Double-beta decay: to quench or not to quench

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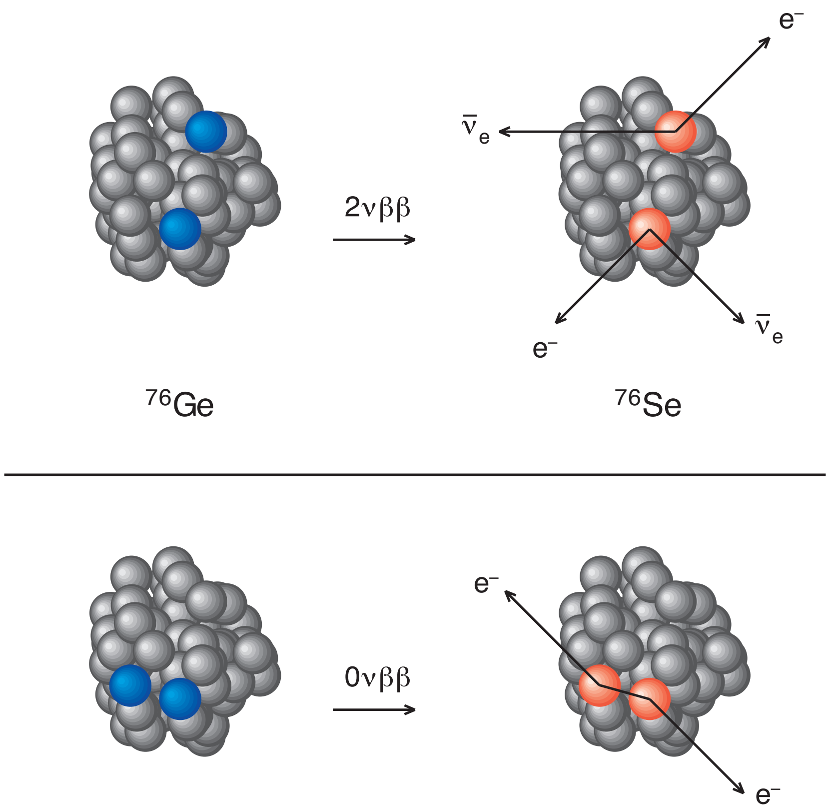
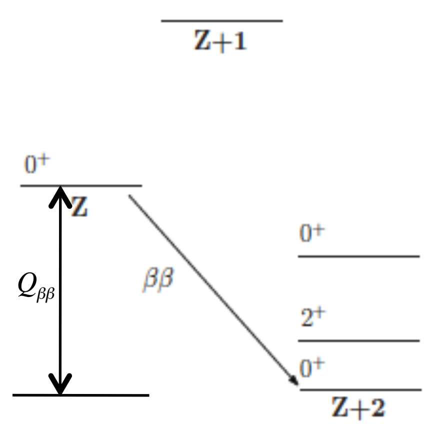
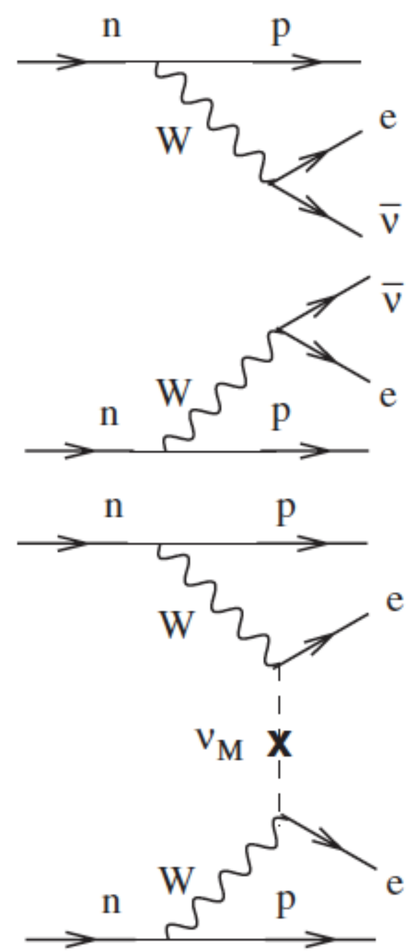
Classical Double Beta Decay Problem







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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

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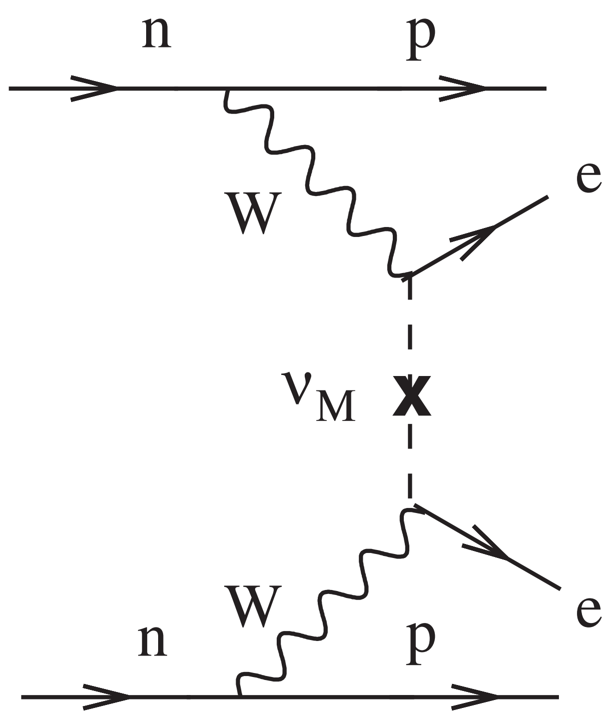
Arthur B. McDonald

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"*

ciDAC

Neutrinoless Double Beta Decay

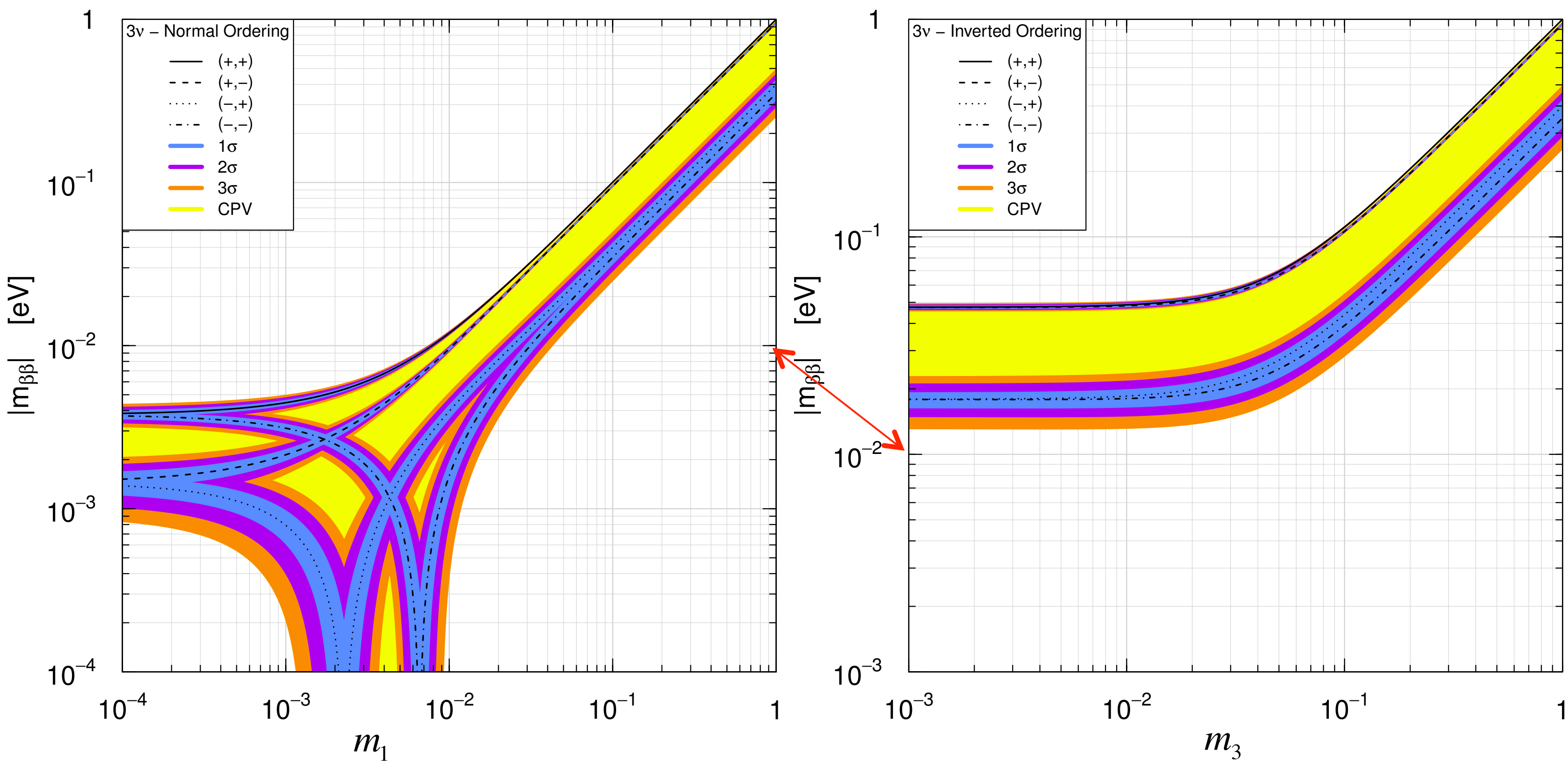


$$T_{1/2}^{-1}(0\nu) = G^{0\nu}(Q_{\beta\beta})\left[M^{0\nu}(0^+)\right]^2\left(\frac{< m_{\beta\beta} >}{m_e}\right)^2$$

