Nuclear structure for tests of fundamental symmetries

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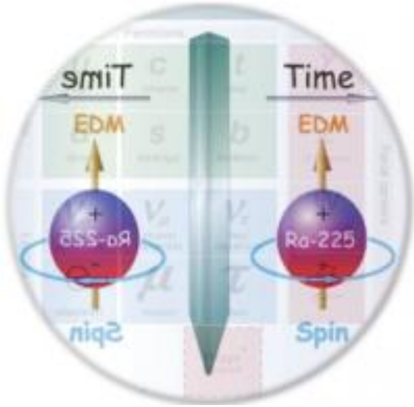
Nuclei, a laboratory for studying fundamental interactions and fundamental symmetries

Fundamental Interactions

Nuclear and particle physicists study fundamental interactions for two basic reasons: to clarify the nature of the most elementary pieces of matter and determine how they fit together and interact. Most of what has been learned so far is embodied in the Standard Model of particle physics, a framework that has been both repeatedly validated by experimental results and is widely viewed as incomplete.



"[Scientists] have been stuck in that model, like birds in a gilded cage, ever since [the 1970s]," wrote Dennis Overbye in a July 2006 **essay** for *The New York Times*. "The Standard Model agrees with every experiment that has been performed since. But it doesn't say anything about the most familiar force of all, gravity. Nor does it explain why the universe is matter instead of antimatter, or why we believe there are such things as space and time."

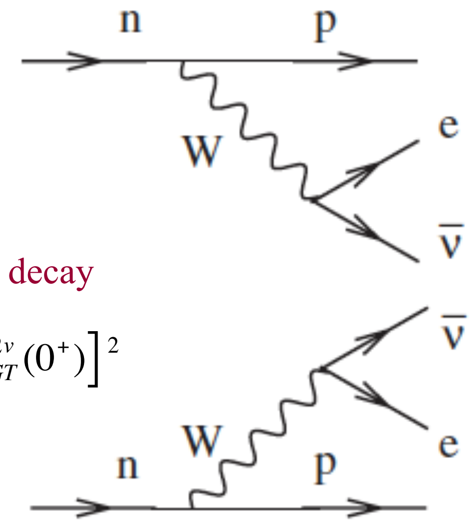
Rare isotopes produced at FRIB's will provide excellent opportunities for scientists to devise experiments that look beyond the Standard Model and search for subtle indications of hidden interactions and minutely broken symmetries and thereby help refine the Standard Model and search for new physics beyond it.

- Double-beta decay: ^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe
- EDM: ^{199}Hg, ^{225}Ra, ^{211}Rn, etc
- PNC: ^{14}N, ^{18}F, ^{19}F, ^{21}Ne (PRL 74, 231 (1995))
- Beta decay: super-allowed, angular correlations, etc

Classical Double Beta Decay Problem

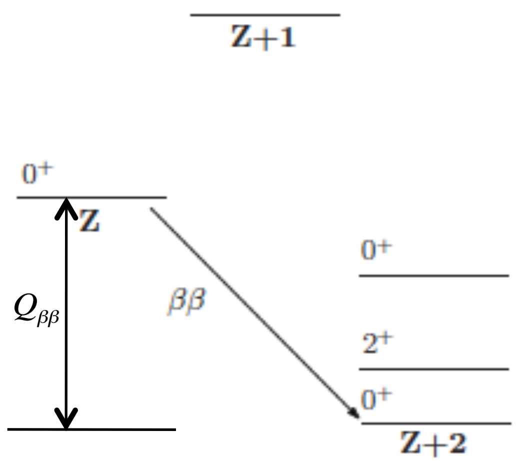
Isotope	$T_{1/2}(2\nu)$ (years)	$M^{2\nu}$
^{48}Ca	$4.4^{+0.6}_{-0.5} \times 10^{19}$	$0.0238^{+0.0015}_{-0.0017}$
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$	$0.0716^{+0.0025}_{-0.0023}$
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$	$0.0503^{+0.0020}_{-0.0018}$
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$	$0.0491^{+0.0023}_{-0.0020}$
^{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

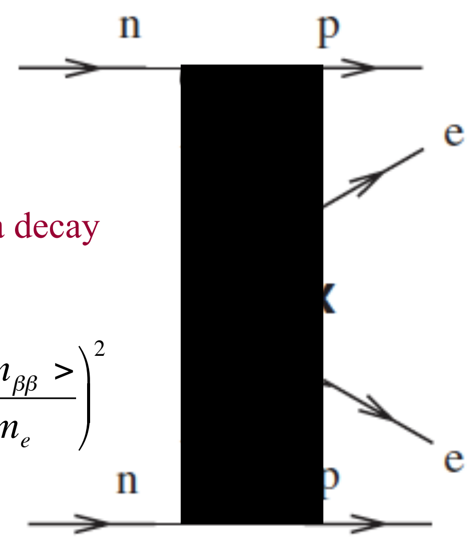
A.S. Barabash, PRC 81 (2010)



2-neutrino double beta decay

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





neutrinoless double beta decay

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

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

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?

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

$4 \times 10^{-3}\ eV^2\ (atmospheric)$

- Tritium decay:

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

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

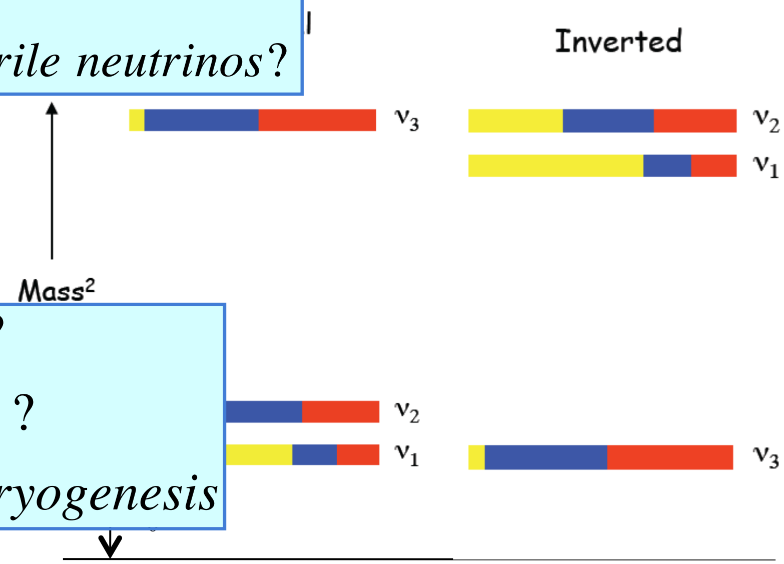
$KATRIN$ (to take data): goal $m_{\nu_e} < 0.3eV$

- Cosmology: CMB power spectrum, BAO, et

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

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

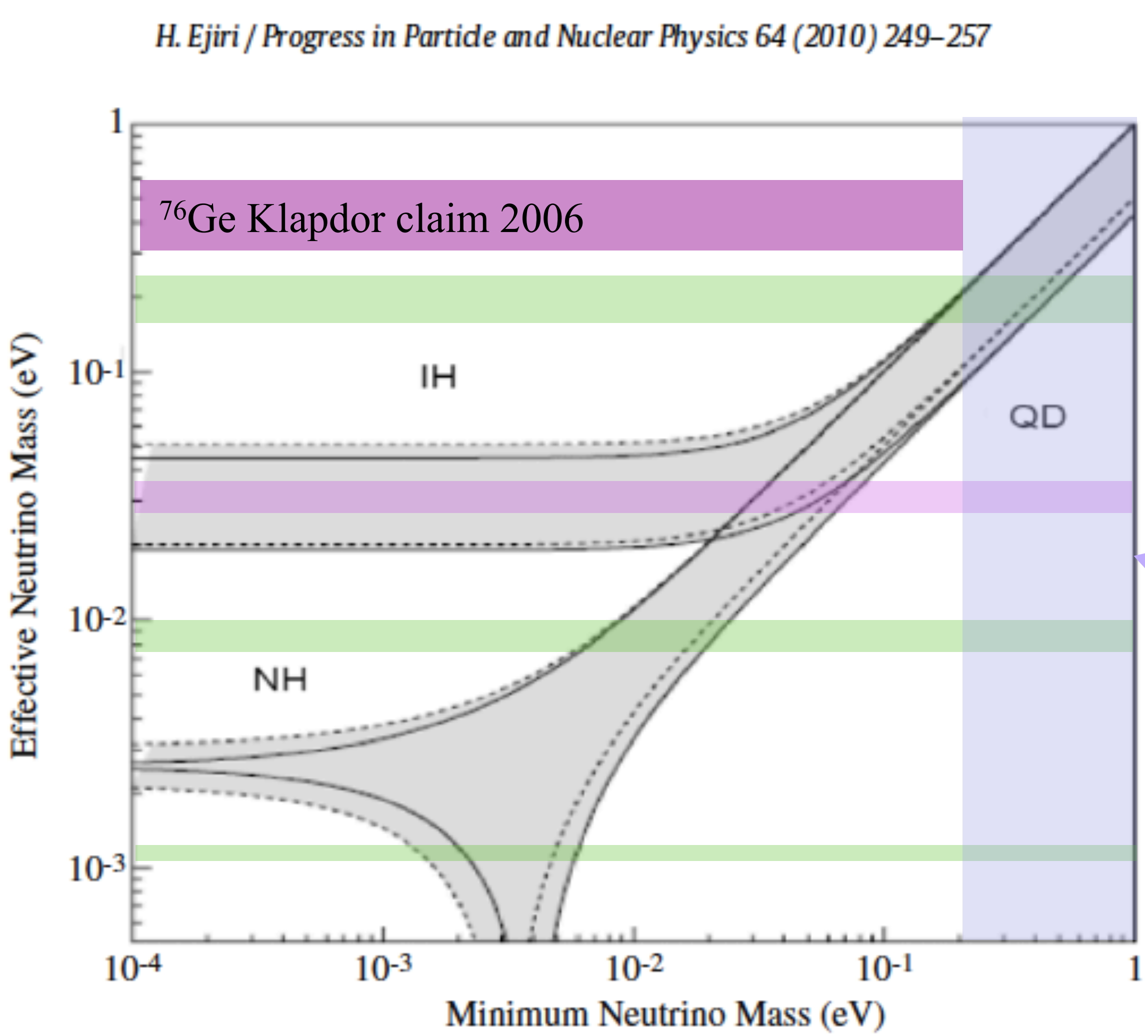
$Goal: 0.01eV\ (5-10\ y)$



Two neutrino mass hierarchies

SciDAC Scientific Discovery through Advanced Computing

Neutrino ββ effective mass



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

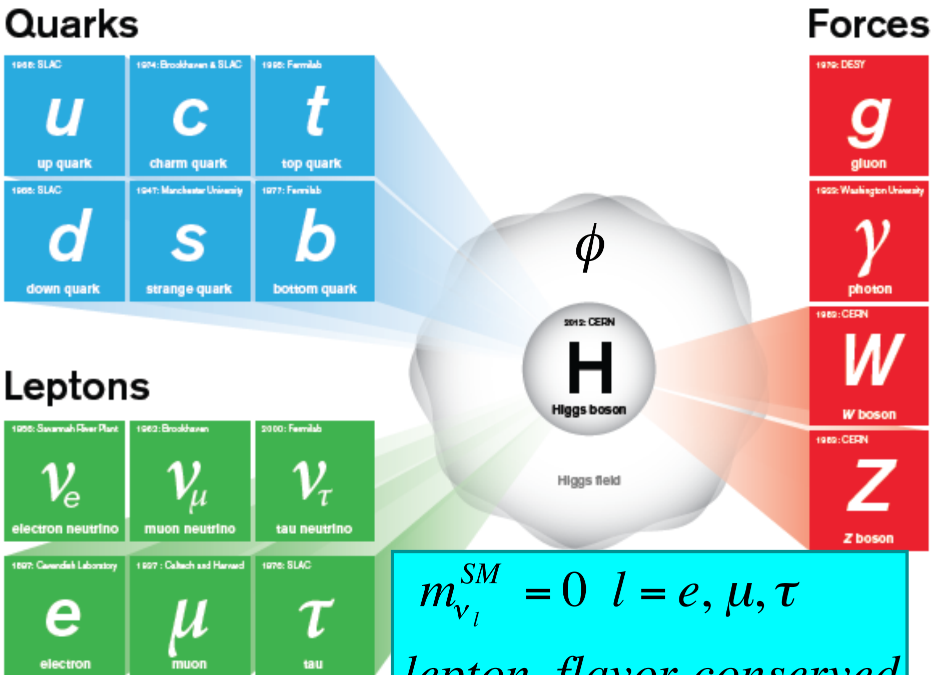
$$= \left| c_{12}^2 c_{13}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

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

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

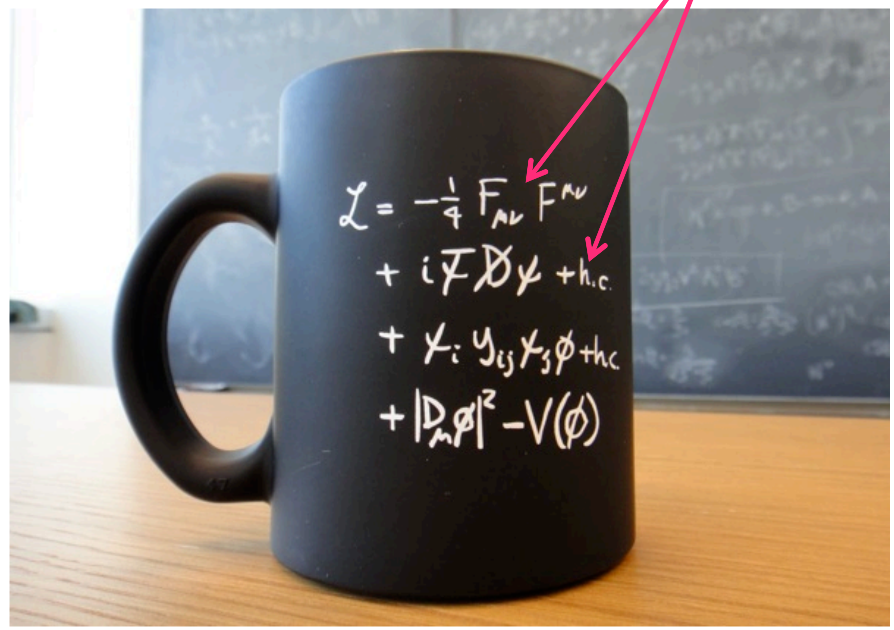
Cosmology constraint

The Minimal Standard Model



$m_{\nu_l}^{SM} = 0 \quad l = e, \mu, \tau$

lepton flavor conserved



?

