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Neutrino mass, double beta decay and nuclear structure

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OUTLINE

- ***Introduction***
  ν-oscillations and ν-masses
- ***The (simpliest, sterile ν, LR-symmetric model)***
  0νββ-decay scenario
- ***Improved description of the 2νββ-decay***
  quenching of g_A
- ***Conclusions***

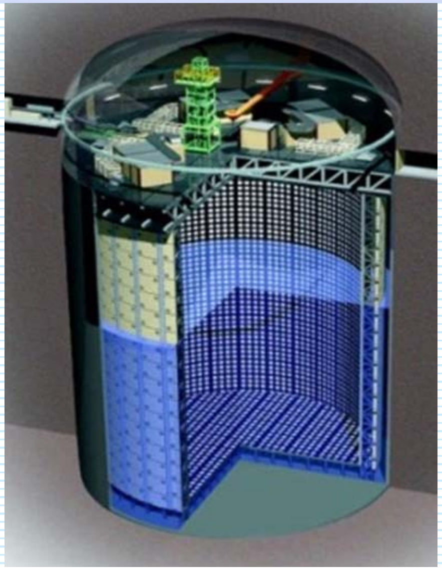
Acknowledgements: **A. Faesler (Tuebingen), P. Vogel (Caltech), S. Kovalenko (Valparaiso U.), M. Krivoruchenko (ITEP Moscow), S. Petcov (SISSA), D. Štefánik, R. Dvornický (Comenius U.) …**

Neutrino oscillations
Dubna, 60-years ago …

Bruno Pontecorvo
Mr. Neutrino
(22.8.1913-24.9.1993)

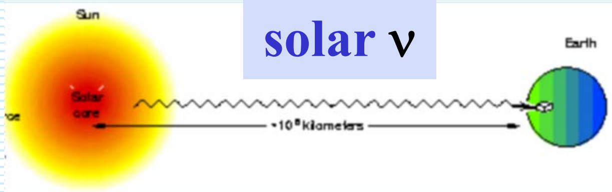
SuperKamiokande

Zh.Eksp.Teor.Fiz, 32 (1957) 32

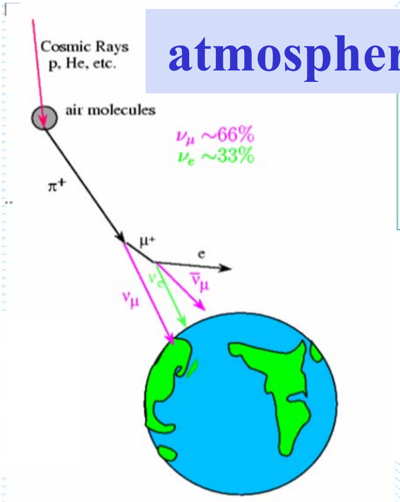


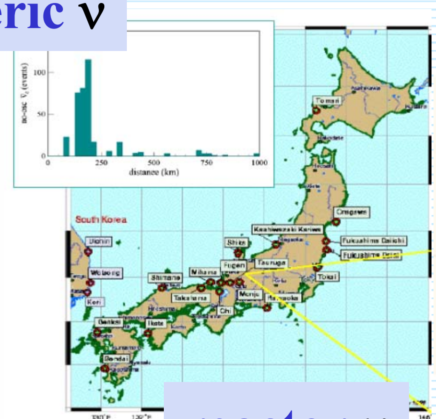
θ_{12}, θ_{23}

solar ν

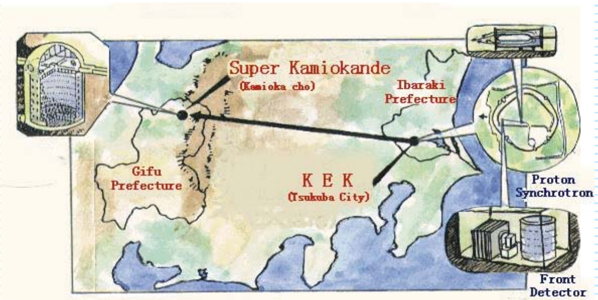


atmospheric ν

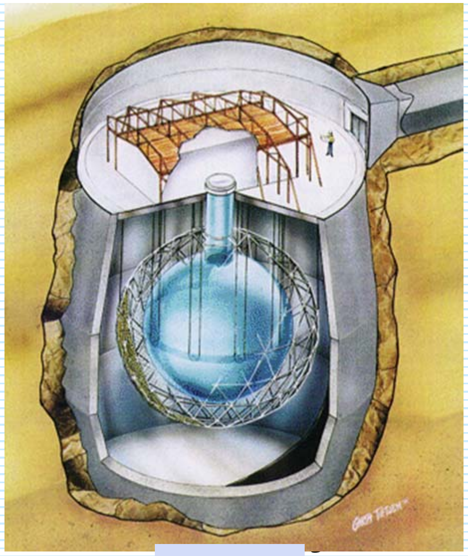




reactor ν



accelerator ν



SNO

Observation of ν-oscillations = the first prove of the BSM physics

mass-squared differences: $\Delta m^2_{SUN} \cong 7.5\ 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{ATM} \cong 2.4\ 10^{-3}\ \mathrm{eV}^2$

The observed small neutrino masses (limits from tritium β-decay, cosmology) have profound implications for our understanding of the Universe and are now a major focus in astro, particle and nuclear physics and in cosmology.

PMNS unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

large off-diagonal values

$$\begin{pmatrix} 0.82 & 0.54 & -0.15 \\ -0.35 & 0.70 & 0.62 \\ 0.44 & -0.45 & 0.77 \end{pmatrix}$$

3 angles: $\theta_{12}=33.36^o$ (solar), $\theta_{13}=8.66^o$ (reactor), $\theta_{23}=40.0^o$ or 50.4^o (atmospheric)

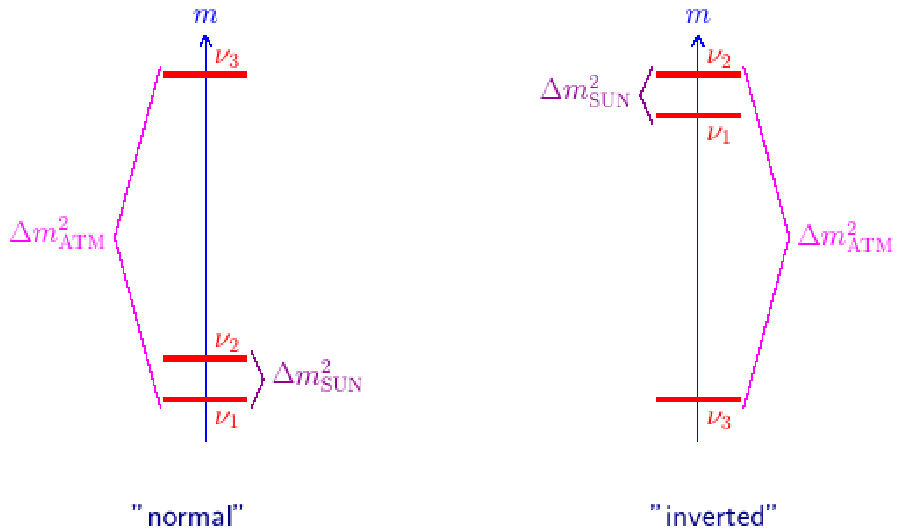
$$U^{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -e^{i\delta}c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

unknown (CP violating) phases: δ, α_1, α_2

Neutrinos mass spectrum

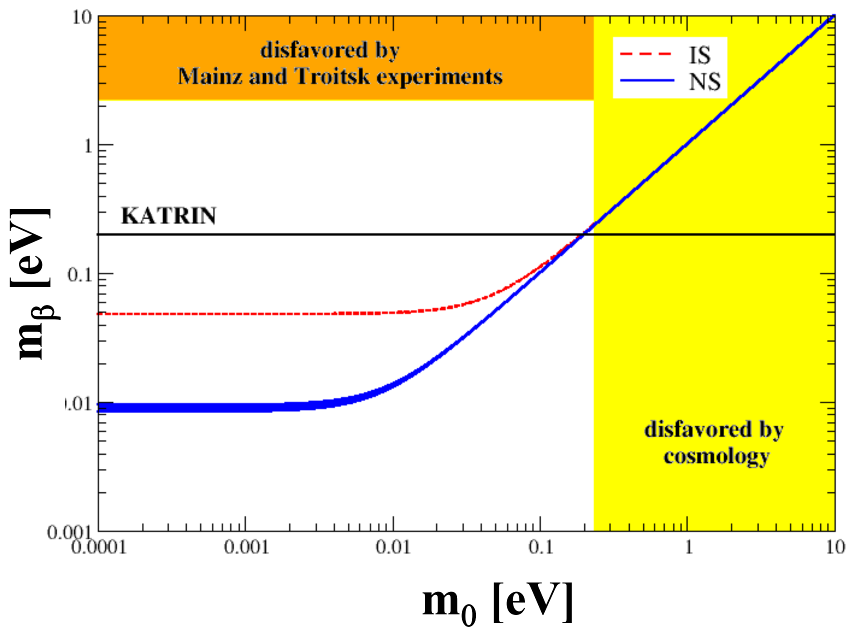
0νββ Measurements

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 e^{i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3\right|$$



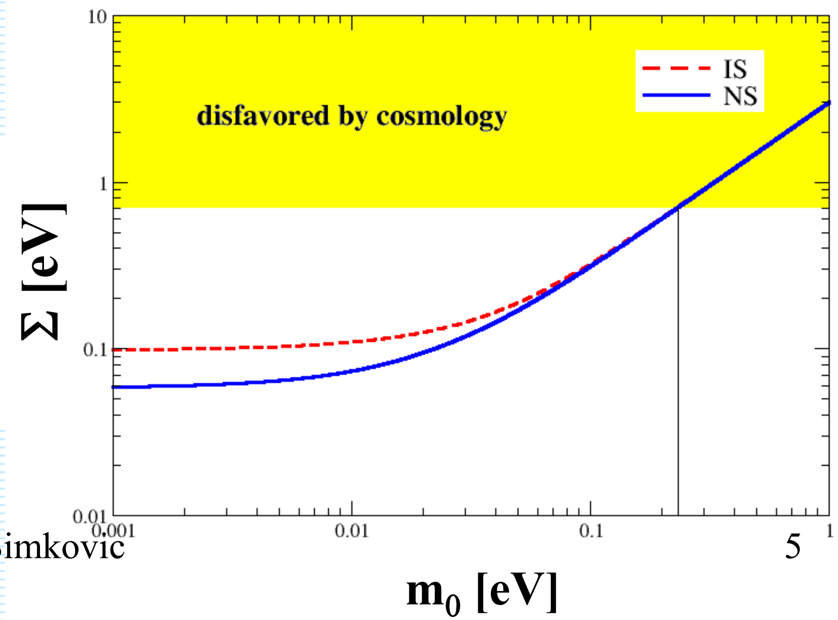
Beta Decay Measurements

$$m_\beta = \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}$$



Cosmological Measurements

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



imkovic

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

Symmetric Theory of Electron and Positron
Nuovo Cim. 14 (1937) 171

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

Minimal SM + EFT

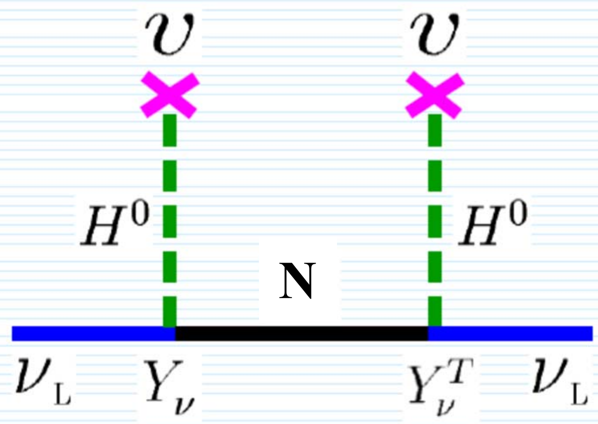
S.M. Bilenky,
Phys.Part.Nucl.Lett. 12 (2015) 453-461

The absence of the right-handed neutrino fields in the Standard Model is the simplest, most economical possibility. In such a scenario Majorana mass term is the only possibility for neutrinos to be massive and mixed. This mass term is generated by the lepton number violating Weinberg effective Lagrangian.

$$\mathcal{L}_5^{eff} = -\frac{1}{\Lambda}\sum_{l_1 l_2}\left(\overline{\Psi}_{l_1 L}^{lep}\tilde{\Phi}\right) \acute{Y}_{l_1 l_2}\left(\tilde{\Phi}^T(\Psi_{l_2 L}^{lep})^c\right)$$

$$m_i = \frac{v}{\Lambda}(y_i v), \quad i = 1, 2, 3$$

$\Lambda \geq 10^{15}$ GeV



Heavy Majorana leptons N_i ($N_i=N^c_i$)
singlet of $SU(2)_L xU(1)_Y$ group
Yukawa lepton number violating int.