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

Neutrino ββ effective mass

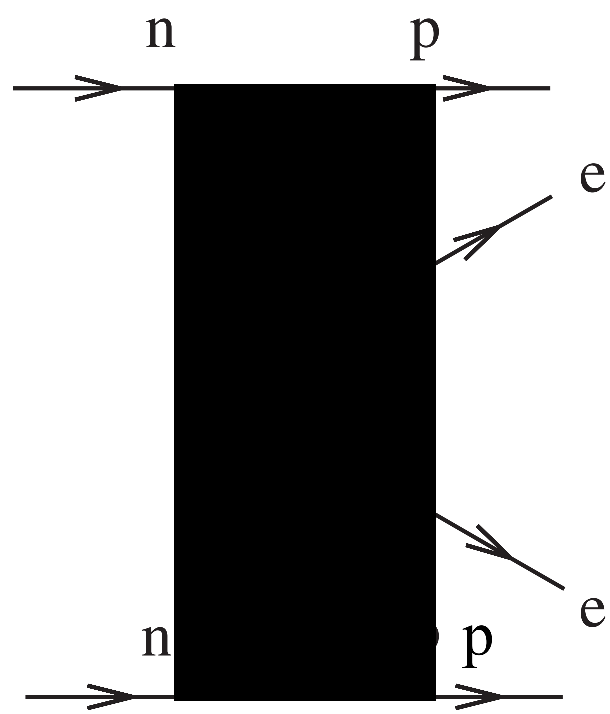
arxiv:1507.08204



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

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

Neutrinoless Double Beta Decay Black Box



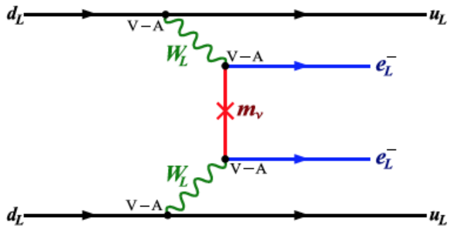
$$|\eta_{\nu L}| = \frac{\langle m_{\beta\beta} \rangle}{m_e} \approx 10^{-6}$$

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

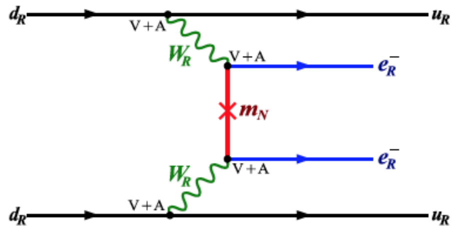
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|\sum_j M_j \eta_j\right|^2 = G^{0\nu}\left|M^{(0\nu)}\eta_{\nu L} + M^{(0N)}(\eta_{NL} + \eta_{NR}) + \tilde{X}_\lambda < \lambda > + \tilde{X}_\eta < \eta > + M^{(0\lambda')}\eta_{\lambda'} + M^{(0\tilde{q})}\eta_{\tilde{q}} + \cdots\right|^2$$

Low-energy LR contributions to $0\nu\beta\beta$ decay

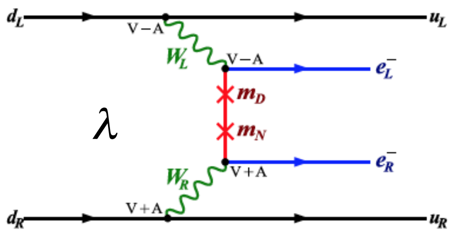
DAS *et al.* PHYSICAL REVIEW D **86**, 055006 (2012)



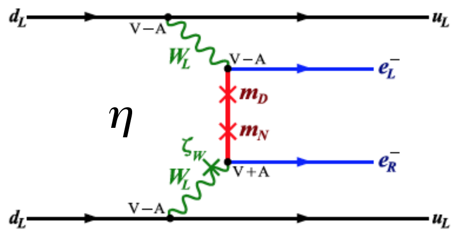
(a)



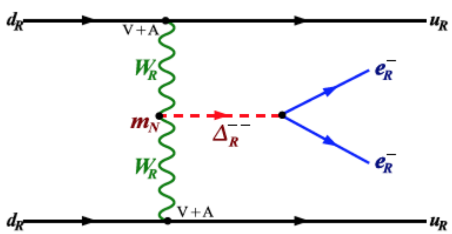
(b)



(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

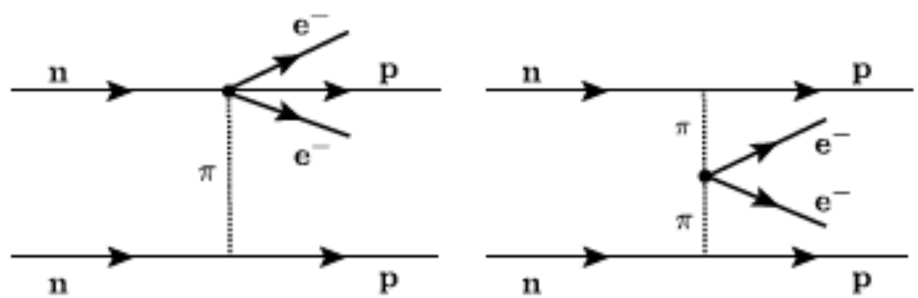
$$-\mathcal{L} \supset \frac{1}{2} h_{\alpha\beta}^{T}\left(\bar{\nu}_{\beta L} \ \ \bar{e}_{\alpha L}\right)\begin{pmatrix} \Delta^{-} & -\Delta^{0} \\ \Delta^{--} & \Delta^{-} \end{pmatrix}\begin{pmatrix} e_R^{c} \\ -\nu_R^{c} \end{pmatrix} + hc$$

No neutrino exchange

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



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

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

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

Two Non-Interfering Mechanisms

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

	Ge/Se		Ge/Te		Ge/Xe		Se/Te		Se/Xe		Te/Xe	
	Ge	Se	Ge	Te	Ge	Xe	Se	Te	Se	Xe	Te	Xe
$G_{01}^{0\nu}\times 10^{14}$	0.237	1.018	0.237	1.425	0.237	1.462	1.018	1.425	1.018	1.462	1.425	1.462
$M^{0\nu}(1/2)$	3.57	3.39	3.57	1.93	3.57	1.76	3.39	1.93	3.39	1.76	1.93	1.76
$M^{0N}(1/2)$	202	187	202	136	202	143	187	136	187	143	136	143
$T^{\nu}_{1/2}(1)/T^{\nu}_{1/2}(2)$	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	

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

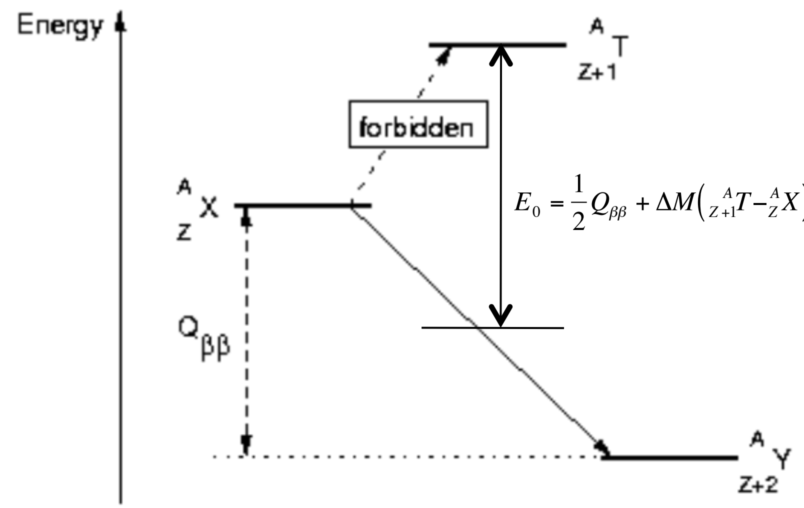
See also PRD 83,113003 (2011)

2ν Double Beta Decay (DBD) of ^{48}Ca

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

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

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



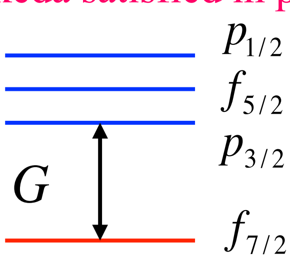
The choice of valence space is important!?

