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Non-Standard Mechanisms of Double Beta Decay

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Dirac versus Majorana

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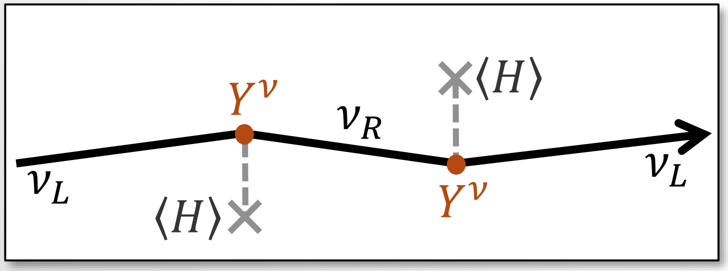
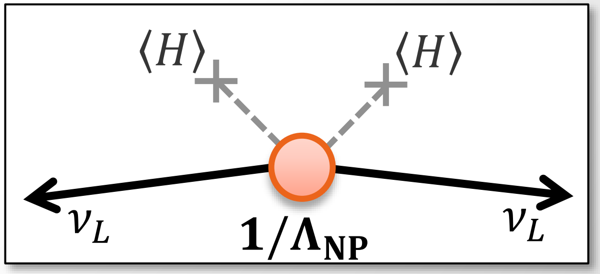
- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino mass

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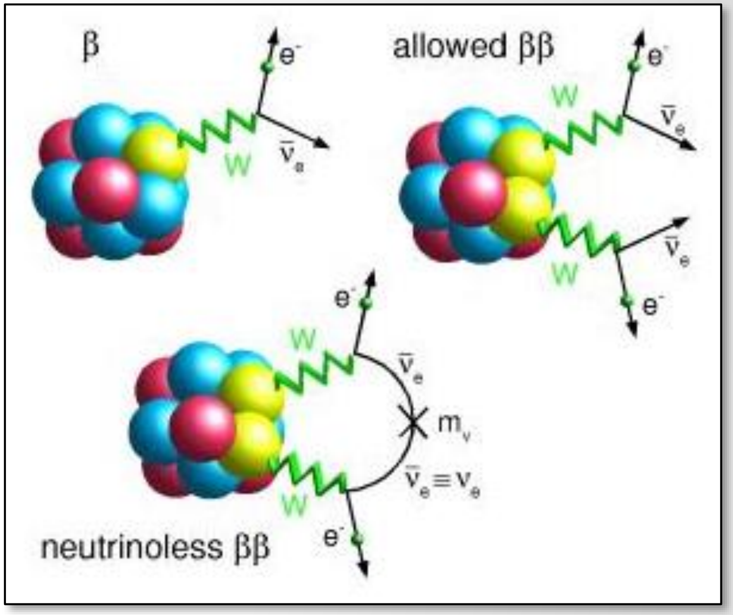
- Single beta decay
  $$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$
  - Kinematic neutrino mass measurement
- Allowed double beta ($\boldsymbol{2\nu\beta\beta}$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($\boldsymbol{0\nu\beta\beta}$) decay
  $$(A,Z)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



Neutrinoless Double β Decay

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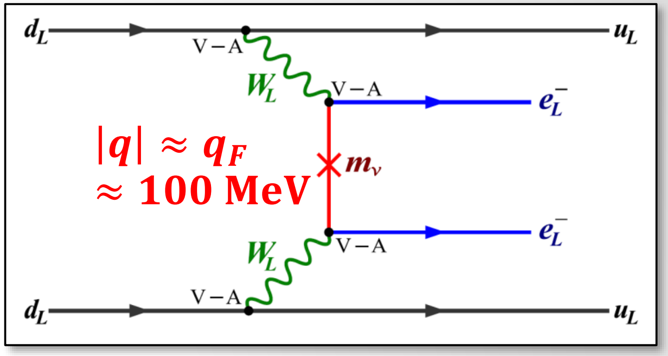
- Half-life

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

- Particle Physics

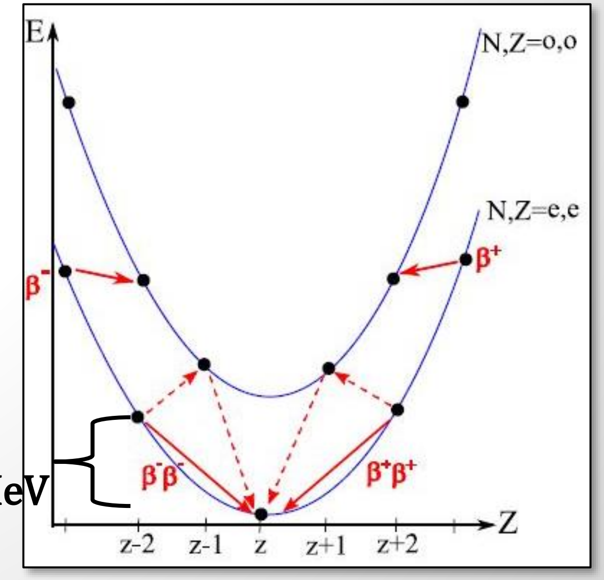


$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu (1+\gamma_5)\gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

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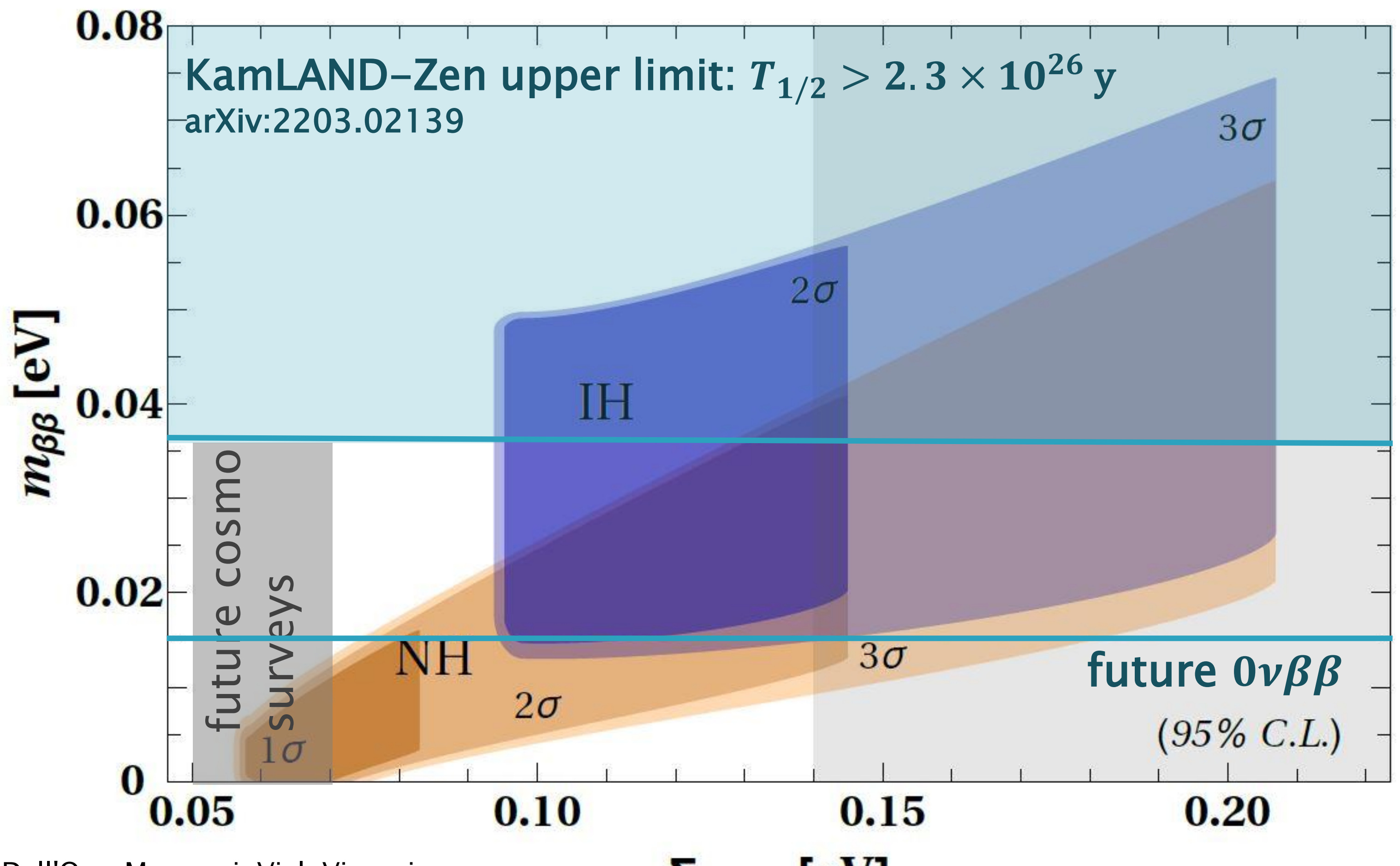
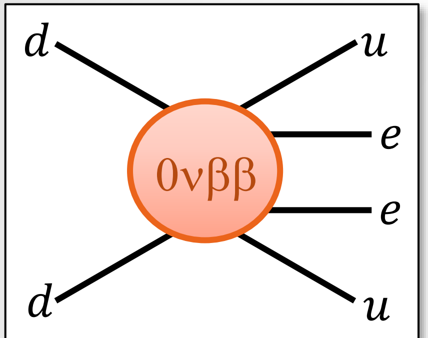
- Effective $0\nu\beta\beta$ Mass



