Probing New Physics with Double Beta Decay

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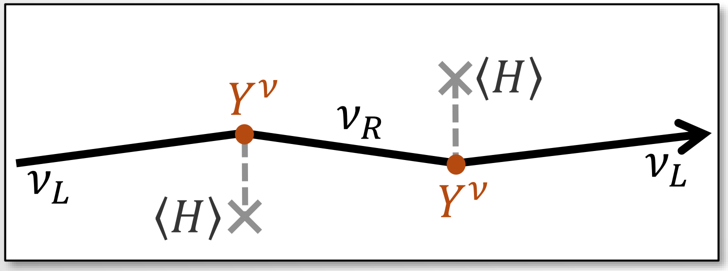
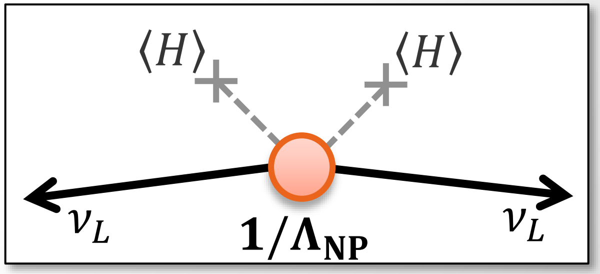
Dirac versus Majorana

- 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

Beta Decays and Neutrinos

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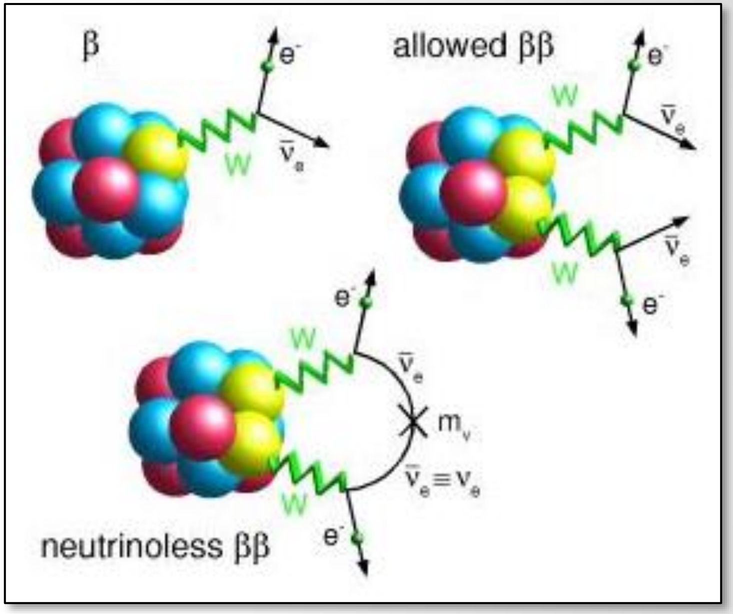
- Single beta decay
  $$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$
  - Kinematic neutrino mass measurement
- Allowed double beta ($\mathbf{2\nu\beta\beta}$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($\mathbf{0\nu\beta\beta}$) decay
  $$(A,Z) \rightarrow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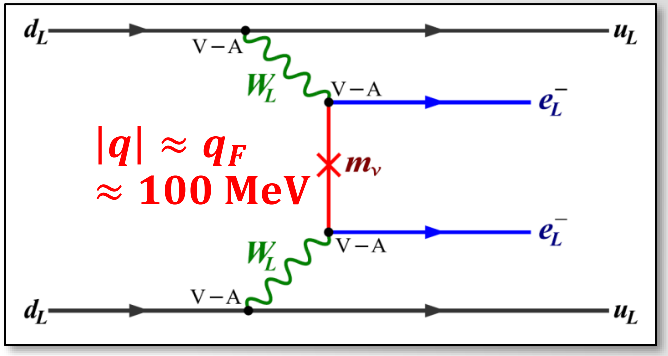
- Half-life

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

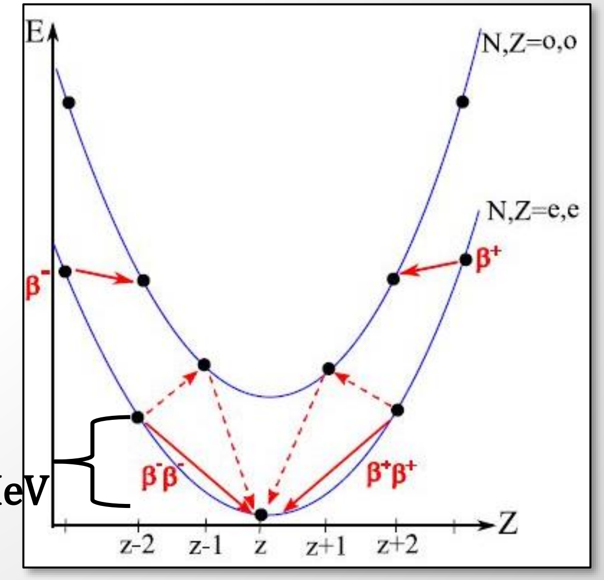


- Particle Physics

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

- 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

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



Neutrinoless Double β Decay

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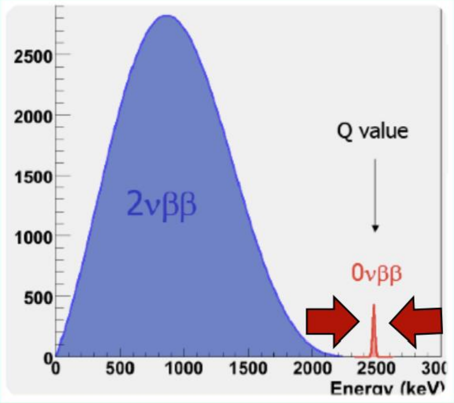
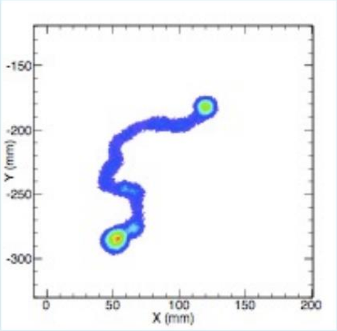
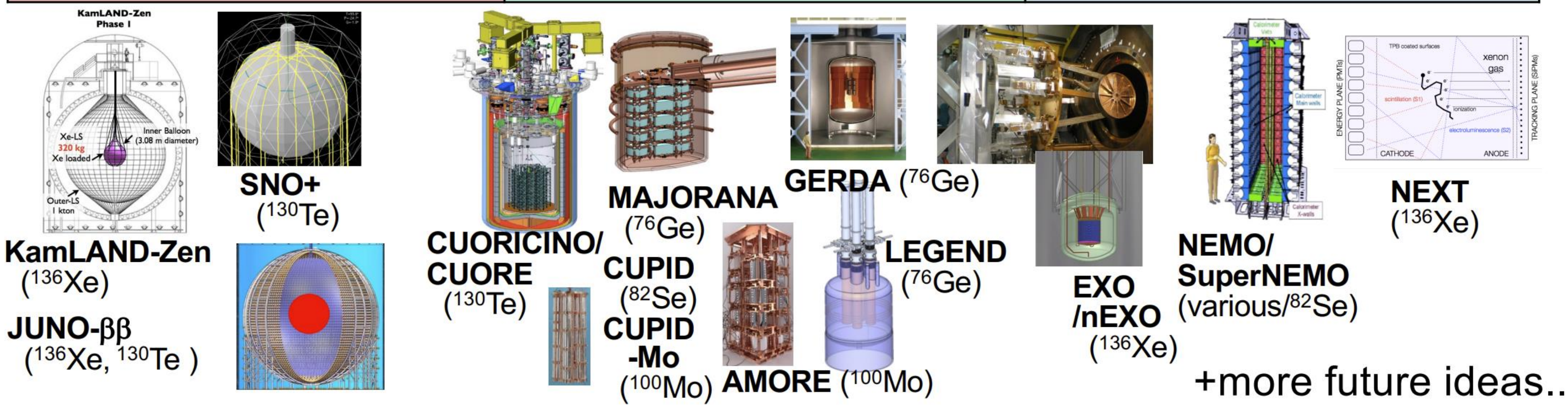
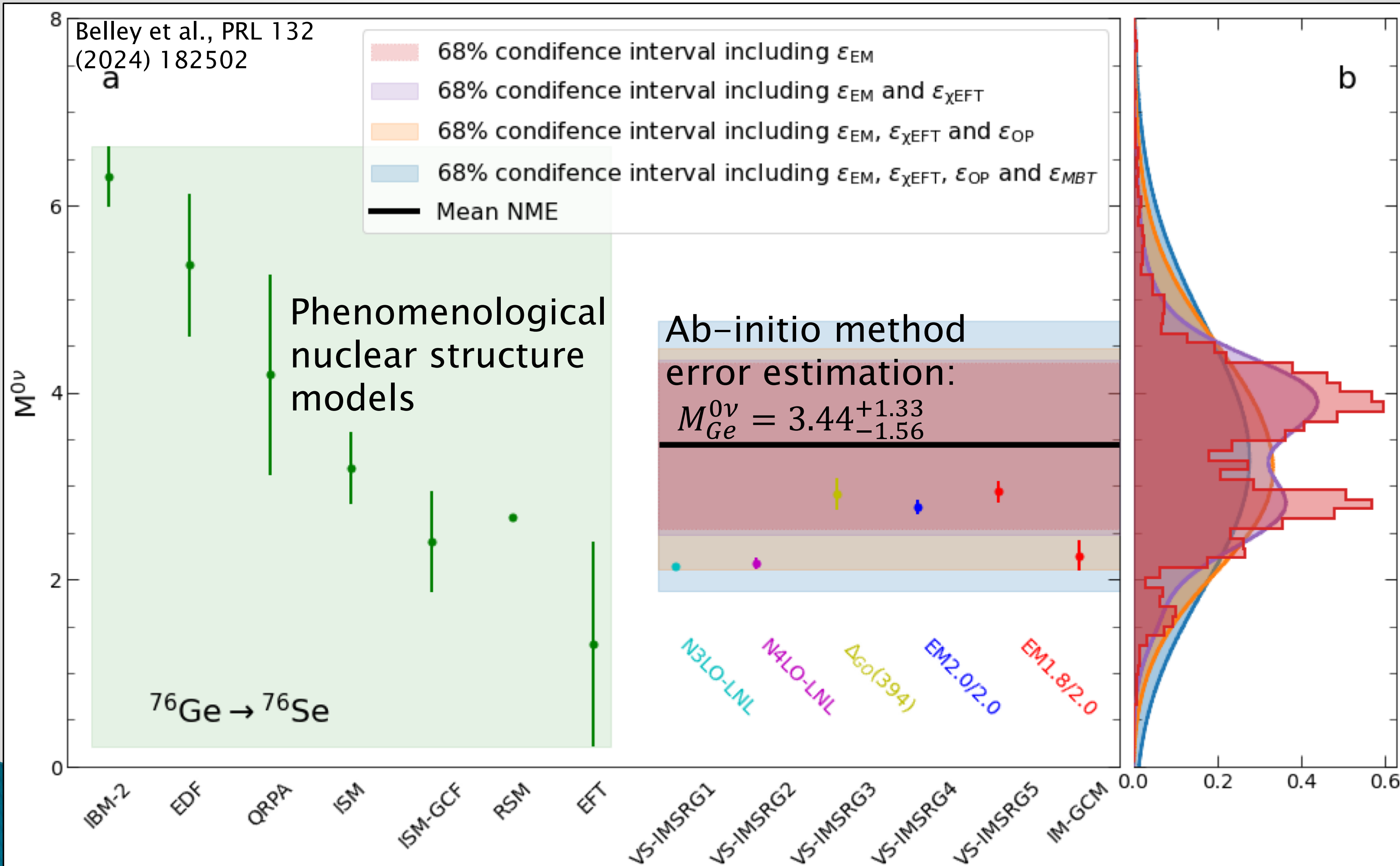
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		



