Neutrinoless Double Beta Decay: Matrix Elements and Atomic Effects

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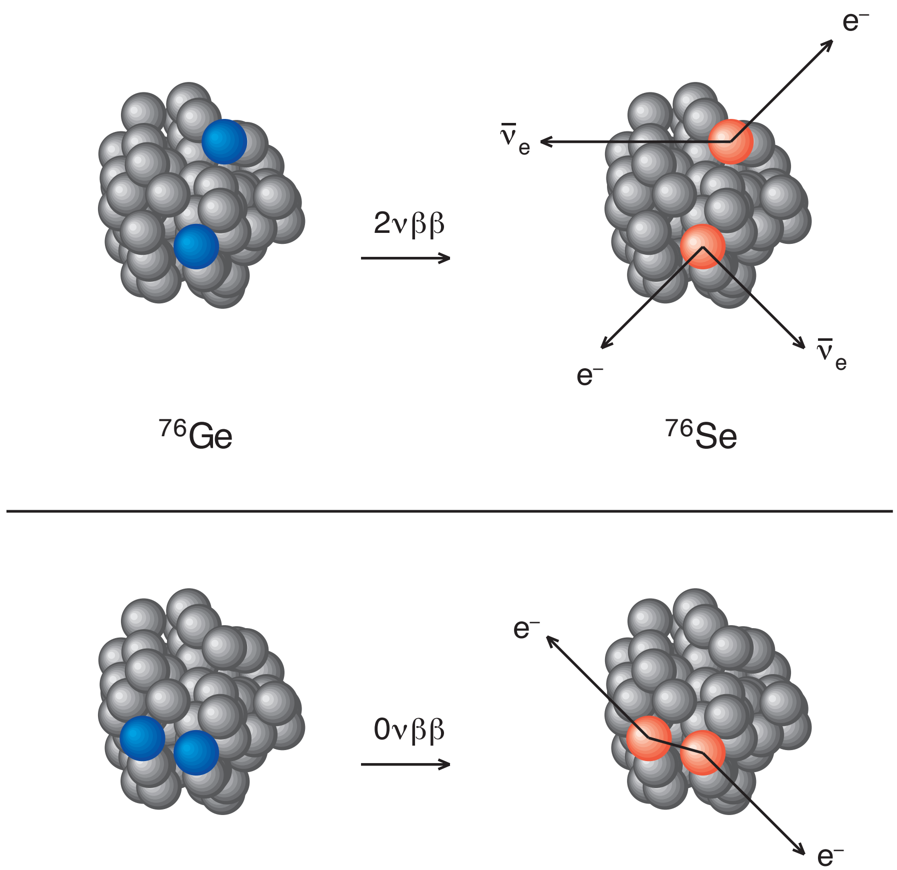
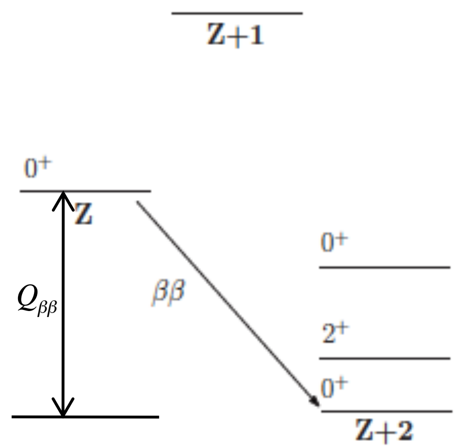
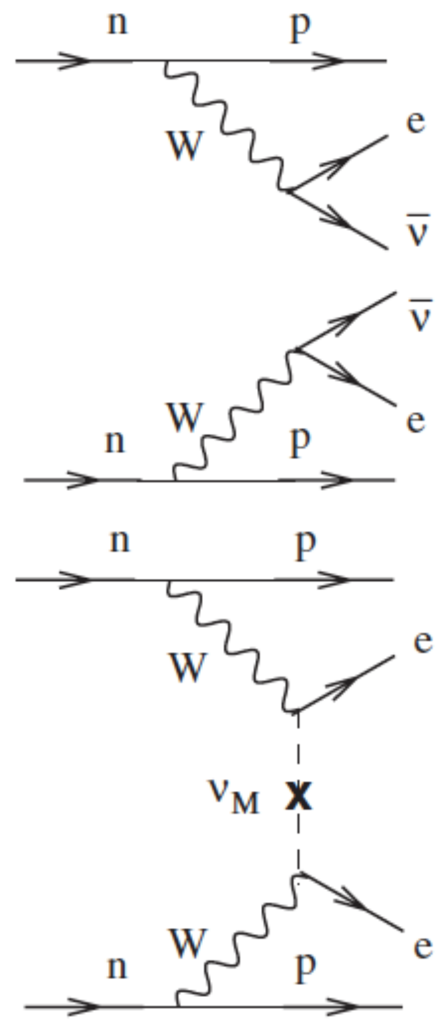
➢**Support from DOE grant DE-SC0015376 is acknowledged**

Classical Double Beta Decay Problem







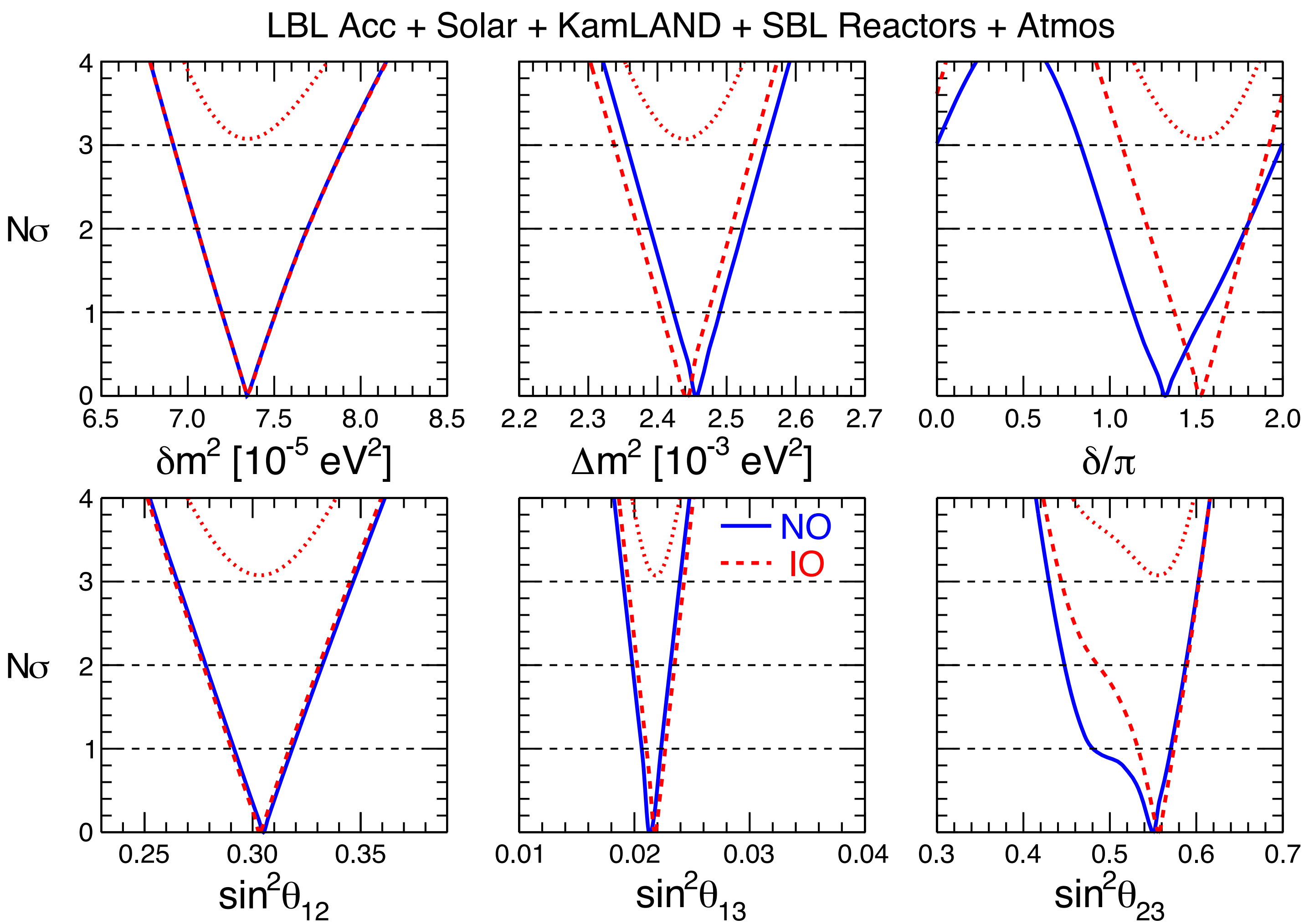
$$\langle m_{\beta\beta} \rangle = \left| \sum_k m_k U_{ek}^2 \right|$$

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

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

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

Neutrino oscillations parameters



Bari group:

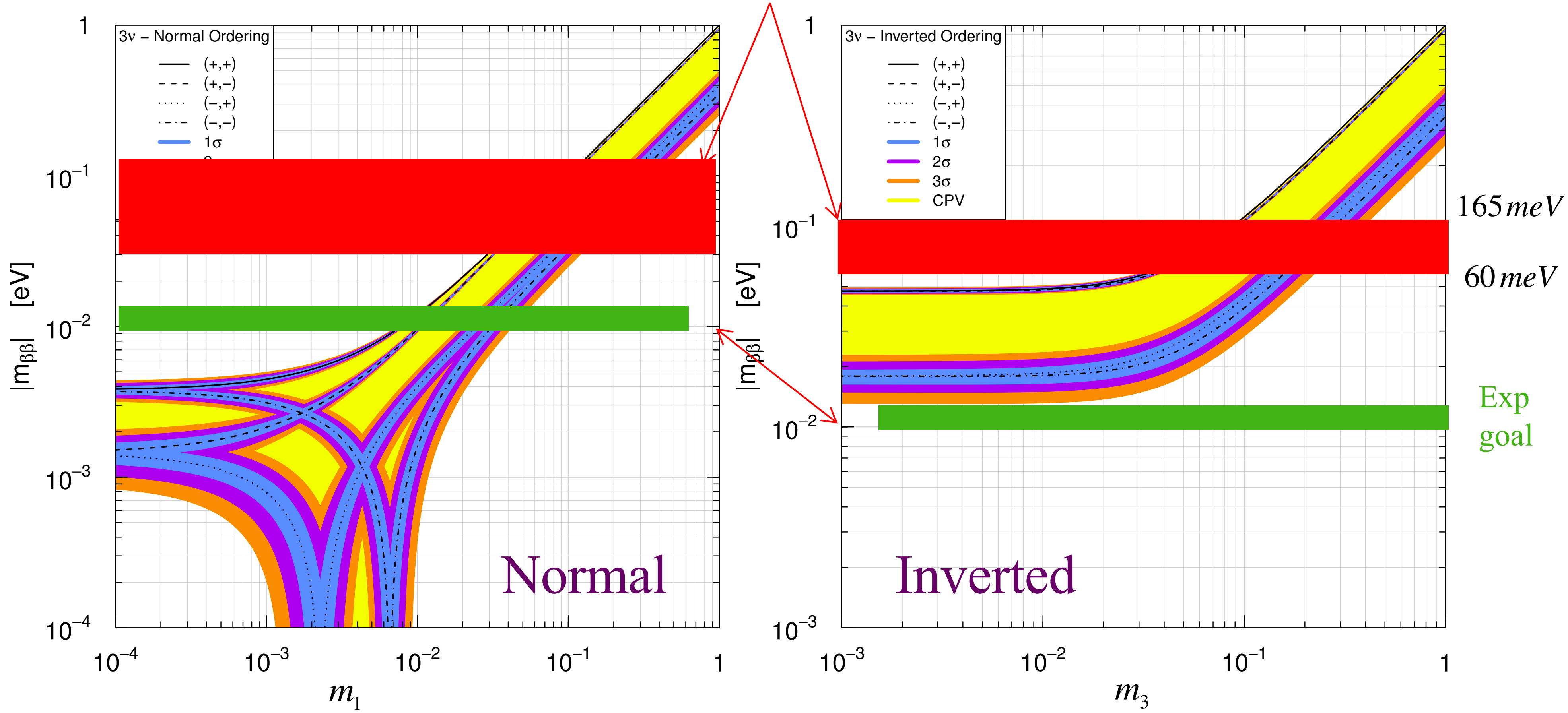
arxiv.org/1804.09678
Prog. Part. Nucl. Phys. 102, 48 (2018)

1806.11051 review: Normal ordering favored at 3.5σ !!

Neutrino ββ effective mass

arxiv:1507.08204

$KamLAND-Zen, PRL\ 117, 082503\ (2016):\ ^{136}Xe$



$$\left|m_{\beta\beta}\right| = \left|\sum_{k=1}^{3} m_k U_{ek}^2\right| = \left|c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right| \quad \Leftarrow T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta})\left[M^{0\nu}(0^+)\right]^2 (\eta_{0\nu})^2$$

