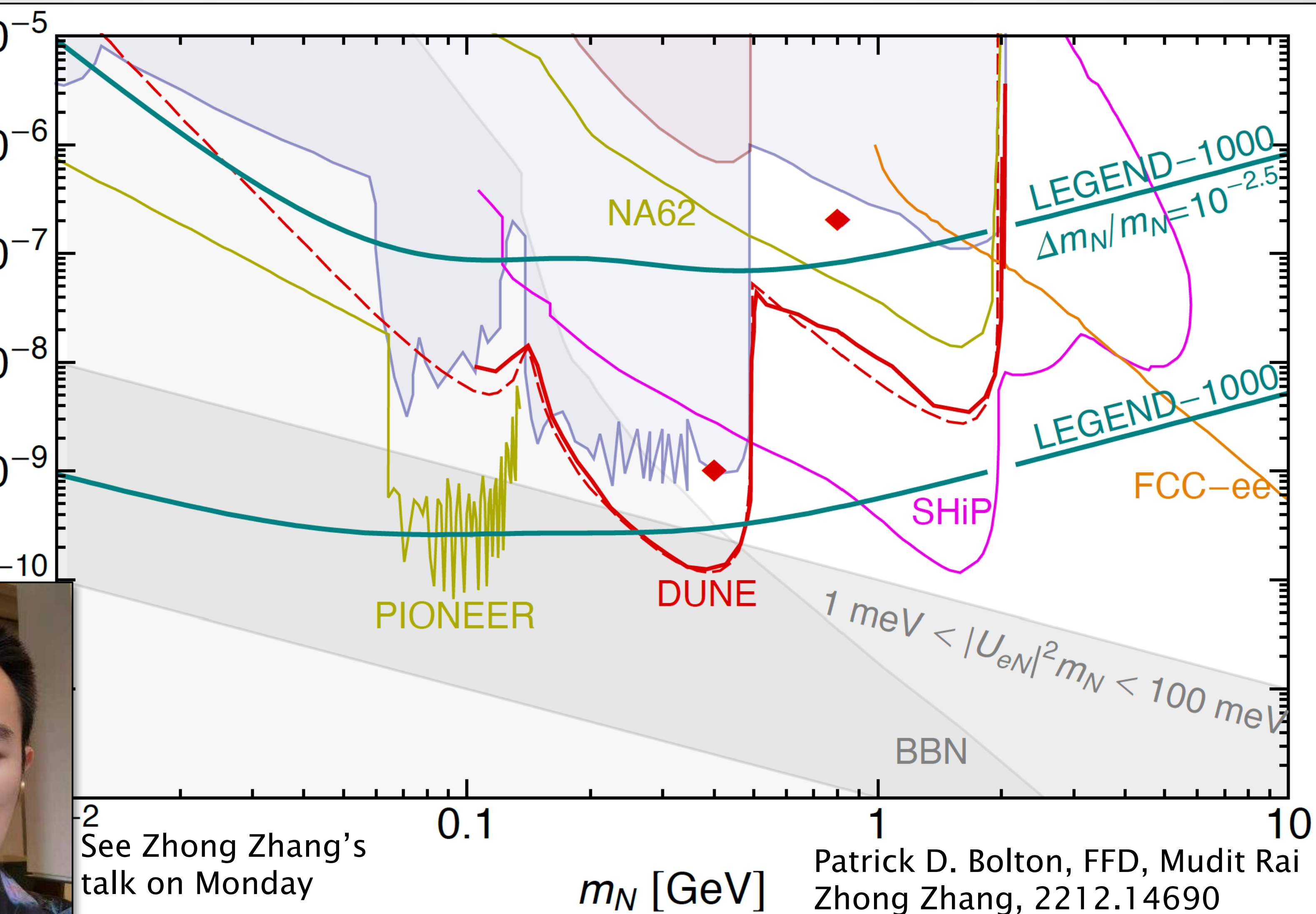

See Zhong Zhang's talk on Monday

Patrick D. Bolton, FFD, Mudit Rai Zhong