+more future ideas...

Scholberg, PPC 2022

Nuclear Matrix Elements



Three Active Neutrinos

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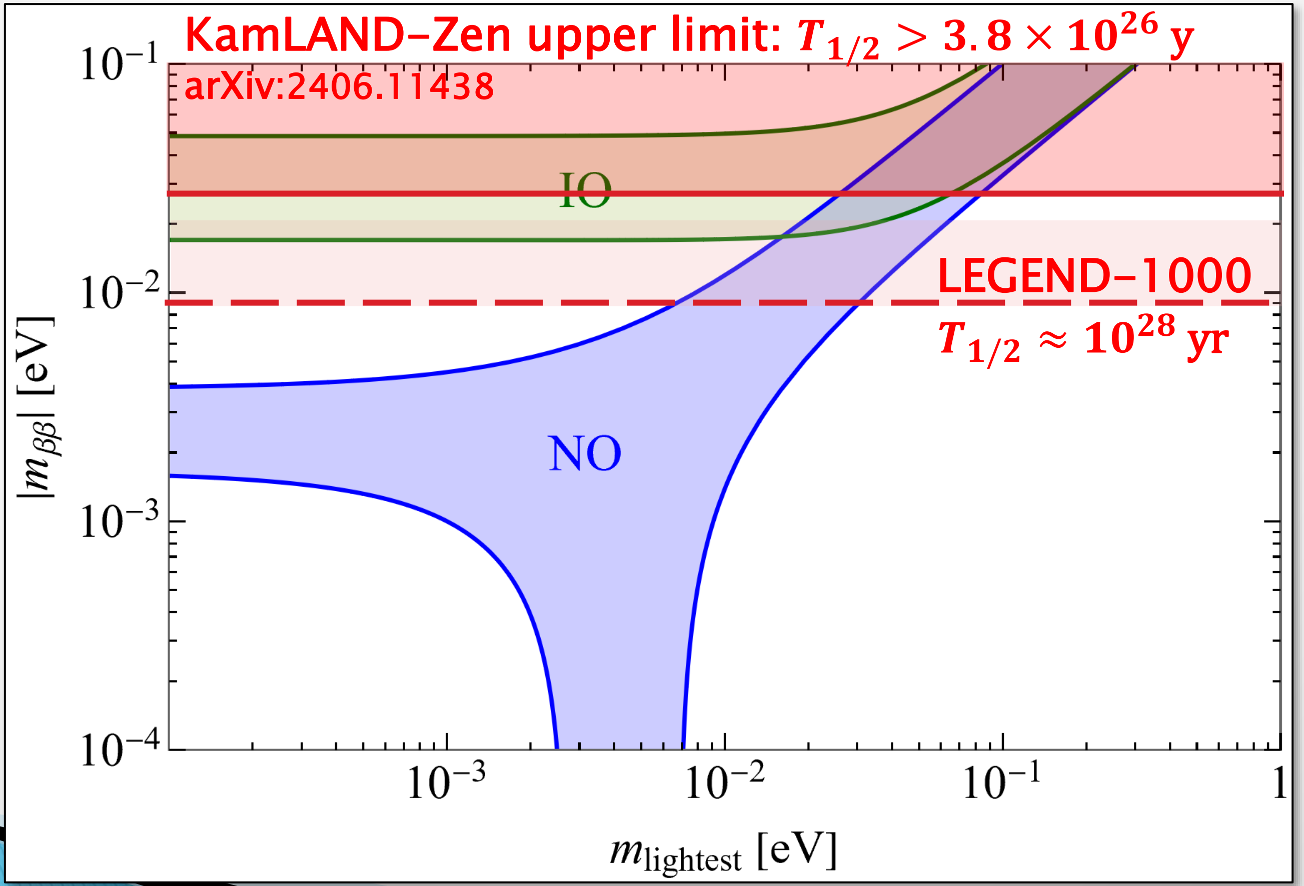
- Effective $0\nu\beta\beta$ Mass

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

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



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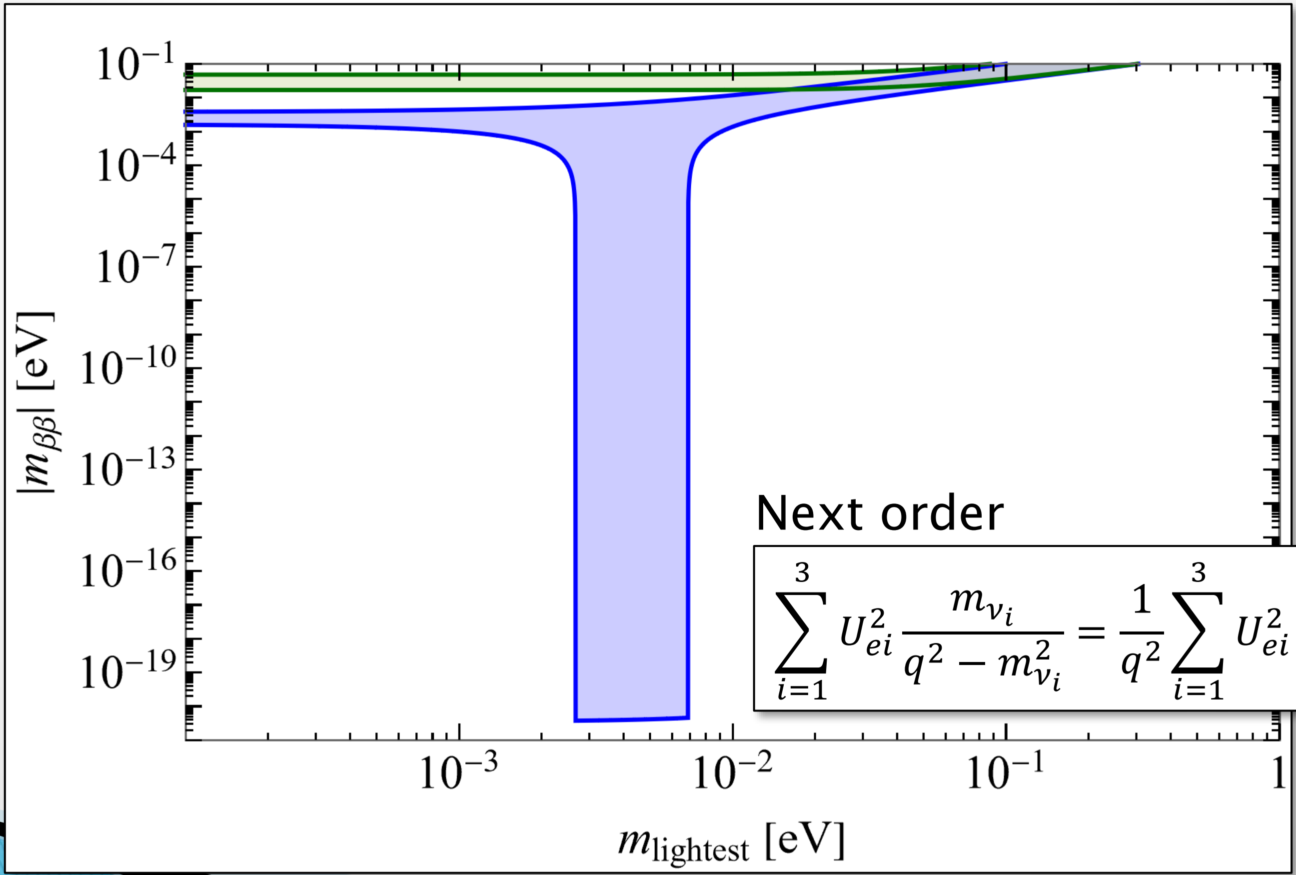


