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Probing New Physics with Double Beta Decay

Frank Deppisch
f.deppisch@ucl.ac.uk

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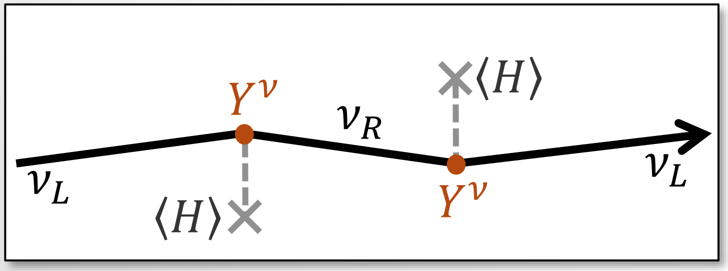
Workshop on SM and Beyond | Corfu2023 | 27/08-07/09/2023

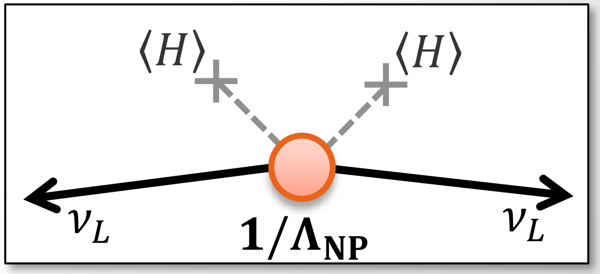
Dirac versus Majorana

- 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 ν Nature

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- Single beta decay

$$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$$

  - Tritium decay, KATRIN: $\boldsymbol{m_\beta \approx 0.2\ \mathrm{eV}}$
  - Project 8: Atomic Tritium + Cyclotron Radiation Spectroscopy: $\boldsymbol{m_\beta \approx 0.05\ \mathrm{eV}}$

- Allowed double beta ($2\nu\beta\beta$) decay

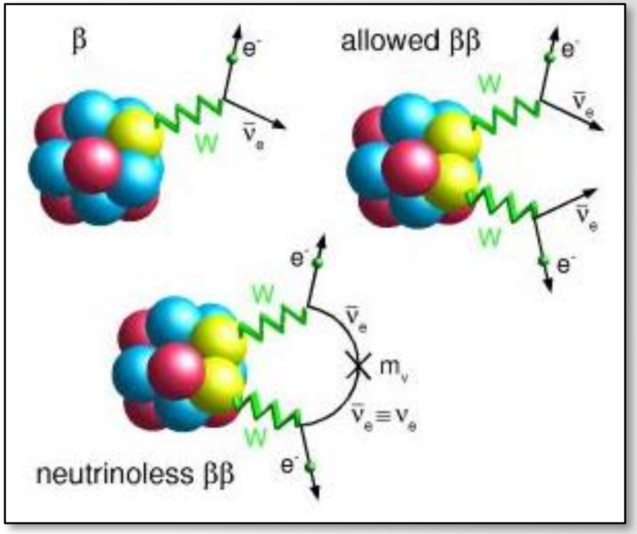
$$(A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

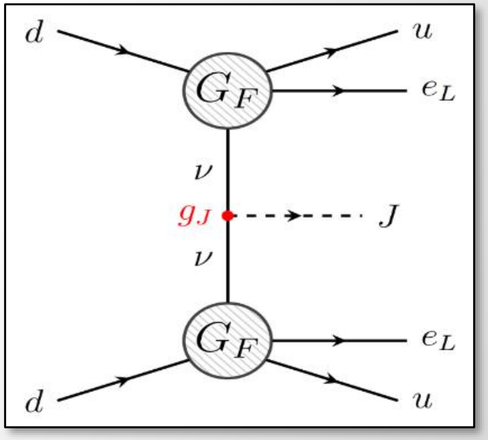
- Neutrinoless double beta ($0\nu\beta\beta$) decay

$$(A,Z) \to (A,Z+2) + 2e^-$$

  - Violation of lepton number
  - Mediated by Majorana neutrinos

- Majoron assisted double beta ($0\nu\beta\beta J$) decay
  - Missing energy → lepton number violated?





Neutrinoless Double β Decay

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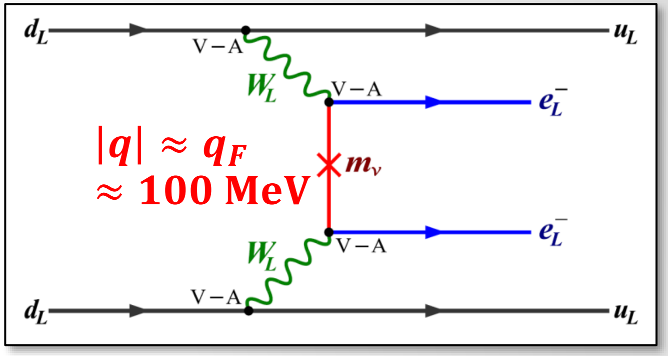
- Half-life

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

- Particle Physics



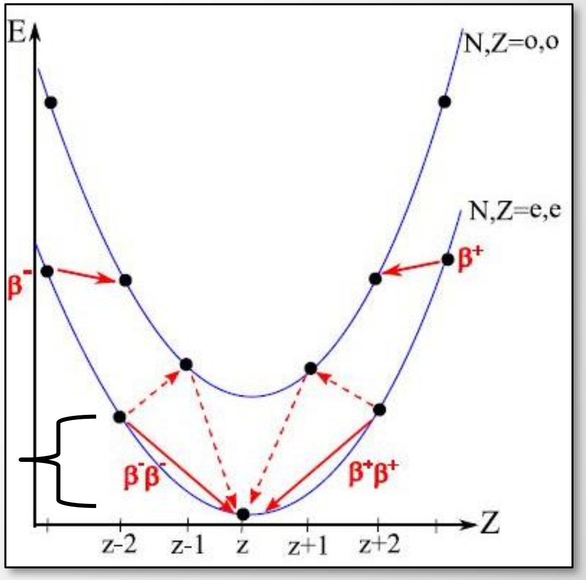
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{G_F^2}{4} \sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx G_F^2 \frac{\gamma_\mu (1+\gamma_5)\gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu} \propto Q^5$

$$\Gamma_{0\nu\beta\beta} \sim m_\nu^2 G_F^4 q_F^2 Q^5 \sim (m_\nu / 0.1\ \text{eV})^2 \left(10^{26}\ \text{yr}\right)^{-1}$$

- Nuclear Physics
  - Nuclear matrix element $M^{0\nu} \approx 1$ but large uncertainties

$Q + 2m_e \approx$ 3–5 MeV



Nuclear Matrix Elements

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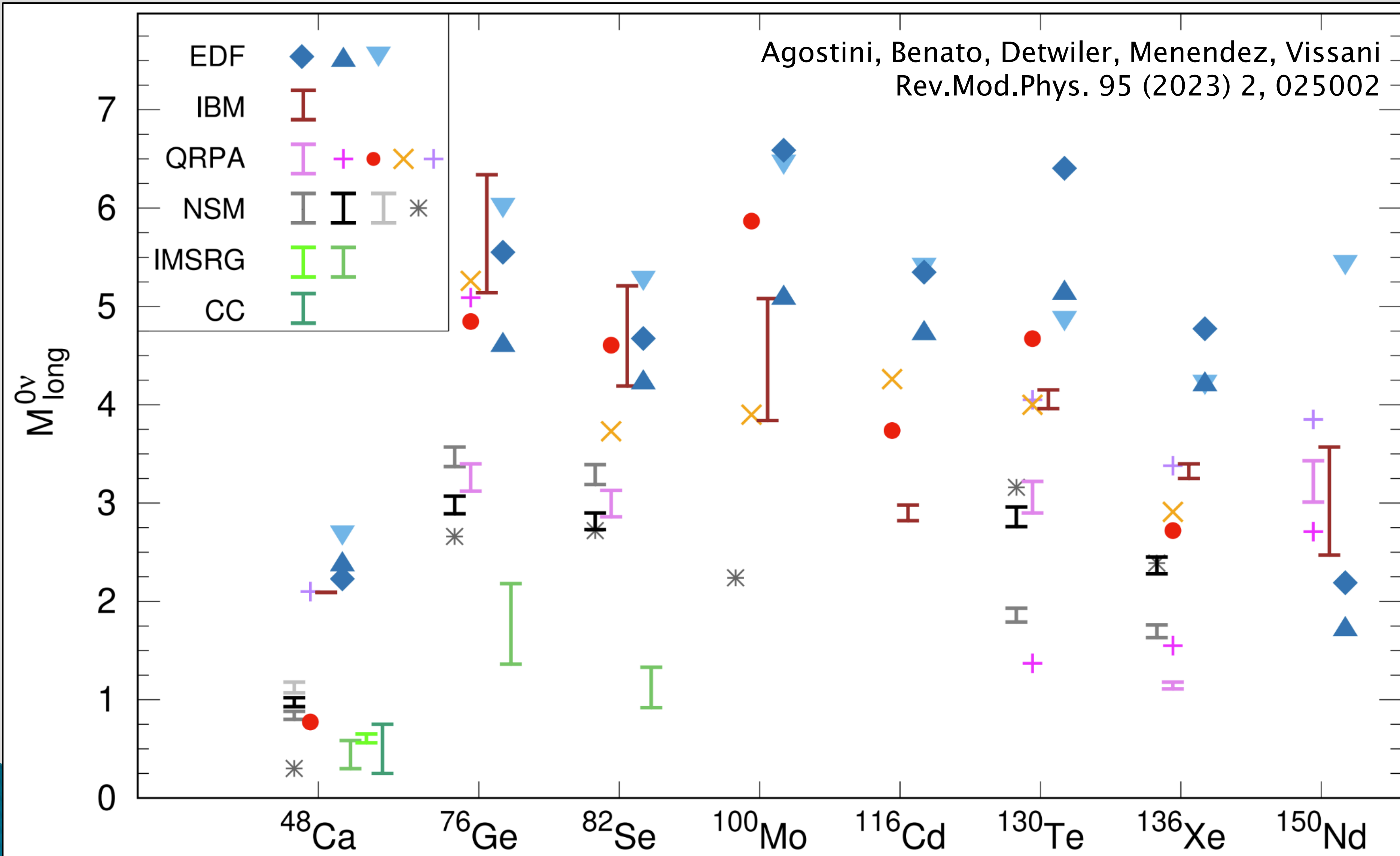