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

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

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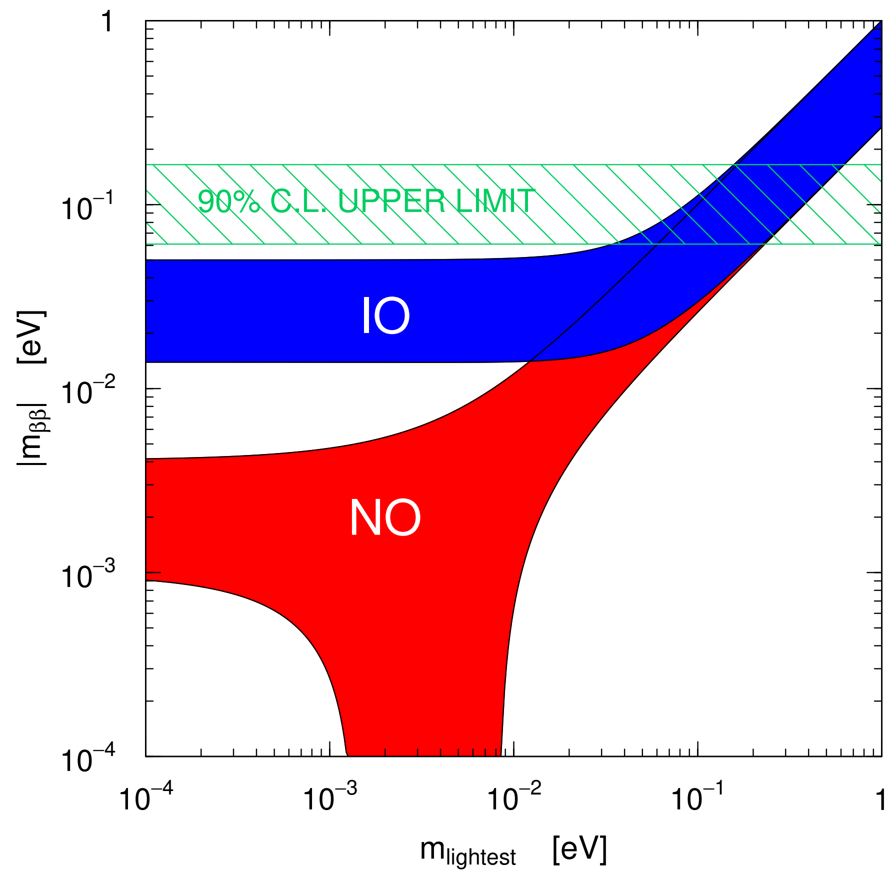
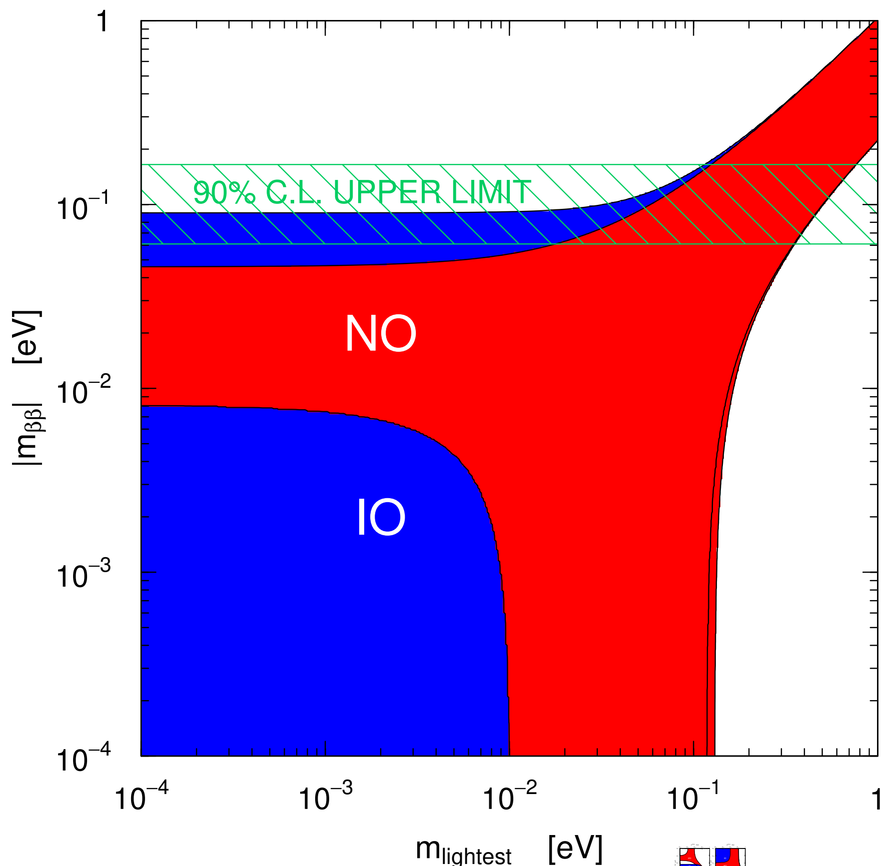
$0\nu\beta\beta$ decay mass mechanism

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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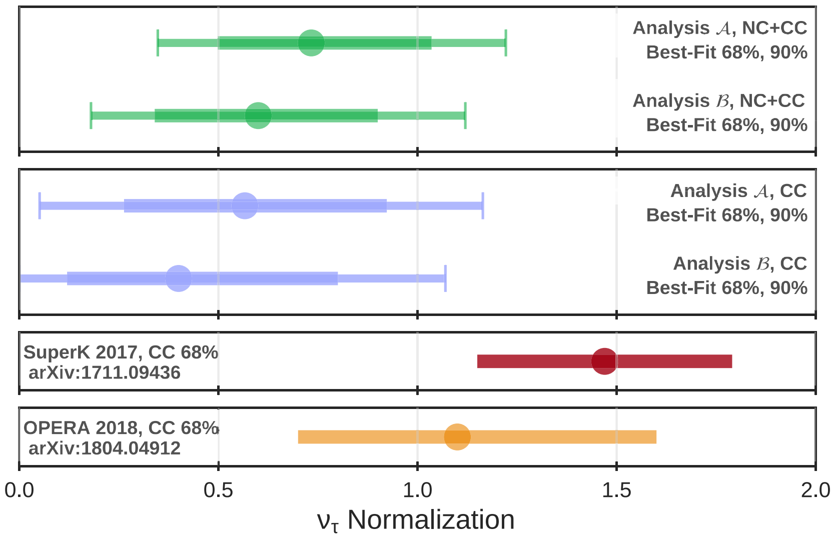
More about the mixing matrix

IceCube: PRD 99, 032007 (2019)



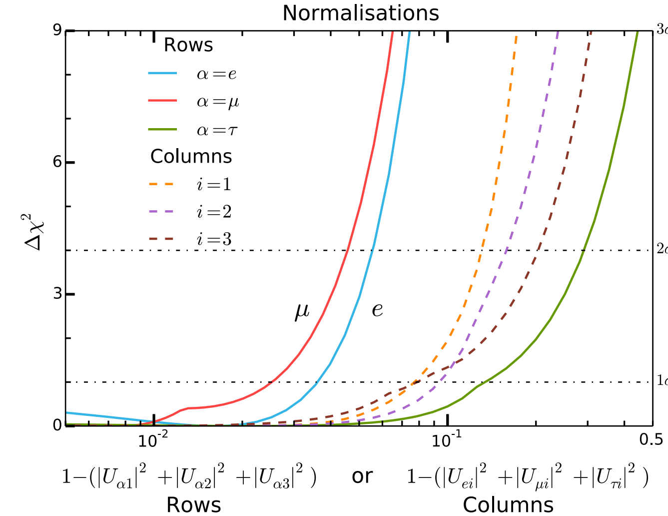
$$|U_{\tau 1}|^2 + |U_{\tau 2}|^2 + |U_{\tau 3}|^2 =?\, 1$$

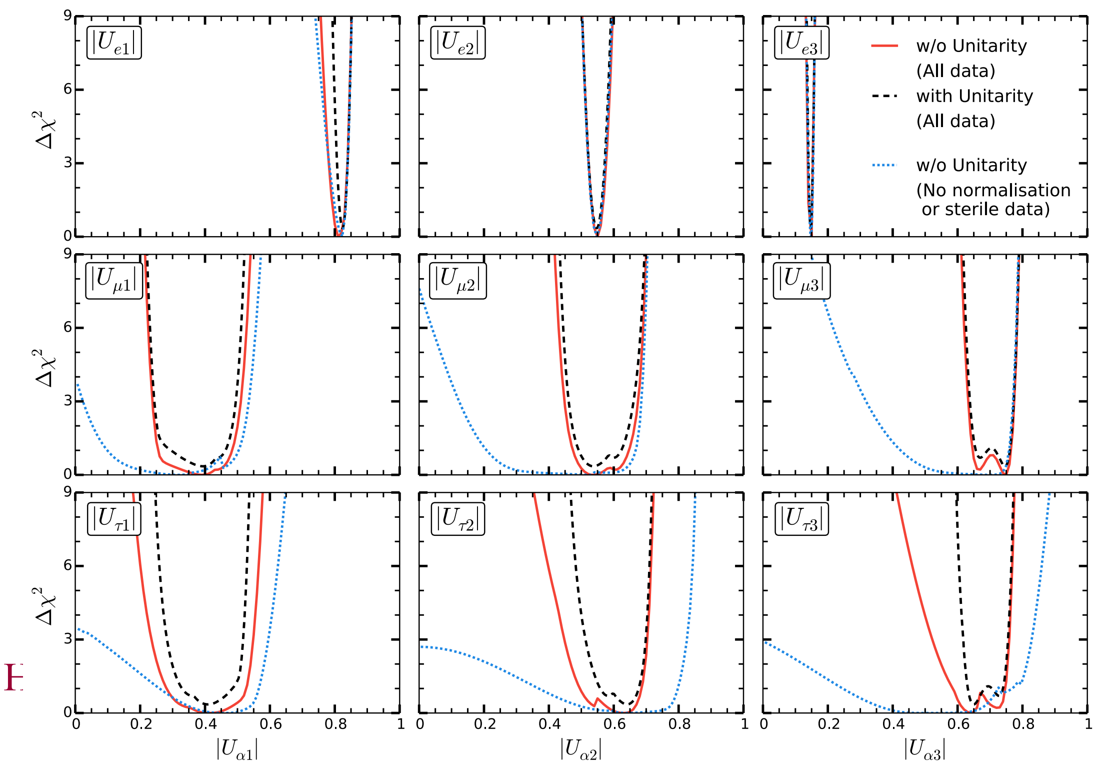
$$U_{\rm PMNS}^{\rm Extended} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{U_{\rm PMNS}^{3\times 3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

PHYSICAL REVIEW D **93,** 113009 (2016)

Unitarity and the three flavor neutrino mixing matrix

Stephen Parke[1] and Mark Ross-Lonergan[2]





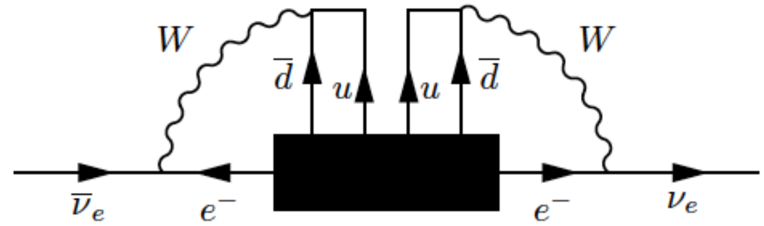
The Black Box Theorems

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)



$0\nu\beta\beta$ observed at some level $\Leftrightarrow$

(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

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

Black box II (all flavors + oscillations)

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

$0\nu\beta\beta$ observed at some level $\Leftrightarrow$

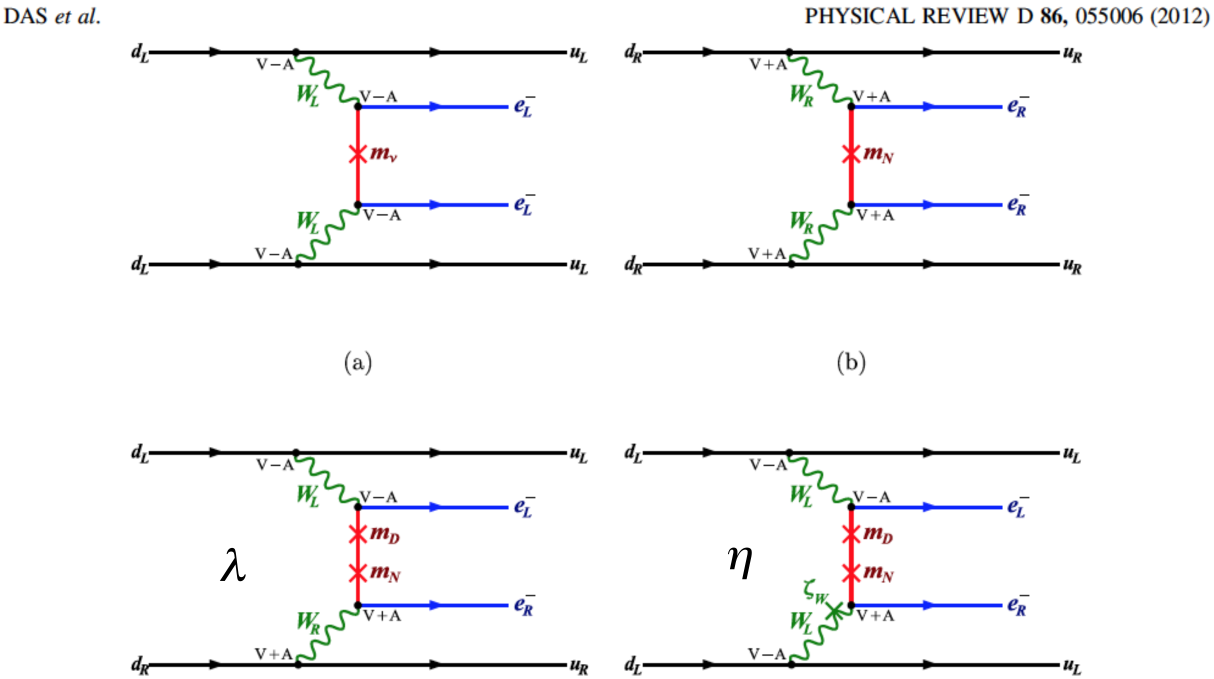
(i) Lepton number conservation is violated by 2 units.

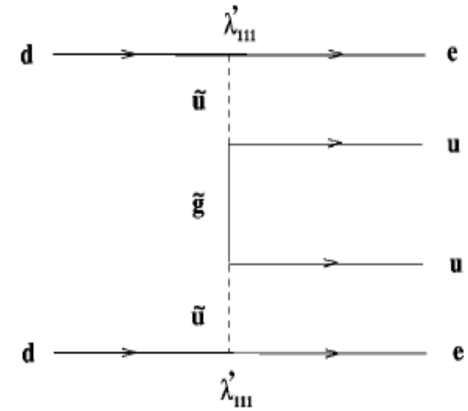
(ii) Neutrinos are Majorana fermions.

Regardless of the dominant $0\nu\beta\beta$ mechanism!

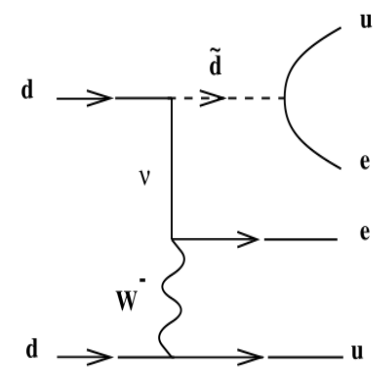
$$(iii)\quad \left\langle m_{\beta\beta}\right\rangle = \left|\sum_{k=1}^{3} m_k U_{ek}^2\right| = \left|c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right| > 0$$

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





Gluino exchange



Squark exchange

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{01} g_A^4 \left| \eta_{0\nu} M_{0\nu} + \left(\eta^L_{N_R} + \eta^R_{N_R}\right) M_{0N} + \eta_{\tilde q} M_{\tilde q} + \eta_{\lambda'} M_{\lambda'} + \eta_\lambda X_\lambda + \eta_\eta X_\eta \right|^2 .$$

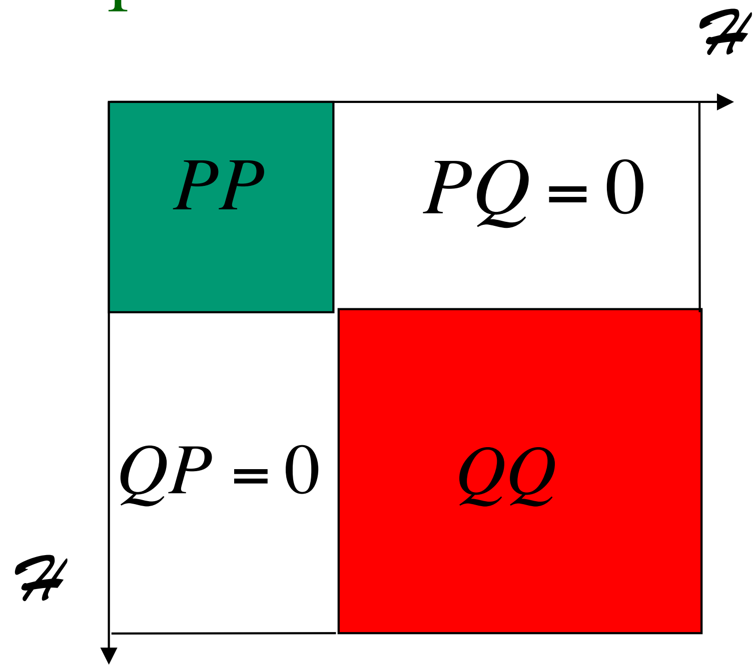
(e)

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

Effective Hamiltonians for Large N $\hbar\omega$ Excitation Model Spaces

Renormalization methods:

