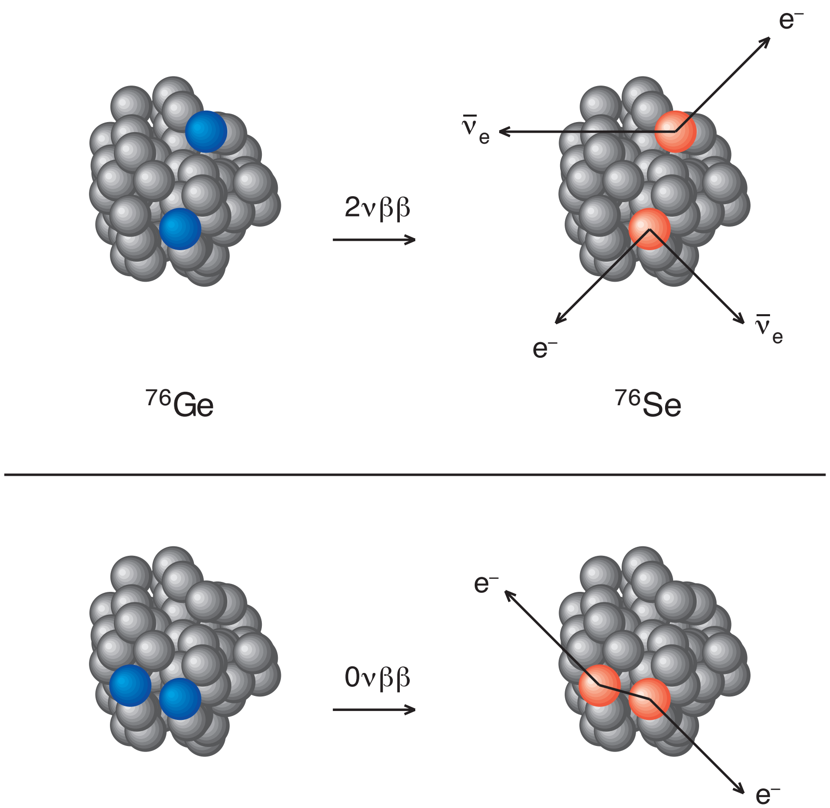
Nuclear matrix elements and the BSM energy scales in the EFT description of 0νββ decay

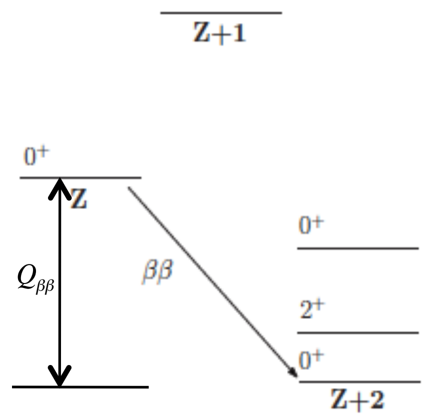
Mihai Horoi

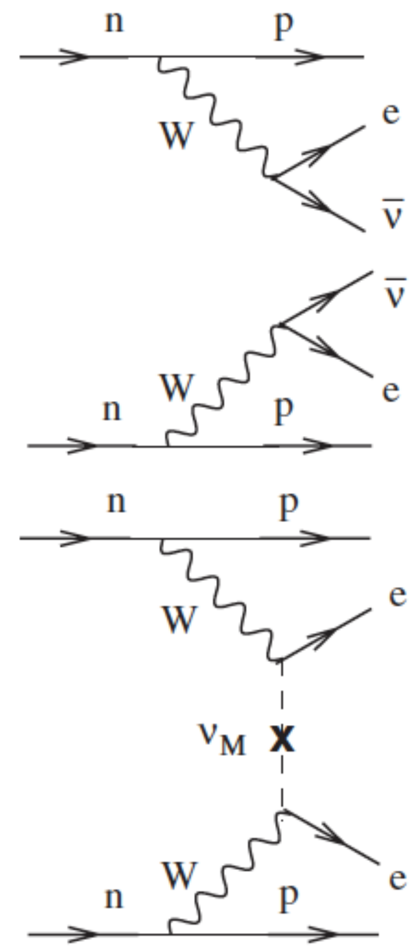
Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA

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

Classical Double Beta Decay Problem







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

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

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:

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

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

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

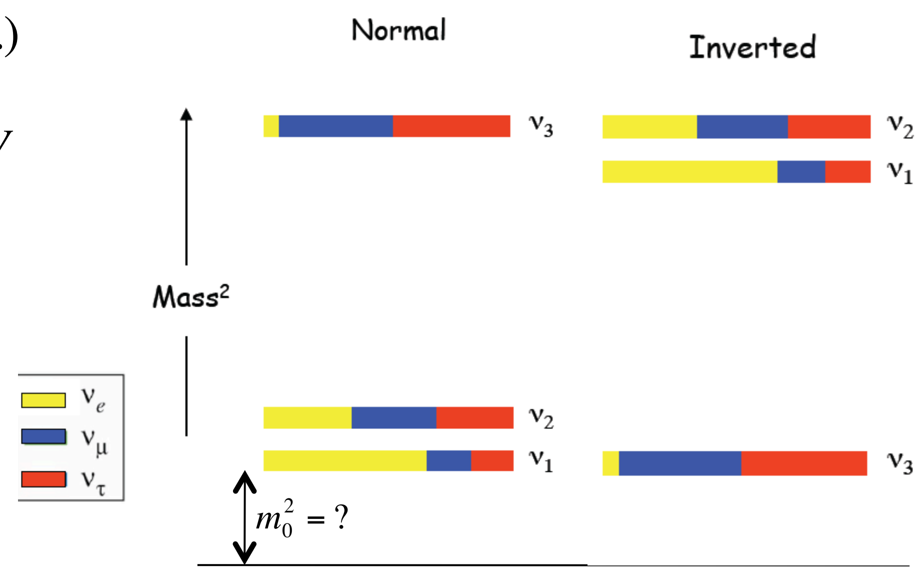
- Cosmology: CMB power spectrum, BAO, etc,

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

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

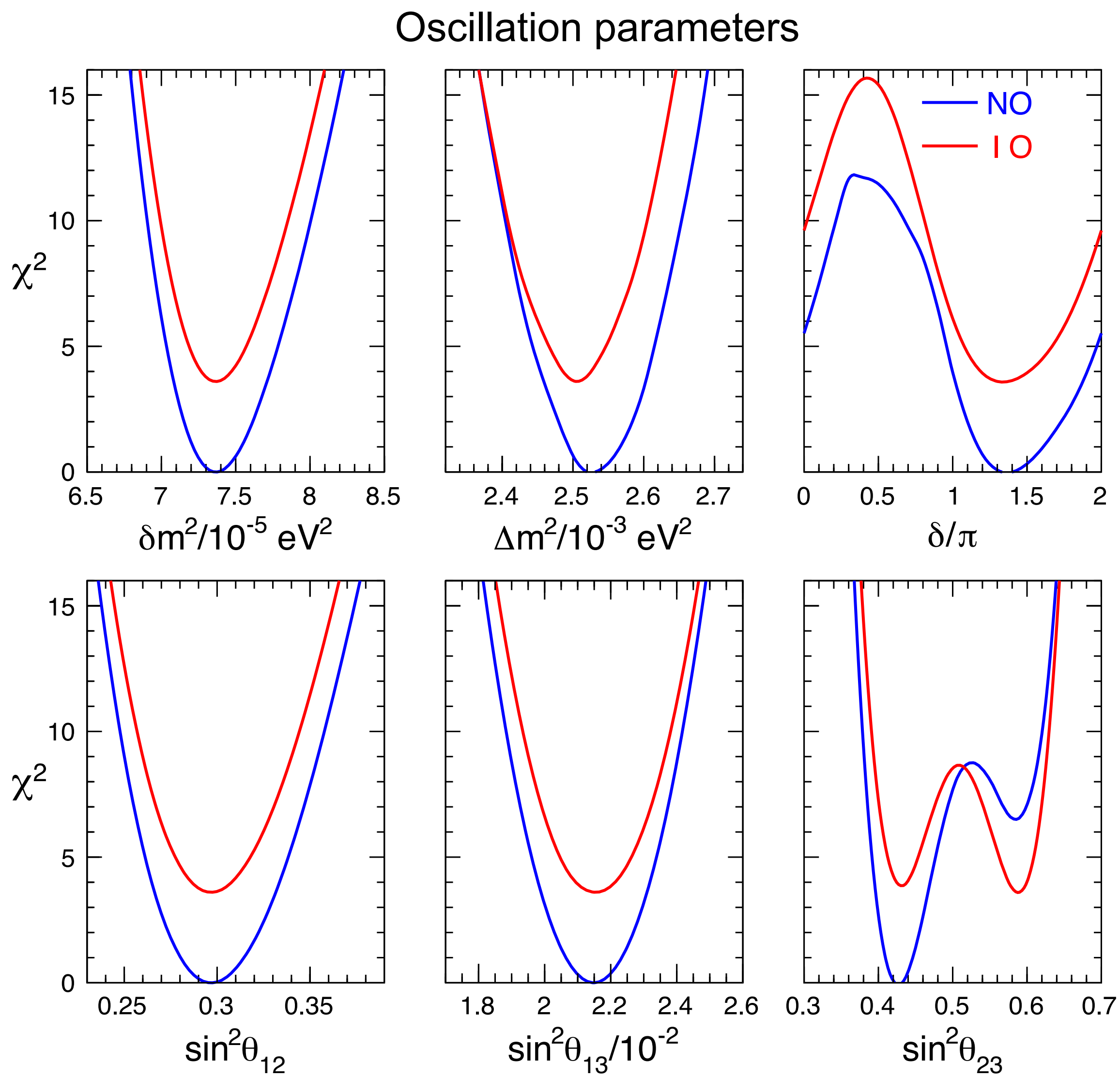
$$\Delta m^2_{21} \approx 7.5 \times 10^{-5}\ eV^2 (solar)$$