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

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

- Plethora of New Physics scenarios



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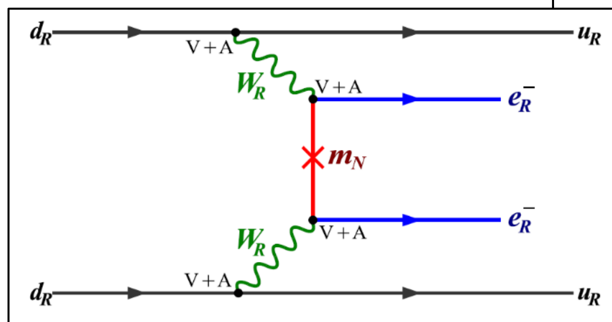
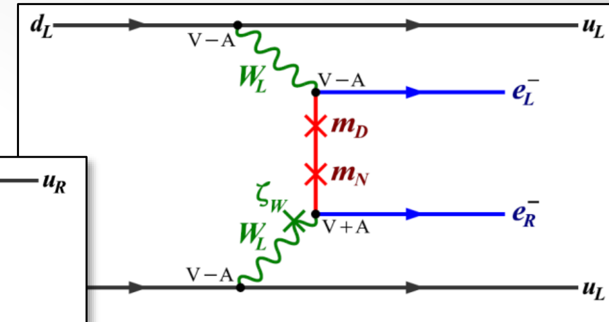
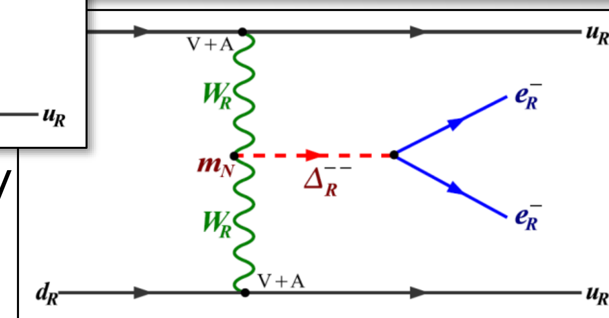
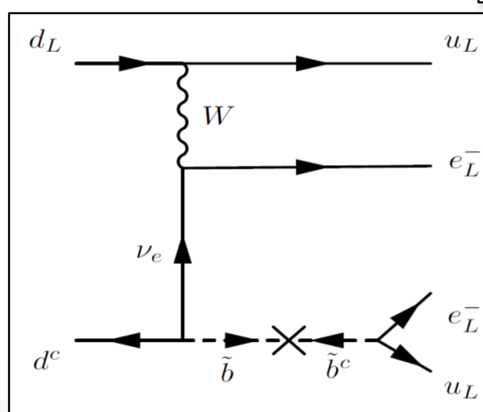
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^{2}$$

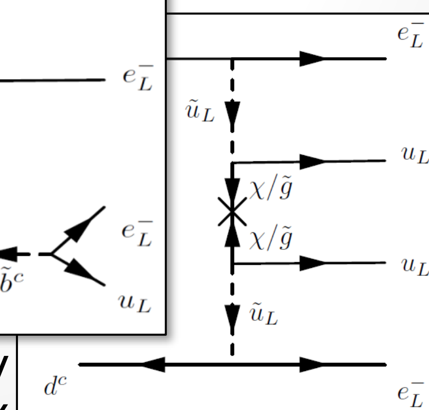






Left-Right Symmetry





R-Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

...

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

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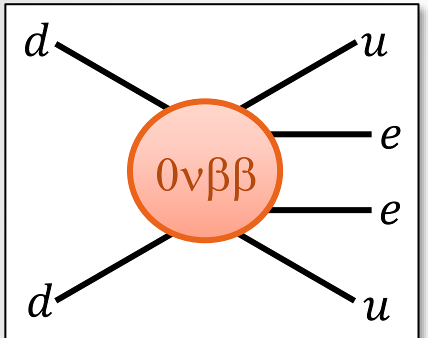
- Plethora of New Physics scenarios



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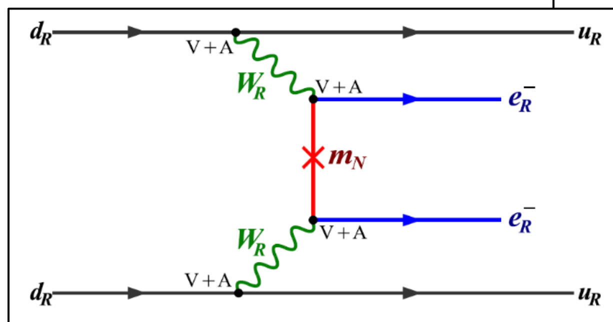
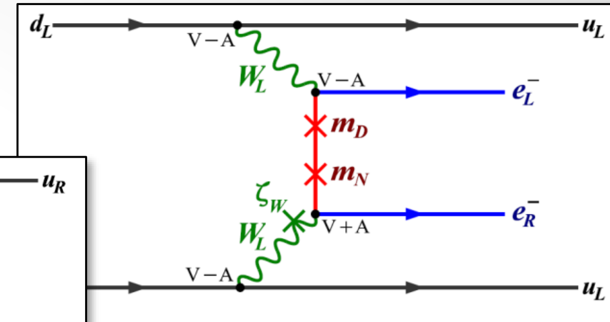
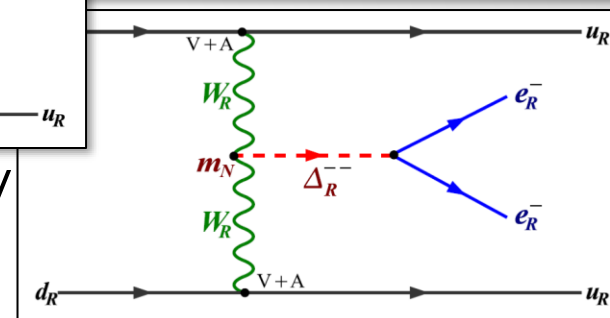