Next order

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

Heavy Sterile Neutrinos

- SM + Sterile Neutrinos

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

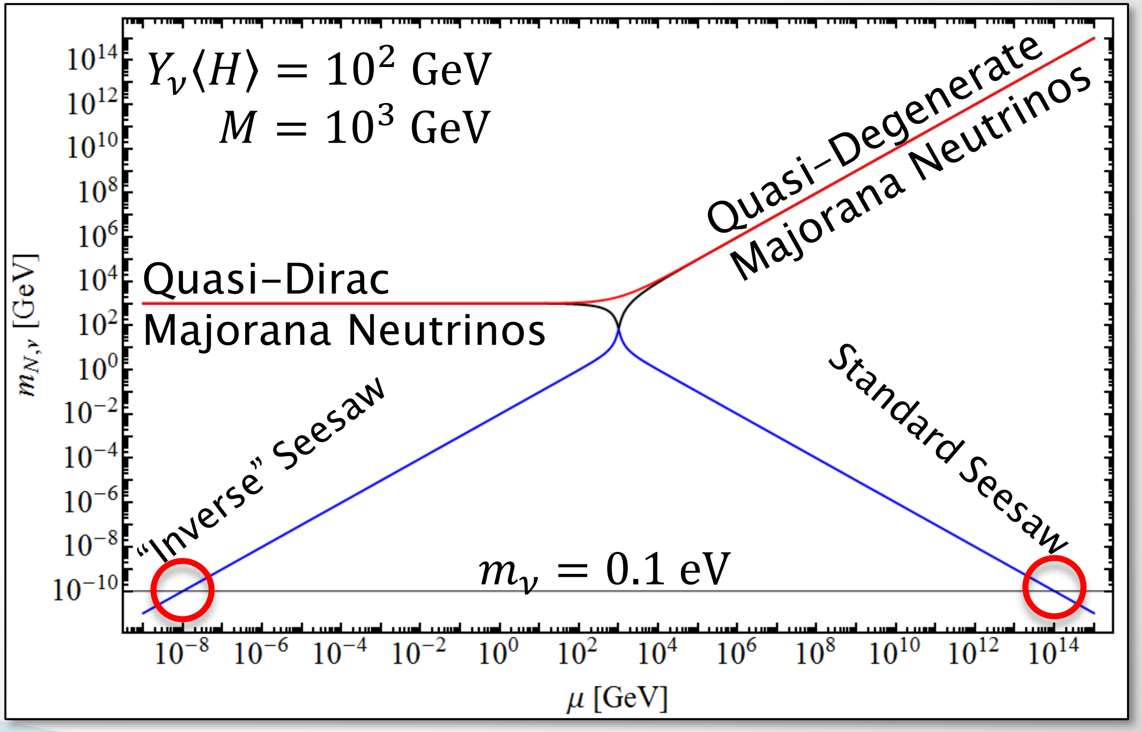
  - Seesaw Mechanism with TeV scale heavy neutrinos
    - Standard Seesaw with small Yukawa couplings

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

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

$$\begin{matrix} & \nu & N_1 & N_2 \end{matrix}$$

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



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

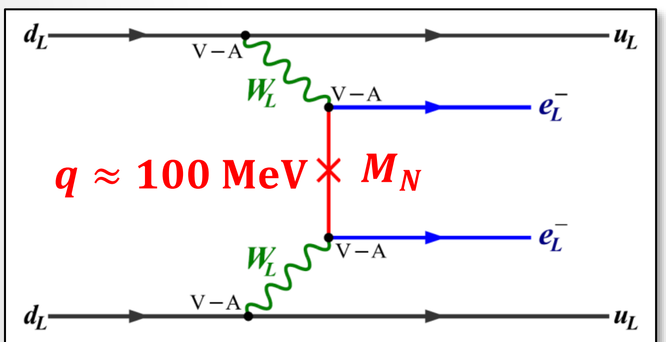
- Masses lighter than ≈ 100 MeV

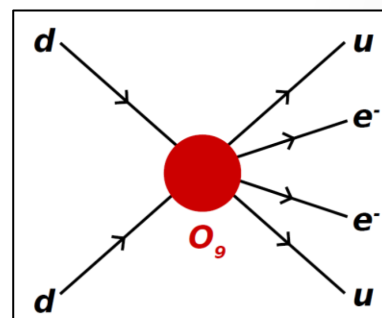
$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}} + s_{14}^2 m_{\nu_4} e^{i\phi_{14}} + \cdots|$$

- Masses heavier than ≈ 100 MeV

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

- Short-distance on nuclear scale





Sterile Neutrino Searches

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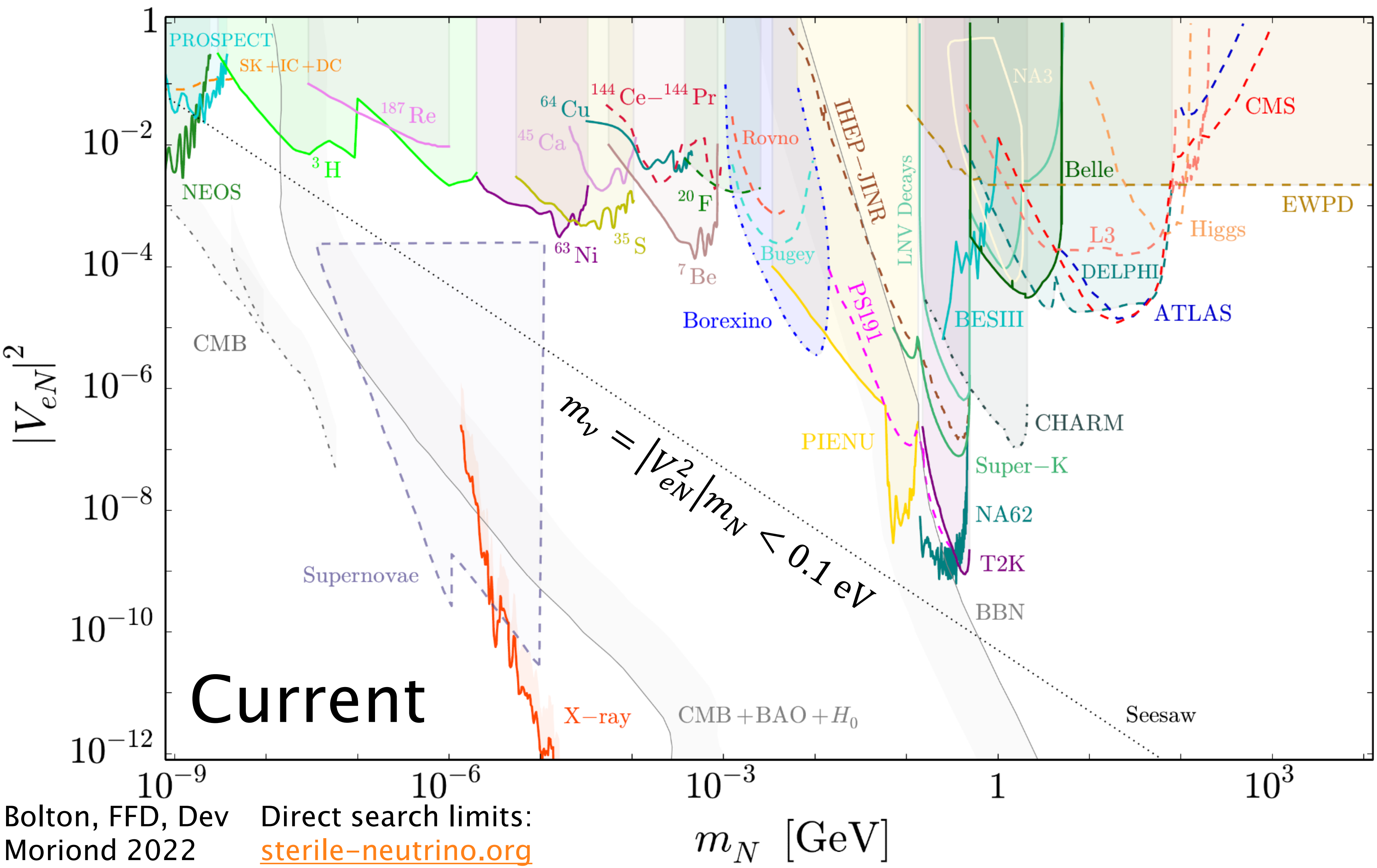

Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

Sterile Neutrino Searches

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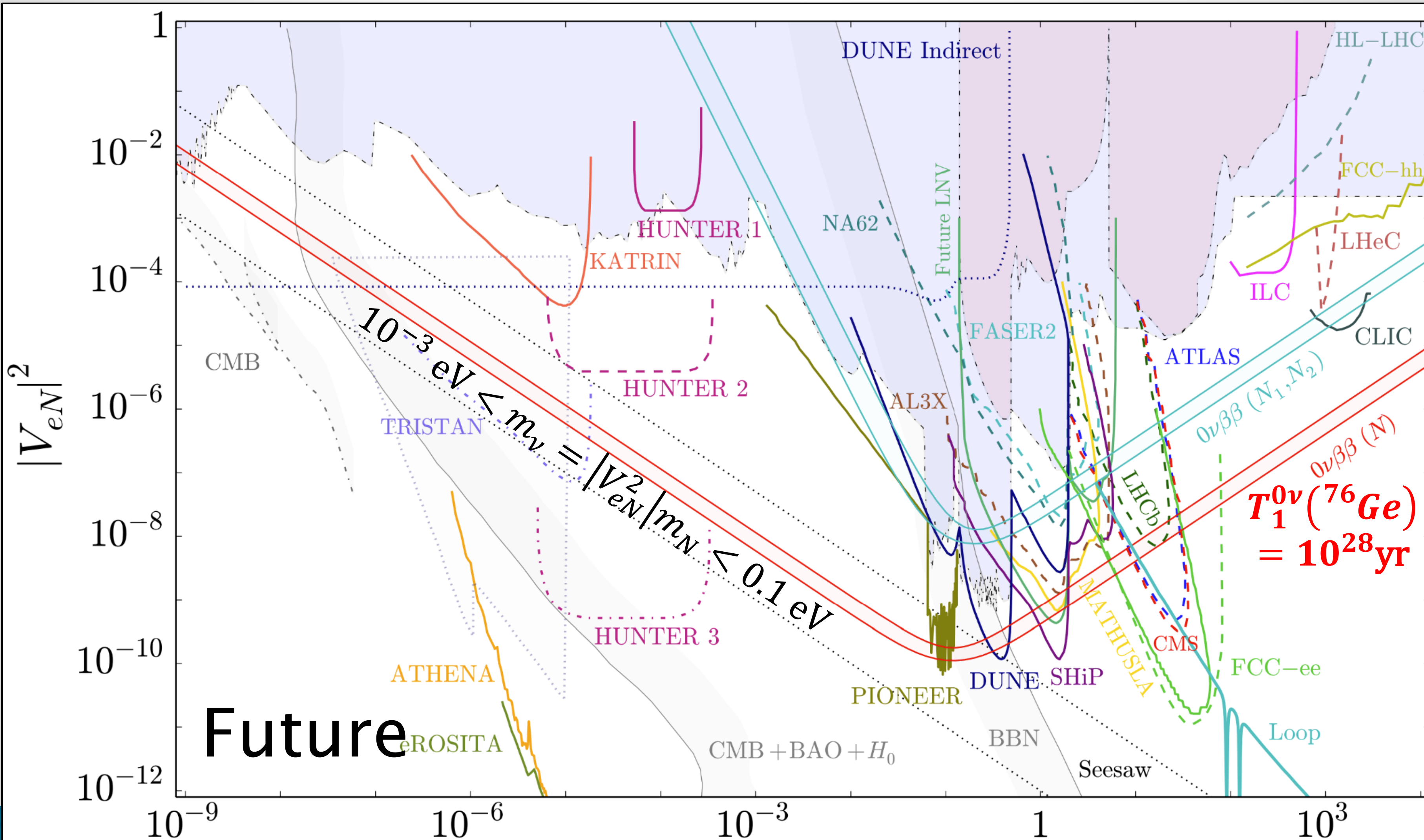