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



Two neutrino mass hierarchies

Neutrino oscillations parameters



Bari group:

arxiv.org/1703.04471

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

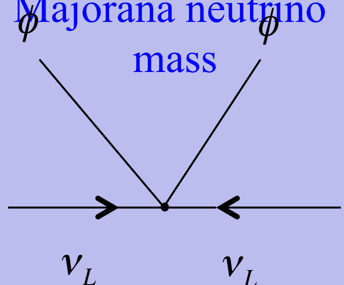
Normal ordering favored at 2σ

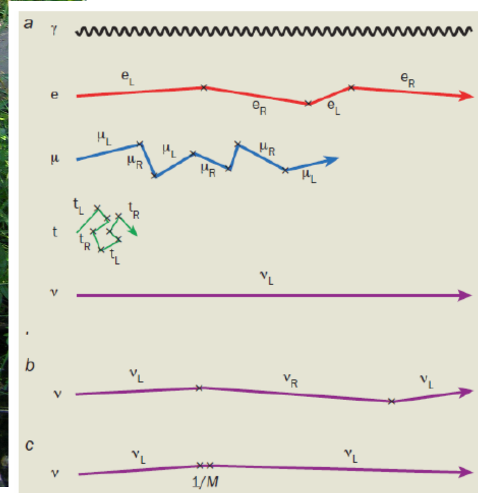
NEUTRINO London 2016 & ICHEP Chicago 2016

André de Gouvêa — Northwestern

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

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





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

$$m_M = m_D m_N^{-1} m_D \quad (m_D \sim Y < \phi >)$$

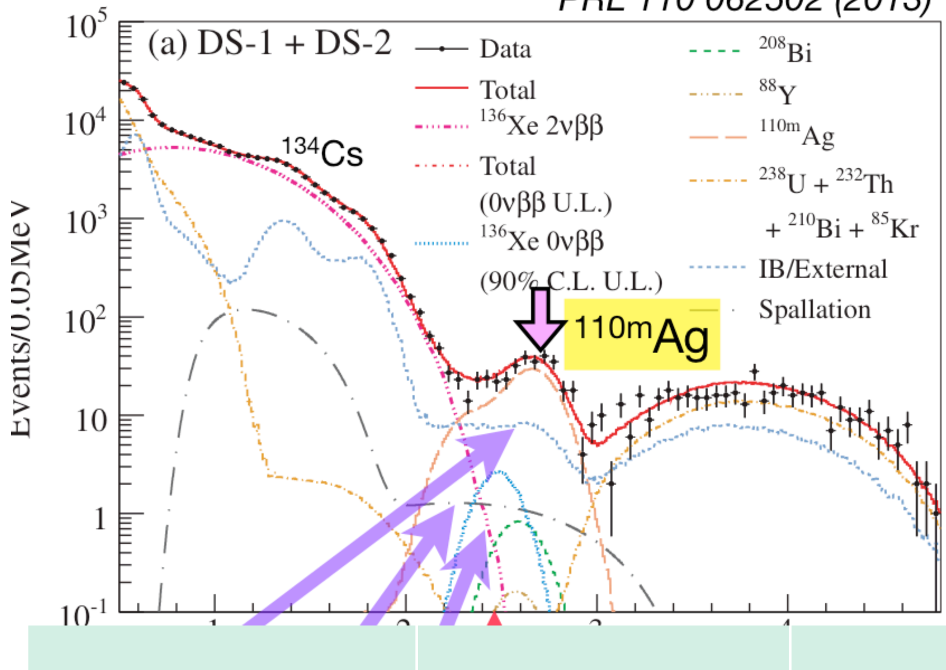
Dirac mass from the Yukawa interaction with Higgs : $\bar{\psi}_i Y_{ij} \psi_j < \phi >$

^{136}Xe ββ Experimental Results

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

Phase1 (before purification)

PRL 110 062502 (2013)



KamLAND-Zen

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

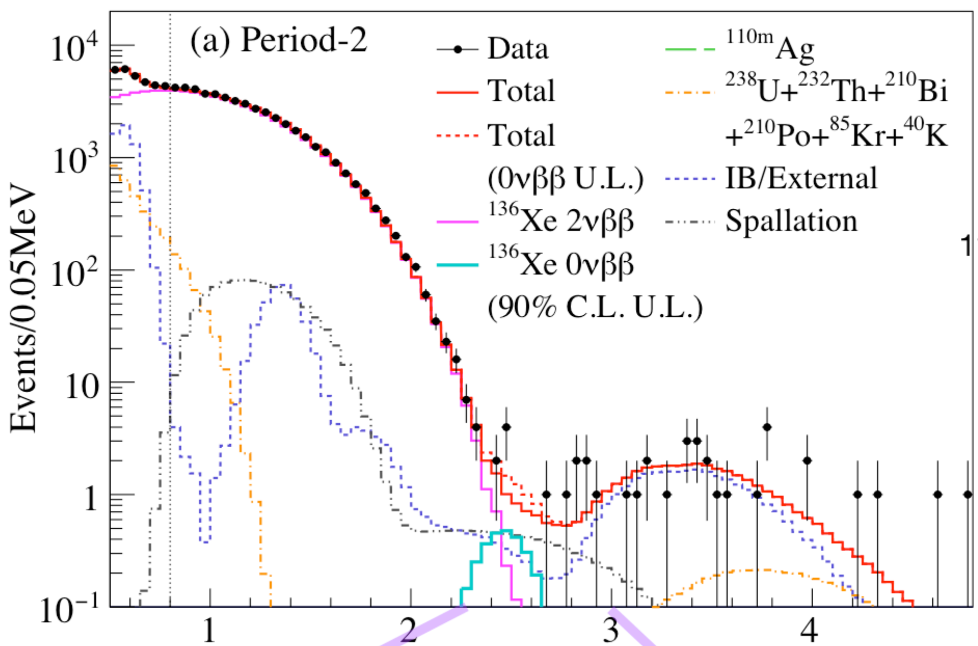
Phase1 $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

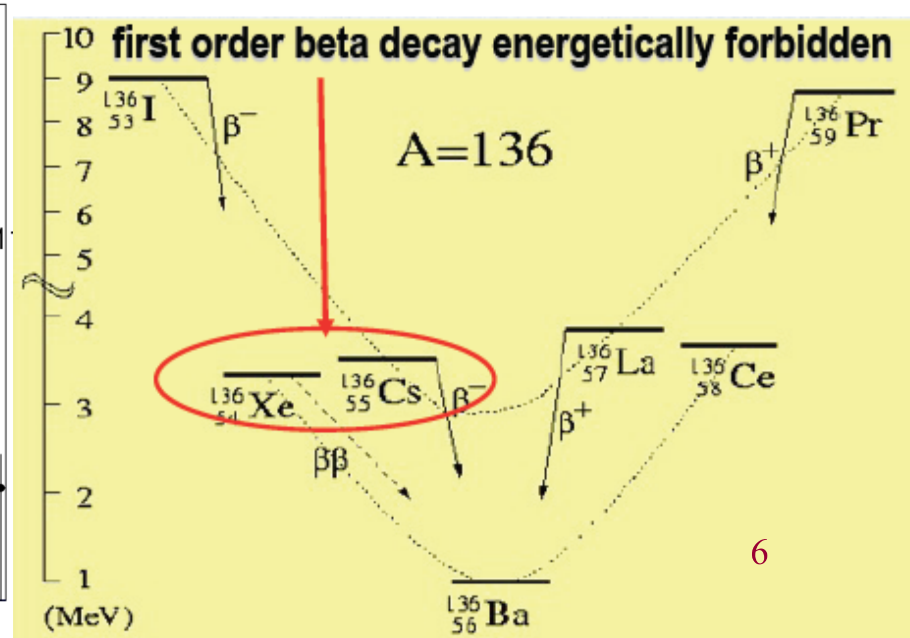
Phase2 $T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr

×6!

