Neutrinoless Double Beta Decay of Atomic Nuclei

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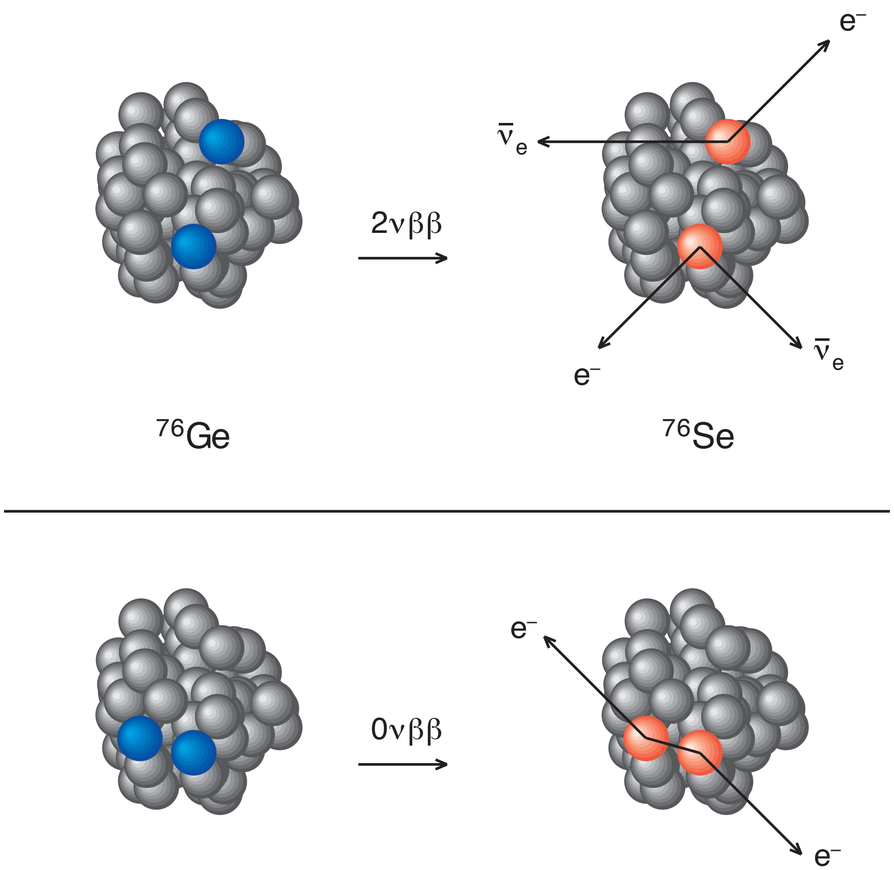
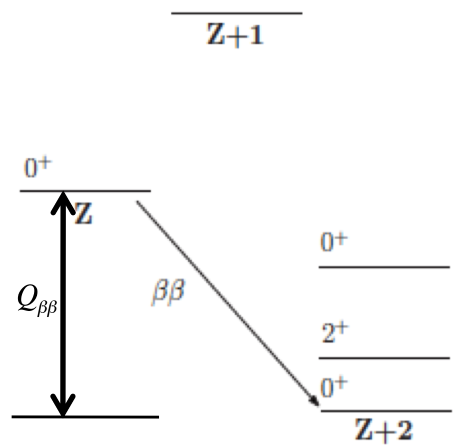
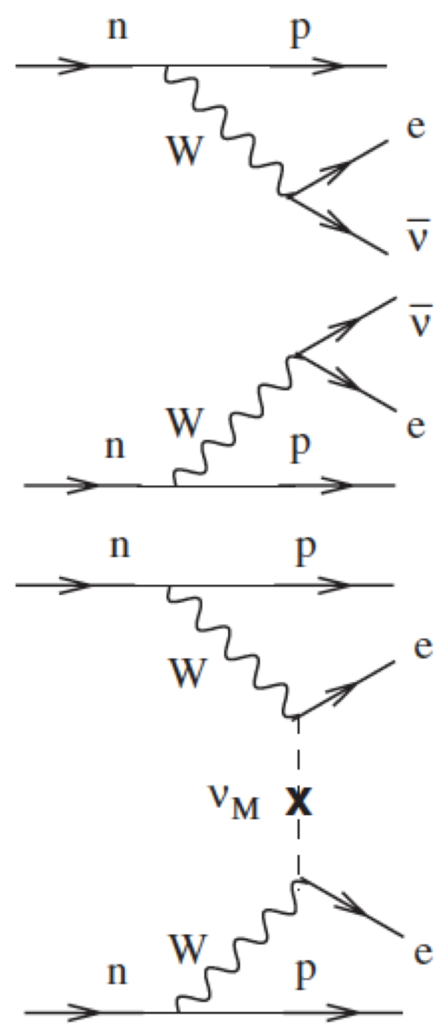
➢**Support from DOE grant DE-SC0015376 is acknowledged**

Classical Double Beta Decay Problem







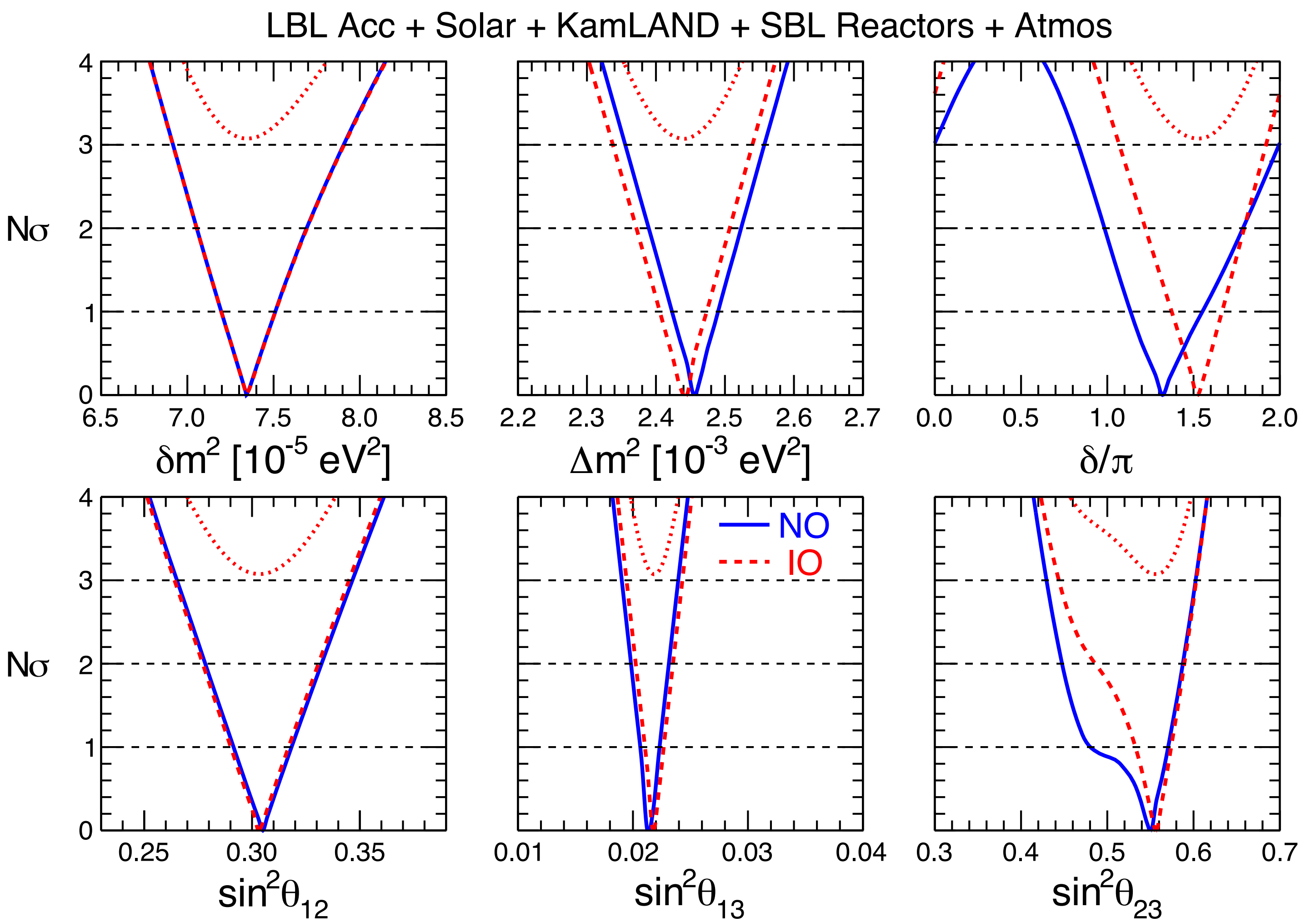
$$\langle m_{\beta\beta} \rangle = \left| \sum_k m_k U_{ek}^2 \right|$$

$$T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta}) \left[M^{0\nu}(0^+) \right]^2 \left(\frac{< m_{\beta\beta} >}{m_e} \right)^2$$

$$\nu_e(x) = \sum_i U_{ei} \nu_i(x)$$

$$\left| \nu_e \right\rangle = \sum_i U_{ei}^* \left| \nu_i \right\rangle$$

Neutrino oscillations parameters



Bari group:

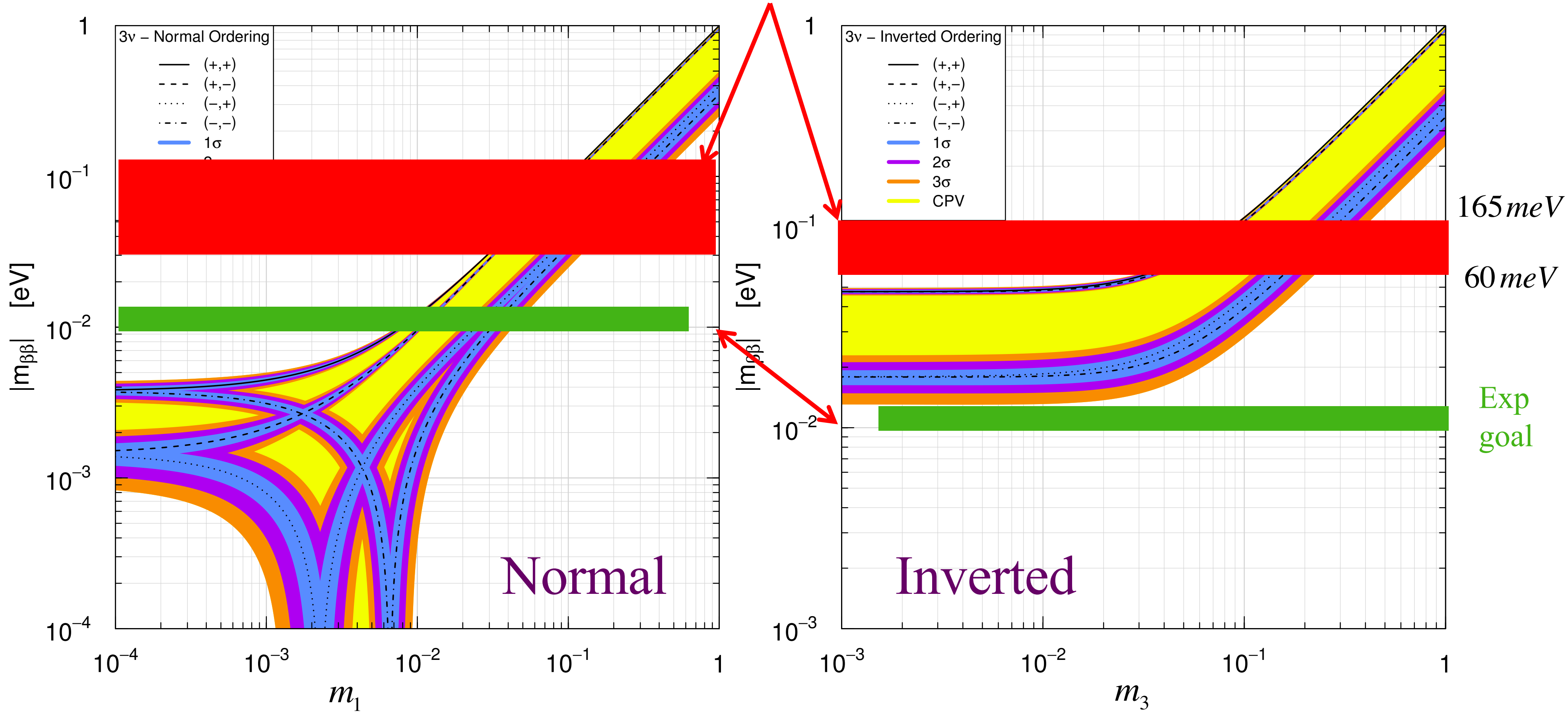
arxiv.org/1804.09678
Prog. Part. Nucl. Phys. 102, 48 (2018)

