Nuclear matrix elements for double-beta decay: a shell model perspective

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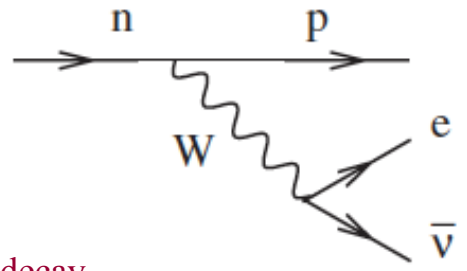
Classical Double Beta Decay Problem

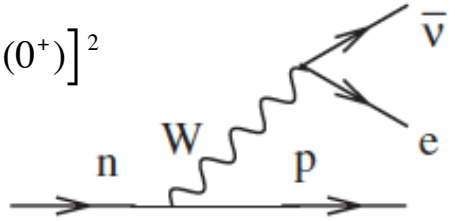
Isotope	$T_{1/2}(2\nu)$ (years)	$M^{2\nu}$
^{48}Ca	$4.4^{+0.6}_{-0.5} \times 10^{19}$	$0.0238^{+0.0015}_{-0.0017}$
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$	$0.0716^{+0.0025}_{-0.0023}$
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$	$0.0503^{+0.0020}_{-0.0018}$
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$	$0.0491^{+0.0023}_{-0.0020}$
^{100}Mo	$(7.1 \pm 0.4) \times 10^{18}$	$0.1258^{+0.0037}_{-0.0034}$
^{100}Mo-^{100}Ru(0^+_1)	$5.9^{+0.8}_{-0.6} \times 10^{20}$	$0.1017^{+0.0056}_{-0.0063}$
^{116}Cd	$(2.8 \pm 0.2) \times 10^{19}$	$0.0695^{+0.0025}_{-0.0024}$
^{128}Te	$(1.9 \pm 0.4) \times 10^{24}$	$0.0249^{+0.0031}_{-0.0023}$
^{130}Te	$(6.8^{+1.2}_{-1.1}) \times 10^{20}$	$0.0175^{+0.0016}_{-0.0014}$
^{150}Nd	$(8.2 \pm 0.9) \times 10^{18}$	$0.0320^{+0.0018}_{-0.0017}$
^{150}Nd-^{150}Sm(0^+_1)	$1.33^{+0.45}_{-0.26} \times 10^{20}$	$0.0250^{+0.0029}_{-0.0034}$
^{238}U	$(2.0 \pm 0.6) \times 10^{21}$	$0.0271^{+0.0053}_{-0.0033}$
^{136}Xe	2.23×10^{21}	0.010

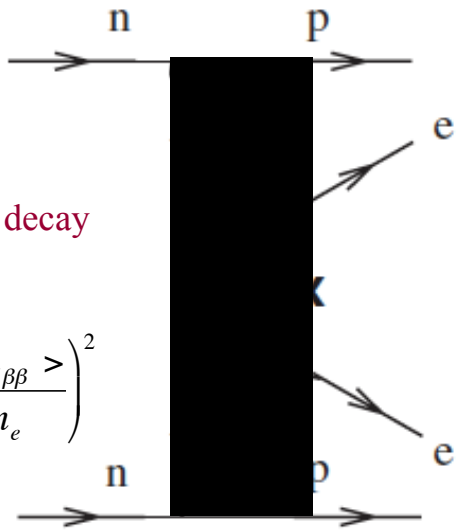
A.S. Barabash, PRC 81 (2010)



2-neutrino double beta decay

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

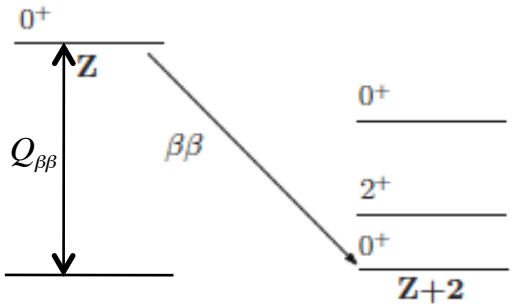




neutrinoless double beta decay

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

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



Adapted from Avignone, Elliot, Engel, Rev. Mod. Phys. 80, 481 (2008) -> RMP08

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

Neutrino Masses

PMNS – matrix

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Neutrino oscillations:
- *NH or IH?*
- $\delta_{CP} = ?$
- *Unitarity of* U_{PMNS}*?*
- *Are there* $m \sim 1eV$ *sterile neutrinos?*

$10^{-5}\ eV^2\ (solar)$

$\times 10^{-3}\ eV^2\ (atmospheric)$

- Tritium decay:

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

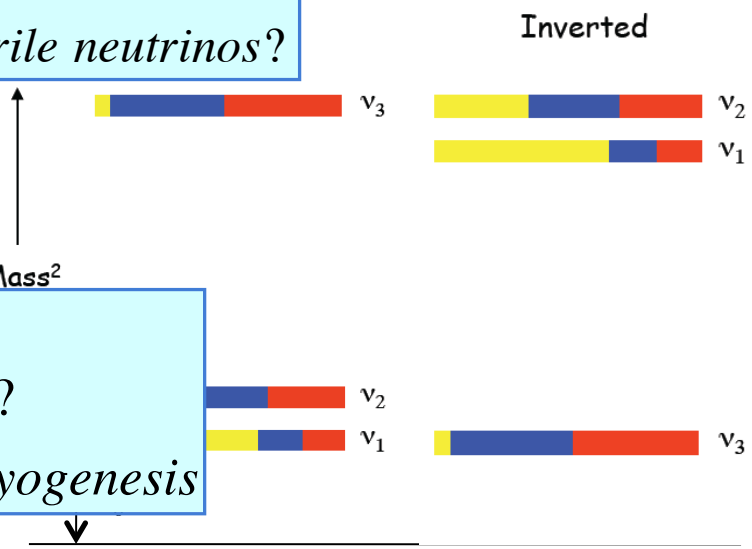
$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 2.$$

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

- Cosmology: CMB power spectrum, BAO, et

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

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

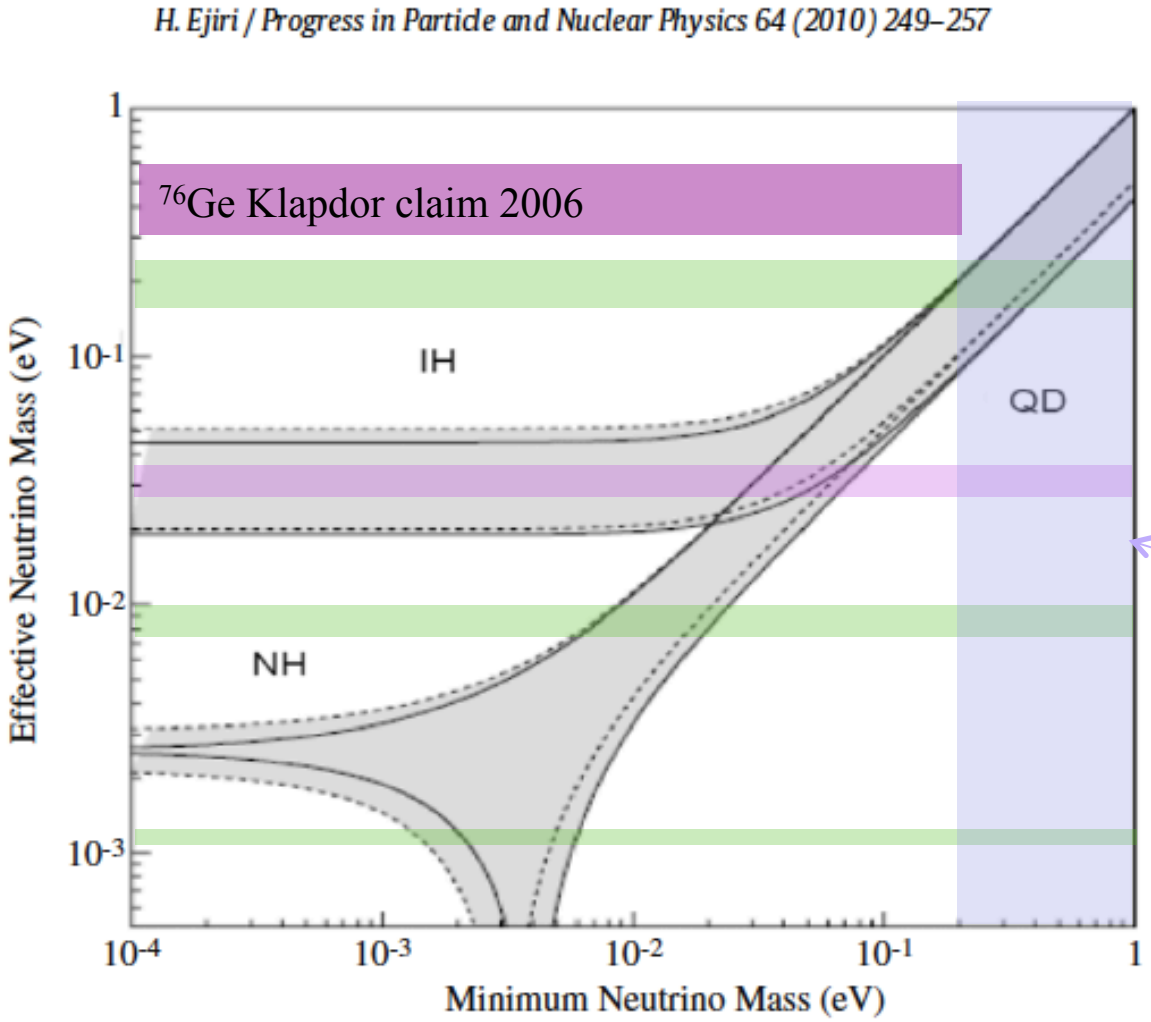


- *Dirac or Majorana?*
- *Majorana CPV* $\alpha_i = ?$
- *Leptogenesis?* $\rightarrow$ *Baryogenesis*

Two neutrino mass hierarchies

SciDAC Scientific Discovery through Advanced Computing

Neutrino ββ effective mass



$$\langle m_{\beta\beta} \rangle = \left| \sum_{k=1}^{3} m_k U_{ek}^2 \right|$$

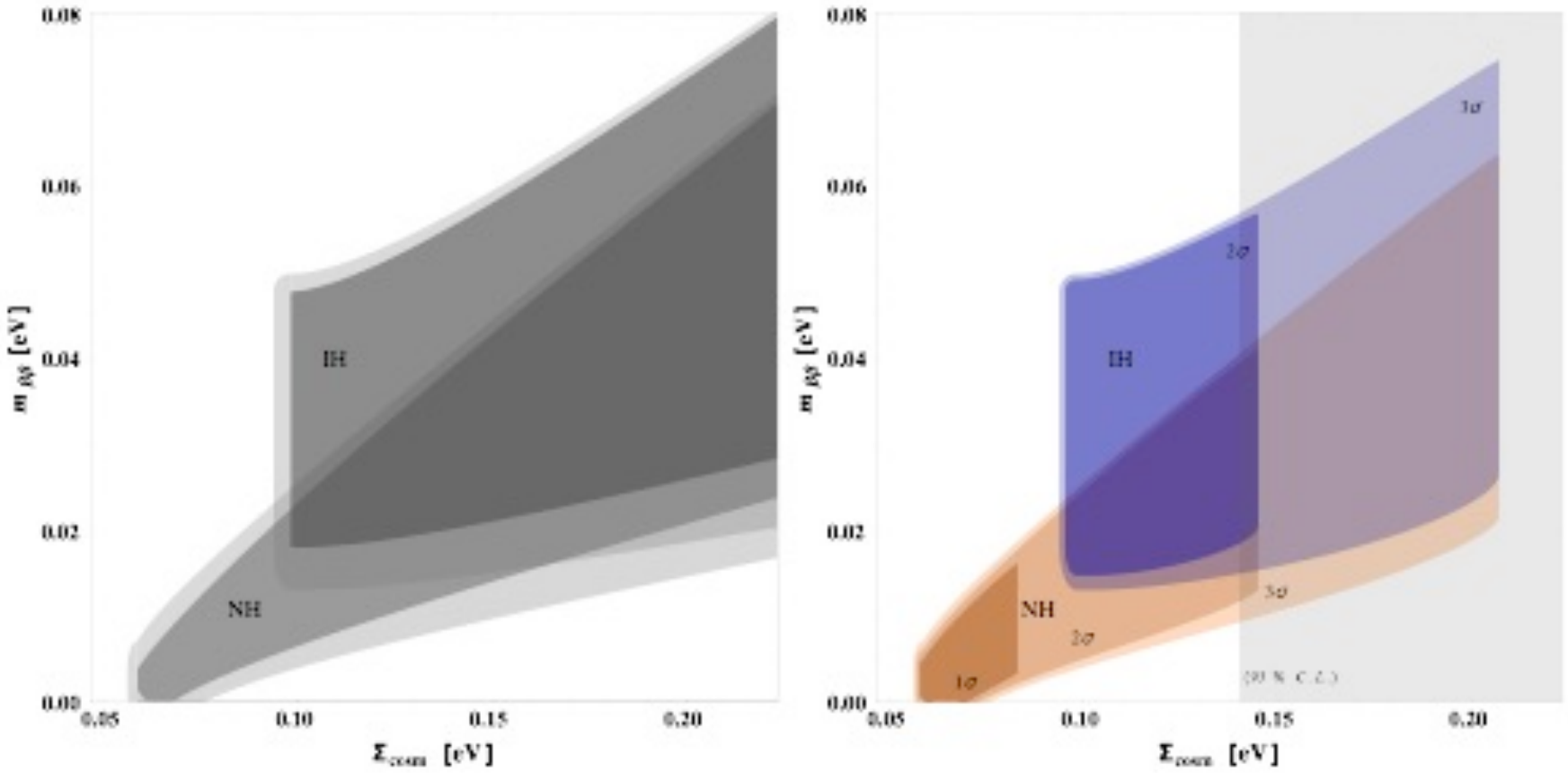
$$= \left| c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