Three Active Neutrinos

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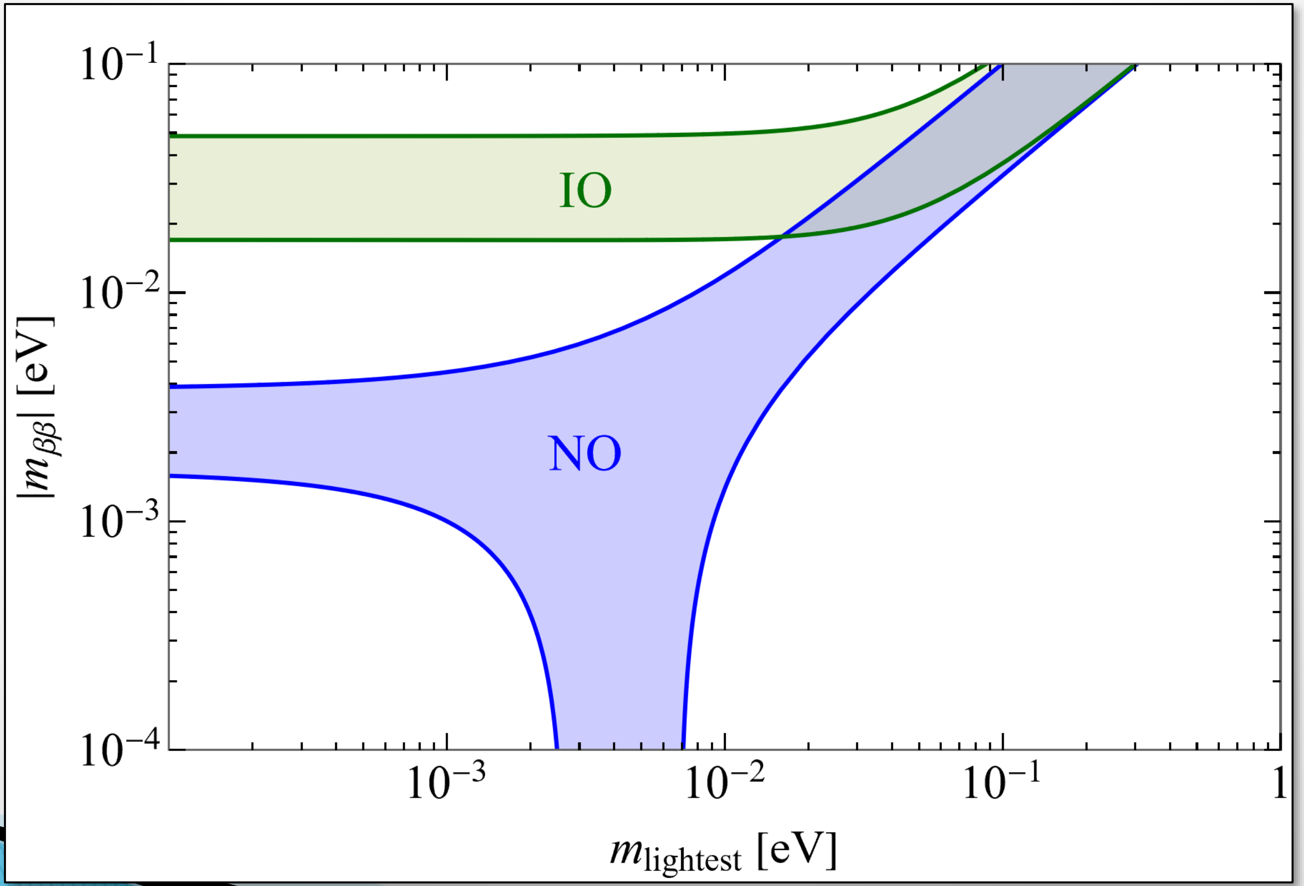
- Effective $0\nu\beta\beta$ Mass

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

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



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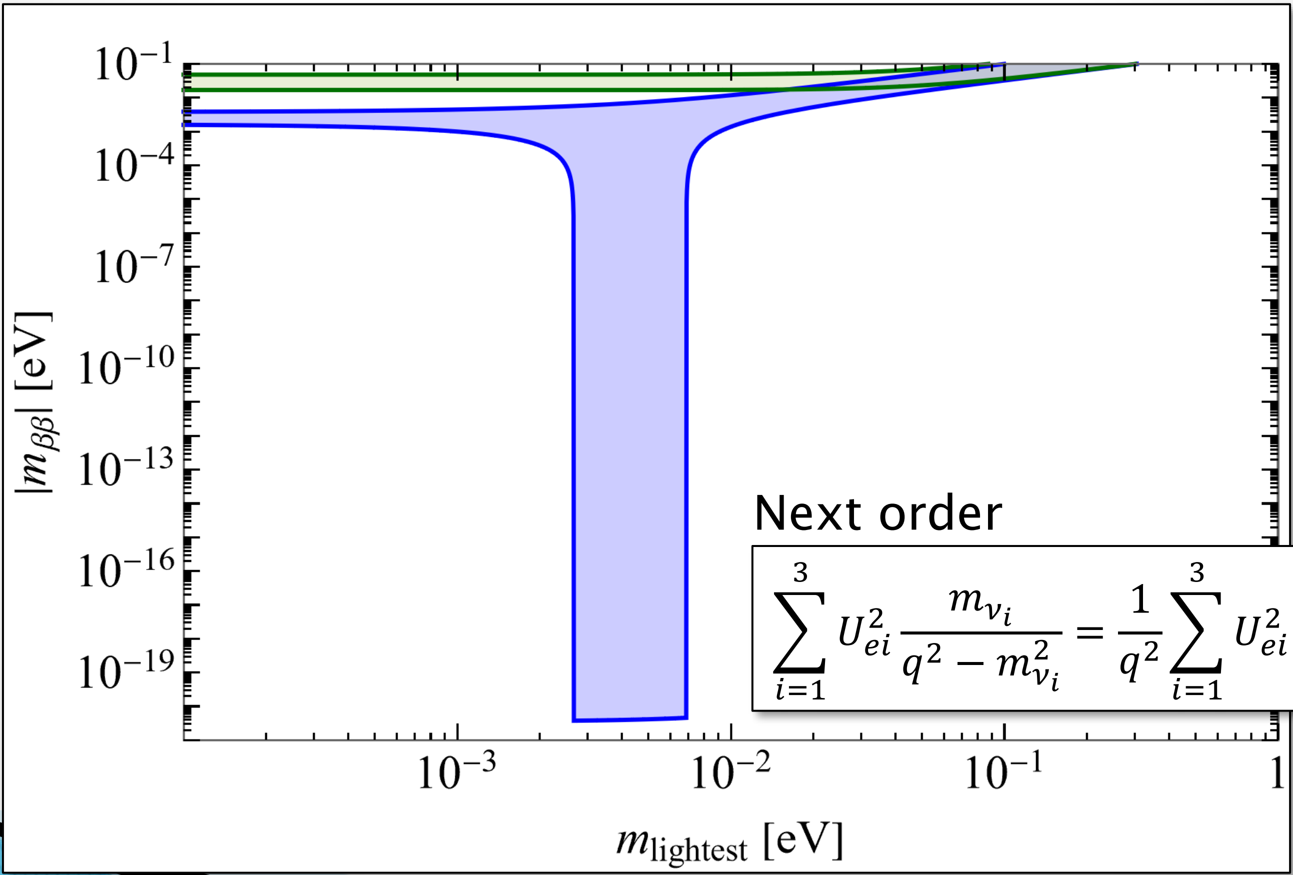

