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(Neutrinoless) Double Beta Decay as Probe of New Physics

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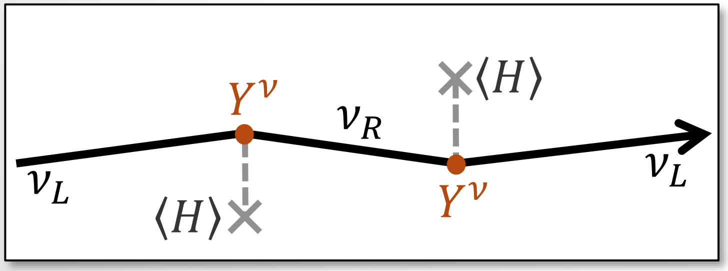
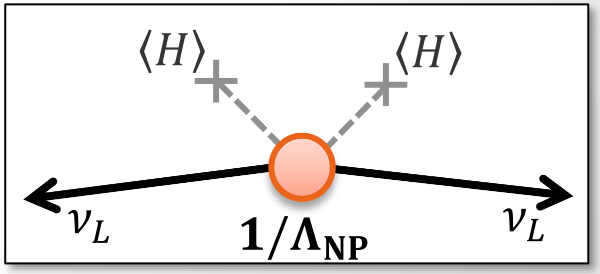
Dirac versus Majorana

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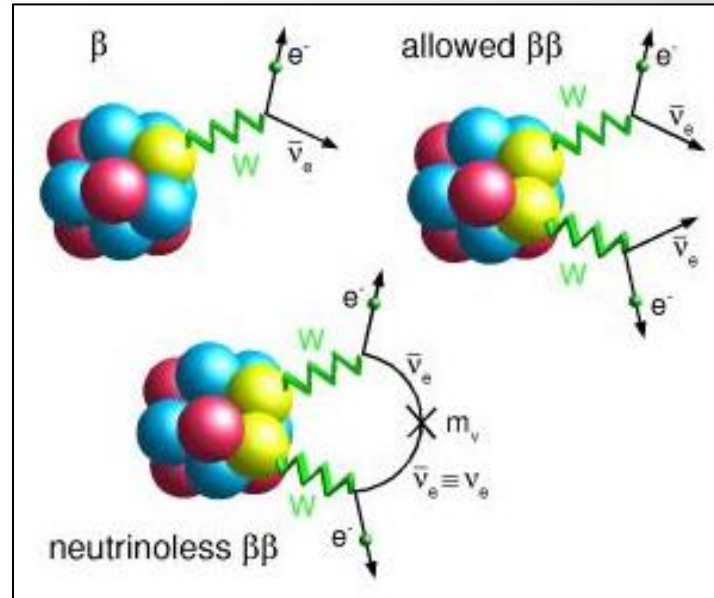
- Origin of neutrino masses beyond the Standard Model
- Crucial role of total lepton number L symmetry
  - Arises accidentally as global $U(1)_L$ in SM from particle content and gauge symmetry
  - L broken non-perturbatively but $B - L$ conserved
  - Global symmetries expected to be broken gravitational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

Beta Decays and Neutrinos

- Single beta decay
$$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$
  - Kinematic neutrino mass measurement
- Allowed double beta ($\mathbf{2\nu\beta\beta}$) decay
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($\mathbf{0\nu\beta\beta}$) 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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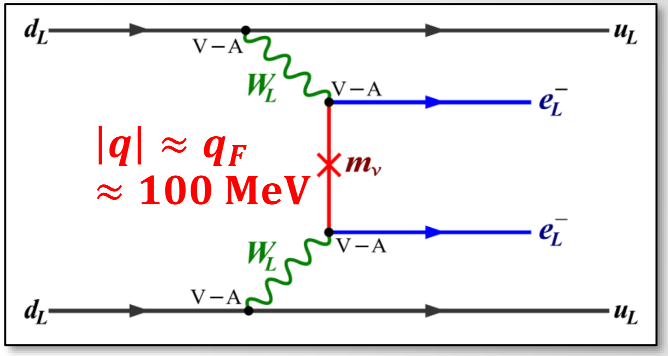
- Half-life

