Probing New Physics with Double Beta Decays

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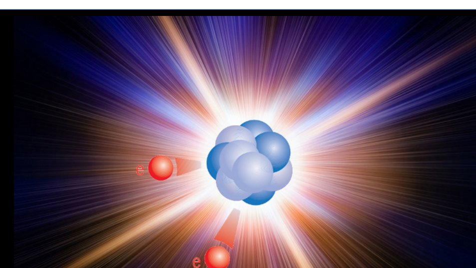
Fermilab Theory Seminar



July 2021

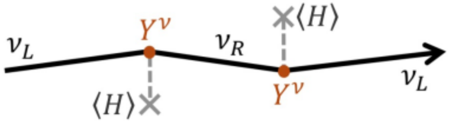
Dirac vs Majorana

- neutrinos – left-handed, neutral and massive fermions

→ two ways to define neutrino mass

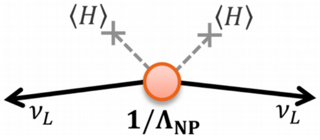

- Dirac mass – as other fermions, but tiny ($\approx 10^{-12}$) couplings to Higgs

$$m_D \nu_L \nu_R^c \subset y_\nu L H \nu_R^c$$



- Majorana mass – only left-handed neutrino → lepton number violation

$$m_M \overline{\nu}_L \nu_L^c$$



Double Beta Decays

- two-neutrino double beta decay

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

- neutrinoless double beta decay
  → LNV, mediated by Majorana neutrinos

$$0\nu\beta\beta: \ (A,Z) \to (A,Z+2) + 2e^-$$

- experiments: $\mathrm{T}_{1/2}^{2\nu\beta\beta} \sim 10^{18}$ - 10^{21} y

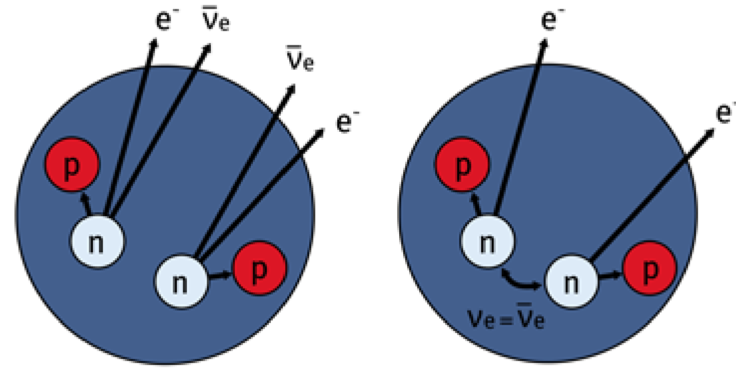
$$\mathrm{T}_{1/2}^{0\nu\beta\beta} \sim (0.1 \text{ eV}/m_\nu)^2 \times 10^{26} \text{ y}$$

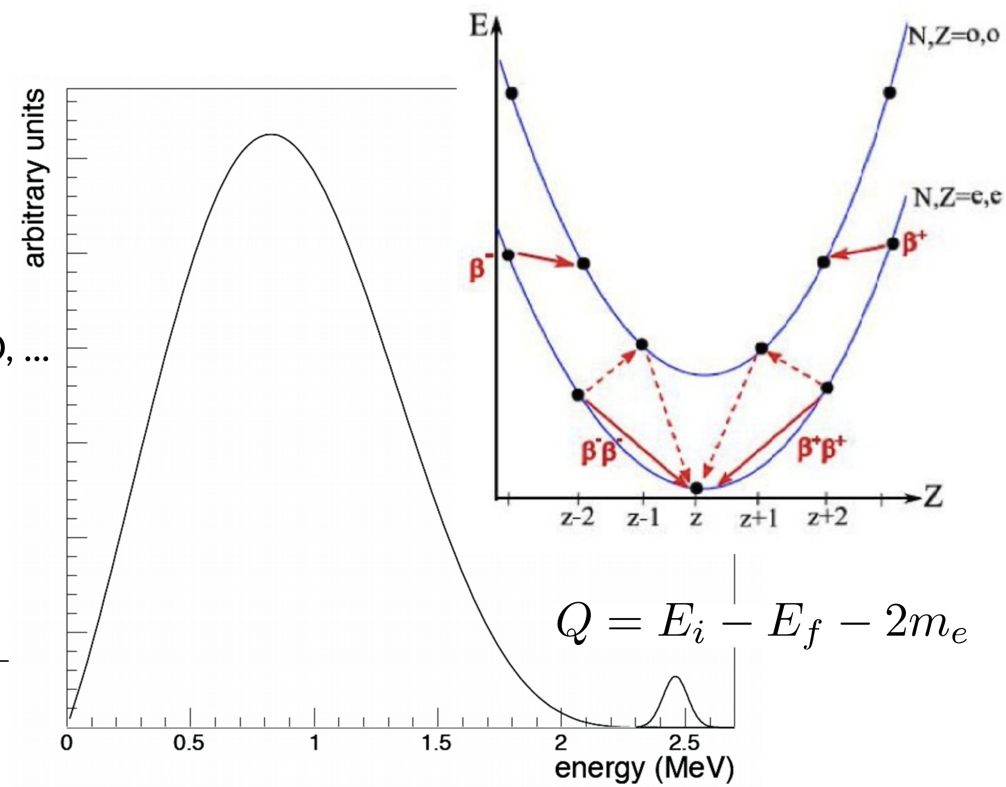
KamLAND-Zen, LEGEND, CUORE, NEMO-3, CUPID, (n)EXO, ...

- a variety of isotopes: ^{76}Ge, ^{136}Xe, ...

- variants

$$0\nu\beta^+\beta^+: \ (A,Z) \to (A,Z-2) + 2e^+$$
$$0\nu\beta^+EC: \ (A,Z) + e^- \to (A,Z-2) + e^+$$
$$0\nu ECEC: \ (A,Z) + 2e^- \to (A,Z-2)$$





$$Q = E_i - E_f - 2m_e$$

Neutrinoless Double Beta Decay

Atomic Physics

leptonic phase space factor

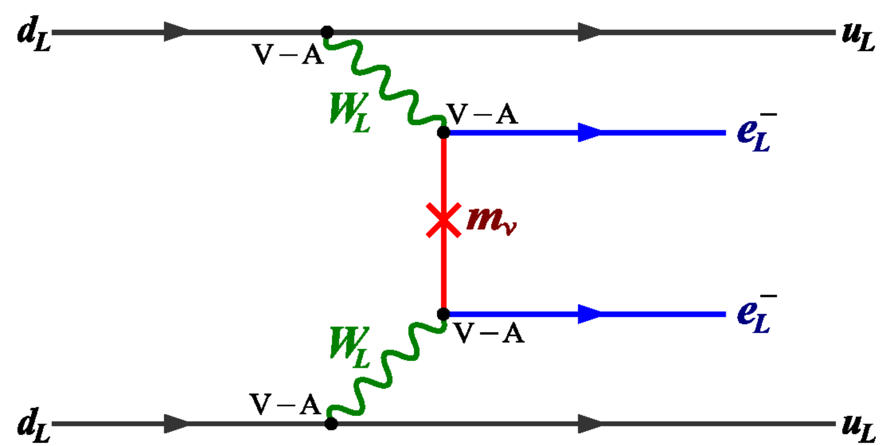
Nuclear Physics

nuclear transition matrix element

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

effective neutrino mass

Particle Physics



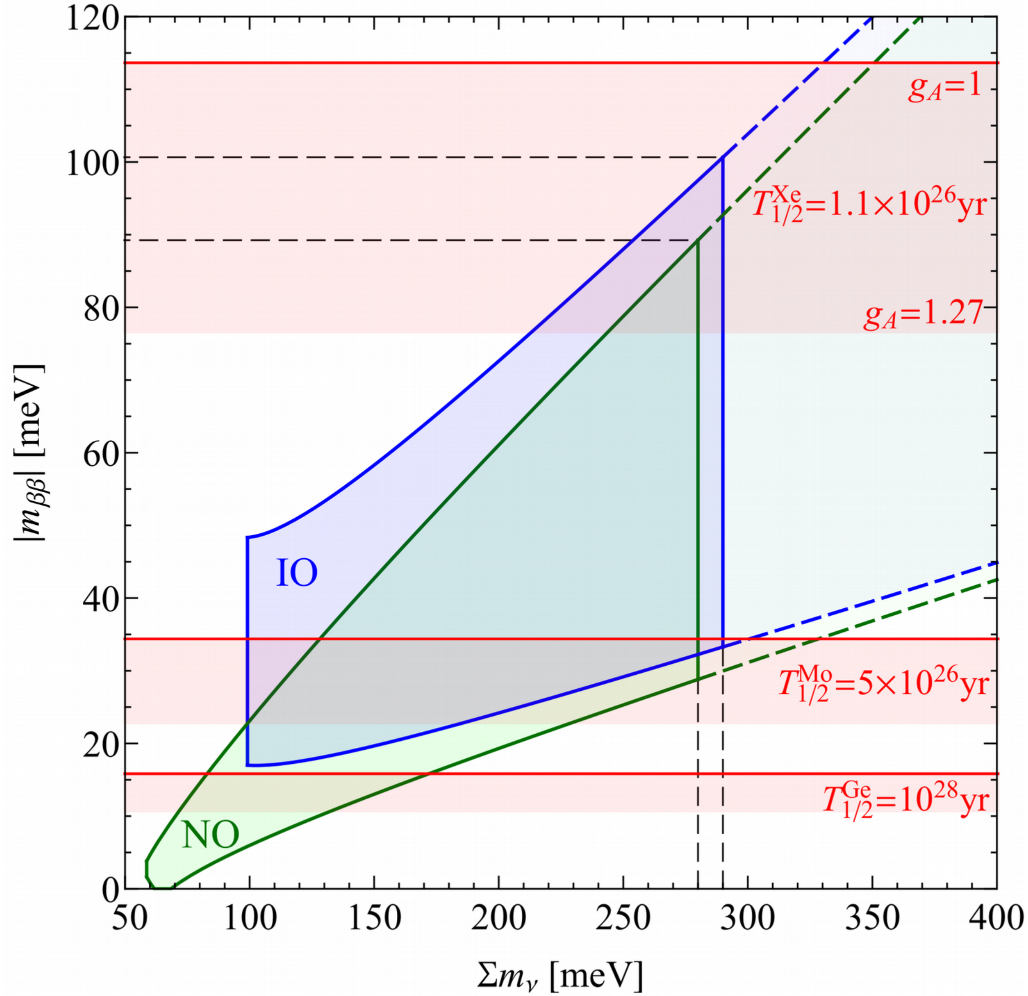
$$A_{\mu\nu}^{\text{lep}} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \bar{e}_2 \gamma_\nu (1-\gamma_5) \frac{q + m_i}{q^2 - m_i^2} (1-\gamma_5)\gamma_\mu e_1^c \approx \bar{e}_2 \frac{\gamma_\nu (1-\gamma_5)\gamma_\mu}{4q^2} e_1^c \boxed{\sum_{i=1}^{3} U_{ei}^2 m_i} \equiv m_{\beta\beta}$$

half-life limit ↔ bound on effective neutrino mass:

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

Three Active Neutrinos

- effective neutrino mass: $m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\phi_{12}} + m_3 s_{13}^2 e^{i(\phi_{13}-2\delta)}$
- two possible ν mass orderings
  - normal vs inverted
- uncertainty from unknown Majorana phases
- accidental cancellation possible for normal ordering
- 0νββ provides bound on $m_{\beta\beta}$
- cosmology gives the upper bound on sum of neutrino masses
- possible exclusion of inverted ordering



F. F. Deppisch, LG, F. Iachello, J. Kotila: PRD 102 [2009.10119]

Nuclear Matrix Elements

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- hadronic current

$$J^\mu(q) = g_V\gamma^\mu - g_A\gamma^\mu\gamma^5 + \frac{ig_W}{2m_N}\sigma^{\mu\nu}q_\nu - g_P\gamma^5 q^\mu$$