Next order

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

Three Active Neutrinos

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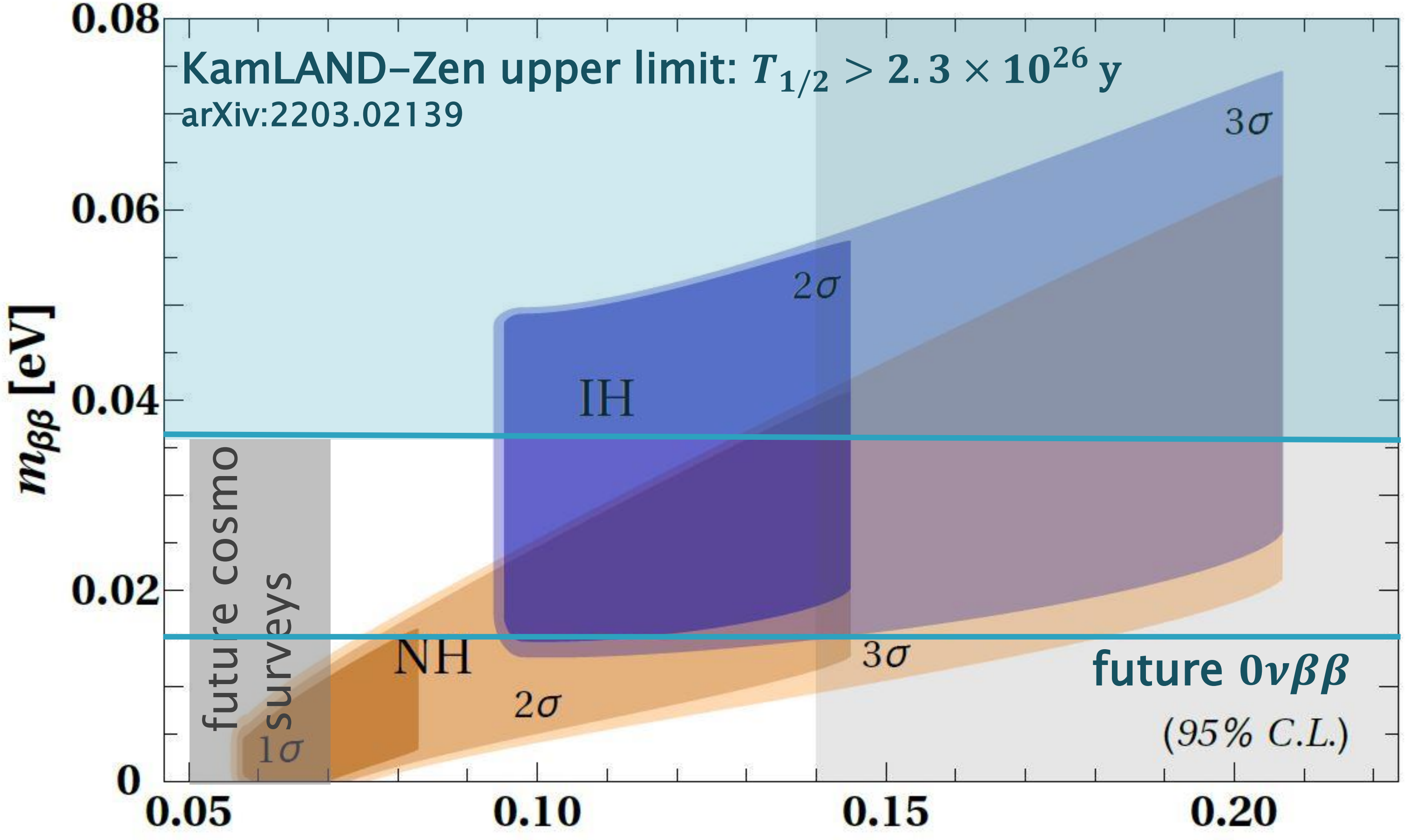
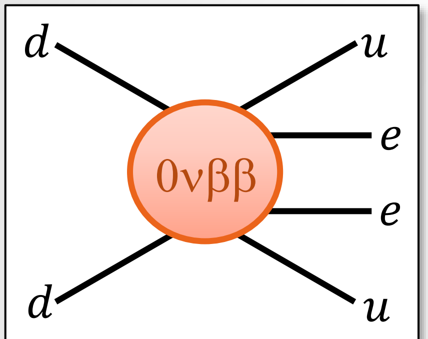
- Effective $0\nu\beta\beta$ Mass



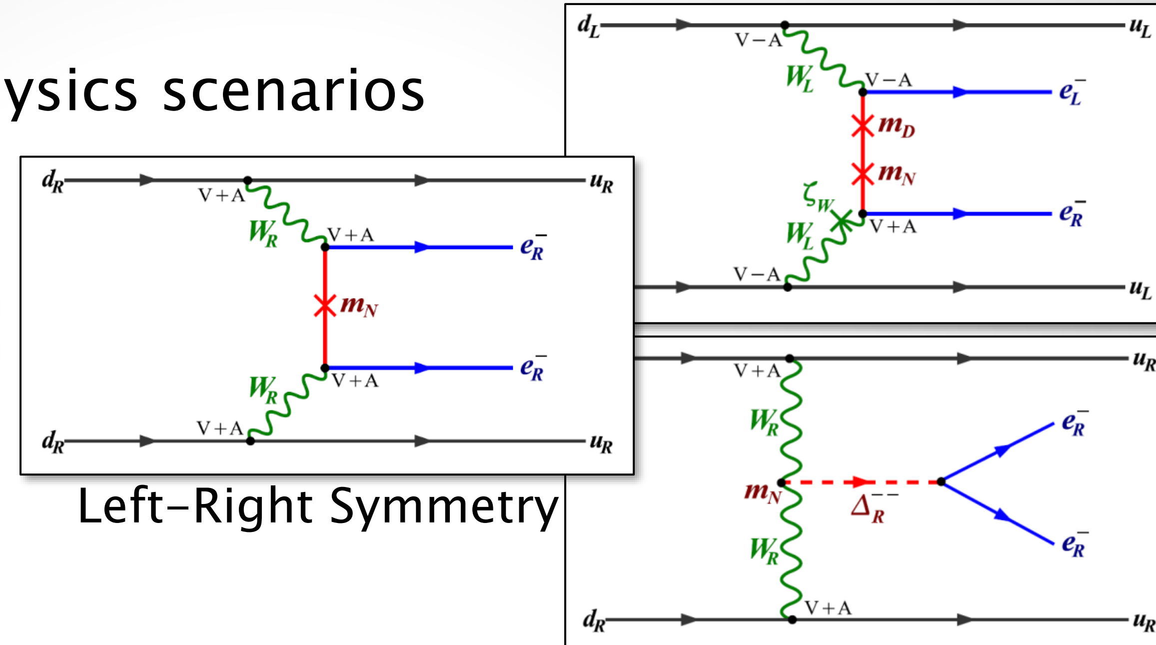
Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

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

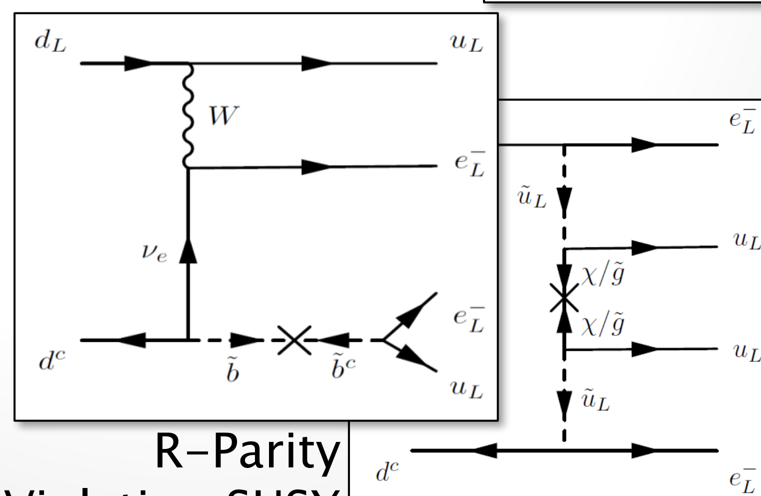
- Plethora of New Physics scenarios



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



Left-Right Symmetry



R-Parity Violating SUSY

Extra Dimensions

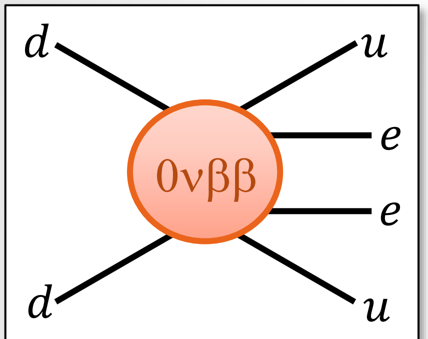
Majorons

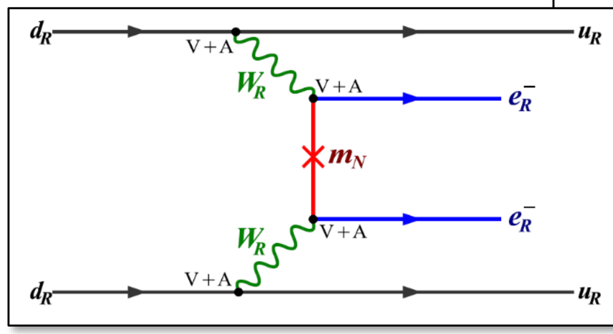
Leptoquarks

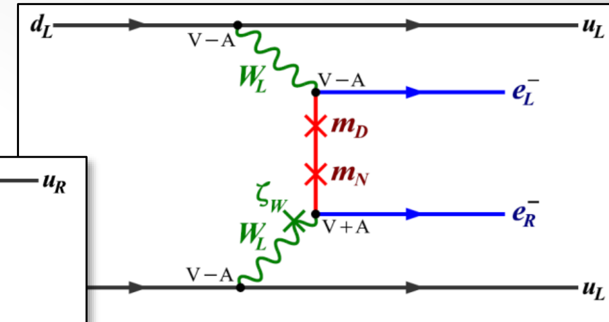
...