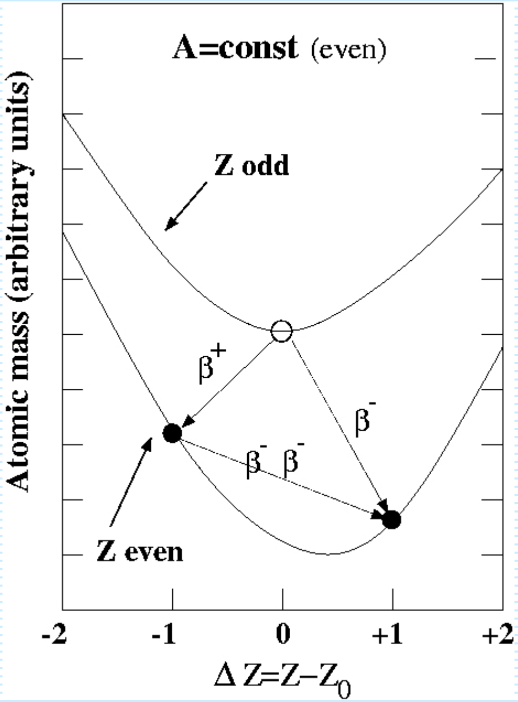
The three Majorana neutrino masses are suppressed by the ratio of the electroweak scale and a scale of a lepton-number violating physics.

The discovery of the ββ-decay and absence of transitions of flavor neutrinos into sterile states would be evidence in favor of this minimal scenario.

I. *The simplest 0νββ-decay scenario*
(SM + EFT scenario)

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

(A,Z) → (A,Z+2) + e⁻ + e⁻



transition	$G^{01}(E_0,Z)$ $\times 10^{14} y$	$Q_{\beta\beta}$ [MeV]	Abund. (%)	$\lvert M^{0\nu}\rvert^2$
$^{150}Nd \rightarrow {}^{150}Sm$	26.9	3.667	6	?
$^{48}Ca \rightarrow {}^{48}Ti$	8.04	4.271	0.2	?
$^{96}Zr \rightarrow {}^{96}Mo$	7.37	3.350	3	?
$^{116}Cd \rightarrow {}^{116}Sn$	6.24	2.802	7	?
$^{136}Xe \rightarrow {}^{136}Ba$	5.92	2.479	9	?
$^{100}Mo \rightarrow {}^{100}Ru$	5.74	3.034	10	?
$^{130}Te \rightarrow {}^{130}Xe$	5.55	2.533	34	?
$^{82}Se \rightarrow {}^{82}Kr$	3.53	2.995	9	?
$^{76}Ge \rightarrow {}^{76}Se$	0.79	2.040	8	?

The NMEs for 0νββ-decay must be evaluated using tools of nuclear theory

Effective mass of Majorana neutrinos (in vacuum)

$$|m_{\beta\beta}| = |c_{12}^2 c_{13}^2 e^{i\alpha_1} m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3|$$

m_1, m_2, m_3, θ_{12}, θ_{13}, α_1, α_2
(3 unknown parameters)

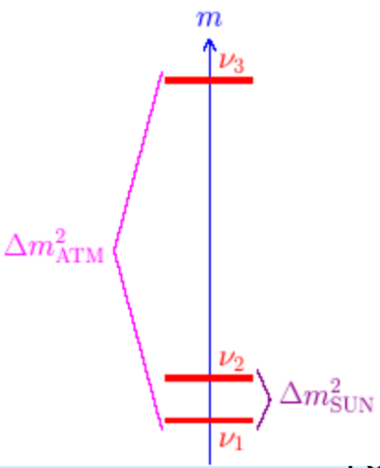
Measured quantity

$$|m_{\beta\beta}|^2 = c_{12}^4 c_{13}^4 m_1^2 + s_{12}^4 c_{13}^4 m_2^2 + s_{13}^4 m_3^2 + 2 c_{12}^2 s_{12}^2 c_{13}^4 m_1 m_2 \cos(\alpha_1 - \alpha_2) + 2 c_{12}^2 c_{13}^2 s_{13}^2 m_1 m_3 \cos\alpha_1 + 2 s_{12}^2 c_{13}^2 s_{13}^2 m_2 m_3 \cos\alpha_2 .$$

Limiting cases

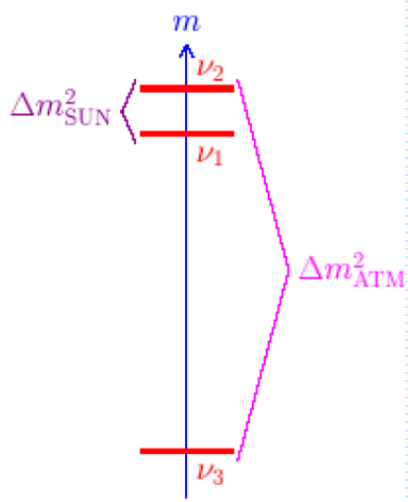
Normal hierarchy

$$m_1 \ll \sqrt{\Delta m^2_{\mathrm{SUN}}}$$
$$m_2 \simeq \sqrt{\Delta m^2_{\mathrm{SUN}}}$$
$$m_3 \simeq \sqrt{\Delta m^2_{\mathrm{ATM}}}$$

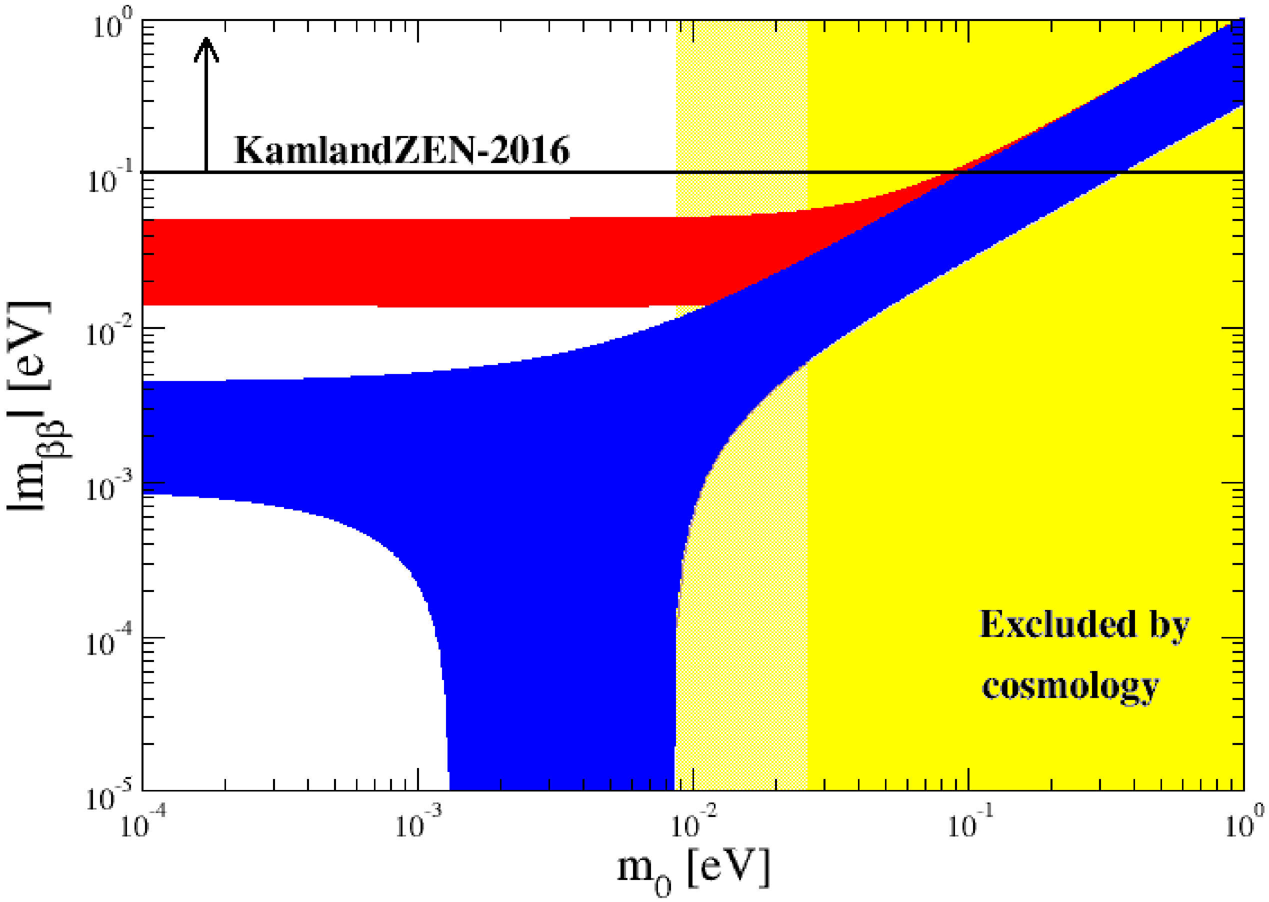


Inverted hierarchy

$$m_3 \ll \sqrt{\Delta m^2_{\mathrm{ATM}}}$$
$$m_1 \simeq m_2 \simeq \sqrt{\Delta m^2_{\mathrm{ATM}}}$$



Issue: Lightest neutrino mass m_0



GUT's

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

β-decay (Mainz, Troitsk)

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

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

Cosmology (Planck)

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

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

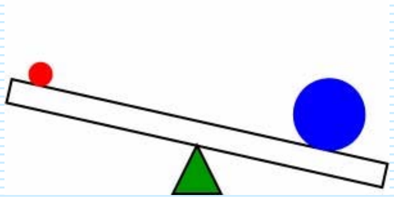
II. *The sterile ν mechanism of the 0νββ-decay*
(D-M mass term, V-A SM int.)

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

Mixing of active-sterile neutrinos

Dirac-Majorana mass term

$$\begin{pmatrix} 0 & m_D \\ m_D & m_{LNV} \end{pmatrix}$$



Light ν mass ≈ $(m_D/m_{LNV})\ m_D$
Heavy ν mass ≈ m_{LNV}

small ν masees due to see-saw mechanism

Possible lepton number violating scale - m_{LNV}

Neutrinos masses may offer a great opportunity to jump beyond the EW framework via see-saw ...