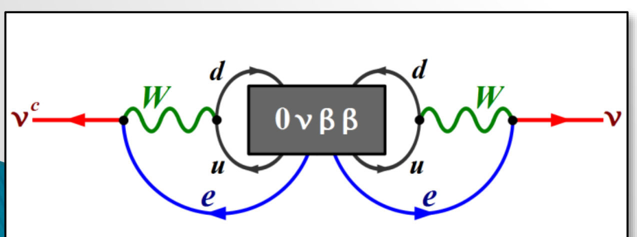


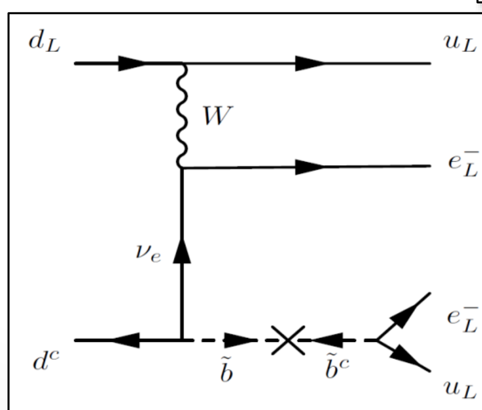
Left-Right Symmetry

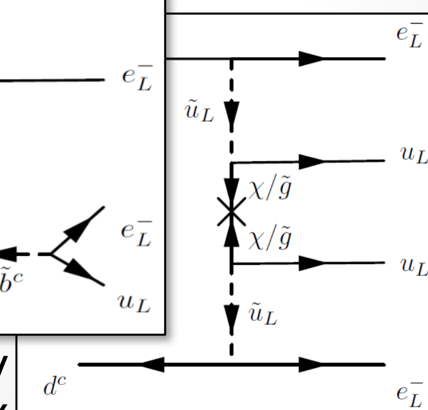
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left|M_{NP}^{0\nu}\right|^{2}$$

- Neutrinos still Majorana

Schechter, Valle
Phys. Rev. D25 (1982) 2951







R-Parity Violating SUSY

Extra Dimensions

Majorons

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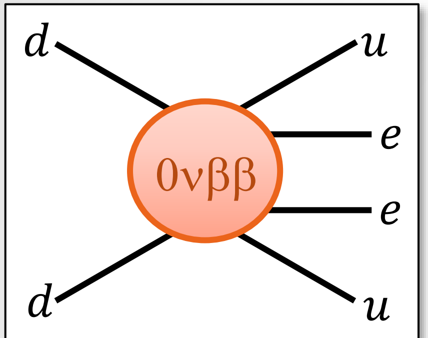
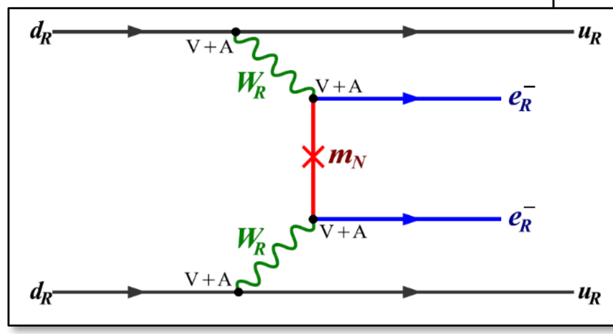
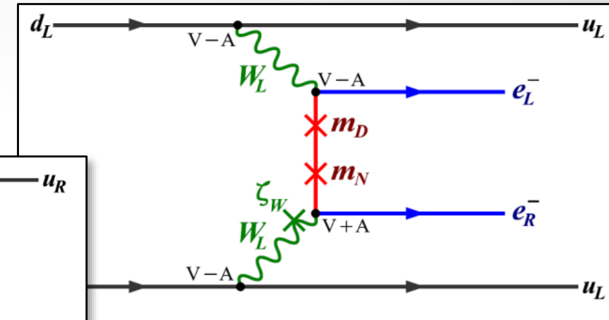
New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry





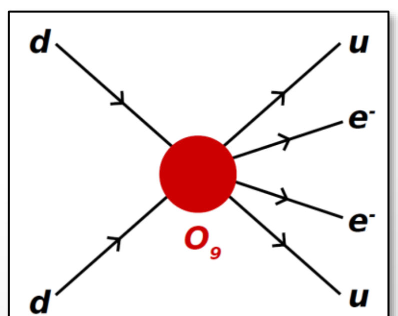


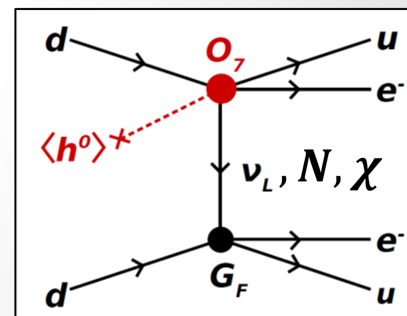
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

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

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

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





See, e.g., Kotila, Ferretti, Iachello, 2110.09141

Short-Range Mechanisms

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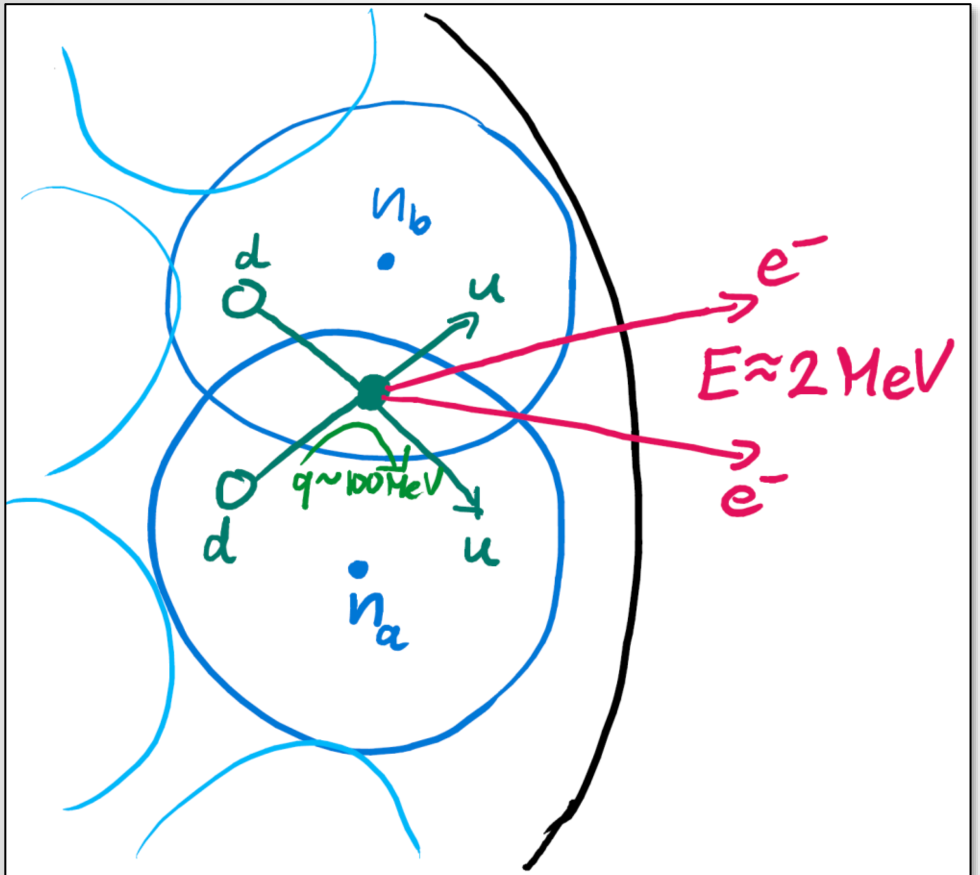

- Evaluation of limits on short-range operators
  (Graf, FFD, Iachello, Kotila, PRD 98, 095023)
  - General parton level operators
    (Paes et al. '01)
  - Nucleon currents

$$\langle p|\,\bar{u}(1\pm\gamma_5)d\,|n\rangle = \bar{N}\tau^+\left[F_S(q^2) \pm F_{PS}(q^2)\gamma_5\right]N',$$

$$\langle p|\,\bar{u}\gamma^\mu(1\pm\gamma_5)d\,|n\rangle = \bar{N}\tau^+\left[F_V(q^2)\gamma^\mu - i\frac{F_W(q^2)}{2m_p}\sigma^{\mu\nu}q_\nu\right]N'$$
$$\pm\bar{N}\tau^+\left[F_A(q^2)\gamma^\mu\gamma_5 - \frac{F_P(q^2)}{2m_p}\gamma_5 q^\mu\right]N',$$

