NEUTRINO OSCILLATION WORKSHOP
Otranto (Lecce), Italy
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Neutrinoless DBD mechanisms and NMEs

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OUTLINE

- ***Introduction***
- ***Standard (conservative) 0νββ-decay picture***
  Majorana ν-mass, NMEs, quenching
- ***Light and heavy ν-exchange, V-A interaction***
  heavy ν- NMEs, limit on U_{eh} mixing
- ***0νββ-decay within the LR-symmetric model***
  importance of light and ν-exchange addressed
- ***Effect of non-standard ν-interactions on the 0νββ-decay***
  complementarity of the cosmology, ν-mass, 0νββ-decay observations
- ***Conclusions***

Amand Faesler, V. Rodin (U. Tuebingen), P. Vogel (Caltech), J. Engel (North Caroline U.), S. Kovalenko (Valparaiso U.), M. Krivoruchenko (ITEP Moscow), J. Vergados (U. Ioannina), S. Petcov (SISSA), D. Štefánik, R. Dvornický (Comenius U.), E. Lisi, G. Fogli (U. Bari) etc

The answer to the question whether neutrinos are their own antiparticles is of central importance, not only to our understanding of neutrinos, but also to our understanding of the origin of mass.

What is the nature of neutrinos?

Actually, when NMEs will be needed to analyze data?

ν $\Rightarrow$

GUT's

Only the 0νββ-decay can answer this fundamental question

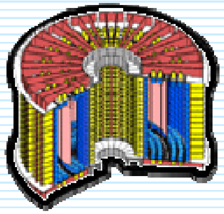
Analogy with kaons: K_0 and $\bar{K}_0$

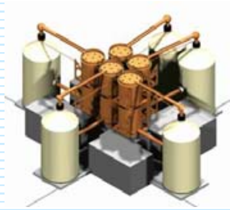
Could we have both?
(light Dirac and heavy Majorana)

Analogy with π_0

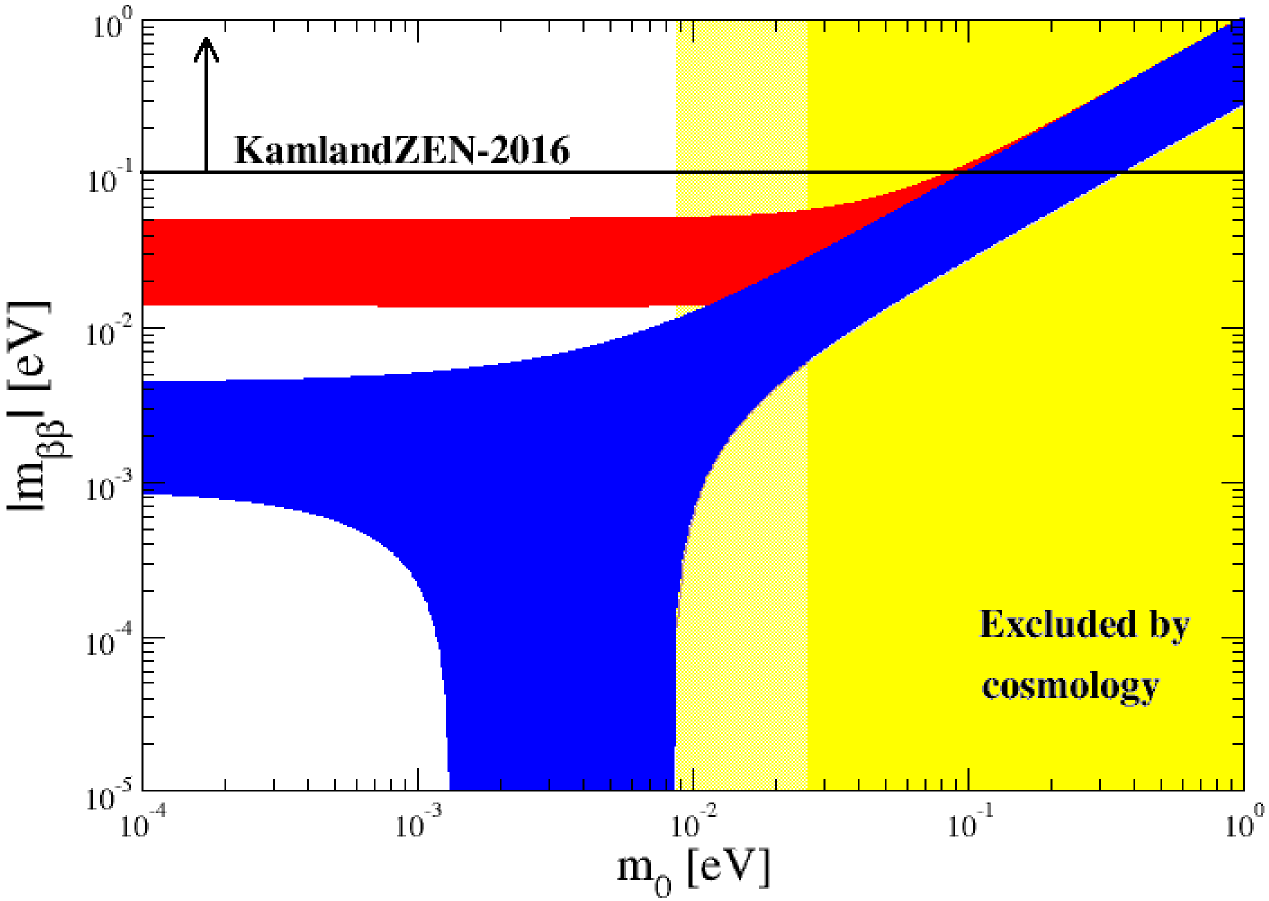
Standard (conservative) 0νββ-decay picture

$$\left(T^{0\nu}_{1/2}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M^{0\nu}_{\nu}\right|^2 G^{0\nu}$$





Issue: Lightest neutrino mass m_0



GUT's

Complementarity of $0\nu\beta\beta$-decay, β-decay and cosmology

β-decay (Mainz, Troitsk)

$$m_\beta^2 = \sum_i |U^L_{ei}|^2 m_i^2 \leq (2.2\ \mathrm{eV})^2$$

KATRIN: $(0.2\ \mathrm{eV})^2$

Cosmology (Planck)

$$\Sigma < 110\ \mathrm{meV}$$

$$m_0 > 26\ \mathrm{meV\ (NS)}$$
$$87\ \mathrm{meV\ (IS)}$$

$m_{\beta\beta}$=0 does not imply that the 0νββ-decay is not allowed!

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M_\nu^{0\nu}\right|^2 G^{0\nu}$$

Represents a simplified expression for the 0νββ-decay rate

Decomposition of ν-propagator

$$\mathcal{P} = \sum_j U_{ej}^2 \frac{m_j}{q^2 - m_j^2} = P_1 + P_3 + P_5 + \cdots$$

S. Pascoli and S.T Petcov, PRD 77, 113003 (2008)

$$P_1 = \frac{1}{q^2}\sum_j U_{ej}^2 m_j = \frac{1}{q^2}\langle m\rangle \quad P_3 = \frac{1}{q^2}\sum_j U_{ej}^2 m_j \frac{m_j^2}{q^2}$$

$m_{\beta\beta} \equiv \langle m \rangle$ $\quad m_j^2 \ll |q^2| \quad |q^2| \sim (100 \text{ MeV})^2$

There are also additional higher order contributions to the 0νββ-decay amplitude

There does not exist symmetry which forbids 0νββ-decay

The 0νββ-decay Nuclear Matrix Elements *must be evaluated using tools of nuclear theory*

The double beta decay process can be observed due to nuclear pairing interaction that favors energetically the even-even nuclei over the odd-odd nuclei

In double beta decay two neutrons bound in the ground state of an initial even-even nucleus are simultaneously transformed into two protons that are bound in the ground state or excited (0^+, 2^+) states of the final nucleus

It is necessary to evaluate, with a sufficient accuracy, wave functions of both nuclei, and evaluate the matrix element of the 0νββ-decay operator connecting them

This can not be done exactly, some approximation and/or truncation is always needed. Moreover, there is no other analogues observable that can be used to judge directly the quality of the result.

Method	g_A	src	$M_\nu^{0\nu}$					
			^{48}Ca	^{76}Ge	^{82}Se	^{96}Zr	^{100}Mo	^{110}Pd
ISM-StMa	1.25	UCOM	0.85	2.81	2.64			
ISM-CMU	1.27	Argonne	0.80	3.37	3.19			
		CD-Bonn	0.88	3.57	3.39			
IBM	1.27	Argonne	1.75	4.68	3.73	2.83	4.22	4.05
QRPA-TBC	1.27	Argonne	0.54	5.16	4.64	2.72	5.40	5.76
		CD-Bonn	0.59	5.57	5.02	2.96	5.85	6.26
QRPA-Jy	1.26	CD-Bonn		5.26	3.73	3.14	3.90	6.52
dQRPA-NC	1.25	without		5.09				
PHFB	1.25	Argonne				2.84	5.82	7.12
		CD-Bonn				2.98	6.07	7.42
NREDF	1.25	UCOM	2.37	4.60	4.22	5.65	5.08	
REDF	1.25	without	2.94	6.13	5.40	6.47	6.58	
Mean value			1.34	4.55	4.02	3.78	5.57	6.12
variance			0.81	1.20	0.91	2.49	0.58	1.78

Method	g_A	src	$M_\nu^{0\nu}$					
			^{116}Cd	^{124}Sn	^{128}Te	^{130}Te	^{136}Xe	^{150}Nd
ISM-StMa	1.25	UCOM		2.62		2.65	2.19	
ISM-CMU	1.27	Argonne		2.00		1.79	1.63	
		CD-Bonn		2.15		1.93	1.76	
IBM	1.27	Argonne	3.10	3.19	4.10	3.70	3.05	2.67
QRPA-TBC	1.27	Argonne	4.04	2.56	4.56	3.89	2.18	
		CD-Bonn	4.34	2.91	5.08	4.37	2.46	3.37
QRPA-Jy	1.26	CD-Bonn	4.26	5.30	4.92	4.00	2.91	
dQRPA-NC	1.25	without				1.37	1.55	2.71
PHFB	1.27	Argonne			3.90	3.81		2.58
		CD-Bonn			4.08	3.98		2.68
NREDF	1.25	UCOM	4.72	4.81	4.11	5.13	4.20	1.71
REDF	1.25	without	5.52	4.33		4.98	4.32	5.60
Mean value			4.34	3.07	4.34	3.42	2.59	3.01
variance			0.79	1.01	0.23	1.67	1.10	1.34

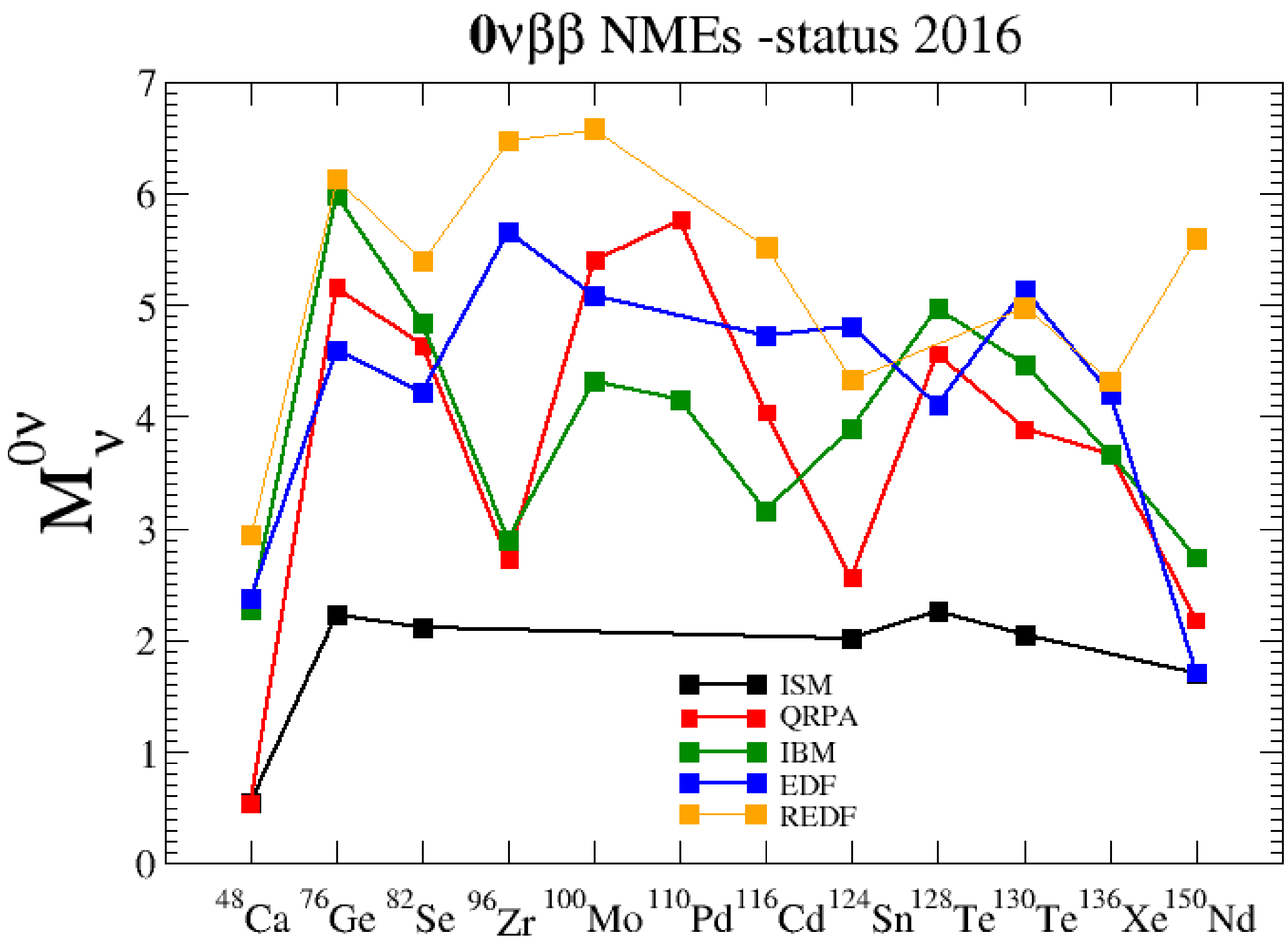
NMEs for unquenched value of g_A

Mean field approaches (PHFB, NREDF, REDF) ⇒ Large NMEs

Interacting Shell Model (ISM-StMa, ISM-CMU) ⇒ small NMEs

Quasiparticle Random Phase Approximation (QRPA-TBC, QRPA-Jy, dQRPQ-NC) ⇒ Intermediate NMEs

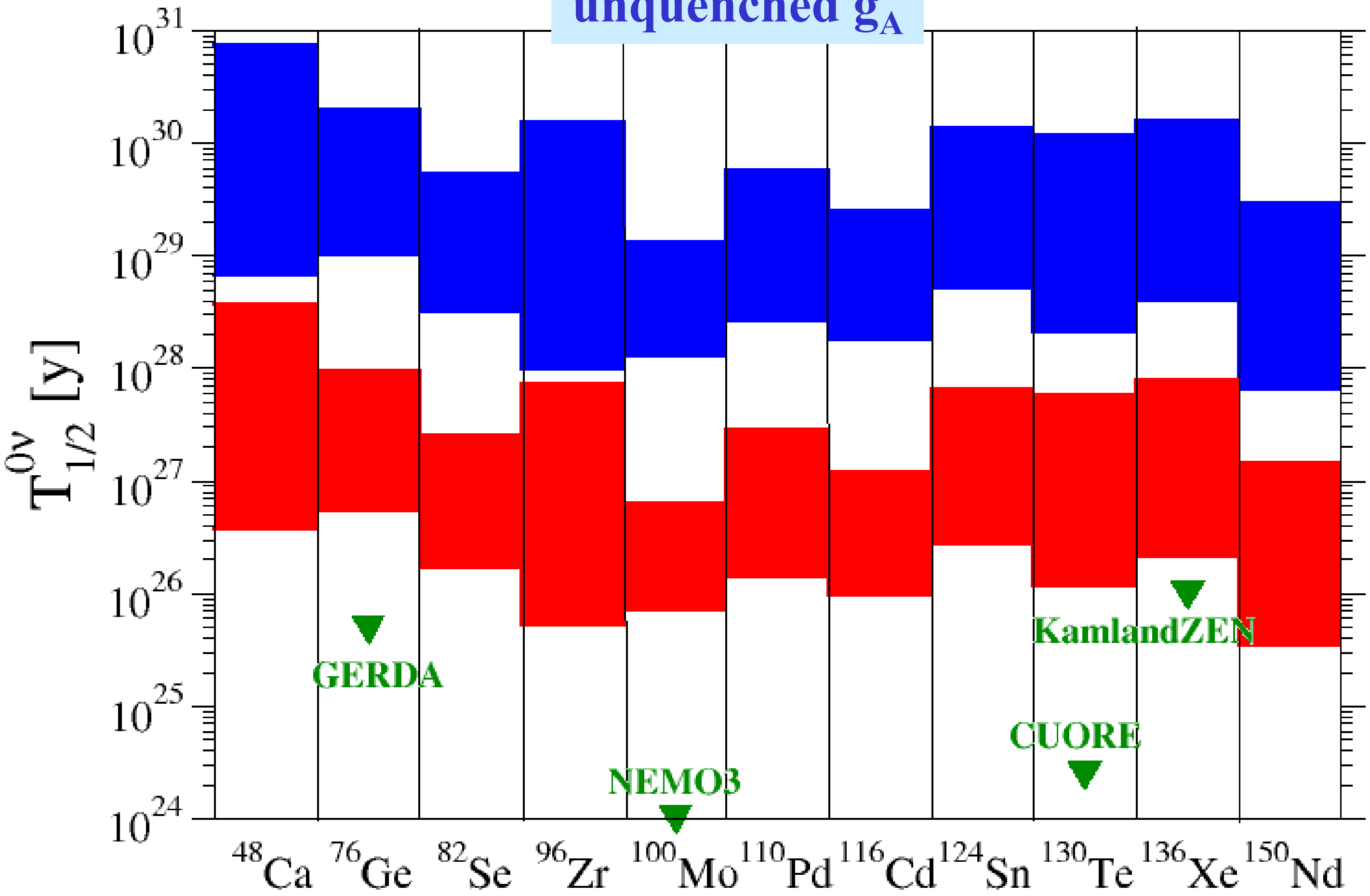
Interacting Boson Model (IBM) ⇒ Close to QRPA results



	mean field meth.	ISM	IBM	QRPA
Large model space	yes	no	yes	yes
Constr. Interm. States	no	yes	no	yes
Nucl. Correlations	limited	all	restricted	restricted