- G-matrix: Physics Reports 261, 125 (1995)
- Lee-Suzuki (NCSM): PRC 61, 044001 (2000)
- $V_{\text{low k}}$: PRC 65, 051301(R) (2002)
- Unitary Correlation Operator: PRC 72, 034002 (2004)
- Similarity Renormalization Group (SRG): PRL 103, 082501 (2009)



"Bare" Nucleon-Nucleon Potentials:

- Argonne V18: PRC 56, 1720 (1997)
- CD-Bonn 2000: PRC 63, 024001 (2000)
- N^3LO: PRC 68, 041001 (2003)
- INOY: PRC 69, 054001 (2004)

$$H = T + \sum_{i<j} V_{ij} + \sum_{i<j<k} V_{ijk} + \cdots$$

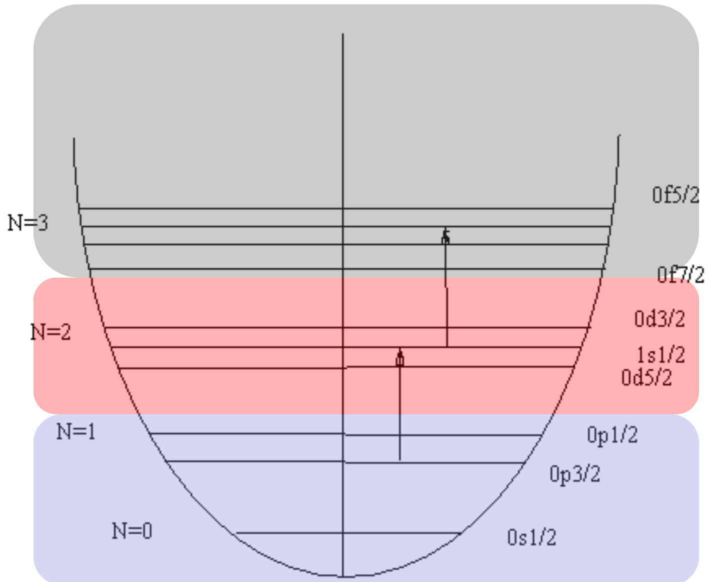
$$\Psi_{\mathcal{H}} \rightarrow \Psi_P = P\Psi_{\mathcal{H}}$$

$$\mathcal{H} = U\,HU^{+} = \mathcal{H}_2 + \mathcal{H}_3 + \mathcal{H}_4 + \ldots$$

$$O \rightarrow U\,O\,U^{+}$$

Shell Model Effective Hamiltonians

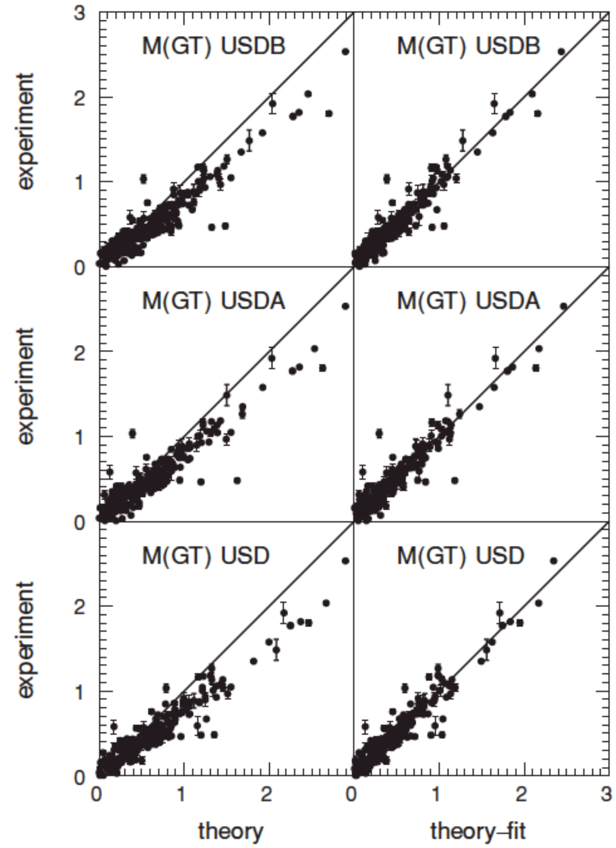
$g_A \sigma\tau \xrightarrow{quenched} g_A 0.77\sigma\tau$



$$H_{valence}\Psi = E_n\Psi$$

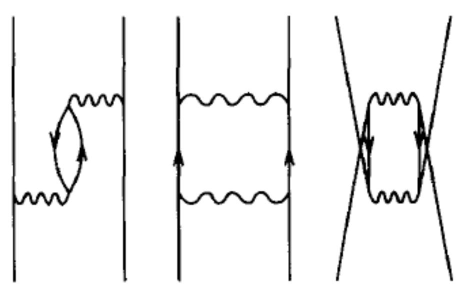
$$H_{valence} = H_{2-body}$$

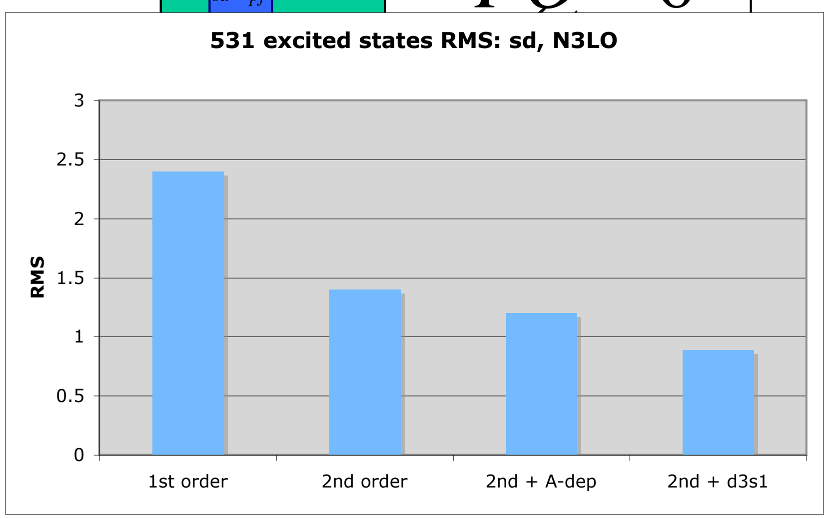
can describe most correlations around the Fermi surface!

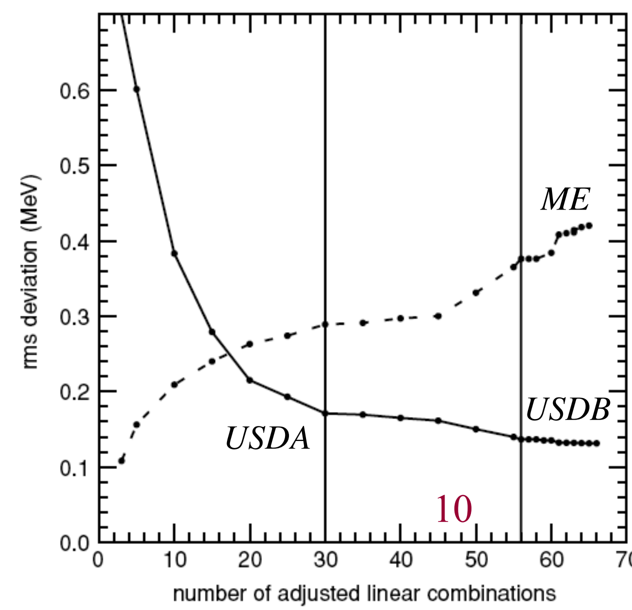


PRC 74, 34315 (2006), 78, 064302 (2008)

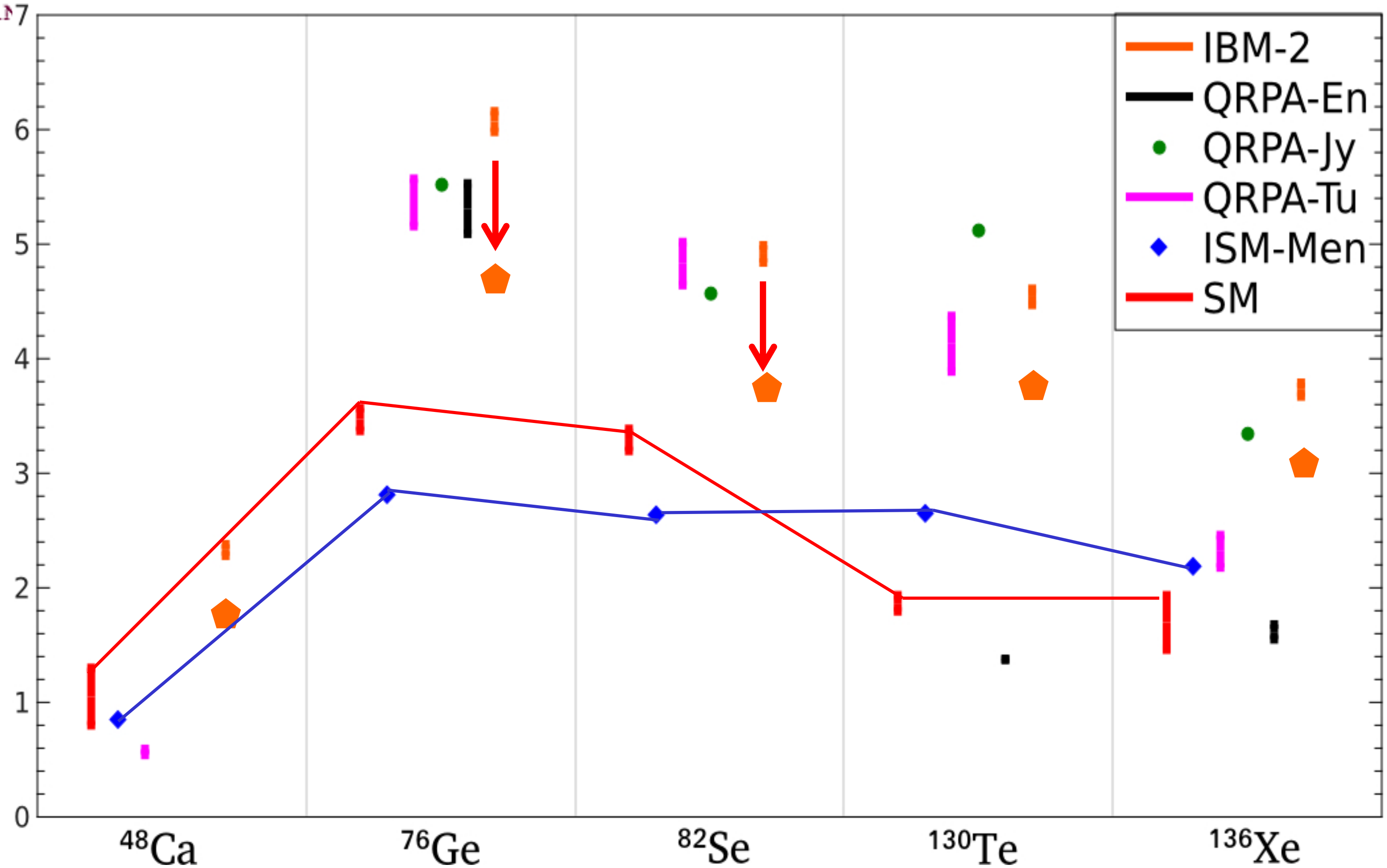
core polarization: Phys.Rep. **261**, 125 (1995)







NME for the light-neutrino exchange mechanism



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).

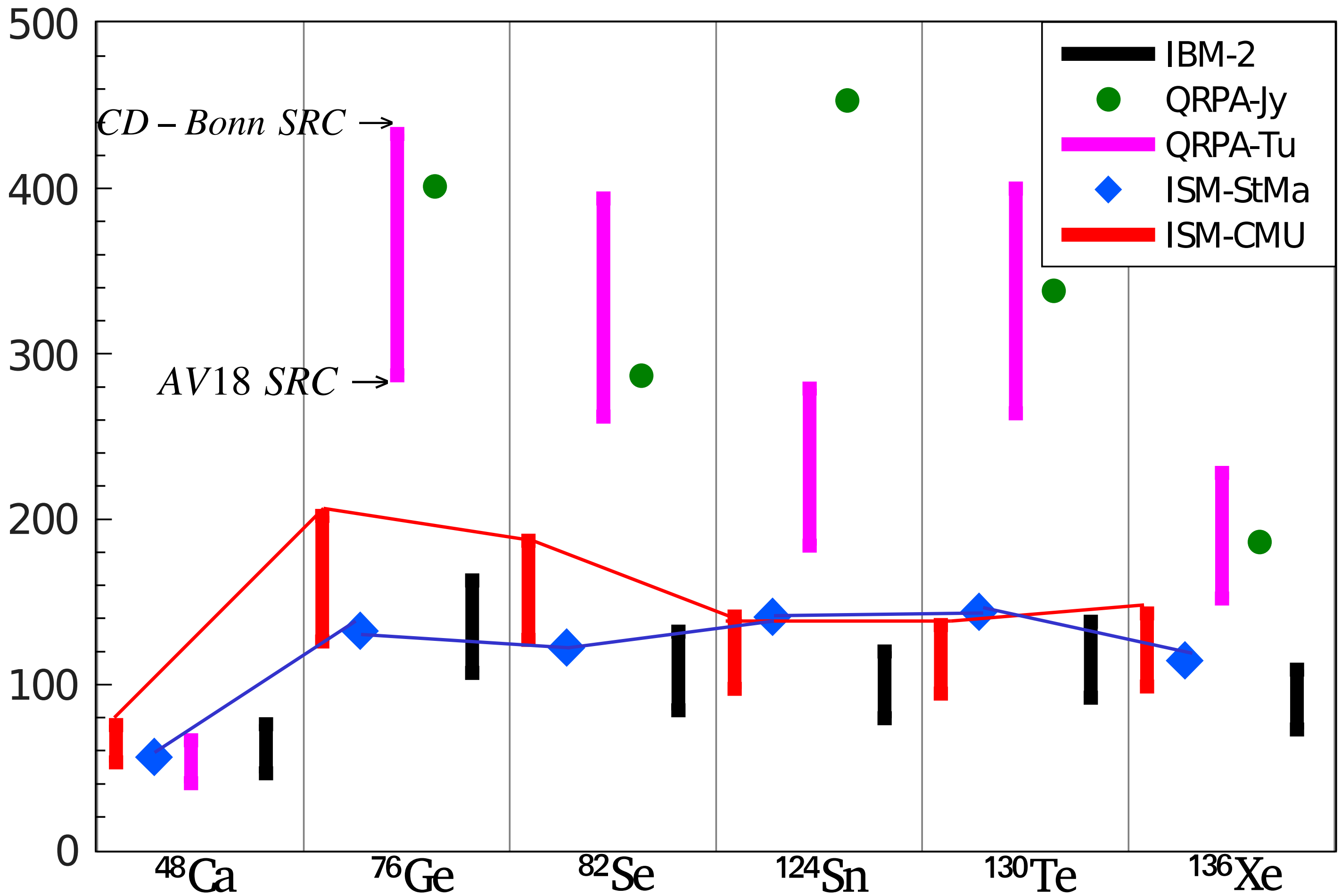
QRPA-Jy J. Suhonen, O. Civitarese, Phys. NPA **847** 207–232 (2010).

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).

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.