Zhang, 2212.14690

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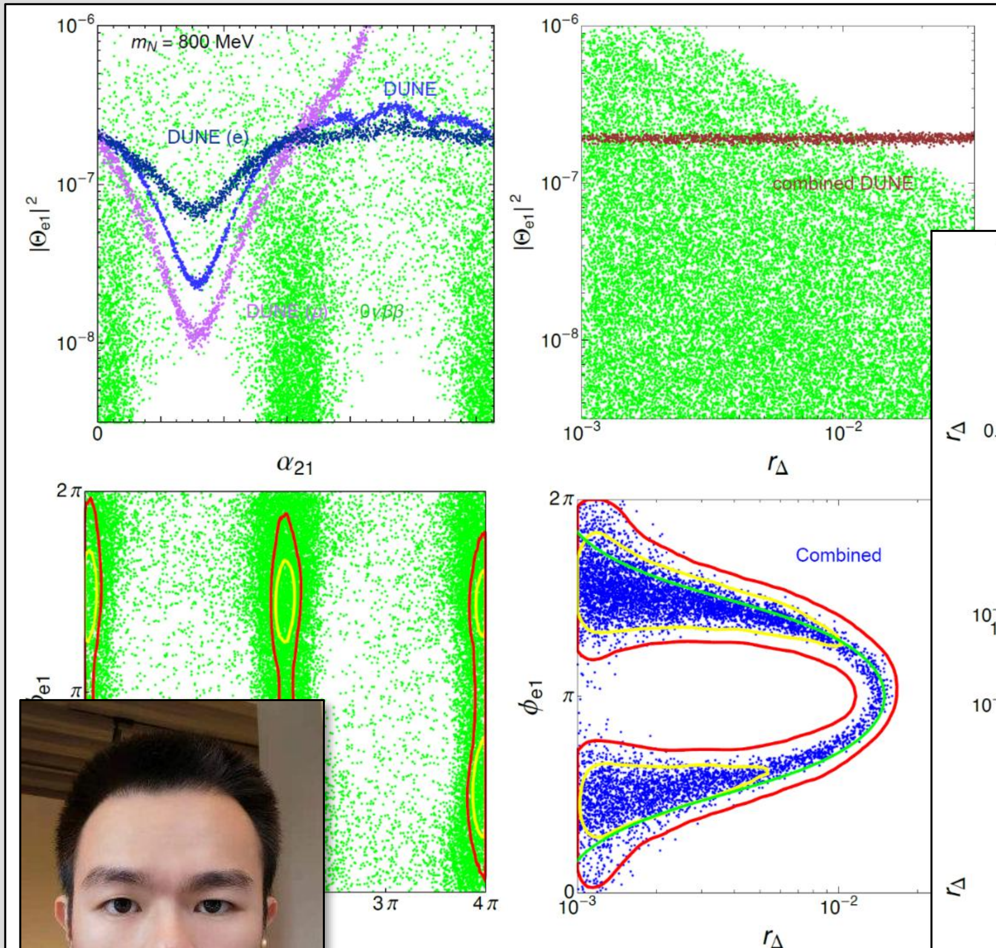

