Limits on New Physics models from present $0\nu\beta\beta$ results

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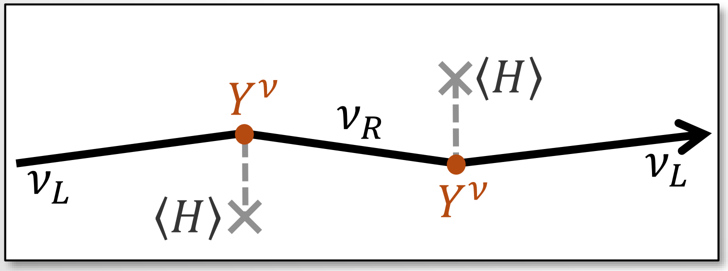
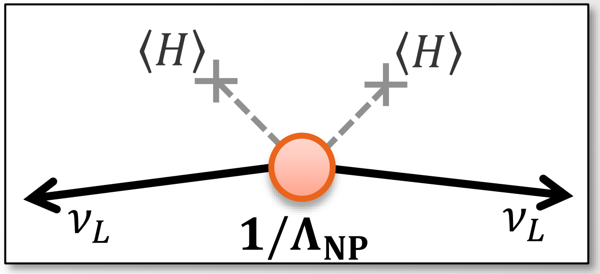
Dirac vs Majorana

- 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 vs Majorana

- 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
  - Already broken non-perturbatively with $B - L$ remaining conserved
  - Global symmetries expected to be broken gravitational effects? Naïve expectation:

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

  - Too small to explain oscillations but too large as subdominant splitting

Neutrinoless Double Beta Decay

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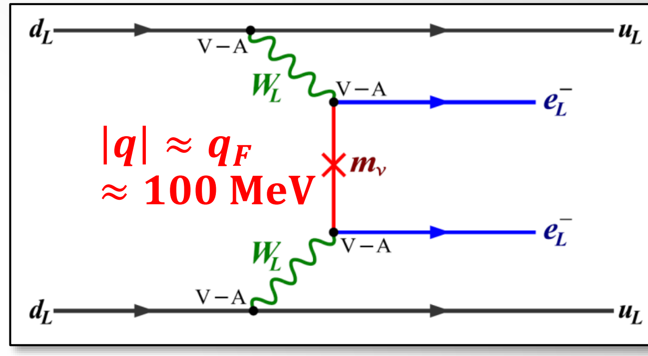
- Half-life

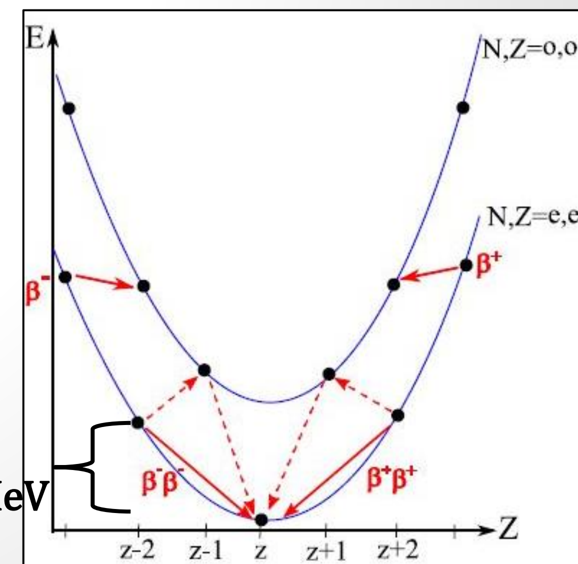
$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$$



- Particle Physics

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

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



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

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

$\boldsymbol{Q + 2m_e}$
$\boldsymbol{\approx 3–5}$ **MeV**

Three Active Neutrinos

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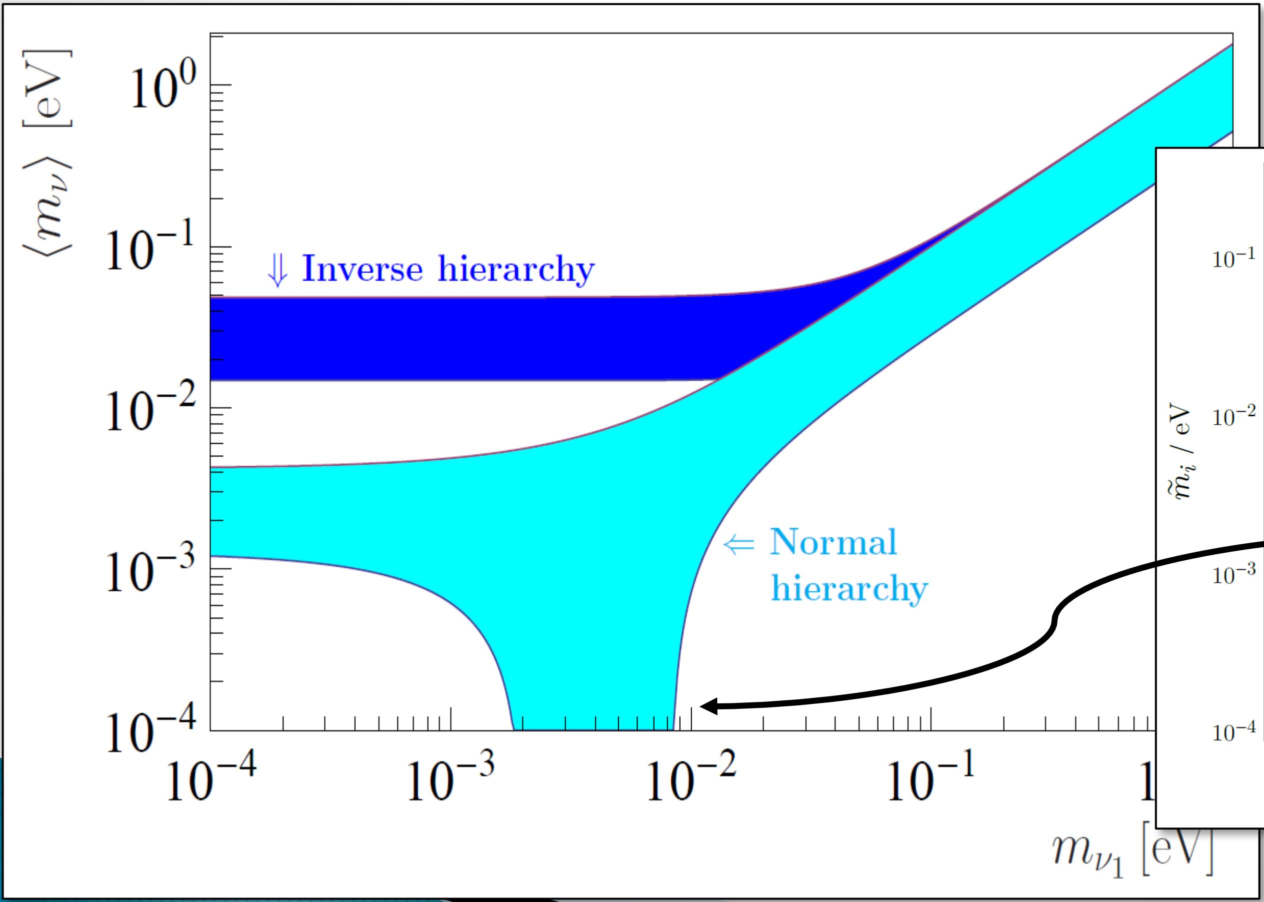
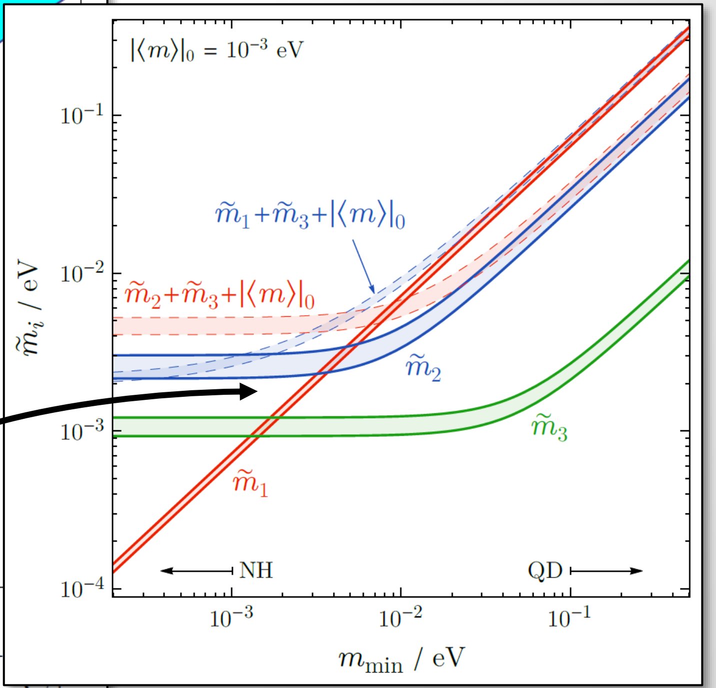
- Effective $0\nu\beta\beta$ Mass