$SU(2)_L$ *doublet*

SM fermion masses:

$$\bar{\psi}_{iL} \phi Y_{ij} \psi_{jR} \rightarrow Y_{ij} < \phi > \bar{\psi}_{iL} \psi_{jR} = (m_D)_{ij} \bar{\psi}_{iL} \psi_{jR}$$

$SU(2)_L$ *doublet* $\quad$ $SU(2)_L$ *singlet*

$\rightarrow$ *neutrino is sterile:* $D_\mu = I\partial_\mu$

Local Gauge invariance of Lagrangian density $\mathcal{L}$:

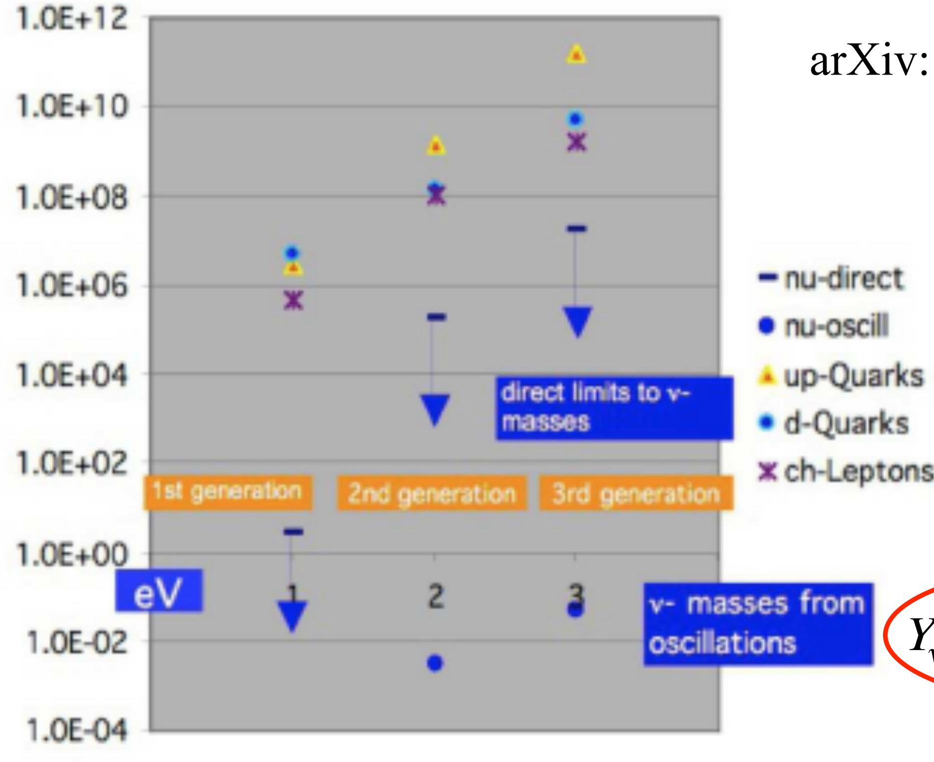
$$D_\mu = I\partial_\mu - igA_\mu^a(x)T^a$$

$T^a \in GA \qquad SM\ group: SU(3)_c \times SU(2)_L \times U(1)_Y$

$EWSB \hookrightarrow SU(3)_c \times U(1)_{em}$

Too Small Yukawa Couplings?

Standard Model
fermion masses



arXiv:1406.5503

$$Y_\nu \approx 10^{-10} - 10^{-9} Y_t$$

$$-\mathcal{L} \supset \frac{1}{2}\overline{\psi}_{iL} Y_{ij} \psi_{jR} \phi \rightarrow \frac{1}{2} m_{Dij} \overline{\psi}_{iL} \psi_{jR} \quad \left(m_{Dij} = Y_{ij}\, \mathrm{v} \right)$$

$$-\mathcal{L} \supset \frac{1}{2} m_{LR} \overline{\nu}'^{c}_{R} \nu'^{c}_{L}$$

Majorana

The origin of Majorana neutrino masses

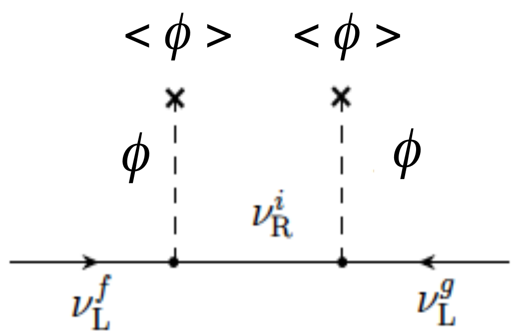
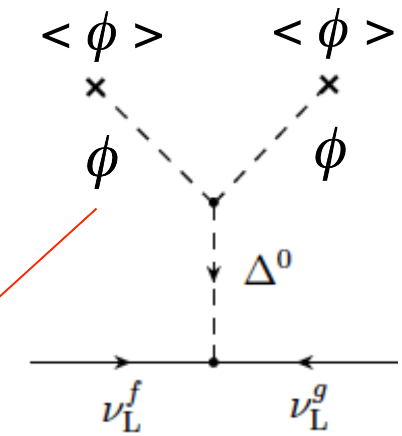


Diagram illustrating the type I see-saw mechanism

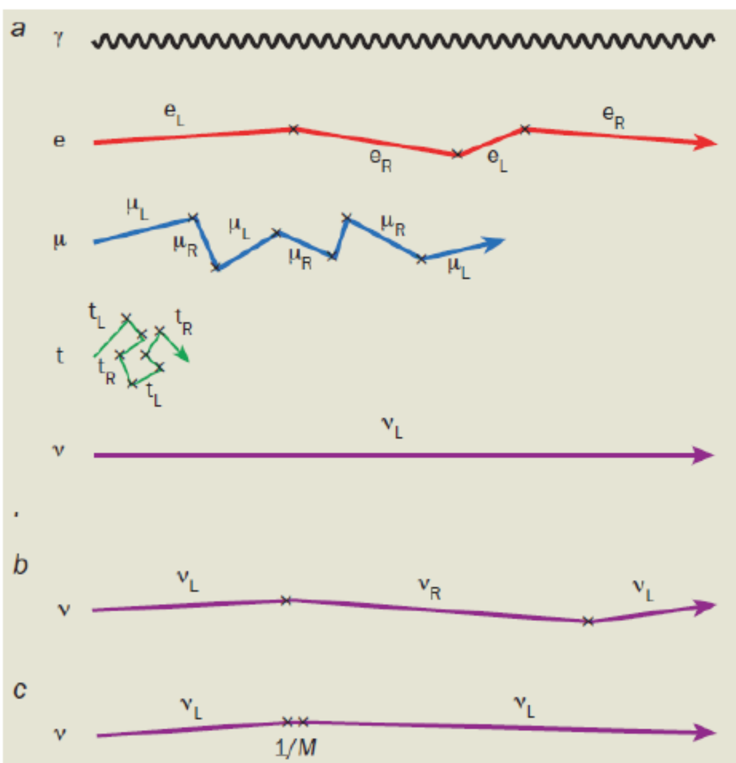
See-saw mechanisms

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

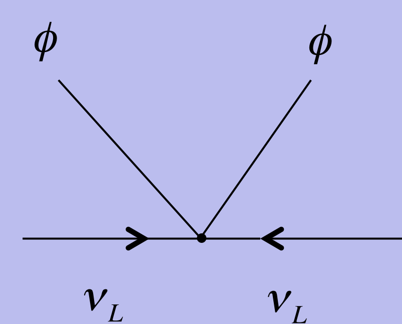
$$m_{LL}^{\nu} \approx m_{LL}^{II} + m_{LL}^{I}$$



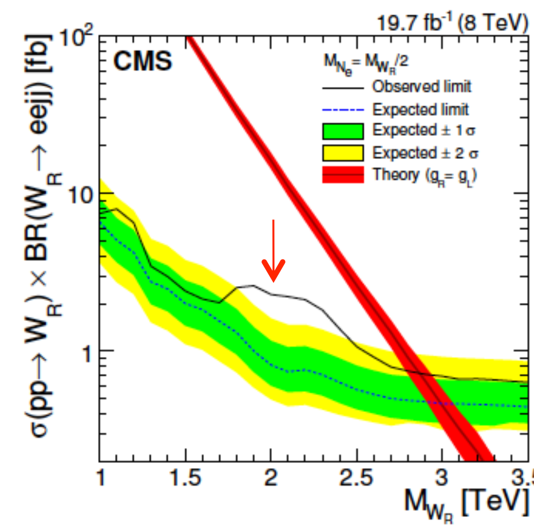
Left-Right Symmetric model



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



W_R search at CMS
arXiv:1407.3683



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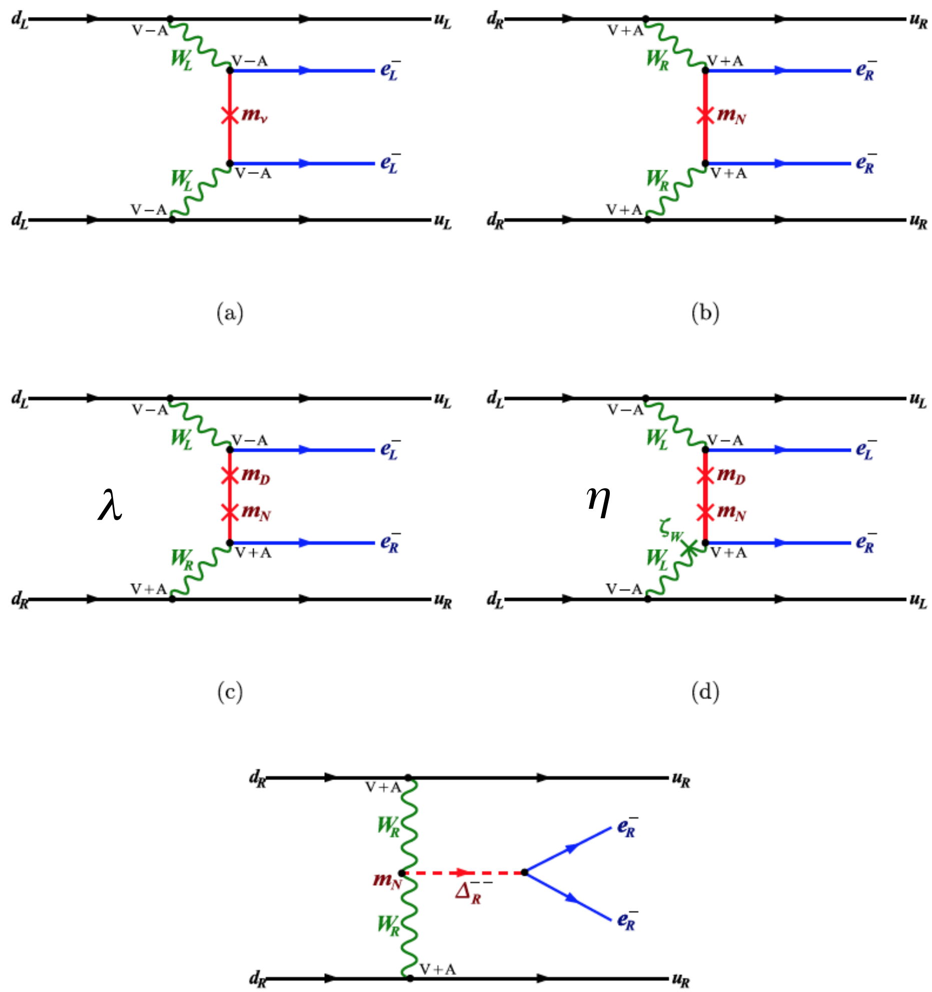
Low-energy LR contributions to 0νββ decay

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



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

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

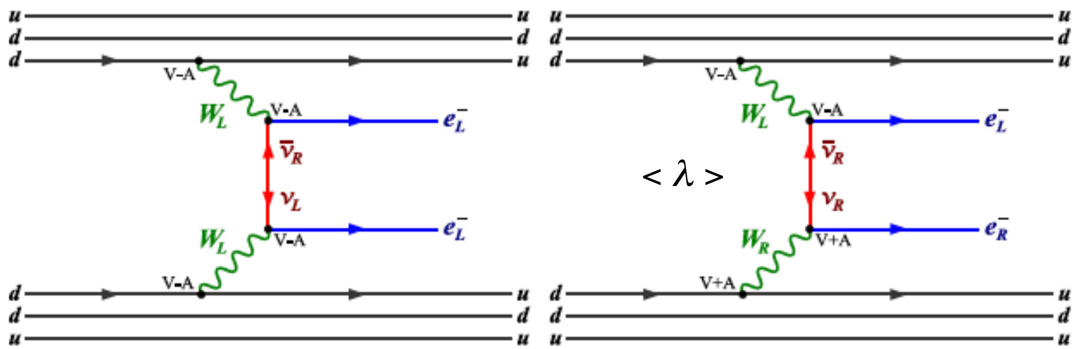
$$-\mathcal{L} \supset \frac{1}{2} h_{\alpha\beta}^T \left(\bar{\nu}_{\beta L} \;\; \bar{e}_{\alpha L}\right)\begin{pmatrix}\Delta^- & -\Delta^0 \\ \Delta^{--} & \Delta^-\end{pmatrix}\begin{pmatrix} e_R^c \\ -\nu_R^c\end{pmatrix} + hc$$

No neutrino exchange

DBD signals from different mechanisms

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

arXiv:1005.1241



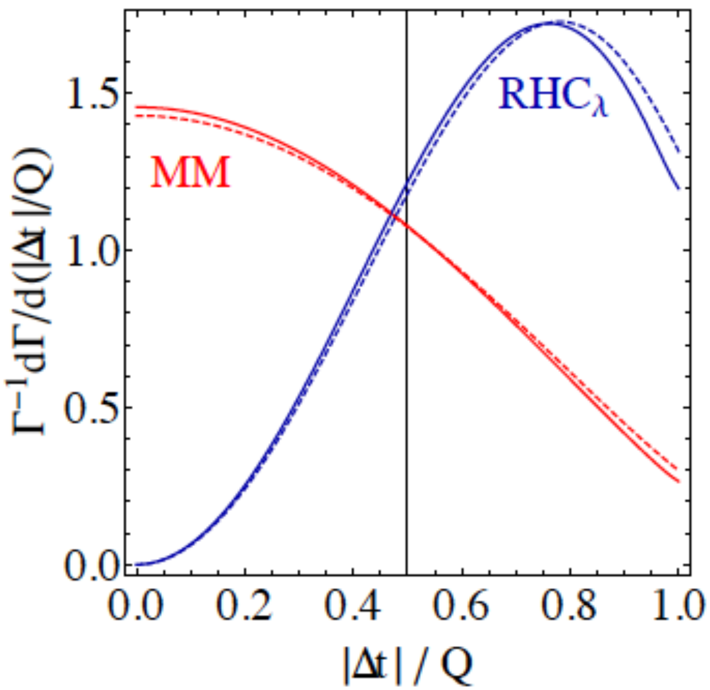
(a) (b)