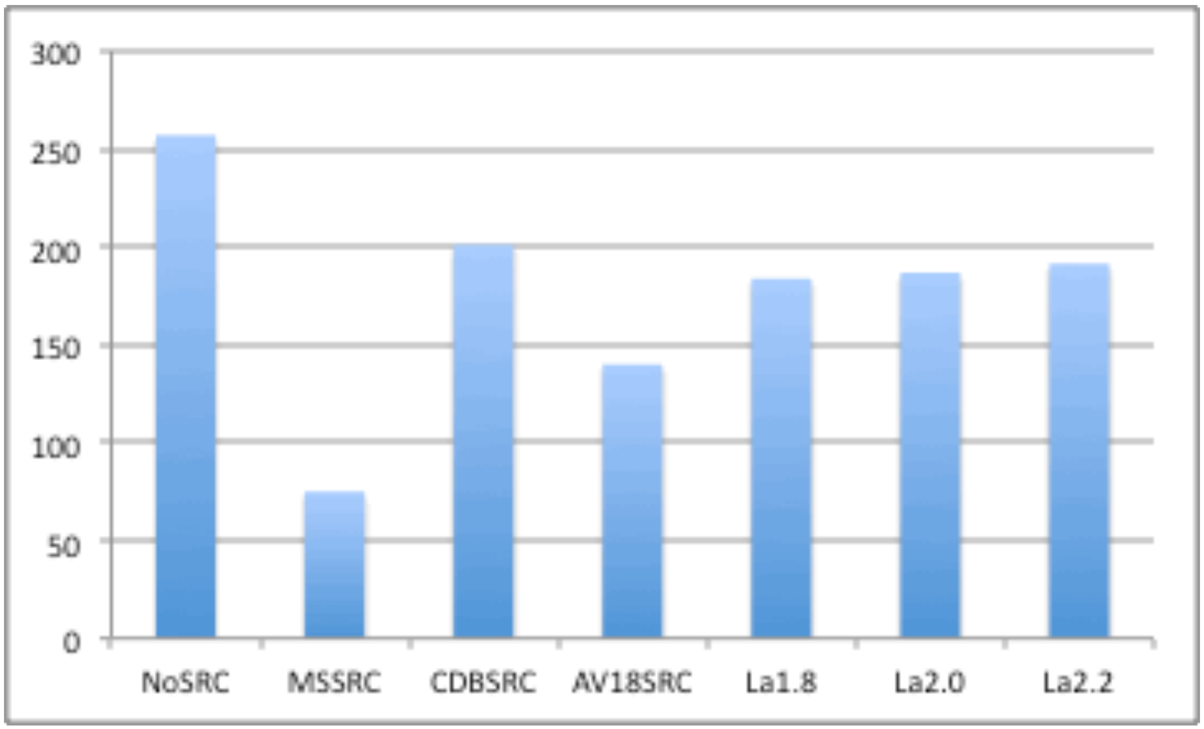
ISM-CMU M. Horoi et. al. PRC **88**, 064312 (2013), PRC **90**, PRC **89**, 054304 (2014), PRC **91**, 024309 (2015), PRL **110**, 222502 (2013).

Towards an effective 0νDBD operator: heavy neutrino-exchange NME

$$O_\lambda = U_\lambda O_{\lambda=\infty} U_\lambda^+$$

^{76}Ge

M^{0N}

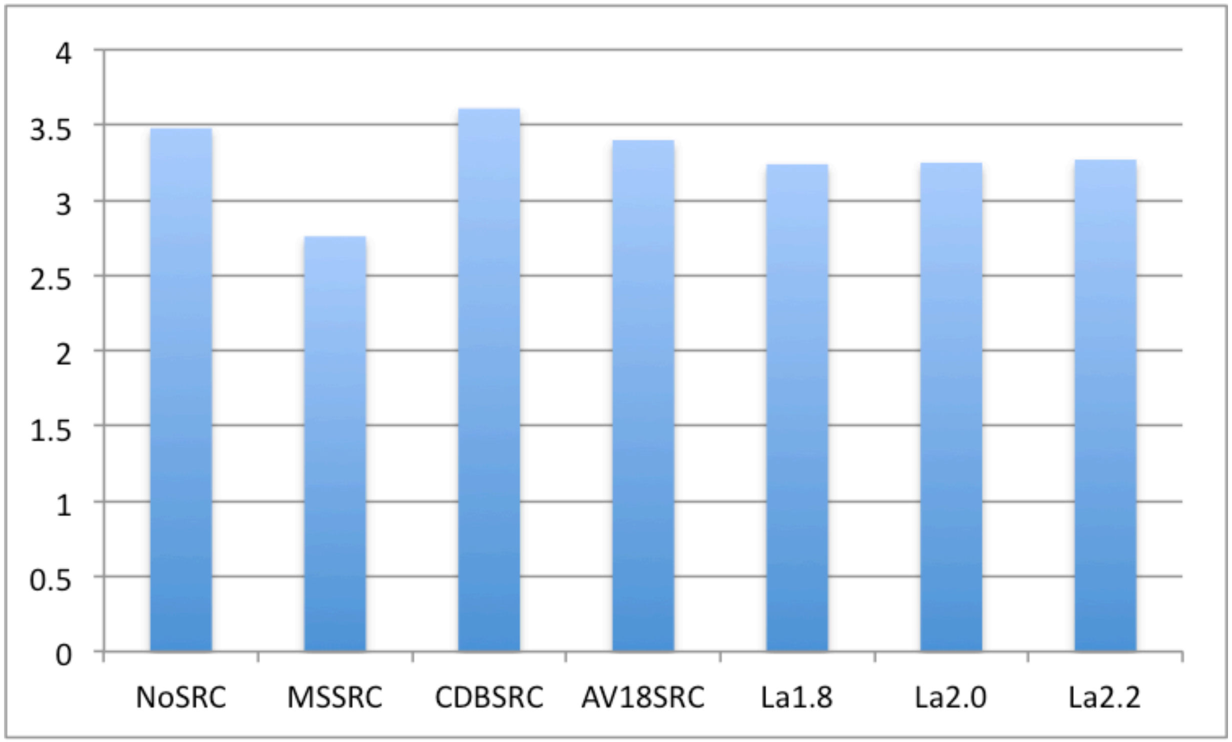


Towards an effective 0νDBD operator: light neutrino-exchange NME

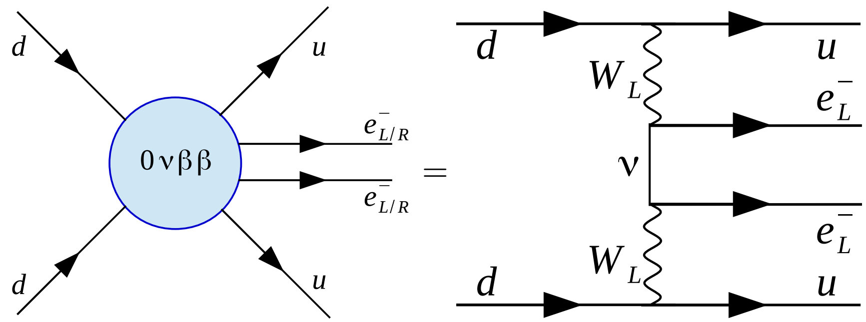
$$O_\lambda = U_\lambda O_{\lambda=\infty} U_\lambda^+$$

^{76}Ge

$M^{0\nu}$

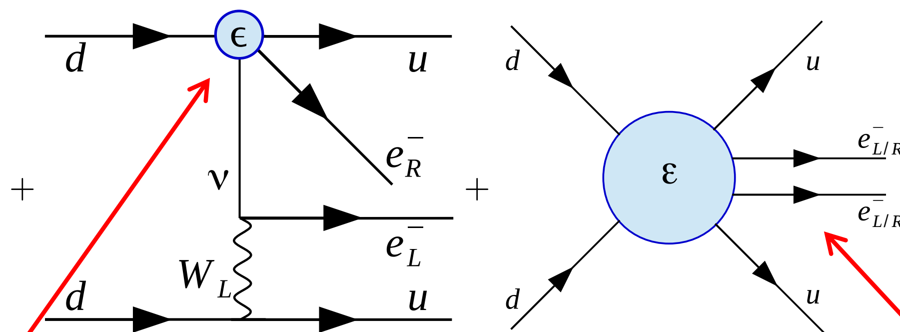


Effective field theory approach



(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

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

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

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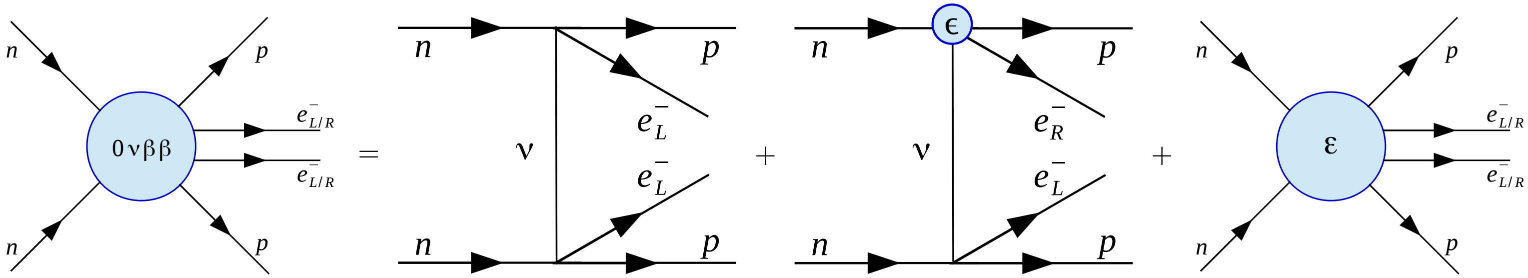
Effective field theory after hadronization

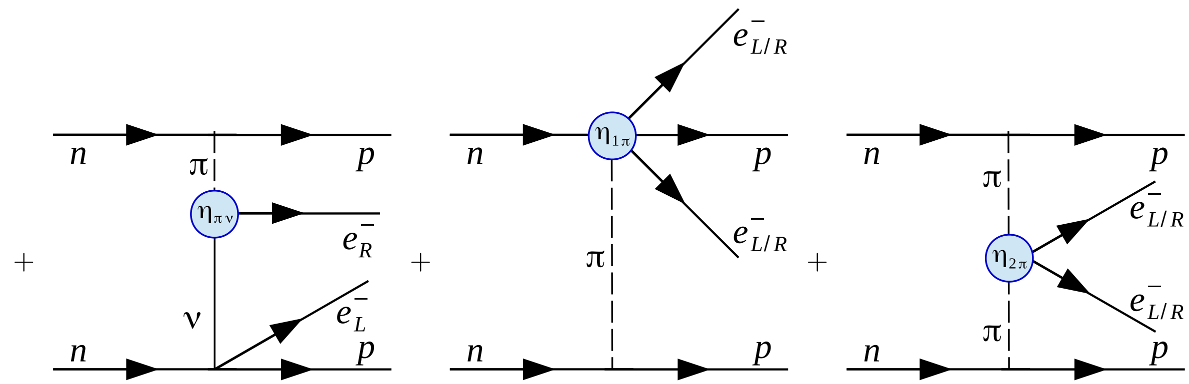


(a) The generic $0\nu\beta\beta$ decay process nucleon-level diagram.

(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.

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

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

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

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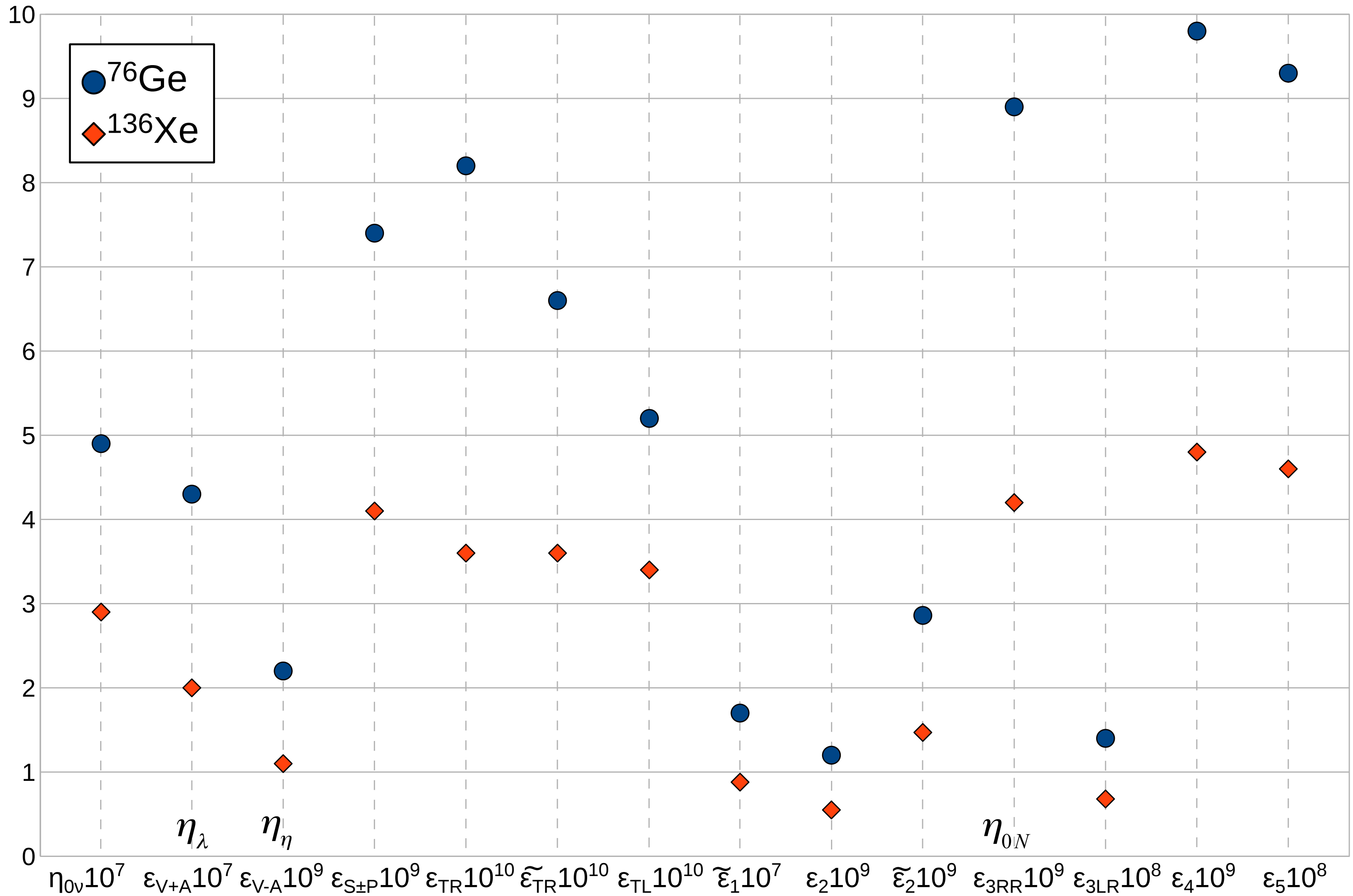
One coupling dominance