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

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

Cosmology constraint

Recent Constraints from Cosmology



$$\Sigma = m_1 + m_2 + m_3$$

$$\Sigma < 84\,\text{meV} \quad (1\sigma\ \text{C. L.})$$
$$\Sigma < 146\,\text{meV} \quad (2\sigma\ \text{C. L.})$$
$$\Sigma < 208\,\text{meV} \quad (3\sigma\ \text{C. L.})$$

arXiV:1505.02722

The origin of Majorana neutrino masses

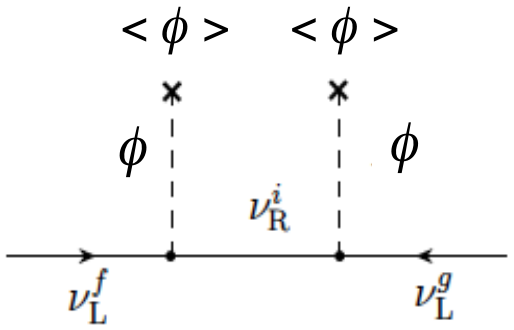
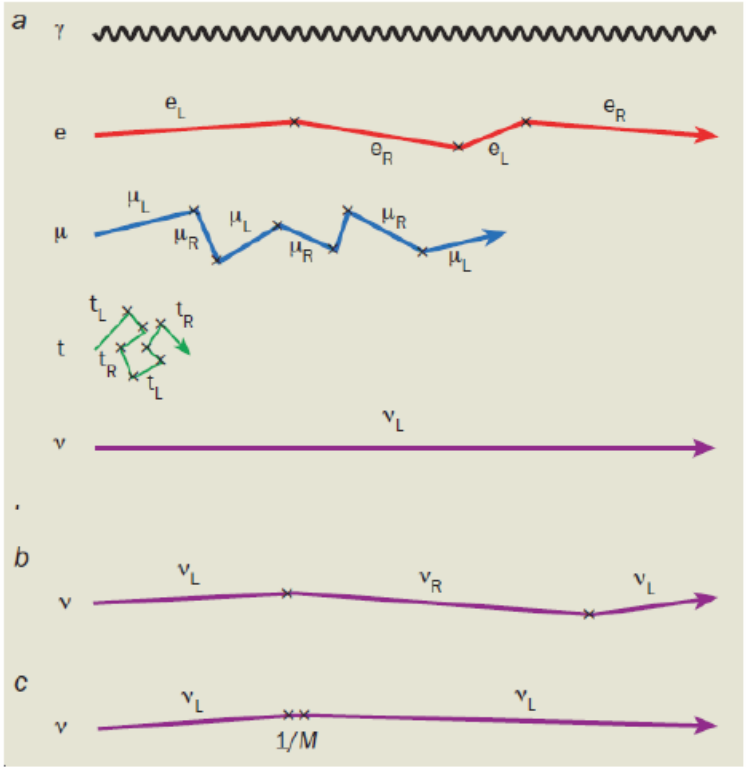


Diagram illustrating the type I see-saw mechanism

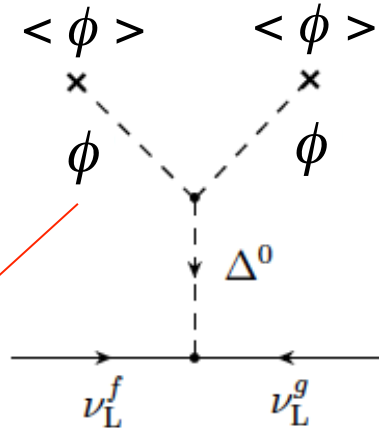


See-saw mechanisms

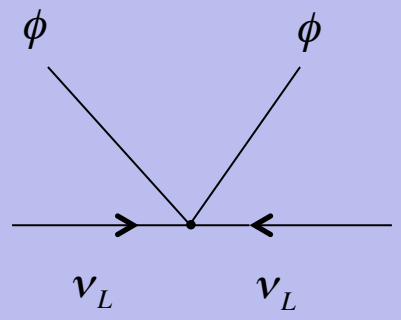
$$\begin{cases} m_{LL}^{\nu} \approx \dfrac{(100\ GeV)^2}{10^{14}\ GeV} = 0.1 eV \\ m_{LL}^{\nu} \approx \dfrac{(300\,keV)^2}{1\ TeV} = 0.1 eV \end{cases}$$

Left-Right Symmetric model

$$m_{LL}^{\nu} \approx m_{LL}^{\mathrm{II}} + m_{LL}^{\mathrm{I}}$$



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



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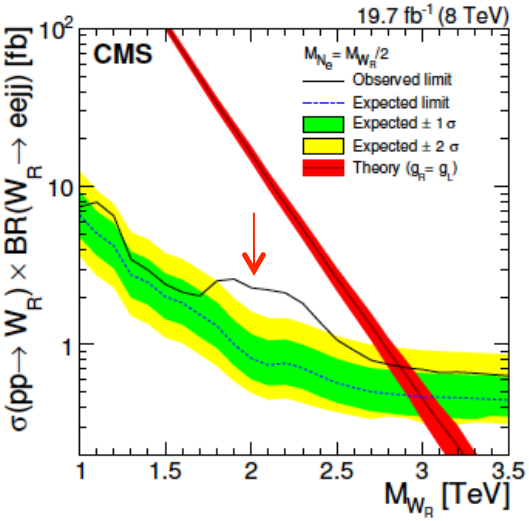
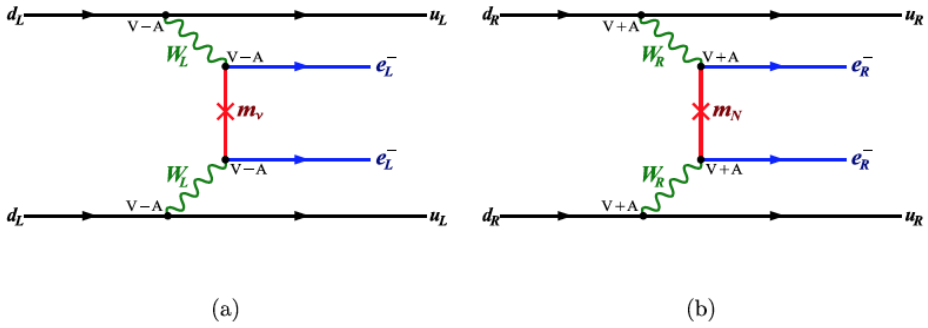
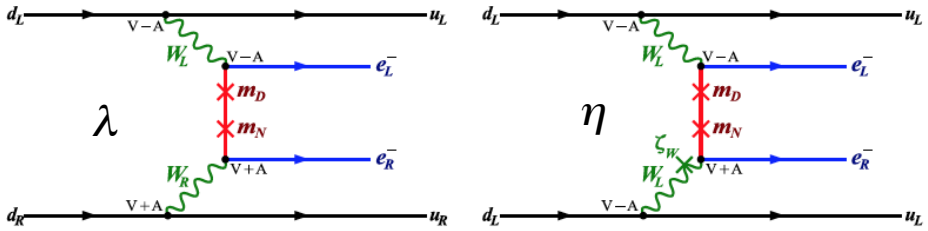
W_R search at CMS arXiv:1407.3683

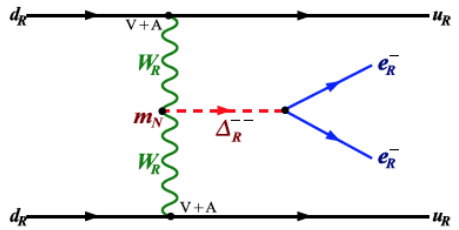


Low-energy LR contributions to 0νββ decay

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







Low-energy effective Hamiltonian

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} j_L^\mu J_{L\mu}^+ + h.c.$$

$$j_{L/R}^\mu = \bar{e}\gamma^\mu\left(1 \mp \gamma^5\right)\nu_e$$

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}}\left[j_L^\mu\left(J_{L\mu}^+ + \kappa J_{R\mu}^+\right) + j_R^\mu\left(\eta J_{L\mu}^+ + \lambda J_{R\mu}^+\right)\right] + h.c.$$

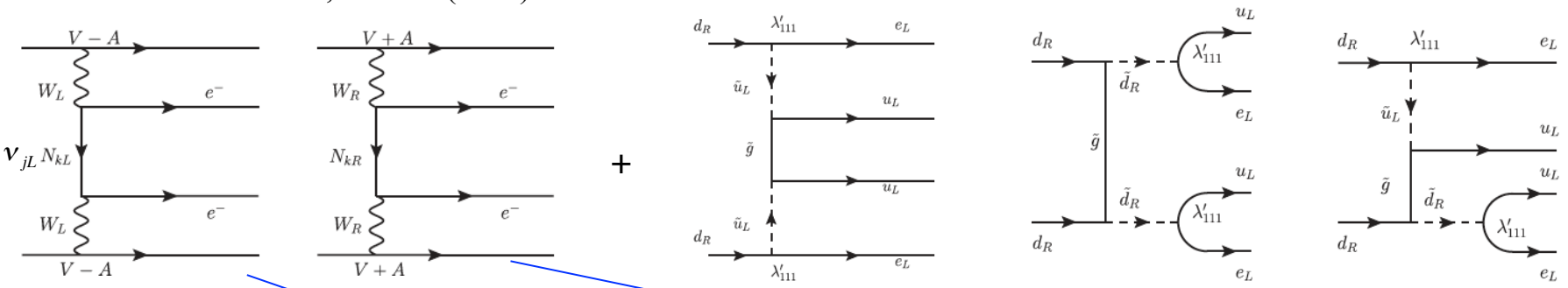
Left – right symmetric model

$$-\mathcal{L} \supset \frac{1}{2} h_{\alpha\beta}^T \left(\bar{\nu}_{\beta L} \;\; \bar{e}_{\alpha L}\right)\begin{pmatrix}\Delta^- & -\Delta^0 \\ \Delta^{--} & \Delta^-\end{pmatrix}\begin{pmatrix}e_R^c \\ -\nu_R^c\end{pmatrix} + hc$$

No neutrino exchange

The 0νDBD half-life

PRD 83, 113003 (2011)



$$\begin{cases} \nu'_{eL} = \sum_k^{light} U_{ek}\nu_{kL} + \sum_k^{heavy} S_{ek}N_{kL} \\ \nu'_{eR} = \sum_k^{light} T^*_{ek}\nu_{kR} + \sum_k^{heavy} V^*_{ek}N_{kR} \end{cases}$$

$$\eta_{\nu L} = \frac{\langle m_{\beta\beta}\rangle}{m_e} \qquad \eta_{NL} = \sum_k^{heavy} S^2_{ek}\frac{m_p}{M_k} \qquad \eta_{NR} = \left(\frac{M_{WL}}{M_{WR}}\right)^4 \sum_k^{heavy} V^{*2}_{ek}\frac{m_p}{M_k}$$

$$\langle\lambda\rangle = \left(\frac{M_{WL}}{M_{WR}}\right)^2 \sum_k^{light} U_{ek}T^*_{ek} \qquad \langle\eta\rangle = \zeta\sum_k^{light} U_{ek}T^*_{ek} \qquad W_R \approx \zeta W_1 + W_2$$