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

- Plethora of New Physics scenarios





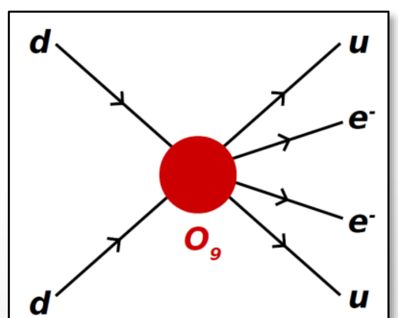


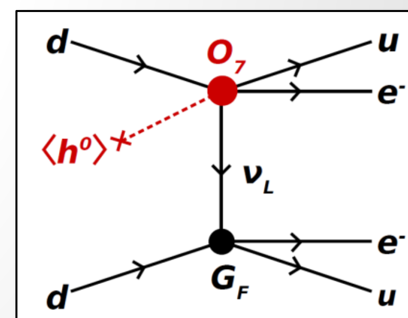
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

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

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

- $0\nu\beta\beta$ probes the TeV scale
- Limits on 7D and 9D eff. operators

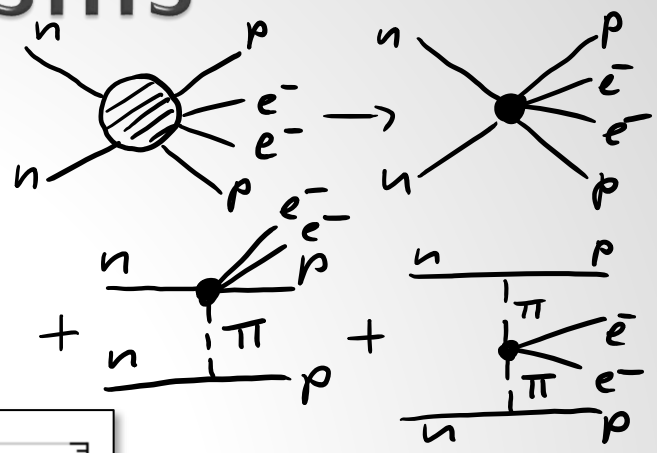


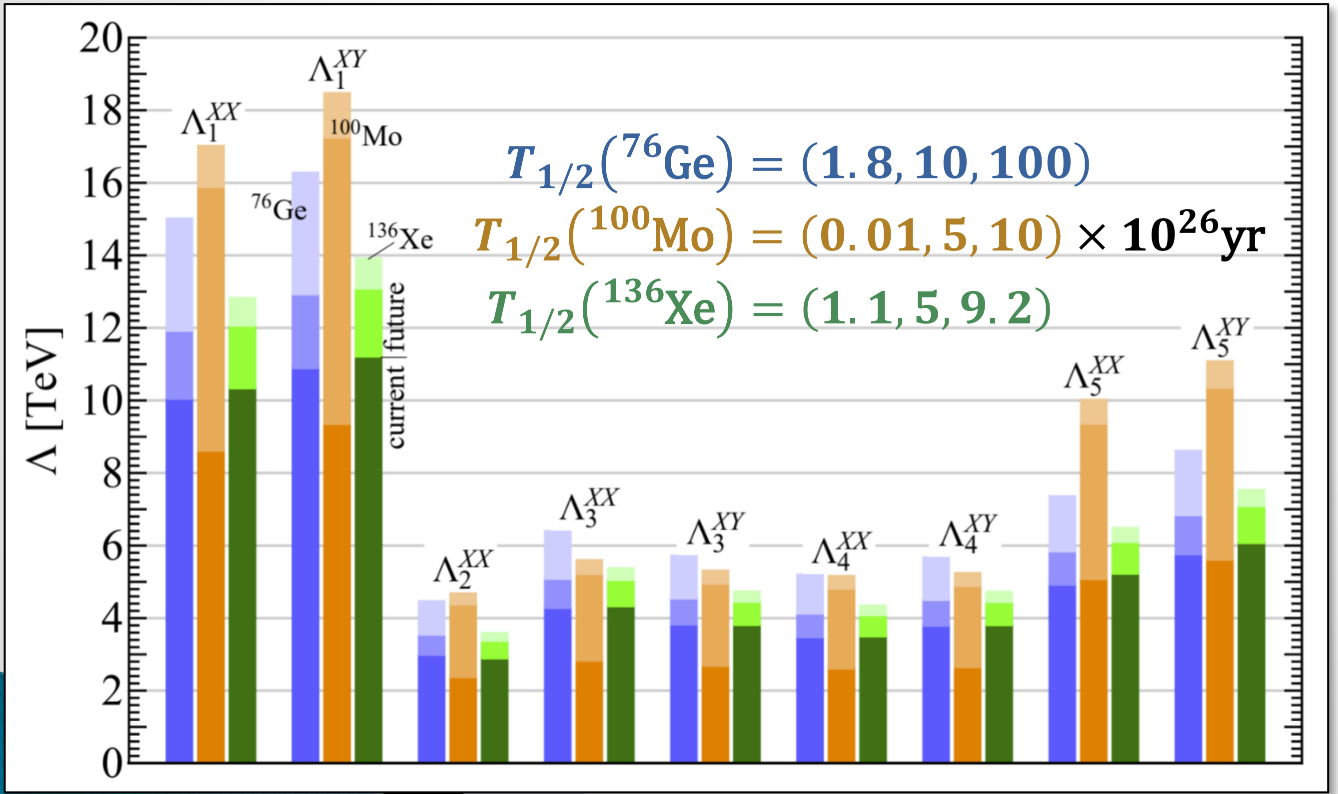


Short-Range Mechanisms

FFD, Graf, Iachello, Kotila, Phys.Rev.D 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)

Neutral Leptons in $0\nu\beta\beta$

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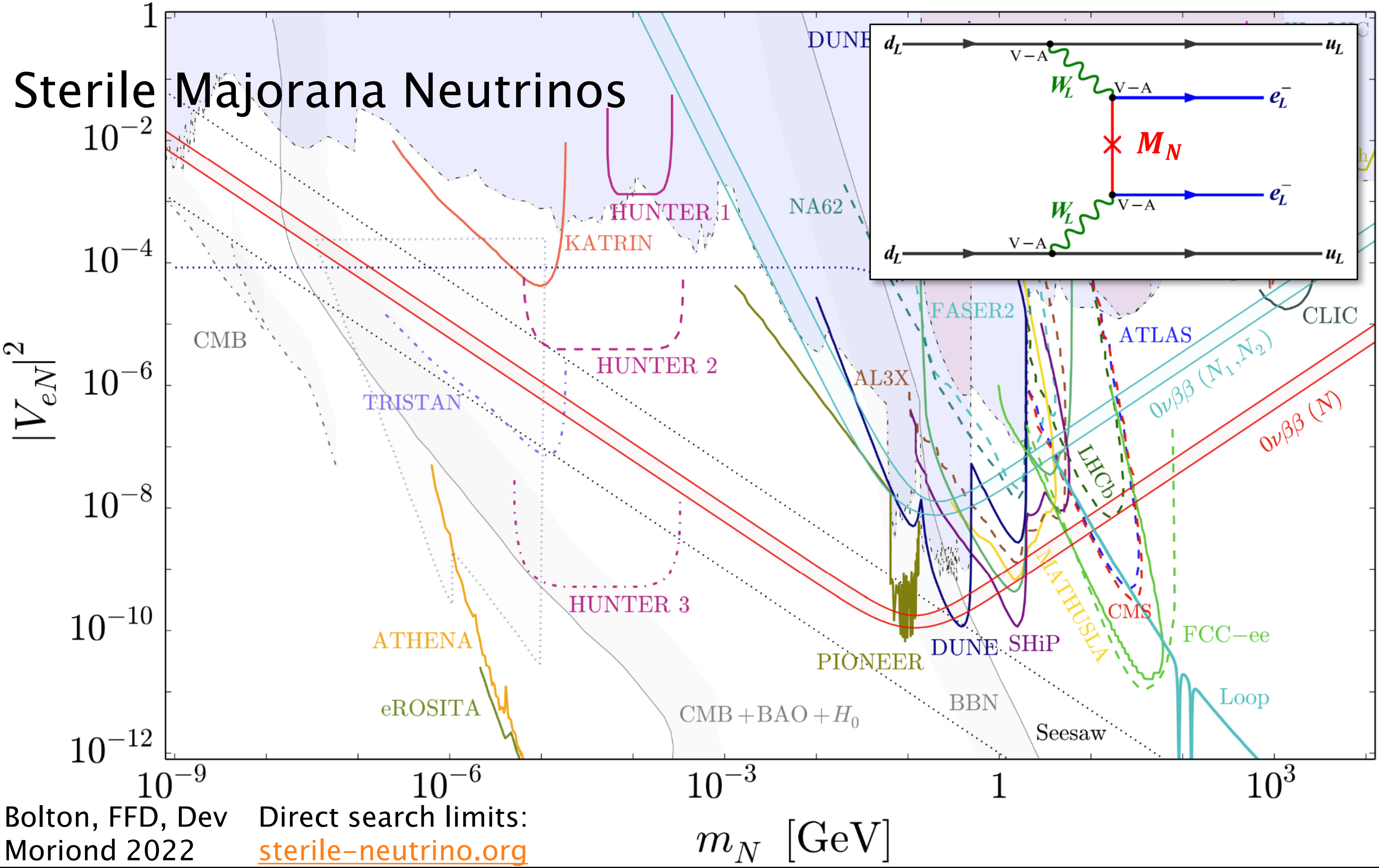
Sterile Majorana Neutrinos