Combined **$T^{0\nu}_{1/2} > 1.07\times10^{26}$ yr**

$- 0.0215\ MeV^{-1}$

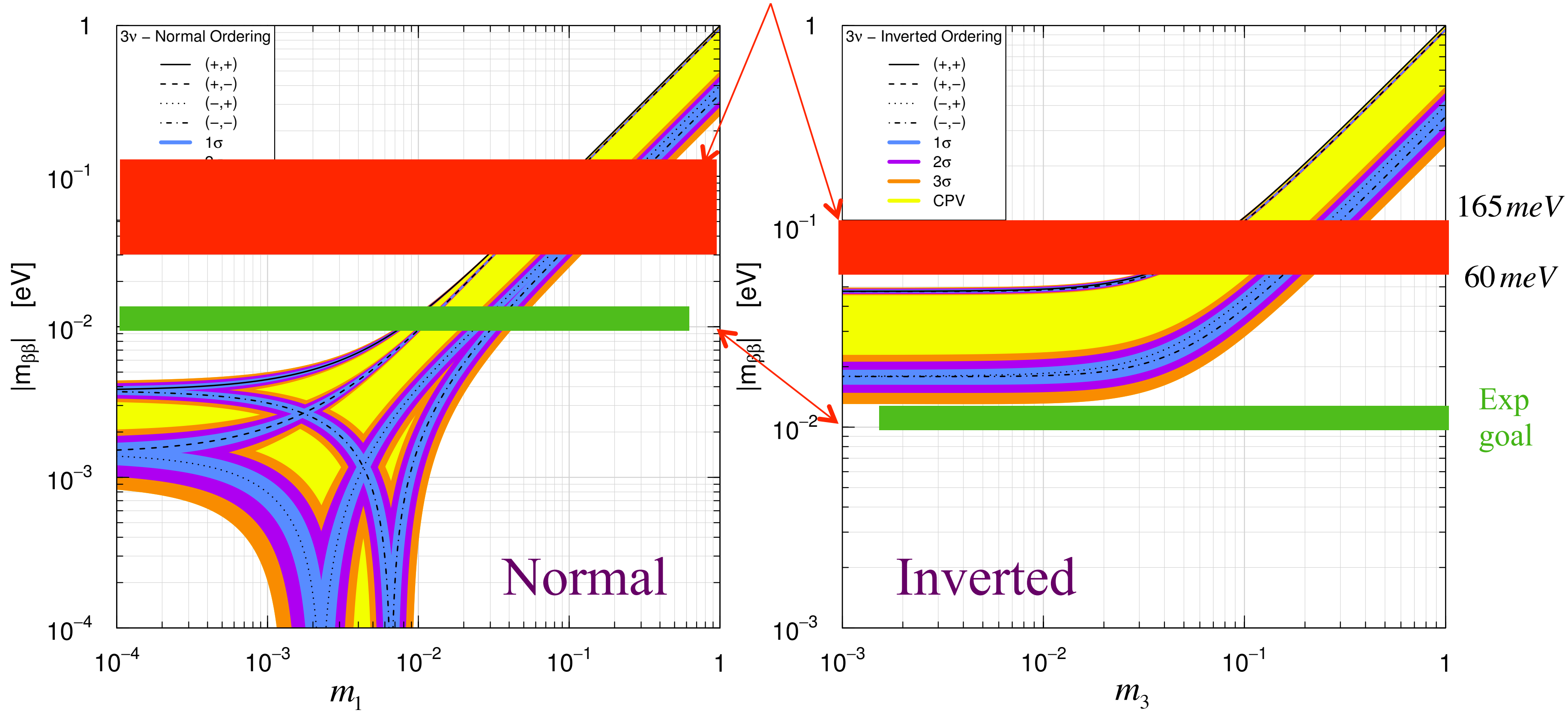




Neutrino ββ effective mass

arxiv:1507.08204

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



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

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

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

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

CENTRAL MICHIGAN UNIVERSITY

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

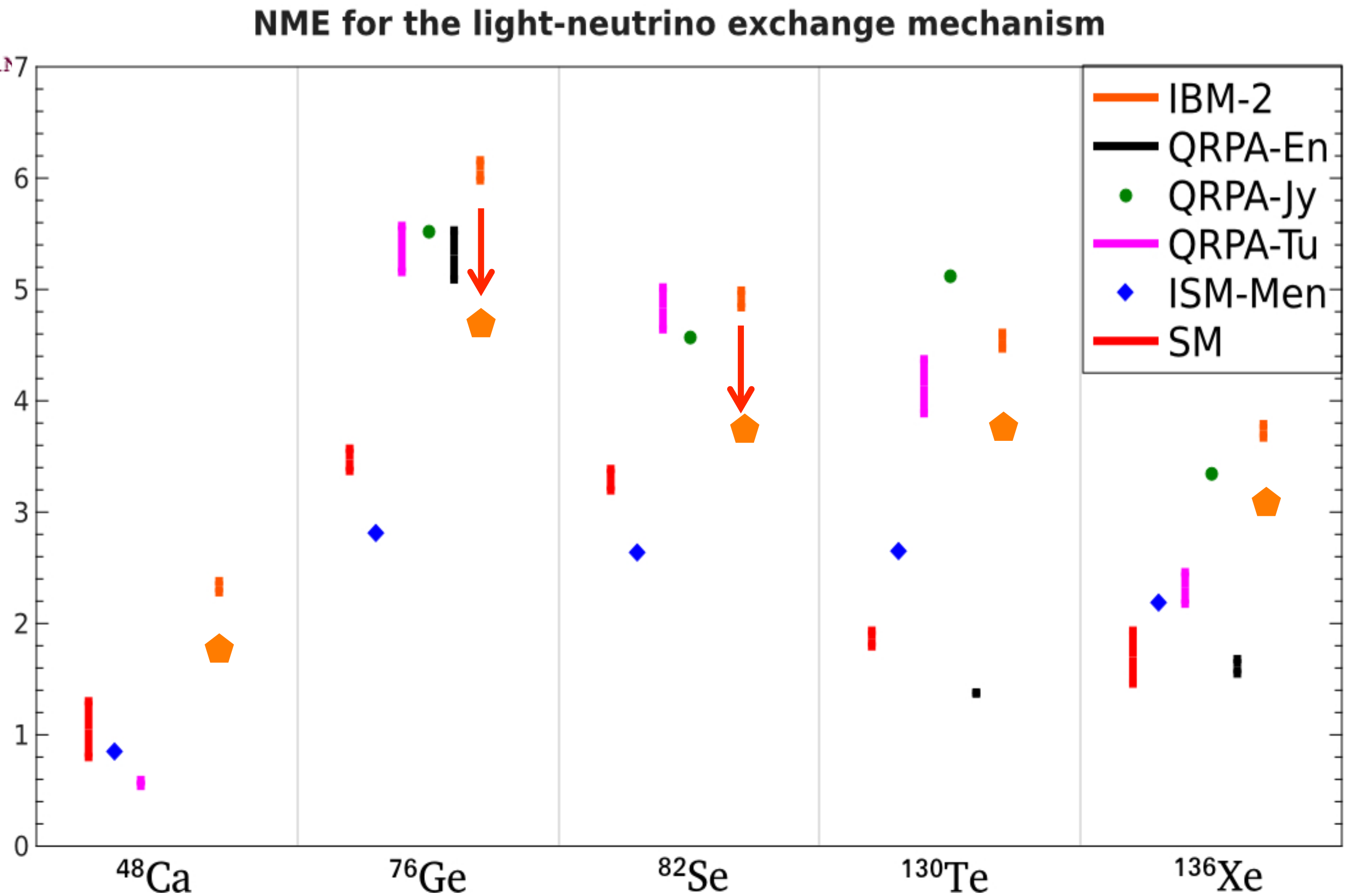
$$M^{0\nu} = M_{GT}^{0\nu} - \left(g_V / g_A\right)^2 M_F^{0\nu} + M_T^{0\nu}$$

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

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

SciDAC Scientific Discovery through Advanced Computing



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

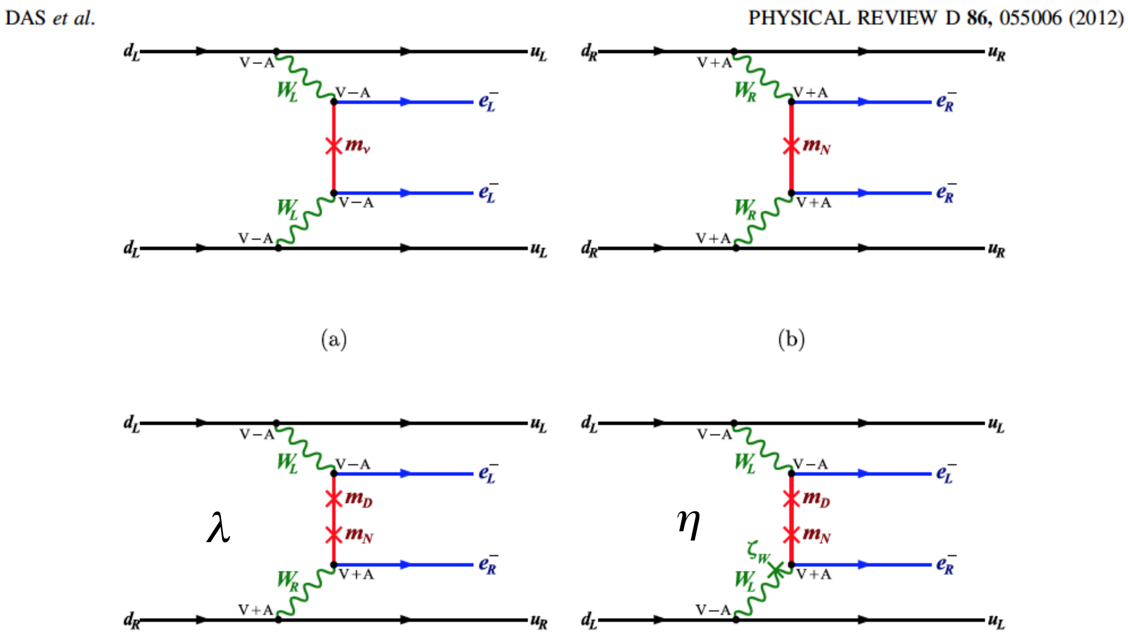
QRPA-En M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).

