Nuclear structure constraints for double-beta decay nuclear matrix elements

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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

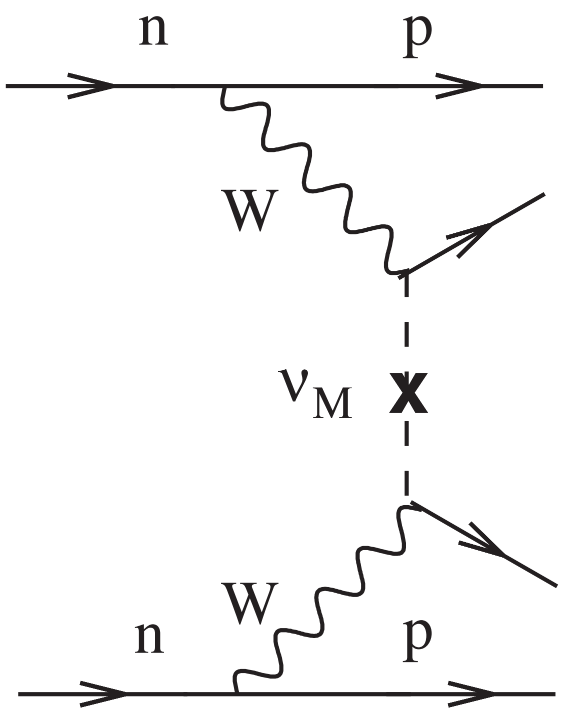
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

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!

Neutrinoless Double Beta Decay

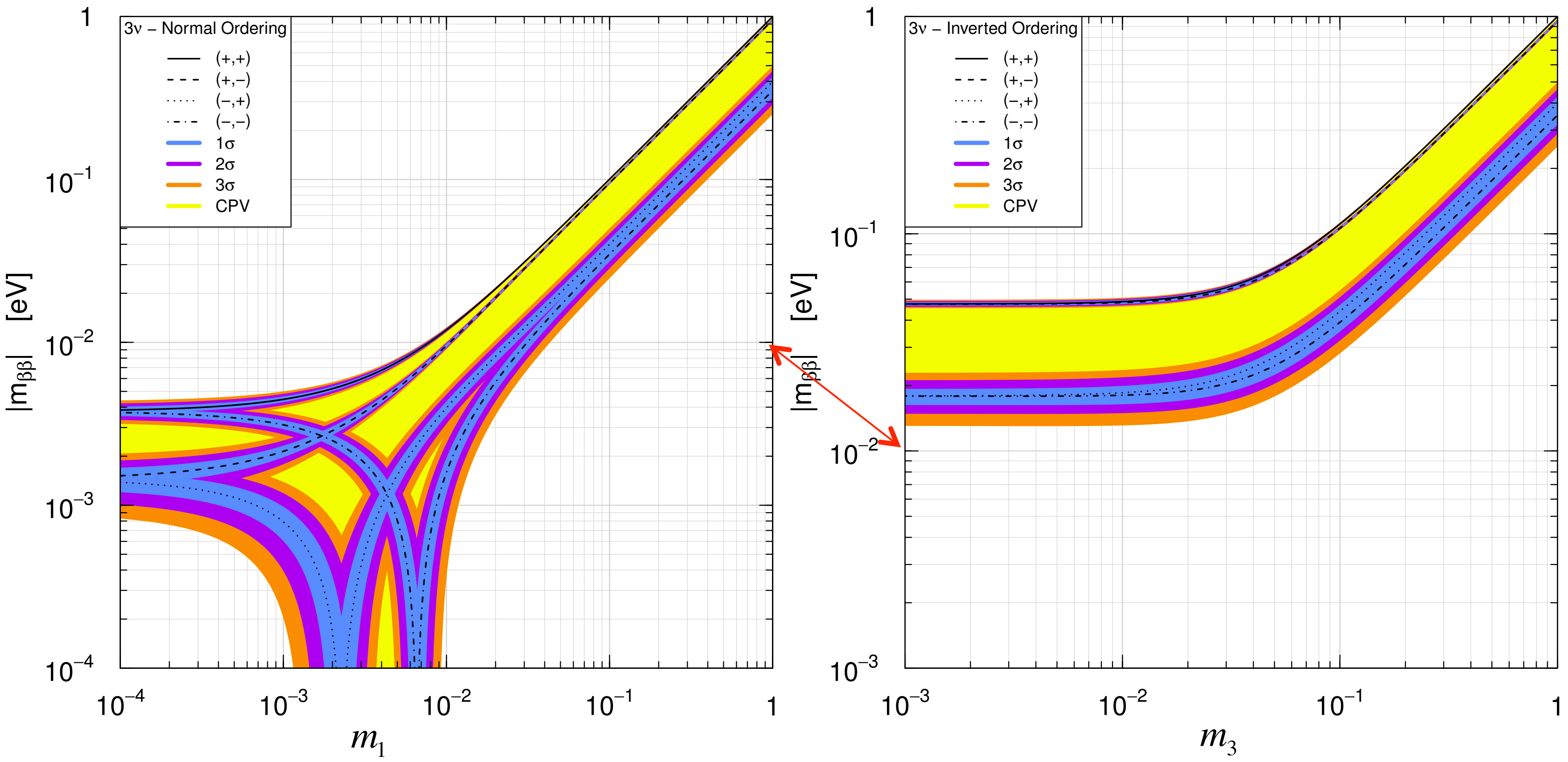


$$T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta})\left[M^{0\nu}(0^+)\right]^2\left(\frac{<m_{\beta\beta}>}{m_e}\right)^2$$

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

Neutrino ββ effective mass

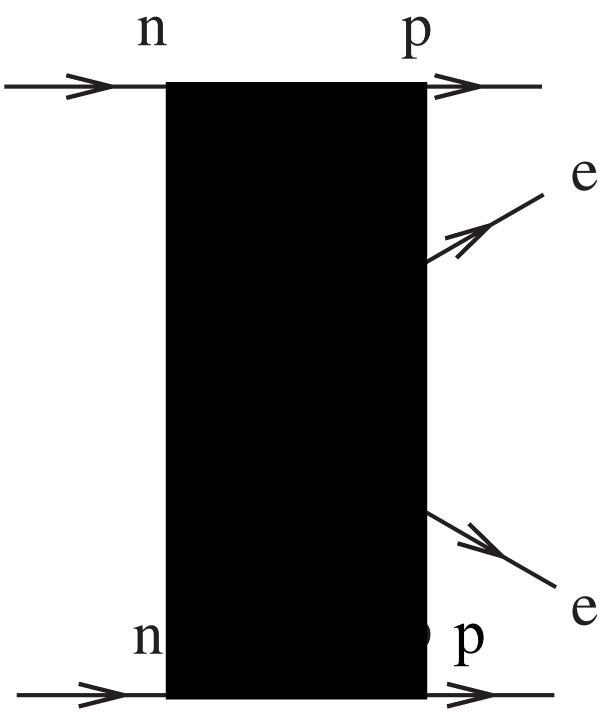
arxiv:1507.08204



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

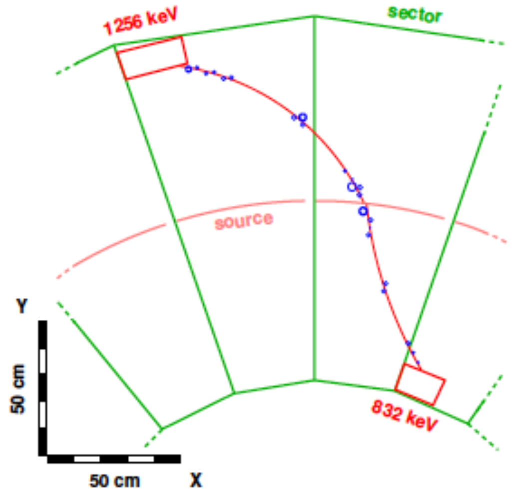
$$\phi_2 = \alpha_2 - \alpha_1 \qquad \phi_3 = -\alpha_1 - 2\delta$$

Neutrinoless Double Beta Decay Black Box

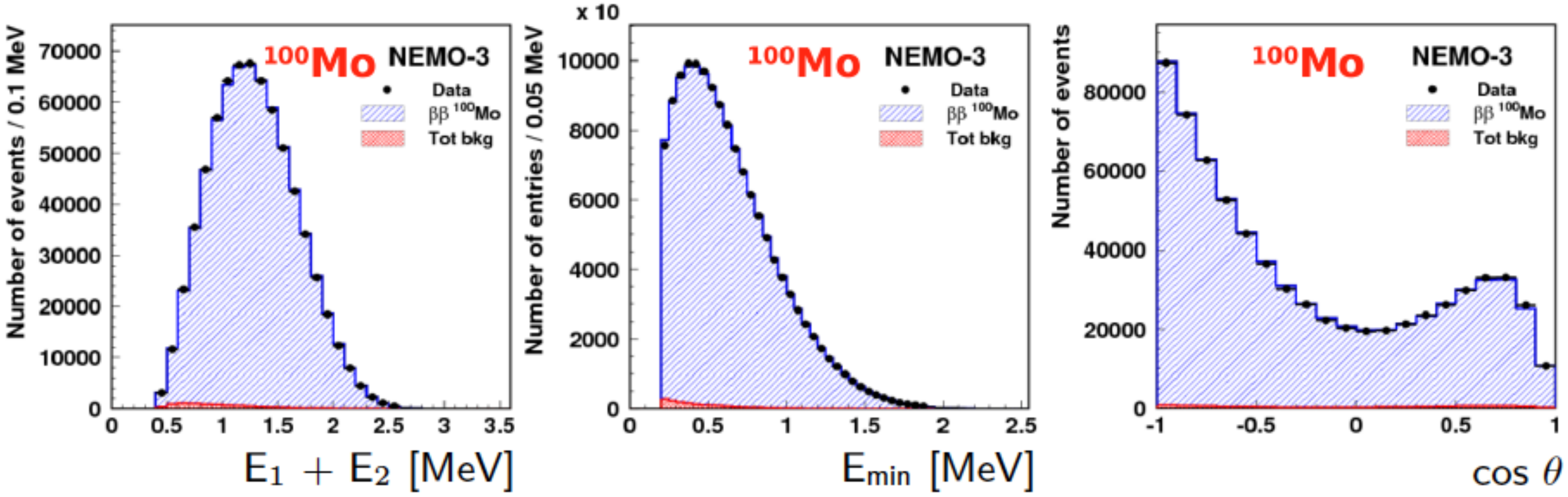


$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|\sum_j M_j\eta_j\right|^2 = G^{0\nu}\left|\enclose{circle}{M^{(0\nu)}}\eta_{\nu L} + \enclose{circle}{M^{(0N)}}\left(\eta_{NL}+\eta_{NR}\right) + \enclose{circle}{\tilde{X}_\lambda} < \lambda > + \enclose{circle}{\tilde{X}_\eta} < \eta > + \enclose{circle}{M^{(0\lambda')}}\eta_{\lambda'} + \enclose{circle}{M^{(0\tilde{q})}}\eta_{\tilde{q}} + \cdots\right|^2$$

NEMO-3 $2\nu2\beta$ of ^{100}Mo Measurement



- 6.9 kg of ^{100}Mo
- ~700 000 $2\nu2\beta$ events collected
- Efficiency $\mathcal{E}_{2\nu} = 4.3$ %
- Signal to background ratio S/B = 76
- Preliminary half-life:
  $\mathcal{T}_{1/2}^{2\nu} = 7.16 \pm 0.01$ (stat) ± 0.54 (syst) 10^{18} y
  compatible with previously published [Phys. Rev. Lett. 95, 182302 (2005)]



- 0.7 % systematical uncertainty on the $2\nu2\beta$ efficiency above 2 MeV

Models, ββ, and LHC

◆ Left-right (LR) symmetric model(s):

- Restore LR symmetry (at some scale), needs new iso-triplet Higgs, W_R, new ββ-decay contributions

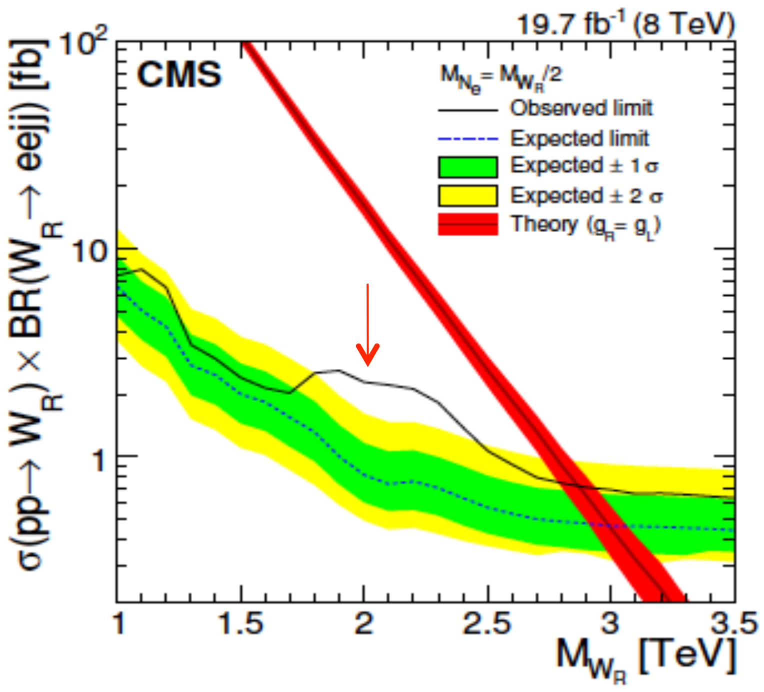
◆ Super-Symmetric (SUSY) model(s):