1806.11051 review: Normal ordering favored at 3.5σ !!

Neutrino ββ effective mass

arxiv:1507.08204

KamLAND – Zen, PRL 117, 082503 (2016) : ^{136}Xe



$$\left|m_{\beta\beta}\right| = \left|\sum_{k=1}^{3} m_k U_{ek}^2\right| = \left|c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

$$\Leftarrow T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta})\left[M^{0\nu}(0^+)\right]^2 (\eta_{0\nu})^2$$

$$\phi_2 = \alpha_2 - \alpha_1 \qquad \phi_3 = -\alpha_1 - 2\delta$$

$$\eta_{0\nu} = \frac{\left|m_{\beta\beta}\right|}{m_e}$$

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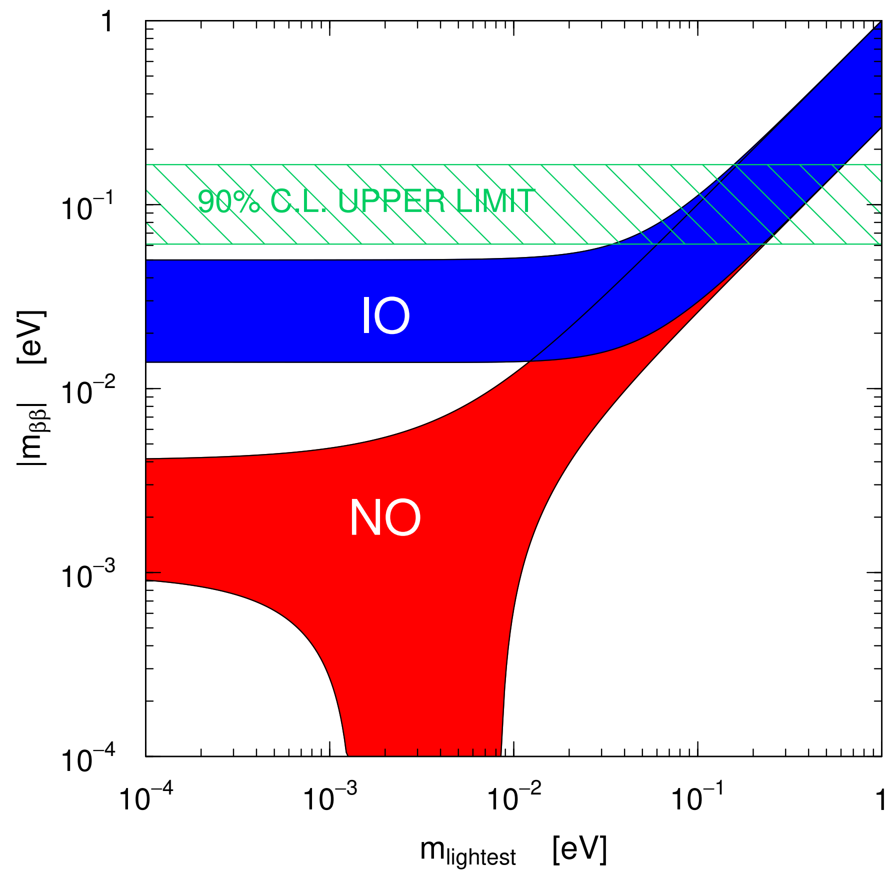
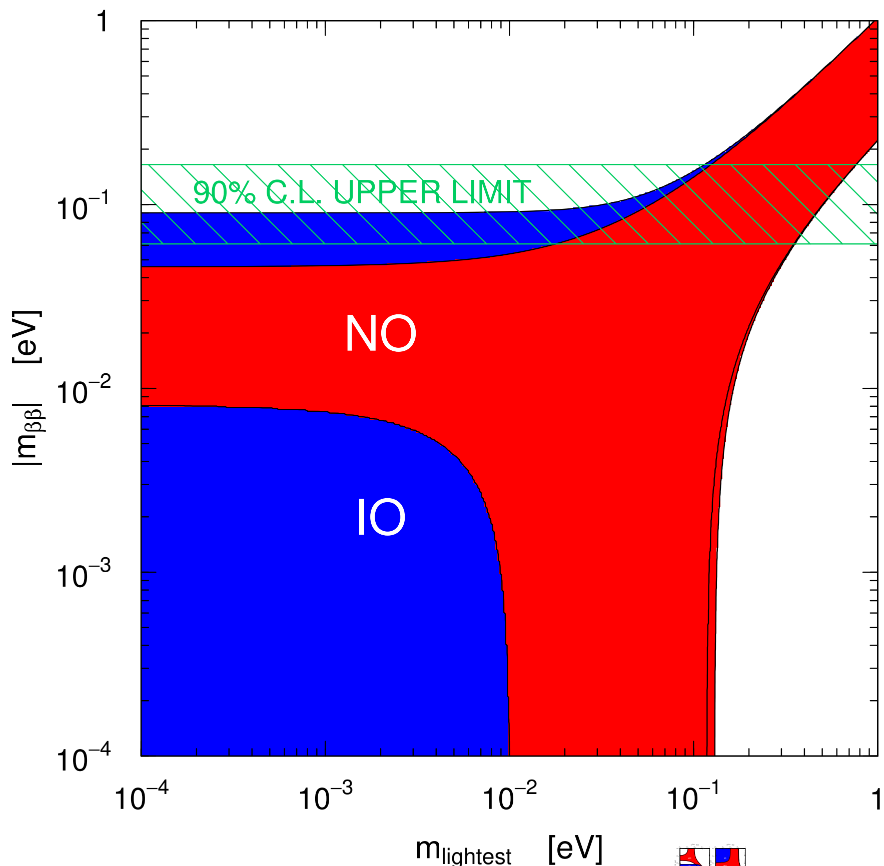
$0\nu\beta\beta$ decay mass mechanism

3 neutrino flavors



3+1(sterile) neutrino flavors



$$\left|m_{\beta\beta}\right| = \left|\sum_{k=1}^{3} m_k U_{ek}^2\right| = \left|c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

$$\Leftarrow T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta})\left[M^{0\nu}(0^+)\right]^2 (\eta_{0\nu})^2$$

$$\phi_2 = \alpha_2 - \alpha_1 \qquad \phi_3 = -\alpha_1 - 2\delta$$

$$\eta_{0\nu} = \frac{\left|m_{\beta\beta}\right|}{m_e}$$

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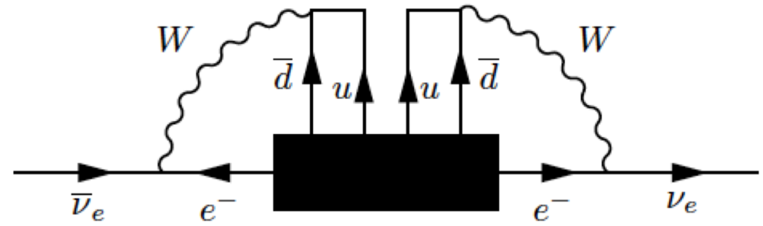
The Black Box Theorems

Black box I (electron neutrino)

J. Schechter and J.W.F Valle, PRD 25, 2951 (1982)

E. Takasugi, PLB 149, 372 (1984)

J.F. Nieves, PLB 145, 375 (1984)



0νββ observed at some level ⇔
(i) Lepton number conservation is violated by 2 units.
(ii) Electron neutrinos are Majorana fermions (with m > 0).

However:

M. Duerr et al, JHEP 06 (2011) 91

$$\left(\delta m_{\nu_e}\right)_{BB} \sim 10^{-24}\, eV << \sqrt{\left|\Delta m^2_{32}\right|} \approx 0.05\, eV$$

Black box II (all flavors + oscillations)

M. Hirsch, S. Kovalenko, I. Schmidt, PLB 646, 106 (2006)

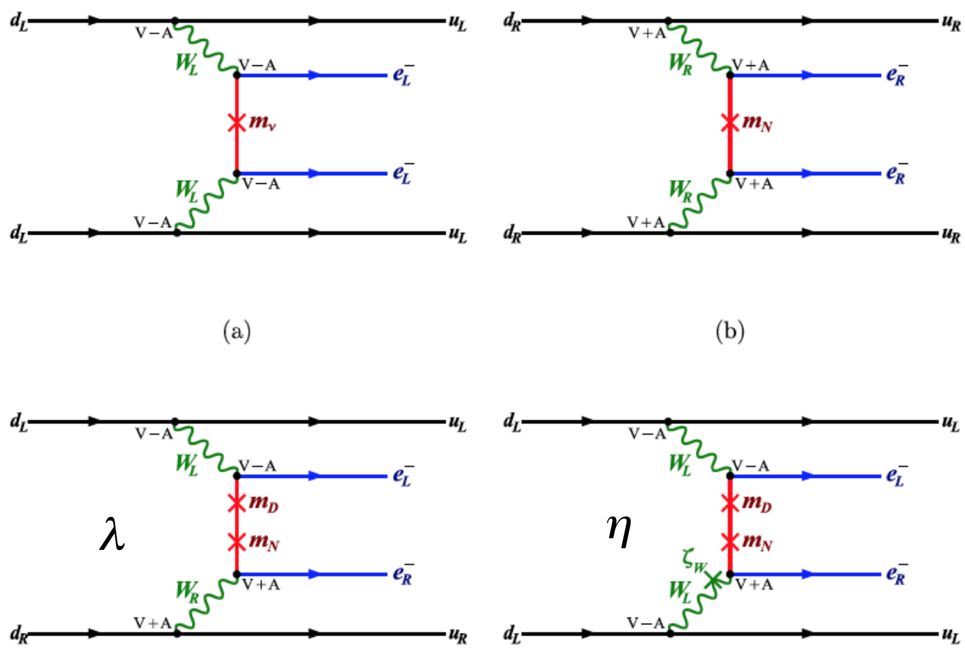
0νββ observed at some level ⇔
(i) Lepton number conservation is violated by 2 units.
(ii) Neutrinos are Majorana fermions.

