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Theoretical Overview of Double Beta Decay

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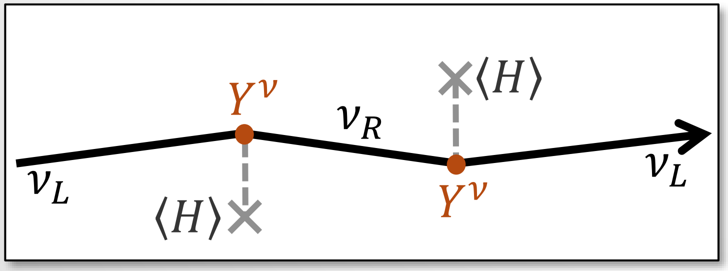
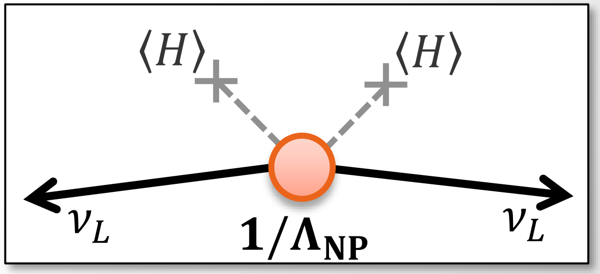
Dirac versus Majorana

- 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



Dirac versus Majorana

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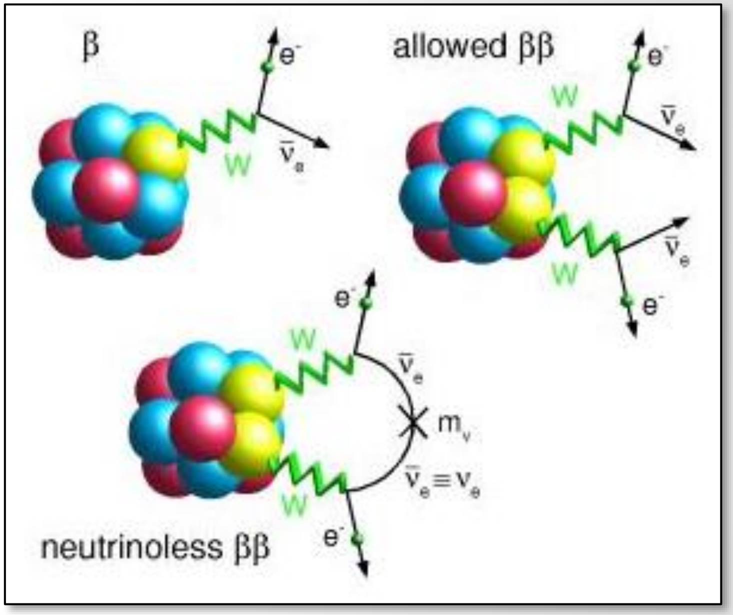
- Origin of neutrino masses beyond the Standard Model
- Crucial role of total lepton number L symmetry
  - Arises accidentally as global $U(1)_L$ in SM from particle content and gauge symmetry
  - L broken non-perturbatively but $B - L$ conserved
  - Global symmetries expected to be broken gravitational effects?

$$m_\nu \approx \frac{v^2}{M_{\text{Planck}}} \approx 10^{-5}\ \text{eV}$$

  - Too small to explain oscillations but too large as subdominant splitting
  - Connection to matter-antimatter asymmetry
    - Leptogenesis through heavy neutrinos in Type-I Seesaw

Beta Decays and Neutrinos

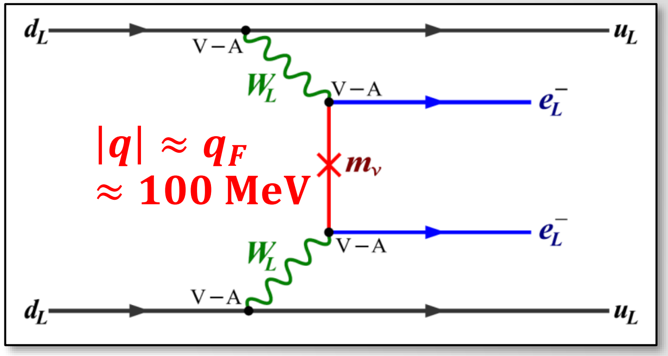
- Single beta decay
  $$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$$
  - Kinematic neutrino mass measurement
- Allowed double beta ($\mathbf{2\nu\beta\beta}$) decay
  $$(A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($\mathbf{0\nu\beta\beta}$) decay
  $$(A,Z) \to (A,Z+2) + 2e^-$$
  -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



Neutrinoless Double β Decay

- Half-life

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



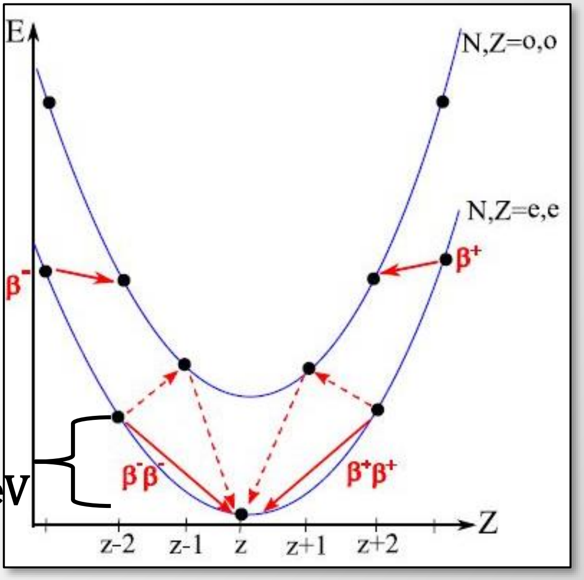
- Particle Physics

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

- Atomic Physics
  - Leptonic phase space $G^{0\nu} \propto Q^5$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu} \approx 1$ but large uncertainties, factor 2–3

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

$Q + 2m_e$
$\approx$ 3–5 MeV



Three Active Neutrinos

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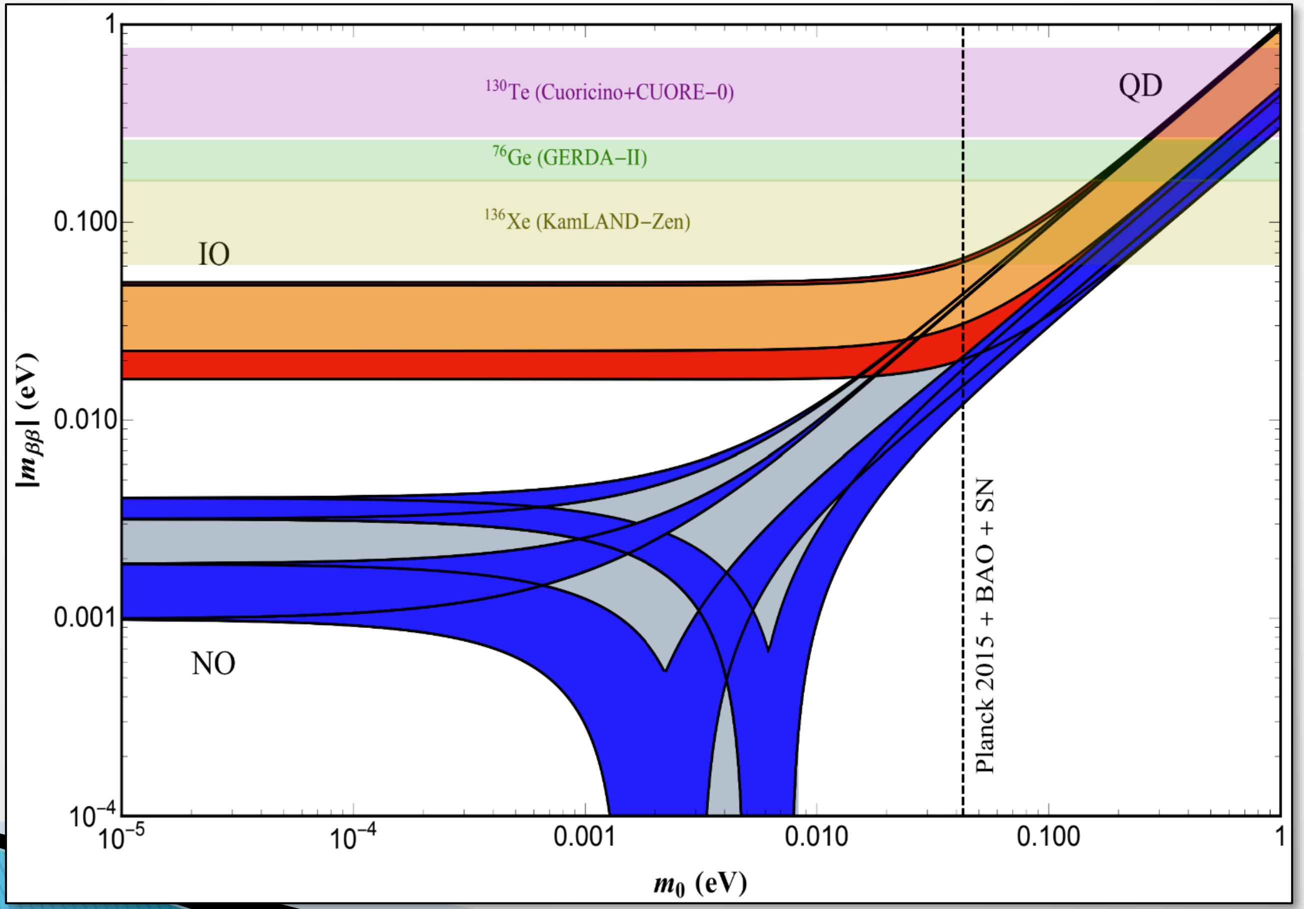
- Effective $0\nu\beta\beta$ Mass