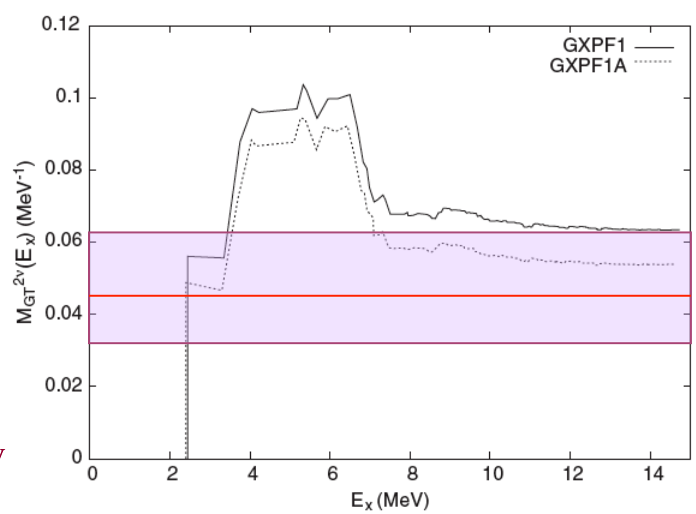
$$B(GT) = \frac{\left|\langle f \| \sigma \cdot \tau \| i \rangle\right|^2}{(2J_i + 1)}$$

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

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

Ikeda satisfied in pf !



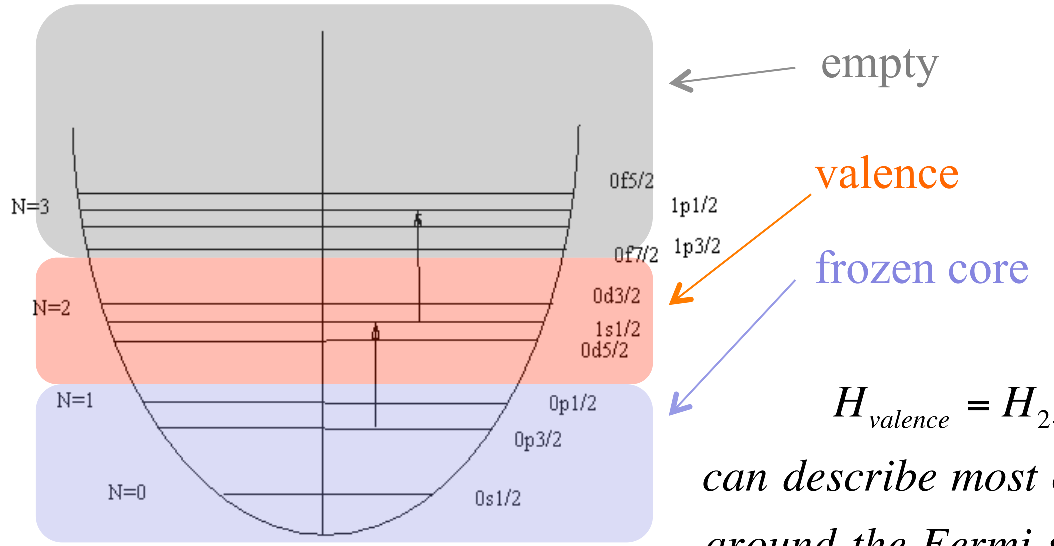


$$g_A \sigma \tau \xrightarrow{quenched} 0.74 g_A \sigma \tau$$

Horoi, Stoica, Brown,

PRC **75**, 034303 (2007)

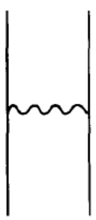
Shell Model GT Quenching



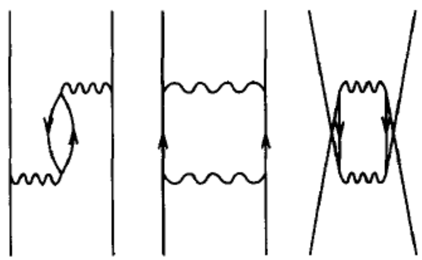
$$H_{valence}\Psi = E_n\Psi$$

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

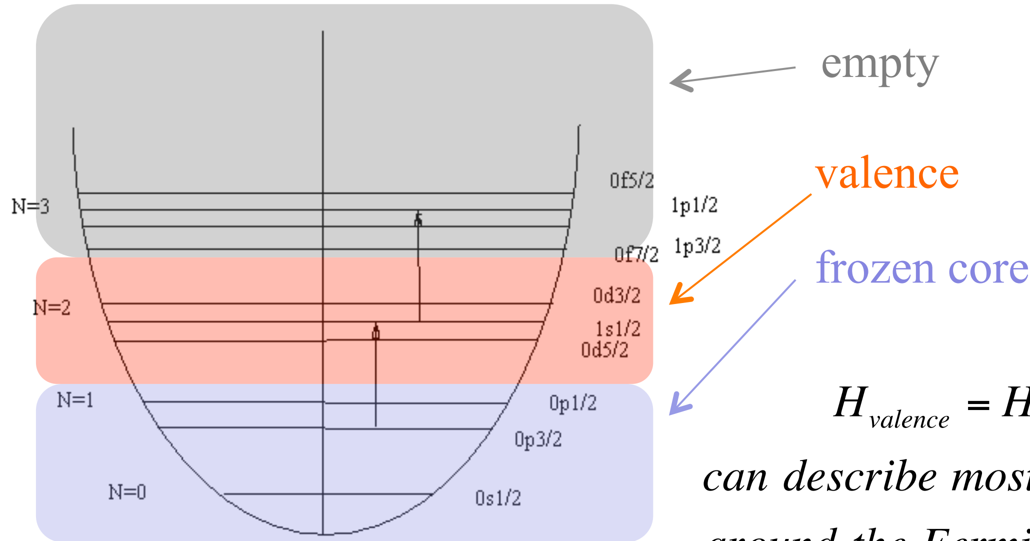
can describe most correlations around the Fermi surface!



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



Shell Model GT Quenching



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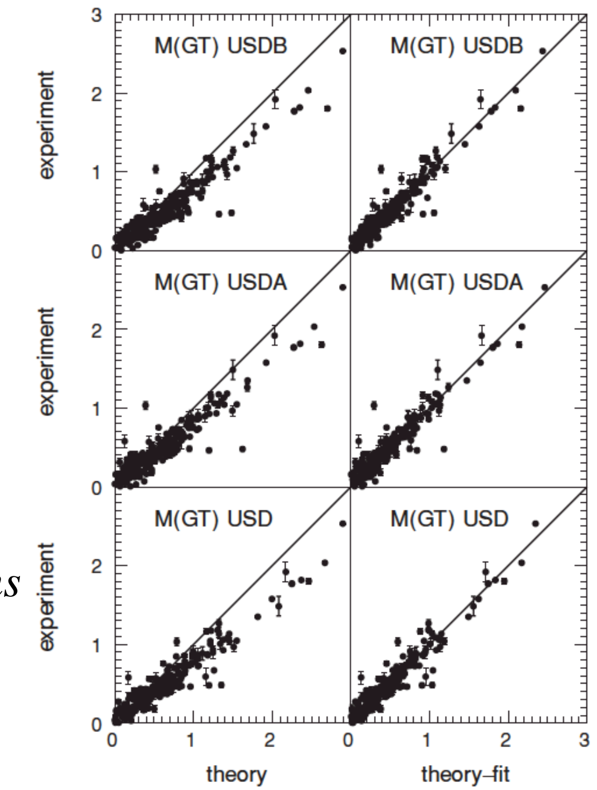
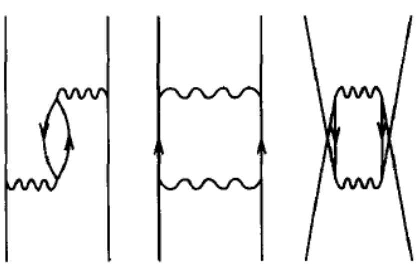


$$\sigma\tau \xrightarrow{quenched} 0.77\sigma\tau$$

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



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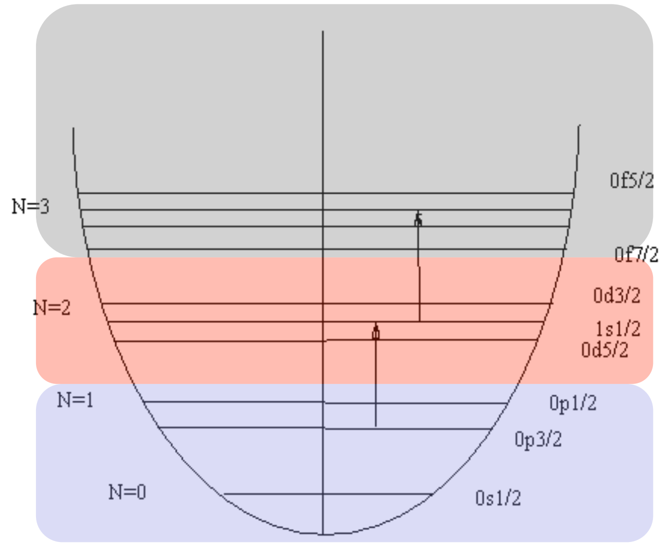
Shell Model GT Quenching