  - Form factors with enhancement for

$$F_{PS}(q^2) = \frac{g_{PS}}{(1+q^2/m_{PS}^2)^2}\frac{1}{1+q^2/m_\pi^2}, \quad g_{PS} = 349$$

$$F_P(q^2) = \frac{g_A}{(1+q^2/m_A^2)^2}\frac{1}{1+q^2/m_\pi^2}\frac{4m_p^2}{m_\pi^2}\left(1-\frac{m_\pi^2}{m_A^2}\right)$$

Short-Range Mechanisms

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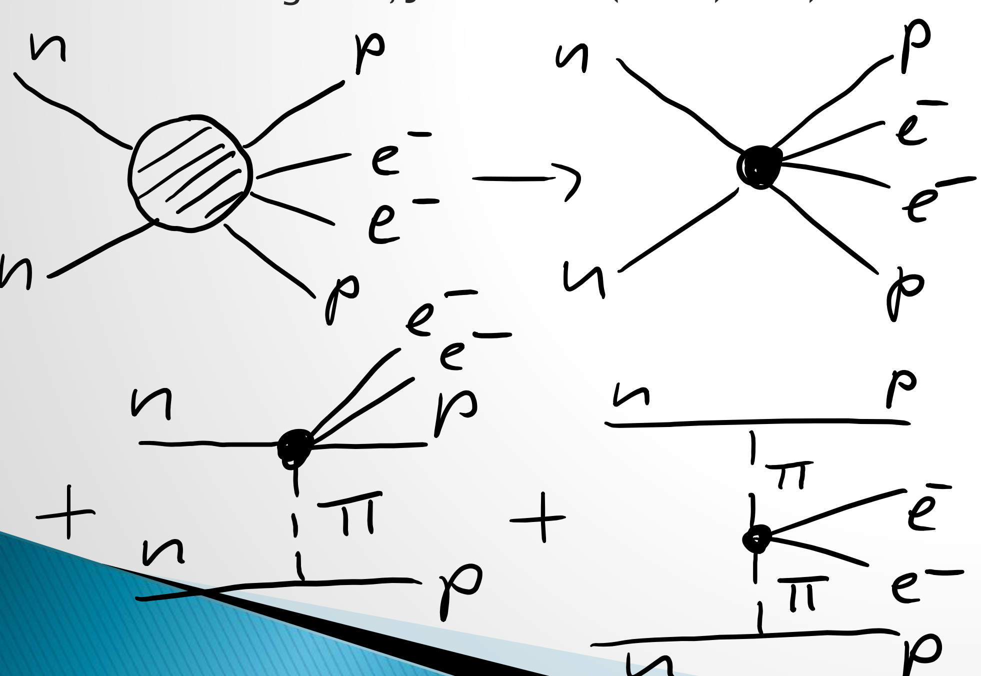
- Pion-mediated contributions
  - R-parity violating SUSY
    (Faessler, Kovalenko, Simkovic, Schwieger, Phys.Rev.Lett. 78 (1997) 183)
  - Chiral EFT with Pion-operators from Lattice QCD
    (Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 1812 (2018) 097)



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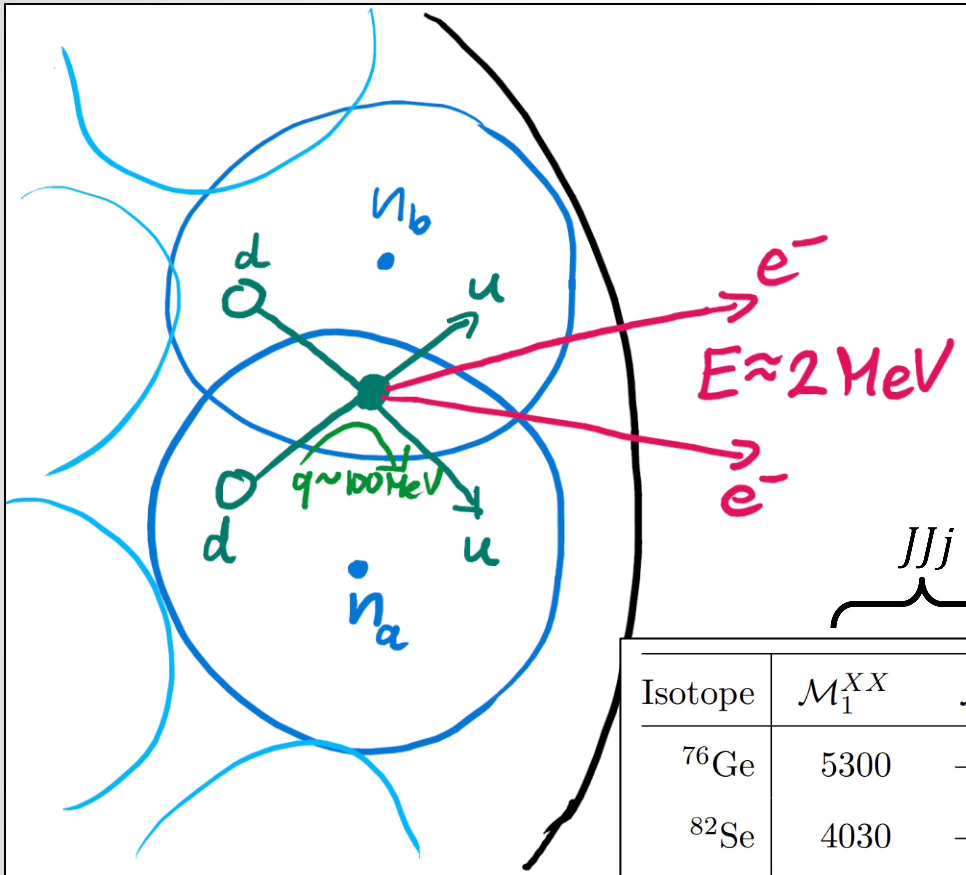
Short-Range Mechanisms



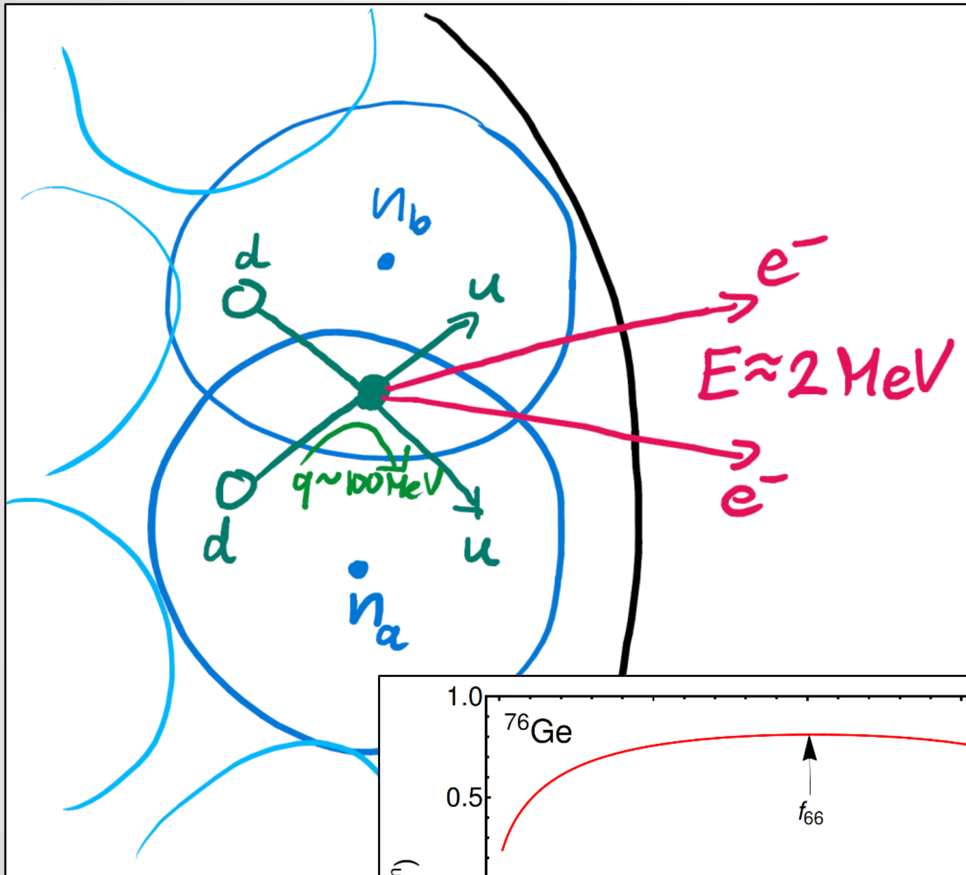
- Evaluation of limits on short-range operators (Graf, FFD, Iachello, Kotila, PRD 98, 095023, PRD 102 (2020) 9, 095016)
  - Evaluation of additional NMEs in IBM-2