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

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

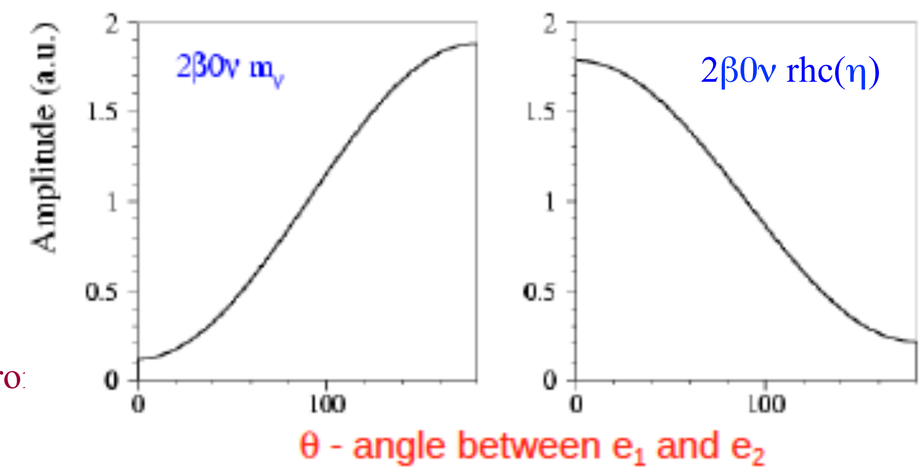
$$\lambda \approx \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sqrt{\frac{m_\nu}{M_R}}. \tag{12}$$

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



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].



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

M. Horo:

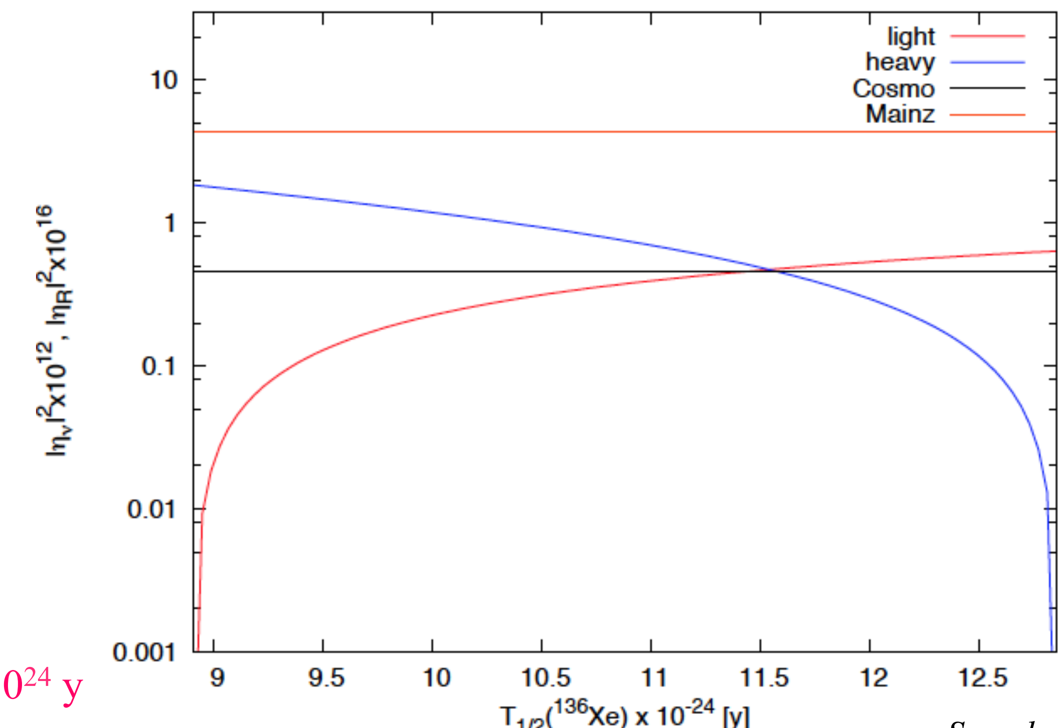
Two Non-Interfering Mechanisms

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

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

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

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

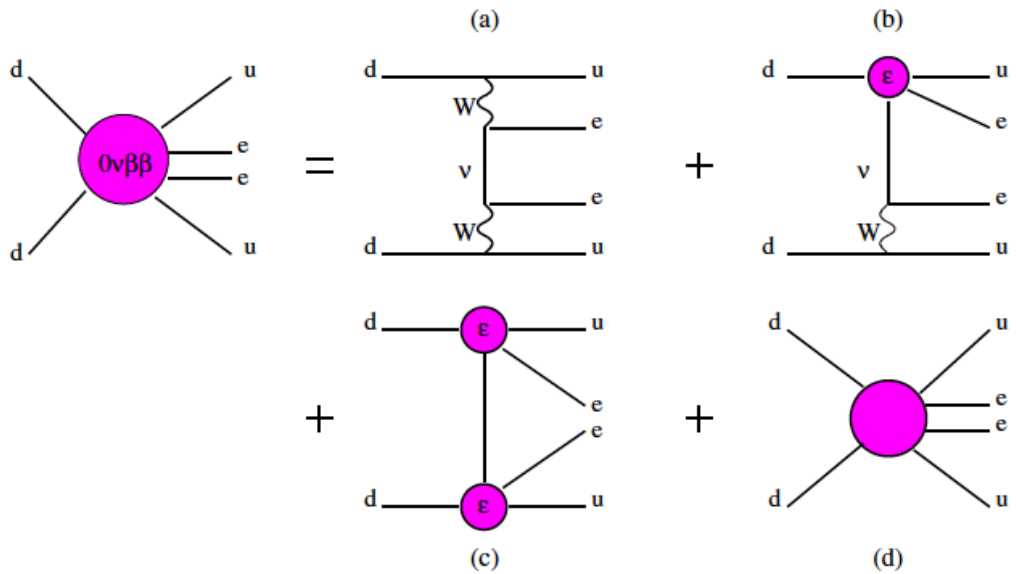


Assume $T_{1/2}(^{76}Ge) = 22.3 \times 10^{24}$ y

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*



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

Doi, Kotani, Takasugi 1983

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

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

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

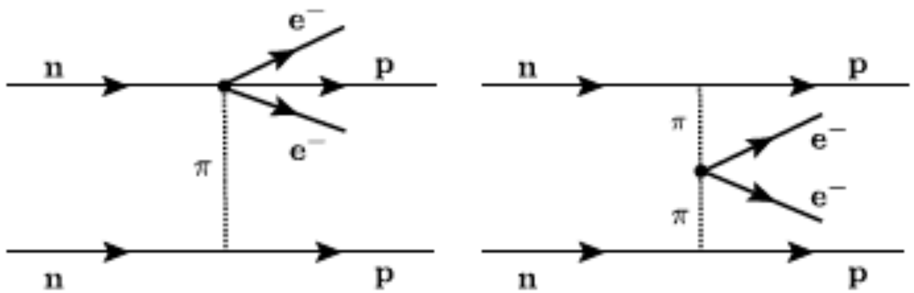
$$A_{\beta\beta} \propto \mathcal{L}$$

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

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



$SUSY\ \&\ LRSM: Prezeau, Ramsey-Musolf, Vogel,\ \ PRC\ 68, 034016\ (2003)$

$$\frac{1}{T_{1/2}}=\frac{1}{64\pi^5\ln 2}\left(\frac{\hbar c}{R}\right)^6\frac{g_A^4}{\hbar}\frac{G_F^4}{\Lambda_{\beta\beta}^2c^4}\int_{m_e}^{E_{\beta\beta}-m_e}\mathrm{d}E_1F(Z+2,E_1)F(Z+2,E_2)\frac{1}{2}\left\{\left[\left|\beta_3\mathcal{M}_2^{\pi\pi}+\frac{\sqrt{2}\Lambda_H}{g_AM}\zeta_5\mathcal{M}_2^{\pi NN}\right|^2+\left|\beta_4\mathcal{M}_2^{\pi\pi}+\frac{\sqrt{2}\Lambda_H}{g_AM}\zeta_6\mathcal{M}_2^{\pi NN}\right|^2\right]p_1E_1p_2E_2-\left[\left|\beta_3\mathcal{M}_2^{\pi\pi}-\frac{\sqrt{2}\Lambda_H}{g_AM}\zeta_5\mathcal{M}_2^{\pi NN}\right|^2-\left|\beta_4\mathcal{M}_2^{\pi\pi}-\frac{\sqrt{2}\Lambda_H}{g_AM}\zeta_6\mathcal{M}_2^{\pi NN}\right|^2\right]p_1p_2m_e^2\right\},$$

Summary of 0νDBD mechanisms

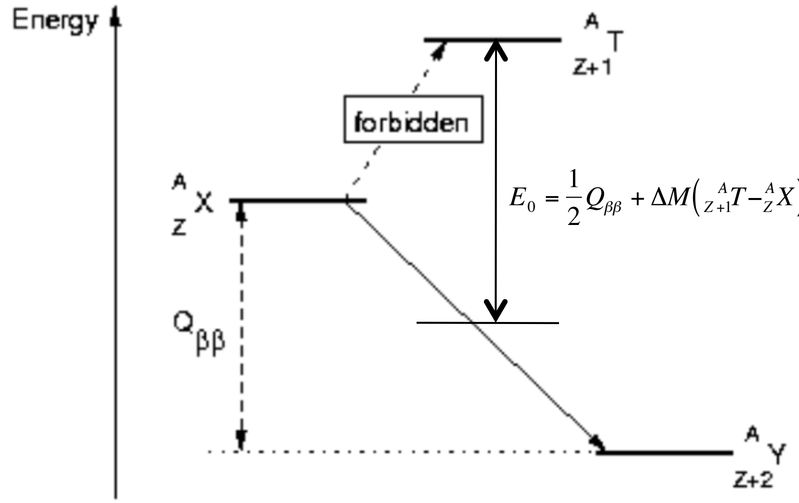
- The mass mechanism (a.k.a. light-neutrino exchange) is likely, and the simplest BSM scenario.
- Low mass sterile neutrino would complicate analysis
- Right-handed heavy-neutrino exchange is possible, and requires knowledge of half-lives for more isotopes.
- η- and λ- mechanisms are possible, but could 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.

2ν Double Beta Decay (DBD) of ^{48}Ca

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

$$M_{\rm GT}^{2\nu}(0^+) = \sum_k \frac{\langle 0_f \| \sigma\tau^- \| 1_k^+ \rangle \langle 1_k^+ \| \sigma\tau^- \| 0_i \rangle}{E_k + E_0}$$

$$^{48}Ca \xrightarrow{2\nu\,\beta\beta} {}^{48}Ti$$



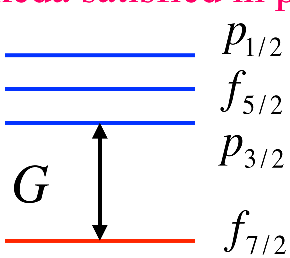
The choice of valence space is important!

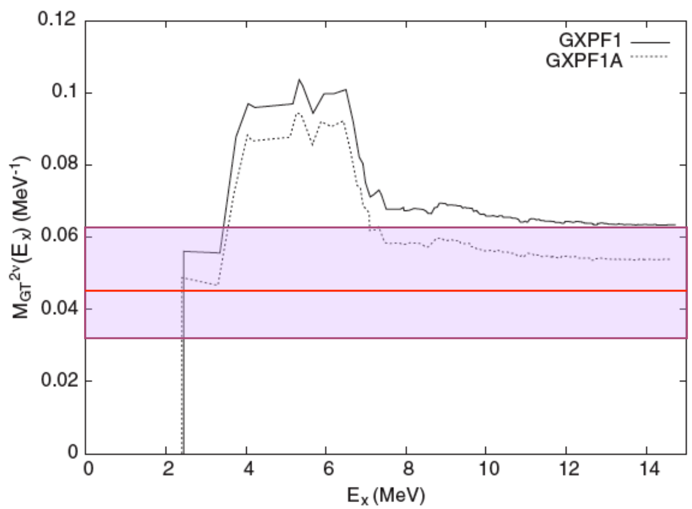
$$B(GT) = \frac{\left|\langle f \| \sigma \cdot \tau \| i \rangle\right|^2}{(2J_i + 1)}$$

ISR	48Ca	48Ti
pf	24.0	12.0
f7 p3	10.3	5.2

$$Ikeda\ sum\ rule(ISR) = \sum B(GT; Z \to Z+1) - \sum B(GT; Z \to Z-1) = 3(N-Z)$$

Ikeda satisfied in pf !