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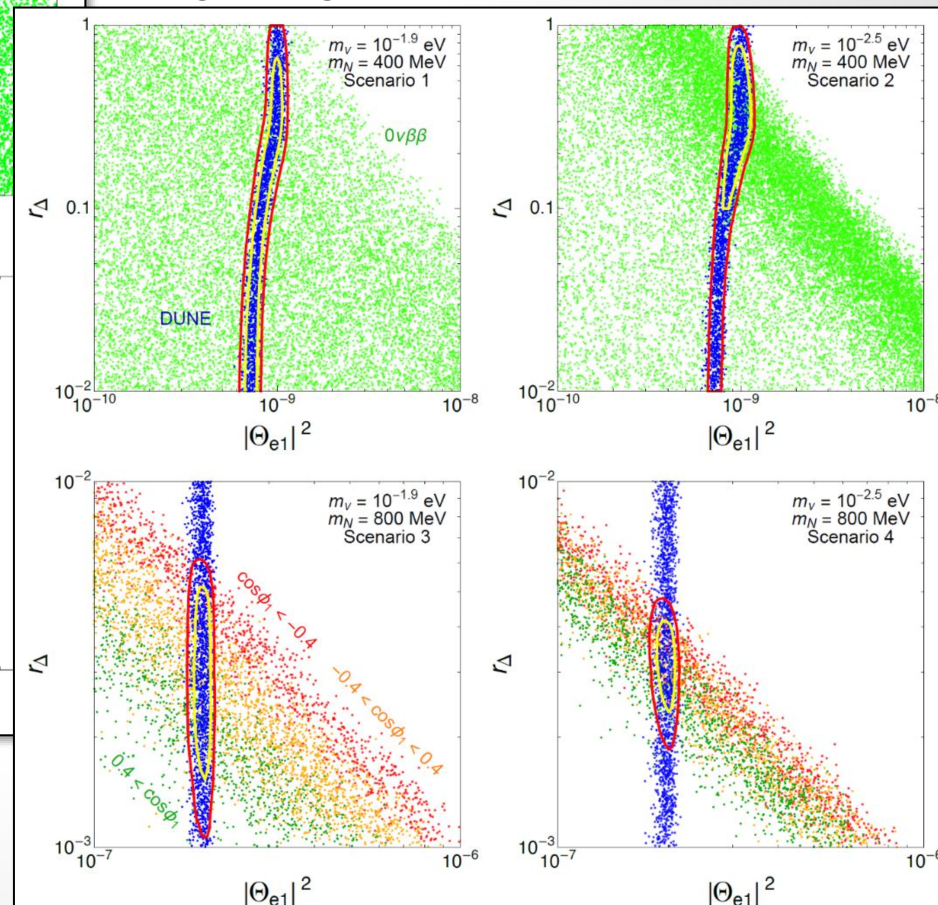

See Zhong Zhang's talk on Monday

Conclusion

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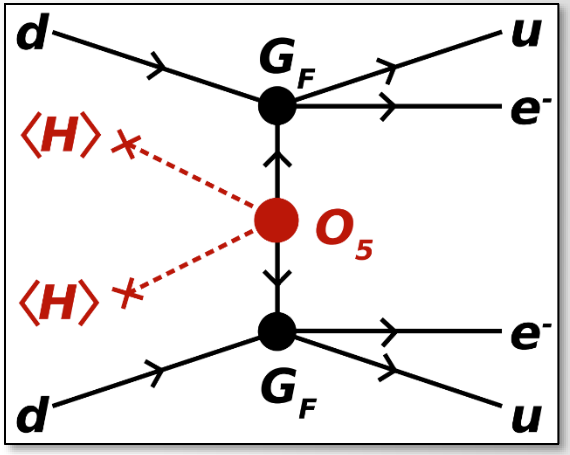
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Effective $0\nu\beta\beta$ mass $m_{\beta\beta} \approx 10 - 100$ meV probes New Physics near GUT scale
  - Sensitive to Majorana HNL for $0.1\ \text{eV} < m_N < 10\ \text{TeV}$
  - Sensitive to nature of HNL: Dirac vs Quasi-Dirac vs Majorana



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

- **HNLs aka sterile neutrinos are natural extension to SM**
  - Sensitivity in $0\nu\beta\beta$ and direct searches such as DUNE
  - Complementarity in probing properties of HNLs
  - Precise prediction of HNL contribution and interference with $m_{\beta\beta}$
  - Strong enhancement for "light" Seesaw with $m_N \ll 100$ MeV
  - Lifted $0\nu\beta\beta$ "floor"?

