# Towards a complete description of the neutrinoless double beta decay

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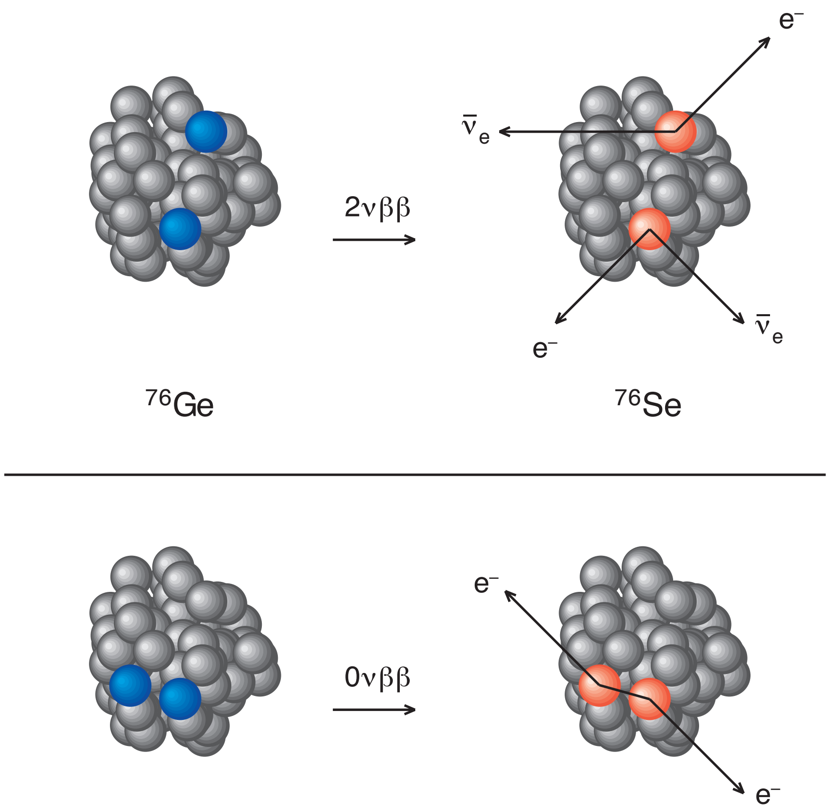
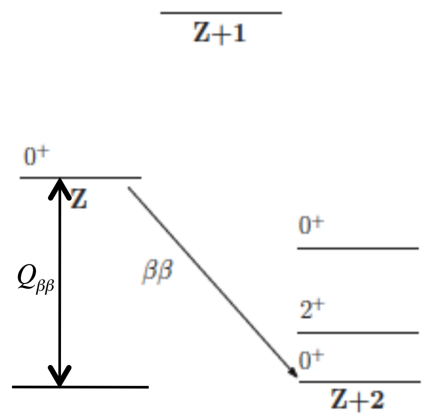
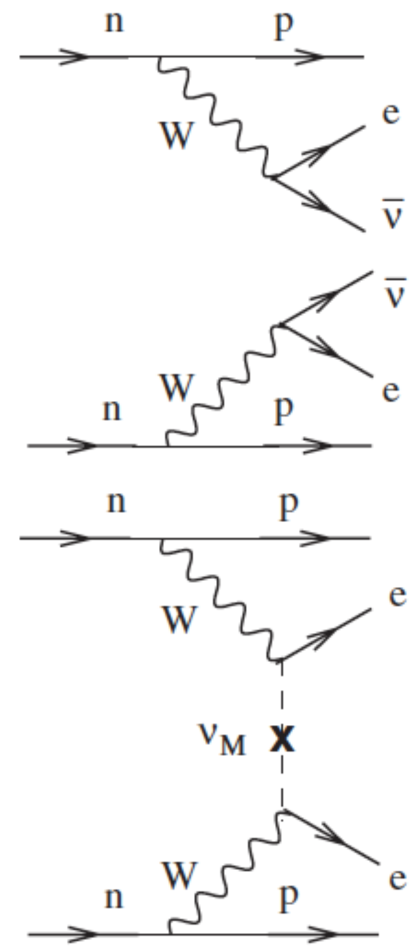
➢**Support from NSF grant PHY-1404442, DOE grants DE-SC0008529, and DE-SC0015376 is acknowledged**

# Classical Double Beta Decay Problem




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

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

# The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

**Takaaki Kajita**

**Prize share:** 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

**Arthur B. McDonald**

**Prize share:** 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

# Neutrino Masses

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i}\,|\nu_\alpha\rangle$$

*PMNS – matrix*

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha 1/2} & 0 & 0 \\ 0 & e^{i\alpha 2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{12} \equiv \cos\theta_{12}\,,\; s_{12} = \sin\theta_{12}\,,\; etc$$

## - Tritium decay:

$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < \; 2.2eV\,(Mainz\;\exp.)$$

$$KATRIN\;(to\;take\,data): goal\;\; m_{\nu_e} < 0.3eV$$

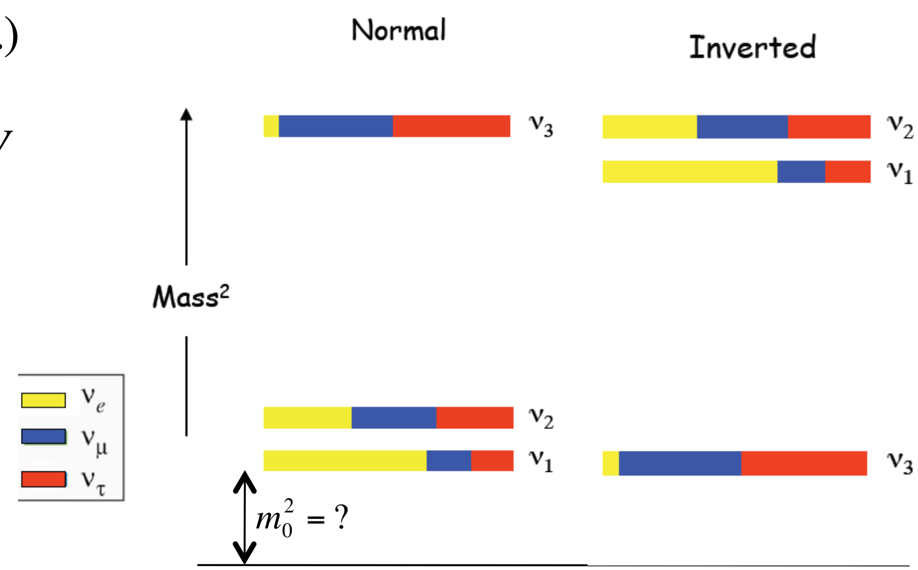
## - Cosmology: CMB power spectrum, BAO, etc,

$$\sum_{i=1}^{3} m_i < 0.23eV$$

$$Goal: 0.01eV\;\;(5-10\;\;y)$$

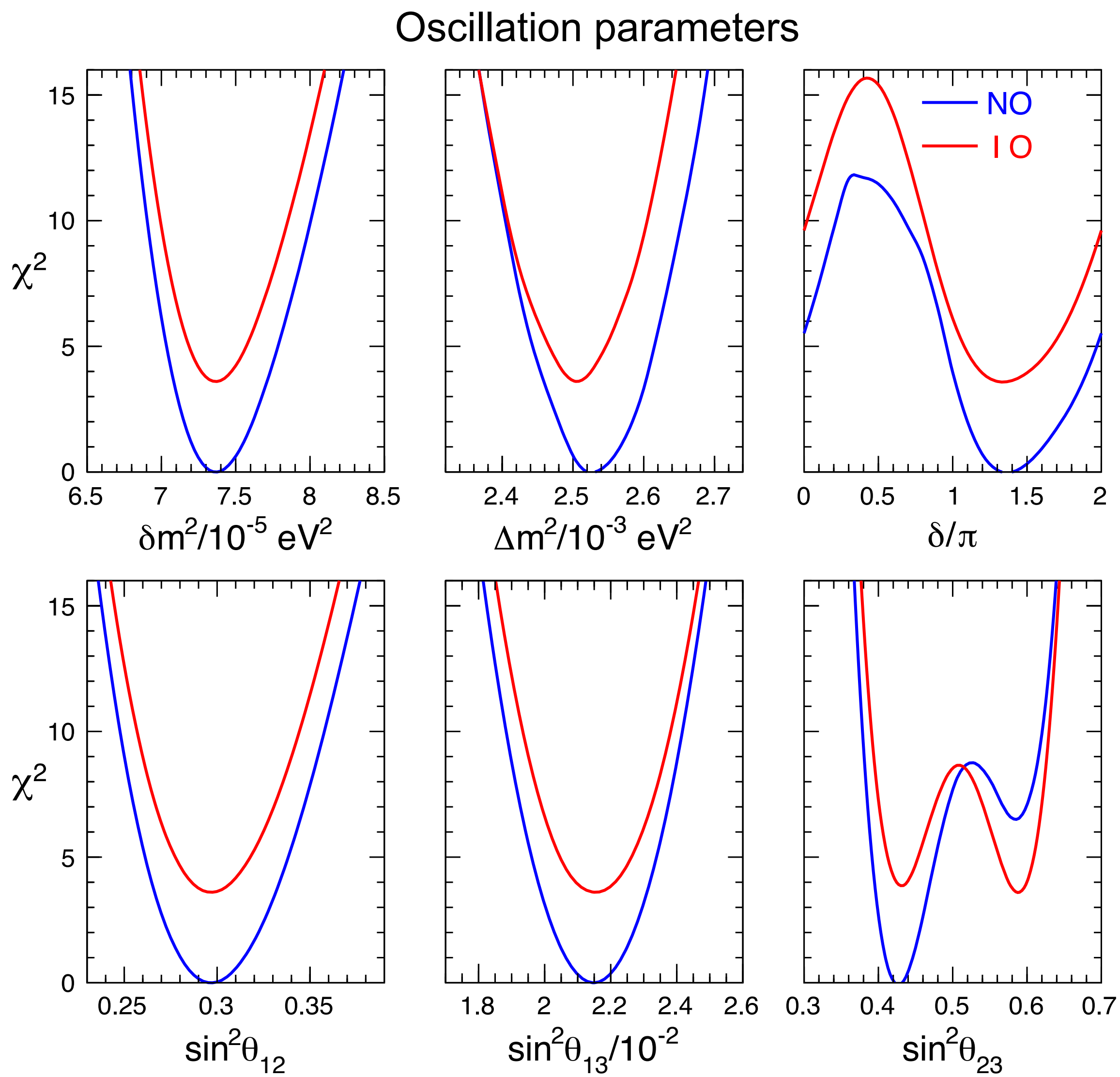
$$\Delta m^2_{21} \approx 7.5\times 10^{-5}\;\;eV^2\,(solar)$$

$$|\Delta m^2_{32}| \approx 2.4\times 10^{-3}\;\;eV^2\,(atmospheric)$$




Two neutrino mass hierarchies

# Neutrino oscillations parameters




Bari group:

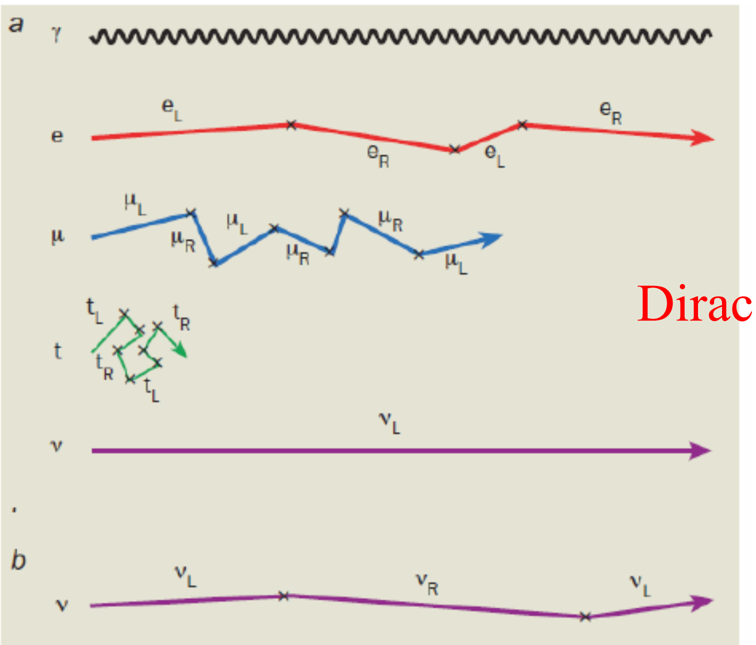
arxiv.org/1703.04471

$$(\Delta\chi^2_{\text{IO-NO}})^{1/2} = 2$$

# Neutrino masses: Dirac vs Majorana

The fermions and the W/Z bosons get mass: by interacting with the Higgs field.

This mechanisms could also work for neutrinos, if they would be Dirac fermions. Then, it would be difficult to explain why their masses (Yukawa couplings) are so small.

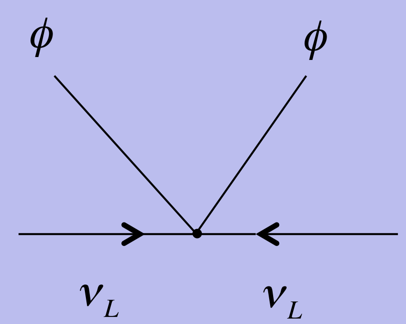



Dirac mass

*The mass terms come from the Yukawa* interaction :

$\bar{\psi}_i Y_{ij}\ \psi_j < \phi > \qquad where\ \ < \phi >= 246\ GeV$

Weinberg's dimension-5 BSM operator contributing to Majorana neutrino mass



## Fork on the Road: Are Neutrinos Majorana or Dirac Fermions?

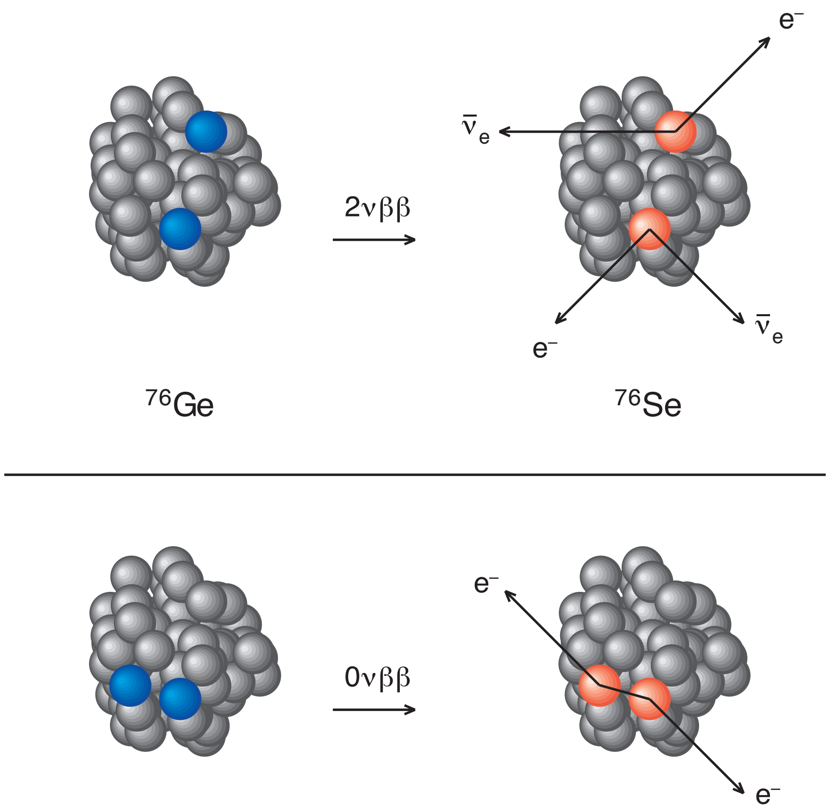
**Best (Only?) Bet: Neutrinoless Double-Beta Decay.**

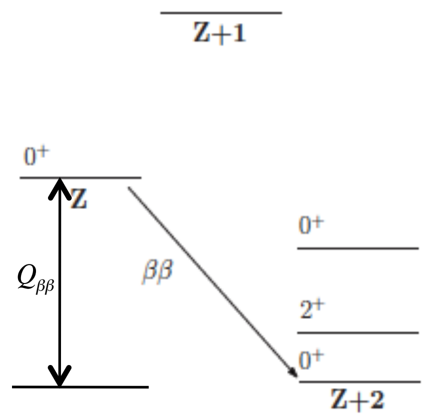
**We learned that neutrinos have mass, but we don't know how to extend the Standard Model!**

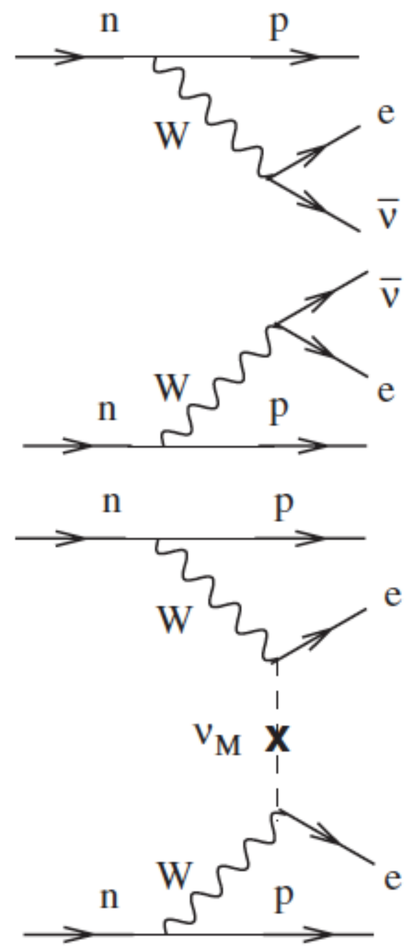
# Nobel prize 2025: Neutrinoless Double Beta Decay?

**Probably the best chance of the low-energy nuclear physics community to get another Nobel prize!**

# Classical Double Beta Decay Problem



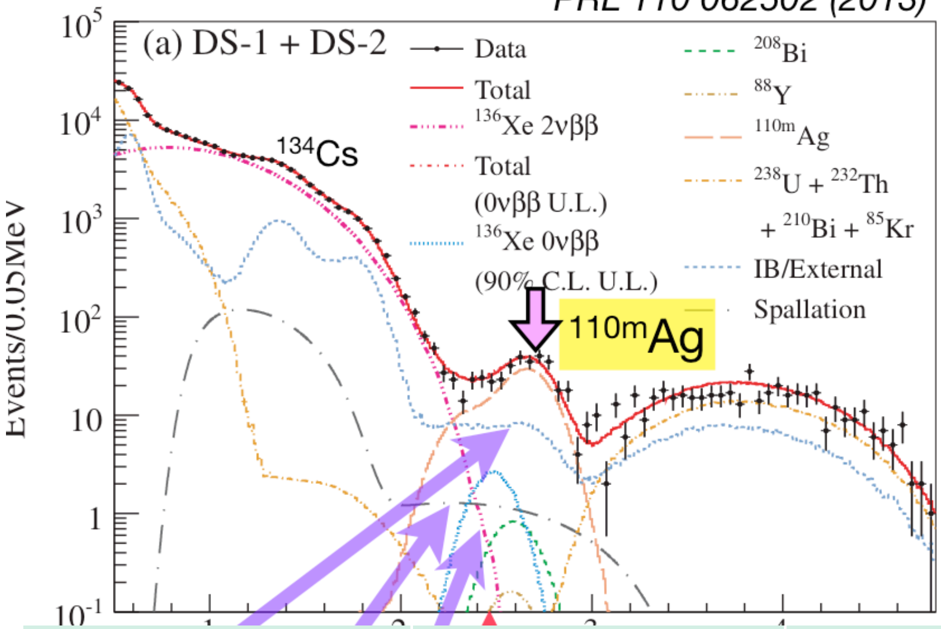




$$\langle m_{\beta\beta} \rangle = \left| \sum_k m_k U_{ek}^2 \right|$$

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

*Phase1 (before purification)*

*PRL 110 062502 (2013)*




# $^{136}$Xe ββ Experimental Results

| | $T^{0\nu}_{1/2}$(lim) | $T^{0\nu}_{1/2}$(Sens) |
|---|---|---|

KamLAND-Zen

Half-life limit (@90%C.L.)