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

Horoi, Stoica, Brown,

PRC **75**, 034303 (2007)

Closure Approximation and Beyond in Shell Model

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

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

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

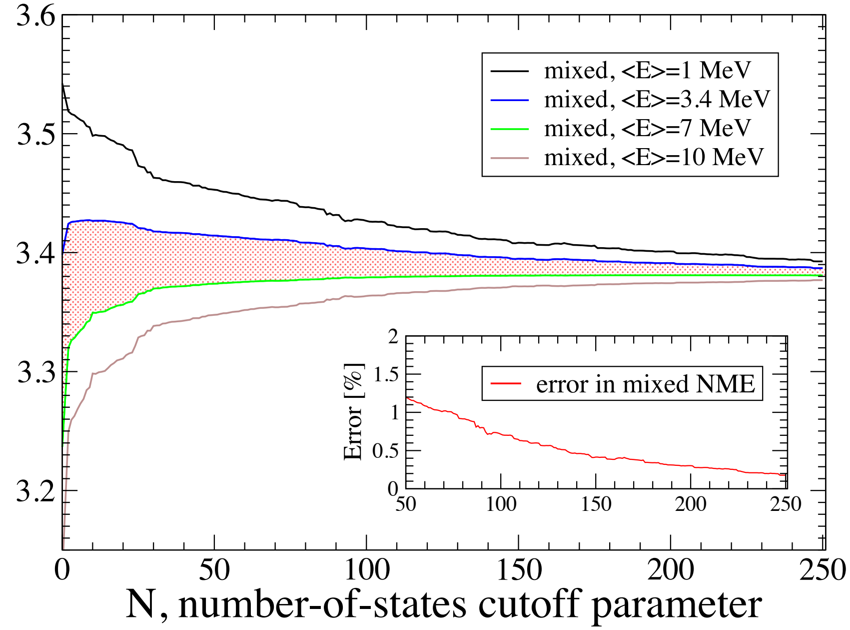
^{82}Se : 10M states

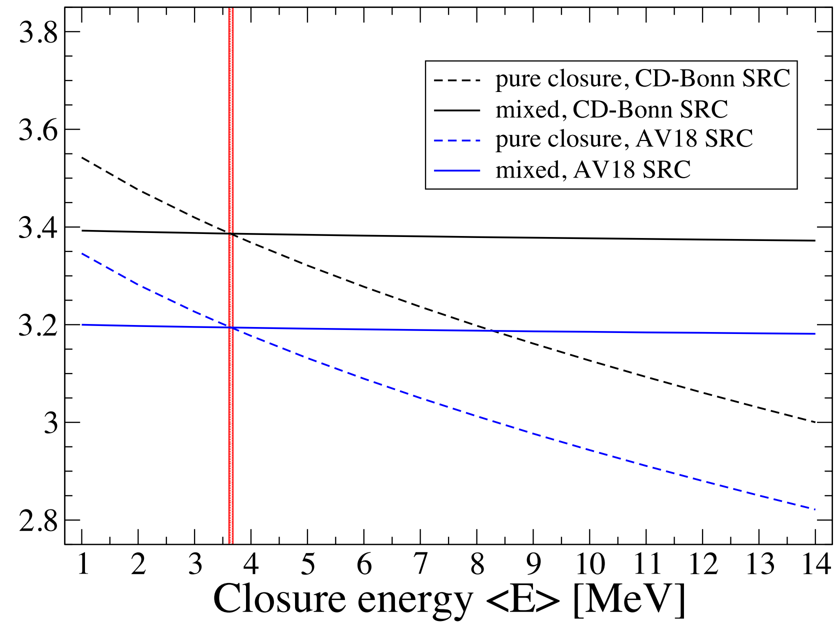
^{130}Te : 22M states

^{76}Ge : 150M states

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

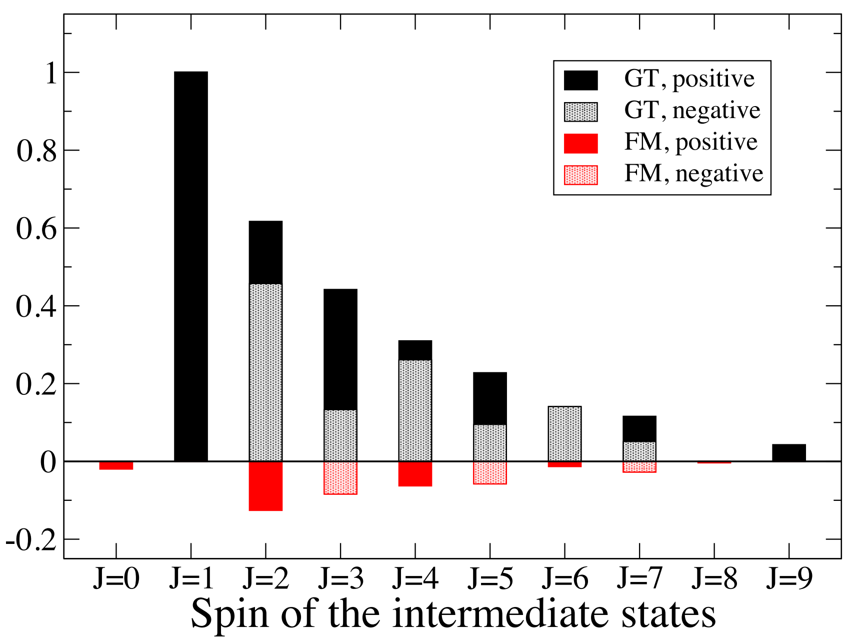
$$\hat{S} = \begin{cases} \sigma_1\tau_1\,\sigma_2\tau_2 & Gamow-Teller\ (GT) \\ \tau_1\tau_2 & Fermi\ (F) \\ \left[3(\vec{\sigma}_1\cdot\hat{n})(\vec{\sigma}_2\cdot\hat{n}) - (\vec{\sigma}_1\cdot\vec{\sigma}_2)\right]\tau_1\tau_2 & Tensor\ (T) \end{cases}$$

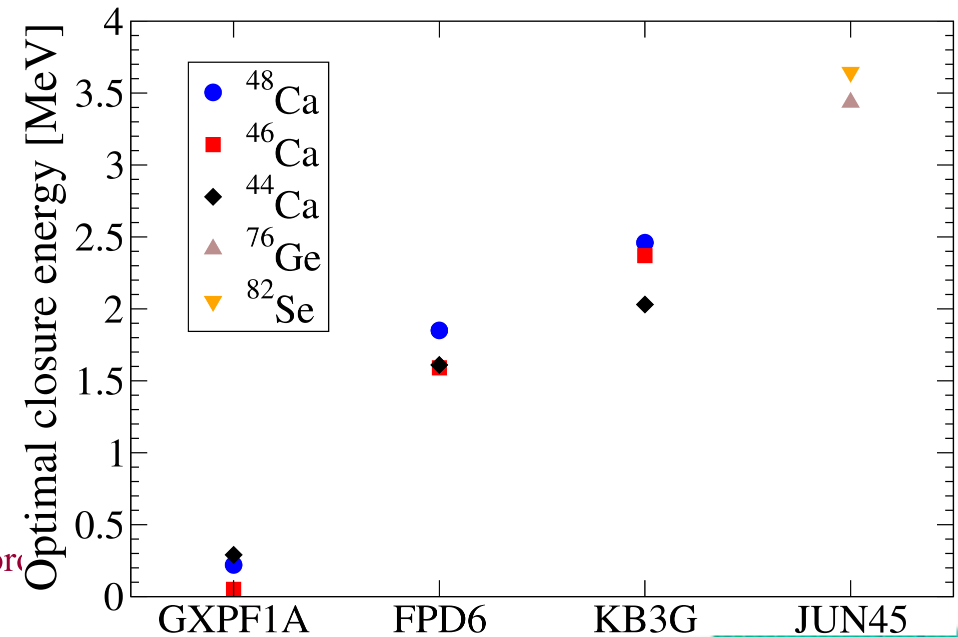




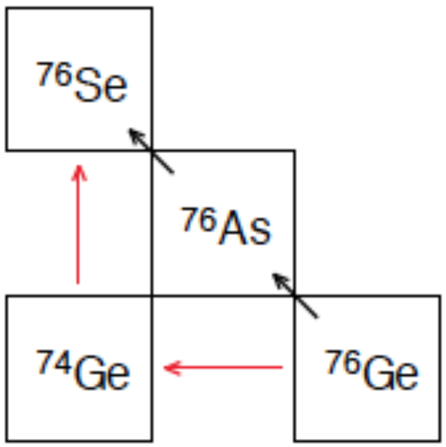
^{82}Se: PRC 89, 054304 (2014)

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



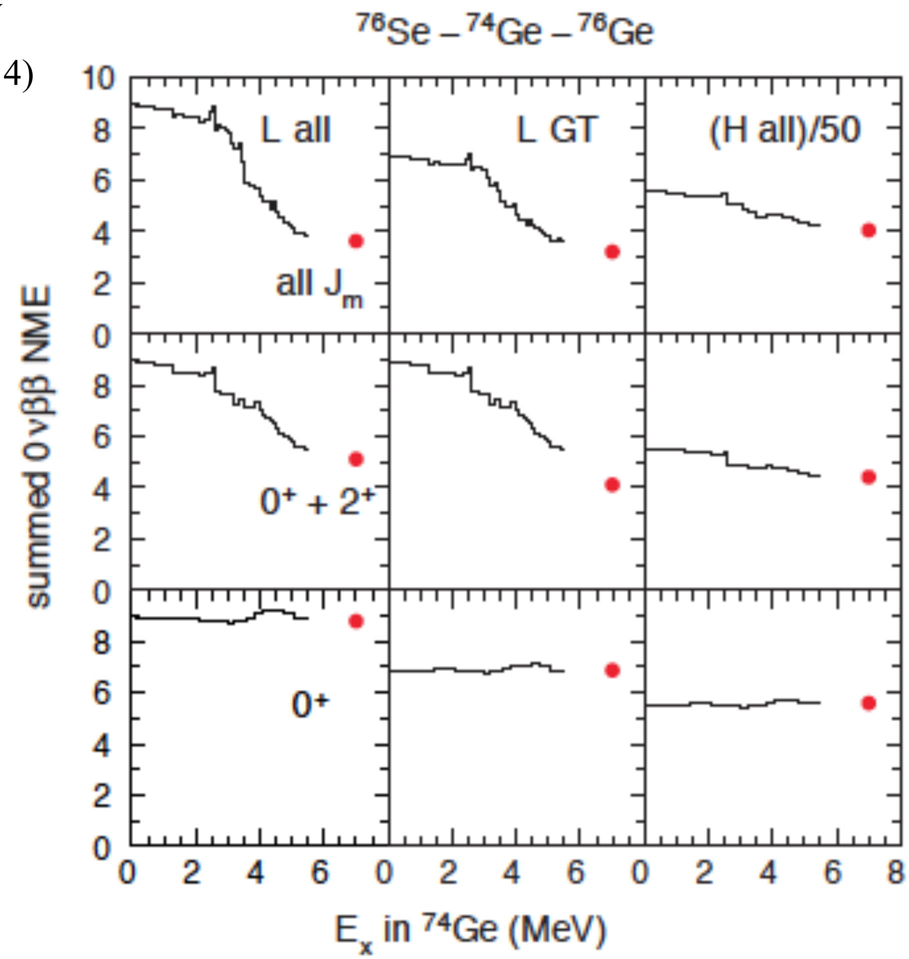


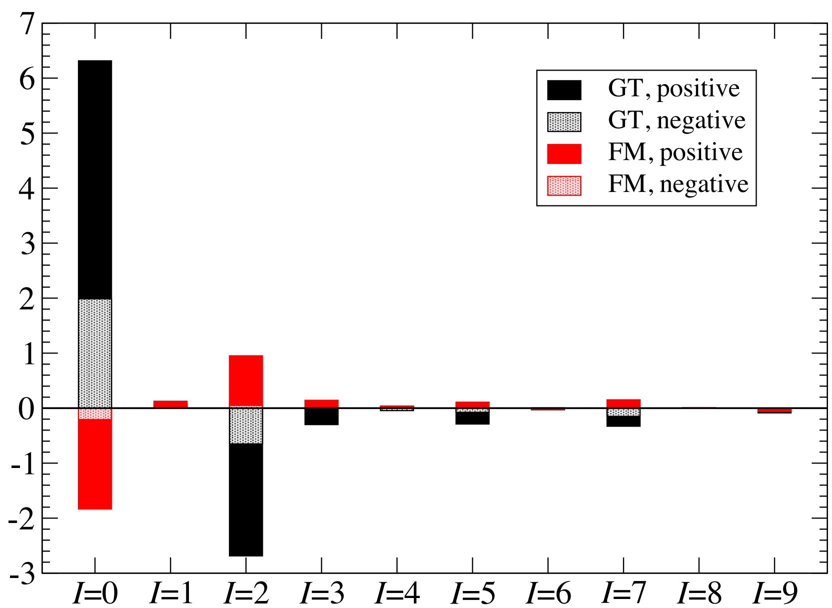
New Approach to calculate NME: New Tests of Nuclear Structure



Brown, Horoi, Senkov

PRL **113**, 262501 (2014)

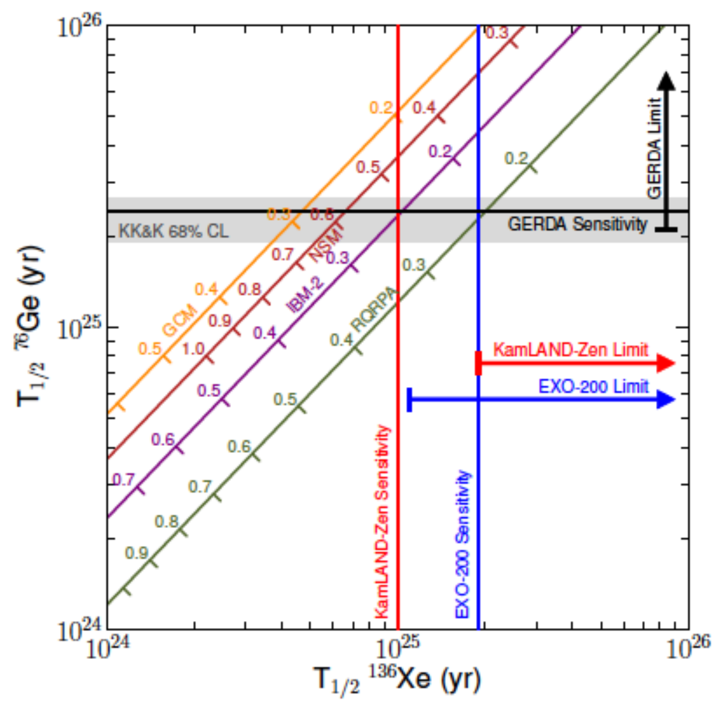




Spin of the neutron-neutron (proton-proton) pairs

^{136}Xe ββ Experimental Results

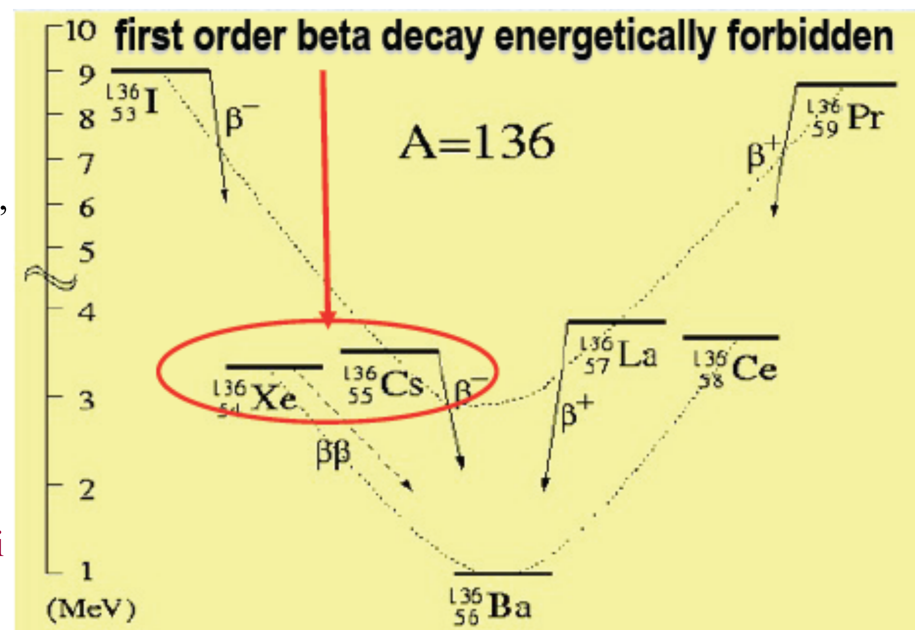
Publication	Experiment	$T^{2\nu}_{1/2}$	$T^{0\nu}_{1/2}$(lim)	$T^{0\nu}_{1/2}$(Sens)
PRL 110, 062502	KamLAND-Zen		> 1.9×10^{25} y	1.1×10^{25} y
PRC 89, 015502	EXO-200	$(2.11 \pm 0.04 \pm 0.21) \times 10^{21}$ y		
Nature 510, 229	EXO-200		>1.1×10^{25} y	1.9×10^{25} y
PRC 85, 045504	KamLAND-Zen	$(2.38 \pm 0.02 \pm 0.14) \times 10^{21}$ y		
		$M^{2\nu}_{exp} = 0.0191 - 0.0215\ MeV^{-1}$		