Conclusion

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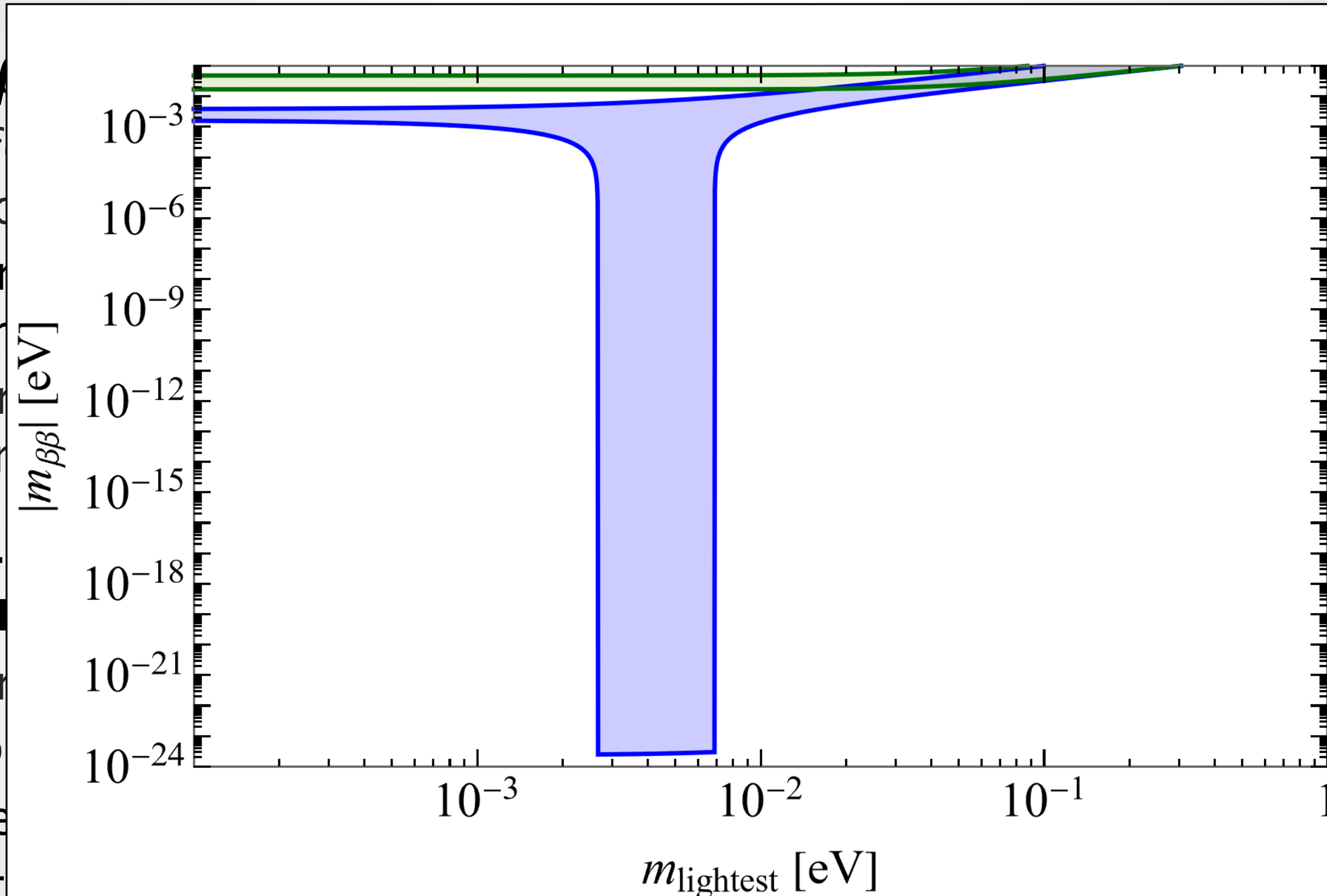
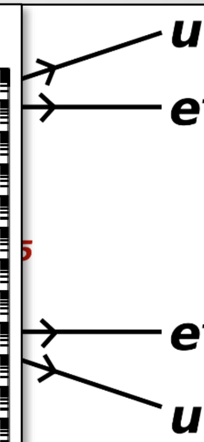
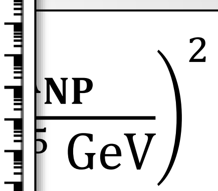
- $0\nu\beta$…
  - Eff…
    pro…
  - Ser…
    for…
  - Ser…
    Dir…
- HNL…
  natu…
  - Ser…
  - Co…
  - Pre… n $m_{\beta\beta}$
  - Str…
  - Lifted $0\nu\beta\beta$ "floor"?