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

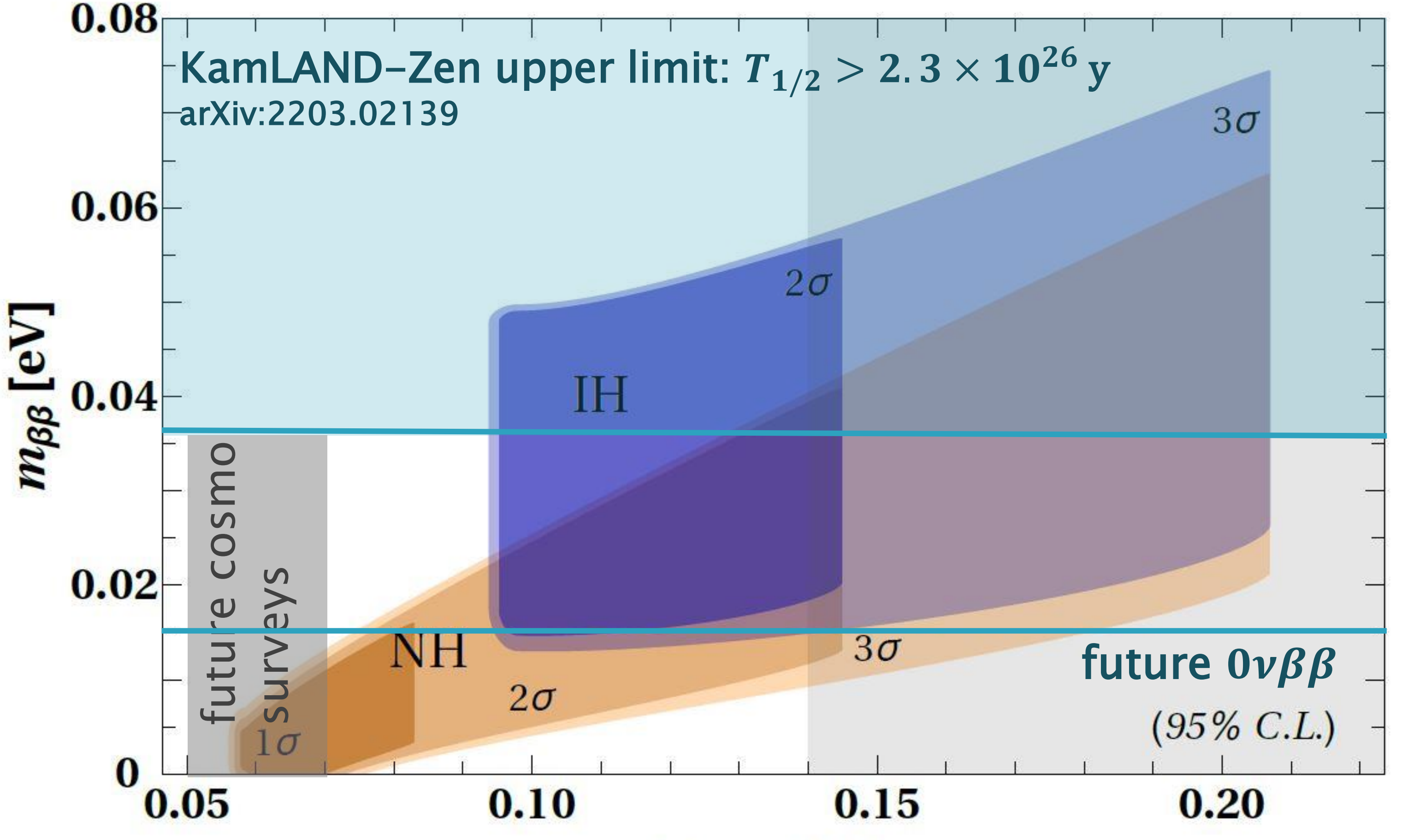
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}| \approx m_\nu \sqrt{1 - \sin^2(2\theta_{12})\sin^2(\phi_{12}/2)}$$



Hagedorn et al.,
Int.J.Mod.Phys.A 33 (2018) 05n06, 1842006

Three Active Neutrinos

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



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

Heavy Sterile Neutrinos

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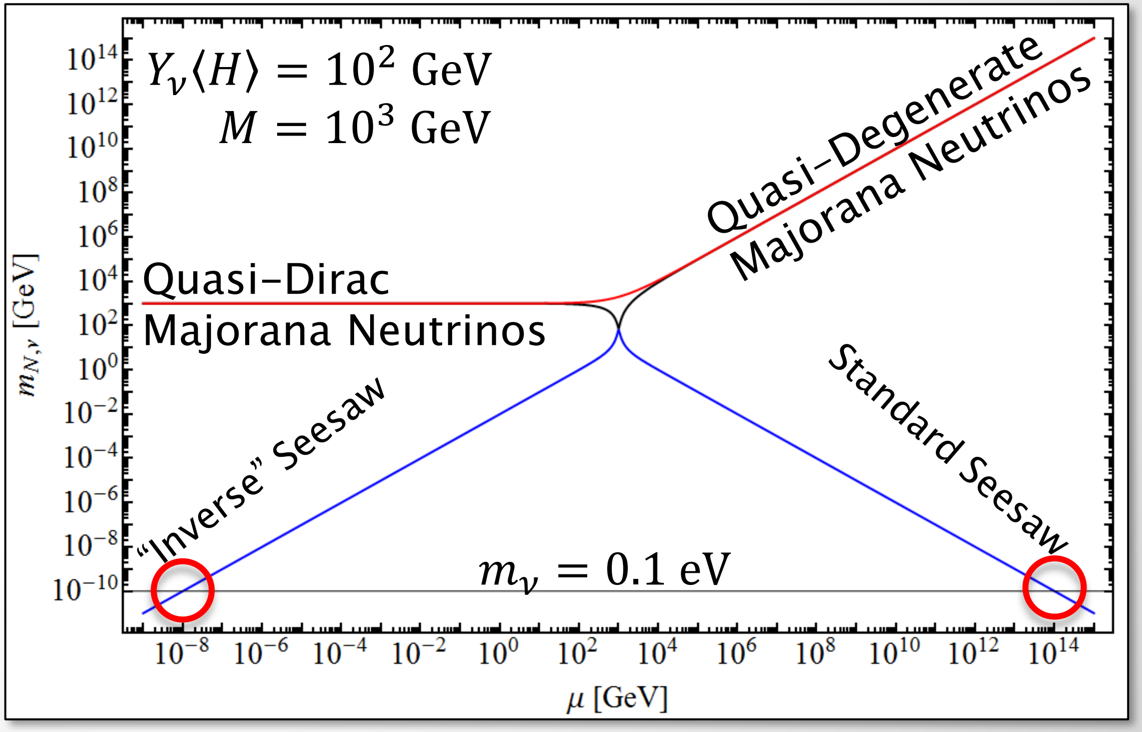
- Correct light neutrino masses for TeV scale heavy neutrinos
  - Seesaw Mechanism with TeV scale heavy neutrinos
    - Standard Seesaw with small Yukawa couplings
    - CLFV remains small