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}\left|\sum_j M_j\eta_j\right|^2 = G^{0\nu}\left|M^{(0\nu)}\eta_{\nu L} + M^{(0N)}\left(\eta_{NL}+\eta_{NR}\right) + \tilde{X}_\lambda\langle\lambda\rangle + \tilde{X}_\eta\langle\eta\rangle + M^{(0\lambda')}\eta_{\lambda'} + M^{(0\tilde{q})}\eta_{\tilde{q}} + \cdots\right|^2$$

(i) η_{NL} neglijible in most models; (ii) $\langle\eta\rangle$ & $\langle\lambda\rangle$ ruled in/out by energy or angular distributions

$$\left[T^{0\nu}_{1/2}\right]^{-1} \cong G^{0\nu}\left|M^{(0\nu)}\eta_{\nu L} + M^{(0N)}\eta_{NR}\right|^2 \approx G^{0\nu}\left[\left|M^{(0\nu)}\right|^2\left|\eta_{\nu L}\right|^2 + \left|M^{(0N)}\right|^2\left|\eta_{NR}\right|^2\right]$$ *No interference terms!*

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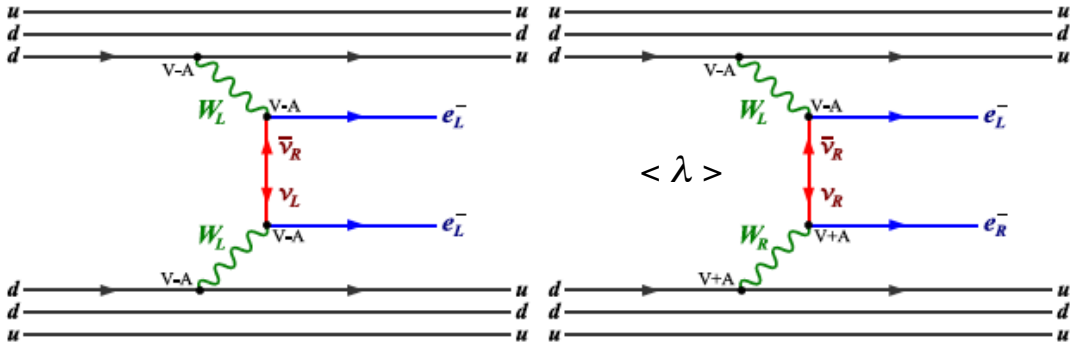
DBD signals from different mechanisms

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

arXiv:1005.1241

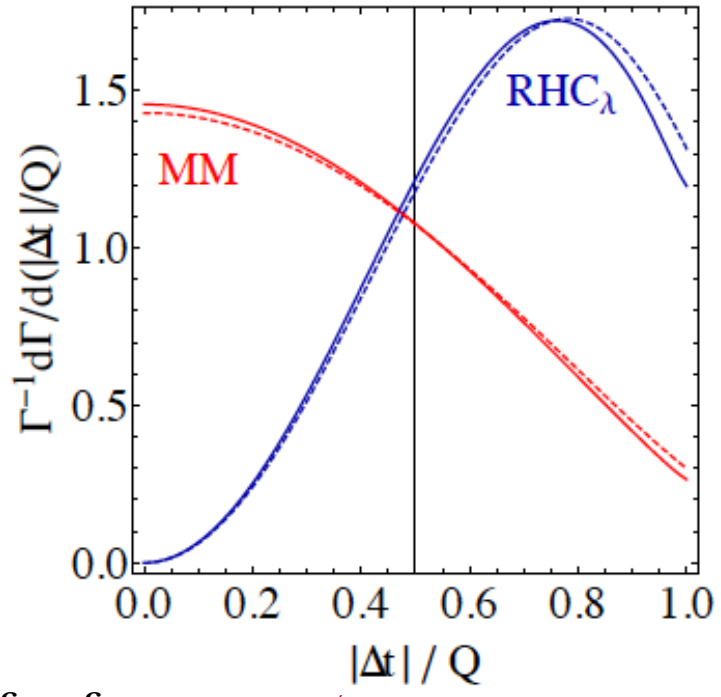


$$\mu \approx \frac{m_\nu}{m_e}, \tag{10}$$

$$\eta \approx \tan\zeta \sqrt{\frac{m_\nu}{M_R}}, \tag{11}$$

$$\lambda \approx \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sqrt{\frac{m_\nu}{M_R}}. \tag{12}$$

$$[T_{1/2}]^{-1} = C_{mm}\mu^2 + C_{\lambda\lambda}\lambda^2 + C_{m\lambda}\mu\lambda. \tag{13}$$



Isotope	C_{mm} [y^{-1}]	$C_{\lambda\lambda}$ [y^{-1}]	$C_{m\lambda}$ [y^{-1}]
^{76}Ge	1.12×10^{-13}	1.36×10^{-13}	-4.11×10^{-14}
^{82}Se	4.33×10^{-13}	1.01×10^{-12}	-1.60×10^{-13}
^{150}Nd	7.74×10^{-12}	2.68×10^{-11}	-3.57×10^{-12}

Table 1: Coefficients used in calculating the $0\nu\beta\beta$ decay rate [30].

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

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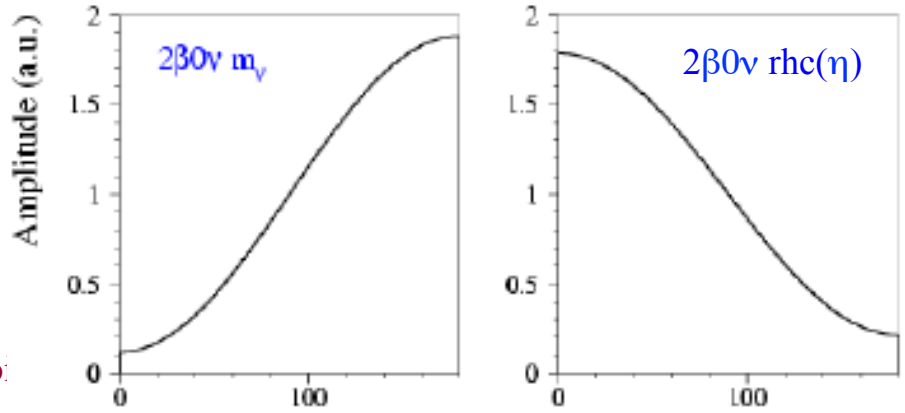
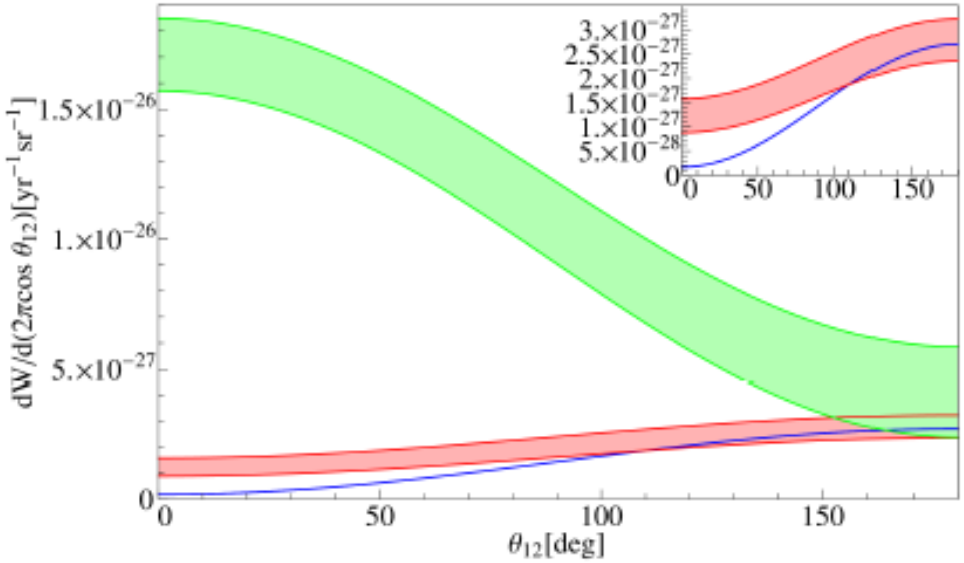


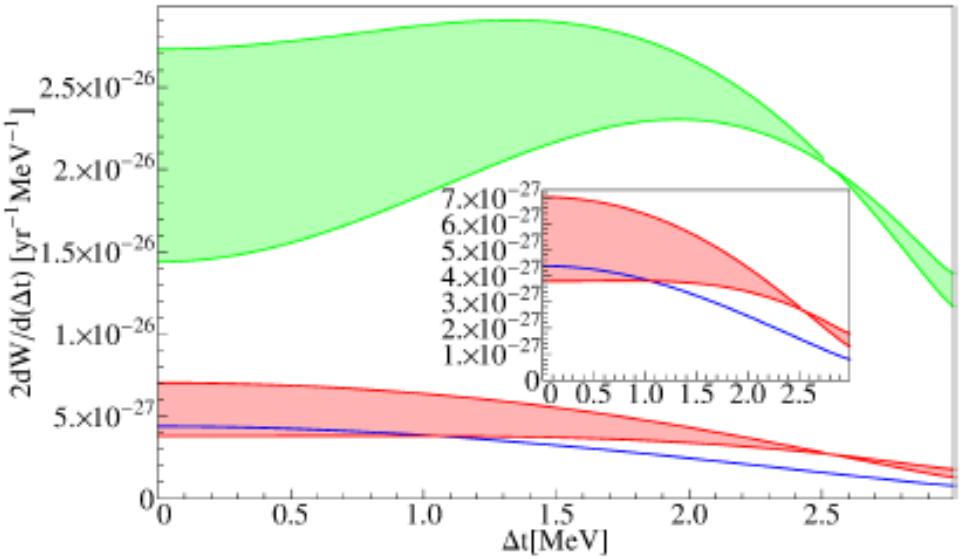
θ - angle between e_1 and e_2

Electron distributions at Super-NEMO

^{82}Se



(a) Angular distribution.



(b) Energy distribution

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

	ν	λ	η
Case 0 Blue	$2 \cdot 10^{-7}$	0	0
Case 1 Red	$2 \cdot 10^{-7}$	$0.5 \cdot 10^{-7}$	$0.5 \cdot 10^{-9}$
Case 1 Green	$2 \cdot 10^{-7}$	$2 \cdot 10^{-7}$	$2 \cdot 10^{-9}$

IU

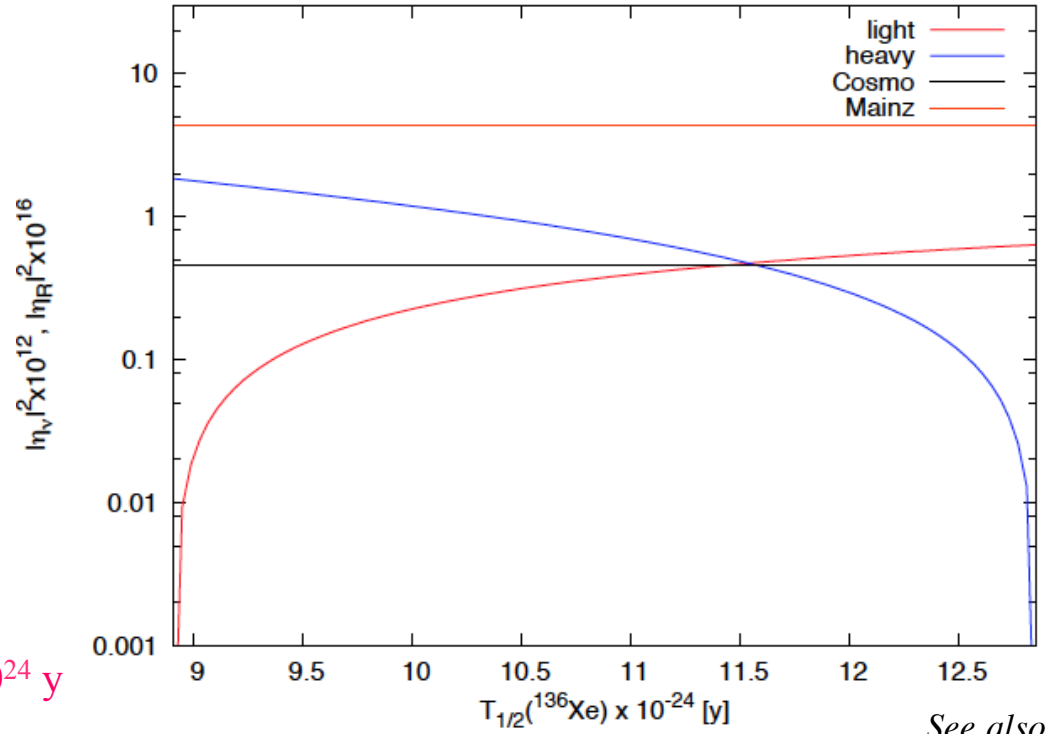
Two Non-Interfering Mechanisms

$$\left[T_{1/2}^{0\nu}\right]^{-1} \approx G^{0\nu}\left[\left|M^{(0\nu)}\right|^2\left|\eta_{\nu L}\right|^2 + \left|M^{(0N)}\right|^2\left|\eta_{NR}\right|^2\right] \quad \textit{No interference terms!}$$

$$\left|\eta_\nu\right|, \left|\eta_{NR}\right| \Leftarrow \begin{cases} \left[G_{Ge}^{0\nu} T_{1/2\,Ge}^{0\nu}\right]^{-1} = \left|M_{Ge}^{(0\nu)}\right|^2\left|\eta_\nu\right|^2 + \left|M_{Ge}^{(0N)}\right|^2\left|\eta_{NR}\right|^2 \\ \left[G_{Xe}^{0\nu} T_{1/2\,Xe}^{0\nu}\right]^{-1} = \left|M_{Xe}^{(0\nu)}\right|^2\left|\eta_\nu\right|^2 + \left|M_{Xe}^{(0N)}\right|^2\left|\eta_{NR}\right|^2 \end{cases}$$

$$\left|\eta_\nu\right| = \frac{\left\langle m_{\beta\beta}\right\rangle}{m_e} \approx 10^{-6}$$

$$\left|\eta_{NR}\right| = \left(\frac{M_{WL}}{M_{WR}}\right)^4 \sum_k^{heavy} V_{ek}^2 \frac{m_p}{M_k} \approx 10^{-8}$$