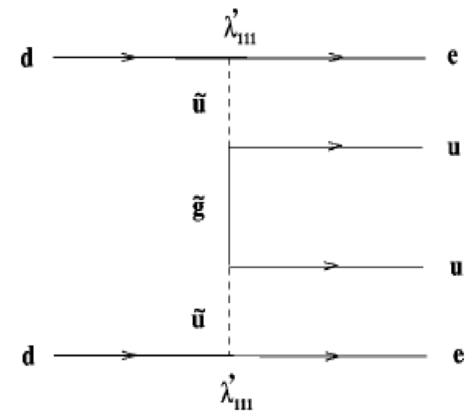
$$(iii)\quad \left\langle m_{\beta\beta}\right\rangle = \left|\sum_{k=1}^{3} m_k U^2_{ek}\right| = \left|c^2_{12}c^2_{13}m_1 + c^2_{13}s^2_{12}m_2 e^{i\phi_2} + s^2_{13}m_3 e^{i\phi_3}\right| > 0$$

Regardless of the dominant 0νββ mechanism!

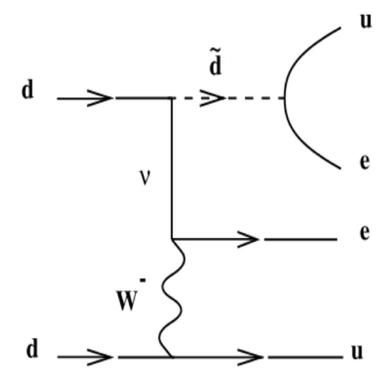
Other models: Left-Right symmetric model and SUSY R-parity violation

DAS *et al.* PHYSICAL REVIEW D 86, 055006 (2012)





Gluino exchange



Squark exchange

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{01} g_A^4 \left| \eta_{0\nu} M_{0\nu} + \left(\eta^L_{N_R} + \eta^R_{N_R}\right) M_{0N} + \eta_{\tilde{q}} M_{\tilde{q}} + \eta_{\lambda'} M_{\lambda'} + \eta_\lambda X_\lambda + \eta_\eta X_\eta \right|^2 .$$

(e)

M. Horoi, A. Neacsu, PRD 93, 113014 (2016)

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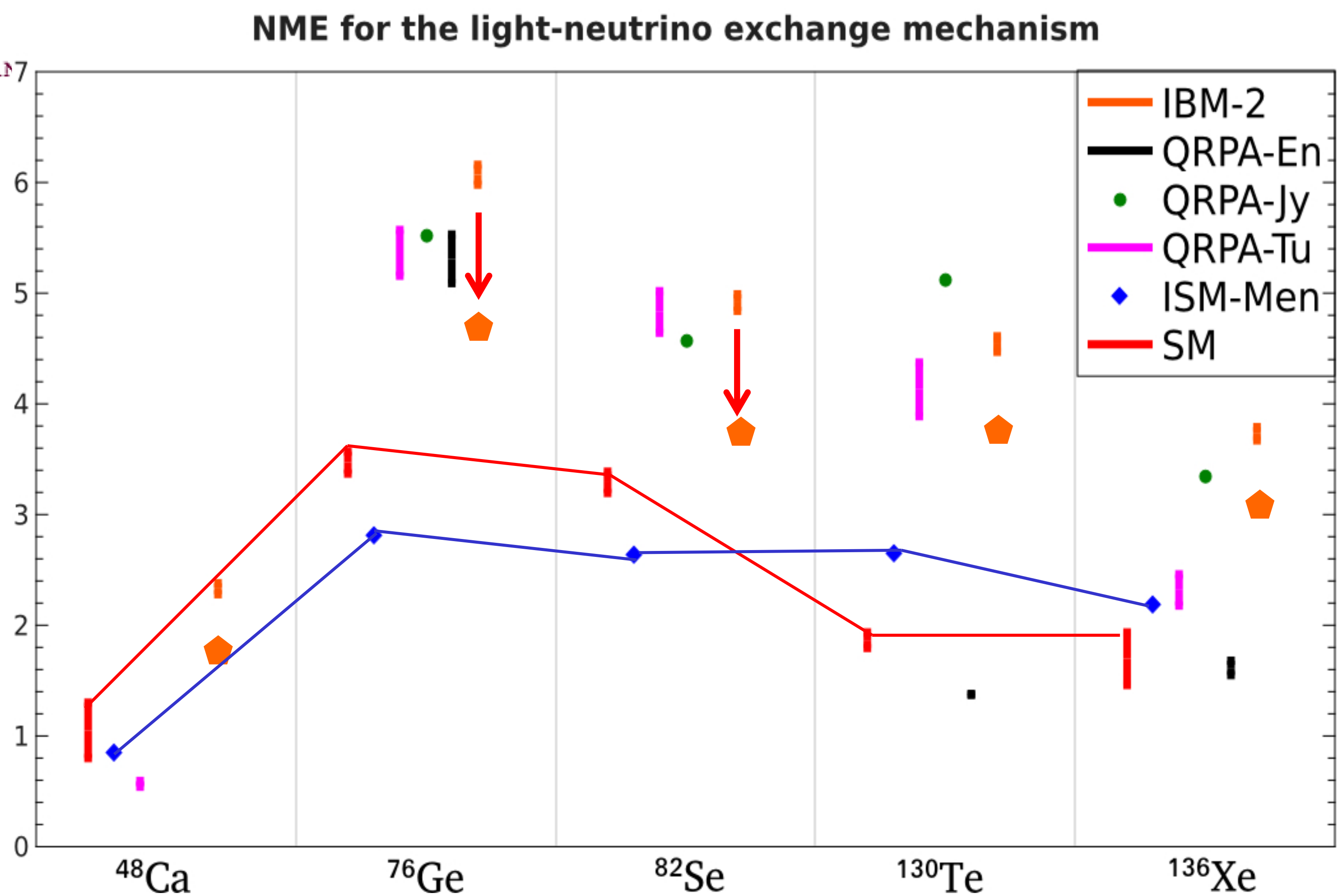

IBA-2 J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **87**, 014315 (2013). → IBM-2 PRC **91**, 034304 (2015)

QRPA-En M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).

QRPA-Jy J. Suhonen, O. Civitarese, Phys. NPA **847** 207–232 (2010).

QRPA-Tu A. Faessler, M. Gonzalez, S. Kovalenko, and F. Simkovic, arXiv:**1408.6077**

ISM-Men J. Menéndez, A. Poves, E. Caurier, F. Nowacki, NPA **818** 139–151 (2009).
SM M. Horoi et. al. PRC **88**, 064312 (2013), PRC **89**, 045502 (2014), PRC **89**, 054304 (2014), PRC **90**, 051301(R) (2014), PRC **91**, 024309 (2015), PRL **110**, 222502 (2013), PRL **113**, 262501(2014).

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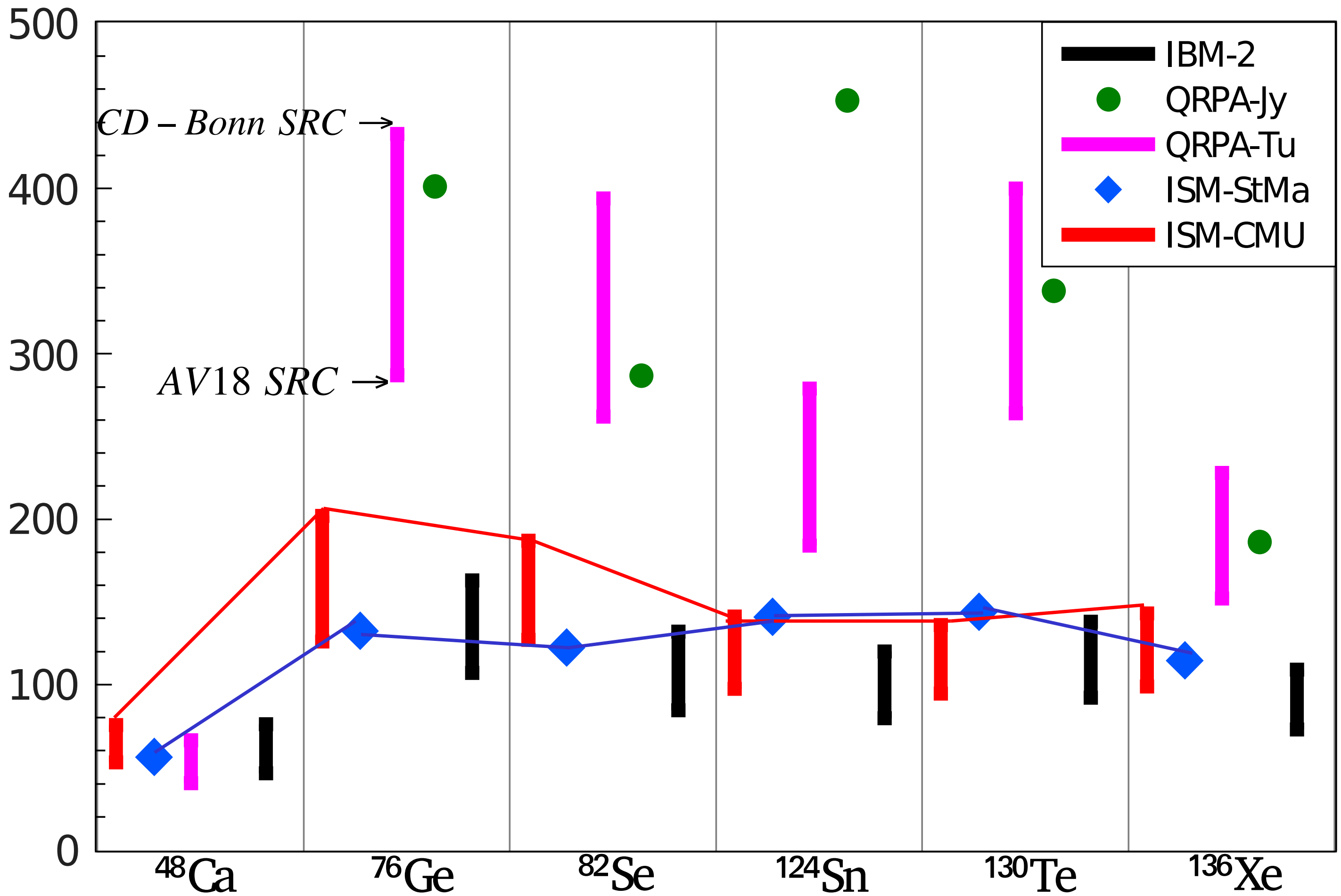
Heavy neutrino-exchange NME M_{0N}