10^{19} GeV — **Planck**

How heavy are the heavy Majorana neutrinos?

10^{16} GeV — **GUT**

to unify strong, weak & electromagnetic forces?

Conventional (Type-one) Seesaw Picture: close to the GUT scale

10^{3} GeV — **TeV**

TeV Seesaw Idea: driven by testability at LHC

to solve the unnatural gauge hierarchy problem?

GeV/5 — **Fermi**

10^{-6} GeV — **kev**

Hot dark mattter

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

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

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_{\rm A}^4 \left| \sum_{\rm N} \left(U^2_{e\rm N} m_{\rm N} \right) m_{\rm p}\, M'^{\,0\nu}(m_{\rm N}, g_{\rm A}^{\rm eff}) \right|^2$$

General case

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

$$M'^{0\nu}(m_{\rm N} \to 0, g_{\rm A}^{\rm eff}) = \frac{1}{m_{\rm p} m_{\rm e}} M'^{0\nu}_\nu(g_{\rm A}^{\rm eff})$$

$$M'^{0\nu}(m_{\rm N} \to \infty, g_{\rm A}^{\rm eff}) = \frac{1}{m_{\rm N}^2} M'^{0\nu}_{\rm N}(g_{\rm A}^{\rm eff})$$

Particular cases

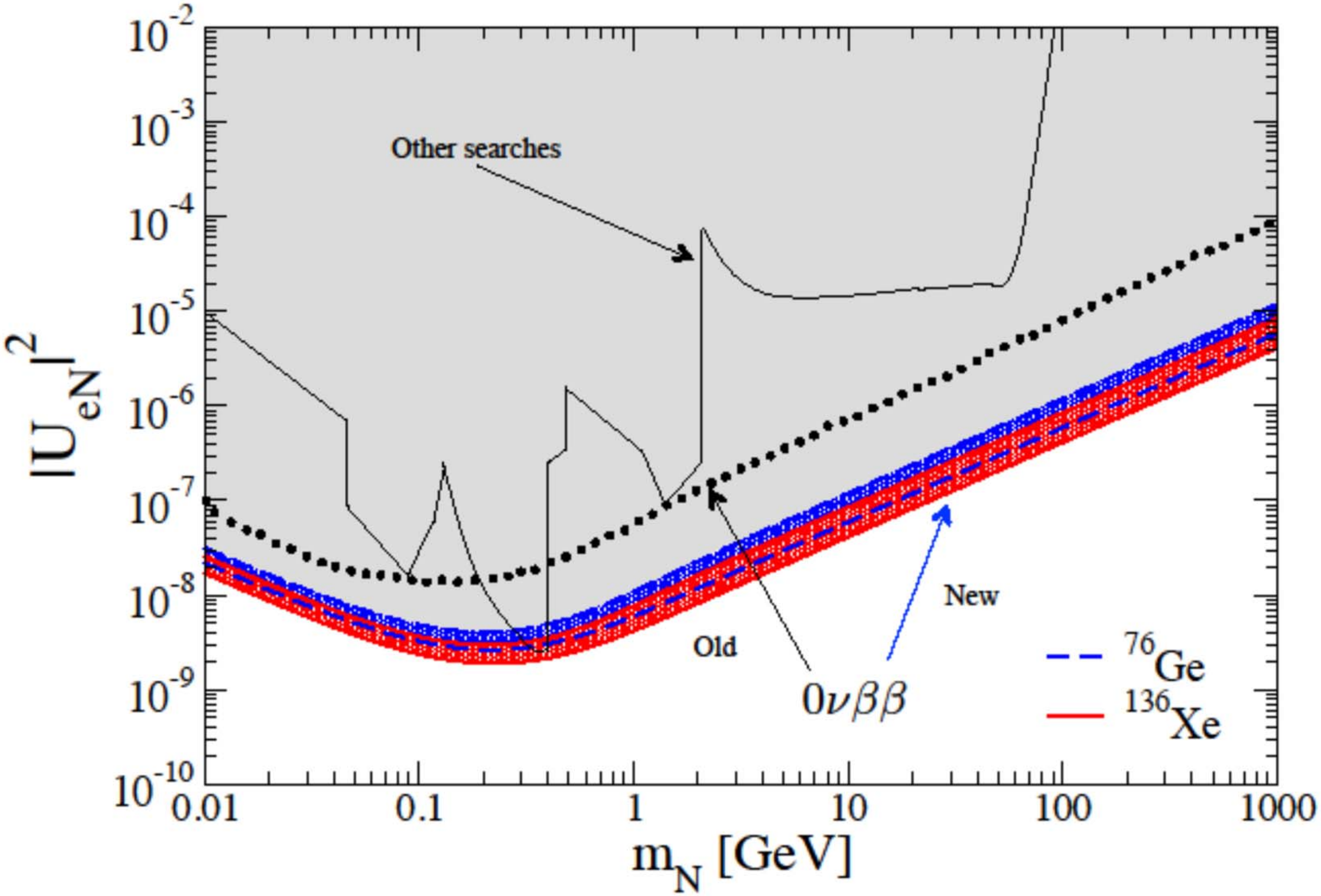
$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_{\rm A}^4 \times \times \begin{cases} \left|\frac{\langle m_\nu\rangle}{m_e}\right|^2 \left| M'^{0\nu}_\nu(g_{\rm A}^{\rm eff})\right|^2 & \text{for } m_{\rm N} \ll p_{\rm F} \\ \left|\langle \frac{1}{m_{\rm N}}\rangle m_{\rm p}\right|^2 \left| M'^{0\nu}_{\rm N}(g_{\rm A}^{\rm eff})\right|^2 & \text{for } m_{\rm N} \gg p_{\rm F} \end{cases}$$

$$\langle m_\nu \rangle = \sum_{\rm N} U^2_{\rm eN} m_{\rm N}$$

$$\left\langle \frac{1}{m_{\rm N}} \right\rangle = \sum_{\rm N} \frac{U^2_{\rm eN}}{m_{\rm N}}$$

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

$T^{0\nu}_{1/2}(^{76}Ge) \geq 3.0\ 10^{25}$ yr
$T^{0\nu}_{1/2}(^{136}Xe) \geq 3.4\ 10^{25}$ yr



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

III. *The 0νββ-decay within L-R symmetric theories*
(D-M mass term, see-saw, V-A and V+A int., exchange of light neutrinos)

Effective β-decay Hamiltonian

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

left- and right-handed lept. currents

$$j_L^\rho = \bar{e}\gamma^\rho(1-\gamma_5)\nu_{eL}$$
$$j_R^\rho = \bar{e}\gamma^\rho(1+\gamma_5)\nu_{eR}$$

Mixing of vector bosons W_L and W_R

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

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

The 0νββ-decay half-life

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

$\langle\lambda\rangle$ - W_L-W_R exch.

$\langle\eta\rangle$ - W_L-W_R mixing

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

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

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

Basis

6x6 neutrino mass matrix

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

$$(\nu_L, (N_R)^c)^T$$

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

15 angles, 10+5 phases

Decomposition

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

The see-saw structure and neglecting mixing between different generations

Approximation

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

$$U_0 \simeq V_0$$

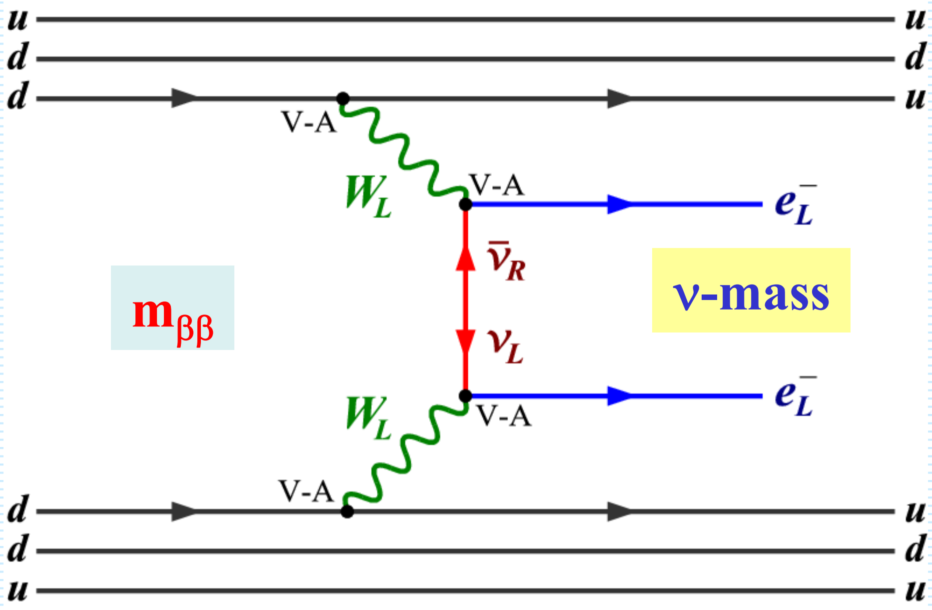
LNV parameters

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

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

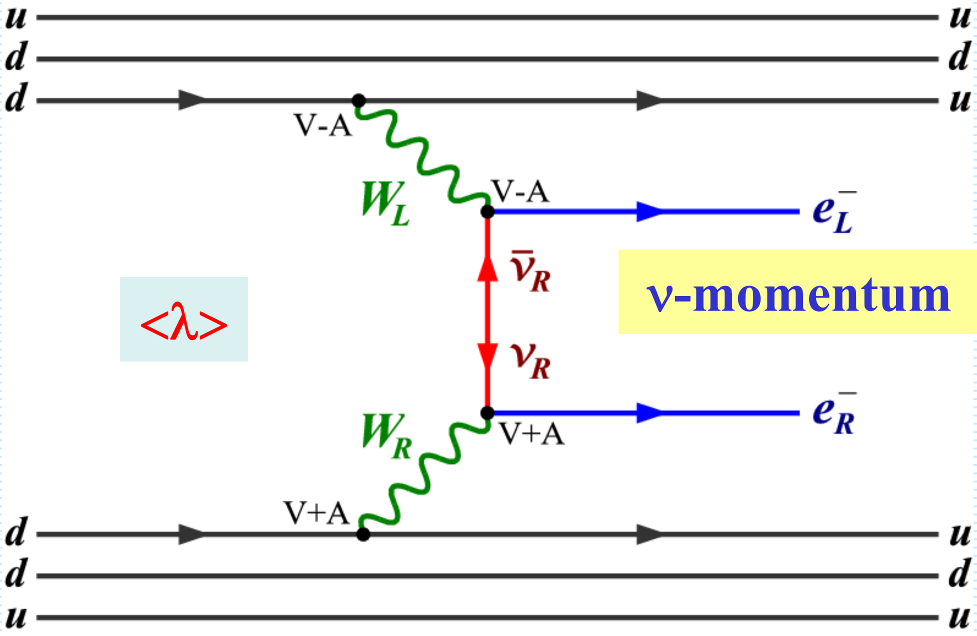
$$|\xi| \simeq 0.82$$

Left-right symmetric models SO(10)