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



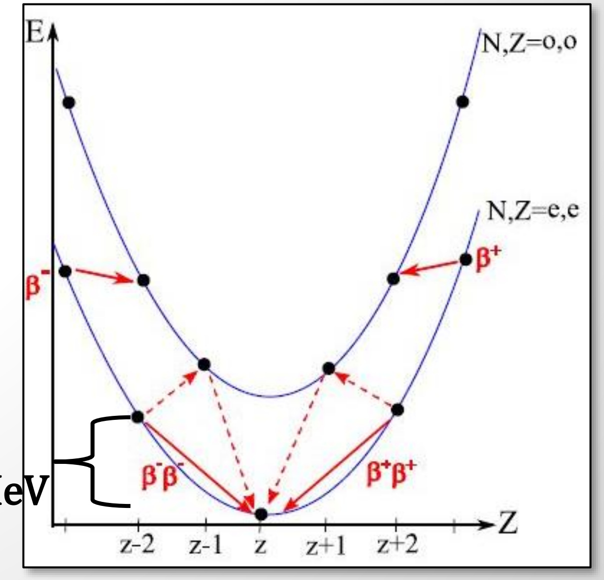
- Particle Physics

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

- 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

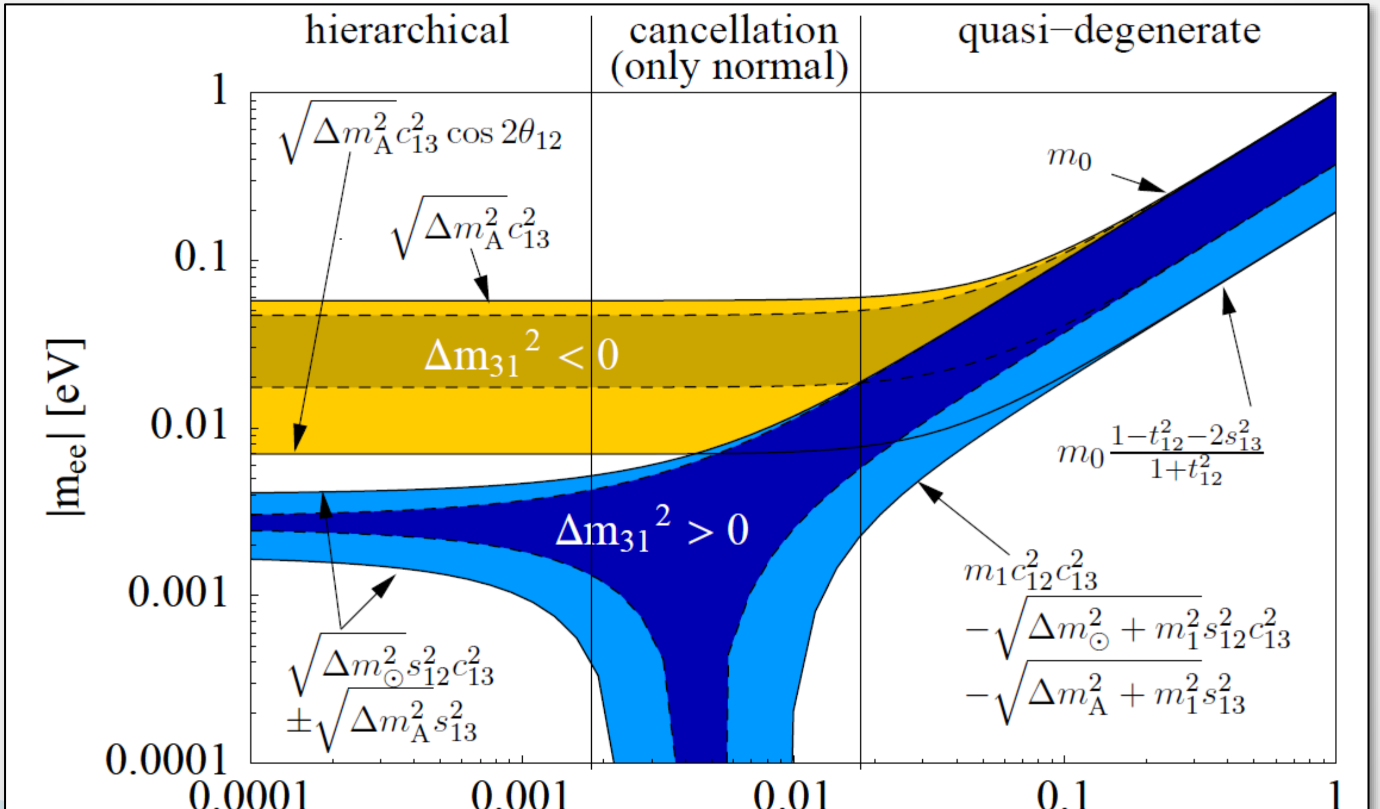


Three Active Neutrinos

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

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

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



Lindner, Merle, Rodejohann, Phys.Rev. D73 (2006) 053005

Three Active Neutrinos

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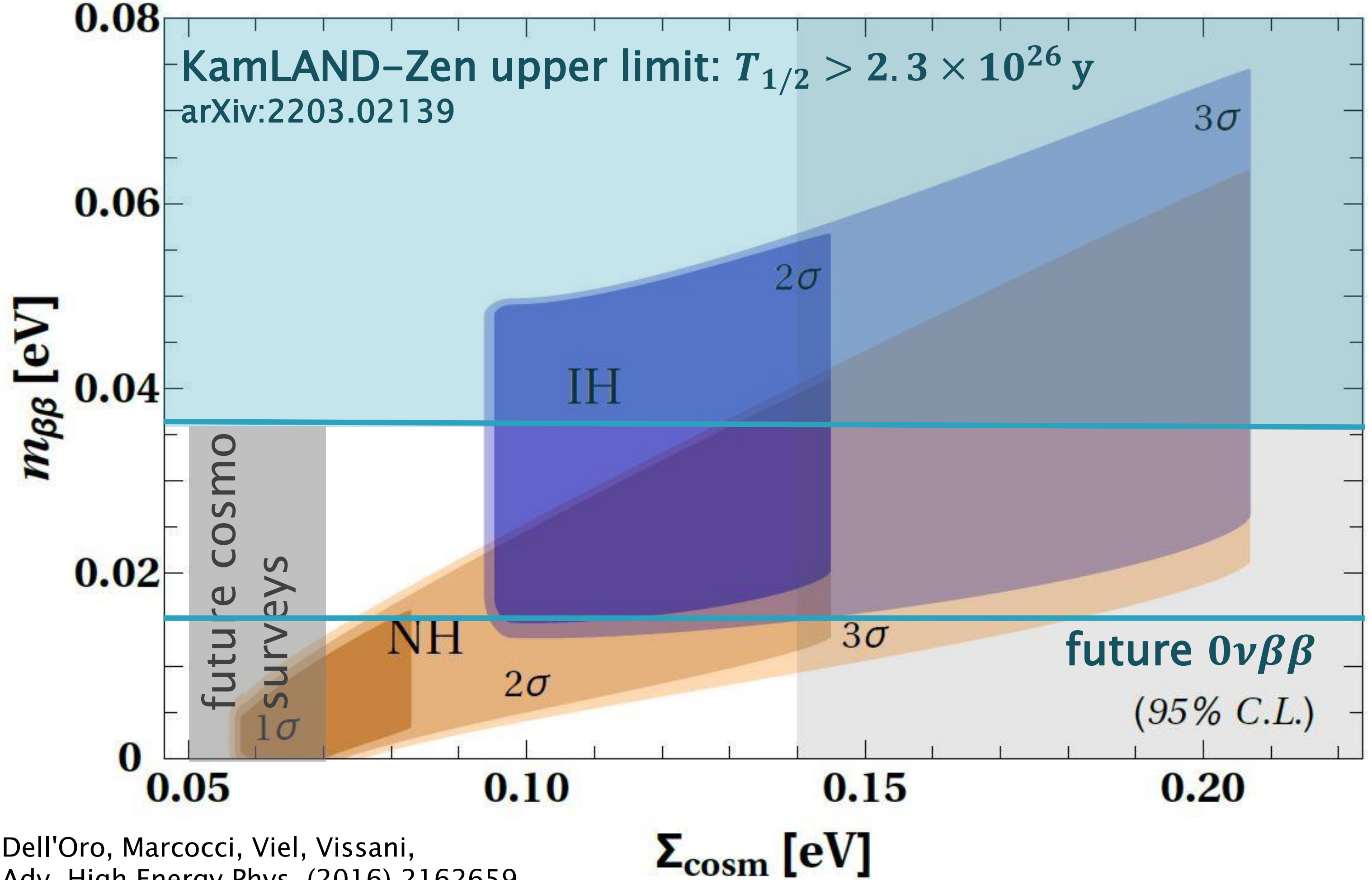
- Effective $0\nu\beta\beta$ Mass



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

Three Active Neutrinos

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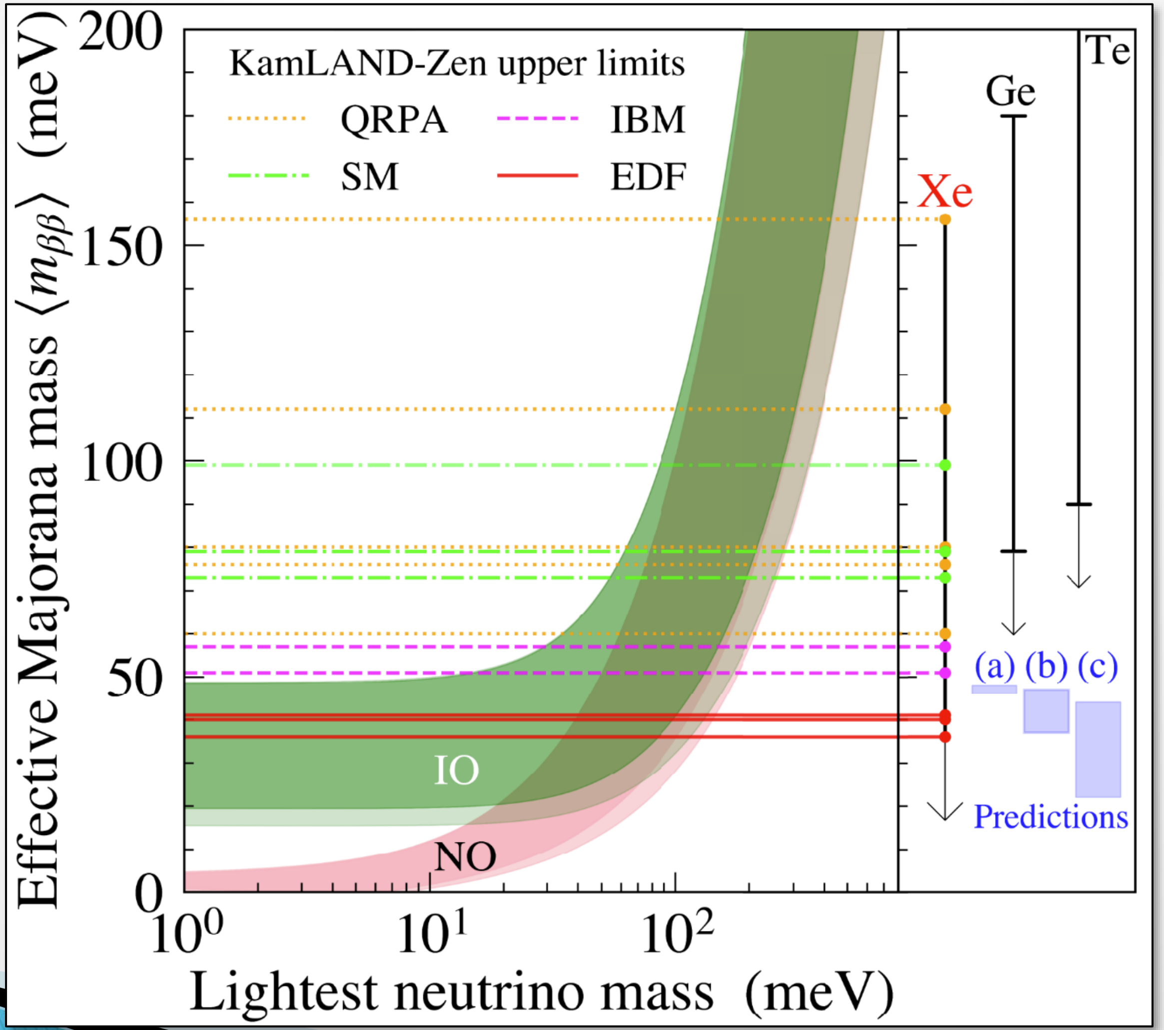
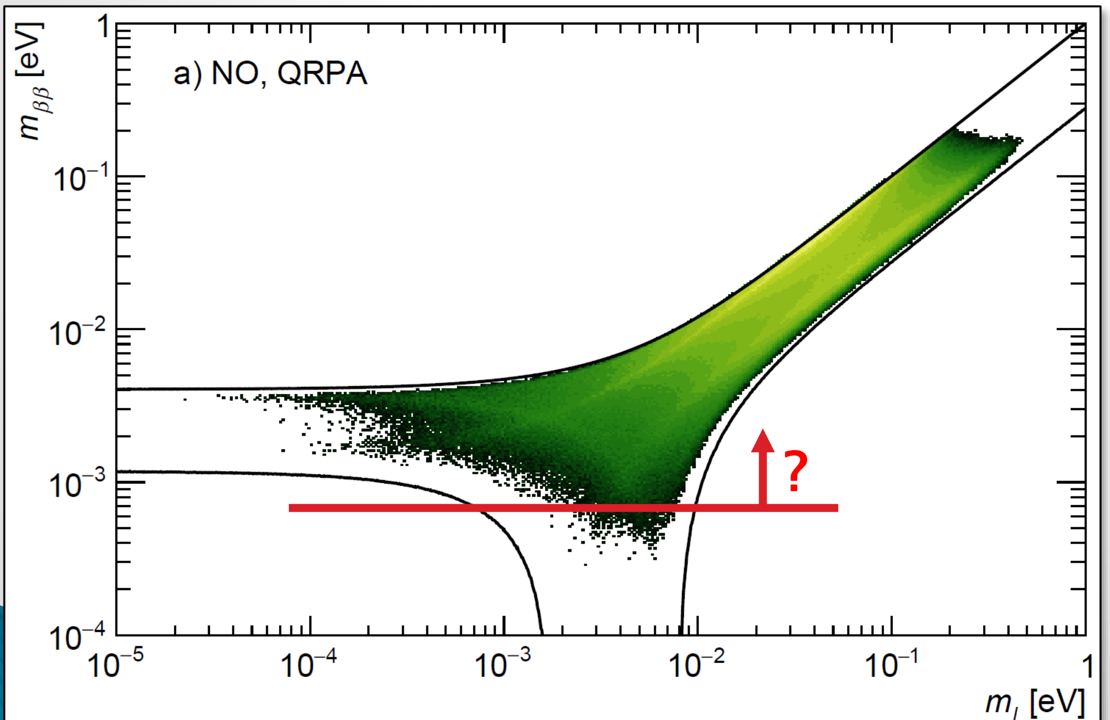
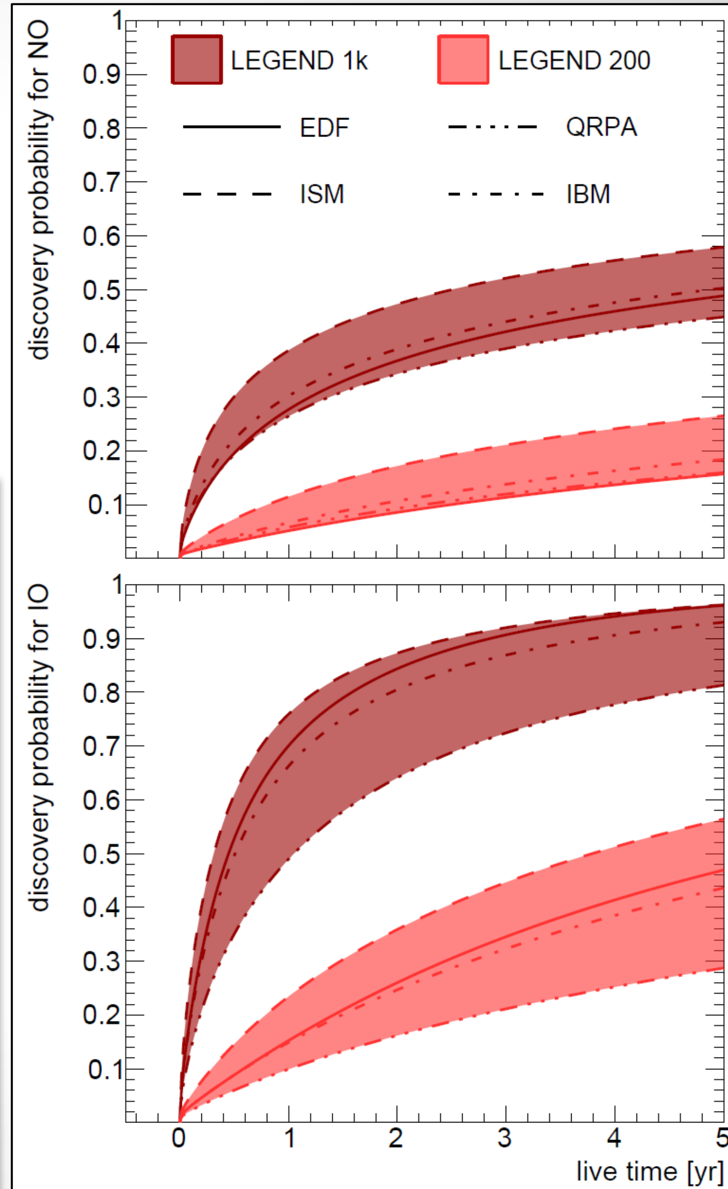
- Current Best Limit from KamLAND-Zen (arXiv:2203.02139)