- Restore fermion-boson symmetry, double the # of particles, may contribute to ββ-decay (R-parity)

Models, ββ, and LHC

- ◆ Left-right (LR) symmet
  - Restore LR symmet
    Higgs, W_R, new ββ-

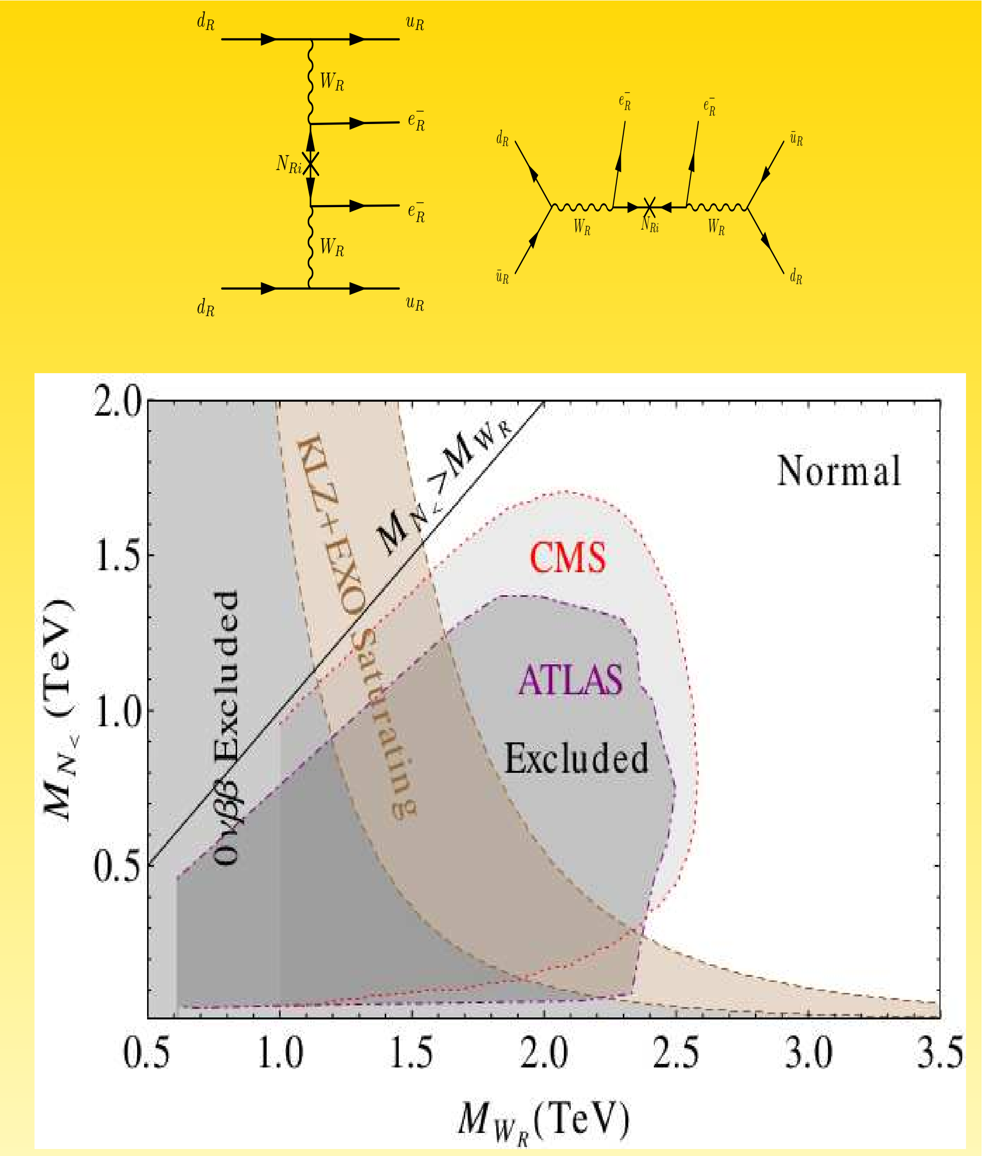
W_R search at CMS arXiv:
1407.3683



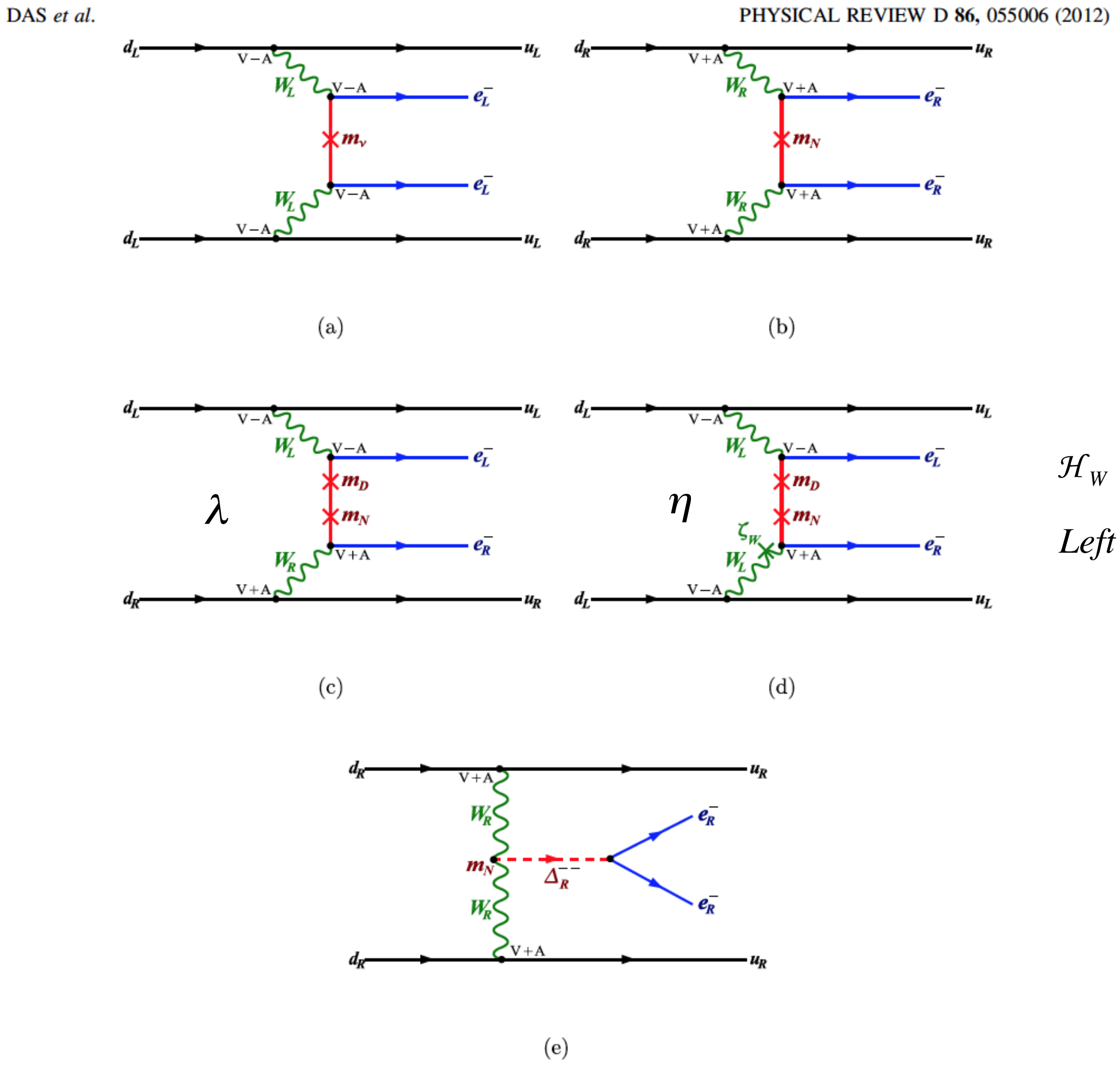
SUSY

-bos

ontri



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

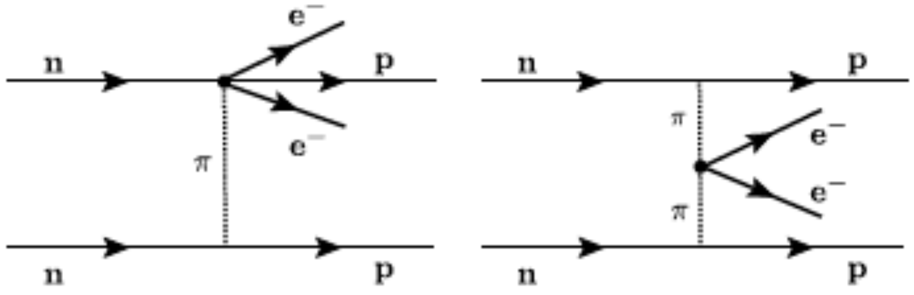
$$-\mathcal{L} \supset \frac{1}{2} h_{\alpha\beta}^T \left(\bar{\nu}_{\beta L} \quad \bar{e}_{\alpha L}\right)\begin{pmatrix}\Delta^- & -\Delta^0 \\ \Delta^{--} & \Delta^-\end{pmatrix}\begin{pmatrix}e_R^c \\ -\nu_R^c\end{pmatrix} + hc$$

No neutrino exchange

More long-range contributions?

$SUSY$ /w $R-parity\ violation$: *e.g.* Rep.Prog.Phys. 75, 106301(2012)

Hadronization /w R-parity v. and heavy neutrino



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

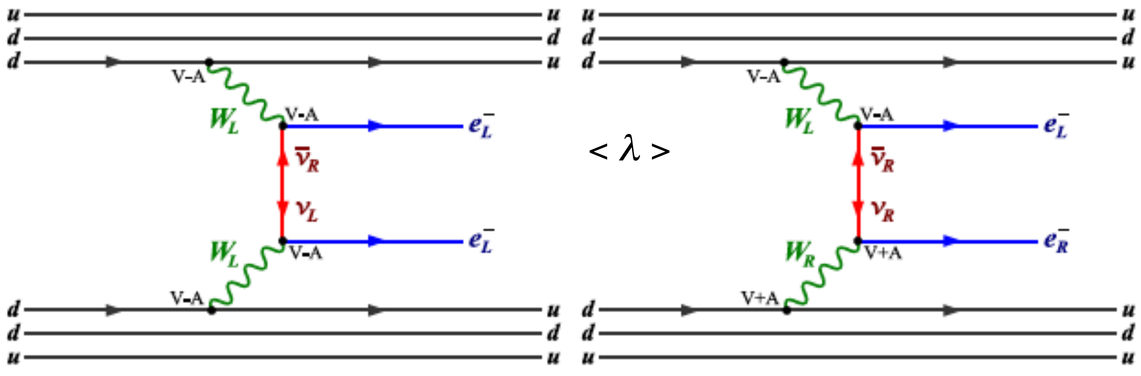
(i) η_{NL} *neglijible in most models;* *(ii)* $\langle\eta\rangle$ & $\langle\lambda\rangle$ *ruled in/out by energy or angular distributions*

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

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)

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

DBD signals from different mechanisms

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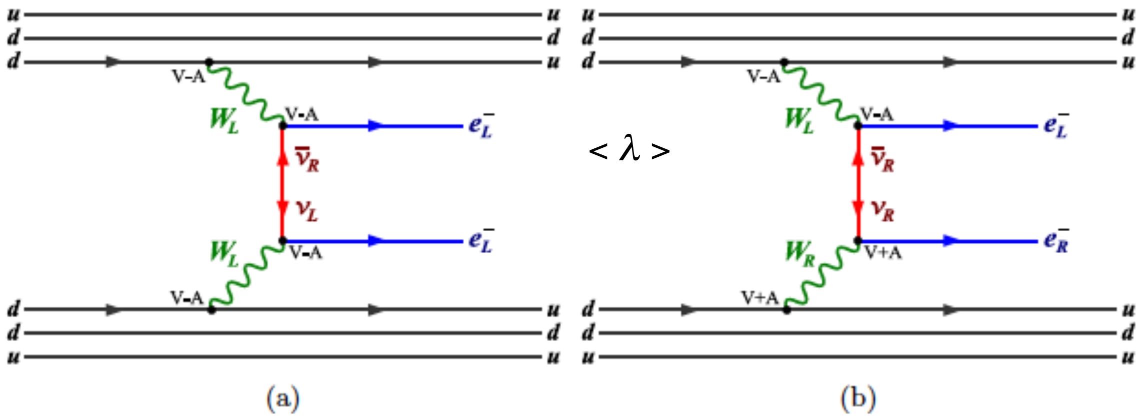