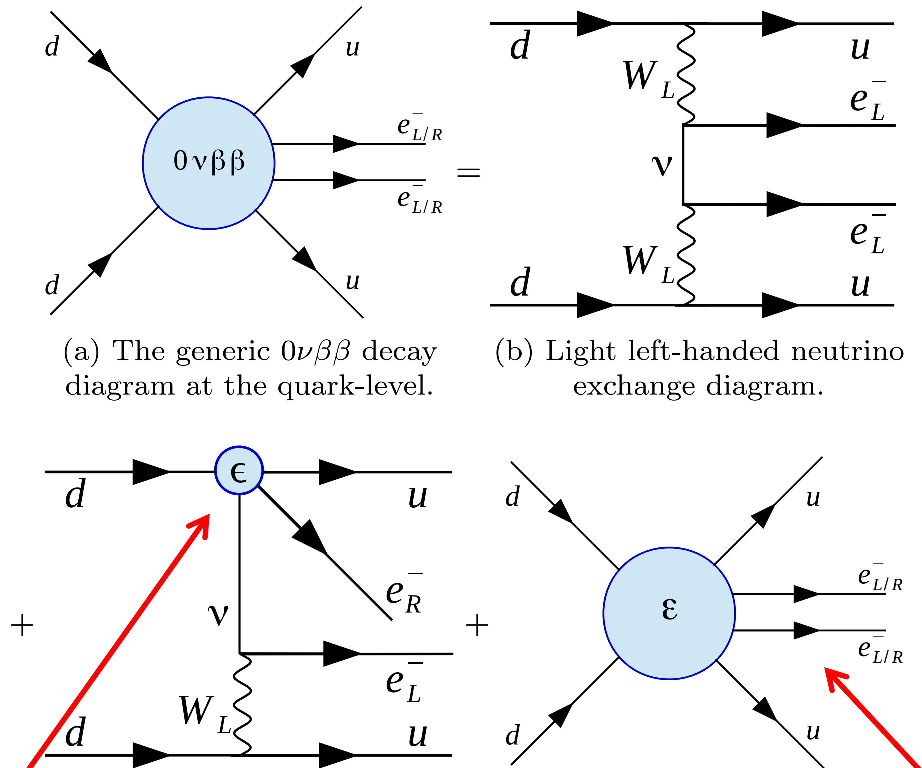
IBA-2 J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **87**, 014315 (2013).

QRPA-Tu A. Faessler, M. Gonzalez, S. Kovalenko, and F. Simkovic, arXiv:**1408.6077.**

QRPA-Jy J. Hivarynen and J. Suhonen, PRC 91, 024613 (2015), **ISM-StMa** J. Menendez, private communication.

ISM-CMU M. Horoi et. al. PRC **88**, 064312 (2013), PRC **90**, PRC **89**, 054304 (2014), PRC **91**, 024309 (2015), PRL **110**, 222502 (2013).

Effective field theory approach



(a) The generic $0\nu\beta\beta$ decay diagram at the quark-level.

(b) Light left-handed neutrino exchange diagram.

(c) The long-range part of the $0\nu\beta\beta$ diagram.

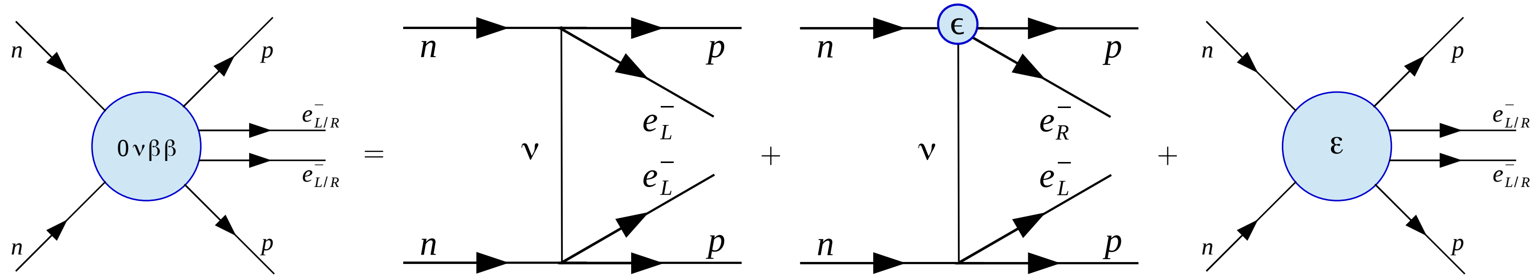
(d) The short-range part of the $0\nu\beta\beta$ diagram.

arxiv:1706.05391

$$\mathcal{L}_6 = \frac{G_F}{\sqrt{2}} \left[j^{\mu}_{V-A} J^{\dagger}_{V-A,\mu} + \sum_{\alpha,\beta}^{*} \epsilon^{\beta}_{\alpha} j_{\beta} J^{\dagger}_{\alpha} \right]$$

$$\mathcal{L}_9 = \frac{G_F^2}{2m_p} \Big[\varepsilon_1 JJj + \varepsilon_2 J^{\mu\nu} J_{\mu\nu} j + \varepsilon_3 J^{\mu} J_{\mu} j + \varepsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \varepsilon_5 J^{\mu} J j_{\mu} \Big],$$

Effective field theory after hadronization

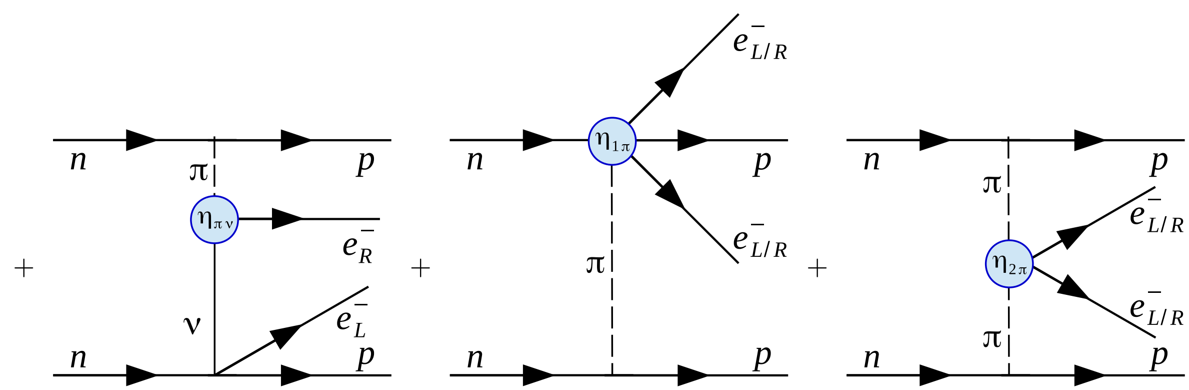


(a) The generic $0\nu\beta\beta$ decay process nucleon-level diagram.

(b) Light left-handed neutrino exchange diagram.

(c) The The nucleon-nucleon long-range $\mathcal{L}_6$ mode.

(d) The nucleon-nucleon short-range part of the $0\nu\beta\beta$ diagram.



(e) The pion-neutrino long-range diagram.

(f) The one-pion long-range diagram.

(g) The two-pion long-range diagram.

$$\left[T^{0\nu}_{1/2}\right]^{-1} = g_A^4 \left[\sum_i |\mathcal{E}_i|^2 \mathcal{M}_i^2 + \mathrm{Re}\left[\sum_{i\neq j} \mathcal{E}_i \mathcal{E}_j \mathcal{M}_{ij}\right]\right]$$

$$\mathcal{E}_{2-7} = \{\epsilon^{V+A}_{V-A},\ \epsilon^{V+A}_{V+A},\ \epsilon^{S+P}_{S\pm P},\ \epsilon^{TR}_{TL},\ \epsilon^{TR}_{TR},\ \eta_{\pi\nu}\}$$

$$\mathcal{E}_{8-15} = \{\varepsilon_1,\ \varepsilon_2,\ \varepsilon_3^{LLz(RRz)},\ \varepsilon_3^{LRz(RLz)},\ \varepsilon_4,\ \varepsilon_6,\ \eta_{1\pi},\ \eta_{2\pi}\}$$

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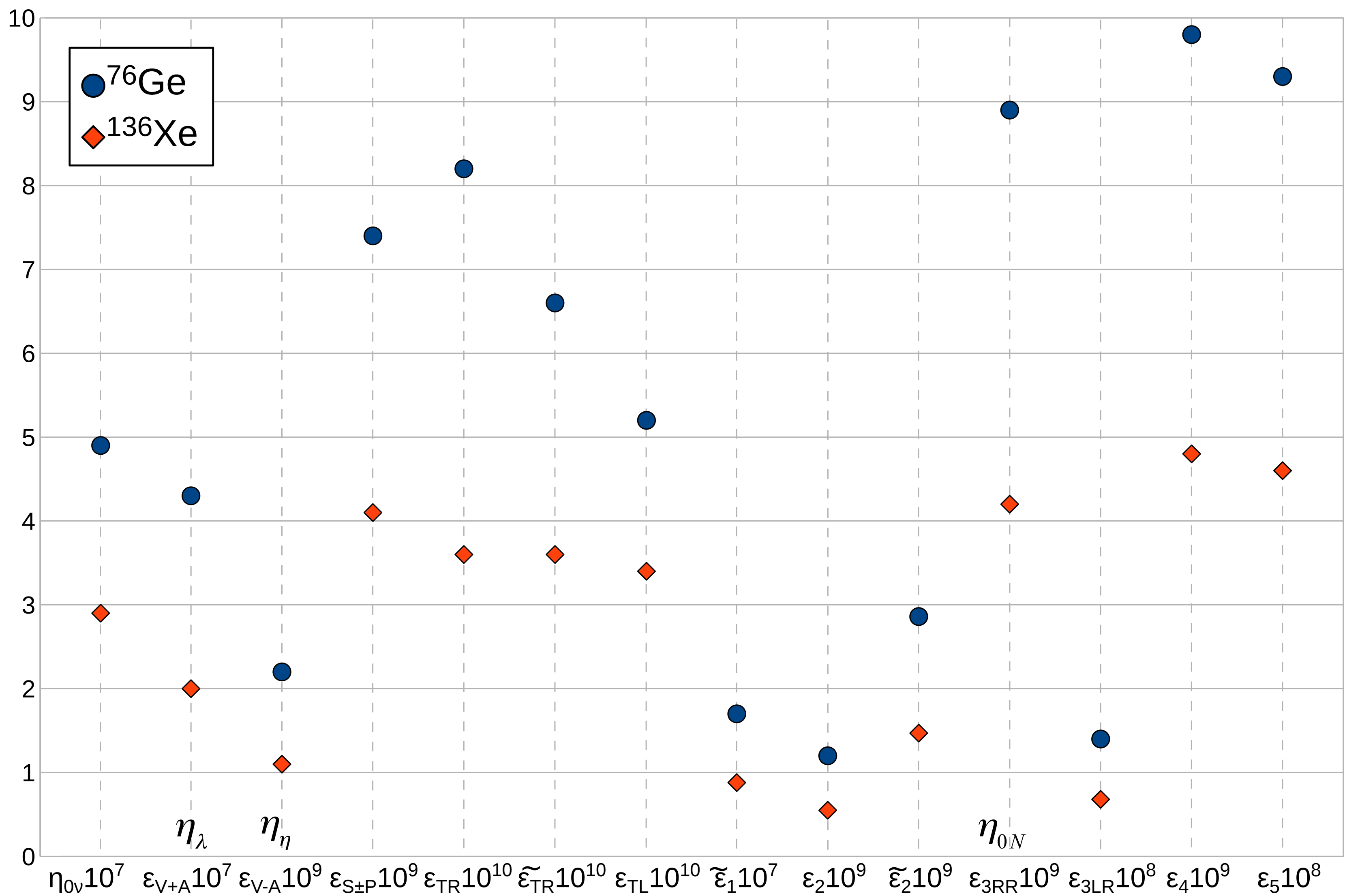
One coupling dominance

$$\left[T^{0\nu}_{1/2}\right]^{-1} = g_A^4 \left[\sum_i |\mathcal{E}_i|^2 \mathcal{M}_i^2 + \mathrm{Re}\left[\sum_{i\neq j} \mathcal{E}_i \mathcal{E}_j \mathcal{M}_{ij}\right]\right]$$

$$\mathcal{E}_{2-7} = \{\epsilon^{V+A}_{V-A},\ \epsilon^{V+A}_{V+A},\ \epsilon^{S+P}_{S\pm P},\ \epsilon^{TR}_{TL},\ \epsilon^{\tilde{TR}}_{TR},\ \eta_{\pi\nu}\} \qquad \mathcal{E}_{8-15} = \{\varepsilon_1,\ \varepsilon_2,\ \varepsilon_3^{LLz(RRz)},\ \varepsilon_3^{LRz(RLz)},\ \varepsilon_4,\ \varepsilon_6,\ \eta_{1\pi},\ \eta_{2\pi}\}$$