Lower Limit on $m_{\beta\beta}$?

- From volume-effect on accidental cancellation in $m_{\beta\beta}$
  - Bayesian analysis with flat priors on Majorana phases
    Agostini, Benato, Detwiler
    Phys. Rev. D 96 (2017) 053001





Sterile Neutrinos

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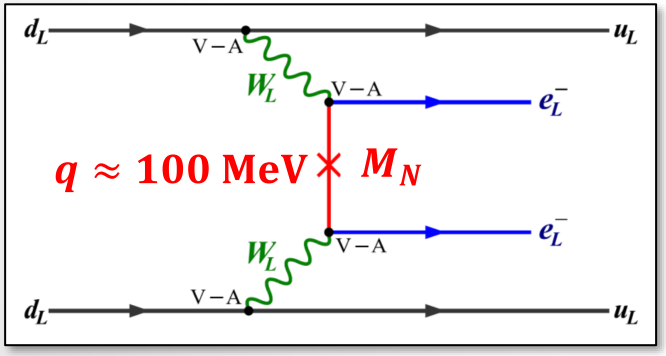
- Masses lighter than ≈ 100 MeV

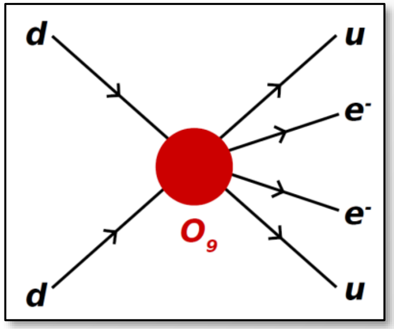
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}} + s_{14}^2 m_{\nu_4} e^{i\phi_{14}} + \cdots|$$

- Masses heavier than ≈ 100 MeV

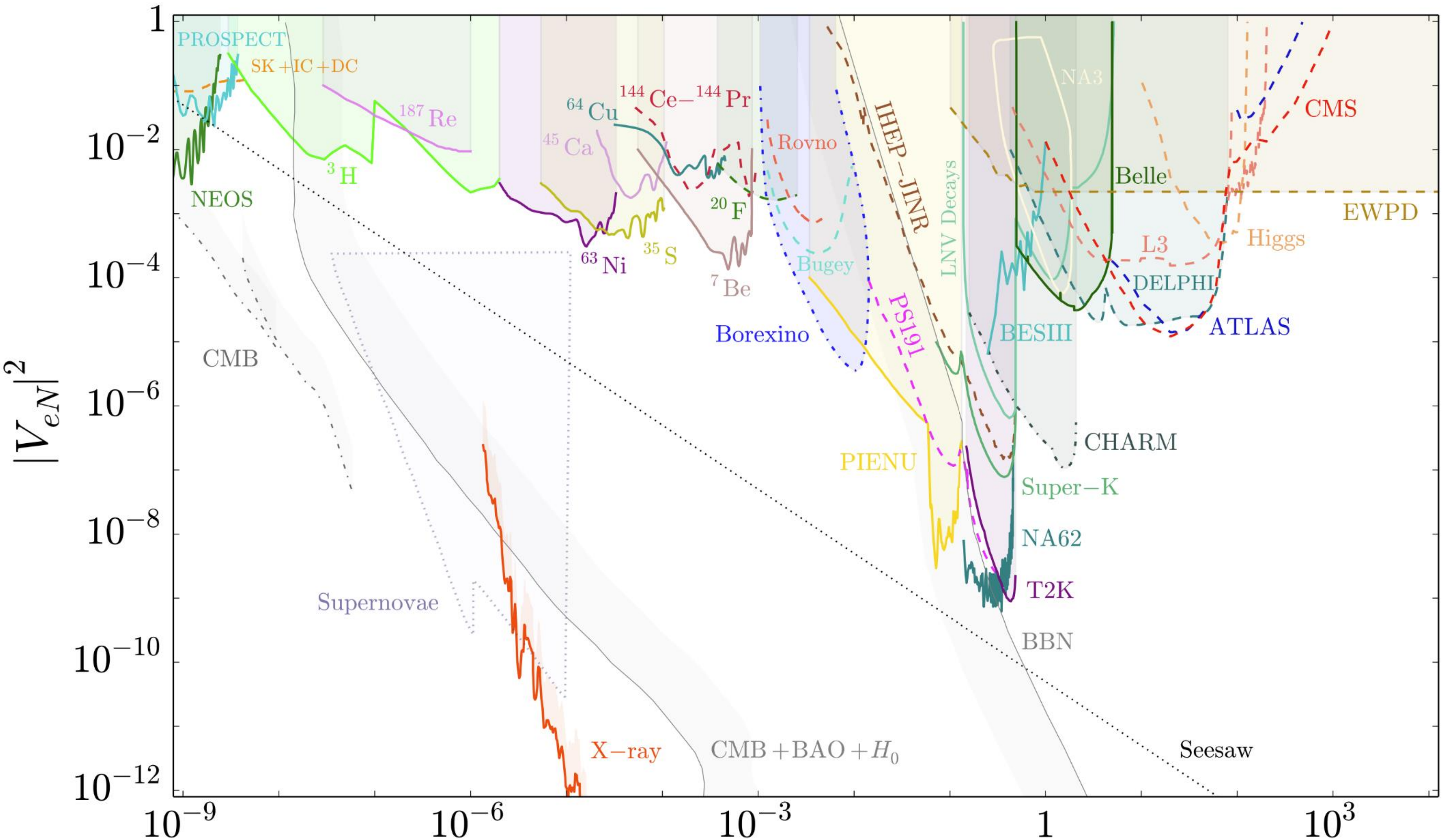
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} V_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + M_{N_i}}{q^2 - M_{N_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{-\gamma_\mu(1+\gamma_5)\gamma_\nu}{4} \sum_{i=1}^{3} \frac{V_{ei}^2}{M_{N_i}} \rightarrow \left\langle \frac{1}{M_N} \right\rangle_{\beta\beta}$$