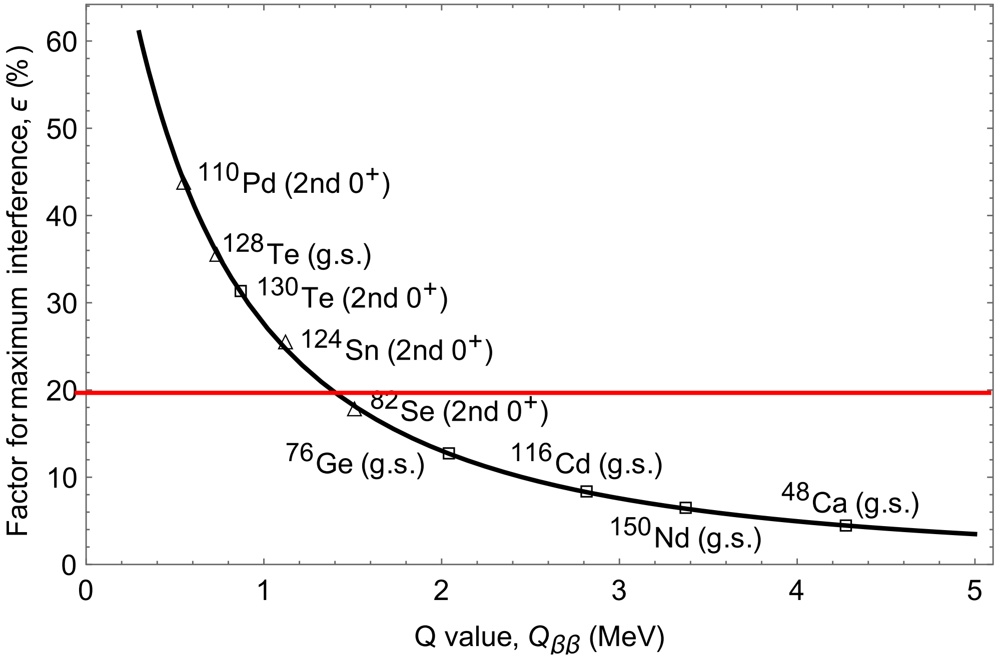
$$\left[T^{0\nu}_{1/2}\right]^{-1} = g_A^4 \left[\sum_i |\mathcal{E}_i|^2 \mathcal{M}_i^2 + \mathrm{Re}\left[\sum_{i\neq j} \cancel{\mathcal{E}_i\mathcal{E}_j} \mathcal{M}_{ij}\right]\right]$$

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



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

Small interference effects

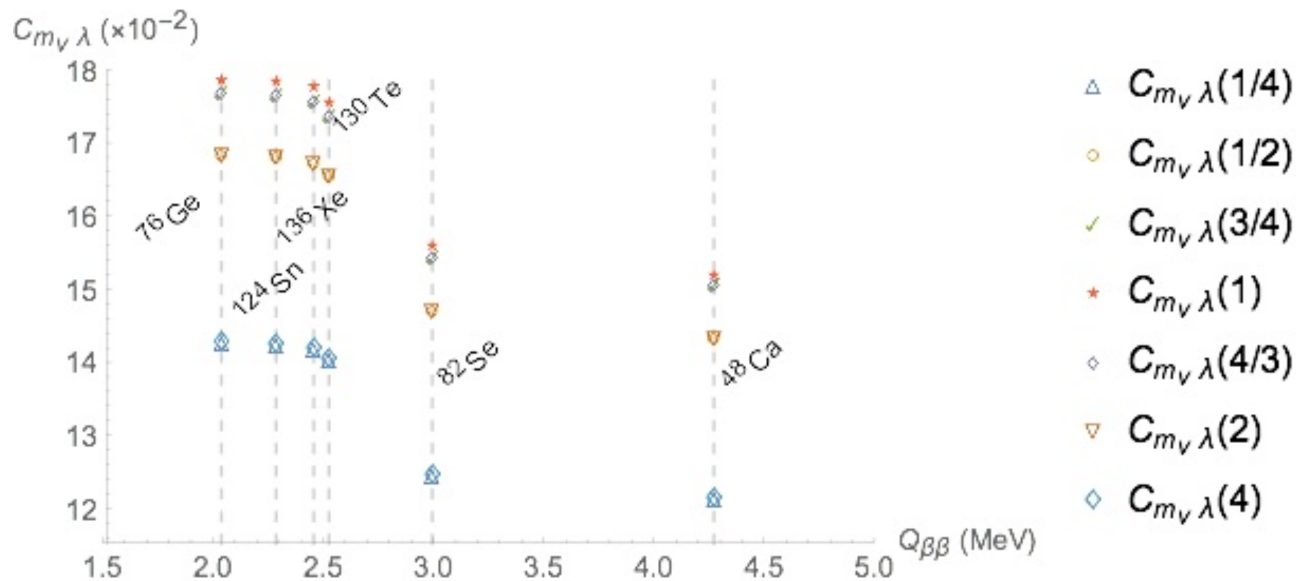


Interference between mass mechanism and heavy neutrino mechanism: F. Ahmed, A. Neacsu, and M. Horoi, Phys. Lett. B 769, 299 (2017).

In LRSM:

$$
\begin{aligned}
[T_{1/2}^{0\nu}]^{-1} = \left|\mathcal{M}_{GT}^{0\nu}\right|^2 \Big[& C_m|\eta_m|^2 + C_N|\eta_N|^2 + C_\lambda|\eta_\lambda|^2 + C_\eta|\eta_\eta|^2 \\
& + C_{mN}|\eta_m||\eta_N|\cos(\phi_m - \phi_N) + C_{m\lambda}|\eta_m||\eta_\lambda|\cos(\phi_m - \phi_\lambda) \\
& + C_{m\eta}|\eta_m||\eta_\eta|\cos(\phi_m - \phi_\eta) + C_{N\lambda}|\eta_N||\eta_\lambda|\cos(\phi_N - \phi_\lambda) \\
& + C_{N\eta}|\eta_N||\eta_\eta|\cos(\phi_N - \phi_\eta) + C_{\lambda\eta}|\eta_\lambda||\eta_\eta|\cos(\phi_\lambda - \phi_\eta) \Big]
\end{aligned}
$$

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

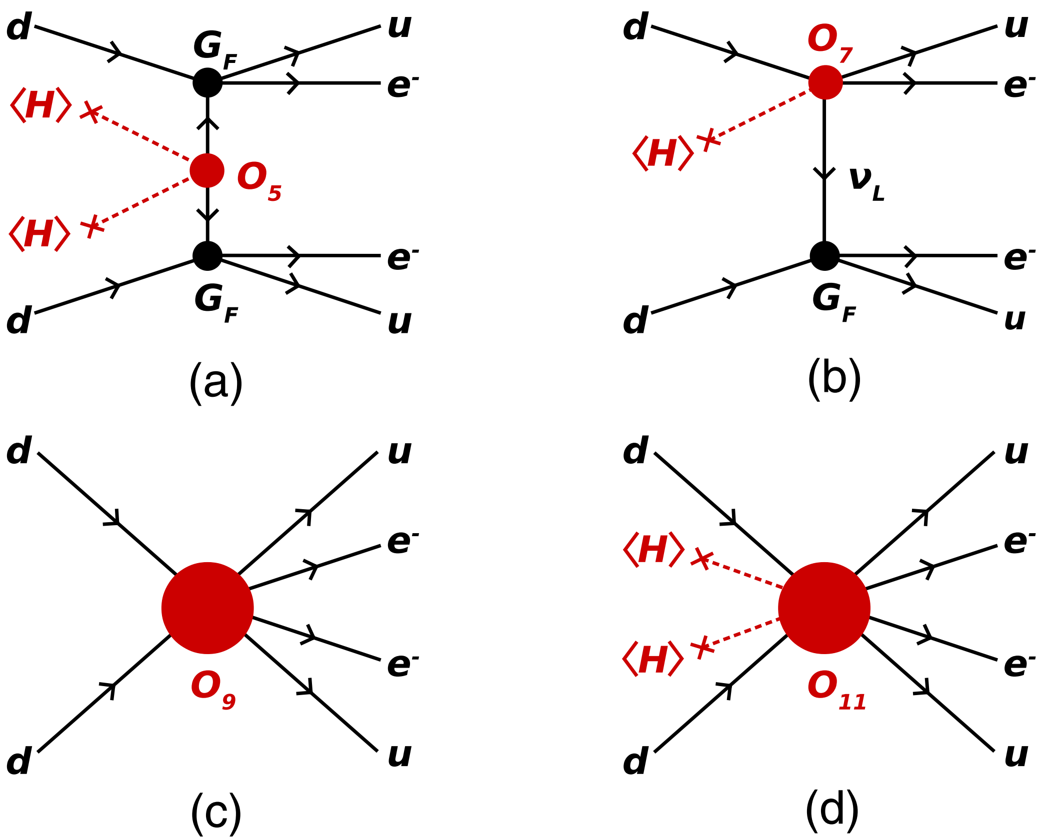


Consequences: - scales for new physics

- 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*)

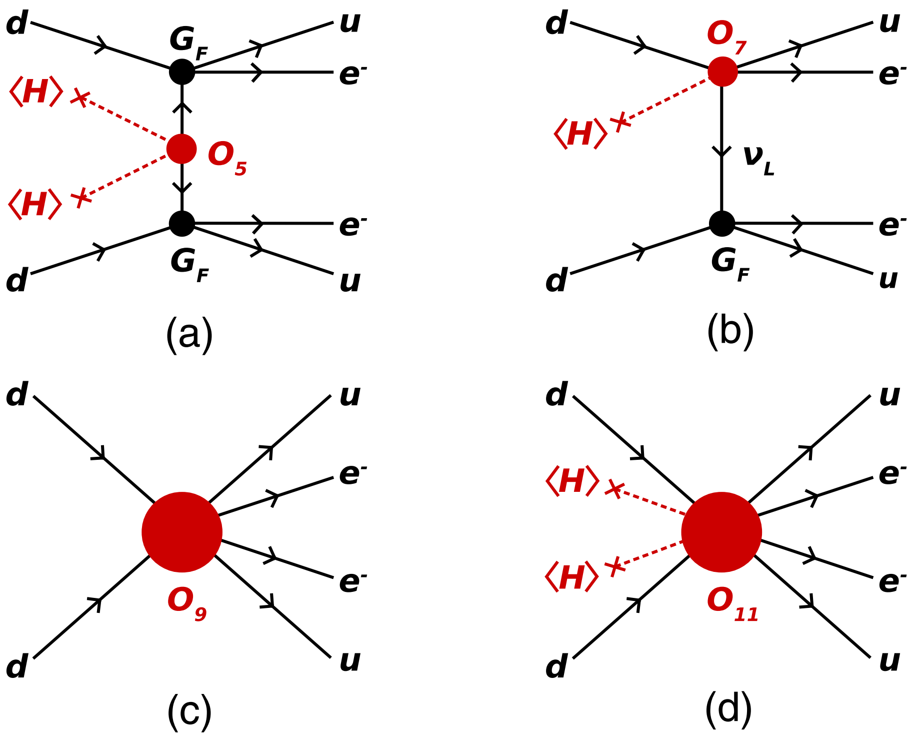
$\mathcal{O}_D$	$\bar{\epsilon}_D$	$\Lambda_D\,(GeV)$
$\mathcal{O}_5$	2.8×10^{-7}	2.12×10^{14}
$\mathcal{O}_7$	2.0×10^{-7}	3.75×10^{4}
$\mathcal{O}_9$	1.5×10^{-7}	2.48×10^{3}
$\mathcal{O}_{11}$	1.5×10^{-7}	1.16×10^{3}

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

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

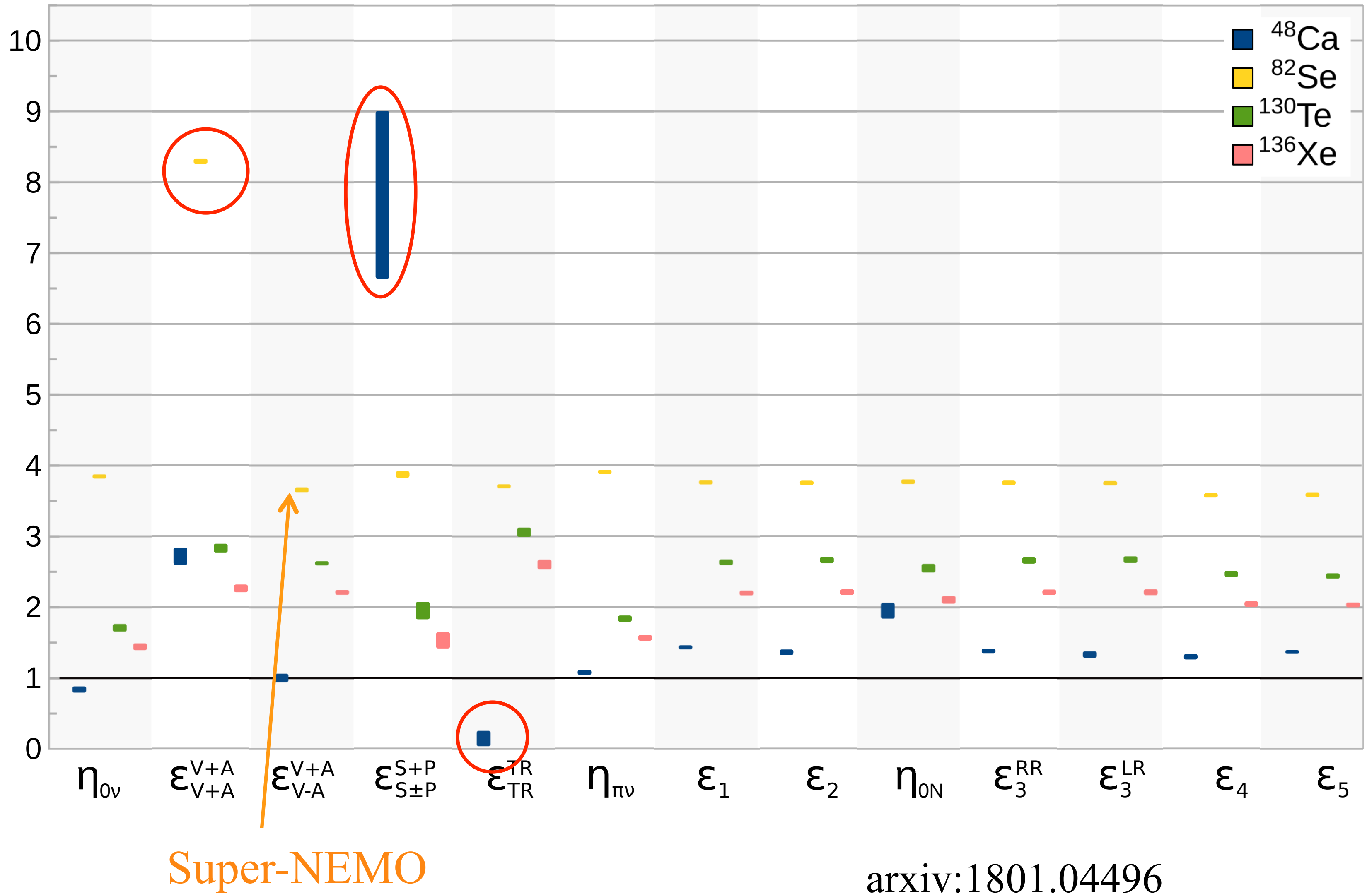
$g \approx 1 \quad v = 174\ GeV \qquad y_e = 3 \times 10^{-6}$ *electron mass Yukawa*

One coupling dominance: which one?