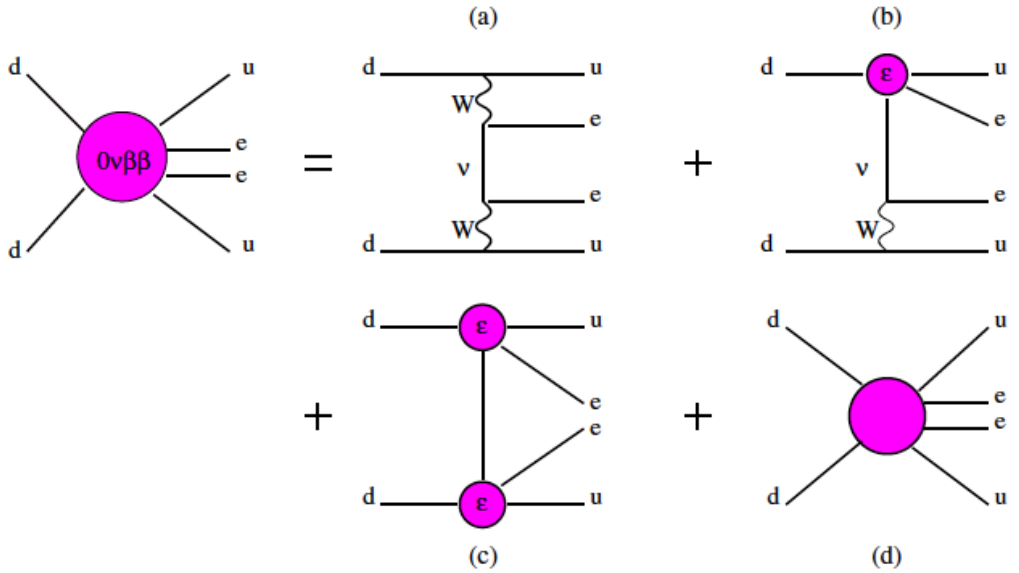


Assume $T_{1/2}(^{76}Ge)=22.3\times10^{24}$ y

See also PRD 83,113003 (2011)

Is there a more general description?

J. Phys. G: Nucl. Part. Phys. **39** (2012) 124007 F F Deppisch *et al*



$G_{01}^{0\nu}$, $G_{06}^{0\nu}$, $G_{09}^{0\nu}$

Doi, *Kotani*, *Takasugi* 1983

$$\epsilon \propto \frac{g_{eff}^2}{\Lambda_{eff}^2}$$

$$\epsilon \propto \frac{g_{eff}^4}{\Lambda_{eff}^5} \Rightarrow \Lambda \gtrsim (1-3)\ \text{TeV}$$

Long-range terms: (a) - (c)

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\left\{ j_{V-A}^{\mu} J_{V-A,\mu}^{\dagger} + \sum_{\alpha,\beta} \epsilon_{\alpha}^{\beta} j_{\beta} J_{\alpha}^{\dagger} \right\}$$

$$A_{\beta\beta} \propto T[\mathcal{L}(t_1)\mathcal{L}(t_2)] \propto \left(j_{V-A} J_{V-A}^{+}\right)\left(j_{\alpha} J_{\beta}^{+}\right)$$

$$\alpha, \beta : V-A,\ V+A,\ S+P, S-P,\ T_L,\ T_R$$

Short-range terms: (d)

$$\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \{\epsilon_1 JJj + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^{\mu} J_{\mu} j + \epsilon_4 J^{\mu} J_{\mu\nu} j^{\nu} + \epsilon_5 J^{\mu} J j_{\mu}\}$$

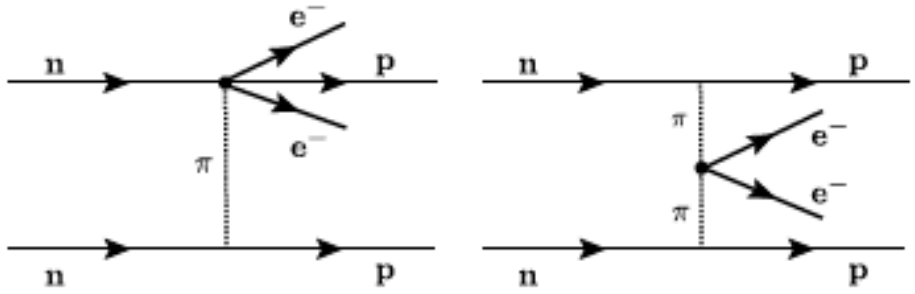
$$A_{\beta\beta} \propto \mathcal{L}$$

$$J^{\mu\nu} = \bar{u} \frac{i}{2}\left[\gamma^{\mu}, \gamma^{\nu}\right]\left(1 \pm \gamma^5\right) d$$

More long-range contributions?

SUSY /w R – parity v.: e.g. Rep.Prog.Phys. 75, 106301(2012)

Hadronization /w R-parity v. and heavy neutrino



SUSY & LRSM : Prezeau, Ramsey – Musolf , Vogel, PRC 68, 034016 (2003)

$$\frac{1}{T_{1/2}} = \frac{1}{64\pi^5 \ln 2}\left(\frac{\hbar c}{R}\right)^6 \frac{g_A^4}{\hbar}\frac{G_F^4}{\Lambda_{\beta\beta}^2 c^4}\int_{m_e}^{E_{\beta\beta}-m_e} dE_1 F(Z+2,E_1)F(Z+2,E_2)\frac{1}{2}\left\{\left[\left|\beta_3 M_2^{\pi\pi} + \frac{\sqrt{2}\Lambda_H}{g_A M}\zeta_5 M_2^{\pi NN}\right|^2 + \left|\beta_4 M_2^{\pi\pi} + \frac{\sqrt{2}\Lambda_H}{g_A M}\zeta_6 M_2^{\pi NN}\right|^2\right] p_1 E_1 p_2 E_2 - \left[\left|\beta_3 M_2^{\pi\pi} - \frac{\sqrt{2}\Lambda_H}{g_A M}\zeta_5 M_2^{\pi NN}\right|^2 - \left|\beta_4 M_2^{\pi\pi} - \frac{\sqrt{2}\Lambda_H}{g_A M}\zeta_6 M_2^{\pi NN}\right|^2\right] p_1 p_2 m_e^2\right\},$$

Summary of 0νDBD mechanisms

- The mass mechanism (a.k.a. light-neutrino exchange) is likely, and the simplest BSM scenario.
- Low mass sterile neutrino would complicate analysis
- Right-handed heavy-neutrino exchange is possible, and requires knowledge of half-lives for more isotopes.
- η- and λ- mechanisms are possible, but could be ruled in/out by energy and angular distributions.
- Left-right symmetric model may be also (un)validated at LHC/colliders.
- SUSY/R-parity, KK, GUT, etc, scenarios need to be checked, but validated by additional means.

Closure Approximation and Beyond in Shell Model

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

$$M_S^{0\nu} = \sum_{\substack{pp'nn' \\ J\,k\,\mathcal{J}}} \left(\tilde{\Gamma}\right) \left\langle 0_f^+ \left\| \left(a_p^+ \tilde{a}_n \right)^J \right\| J_k \right\rangle \left\langle J_k \left\| \left(a_{p'}^+ \tilde{a}_{n'} \right)^J \right\| 0_i^+ \right\rangle \left\langle p\,p';\mathcal{J} \left| \int q^2 dq \left[\hat{S} \frac{h(q) j_\kappa(qr) G_{FS}^2 f_{SRC}^2}{q\left(q + E_k^J\right)} \tau_{1-} \tau_{2-} \right] \right| n\,n';\mathcal{J} \right\rangle - beyond$$

Challenge: there are about 100,000 J_k states in the sum for 48Ca

Much more intermediate states for heavier nuclei, such as ^{76}Ge!!!

No-closure may need states out of the model space (not considered).