- Short-distance on nuclear scale





Sterile Neutrinos



Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

Sterile Neutrinos

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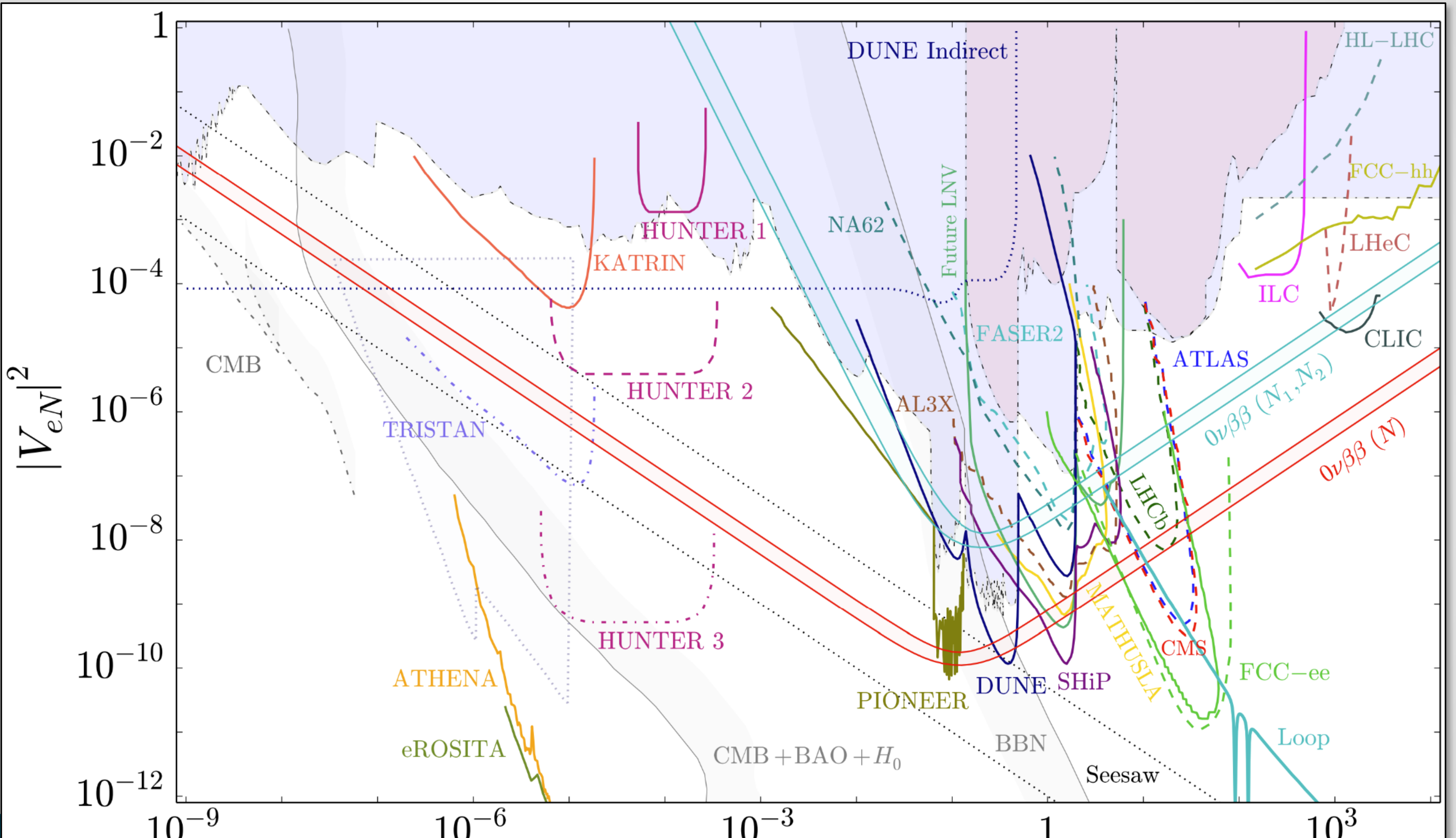

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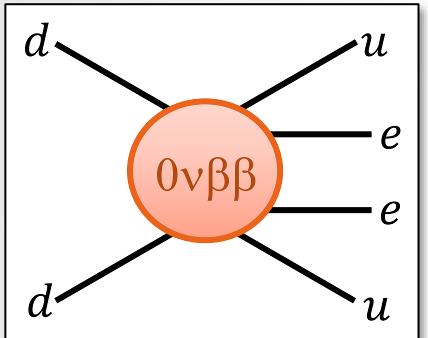
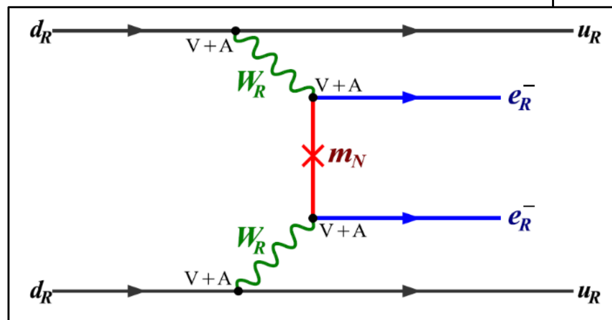
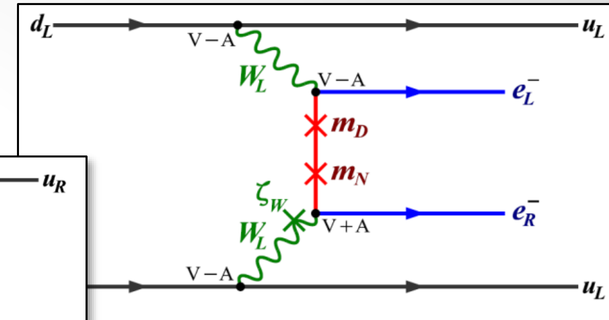
New Physics and $0\nu\beta\beta$

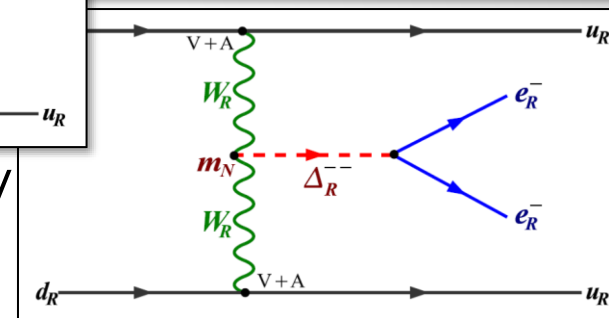
- Plethora of New Physics scenarios



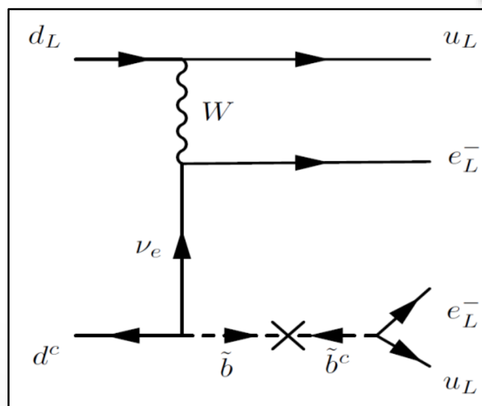
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

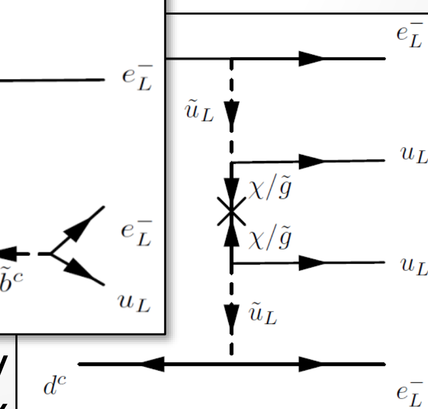






Left-Right Symmetry





R-Parity Violating SUSY

Extra Dimensions

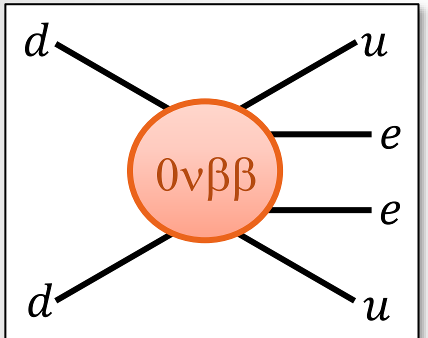
Majorons

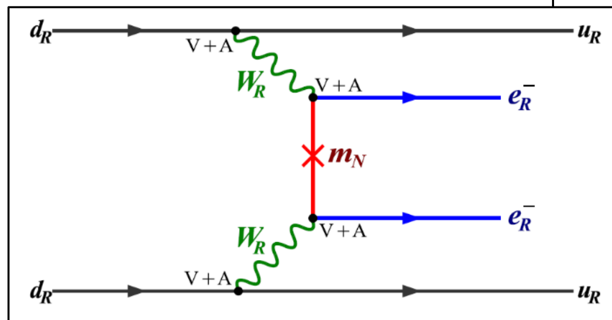
Leptoquarks

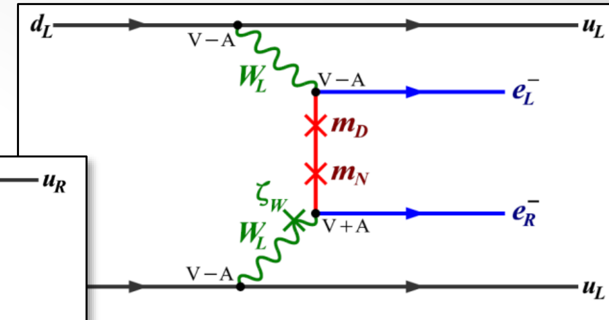
...