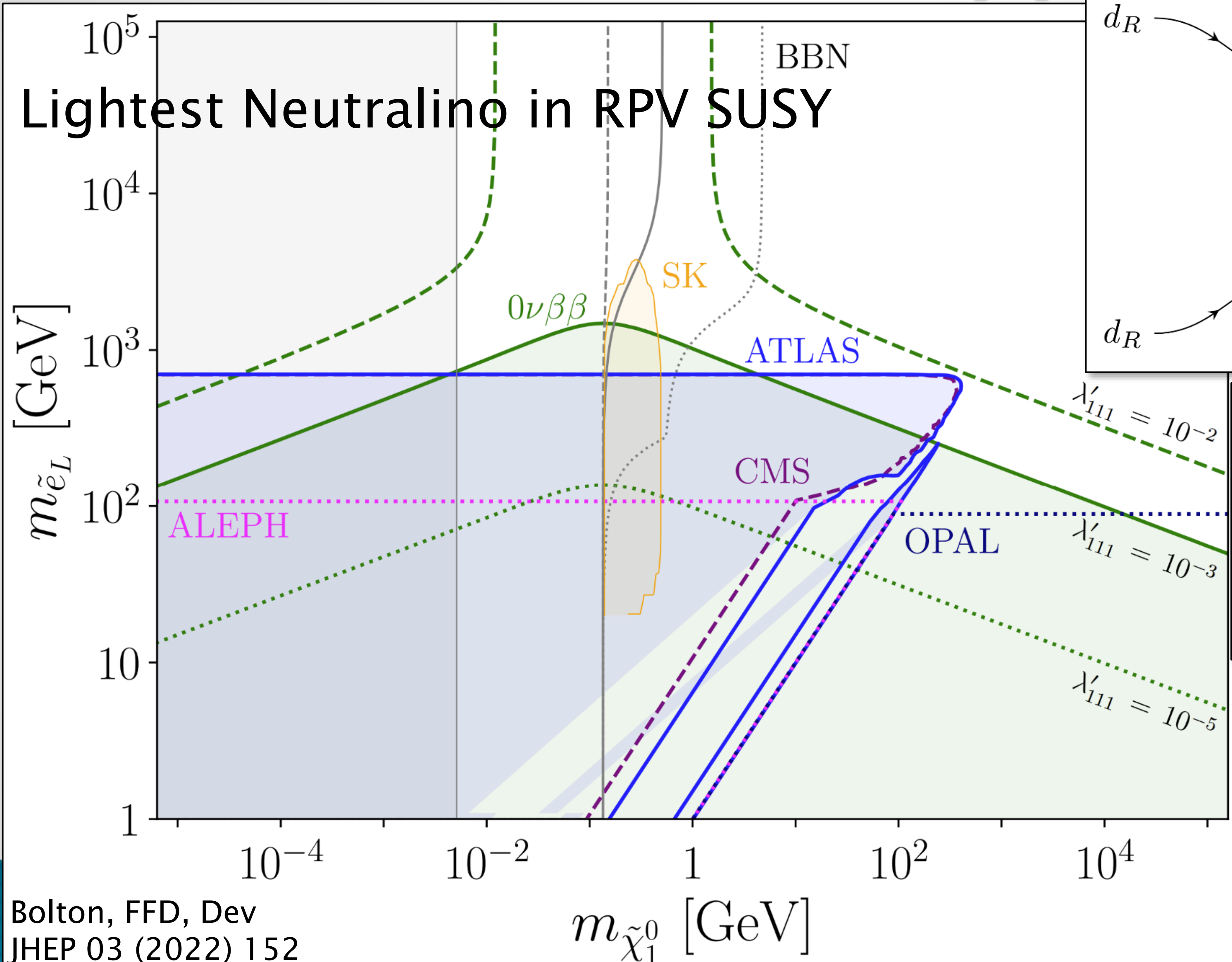


Bolton, FFD, Dev Moriond 2022

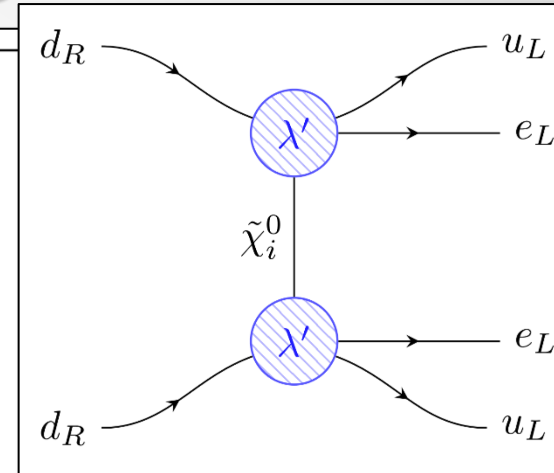
Direct search limits: sterile-neutrino.org

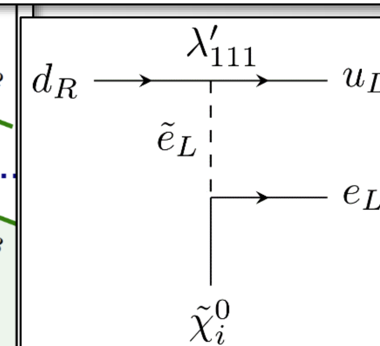
Neutral Leptons in $0\nu\beta\beta$

Lightest Neutralino in RPV SUSY



Bolton, FFD, Dev
JHEP 03 (2022) 152





Majorons and RH Currents

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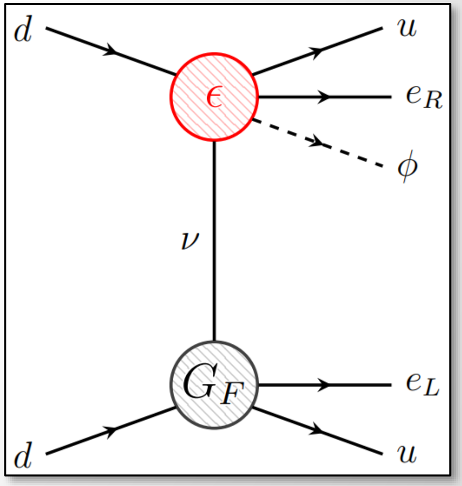
Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

- Effective RH lepton currents with massless scalar ϕ

$$\mathcal{L}_{0\nu\beta\beta\phi} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left(j_L^\mu J_{L\mu} + \frac{\epsilon_{RL}^\phi}{m_p} j_R^\mu J_{L\mu}\phi + \frac{\epsilon_{RR}^\phi}{m_p} j_R^\mu J_{R\mu}\phi \right) + \text{h.c.}$$

- Giving rise to long-range contribution to $0\nu\beta\beta\phi$ decay

$$\mathcal{M} = \epsilon_{RX}^\phi \frac{(G_F\cos\theta_C)^2}{\sqrt{2}m_p} \sum_N \int d^3x d^3y \int \frac{d^3q}{2\pi^2\omega}\phi(\mathbf{y})e^{i\mathbf{q}(\mathbf{x}-\mathbf{y})}$$
$$\times \left\{ \left[\frac{J_{LX}^{\rho\sigma}(\mathbf{x},\mathbf{y})u_{\rho\sigma}^L(E_1\mathbf{x},E_2\mathbf{y})}{\omega+\mu_N-\frac{1}{2}(E_1-E_2-E_\phi)} - \frac{J_{XL}^{\rho\sigma}(\mathbf{x},\mathbf{y})u_{\rho\sigma}^R(E_1\mathbf{x},E_2\mathbf{y})}{\omega+\mu_N-\frac{1}{2}(E_1-E_2+E_\phi)} \right] - \left[E_1 \leftrightarrow E_2 \right] \right\}$$