(a) (b)

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

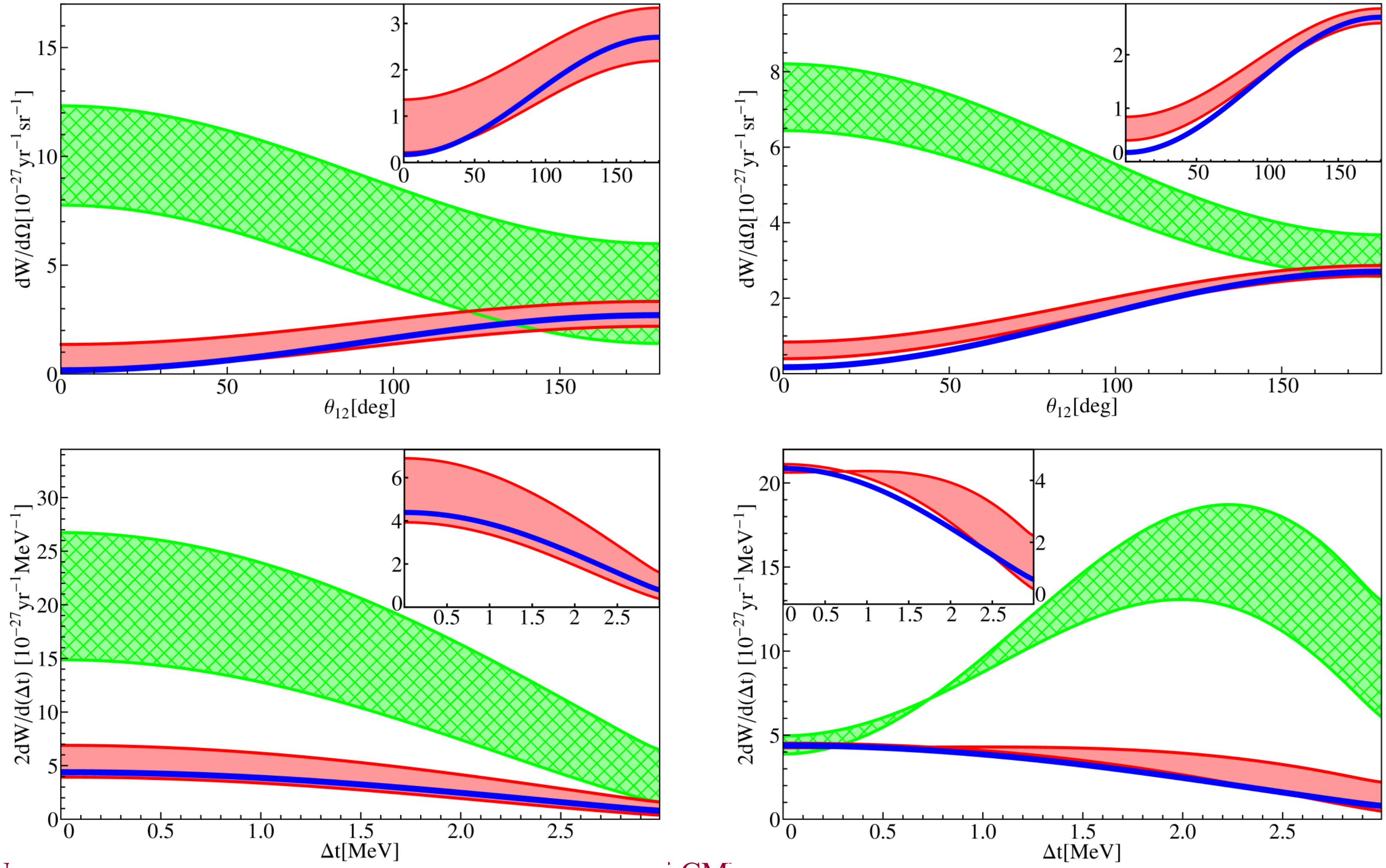
$$\frac{\mathrm{d}^2W^{0\nu}_{0^+\to0^+}}{\mathrm{d}\epsilon_1\mathrm{dcos}\theta_{12}} = \frac{a_{0\nu}\omega_{0\nu}(\epsilon_1)}{2\left(m_eR\right)^2}\left[A(\epsilon_1)+B(\epsilon_1)\cos\theta_{12}\right]$$

$$\frac{2\mathrm{d}W^{0\nu}_{0^+\to0^+}}{\mathrm{d}(\Delta t)} = \frac{2a_{0\nu}}{\left(m_eR\right)^2}\frac{\omega_{0\nu}(\Delta t)}{m_ec^2}A(\Delta t)$$

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

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

$<\lambda>$ dominates $\qquad$ $<\eta>$ dominates



Two Non-Interfering Mechanisms

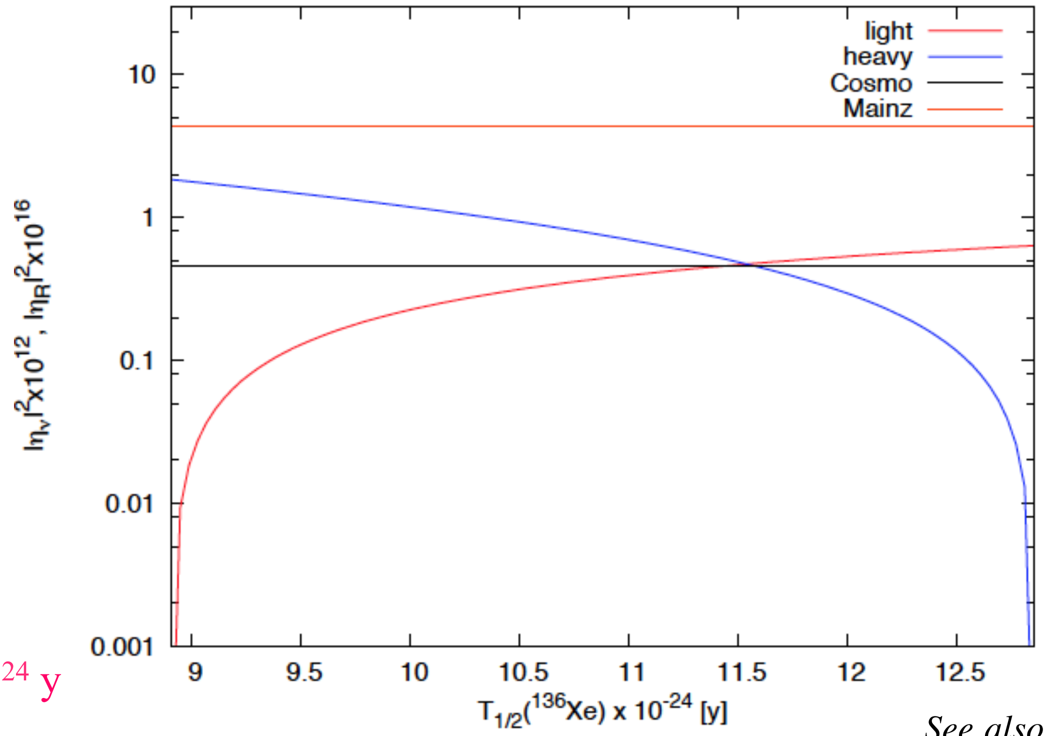
$$\left[T_{1/2}^{0\nu}\right]^{-1} \approx G^{0\nu}\left[\left|M^{(0\nu)}\right|^{2}\left|\eta_{\nu L}\right|^{2}+\left|M^{(0N)}\right|^{2}\left|\eta_{NR}\right|^{2}\right]$$

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)

Two Non-Interfering Mechanisms

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

See also PRD 83, 113003 (2011)

Two Non-Interfering Mechanisms

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

	Ge/Se		Ge/Te		Ge/Xe		Se/Te		Se/Xe		Te/Xe	
	Ge	Se	Ge	Te	Ge	Xe	Se	Te	Se	Xe	Te	Xe
$G^{0\nu}_{01} \times 10^{14}$	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
$T^{\nu}_{1/2}(1)/T^{\nu}_{1/2}(2)$	3.87		1.76		1.50		0.45		0.39		0.85	
$T^{N}_{1/2}(1)/T^{N}_{1/2}(2)$	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)

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Summary of 0νDBD mechanisms

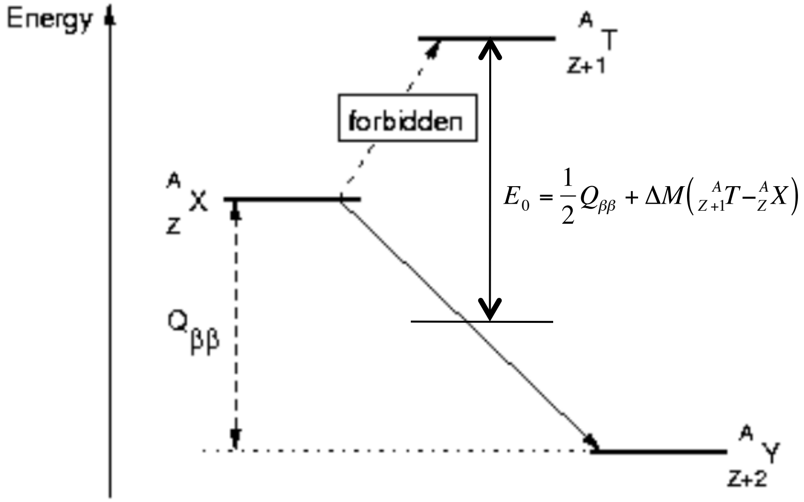
- The mass mechanism (a.k.a. light-neutrino exchange) is likely, and the simplest BSM scenario.
- Right-handed heavy neutrino-exchange is possible, and requires knowledge of **half-lives for more isotopes.**
- η- and λ- mechanisms are possible, but could be ruled in/out by **energy and angular distributions**.
- 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

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

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

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



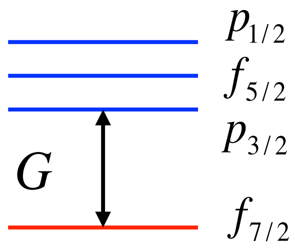
The choice of valence space
is important!

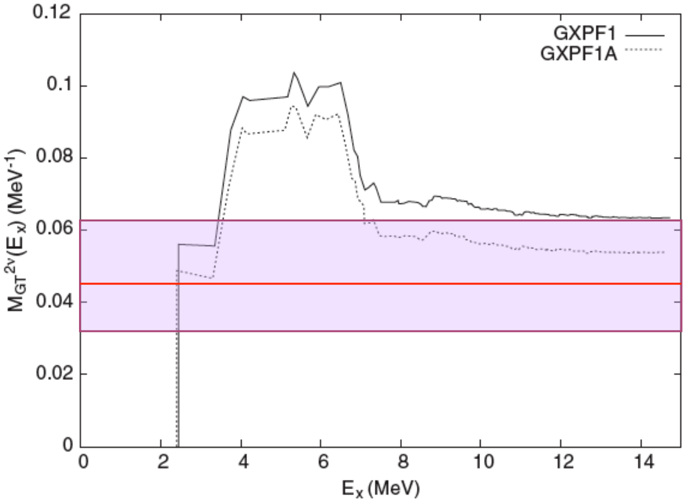
$$B(GT) = \frac{\left|\langle f \| \sigma\cdot\tau \| i\rangle\right|^2}{(2J_i+1)}$$

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 !



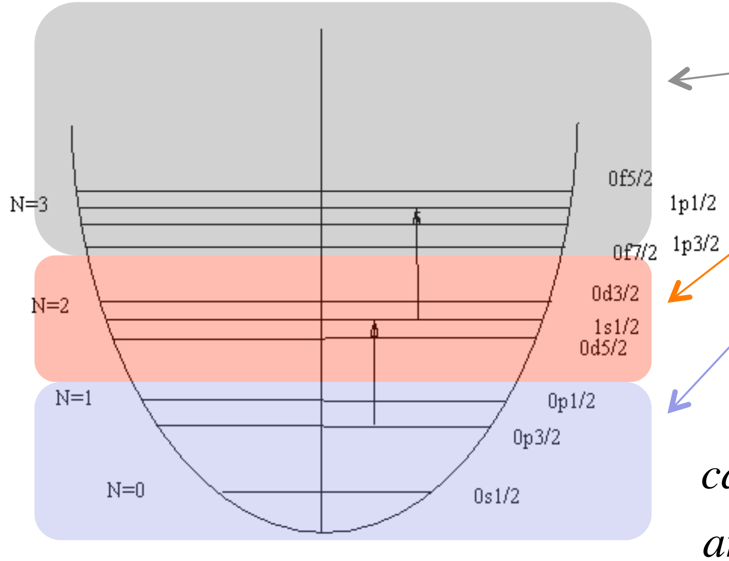


$$g_A\sigma\tau \xrightarrow{quenched} 0.74 g_A\sigma\tau$$

Horoi, Stoica, Brown,

PRC **75**, 034303 (2007)

Shell Model GT Quenching



empty

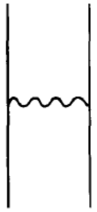
valence

frozen core

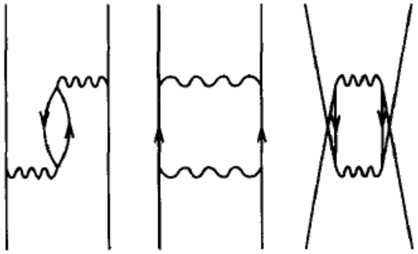
$$H_{valence}\Psi = E_n\Psi$$

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

can describe most correlations around the Fermi surface!