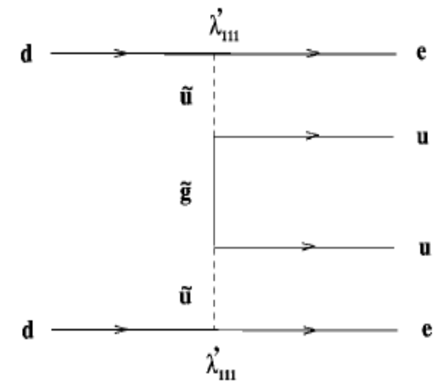
QRPA-Jy J. Suhonen, O. Civitarese, Phys. NPA **847** 207–232 (2010).

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).

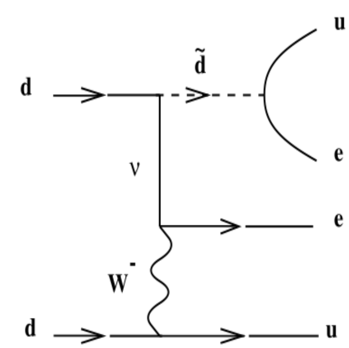
Other models: Left-Right symmetric model and SUSY R-parity violation





Gluino exchange

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



Squark exchange

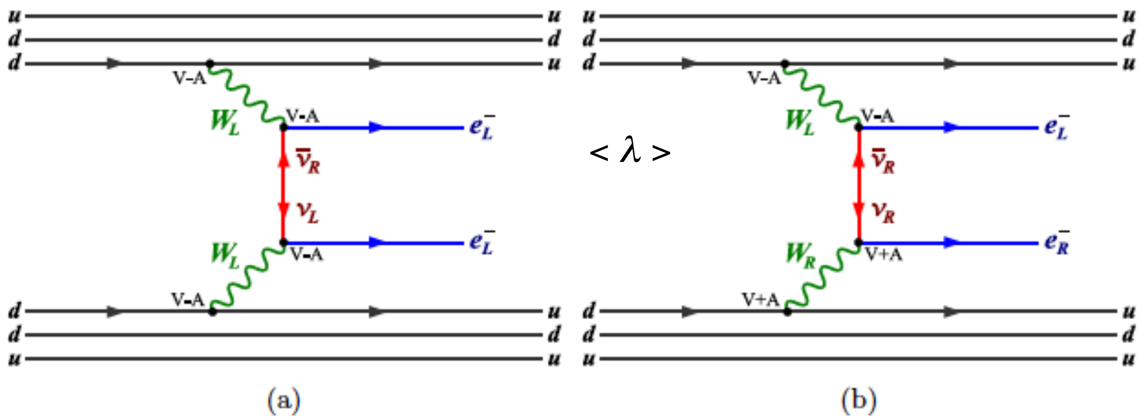
(e)

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



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

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

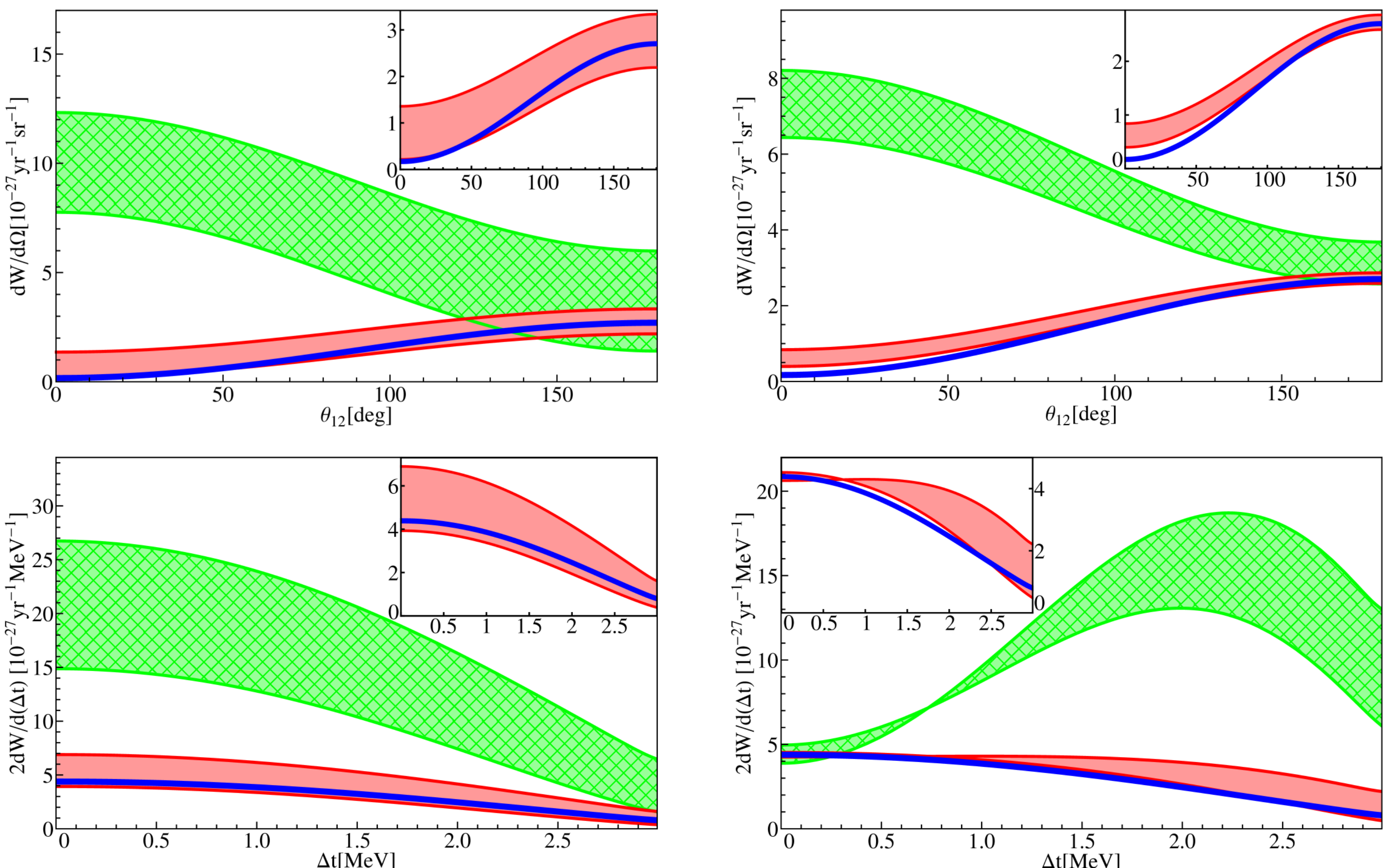
$$\frac{2\mathrm{d}W^{0\nu}_{0^+\to 0^+}}{\mathrm{d}(\Delta t)} = \frac{2a_{0\nu}}{(m_e R)^2}\frac{\omega_{0\nu}(\Delta t)}{m_e c^2}A(\Delta t)$$

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

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

$< \lambda >$ dominates

$< \eta >$ dominates



Two Non-Interfering Mechanisms

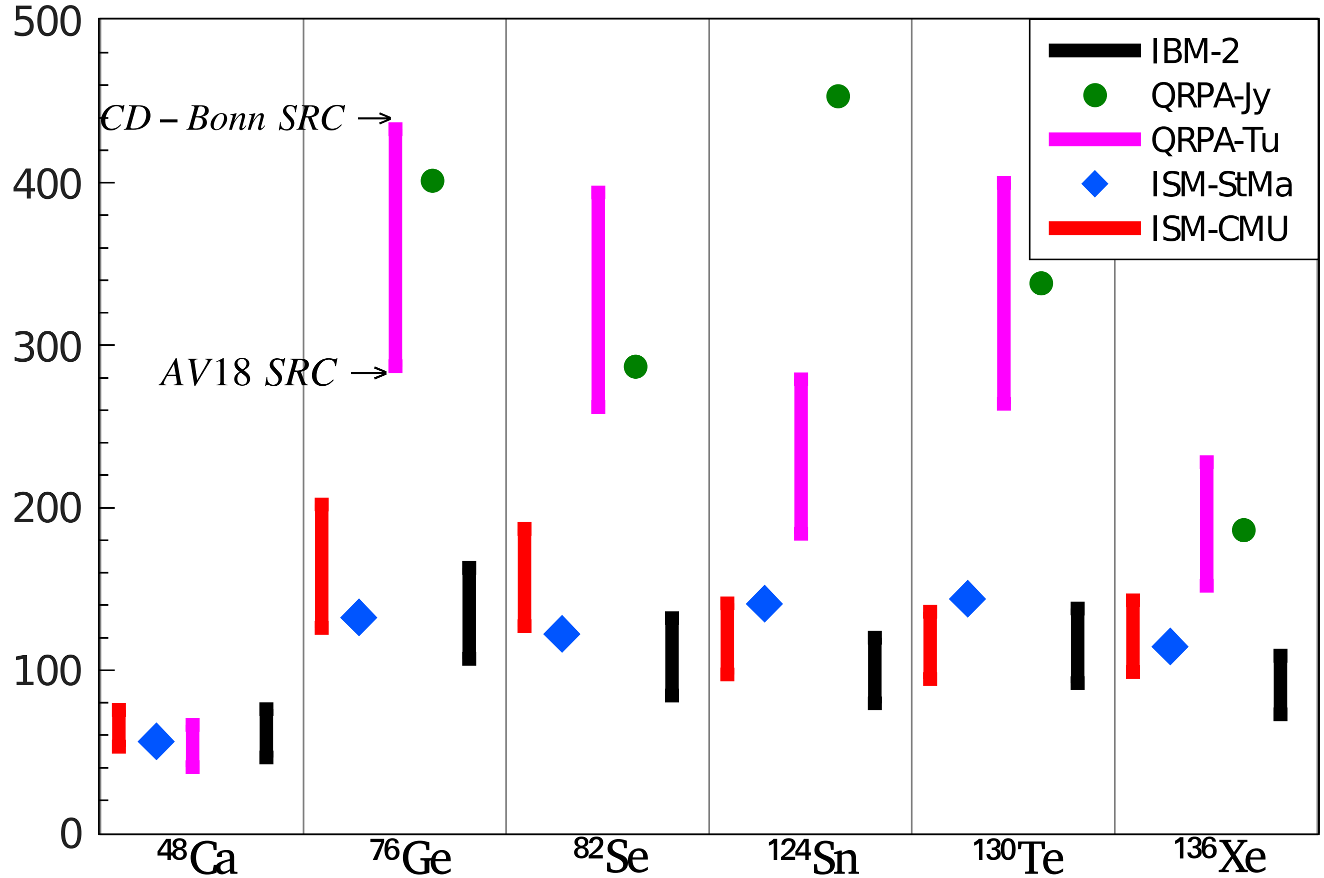
$$r(\nu/N) \equiv T_{1/2}^{\nu/N}(1)/T_{1/2}^{\nu/N}(2) = \frac{G_{01}^{0\nu}(2)\left|M^{0\nu/N}(2)\right|^2}{G_{01}^{0\nu}(1)\left|M^{0\nu/N}(1)\right|^2}$$