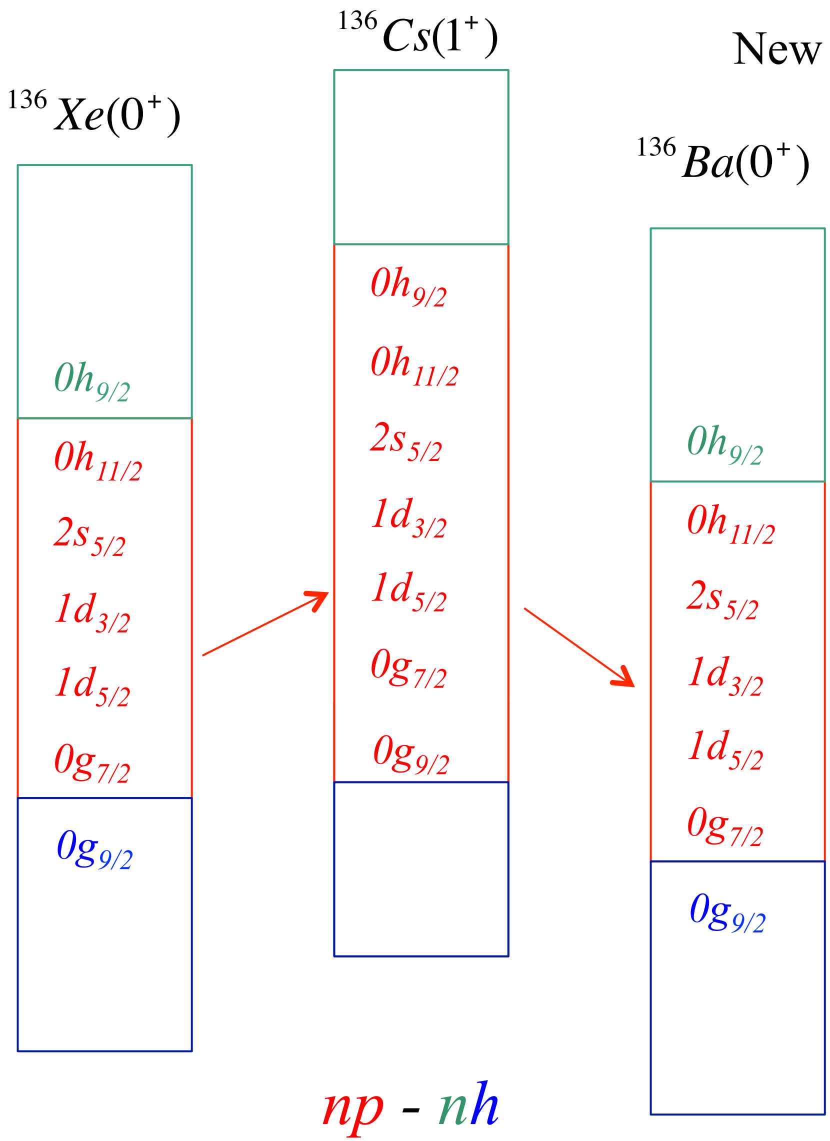
EXO-200

arXiv:1402.6956,
Nature 510, 229

M. Horoi



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



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

Horoi, Brown, PRL **111**, (2013)

What Experimental Searches Do Exist?

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	

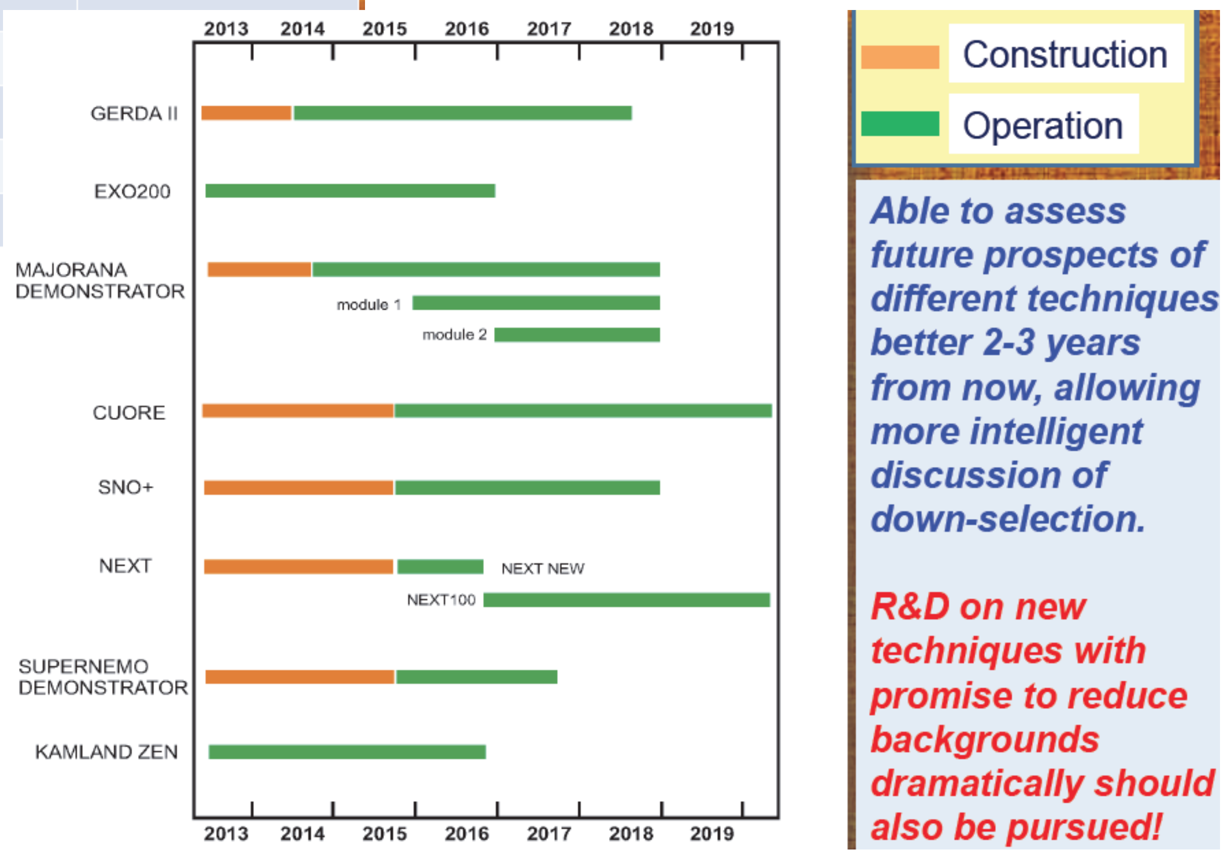
S. Vigdor talk at LRP Town Meeting, Chicago, Sep 28-29, 2014

Goals (DNP14 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)*



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!

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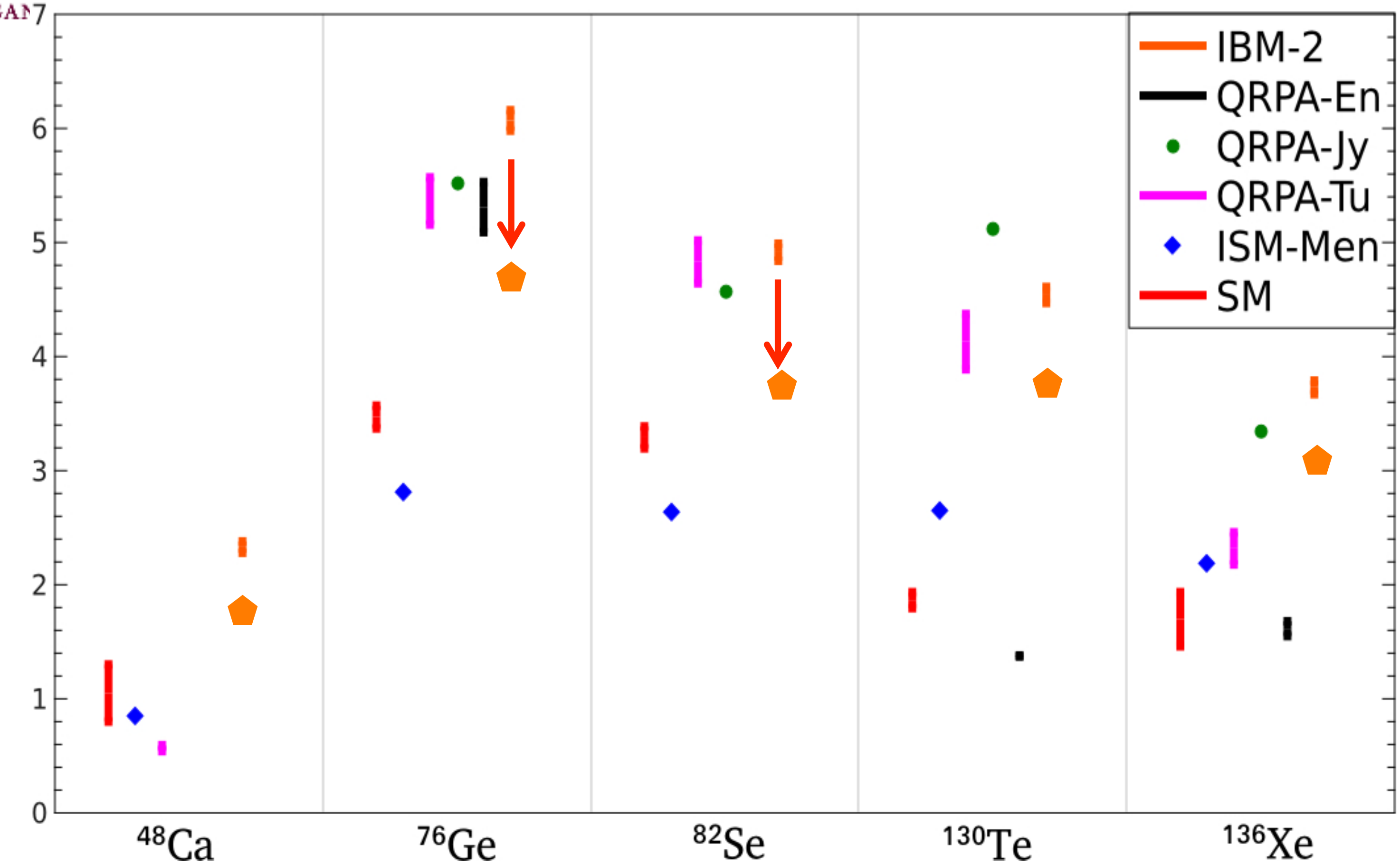
NME for the light-neutrino exchange mechanism



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

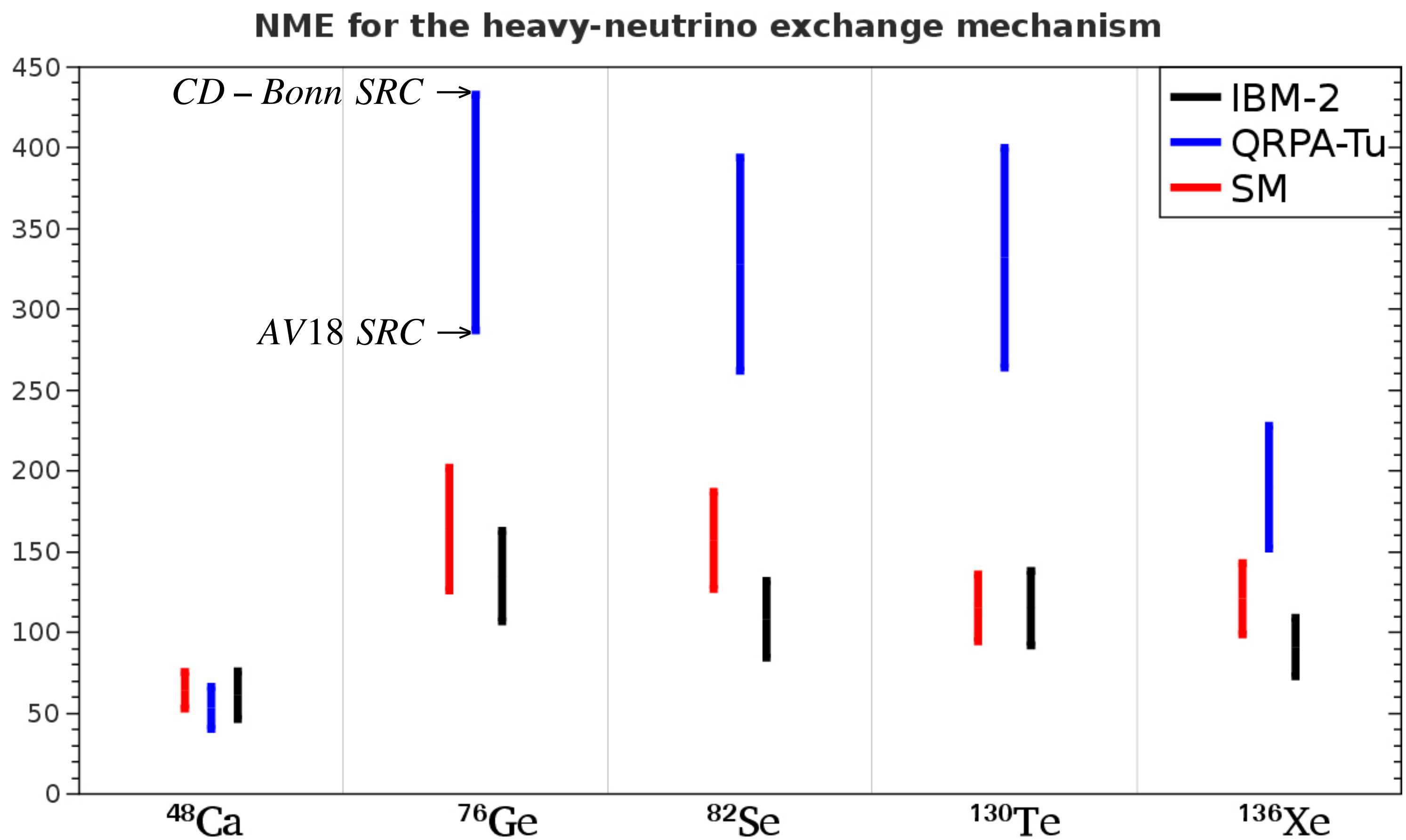
QRPA-En M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).