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



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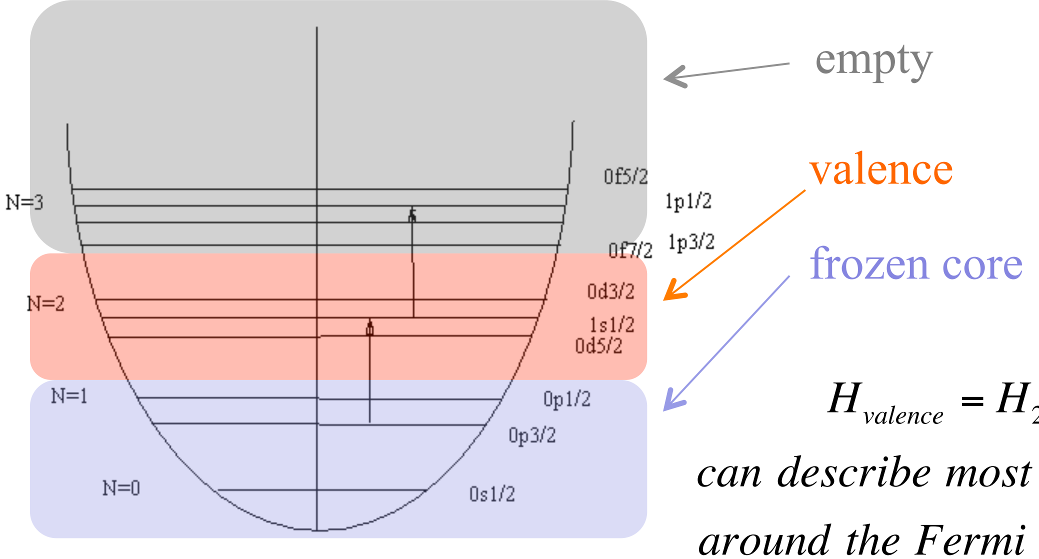
Shell Model GT Quenching



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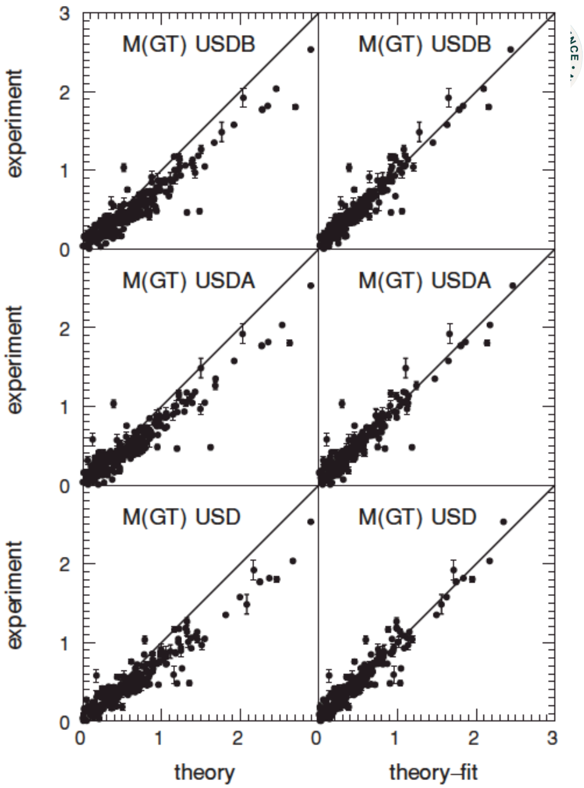
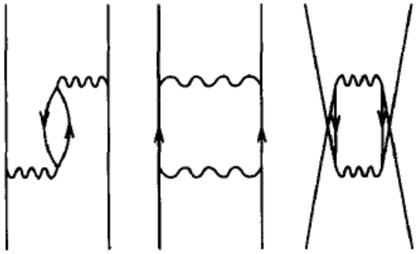
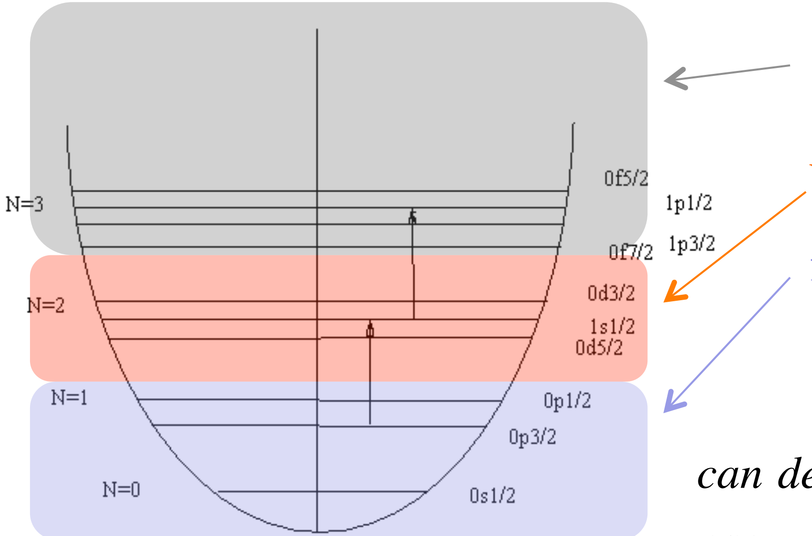


$$\sigma\tau \xrightarrow{quenched} 0.77\sigma\tau$$

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



Shell Model GT Quenching



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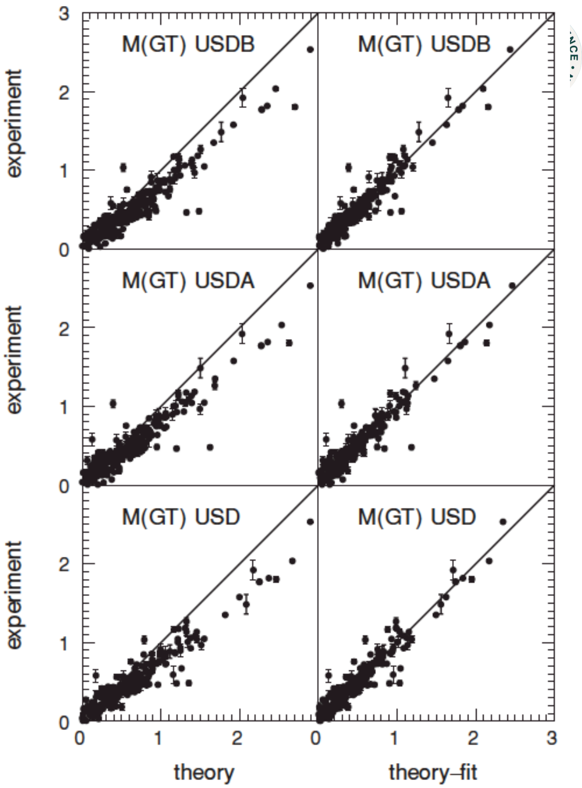
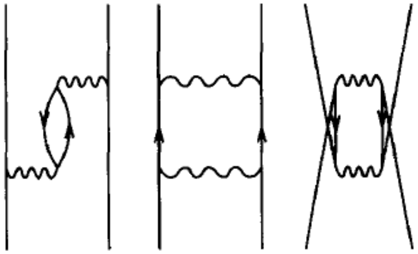


core polarization: Phys.Rep. **261**, 125 (1995)



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

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

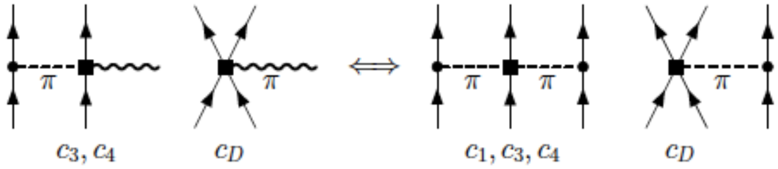


FIG. 1: Chiral 2b currents and 3N force contributions.

J. Menendez, D. Gazit and A. Schwenk, arXiV:1103.3622, PRL

Closure Approximation and Beyond in Shell Model

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

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

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

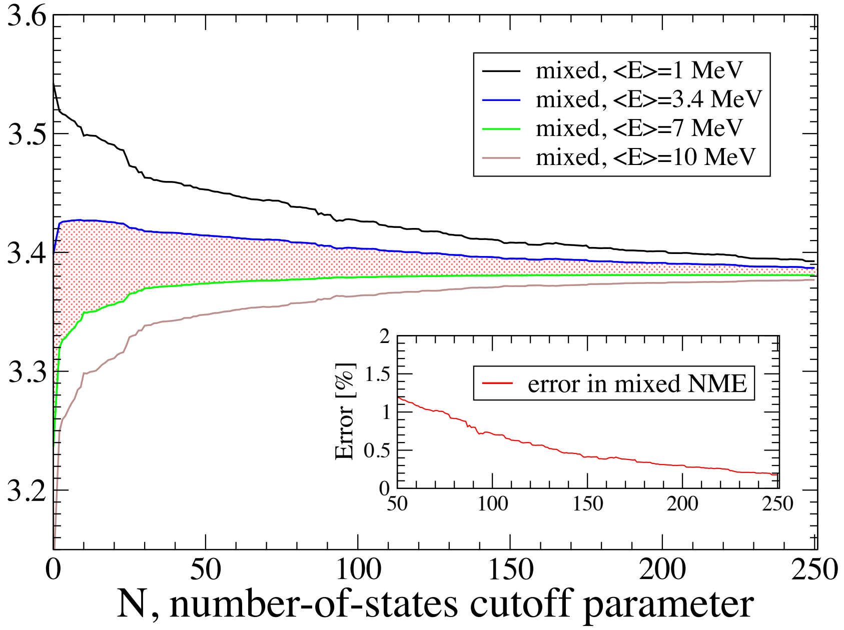
^{82}Se : 10M states

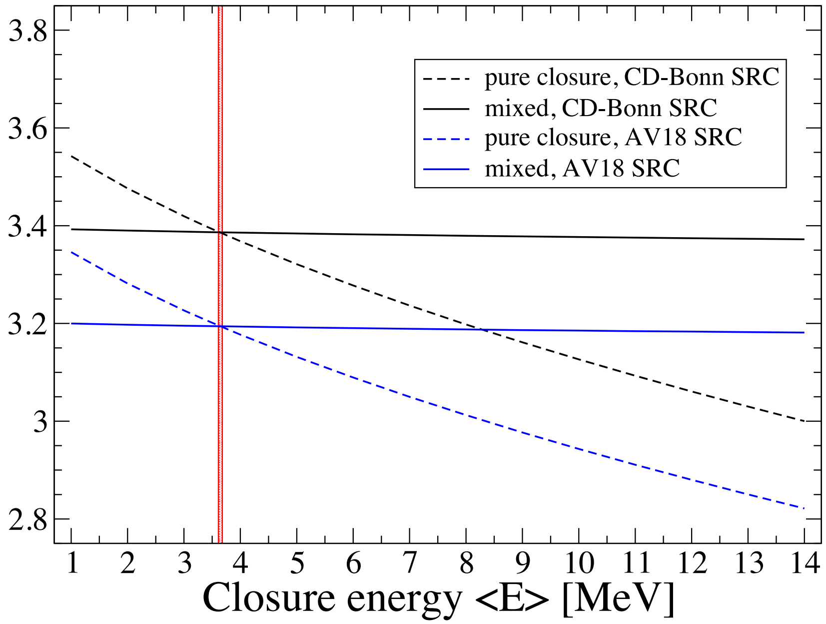
^{130}Te : 22M states

^{76}Ge : 150M states

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

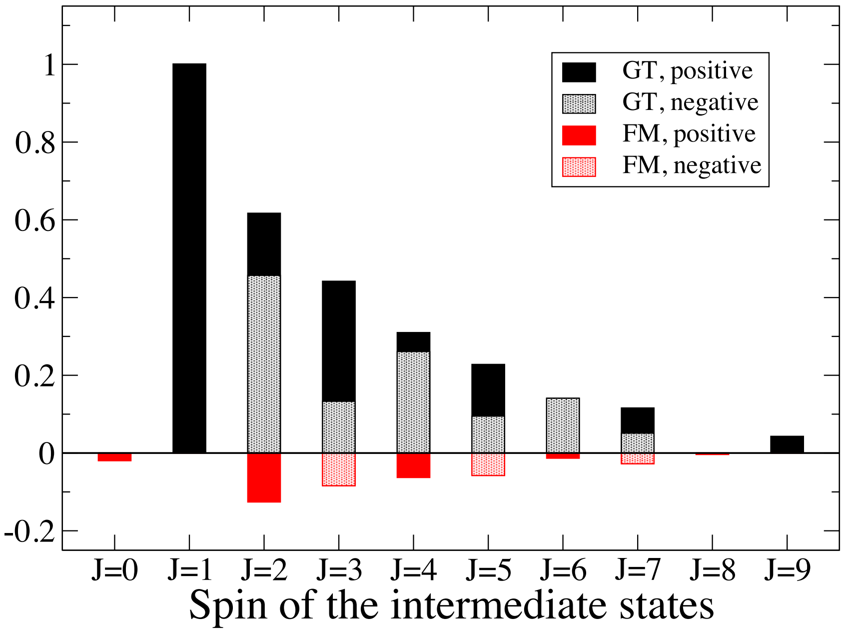
$$\hat{S} = \begin{cases} \sigma_1\tau_1\,\sigma_2\tau_2 & Gamow-Teller\ (GT) \\ \tau_1\tau_2 & Fermi\ (F) \\ \left[3(\vec{\sigma}_1\cdot\hat{n})(\vec{\sigma}_2\cdot\hat{n}) - (\vec{\sigma}_1\cdot\vec{\sigma}_2)\right]\tau_1\tau_2 & Tensor\ (T) \end{cases}$$