$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}| \underbrace{\approx m_\nu \sqrt{1 - \sin^2(2\theta_{12})\sin^2(\phi_{12}/2)}}_{\text{degenerate } \& \ \theta_{13} \approx 0}$$



Possible cancellation due to Majorana phases ϕ_1, ϕ_2



Penedo, Petcov
Phys. Lett. B786 (2018) 410

Three Active Neutrinos

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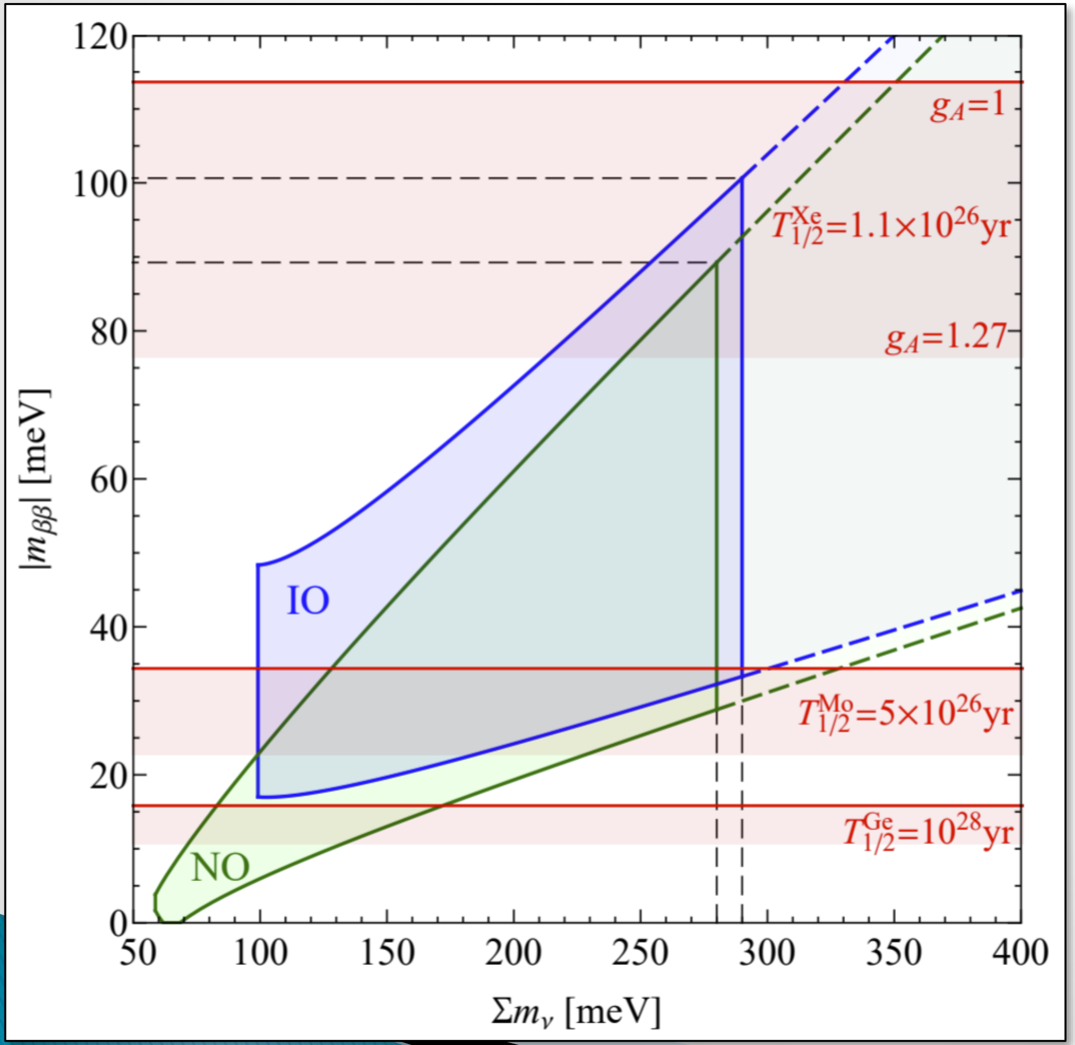

- NMEs from IBM-2 with $g_A = 1.0$

FFD, Graf, Iachello, Kotila
PRD 102 (2020) 9, 095016

Heavy Sterile Neutrinos

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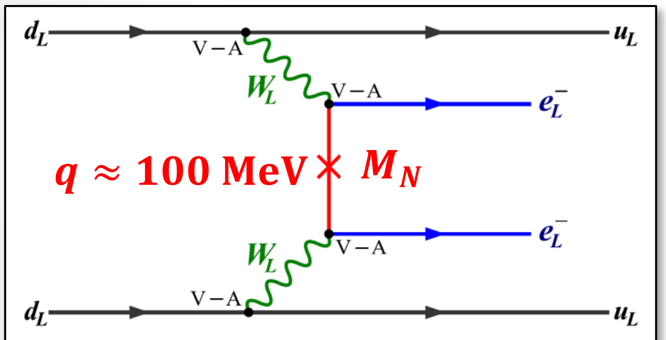
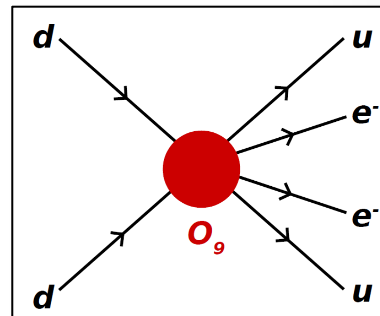
- with masses larger than ≈ 100 MeV

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

- Short-distance on nuclear scale





- Light neutrino mass via seesaw

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

'Vanilla' seesaw $\mu_R \gg m_D$

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

Heavy Sterile Neutrinos

UCL
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- with masses larger than ≈ 100 MeV

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

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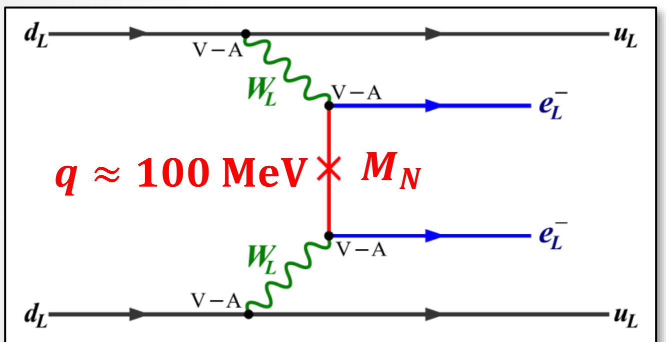