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).



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

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%)

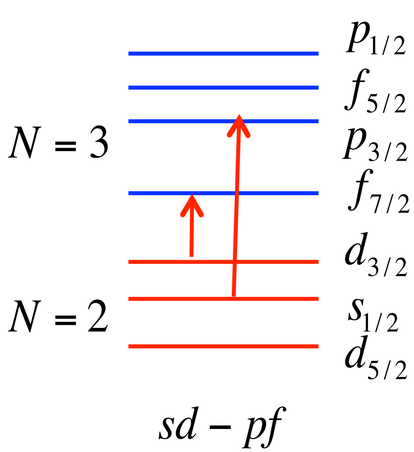
SDPFU: PRC 79, 014310 (2009)

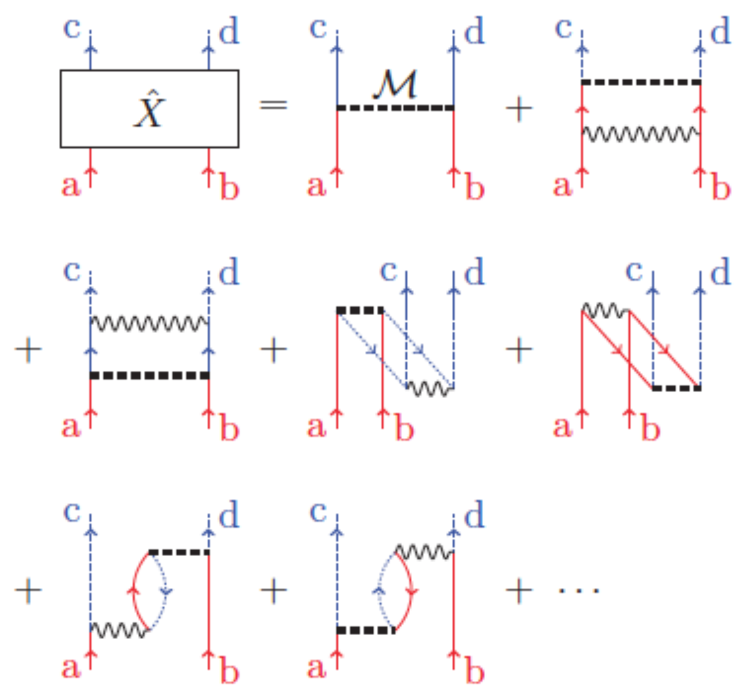
SDPFMUP: PRC 86, 051301(R) (2012)

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

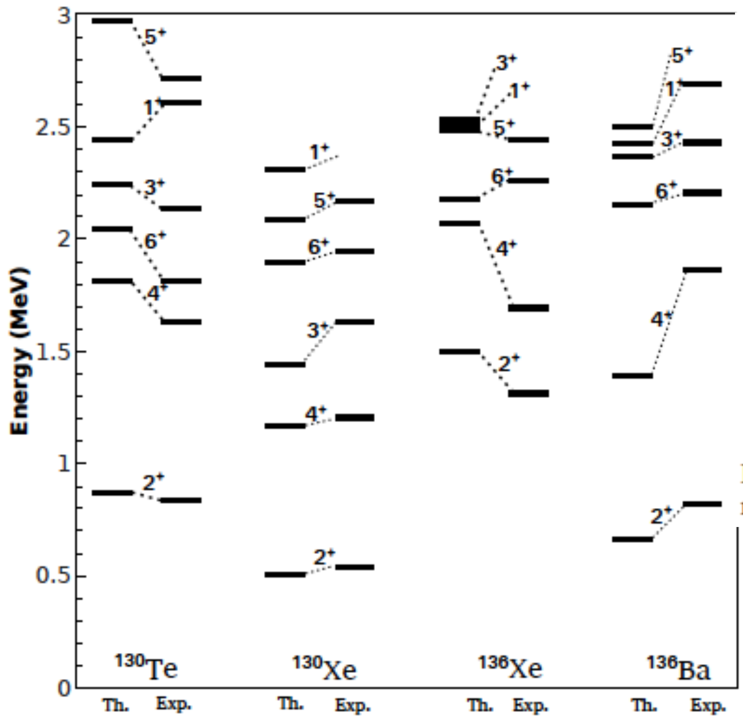
arXiv:1308.3815, PRC 89, 045502 (2014)

PRC 87, 064315 (2013)





Experimental info needed



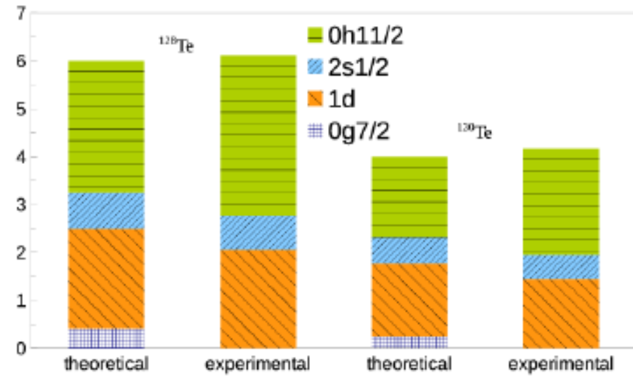


FIG. 2. (Color on-line) Theoretical and experimental [58] neutron shell vacancies for ^{128}Te and ^{130}Te.

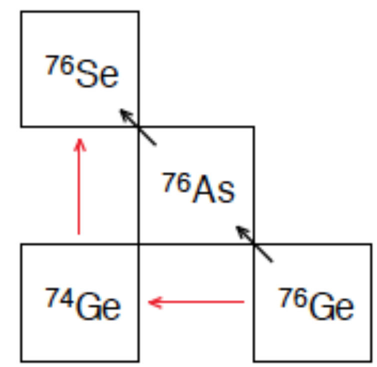
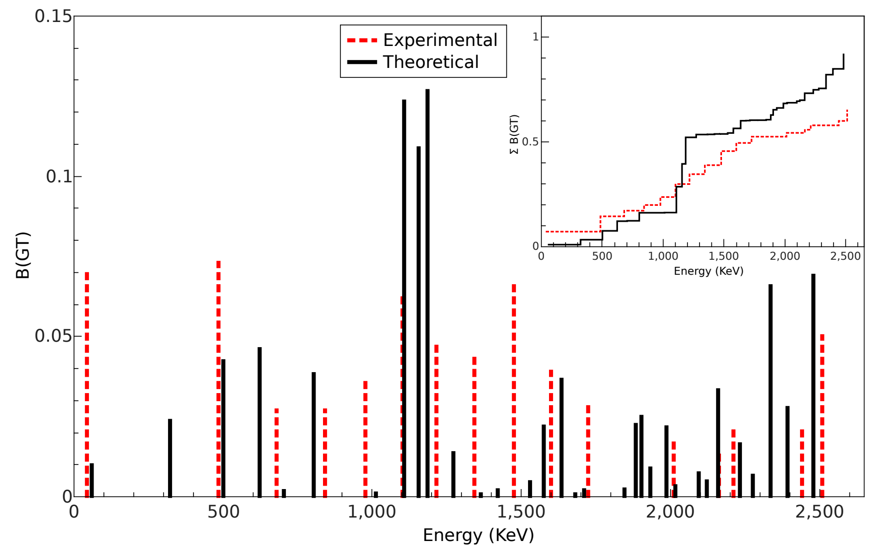


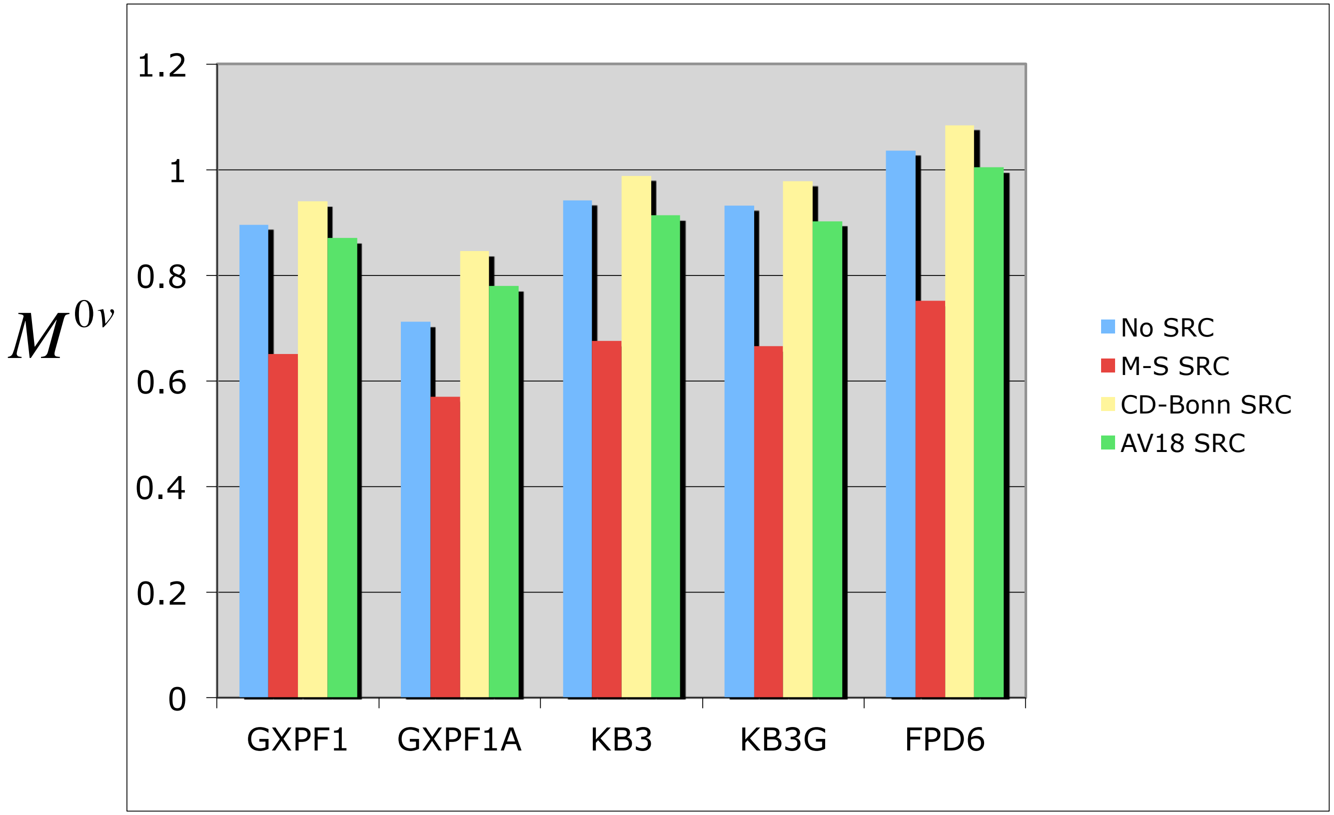
TABLE I. The calculated $B(E2)\uparrow$ values on the first line compared to the adopted ones on the second line.