	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 0νDBD operator

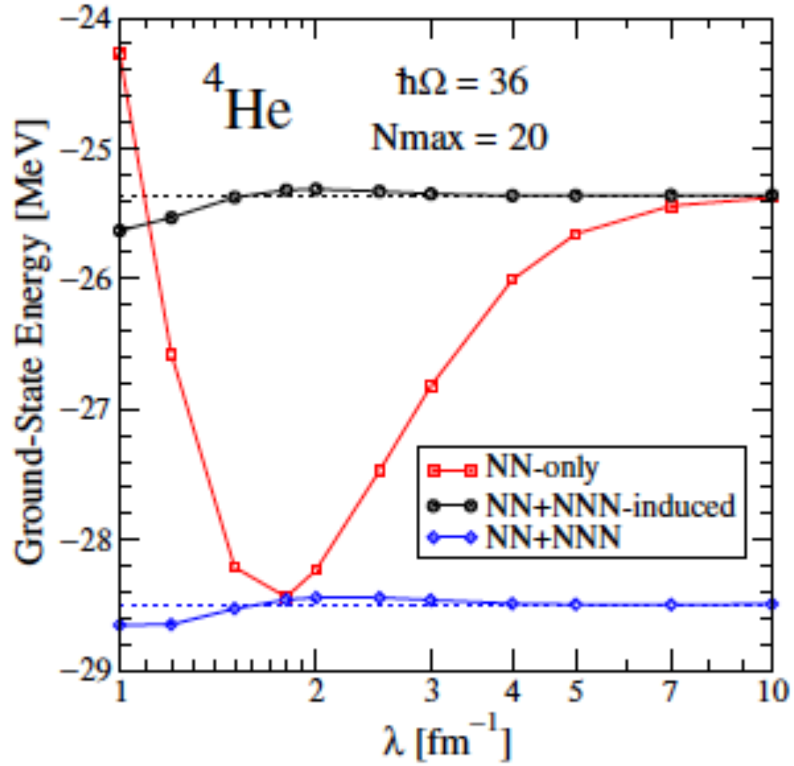
Similarity Renormalization Group (SRG) evolution