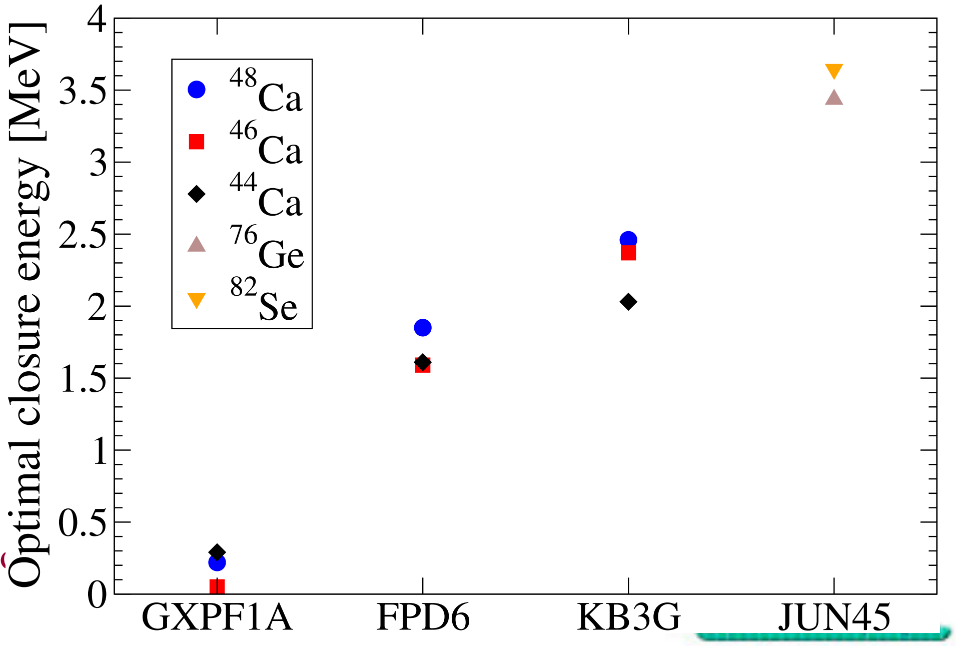




^{82}Se: PRC 89, 054304 (2014)

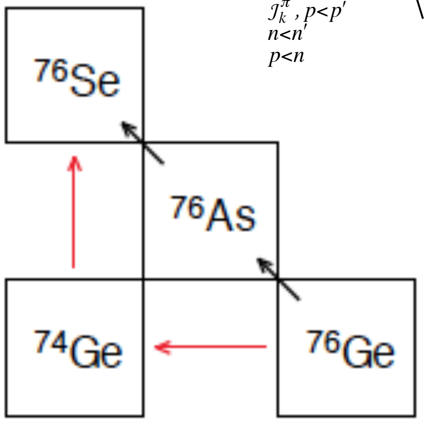
$$M_{mixed}(N) = M_{no-closure}(N) + \left[M_{closure}(N=\infty) - M_{closure}(N)\right]$$

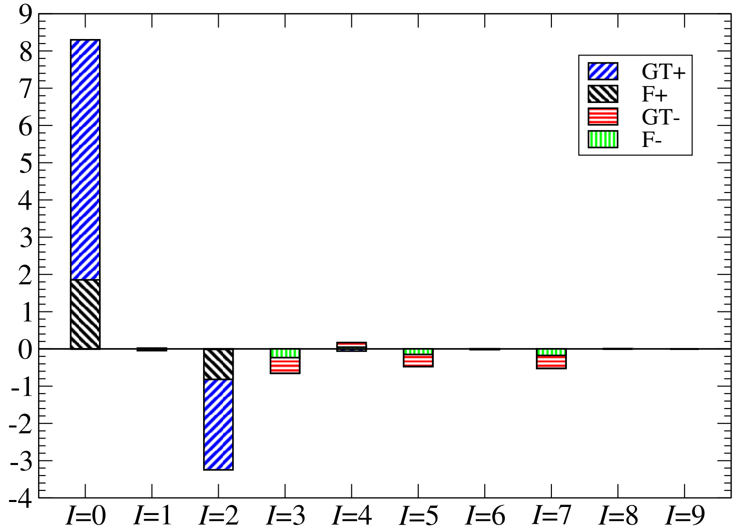




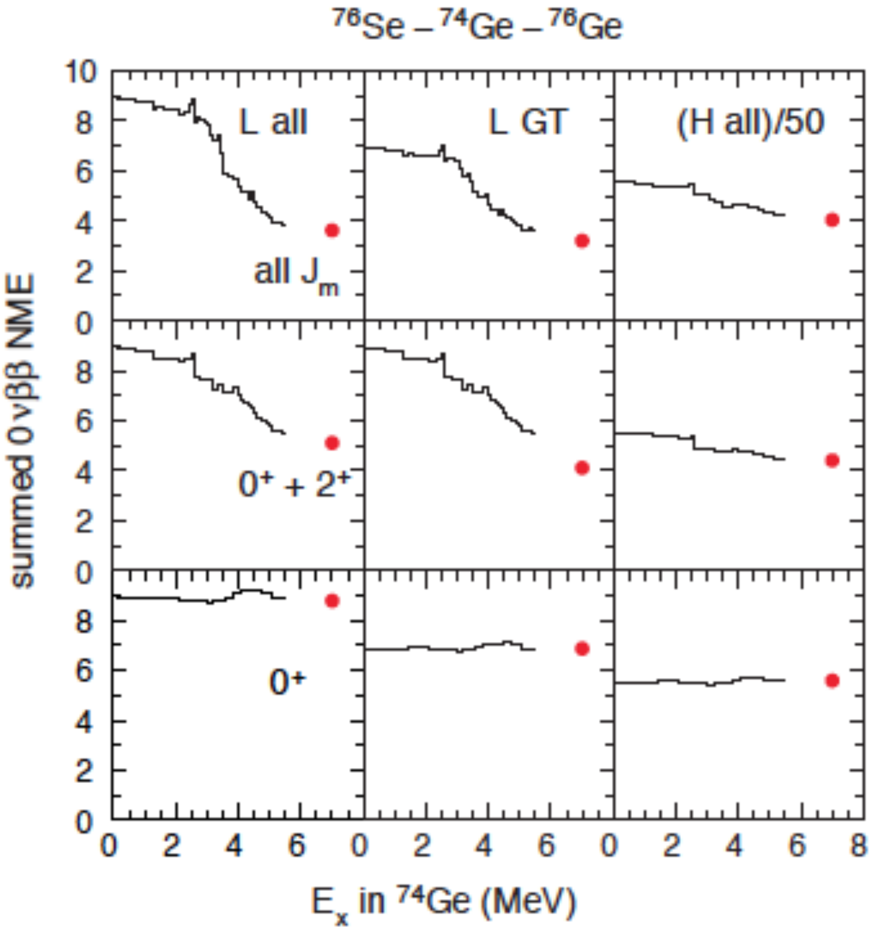
New Approach for NME: Novel Tests of Nuclear Structure

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





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



Brown, Horoi, Senkov

PRL **113**, 262501 (2014)

Two-nucleon transfer

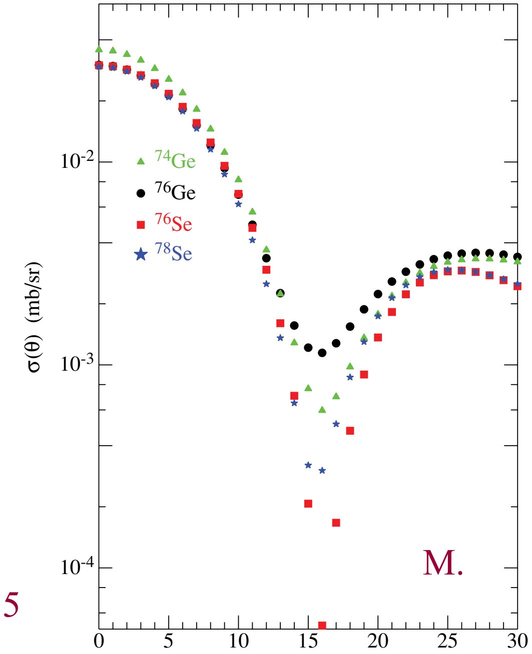
PHYSICAL REVIEW C **75**, 051301(R) (2007)

Pair correlations in nuclei involved in neutrinoless double β decay: ^{76}Ge and ^{76}Se

S. J. Freeman,[1] J. P. Schiffer,[2,*] A. C. C. Villari,[3] J. A. Clark,[4] C. Deibel,[4] S. Gros,[2] A. Heinz,[4] D. Hirata,[3,5] C. L. Jiang,[2]
B. P. Kay,[1] A. Parikh,[4] P. D. Parker,[4] J. Qian,[4] K. E. Rehm,[2] X. D. Tang,[2] V. Werner,[4] and C. Wrede[4]

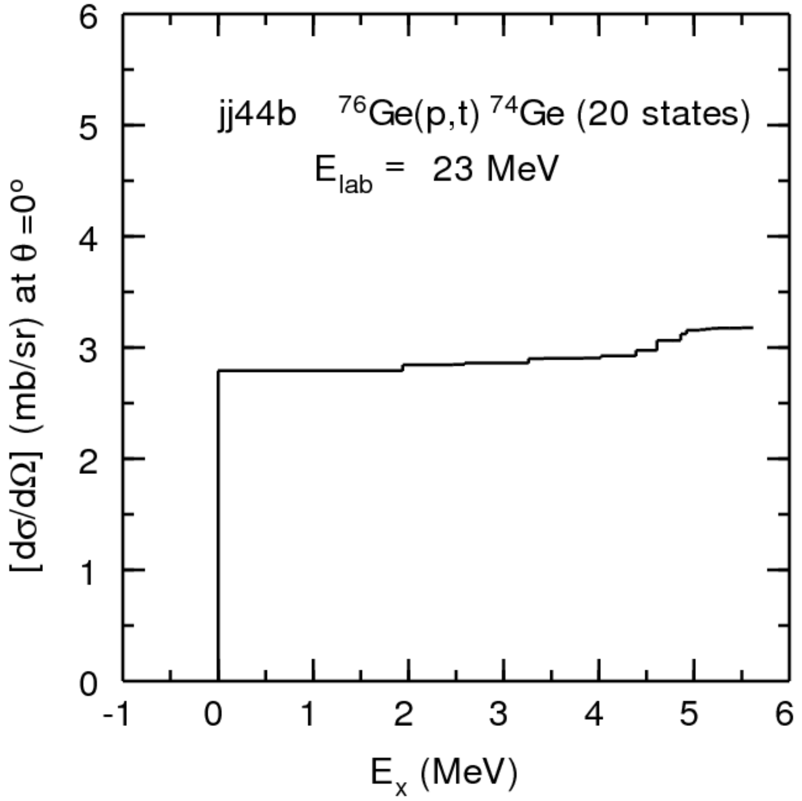
TABLE II. 3° laboratory cross sections and ratios to DWBA. Cross sections are for the ground-state to ground-state transitions.

Target	σ_{exp}(lab) (mb/sr)	σ_{DWBA} (mb/sr)	$\sigma_{\text{exp}}/\sigma_{\text{DWBA}}$
^{74}Ge	6.4	0.0438	147
^{76}Ge	6.7	0.0499	135
^{76}Se	6.0	0.0437	137
^{78}Se	7.1	0.0431	164



M.

Prepared by Alex Brown



What Experimental Searches Do Exist?