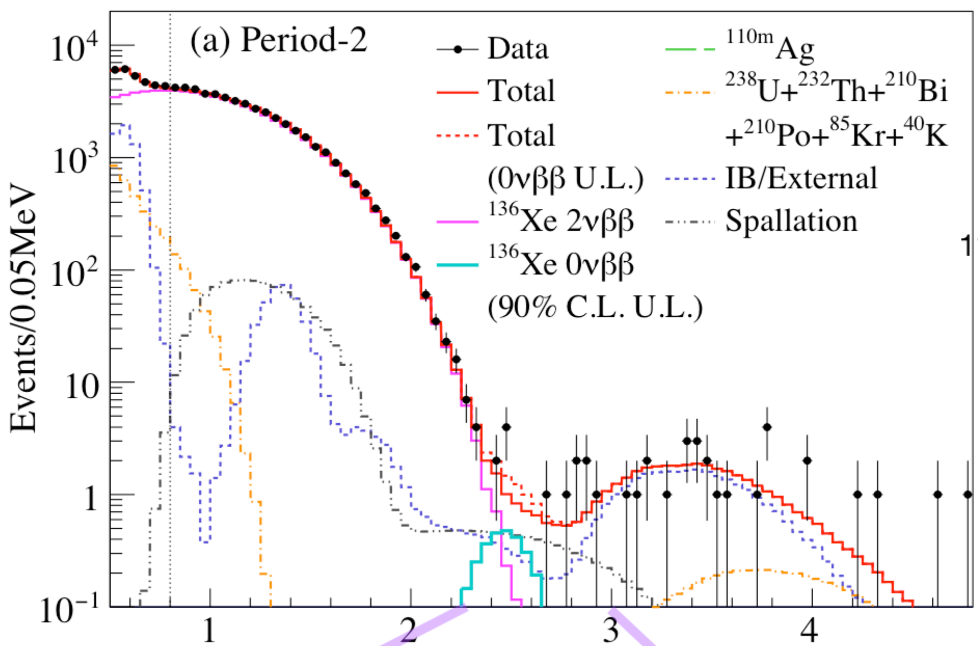
Phase1 $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

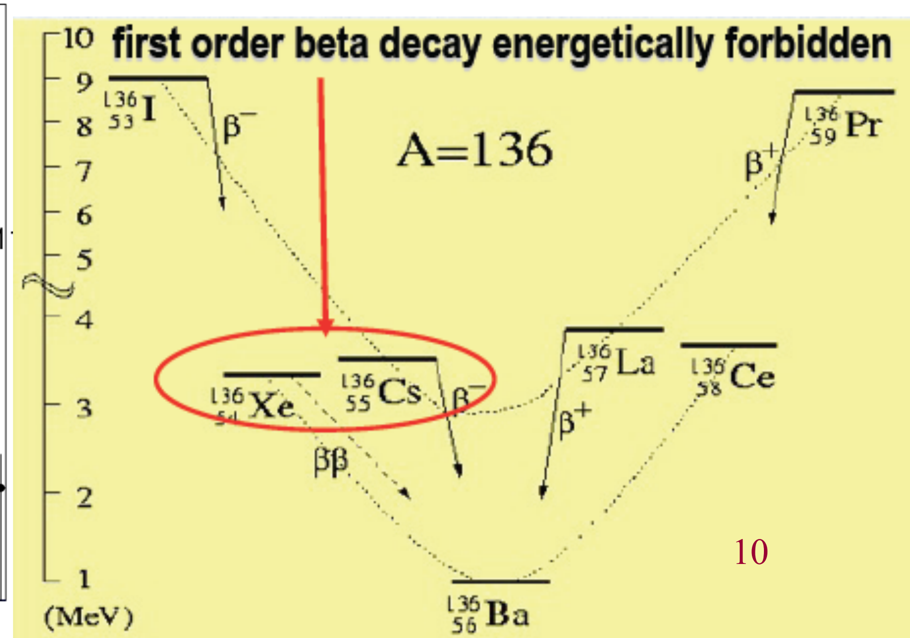
Phase2 $T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr

×6!

Combined **$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr**

$-0.0215\ MeV^{-1}$

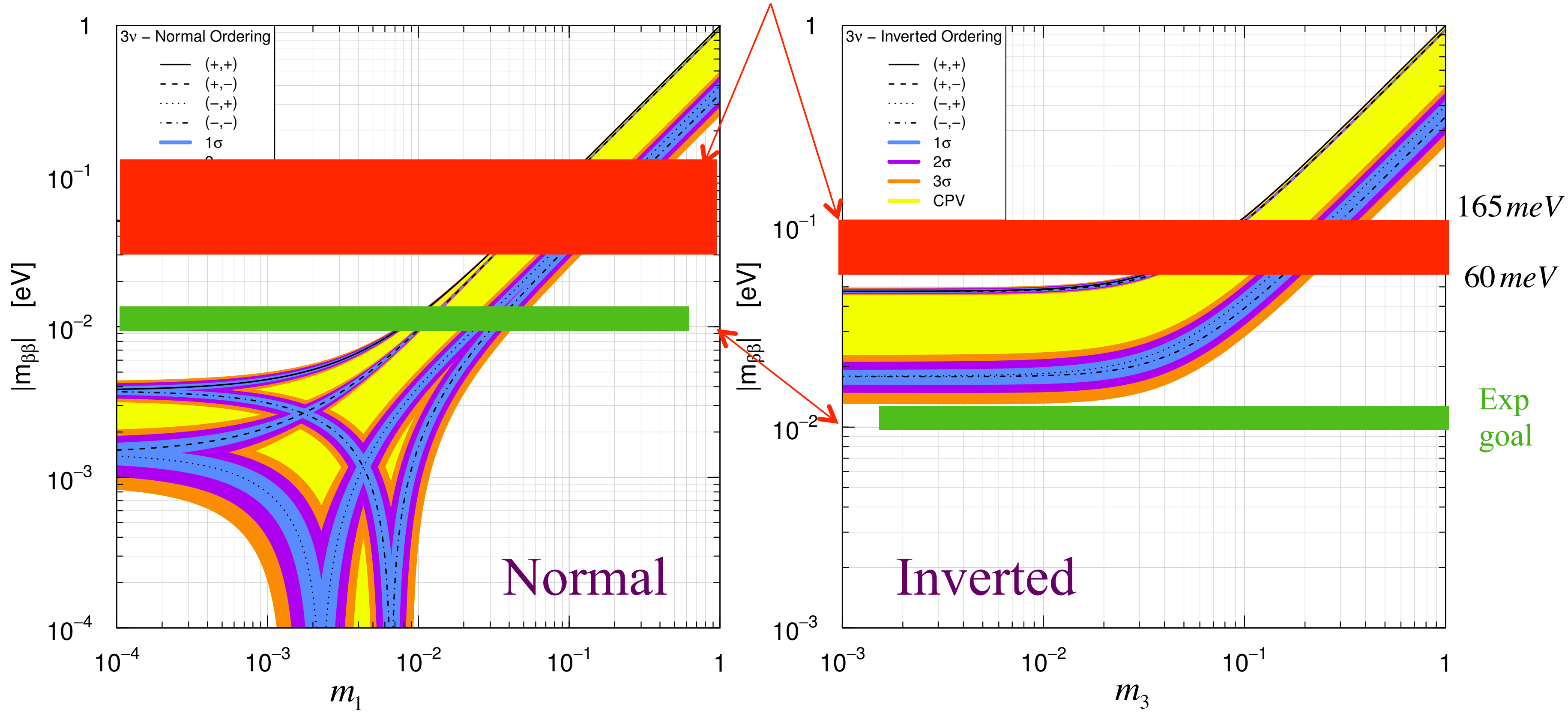


# Neutrino ββ effective mass

arxiv:1507.08204

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




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

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

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

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

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# Shell Model Nuclear Matrix Elements

$$M_S^{0\nu} = \sum_{\substack{\mathcal{J},\, p<p' \\ n<n' \\ p<n}} (\Gamma) \overbrace{\left\langle 0_f^+ \left| \left[ \left( a_p^+ a_{p'}^+ \right)^{\mathcal{J}} \left( \tilde{a}_{n'} \tilde{a}_n \right)^{\mathcal{J}} \right]^0 \right| 0_i^+ \right\rangle}^{many-body} \overbrace{\left\langle p\, p'; \mathcal{J} \left| \int q^2 dq \left[ \hat{S} \frac{h(q) j_\kappa(qr) G_{FS}^2 f_{SRC}^2}{q(q+<E>)} \tau_{1-} \tau_{2-} \right] \right| n\, n'; \mathcal{J} \right\rangle_{as}}^{two-body} - closure$$

Short range correlations (SRC): $f_{SRC} = 1 - c\, e^{a r^2} \left( 1 - b r^2 \right)$

$$M^{0\nu} = M_{GT}^{0\nu} - \left( g_V / g_A \right)^2 M_F^{0\nu} + M_T^{0\nu}$$

$$\hat{S} = \begin{cases} \sigma_1 \tau_1\, \sigma_2 \tau_2 & Gamow-Teller\ (GT) \\ \tau_1 \tau_2 & Fermi\ (F) \\ \left[ 3(\vec{\sigma}_1 \cdot \hat{n})(\vec{\sigma}_2 \cdot \hat{n}) - (\vec{\sigma}_1 \cdot \vec{\sigma}_2) \right] \tau_1 \tau_2 & Tensor\ (T) \end{cases}$$

TABLE II. Parameters for the short-range correlation (SRC) parametrization of Eq. (11).

| | SRC | $a$ | $b$ | $c$ |
|---|---|---|---|---|
| MS SRC | Miller-Spencer | 1.10 | 0.68 | 1.00 |
| CDB SRC | CD-Bonn | 1.52 | 1.88 | 0.46 |
| AV18 SRC | AV18 | 1.59 | 1.45 | 0.92 |