0νββ –half lives for NH and IH with included undertainties in NMEe

unquenched g_A



NH

IH

NH: $m_1 \ll m_2 \ll m_3$ $\quad m_3 \simeq \sqrt{\Delta m^2}$

$m_1 \ll \sqrt{\delta m^2}. \quad m_2 \simeq \sqrt{\delta m^2}$

$1.4 \text{ meV} \leq m_{\beta\beta} \leq 3.6 \text{ meV}$

IH: $m_3 \ll m_1 < m_2$ $\quad m_1 \simeq m_2 \simeq \sqrt{\Delta m^2}$

$m_3 \ll \sqrt{\Delta m^2}$

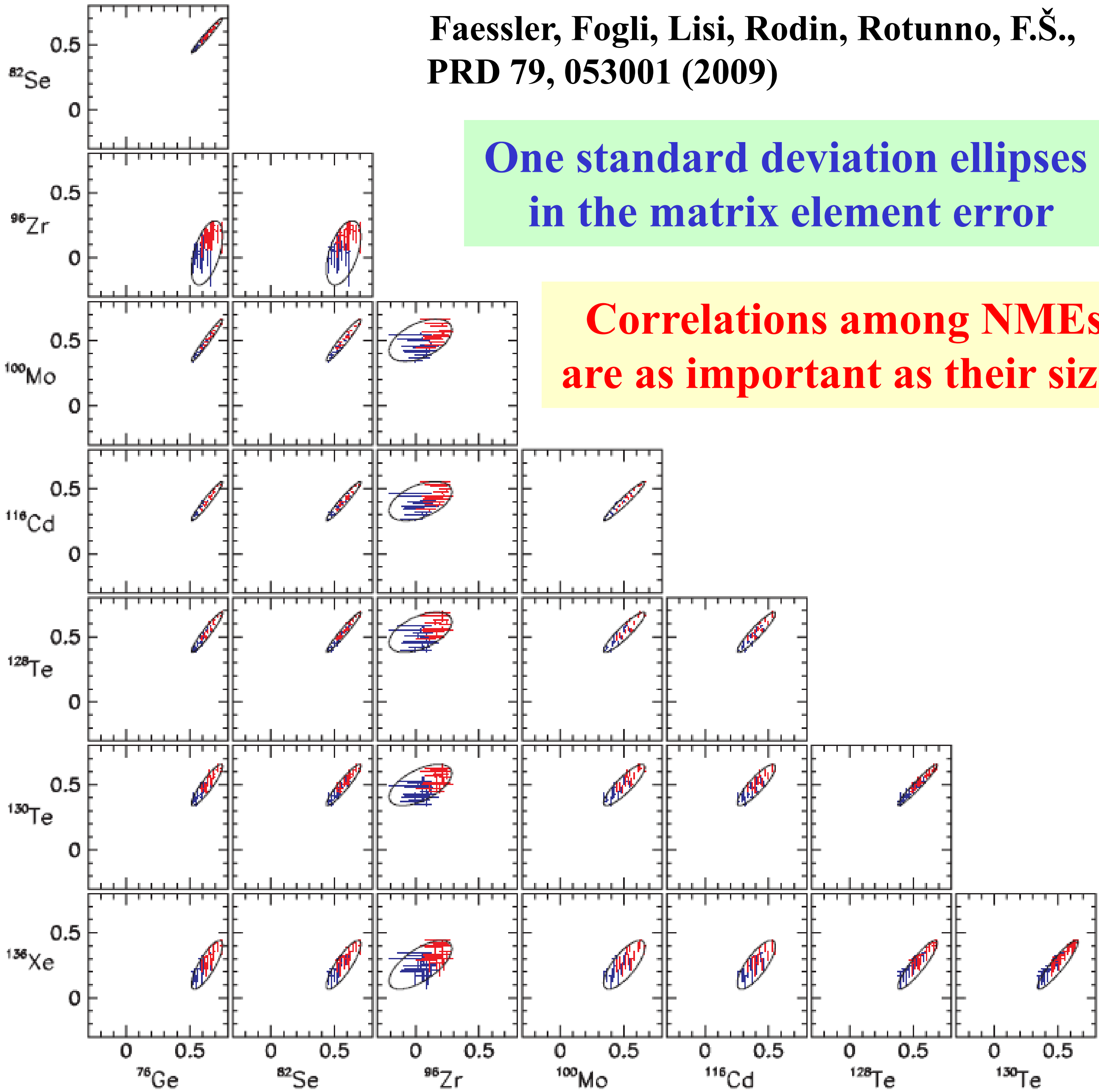
$20 \text{ meV} \leq m_{\beta\beta} \leq 49 \text{ meV}$

Lightest ν-mass equal to zero

Could multiple $0\nu\beta\beta$ measurements be helpful to extract $m_{\beta\beta}$?

Problem:
Uncertainties in NME from different nuclei are highly correlated.

Faessler, Fogli, Lisi, Rodin, Rotunno, F.Š., PRD 79, 053001 (2009)



One standard deviation ellipses in the matrix element error

Correlations among NMEs are as important as their size.

Calculations:
varying method (QRPA, RQRPA),
the value g_A^{eff} (1.0 and 1.25),
the treatment of src (Jastr. and UCOM),
the size of model space (3 choices)

Is this expression accurate enough?

$$\left(T^{0\nu}_{1/2}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M^{0\nu}_{\nu}\right|^2 G^{0\nu}$$

The 0νββ-decay with emission of electrons in $p_{1/2}$ wave state

D. Štefánik, R. Dvornický, F.Š., Nuclear Theory 33 (2014) 115

$$\psi(\mathbf{r},p,s) \simeq \psi_{s_{1/2}}(\mathbf{r},p,s) + \psi_{p_{1/2}}(\mathbf{r},p,s) =$$
$$\begin{pmatrix} g_{-1}(\varepsilon,r)\chi_s \\ f_{+1}(\varepsilon,r)\,(\vec{\sigma}\cdot\hat{\mathbf{p}})\,\chi_s \end{pmatrix} + \begin{pmatrix} i g_{+1}(\varepsilon,r)\,(\vec{\sigma}\cdot\hat{\mathbf{r}})\,(\vec{\sigma}\cdot\hat{\mathbf{p}})\,\chi_s \\ -i f_{-1}(\varepsilon,r)\,(\vec{\sigma}\cdot\hat{\mathbf{r}})\,\chi_s \end{pmatrix}$$

Exact relativ. electron w.f.

$$J^{\rho}(\mathbf{x}) = \sum_n \tau_n^+ \delta(\mathbf{x}-\mathbf{r}_n)\left[(g_V - g_A C_n)\, g^{\rho 0} + g^{\rho k}\right.$$
$$\left.\times\left(g_A\sigma_n^k - g_V D_n^k - g_P\left(p_n^k - p_n'^k\right)\frac{\vec{\sigma}_n\cdot\left(\mathbf{p}_n - \mathbf{p}_n'\right)}{2m_N}\right)\right]$$

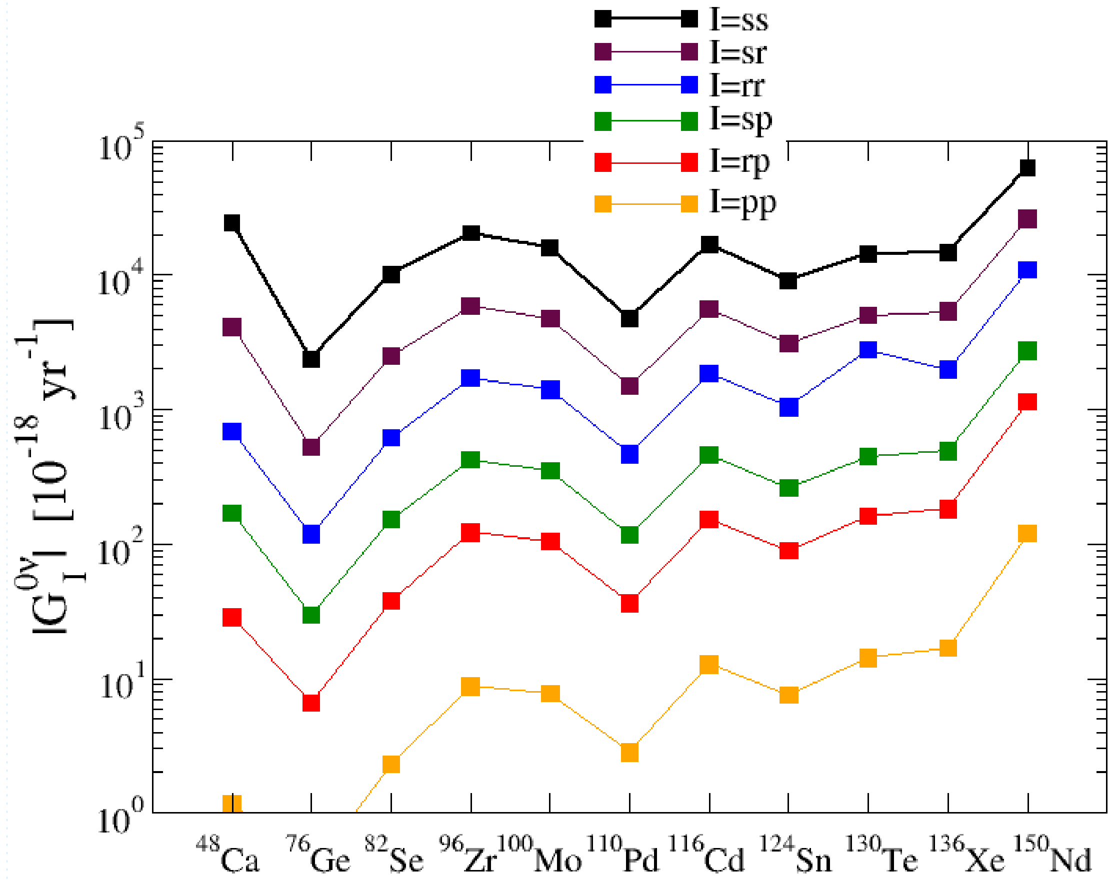
Higher order terms of nucleon current with nucleon recoil (odd parity operators)

$$C_n = \frac{\vec{\sigma}_n\cdot\left(\mathbf{p}_n + \mathbf{p}_n'\right)}{2m_N} - \frac{g_P}{g_A}\left(E_n - E_n'\right)\frac{\vec{\sigma}_n\cdot\left(\mathbf{p}_n - \mathbf{p}_n'\right)}{2m_N}$$

$$\mathbf{D}_n = \frac{\left(\mathbf{p}_n + \mathbf{p}_n'\right)}{2m_N} - i\left(1 + \frac{g_M}{g_V}\right)\frac{\vec{\sigma}_n\times\left(\mathbf{p}_n - \mathbf{p}_n'\right)}{2m_N}.$$

$0\nu\beta\beta$-decay rate with $p_{1/2}$ electrons (2 additional NMEs and 5 phase-space factors)

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \frac{|m_{\beta\beta}|^2}{m_e^2} g_A^4 \left(2Re\left\{M_s M_r^*\right\} G_{sr} + 2Re\left\{M_s M_p^*\right\} G_{sp} + 2Re\left\{M_r M_p^*\right\} G_{rp} + G_{ss}\left|M_s\right|^2 + G_{rr}\left|M_r\right|^2 + G_{pp}\left|M_p\right|^2\right),$$



Calculated phase-space factor for $0\nu\beta\beta$-decay with emission of $s_{1/2}$ and $p_{1/2}$ electrons ($m_{\beta\beta}$ mechanism)

Effect of $p_{1/2}$ wave is below 10%

Some kinematical factor large but corresponding NMEs are small.

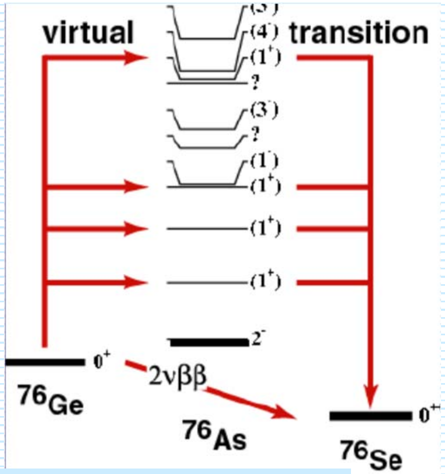
$g_A^4 = (1.269)^4 = 2.6$

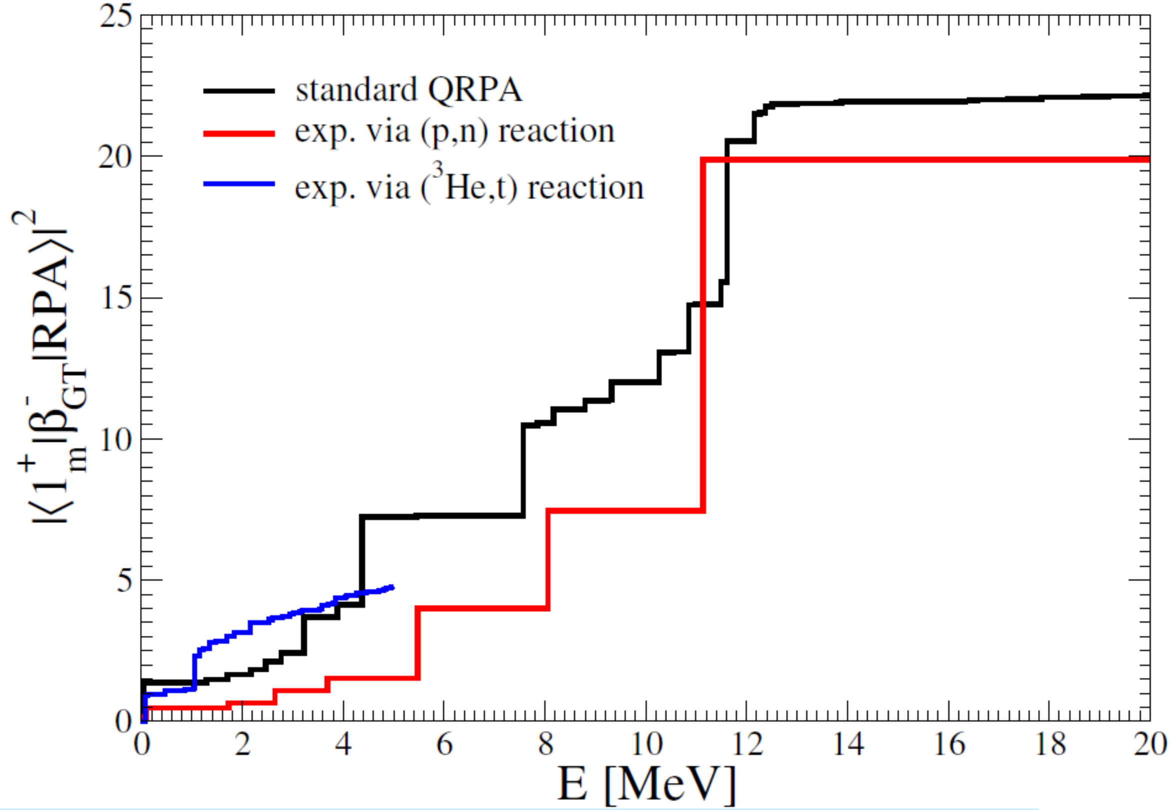
Quenching of g_A (from exp.: $T_{1/2}^{0\nu}$ up 2.5 x larger)

$(g^{eff}_A)^4 = 1.0$

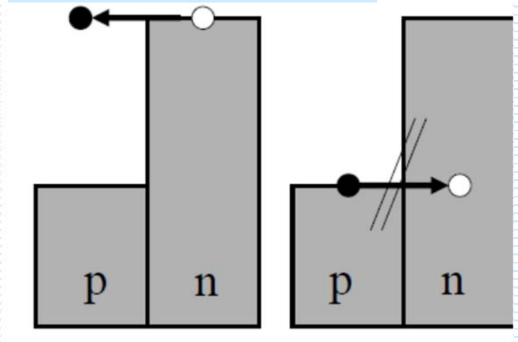
Strength of GT trans. (approx. given by Ikeda sum rule =3(N-Z)) has to be quenched to reproduce experiment

$$^{76}_{32}Ge_{44} \Rightarrow$$
$$S_{\beta^-} - S_{\beta^+} = 3(N-Z) = 36$$





Pauli blocking



Cross-section for charge exchange reaction:

$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{\mu}{\pi\hbar}\right]^2 \frac{k_f}{k_i} N_d \, |V_{\sigma\tau}|^2 \, |\langle f \,|\, \sigma\tau \,|\, i \rangle|^2$$