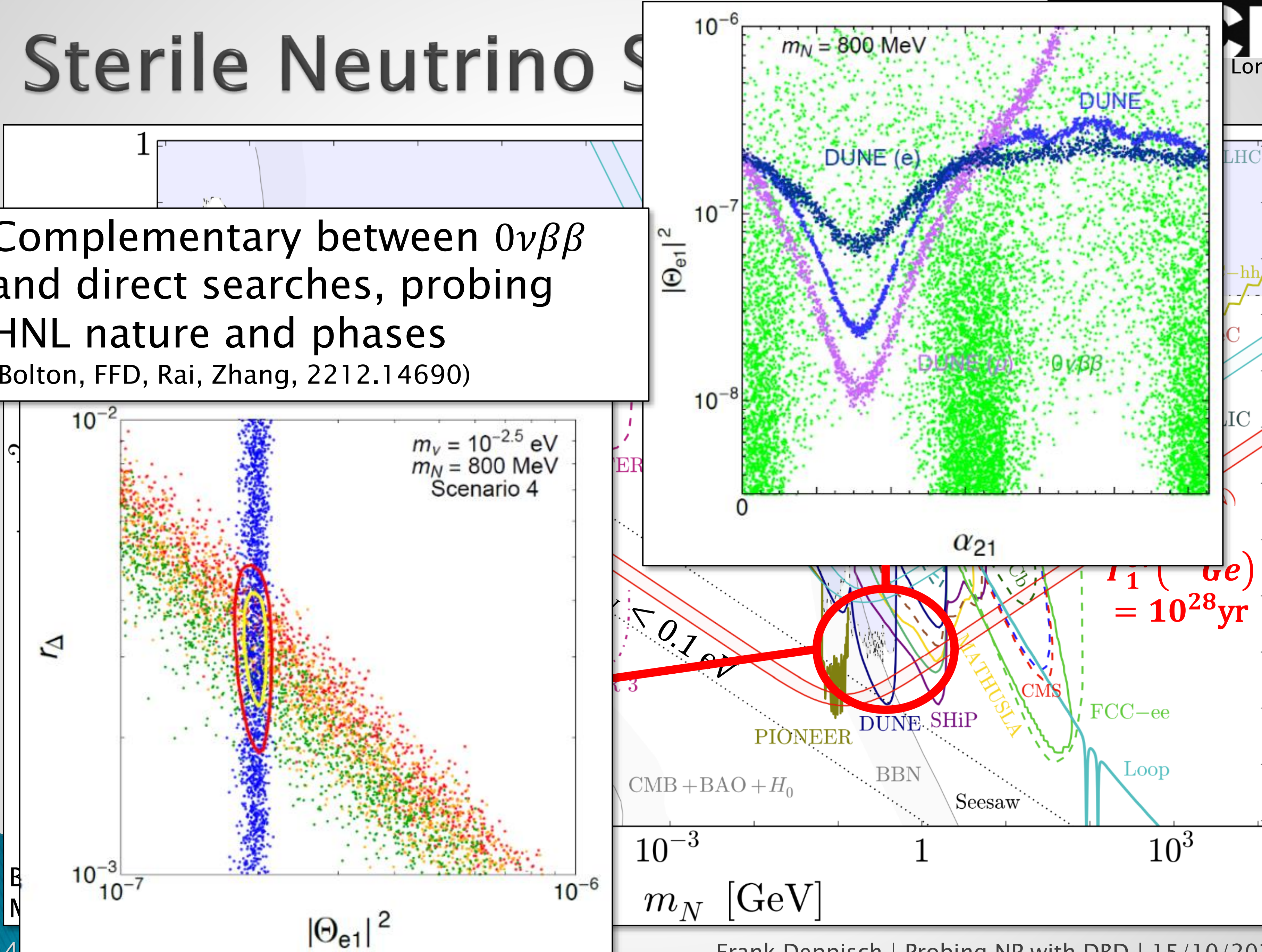
Bolton, FFD, Dev Moriond 2022

Direct search limits: sterile-neutrino.org

Sterile Neutrino S

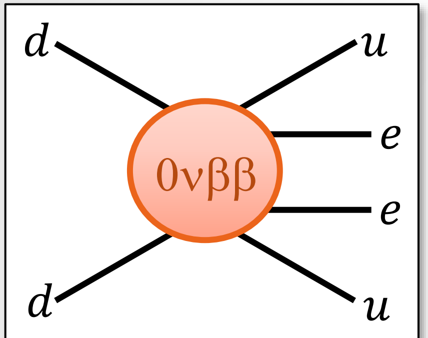
Complementary between $0\nu\beta\beta$ and direct searches, probing HNL nature and phases

(Bolton, FFD, Rai, Zhang, 2212.14690)

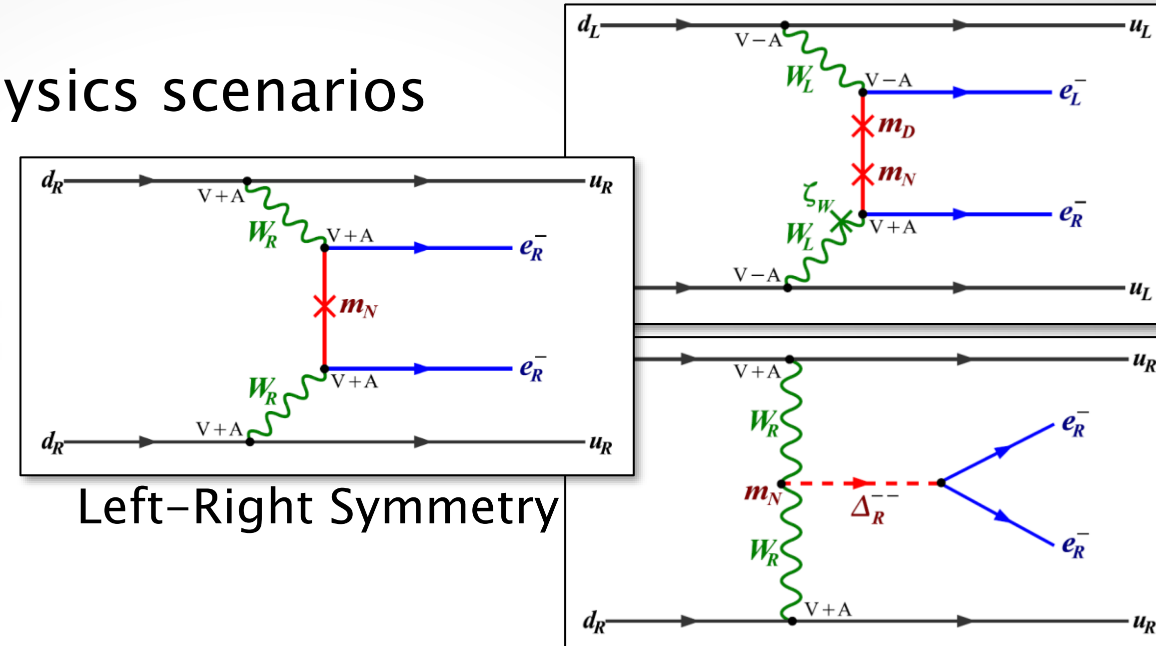


New Physics and $0\nu\beta\beta$

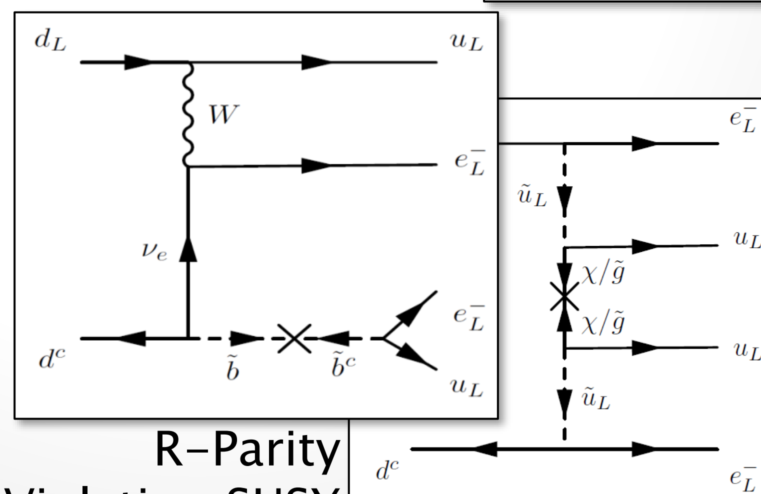
- Plethora of New Physics scenarios



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



Left-Right Symmetry



R-Parity Violating SUSY

Extra Dimensions

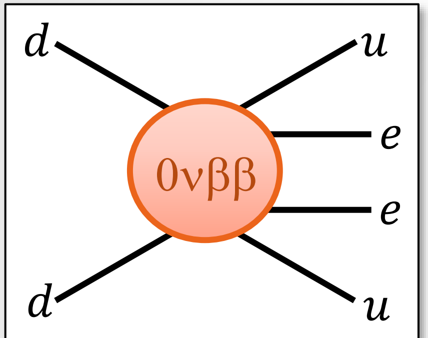
Majorons

Leptoquarks

...