- non-relativistic expansion → nuclear matrix elements

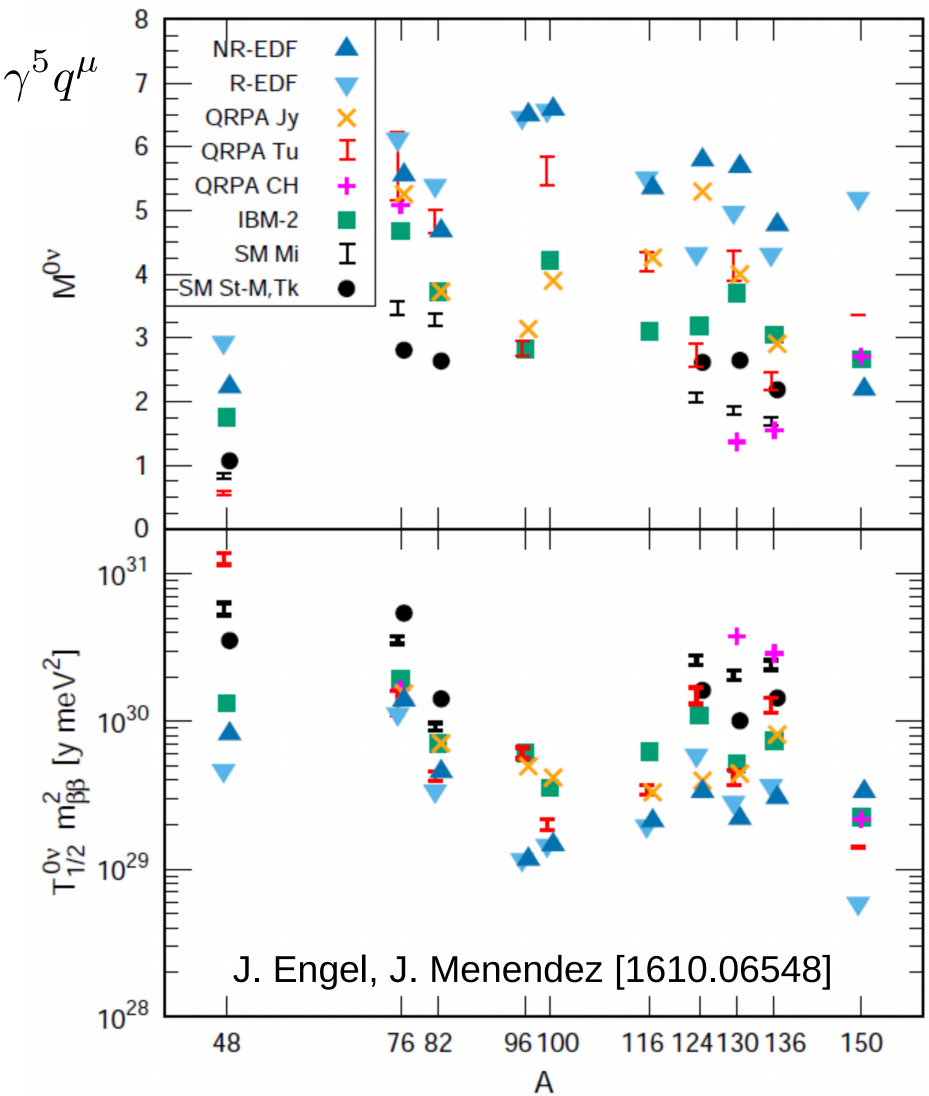
$$\mathcal{M}_{0\nu} = g_A^2\mathcal{M}_{GT} - g_V^2\mathcal{M}_F + g_A^2\mathcal{M}_T$$

$$\mathcal{M}_F = \langle h^F(q^2)\rangle$$

$$\mathcal{M}_{GT} = \langle h^{GT}(q^2)(\sigma_a\cdot\sigma_b)\rangle$$

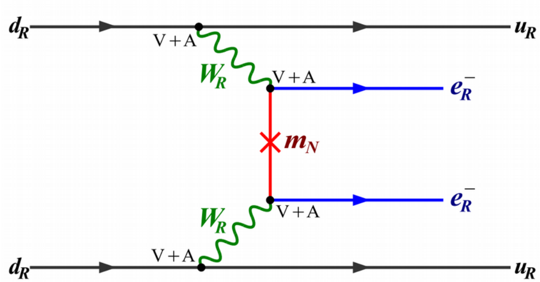
$$\mathcal{M}_T = \left\langle h^T(q^2)3(\sigma_a\cdot r_{ab})(\sigma_b\cdot r_{ab}) - (\sigma_a\cdot\sigma_b)\right\rangle$$

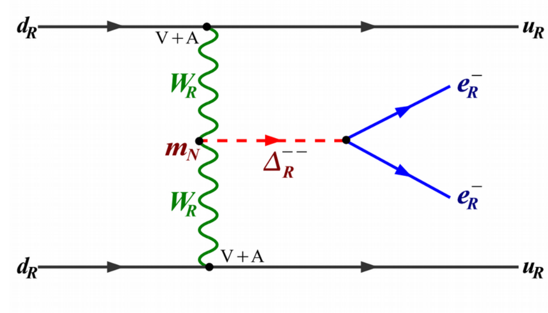
- dependence on isotope and operator
- alternative derivation: chiral EFT
- calculation – many-body problem
- different nuclear structure models, factor of 2-3 uncertainties

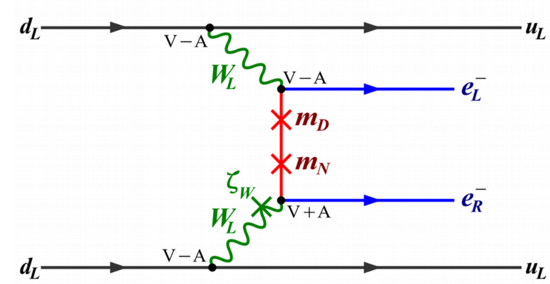


New Physics & 0νββ

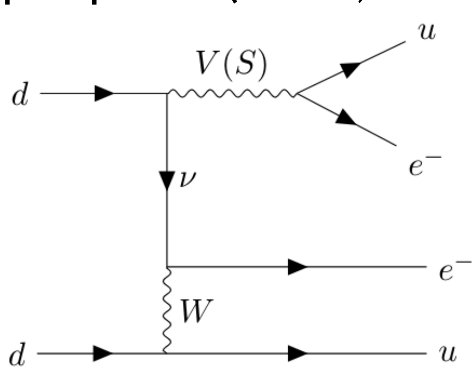
- plethora of New Physics scenarios may be responsible for **0νββ**
- **left-right symmetric models** $SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

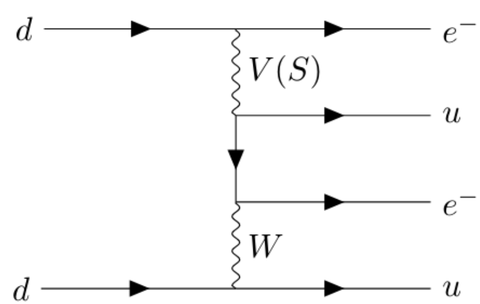


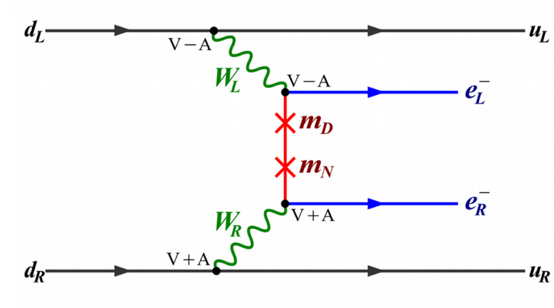




- leptoquarks (scalar, vector)







- R-parity violating SUSY, Majorons, Extra Dimensions …

F. F. Deppisch, M. Hirsch, H. Päs: J. Phys. G 39 (2012), 124007

New Physics & 0νββ

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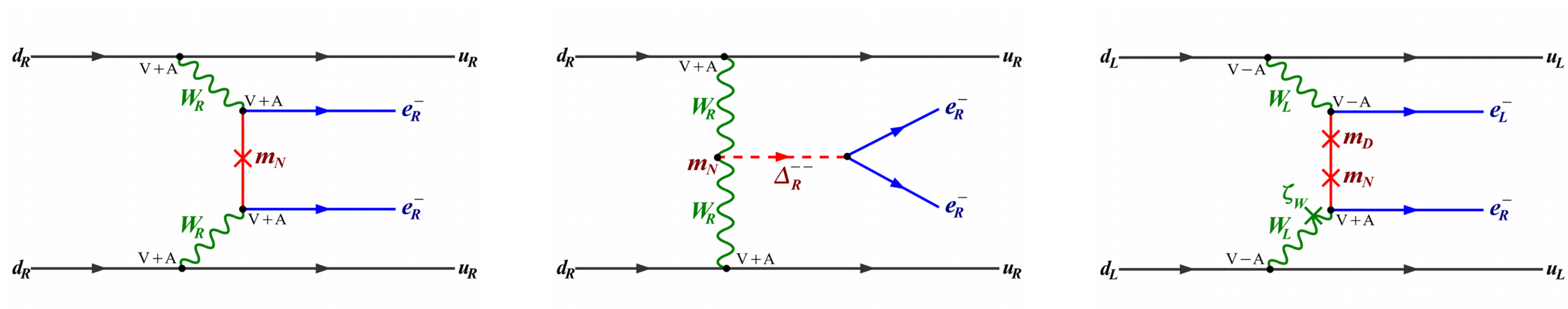

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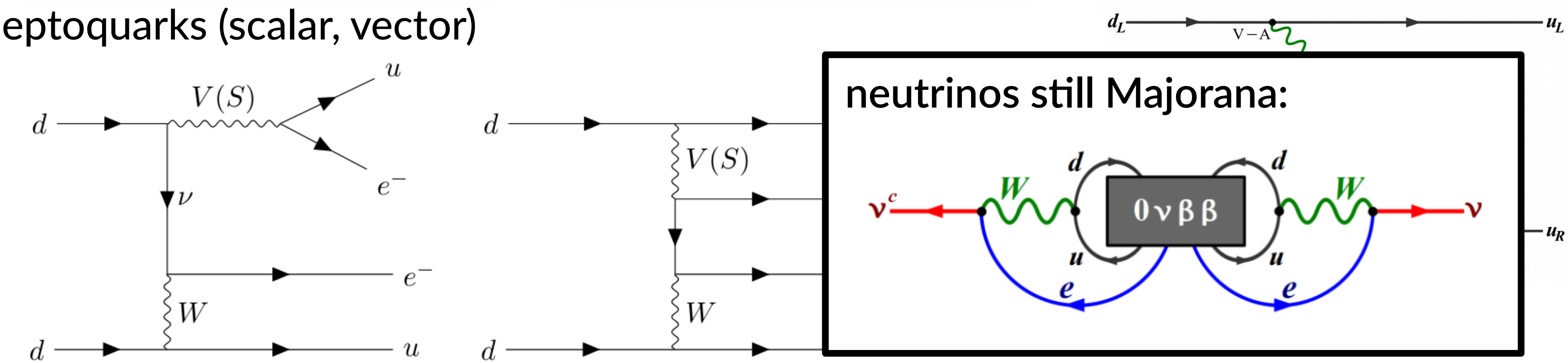

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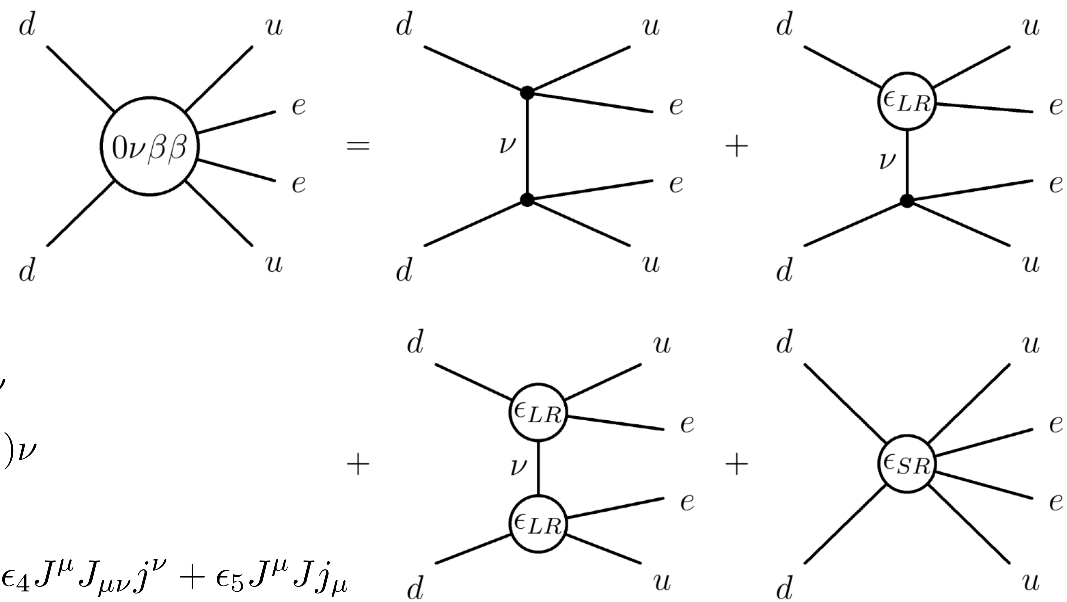
Effective Approach to 0νββ