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

  - "Bent" Seesaw mechanisms
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

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

    - Potentially large CLFV
    - In the limit $\mu \to 0$, no LNV but CLFV



Sterile Neutrinos

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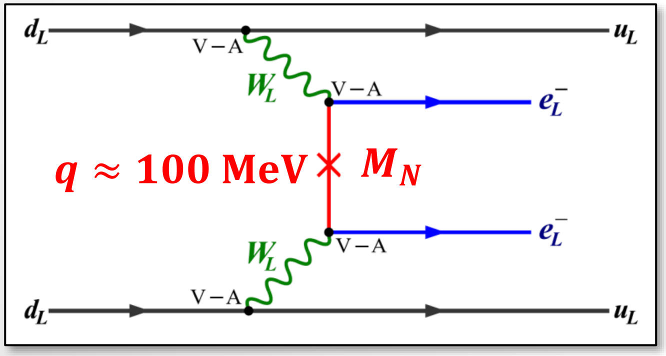
- Masses lighter than ≈ 100 MeV

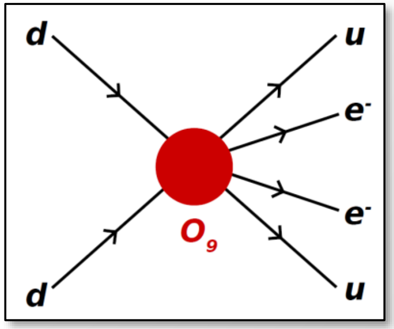
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}} + s_{14}^2 m_{\nu_4} e^{i\phi_{14}} + \cdots|$$

- Masses heavier than ≈ 100 MeV

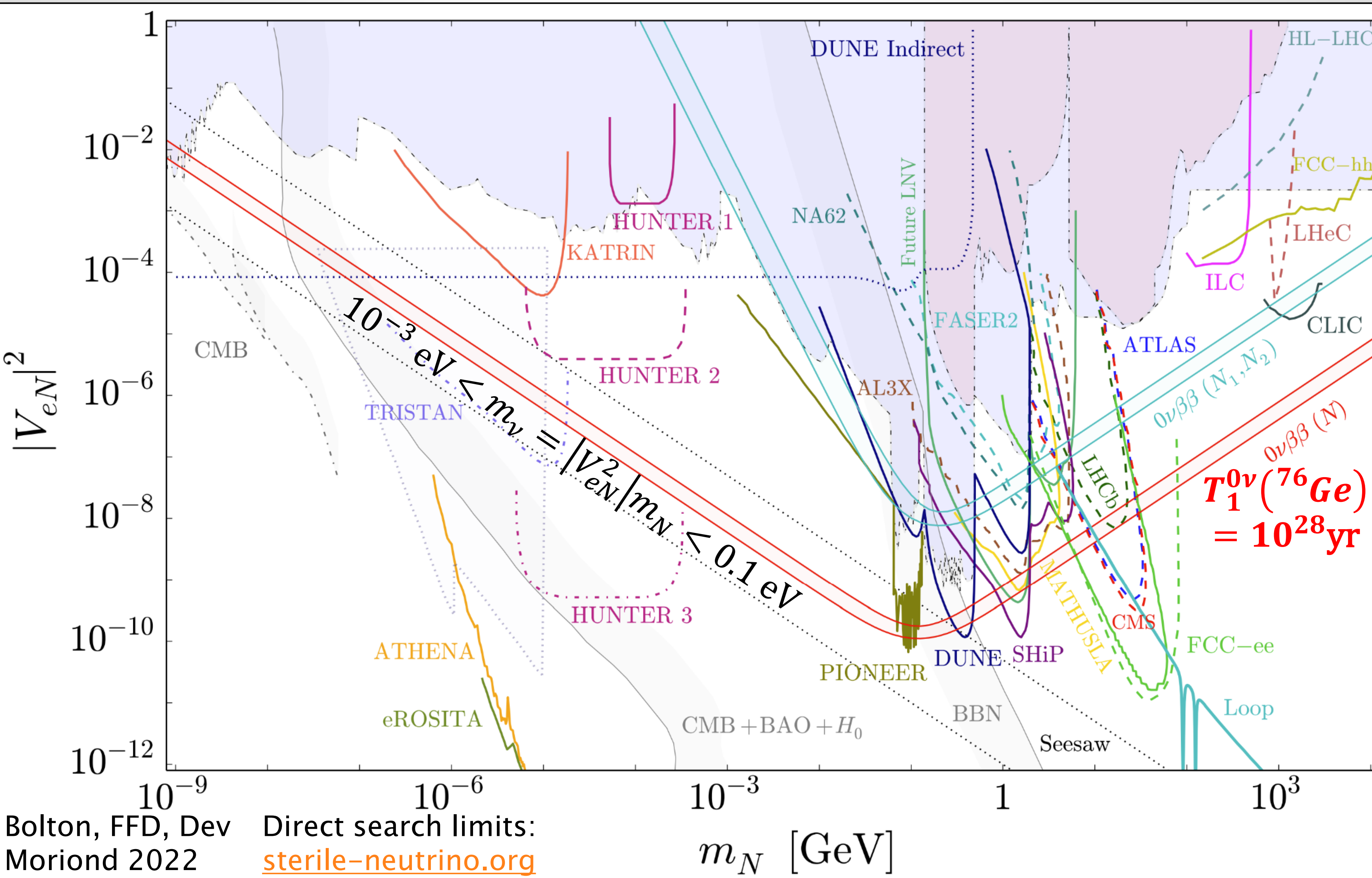
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4} \sum_{i=1}^{3} \frac{V_{ei}^2}{M_{N_i}} \rightarrow \left\langle \frac{1}{M_N} \right\rangle_{\beta\beta}$$