$T^{0\nu}_{1/2}(^{76}Ge) > 5.3\times10^{25}$ *years* $\qquad T^{0\nu}_{1/2}(^{136}Xe) > 1.1\times10^{26}$ *years*

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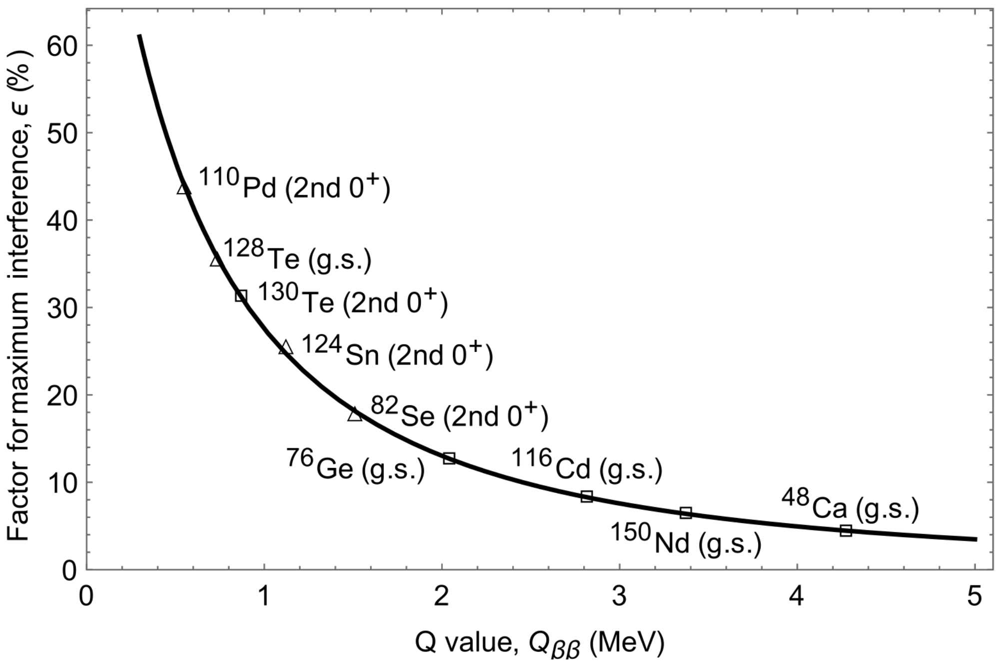
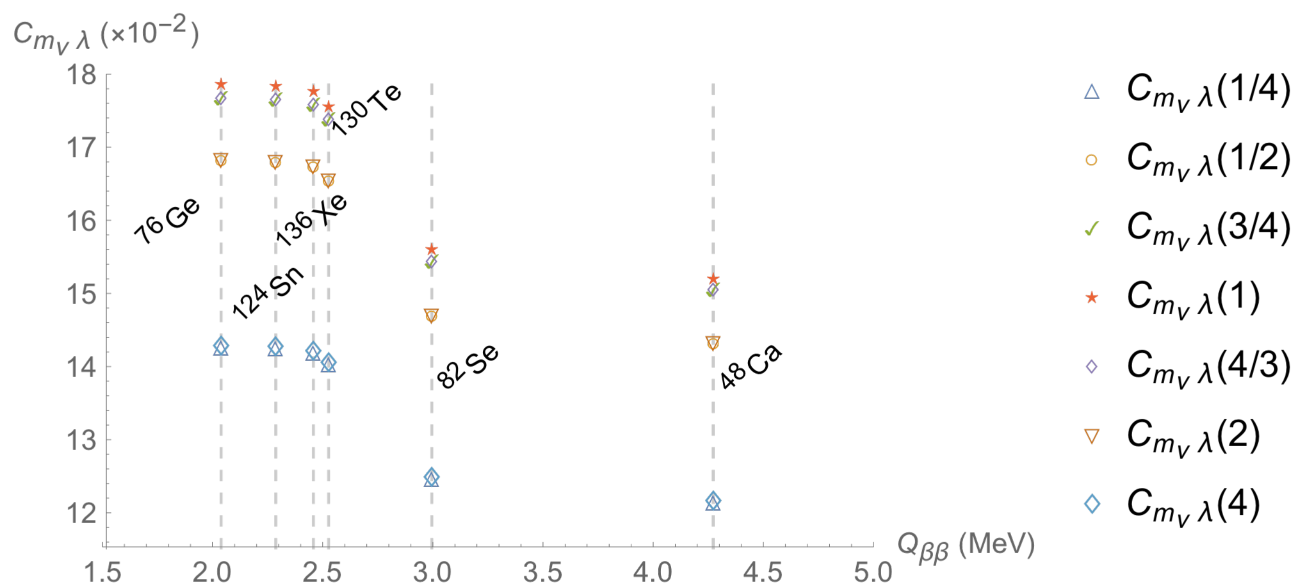
Small interference effects



Interference between mass mechanism and heavy neutrino mechanism: F. Ahmed, A. Neacsu, and M. Horoi, Phys. Lett. B 769, 299 (2017).

Interference between mass mechanism and lambda mechanism: F. Ahmed, and M. Horoi, in preparation.

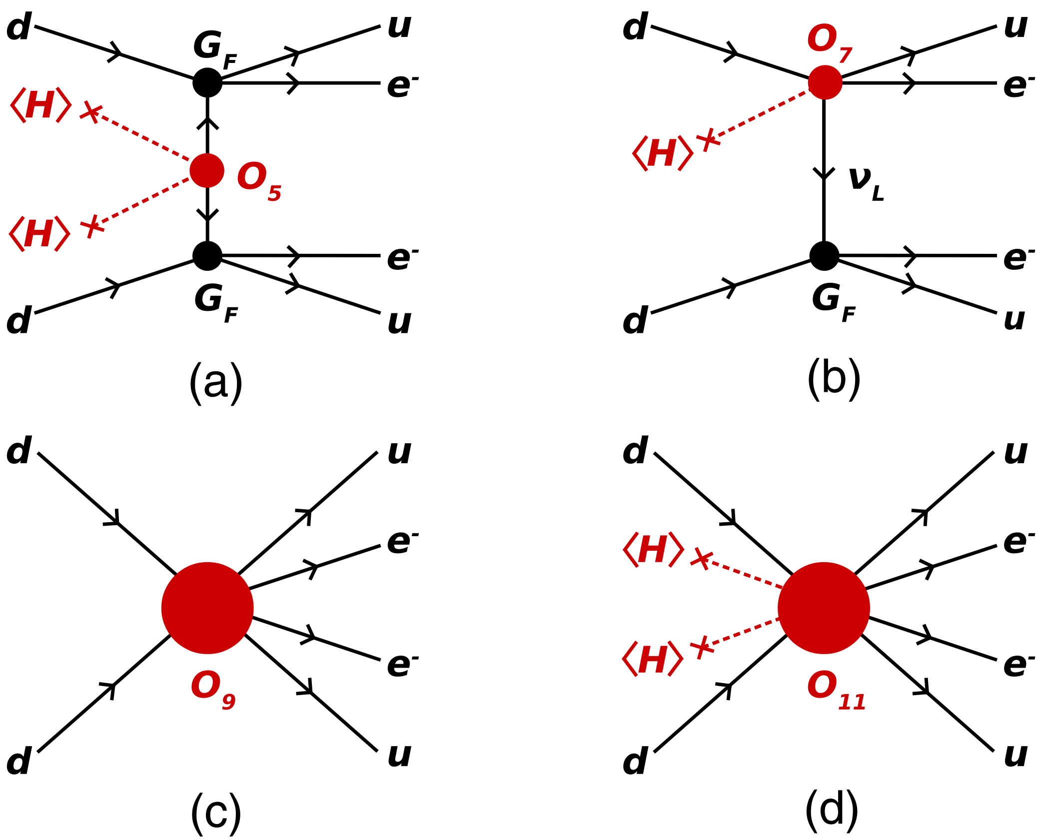


Consequences: - scales for new physics

- baryogenesis via leptogenesis

PHYSICAL REVIEW D **92,** 036005 (2015)

$$\mathcal{L}_D = \frac{g}{\Lambda_D^{D-4}} \mathcal{O}_D$$



$$m_e \bar{\epsilon}_5 = \frac{g^2 v^2}{\Lambda_5}, \qquad \frac{G_F \bar{\epsilon}_7}{\sqrt{2}} = \frac{g^3 v}{2\Lambda_7^3},$$

$$\frac{G_F^2 \bar{\epsilon}_9}{2m_p} = \frac{g^4}{\Lambda_9^5}, \qquad \frac{G_F^2 \bar{\epsilon}_{11}}{2m_p} = \frac{g^6 v^2}{\Lambda_{11}^7}$$

$g \approx 1 \quad v = 174$ GeV (Higgs expectation value)