- effectively, a variety of different mechanisms beyond the standard scenario may contribute to 0νββ – long-range and short-range
  - e.g. 0303205, 1208.0727, 1708.09390, 1806.02780, 1806.06058, 2009.10119
- 0νββ half-life limit sets constraints on effective couplings - accurate calculation of nuclear matrix elements and phase-space factors is crucial for estimating these limits

$$T_{1/2}^{-1} = \boxed{|\epsilon|^2} \mathcal{G}_{0\nu} |\mathcal{M}_{0\nu}|^2$$



$$\mathcal{L}_{LR} = \frac{G_F}{\sqrt{2}} J^{\dagger}_{V-A\mu} j^{\mu}_{V-A} + \tilde{\sum_{\alpha,\beta}} \epsilon_{\alpha}^{\beta} J^{\dagger}_{\alpha} j_{\beta}$$

$$J^{\dagger}_{S\pm P} = \bar{u}(1 \pm \gamma_5)d, \; j_{S\pm P} = \bar{e}(1 \pm \gamma_5)\nu$$

$$J^{\dagger}_{V\pm A} = \bar{u}\gamma^{\mu}(1 \pm \gamma_5)d, \; j_{V\pm A} = \bar{e}\gamma^{\mu}(1 \pm \gamma_5)\nu$$

$$J^{\dagger}_{T_{R,L}} = \bar{u}\sigma^{\mu\nu}(1 \pm \gamma_5)d, \; j_{T_{R,L}} = \bar{e}\sigma^{\mu\nu}(1 \pm \gamma_5)\nu$$

$$\mathcal{L}_{SR} = \frac{G_F^2}{2m_p} \epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu}$$

$$J = \bar{u}(1 \pm \gamma_5)d, \; J^{\mu} = \bar{u}\gamma^{\mu}(1 \pm \gamma_5)d, \; J^{\mu\nu} = \bar{u}\frac{i}{2}[\gamma^{\mu}, \gamma_{\nu}](1 \pm \gamma_5)d, \; j = \bar{e}(1 \pm \gamma_5)e^C, \; j^{\mu} = \bar{e}\gamma^{\mu}(1 \pm \gamma_5)e^C$$

Effective Approach to 0νββ

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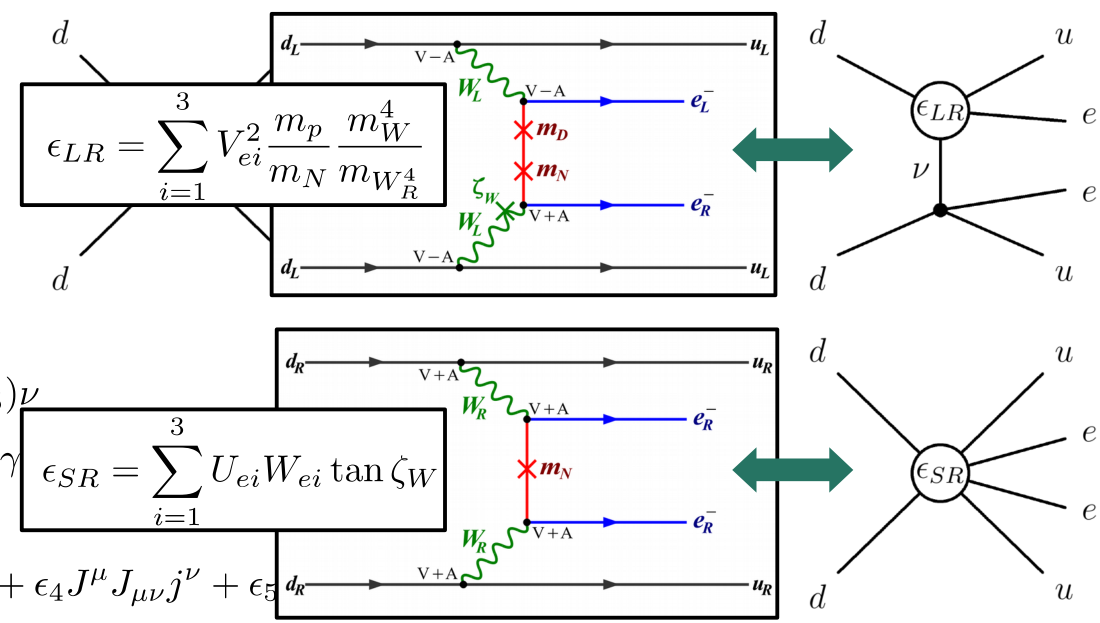


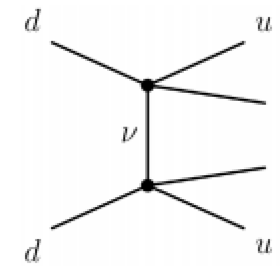
$$\mathcal{L}_{SR} = \frac{G_F^2}{2m_p} \epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 \ldots$$

$$J = \bar{u}(1 \pm \gamma_5)d, \; J^{\mu} = \bar{u}\gamma^{\mu}(1 \pm \gamma_5)d, \; J^{\mu\nu} = \bar{u}\frac{i}{2}[\gamma^{\mu}, \gamma_{\nu}](1 \pm \gamma_5)d, \; j = \bar{e}(1 \pm \gamma_5)e^C, \; j^{\mu} = \bar{e}\gamma^{\mu}(1 \pm \gamma_5)e^C$$

0νββ Mechanisms

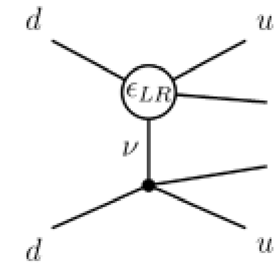
- standard mass mechanism

$$\Gamma^{0\nu\beta\beta}_{m_\nu} \sim m_\nu^2 G_F^4 m_F^2 Q_{\beta\beta}^5 \sim \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)^2 (10^{26}\ \mathrm{y})^{-1}$$



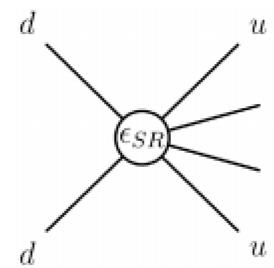
- non-standard long-range mechanisms

$$\Gamma^{0\nu\beta\beta}_{\mathrm{LR}} \sim v^2 \Lambda_{O_7}^{-6} G_F^2 m_F^4 Q_{\beta\beta}^5 \sim \left(\frac{10^5\ \mathrm{GeV}}{\Lambda_{O_7}}\right)^6 (10^{26}\ \mathrm{y})^{-1}$$



- non-standard short-range mechanisms

$$\Gamma^{0\nu\beta\beta}_{\mathrm{SR}} \sim \Lambda_{O_9}^{-10} m_F^6 Q_{\beta\beta}^5 \sim \left(\frac{5\ \mathrm{TeV}}{\Lambda_{O_9}}\right)^{10} (10^{26}\ \mathrm{y})^{-1}$$



- due to the intrinsic helicity flip, non-standard long-range mechanisms in typical scenarios suppressed indirectly by neutrino mass

- e.g. left-right symmetric models: small Yukawa coupling $(y_\nu v = \sqrt{m_\nu M_N})$

$$\Rightarrow \Gamma^{0\nu\beta\beta}_{\mathrm{LR}} \sim \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{5\ \mathrm{TeV}}{\Lambda_{\mathrm{LR}}}\right)^5 (10^{26}\ \mathrm{y})^{-1}$$

J. C. Helo, M. Hirsch and T. Ota, JHEP 06, 006 (2016), [1602.03362]

Short-Range 0νββ Mechanisms

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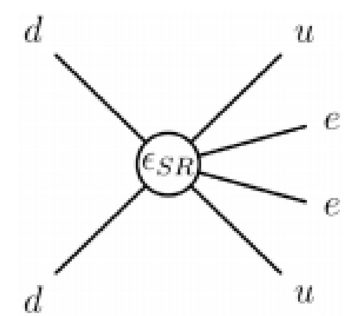
- example: general formula for half-life of **0νββ** induced by the short-range mechanisms + the standard mechanism and their mutual interference:

$$\begin{aligned} T_{1/2}^{-1} = & \, G_{11+}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I^L I + \epsilon_\nu \mathcal{M}_\nu \right|^2 + G_{11+}^{(0)} \left| \sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right|^2 \\ & + G_{11-}^{(0)} 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right) \left(\sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right)^* \right] \\ & + G_{66}^{(0)} \left| \sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right|^2 + G_{16}^{(0)} 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^L \mathcal{M}_I + \epsilon_\nu \mathcal{M}_\nu \right) \left(\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right)^* \right] \\ & - G_{16}^{(0)} 2\mathrm{Re} \left[\left(\sum_{I=1}^{3} \epsilon_I^R \mathcal{M}_I \right) \left(\sum_{I=4}^{5} \epsilon_I \mathcal{M}_I \right)^* \right] \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{SR} = \frac{G_F^2}{2m_p} [& \epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_\mu j \\ & + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j_\mu] \end{aligned}$$



F. F. Deppisch, LG, F. Iachello, J. Kotila: PRD 98 [1806.06058] & PRD 102 [2009.10119]

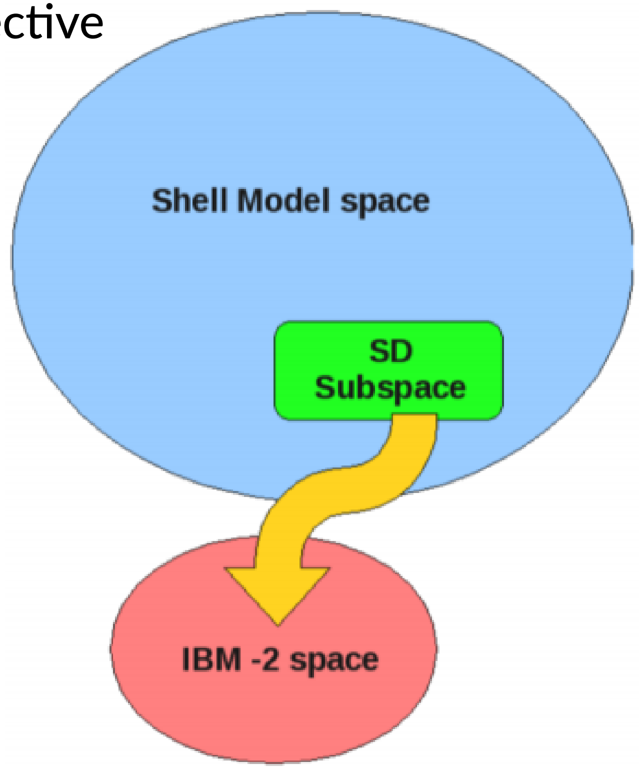
- phase-space factors $G^{(0)}$ – evaluated using radial electron wave functions satisfying the Dirac equation with potential taking into account the finite nuclear size and the electron screening

- nuclear matrix elements $\mathcal{M}_I$ – hadronization procedure + IBM-2

Nuclear Model: IBM-2

- numerical values of relevant NMEs computed using the Interacting Boson Model (collaboration with F. Iachello) for a large variety of isotopes
- IBM-2 – the very large shell model space truncated to states built from pairs of nucleons with J = 0, 2
- these pairs - bosons - are then assumed to be collective
- Hamiltonian constructed phenomenologically, two and four valence-nucleon states generated by a schematic interaction
- fermion operators - mapped onto a boson space
- matrix elements of the mapped operators evaluated with realistic wave functions

J. Barea and F. Iachello, Phys. Rev. C79 [044301] (2009)



Constraints on New Physics

- considering a single contribution at a time: $T_{1/2}^{-1} = \boxed{|\epsilon|^2} \mathcal{G}_{0\nu} |\mathcal{M}_{0\nu}|^2$

  → NMEs + PSFs + exp. limits on half-life → bounds on effective couplings

$m_{\beta\beta} = \sum U_{ei}^2 m_{\nu_i}$ $\qquad \epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu}$

Isotope	$T_{1/2}^{\mathrm{exp}}$ [yr]		$\lvert m_{\beta\beta}\rvert$ [meV]	$\lvert\epsilon_1^{XX}\rvert$	$\lvert\epsilon_1^{XY}\rvert$	$\lvert\epsilon_2^{XX}\rvert$	$\lvert\epsilon_3^{XX}\rvert$	$\lvert\epsilon_3^{XY}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5^{XX}\rvert$	$\lvert\epsilon_5^{XY}\rvert$
				$[10^{-10}]$							
^{76}Ge	1.8×10^{26}	[9]	118	2.90	2.84	88.4	77.1	154	130	102	68.1
^{82}Se	2.4×10^{24}	[77]	599	15.9	15.5	445	375	768	654	764	440
^{96}Zr	9.2×10^{21}	[78]	9130	85.5	84.8	5640	8510	12600	11300	1200	1110
^{100}Mo	1.1×10^{24}	[79]	733	6.10	6.04	401	608	901	774	84.1	77.5
^{116}Cd	2.2×10^{23}	[80]	2720	22.3	22.1	1430	2090	3170	2800	321	294
^{128}Te	1.1×10^{23}	[81]	13300	283	277	9300	8080	17300	12100	7630	5390
^{130}Te	3.2×10^{25}	[82]	252	5.38	5.27	178	153	336	270	158	112
^{136}Xe	1.1×10^{26}	[83]	114	2.50	2.45	83.4	72.5	157	127	74	52.4
^{150}Nd	2.0×10^{22}	[84]	3830	45.5	45.1	2730	3590	6190	5240	659	596

F. F. Deppisch, LG, F. Iachello, J. Kotila: PRD 102 [2009.10119]

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  → NMEs + PSFs + exp. limits on half-life → bounds on effective couplings

$$m_{\beta\beta} = \sum U_{ei}^2 m_{\nu_i} \qquad \epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu}$$