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

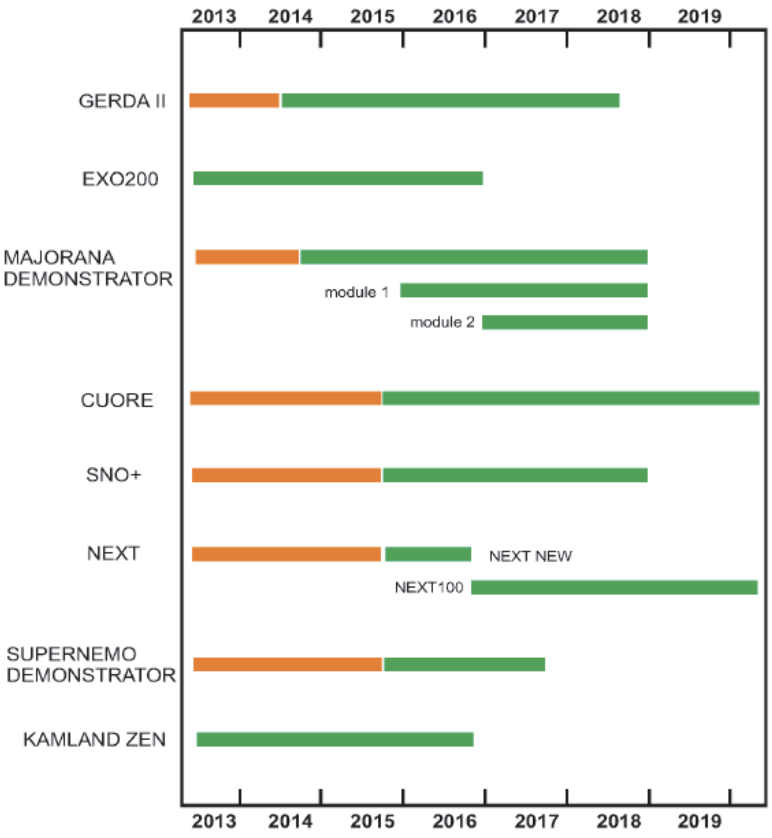
Current Project	Isotope	Isotope Mass (kg fiducial)	Currently Achieved Lower Limit (10^{26} yr)
CUORE	^{130}Te	206	>0.028
MAJORANA	^{76}Ge	24.7	
GERDA	^{76}Ge	18-20	>0.21
EXO200	^{136}Xe	79	>0.11
NEXT-100	^{136}Xe	61	
SuperNEMO	^{82}Se+	7	
KamLAND-Zen	^{136}Xe	434	
SNO+	^{130}Te	160	
LUCIFER	^{82}Se	8.9	

Goals (DNP14 DBD workshop):

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

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

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



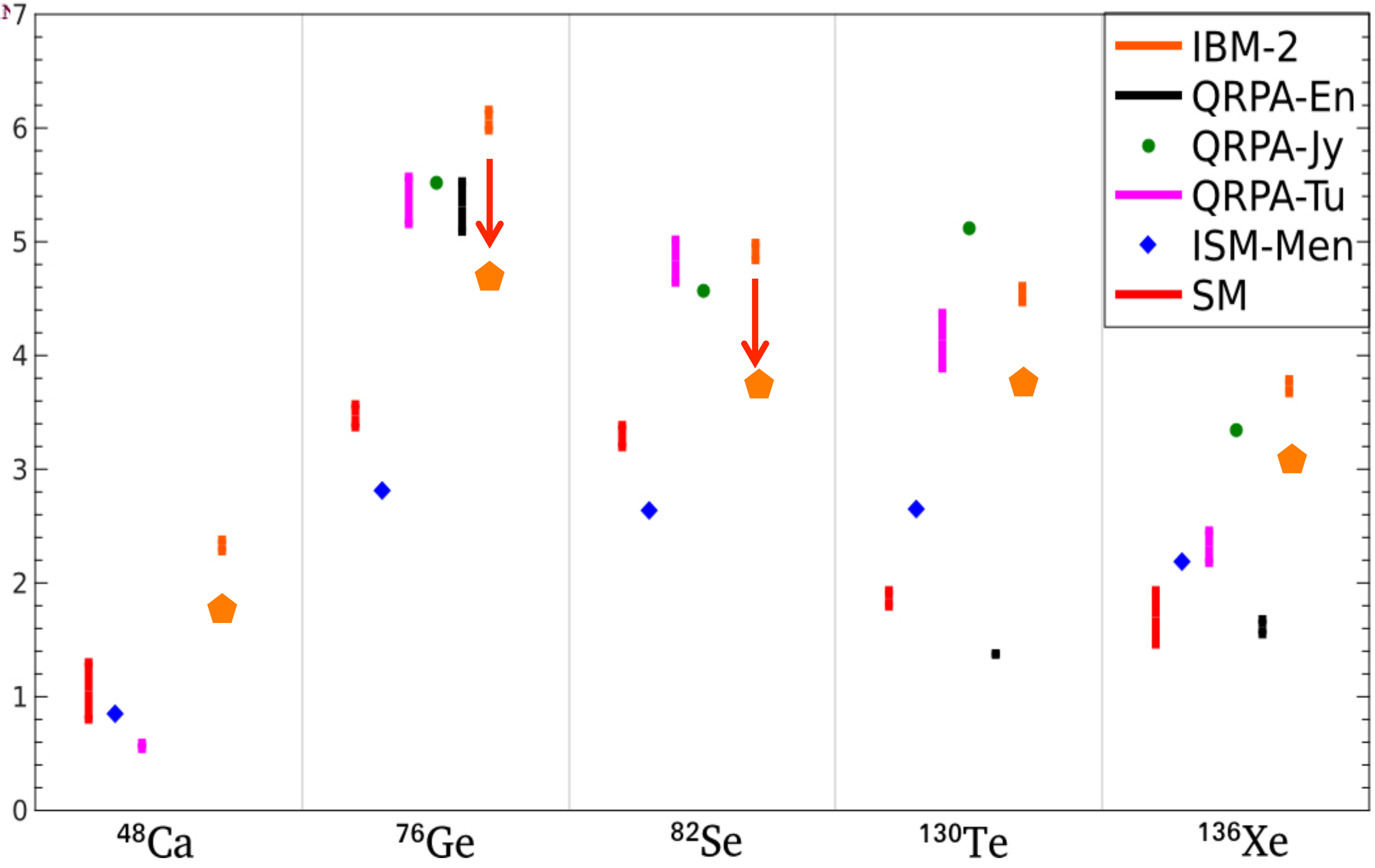
🟧 Construction

🟩 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!

NME for the light-neutrino exchange mechanism



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

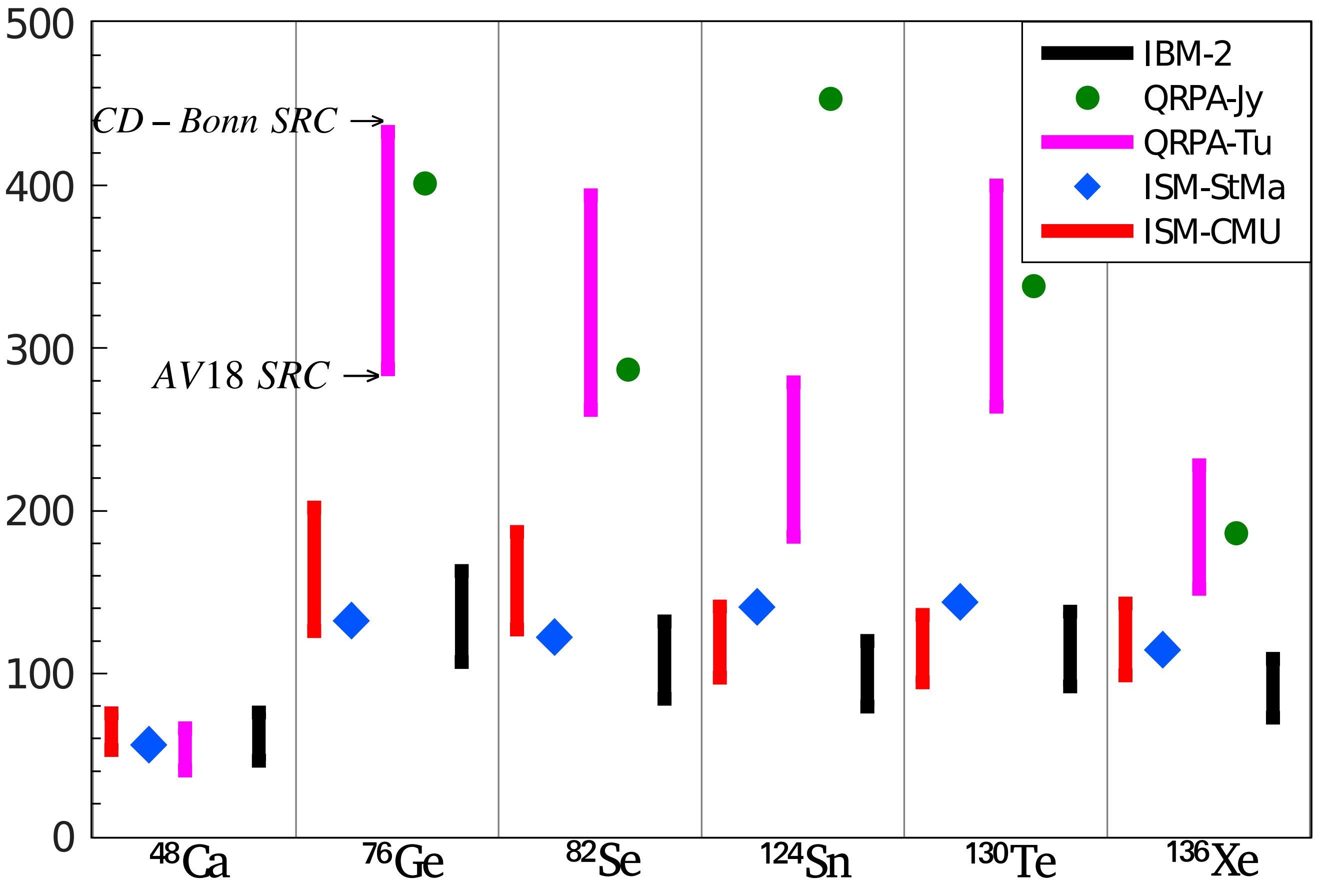
QRPA-En M. T. Mustonen and J. Engel, Phys. Rev. C **87**, 064302 (2013).

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

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

ISM-Men J. Menéndez, A. Poves, E. Caurier, F. Nowacki, NPA **818** 139–151 (2009).
SM M. Horoi et. al. PRC **88**, 064312 (2013), PRC **89**, 045502 (2014), PRC **89**, 054304 (2014), PRC **90**, 051301(R) (2014), PRC **91**, 024309 (2015), PRL **110**, 222502 (2013), PRL **113**, 262501(2014).

Heavy neutrino-exchange NME



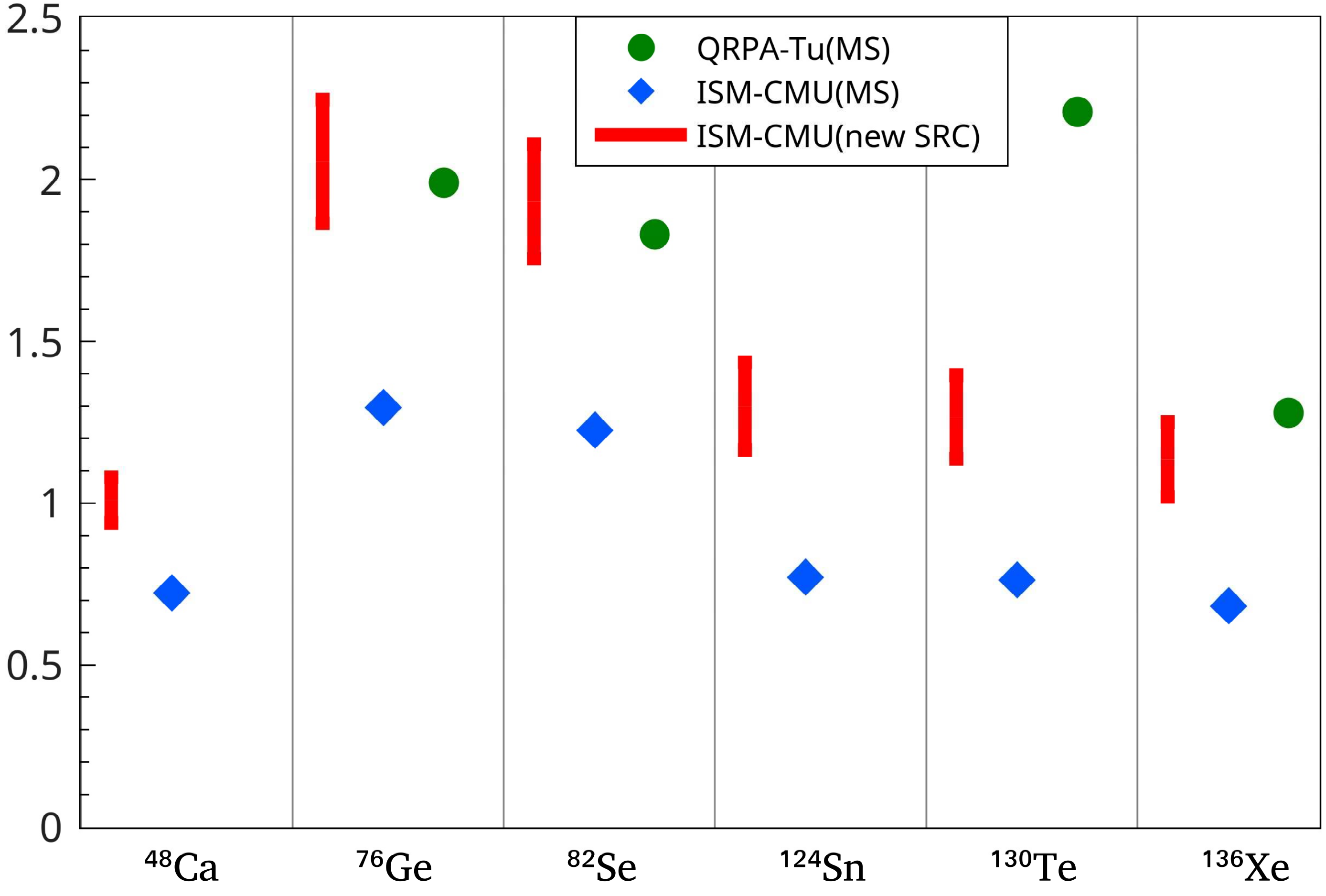
IBA-2 J. Barea, J. Kotila, and F. Iachello, Phys. Rev. C **87**, 014315 (2013).