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

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



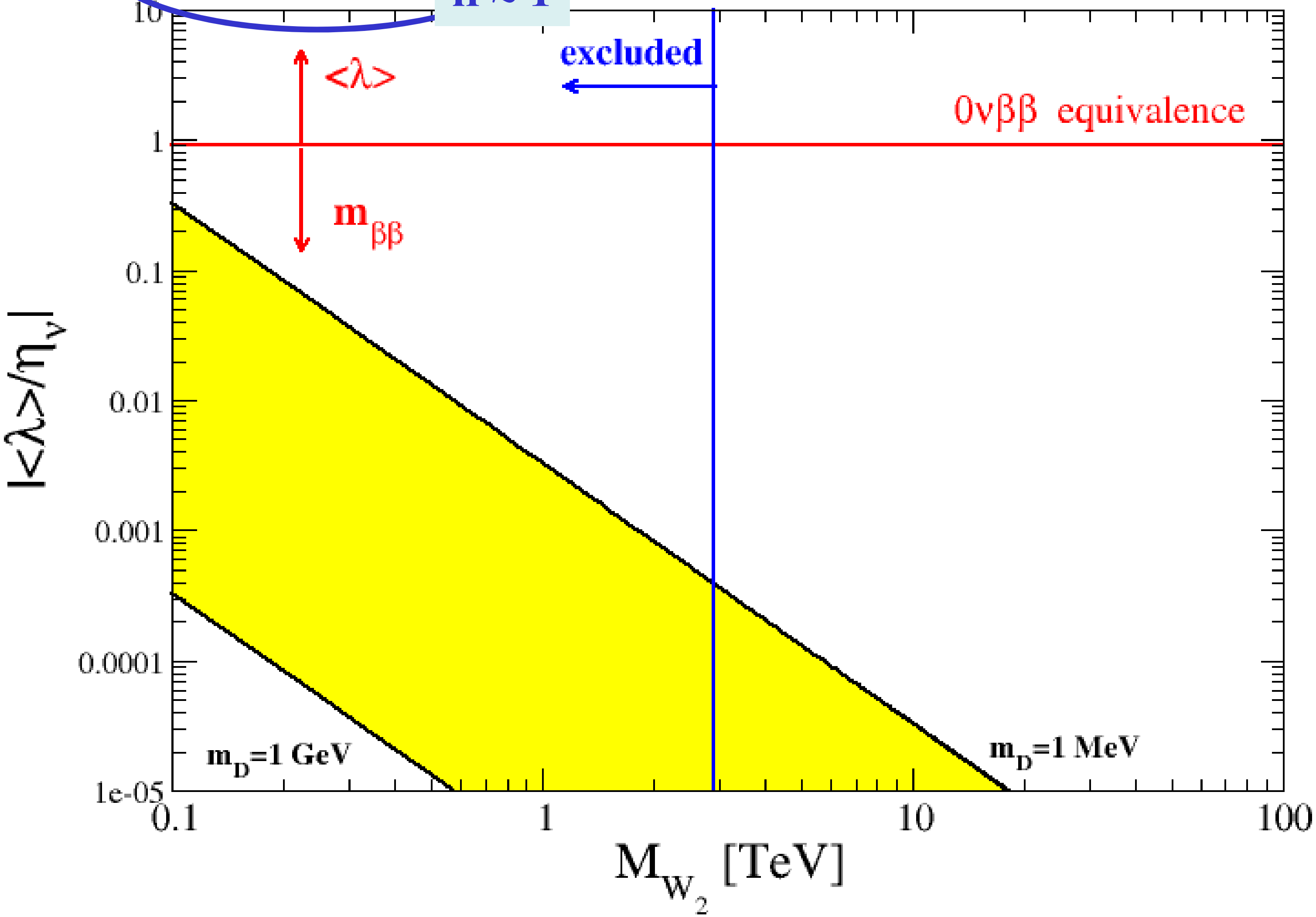
$$\langle\lambda\rangle = \lambda \, |\sum_{j=1}^{3} U_{ej} T_{ej}^{*}|$$

$$\langle\eta\rangle = \eta \, |\sum_{j=1}^{3} U_{ej} T_{ej}^{*}|$$

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

if ≈ 1

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



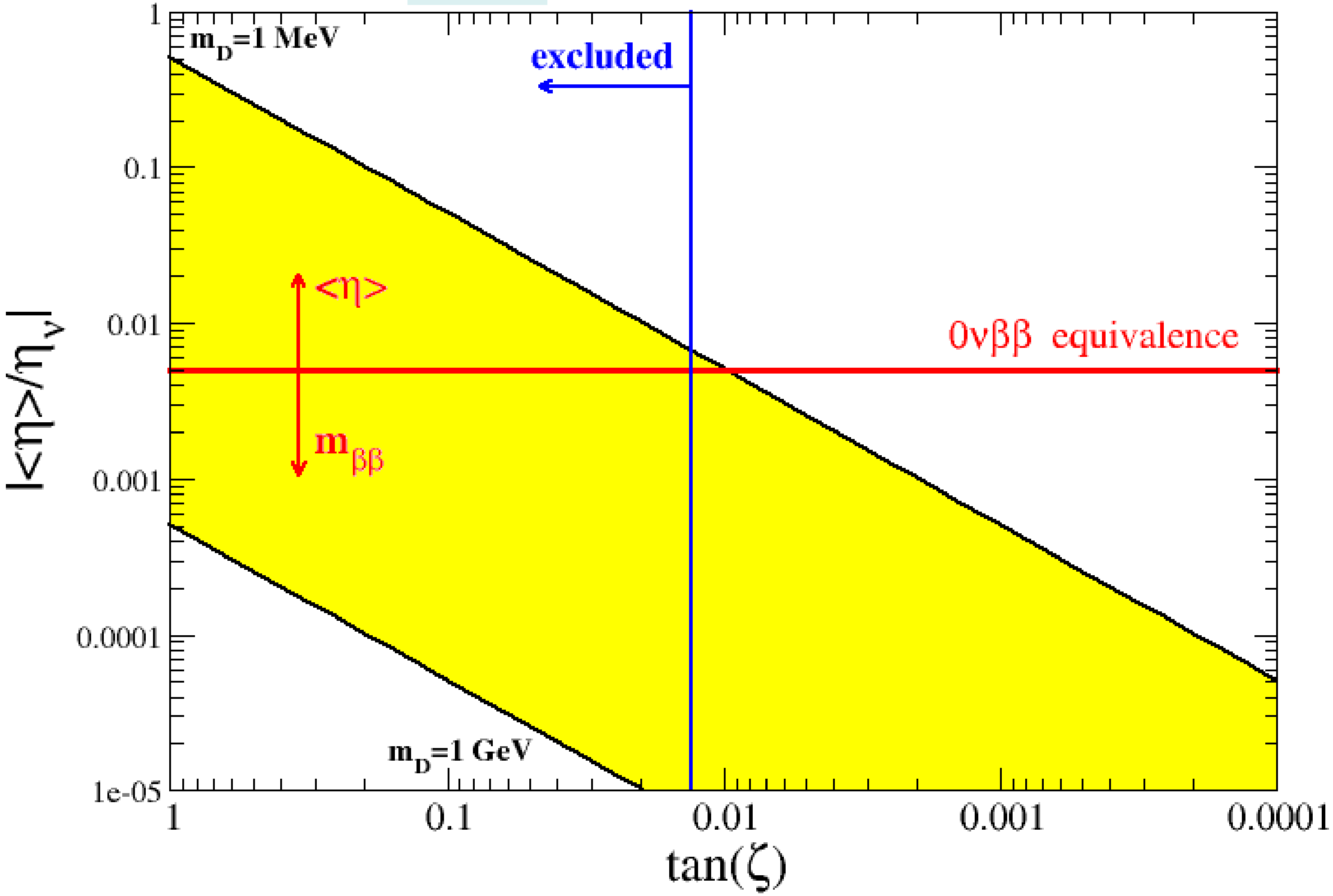
Clear dominance of $m_{\beta\beta}$ over <λ> mechanism by current constraint on mass of heavy vector boson

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

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

if ≈ 1

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



5/30/2017

Dominance of $m_{\beta\beta}$ over <λ> mech., but might be also comparable

IV. *The 0νββ-decay within L-R symmetric theories*

(D-M mass term, see-saw, V-A and V+A int., exchange of heavy neutrinos)

J.D.Vergados, H. Ejiri, , F.Š., Int. J. Mod. Phys. E25, 1630007(2016)

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

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

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

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

$\eta_\nu >> \eta^L_N$

η_ν and η^R_N might be comparable, if e.g.

$$\sum_i (U_0)^2_{ei} \frac{m_i \, m_{LNV}}{m_D^2} \simeq \sum_i (V_0)^2_{ei} \frac{m_{LNV}}{M_i}$$
$$\frac{m_D^2}{m_e m_p} M^{0\nu}_\nu \simeq \left(\frac{M_{W_1}}{M_{W_2}}\right)^2 M^{0\nu}_N$$

The $0\nu\beta\beta$-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 $0\nu\beta\beta$-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