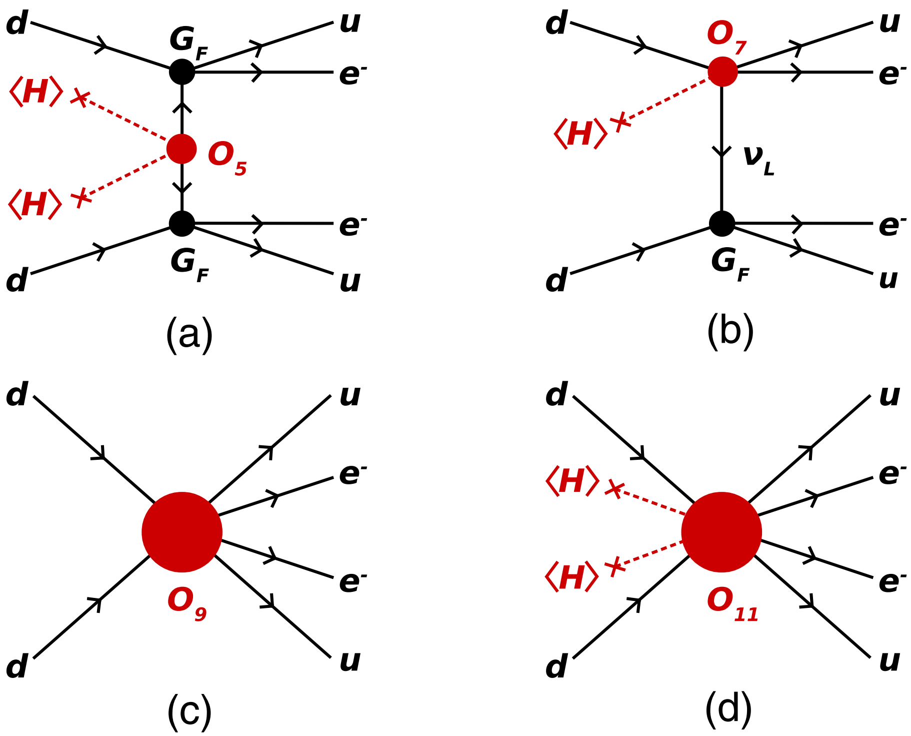
$\mathcal{O}_D$	$\bar{\epsilon}_D$	$\Lambda_D\,(GeV)$
$\mathcal{O}_5$	2.8×10^{-7}	2.12×10^{14}
$\mathcal{O}_7$	2.0×10^{-7}	3.75×10^{4}
$\mathcal{O}_9$	1.5×10^{-7}	2.48×10^{3}
$\mathcal{O}_{11}$	1.5×10^{-7}	1.16×10^{3}

Consequences: - scales for new physics

- baryogenesis via leptogenesis

PHYSICAL REVIEW D **92,** 036005 (2015)

$$\mathcal{L}_D = \frac{g}{(\Lambda_D)^{D-4}} \mathcal{O}_D$$



$$m_e \bar{\epsilon}_5 = \frac{g^2 (yv)^2}{\Lambda_5}, \qquad \frac{G_F \bar{\epsilon}_7}{\sqrt{2}} = \frac{g^3 (yv)}{2(\Lambda_7)^3},$$

$$\frac{G_F^2 \bar{\epsilon}_9}{2m_p} = \frac{g^4}{(\Lambda_9)^5}, \qquad \frac{G_F^2 \bar{\epsilon}_{11}}{2m_p} = \frac{g^6 (yv)^2}{(\Lambda_{11})^7}$$

TABLE VIII. The BSM effective scale (in GeV) for different dimension-D operators at the present ^{136}Xe half-life limit (Λ_D^0) and for $T_{1/2} \approx 1.1 \times 10^{28}$ years (Λ_D).

$\mathcal{O}_D$	$\bar{\epsilon}_D$	$\Lambda_D^0(y=1)$	$\Lambda_D^0(y=y_e)$	$\Lambda_D(y=y_e)$
$\mathcal{O}_5$	$2.8 \cdot 10^{-7}$	$2.12 \cdot 10^{14}$	1904	19044
$\mathcal{O}_7$	$2.0 \cdot 10^{-7}$	$3.75 \cdot 10^{4}$	541	1165
$\mathcal{O}_9$	$1.5 \cdot 10^{-7}$	$2.47 \cdot 10^{3}$	2470	3915
$\mathcal{O}_{11}$	$1.5 \cdot 10^{-7}$	$1.16 \cdot 10^{3}$	31	43

$$\eta_N \propto \frac{1}{m_{W_R}^4 m_N}$$

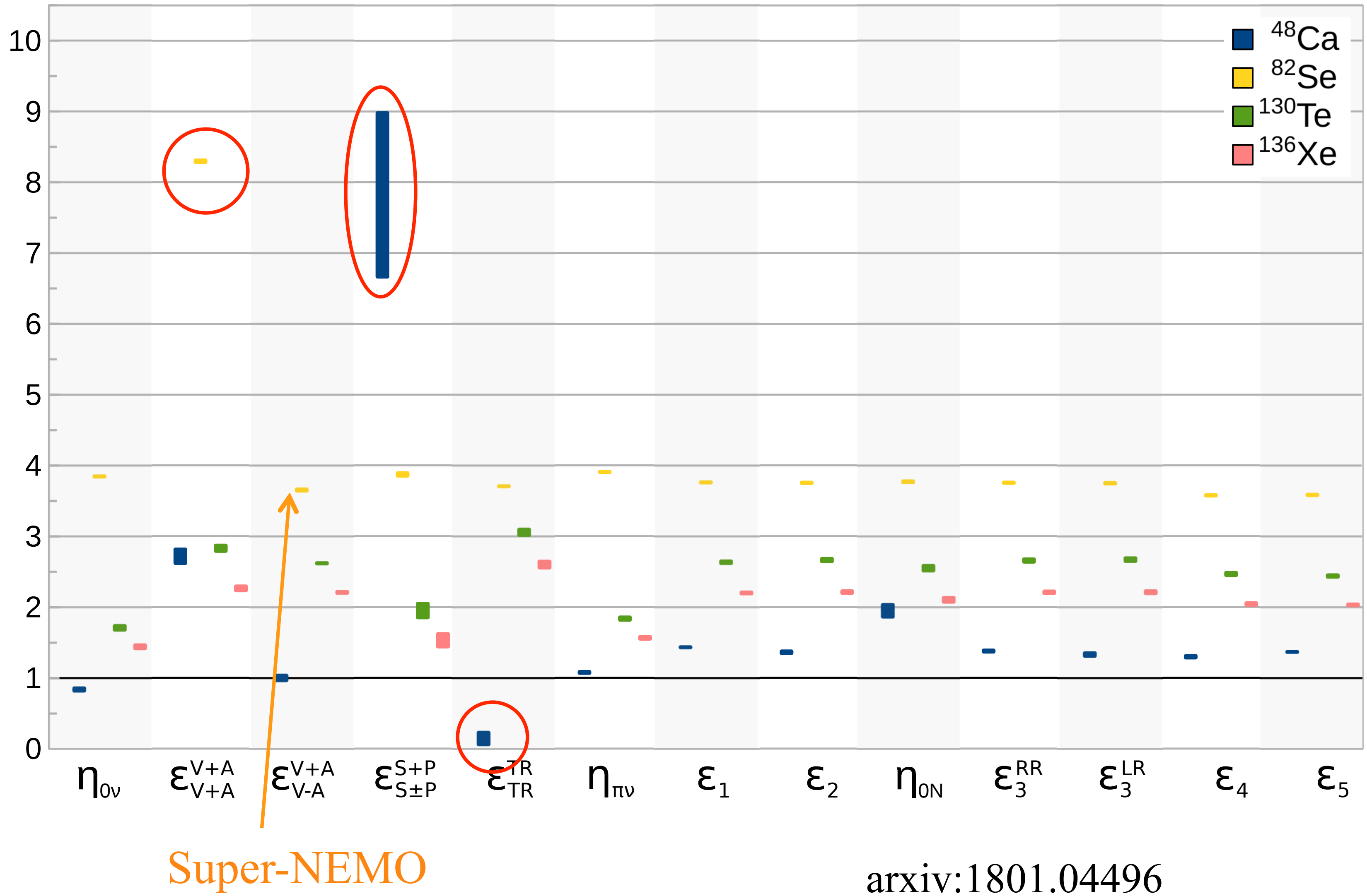
$g \approx 1 \quad v = 174\ GeV \qquad y_e = 3 \times 10^{-6}$ *electron mass Yukawa*

One coupling dominance: which one?

$$\left[T^{0\nu}_{1/2}\right]^{-1} = g_A^4 \left[\sum_i |\mathcal{E}_i|^2 \mathcal{M}_i^2 + \mathrm{Re}\left[\sum_{i\neq j} \mathcal{E}_i \mathcal{E}_j^* \mathcal{M}_{ij}\right]\right]$$

T[^{76}Ge]/T[^{A}Z]

CMU Hamiltonians



arxiv:1801.04496

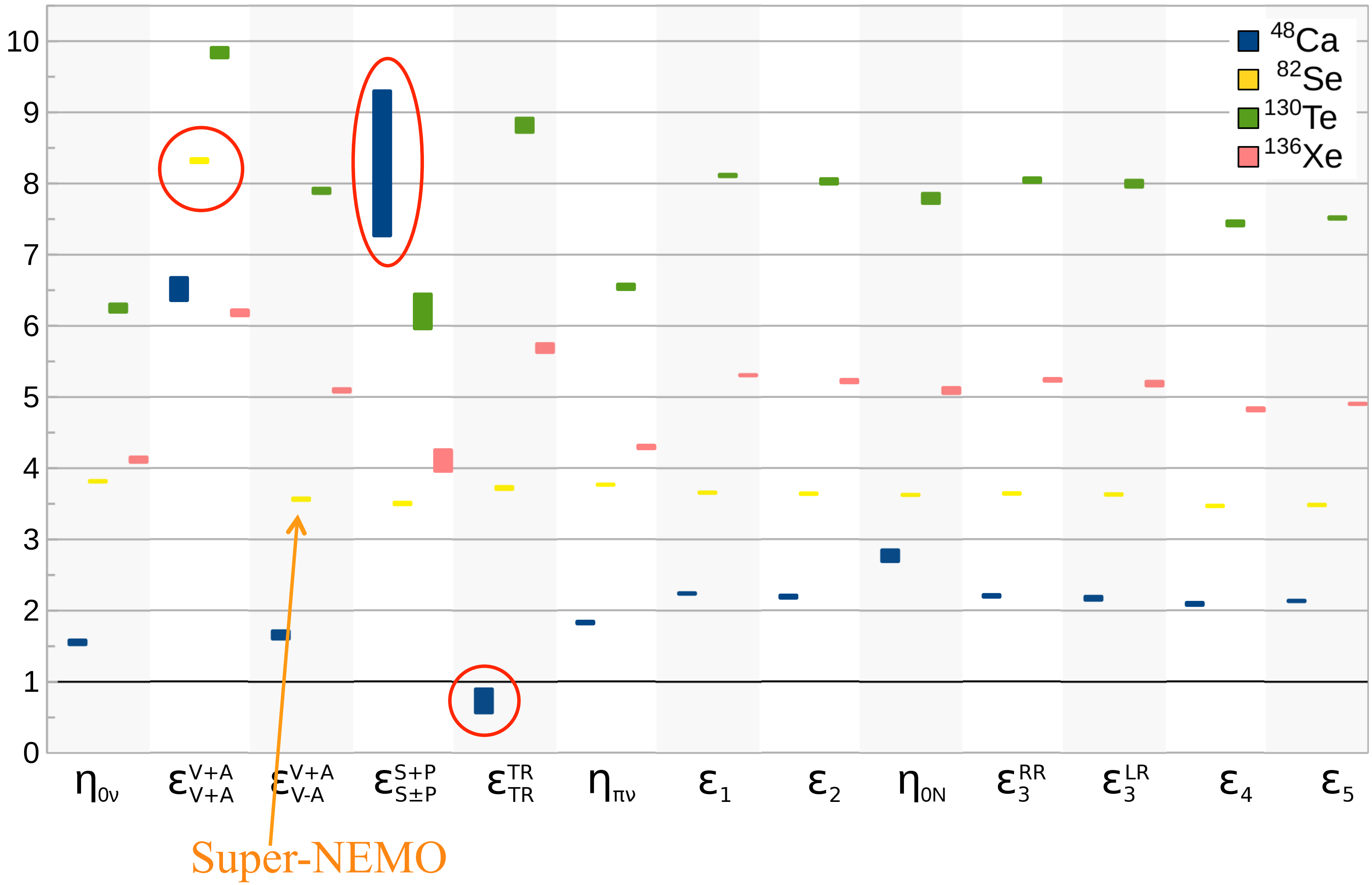
PRC 98, 035502 (2018)