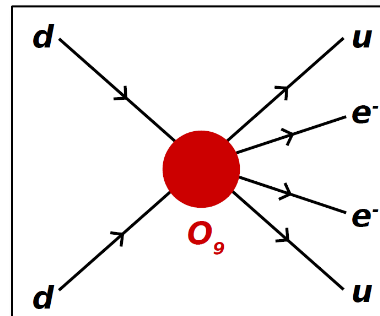

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Inverse seesaw

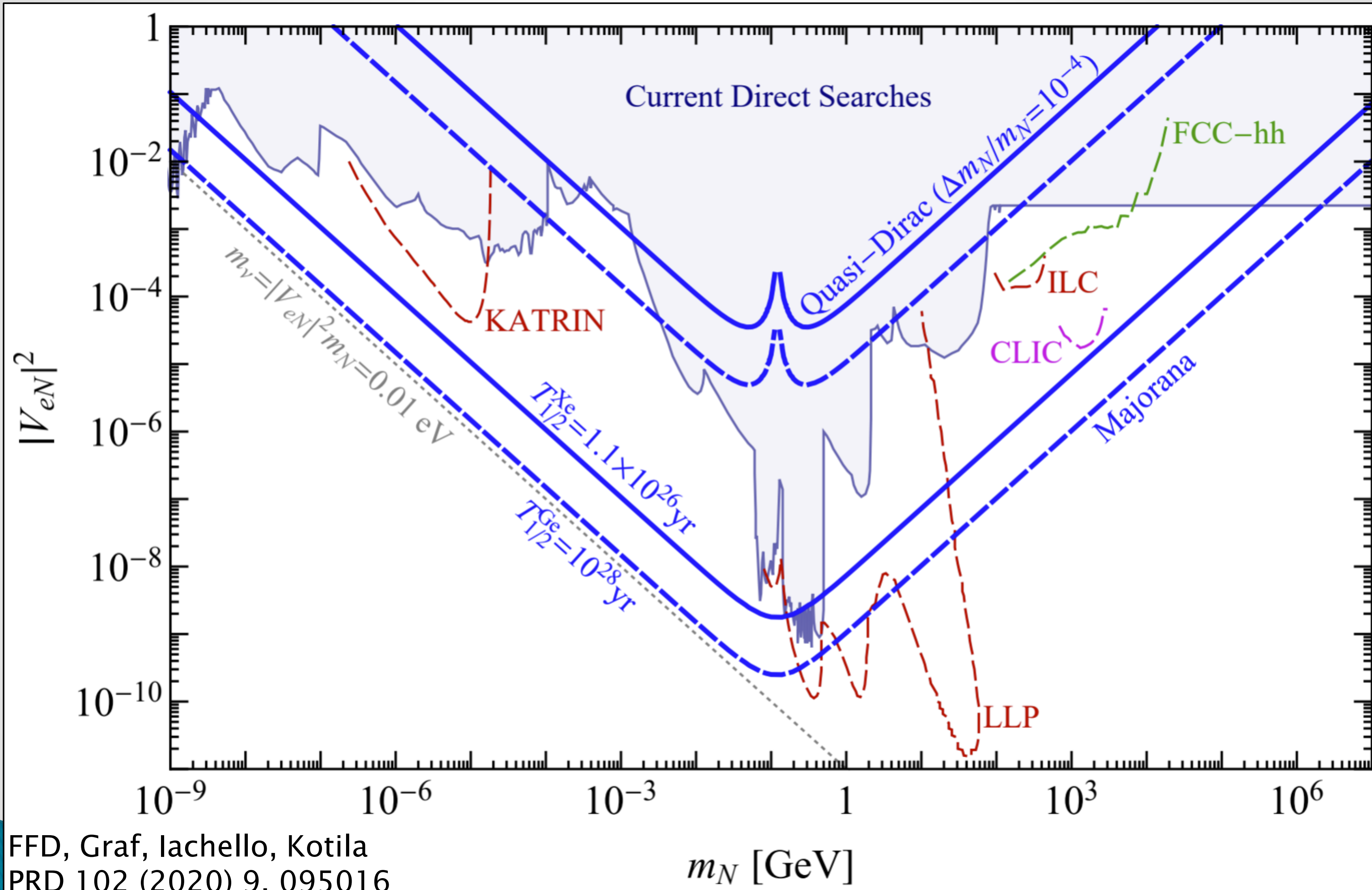
$M \gg \mu_S, \mu_R, m_D$

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

Quasi-Dirac N

Approximate L conservation

Heavy Sterile Neutrinos



FFD, Graf, Iachello, Kotila
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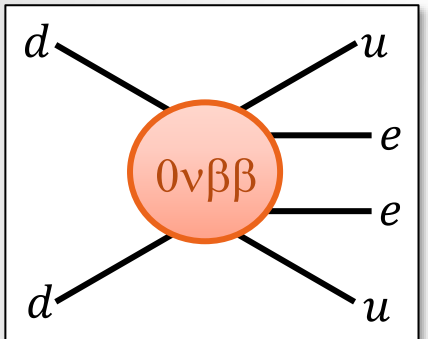
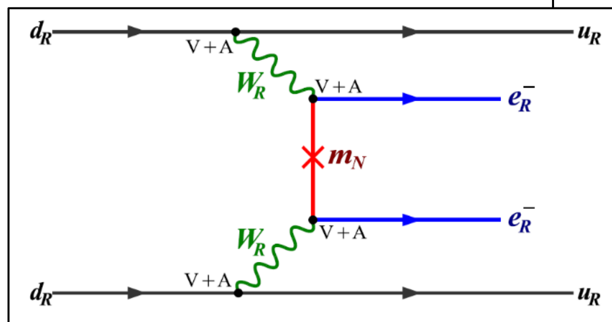
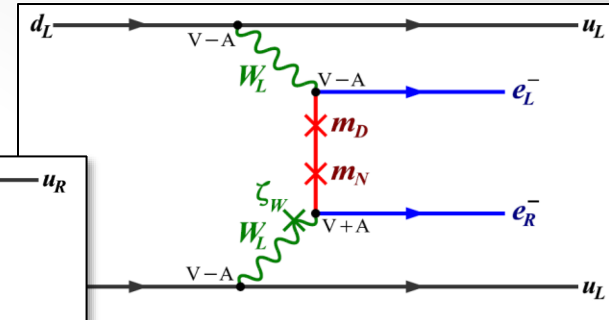
New Physics and $0\nu\beta\beta$

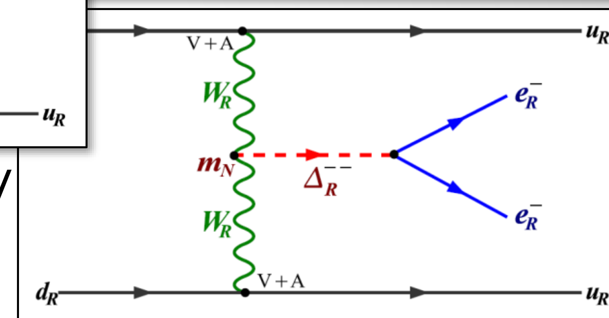
- Plethora of New Physics scenarios



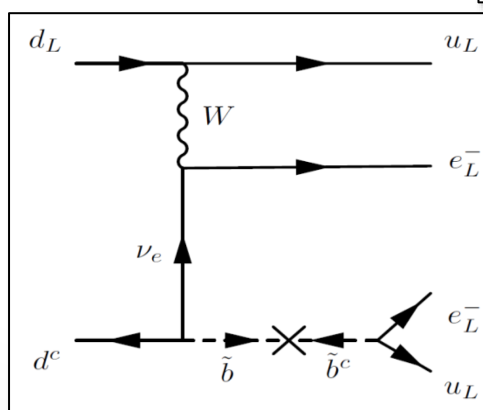
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

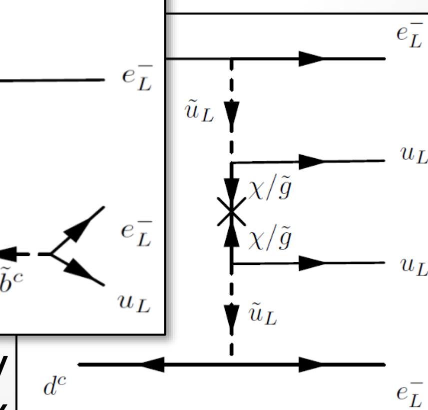






Left-Right Symmetry





R-Parity
Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

...