Minimal model spaces

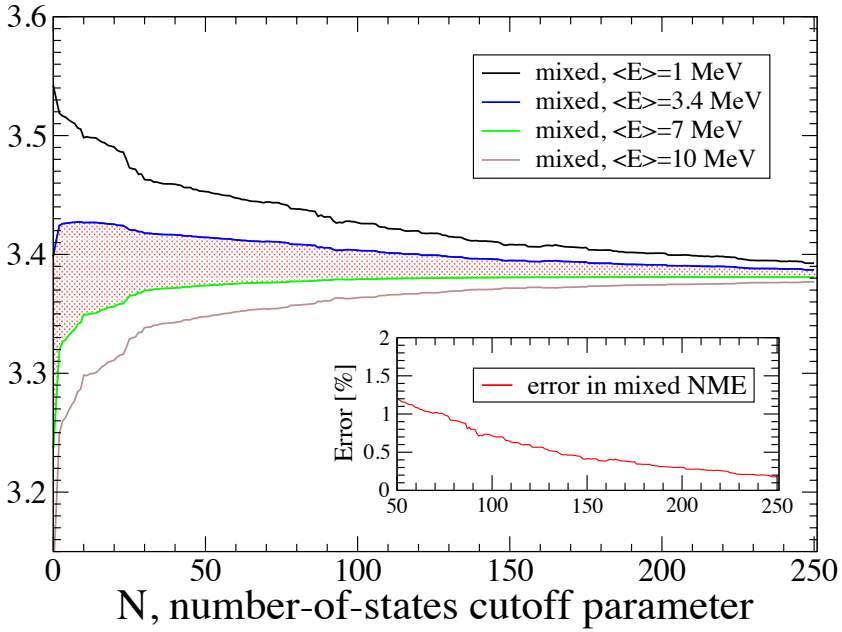
^{82}Se : 10M states

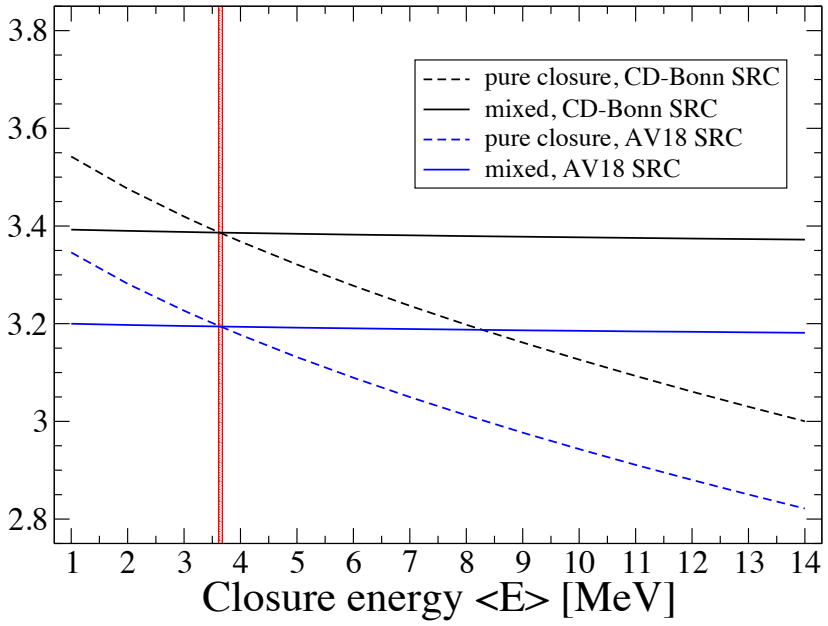
^{130}Te : 22M states

^{76}Ge : 150M states

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

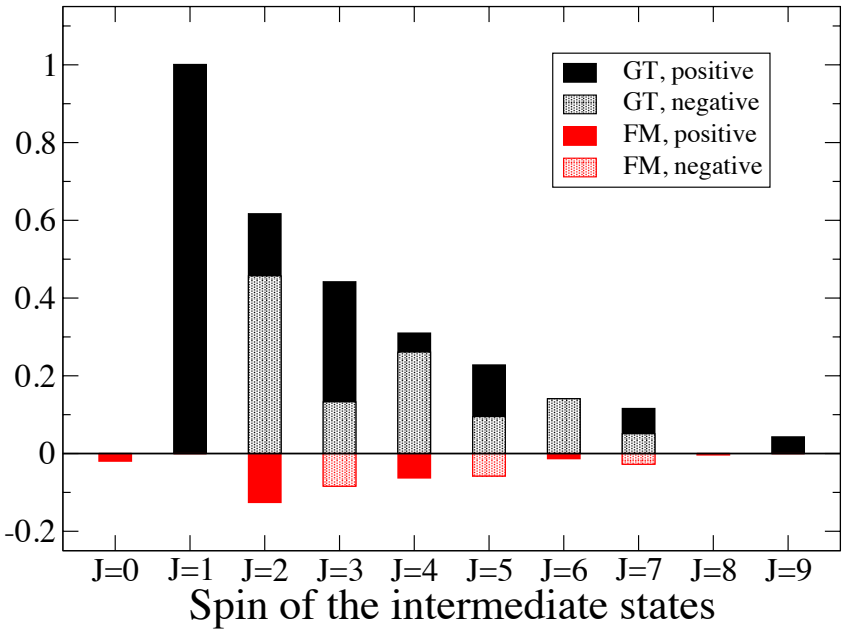
$$\hat{S} = \begin{cases} \sigma_1 \tau_1 \sigma_2 \tau_2 & Gamow-Teller\ (GT) \\ \tau_1 \tau_2 & Fermi\ (F) \\ \left[3(\vec{\sigma}_1 \cdot \hat{n})(\vec{\sigma}_2 \cdot \hat{n}) - (\vec{\sigma}_1 \cdot \vec{\sigma}_2)\right] \tau_1 \tau_2 & Tensor\ (T) \end{cases}$$

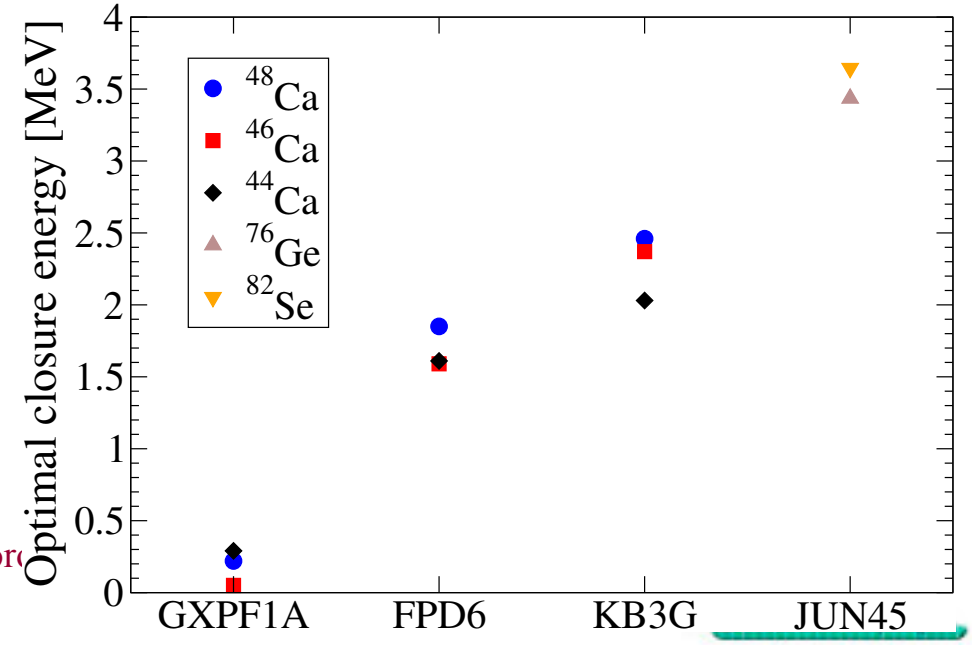




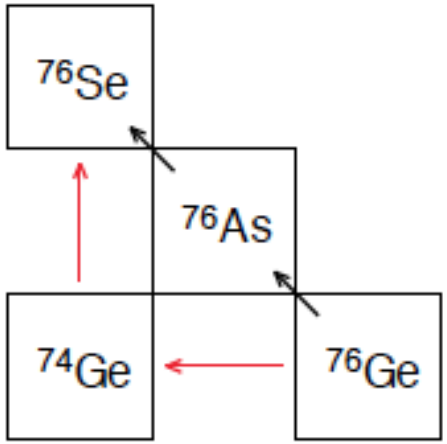
^{82}Se: PRC 89, 054304 (2014)

$$M_{mixed}(N) = M_{no-closure}(N) + \left[M_{closure}(N=\infty) - M_{closure}(N) \right]$$



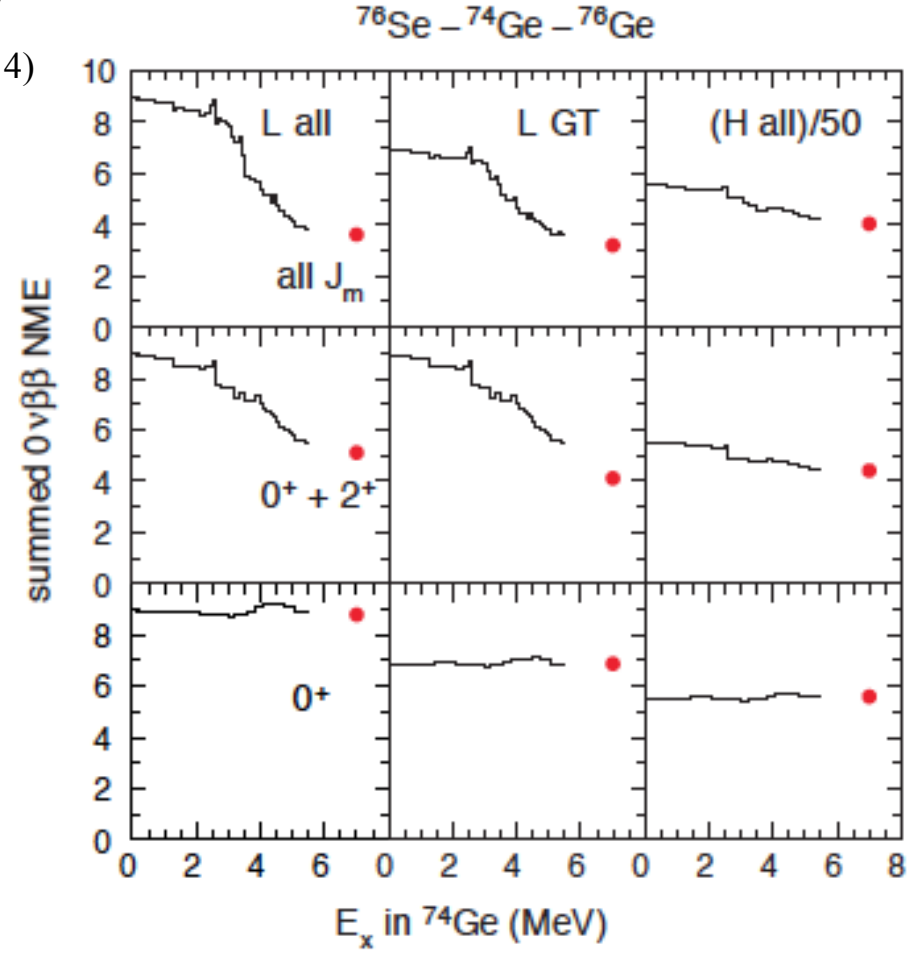


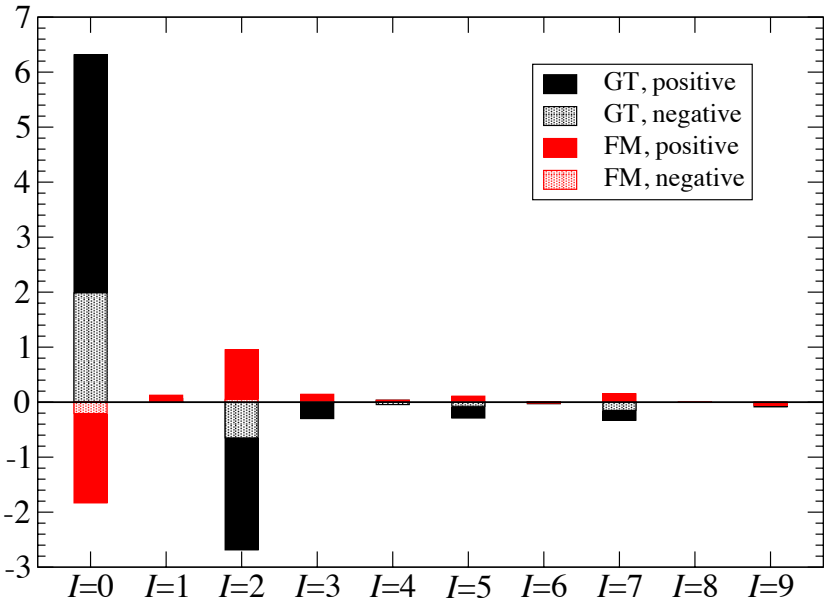
New Approach to calculate NME: New Tests of Nuclear Structure



Brown, Horoi, Senkov

PRL **113**, 262501 (2014)





Spin of the neutron-neutron (proton-proton) pairs

What Experimental Searches Do Exist?

S. Vigdor talk at LRP Town Meeting, Chicago, Sep 28-29, 2014

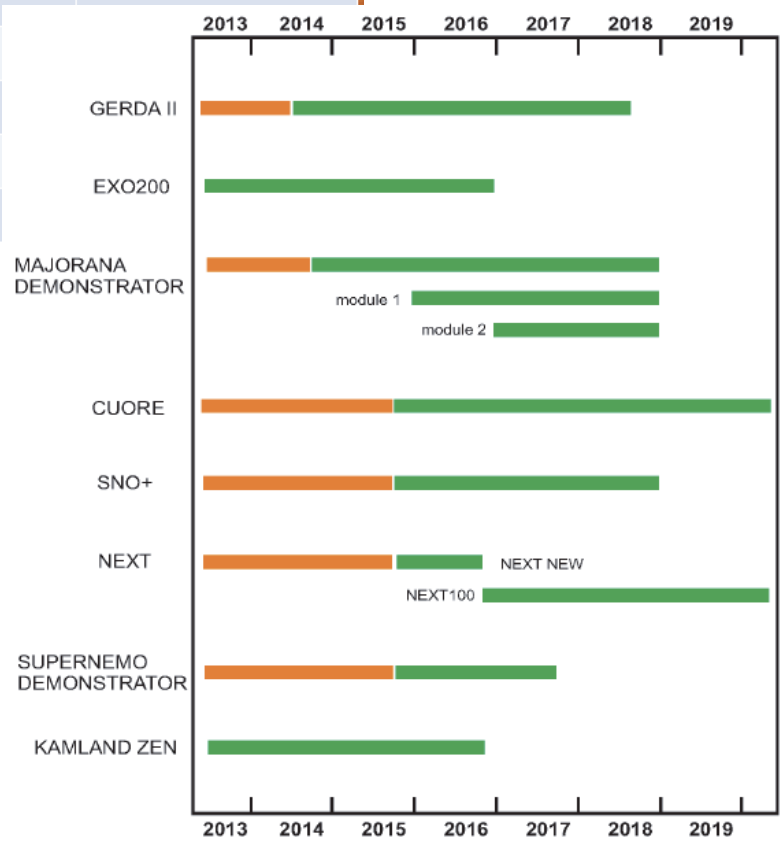
Current Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved Lower Limit (10^{26} yr)
CUORE	^{130}Te	206	>0.028
MAJORANA	^{76}Ge	24.7	
GERDA	^{76}Ge	18-20	>0.21
EXO200	^{136}Xe	79	>0.11
NEXT-100	^{136}Xe	61	
SuperNEMO	^{82}Se+	7	
KamLAND-Zen	^{136}Xe	434	
SNO+	^{130}Te	160	
LUCIFER	^{82}Se	8.9	