One coupling dominance: which one?

$$\left[T^{0\nu}_{1/2}\right]^{-1} = g_A^4 \left[\sum_i |\mathcal{E}_i|^2 \mathcal{M}_i^2 + \mathrm{Re}\left[\sum_{i\neq j} \cancel{\mathcal{E}\ldots}\,\mathcal{M}_{ij}\right]\right]$$

T[^{76}Ge]/T[^{A}Z]

Strasbourg-Madrid Hamiltonians



PRC 98, 035502 (2018)

Other BSM Physics Contributions

PRL **112,** 142503 (2014) PHYSICAL REVIEW LETTERS week ending 11 APRIL 2014

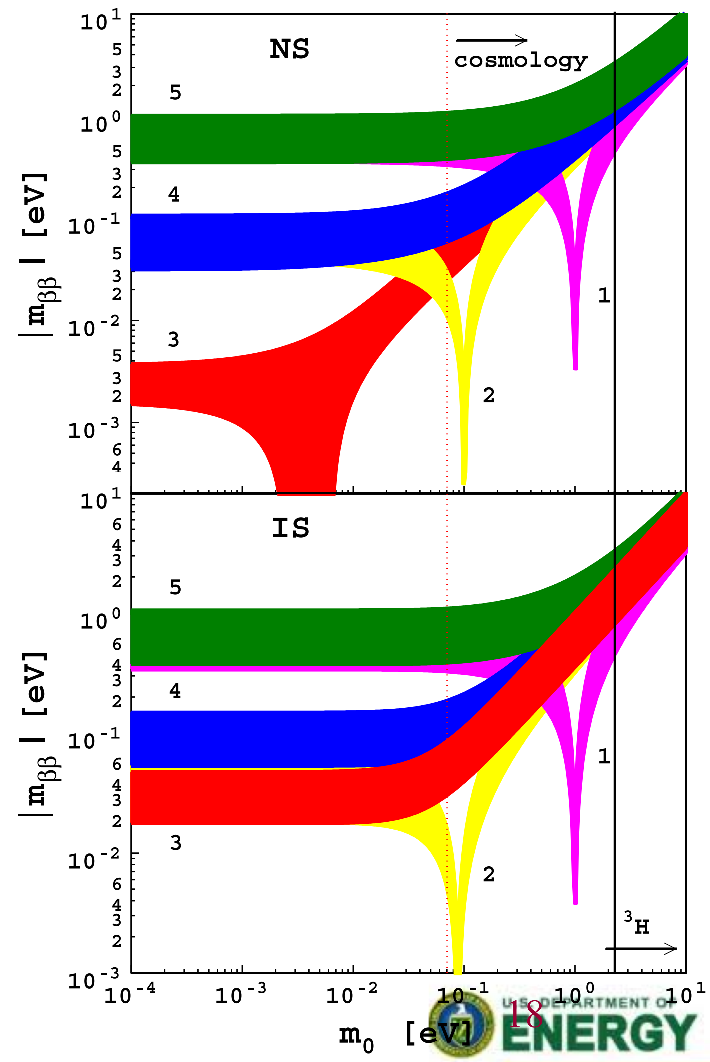
Neutrino Propagation in Nuclear Medium and Neutrinoless Double-β Decay

S. Kovalenko,[1] M. I. Krivoruchenko,[2,3] and F. Šimkovic[4,5,6]

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda^2_{\text{LNV}}} \sum_{i,j,q} (g^q_{ij} \overline{\nu^C_{Li}} \nu_{Lj} \cdot \bar{q}q + \text{H.c.}) + \frac{1}{\Lambda^3} \sum_{i,j,q} h^q_{ij} \overline{\nu_{Li}} i\gamma^\mu \overset{\leftrightarrow}{\partial}_\mu \nu_{Lj} \cdot \bar{q}q,$$

$$\mathcal{L}_{\text{eff}} = \frac{\langle \bar{q}q \rangle}{\Lambda^2_{\text{LNV}}} (\overline{\nu^C_{Li}} g_{ij} \nu_{Lj} + \text{H.c.}) + \frac{\langle \bar{q}q \rangle}{\Lambda^3} \overline{\nu_{Li}} h_{ij} i\gamma^\mu \overset{\leftrightarrow}{\partial}_\mu \nu_{Lj},$$

$$m_{\beta\beta} = \sum_{i=1}^{n} (V^L_{ei})^2 \xi_i \frac{|m_i - \langle \bar{q}q \rangle g|}{(1 - \langle \bar{q}q \rangle h)^2}.$$



How about some other contributions from SM? E.g. high density atomic electrons.

Neutrinos in atomic nuclei

Atomic nucleus is a high electron density medium:

Consider 2 electrons in the lowest s-orbital of an Hydrogen-like atom

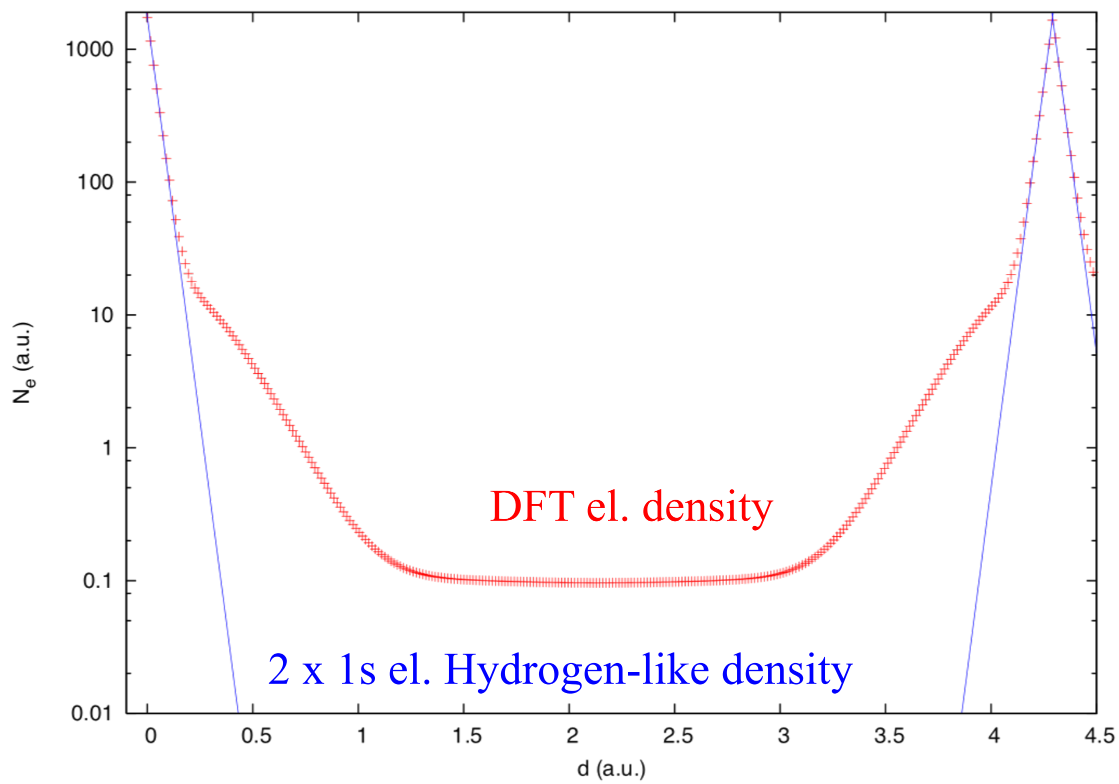
Electron density near nucleus:

$$N_e(r) \approx \frac{2}{\pi}\left(\frac{Z}{a_B}\right)^3 e^{-2rZ/a_B}$$

Electron density inside nucleus:

$$N_e(0) \approx \frac{2}{\pi}\left(\frac{Z}{a_B}\right)^3$$

$$\rho_{Sun\,core} \approx 150\ g/cm^3$$



$$Equivalent\ matter\ density: \rho = m_N N_e = 1.67\times10^6 \frac{2}{\pi}\left(\frac{Z}{53}\right)^3\ in\ g/cm^2 >> \rho_{Sun}$$

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Neutrinos in atomic nuclei

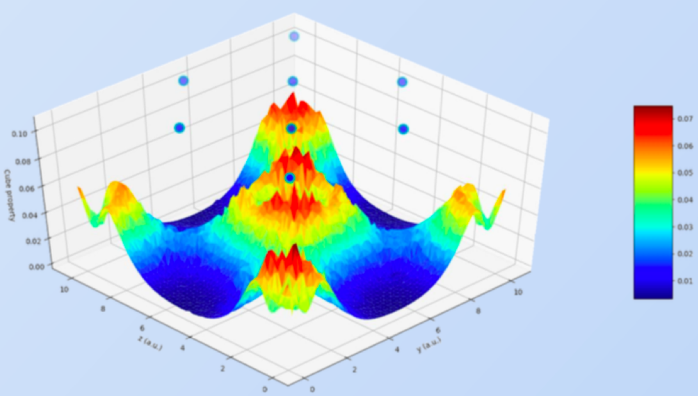
Reconstructing Electron Charge Density

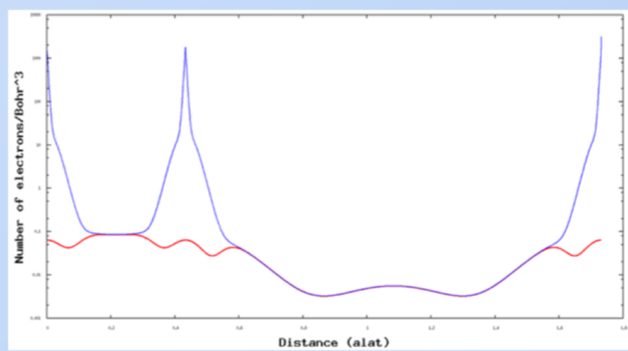
T. E. Stearns, M. Fornari, M. Horoi, A. Zettel
Dept. of Physics, Central Michigan University

Electronic Structure Collides with Neutrino Physics

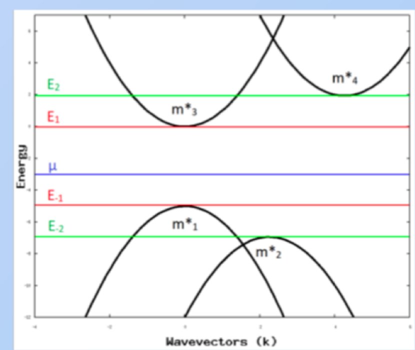
A common method used by programs to compute the electronic structure involves treating the core electrons in an atom as "frozen". This allows the calculation to focus on the electrons that participate in the chemical bonding, vastly improving computation speed. However, the resultant charge density is incomplete, since it contains only the valence electrons. Neutrinos may respond differently when the medium in which they travel is highly charged. In order to describe the interaction of neutrinos travelling through Earth, it is necessary to reconstruct the total charge density by adding the core electrons to the valence charge.