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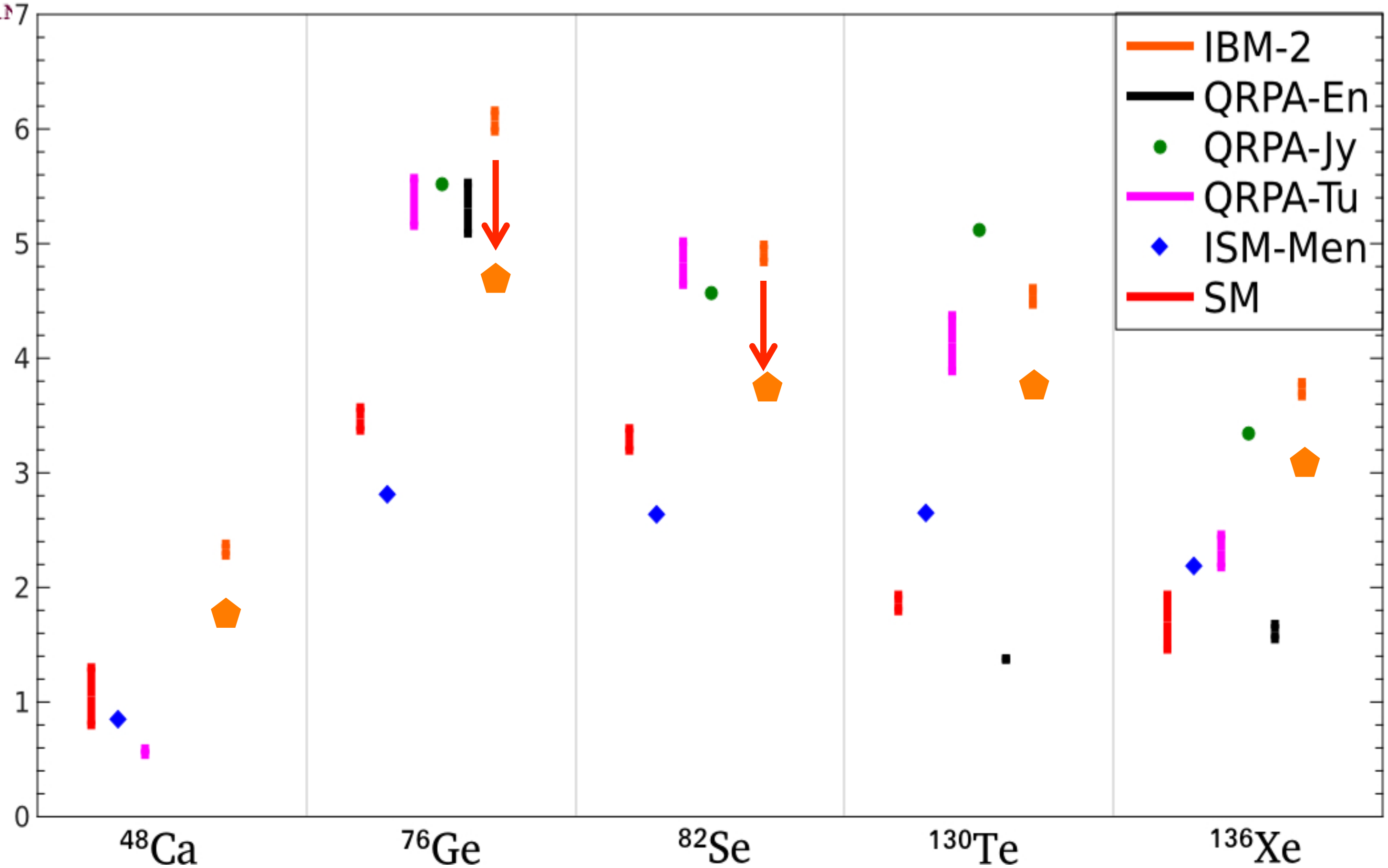
# NME for the light-neutrino exchange mechanism




**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).

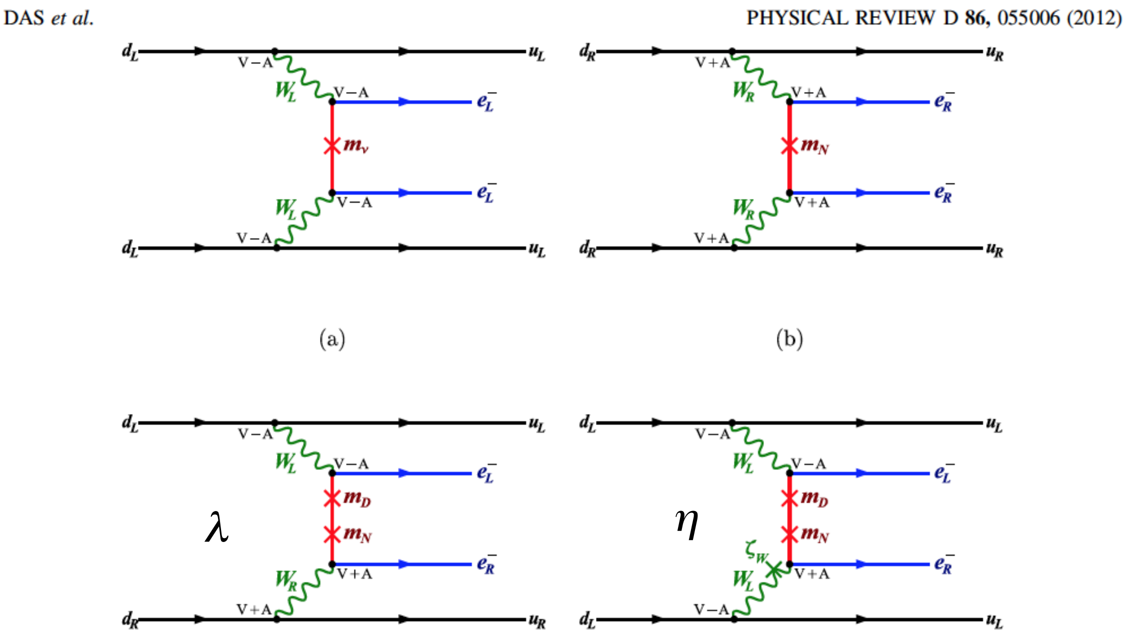
**QRPA-Jy** J. Suhonen, O. Civitarese, Phys. NPA **847** 207–232 (2010).

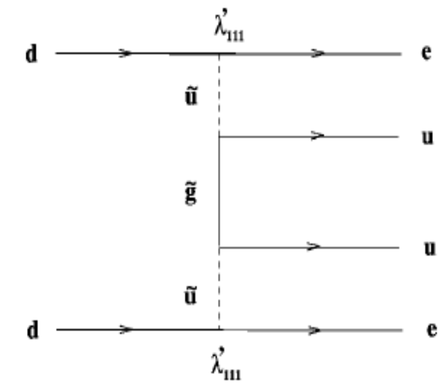
**QRPA-Tu** A. Faessler, M. Gonzalez, S. Kovalenko, and F. Simkovic, arXiv:**1408.6077**

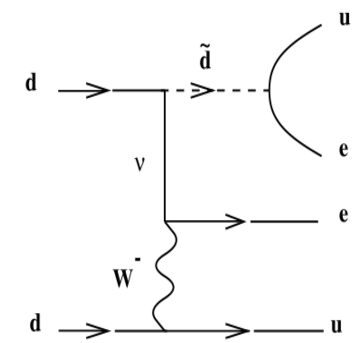
**ISM-Men** J. Menéndez, A. Poves, E. Caurier, F. Nowacki, NPA **818** 139–151 (2009).

**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).

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





Gluino exchange


Squark exchange

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

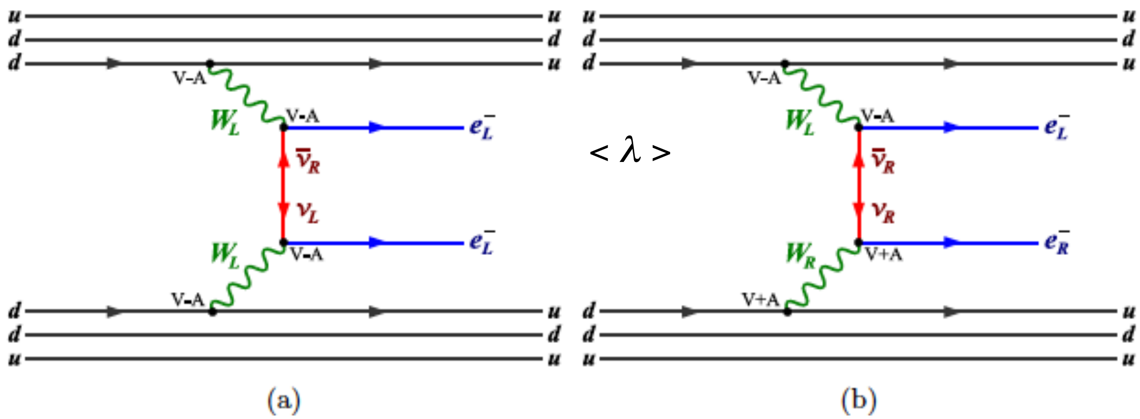
(e)

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

# DBD signals from different mechanisms

R. Arnold et al.: Probing New Physics Models of Neutrinoless Double Beta Decay with SuperNEMO

arXiv:1005.1241




$$\left[T_{1/2}^{0\nu}\right]^{-1} = \left|M_{GT}^{(0\nu)}\right|^2 \{C_{\nu^2} + C_{\nu\lambda}\cos\phi_1 + C_{\nu\eta}\cos\phi_2 + C_{\lambda^2} + C_{\eta^2} + C_{\lambda\eta}\cos(\phi_1 - \phi_2)\},$$

$$\frac{d^2W^{0\nu}_{0^+\to 0^+}}{d\epsilon_1 d\cos\theta_{12}} = \frac{a_{0\nu}\omega_{0\nu}(\epsilon_1)}{2\,(m_eR)^2}\left[A(\epsilon_1) + B(\epsilon_1)\cos\theta_{12}\right]$$