Goals (*DNP*14 *DBD workshop*):

$T_{1/2} > 1 \times 10^{26}\, y$, *after ? years*

$T_{1/2} > 2.4 \times 10^{26}\, y$, *after 3 years*

$T_{1/2} > 6 \times 10^{27}\, y$, *after 5 years*! (*nEXO*)

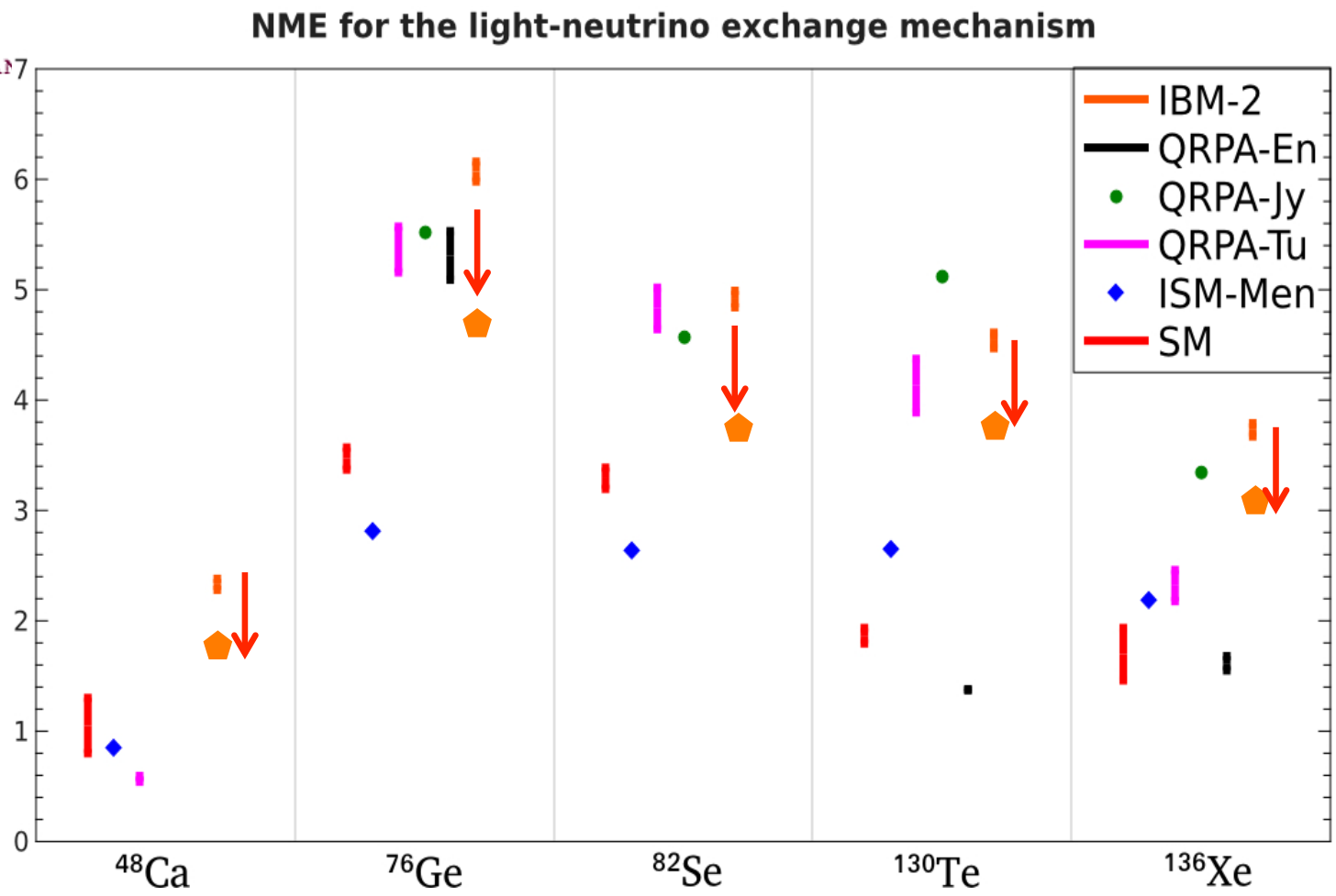


Construction

Operation

Able to assess future prospects of different techniques better 2-3 years from now, allowing more intelligent discussion of down-selection.

R&D on new techniques with promise to reduce backgrounds dramatically should also be pursued!



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

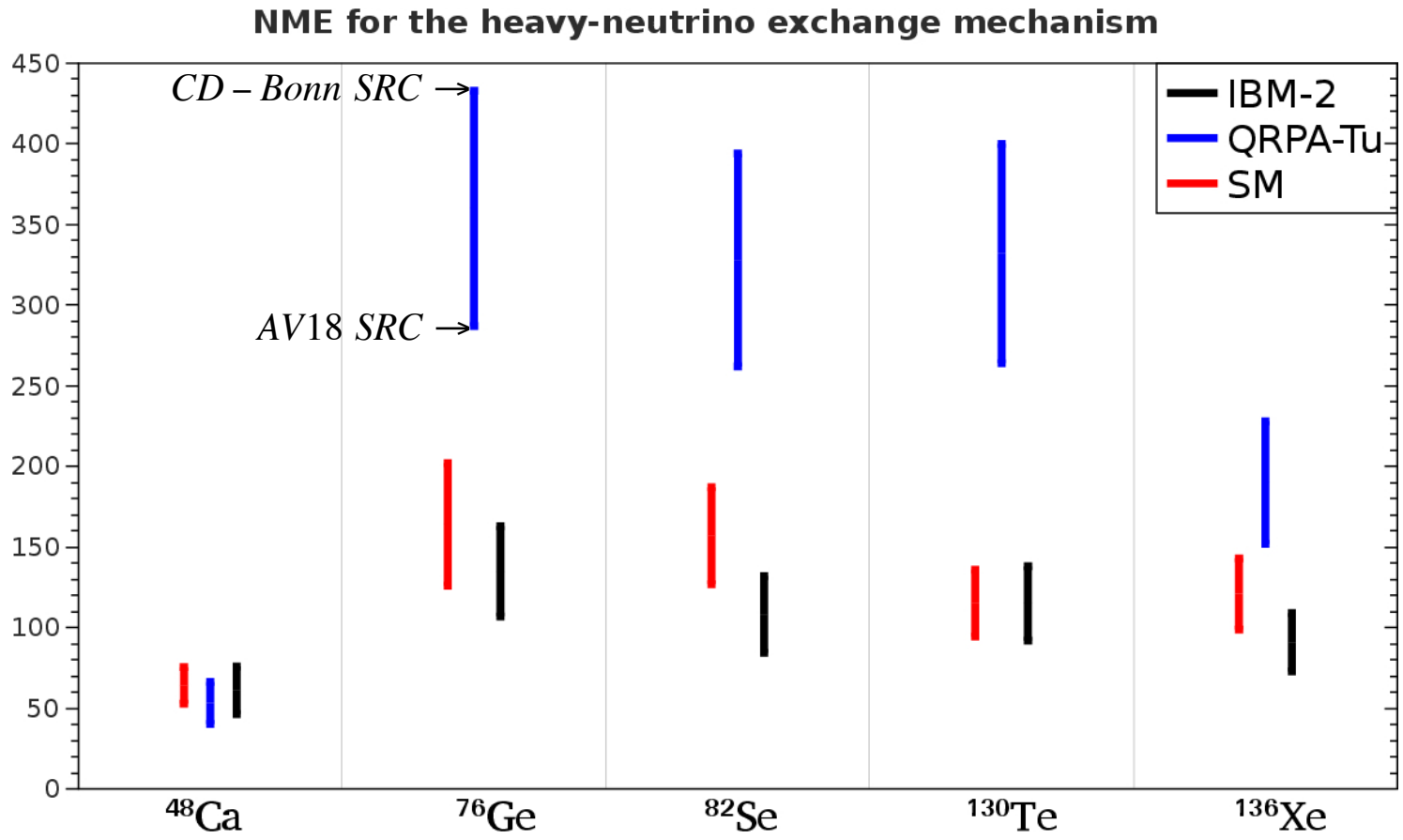
QRPA-En M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).

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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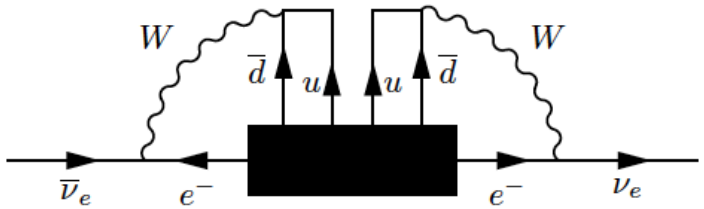
Take-Away Points

Observation of 0νββ will signal **New Physics Beyond the Standard Model**.

Black box theorem (all flavors + oscillations)



0νββ observed ⇔ at some level

(i) Neutrinos are Majorana fermions.

(ii) Lepton number conservation is violated by 2 units

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

Regardless of the dominant 0νββ mechanism!

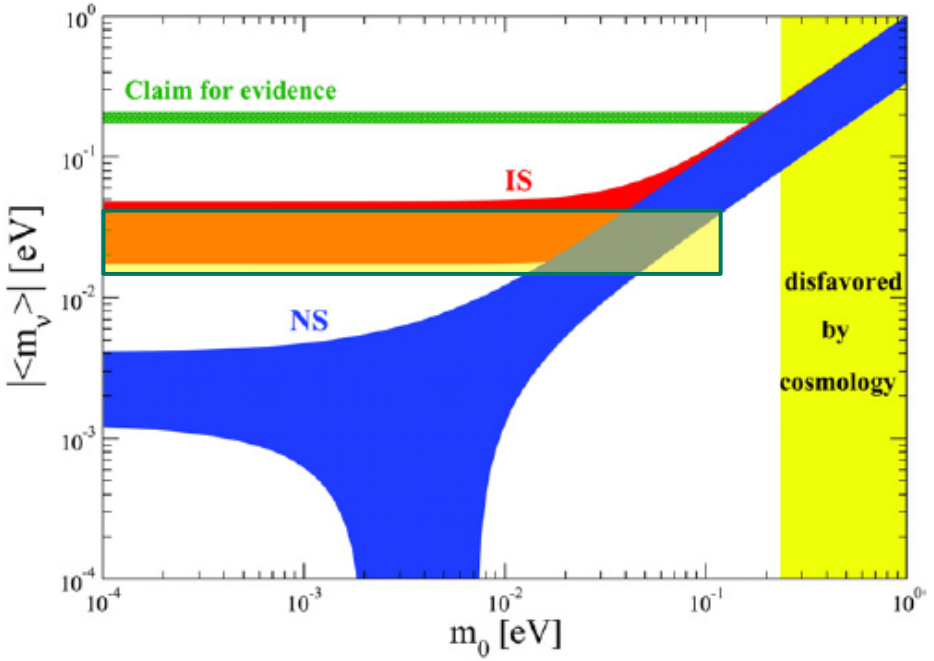
Take-Away Points

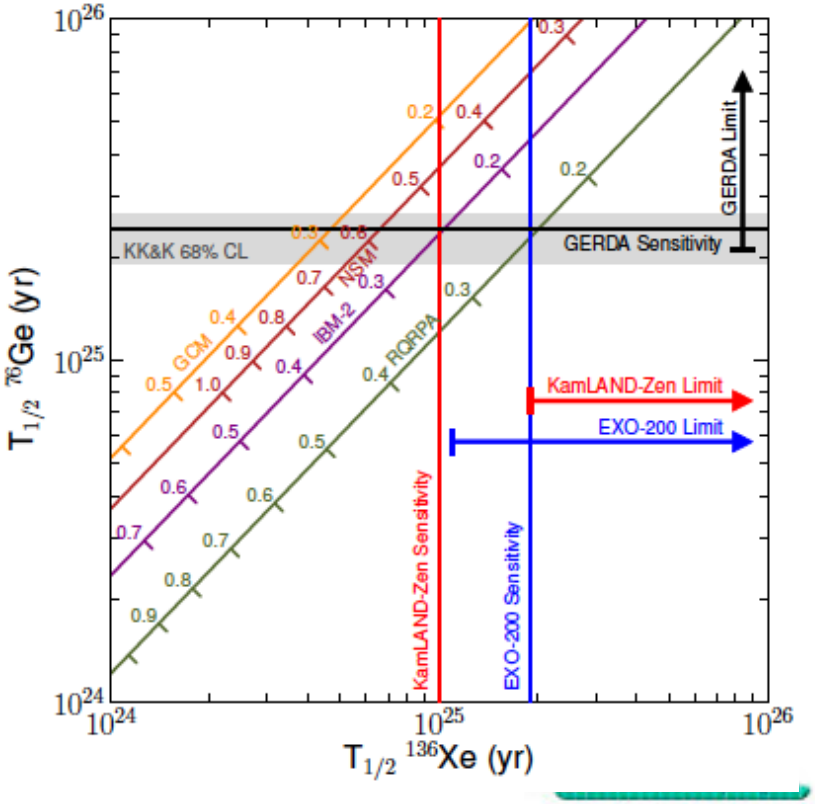
The analysis and guidance of the experimental efforts need **accurate Nuclear Matrix Elements.**