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

- Plethora of New Physics scenarios



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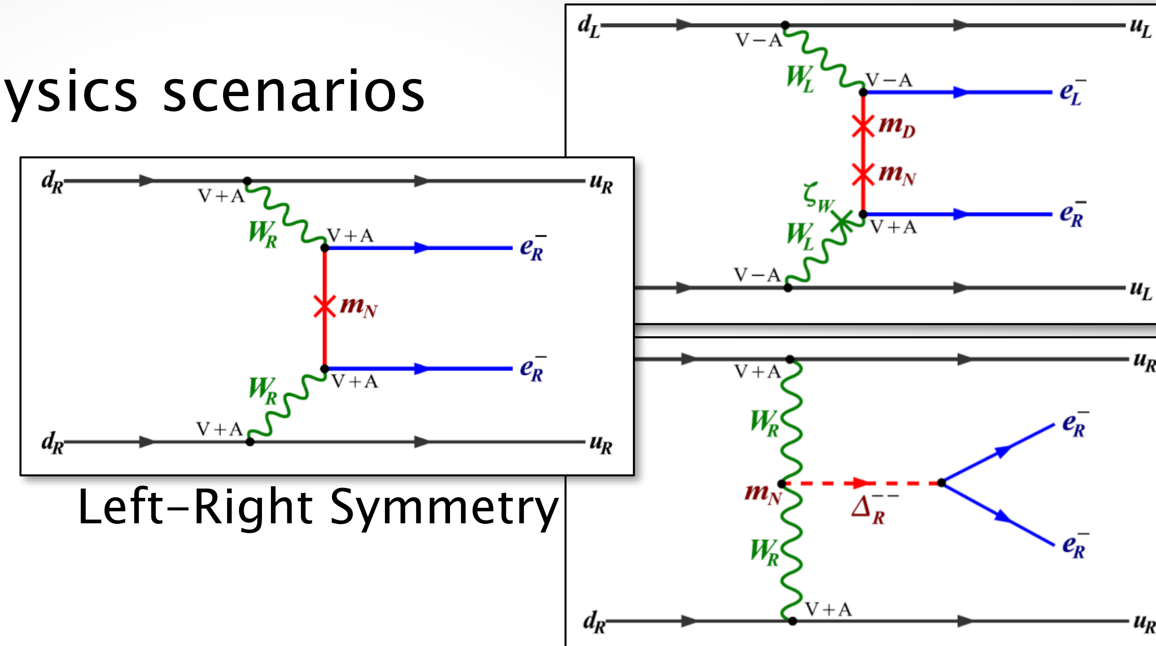
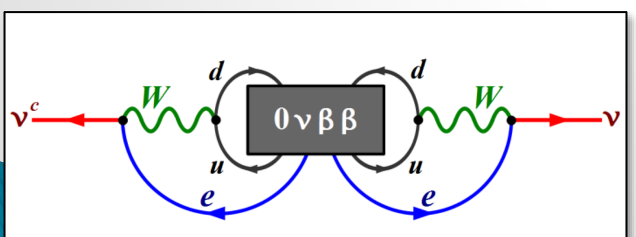


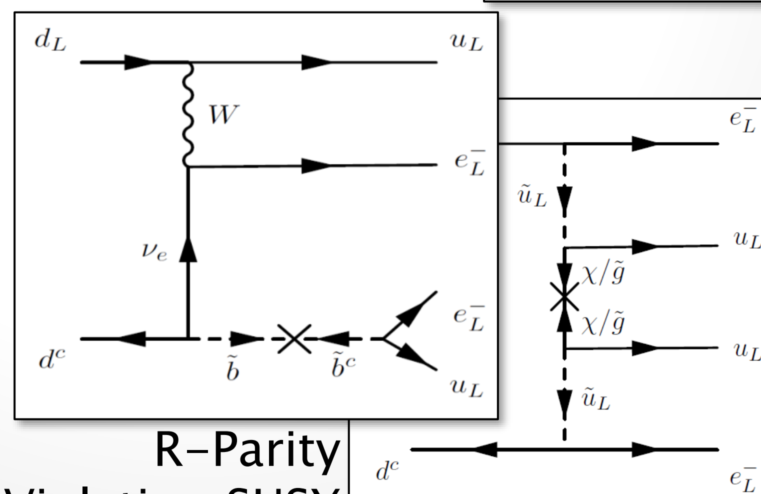
Left–Right Symmetry

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

- Neutrinos still Majorana

Schechter, Valle, Phys.Rev.D 25 (1982) 2951





R–Parity Violating SUSY

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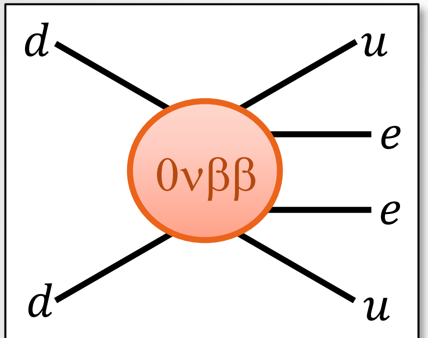
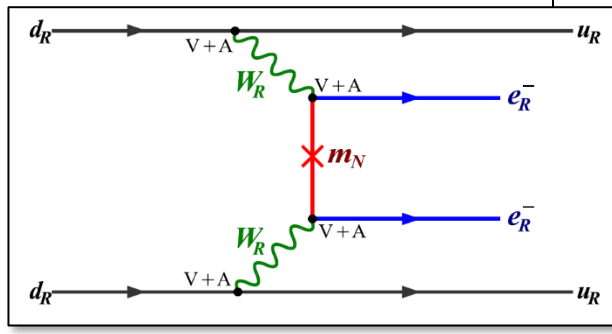
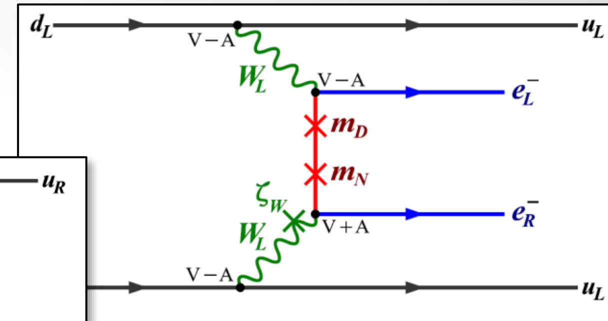
New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry





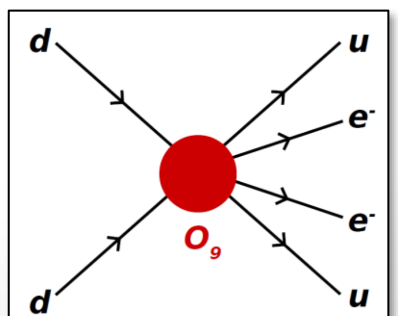


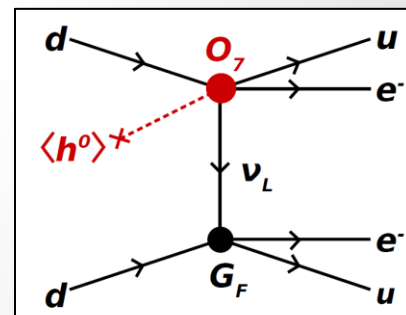
$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

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

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

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





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

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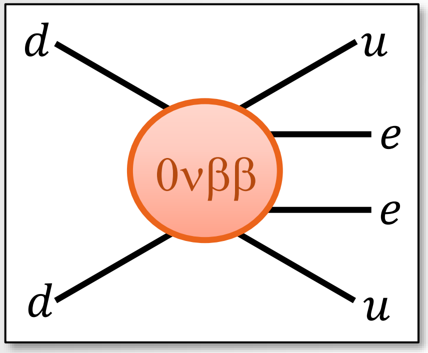
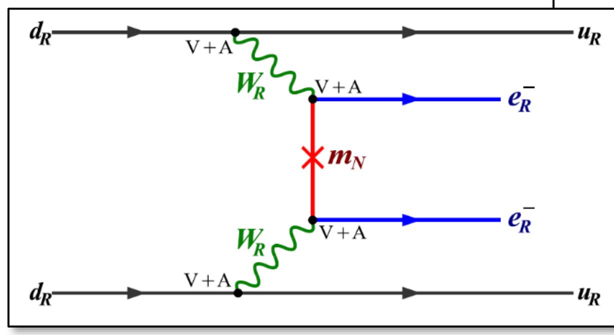
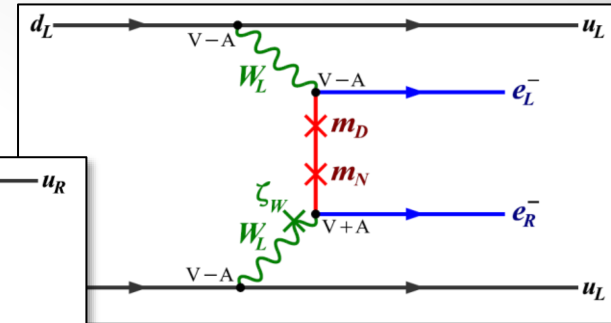
- Examples in Left-Right Symmetry







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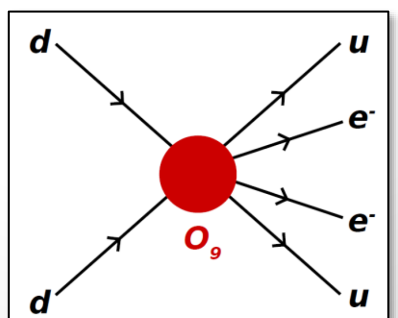
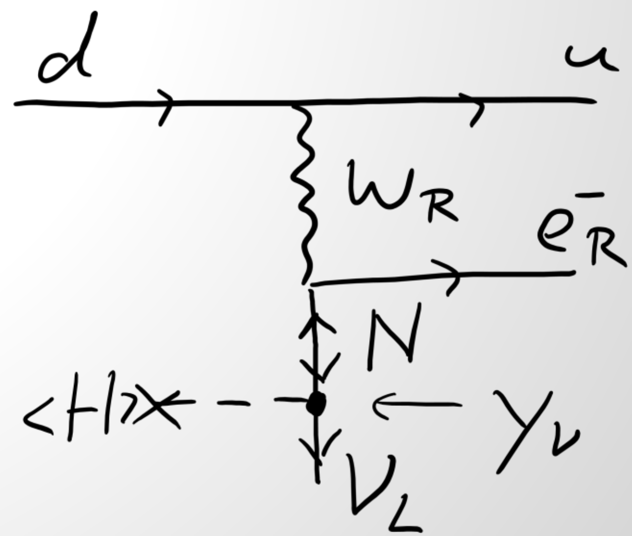
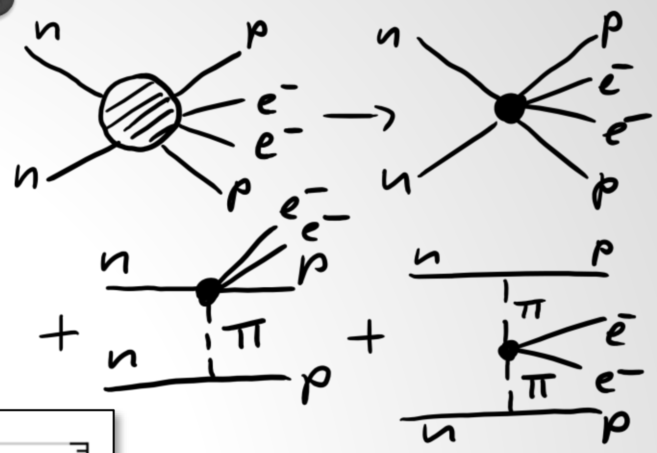