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

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

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

N3LO 500



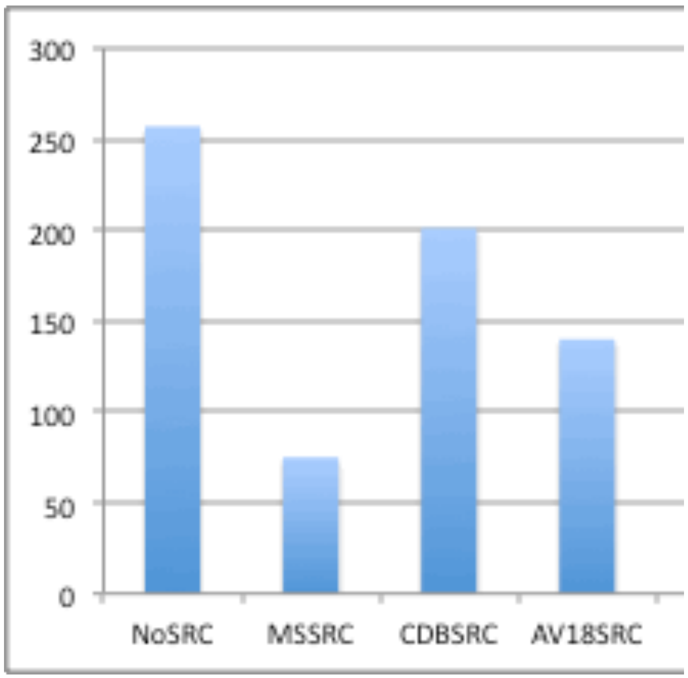
arXiv:1302.5473

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

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

^{76}Ge

M^{0N}



Evolved operator

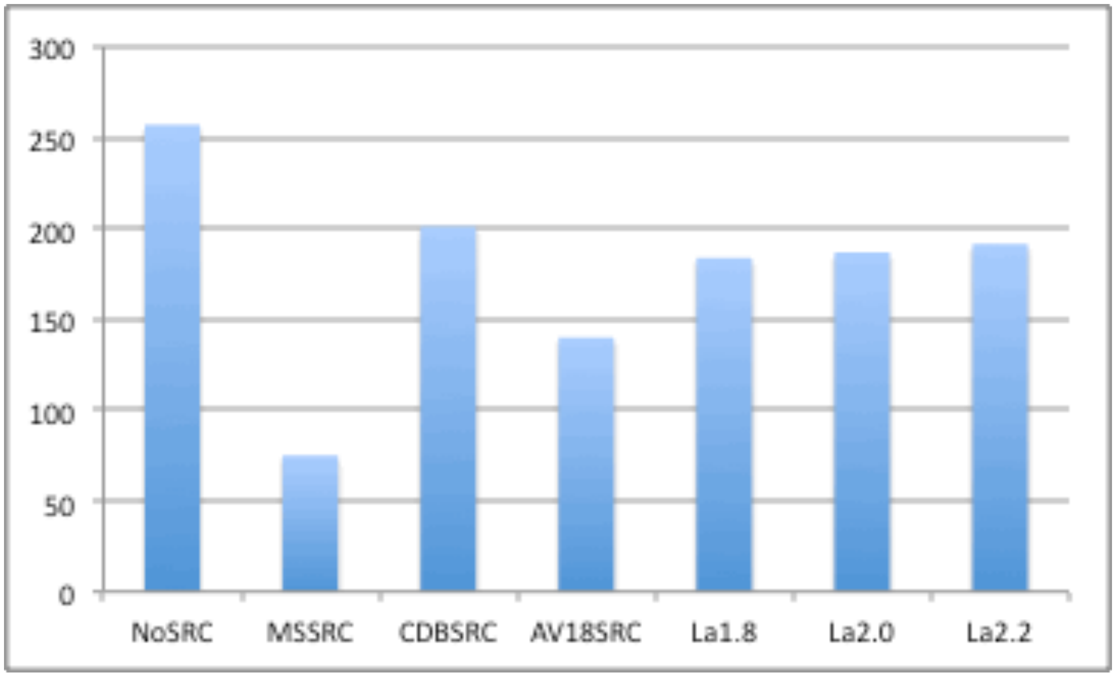
coming here

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

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

^{76}Ge

M^{0N}

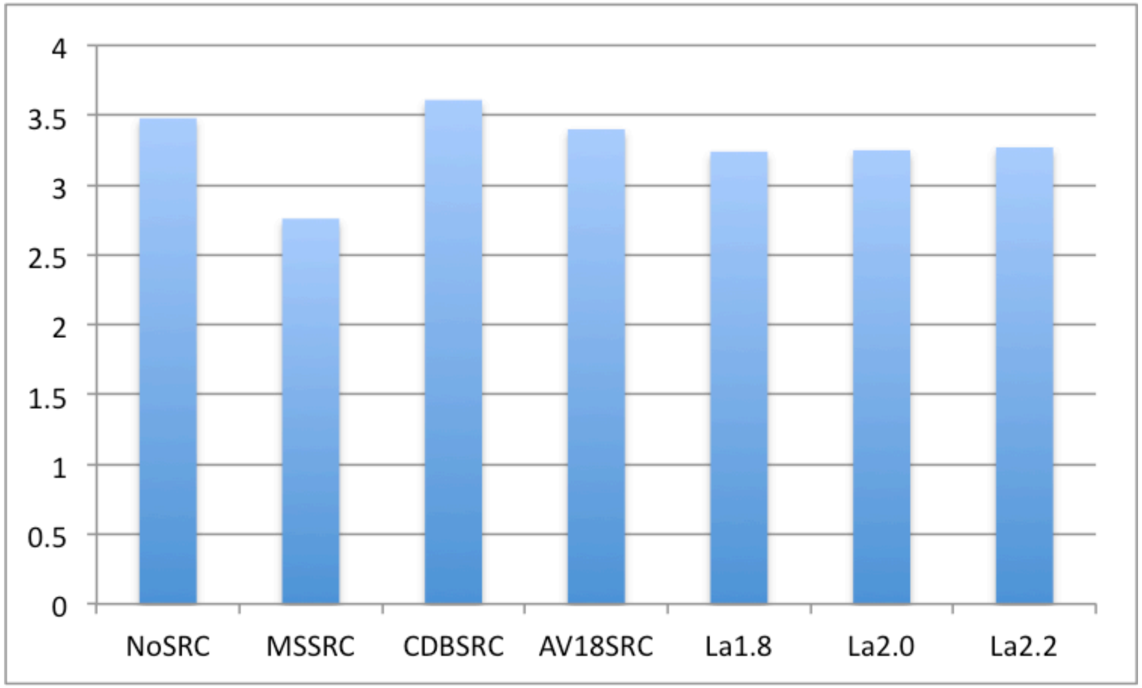


Towards an effective 0νDBD operator: light neutrino-exchange NME

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

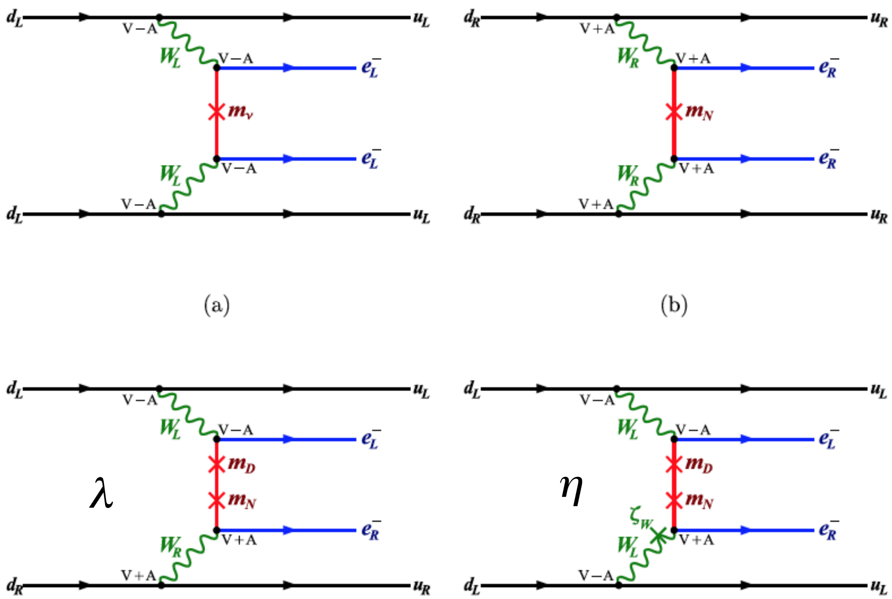
^{76}Ge

$M^{0\nu}$

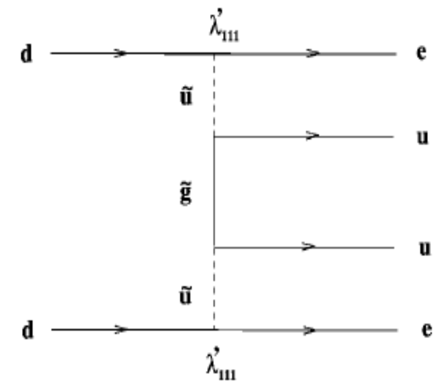


Other models: Left-Right symmetric model and SUSY R-parity violation

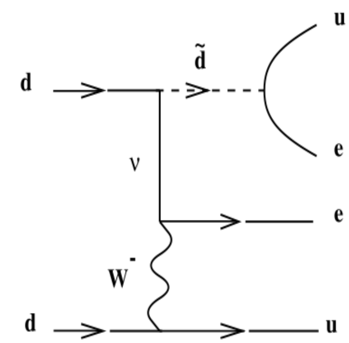
DAS *et al.* PHYSICAL REVIEW D 86, 055006 (2012)



(a) (b)



Gluino exchange



Squark exchange

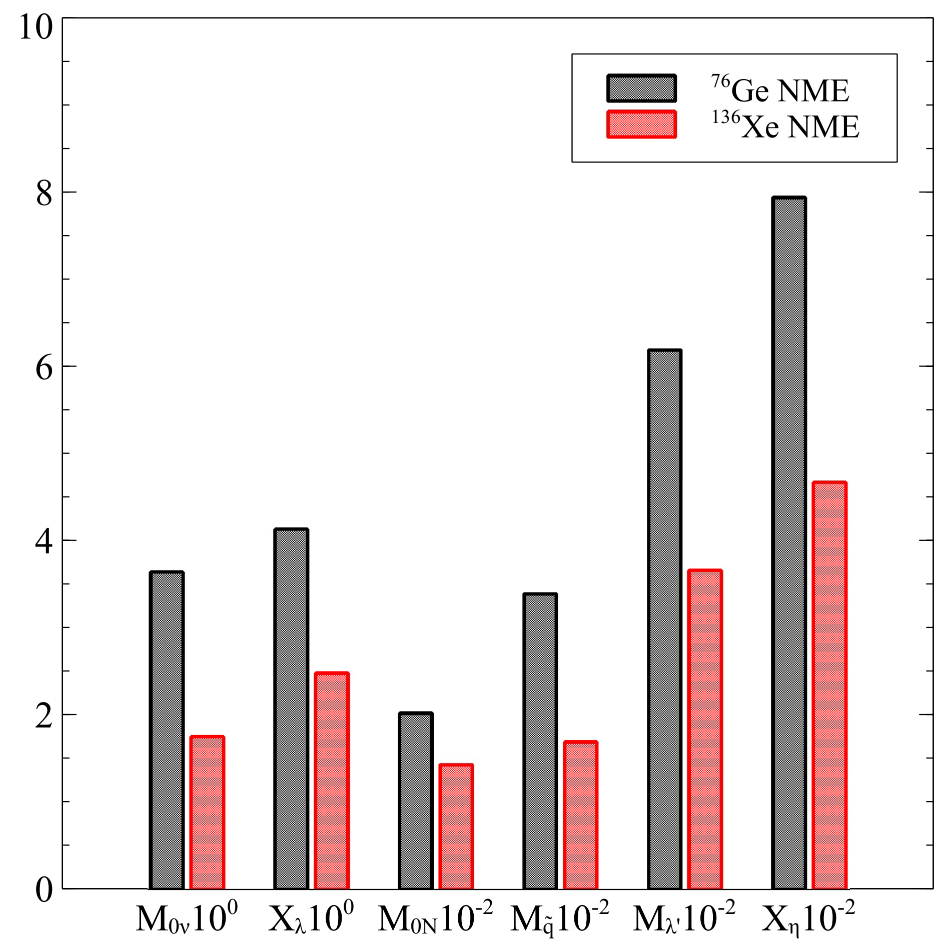
$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{01} g_A^4 \left| \eta_{0\nu} M_{0\nu} + \left(\eta^L_{N_R} + \eta^R_{N_R}\right) M_{0N} + \eta_{\tilde{q}} M_{\tilde{q}} + \eta_{\lambda'} M_{\lambda'} + \eta_\lambda X_\lambda + \eta_\eta X_\eta \right|^2 .$$

(e)

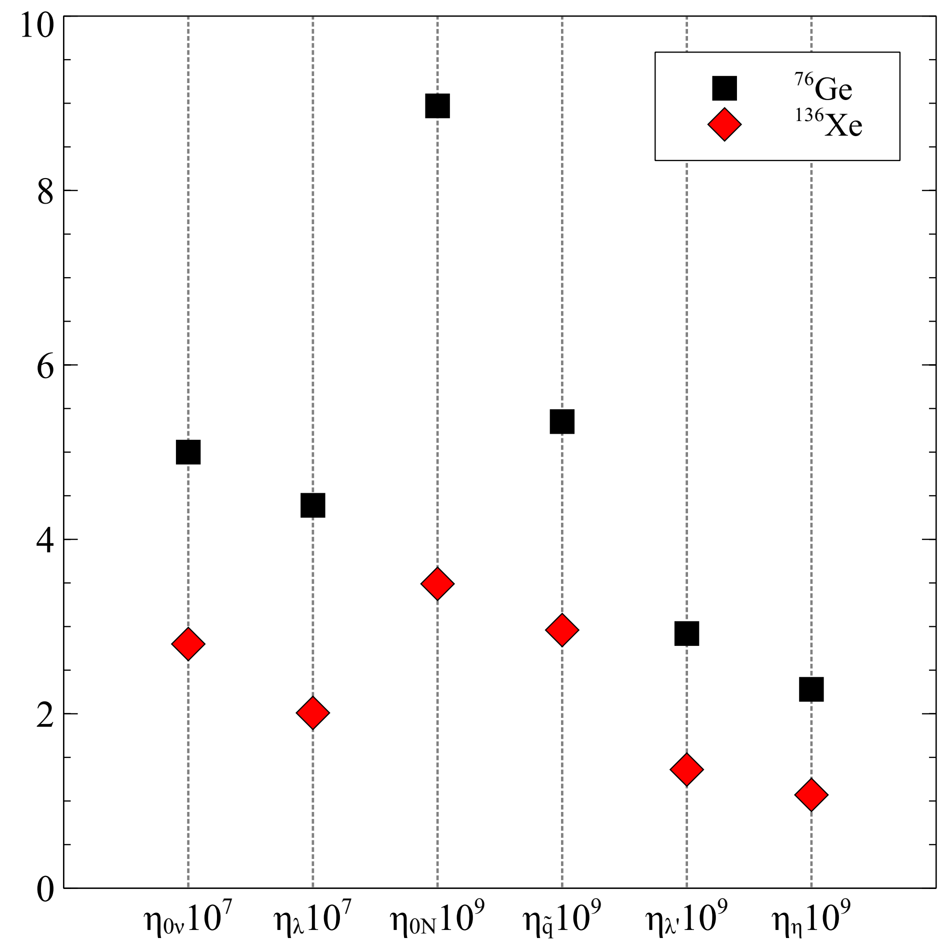
M. Horoi, A. Neacsu, PRD 93, 113014 (2016)