	^{128}Te	^{130}Te	^{132}Te	^{130}Xe	^{132}Xe	^{136}Xe	^{136}Ba
$B(E2)\uparrow_{th.}$	0.202	0.153	0.085	0.502	0.390	0.215	0.479
$B(E2)\uparrow_{ad.}$	0.380	0.297	0.207	0.634	0.468	0.217	0.413



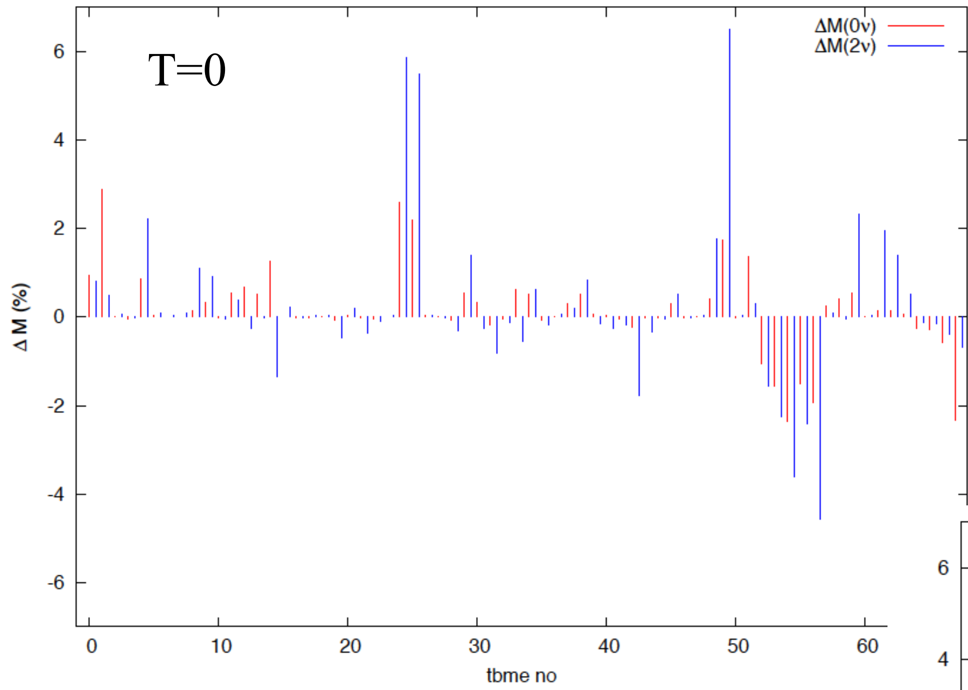
^{48}Ca: $M^{0\nu}$ vs the Effective Interaction and SRC

M. Horoi, S. Stoica, arXiv:0911.3807, Phys. Rev. C **81**, 024321 (2010)



$$Prediction: \langle M^{0\nu} \rangle = 0.85 \pm 0.15 \xrightarrow{T_{1/2}(0\nu)\geq 10^{26}\,y} \langle m_{\beta\beta} \rangle \leq 0.230 \pm 0.045 eV$$

Effects of Changing Matrix Elements of Hamiltonian: ^{82}Se



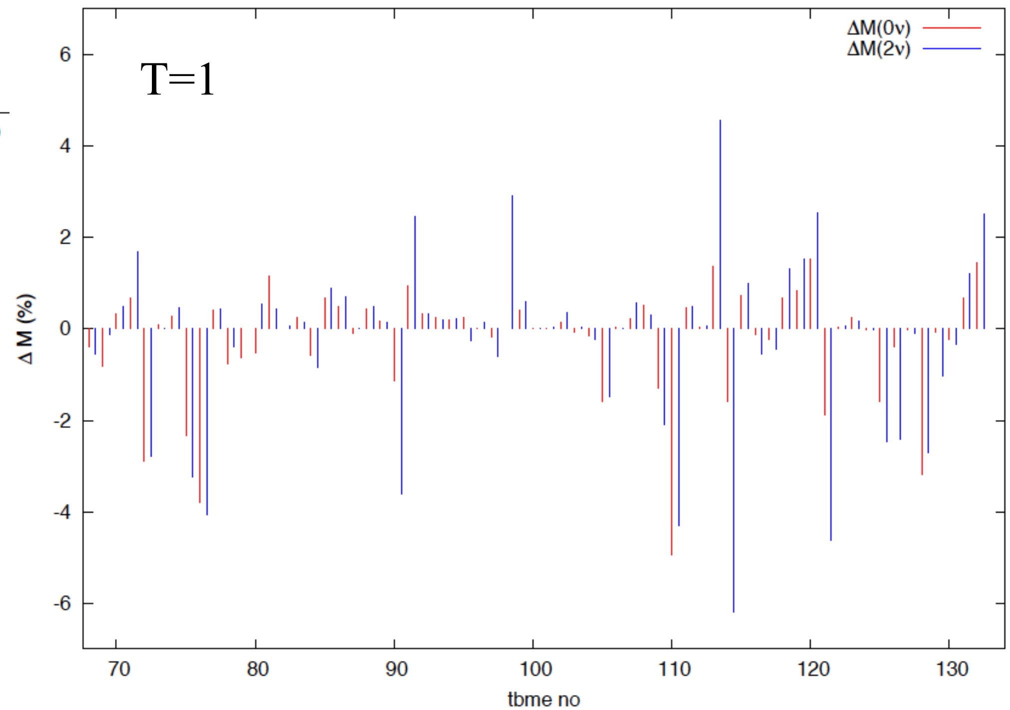
$$\Delta ME / ME = 5\%$$

$$\Delta M \equiv \frac{\Delta NME}{NME} \times 100$$

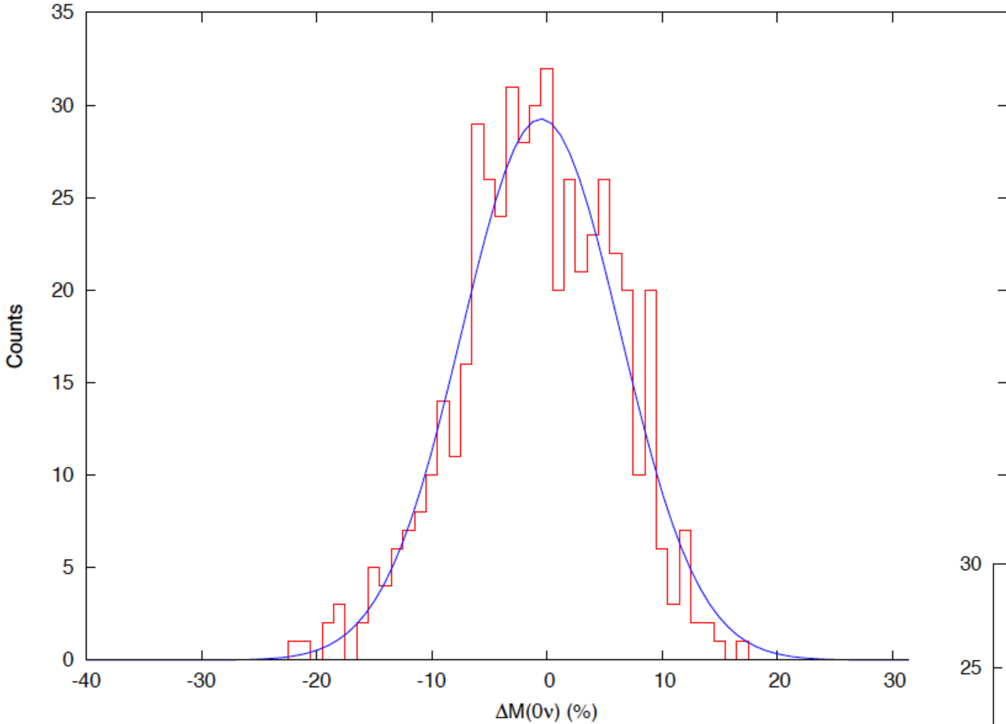
Ideal Coherent sums:

$$\sum \Delta M(0\nu) = 80\%$$

$$\sum \Delta M(2\nu) = 130\%$$



Effects of Changing Matrix Elements of Hamiltonian: ^{82}Se



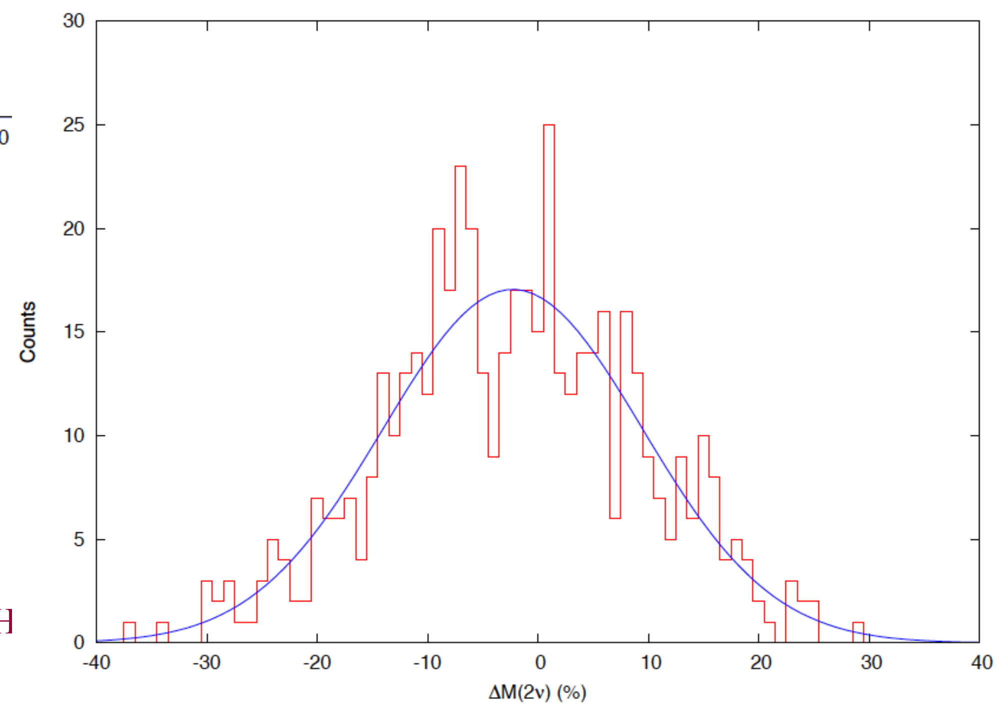
Random Changes

$\Delta ME\ /\ ME < 5\%$

Ideal Coherent sums :

$$\sum \Delta M(0\nu) = 80\%$$

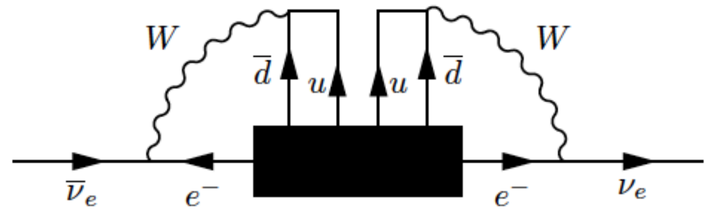
$$\sum \Delta M(2\nu) = 130\%$$



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!

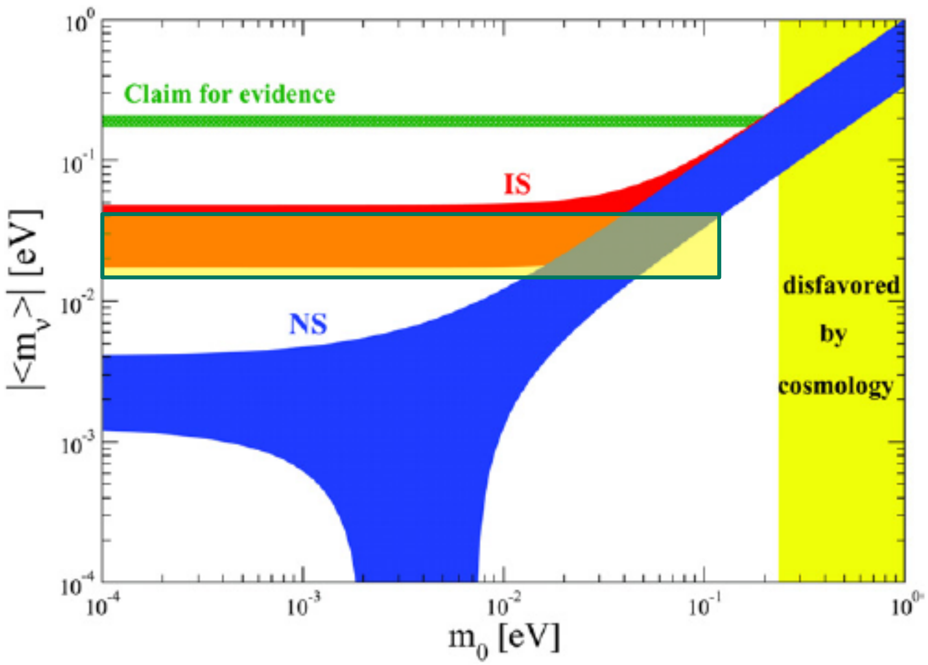
Take-Away Points

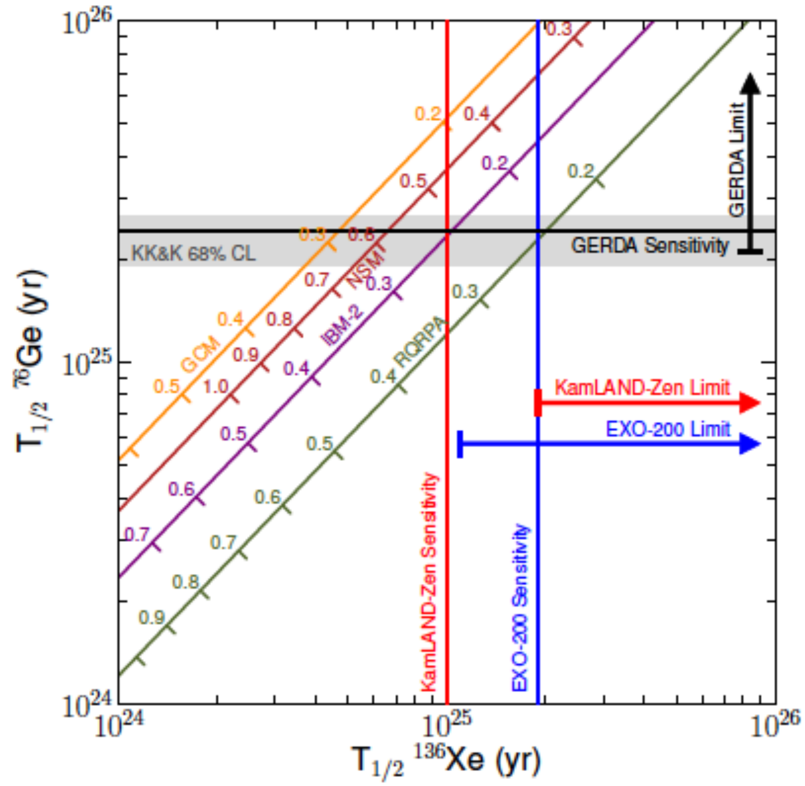
The analysis and guidance of the experimental efforts need **accurate Nuclear Matrix Elements.**