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

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

CMU Hamiltonians



arxiv:1801.04496

PRC 98, 035502 (2018)

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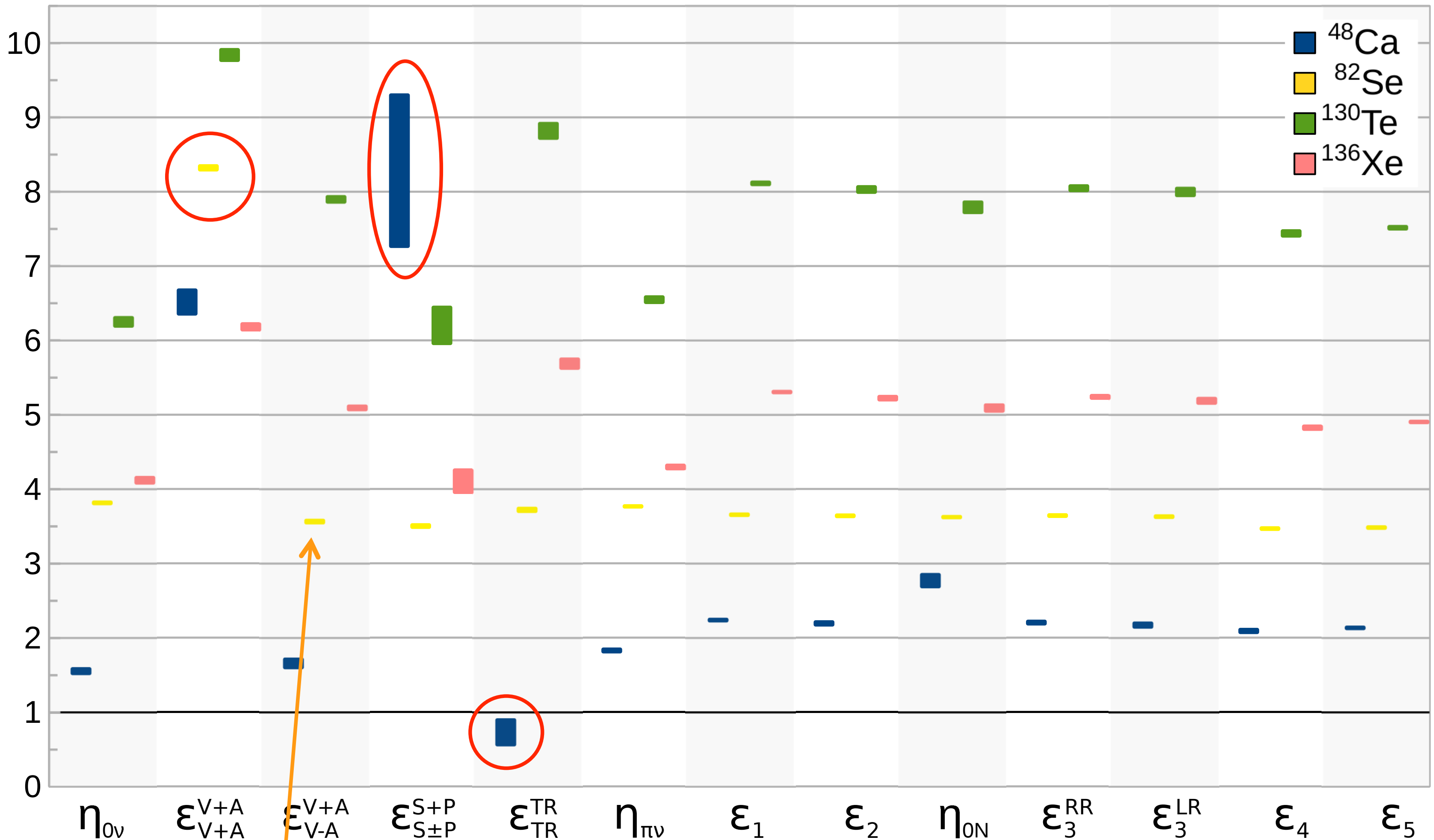
One coupling dominance: which one?

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

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

Strasbourg-Madrid Hamiltonians



Super-NEMO

PRC 98, 035502 (2018)

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Other BSM Physics Contributions

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

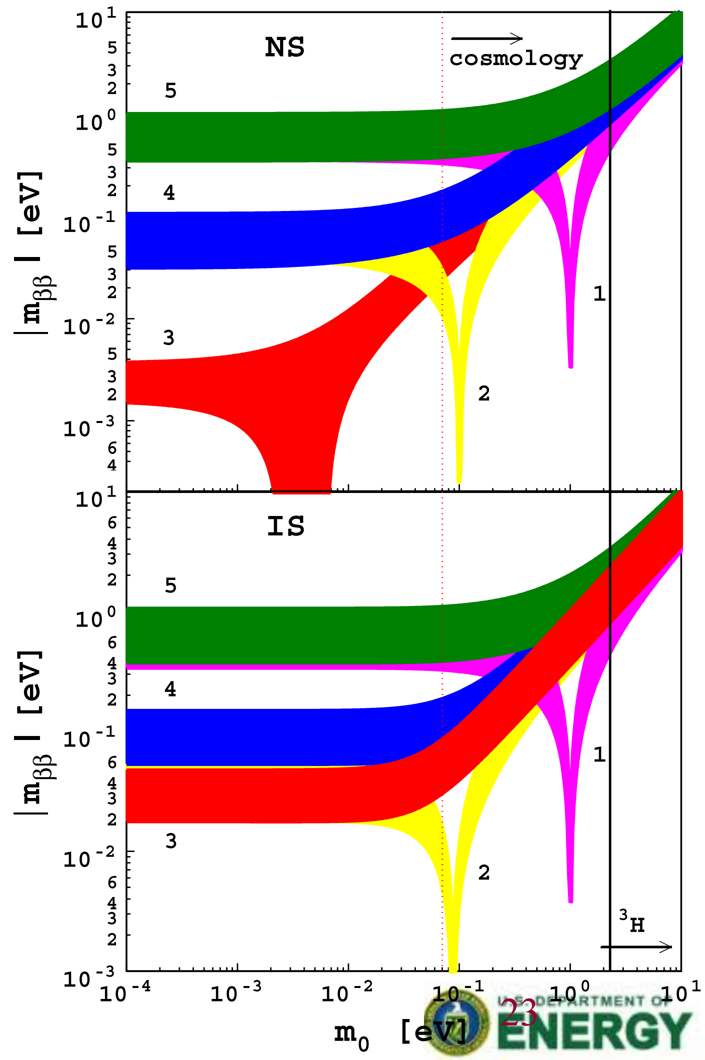
Neutrino Propagation in Nuclear Medium and Neutrinoless Double-β Decay

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

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda_{\rm LNV}^2}\sum_{i,j,q}(g_{ij}^q \overline{\nu_{Li}^C}\nu_{Lj}\cdot \bar{q}q + \text{H.c.}) + \frac{1}{\Lambda^3}\sum_{i,j,q} h_{ij}^q \overline{\nu_{Li}} i\gamma^\mu \overleftrightarrow{\partial}_\mu \nu_{Lj}\cdot \bar{q}q,$$

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

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



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

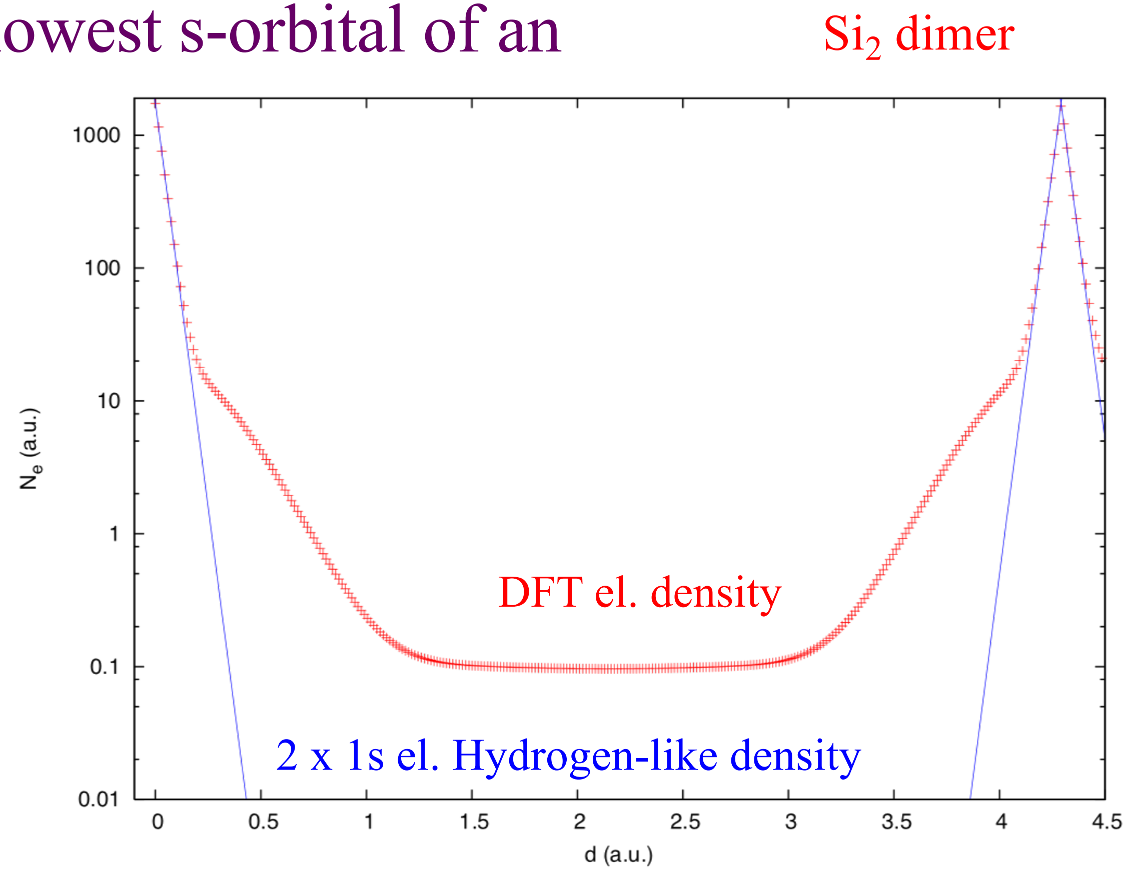
Electron density near nucleus:

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

Electron density inside nucleus:

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

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



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

Neutrinos in matter: local mass eigenstates

$$H = \frac{1}{2E}\left[U_{vac}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix}U_{vac}^{+} + \begin{pmatrix}2EV & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]$$

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

Time (space) dependent flavor amplitudes evolution:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

Local in-matter mass eigenstates approach:

$$H = \frac{1}{2E}U_m\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta M_{21}^2 & 0\\ 0 & 0 & \Delta M_{31}^2\end{pmatrix}U_m^{+}$$

$$\nu_f = U_m \nu_m$$

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

Time dependence of ν_m: $$i\dot{\nu}_m = U_m^\dagger\left(H_0 + V\right)U_m\nu_m - iU_m^\dagger\dot{U}_m\nu_m$$

$$i\frac{\Delta\nu_f}{\Delta t} \approx 0$$

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Neutrinoless double beta decay in vacuum

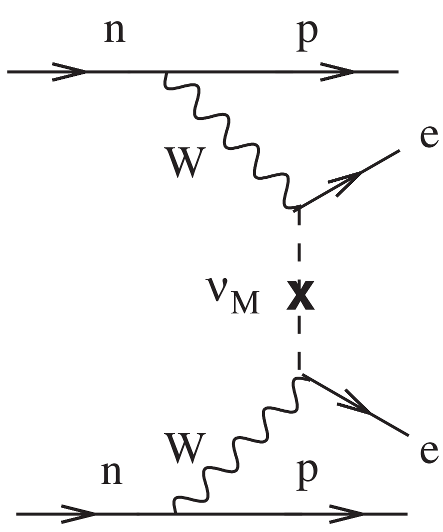
$$A_{0\beta\beta} \propto NP = \langle 0 | \, T \left[\psi_{eL}(x_1) \psi_{eL}^T(x_2) \right] | 0 \rangle \qquad \psi_e(x) = \sum_{a=1}^{N(3)} U_{ea} \psi_a(x)$$

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

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

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

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



Neutrinoless double beta decay of atomic nuclei

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

Conclusions:

- the in-matter propagator still contains the vacuum PMNS matrix and masses!
- The formalism allows the extension of this result if sterile neutrinos are present (a = 1…4,(5))
- The propagators for long range 0νββ diagrams seem to remain unchanged (work not finished yet)

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

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

In atomic nuclei NP = In vacuum NP

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

Are there any effects of the spikes in the electron density?

Answer 1: potentially for Majoron decay!

PHYSICAL REVIEW D VOLUME 45, NUMBER 5 1 MARCH 1992

Majoron decay of neutrinos in matter

C. Giunti, C. W. Kim, and U. W. Lee
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W. P. Lam

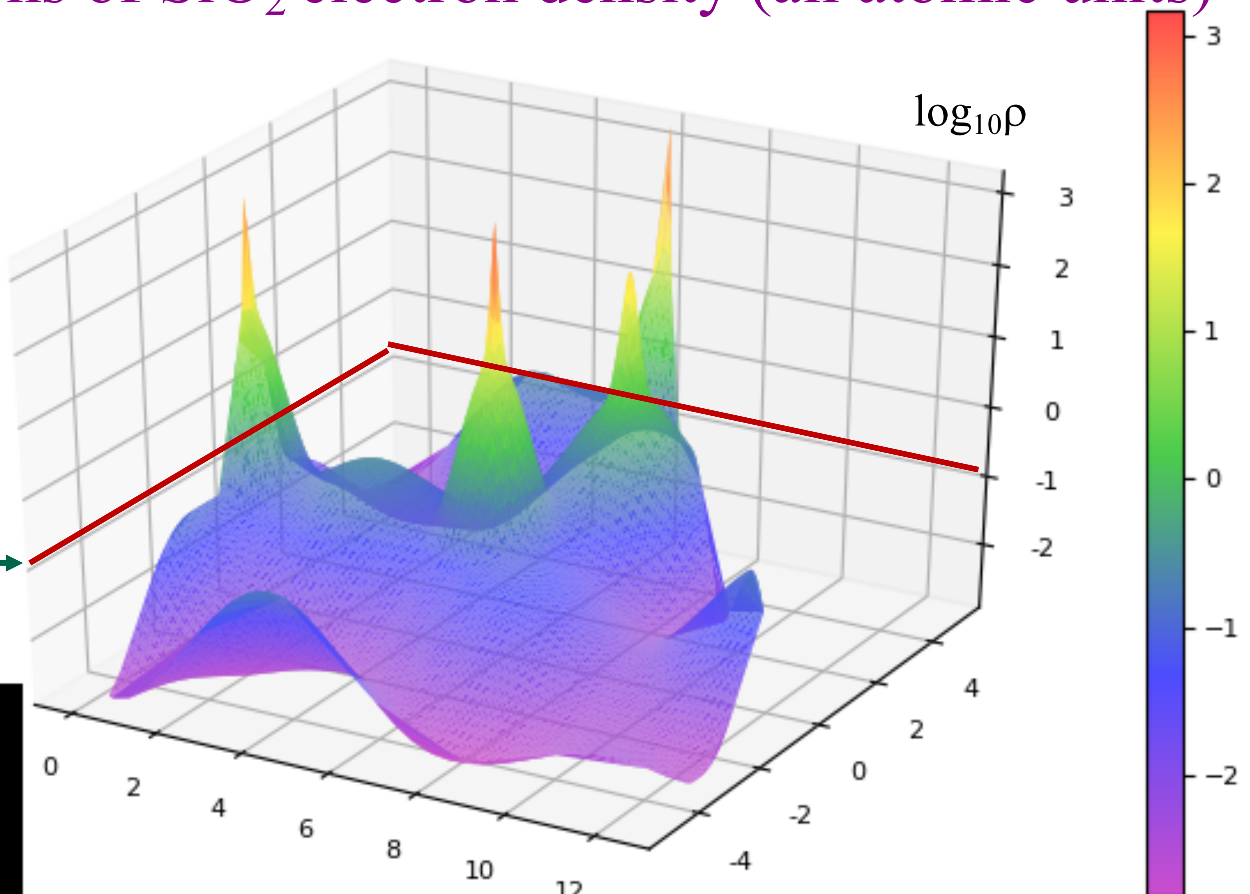
with production of any massless pseudoscalar boson. In particular, we discuss the two-generation case and show that *in matter* the helicity-flipping decays are dominant over the helicity-conserving decays. The implications of the Majoron decay for the neutrinos from astrophysical objects are also briefly discussed.