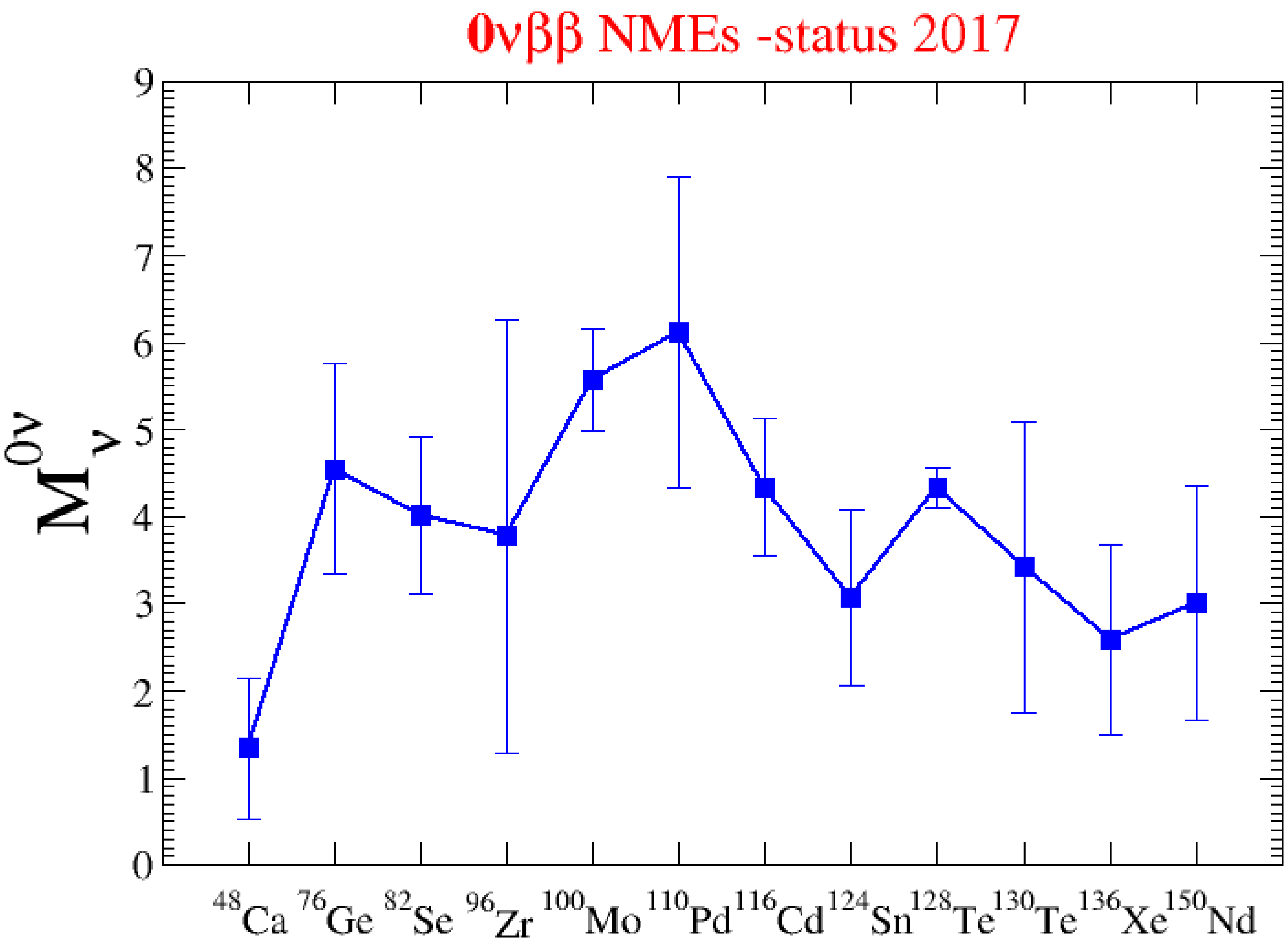
NMEs for unquenched value of g_A

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

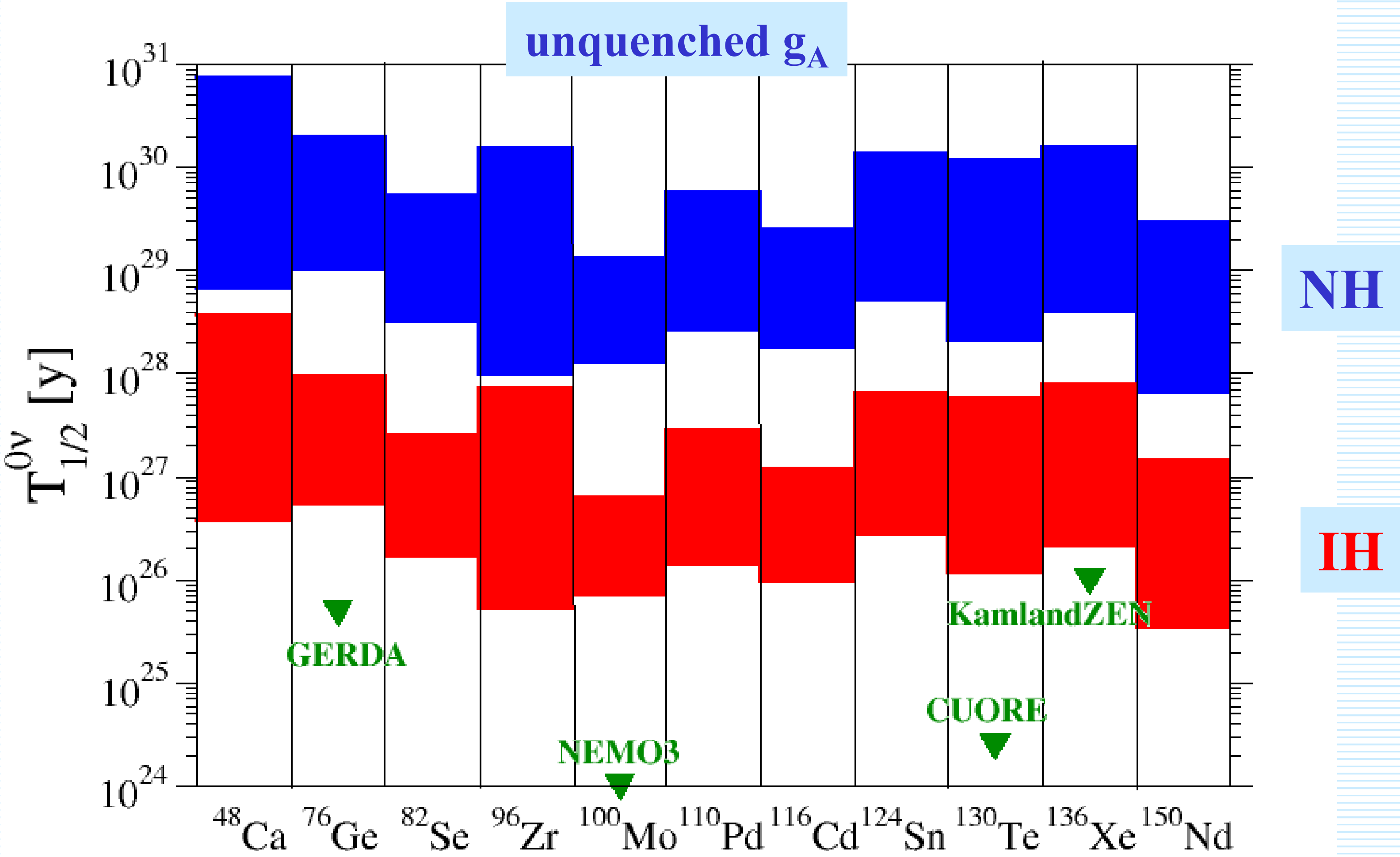
Interacting Boson Model (IBM)
⇒ Close to QRPA results



J.D.Vergados, H. Ejiri, , F.Š., Int. J. Mod. Phys. E25, 1630007(2016)

	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



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

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

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

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

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

Lightest ν-mass equal to zero

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

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

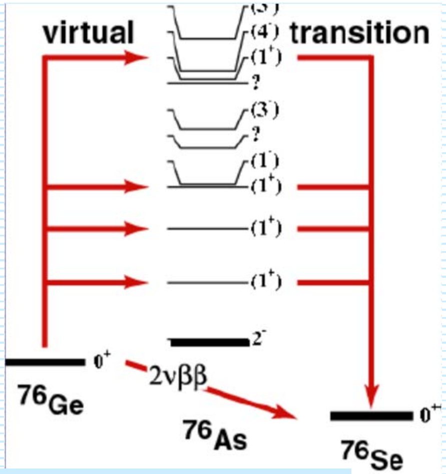
$g_A^4 = (1.269)^4 = 2.6$

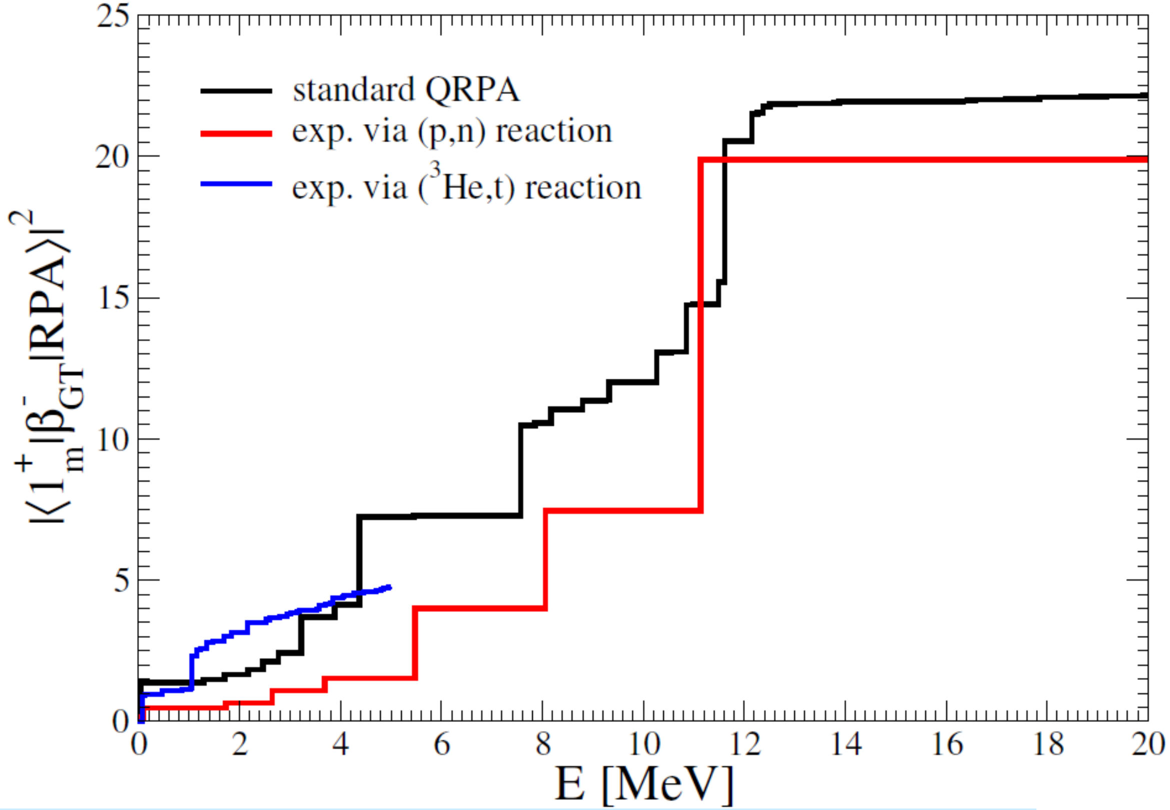
$(g^{eff}_A)^4 = 1.0$

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

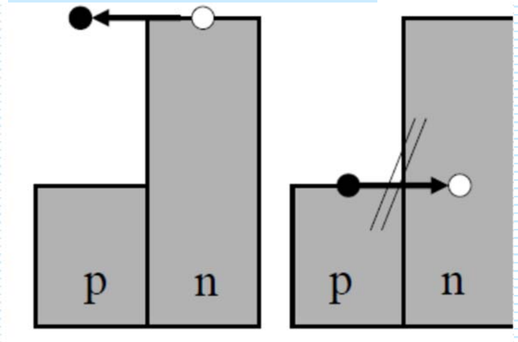
$^{76}_{32}Ge_{44} \Rightarrow$

$S_{\beta^-} - S_{\beta^+} = 3(N-Z) = 36$





Pauli blocking



Cross-section for charge exchange reaction:

$$\left[\frac{d\sigma}{d\Omega}\right] = \left[\frac{\mu}{\pi\hbar}\right]^2 \frac{k_f}{k_i} N_d \underbrace{|V_{\sigma\tau}|^2}_{\text{largest at 100 - 200 MeV/A}} |\langle f\,|\,\sigma\tau\,|\,i\rangle|^2$$

$q = 0!!$

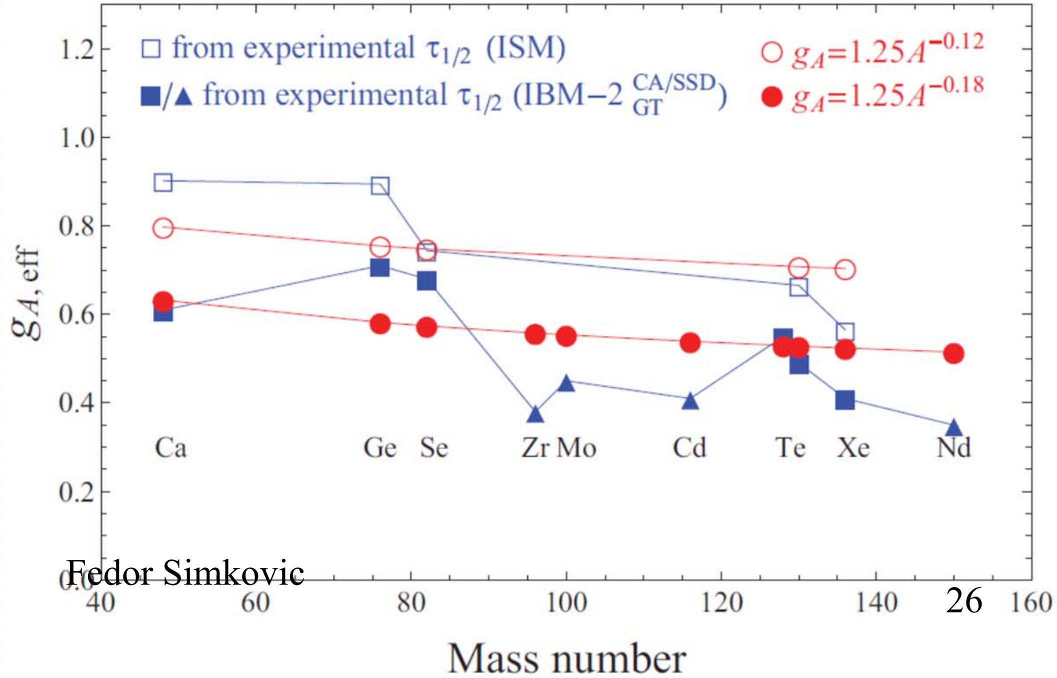
Quenching of g_A *(from theory: $T_{1/2}^{0\nu}$ up 50 x larger)*