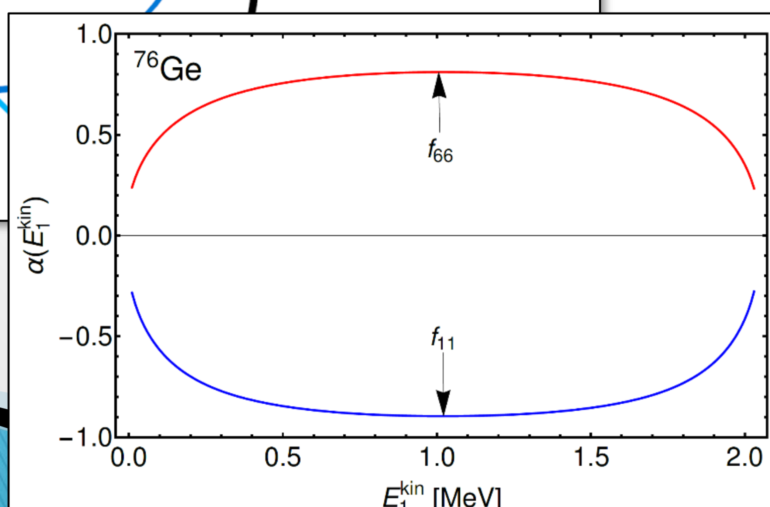
Operators: JJj → $\mathcal{M}_1^{XX}$, $\mathcal{M}_1^{XY}$; $J_{\mu\nu}J^{\mu\nu}j$ → $\mathcal{M}_2^{XX}$; $J_\mu J^\mu j$ → $\mathcal{M}_3^{XX}$, $\mathcal{M}_3^{XY}$; $J^\mu J_{\mu\nu} j^\nu$ → $\mathcal{M}_4^{XX}$; $J_\mu J j^\mu$ → $\mathcal{M}_5^{XX}$, $\mathcal{M}_5^{XY}$

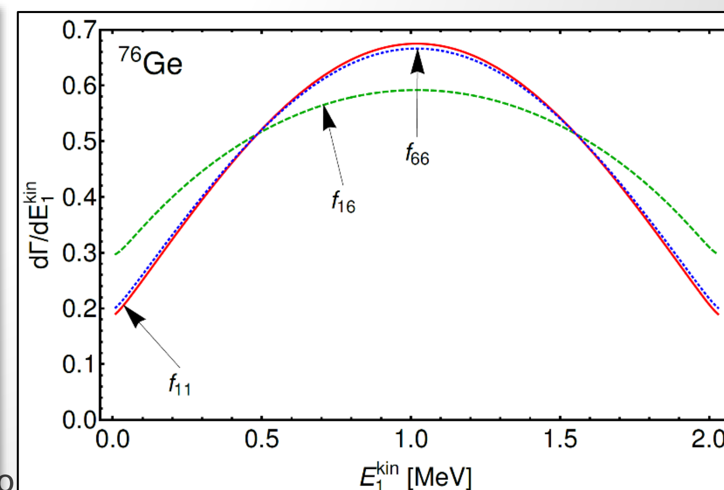
Isotope	$\mathcal{M}_1^{XX}$	$\mathcal{M}_1^{XY}$	$\mathcal{M}_2^{XX}$	$\mathcal{M}_3^{XX}$	$\mathcal{M}_3^{XY}$	$\mathcal{M}_4^{XX}$	$\mathcal{M}_5^{XX}$	$\mathcal{M}_5^{XY}$
^{76}Ge	5300	−5400	−174	−200	99.8	−158	202	−301
^{82}Se	4030	−4110	−144	−171	83.3	−134	114	−199
^{96}Zr	8500	−8570	−129	−85.4	57.7	−88.6	832	−904
^{100}Mo	12400	−12500	−189	−124	83.9	−134	1230	−1340
^{110}Pd	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Short-Range Mechanisms

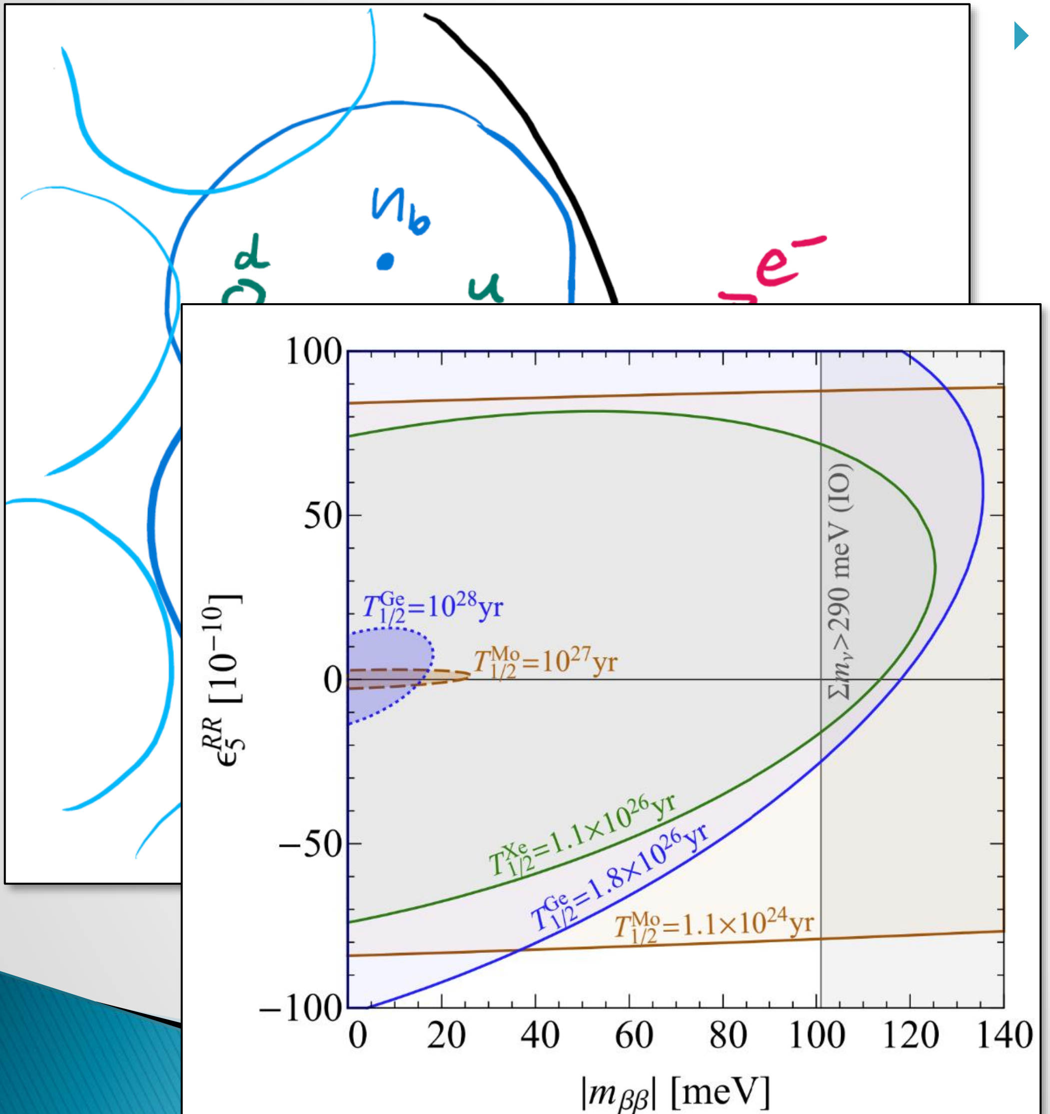
- Evaluation of limits on short-range operators (Graf, FFD, Iachello, Kotila, PRD 98, 095023, PRD 102 (2020) 9, 095016)
  - Evaluation of additional NMEs in IBM-2
  - Numerical determination of e^- wavefunctions (nuclear Coulomb potential and e^- cloud screening ➔ e^- energy and angular distribution