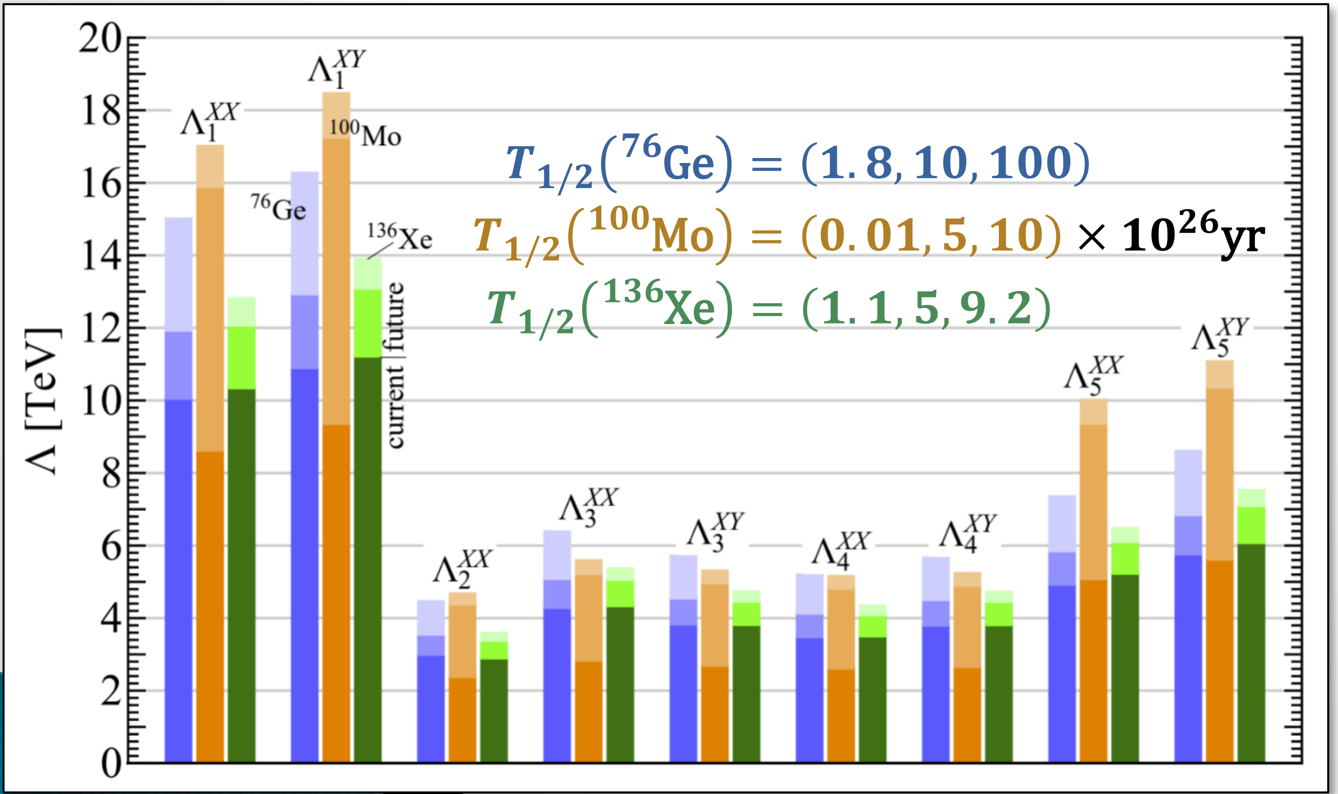


New Physics and $0\nu\beta\beta$

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)

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

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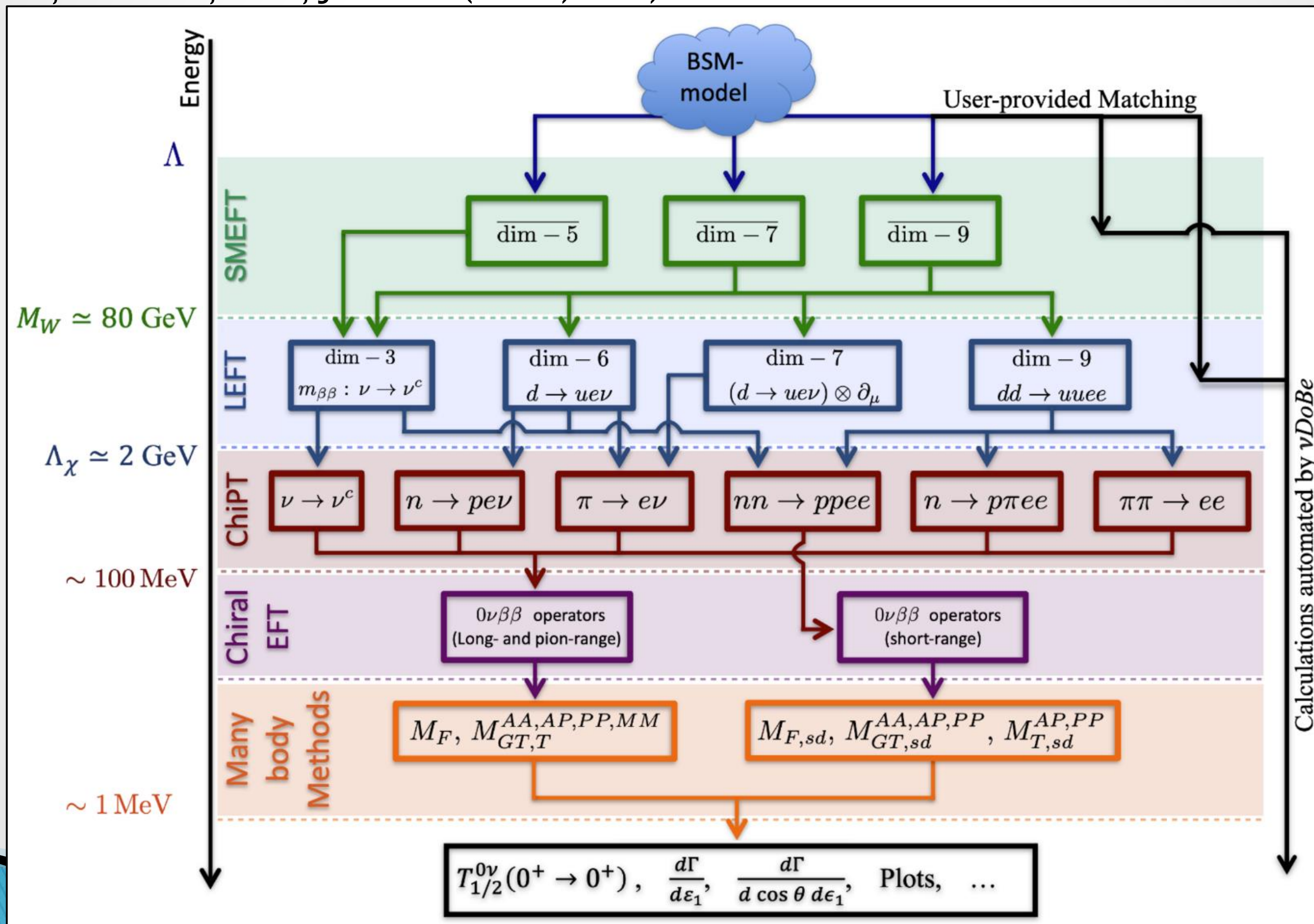
- Automated calculation of EFT operator limits: νDoBe
(Scholer, de Vries, Graf, JHEP 08 (2023) 043)

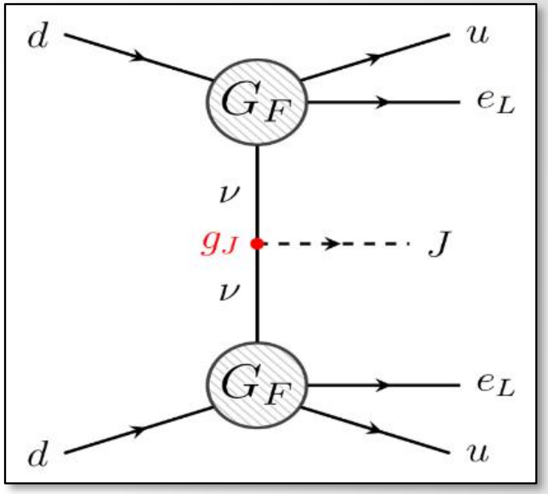


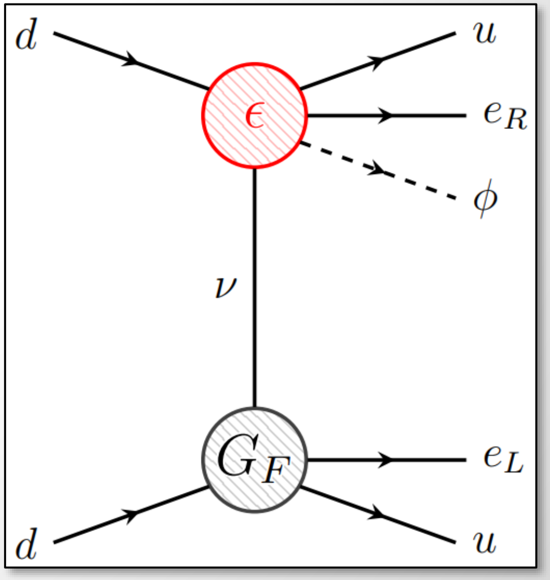
Exotic Particle Emission

Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

- Majoron(-like) J emission
- Majoron-like ϕ emission assisted by RH current
- Non-standard energy distribution
- Searched for in EXO-200 (PRD 104 (2021) 11, 112002)