Isotope	$T_{1/2}^{\text{exp}}$ [yr]		$\lvert m_{\beta\beta}\rvert$ [meV]
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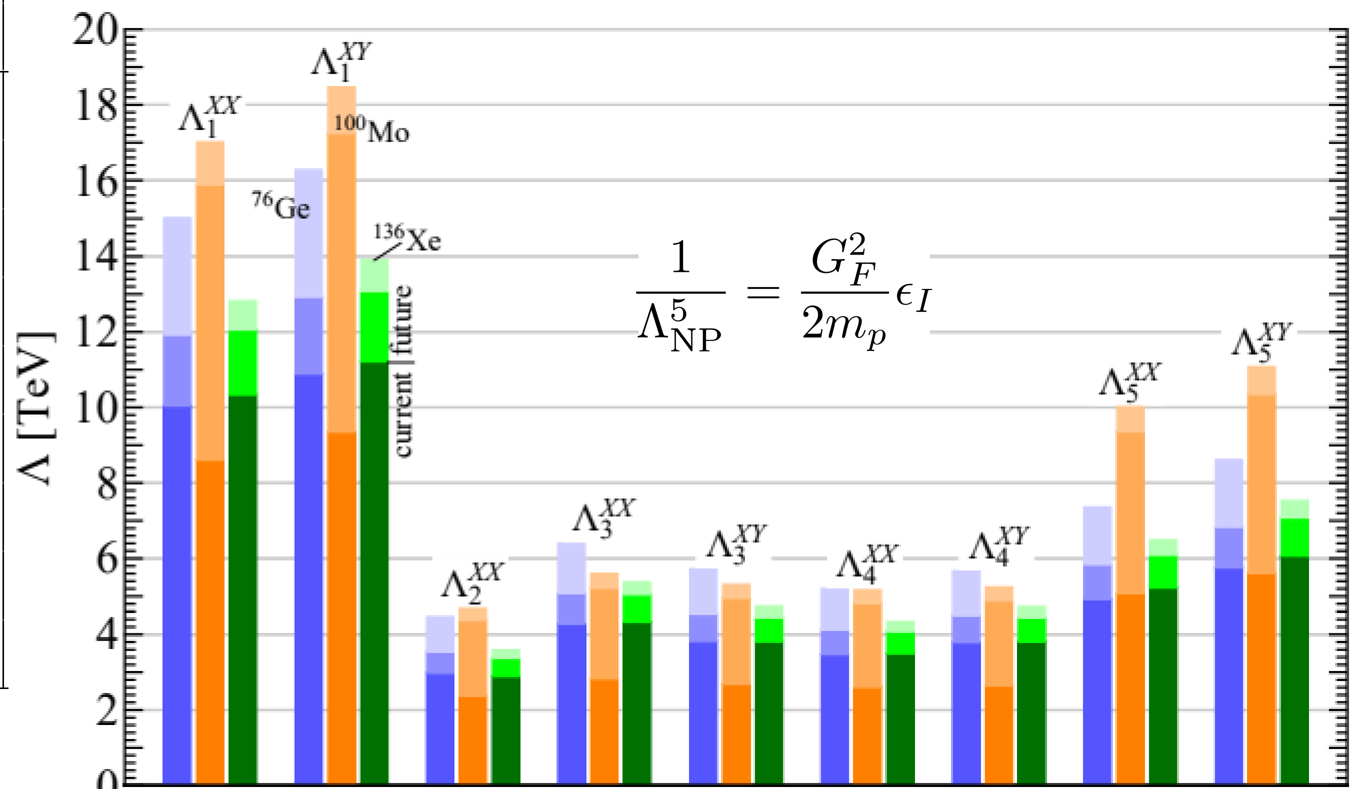
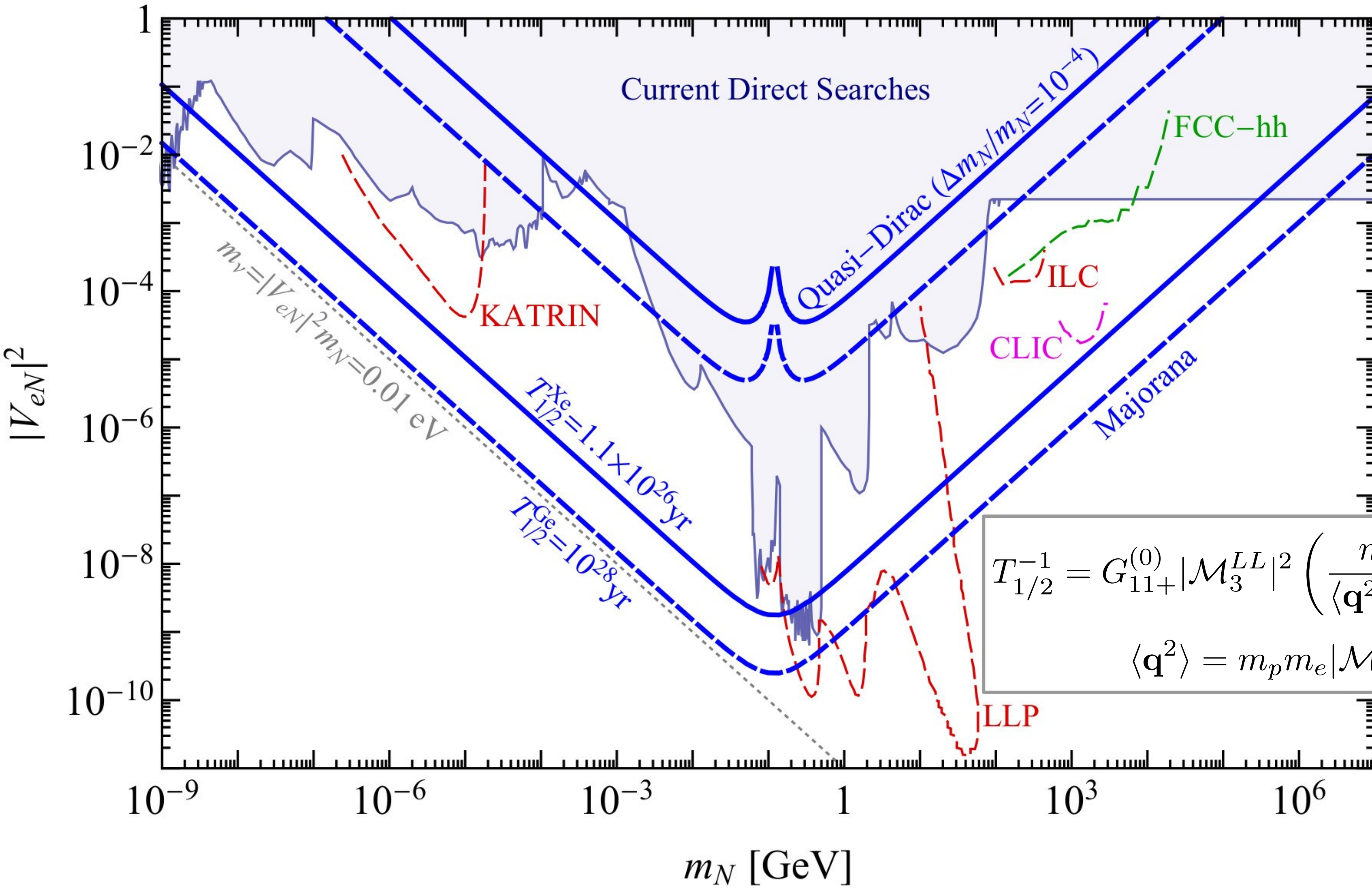
^{100}Mo	1.1×10^{24}	[79]	733
^{116}Cd	2.2×10^{23}	[80]	2720
^{128}Te	1.1×10^{23}	[81]	13300
^{130}Te	3.2×10^{25}	[82]	252
^{136}Xe	1.1×10^{26}	[83]	114
^{150}Nd	2.0×10^{22}	[84]	3830

$|\epsilon_1^{XX}|$ $|\epsilon_1^{XY}|$ $|\epsilon_2^{XX}|$ $|\epsilon_3^{XX}|$ $|\epsilon_3^{XY}|$ $|\epsilon_4|$ $|\epsilon_5^{XX}|$ $|\epsilon_5^{XY}|$



F. F. Deppisch, LG, F. Iachello, J. Kotila: PRD 102 [2009.10119]

Sterile Neutrino Constraint



$$T_{1/2}^{-1} = G_{11+}^{(0)} |\mathcal{M}_3^{LL}|^2 \left(\frac{m_p m_N}{\langle \mathbf{q}^2 \rangle + m_N^2} \right)^2 |V_{eN}|^4$$

$$\langle \mathbf{q}^2 \rangle = m_p m_e |\mathcal{M}_3^{LL}/\mathcal{M}_\nu|$$

F. F. Deppisch, LG, F. Iachello, J. Kotila: PRD 102 [2009.10119]

Distinguishing 0νββ Mechanisms

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- phase-space observables – electron energy spectra, angular correlation
- comparison with other ββ modes → β+β+, ECβ+, ECEC - typically suppressed
- decay rate ratios for different isotopes $\mathrm{R}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}^{\mathcal{O}_i}(^{76}\mathrm{Ge})|^2 G^{\mathcal{O}_i}(^{76}\mathrm{Ge})}{|\mathcal{M}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})|^2 G^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}$
  - → ratio of half-lives = ratio of NMEs x ratio of PSFs, the unknown coupling drops out $\mathrm{R}_{ij}(^{A}X) = \frac{R^{\mathcal{O}_i}(^{A}X)}{R^{\mathcal{O}_j}(^{A}X)}$
  - distinguishing 2 specific operators quantified using
- applied to the "master formula" framework of 1806.02780

V. Ciriigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti: JHEP 12 [1806.02780]

  - PSFs → 4 distinguishable groups of operators
  - ratios: in principle 12 distinguishable groups of operators
    - main issue: unknown low energy constants (LECs) → large uncertainties → LQCD computations vital

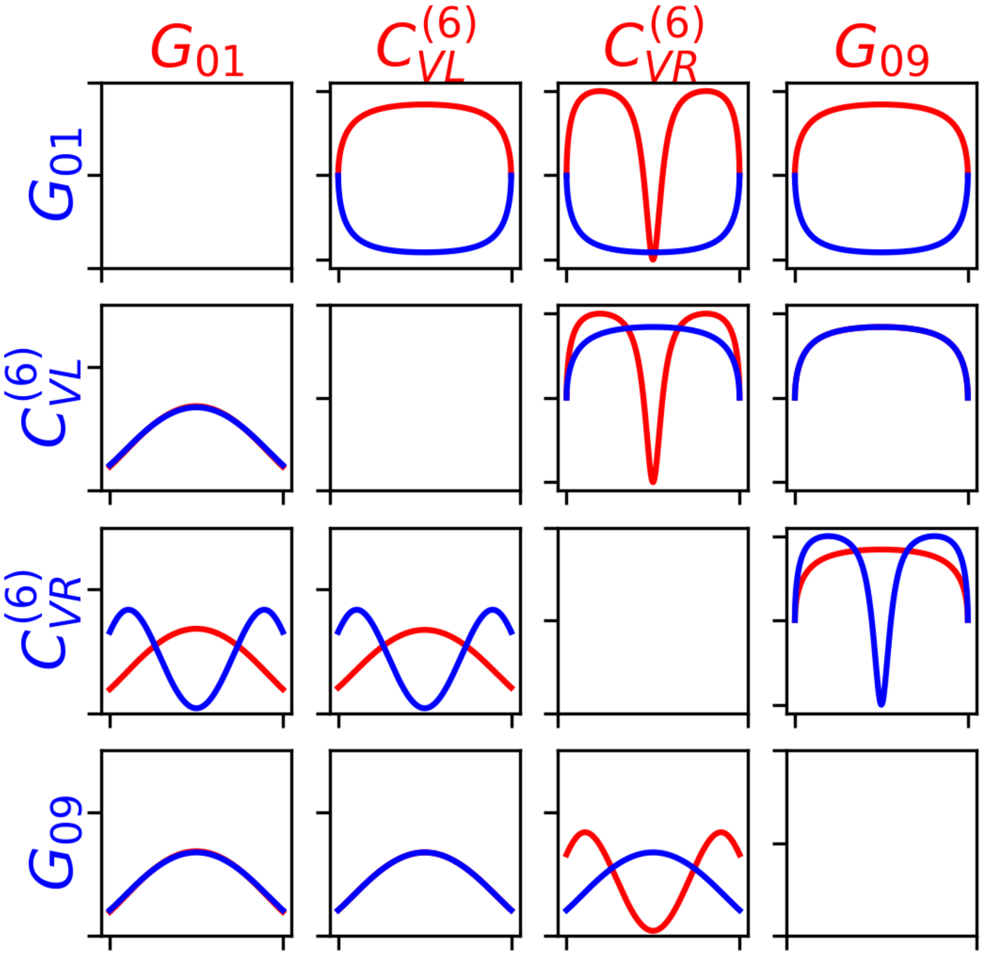
Distinguishing: Phase Space

- electron energy spectra and angular correlation of the emitted electrons

$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}} \Big[C^{(6)}_{\mathrm{VL}} \left(\overline{u_L}\gamma^\mu d_L\right) \left(\overline{e_R}\gamma_\mu \nu^c_L\right) + C^{(6)}_{\mathrm{VR}} \left(\overline{u_R}\gamma^\mu d_R\right) \left(\overline{e_R}\gamma_\mu \nu^c_L\right) + C^{(6)}_{\mathrm{SL}} \left(\overline{u_R} d_L\right) \left(\overline{e_L} \nu^c_L\right) + C^{(6)}_{\mathrm{SR}} \left(\overline{u_L} d_R\right) \left(\overline{e_L} \nu^c_L\right) + C^{(6)}_{\mathrm{T}} \left(\overline{u_L}\sigma^{\mu\nu} d_R\right) \left(\overline{e_L}\sigma_{\mu\nu} \nu^c_L\right) \Big] + h.c.$$