  - No suppression with ν mass

- Calculation follows long-range η and λ $0\nu\beta\beta$ modes
  Doi, Kotani, Takasugi, Prog. Theor. Phys. Suppl. 83 (1985) 1

Majorons and RH Currents

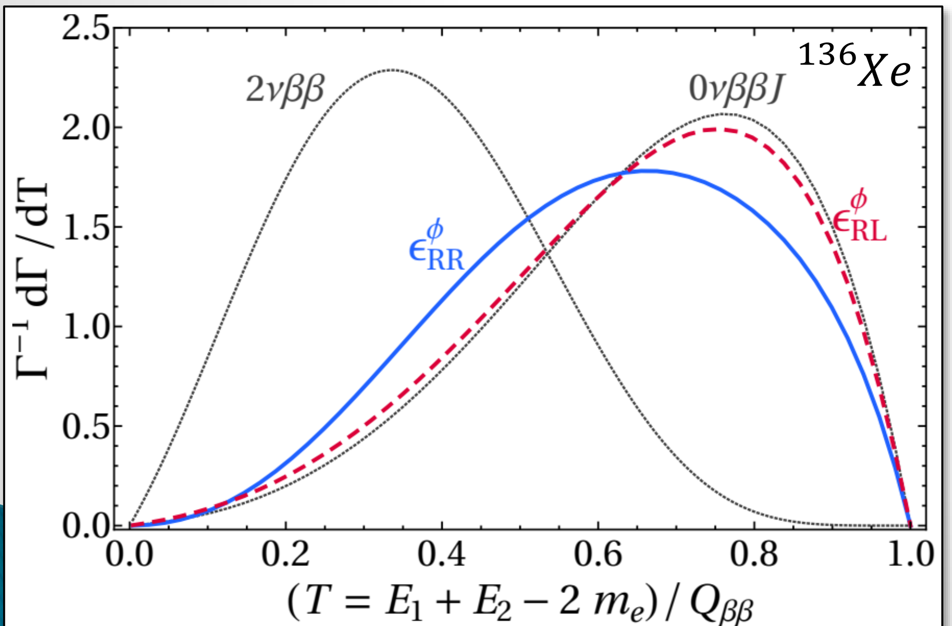
University College London

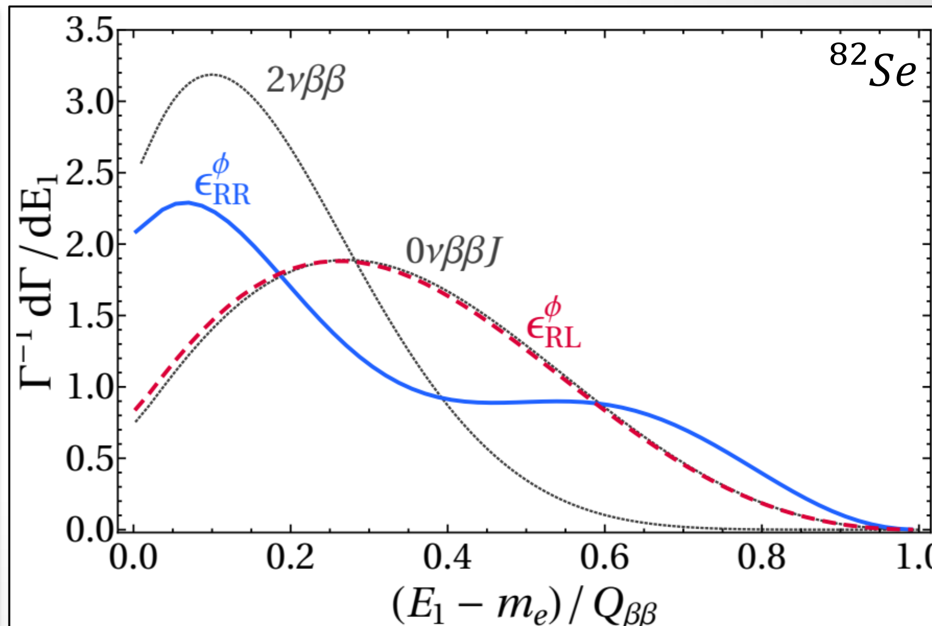
Cepedello, FFD, González, Hati, Hirsch, Phys.Rev.Lett. 122 (2019) 18, 181801

- Effective RH lepton currents with massless scalar ϕ

$$\mathcal{L}_{0\nu\beta\beta\phi} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left(j_L^\mu J_{L\mu} + \frac{\epsilon_{RL}^\phi}{m_p} j_R^\mu J_{L\mu} \phi + \frac{\epsilon_{RR}^\phi}{m_p} j_R^\mu J_{R\mu} \phi \right) + \text{h.c.}$$

- Non-standard total and single electron energy distributions





Majorons and RH Currents

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

- Sensitivity (massless ϕ, recasting single Majoron searches)

Isotope	$T_{1/2}$ [y]	$\vert\epsilon^{\phi}_{RL}\vert$	$\vert\epsilon^{\phi}_{RR}\vert$
^{82}Se	3.7×10^{22} [14]	4.1×10^{-4}	4.6×10^{-2}
^{136}Xe	2.6×10^{24} [13]	1.1×10^{-4}	1.1×10^{-2}
^{82}Se	1.0×10^{24}	8.0×10^{-5}	8.8×10^{-3}
^{136}Xe	1.0×10^{25}	5.7×10^{-5}	5.8×10^{-3}

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

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

UV Model: LR Symmetry

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

- Extended Gauge Symmetry

$$G_{LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$$

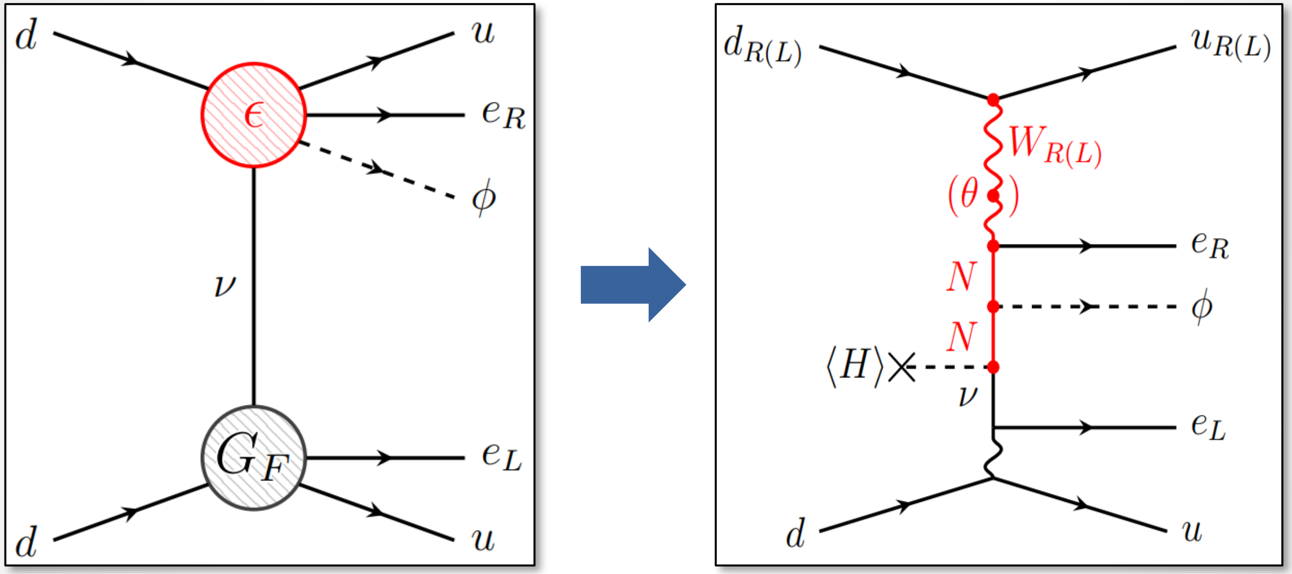
- Minimal LR model: $X = B - L$
- We consider $X \neq B - L$ broken but $B - L$ conserved
- Dirac neutrinos (and charged SM fermions) via Dirac seesaw via heavy, vector-like fermions
(Bolton, FFD, Hati, Sarkar, Phys.Rev.D 100 (2019) 3, 035013)

Field	$SU(2)_L$	$SU(2)_R$	$B-L$	ζ	X	$SU(3)_C$
q_L	2	1	1/3	0	1/3	3
q_R	1	2	1/3	0	1/3	3
ℓ_L	2	1	-1	0	-1	1
ℓ_R	1	2	-1	0	-1	1
$U_{L,R}$	1	1	1/3	+1	4/3	3
$D_{L,R}$	1	1	1/3	-1	-2/3	3
$E_{L,R}$	1	1	-1	-1	-2	1
$N_{L,R}$	1	1	-1	+1	0	1
χ_L	2	1	0	+1	1	1
χ_R	1	2	0	+1	1	1
ϕ	1	1	2	-2	0	1