$q = 0!!$

largest at 100 - 200 MeV/A

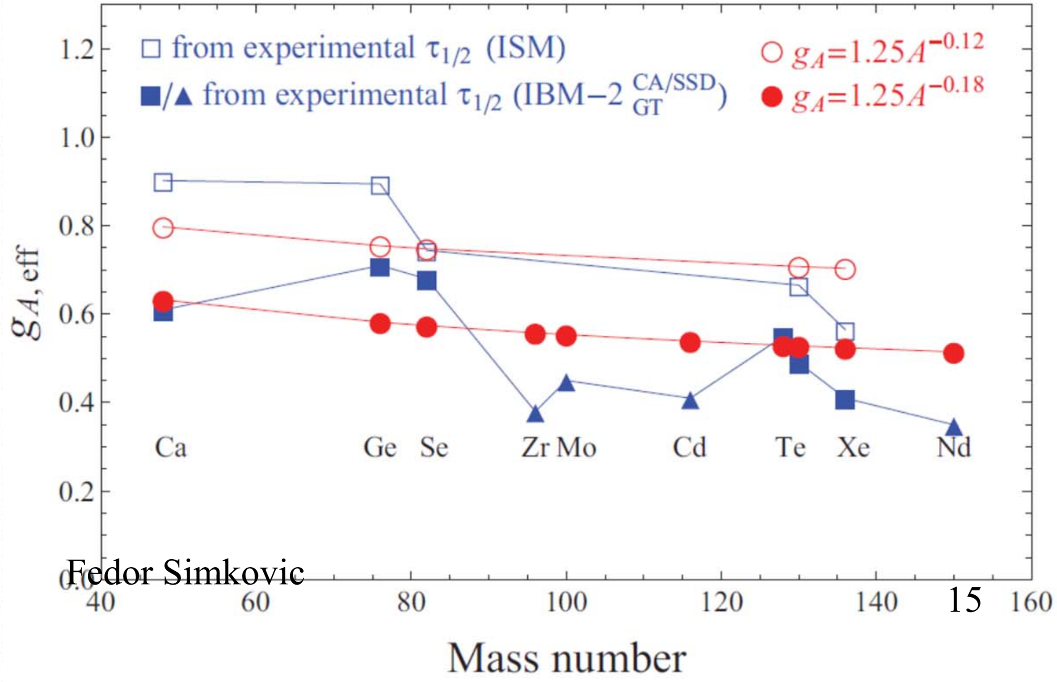
Quenching of g_A (from theory: $T_{1/2}^{0\nu}$ up 50 x larger)

$(g^{eff}_A)^4 \simeq 0.66$ (^{48}Ca), 0.66 (^{76}Ge), 0.30 (^{76}Se), 0.20 (^{130}Te) and 0.11 (^{136}Xe)
The Interacting Shell Model (ISM), which describes qualitatively well energy spectra, does reproduce experimental values of $M^{2\nu}$ only by consideration of significant quenching of the Gamow-Teller operator, typically by 0.45 to 70%.

$(g^{eff}_A)^4 \simeq (1.269\ A^{-0.18})4 = 0.063$ **(The Interacting Boson Model). This is an incredible result. The quenching of the axial-vector coupling within the IBM-2 is more like 60%.**

J. Barea, J. Kotila, F. Iachello, PRC 87, 014315 (2013).

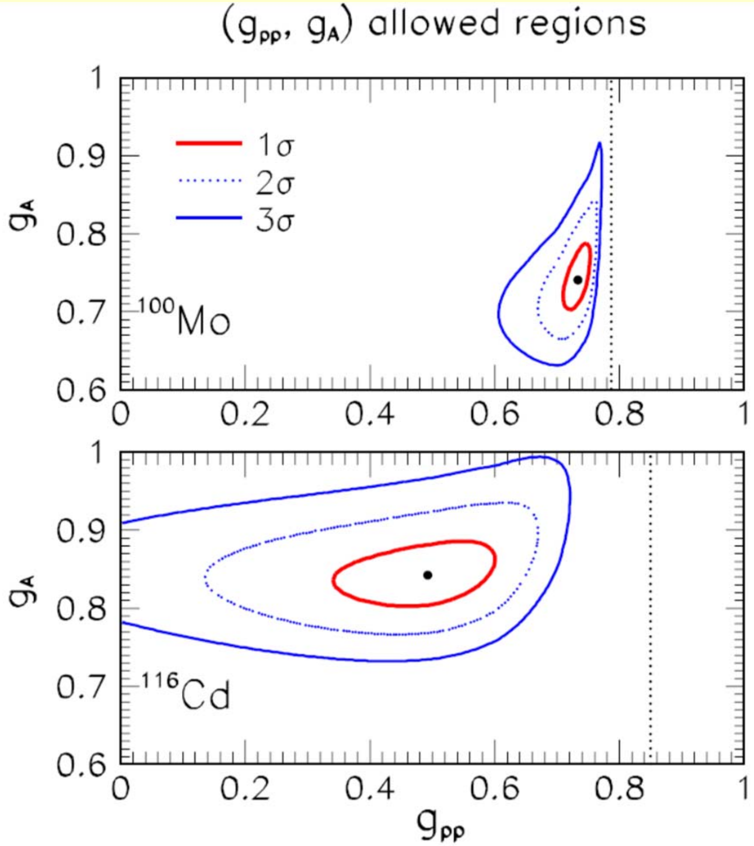
It has been determined by theoretical prediction for the 2νββ-decay half-lives, which were based on within closure approximation calculated corresponding NMEs, with the measured half-lives.

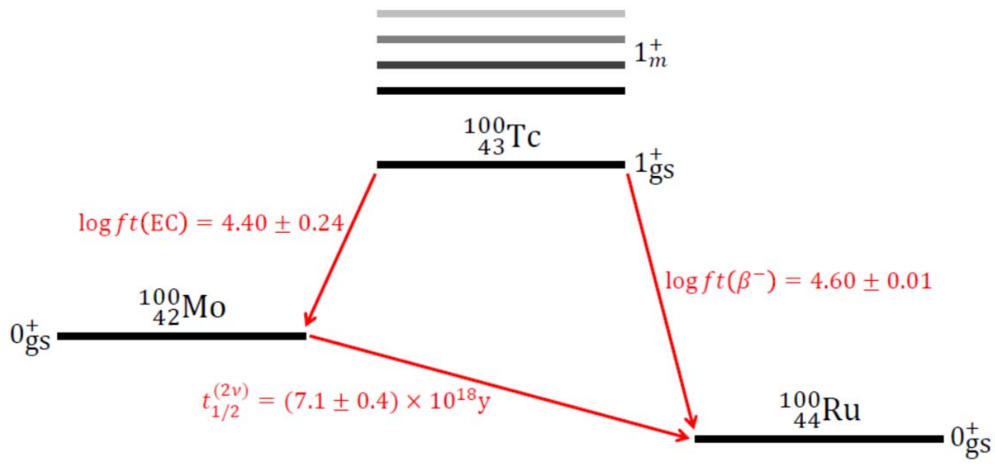


Faessler, Fogli, Lisi, Rodin, Rotunno, F. Š, J. Phys. G 35, 075104 (2008).

$(g^{eff}_A)^4 = 0.30$ and 0.50 for ^{100}Mo and ^{116}Cd, respectively (The QRPA prediction).

g^{eff}_A was treated as a completely free parameter alongside g_{pp} (used to renormalize particl-particle interaction) by performing calculations within the QRPA and RQRPA. It was found that a least-squares fit of g^{eff}_A and g_{pp}, where possible, to the β-decay rate and β+/EC rate of the $J = 1^+$ ground state in the intermediate nuclei involved in double-beta decay in addition to the $2\nu\beta\beta$ rates of the initial nuclei, leads to an effective g^{eff}_A of about 0.7 or 0.8.





Extended calculation also for neighbour isotopes performed by

F.F. Depisch and J. Suhonen, arXiv:1606.02908[nucl-th]

r Simkovic

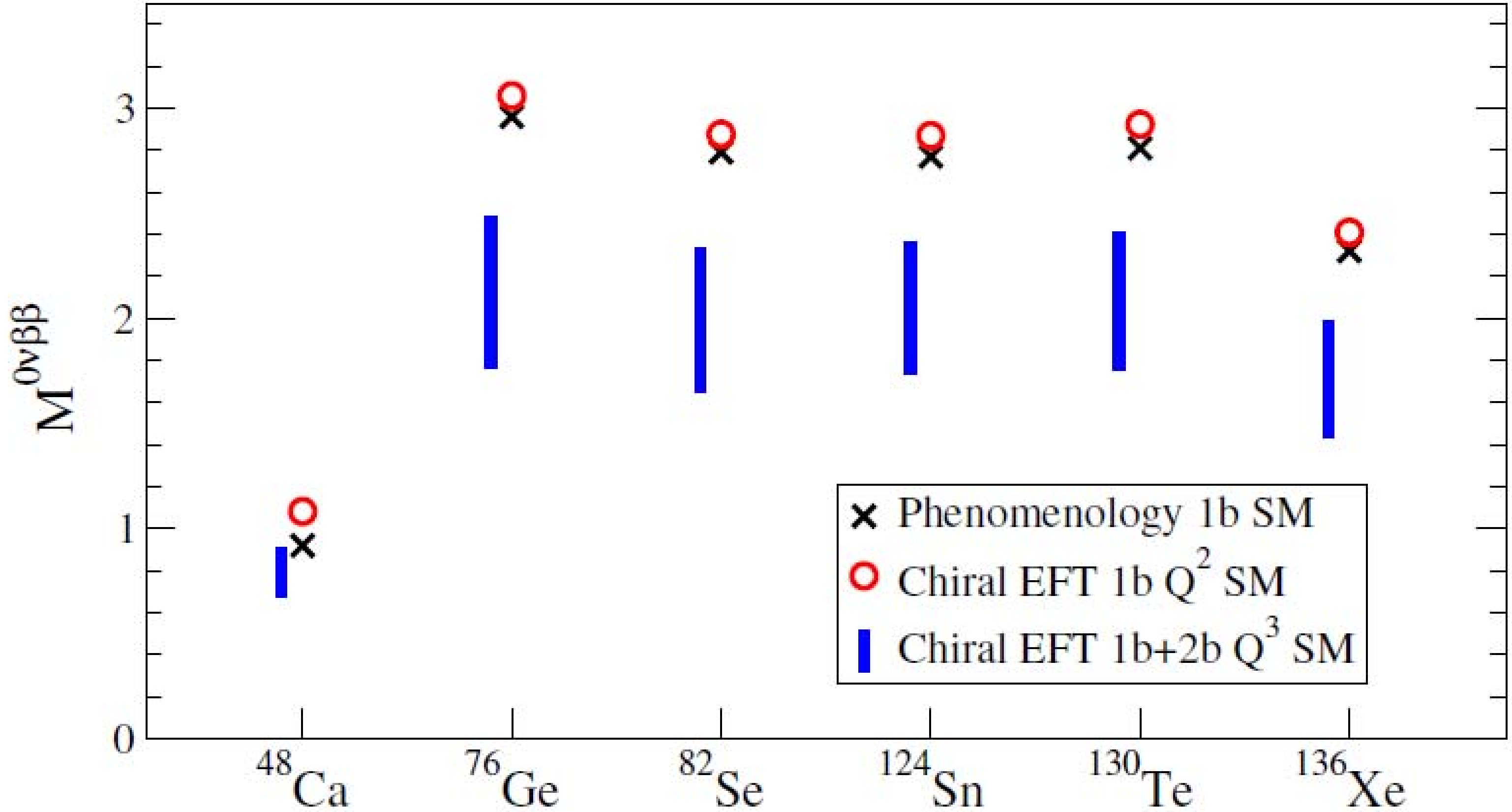
Dependence of g^{eff}_A on A was not established.

Quenching of g_A and two-body currents

Menendez, Gazit, Schwenk, PRL 107 (2011) 062501; MEDEX13 contribution

$$\mathbf{J}^{\text{eff}}_{i,2b} = -g_A \boldsymbol{\sigma}_i \tau_i^- \frac{\rho}{F_\pi^2} \left[\frac{2}{3} c_3 \frac{p^2}{4m_\pi^2 + p^2} + I(\rho, P) \left(\frac{1}{3}(2c_4 - c_3) + \frac{1}{6m} \right) \right] = -g_A \delta(p) \boldsymbol{\sigma}_i \tau_i^-$$

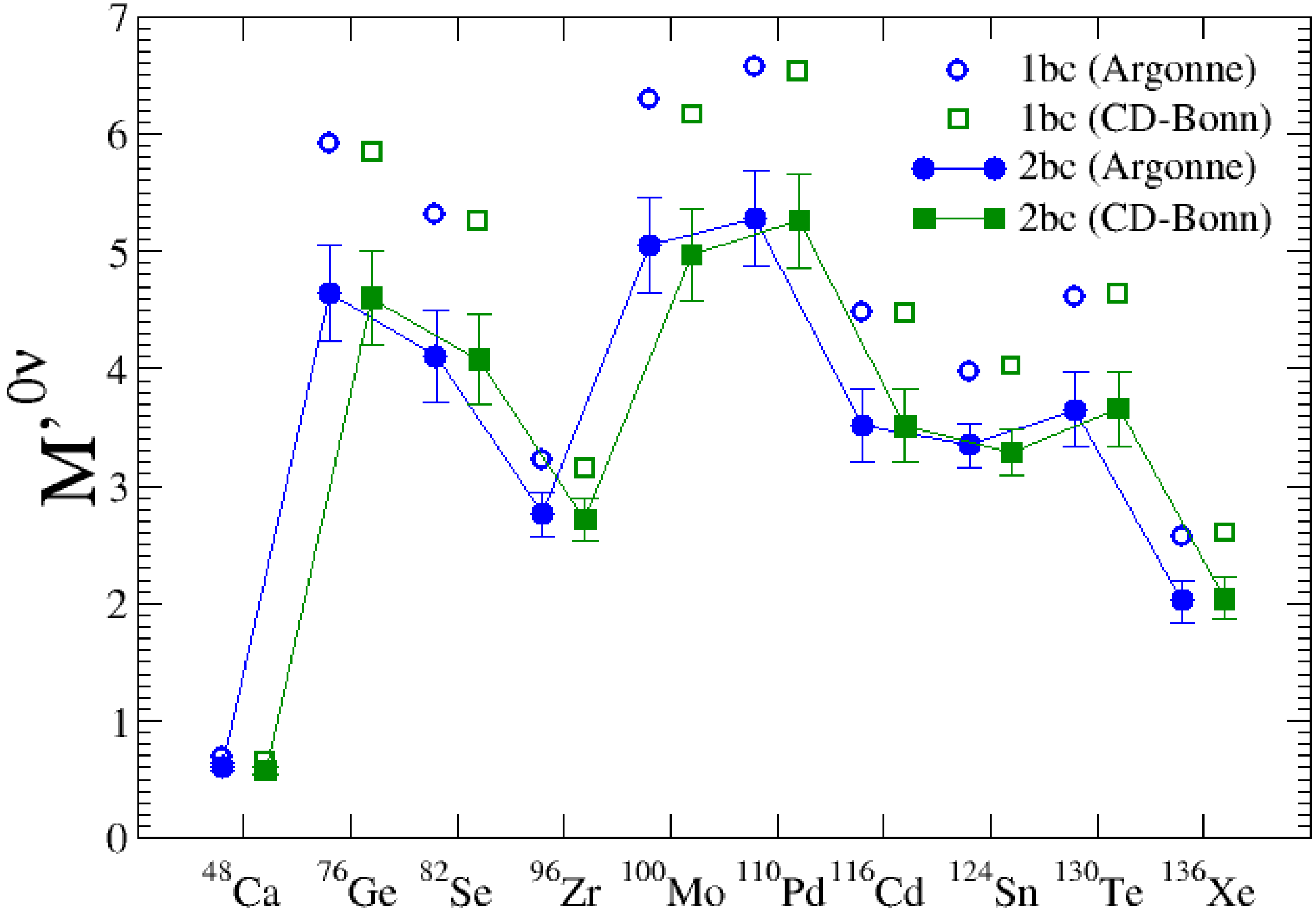
The 0νββ operator calculated within effective field theory. Corrections appear as 2-body current predicted by EFT. The 2-body current contributions are related to the quenching of Gamow-Teller transitions found in nuclear structure calc.



Quenching of g_A, two-body currents and QRPA

(Suppression of the 0νββ-decay NME of about 20%)

Engel, Vogel, Faessler, F.Š., PRC 89 (2014) 064308



But, a strong suppression of 2νββ-decay half-life, ($g_A^{eff} = g_A\delta(p=0) = 0.7\text{-}1.0$)

The DBD Nuclear Matrix Elements and the SU(4) symmetry

D. Štefánik, F.Š., A. Faessler, PRC 91, 064311 (2015)

Suppression of the Two Neutrino Double Beta Decay by Nuclear Structure Effects

P. Vogel, M.R. Zirnbauer, PRL (1986) 3148

O. Civitarese, A. Faessler, T. Tomoda, PLB 194 (1987) 11

E. Bender, K. Muto, H.V. Klapdor, PLB 208 (1988) 53

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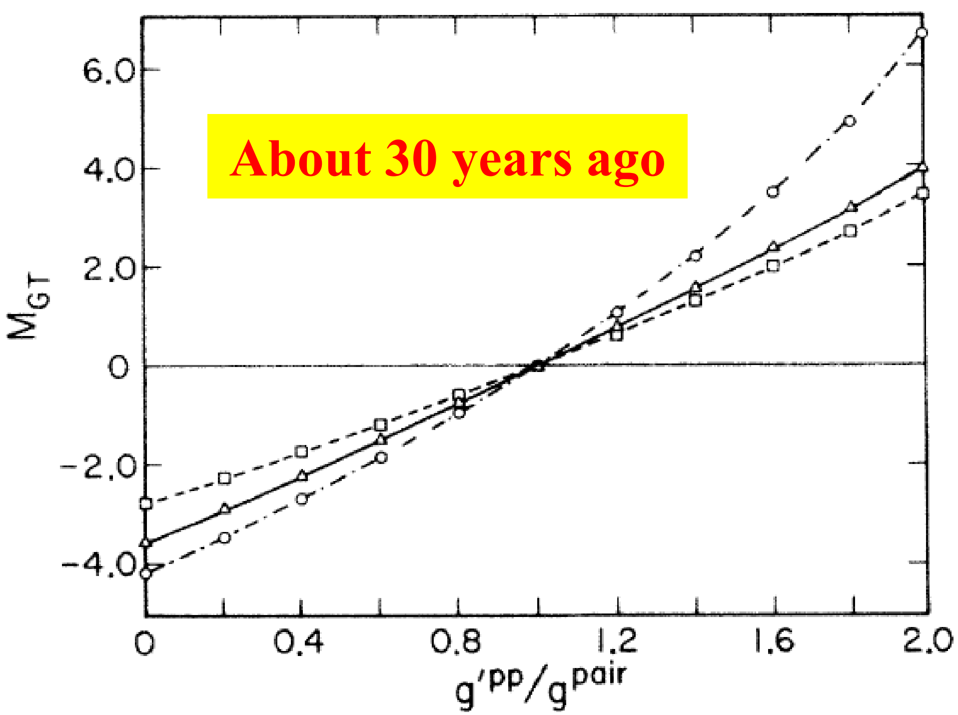


The isospin is known to be a good approximation in nuclei

In heavy nuclei the SU(4) symmetry is strongly broken by the spin-orbit splitting.