Short-Range Mechanisms



- Evaluation of limits on short-range operators
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  - Evaluation of additional NMEs in IBM-2
  - Numerical determination of e^- wavefunctions (nuclear Coulomb potential and e^- cloud screening ➔ e^- energy and angular distribution
  - Interference with standard mass contribution

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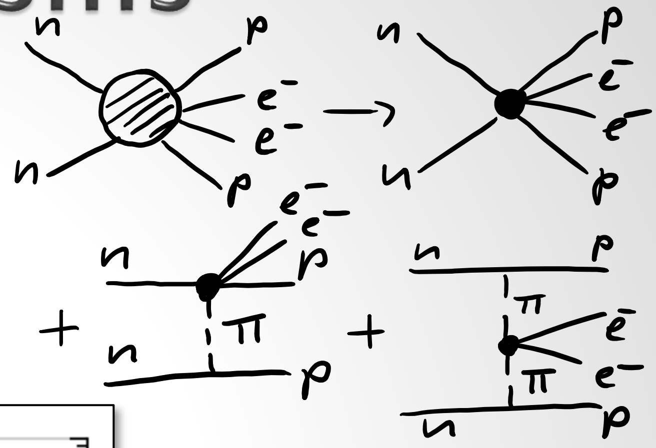
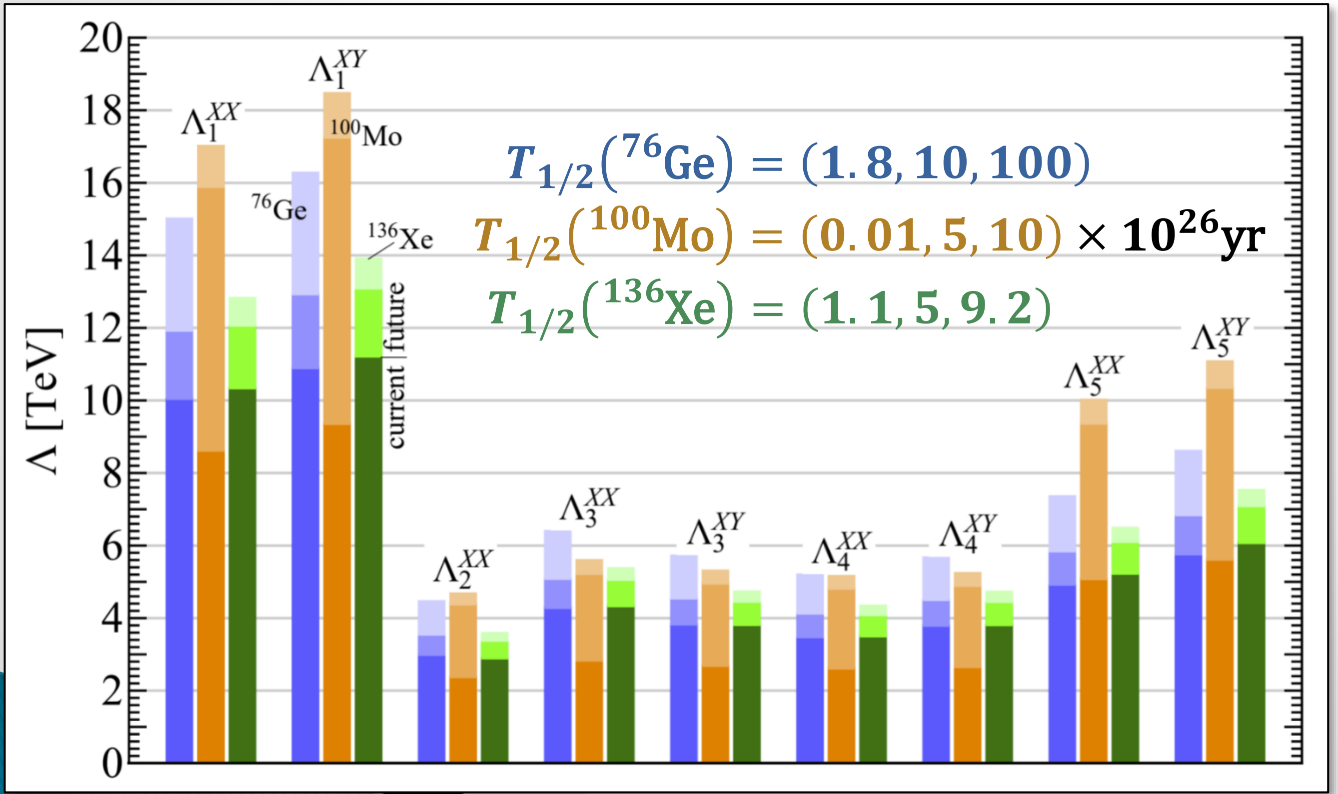
Short-Range Mechanisms

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

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- Chiral EFT with Pion operators from Lattice QCD (Cirigliano, Dekens, de Vries, Graesser, Mereghetti, JHEP 1812 (2018) 097)

Example: Sterile Neutrinos

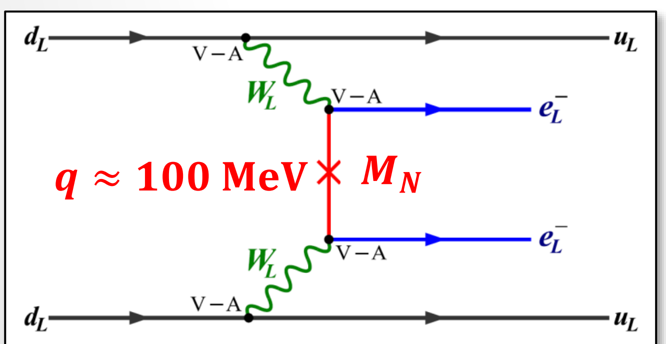
- Masses lighter than ≈ 100 MeV

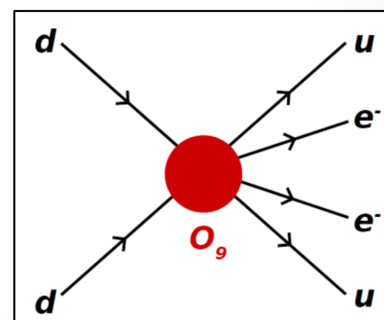
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}} + s_{14}^2 m_{\nu_4} e^{i\phi_{14}} + \cdots|$$