- Charge Density is the probability that an electron will occupy a given volume of space.
- The program used during this project was *Quantum ESPRESSO*[1], a plane wave based density functional theory calculation suite. It uses pseudopotentials to replace the core electrons.
- Pseudopotentials approximate the energy from the coulomb interaction between the core electrons and the valence electrons.
- Since the core electrons are chemically inactive, the density in the core regions of an atom in a material can be reconstructed from the pseudopotential.
- We tried a number of utilities to reconstruct the total density, including *Abinit*[2], *GPAW*[3], and *Critic2*[4]. *Quantum ESPRESSO* returned the best results.
- Eventually, this data will be used in a neutrino simulation by Adam Zettel and Dr. Horoi. Please see their poster for more information.





The total (blue) and valence (red) charge density of cubic silicon plotted logarithmically along a diagonal (1 1 1) line. Notice how both plots follow each other very closely, except in the areas where



An example of parabolic band structure. The blue line is the chemical potential, or Fermi energy. The red and green lines

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Neutrinos in matter: local mass eigenstates

$$H = U_{vac} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U_{vac}^{+} + \begin{pmatrix} 2EV & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V(eV) = \pm 7.6 \times 10^{-14} m_p(g) N_e(cm^{-3})$$

$$H = U_{mat} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta M_{21}^2 & 0 \\ 0 & 0 & \Delta M_{31}^2 \end{pmatrix} U_{mat}^{+}$$

(Anti)neutrinos are ”emitted” in matter in the local (lowest)highest “mass eigenstates”.

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Neutrinoless double beta decay in vacuum

$$A_{0\beta\beta} \propto NP = \langle 0| T \left[\psi_{eL}(x_1)\psi^T_{eL}(x_2)\right] |0\rangle$$

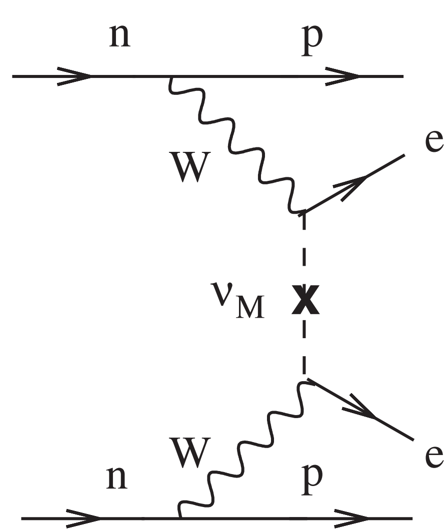
$$\psi_e(x) = \sum_{a=1}^{N(3)} U_{ea}\psi_a(x)$$

$$NP = \sum_{a=1}^{3} U_{ea}^2 \langle 0| T \left[\psi_{aL}(x_1)\psi^T_{aL}(x_2)\right] |0\rangle$$
$$= \sum_{a=1}^{3} U_{ea}^2 \left[-i \int \frac{d^4p}{(2\pi)^4} \frac{m_a e^{-ip(x_1-x_2)}}{p^2-m_a^2+i\epsilon} P_L \mathcal{C}\right]$$

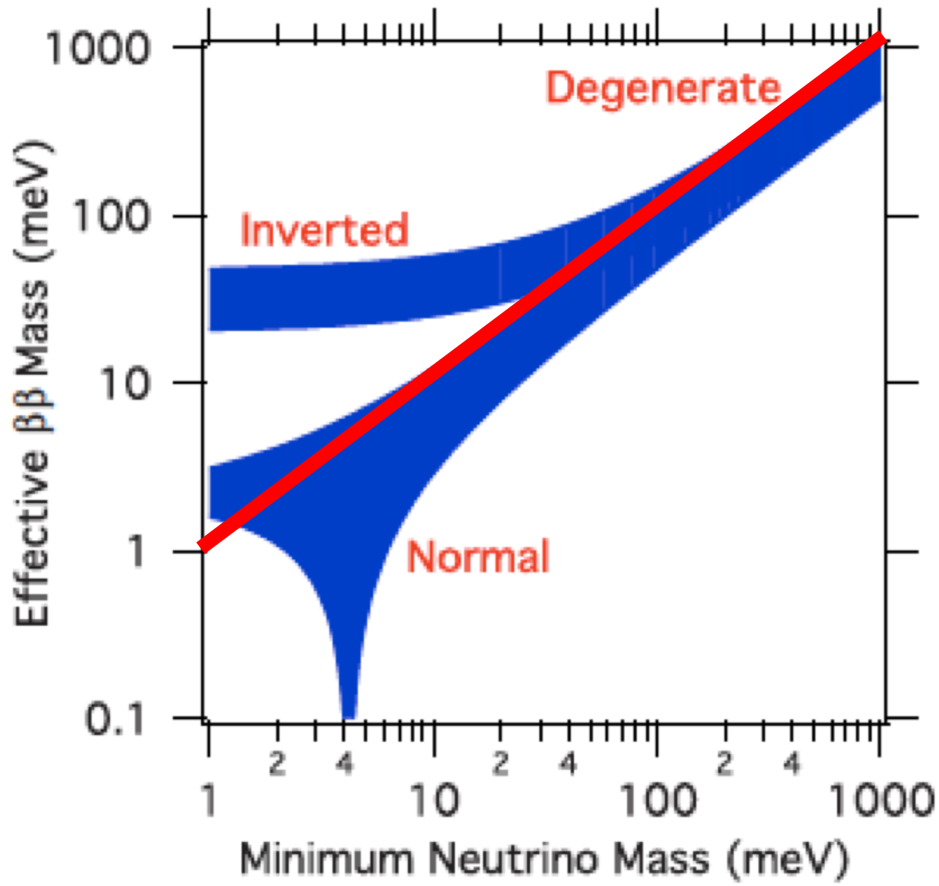
$$P_L = \frac{1}{2}\left(1-\gamma^5\right) \qquad \hat{\psi}(x) = C\psi^*(x)$$

$P_L C$ product is further used to process the electron current, and one finally gets:

$$\frac{1}{T_{1/2}} = G(Z,Q)\,|M_{0\nu}|^2 \left|\sum_{a=1}^{3} U_{ea}^2 m_a\right|^2 / m_e^2$$



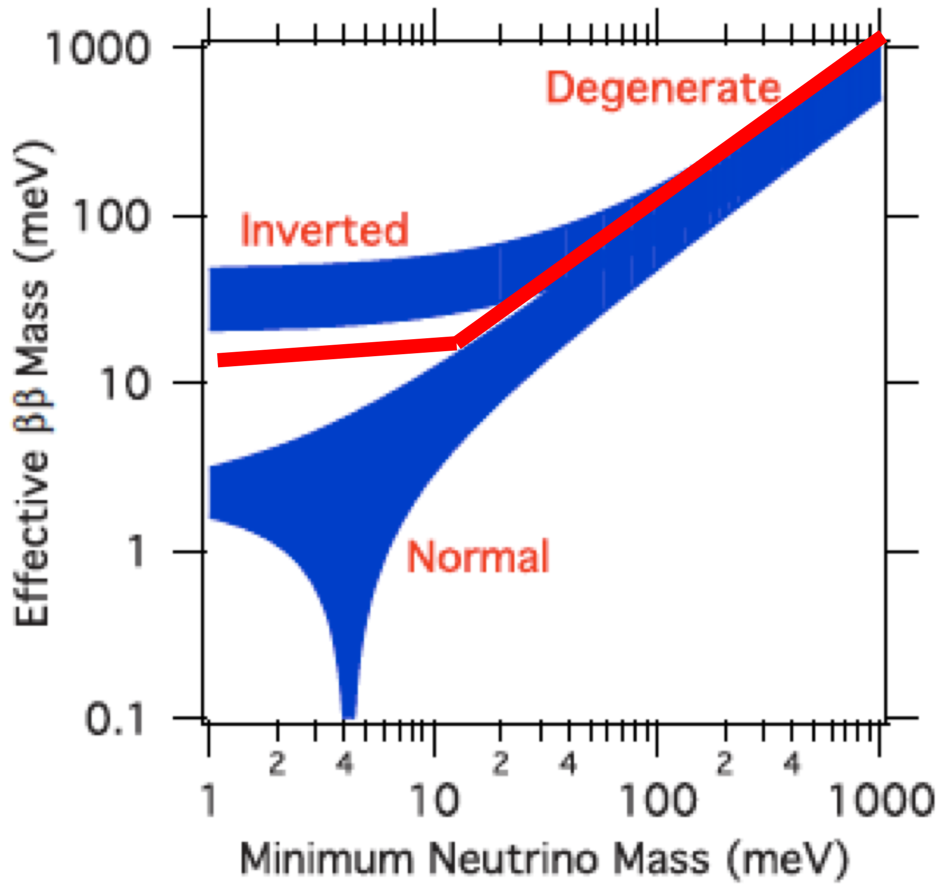
Effective neutrino mass



$$\left|m_{\beta\beta}\right| = \left|U_{e j_l}^{2} m_{j_l}\right| \quad \Leftarrow T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta})\left[M^{0\nu}(0^+)\right]^2(\eta_{0\nu})^2$$

$$\eta_{0\nu} = \frac{\left|m_{\beta\beta}\right|}{m_e}$$

Effective neutrino mass



$$\left|m_{\beta\beta}\right| = \left|U_{e j_h}^2 m_{j_h}\right| \qquad \Leftarrow T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta})\left[M^{0\nu}(0^+)\right]^2(\eta_{0\nu})^2$$

$$\eta_{0\nu} = \frac{\left|m_{\beta\beta}\right|}{m_e}$$

Neutrinoless double beta decay of atomic nuclei

Details are rather complex and can be found in arXiv:1803.06332

In short: the vacuum result stands!

$$\langle 0|\, T\left[\Phi_e^W(x_1)\left(\Phi_e^W(x_2)\right)^T\right]|0\rangle = -i\sum_a U_{ea}^2 \int \frac{d^4p}{(2\pi)^4}\frac{m_a e^{-ip(x_1-x_2)}}{p^2 - m_a^2 + i\epsilon}\left(i\sigma^2\right)$$

$$P_L C = \begin{pmatrix} 0 & 0 \\ 0 & i\sigma^2 \end{pmatrix}$$

$$\textit{In atomic nuclei NP} = \textit{In vacuum NP}$$

$$\textit{Vacuum result stands}:\ m_{\beta\beta} = \left|\sum_{a=1}^{3} U_{ea}^2 m_a\right|$$

Summary

- Neutrinoless DBD, if observed, will represent a big step forward in our understanding of the neutrinos, and of physics beyond the Standard Model.
- Ratios of half-lives for several isotopes are essential to account for alternative decay mechanisms.
- The effects of the high electron densities in atomic nuclei were investigated and they do not change the neutrino emission or detection, nor the $0\nu\beta\beta$ outcome.
- These results look simple, but the road to them is complex. Consequences to matter effects neutrino oscillations could be interesting.