What is beyond this behavior? Is it an artifact of the QRPA?

s.p. mean-field

Conserves SU(4) symmetry

$$H = \underbrace{e_n N_n + e_p N_p - g_{pair}\left(\sum_{M_T=-1,0,1} A^\dagger_{0,1}(0,M_T)A_{0,1}(0,M_T) + \sum_{M_S=-1,0,1} A^\dagger_{1,0}(M_S,0)A_{1,0}(M_S,0)\right) + g_{ph}\sum_{a,b} E^\dagger_{a,b}E_{a,b}}_{H_0}$$

$$\underbrace{+\,(g_{pair} - g_{pp}^{T=0}) \sum_{M_S=-1,0,1} A^\dagger_{1,0}(M_S,0)A_{1,0}(M_S,0) + (g_{pair} - g_{pp}^{T=1})A^\dagger_{0,1}(0,0)A_{0,1}(0,0)\,.}_{H_I}$$

H_I violates SU(4) symmetry

g_{pair}- strength of isovector like nucleon pairing (L=0, S=0, T=1, M_T=±1)
$g_{pp}^{T=1}$- strength of isovector spin-0 pairing (L=0, S=0, T=1, M_T=0
$g_{pp}^{T=0}$- strength of isoscalar spin-1 pairing (L=0, S=1, T=0)
g_{ph}- strength of particle-hole force

M_F and M_{GT} do not depend on the mean-field part of **H** and are governed by a weak violation of the **SU(4)** symmetry by the particle-particle interaction of **H**

$$M_F^{2\nu} = -\frac{48\sqrt{\frac{33}{5}}\,(g_{pair} - g_{pp}^{T=1})}{(5g_{pair} + 3g_{ph})(10g_{pair} + 6g_{ph})}$$

$$M_{GT}^{2\nu} = \frac{144\sqrt{\frac{33}{5}}}{5g_{pair} + 9g_{ph}}\left\{\frac{(g_{pair} - g_{pp}^{T=0})}{(10g_{pair} + 20g_{ph})} + \frac{2g_{ph}(g_{pair} - g_{pp}^{T=1})}{(10g_{pair} + 20g_{ph})(10g_{pair} + 6g_{ph})}\right\}$$

The $0\nu\beta\beta$-decay mechanisms with light and heavy neutrinos (V-A interaction)

Left-handed neutrinos: Majorana neutrino mass eigenstate N with arbitrary mass m_N

Faessler, Gonzales, Kovalenko, F. Š., PRD 90 (2014) 096010]

$$N = \sum_{\alpha=s,e,\mu,\tau} U_{N\alpha}\, \nu_\alpha$$

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_A^4 \left| \sum_N \left(U^2_{eN} m_N\right) m_p\, M'^{0\nu}(m_N, g_A^{\rm eff}) \right|^2$$

General case

$$M'^{0\nu}(m_N, g_A^{\rm eff}) = \frac{1}{m_p m_e} \frac{R}{2\pi^2 g_A^2} \sum_n \int d^3x\, d^3y\, d^3p \times e^{ip\cdot(\mathbf{x}-\mathbf{y})} \frac{\langle 0_F^+|J^{\mu\dagger}(\mathbf{x})|n\rangle\langle n|J^\dagger_\mu(\mathbf{y})|0_I^+\rangle}{\sqrt{p^2+m_N{}^2}\left(\sqrt{p^2+m_N{}^2}+E_n-\frac{E_I-E_F}{2}\right)}$$

$$M'^{0\nu}(m_N\to 0, g_A^{\rm eff}) = \frac{1}{m_p m_e} M'^{0\nu}_\nu(g_A^{\rm eff})$$

$$M'^{0\nu}(m_N\to \infty, g_A^{\rm eff}) = \frac{1}{m_N^2} M'^{0\nu}_N(g_A^{\rm eff})$$

Particular cases

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_A^4 \times \times \begin{cases} \left|\frac{\langle m_\nu\rangle}{m_e}\right|^2 \left|M'^{0\nu}_\nu(g_A^{\rm eff})\right|^2 & \text{for } m_N \ll p_F \\ \left|\langle\frac{1}{m_N}\rangle m_p\right|^2 \left|M'^{0\nu}_N(g_A^{\rm eff})\right|^2 & \text{for } m_N \gg p_F \end{cases}$$

$$\langle m_\nu\rangle = \sum_N U^2_{eN} m_N$$

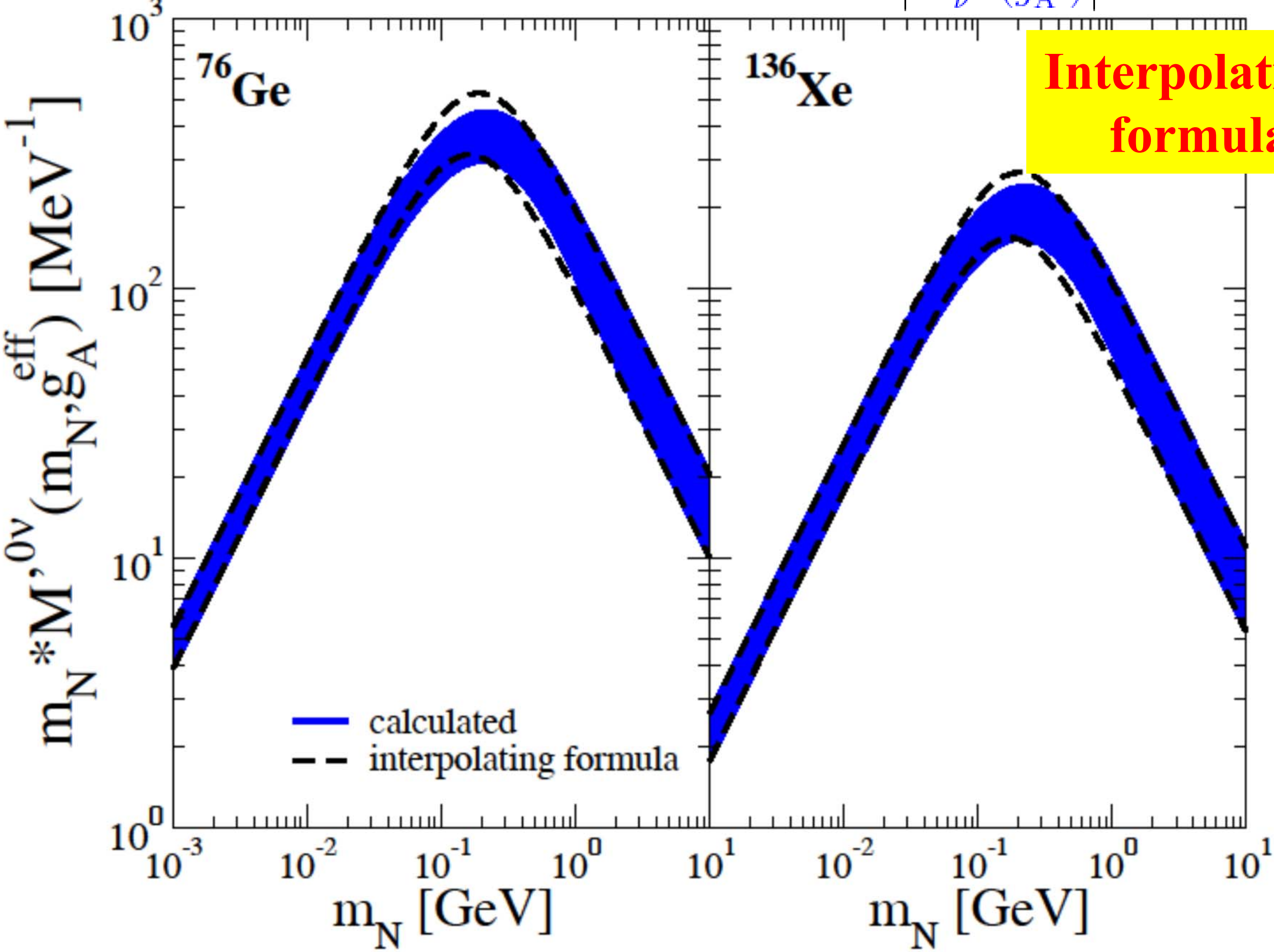
$$\left\langle \frac{1}{m_N} \right\rangle = \sum_N \frac{U^2_{eN}}{m_N}$$

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A} \cdot \left| m_p \sum_N U^2_{eN} \frac{m_N}{\langle p^2 \rangle + m_N^2} \right|^2,$$

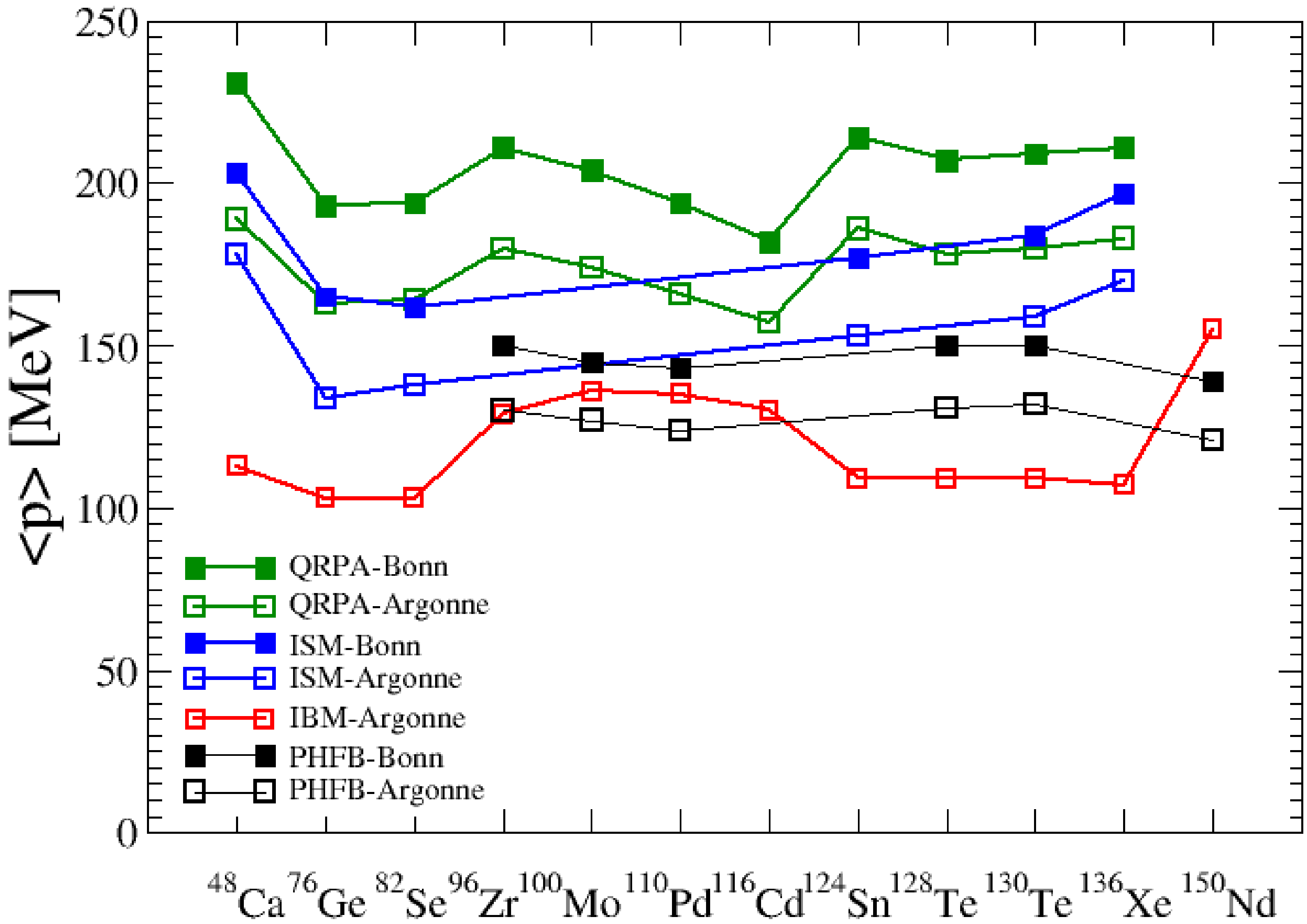
$$\mathcal{A} = G^{0\nu} g_A^4 \left| M'^{0\nu}_N (g_A^{\text{eff}}) \right|^2,$$

$$\langle p^2 \rangle = m_p m_e \left| \frac{M'^{0\nu}_N (g_A^{\text{eff}})}{M'^{0\nu}_\nu (g_A^{\text{eff}})} \right|^2 \approx 200 \;\; MeV$$