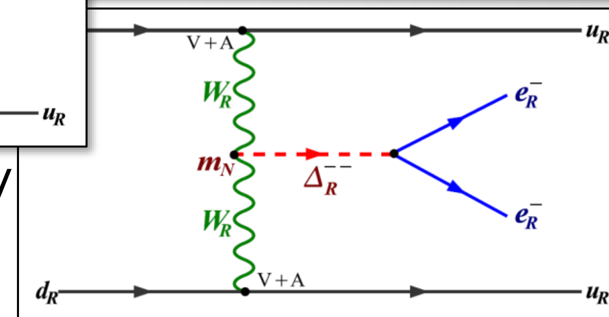
New Physics and $0\nu\beta\beta$

- Plethora of New Physics scenarios







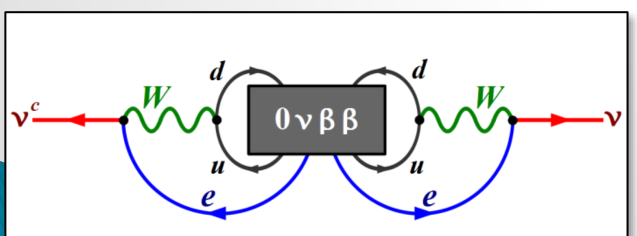


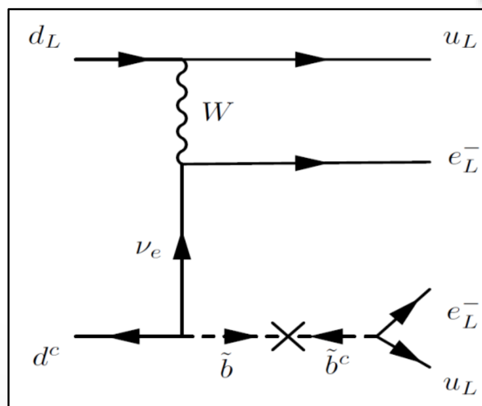
Left-Right Symmetry

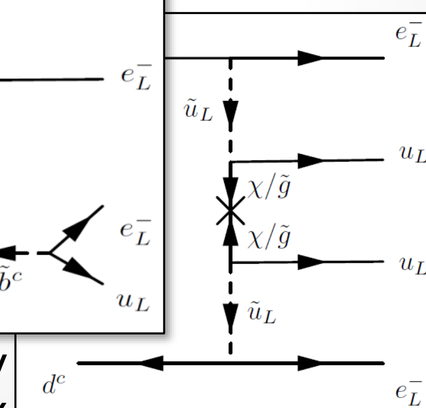
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left|M_{NP}^{0\nu}\right|^2$$

- Neutrinos still Majorana

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







R-Parity Violating SUSY

Extra Dimensions

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

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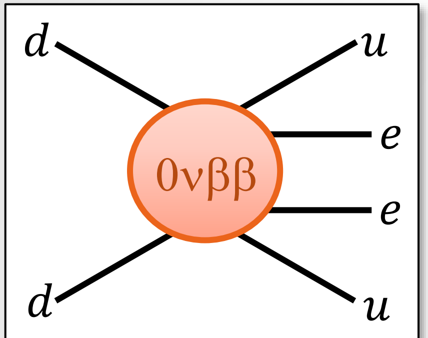
- Examples in Left-Right Symmetry



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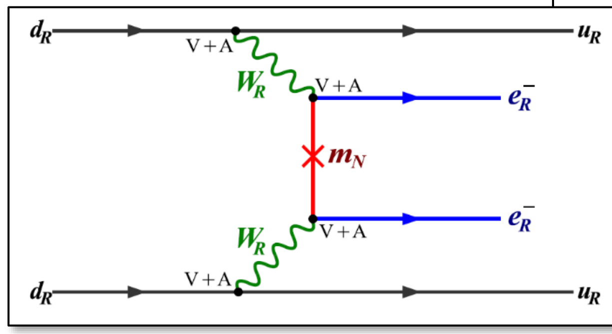
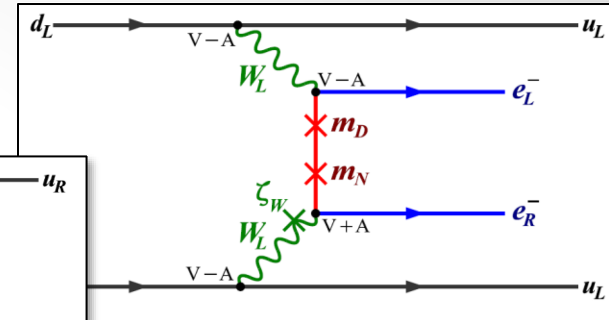


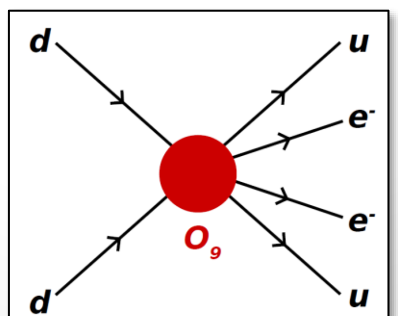


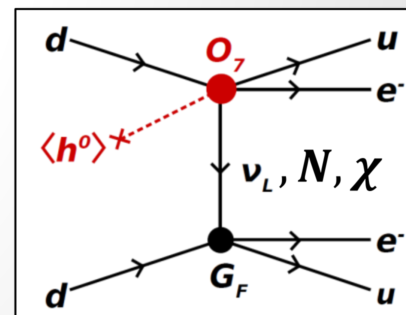
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left|M_{NP}^{0\nu}\right|^2$$

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

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

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





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

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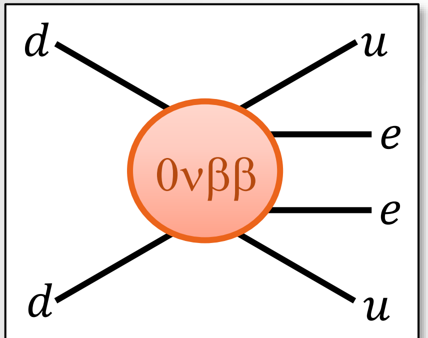
- Examples in Left-Right Symmetry



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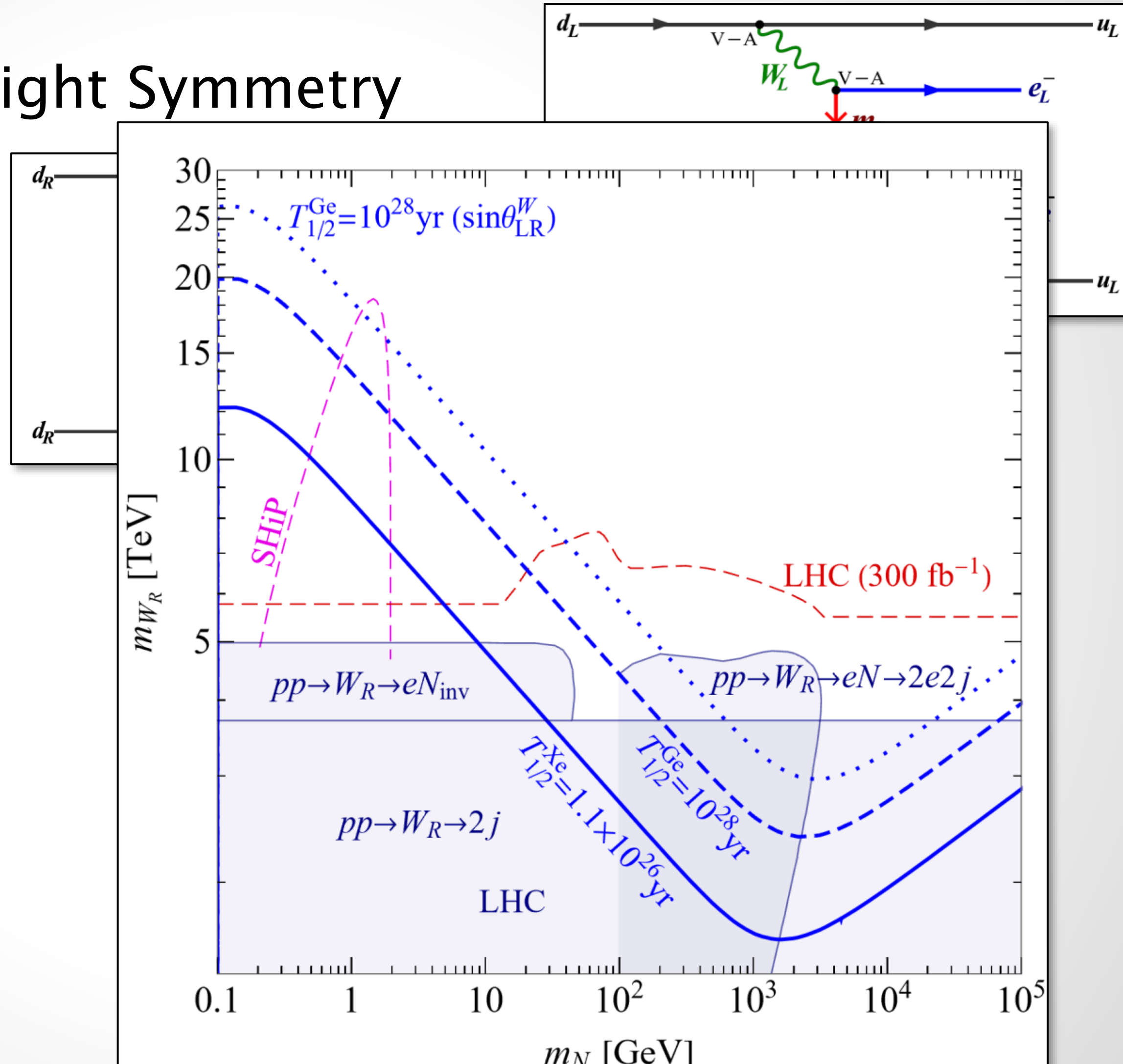