- Short-distance on nuclear scale





HNL – Future Sensitivities

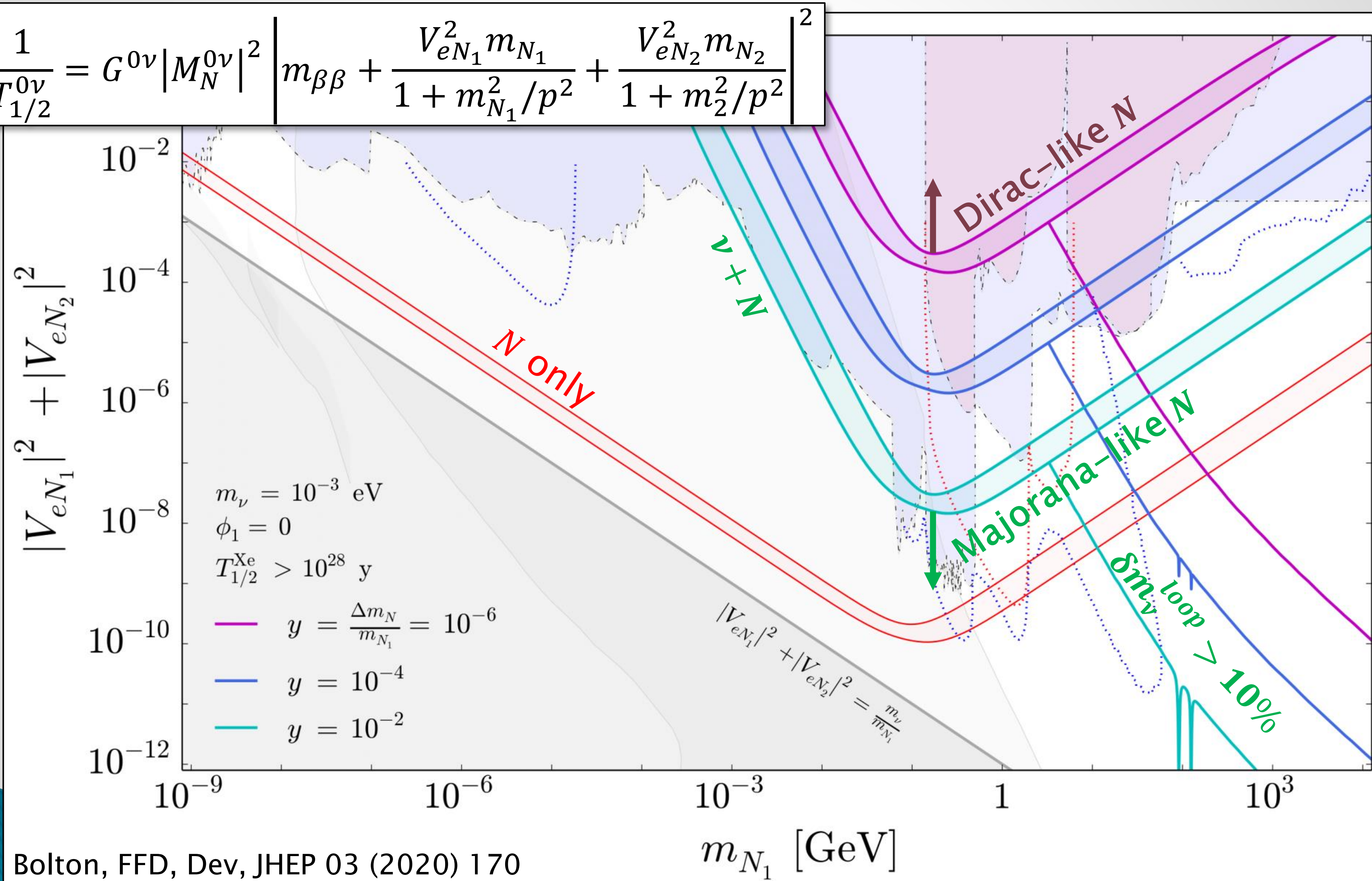


Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

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

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

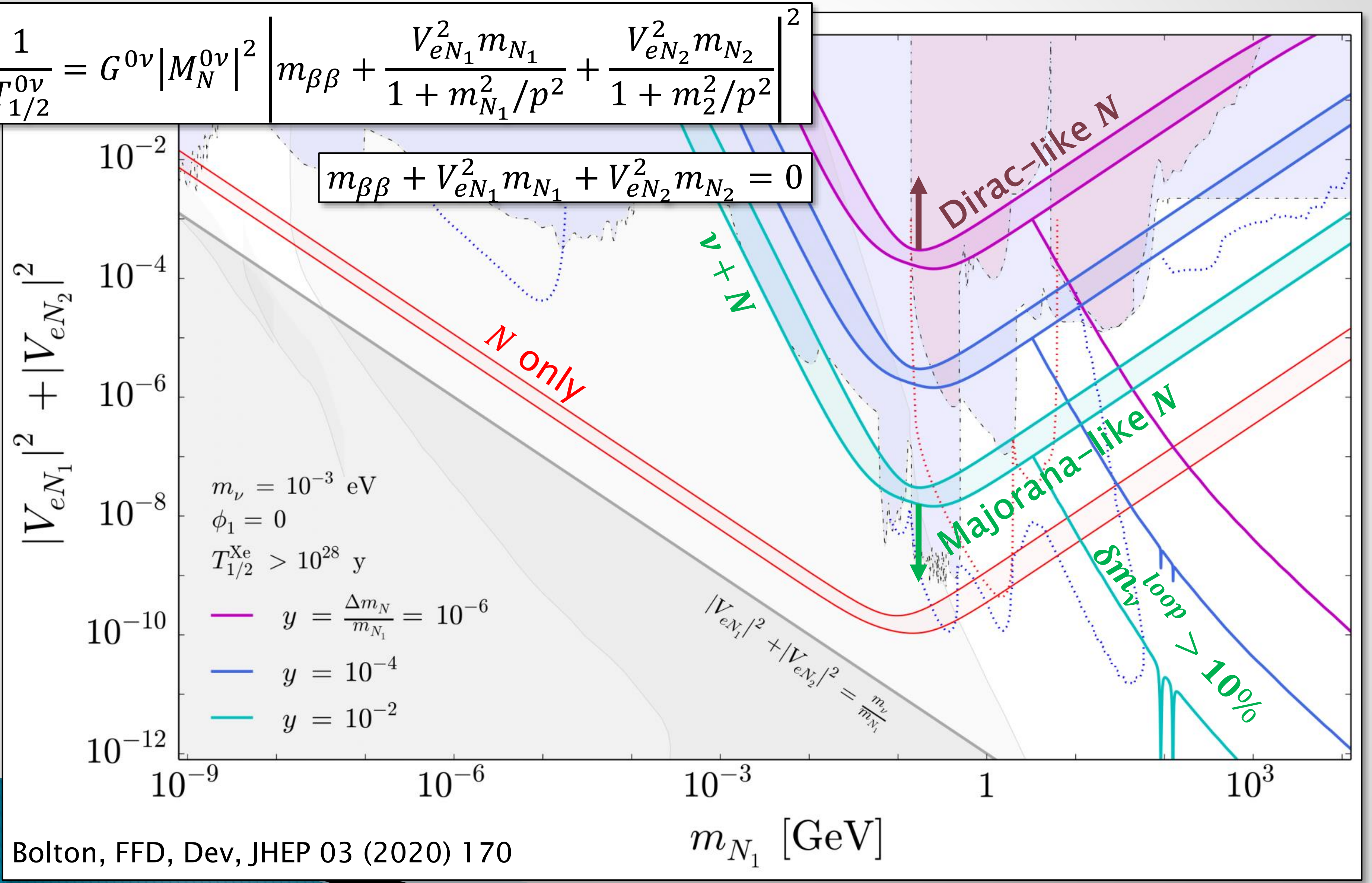


Bolton, FFD, Dev, JHEP 03 (2020) 170

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

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

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



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

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

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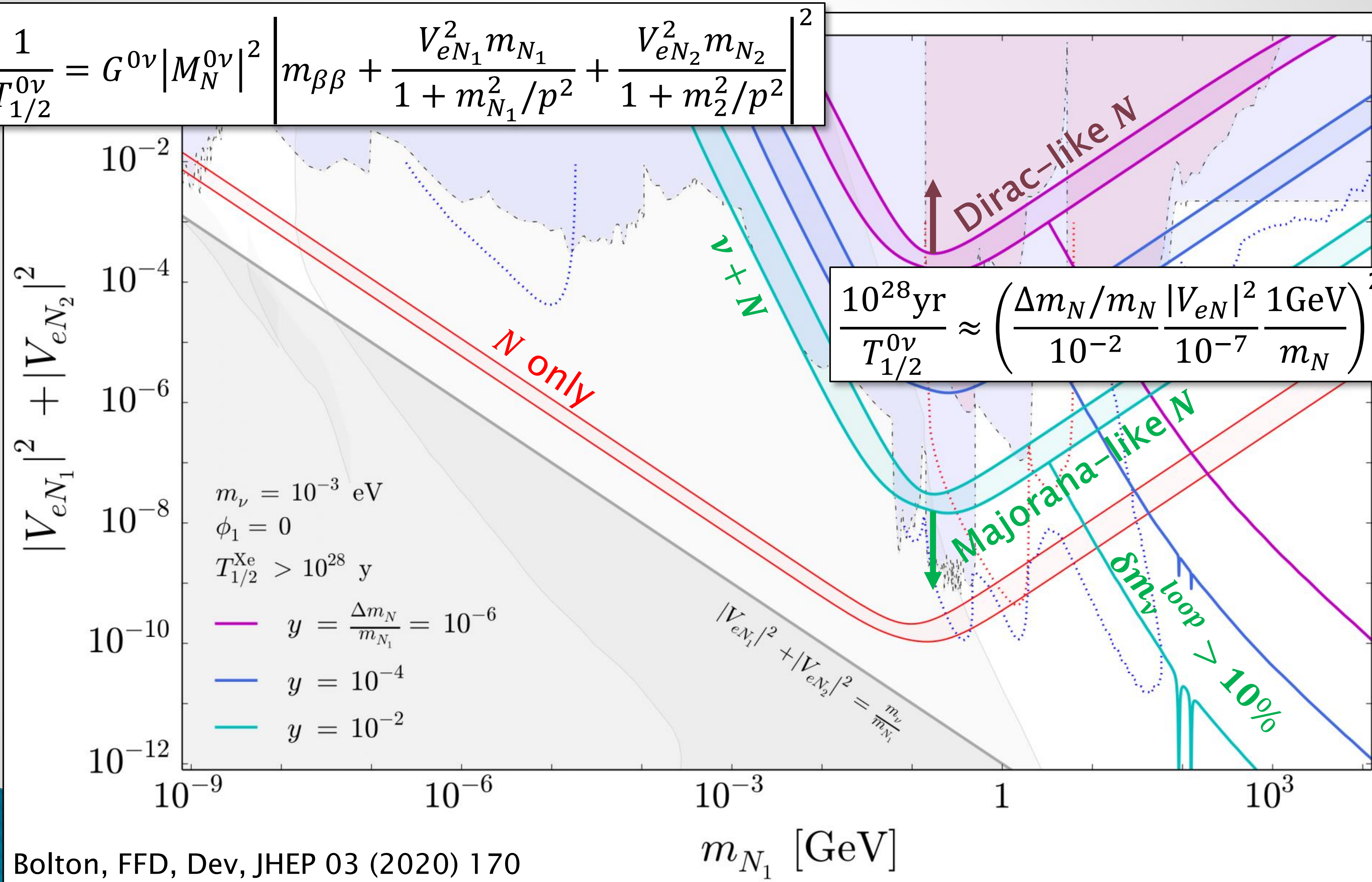