UV Model: LR Symmetry

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

- UV Diagram



- Sensitivity from ϵ_{RL}^{ϕ}

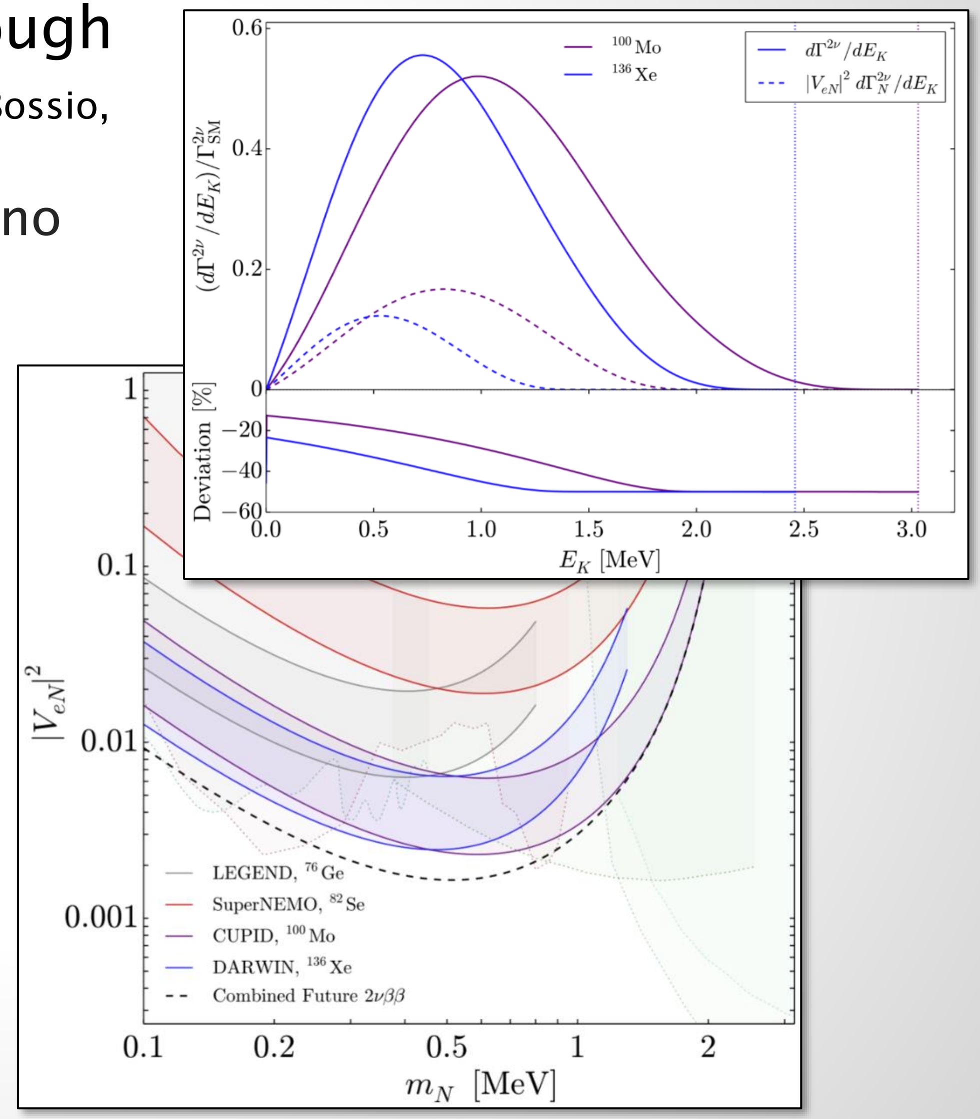
$$\frac{T_{1/2}^{\text{Xe}}}{10^{25}\ \text{y}} \approx \left(\frac{1.4\times 10^{-4}}{g_R^2 \kappa y_N y_\nu}\right)^2 \left(\frac{m_{W_R}}{25\ \text{TeV}}\right)^4 \left(\frac{m_N}{100\ \text{MeV}}\right)^4$$

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

Bolton, FFD, Graf, Simkovic, Phys.Rev.D 103 (2021) 055019

- Sterile neutrino search through energy endpoint (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 limit at GERDA (JCAP 12 (2022) 012)

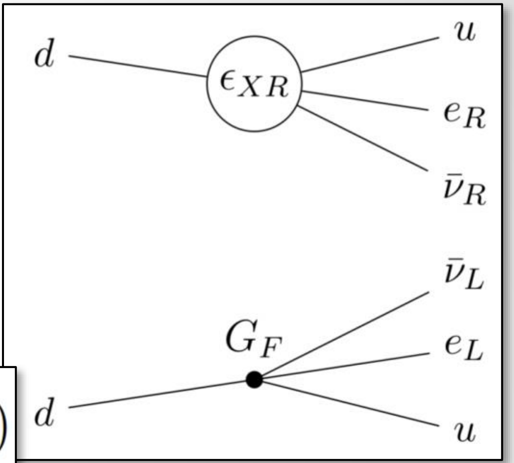
$$|V_{eN}|^2 < 1.3 \times 10^{-2}$$



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

FFD, Graf, Simkovic, Phys.Rev.Lett. 125 (2020) 17, 171801

- Lepton number conserving RH currents
  - Exotic charged currents probed e.g.
    - in neutron and single β decay
    - at LHC in $pp \to eX + MET$
  - Limits on RH currents



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

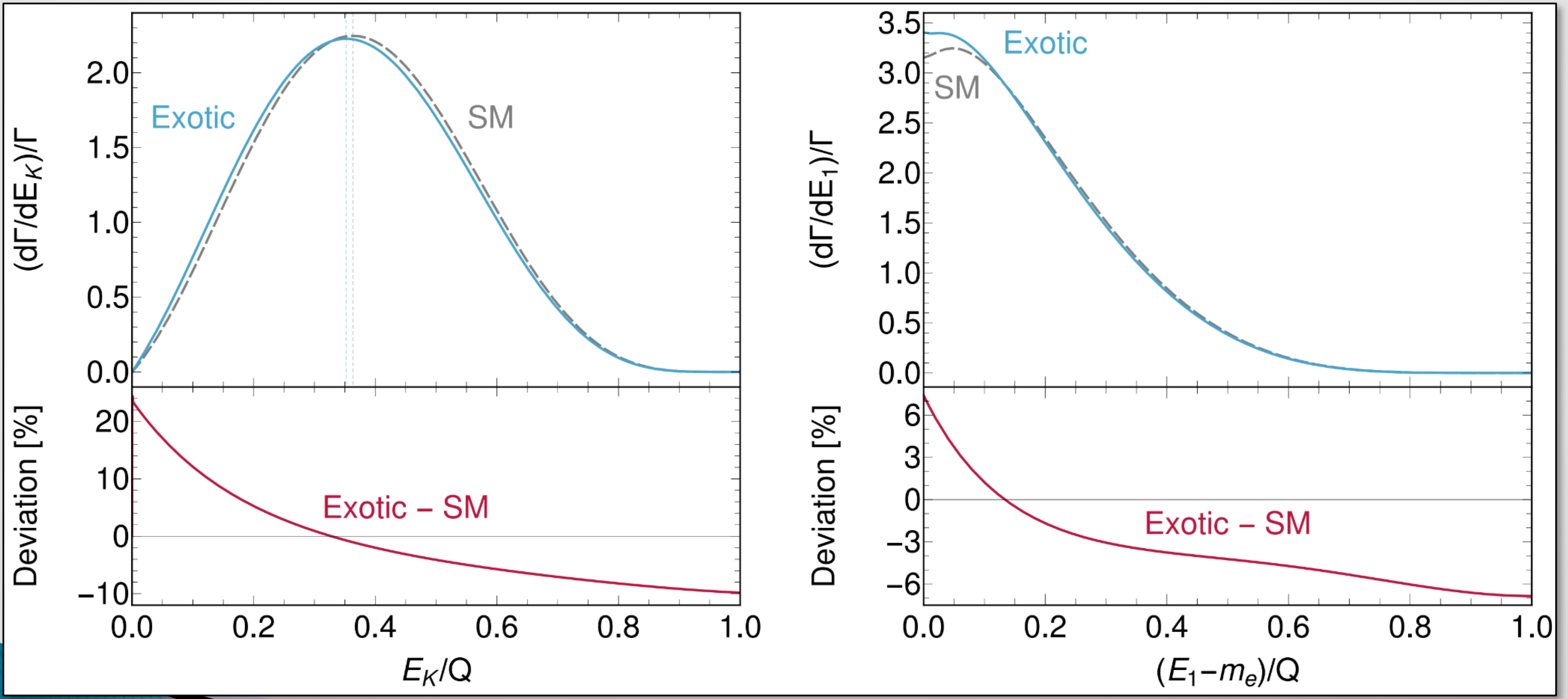
less severe due to lack of interference with SM