empty

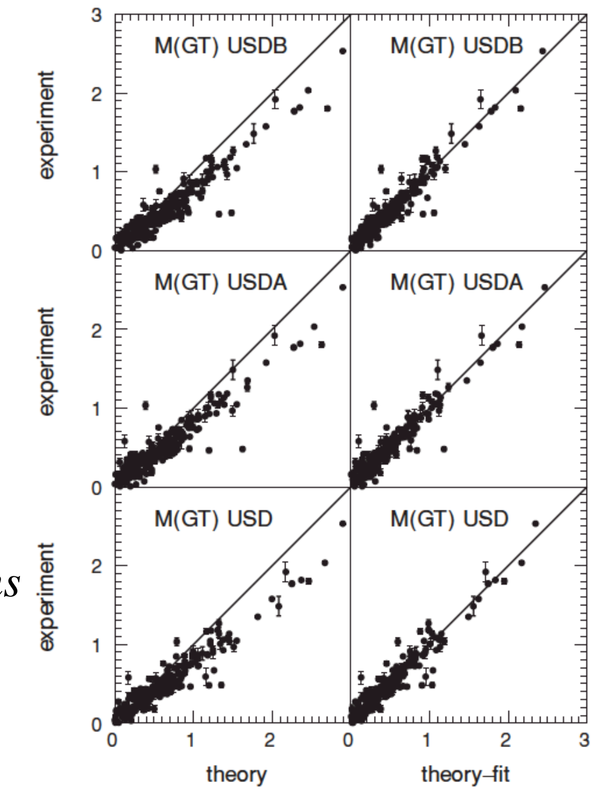
valence

frozen core

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

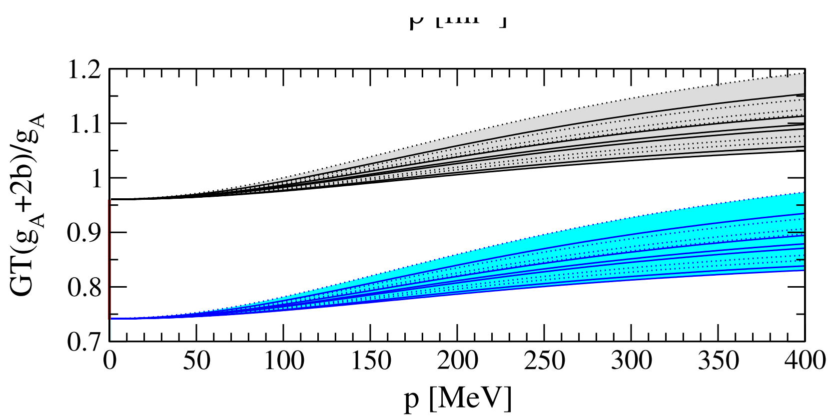
$$H_{valence} = H_{2-body}$$

can describe most correlations around the Fermi surface!



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

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



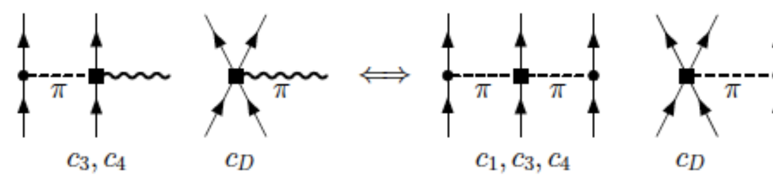


FIG. 1: Chiral 2b currents and 3N force contributions.

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

SciDAC Scientific Discovery through Advanced Computing

The g_A problem

PHYSICAL REVIEW C **87**, 014315 (2013)

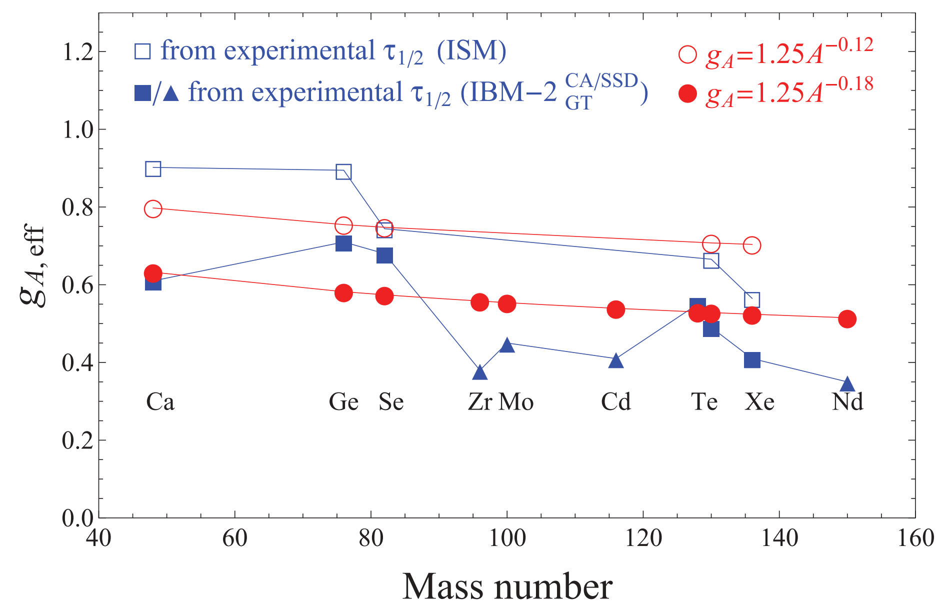


FIG. 13. (Color online) Value of $g_{A,\mathrm{eff}}$ extracted from experiment for IBM-2 and the ISM.

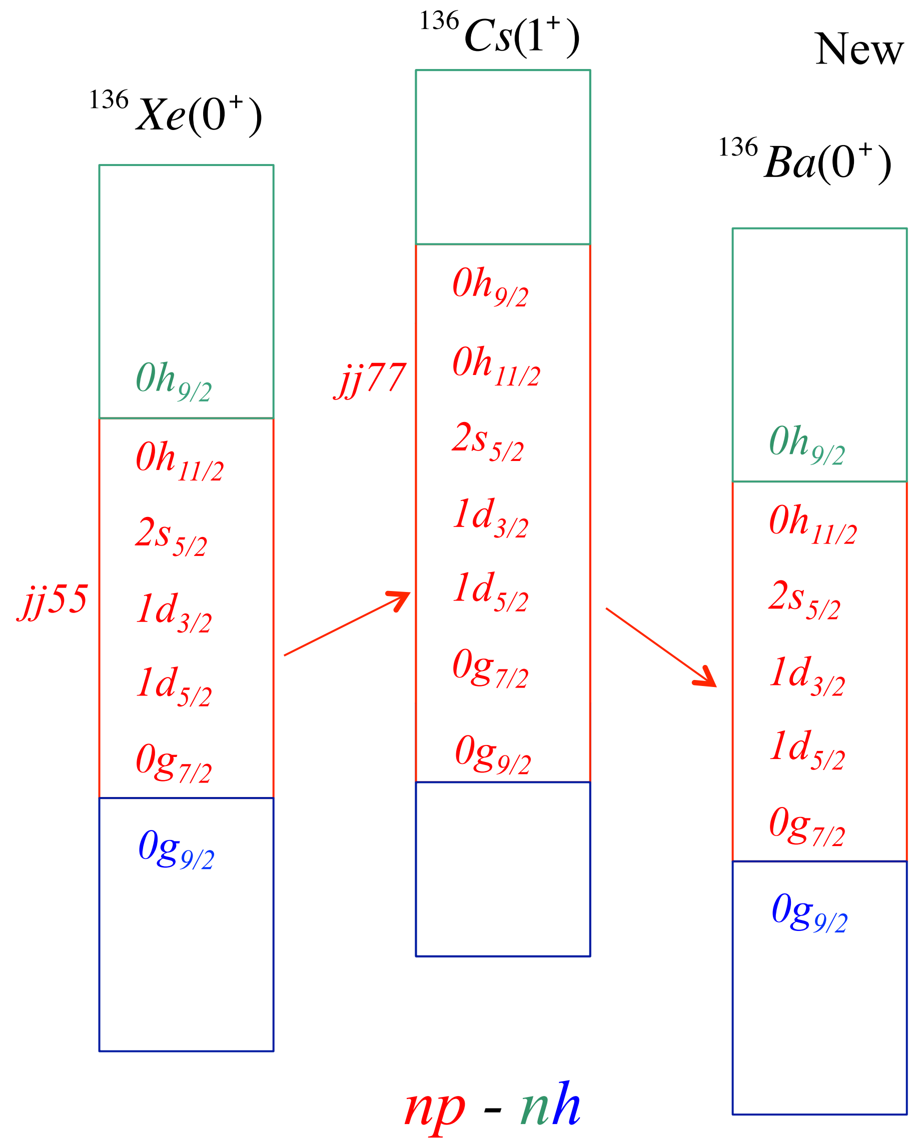
Phys. Lett. B 711, 62 (2012)

Table 2
The ISM predictions for the matrix element of several 2ν double beta decays (in MeV^{-1}). See text for the definitions of the valence spaces and interactions.