$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}\left|M_N^{0\nu}\right|^2 \left| m_{\beta\beta} + \frac{V_{eN_1}^2 m_{N_1}}{1 + m_{N_1}^2/p^2} + \frac{V_{eN_2}^2 m_{N_2}}{1 + m_2^2/p^2} \right|^2$$

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

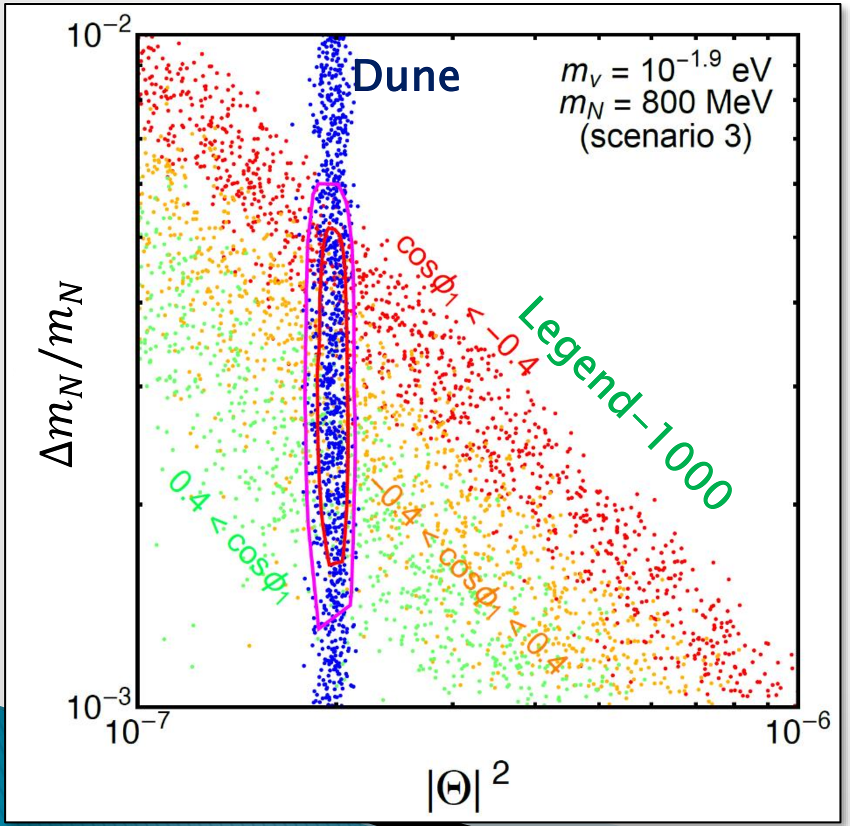


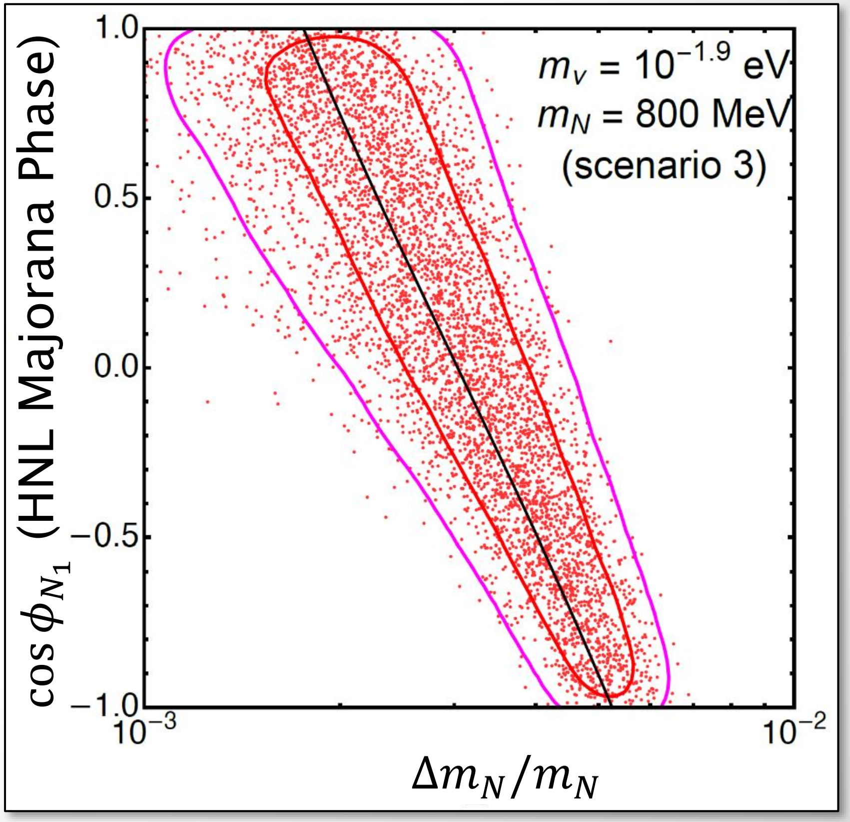
Bolton, FFD, Dev, JHEP 03 (2020) 170

Complementarity

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

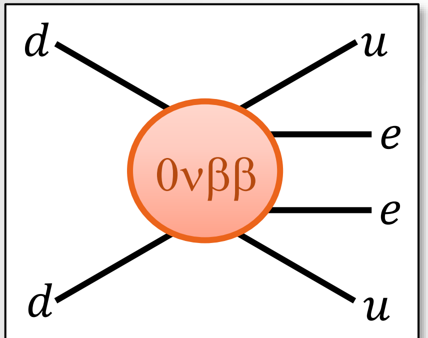
- Between direct searches and $0\nu\beta\beta$
  - Simulation of DUNE-like setup
  - Measurement of events at "DUNE" and $0\nu\beta\beta$ decay at LEGEND-1000 near expected sensitivity