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

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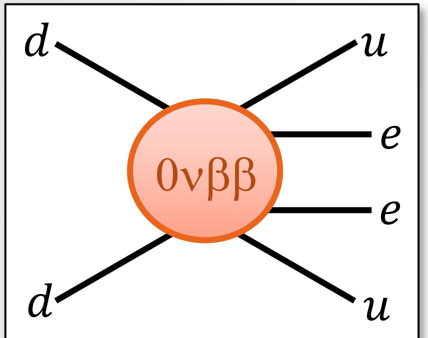
- Plethora of New Physics scenarios



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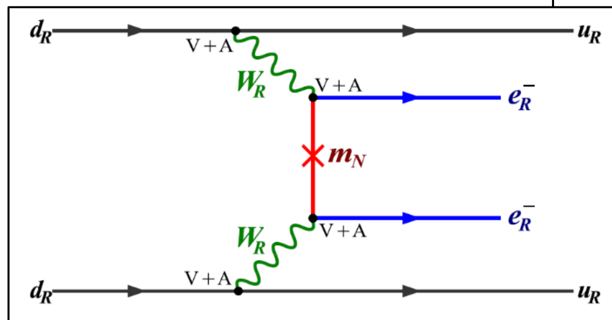
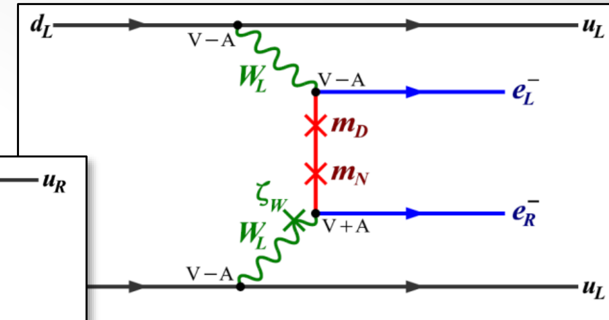
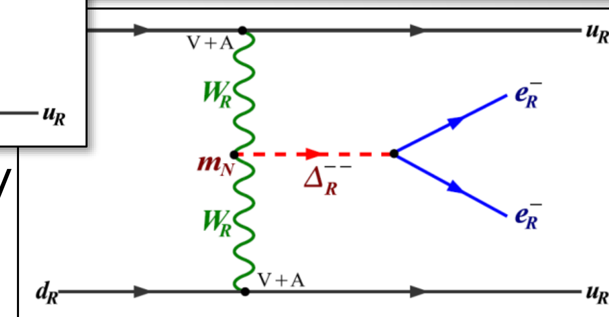


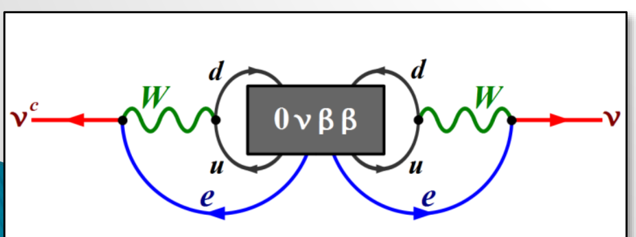


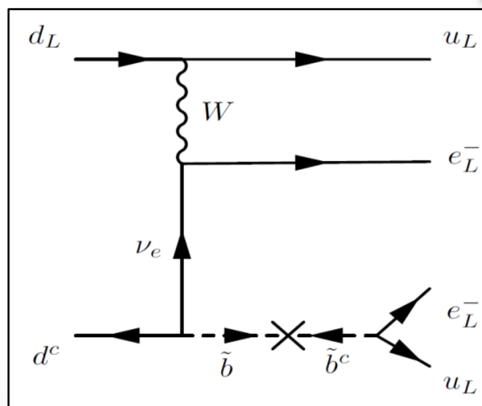


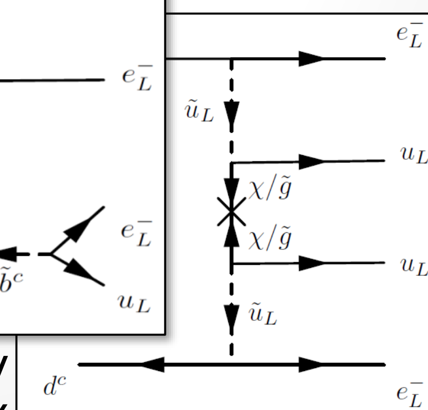
Left-Right Symmetry

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

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





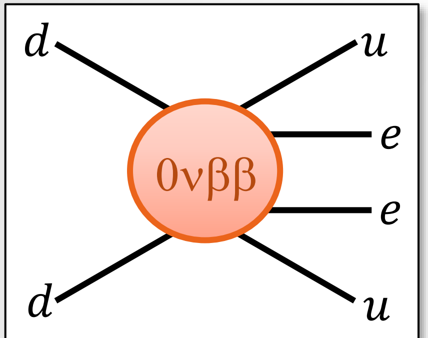


R-Parity Violating SUSY

- Extra Dimensions
- Majorons
- Leptoquarks
- …

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

- Examples in Left-Right Symmetry



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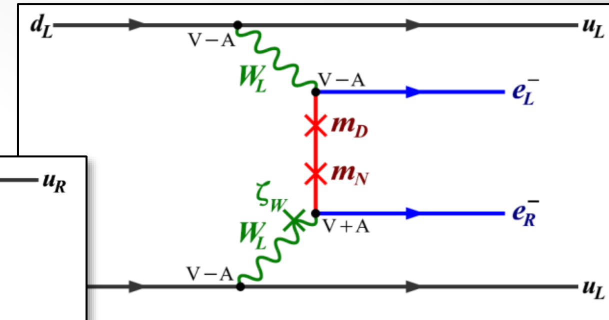
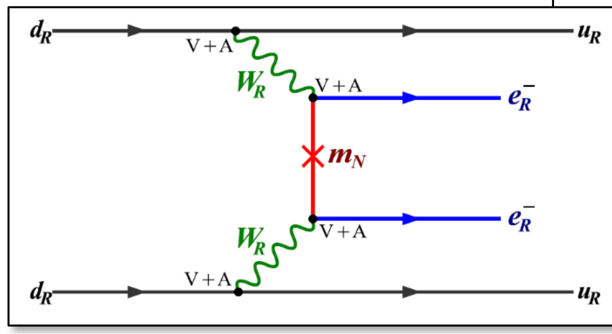


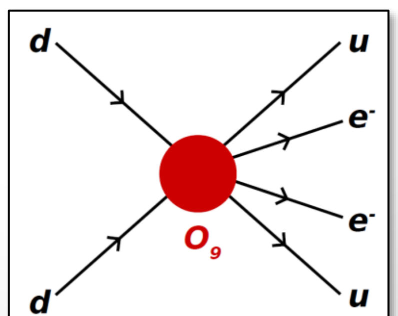


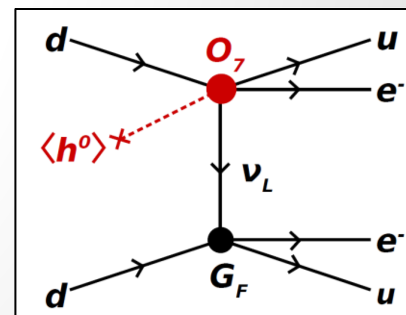
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^{2}$$