	$M^{2\nu}$(exp)	q	$M^{2\nu}$(th)	INT
^{48}Ca → ^{48}Ti	0.047 ± 0.003	0.74	0.047	kb3
^{48}Ca → ^{48}Ti	0.047 ± 0.003	0.74	0.048	kb3g
^{48}Ca → ^{48}Ti	0.047 ± 0.003	0.74	0.065	gxpf1
^{76}Ge → ^{76}Se	0.140 ± 0.005	0.60	0.116	gcn28:50
^{76}Ge → ^{76}Se	0.140 ± 0.005	0.60	0.120	jun45
^{82}Se → ^{82}Kr	0.098 ± 0.004	0.60	0.126	gcn28:50
^{82}Se → ^{82}Kr	0.098 ± 0.004	0.60	0.124	jun45
^{128}Te → ^{128}Xe	0.049 ± 0.006	0.57	0.059	gcn50:82
^{130}Te → ^{130}Xe	0.034 ± 0.003	0.57	0.043	gcn50:82
^{136}Xe → ^{136}Ba	0.019 ± 0.002	0.45	0.025	gcn50:82

$$G^{2\nu},\ G^{0\nu} \propto g_A^4$$

^{136}Xe 2νββ Results $M^{2\nu}_{exp} = 0.022\ MeV^{-1}$



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*

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

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

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

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

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

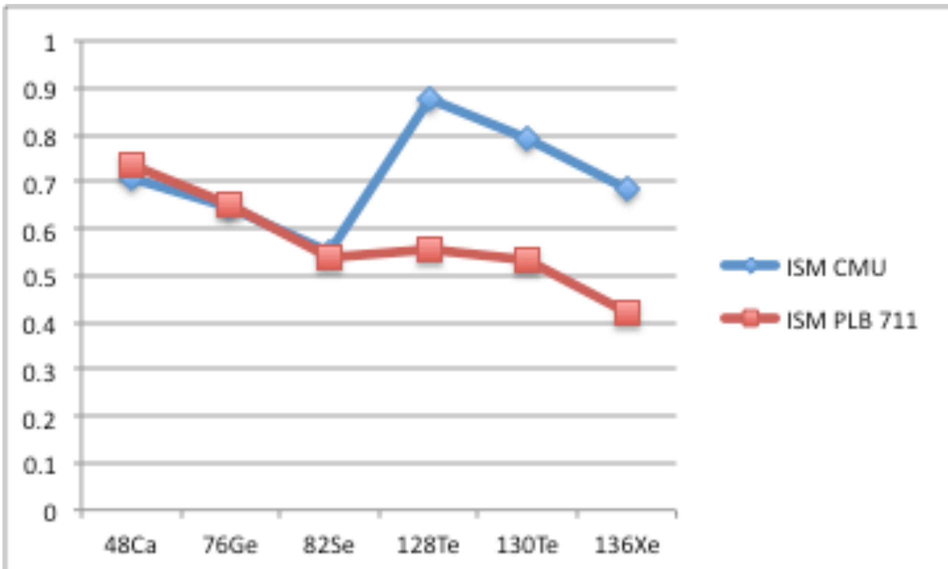
$$Ikeda: \quad 3(N-Z) = 84$$

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)

The g_A problem

q_{exp}



Phys. Lett. B 711, 62 (2012)

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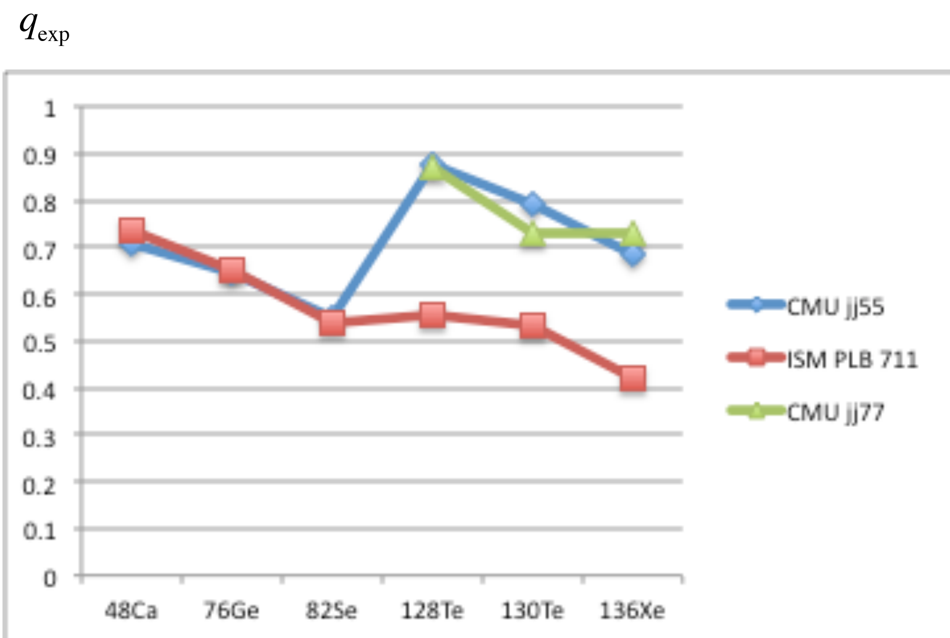
The g_A problem



Physics Letters B 711 (2012) 62–64

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Closure Approximation and Beyond in Shell Model

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

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

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

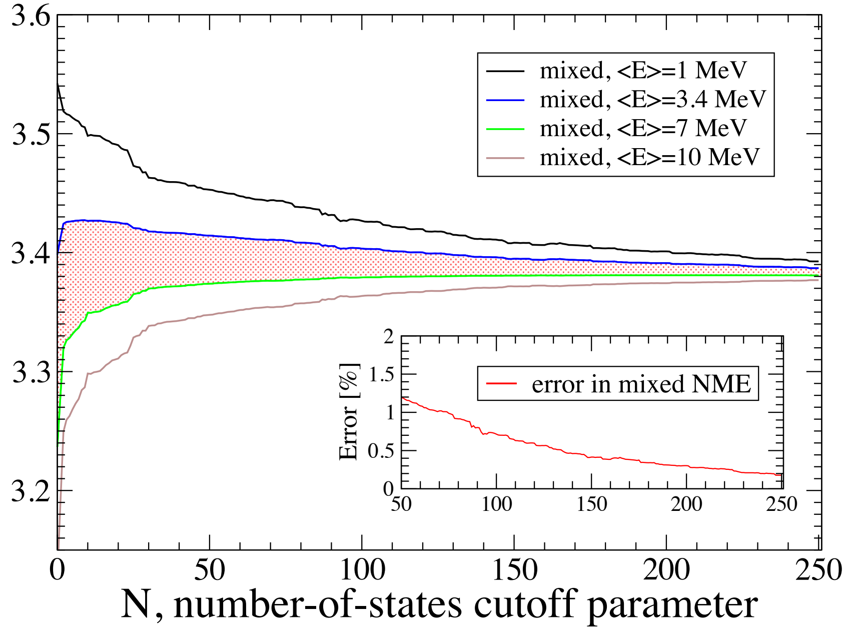
^{82}Se : 10M states

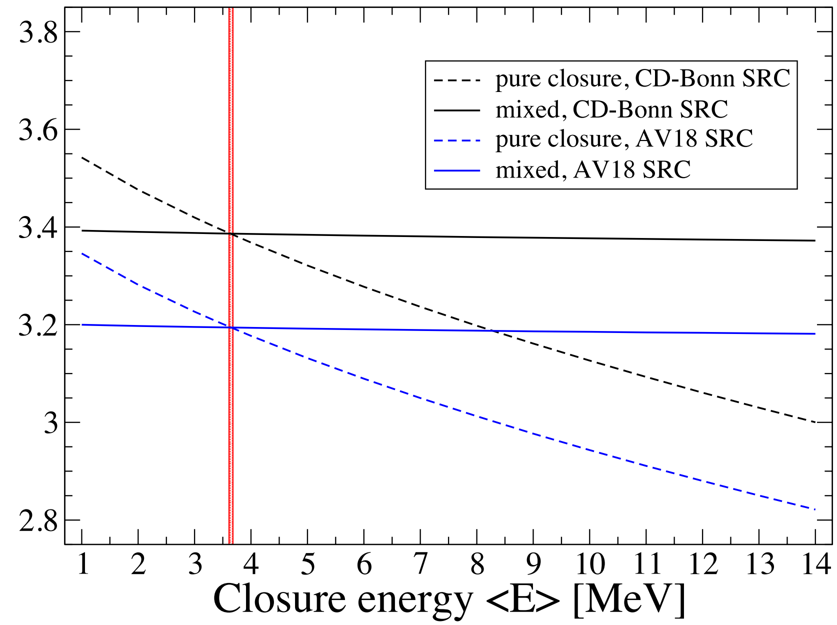
^{130}Te : 22M states

^{76}Ge : 150M states

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

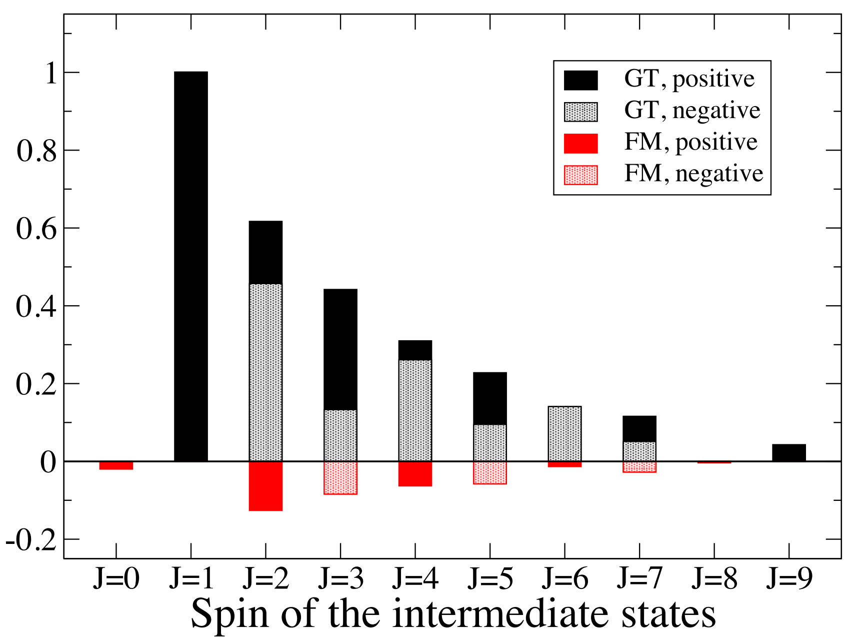
$$\hat{S} = \begin{cases} \sigma_1\tau_1\, \sigma_2\tau_2 & Gamow-Teller\ (GT) \\ \tau_1\tau_2 & Fermi\ (F) \\ \left[3(\vec{\sigma}_1\cdot\hat{n})(\vec{\sigma}_2\cdot\hat{n}) - (\vec{\sigma}_1\cdot\vec{\sigma}_2)\right]\tau_1\tau_2 & Tensor\ (T) \end{cases}$$