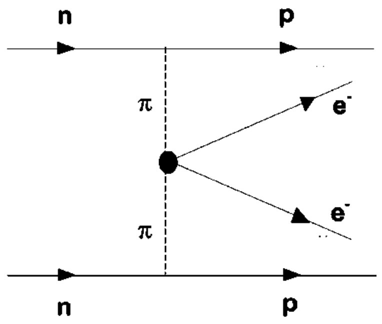
QRPA-Tu A. Faessler, M. Gonzalez, S. Kovalenko, and F. Simkovic, arXiv:**1408.6077.**

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).

2π-exchange NME





QRPA-Tu A. Faessler, S. Kovalenko, and F. Simkovic, PRD 58, 115004 (1998). MS: Miller-Spencer SRC.

ISM M. Horoi et al, to be published. New SRC: AV18 (low) & CD-Bonn (high).

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

M(0v)	SDPFU	SDPFMUP
$0\ \hbar\omega$	0.941	0.623
$0{+}2\,\hbar\omega$	1.182 (26%)	1.004 (61%)

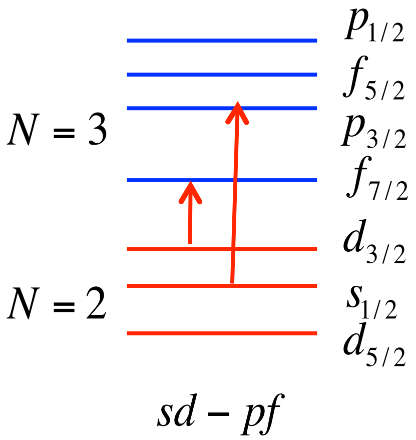
	M(0v)
$0\ \hbar\omega$ / GXPF1A	0.733
$0\ \hbar\omega+2^{nd}$ ord./GXPF1A	1.301 (77%)

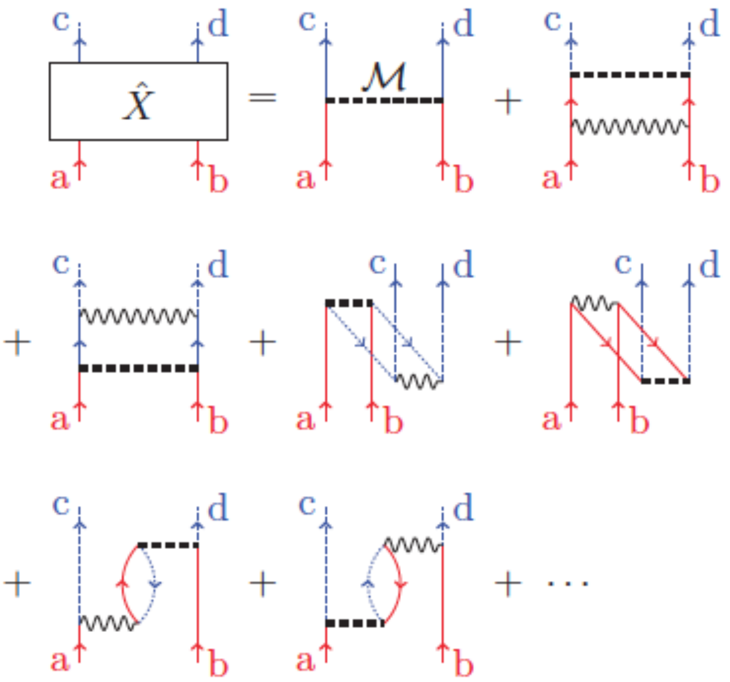
SDPFU: PRC 79, 014310 (2009)

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

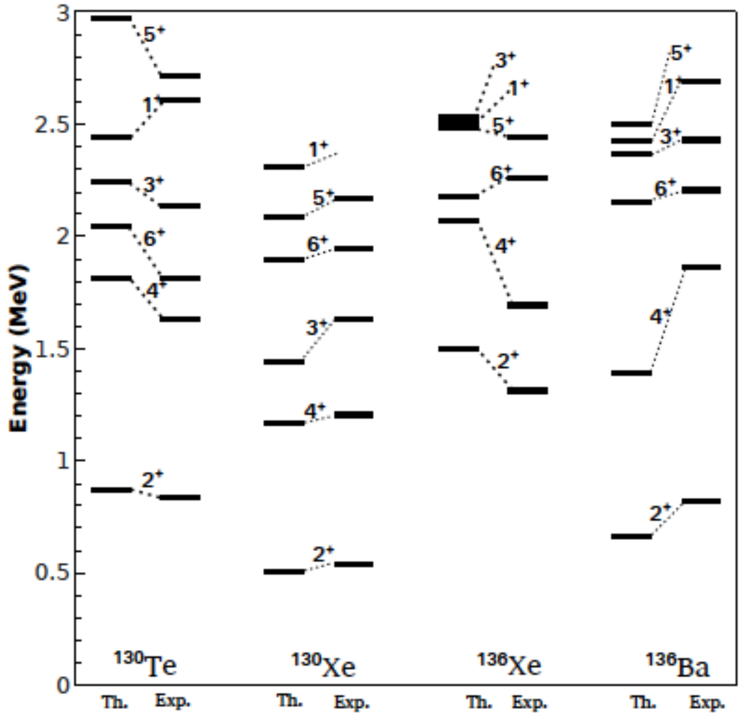
arXiv:1308.3815, PRC 89, 045502 (2014)

PRC 87, 064315 (2013)





Experimental info needed



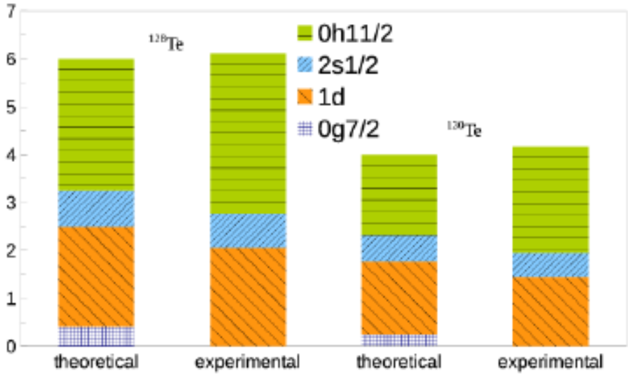
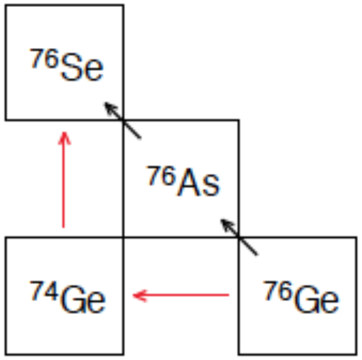


FIG. 2. (Color on-line) Theoretical and experimental [58] neutron shell vacancies for ^{128}Te and ^{130}Te.



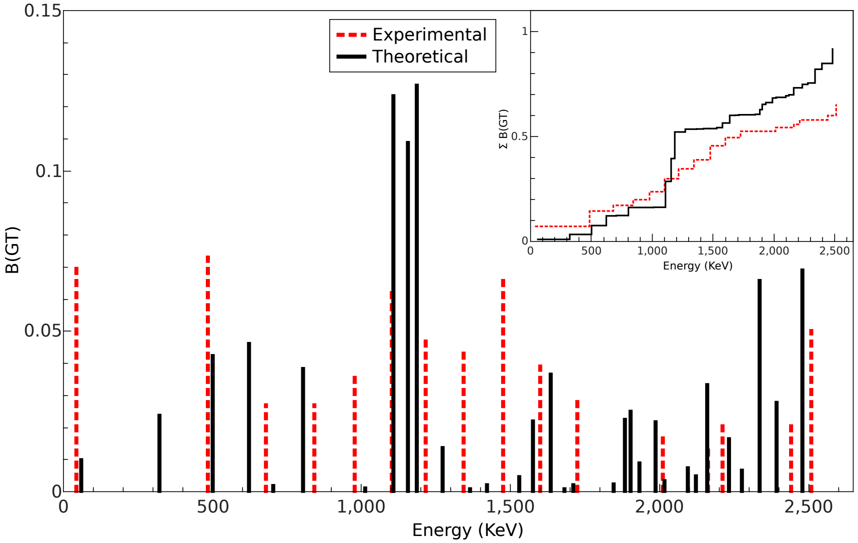
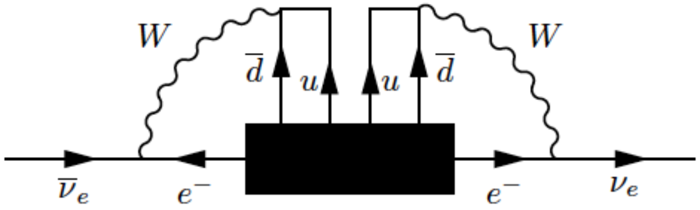


TABLE I. The calculated $B(E2)\uparrow$ values on the first line compared to the adopted ones on the second line.

	^{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

Take-Away Points

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



Black box theorem (all flavors + oscillations)

(i) Neutrinos are Majorana fermions.

0νββ observed ⇔

at some level

(ii) Lepton number conservation is violated by 2 units

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

Regardless of the dominant 0νββ mechanism!

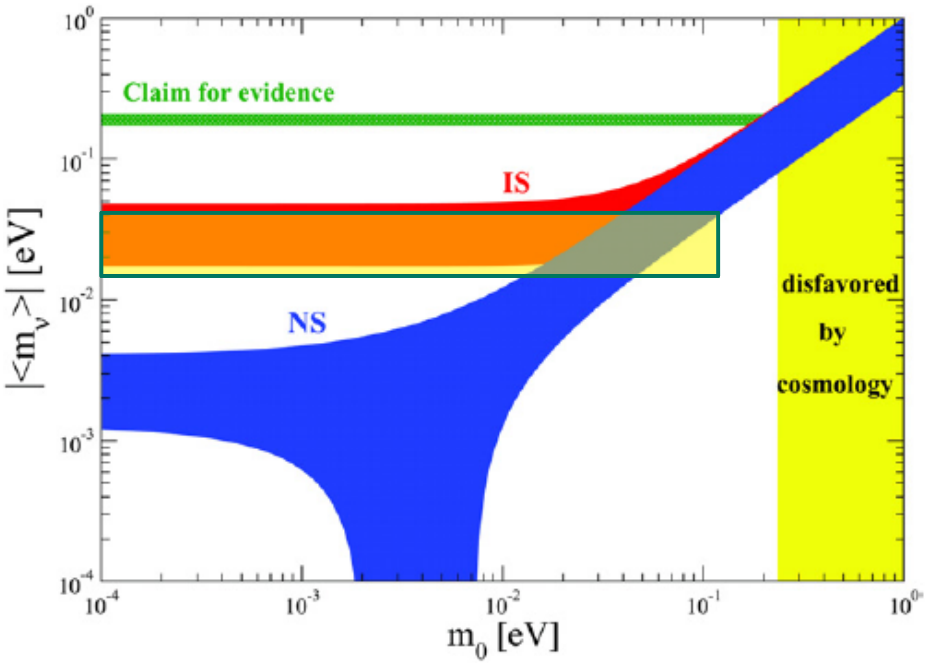
Take-Away Points

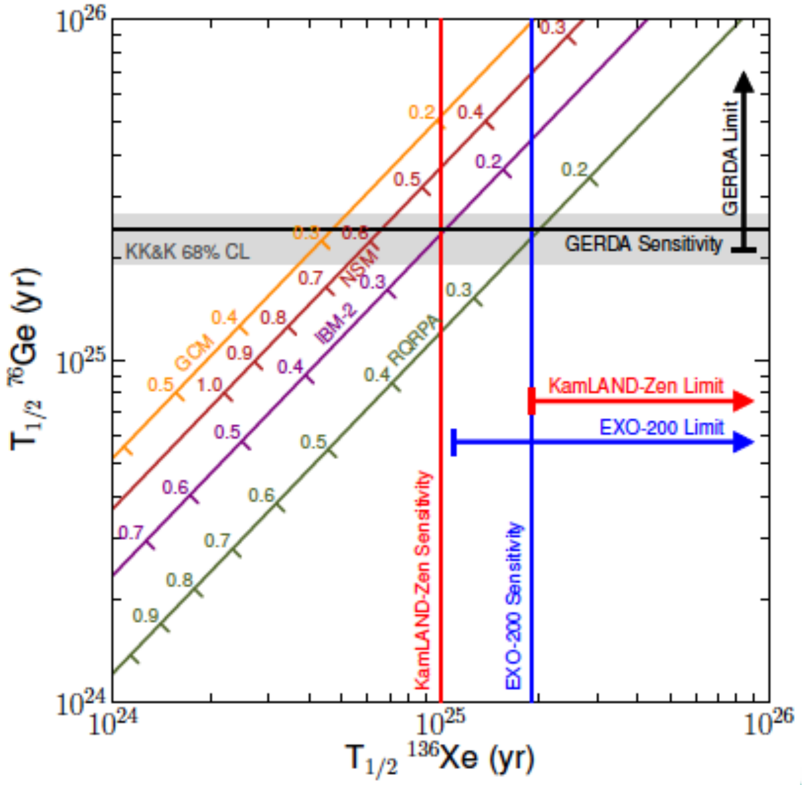
The analysis and guidance of the experimental efforts need **accurate Nuclear Matrix Elements.**