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

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

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





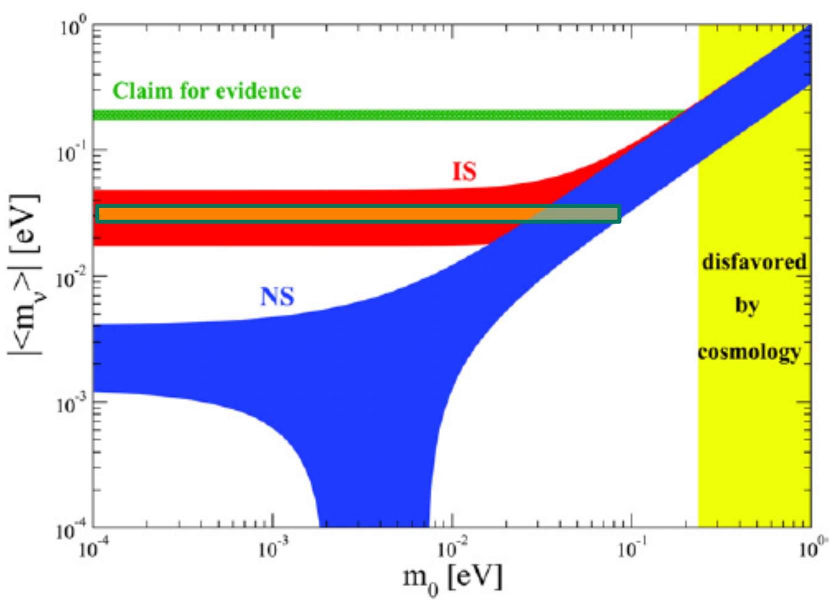
Take-Away Points

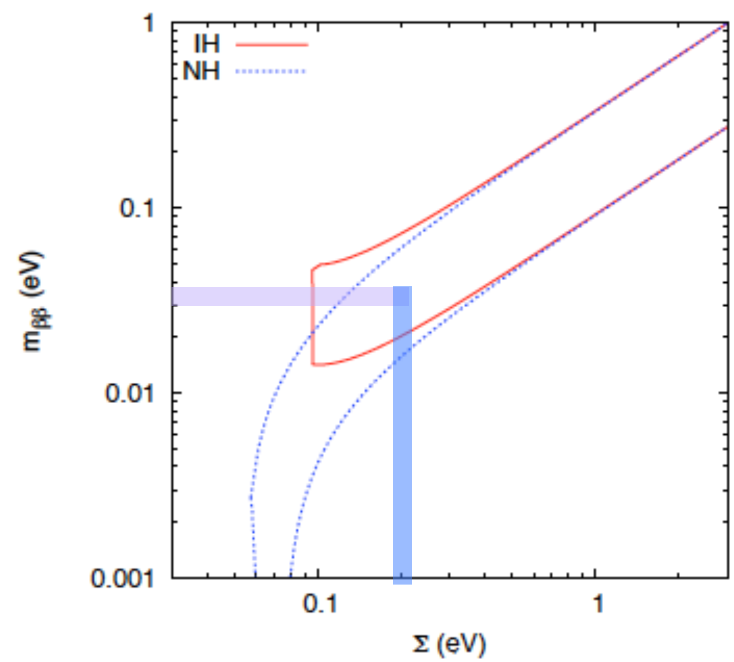
Extracting information about Majorana CP-violation phases may require the mass hierarchy from LBNE(DUNE), cosmology, etc, but also **accurate Nuclear Matrix Elements**.

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

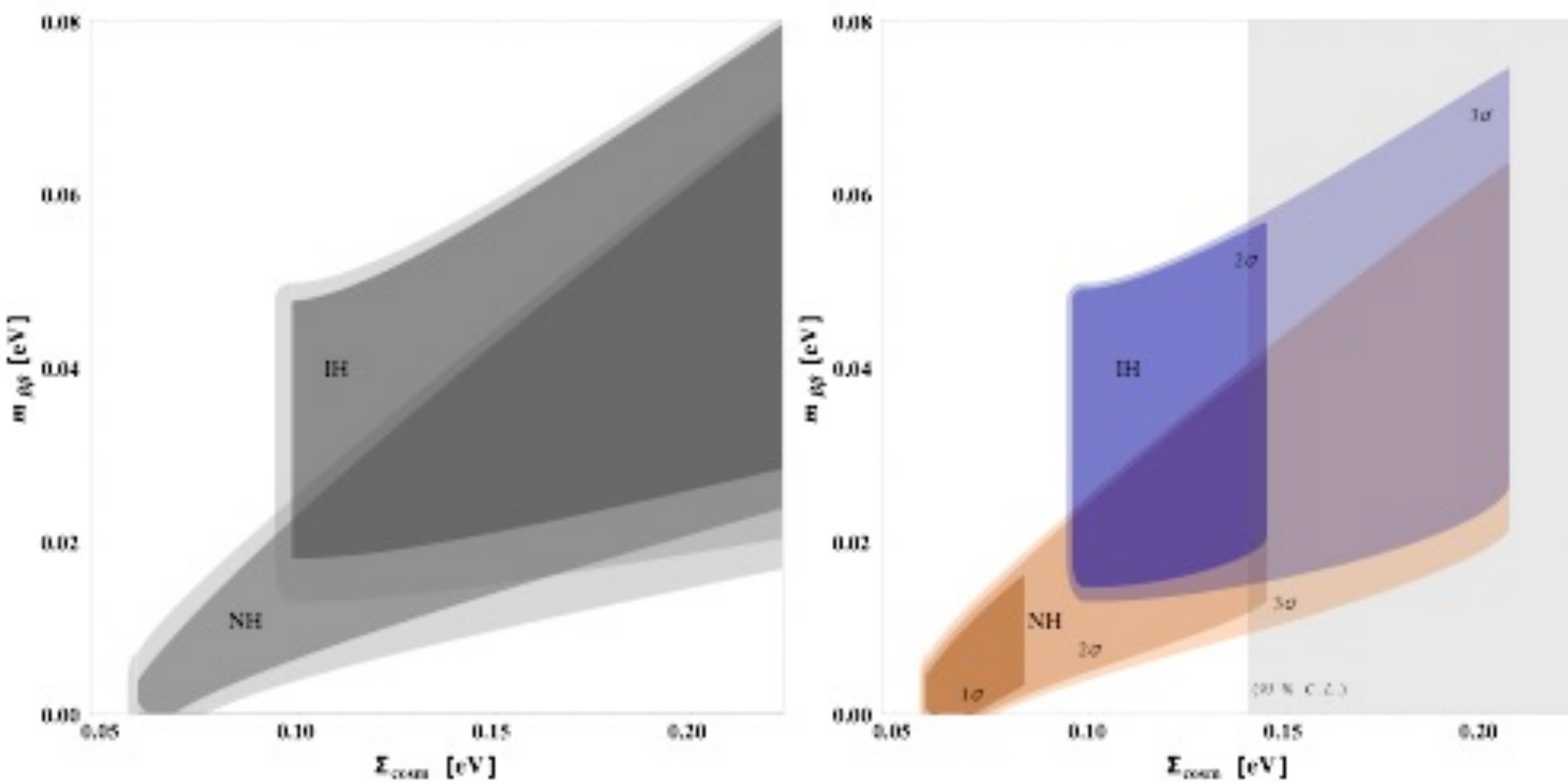
$$\phi_2 = \alpha_2 - \alpha_1 \qquad \phi_3 = -\alpha_1 - 2\delta$$

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





Recent Constraints from Cosmology



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

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

arXiV:1505.02722

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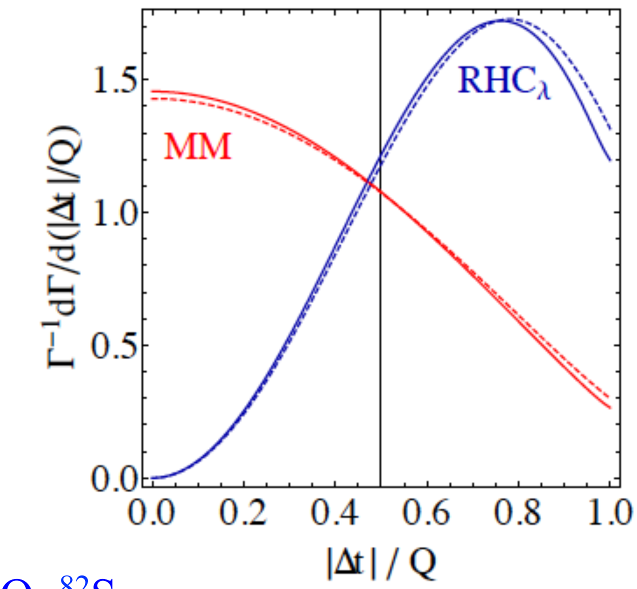
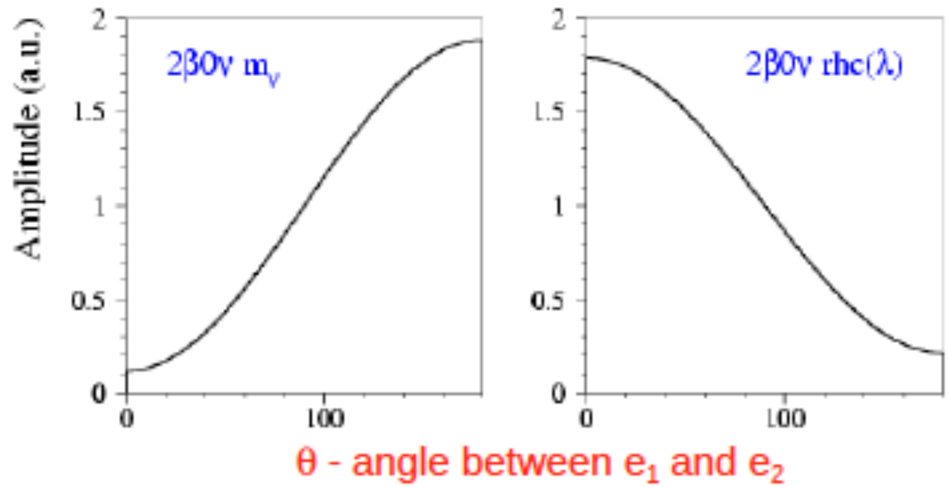
Take-Away Points

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



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

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

SciDAC Scientific Discovery through Advanced Computing

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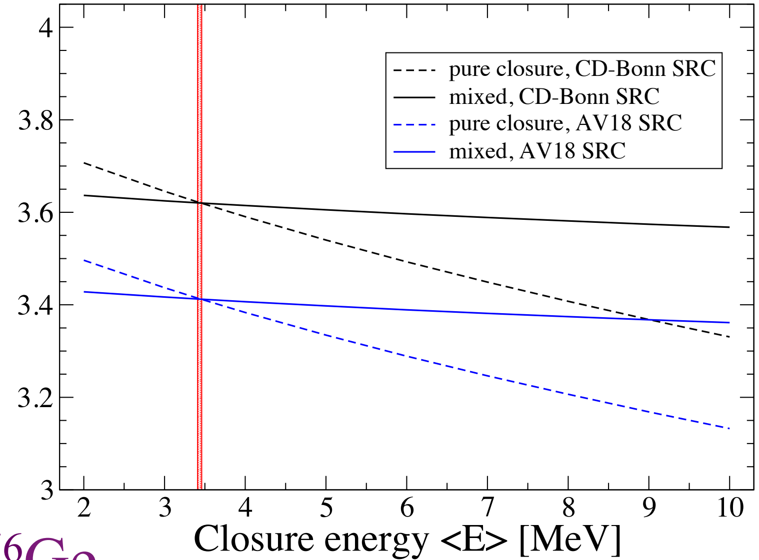
Take-Away Points

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

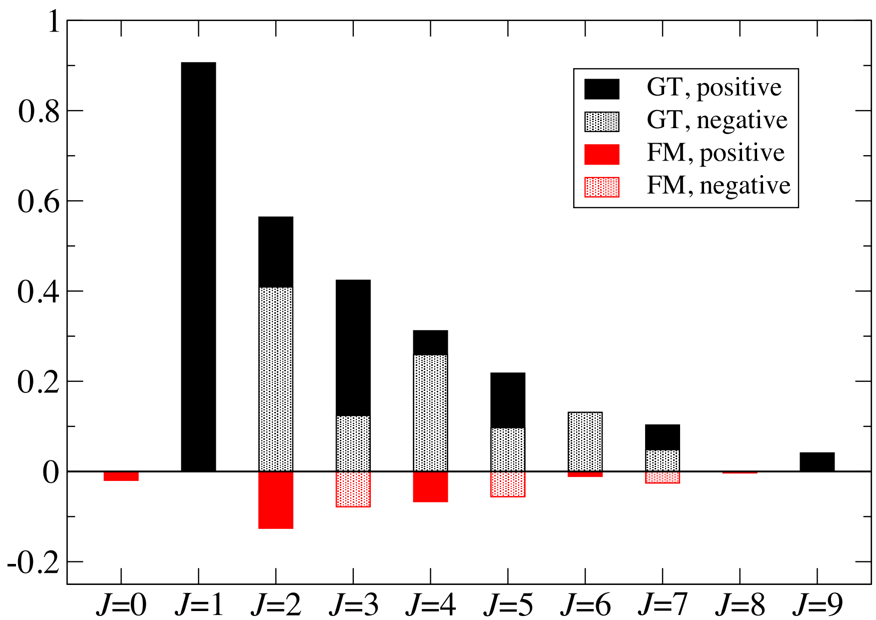
The method provides **optimal closure energies** for the mass mechanism.

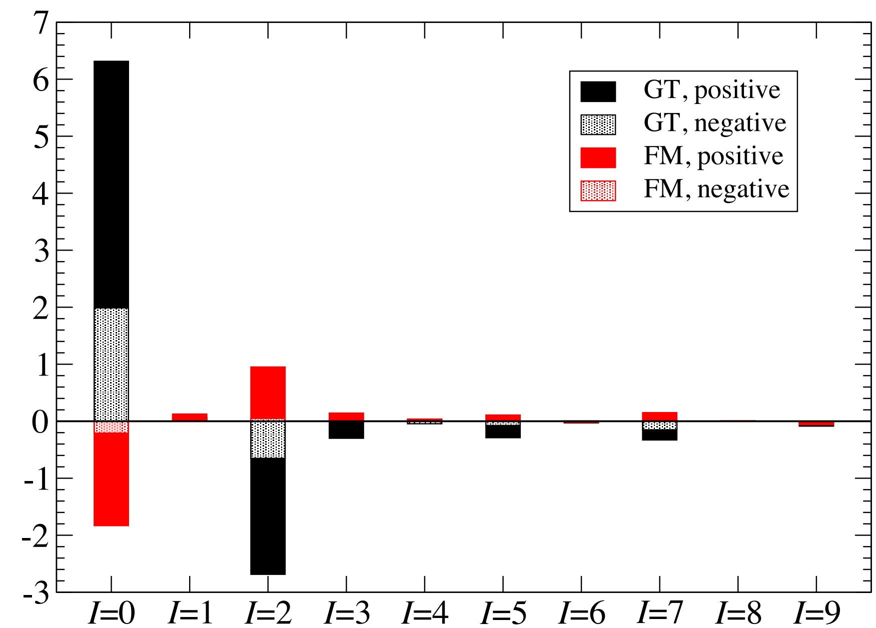
Decomposition of the matrix elements can be used for **selective quenching** of classes of states, and for testing nuclear structure.



^{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