$(g^{eff}_A)^4 \simeq$ 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%.**

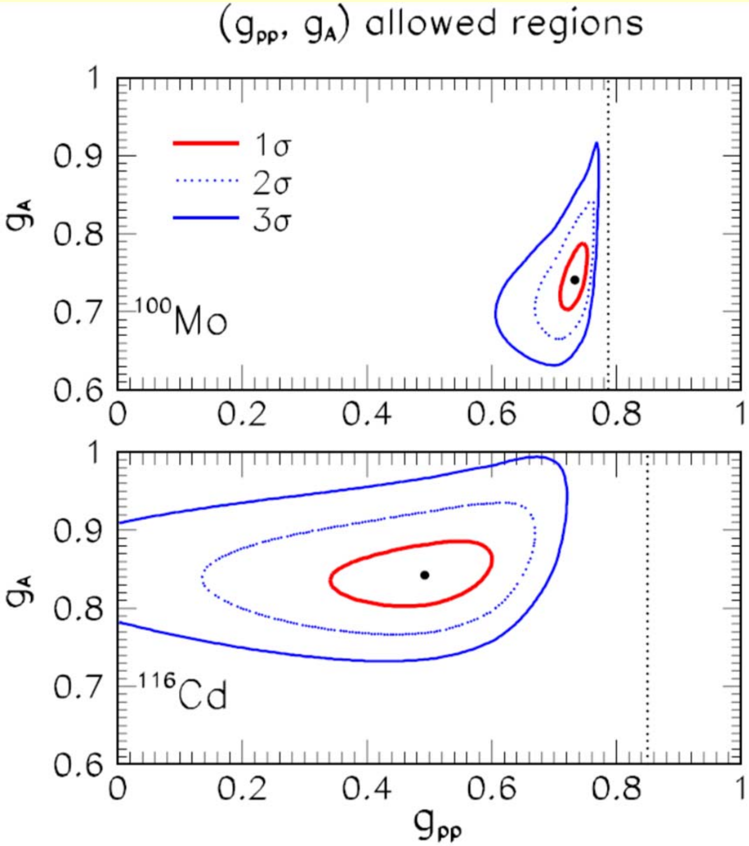
J. Barea, J. Kotila, F. Iachello, PRC 87, 014315 (2013).

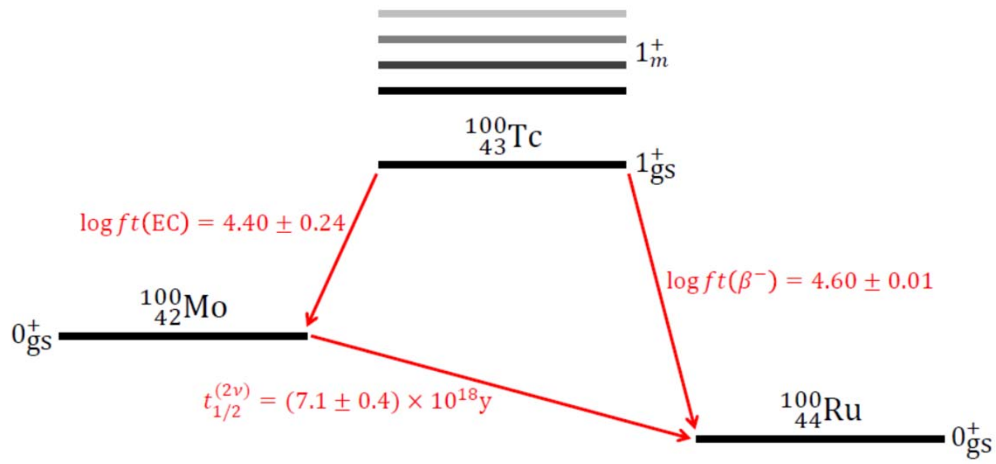
It has been determined by theoretical prediction for the 2νββ-decay half-lives, which were based on within closure approximation calculated corresponding NMEs, with the measured half-lives.



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 2νββ 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, PRC 94, 055501 (2016)

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

Understanding of the 2νββ-decay NMEs is of crucial importance for correct evaluation of the 2νββ-decay NMEs

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$$

Both 2νββ and 0νββ operators connect the same states. Both change two neutrons into two protons.

Explaining 2νββ-decay is necessary but not sufficient

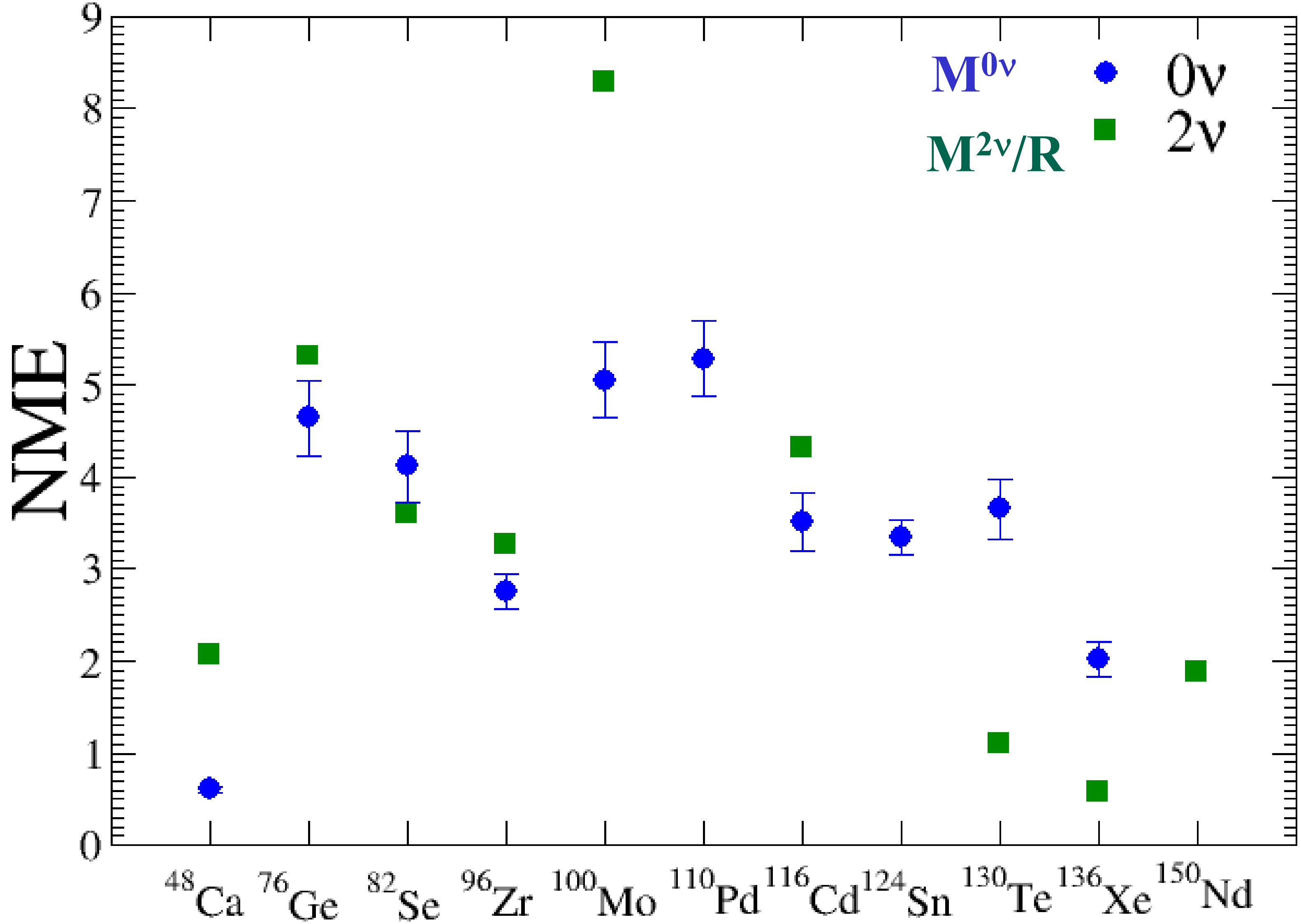
There is no reliable calculation of the *2νββ-decay NMEs*

Calculation via intermediate nuclear states: QRPA (sensitivity to pp-int.)
ISM (quenching, truncation of model space, spin-orbit partners)

Calculation via closure NME: IBM, PHFB

No calculation: EDF

F. Š., Nucl.Part.Phys.Proc. 265-266 (2015) 19-24



Improved description of the 2νββ-decay rate

F.Š., R. Dvornický, D. Štefánik and A. Faessler, to be submitted

$$\left[T^{2\nu\beta\beta}_{1/2}\right]^{-1} = \frac{m_e}{8\pi^7 \ln 2}(G_\beta m_e^2)^4 \left(g_A^{\rm eff}\right)^4 I^{2\nu}$$

Half-life without factorization of NMEs and phase space

$$\begin{aligned} I^{2\nu} &= \frac{1}{m_e^{11}}\int_{m_e}^{E_i-E_f-m_e} F_0(Z_f,E_{e_1})p_{e_1}E_{e_1}dE_{e_1} \\ &\times \int_{m_e}^{E_i-E_f-E_{e_1}} F_0(Z_f,E_{e_2})p_{e_2}E_{e_2}dE_{e_2} \\ &\times \int_{0}^{E_i-E_f-E_{e_1}-E_{e_2}} E_{\nu_1}^2 E_{\nu_2}^2 \mathcal{A}^{2\nu} dE_{\nu_1} \end{aligned}$$

$$\mathcal{A}^{2\nu} = \left[\frac{1}{4}|M^K_{GT}+M^L_{GT}|^2 + \frac{1}{12}|M^K_{GT}-M^L_{GT}|^2\right]$$

$$M^{K,L}_{GT} = m_e \sum_n M_n \frac{E_n-(E_i+E_f)/2}{[E_n-(E_i+E_f)/2]^2-\varepsilon^2_{K,L}}$$

$$M_n = \langle 0_f^+ \parallel \sum_m \tau_m^- \sigma_m \parallel 1_n^+\rangle\langle 1_n^+ \parallel \sum_m \tau_m^- \sigma_m \parallel 0_i^+\rangle$$

$$\begin{aligned} \epsilon_K &= (E_{e_2}+E_{\nu_2}-E_{e_1}-E_{\nu_1})/2 \\ \epsilon_L &= (E_{e_1}+E_{\nu_2}-E_{e_2}-E_{\nu_1})/2 \end{aligned}$$

$$M_{GT}^{K,L} = m_e \sum_n M_n \frac{E_n - (E_i + E_f)/2}{[E_n - (E_i + E_f)/2]^2 - \varepsilon_{K,L}^2}$$

Standard approximation which allows factorization of NME and phase space

$$M_{GT}^{K,L} \simeq M_{GT}^{2\nu} = m_e \sum_n \frac{M_n}{E_n - (E_i + E_f)/2}$$