New Physics and $0\nu\beta\beta$

- Plethora of New Physics scenarios



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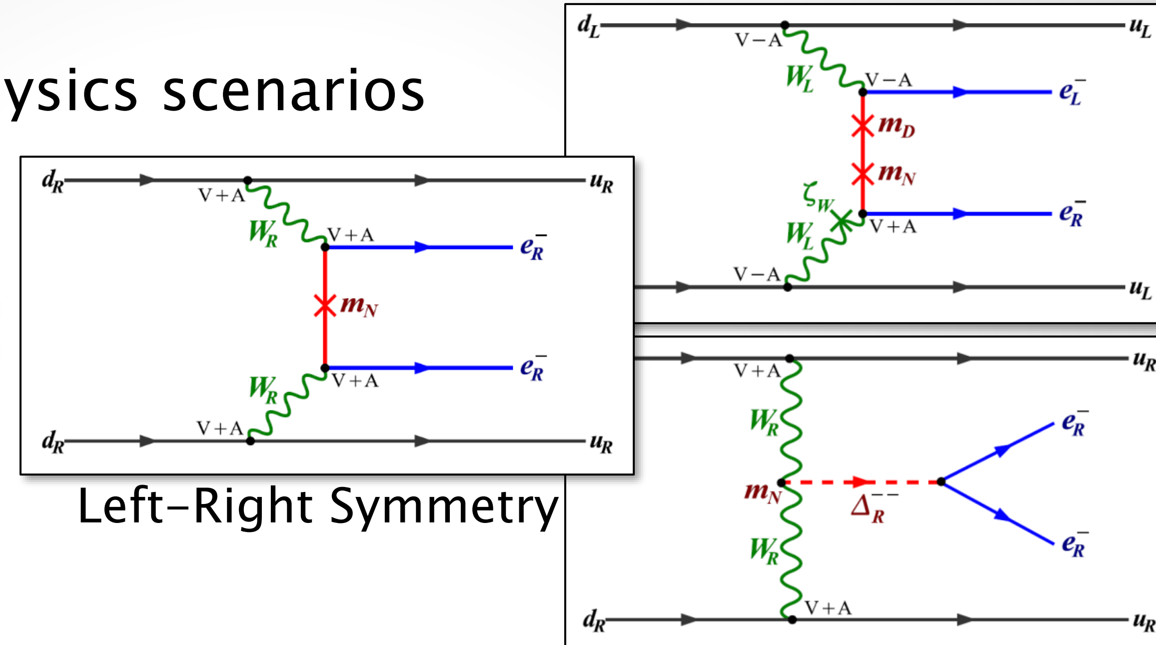
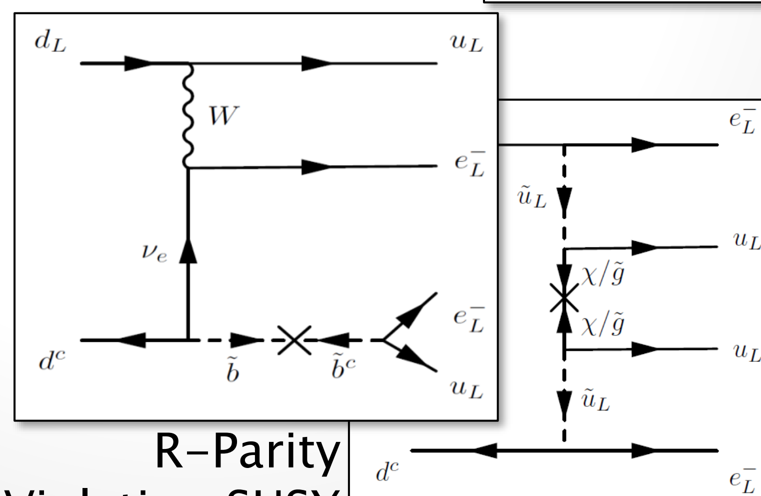


Left-Right Symmetry

$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$



R-Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

…

New Physics and $0\nu\beta\beta$

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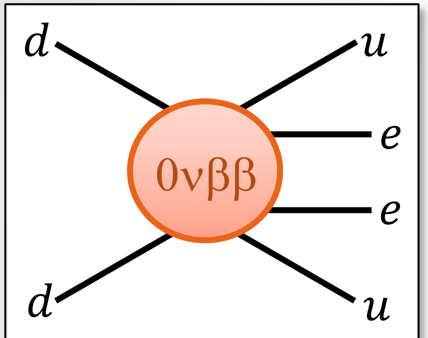
- Plethora of New Physics scenarios



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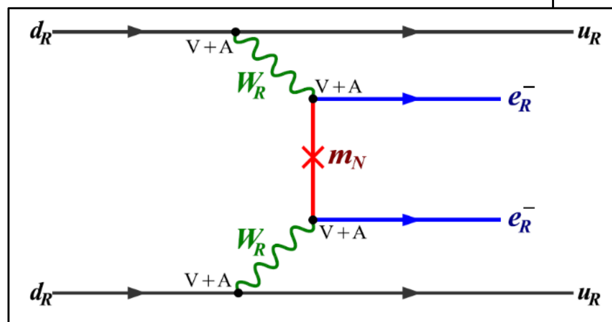
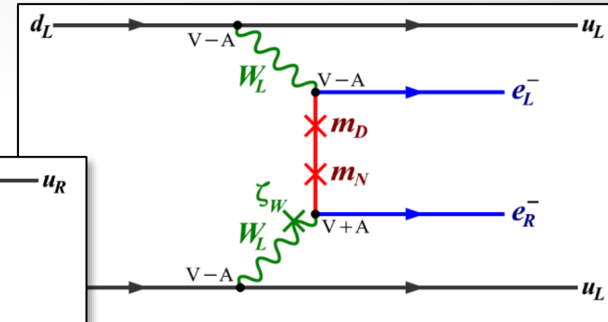
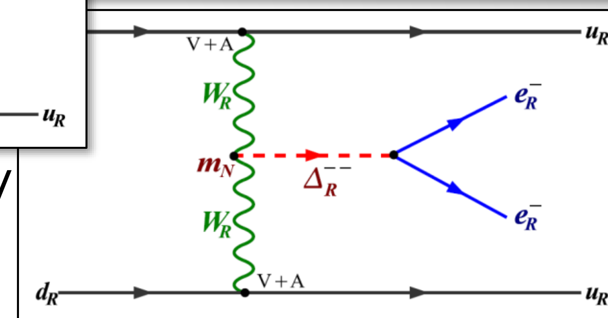


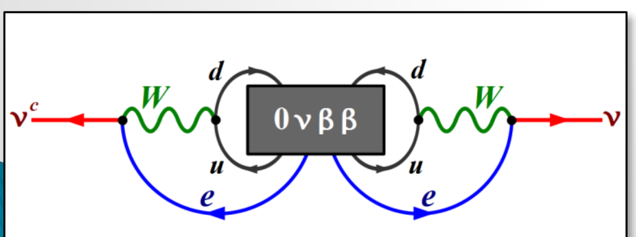


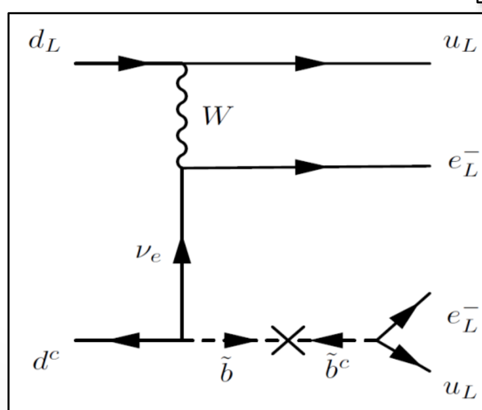


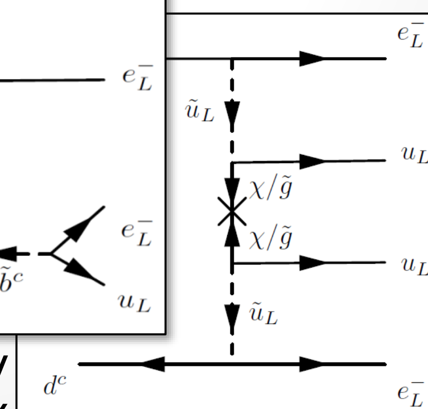
Left–Right Symmetry

$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left|M_{NP}^{0\nu}\right|^2$$