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

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

FFD, Graf, Simkovic, Phys.Rev.Lett. 125 (2020) 17, 171801

- Lepton number conserving RH currents
  - Main effect: Opposite angular distribution
  - Small modification of energy distribution



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

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

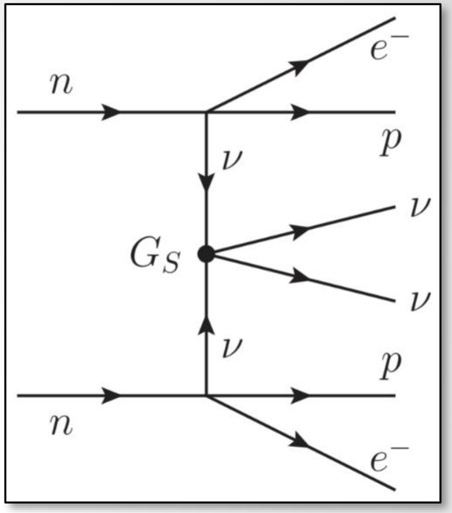
- Neutrino self-interactions
  - Same signature as SM $2\nu\beta\beta$ decay

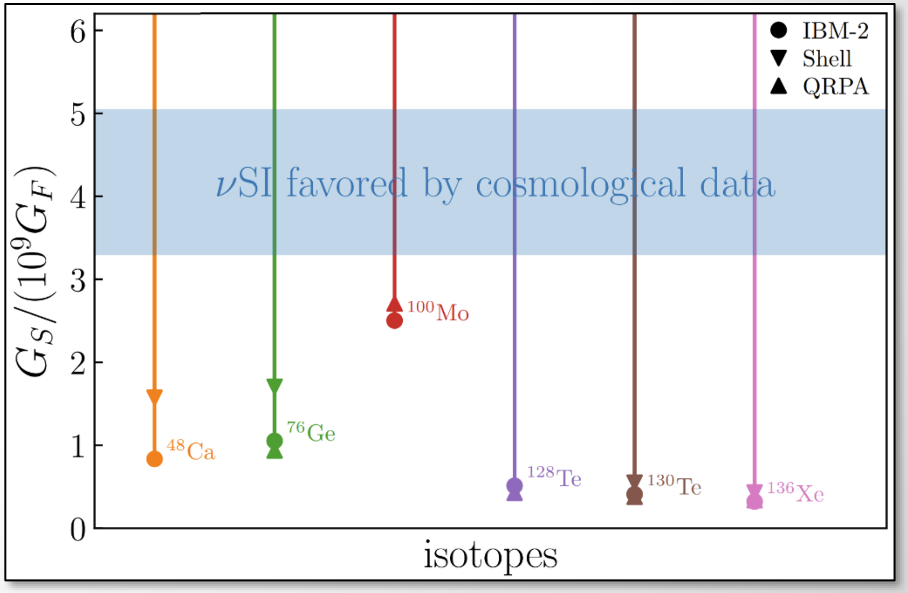
$$\Gamma_{2\nu} + \Gamma_{\nu\mathrm{SI}} \approx \left(|\mathcal{M}_{2\nu}|^2 + \left| \frac{G_S m_e}{2R} \right|^2 \frac{|\mathcal{M}_{0\nu}|^2}{4\pi^2} \right) \mathcal{G}_{2\nu}$$

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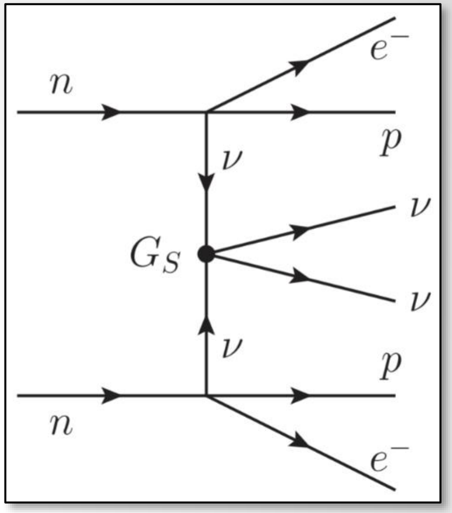
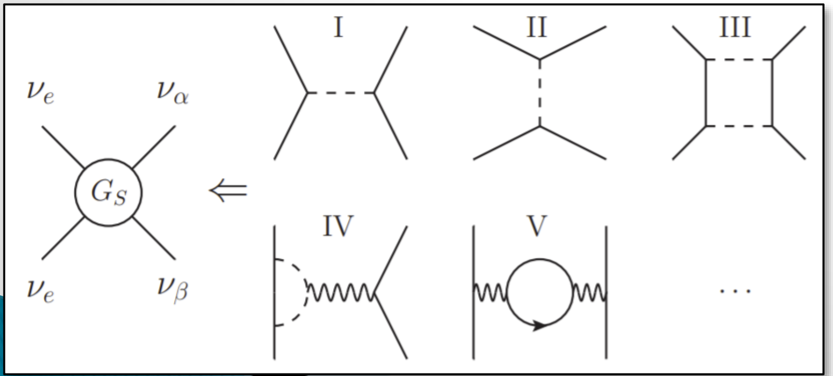
FFD, Graf, Rodejohann, Xu, Phys.Rev.D 102 (2020) 5, 051701

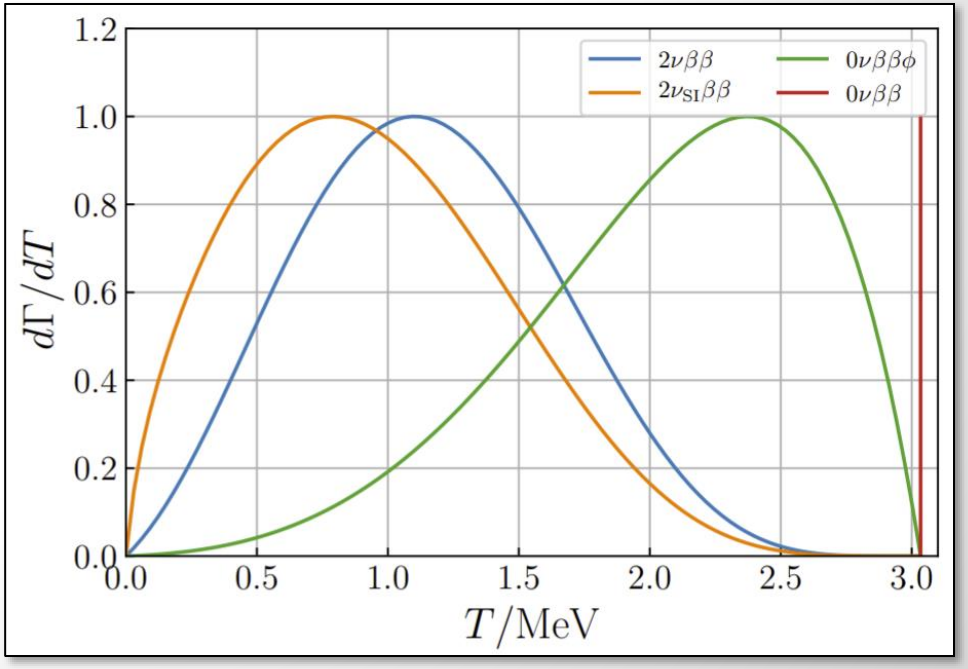
- Neutrino self-interactions
  - Same signature as SM $2\nu\beta\beta$ decay

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

  - Interference with SM $2\nu\beta\beta$ decay neglected
  - Modification of energy spectrum for light mediator(s), e.g., s-channel scalar $m_\phi = Q + 0.1 m_e$



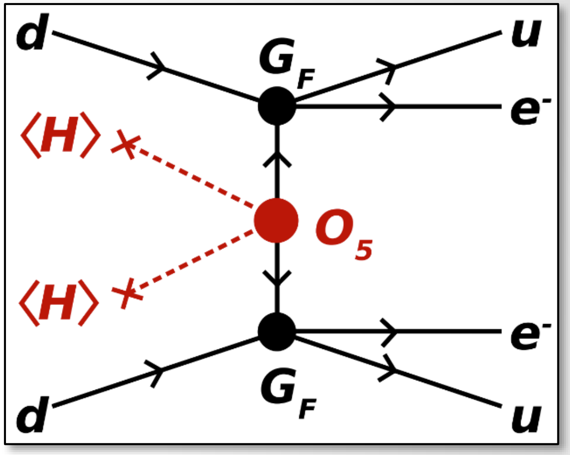




Conclusion

University College London

- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - Universal probe of LNV
  - Proof that light ν are Majorana
  - $m_{\beta\beta} = O(10\,\mathrm{meV})$ ←→ LNV near GUT scale through dim-5 Weinberg operator
  - LNV at scales $\Lambda \approx 1\,\mathrm{eV} - 100\,\mathrm{TeV}$
- **$2\nu\beta\beta$ is sensitive to New Physics**
  - Ongoing and future searches probe $2\nu\beta\beta$ decay with high statistics
  - Examples considered
    - Majoron emission with RH current
    - Exotic RH currents
    - Sterile neutrino endpoint search
    - Neutrino self-interactions



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