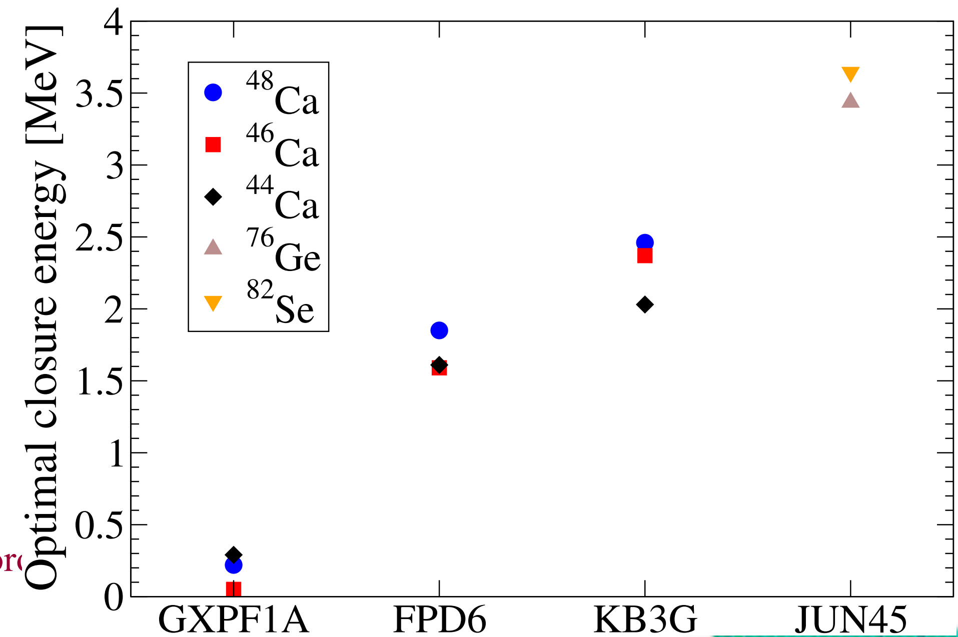




^{82}Se: PRC 89, 054304 (2014)

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





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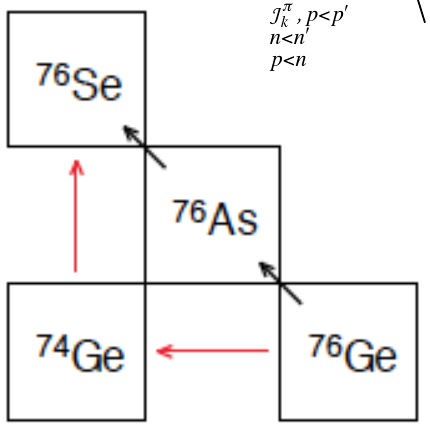
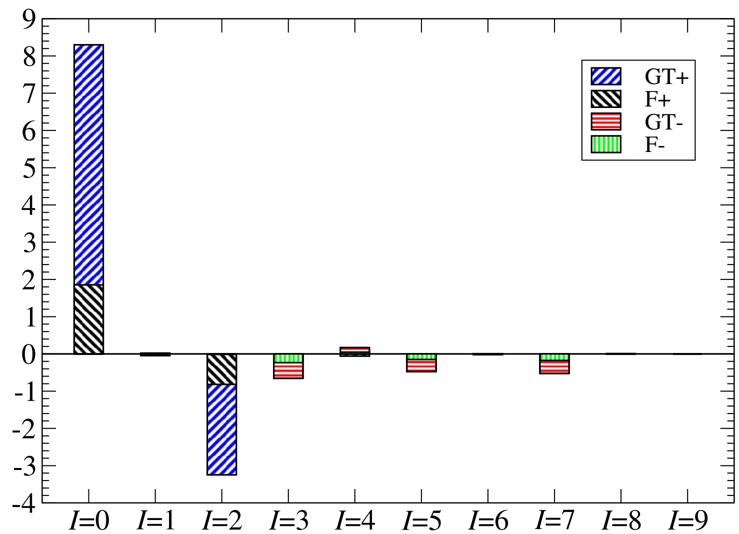
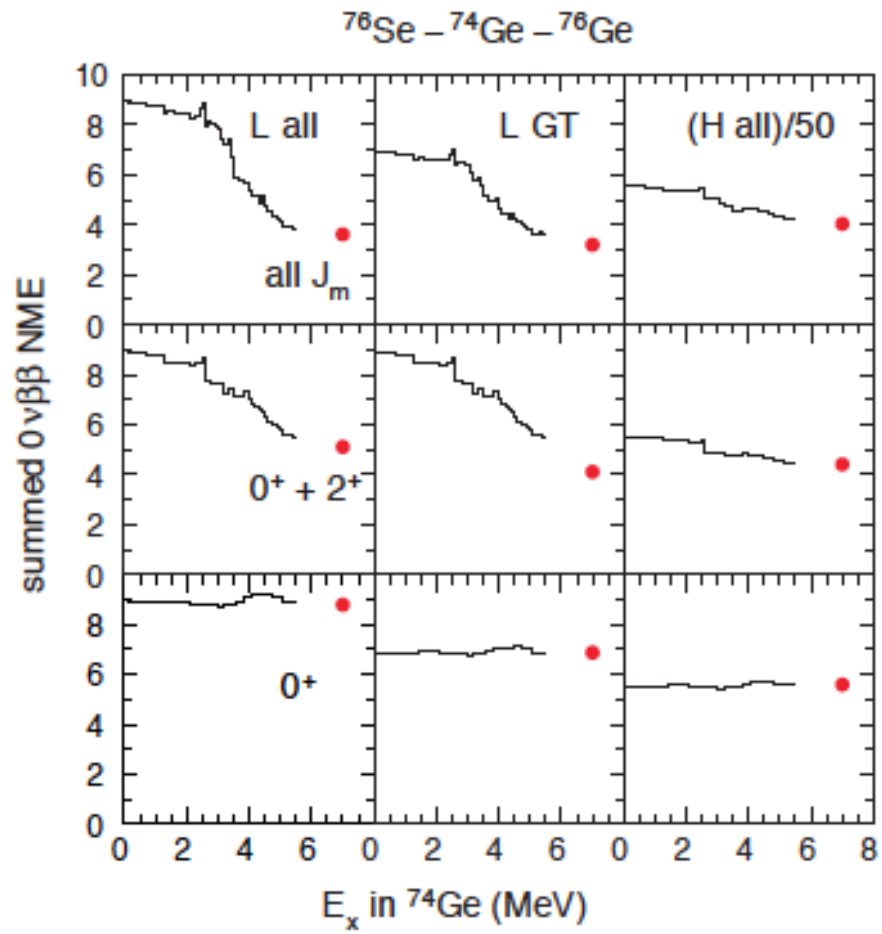
New Approach for NME: Novel Tests of Nuclear Structure

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





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



Brown, Horoi, Senkov

PRL **113**, 262501 (2014)