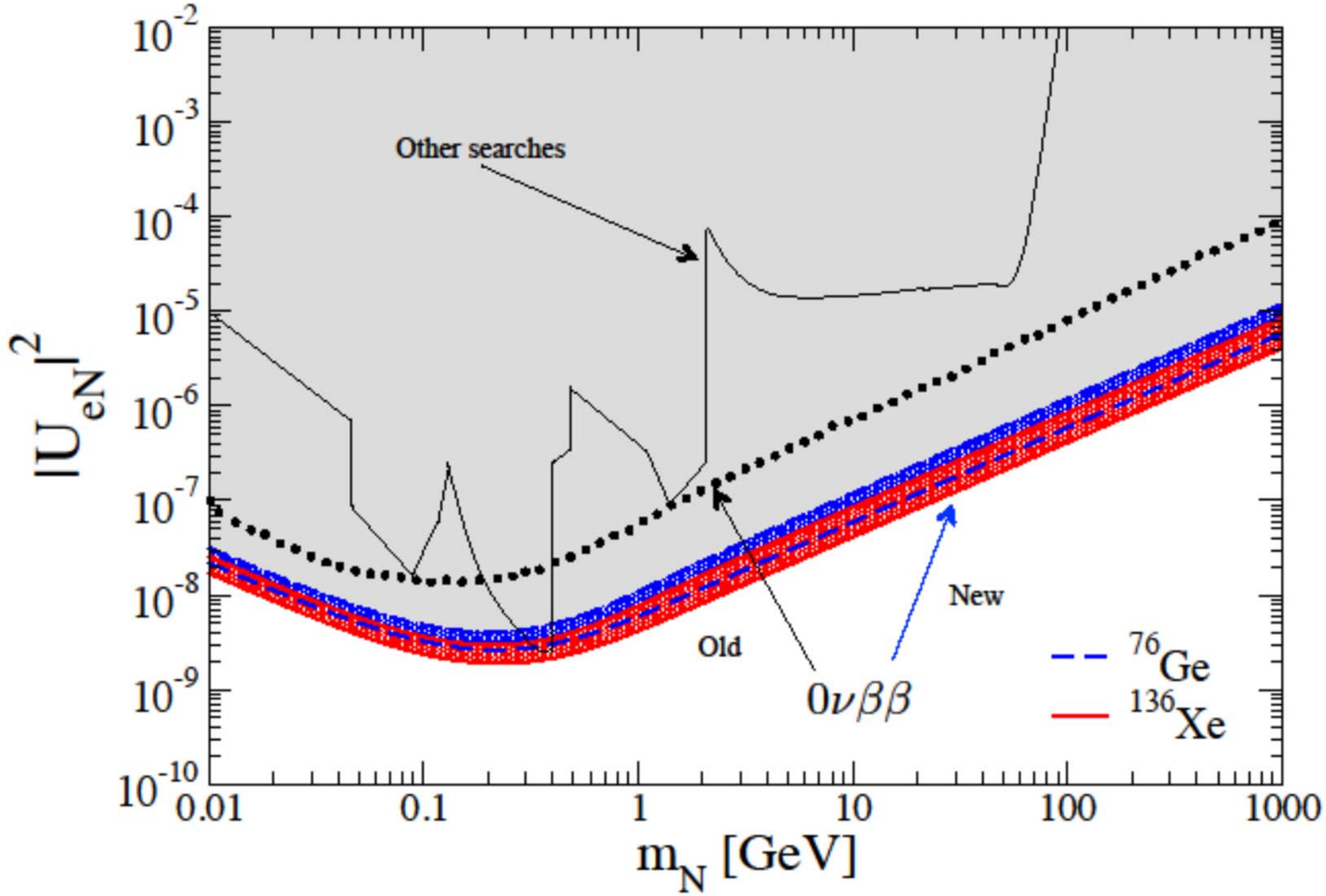
Interpolating formula



Averaged neutrino momentum calculated from NMEs

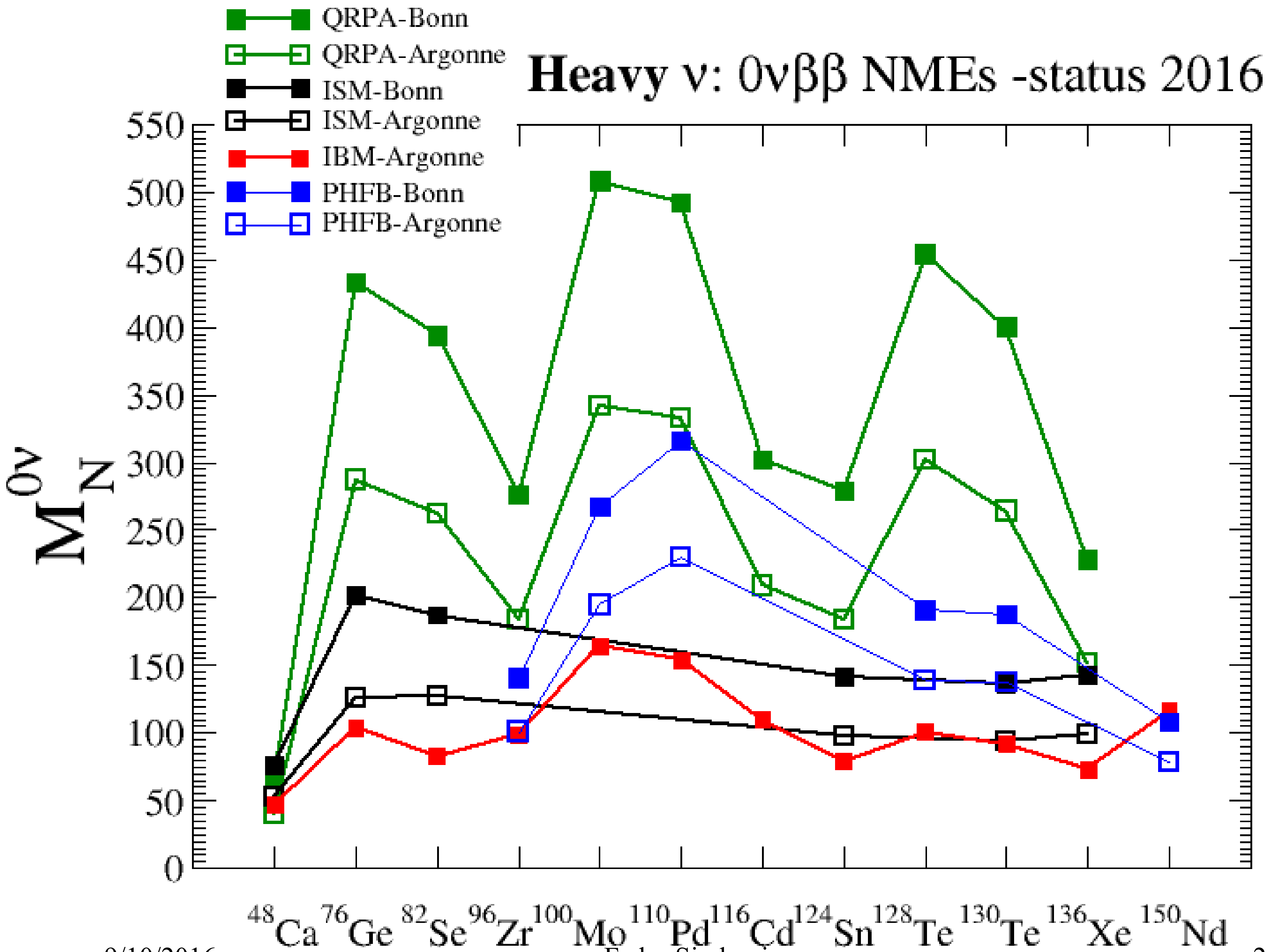


Exclusion plot in $|U_{eN}|^2 - m_N$ plane

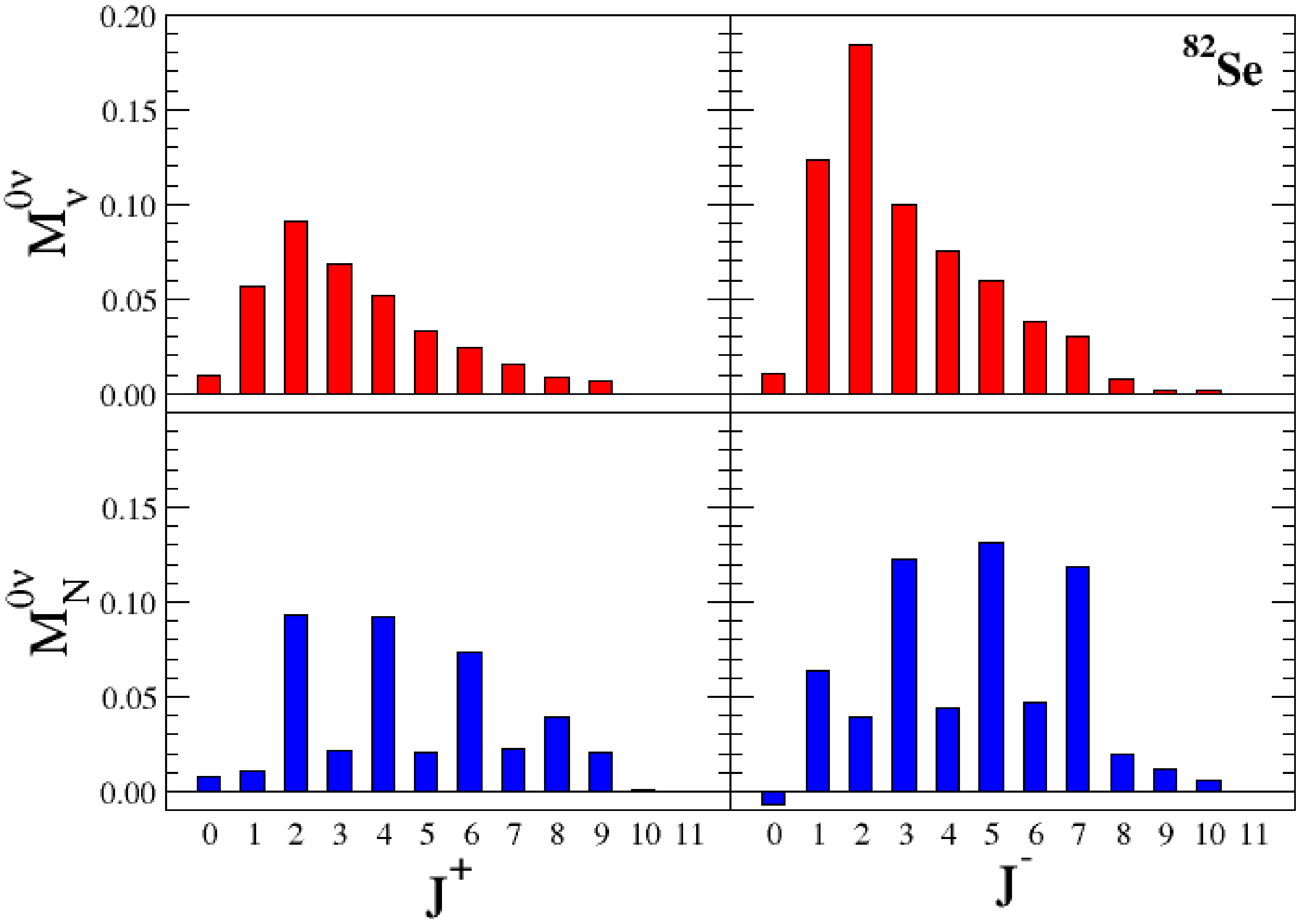


Improvements: i) QRPA (constrained Hamiltonian by 2νββ half-life, self-consistent treatment of src, restoration of isospin symmetry …), ii) More stringent limits on the 0νββ half-life

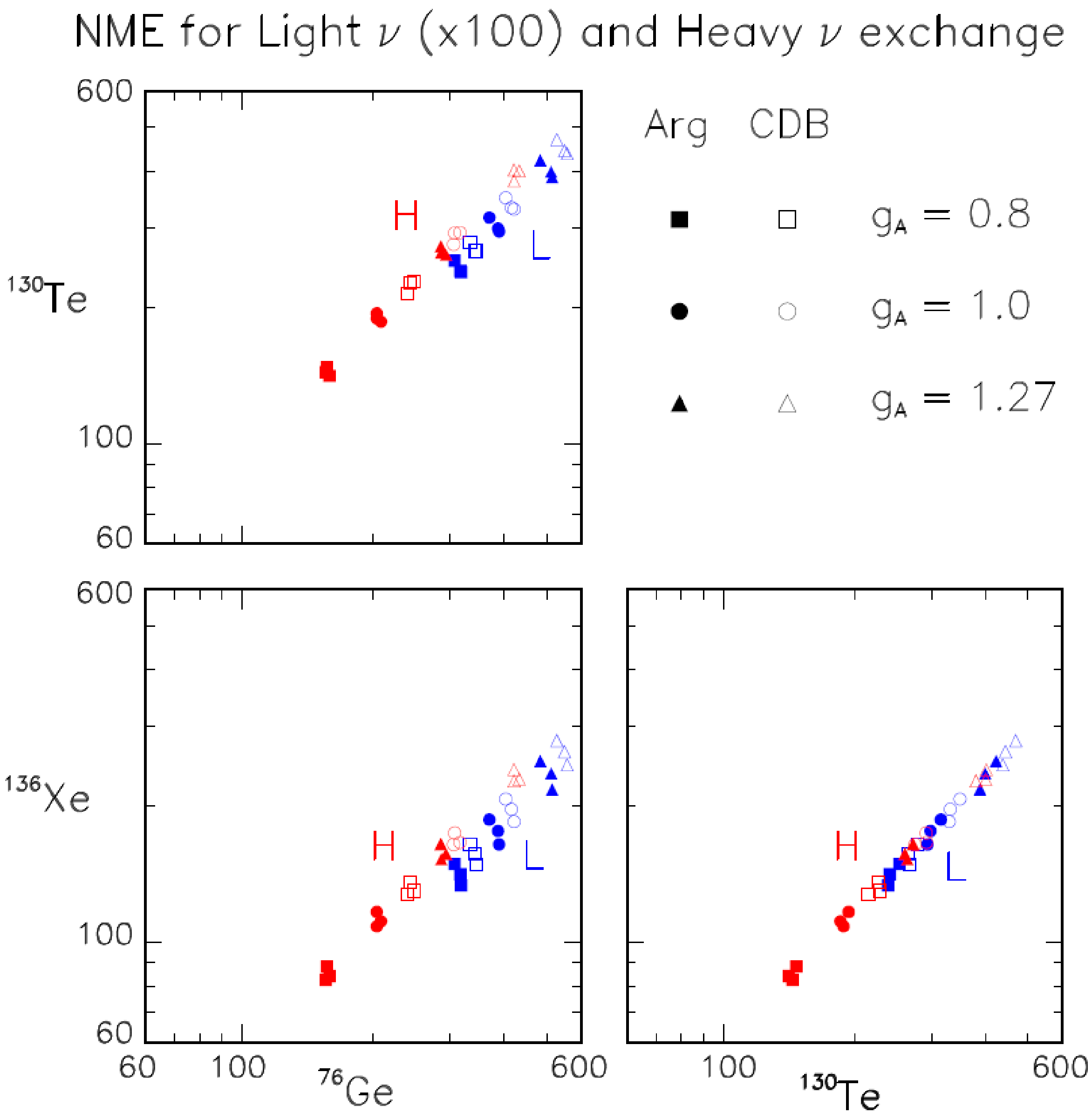
Heavy ν: 0νββ NMEs -status 2016



Multipole decomposition of NMEs normalized to unity



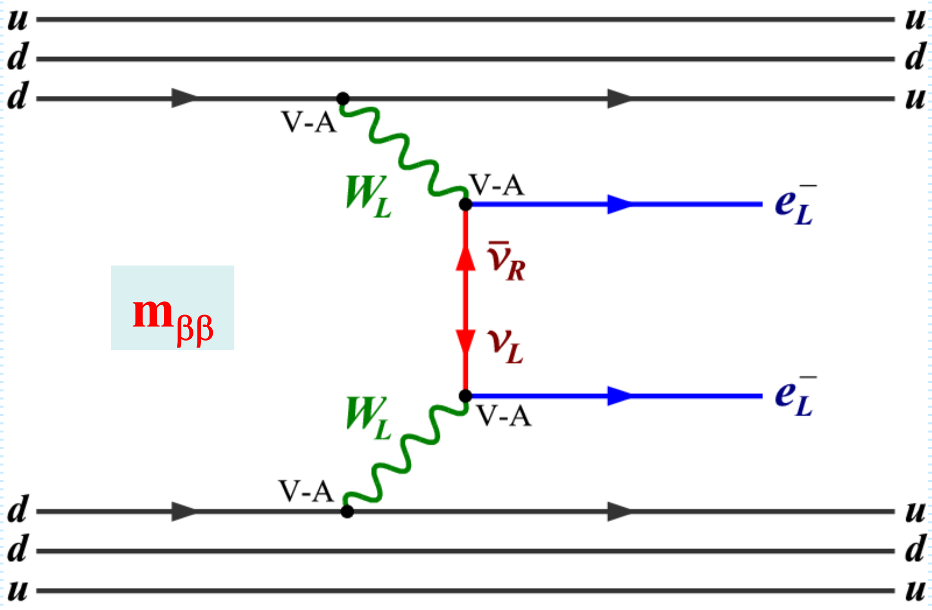
Only positive signs:
There is a correlation of errors;
It is practically not possible to distinguish both mechanisms even observating the 0νββ-decay for 3 nuclei



E. Lisi, A. Rotunno, F. Š., PRD 92, 093004 (2015)

The $0\nu\beta\beta$-decay with right-handed currents revisited (exchange of light neutrinos)

D. Štefánik, R. Dvornický, F.Š., P. Vogel, PRC 92, 055502 (2015)



$$H^\beta = \frac{G_\beta}{\sqrt{2}} \left[j_L{}^\rho J^\dagger_{L\rho} + \chi j_L{}^\rho J^\dagger_{R\rho} + \eta j_R{}^\rho J^\dagger_{L\rho} + \lambda j_R{}^\rho J^\dagger_{R\rho} + h.c. \right]$$

$$\eta \simeq -\tan\zeta, \quad \chi = \eta$$
$$\lambda \simeq (M_{W_1}/M_{W_2})^2.$$

$$j_L{}^\rho = \bar{e}\gamma_\rho(1-\gamma_5)\nu_{eL}$$

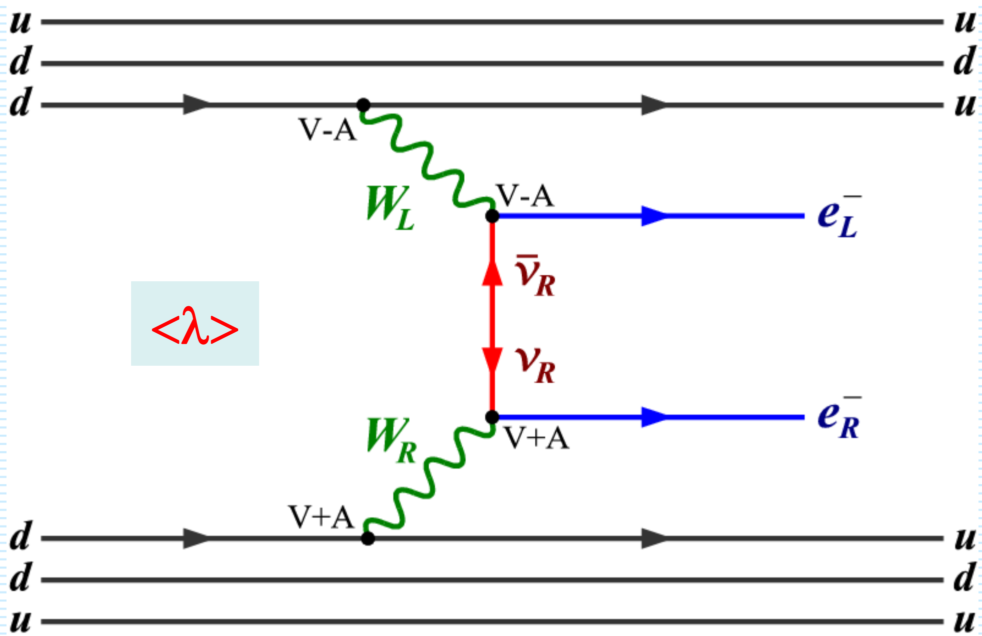
$$j_R{}^\rho = \bar{e}\gamma_\rho(1+\gamma_5)\nu_{eR}$$

Left-right symmetric models SO(10)

$$\begin{pmatrix} W_L^- \\ W_R^- \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^- \\ W_2^- \end{pmatrix}$$

$$\nu_{eL} = \sum_{j=1}^{3} \left(U_{ej}\nu_{jL} + S_{ej}(N_{jR})^C \right)$$

$$\nu_{eR} = \sum_{j=1}^{3} \left(T^*_{ej}(\nu_{jL})^C + V^*_{ej}N_{jR} \right)$$



Fedor

3x3 block matrices U, S, T, V are generalization of PMNS matrix

Zhi-zhong Xing, Phys. Rev. D **85**, 013008 (2012)

6x6 neutrino mass matrix

Basis

$$\mathcal{U} = \begin{pmatrix} U & S \\ T & V \end{pmatrix}$$

$$(\nu_L, (N_R)^{\bar{C}})^T$$

$$\mathcal{M} = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}$$

15 angles, 10+5 phases

Decomposition

$$\mathcal{U} = \begin{pmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & U_0 \end{pmatrix} \begin{pmatrix} A & R \\ S & B \end{pmatrix} \begin{pmatrix} V_0 & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{pmatrix}$$