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

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

- $0\nu\beta\beta$ probes the TeV scale
- Limits on 6D and 9D eff. operators

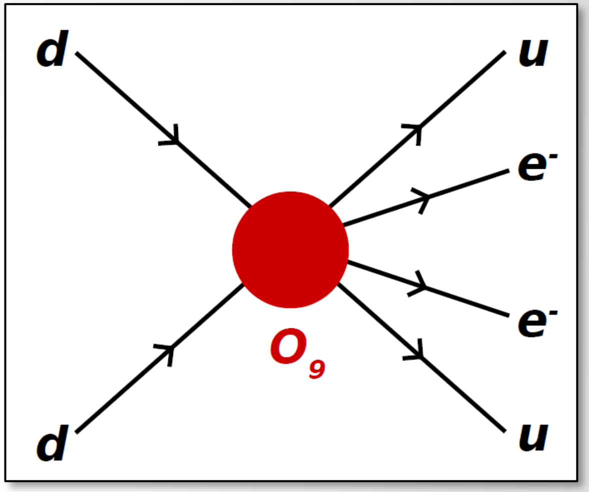




Short-Range Mechanisms

- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - General parton level operators (Paes et al. '01)

$$L = \frac{G_F^2}{2m_p}\left(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^{\mu}J_{\nu}j + \epsilon_4 J^{\mu}J_{\mu\nu}j^{\nu} + \epsilon_5 J^{\mu}Jj_{\mu}\right)$$



Short–Range Mechanisms

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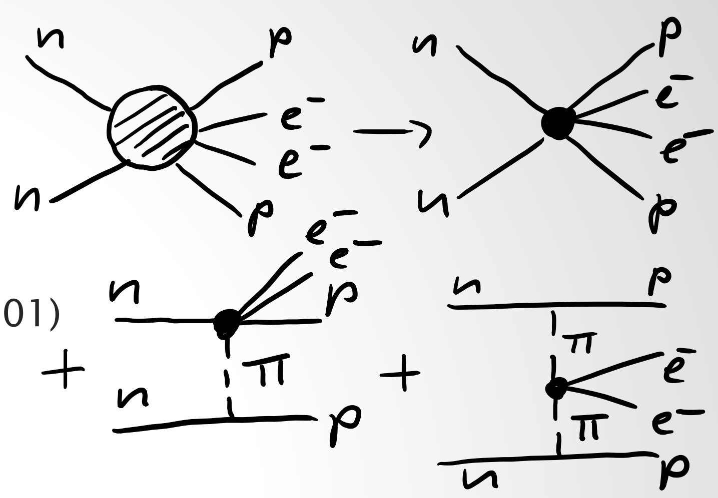
- Evaluation of limits on short–range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - General parton level operators (Paes et al. ‘01)
  - NMEs from IBM–2 with $g_A = 1.0$ and short–range correlations in Argonne parametrization



$F_S(q^2) = \dfrac{g_S}{(1+q^2/m_V^2)^2}$,	$g_S = 1.0$ [42],
$F_{PS}(q^2) = \dfrac{g_{PS}}{(1+q^2/m_V^2)^2}\dfrac{1}{1+q^2/m_\pi^2}$,	$g_{PS} = 349$ [42],
$F_V(q^2) = \dfrac{g_V}{(1+q^2/m_V^2)^2}$,	$g_V = 1.0$,
$F_W(q^2) = \dfrac{g_W}{(1+q^2/m_V^2)^2}$,	$g_W = 3.7$,
$F_A(q^2) = \dfrac{g_A}{(1+q^2/m_A^2)^2}$,	$g_A = 1.27$ [43],
$F_P(q^2) = \dfrac{g_P}{(1+q^2/m_A^2)^2}\dfrac{1}{1+q^2/m_\pi^2}$,	$g_P = 4g_A\dfrac{m_p^2}{m_\pi^2}\left(1-\dfrac{m_\pi^2}{m_A^2}\right) = 231$ [44],
$F_{T_i}(q^2) = \dfrac{g_{T_i}}{(1+q^2/m_V^2)^2}$,	$g_{T_{1,2,3}} = 1.0, -3.3, 1.34$ [40].

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)

Short-Range Mechanisms

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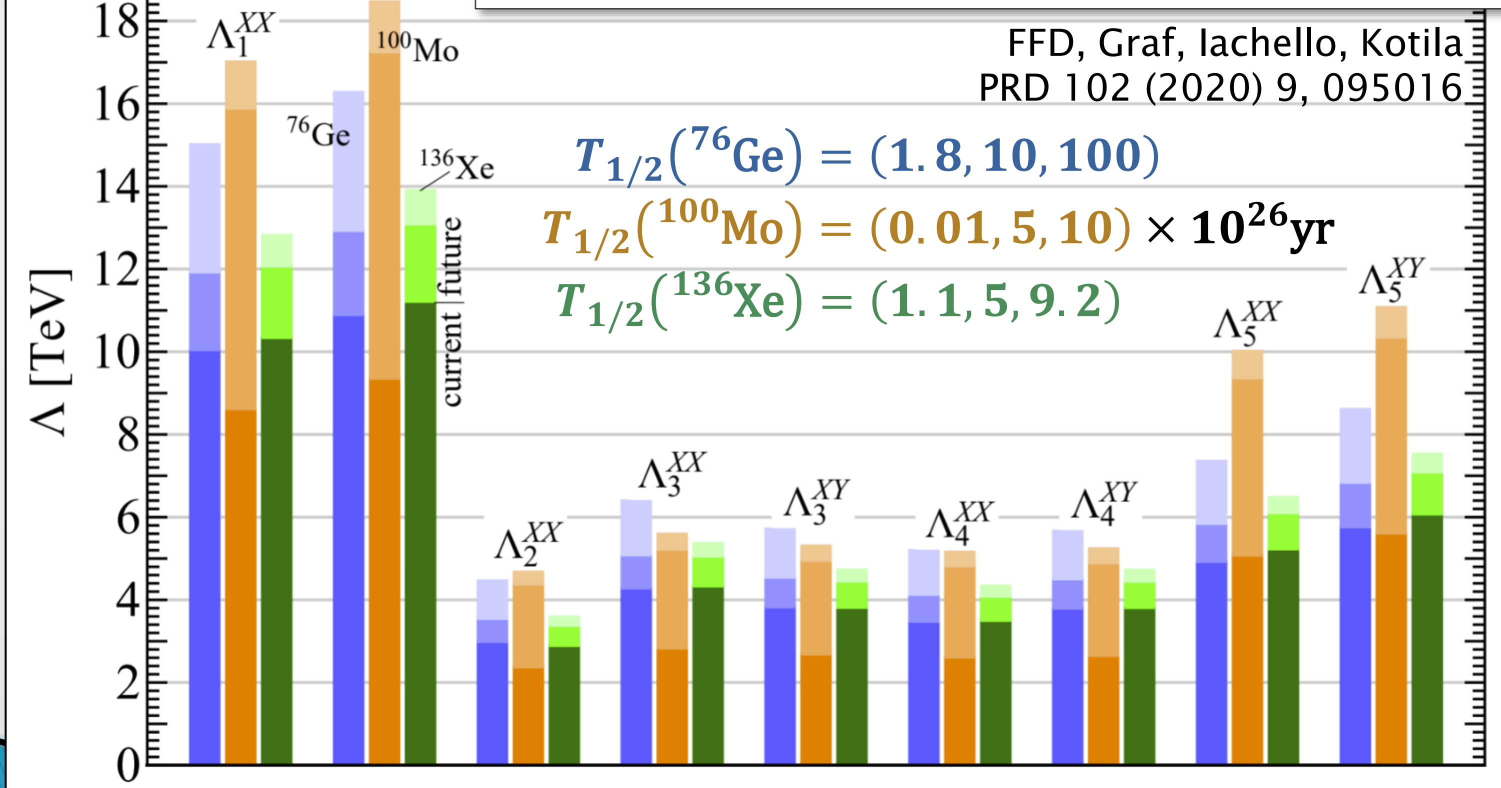
- Evaluation of limits on short-range operators

$$L = \frac{G_F^2}{2m_p}\left(\epsilon_1 JJj + \epsilon_2 J^{\mu\nu}J_{\mu\nu}j + \epsilon_3 J^{\mu}J_{\nu}j + \epsilon_4 J^{\mu}J_{\mu\nu}j^{\nu} + \epsilon_5 J^{\mu}Jj_{\mu}\right)$$