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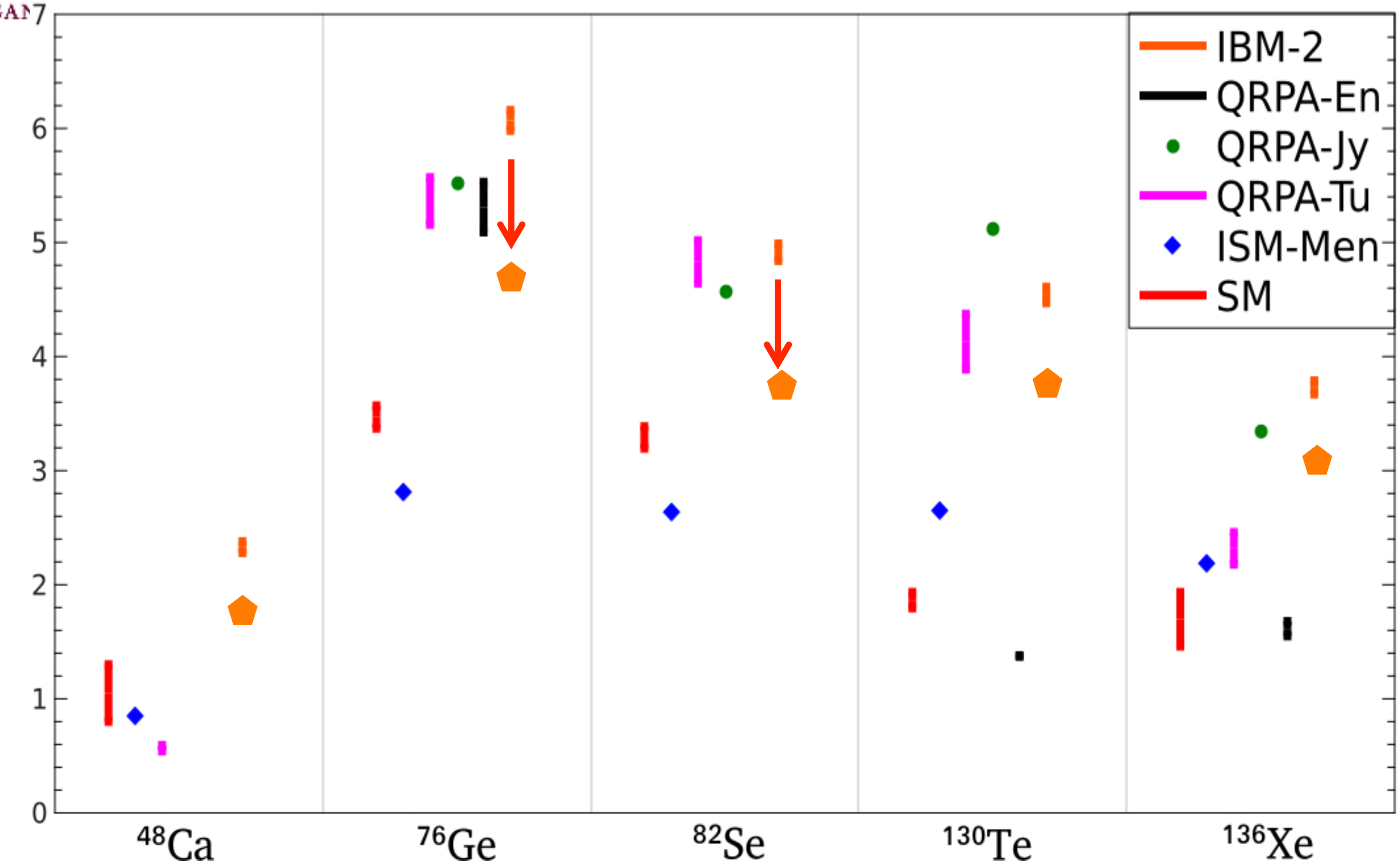
NME for the light-neutrino exchange mechanism



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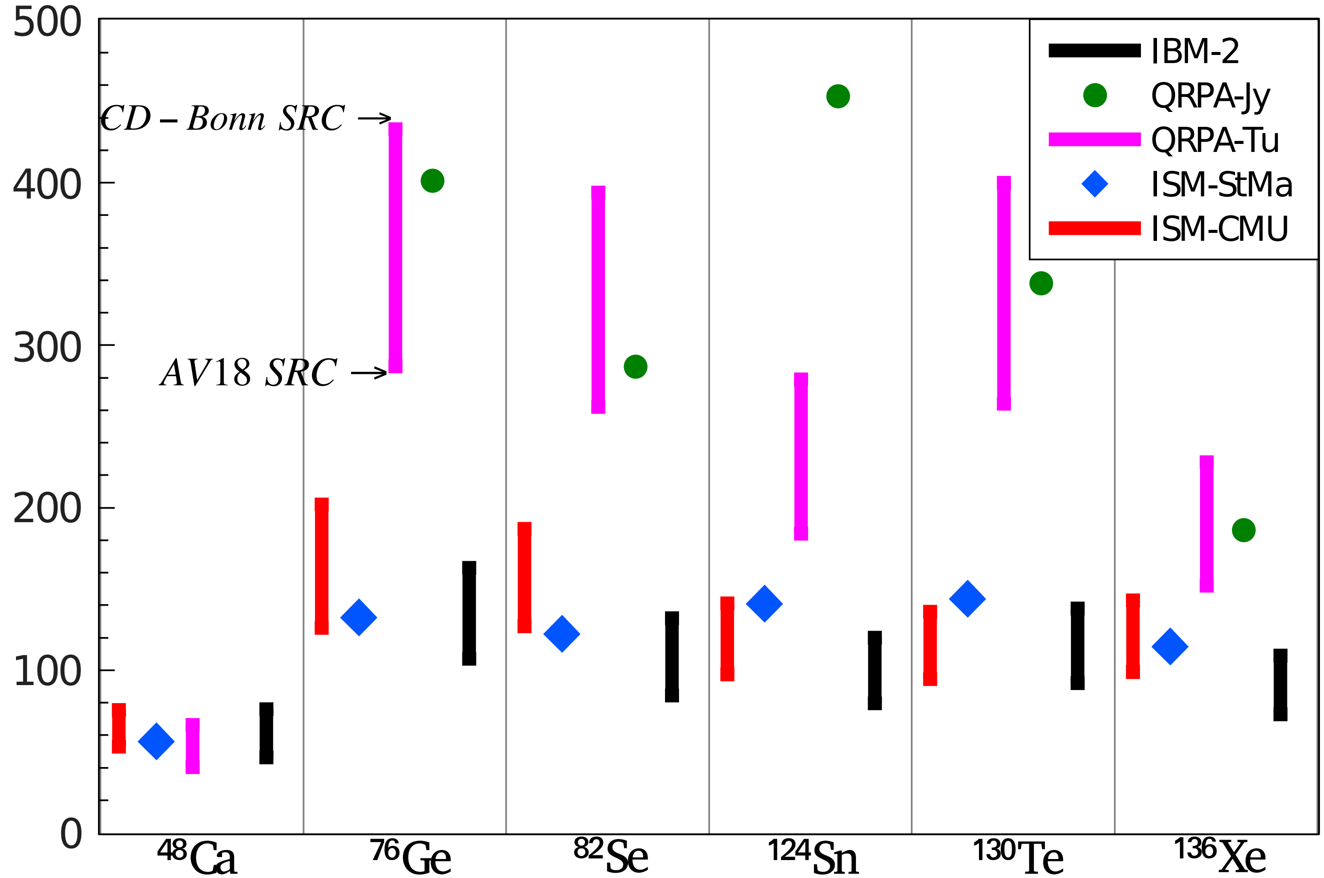
Heavy neutrino-exchange NME



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.**

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

See also PRL 116, 112502 (2016)

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

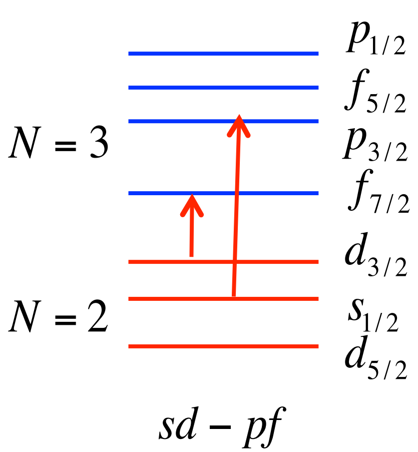
	M(0v)
$0\ \hbar\omega$/ GXPF1A	0.733
$0\ \hbar\omega+2^{nd}$ ord./GXPF1A	1.301 (77%)

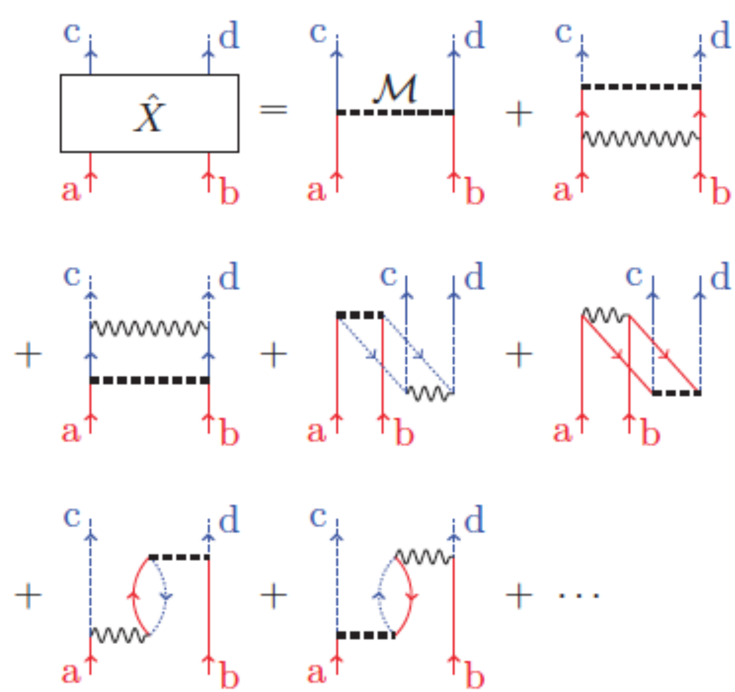
SDPFU: PRC 79, 014310 (2009)

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

arXiv:1308.3815, PRC 89, 045502 (2014)

PRC 87, 064315 (2013)