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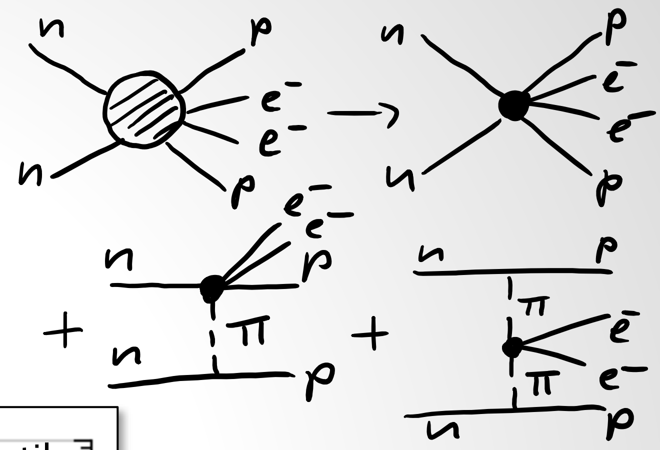
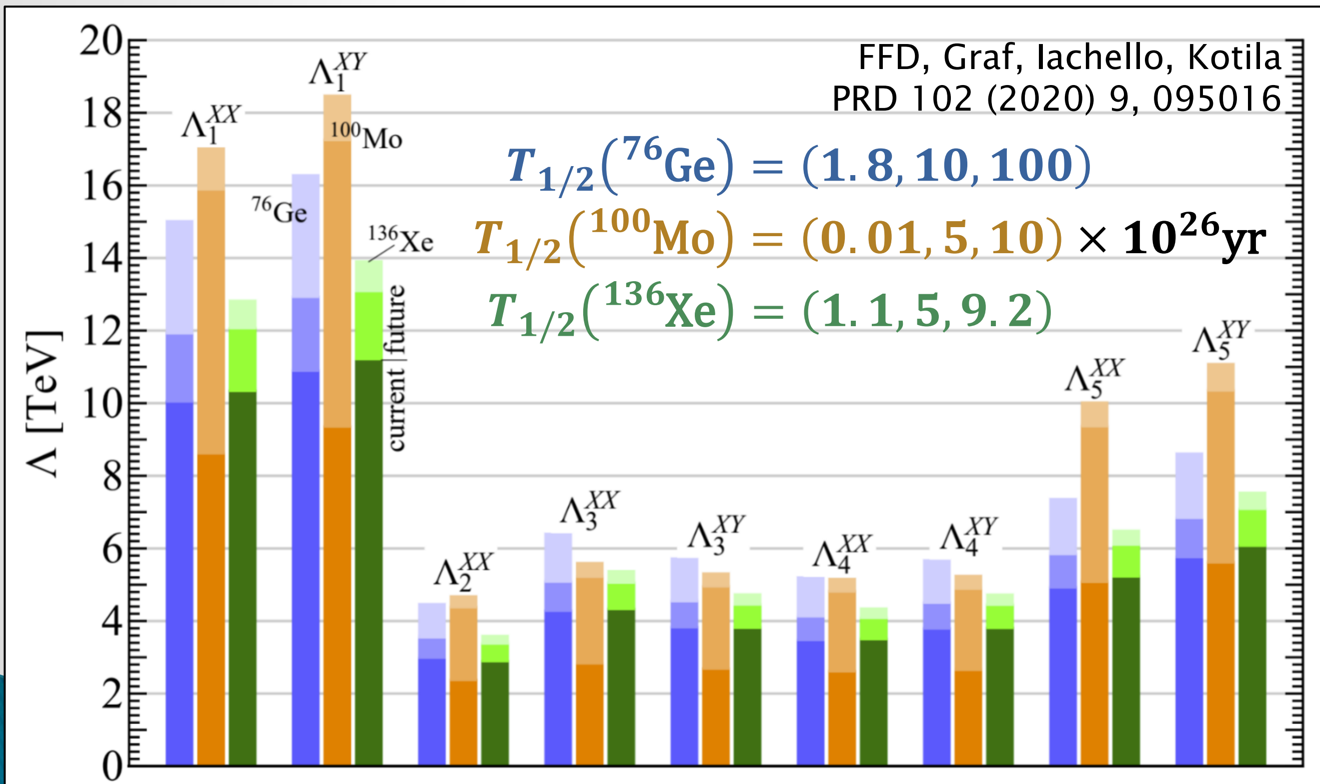
Heavy New Physics

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





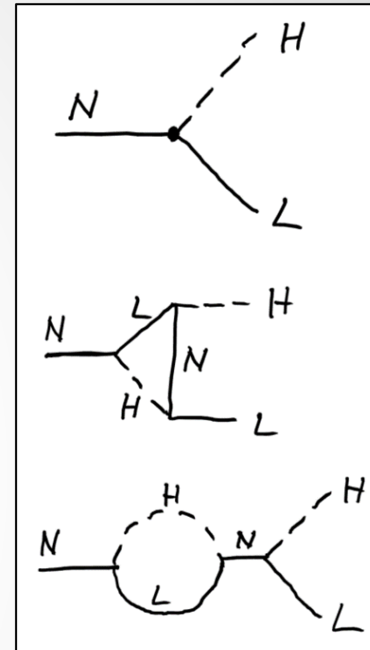
Pion-mediated contributions

- 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)

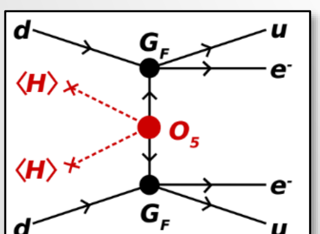
Falsifying Baryogenesis

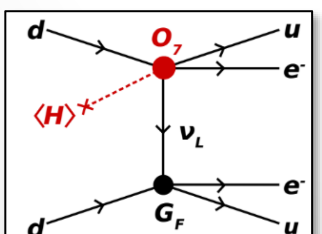
- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100$ GeV
    - Observed asymmetry

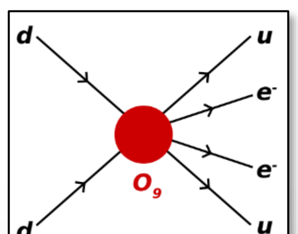
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$

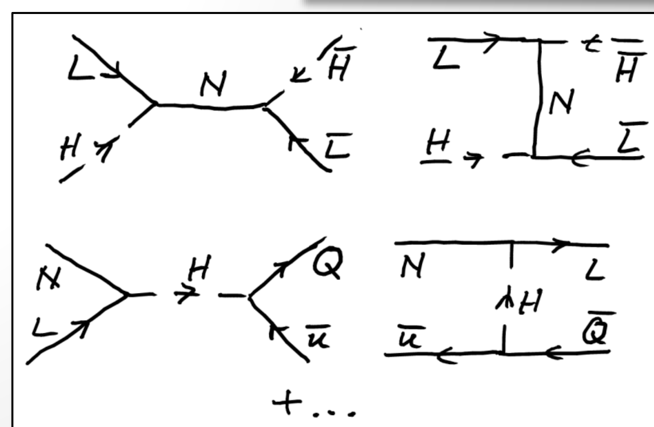


- What if we observe lepton number violating processes in $0\nu\beta\beta$?