- 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





Example: Sterile Neutrinos

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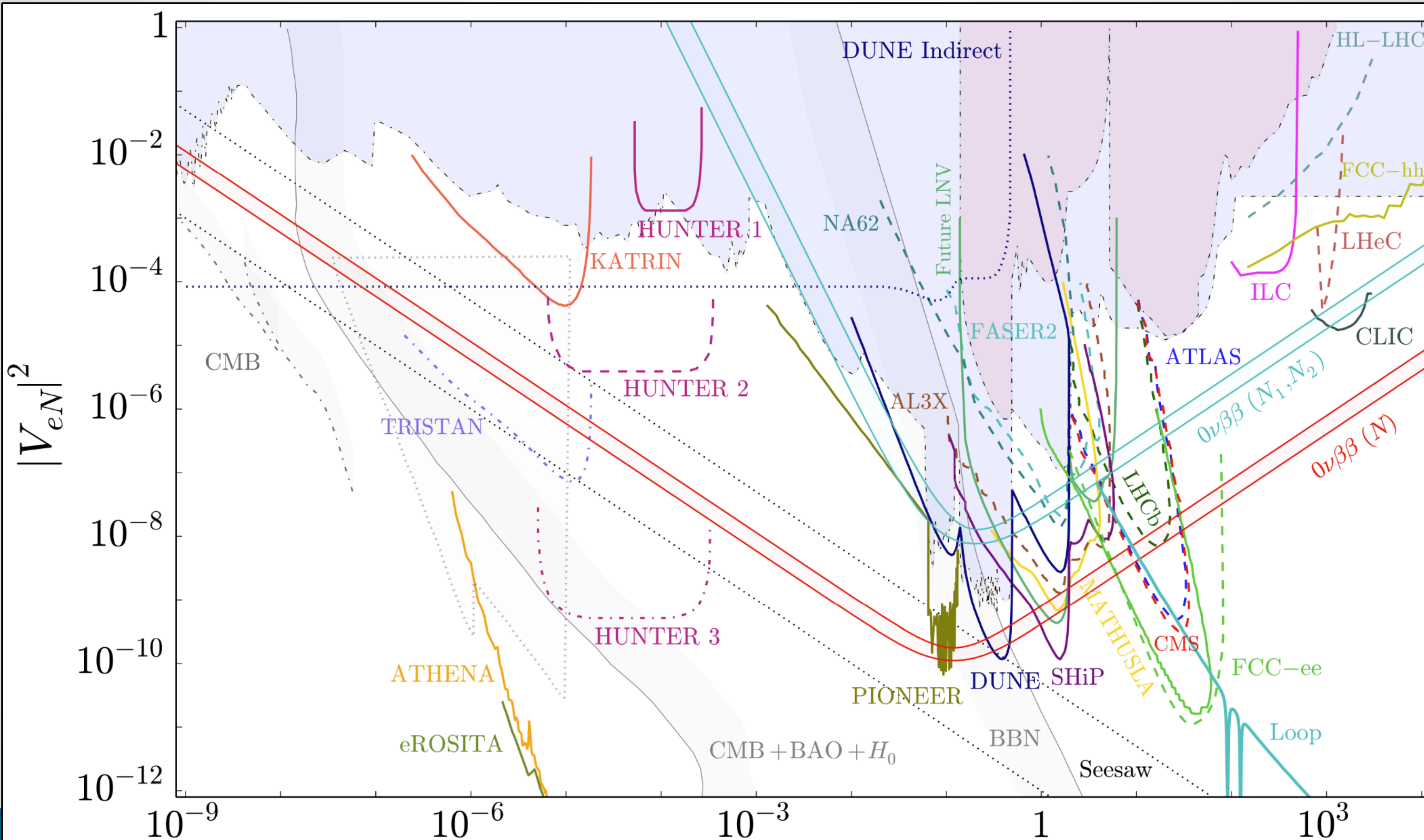
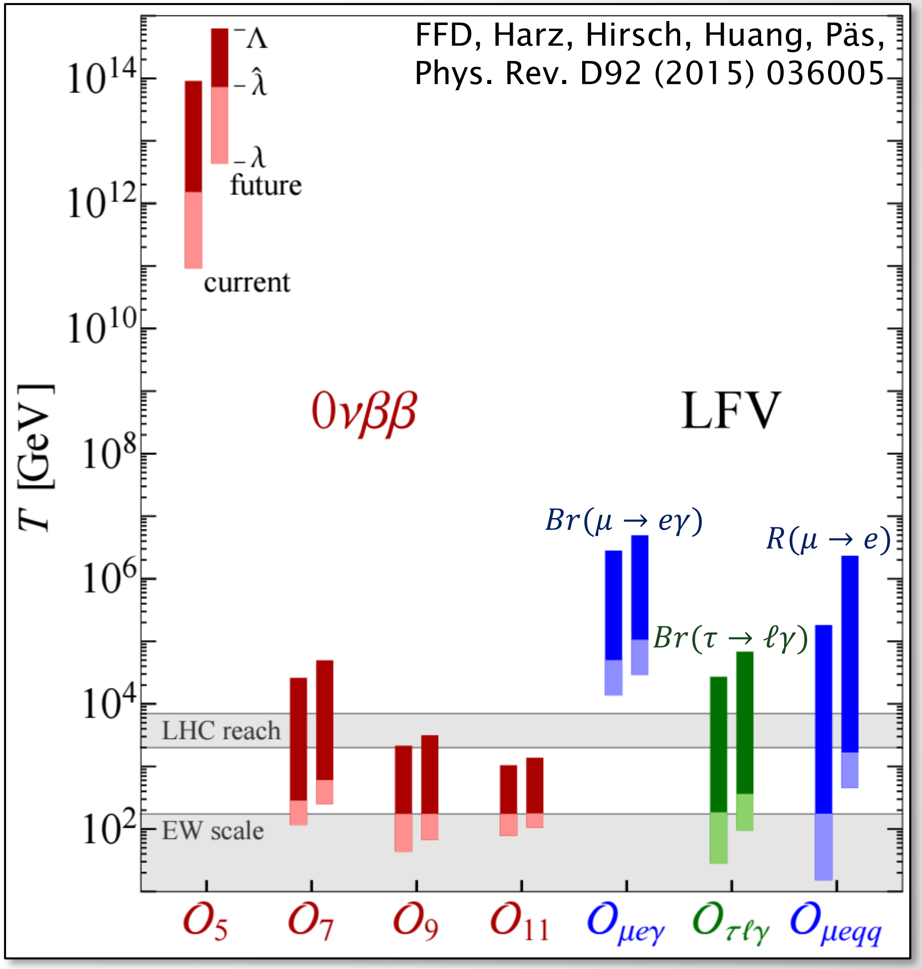


Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

Application: Falsifying Baryogenesis

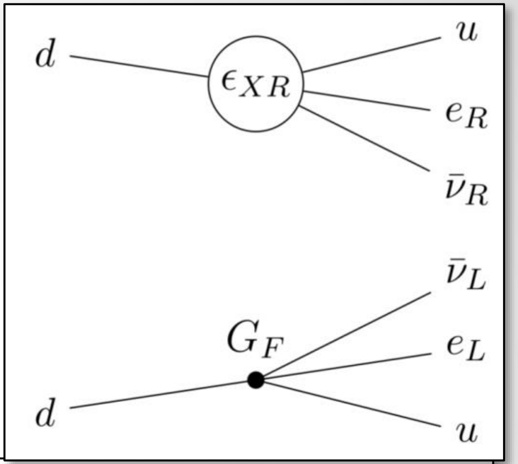
- Temperature ranges of strong equilibration
  - Assumes observation of corresponding process!
- Observation of LNV
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**
    FFD, Harz, Hirsch, PRL 112 (2014), FFD, Harz, Hirsch, Huang, Päs, PRD 92 (2015)