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





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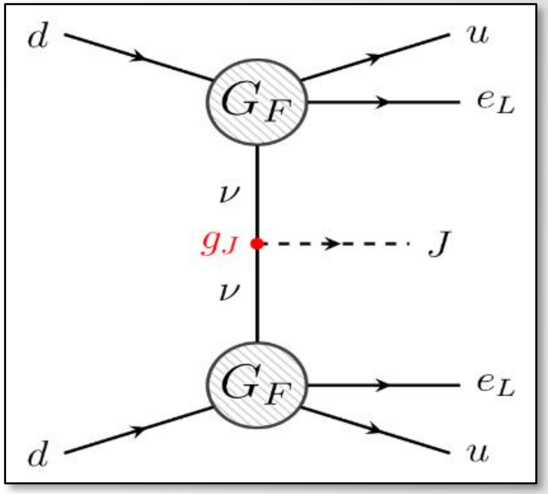
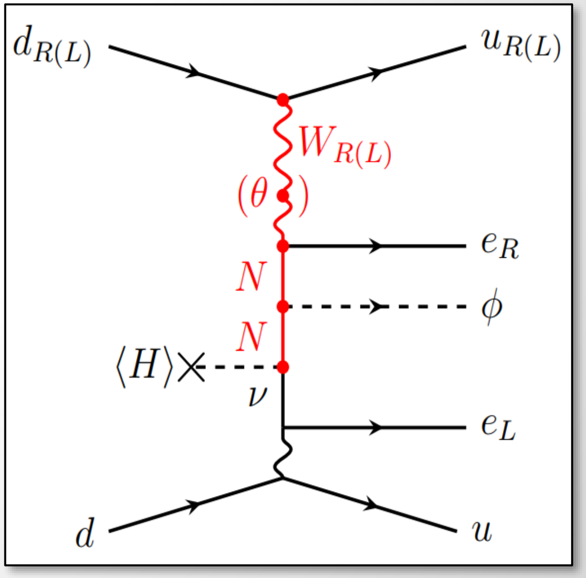
$$T_{1/2}^{Xe} > 4 \times 10^{24}\ \mathrm{y}$$

- Sensitivity to Left-Right symmetric model with Dirac neutrinos

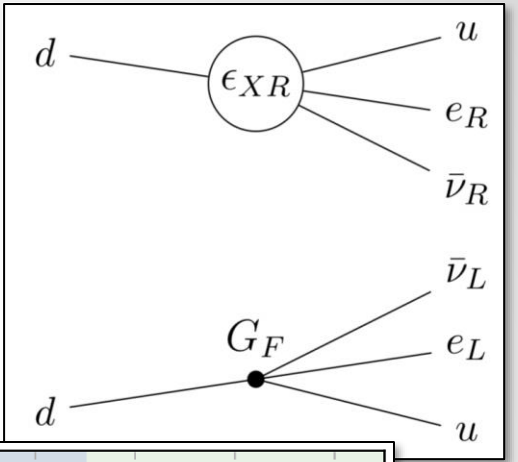
$$\frac{T_{1/2}^{\mathrm{Xe}}}{10^{25}\ \mathrm{y}} \approx \left(\frac{1.4\times 10^{-4}}{g_R^2 \kappa y_N y_\nu}\right)^2 \left(\frac{m_{W_R}}{25\ \mathrm{TeV}}\right)^4 \left(\frac{m_N}{100\ \mathrm{MeV}}\right)^4$$

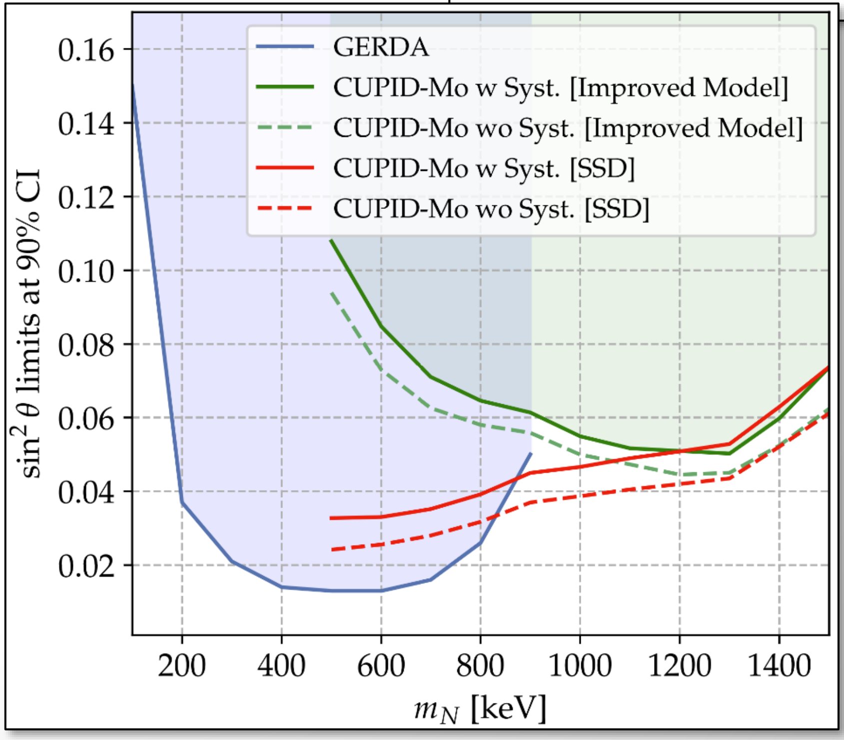




New Physics in $2\nu\beta\beta$

- Sterile neutrino search through energy endpoint (Bolton, FFD, Graf, Simkovic, Phys.Rev.D 103 (2021) 055019; also, Agostini, Bossio, Ibarra, Marcano, 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 limits:
    - GERDA (JCAP 12 (2022) 012)
    - CUPID-Mo (arXiv:2405.10766)





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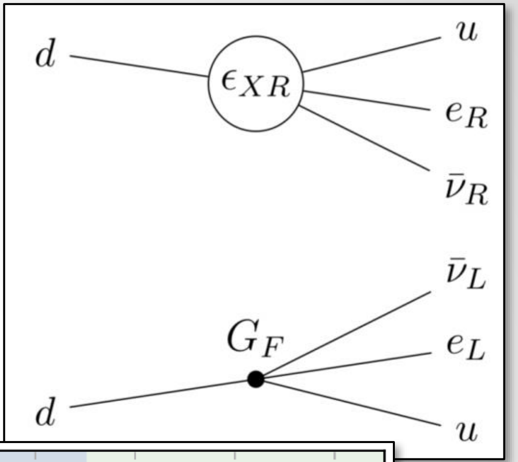
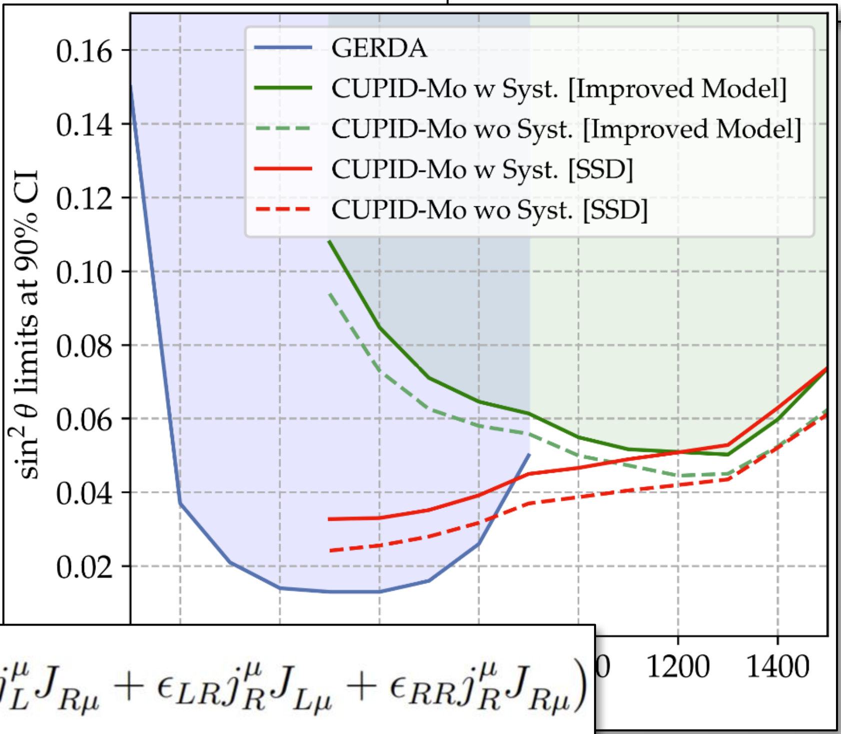
    - CUPID-Mo (arXiv:2405.10766)
- Lepton number conserving RH currents (FFD, Graf, Simkovic, Phys.Rev.Lett. 125 (2020) 17, 171801)





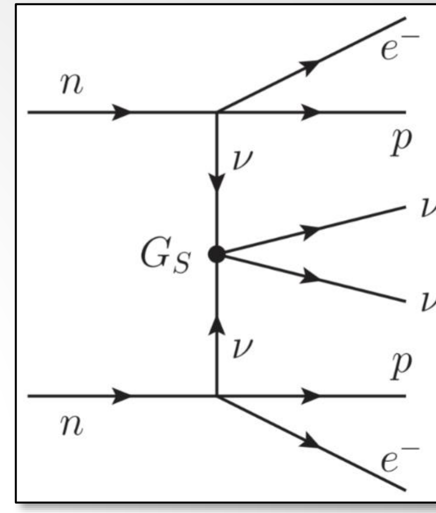
$$\frac{G_F \cos\theta_C}{\sqrt{2}}\left((1+\delta_{\text{SM}}+\epsilon_{LL})j_L^{\mu}J_{L\mu}+\epsilon_{RL}j_L^{\mu}J_{R\mu}+\epsilon_{LR}j_R^{\mu}J_{L\mu}+\epsilon_{RR}j_R^{\mu}J_{R\mu}\right)$$