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

$$\left\langle m_{\beta\beta}\right\rangle \equiv \left\langle m_\nu\right\rangle = \left|c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

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





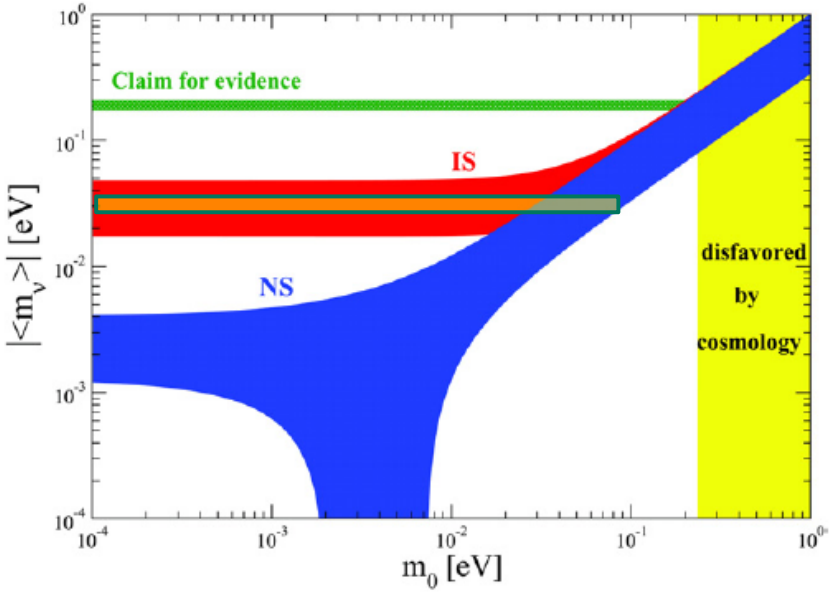
Take-Away Points

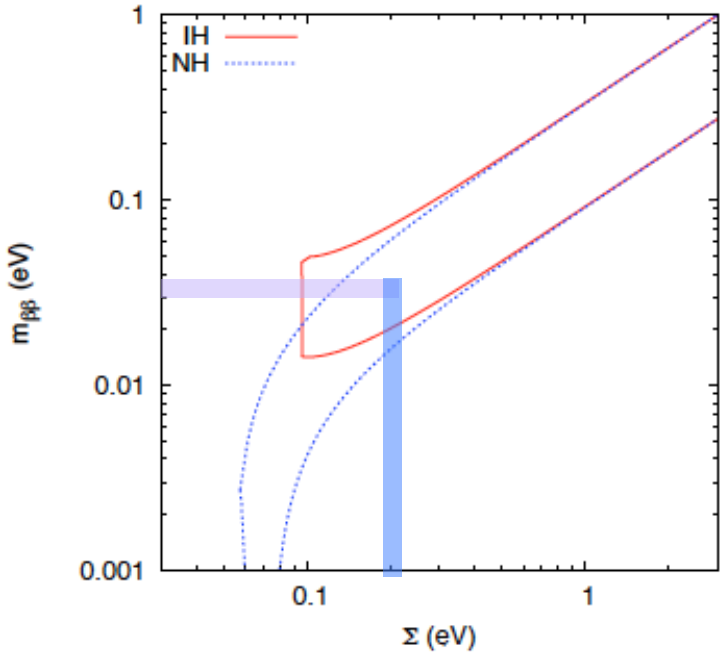
Extracting information about Majorana CP-violation phases may require the mass hierarchy from LBNE(DUNE), cosmology, etc, but also **accurate Nuclear Matrix Elements**.

$$\left\langle m_{\beta\beta} \right\rangle = \left| c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

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

$$\Sigma = m_1 + m_2 + m_3 \quad \textit{from cosmology}$$





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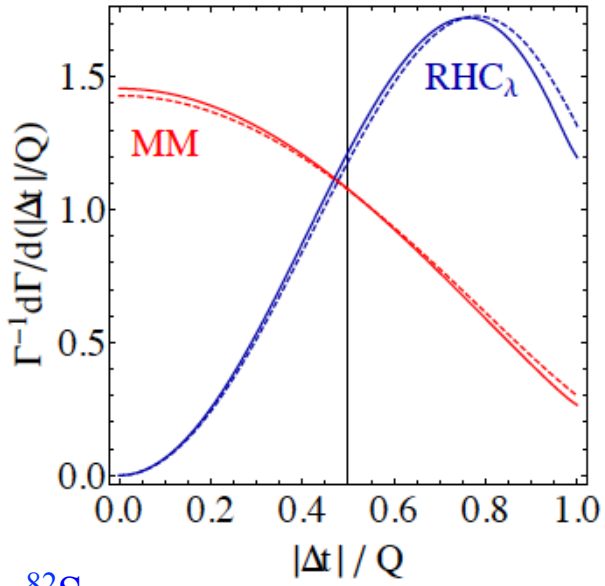
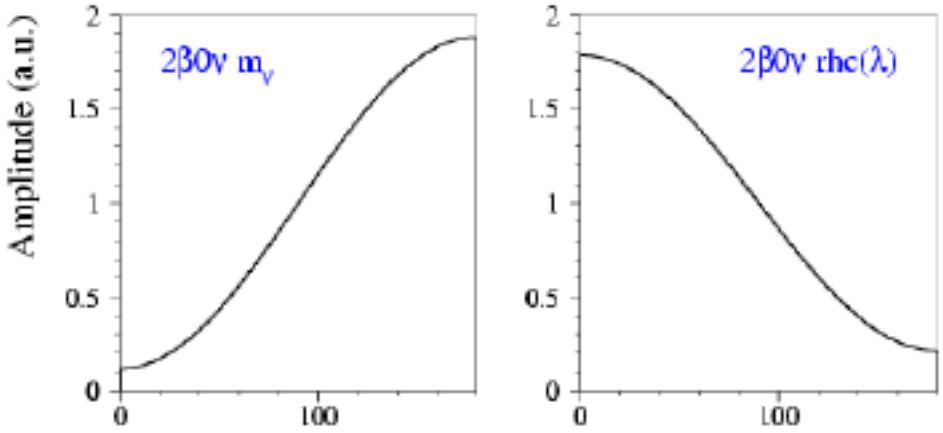
Take-Away Points

Alternative mechanisms to 0νββ need to be carefully tested: many isotopes, energy and angular correlations.

These analyses also require **accurate Nuclear Matrix Elements**.



SuperNEMO: ^{82}Se



$$|\eta_\nu|, |\eta_{NR}| \Leftarrow \begin{cases} \left[G^{0\nu}_{Ge} T^{0\nu}_{1/2Ge}\right]^{-1} = \left|M^{(0\nu)}_{Ge}\right|^2 |\eta_\nu|^2 + \left|M^{(0N)}_{Ge}\right|^2 |\eta_{NR}|^2 \\ \left[G^{0\nu}_{Xe} T^{0\nu}_{1/2Xe}\right]^{-1} = \left|M^{(0\nu)}_{Xe}\right|^2 |\eta_\nu|^2 + \left|M^{(0N)}_{Xe}\right|^2 |\eta_{NR}|^2 \end{cases}$$

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu} \left| \sum_j M_j \eta_j \right|^2 = G^{0\nu} \left| M^{(0\nu)} \eta_{\nu L} + M^{(0N)} \left(\eta_{NL} + \eta_{NR}\right) + \tilde{X}_\lambda < \lambda > + \tilde{X}_\eta < \eta > + M^{(0\lambda')} \eta_{\lambda'} + M^{(0\tilde{q})} \eta_{\tilde{q}} + \cdots \right|^2$$

SciDAC Scientific Discovery through Advanced Computing

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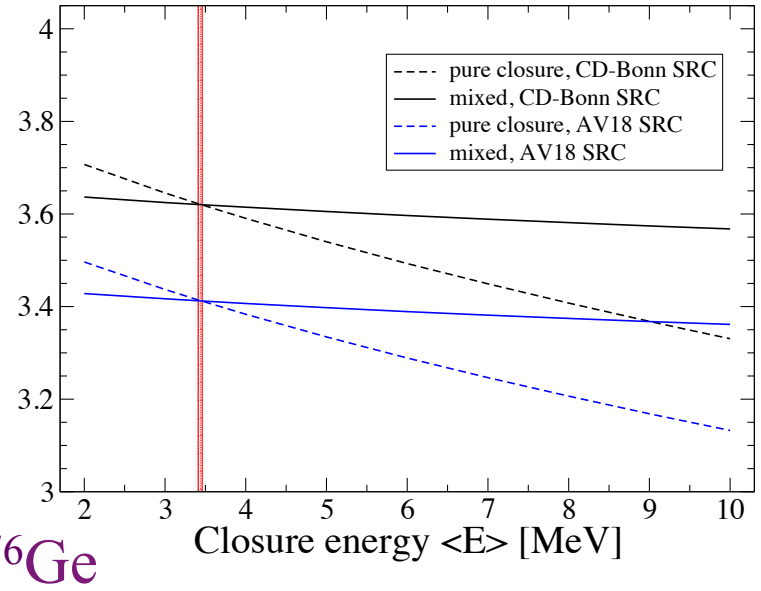
Take-Away Points

Accurate shell model NME for **different decay mechanisms** were recently calculated.

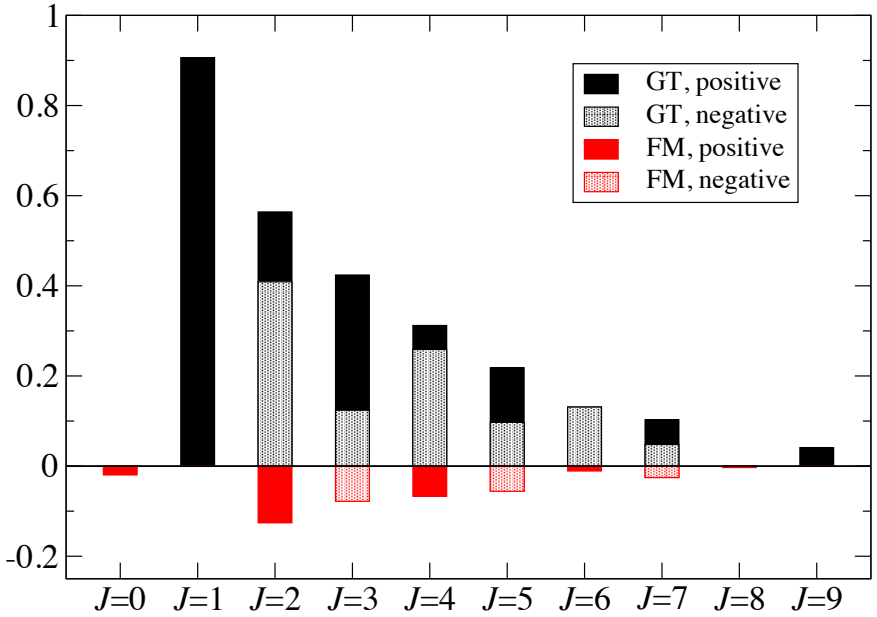
The method provides **optimal closure energies** for the mass mechanism.