Let perform Taylor expansion

$$\frac{\varepsilon_{K,L}}{E_n - (E_i + E_f)/2}$$

$$\epsilon_{K,L} \in (-\frac{Q}{2}, \frac{Q}{2})$$

$$E_n - \frac{E_i + E_f}{2} = \frac{Q}{2} + m_e + (E_n - E_i) > |\epsilon_{K,L}|$$

Improved description of the 0νββ–decay rate

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \equiv \frac{\Gamma^{2\nu}}{\ln(2)} \simeq \frac{\Gamma_0^{2\nu}+\Gamma_2^{2\nu}+\Gamma_4^{2\nu}}{\ln(2)}$$

$$\frac{\Gamma_0^{2\nu}}{\ln(2)} = \left(g_A^{\rm eff}\right)^4 \mathcal{M}_0 G_0^{2\nu}$$
$$\frac{\Gamma_2^{2\nu}}{\ln(2)} = \left(g_A^{\rm eff}\right)^4 \mathcal{M}_2 G_2^{2\nu}$$
$$\frac{\Gamma_4^{2\nu}}{\ln(2)} = \left(g_A^{\rm eff}\right)^4 \left(\mathcal{M}_4 G_4^{2\nu} + \mathcal{M}_{22} G_{22}^{2\nu}\right)$$

Taylor expansion up to ε^4

$$G_J^{2\nu} = \frac{c_{2\nu}}{m_e^{11}} \int_{m_e}^{E_i-E_f-m_e} F_0(Z_f,E_{e_1}) p_{e_1} E_{e_1} dE_{e_1}$$
$$\times \int_{m_e}^{E_i-E_f-E_{e_1}} F_0(Z_f,E_{e_2}) p_{e_2} E_{e_2} dE_{e_2}$$
$$\times \int_0^{E_i-E_f-E_{e_1}-E_{e_2}} E_{\nu_1}^2 E_{\nu_2}^2 \mathcal{A}_J^{2\nu} dE_{\nu_1}, \quad (\text{J}=0,\ 2,\ 4,\ 22)$$

$$\mathcal{A}_0^{2\nu} = 1 \quad \mathcal{A}_2^{2\nu} = \frac{\varepsilon_K^2+\varepsilon_L^2}{(2m_e)^2},$$
$$\mathcal{A}_{22}^{2\nu} = \frac{\varepsilon_K^2\varepsilon_L^2}{(2m_e)^4} \quad \mathcal{A}_2^{2\nu} = \frac{\varepsilon_K^4+\varepsilon_L^4}{(2m_e)^4}$$

Phase space factors

	2νββ-decay			
nucl.	$G_0^{2\nu}$ [yr^{-1}]	$G_2^{2\nu}$ [yr^{-1}]	$G_4^{2\nu}$ [yr^{-1}]	$G_{22}^{2\nu}$ [yr^{-1}]
^{76}Ge	$4.816\ 10^{-20}$	$1.015\ 10^{-20}$	$1.332\ 10^{-21}$	$6.284\ 10^{-22}$
^{82}Se	$1.591\ 10^{-18}$	$7.037\ 10^{-19}$	$1.952\ 10^{-19}$	$8.931\ 10^{-20}$
^{100}Mo	$3.303\ 10^{-18}$	$1.509\ 10^{-18}$	$4.320\ 10^{-19}$	$1.986\ 10^{-19}$
^{130}Te	$1.530\ 10^{-18}$	$4.953\ 10^{-19}$	$9.985\ 10^{-20}$	$4.707\ 10^{-20}$
^{136}Xe	$1.433\ 10^{-18}$	$4.404\ 10^{-19}$	$8.417\ 10^{-20}$	$3.986\ 10^{-20}$

$$\mathcal{M}_0 = \left|M^{2\nu}_{GT-1}\right|^2$$

$$\mathcal{M}_2 = \Re\{M^{2\nu}_{GT-1} M^{2\nu}_{GT-3}\}$$

$$\mathcal{M}_{22} = \frac{1}{3}\left|M^{2\nu}_{GT-3}\right|^2$$

$$\mathcal{M}_4 = \frac{1}{3}\left|M^{2\nu}_{GT-3}\right|^2 + \Re\{M^{2\nu}_{GT-1} M^{2\nu}_{GT-5}\}$$

$$M^{2\nu}_{GT-1} \equiv M^{2\nu}_{GT}$$

3 different NMEs

$$M^{2\nu}_{GT-3} = \sum_n M_n \frac{4\ m_e^3}{(E_n - (E_i + E_f)/2)^3}$$

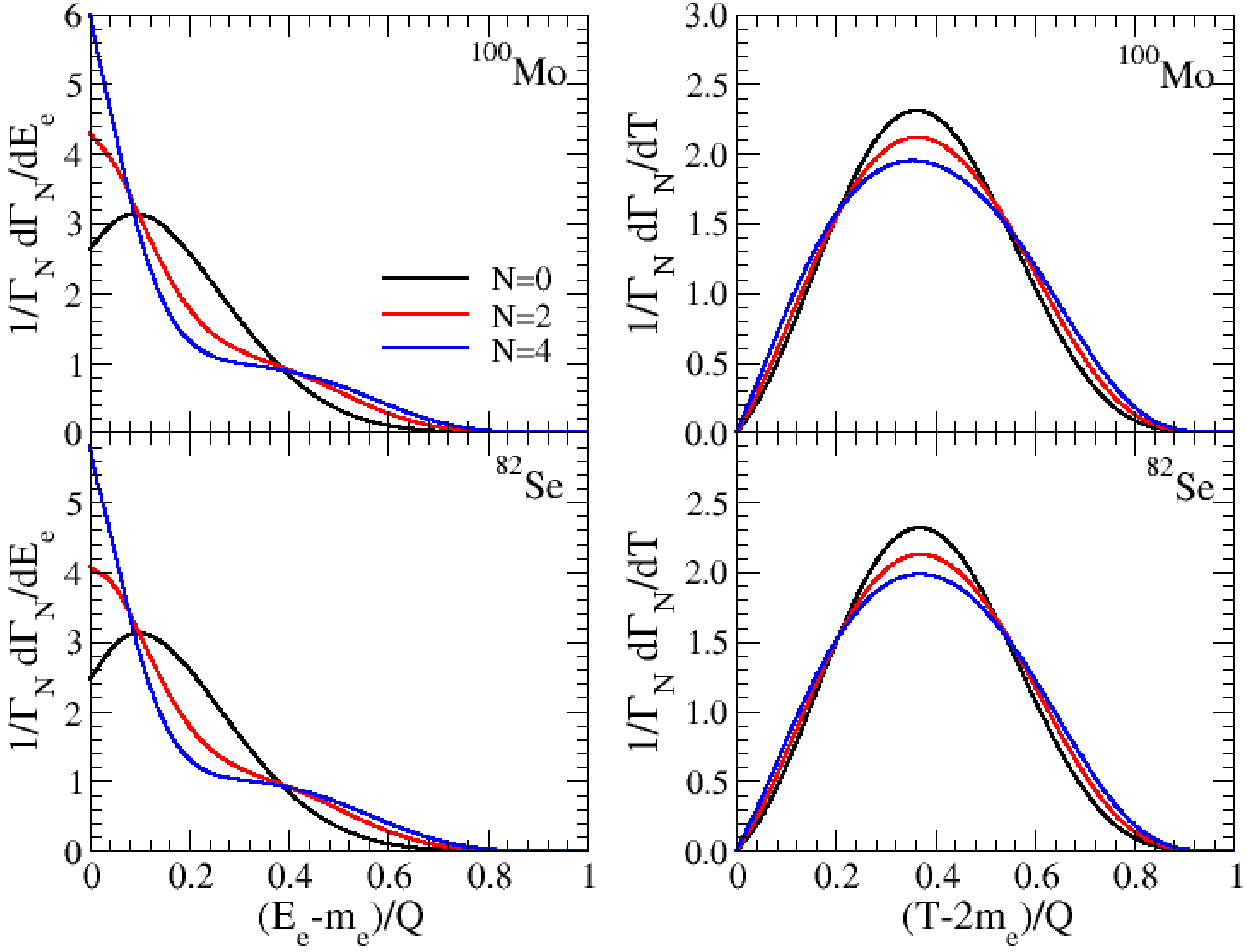
$$M^{2\nu}_{GT-5} = \sum_n M_n \frac{16\ m_e^5}{(E_n - (E_i + E_f)/2)^5}$$

QRPA

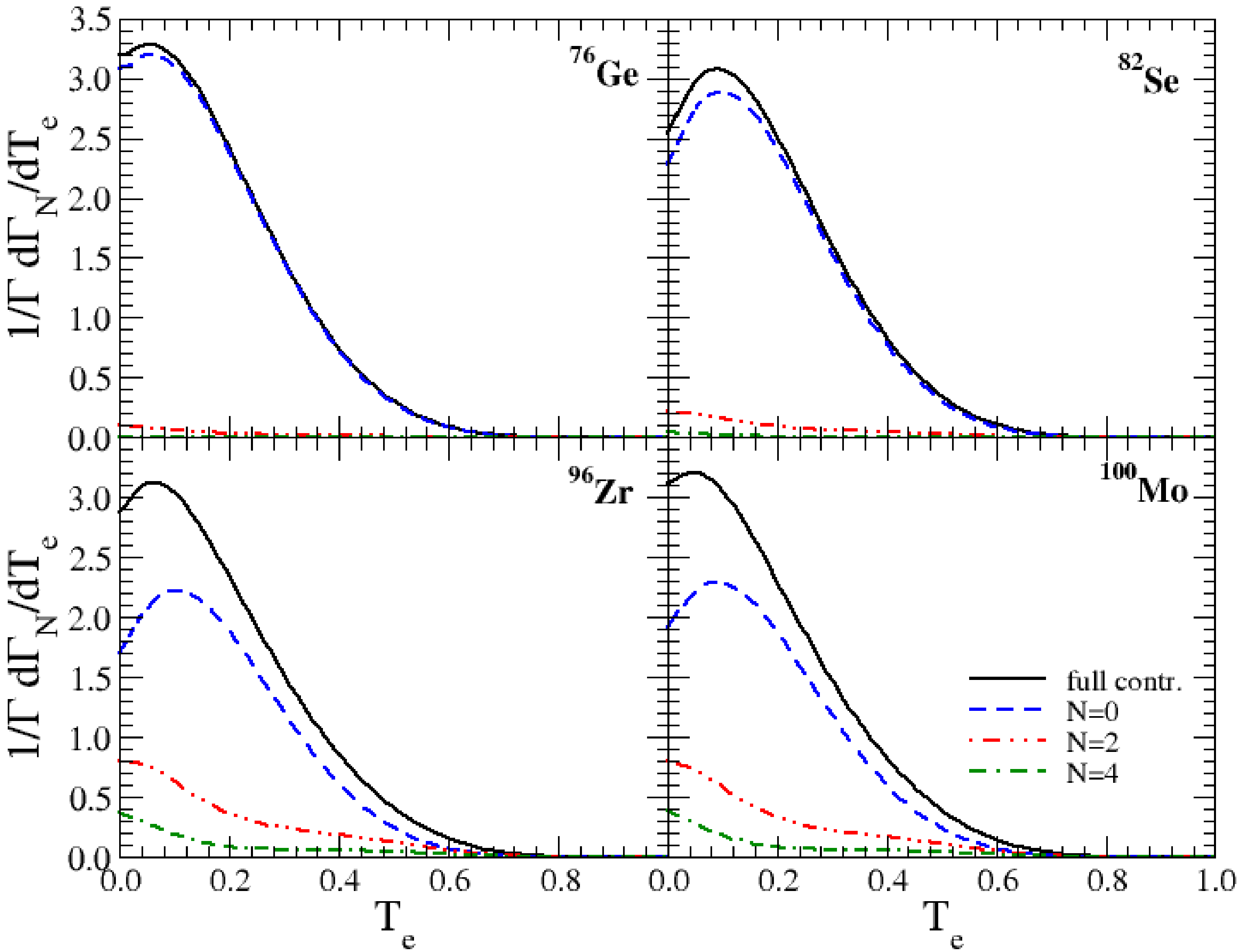
$2\nu\beta\beta$-decay NMEs and their ratios