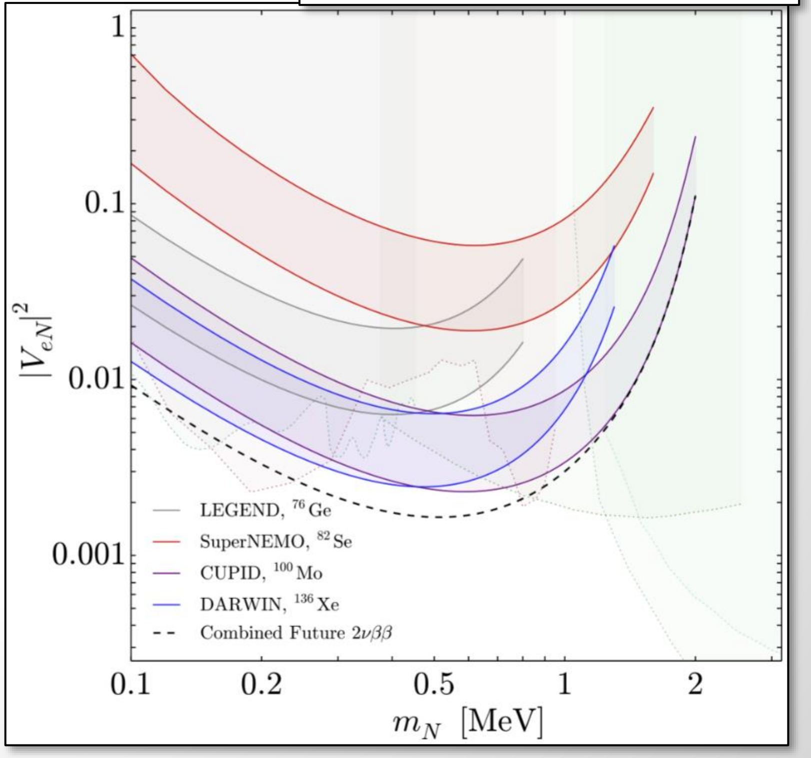


Non-Standard $2\nu\beta\beta$

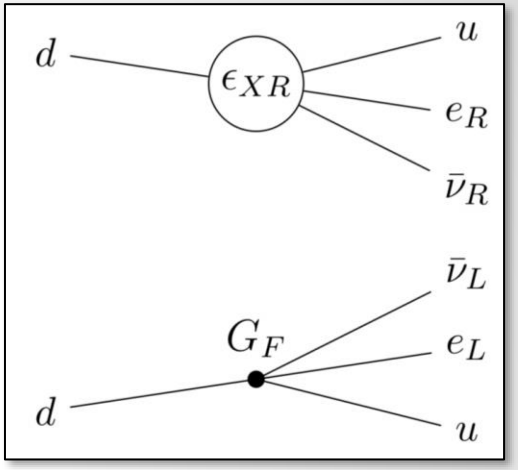
- Sterile neutrino search through energy endpoint
  (Bolton, FFD, Graf, Simkovic, PRD 103 (2021); Agostini et al., PLB 815 (2021))
  - Emission of one sterile neutrino in double beta decay: $\nu N\beta\beta$
  - Same principle as endpoint searches in single β decays
  - Observed limit at GERDA (JCAP 12 (2022) 012)

$$|V_{eN}|^2 < 1.3 \times 10^{-2}$$





Non-Standard $2\nu\beta\beta$



- Lepton-number conserving right-handed currents
  (FFD, Graf, Simkovic, PRL 125 (2020))
  - Exotic charged currents probed e.g.
    - in neutron and single β decay
    - at LHC in $pp \to eX + MET$
  - Limits on RH currents

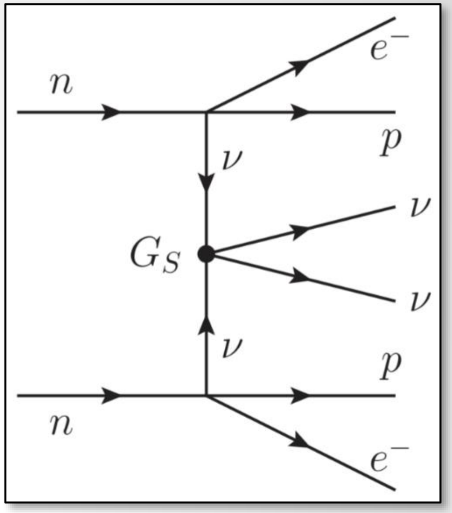
$$\frac{G_F \cos\theta_C}{\sqrt{2}} \left((1 + \delta_{\rm SM} + \epsilon_{LL}) j_L^\mu J_{L\mu} + \epsilon_{RL} j_L^\mu J_{R\mu} + \epsilon_{LR} j_R^\mu J_{L\mu} + \epsilon_{RR} j_R^\mu J_{R\mu} \right)$$

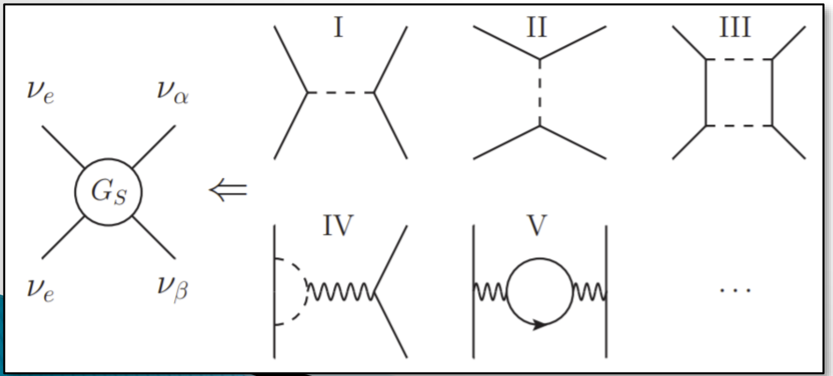
  less severe due to lack of interference with SM

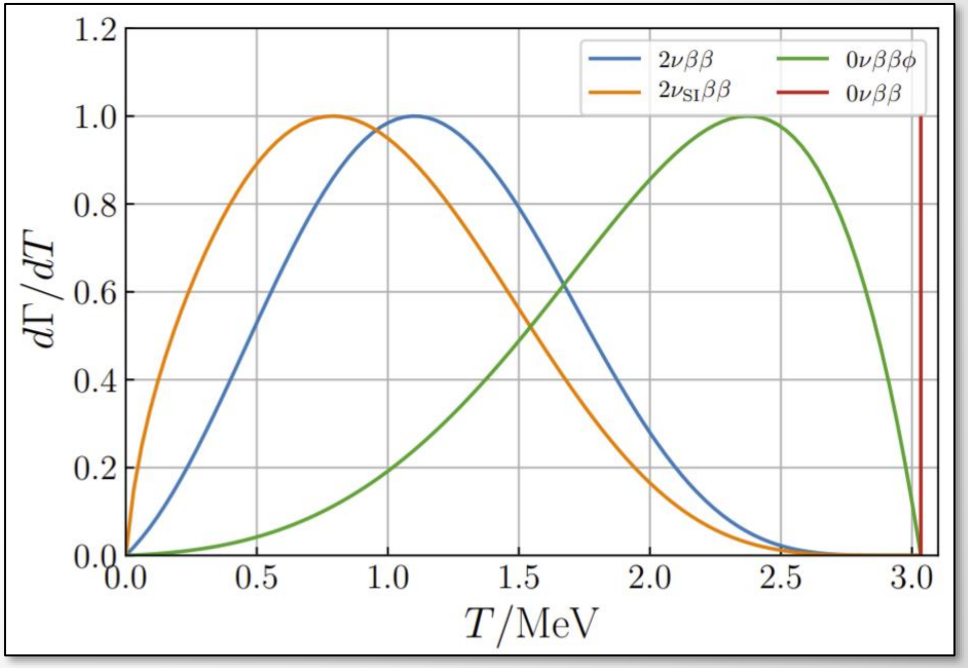
- Modification of angular and energy distribution in $2\nu\beta\beta$ decay
  - Current limit $\epsilon_{XR} < 3 \times 10^{-2}$ from NEMO3 competitive to other searches

Non-Standard $2\nu\beta\beta$

- Neutrino self-interactions
  (FFD, Graf, Rodejohann, Xu, PRD 102 (2020))
  - Same signature as SM $2\nu\beta\beta$ decay
  - Potential interference with SM $2\nu\beta\beta$ decay
  - Non-observation of enhanced rate excludes regime $G_S \approx 4 \times 10^9\, G_F$ suggested to resolve Hubble tension
    (Kreisch, Cyr-Racine, Doré, PRD 101 (2020) 12, 123505)







Conclusion

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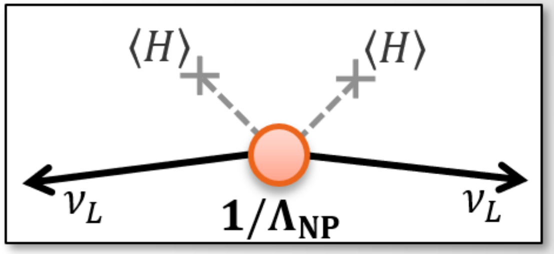
- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Determination of absolute mass scale
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Universal probe of LNV physics
    - LNV physics near GUT scale
    - **Direct sensitivity to LNV physics at scales $m_N \approx 1$ eV – 100 TeV via short- and long-range contributions**



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

- **$2\nu\beta\beta$ is sensitive to New Physics**
  - Ongoing and future searches probe $2\nu\beta\beta$ decay with high statistics
  - Endpoint searches for sterile neutrinos
  - Exotic (right-handed) currents
  - Neutrino self-interactions