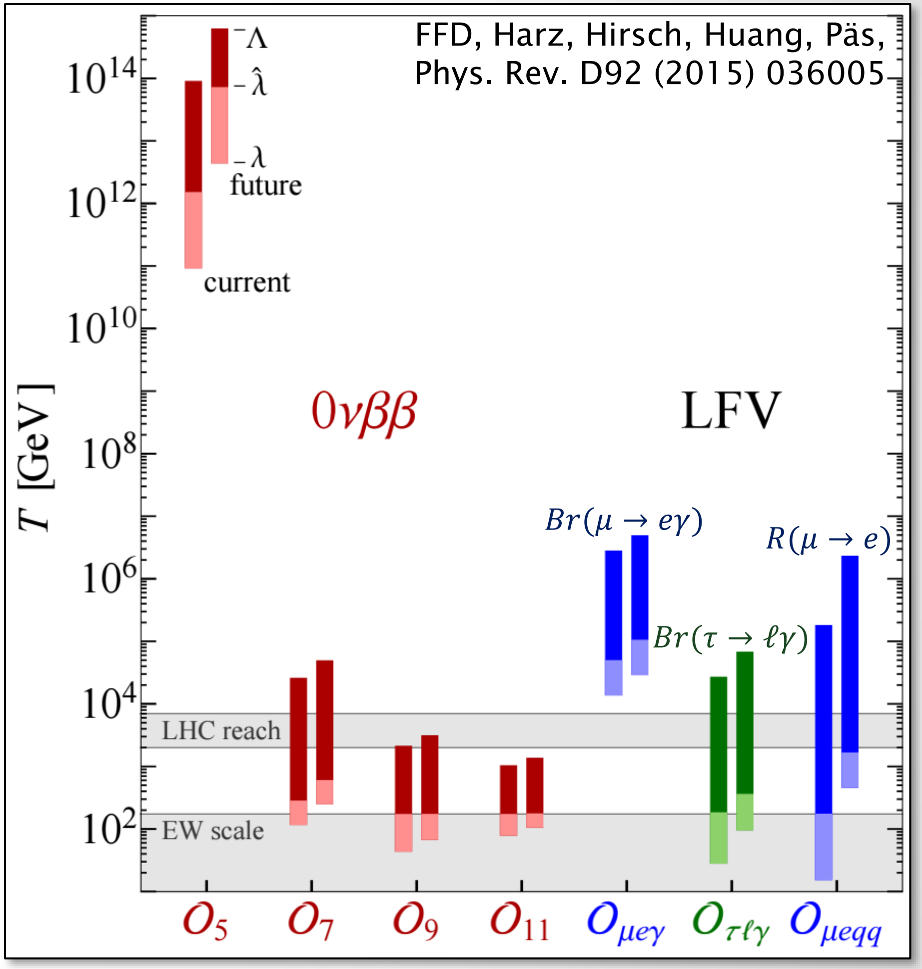






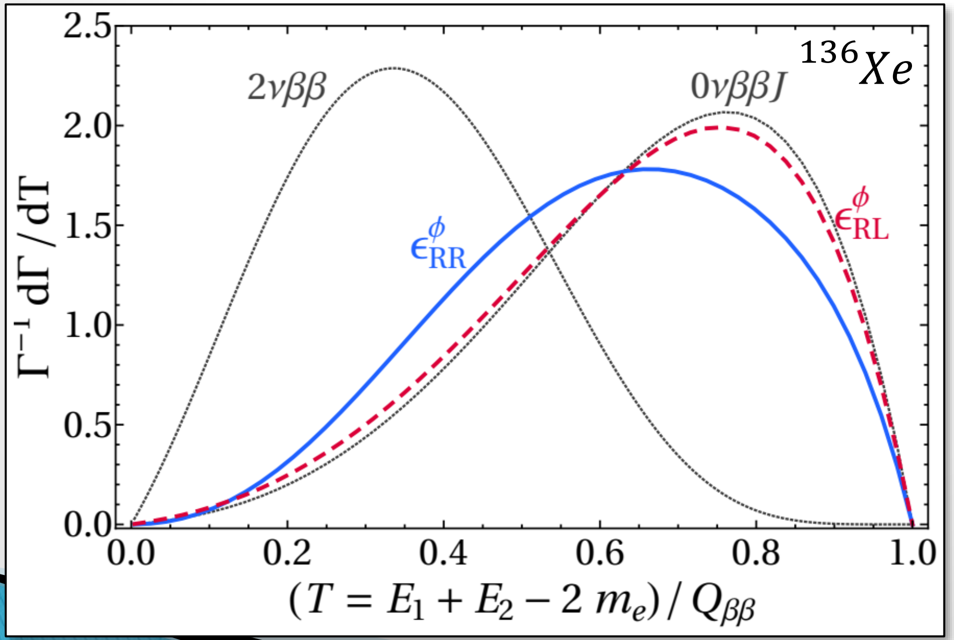
Falsifying Baryogenesis

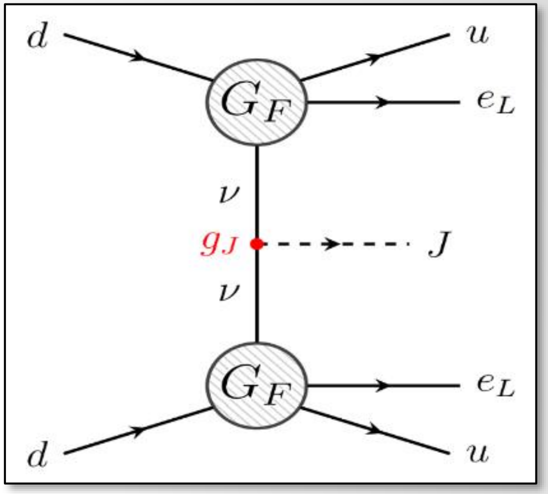
- Temperature ranges of strong equilibration
  - **Assumes observation of corresponding process!**
- Observation of LNV
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**

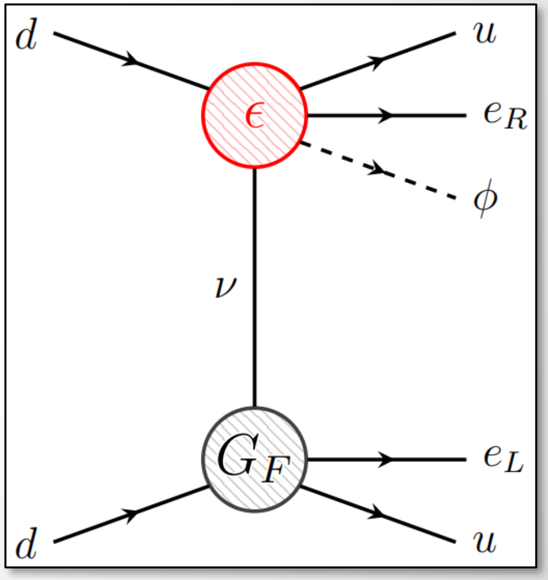


Exotic particle emission in double beta decay

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







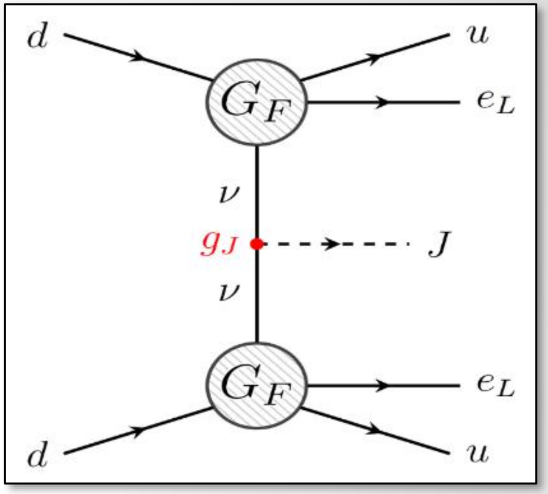
Exotic particle emission in double beta decay

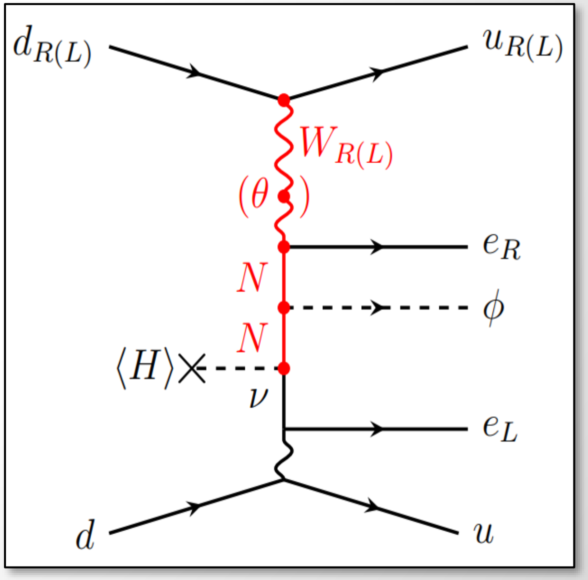
- Majoron(-like) J emission
- Majoron-like ϕ emission assisted by RH current
  (Cepedello, FFD, González, Hati, Hirsch, PRL 122 (2019) 181801)
- Sensitivity to Left-Right symmetric model with Dirac neutrinos

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

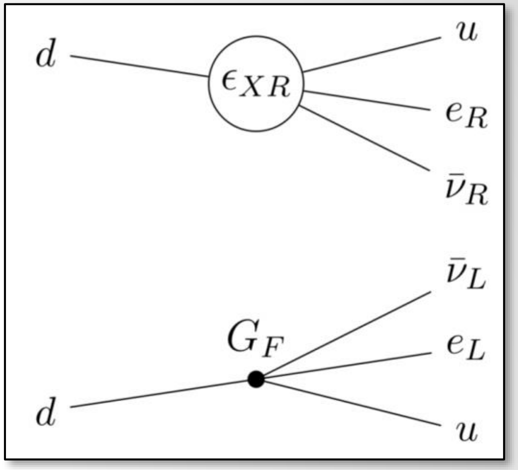
- Searched for in EXO-200
  (Phys.Rev.D 104 (2021) 11, 112002)

$$T_{1/2}^{Xe} > 4\times 10^{24}\mathrm{y}$$





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



- Lepton-number conserving right-handed currents
  (FFD, Graf, Simkovic, PRL 125 (2020) 17, 171801)
  - Exotic charged currents probed e.g.
    - in neutron and single β decay
    - at LHC in $pp \to eX + MET$
  - Limits on RH currents