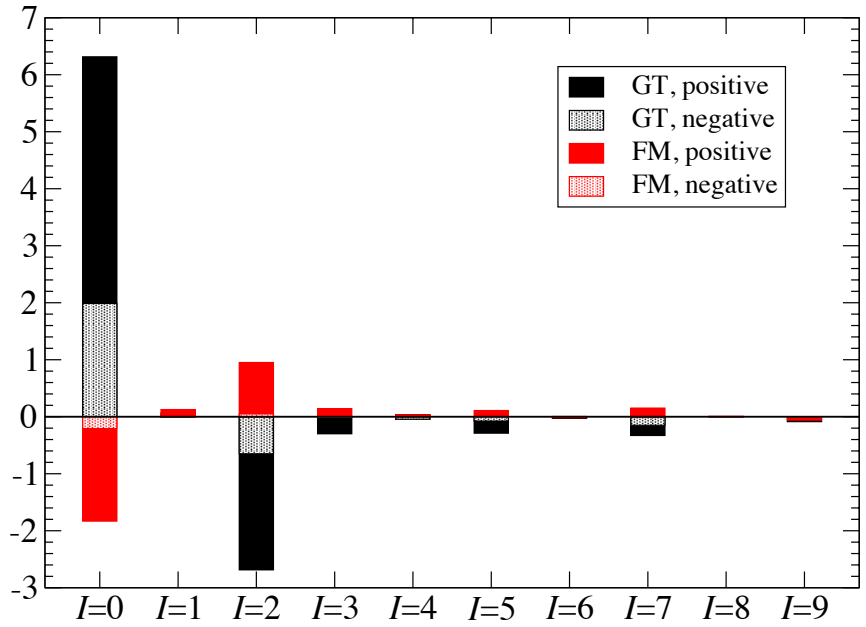
Decomposition of the matrix elements can be used for **selective quenching** of classes of states, and for testing nuclear structure.



^{76}Ge

$$M_{mixed}(N) = M_{no-closure}(N) + \left[M_{closure}(N=\infty) - M_{closure}(N) \right]$$





Collaborators:

- Alex Brown, NSCL@MSU
- Roman Senkov, CMU and CUNY
- Andrei Neacsu, CMU
- Jonathan Engel, UNC
- Jason Holt, TRIUMF

The effect of larger model spaces for ^{48}Ca

M(0ν)	SDPFU	SDPFMUP
0 $\hbar\omega$	0.941	0.623
0+2 $\hbar\omega$	1.182 (26%)	1.004 (61%)

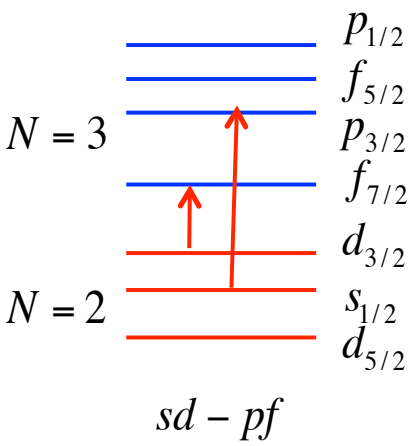
	M(0ν)
0 $\hbar\omega$ / GXPF1A	0.733
0 $\hbar\omega$ +2nd ord./GXPF1A	1.301 (77%)

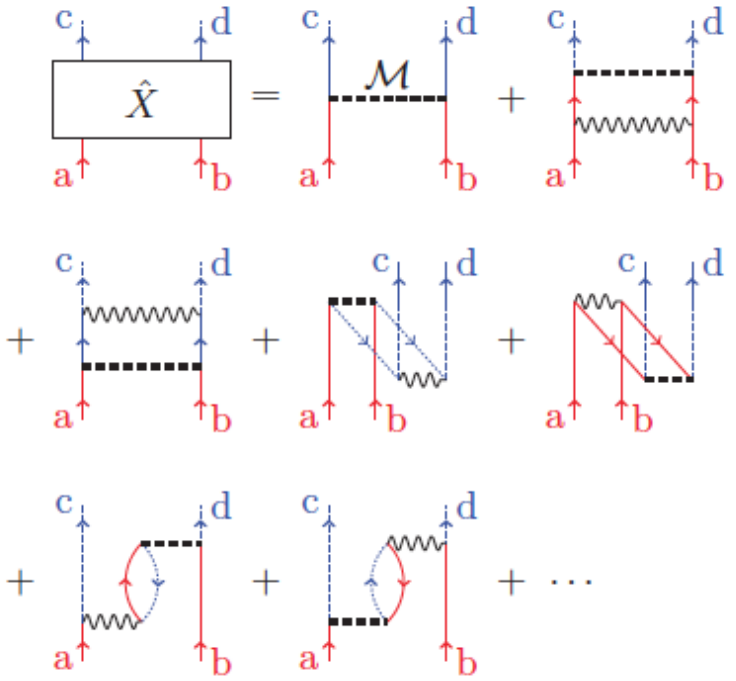
SDPFU: PRC 79, 014310 (2009)

SDPFMUP: PRC 86, 051301(R) (2012)

arXiv:1308.3815, PRC 89, 045502 (2014)

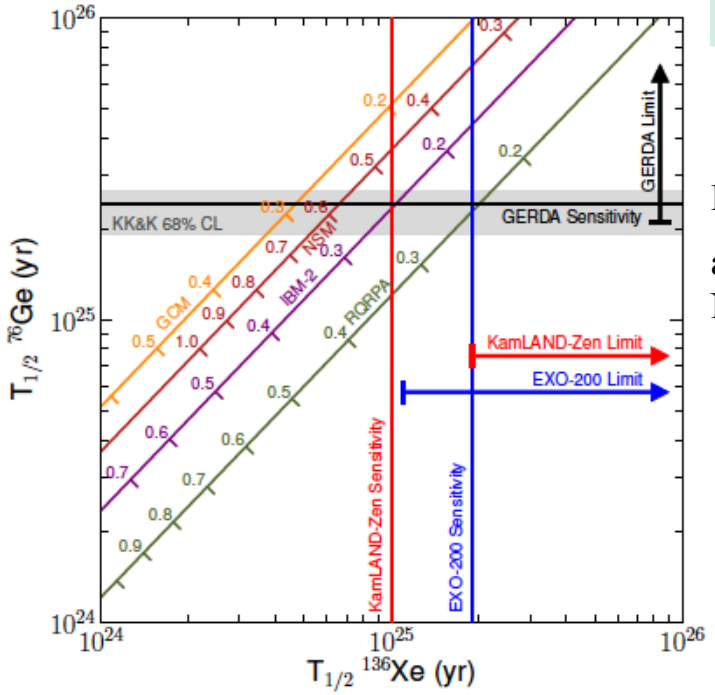
PRC 87, 064315 (2013)





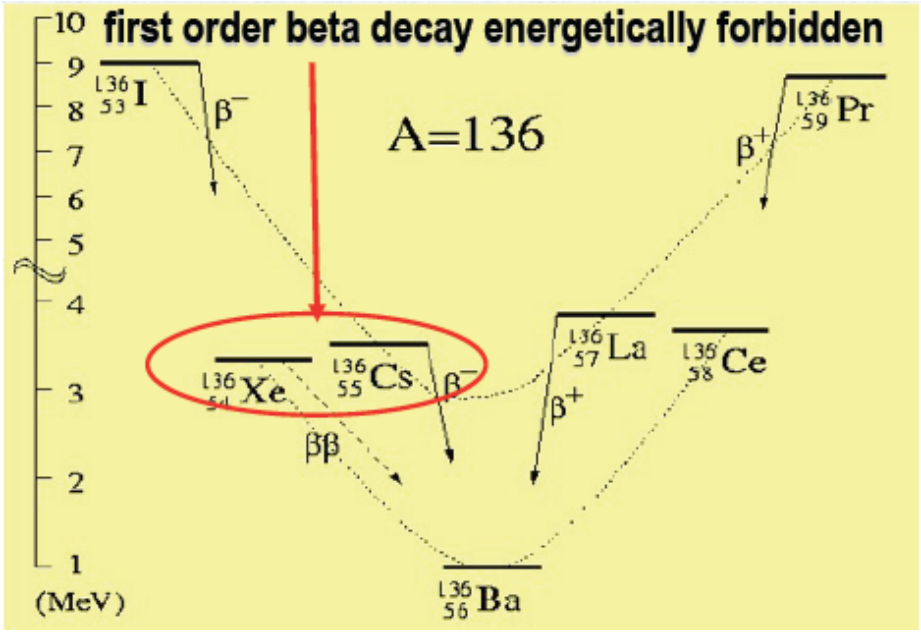
^{136}Xe ββ Experimental Results

Publication	Experiment	$T^{2\nu}_{1/2}$	$T^{0\nu}_{1/2}$(lim)	$T^{0\nu}_{1/2}$(Sens)
PRL 110, 062502	KamLAND-Zen		$> 1.9\times10^{25}$ y	1.1×10^{25} y
PRC 89, 015502	EXO-200	$(2.11\pm0.04\pm0.21)\times10^{21}$ y		
Nature 510, 229	EXO-200		$>1.1\times10^{25}$ y	1.9×10^{25} y
PRC 85, 045504	KamLAND-Zen	$(2.38\pm0.02\pm0.14)\times10^{21}$ y		
		$M^{2\nu}_{\text{exp}} = 0.0191 - 0.0215\ MeV^{-1}$		



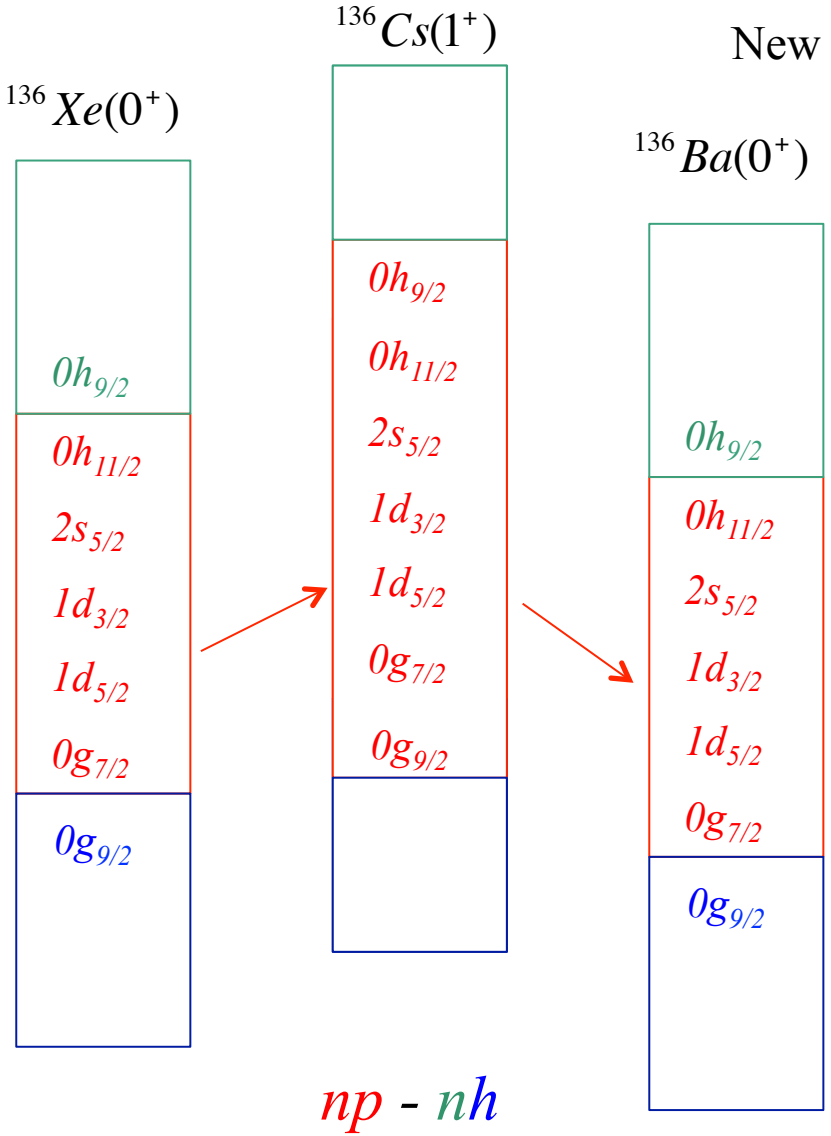
EXO-200

arXiv:1402.6956,
Nature 510, 229



M. Horoi

^{136}Xe 2νββ Results $M^{2\nu}_{\text{exp}} = 0.019\ MeV^{-1}$



New effective interaction, $\sigma\tau \rightarrow 0.74\,\sigma\tau$ quenching

$0g_{7/2}\ 1d_{5/2}\ 1d_{3/2}\ 2s_{5/2}\ 0h_{11/2}$ *model space*

$$\sum B(GT;Z \rightarrow Z+1) - \sum B(GT;Z \rightarrow Z-1) = 52$$

Ikeda: $3(N-Z) = 84$

$$M^{2\nu} = 0.064\ MeV^{-1}$$

$0g_{9/2}\ 0g_{7/2}\ 1d_{5/2}\ 1d_{3/2}\ 2s_{5/2}\ 0h_{11/2}\ 0h_{9/2}$

$$\sum B(GT;Z \rightarrow Z+1) - \sum B(GT;Z \rightarrow Z-1) = 84$$

Ikeda: $3(N-Z) = 84$

n (0+)	n (1+)	M(2v)
0	0	0.062
0	1	0.091
1	1	0.037
1	2	0.020

PRL **111**, (2013)