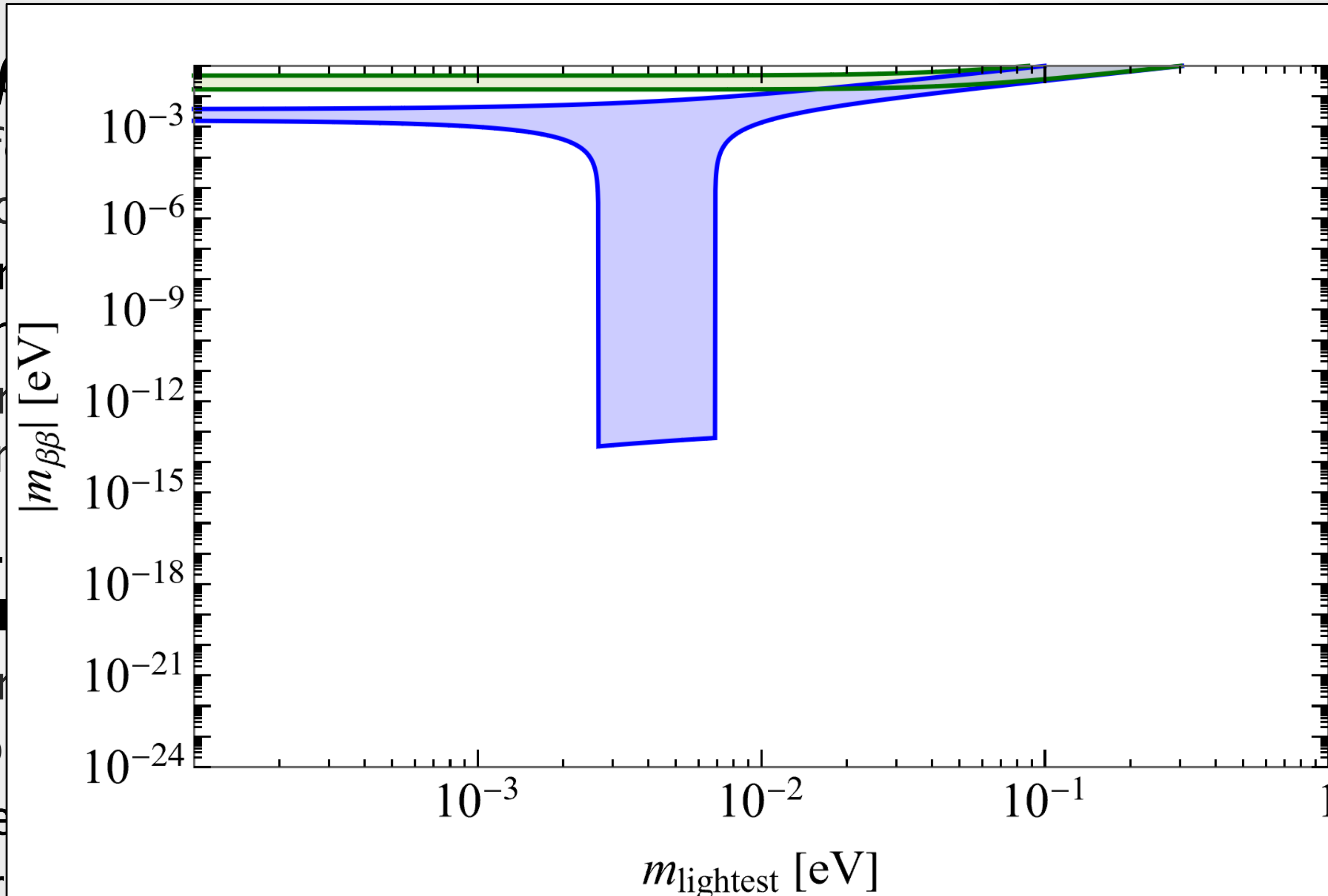


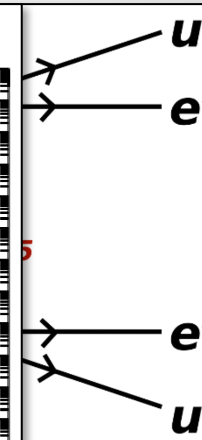




Conclusion

- **$0\nu\beta$**
  - Eff
    pro
  - Ser
    for
  - Ser
    Dir
- **HNL**
  natu
  - Ser
  - Co
  - Pre ... $m_{\beta\beta}$
  - Str
  - Lifted $0\nu\beta\beta$ "floor"?





NP ... GeV ... 2

Conclusion

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“Searching for sterile neutrinos at Christmas” according to Bing AI Image Generator