$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v} \Big[C^{(7)}_{\mathrm{VL}} \left(\overline{u_L}\gamma^\mu d_L\right) \left(\overline{e_L} \overleftrightarrow{\partial}_\mu \nu^c_L\right) + C^{(7)}_{\mathrm{VR}} \left(\overline{u_R}\gamma^\mu d_R\right) \left(\overline{e_L} \overleftrightarrow{\partial}_\mu \nu^c_L\right) \Big] + h.c.$$

$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5} \sum_i \Big[\Big(C^{(9)}_{i,R} \left(\overline{e_R} e^c_R\right) + C^{(9)}_{i,L} \left(\overline{e_L} e^c_L\right) \Big) \mathcal{O}_i + C^{(9)}_i \left(\overline{e}\gamma_\mu\gamma_5 e^c\right) \mathcal{O}^\mu_i \Big]$$



Distinguishing: Isotope Ratios

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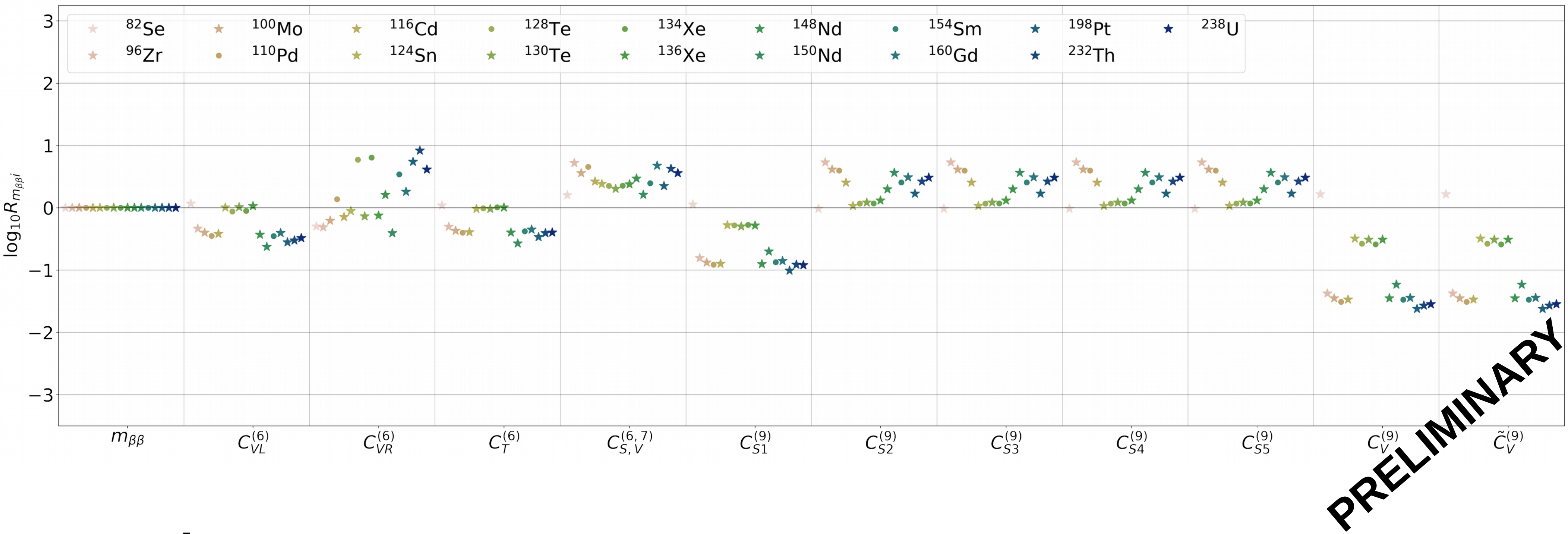


$$\mathcal{L}_{\Delta L=2}^{(6)} = \frac{2G_F}{\sqrt{2}}\Big[C_{\mathrm{VL}}^{(6)}\left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_R}\gamma_\mu \nu_L^c\right) + C_{\mathrm{VR}}^{(6)}\left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_R}\gamma_\mu \nu_L^c\right)$$
$$+ C_{\mathrm{SL}}^{(6)}\left(\overline{u_R} d_L\right)\left(\overline{e_L}\nu_L^c\right) + C_{\mathrm{SR}}^{(6)}\left(\overline{u_L} d_R\right)\left(\overline{e_L}\nu_L^c\right)$$
$$+ C_{\mathrm{T}}^{(6)}\left(\overline{u_L}\sigma^{\mu\nu} d_R\right)\left(\overline{e_L}\sigma_{\mu\nu}\nu_L^c\right)\Big] + h.c.$$

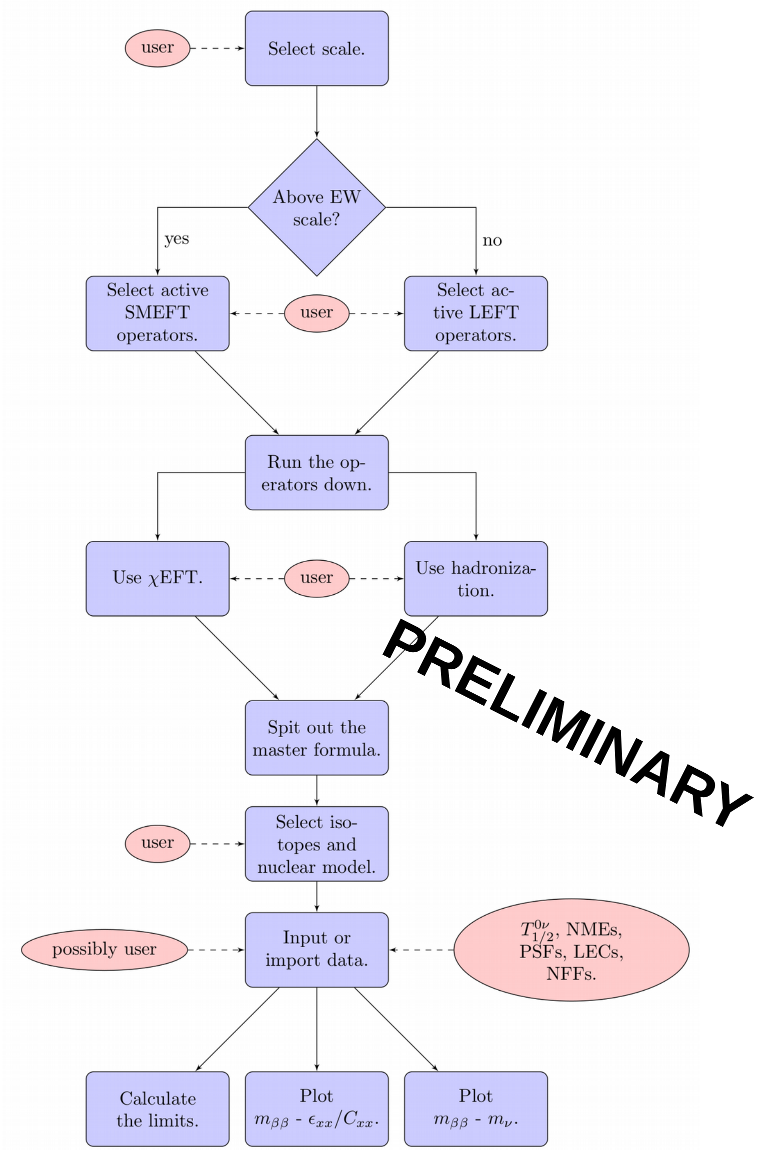
$$\mathcal{L}_{\Delta L=2}^{(7)} = \frac{2G_F}{\sqrt{2}v}\Big[C_{\mathrm{VL}}^{(7)}\left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{e_L}\overset{\leftrightarrow}{\partial}_\mu \nu_L^c\right) + C_{\mathrm{VR}}^{(7)}\left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{e_L}\overset{\leftrightarrow}{\partial}_\mu \nu_L^c\right)\Big] + h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(9)} = \frac{1}{v^5}\sum_i \Big[\Big(C_{i,R}^{(9)}\left(\overline{e_R} e_R^c\right) + C_{i,L}^{(9)}\left(\overline{e_L} e_L^c\right)\Big)\mathcal{O}_i + C_i^{(9)}\left(\bar{e}\gamma_\mu\gamma_5 e^c\right)\mathcal{O}_i^\mu\Big]$$

LG, M. Lindner, O. Scholer: in preparation

0νββ Tool

- user inputs:
  - scale + selection of operators
  - isotope(s), type of NMEs
- data inputs:
  - nuclear matrix elements
  - phase-space factors
  - low-energy constants or nucleon form factors
- outputs:
  - half-life formula for the given case
  - limits on selected couplings
  - $m_{\beta\beta}$ vs. m_ν plots, etc.
  - chosen contour plots showing correlations of different parameters

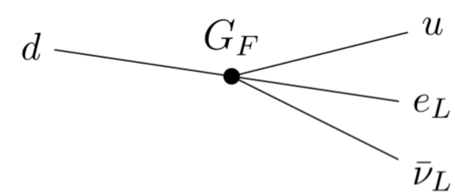


What about 2νββ?

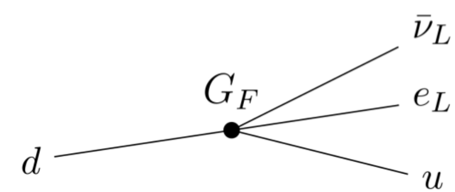
- searches for 0νββ decay growing – tonne-scale experiments planned
- → background: large amount of the 2νββ decay data collected ~ 10^5 – 10^6 events
- decay rate: $[\mathrm{T}_{1/2}^{2\nu\beta\beta}]^{-1} = G_{2\nu\beta\beta}|M_{2\nu\beta\beta}|^2$

phase space factor (lepton part)

nuclear matrix element (nucleon part)



$$\frac{\mathrm{d}\Gamma^{2\nu}}{\mathrm{d}E_{e_1}\mathrm{d}E_{e_2}\mathrm{d}\cos\theta} = \frac{\Gamma^{2\nu}}{2}\boxed{\frac{\mathrm{d}\Gamma^{2\nu}_{\mathrm{norm}}}{\mathrm{d}E_{e_1}\mathrm{d}E_{e_2}}}\left(1+\boxed{\kappa^{2\nu}(E_{e_1},E_{e_2})}\cos\theta\right)$$



- New Physics in 2νββ decay? What would it look like?
  - right-handed currents? F. F. Deppisch, LG, F. Simkovic: PRL 125 [2003.11836]
  - neutrino self-interactions? F. F. Deppisch, LG, W. Rodejohann, X. Xu: PRD RC 102 [2004.11919]
  - sterile neutrinos or light fermions? P. D. Bolton, F. F. Deppisch, LG, F. Simkovic: PRD 103 [2011.13387]
    M. Agostini, E. Bossio, A. Ibarra, X. Marcano: PLB 815 [2012.09281]

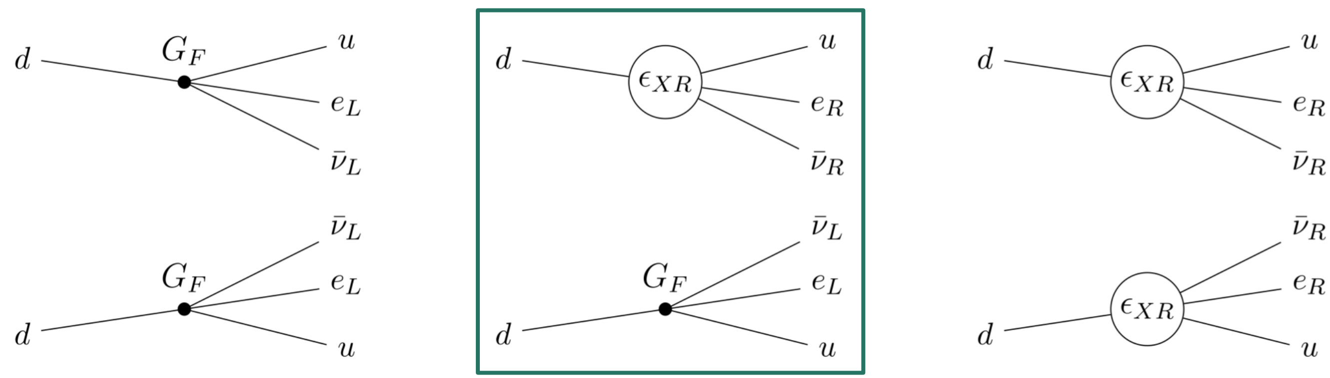
Exotic 2νββ Decay – RHCs

- 2νββ decay in presence of right-handed currents? → Lagrangian:

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

with $j^\mu_{L,R} = \bar{e}\gamma^\mu(1 \mp \gamma_5)\nu,\ J^\mu_{L,R} = \bar{u}\gamma^\mu(1 \mp \gamma_5)d$

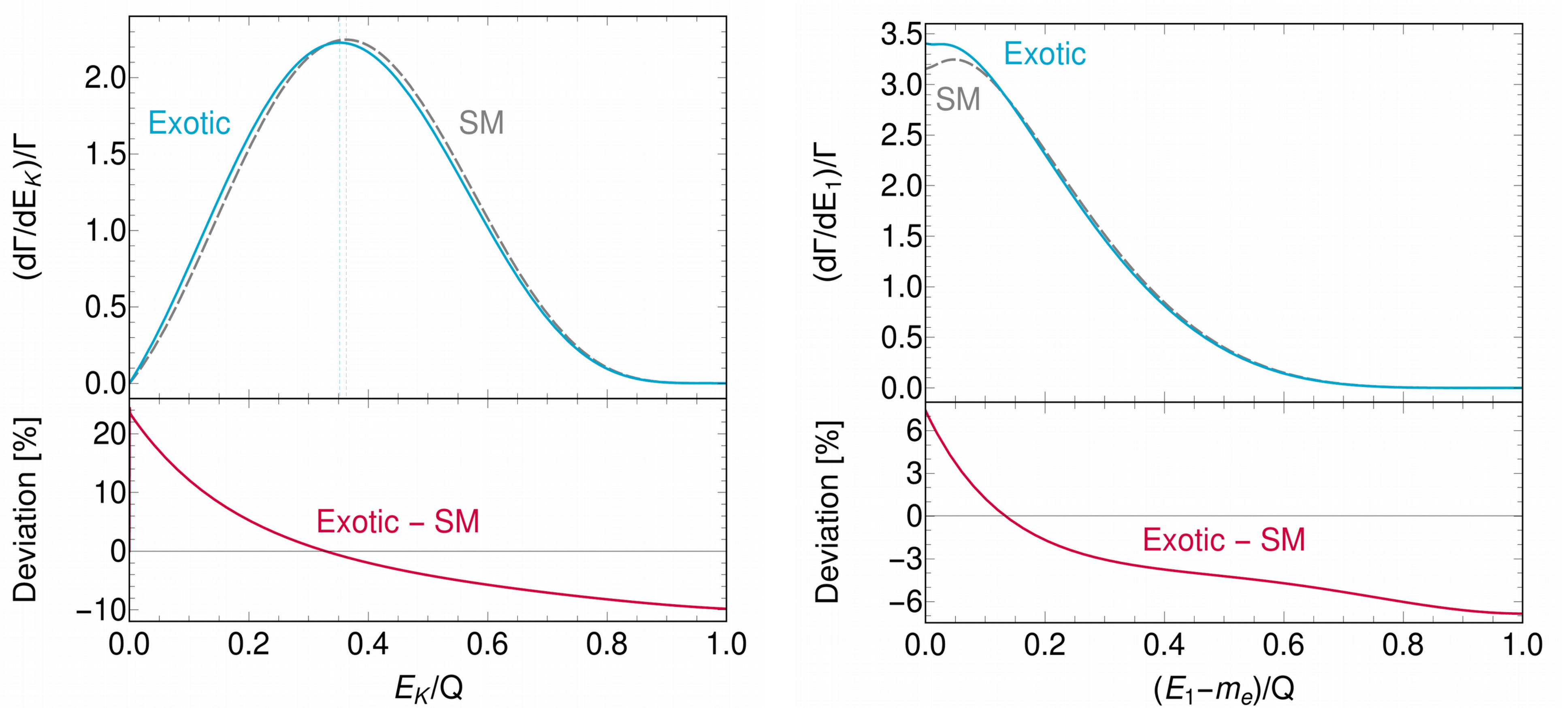
- contributions:



- take the one linear in exotic effective coupling ϵ_{XR}, calculate the observables and get the bound imposed by the experimental data
- rate: $[T_{1/2}^{2\nu\beta\beta}]^{-1} = \epsilon_{XR}^2 G_{2\nu\beta\beta} |M_{2\nu\beta\beta}|^2$
- here, results for ^{100}Mo, but other isotopes similar

Electron Energy Distribution

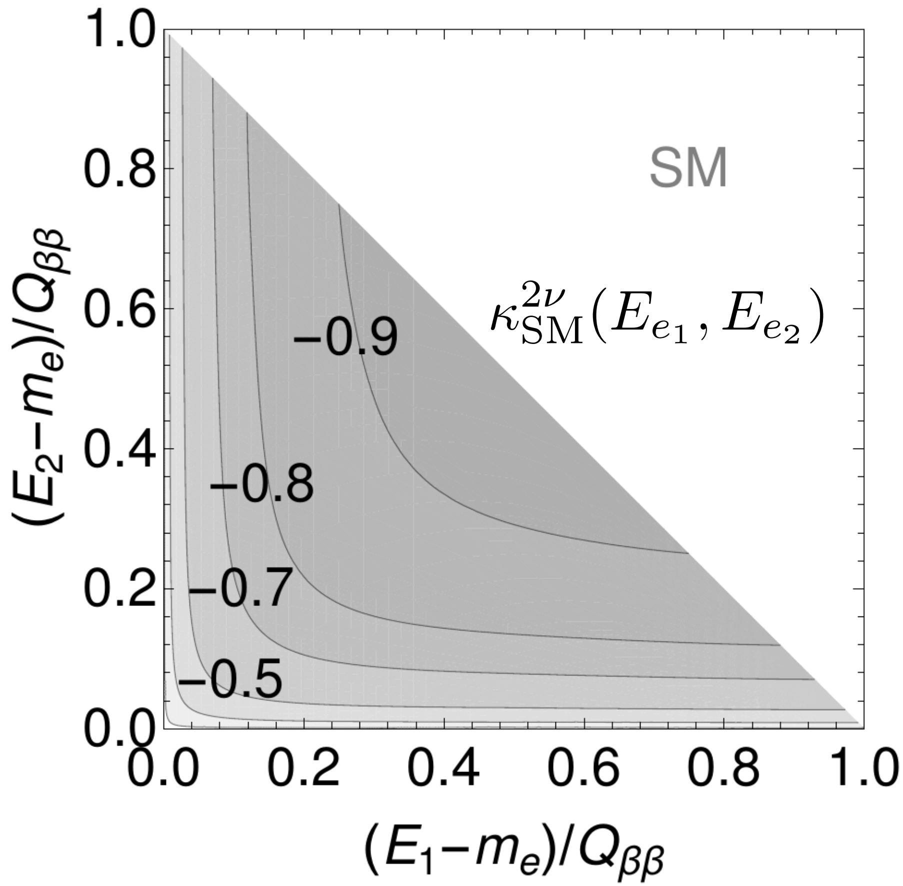
- $2\nu\beta\beta$ decay (both the SM and the exotic RHC-induced contributions) distribution in total kinetic (left) and single electron kinetic (right) energy

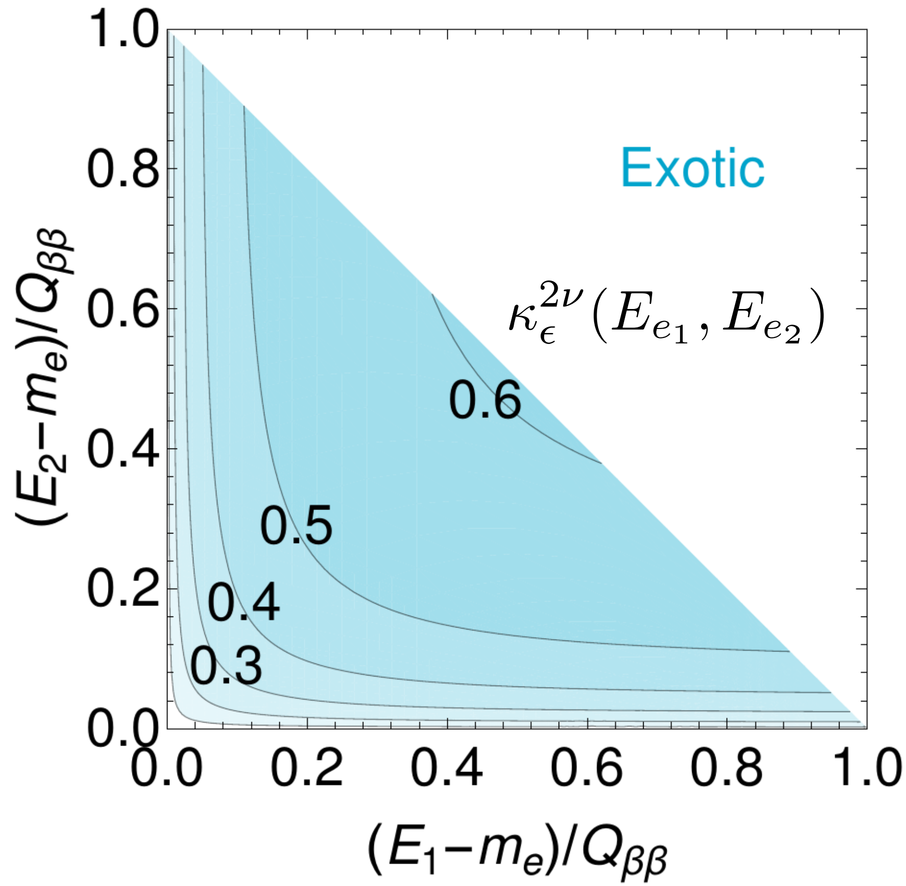


F. F. Deppisch, LG, F. Simkovic: PRL 125 [2003.11836]

Electron Angular Correlation

- angular correlation of the electrons in the SM 2νββ decay (left) and the exotic 2νββ decay induced by right-handed lepton currents (right)

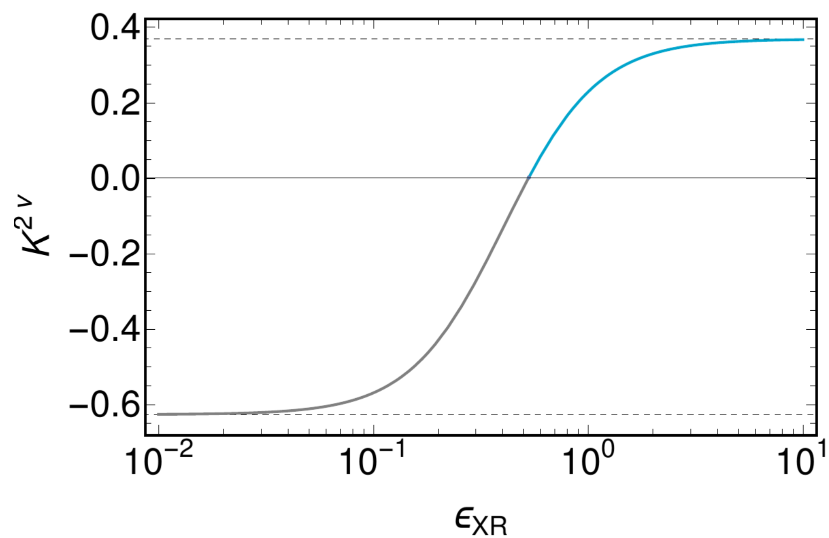




F. F. Deppisch, LG, F. Simkovic: PRL 125 [2003.11836]

Bound on ϵ_{XR} Coupling

- total rate – nuclear matrix elements not accurate enough
- electron energy distribution – small deviations, could be probed, but certain degeneracy given by nuclear structure effects
- best option: measure the angular correlation of the emitted electrons and look for the forward-backward asymmetry
- possible at NEMO-3 experiment using ^{100}Mo (or in future at SuperNEMO)
- insensitive of the overall rate
- largely insensitive to the NMEs



- NMEs: QRPA used in our case, but very similar results expected to be obtained with other nuclear structure models

Bound on ϵ_{XR} Coupling

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- angular distribution: $\frac{\mathrm{d}\Gamma^{2\nu}}{\mathrm{d}\cos\theta} = \frac{\Gamma^{2\nu}}{2}\left(1 + K^{2\nu}\cos\theta\right)$

  with correlation factor: $K^{2\nu} \approx K^{2\nu}_{\mathrm{SM}} + \alpha\,\epsilon^2_{XR}$, for ^{100}Mo: $\alpha \approx 6.1$

- forward-backward asymmetry: $A^{2\nu}_{\theta} = \frac{N_{\theta>\pi/2} - N_{\theta<\pi/2}}{N_{\theta>\pi/2} + N_{\theta<\pi/2}} = \frac{1}{2}K^{2\nu}$

- estimated accuracy of NEMO-3: $K^{2\nu}_{\mathrm{SM}} = -0.63 \pm 0.0027$

  → bound on the effective coupling at 90% CL: $\boldsymbol{\epsilon_{XR} \lesssim 2.7 \times 10^{-2}}$

- more stringent limit than the one obtained from the standard beta decay measurements

- SuperNEMO would further improve this bound to: $\epsilon_{XR} \lesssim 4.8 \times 10^{-3}$