Interference with $m_{\beta\beta}$

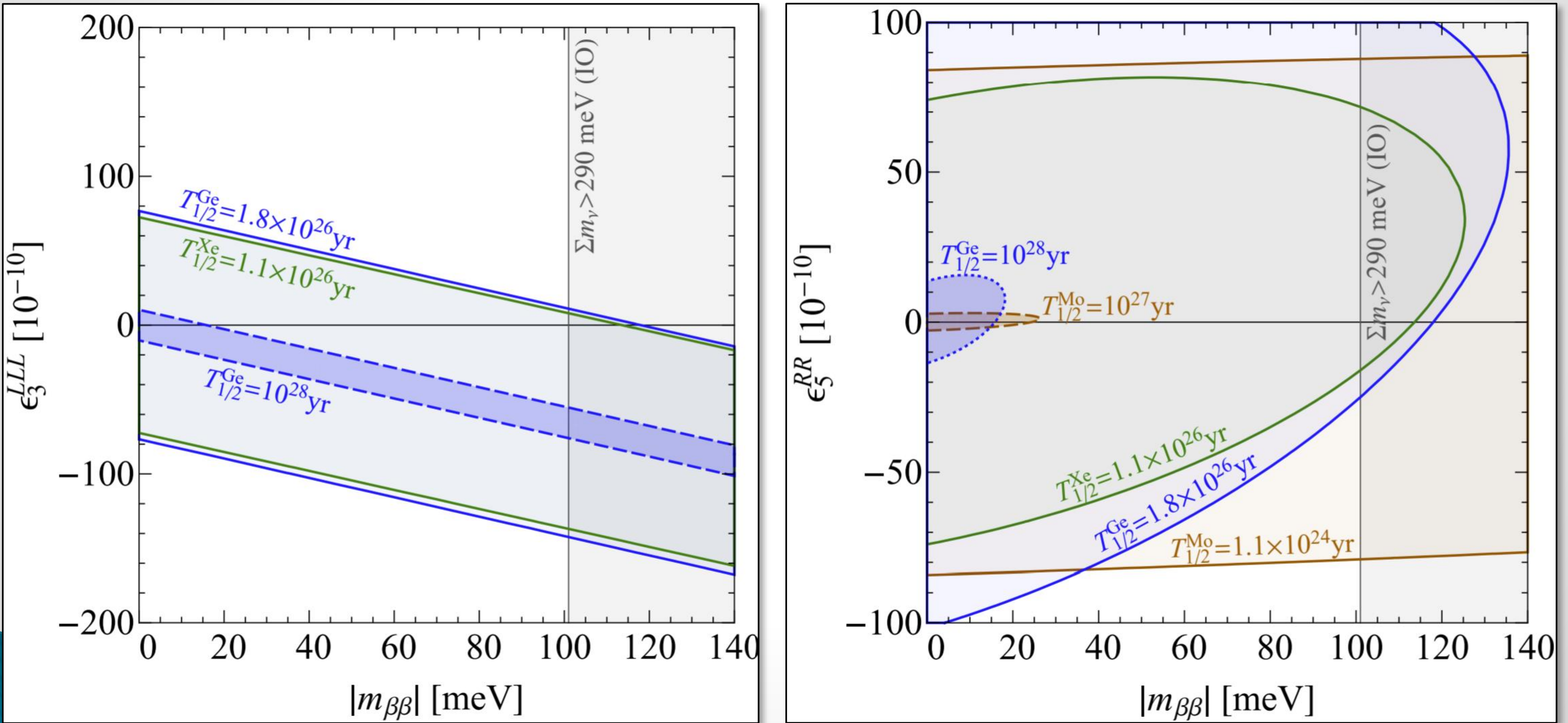
Same lepton current

$$T_{1/2}^{-1} = G_\nu \left| \frac{m_{\beta\beta}}{m_e} \mathcal{M}_\nu + \epsilon \mathcal{M}_\epsilon \right|^2$$

e.g. heavy neutrino exchange
Mitra, Pascoli, Wong, Phys. Rev. D 90 (2014) 093005

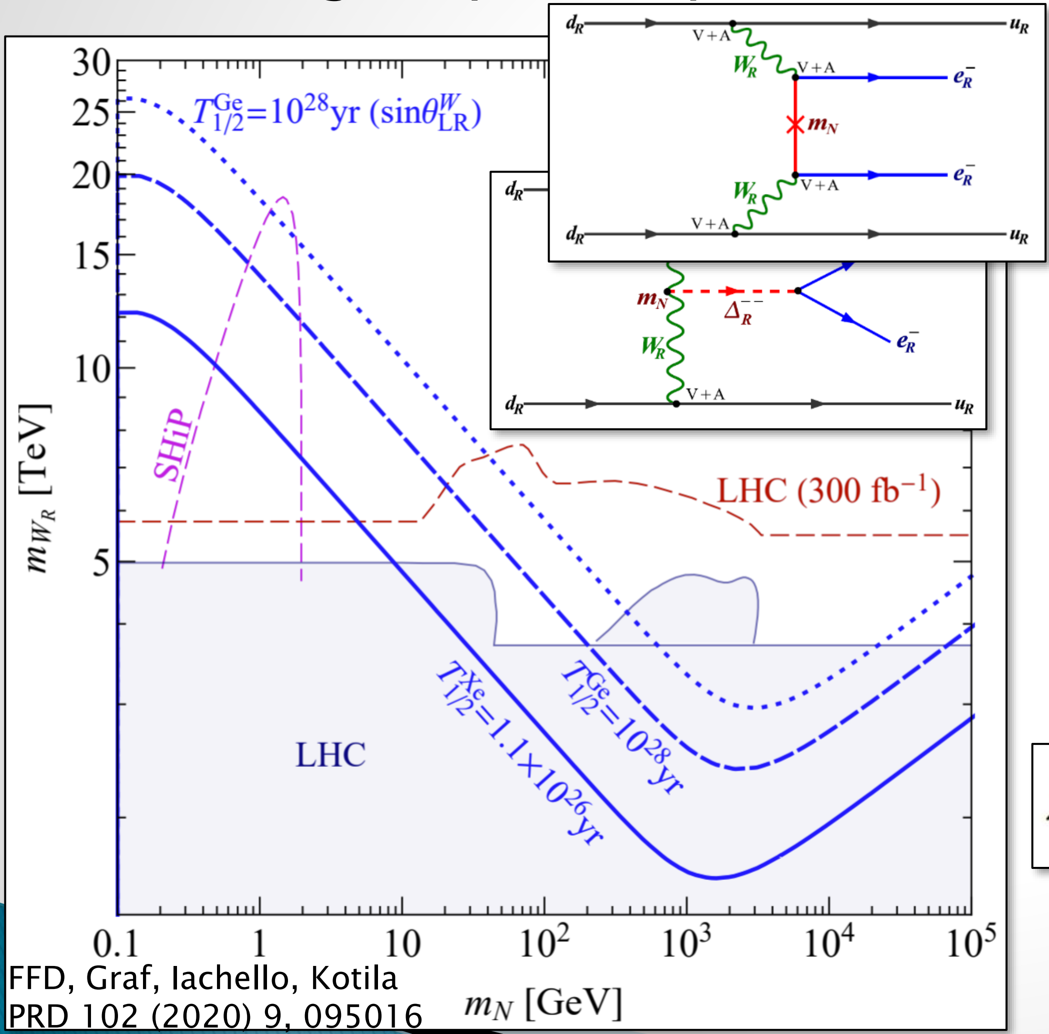
Different currents

$$T_{1/2}^{-1} = \frac{|m_{\beta\beta}|^2}{m_e^2} |\mathcal{M}_\nu|^2 G_\nu + |\epsilon|^2 |\mathcal{M}_\epsilon|^2 G_\epsilon + 2Re\left[\frac{m_{\beta\beta}}{m_e} \epsilon^* \mathcal{M}_\nu \mathcal{M}_\epsilon^*\right] G_{\nu\epsilon}$$