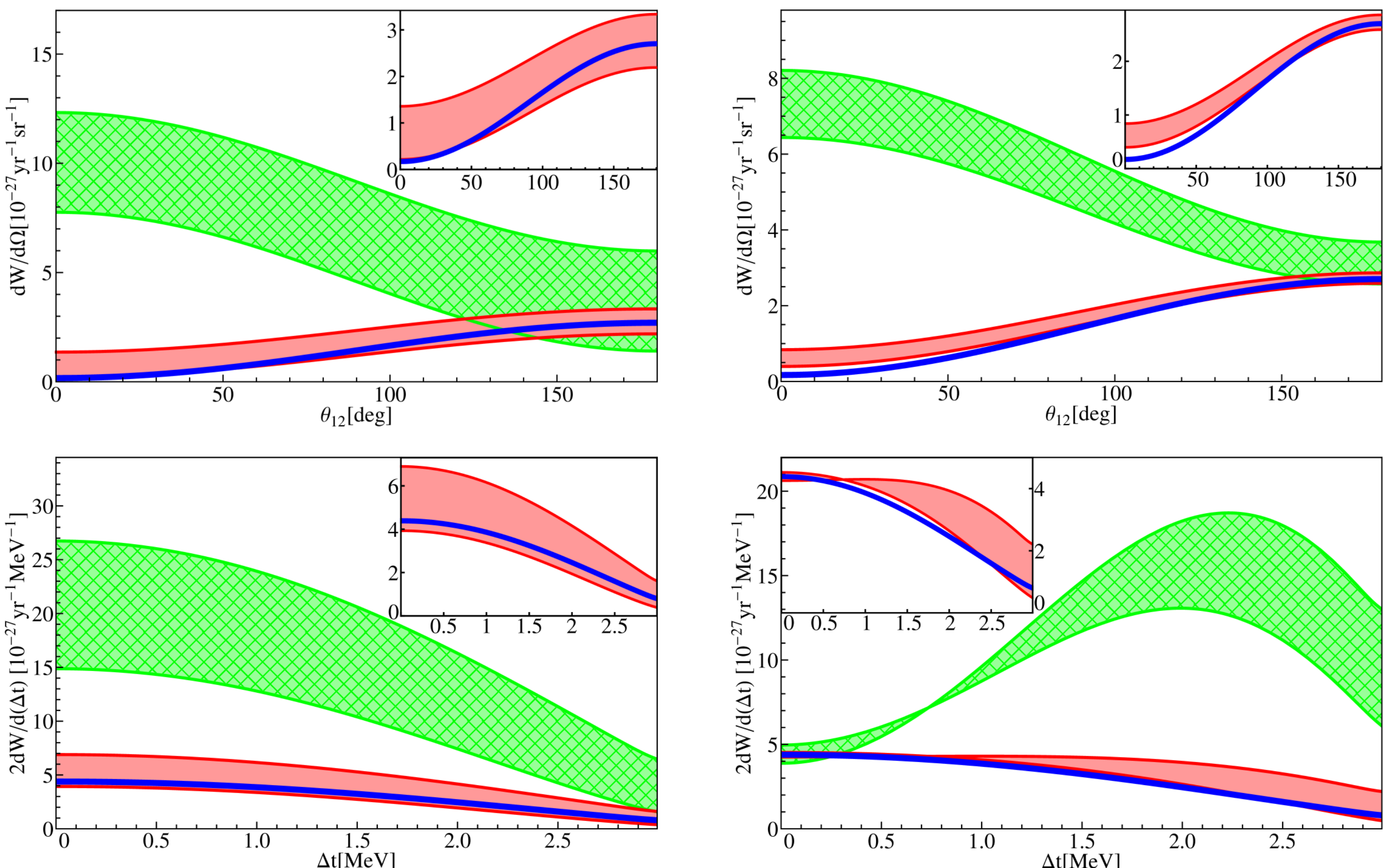
$$\frac{2dW^{0\nu}_{0^+\to 0^+}}{d(\Delta t)} = \frac{2a_{0\nu}}{(m_eR)^2}\frac{\omega_{0\nu}(\Delta t)}{m_ec^2}A(\Delta t)$$

$$t = \varepsilon_{e1} - \varepsilon_{e2}$$

# λ and η mechanisms ($^{82}Se$): look for green

$<\lambda>$ dominates

$<\eta>$ dominates



# Two Non-Interfering Mechanisms

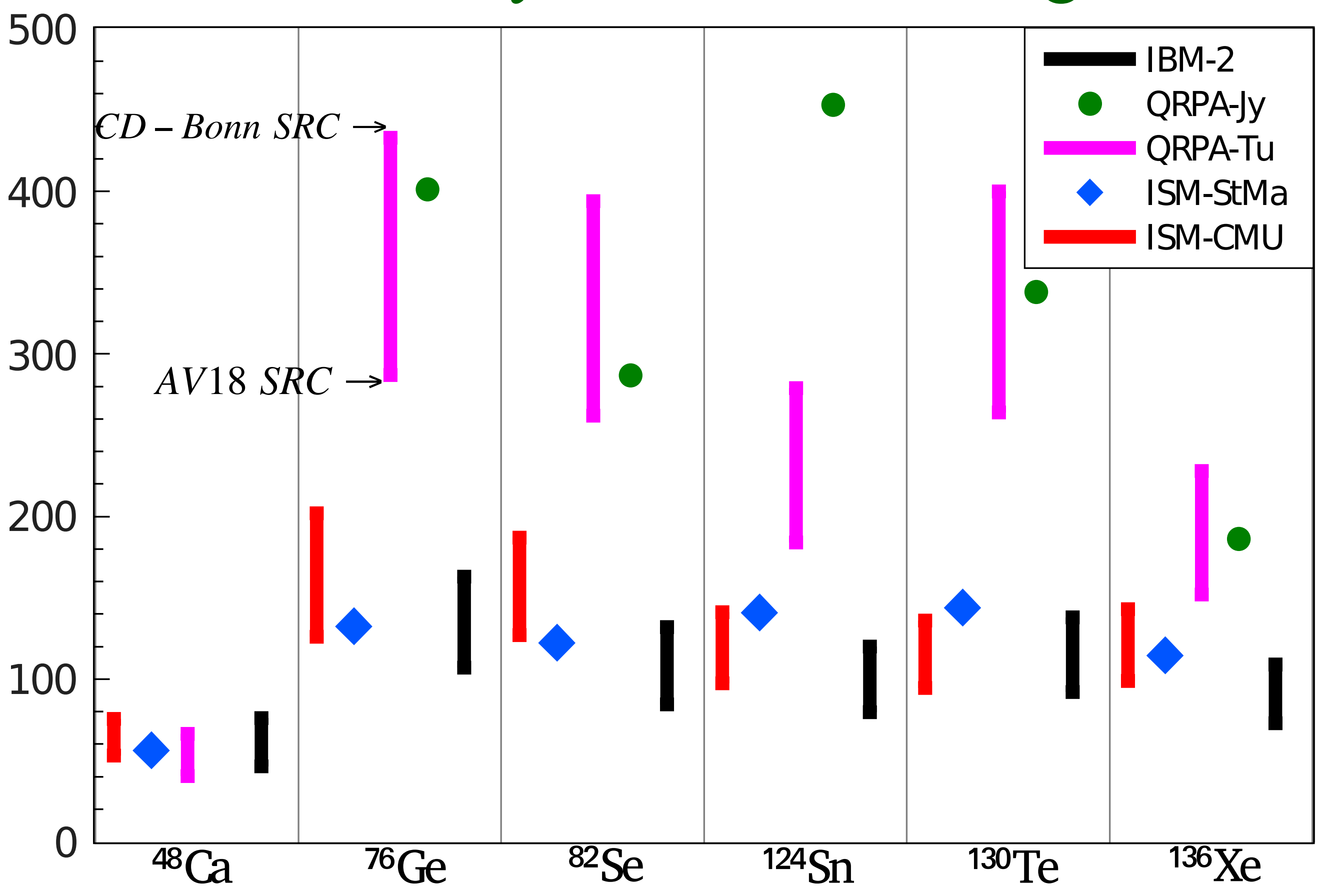
$$r(\nu / N) \equiv T_{1/2}^{\nu/N}(1) / T_{1/2}^{\nu/N}(2) = \frac{G_{01}^{0\nu}(2)\left|M^{0\nu/N}(2)\right|^2}{G_{01}^{0\nu}(1)\left|M^{0\nu/N}(1)\right|^2}$$

| | Ge/Se | | Ge/Te | | Ge/Xe | | Se/Te | | Se/Xe | | Te/Xe | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ge | Se | Ge | Te | Ge | Xe | Se | Te | Se | Xe | Te | Xe |
| $G_{01}^{0\nu} \times 10^{14}$ | 0.237 | 1.018 | 0.237 | 1.425 | 0.237 | 1.462 | 1.018 | 1.425 | 1.018 | 1.462 | 1.425 | 1.462 |
| $M^{0\nu}(1/2)$ | 3.57 | 3.39 | 3.57 | 1.93 | 3.57 | 1.76 | 3.39 | 1.93 | 3.39 | 1.76 | 1.93 | 1.76 |
| $M^{0N}(1/2)$ | 202 | 187 | 202 | 136 | 202 | 143 | 187 | 136 | 187 | 143 | 136 | 143 |
| $T_{1/2}^{\nu}(1)/T_{1/2}^{\nu}(2)$ | 3.87 | | 1.76 | | 1.50 | | 0.45 | | 0.39 | | 0.85 | |
| $T_{1/2}^{N}(1)/T_{1/2}^{N}(2)$ | 3.68 | | 2.73 | | 3.09 | | 0.74 | | 0.84 | | 1.13 | |
| $R(N/\nu)$ present | 0.95 | | 1.55 | | 2.06 | | 1.63 | | 2.17 | | 1.33 | |
| $R(N/\nu)$ [45] | 1.02 | | 1.39 | | 1.42 | | 1.36 | | 1.39 | | 1.03 | |

$$R(N / \nu) = r(N) / r(\nu)$$

*See also PRD* 83, 113003 (2011)