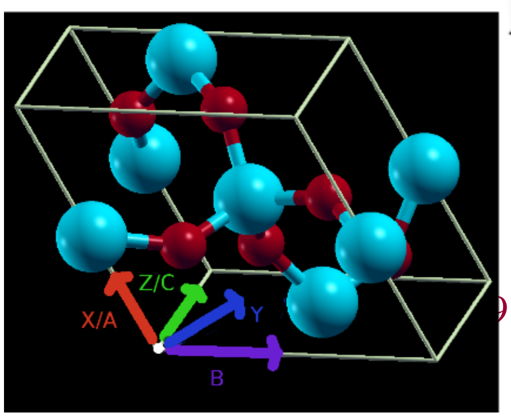
Are there any effects of the spikes in the electron density?

Answer 2: matter effects in neutrino oscillations?

DFT calculations of SiO_2 electron density (all atomic units)

Average flat density used in matter effects



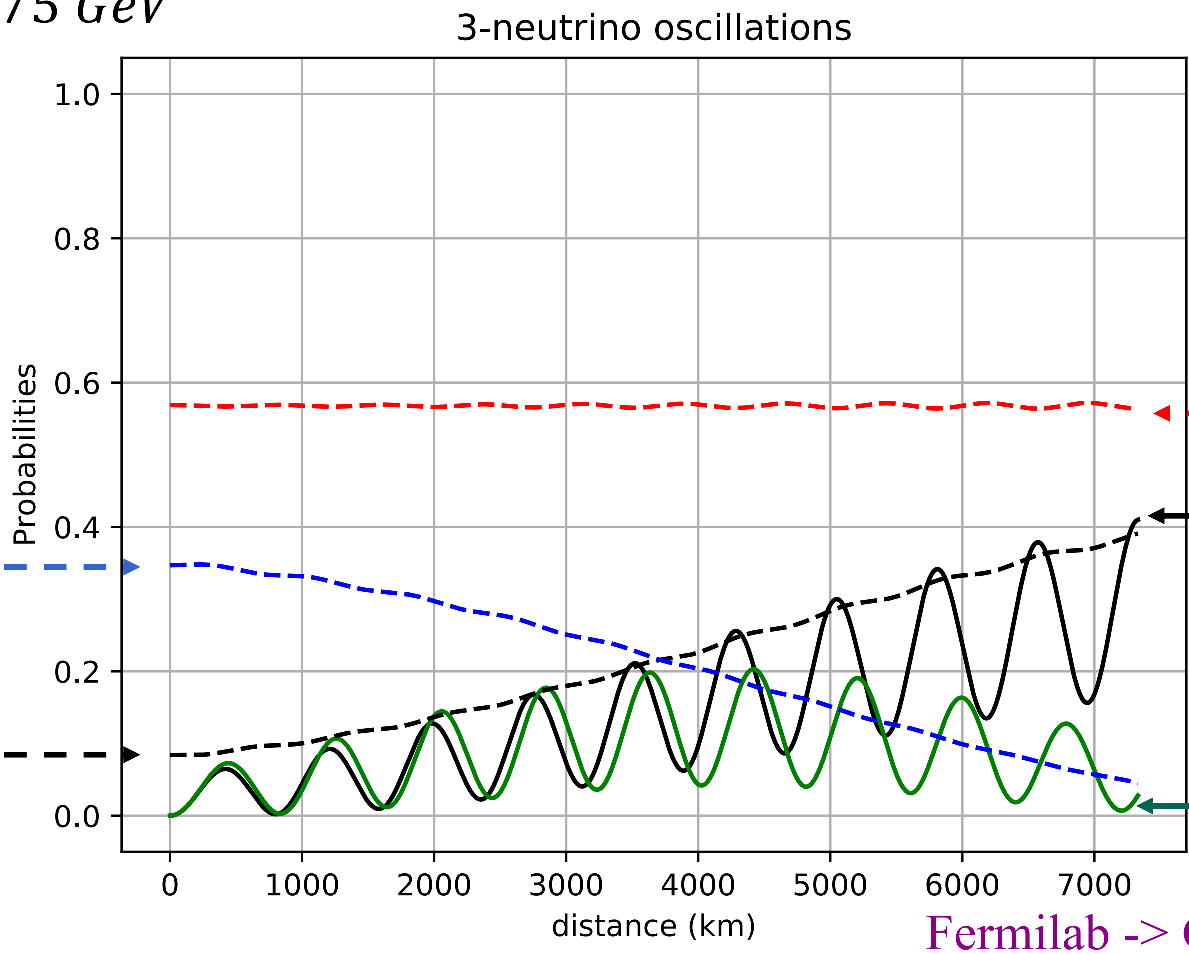


Are there any effects of the spikes in the electron density?

Answer 2: yes for matter effects in neutrino oscillations!

$E_{\nu_\mu} = 0.75\ GeV$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$



$P_{\nu_\mu \nu_3}$

$P_{\nu_\mu \nu_e}$ mixed-spikes

$P_{\nu_\mu \nu_2}$

$P_{\nu_\mu \nu_1}$

$P_{\nu_\mu \nu_e}$ flat

Fermilab -> Gran Sasso or CERN -> Sanford

Are there any effects of the spikes in the electron density?

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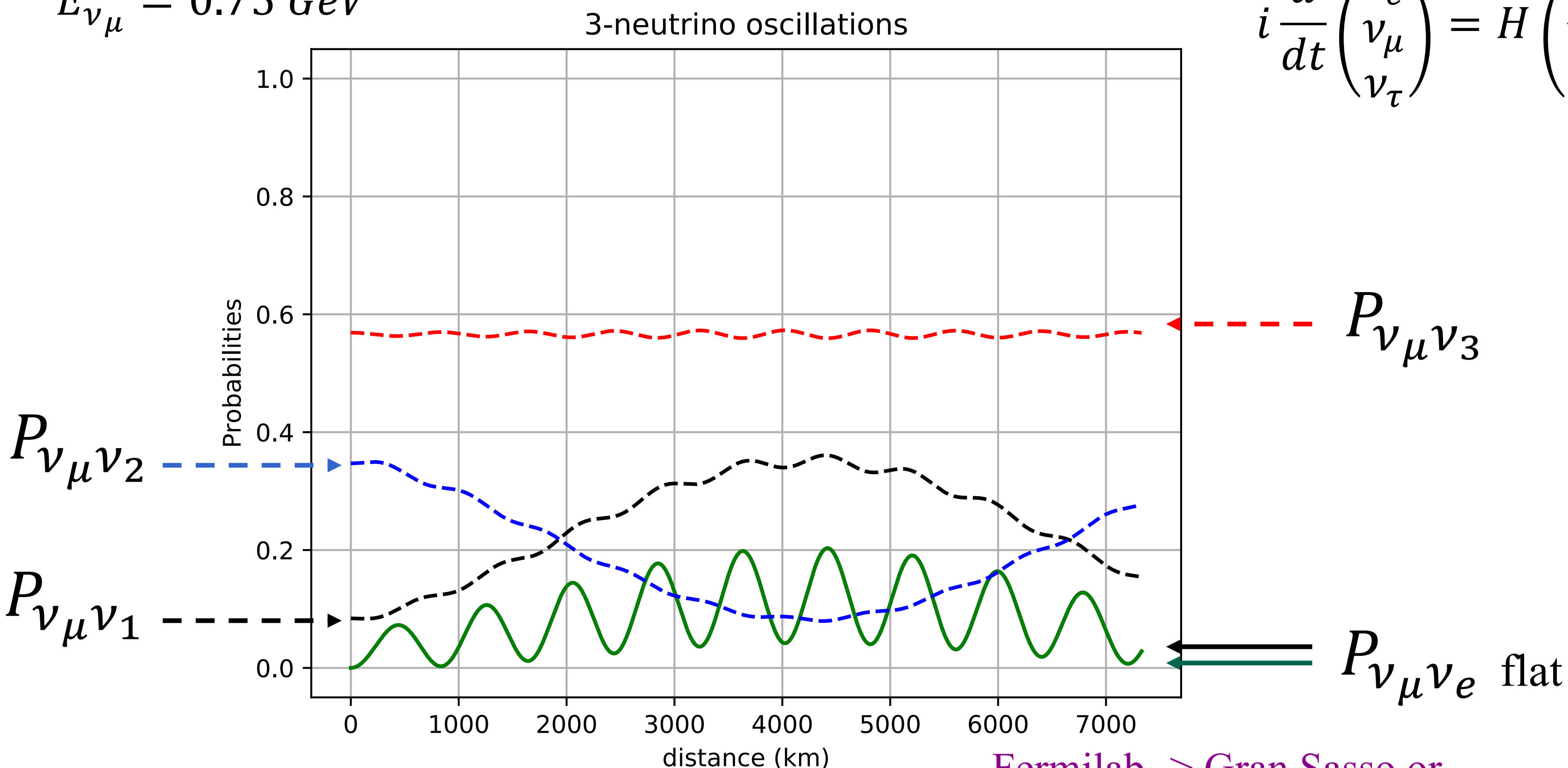
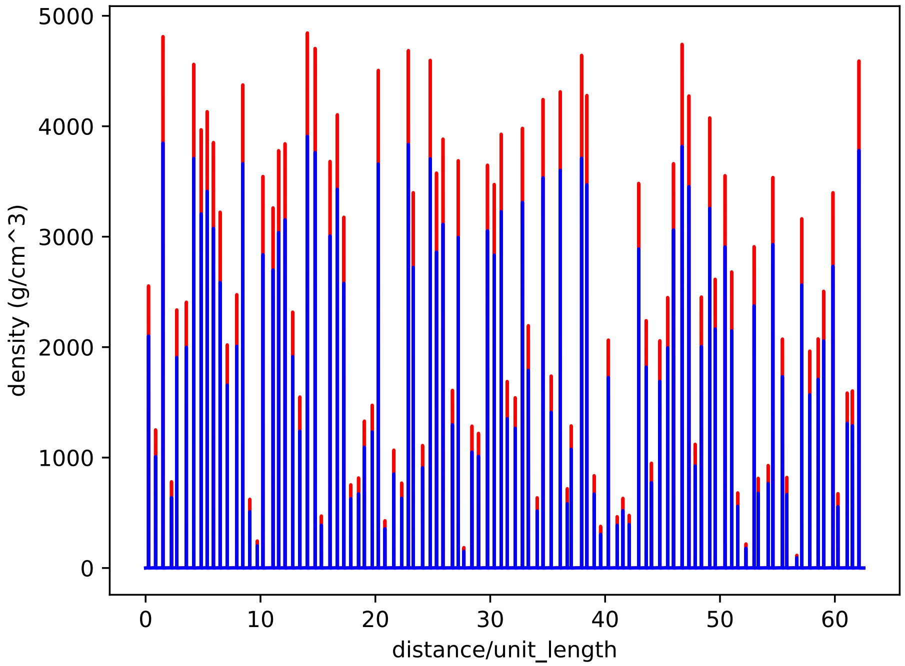
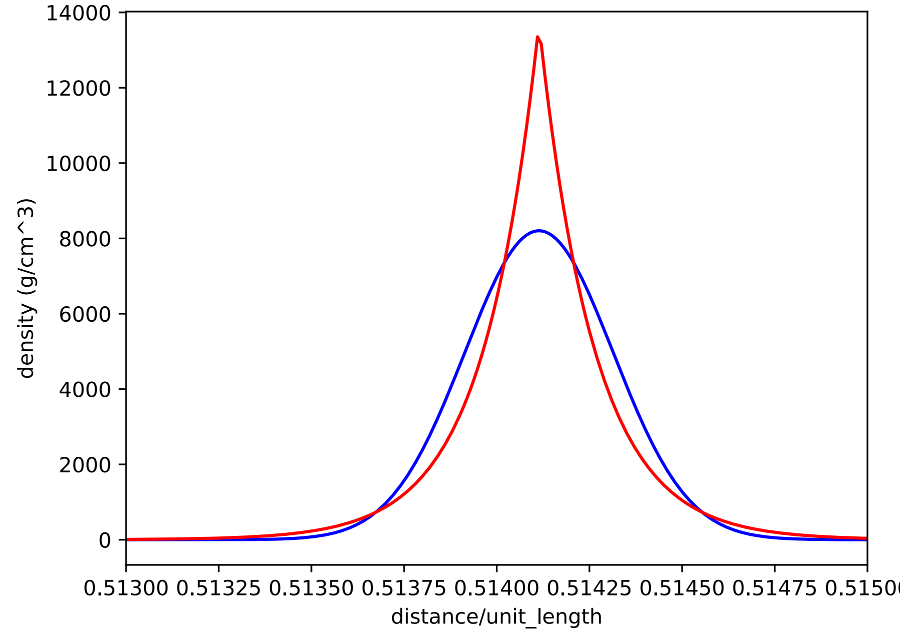