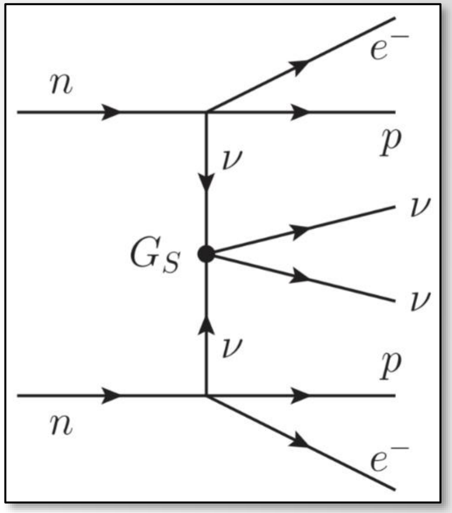
$$\frac{G_F \cos\theta_C}{\sqrt{2}}\left((1+\delta_{\rm SM}+\epsilon_{LL})j_L^\mu J_{L\mu}+\epsilon_{RL}j_L^\mu J_{R\mu}+\epsilon_{LR}j_R^\mu J_{L\mu}+\epsilon_{RR}j_R^\mu J_{R\mu}\right)$$

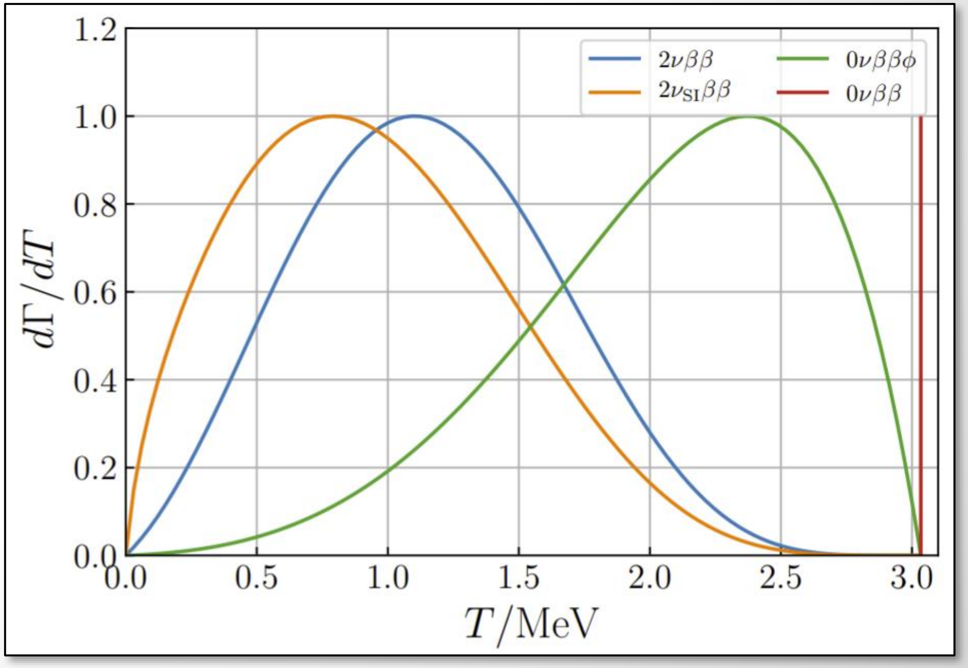
less severe due to lack of interference with SM

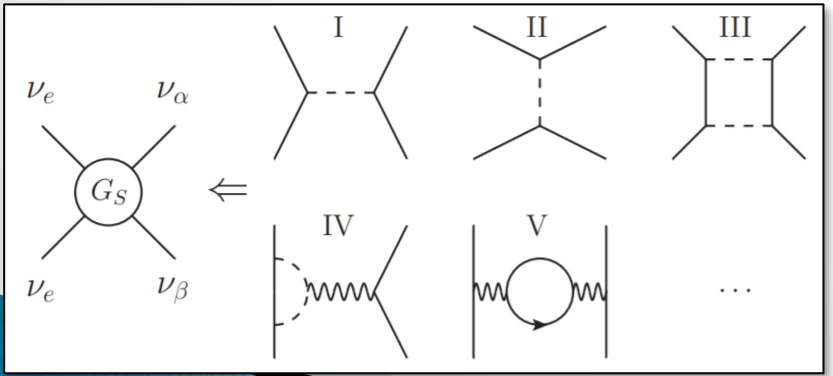
- Modification of angular and energy distribution in $2\nu\beta\beta$ decay
  - Current limit $\epsilon_{XR} < 2.7 \times 10^{-2}$ from NEMO3 competitive to other searches

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

- Neutrino self-interactions
  (FFD, Graf, Rodejohann, Xu,
  PRD 102 (2020) 5, 051701)
  - 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)

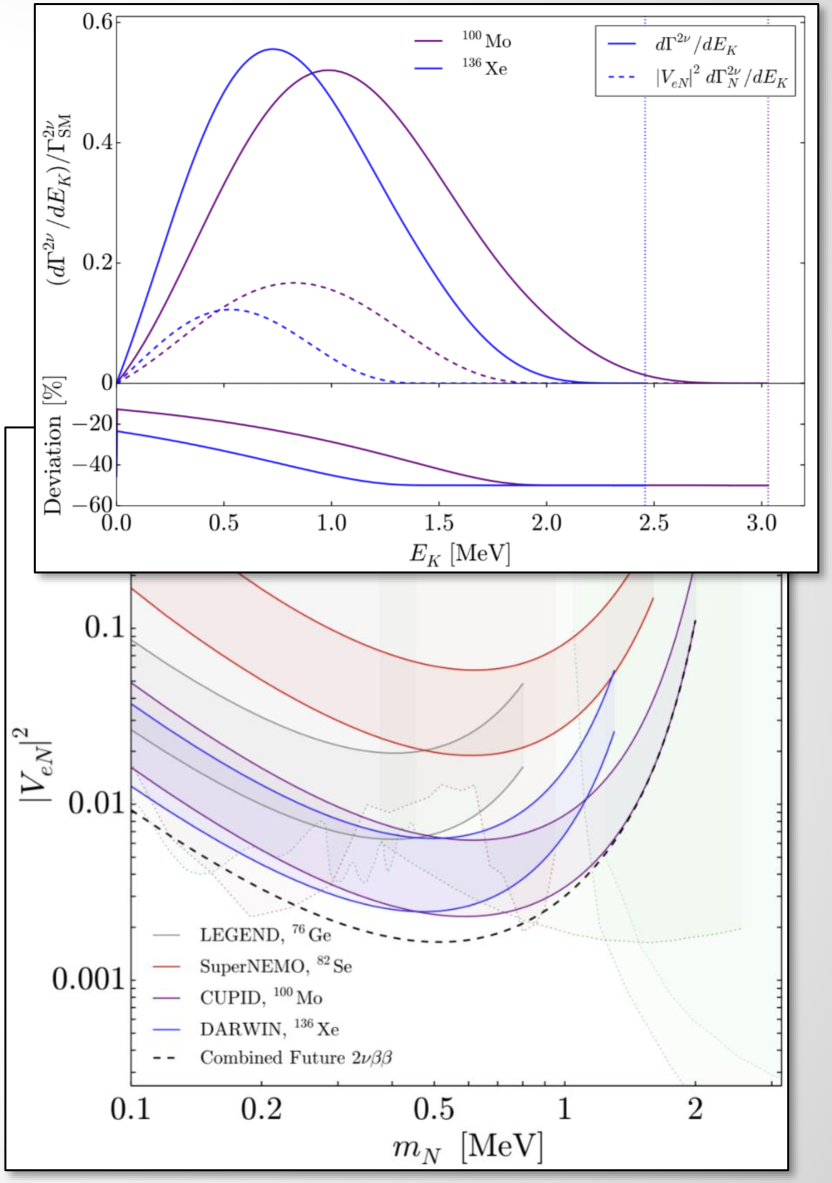






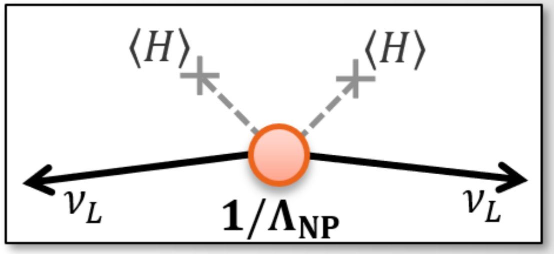
New Physics in $2\nu\beta\beta$

- Sterile neutrino search through energy endpoint
  (Bolton, FFD, Graf, Simkovic, PRD 103 (2021) 5, 055019; Agostini, Bossio, Ibarra, Marcano, arXiv:2021.09281)
  - 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: $|V_{eN}|^2 < 0.013$ (Krause, NDM22)



Conclusion

- **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 $m_N \approx 1\ \text{eV} - 100\ \text{TeV}$
    - Search for exotic MeV-scale particles
  - Ab-initio EFT, hadron and nuclear methods as pathway to precise Nuclear Matrix Elements



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

- **$2\nu\beta\beta$ is sensitive to New Physics as well**
  - Ongoing and future searches will probe $2\nu\beta\beta$ decay with high statistics
- **Broad New Physics programme at double beta decay experiments**