# 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 0$\nu$DBD operator

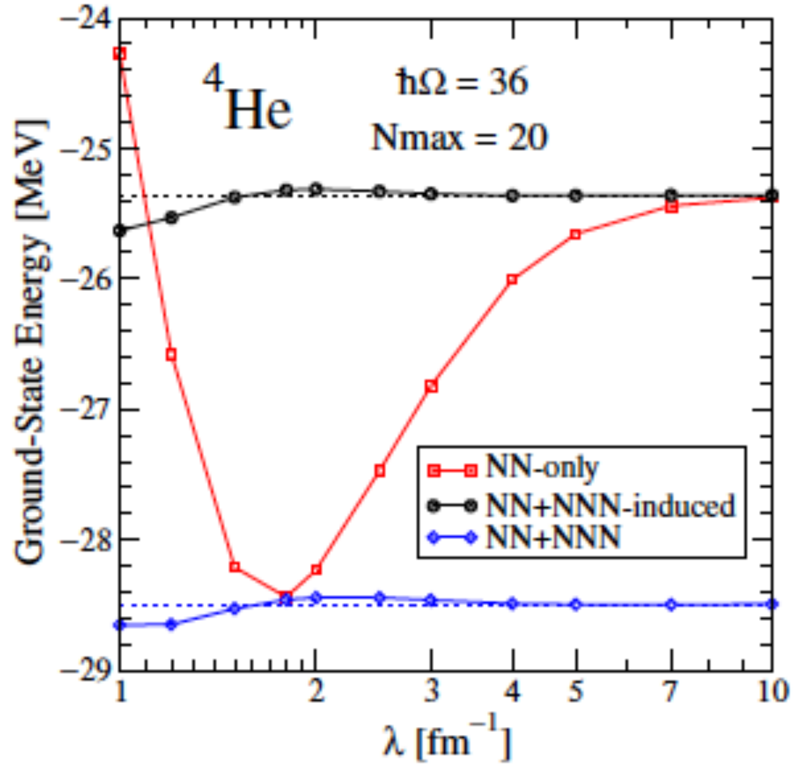
Similarity Renormalization Group (SRG) evolution

$$H_\lambda = U_\lambda H_{\lambda=\infty} U_\lambda^\dagger$$

$$\frac{dH_\lambda}{d\lambda} = -\frac{4}{\lambda^5}[[G, H_\lambda], H_\lambda]$$