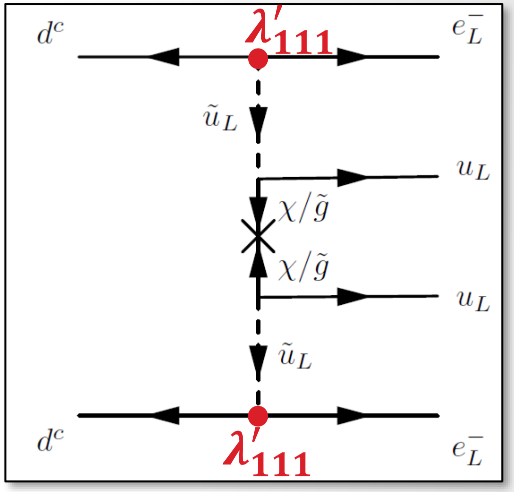
Example Scenarios

- Left-Right Symmetry



FFD, Graf, Iachello, Kotila
PRD 102 (2020) 9, 095016

- R-Parity Violating SUSY

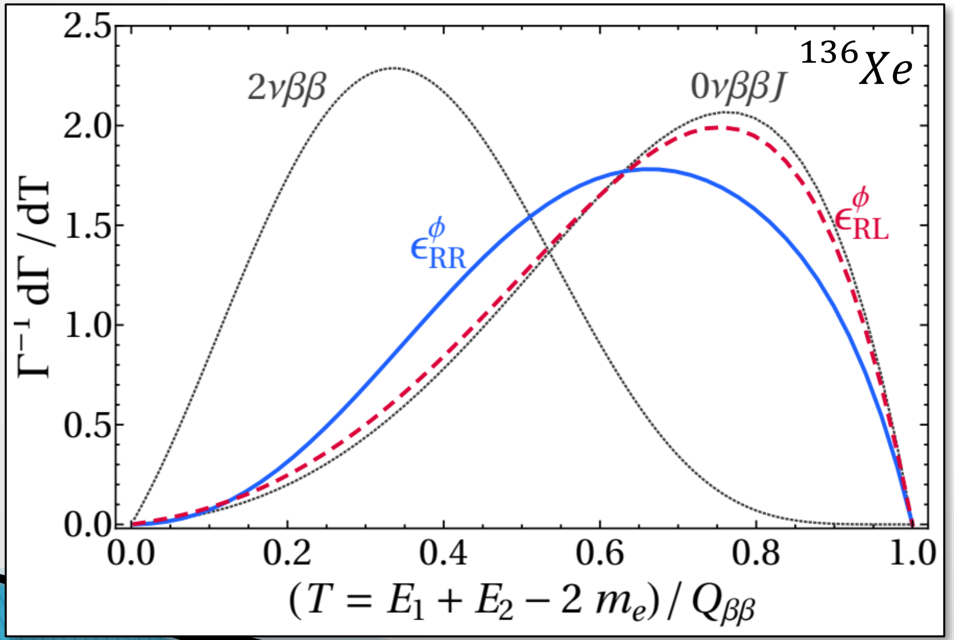


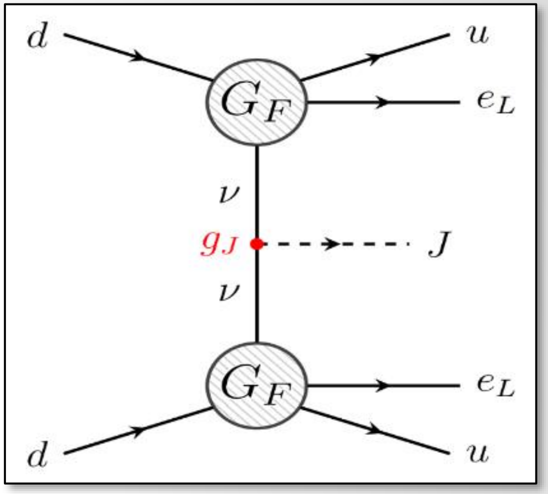
  - Enhancement due to large pseudoscalar form factor

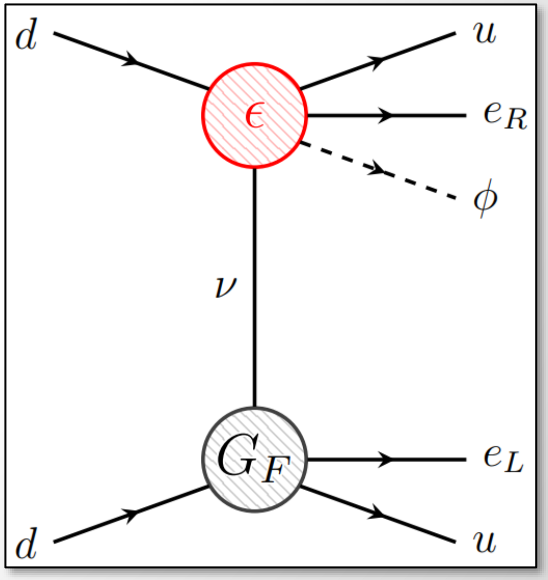
$$\lambda'_{111} < 7.0 \times 10^{-3} \left(\frac{m_{\tilde{q}}}{1\,\mathrm{TeV}}\right)^2 \left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^{1/2}$$

Exotic particle emission in double beta decay

- Majoron(-like) J emission
- Majoron-like ϕ emission assisted by RH current
  (Cepedello, FFD, González, Hati, Hirsch, PRL 122 (2019) 181801)
- Electron energy distribution



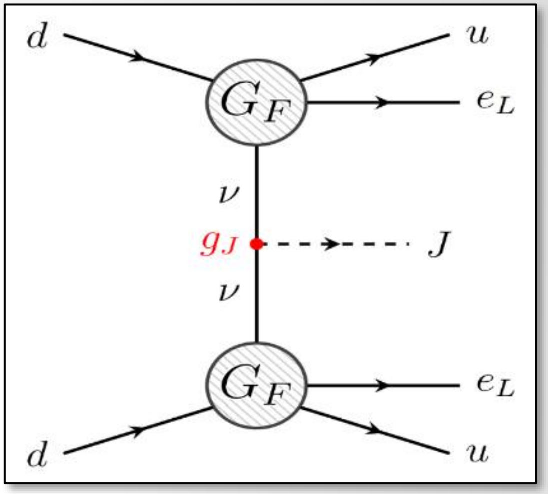


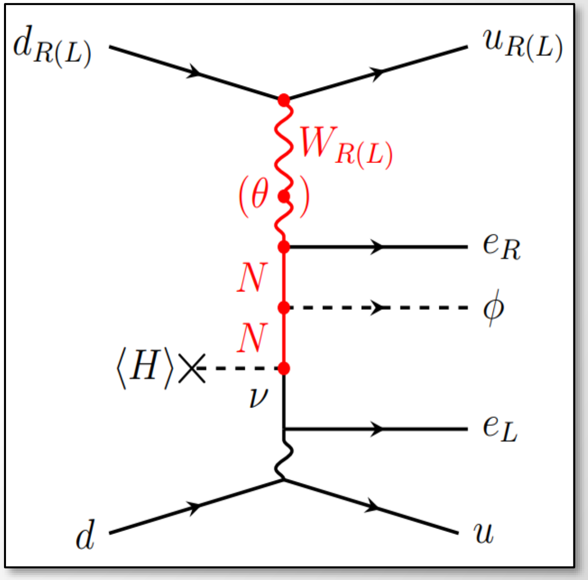


Exotic particle emission in double beta decay

- Majoron(-like) J emission
- Majoron-like ϕ emission assisted by RH current
  (Cepedello, FFD, González, Hati, Hirsch, PRL 122 (2019) 181801)
  - Sensitivity to Left-Right symmetric model