Towards an effective 0νDBD operator

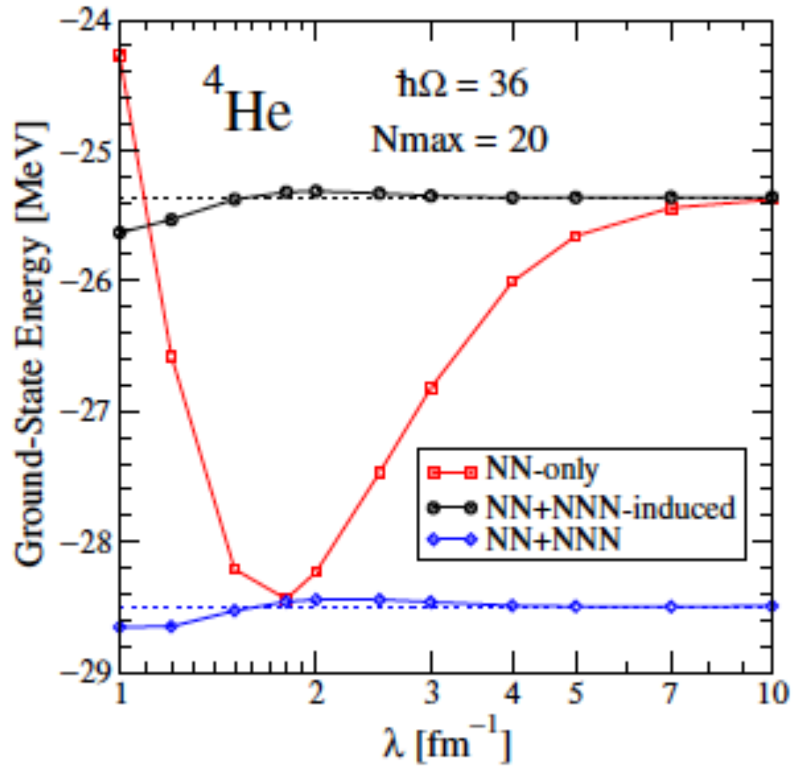
SRG evolution

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

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

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

N3LO 500



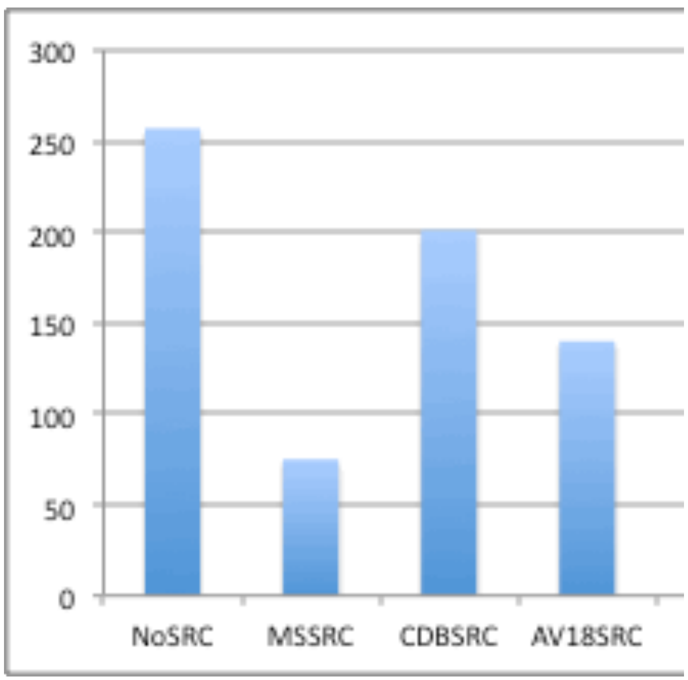
arXiv:1302.5473

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

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

^{76}Ge

M^{0N}



Evolved operator

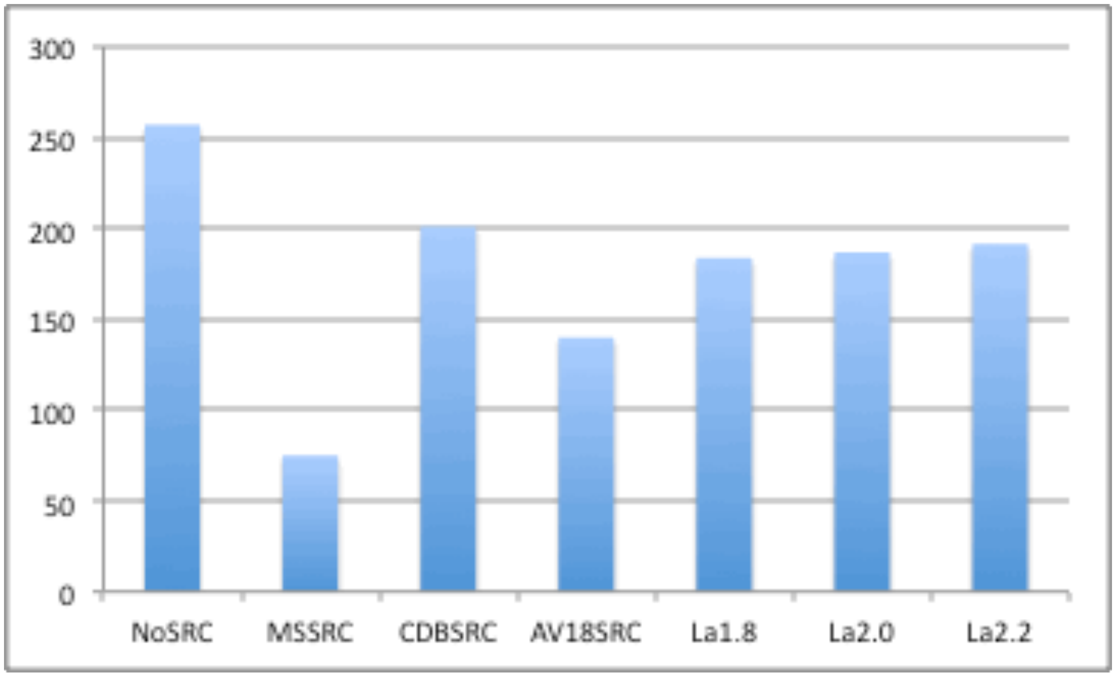
coming here

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

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

^{76}Ge

M^{0N}

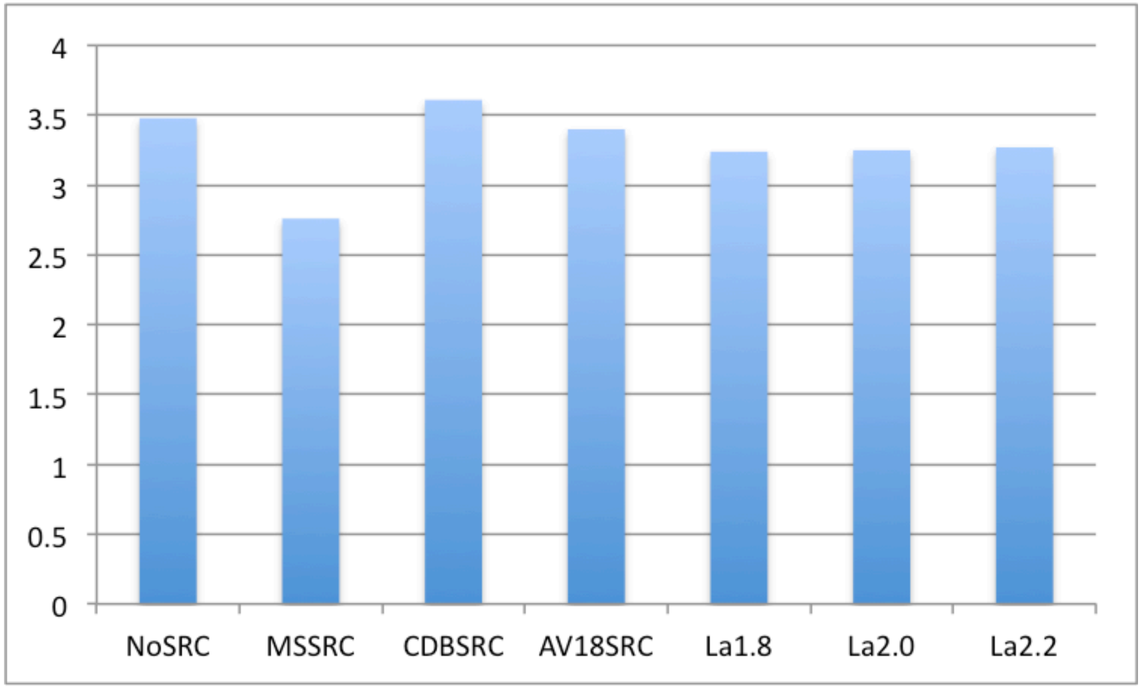


Towards an effective 0νDBD operator: light neutrino-exchange NME

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

^{76}Ge

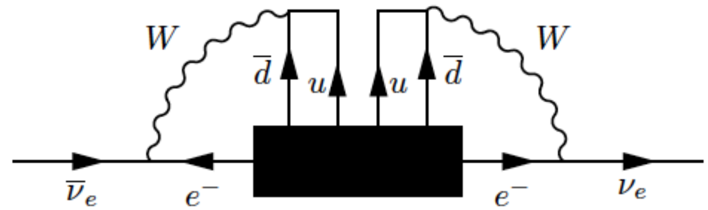
$M^{0\nu}$



In Conclusion

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!

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- Andrei Neacsu, CMU
- Jonathan Engel, UNC
- Jason Holt, TRIUMF
- Petr Navratil, TRIUMF
- Sofia Quaglioni, LLNL
- Micah Schuster, ORNL