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

N3LO 500



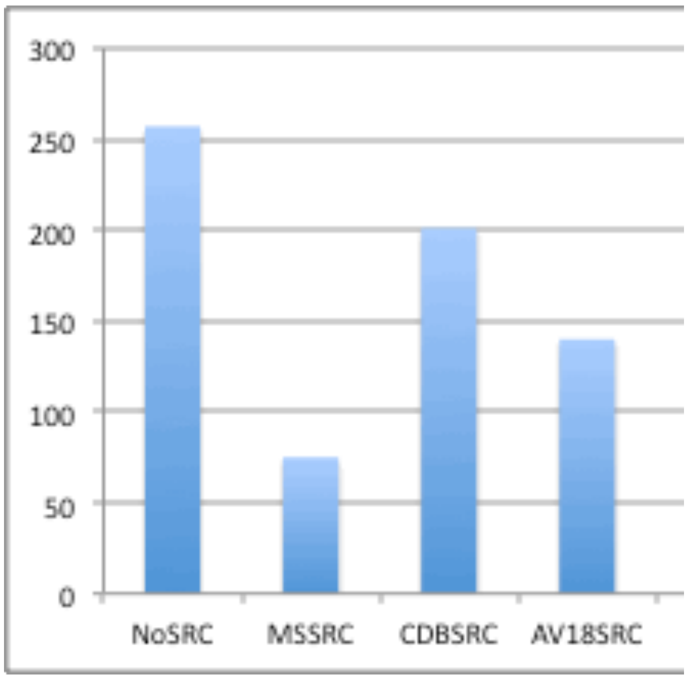

arXiv:1302.5473

# Towards an effective 0$\nu$DBD operator: heavy neutrino-exchange NME

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

$^{76}Ge$

$M^{0N}$



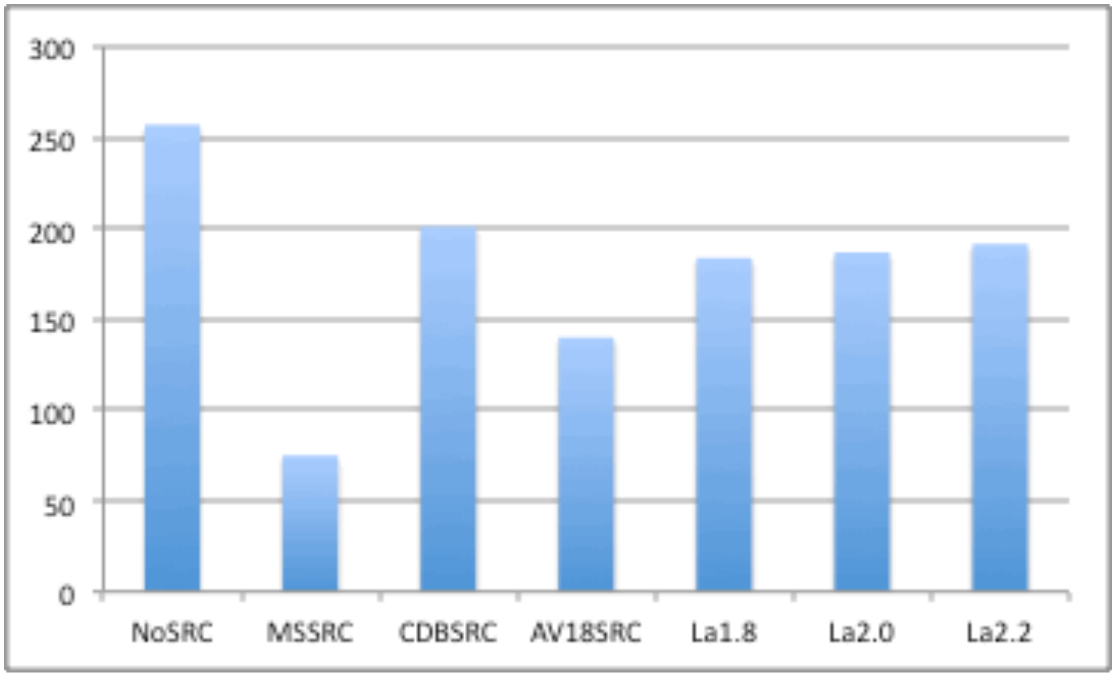

**Evolved operator coming here**

# Towards an effective 0$\nu$DBD operator: heavy neutrino-exchange NME

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

$^{76}$Ge

$M^{0N}$

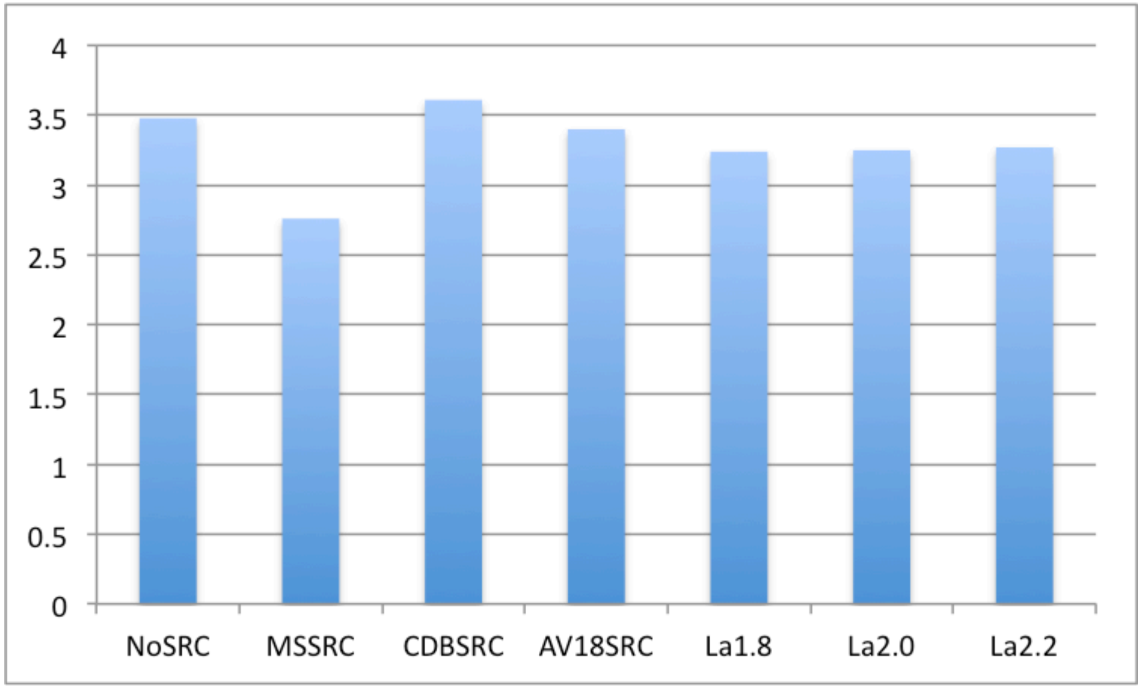


# Towards an effective $0\nu$DBD operator: light neutrino-exchange NME

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

$^{76}$Ge

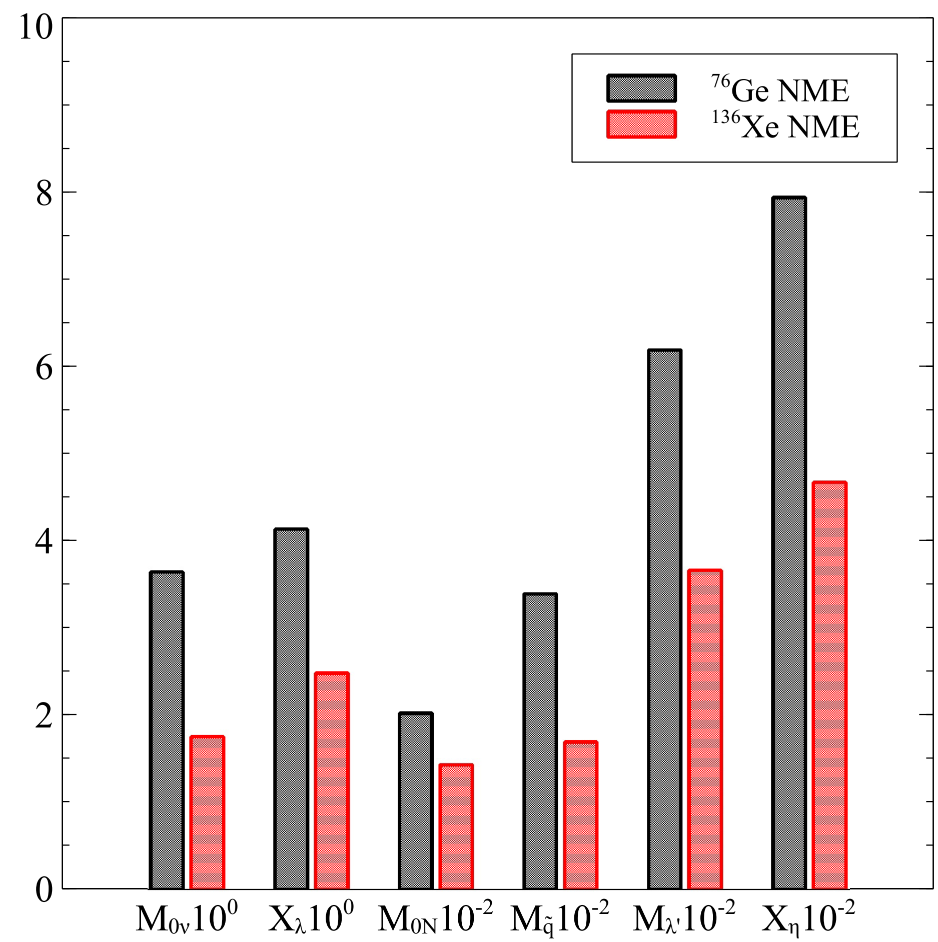
$M^{0\nu}$



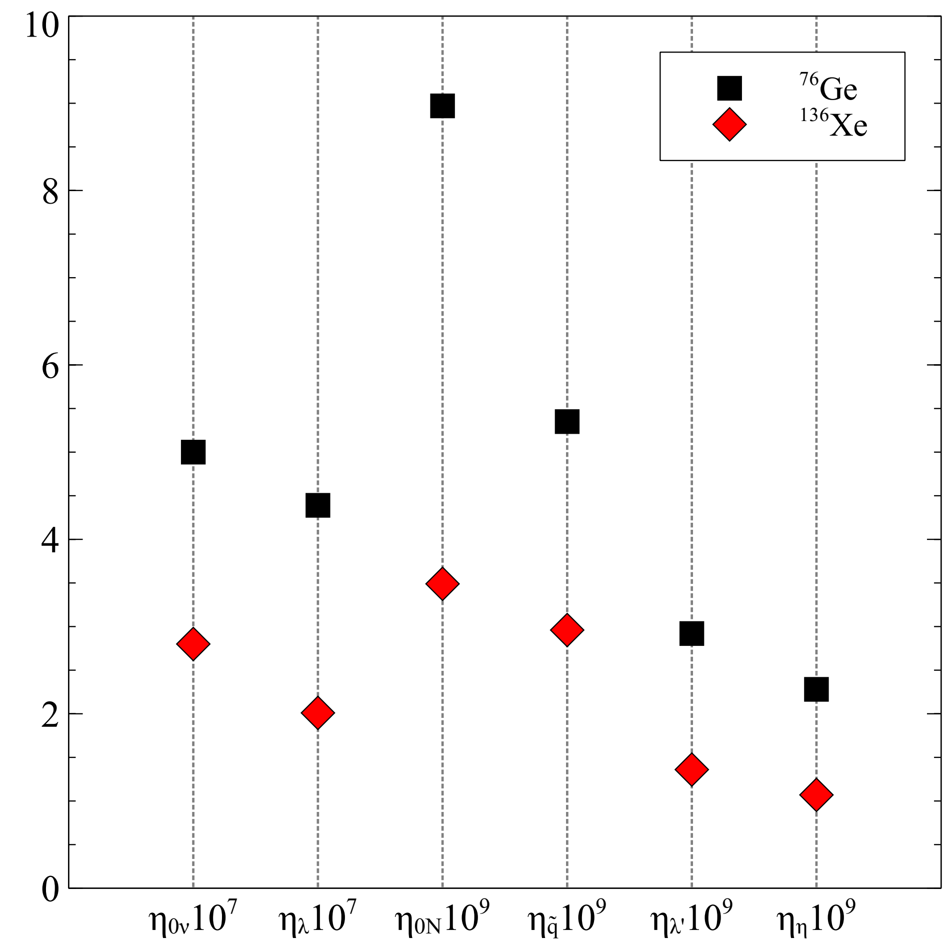
CENTRAL MICHIGAN UNIVERSITY

# One mechanism dominance

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




$T_{1/2}^{0\nu}(^{76}Ge) > 5\times10^{25}$ *years* $T_{1/2}^{0\nu}(^{136}Xe) > 1.1\times10^{26}$ *years*



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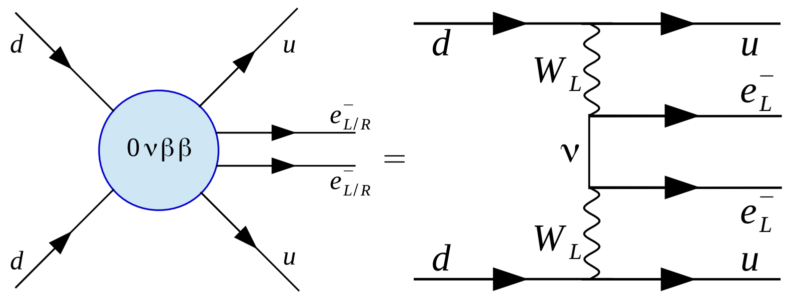
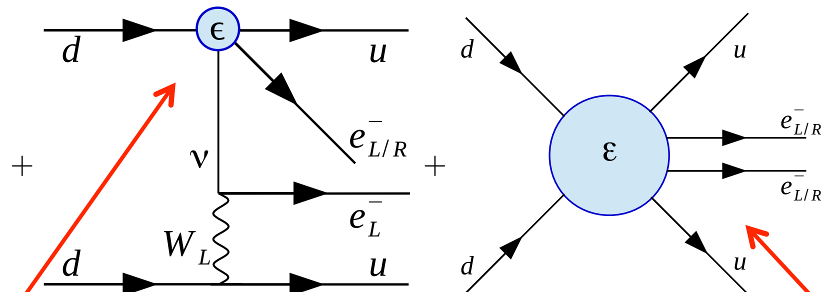
# Effective field theory approach




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

(b) Light left-handed neutrino exchange diagram.



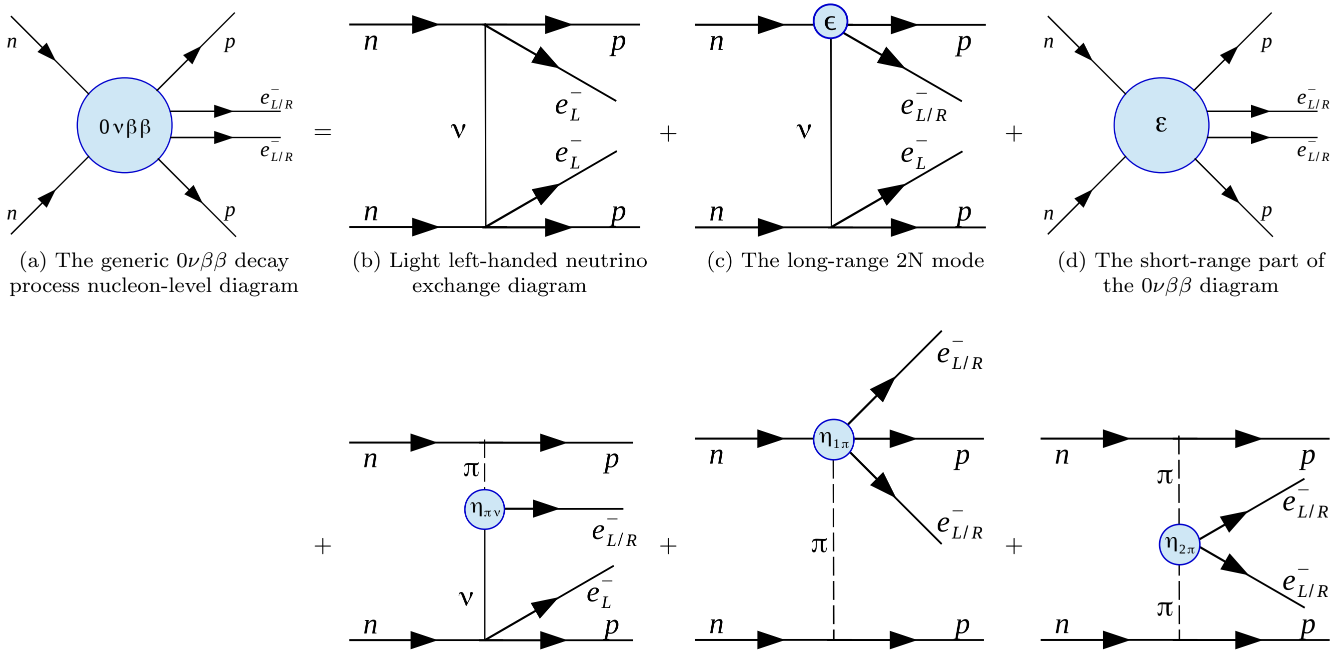

(c) The long-range part of the $0\nu\beta\beta$ diagram.