- Neutrinos still Majorana
  Schechter, Valle
  Phys. Rev. D25 (1982) 2951







R–Parity Violating SUSY

Extra Dimensions

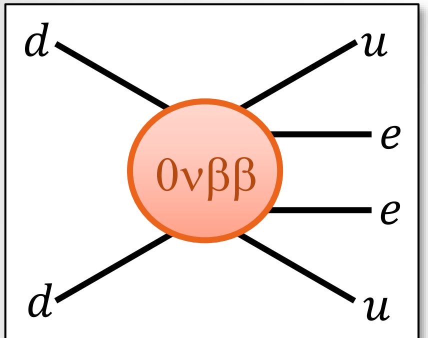
Majorons

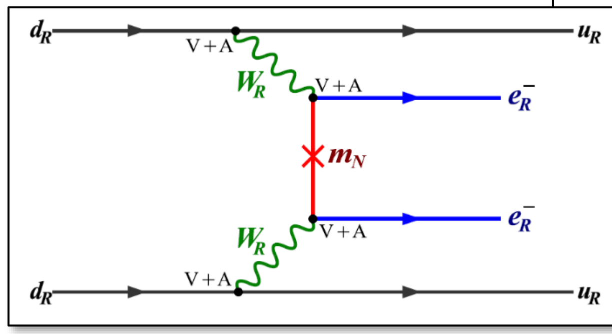
Leptoquarks

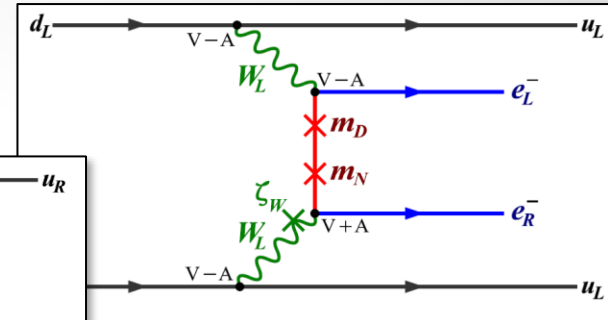
…

New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry





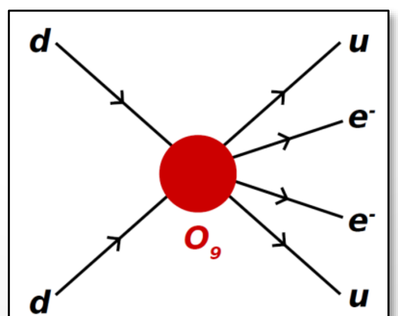


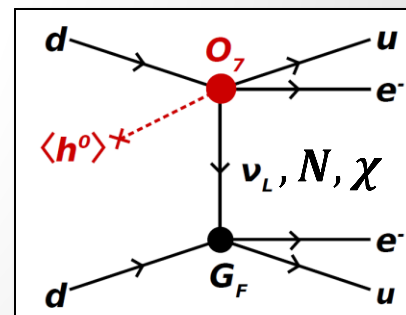
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left|M_{NP}^{0\nu}\right|^2$$

$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \mathrm{TeV})^5}$$

$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan\zeta_W \approx \frac{10^{-9}}{(\Lambda/10\ \mathrm{TeV})^3}$$

- $0\nu\beta\beta$ probes LNV at the TeV scale and above

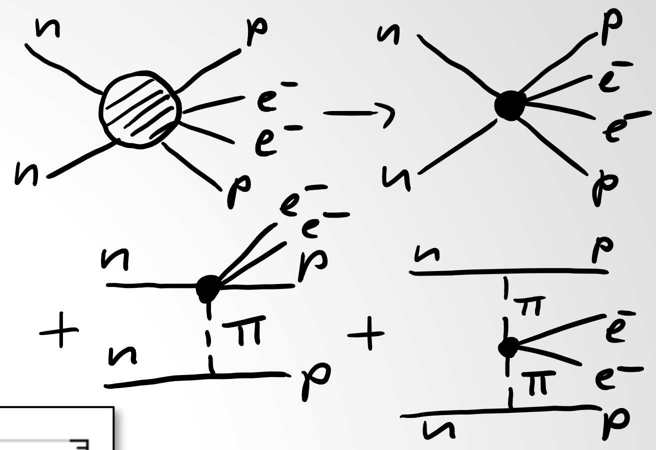


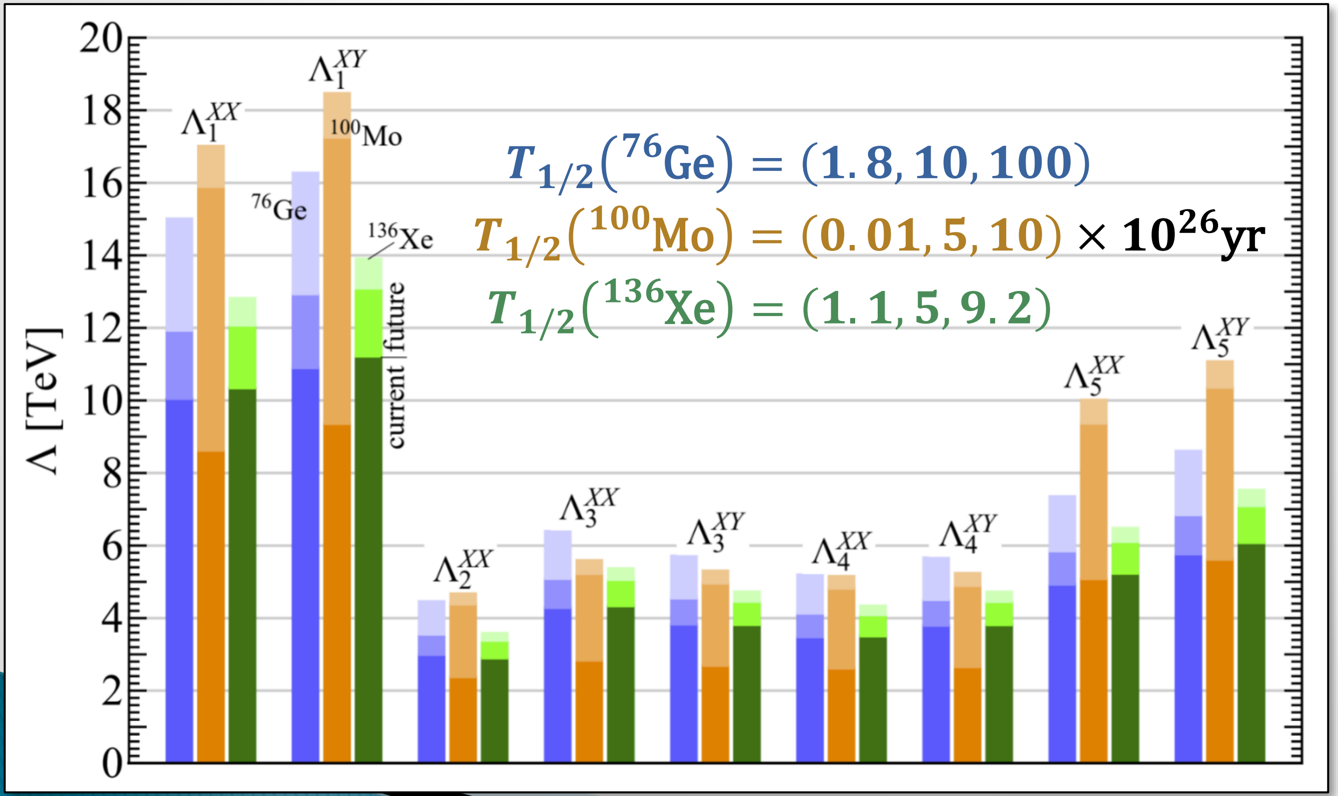


Heavy New Physics

FFD, Graf, Iachello, Kotila, PRD 102 (2020)