Type seesaw I

$$A \approx \mathbf{1}, B \approx \mathbf{1}, R \approx \frac{m_D}{m_{LNV}}\mathbf{1}, S \approx -\frac{m_D}{m_{LNV}}\mathbf{1}$$

Approximation

$$U_0 \simeq V_0$$

LNV parameters

$$\langle\lambda\rangle \approx (M_{W_1}/M_{W_2})^2 \frac{m_D}{m_{LNV}} |\xi|$$

$$\langle\eta\rangle \approx -\tan\zeta \frac{m_D}{m_{LNV}} |\xi| ,$$

$$|\xi| = |c_{23}c_{12}^2 c_{13} s_{13}^2 - c_{12}^3 c_{13}^3 - c_{13}c_{23}c_{12}^2 s_{13}^2 - c_{12}c_{13}\left(c_{13}^2 s_{12}^2 + s_{13}^2\right)| \simeq 0.82$$

The 0νββ-decay rate with right-handed currents

$$\left[T_{1/2}^{0\nu}\right]^{-1} = \frac{\Gamma^{0\nu}}{\ln 2} = g_A^4\,|M_{GT}|^2 \left\{ C_{mm}\left(\frac{|m_{\beta\beta}|}{m_e}\right)^2 + C_{m\lambda}\frac{|m_{\beta\beta}|}{m_e}\langle\lambda\rangle\cos\psi_1 + C_{m\eta}\frac{|m_{\beta\beta}|}{m_e}\langle\eta\rangle\cos\psi_2 + C_{\lambda\lambda}\langle\lambda\rangle^2 + C_{\eta\eta}\langle\eta\rangle^2 + C_{\lambda\eta}\langle\lambda\rangle\langle\eta\rangle\cos(\psi_1-\psi_2) \right\}$$

Two additioanal phase-space factor G_{010} and G_{011}
(For w.f. A $G_{010}=G_{03}$, $G_{011}=G_{04}$)

The induced pseudoscalar term included

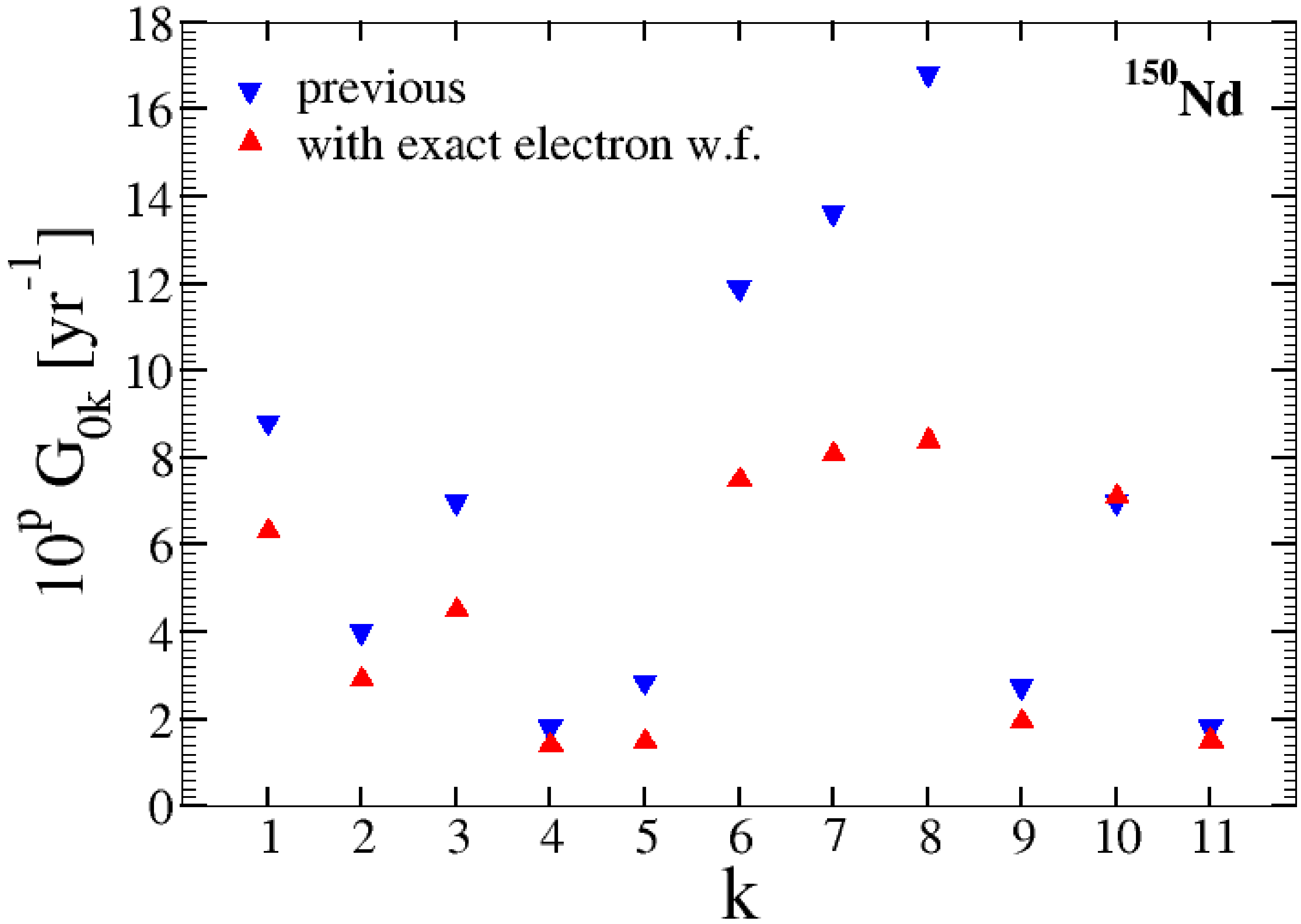
$$\begin{aligned}
\langle\lambda\rangle &= \lambda|\sum_j U_{ej}V_{ej}(g'_V/g_V)|,\\
\langle\eta\rangle &= \eta|\sum_j{}' U_{ej}V'_{ej}|,\\
\psi_1 &= \arg[\{\sum_j{}' m_j U_{ej}^2\}\{\sum_j{}' U_{ej}V_{ej}(g'_V/g_V\\
\psi_2 &= \arg[\{\sum_j{}' m_j U_{ej}^2\}\{\sum_j{}' U_{ej}V'_{ej}\}^*].
\end{aligned}$$

$$\begin{aligned}
C_{mm} &= (1-\chi_F+\chi_T)^2 G_{01},\\
C_{m\lambda} &= -(1-\chi_F+\chi_T)\left[\chi_{2-}G_{03}-\chi_{1+}G_{04}\right],\\
C_{m\eta} &= (1-\chi_F+\chi_T)\\
&\times \left[\chi_{2+}G_{03}-\chi_{1-}G_{04}-\chi_P G_{05}+\chi_R G_{06}\right],\\
C_{\lambda\lambda} &= \chi_{2-}^2 G_{02}+\frac{1}{9}\chi_{1+}^2 G_{011}-\frac{2}{9}\chi_{1+}\chi_{2-}G_{010},\\
C_{\eta\eta} &= \chi_{2+}^2 G_{02}+\frac{1}{9}\chi_{1-}^2 G_{011}-\frac{2}{9}\chi_{1-}\chi_{2+}G_{010}+\chi_P^2 G_{08}\\
&- \chi_P\chi_R G_{07}+\chi_R^2 G_{09},\\
C_{\lambda\eta} &= -2[\chi_{2-}\chi_{2+}G_{02}-\frac{1}{9}\left(\chi_{1+}\chi_{2+}+\chi_{2-}\chi_{1-}\right)G_{010}\\
&+ \frac{1}{9}\chi_{1+}\chi_{1-}G_{011}]. \qquad (37)
\end{aligned}$$

Phase-space factors for ^{150}Nd

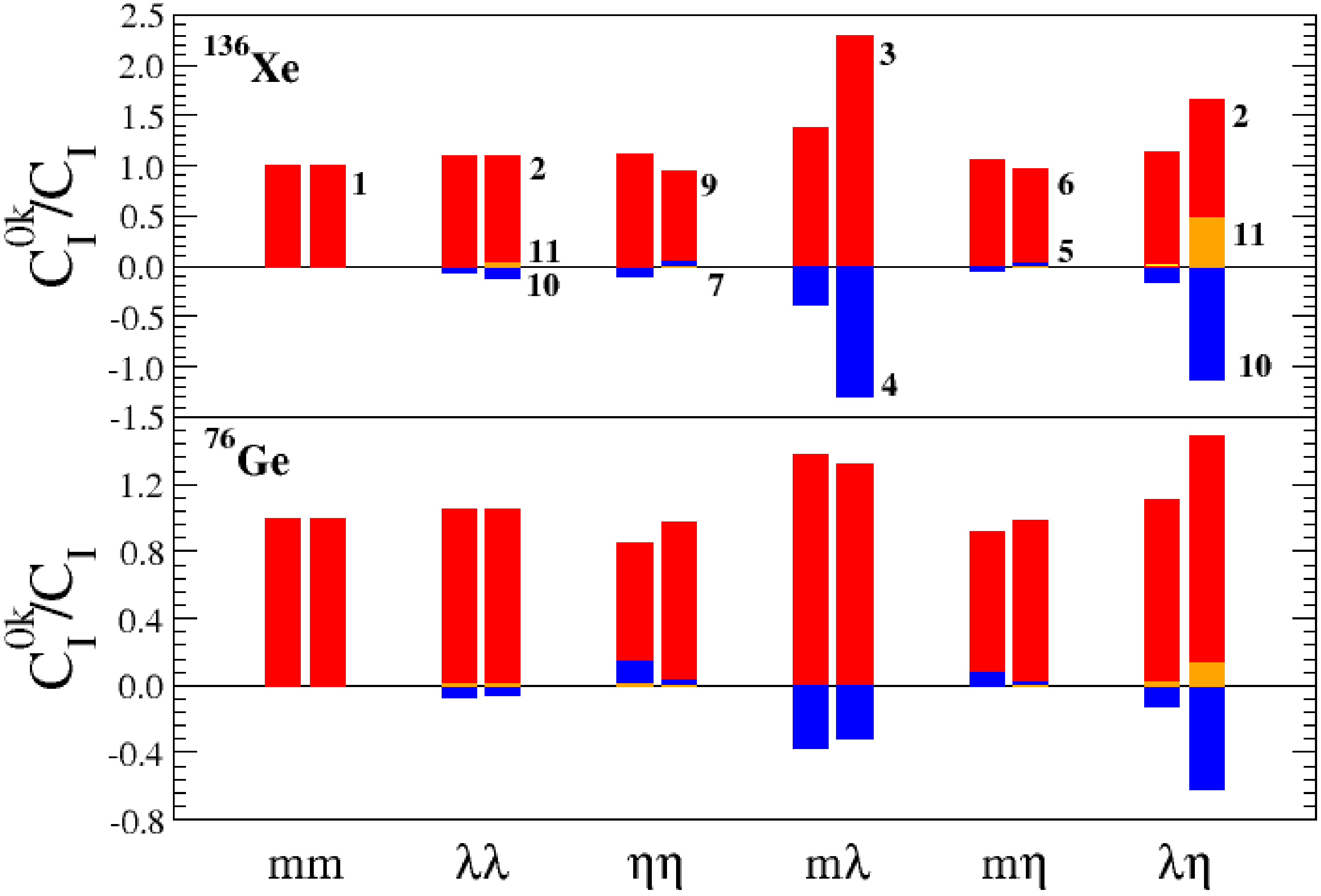
$$\Psi(\varepsilon, \boldsymbol{r}) = \Psi^{(s_{1/2})}(\varepsilon, \boldsymbol{r}) + \Psi^{(p_{1/2})}(\varepsilon, \boldsymbol{r})$$

The exact Dirac wave functions with finite nuclear size corrections, which are taken into account in by a uniform charge distribution in a sphere of nucleus, and the screening of atomic electrons



Simplified expressions for $T_{1/2}^{0\nu}$ for <η> and <λ> mech.

$$\left(T_{1/2}^{0\nu}\right)^{-1} \approx |\langle\eta\rangle|^2\, G_{09}\, |M_{\eta\eta}|^2 \qquad \left(T_{1/2}^{0\nu}\right)^{-1} \approx |\langle\lambda\rangle|^2\, G_{02}\, |M_{\lambda\lambda}|^2$$



Current constraints on the effective neutrino mass and effective right-handed current parameters

	^{76}Ge		^{136}Xe	
w.f.	A	D	A	D
	QRPA			
$\lvert m_{\beta\beta}\rvert$ [eV]	0.321	0.333	0.285	0.315
$\lvert m_{\beta\beta}\rvert$ [eV] (for $\langle\eta\rangle = \langle\eta\rangle = 0$)	0.271	0.284	0.251	0.285
$\langle\eta\rangle \times 10^{-9}$	3.093	3.239	2.077	2.337
$\langle\lambda\rangle \times 10^{-7}$	4.943	5.163	3.822	4.370
	ISM			
$\lvert m_{\beta\beta}\rvert$ [eV]	0.515	0.535	0.222	0.245
$\lvert m_{\beta\beta}\rvert$ [eV] (for $\langle\eta\rangle = \langle\eta\rangle = 0$)	0.436	0.458	0.193	0.220
$\langle\eta\rangle \times 10^{-9}$	6.370	6.760	2.975	3.291
$\langle\lambda\rangle \times 10^{-7}$	8.462	8.841	3.000	3.378

$^{76}Ge\ T^{0\nu}_{1/2} \geq 3.0\times 10^{25}$

$^{136}Xe\ T^{0\nu}_{1/2} \geq 3.4 \times 10^{25}$

ISM E. Caurier, F. Nowacki, A. Poves and J. Retamosa, Phys. Rev. Lett. **77**, 1954 (1996)

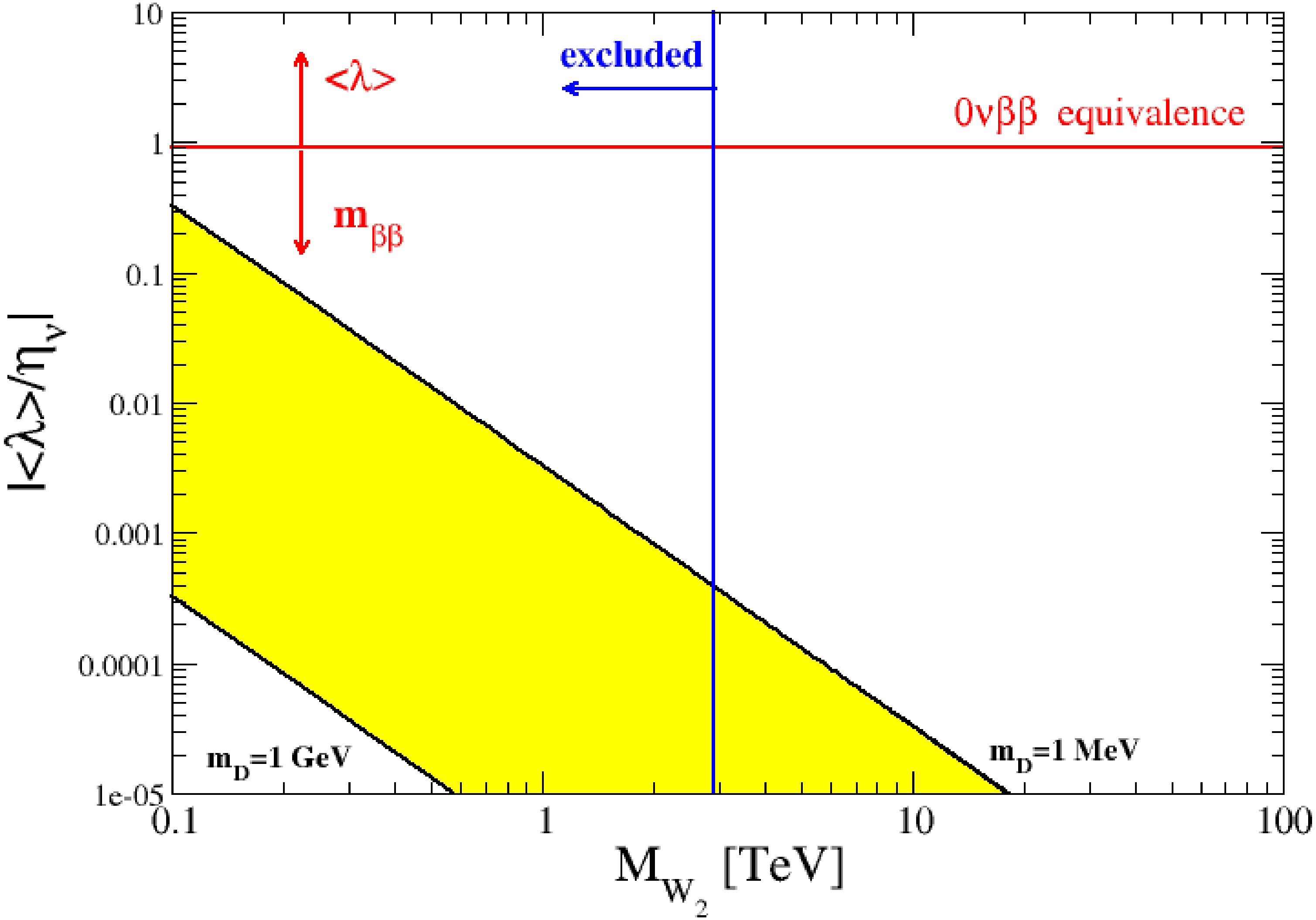
QRP K. Muto, E. Bender and H.V. Klapdor, Z. Phys. A **334**, 187 (1989)