- estimates only, a dedicated experimental analysis necessary

Exotic 2νββ – Sterile Neutrino

- idea: one of the neutrinos emitted in the decay is sterile
- consider either mixing with the active neutrinos, or right-handed current

$$\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left[(1+\delta_{\mathrm{SM}}) j_L^{\mu} J_{L\mu} + V_{eN} j_L^{N\mu} J_{L\mu} + \epsilon_{LR} j_R^{N\mu} J_{L\mu} + \epsilon_{RR} j_R^{N\mu} J_{R\mu} \right] + \mathrm{h.c.}$$

- total differential 2νββ decay rate – incoherent sum of the sterile neutrino and SM rates for a given sterile mass m_N and total electron kinetic energy E_K

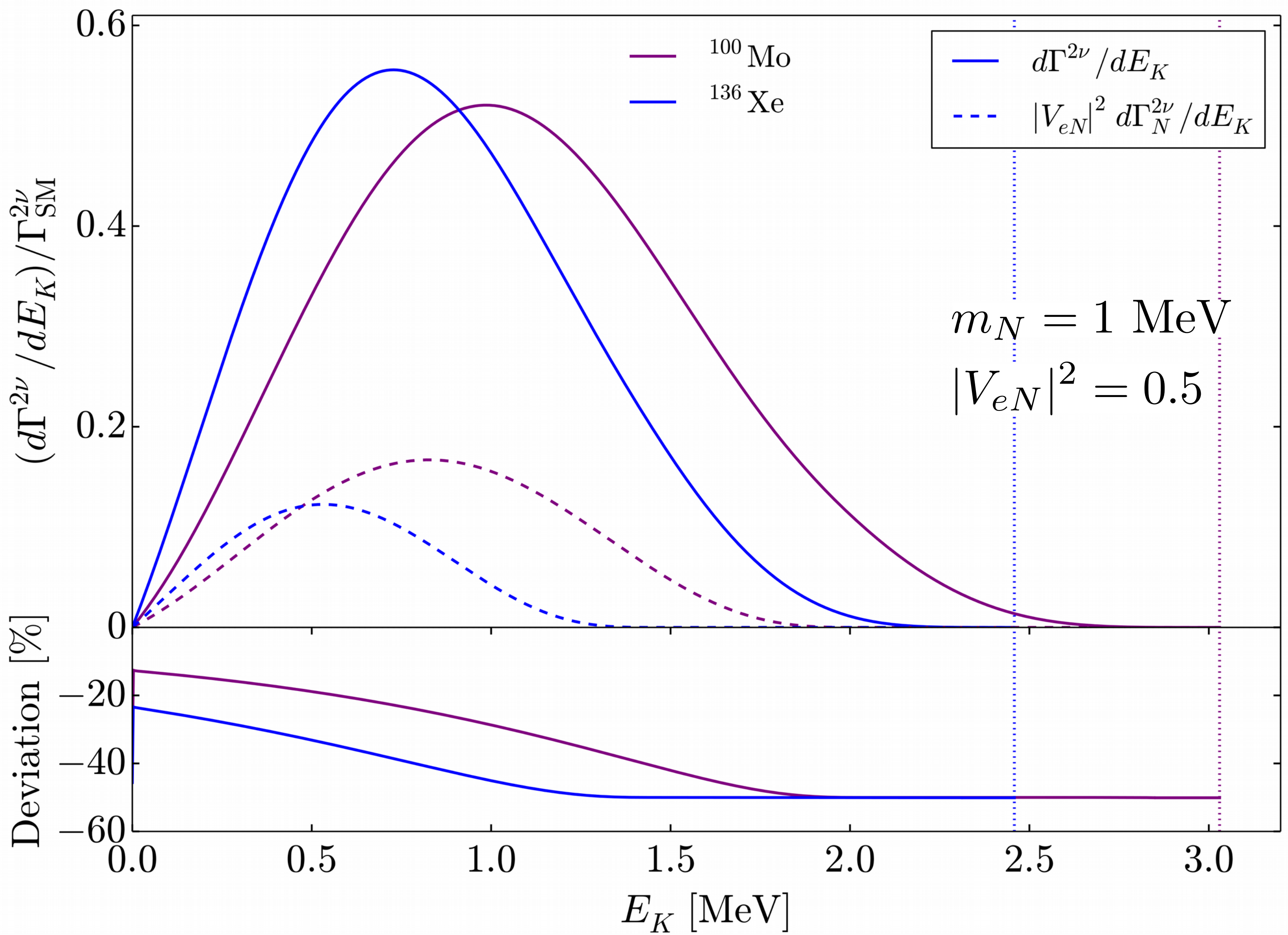
$$\frac{d\Gamma^{2\nu}(\boldsymbol{\xi})}{dE_K} = (1-|V_{eN}|^2)^2 \frac{d\Gamma^{2\nu}_{\mathrm{SM}}}{dE_K} + (1-|V_{eN}|^2)|V_{eN}|^2 \frac{d\Gamma^{2\nu}_N(m_N)}{dE_K}$$

- similar expression for the case with the right-handed coupling

$$\frac{d\Gamma^{2\nu}(\boldsymbol{\xi})}{dE_K} = \frac{d\Gamma^{2\nu}_{\mathrm{SM}}}{dE_K} + |\epsilon_{XR}|^2 \frac{d\Gamma^{2\nu}_N(m_N)}{dE_K}$$

- again: right-handed current modifies also the angular correlation

Exotic 2νββ – Sterile Neutrino



P. D. Bolton, F. F. Deppisch, LG, F. Simkovic: PRD 103 [2011.13387]

Exotic 2νββ – Sterile Neutrino

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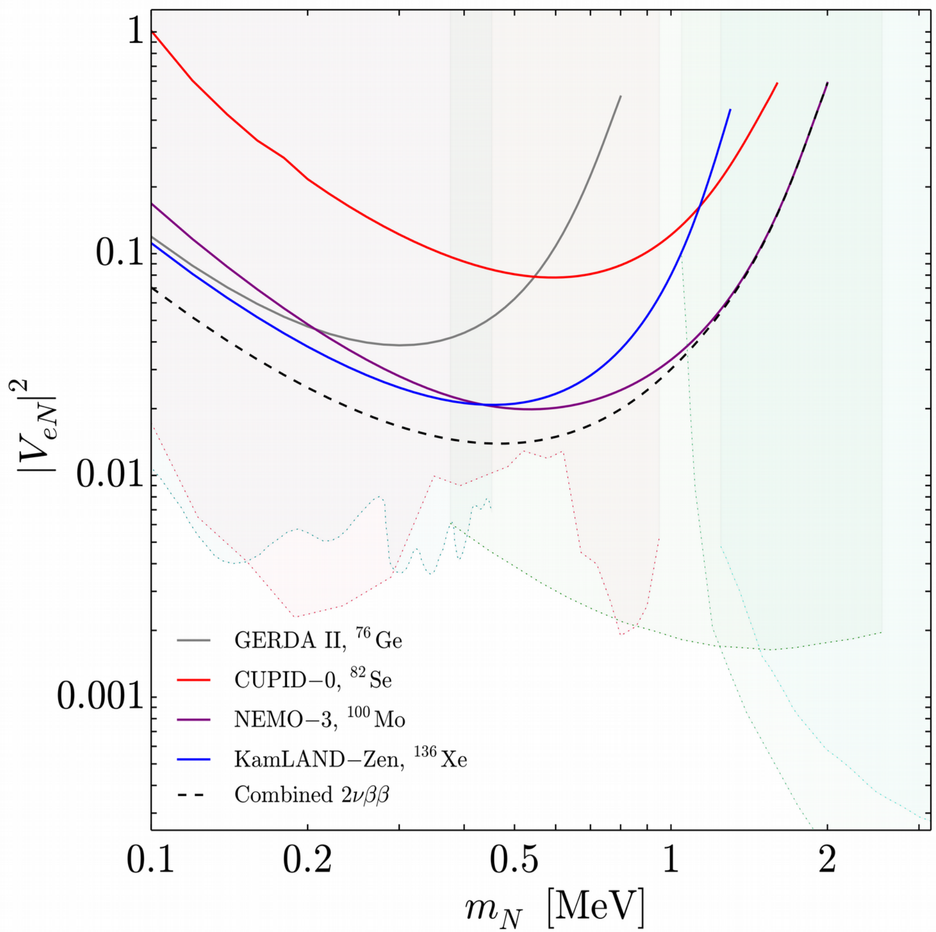

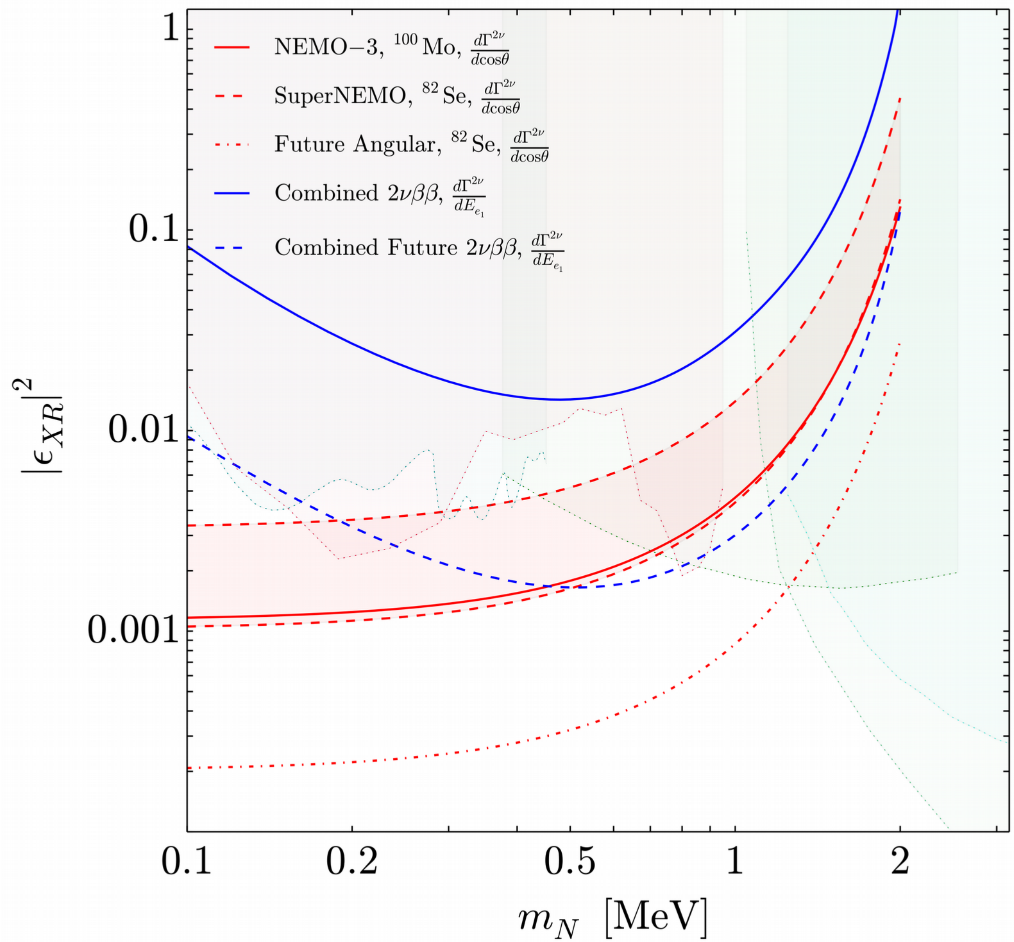

P. D. Bolton, F. F. Deppisch, LG, F. Simkovic: PRD 103 [2011.13387]

νSI & Hubble Tension

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- observations: discrepancy between Cosmic Microwave Background (CMB) and local measurements (redshifts of Type Ia supernovae) of the Hubble constant
- → “Hubble tension” of about 4σ
- if correct, new cosmology or particle physics
- possible solution: neutrino self-interaction (νSI)
- νSI would inhibit the free streaming of neutrinos in the early Universe
- effectively: $G_S\,(\nu\nu)\,(\nu\nu)$, where G_S should be much larger than G_F
- strong interaction, but only neutrinos involved → not easy to test in a lab, light scalar mediator probed by meson decays, Z invisible decay, LHC searches, supernova neutrinos … what about double beta decay?