- Limits on short-range operators
  - NMEs from IBM-2 with $g_A = 1.0$ and short-range correlations in Argonne parametrization





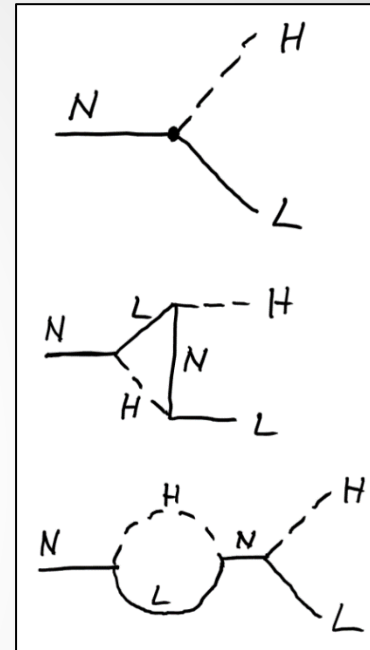
Pion-mediated contributions

- R-parity violating SUSY (Faessler, Kovalenko, Simkovic, Schwieger, Phys.Rev.Lett. 78 (1997) 183)
- Chiral EFT with Pion operators from Lattice QCD (Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 1812 (2018) 097)

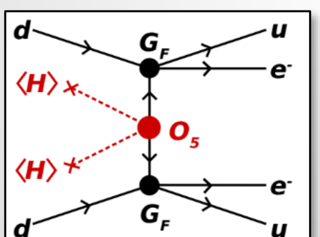
Falsifying Baryogenesis

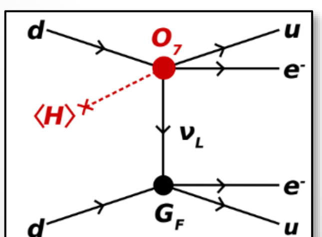
- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\,\mathrm{GeV}$
    - Observed asymmetry

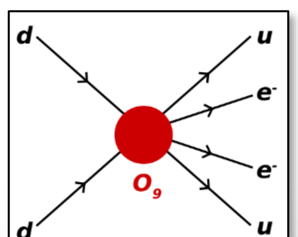
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$

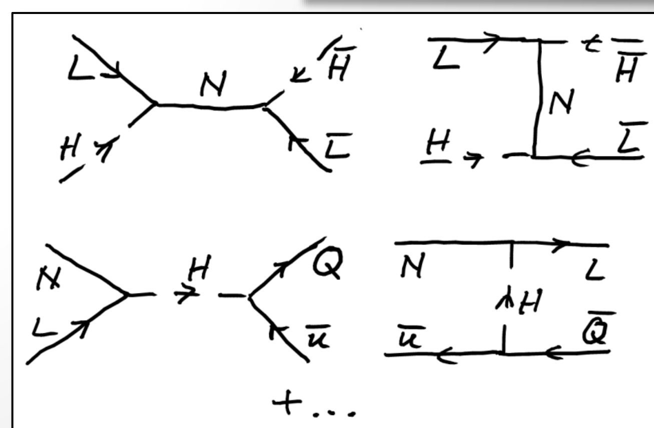


- What if we observe lepton number violating processes in $0\nu\beta\beta$?



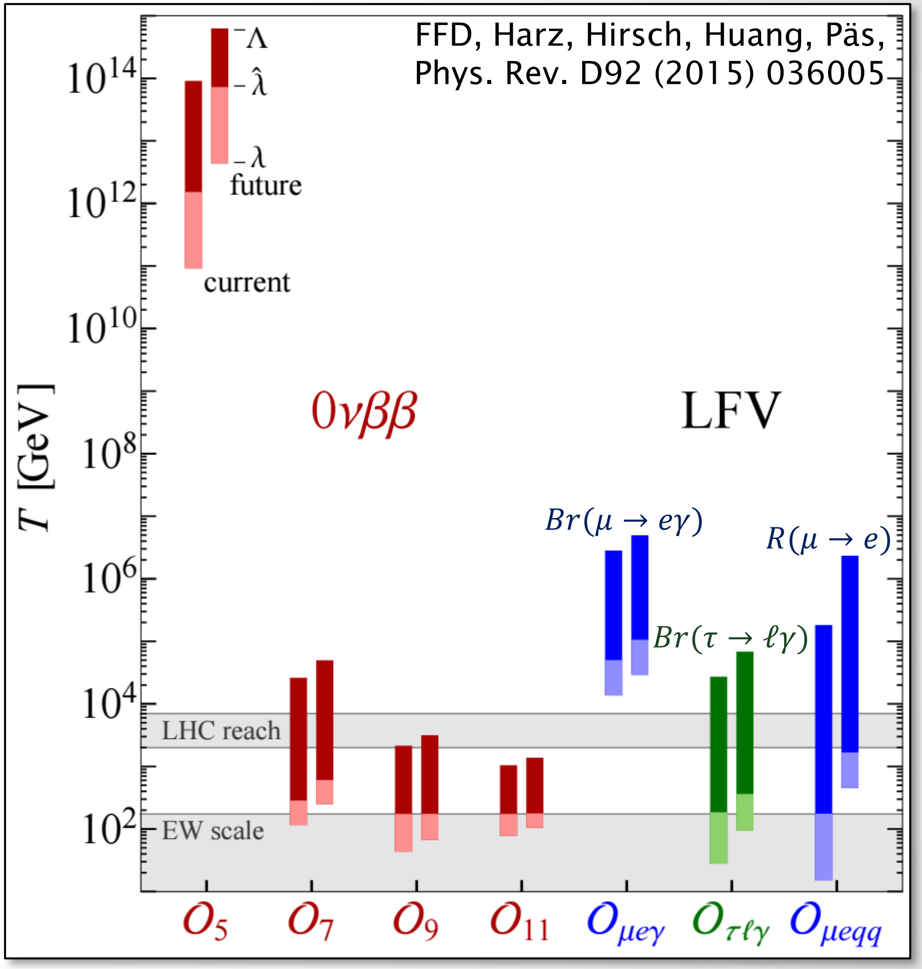






Falsifying Baryogenesis

- Temperature ranges of strong equilibration
  - **Assumes observation of corresponding process!**
- Observation of LNV
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**



Conclusion

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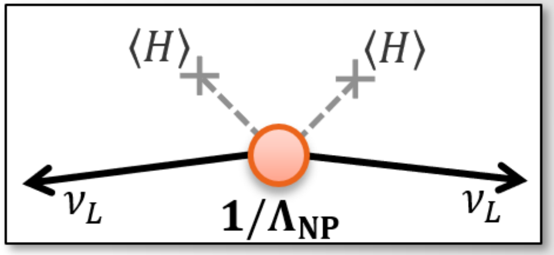
- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Determination of absolute mass scale
- **$0\nu\beta\beta$ crucial probe for BSM physics**
  - Universal probe of LNV physics
    - LNV physics near GUT scale
    - Direct sensitivity to LNV physics at scales $m_N \approx 1\ \mathrm{eV} - 100\ \mathrm{TeV}$
    - Light exotic particles
  - Sensitive to CP properties of light and GeV-scale ν



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

- **$2\nu\beta\beta$ sensitive to New Physics**
  - Ongoing and future searches probe $2\nu\beta\beta$ decay with high statistics
  - E.g., exotic (right-handed) currents, ν self-interactions, sterile ν mass endpoint