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

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

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





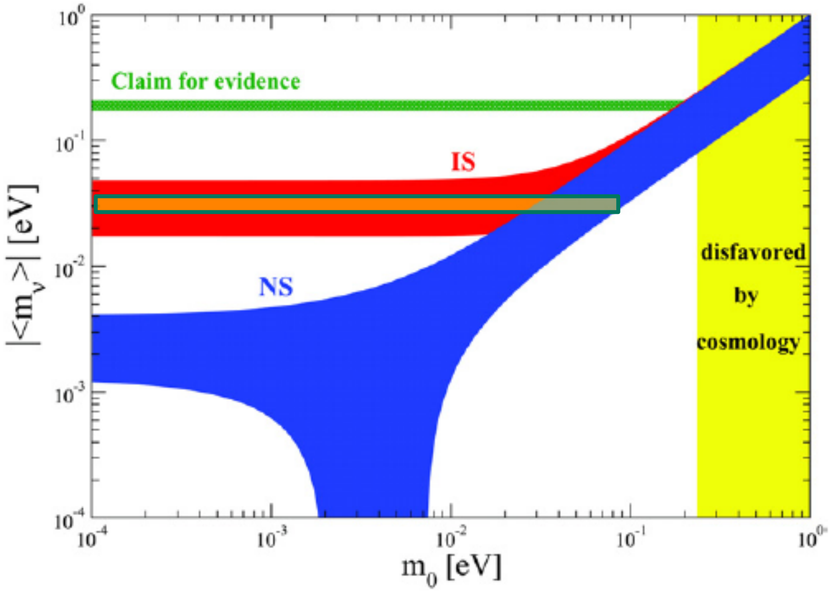
Take-Away Points

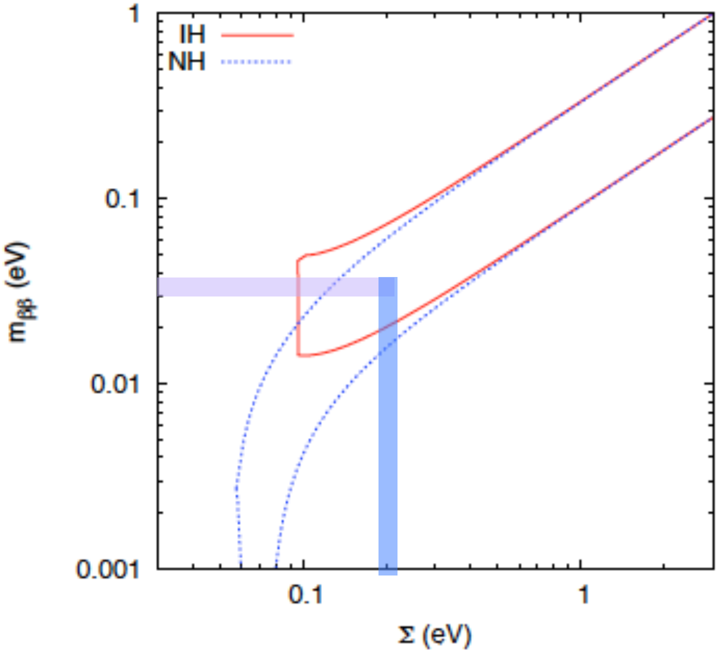
Extracting information about Majorana CP-violation phases may require the mass hierarchy from LBNE(DUNE), cosmology, etc, but also **accurate Nuclear Matrix Elements**.

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

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

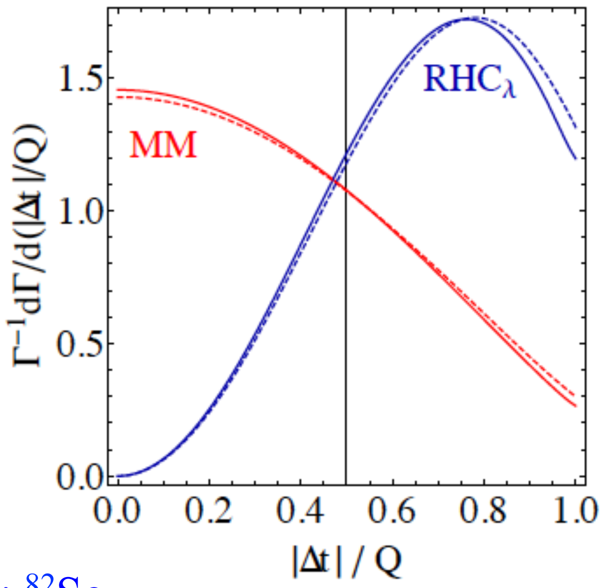
$$\Sigma = m_1 + m_2 + m_3 \quad \textit{from cosmology}$$





CENTRAL MICHIGAN UNIVERSITY

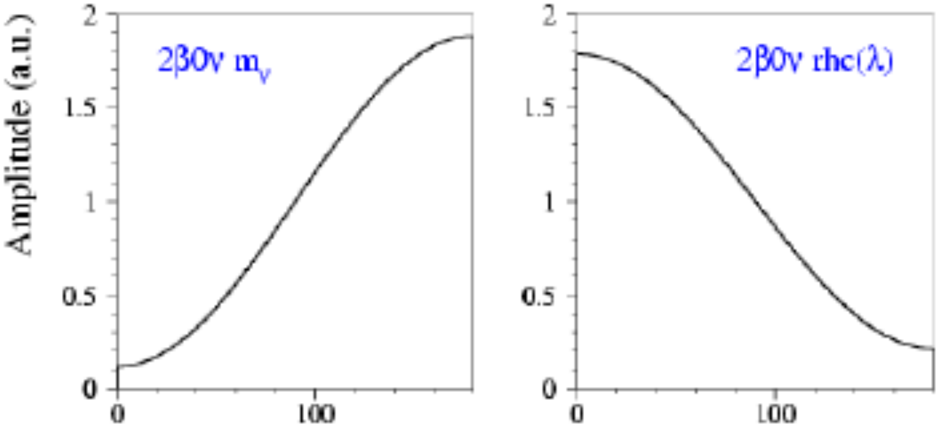
Take-Away Points



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



θ - angle between e_1 and e_2

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

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

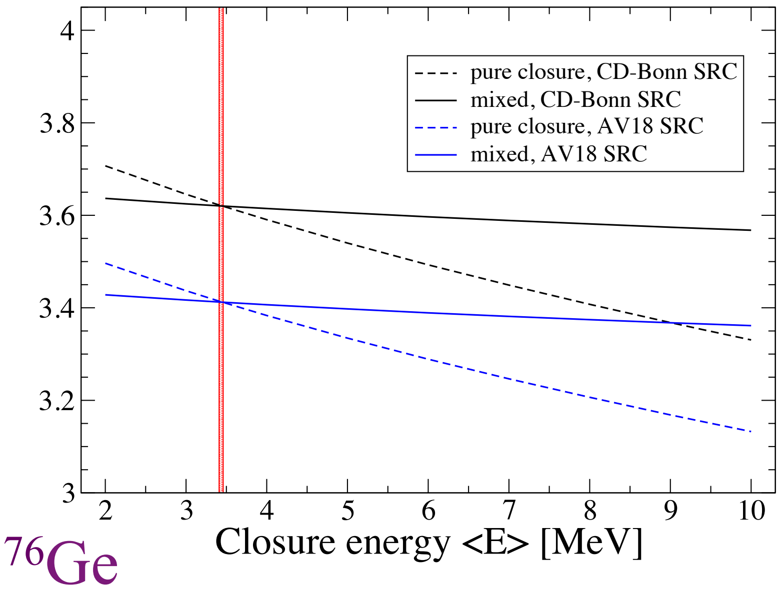
SciDAC Scientific Discovery through Advanced Computing

Take-Away Points

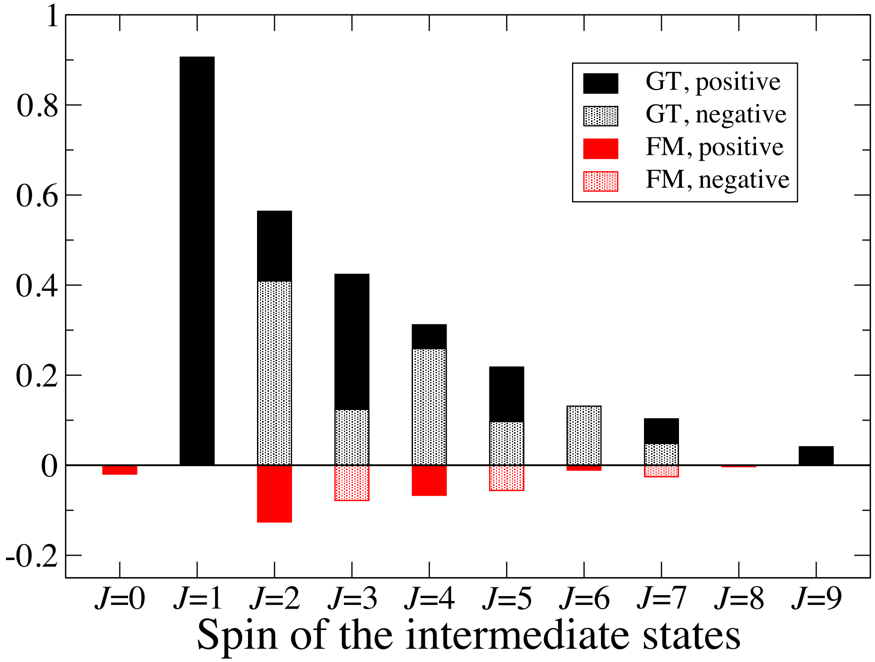
Accurate shell model NME for **different decay mechanisms** were recently calculated.

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

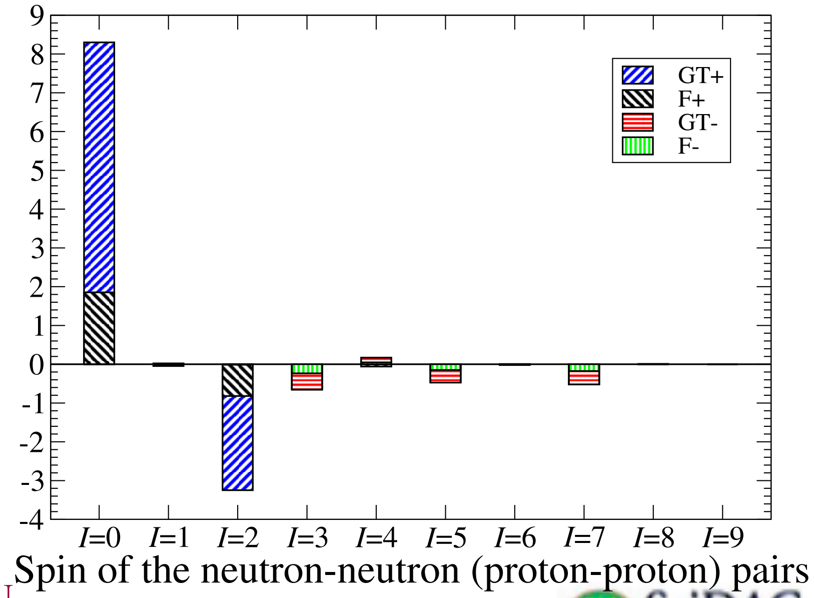
Decomposition of the matrix elements can be used for **selective quenching** of classes of states, and for testing nuclear structure.



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



roi CMU



Collaborators:

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