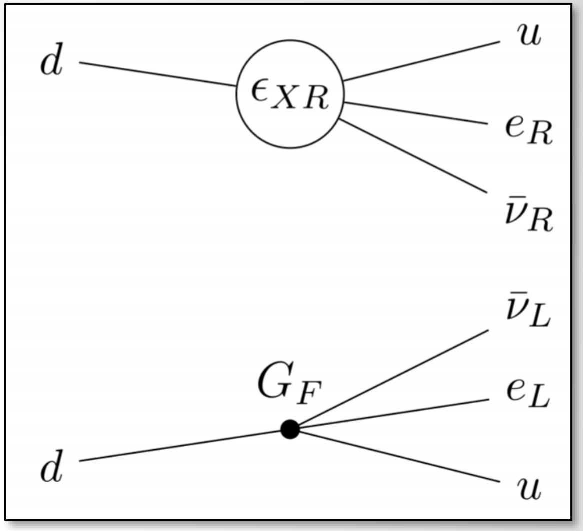
$$\frac{T_{1/2}^{\mathrm{Xe}}}{10^{25}\ \mathrm{y}} \approx \left(\frac{1.4\times 10^{-4}}{g_R^2 \kappa y_N y_\nu}\right)^2 \left(\frac{m_{W_R}}{25\ \mathrm{TeV}}\right)^4 \left(\frac{m_N}{100\ \mathrm{MeV}}\right)^4$$

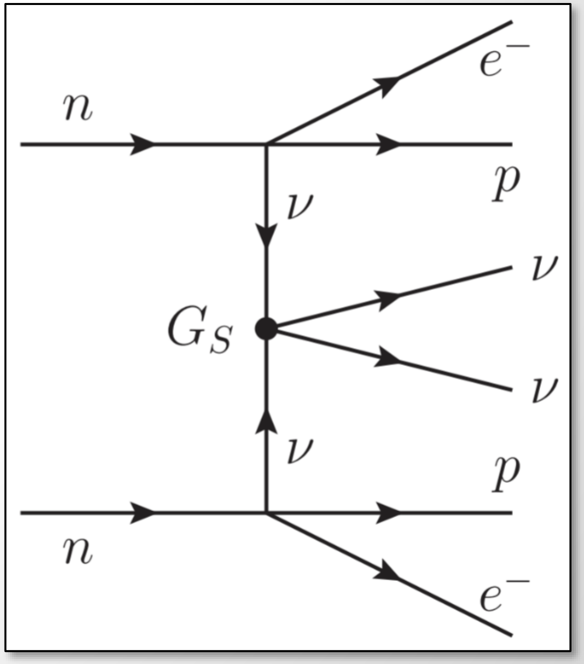




New Physics in $2\nu\beta\beta$

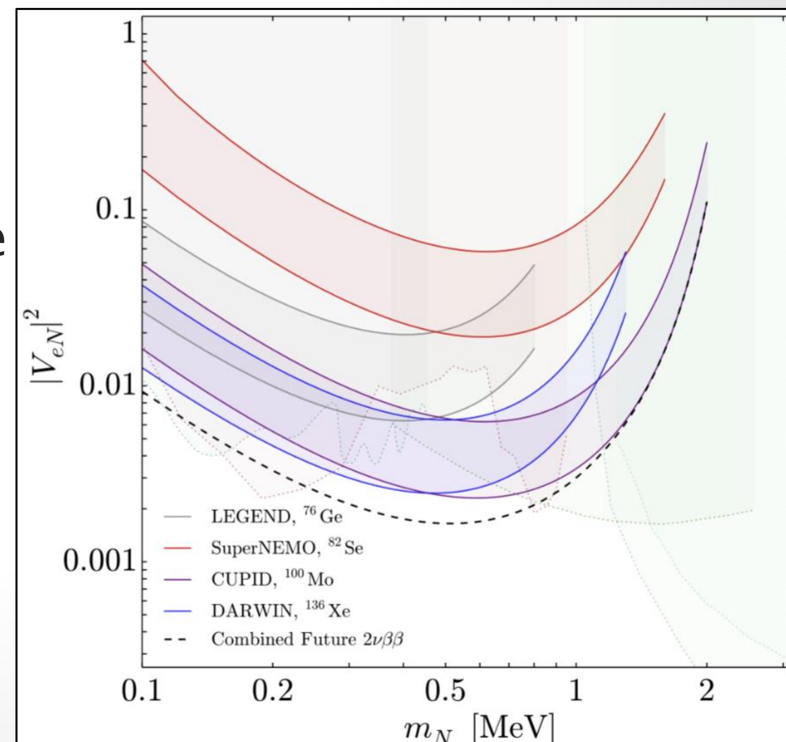
- Lepton-number conserving right-handed currents
  (FFD, Graf, Simkovic, PRL 125 (2020) 17, 171801)
  - Estimated current limit $\epsilon_{XR} < 2.7 \times 10^{-2}$ from NEMO3 (angular correlation) competitive to other searches
- Neutrino self-interactions
  (FFD, Graf, Rodejohann, Xu,
  PRD 102 (2020) 5, 051701)
  - Excludes strongly interacting regime $G_S \approx 4 \times 10^9\, G_F$ suggested to resolve Hubble tension





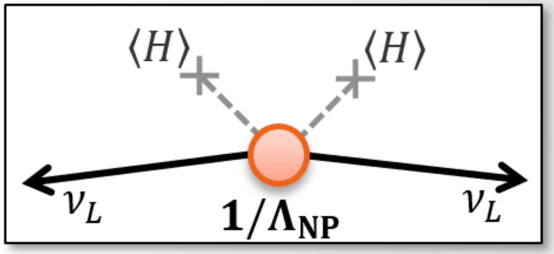
New Physics in $2\nu\beta\beta$

- Lepton-number conserving right-handed currents
  (FFD, Graf, Simkovic, PRL 125 (2020) 17, 171801)
  - Estimated current limit $\epsilon_{XR} < 2.7 \times 10^{-2}$ from NEMO3 (angular correlation) competitive to other searches
- Neutrino self-interactions
  (FFD, Graf, Rodejohann, Xu, PRD 102 (2020) 5, 051701)
  - Excludes strongly interacting regime $G_S \approx 4 \times 10^9\, G_F$ suggested to resolve Hubble tension
- Sterile neutrino search through energy endpoint
  (Bolton, FFD, Graf, Simkovic, arXiv:2011.13387; Agostini, Bossio, Ibarra, Marcano, arXiv:2012.09281)



Conclusion

- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Natural suppression of charged LFV?
  - Determination of absolute mass scale



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

- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Standard interpretation: New Physics near GUT scale breaking lepton number
  - Also: Direct sensitivity to sterile neutrinos at scales $m_N \approx 1\ \mathrm{eV} - 1\ \mathrm{TeV}$
- **$2\nu\beta\beta$ is becoming sensitive to New Physics as well**
- **Importance of probing LNV around the TeV scale**
  - Can we discover mechanisms of neutrino mass generation?
  - Impact on baryon asymmetry of the Universe