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e} = \sum_i ((U_0)_{ei})^2 \frac{m_i}{m_e} \approx \frac{m_D}{m_{LNV}} \frac{m_D}{m_e} \sum_i (U_0)^2_{ei} \frac{m_i \, m_{LNV}}{m_D^2}$$

if ≈ 1

$$|\langle\lambda\rangle| \approx \frac{m_D}{m_{LNV}} \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 |\xi|$$

$$\begin{aligned} |\xi| &= |c_{23}c_{12}^2c_{13}s_{13}^2 - c_{12}^3c_{13}^3 \\ &\quad - c_{13}c_{23}c_{12}^2s_{13}^2 - c_{12}c_{13}c_{13}^2s_{12}^2 + s_{13}^2| \\ &\simeq 0.82 \end{aligned}$$



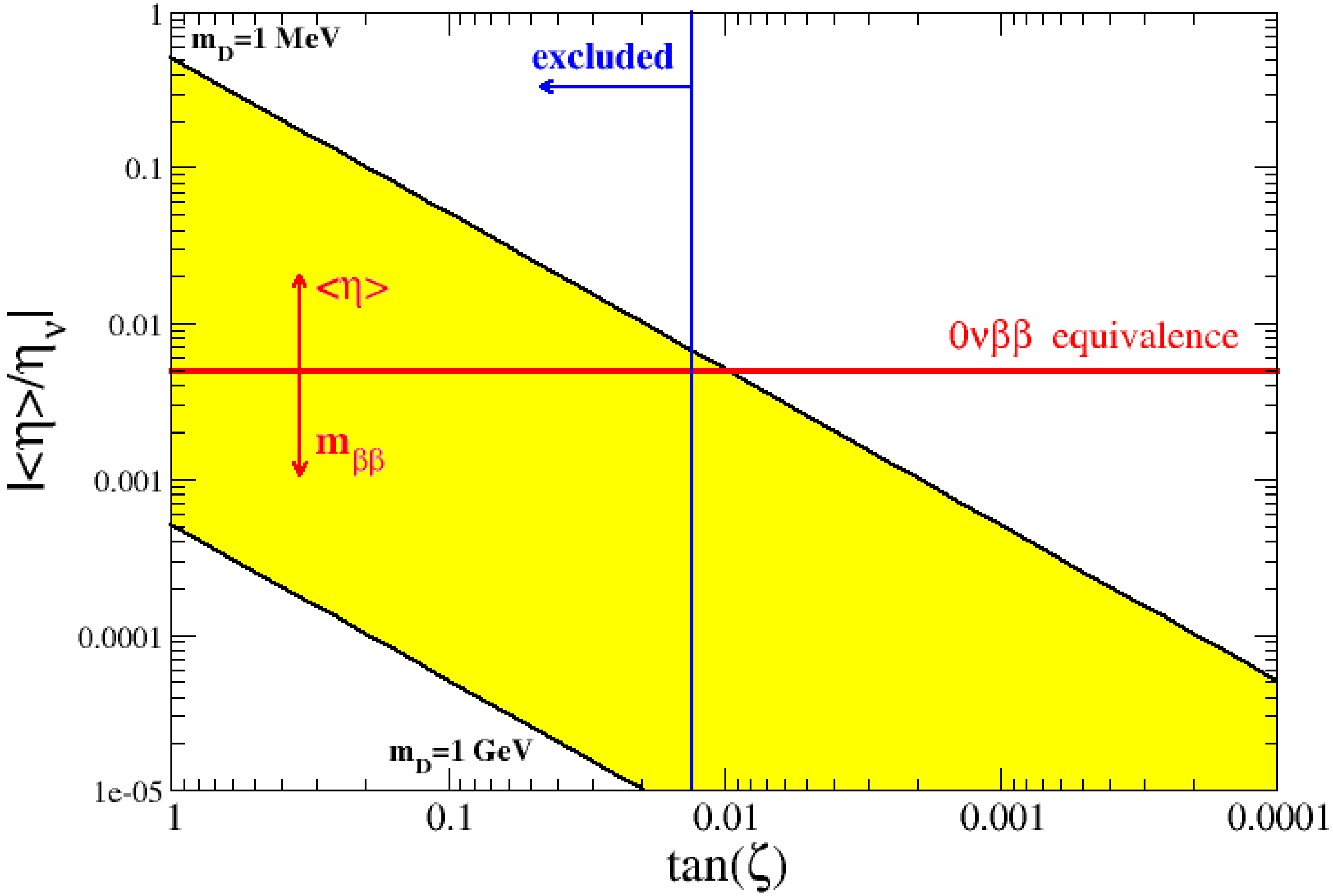
$$\eta_\nu = \frac{m_{\beta\beta}}{m_e} = \sum_i ((U_0)_{ei})^2 \frac{m_i}{m_e}$$

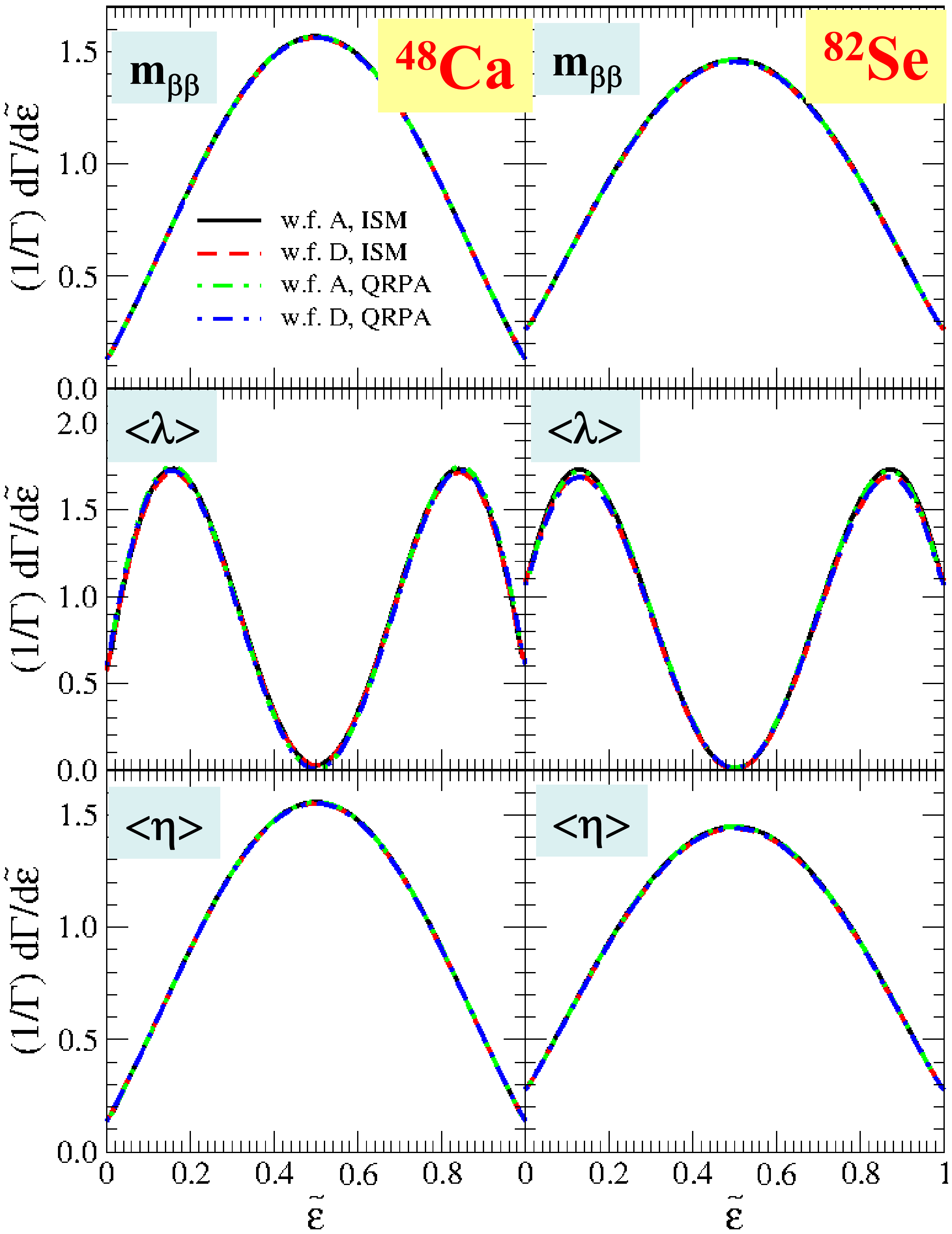
$$\approx \frac{m_D}{m_{LNV}} \frac{m_D}{m_e} \sum_i (U_0)^2_{ei} \frac{m_i\ m_{LNV}}{m_D^2}$$

if ≈ 1

$$|\langle\eta\rangle| \approx \frac{m_D}{m_{LNV}} \tan(\zeta)\ |\xi|$$

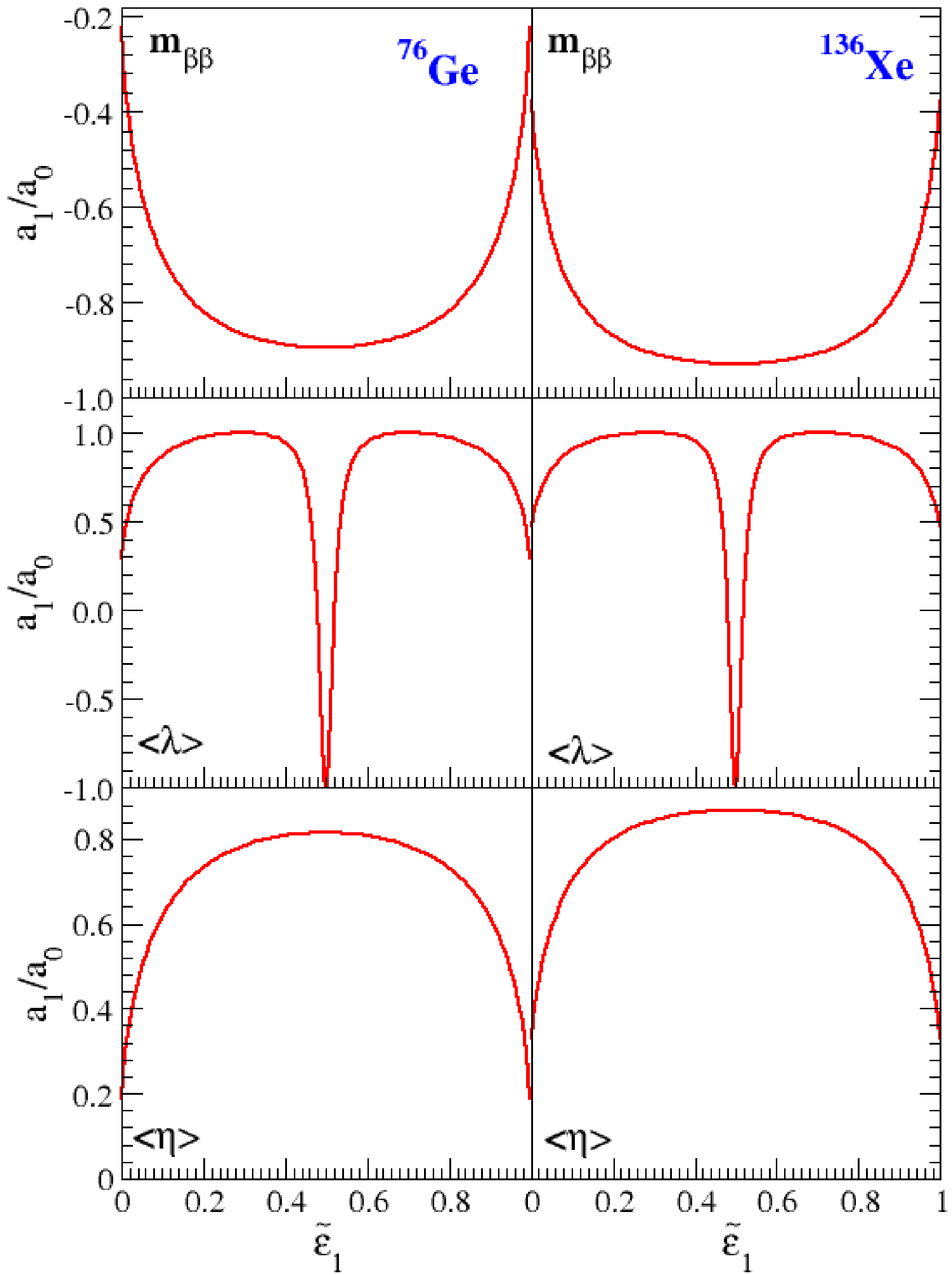
$$|\xi| = |c_{23}c_{12}^2c_{13}s_{13}^2 - c_{12}^3c_{13}^3 - c_{13}c_{23}c_{12}^2s_{13}^2 - c_{12}c_{13}c_{13}^2s_{12}^2 + s_{13}^2| \simeq 0.82$$





The single differential decay rate normalized to the total decay rate as function of electron energy for 3 limiting cases:

SuperNEMO experiment can measure it



Angular correlation factor as function of electron energy

$$\frac{d\Gamma}{d\cos\theta\, d\tilde{\varepsilon}_1} = a_0\left(1 + a_1/a_0 \cos\theta\right)$$

SuperNEMO experiment can measure it

The 0νββ-decay with right-handed currents revisited (exchange of heavy neutrinos)

J.D.Vergados, H. Ejiri, , F.Š., submitted

$$\left(T^{0\nu}_{1/2} G^{0\nu} g_A^4\right)^{-1} = \left|\eta_\nu M^{0\nu}_\nu + \eta^L_N M^{0\nu}_N\right|^2 + \left|\eta^R_N M^{0\nu}_N\right|^2$$

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e} = \sum_i ((U_0)_{ei})^2 \frac{m_i}{m_e} \approx \frac{m_p}{m_{LNV}} \frac{m_D^2}{m_e m_p} \sum_i (U_0)^2_{ei} \frac{m_i\, m_{LNV}}{m_D^2}$$

$$\eta^R_N = \frac{m_p}{m_{LNV}} \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 \sum_i (U^{22}_{ei})^2 \frac{m_{LNV}}{M_i} \approx \frac{m_p}{m_{LNV}} \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 \sum_i (V_0)^2_{ei} \frac{m_{LNV}}{M_i}$$

Suppressed mechanism:

$$\eta^L_N = \frac{m_p}{m_{LNV}} \sum_i (U^{(12)}_{ei})^2 \frac{m_{LNV}}{M_i} \approx \frac{m_p}{m_{LNV}} \left(\frac{m_D}{m_{LNV}}\right)^2 \sum_i \frac{m_{LNV}}{M_i}$$

Could be of comparable Importance, if e.g.

$$\sum_i (U_0)^2_{ei} \frac{m_i\, m_{LNV}}{m_D^2} \simeq \sum_i (V_0)^2_{ei} \frac{m_{LNV}}{M_i}$$

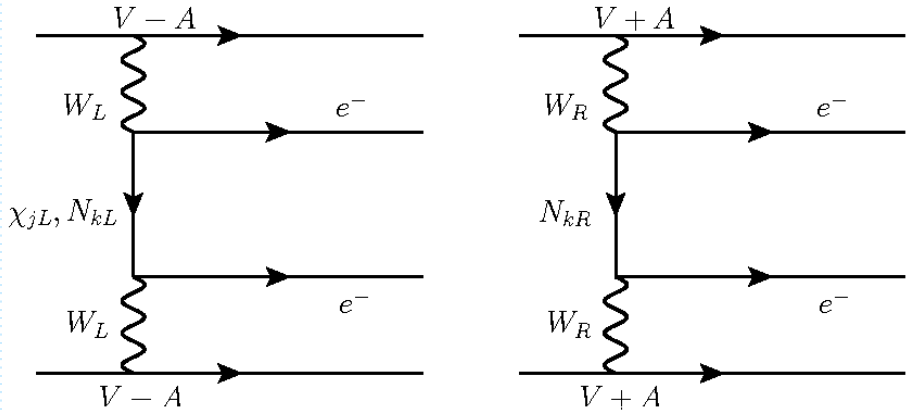
$$\frac{m_D^2}{m_e m_p} M^{0\nu}_\nu \simeq \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 M^{0\nu}_N$$

Two non-interfering mechanisms of the $0\nu\beta\beta$-decay (light LH and heavy RH neutrino exchange)

Half-life:

$$\frac{1}{T^{0\nu}_{1/2,i}G^{0\nu}_i(E,Z)} \cong |\eta_\nu|^2|M'^{0\nu}_{i,\nu}|^2 + |\eta_R|^2|M'^{0\nu}_{i,N}|^2$$

$$\eta_\nu = \frac{m_{\beta\beta}}{m_e}$$



Set of equations:

$$\frac{1}{T_1G_1} = |\eta_\nu|^2|M'^{0\nu}_{1,\nu}|^2 + |\eta_R|^2|M'^{0\nu}_{1,N}|^2$$

$$\frac{1}{T_2G_2} = |\eta_\nu|^2|M'^{0\nu}_{2,\nu}|^2 + |\eta_R|^2|M'^{0\nu}_{2,N}|^2$$

Solutions:

$$|\eta_\nu|^2 = \frac{|M'^{0\nu}_{2,N}|^2/T_1G_1 - |M'^{0\nu}_{1,N}|^2/T_2G_2}{|M'^{0\nu}_{1,\nu}|^2|M'^{0\nu}_{2,N}|^2 - |M'^{0\nu}_{1,N}|^2|M'^{0\nu}_{2,\nu}|^2}$$

$$|\eta_R|^2 = \frac{|M'^{0\nu}_{1,\nu}|^2/T_2G_2 - |M'^{0\nu}_{2,\nu}|^2/T_1G_1}{|M'^{0\nu}_{1,\nu}|^2|M'^{0\nu}_{2,N}|^2 - |M'^{0\nu}_{1,N}|^2|M'^{0\nu}_{2,\nu}|^2}$$

$$\eta^R_N = \left(\frac{M_W}{M_{WR}}\right)^4 \sum_k^{heavy} V^2_{ek}\,\frac{m_p}{M_k}$$

A. Faessler, A. Meroni, S.T. Petcov, F. Š., J.D. Vergados, Phys. Rev. D 83, 113003 (2011); JHEP 1302, 025 (2013)

Two non-interfering mechanisms of the $0\nu\beta\beta$-decay
(light LH and heavy RH neutrino exchange)

Pure $m_{\beta\beta}$ mech.