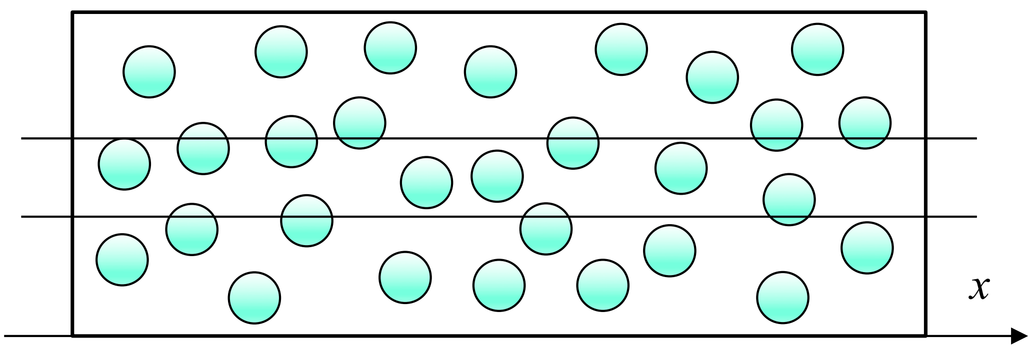
Fermilab -> Gran Sasso or

CERN -> Sanford

Matter density model

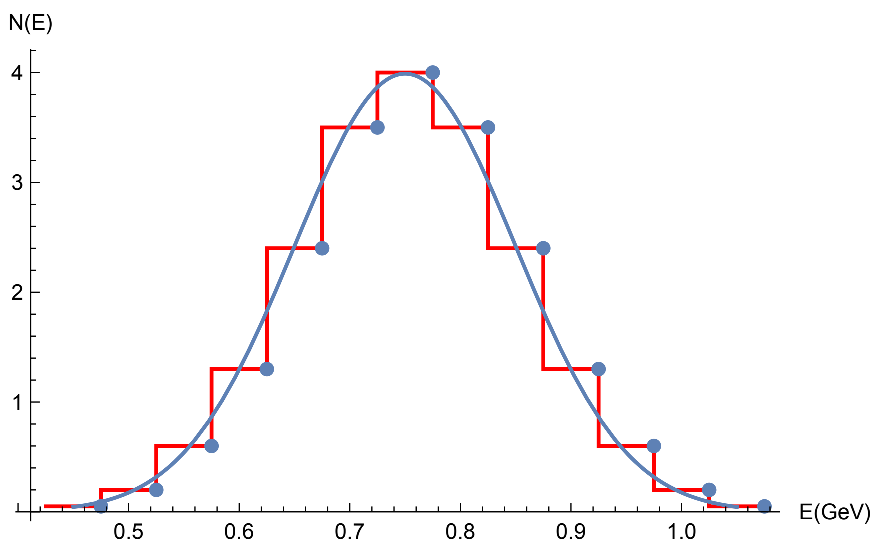


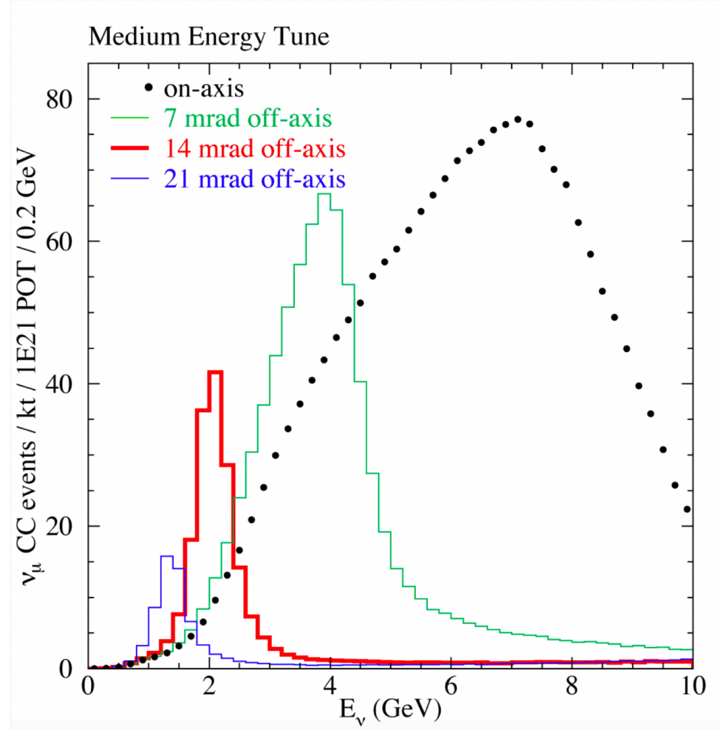




- Different spike shapes produce the same result
- The 3D topology of atoms can be simulated in 1D with random spikes
- Actual density is a mixture: $\rho_{mixed\_spikes}=0.6\rho_{spikes}+0.4\rho_{flat}$
- $\rho_{ave}= \rho_{flat} =3.8$ g/cm^3 (PREM)

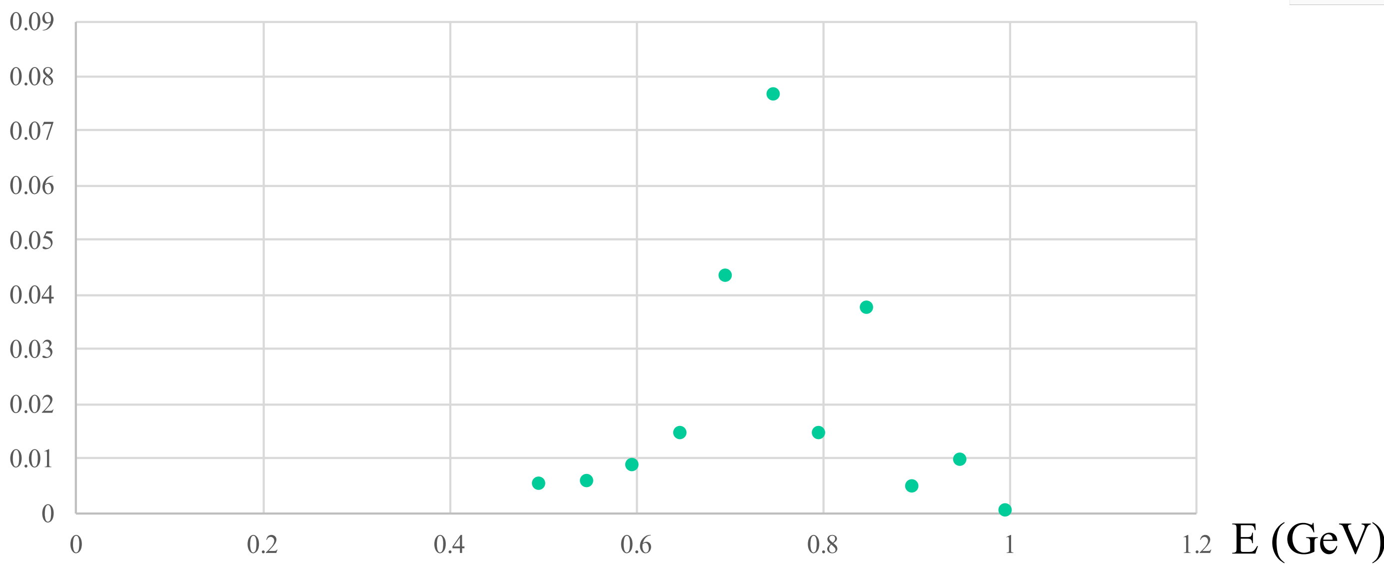
Energy distribution





NUMI beam

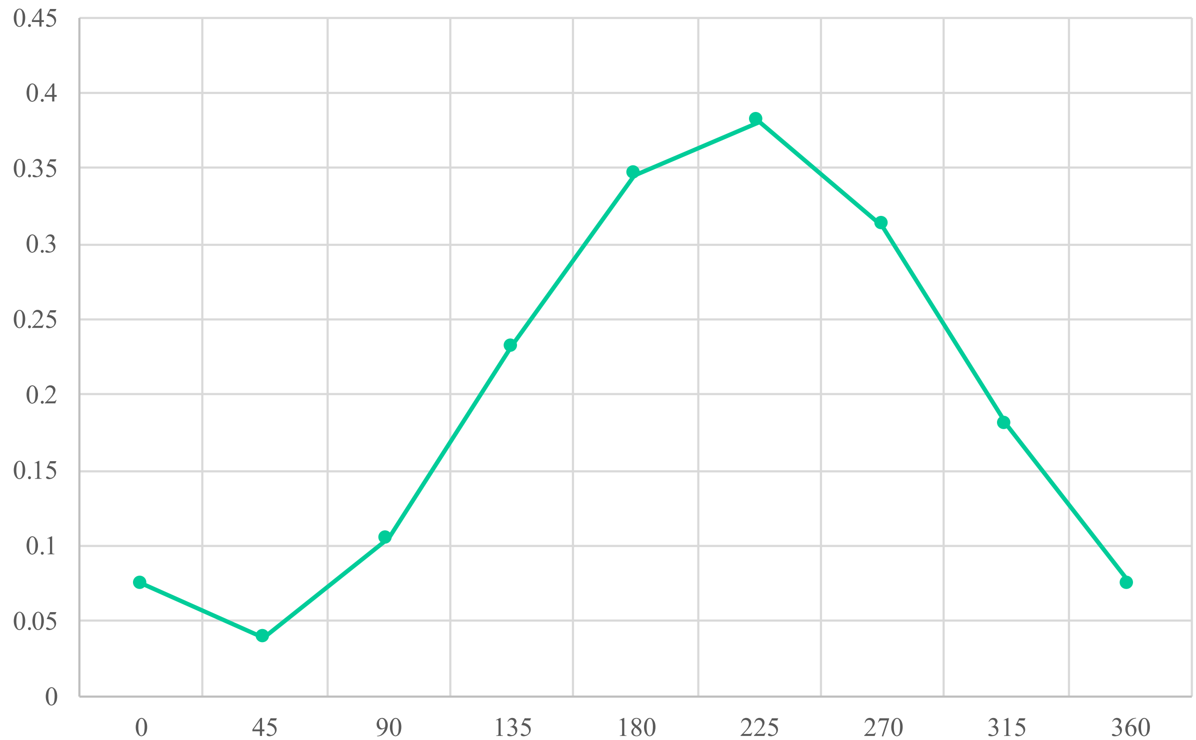
$$\langle P_{mixed\_spikes} - P_{flat} \rangle = 0.22$$



Dependence on δ_{CP}

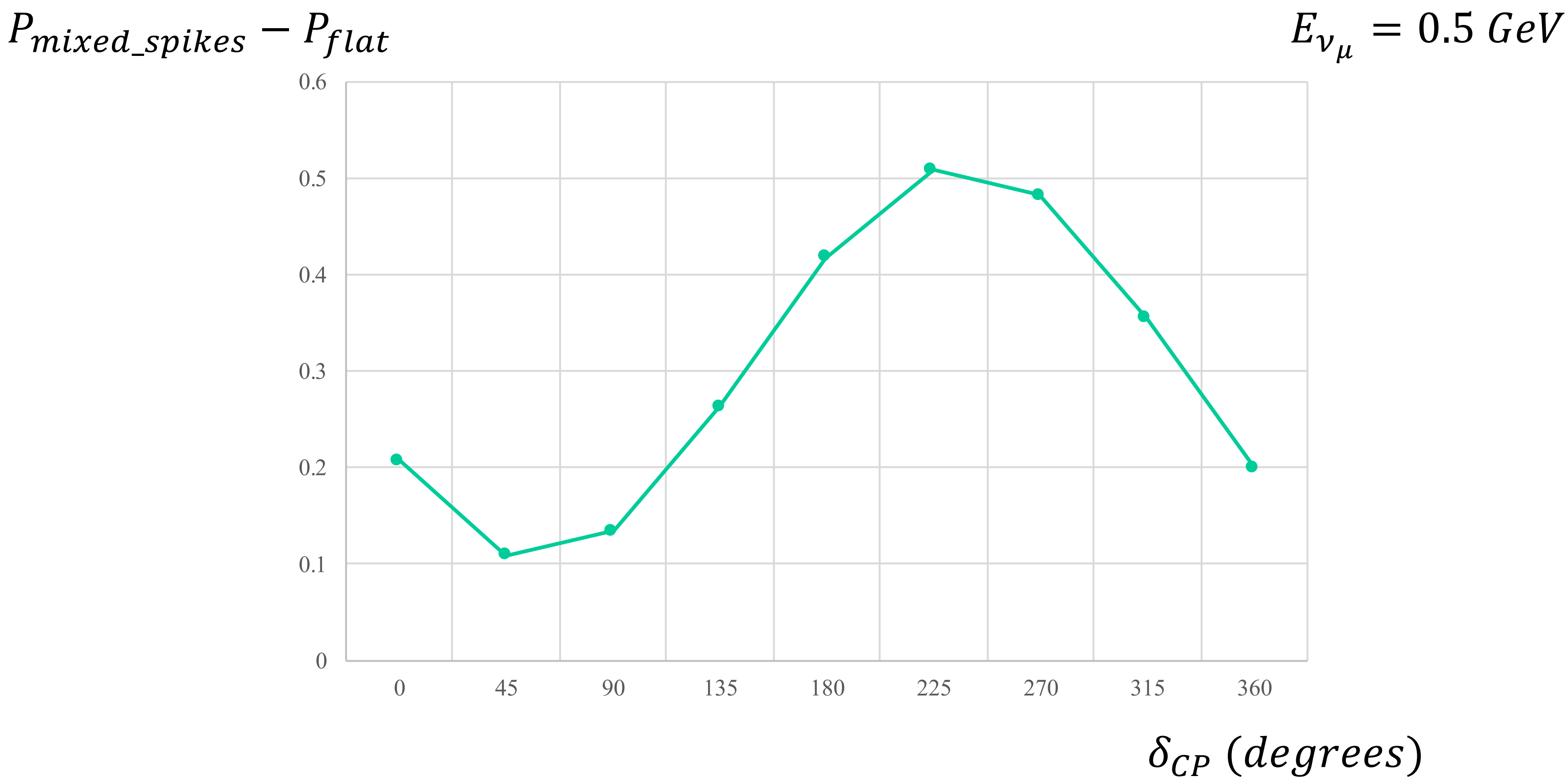
$P_{mixed\_spikes} - P_{flat}$

$E_{\nu_\mu} = 0.75\ GeV$



$\delta_{CP}\ (degrees)$

Dependence on δ_{CP}

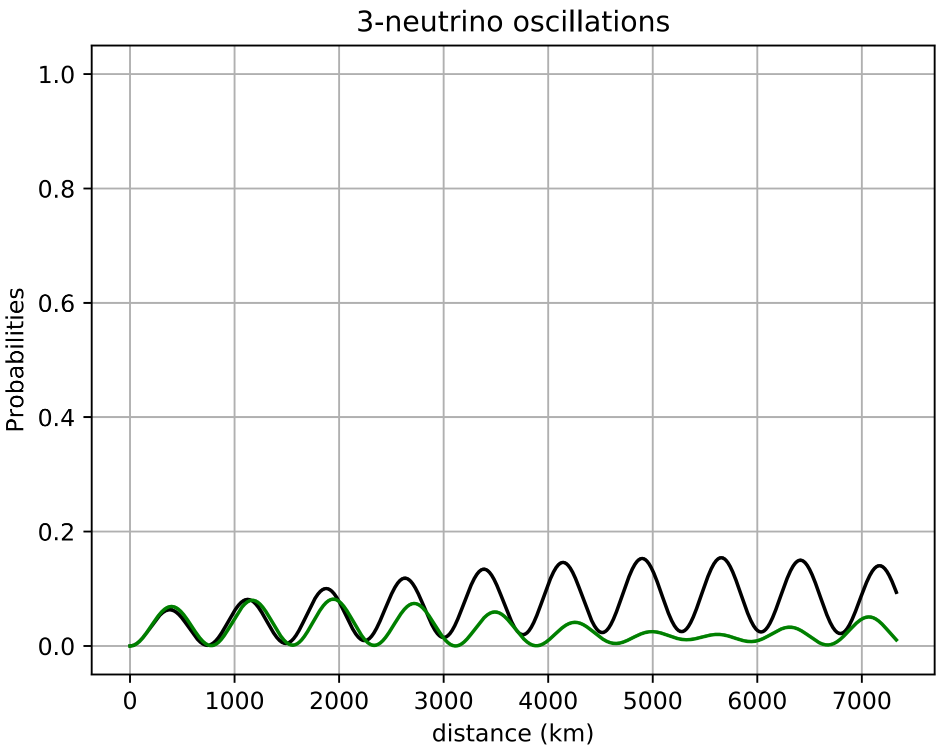


Summary

- Neutrinoless DBD ($0\nu\beta\beta$), if observed, will represent a big step forward in our understanding of the neutrinos, and of the physics beyond Standard Model.
- Ratios of half-lives for several isotopes are essential to account for alternative $0\nu\beta\beta$ 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.
- The effects of the high electron densities around atomic nuclei may be observed in Majoron decay and in (very) long baseline neutrino oscillations experiments.

Dependence on δ_{CP}

$E_{\nu_\mu} = 0.75\ GeV$



$E_{\nu_\mu} = 0.5\ GeV$