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

FFD, Graf, Rodejohann, Xu, Phys.Rev.D 102 (2020) 5, 051701

- Neutrino self-interactions
  - Same signature as SM $2\nu\beta\beta$ decay

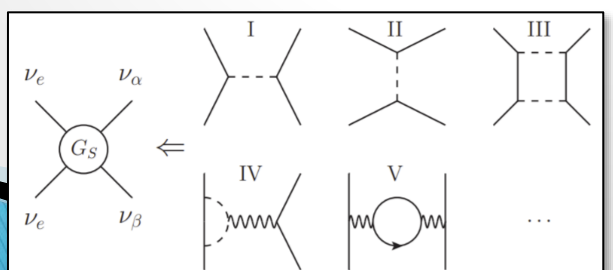
$$\Gamma_{2\nu} + \Gamma_{\nu\mathrm{SI}} \approx \left(|\mathcal{M}_{2\nu}|^2 + \left| \frac{G_S m_e}{2R} \right|^2 \frac{|\mathcal{M}_{0\nu}|^2}{4\pi^2} \right) \mathcal{G}_{2\nu}$$

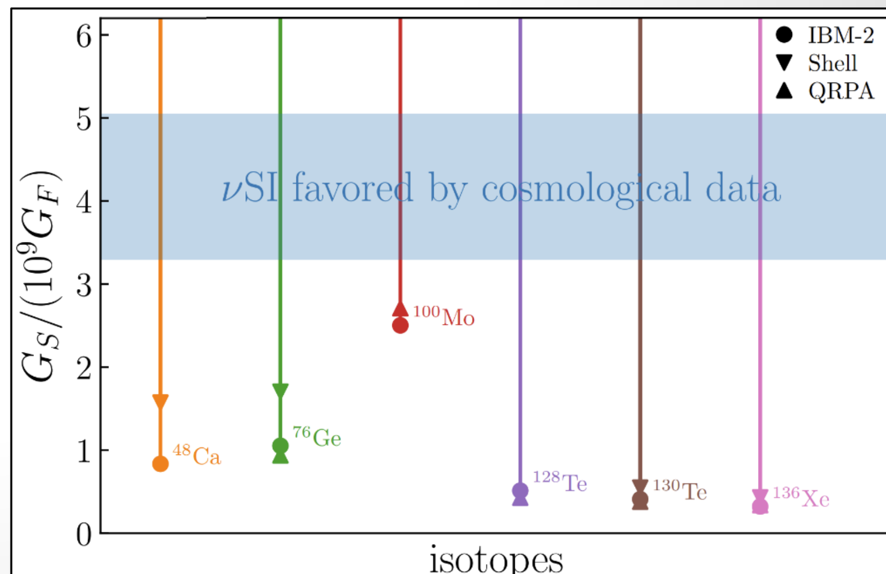


  - Interference with SM $2\nu\beta\beta$ decay neglected
  - Non-observation of enhanced rate

$$\Gamma_{\nu\mathrm{SI}}/\Gamma_{2\nu}^{\mathrm{ex}} < 1$$

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)





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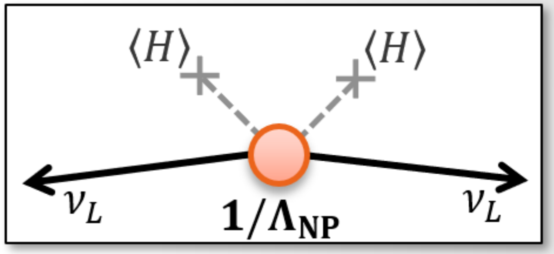
Conclusion

- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana?
  - Mechanism of neutrino mass generation?
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Universal probe of LNV physics
    - LNV physics near GUT scale
    - Direct sensitivity to LNV physics at scales $m_N \approx 1\ \mathrm{eV} - 100\ \mathrm{TeV}$
    - Observation can falsify high-scale baryogenesis scenarios
    - Light exotic particles

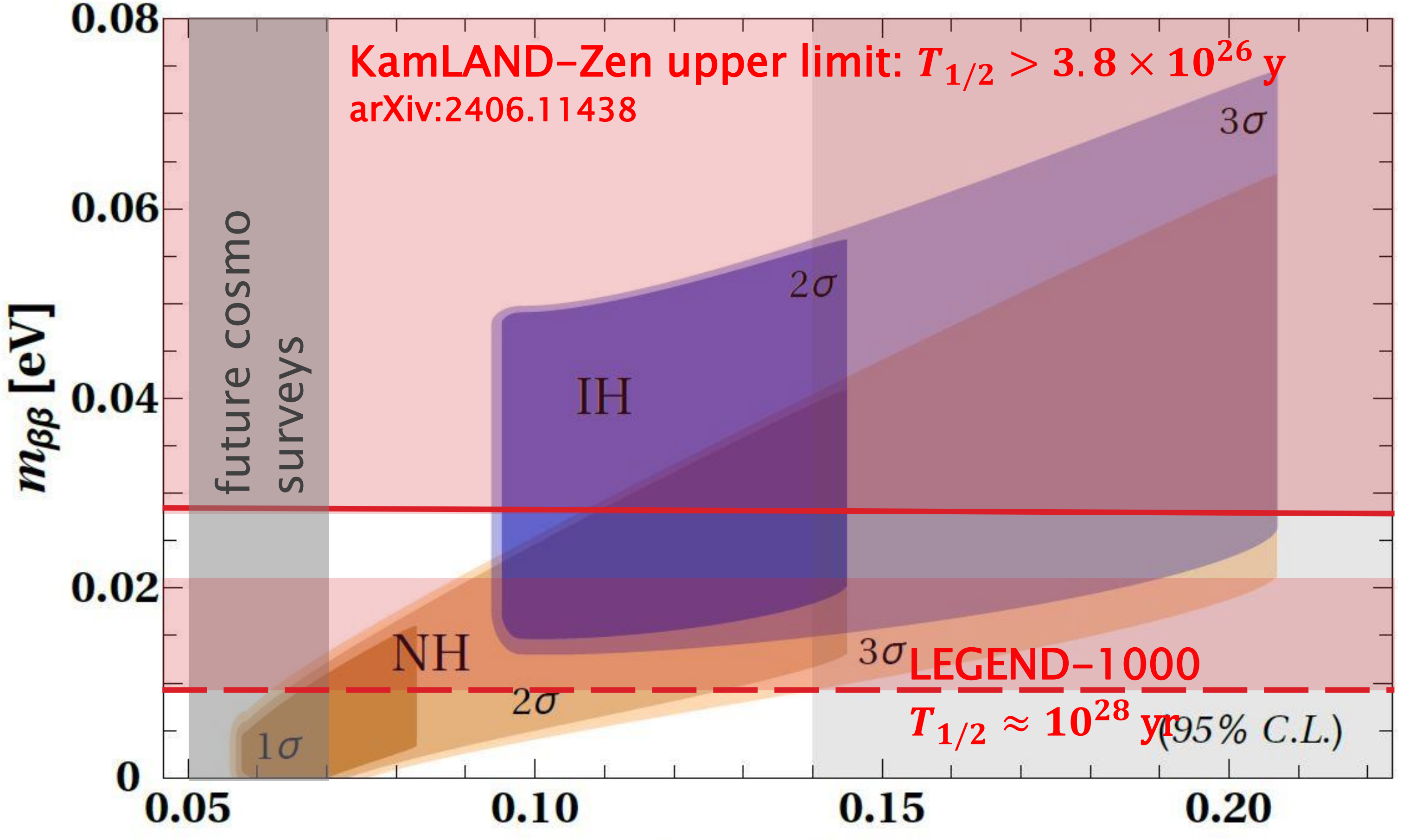


$$\frac{T_{1/2}^{0\nu\beta\beta}}{10^{28}\ \mathrm{y}} \approx \left(\frac{\Lambda_{\mathrm{NP}}}{10^{15}\ \mathrm{GeV}}\right)^2$$

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

Three Active Neutrinos

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

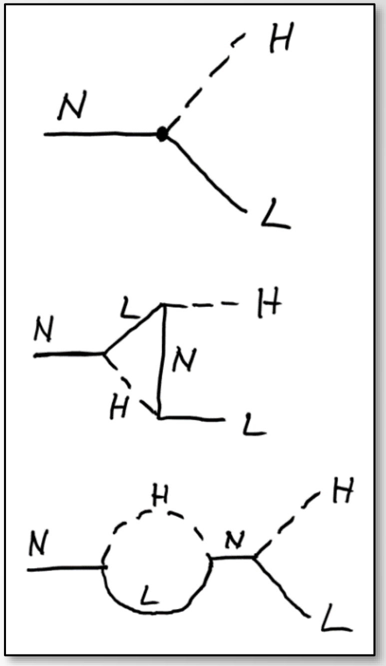


Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

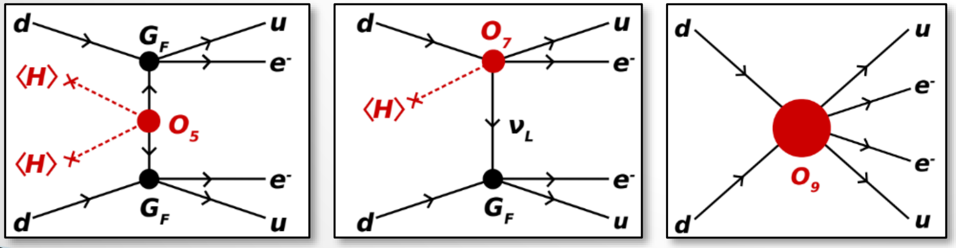
Falsifying Baryogenesis

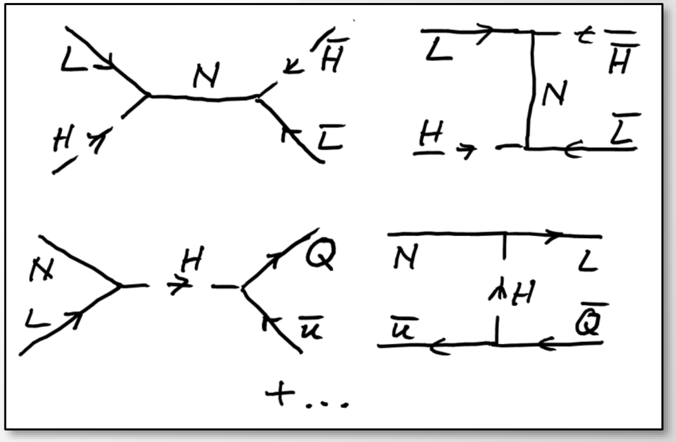
- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\ \mathrm{GeV}$
    - Observed asymmetry

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



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





Falsifying Baryogenesis

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- 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, Phys.Rev.Lett. 112 (2014) 221601, FFD, Harz, Hirsch, Huang, Päs, Phys.Rev.D 92 (2015) 3, 036005