The positivity condition:

$$\frac{T_1 G_1 |M'^{0\nu}_{1,N}|^2}{G_2 |M'^{0\nu}_{2,N}|^2} \le T_2 \le \frac{T_1 G_1 |M'^{0\nu}_{1,\nu}|^2}{G_2 |M'^{0\nu}_{2,\nu}|^2}$$

Very narrow ranges!

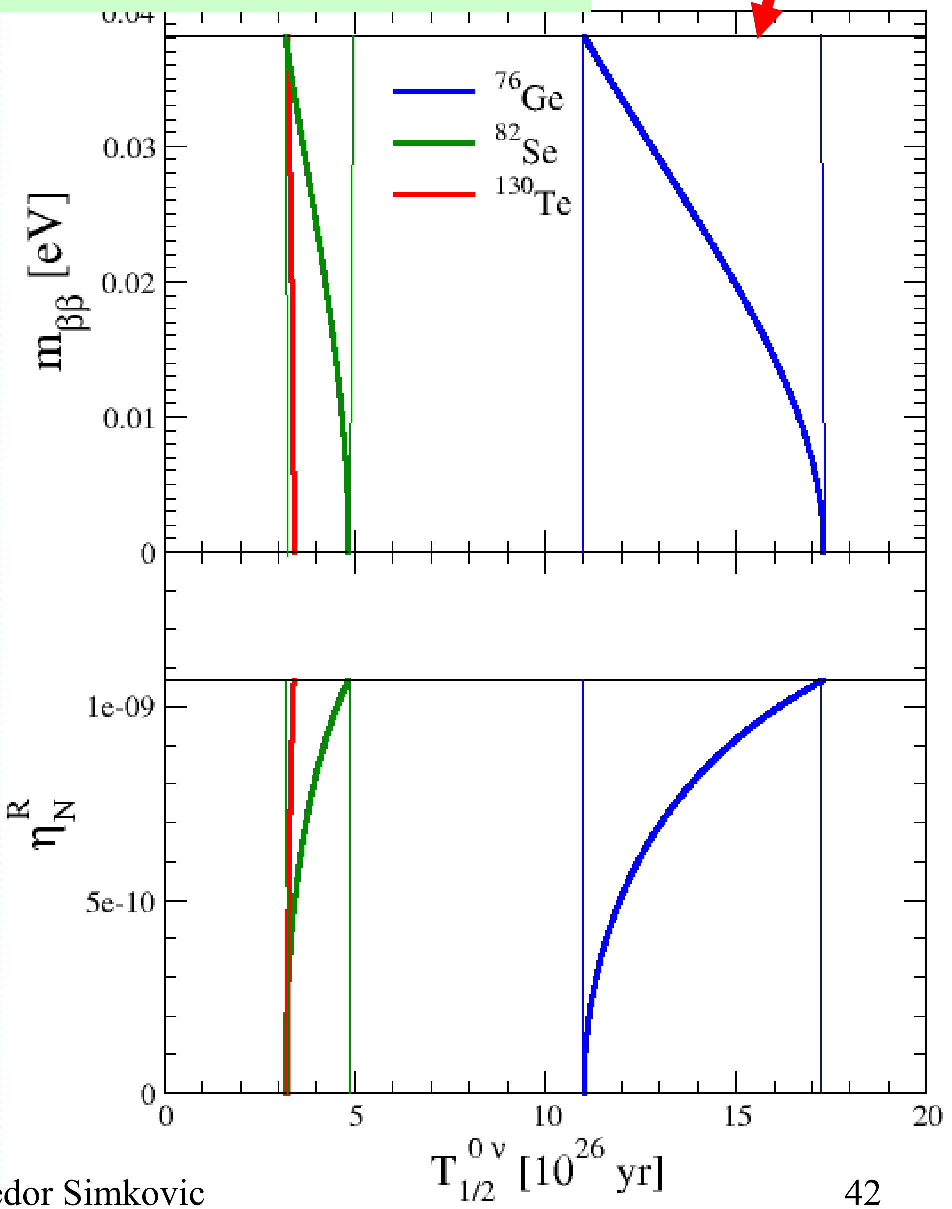
$$1.10 \le \frac{T^{0\nu}_{1/2}(^{76}Ge)}{T^{0\nu}_{1/2}(^{136}Xe)} \le 1.73$$

$$3.17 \le \frac{T^{0\nu}_{1/2}(^{82}Se)}{T^{0\nu}_{1/2}(^{136}Xe)} \le 4.83$$

$$3.22 \le \frac{T^{0\nu}_{1/2}(^{130}Te)}{T^{0\nu}_{1/2}(^{136}Xe)} \le 3.40$$

Assumption:

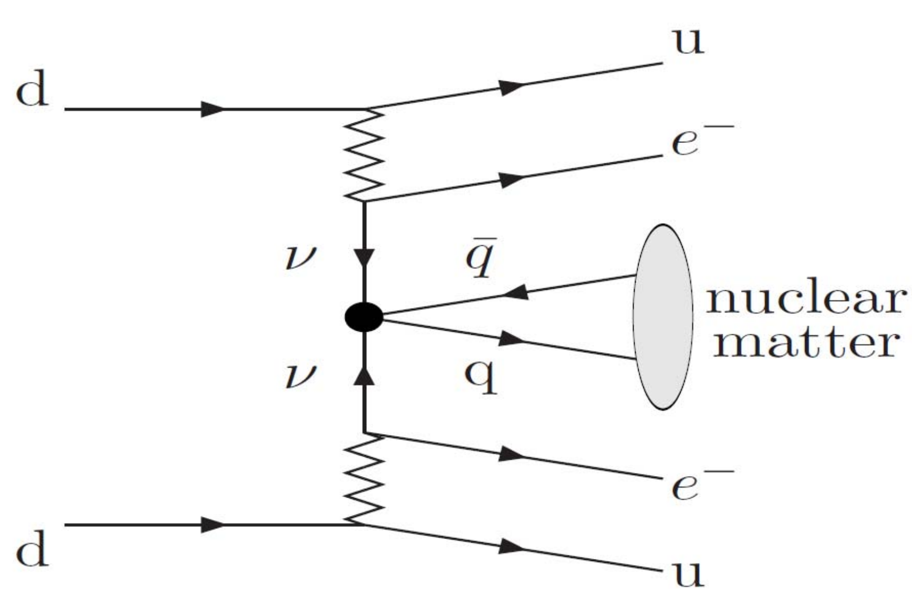
$$T^{0\nu}_{1/2}(^{136}Xe) = 1.0\ 10^{27} yr$$

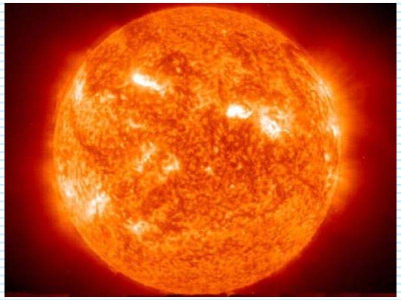


Nuclear medium effect on the light neutrino mass exchange mechanism of the $0\nu\beta\beta$ decay

S.G. Kovalenko, M.I. Krivoruchenko, F. Š., Phys. Rev. Lett. 112 (2014) 142503

A novel effect in $0\nu\beta\beta$ decay related with the fact, that its underlying mechanisms take place in the nuclear matter environment:
+ Low energy 4-fermion $\Delta L \neq 0$ Lagrangian
+ In-medium Majorana mass of neutrino
+ $0\nu\beta\beta$ constraints on the universal scalar couplings

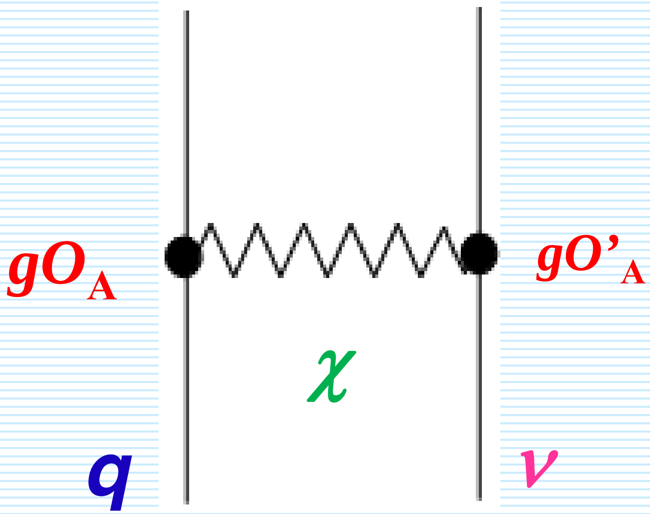




Non-standard ν–int. discussed e.g., in the context of ν–osc. at Sun

$\rho_{Sun} = 1.4\ g/cm^3$
$\rho_{Earth} = 5.5\ g/cm^3$
$\rho_{nucleus} = 2.3\ 10^{14}\ g/cm^3$

Non-standard interactions might be easily detected in nucleus rather than in vacuum



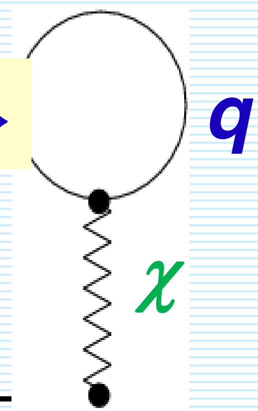
Low energy 4-fermion $\Delta L \neq 0$ Lagrangian

$$L_{\text{eff}} = \frac{g^2}{m_\chi^2} \sum_A (\bar{q} O_A q)(\bar{\nu} O'_A \nu),$$

$$m_\chi \gtrsim M_W .$$

$0\nu\beta\beta$-decay

density →



oscillation experiments
tritium β-decay, cosmology

$$\Sigma_\nu^{\text{vac}} = \text{-}\times\text{-},$$

$$\Sigma_\nu^{\text{medium}} = \text{-}\times\text{-} +$$

Classification of the vertices gO_A and gO'_A

$$\mathcal{L}_{\mathrm{free},\nu} = \frac{1}{4}\sum_i \bar{\nu}_i i\gamma^\mu \overleftrightarrow{\partial}_\mu \nu_i - \frac{1}{2}\sum_i m_i \bar{\nu}_i \nu_i.$$

$$\mathcal{L}_{\mathrm{eff}} = \frac{g_\chi}{m_\chi^2}\bar{q}q\sum_{a=1}^{6}\sum_{ij} g_{ij}^a J_{ij}^a$$

In nuclei, mean fields are created by scalar and vector currents (σ, ω).

Vector currents do not flip the spin of neutrinos
and do not contribute to the 0νββ decay.

Symmetric and antisymmetric scalar neutrino currents J^a_{ij}

a	S	a	S	a	A
1	$\bar{\nu}_i^c \nu_j$	3	$\partial_\mu(\bar{\nu}_i^c \gamma_5 \gamma^\mu \nu_j)$	5	$\partial_\mu(\bar{\nu}_i^c \gamma^\mu \nu_j)$
2	$\bar{\nu}_i^c i\gamma_5 \nu_j$	4	$\bar{\nu}_i^c \gamma^\mu i \overleftrightarrow{\partial}_\mu \nu_j$	6	$\bar{\nu}_i^c \gamma_5 \gamma^\mu i \overleftrightarrow{\partial}_\mu \nu_j$

g^a_{ij} are real symmetric for a = 1,2,3,4 and imaginary antisymmetric for a = 5,6. In the limit of $R = \infty$, the currents a = 3,5 vanish.

Mean field: $\bar{q}q \rightarrow \langle \bar{q}q \rangle$ **and** $\langle \bar{q}q \rangle \approx 0.5 \langle q^\dagger q \rangle \approx 0.25\,\mathrm{fm}^{-3}$

The effect depends on $\langle \chi \rangle = -\frac{g_\chi}{m_\chi^2} \langle \bar{q}q \rangle$

A comparison with G_F:

$$\frac{g_\chi g_{ij}^a}{m_\chi^2} = \frac{G_F}{\sqrt{2}} \varepsilon_{ij}^a$$

Typical scale: $\langle \chi \rangle g_{ij}^a = -\frac{G_F}{\sqrt{2}} \langle \bar{q}q \rangle \varepsilon_{ij}^a \approx -25\, \varepsilon_{ij}^a \ \mathrm{eV}$

We expect:

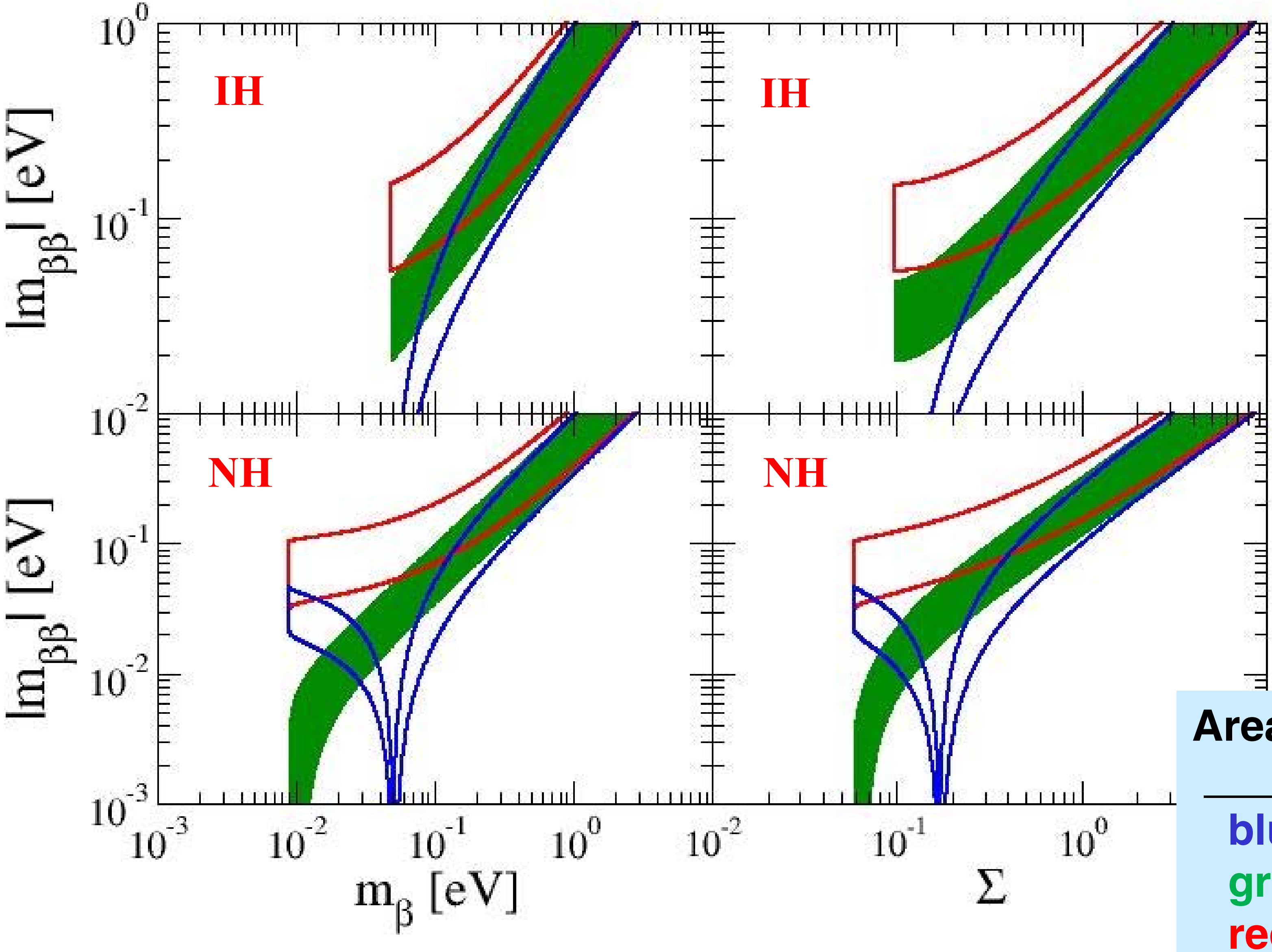
$$25\, \varepsilon_{ij}^a < 1 \rightarrow m_\chi^2 > 25 \frac{g_\chi g_{ij}^a \sqrt{2}}{G_F} \sim 1\,\mathrm{TeV}^2$$

Universal scalar interaction $g_{ij}^a = \delta_{ij} g_a \quad \varepsilon_{ij}^a = \delta_{ij} \varepsilon_a$

In medium effective Majorana ν mass

$$m_{\beta\beta} = \sum_{i=1}^{n} U_{ei}^2 \xi_i \frac{\sqrt{(m_i + \langle \chi \rangle g_1)^2 + (\langle \chi \rangle g_2)^2}}{(1 - \langle \chi \rangle g_4)^2}.$$

Complementarity between β-decay, 0νββ –decay and cosmological measurements might be spoiled



Area	$\langle\chi\rangle g_1$ [eV]
blue	-0.05
green	0
red	1

Instead of Conclusions

We are at the beginning of the Road…

The observation will prove Majorana nature of neutrinos.
The spectrum of neutrino masses might remain undetermined.