N. Blinov, K. J. Kelly, G. Z. Krnjaic, S. D. McDermott: PRL 123 [1905.02727]

K.-F. Lyu, E. Stamou, Emmanuel, L.-T. Wang: PRD 103 [2004.10868]

ββ Decay Induced by νSI

- previous literature: indirect limit on νSI from neutrinoless double beta decay with Majoron emission   K. Blum, Y. Nir, M. Shavit: PLB 785 [1802.08019]

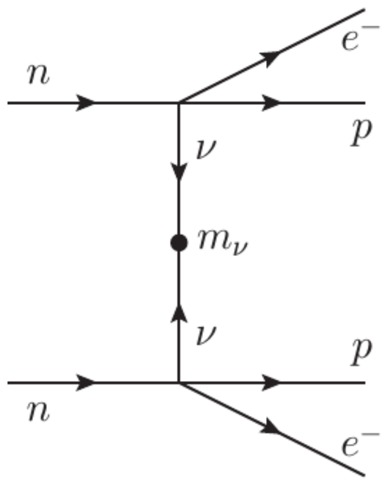
  T. Brune, H. Paes: PRD 99 [1808.08158]

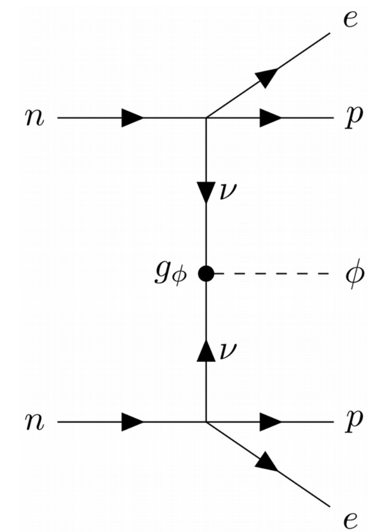
- assumed: scalar emitted, thus its mass constrained the Q value of the decay

- bound on ννϕ: $g_\phi \lesssim 10^{-4} - 10^{-5}$

  → for m_ϕ = 1 MeV: $G_S \lesssim (10 - 10^3)\, G_F$

- the limit does not apply for m_ϕ > Q and assumes that a light scalar is mediated





- our approach: effective interaction, derive a bound independent of the undelying physics and applicable for m_ϕ > Q

ββ Decay Induced by νSI

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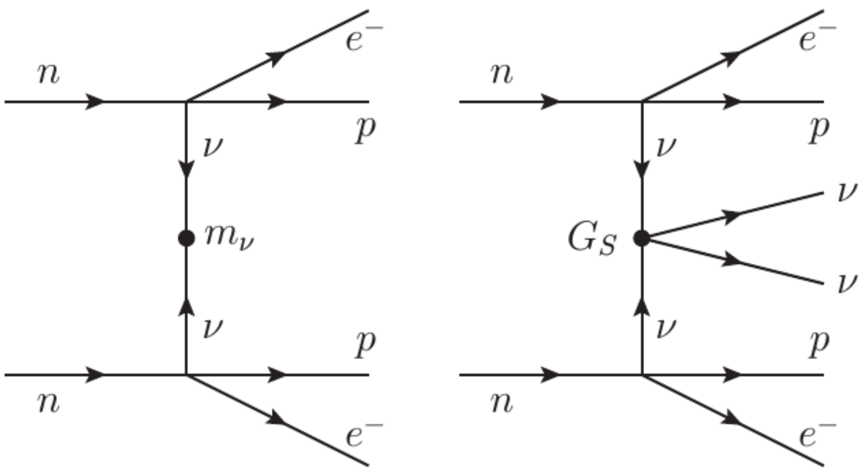
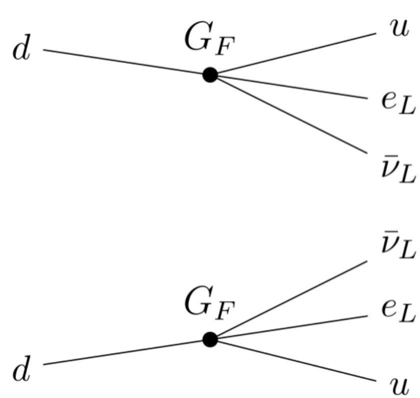
- idea: effective νSI $G_S\,(\nu\nu)\,(\nu\nu)$ would induce a new, exotic contribution to double beta decay – see the figure:



- rate: $\Gamma_{\nu\mathrm{SI}} = \left|\frac{G_S m_e}{2R}\right|^2 \mathcal{G}_{\nu\mathrm{SI}} |\mathcal{M}_{0\nu}|^2$
- nuclear matrix element approximately same as for 0νββ decay
- phase space ~ 2νββ decay

$$\mathcal{G}_{\nu\mathrm{SI}} = \frac{2c_{\nu\mathrm{SI}}}{15} \int dp_1 dp_2 p_1^2 p_2^2 (Q - T_{12})^5 F^2(p_1, p_2)$$

→ νSI could affect 2νββ decay – total rate, but also spectra



- compare to 2νββ rate: $\Gamma_{2\nu} = G_{2\nu} |M_{2\nu}|^2$

F. F. Deppisch, LG, W. Rodejohann, X. Xu: PRD RC 102 [2004.11919]

ββ Decay Induced by νSI

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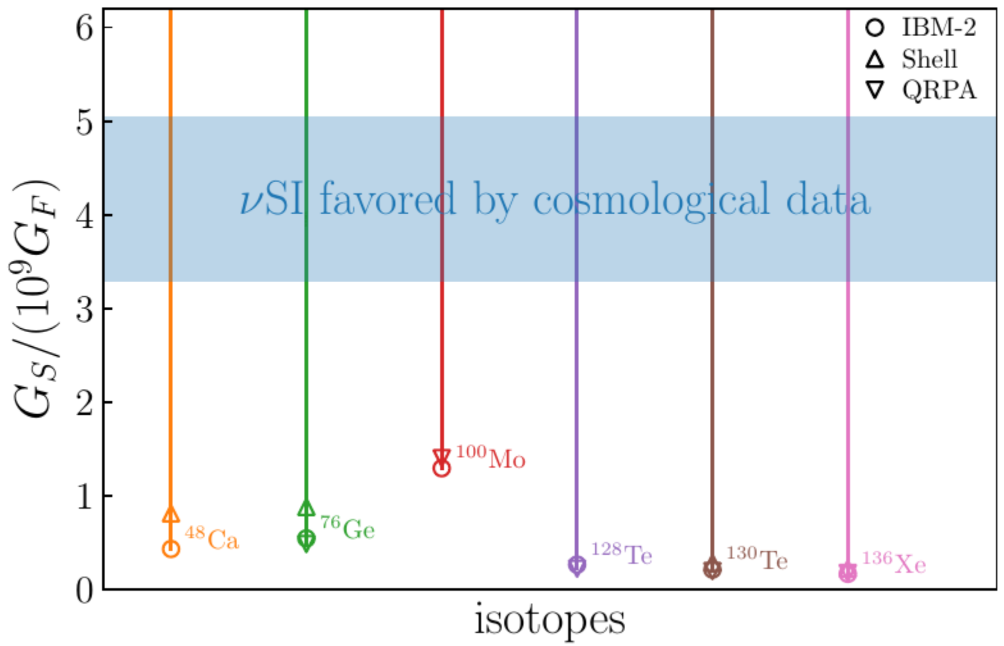
- using condition $\Gamma_{\nu\mathrm{SI}}/\Gamma^{\mathrm{ex}}_{2\nu} < 1$ effective self-interaction G_S can be constrained using the predicted total rate
- result: νSI preferred by cosmology is disfavoured by 2νββ decay experimental data



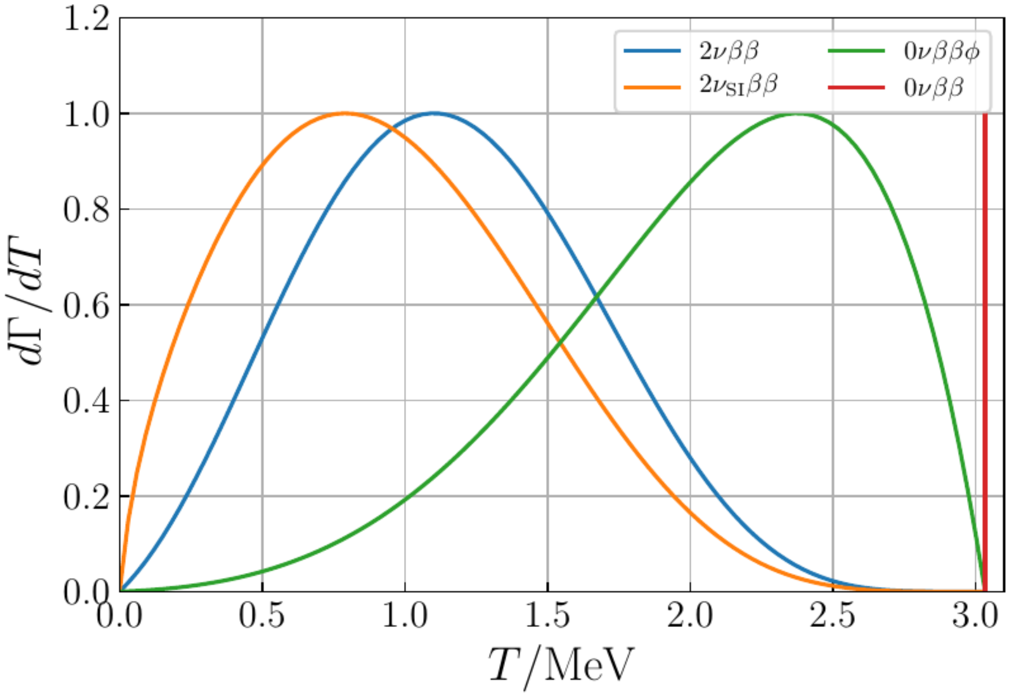
	^{48}Ca	^{76}Ge	^{136}Xe	^{100}Mo	^{128}Te	^{130}Te
Q/MeV	4.263 [46]	2.039 [47]	2.458 [48]	3.034 [47]	0.8659 [49]	2.527 [50]
$T^{2\nu}_{1/2}$/year	5.30×10^{19}	1.88×10^{21}	2.17×10^{21}	6.88×10^{18}	2.25×10^{24}	7.91×10^{20}
$(\Gamma_{\nu\mathrm{SI}})^{-1}$/year	2.52×10^{18}	1.42×10^{20}	1.55×10^{19}	2.94×10^{18}	4.04×10^{22}	9.08×10^{18}
$\Gamma_{\nu\mathrm{SI}}/\Gamma^{\mathrm{ex}}_{2\nu}$	78.6	49.5	528	8.76	209	326
$G_S/G_F <$	4.32×10^{8}	5.44×10^{8}	1.67×10^{8}	1.29×10^{9}	2.65×10^{8}	2.12×10^{8}

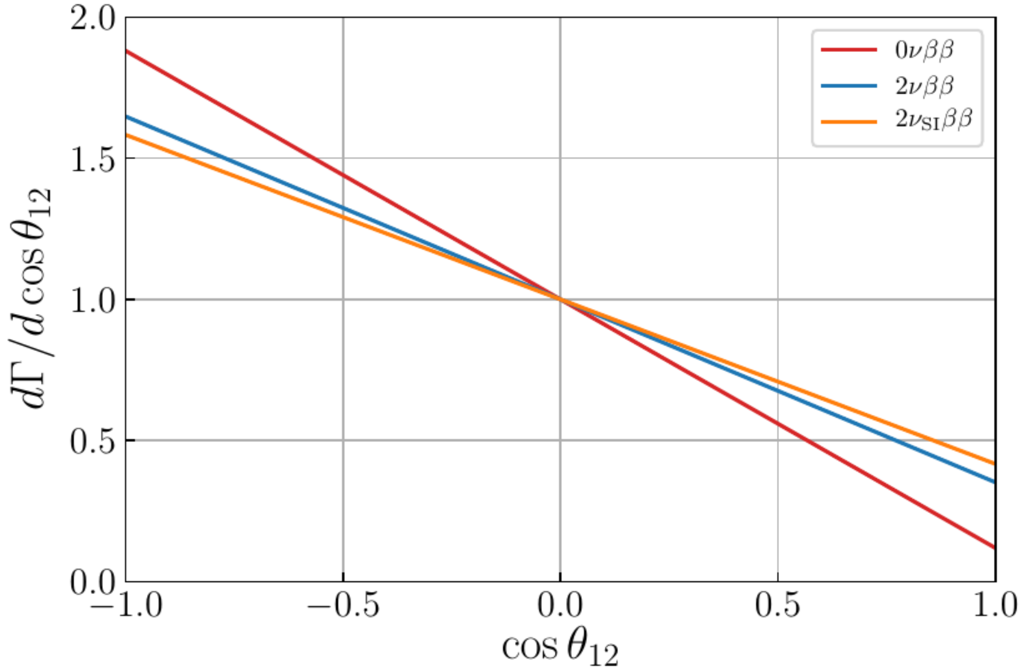
F. F. Deppisch, LG, W. Rodejohann, X. Xu: PRD RC 102 [2004.11919]

ββ Decay Induced by νSI

- for energy dependent G_s and $m_\phi \gtrsim Q$: total kinetic energy distribution of the emitted electrons is distorted, angular correlation also affected

  → possibly by an order of magnitude more stringent limit than from the total rate





F. F. Deppisch, LG, W. Rodejohann, X. Xu: PRD RC 102 [2004.11919]

Conclusion

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- $0\nu\beta\beta$ – interface of particle, nuclear, atomic physics
- a variety of different mechanisms besides the standard light neutrino exchange can contribute to $0\nu\beta\beta$ → effective description
- to investigate the underlying new particle physics – necessary to distinguish among different $0\nu\beta\beta$ mechanisms – difficult → complementarity
- combining various contributions → involved, tedious calculations with a variety of inputs → $0\nu\beta\beta$ Tool on the way
- observation of $0\nu\beta\beta$ decay is the primary goal of the searches, but the collected $2\nu\beta\beta$ decay data can also probe new physics
- $2\nu\beta\beta$ decay can put constraints e.g. on right-handed currents, sterile neutrinos, neutrino self-interactions

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Thank You for attention!