One mechanism dominance

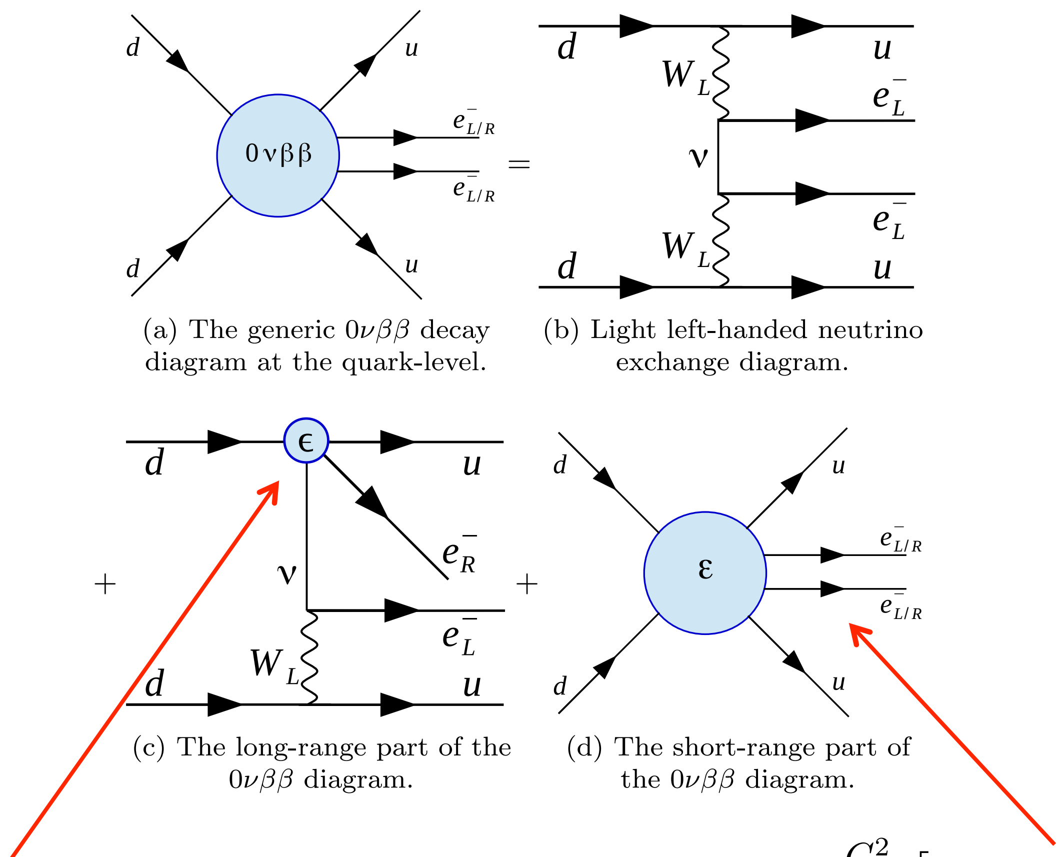
$$\left[T^{0\nu}_{1/2}\right]^{-1} = G_{01} g_A^4 \left| \eta_{0\nu} M_{0\nu} + \left(\eta^L_{N_R} + \eta^R_{N_R}\right) M_{0N} + \eta_{\tilde{q}} M_{\tilde{q}} + \eta_{\lambda'} M_{\lambda'} + \eta_\lambda X_\lambda + \eta_\eta X_\eta \right|^2 .$$



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



Effective field theory approach



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

(b) Light left-handed neutrino exchange diagram.

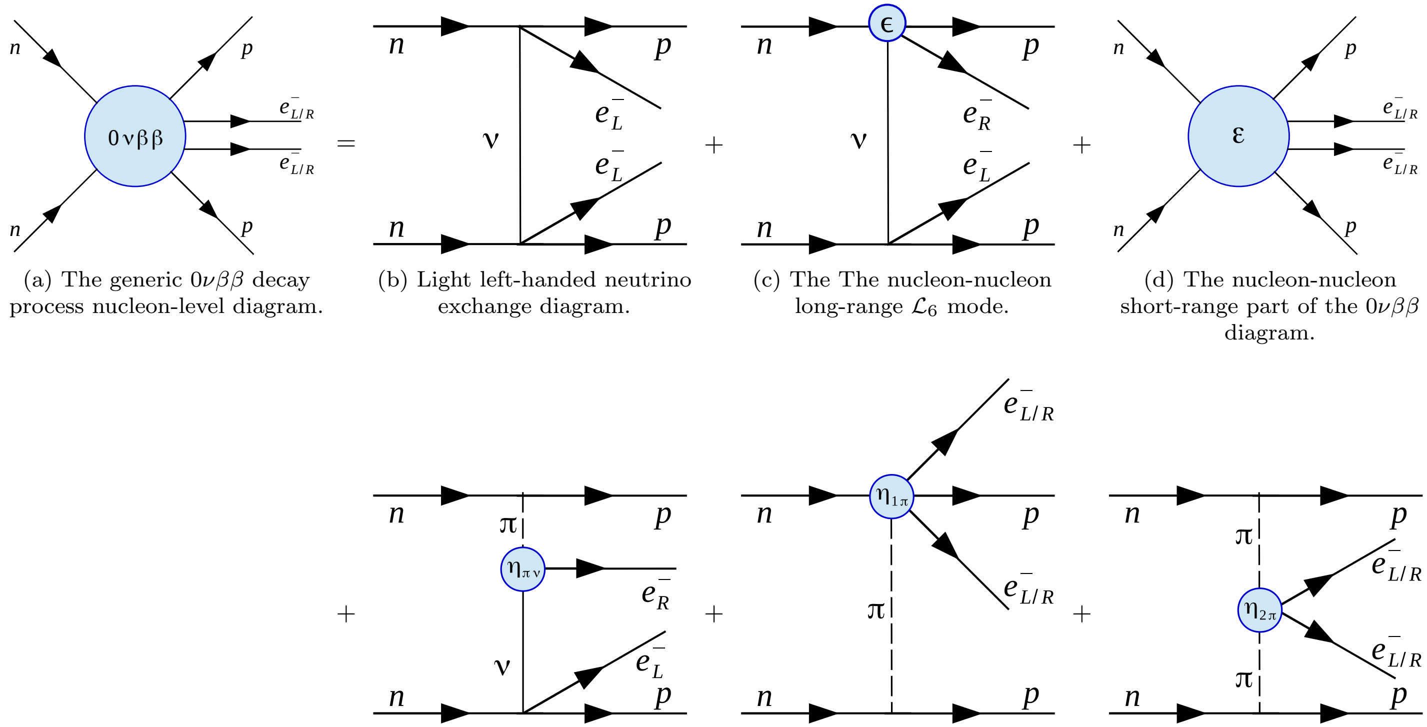
(c) The long-range part of the $0\nu\beta\beta$ diagram.

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

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

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

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.

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

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

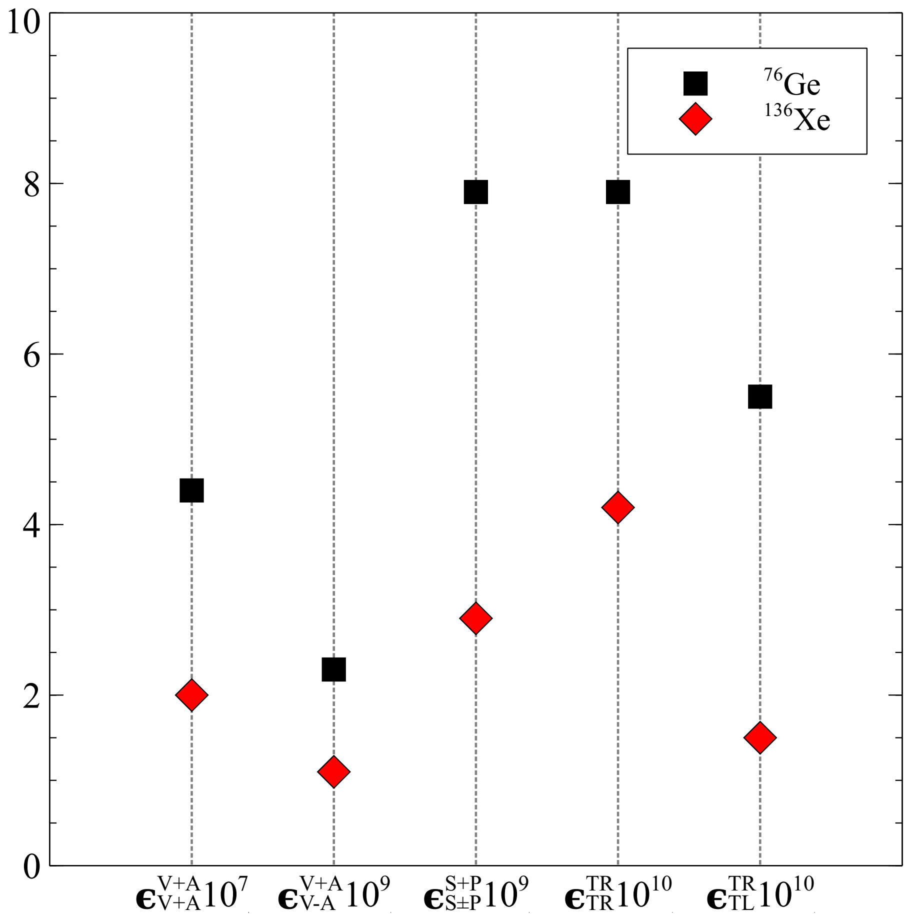
$$\mathcal{E}_{8-15} = \{\varepsilon_1,\ \varepsilon_2,\ \varepsilon_3^{LLz(RRz)},\ \varepsilon_3^{LRz(RLz)},\ \varepsilon_4,\ \varepsilon_6,\ \eta_{1\pi},\ \eta_{2\pi}\}$$