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

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

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

# 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 long-range 2N mode
(d) The short-range part of the $0\nu\beta\beta$ diagram
(e) The pion-neutrino long-range diagram
(f) The one-pion long-range contribution of the $\not{R}_p$ SUSY induced $0\nu\beta\beta$ diagram
(g) The two-pion long-range contribution of the $\not{R}_p$ SUSY induced $0\nu\beta\beta$ 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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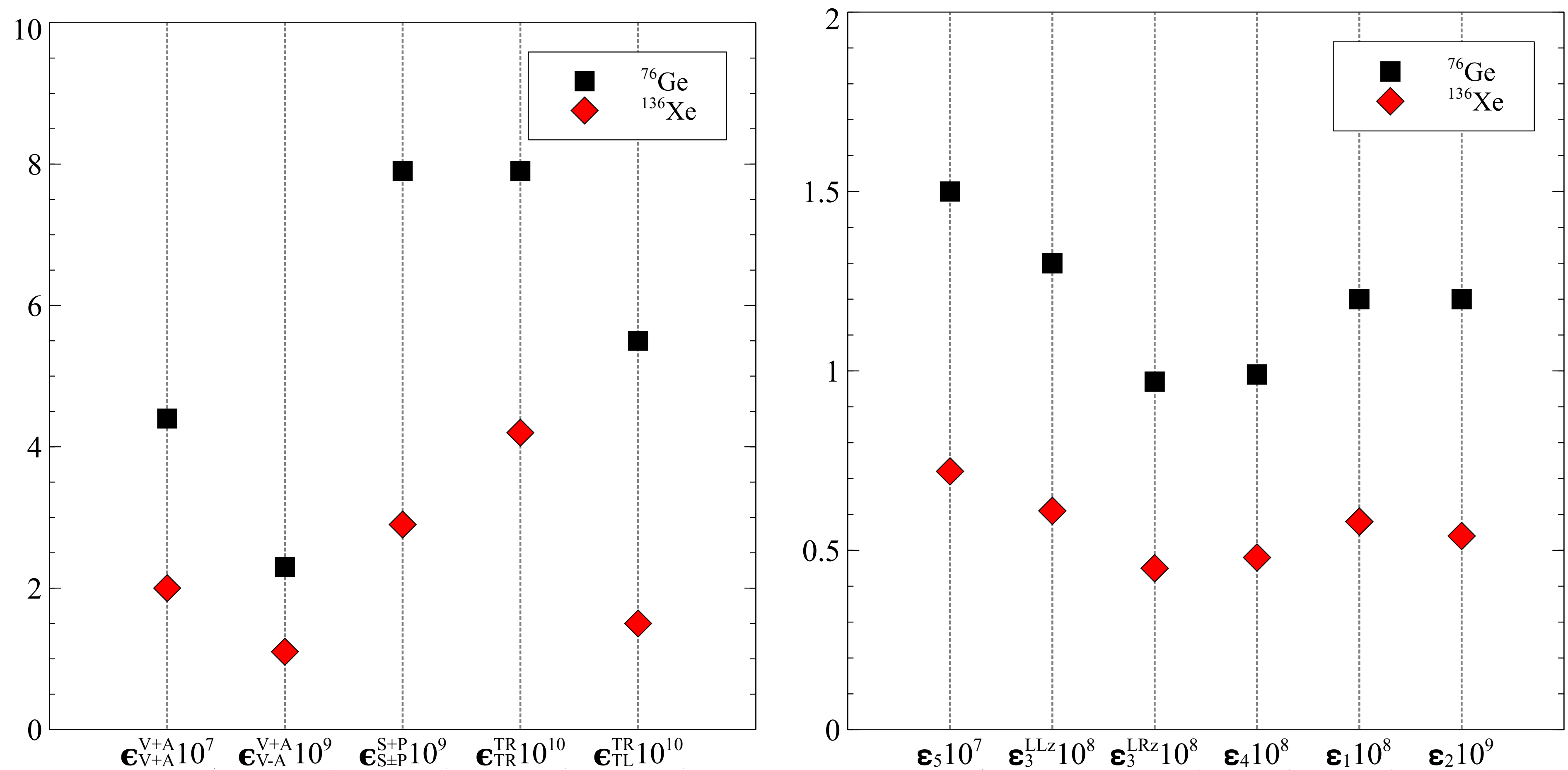
$$\left[T_{1/2}^{0\nu}\right]^{-1} = g_A^4 \left[ \sum_i |\mathcal{E}_i|^2 \mathcal{M}_i^2 + \mathrm{Re}\left[ \sum_{i \neq j} \mathcal{E} \mathcal{M}_{ij} \right] \right]$$

# One coupling dominance

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

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




$$T_{1/2}^{0\nu}(^{76}Ge) > 5\times10^{25}\ years \qquad T_{1/2}^{0\nu}(^{136}Xe) > 1.1\times10^{26}\ years$$



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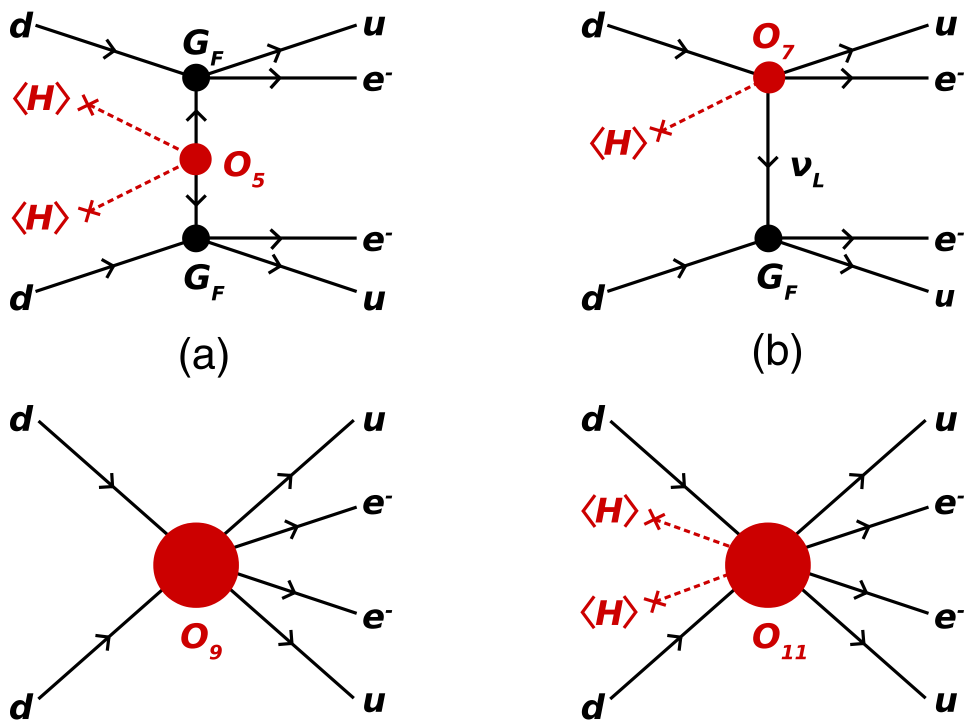
# Consequences: - scales for new physics

# - baryogenesis via leptogenesis

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

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




(a) (b) (c) (d)

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

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

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

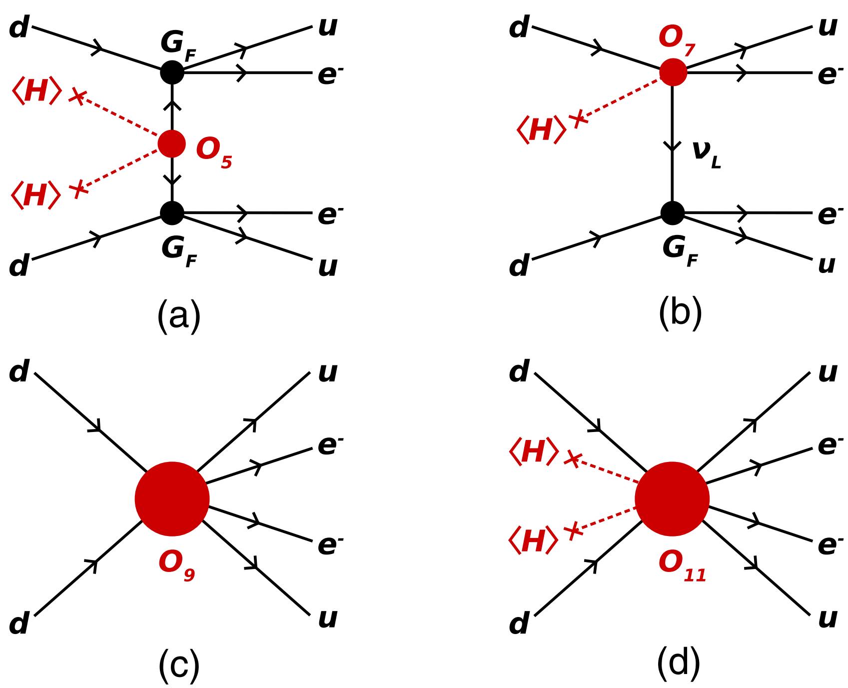
| $\mathcal{O}_D$ | $\bar{\epsilon}_D$ | $\Lambda_D$ |
|---|---|---|
| $\mathcal{O}_5$ | $2.8\times10^{-7}$ | $2.12\times10^{14}$ |
| $\mathcal{O}_7$ | $2.0\times10^{-7}$ | $3.75\times10^{4}$ |
| $\mathcal{O}_9$ | $1.5\times10^{-7}$ | $2.48\times10^{3}$ |
| $\mathcal{O}_{11}$ | $1.5\times10^{-7}$ | $1.16\times10^{3}$ |

# Consequences: - scales for new physics

# - baryogenesis via leptogenesis

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

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




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

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

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

| $\mathcal{O}_D$ | $\bar{\epsilon}_D$ | $\Lambda_D^0(y=1)$ | $\Lambda_D^0(y=y_e)$ | $\Lambda_D(y=y_e)$ |
|---|---|---|---|---|
| $\mathcal{O}_5$ | $2.8 \cdot 10^{-7}$ | $2.12 \cdot 10^{14}$ | 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 |

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

$y_e = 3 \times 10^{-6}$ *electron mass Yukawa*

# Summary

- The physics of the neutrinos is very exciting and offers a lot of research opportunities.
- Double beta decay (DBD), if observed, will represent a big step forward in our understanding of the neutrinos, and of physics beyond the Standard Model. A Nobel prize may be awarded for its discovery.
- The physics learned from DBD is complementary to that learned from Large Hadron Collider (future colliders).
- Better nuclear matrix elements and effective DBD operators are needed, especially for the short range mechanisms. And we are working hard for that!

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