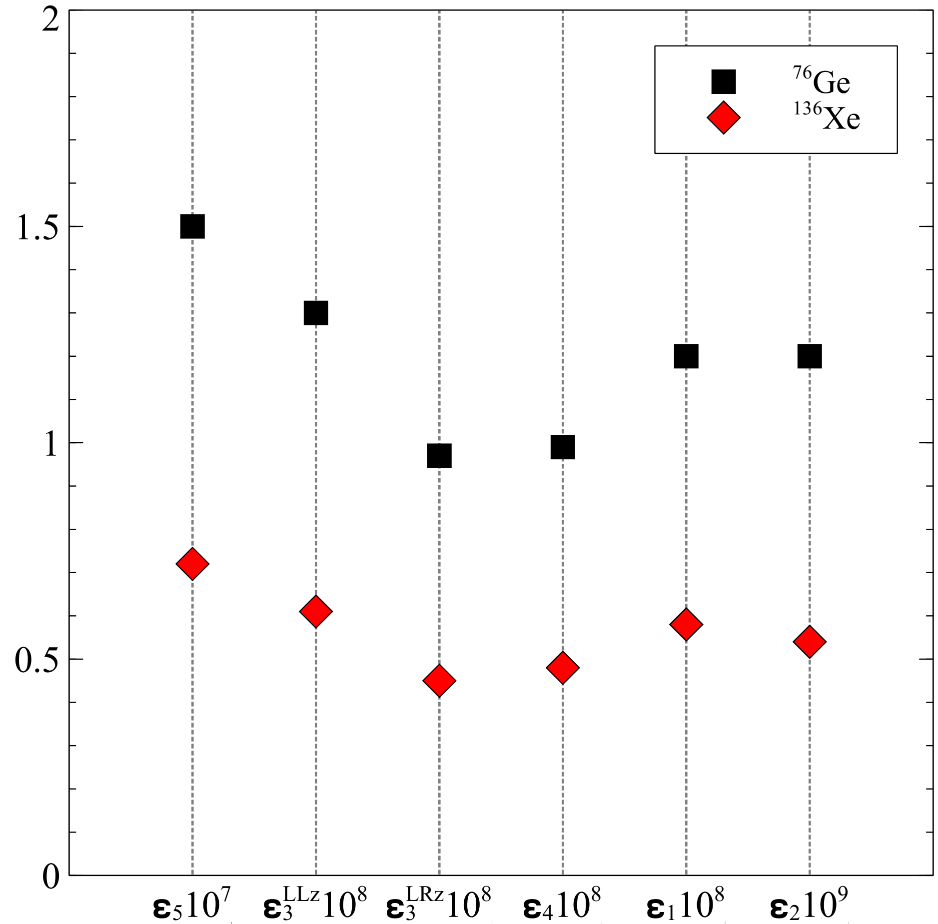
$$\left[T^{0\nu}_{1/2}\right]^{-1} = g_A^4 \left[\sum_i |\mathcal{E}_i|^2 \mathcal{M}_i^2 + \mathrm{Re}\left[\sum_{i\neq j} \mathcal{E}_i \mathcal{E}_j \mathcal{M}_{ij}\right]\right]$$

One coupling dominance

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

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





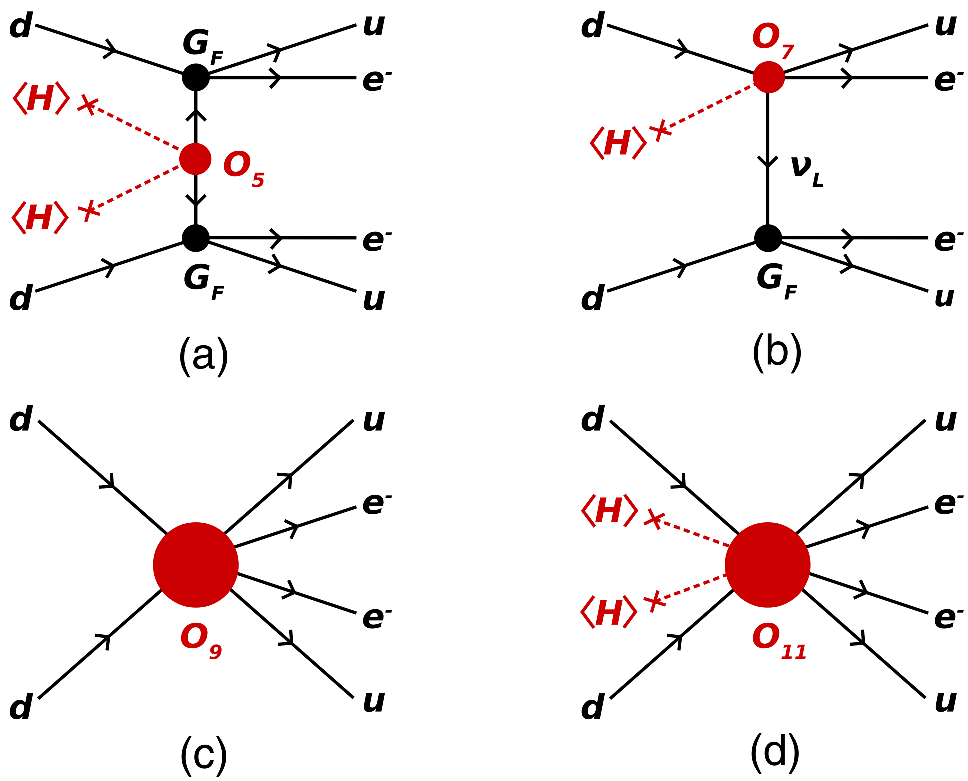
$T^{0\nu}_{1/2}(^{76}Ge) > 5\times 10^{25}$ *years* $\quad T^{0\nu}_{1/2}(^{136}Xe) > 1.1\times 10^{26}$ *years*

Consequences: - scales for new physics

- baryogenesis via leptogenesis

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

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



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

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

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

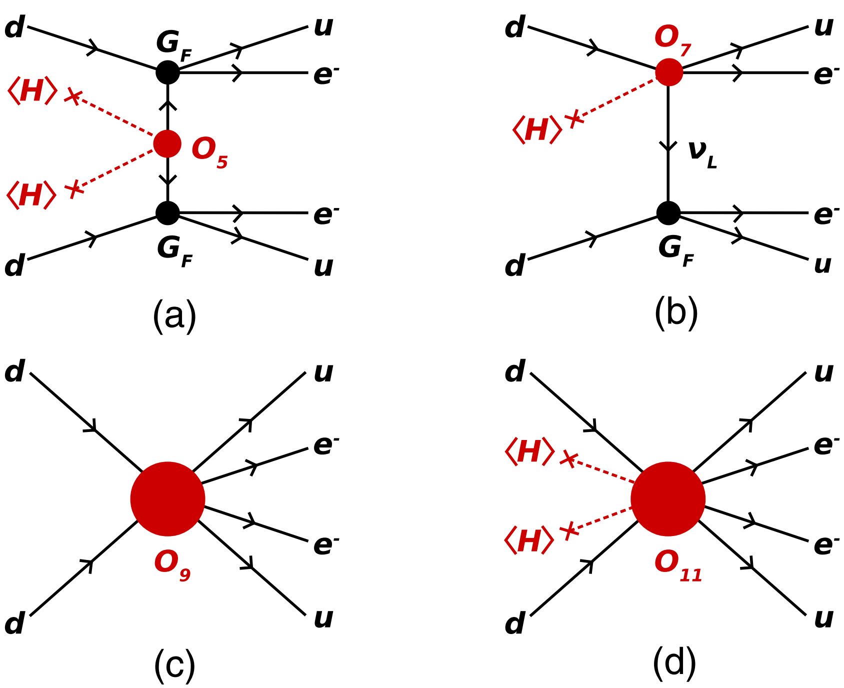
$\mathcal{O}_D$	$\bar{\epsilon}_D$	Λ_D
$\mathcal{O}_5$	2.8×10^{-7}	2.12×10^{14}
$\mathcal{O}_7$	2.0×10^{-7}	3.75×10^{4}
$\mathcal{O}_9$	1.5×10^{-7}	2.48×10^{3}
$\mathcal{O}_{11}$	1.5×10^{-7}	1.16×10^{3}

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*

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!

Collaborators:

- Alex Brown, NSCL@MSU
- **Roman Senkov, CUNY/CMU**
- **Andrei Neacsu, CMU**
- Jonathan Engel, UNC
- Jason Holt, TRIUMF
- Petr Navratil, TRIUMF
- Sofia Quaglioni, LLNL
- Micah Schuster, ORNL
- **Changfeng Jiao, CMU**

MS Theses:

- Fahim Ahmed, CMU
- Shiplu Sarker, CMU/ISU