nucl.	$g_A^{\rm eff}$	$M^{2\nu}_{GT-1}$	$M^{2\nu}_{GT-3}$	$M^{2\nu}_{GT-5}$	$\xi^{2\nu}_{13}$	$\xi^{2\nu}_{15}$	$P^{2\nu}_0$	$P^{2\nu}_2$	$P^{2\nu}_4$	$T^{2\nu-exp}_{1/2}$ [yr]
^{76}Ge	0.800	0.175	0.0214	0.00445	0.1220	0.0254	0.9741	0.0250	0.0009	$1.65\ 10^{21}$
	1.000	0.111	0.0133	0.00263	0.1204	0.0237	0.9745	0.0247	0.0008	
	1.269	0.689	0.00716	0.00716	0.1040	0.0170	0.9780	0.0214	0.0006	
^{82}Se	0.800	0.124	0.0216	0.00645	0.1745	0.0521	0.9213	0.0711	0.0076	$0.92\ 10^{20}$
	1.000	0.0795	0.0129	0.00355	0.1620	0.0446	0.9271	0.0664	0.0065	
	1.269	0.0498	0.00643	0.00136	0.1290	0.0272	0.9421	0.0538	0.0041	
^{100}Mo	0.800	0.292	0.123	0.0453	0.4230	0.1553	0.8163	0.1578	0.0259	$7.1\ 10^{18}$
	1.000	0.184	0.0876	0.0322	0.4752	0.1745	0.7972	0.1731	0.0297	
	1.269	0.112	0.0633	0.0233	0.5646	0.2075	0.7661	0.1976	0.0363	
^{130}Te	0.800	0.0466	0.00873	0.00239	0.1873	0.0512	0.9389	0.0569	0.0042	$6.9\ 10^{20}$
	1.000	0.0298	0.00577	0.00144	0.1937	0.0482	0.9371	0.0588	0.0041	
	1.269	0.0185	0.00373	0.00078	0.2015	0.0420	0.9352	0.0610	0.0038	
^{136}Xe	0.800	0.0268	0.00706	0.00232	0.2637	0.0866	0.9190	0.0745	0.0065	$2.19\ 10^{21}$
	1.000	0.0170	0.00526	0.00169	0.3098	0.0995	0.9059	0.0863	0.0078	
	1.269	0.0104	0.00403	0.00126	0.3867	0.1207	0.8848	0.1051	0.0101	

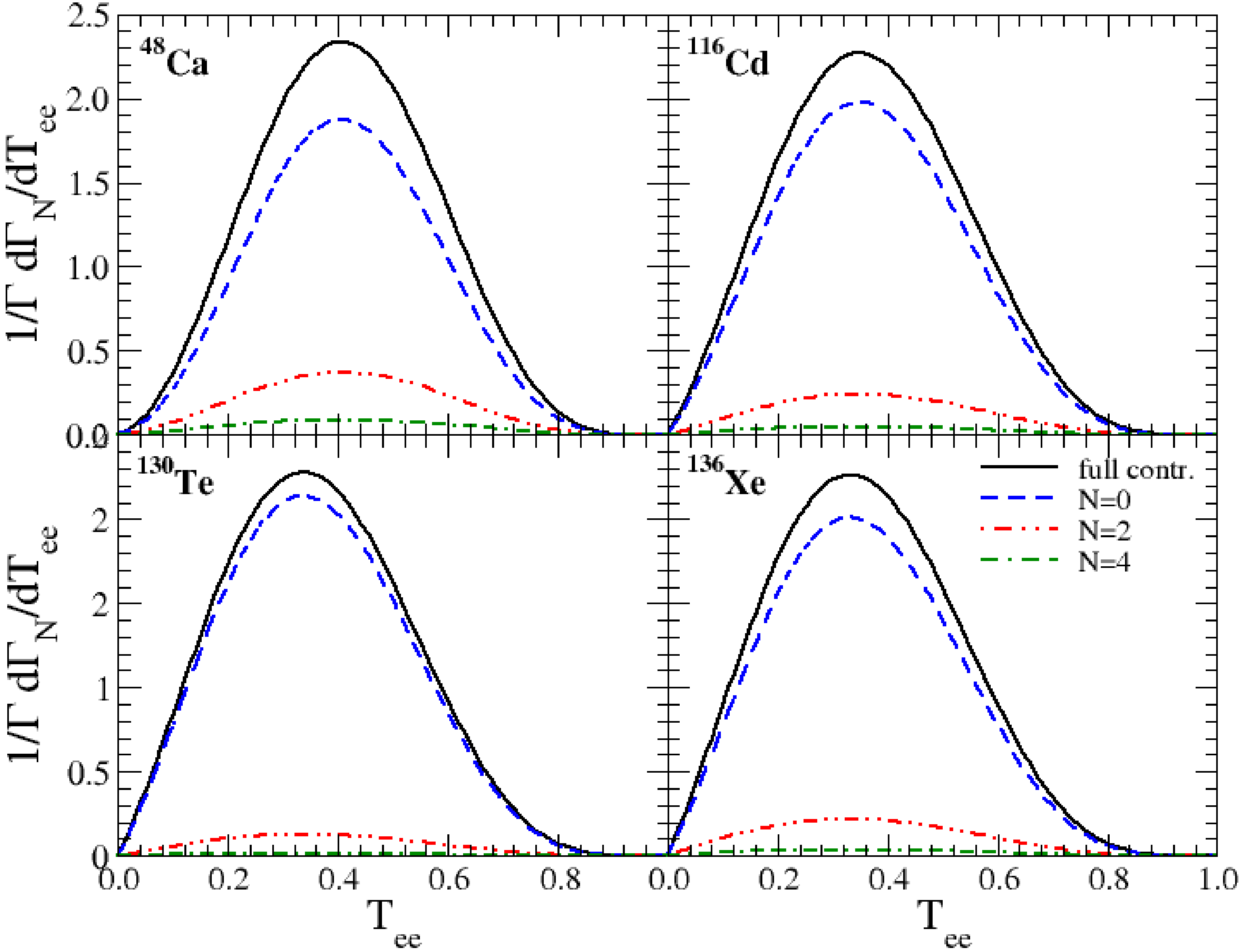
Normalized to unity different partial energy distributions



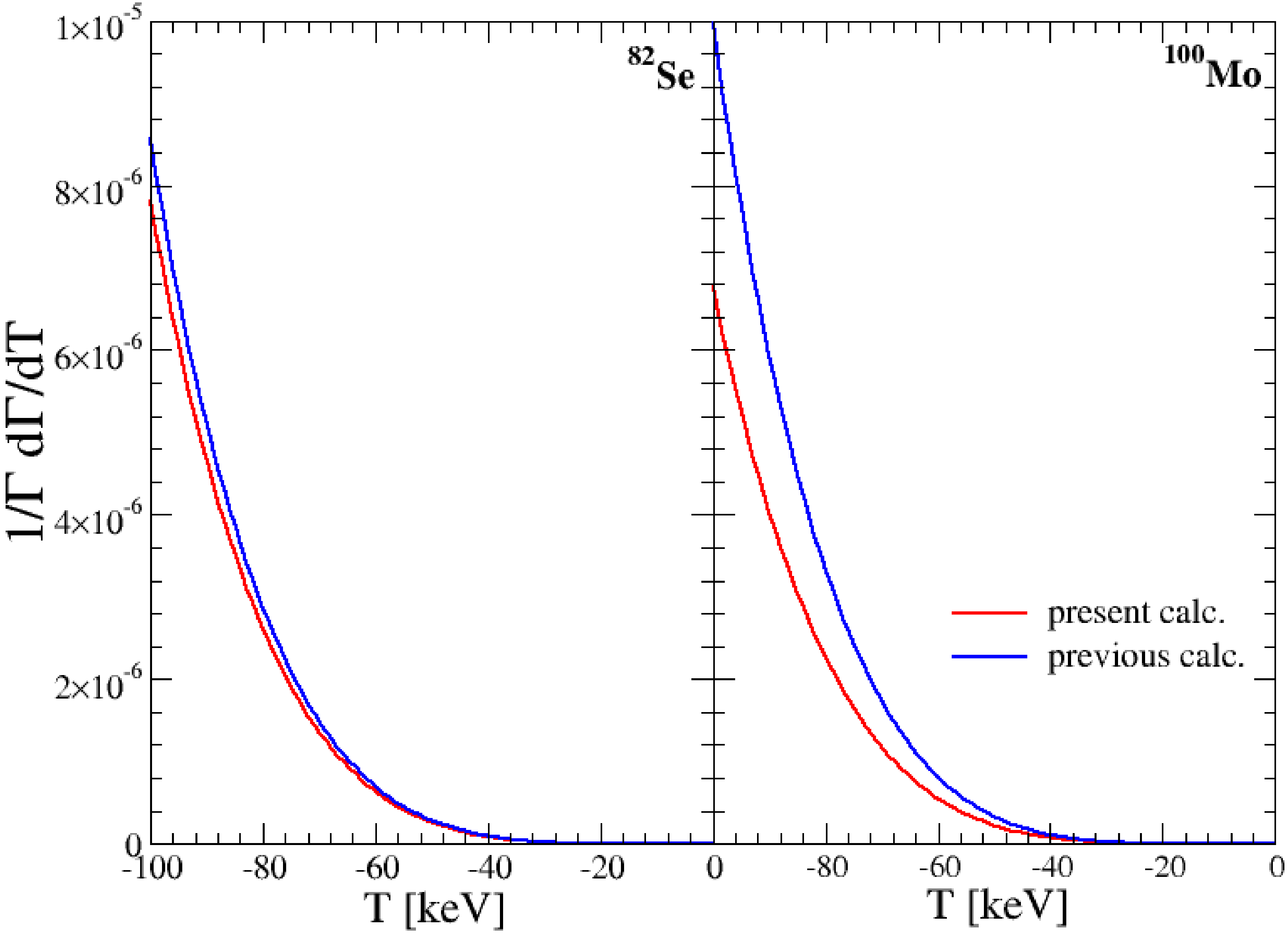
The single electron energy distribution



The sum electron energy distribution



The endpoint of the spectrum of differential decay rate vs. the sum of kinetic energy of emitted electrons



The half-life and ratios of NMEs

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} = \left(g_A^{\rm eff}\right)^4 \left|M_{GT-1}^{2\nu}\right|^2 \left(G_0^{2\nu} + \Re\{\xi_{13}^{2\nu}\}G_2^{2\nu} + \frac{1}{3}\left|\xi_{13}^{2\nu}\right|^2 G_{22}^{2\nu} + \left(\frac{1}{3}\left|\xi_{13}^{2\nu}\right|^2 + \Re\{\xi_{15}^{2\nu}\}\right) G_4^{2\nu}\right)$$

$$\xi_{13}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}$$

$$\xi_{15}^{2\nu} = \frac{M_{GT-5}^{2\nu}}{M_{GT-1}^{2\nu}}$$

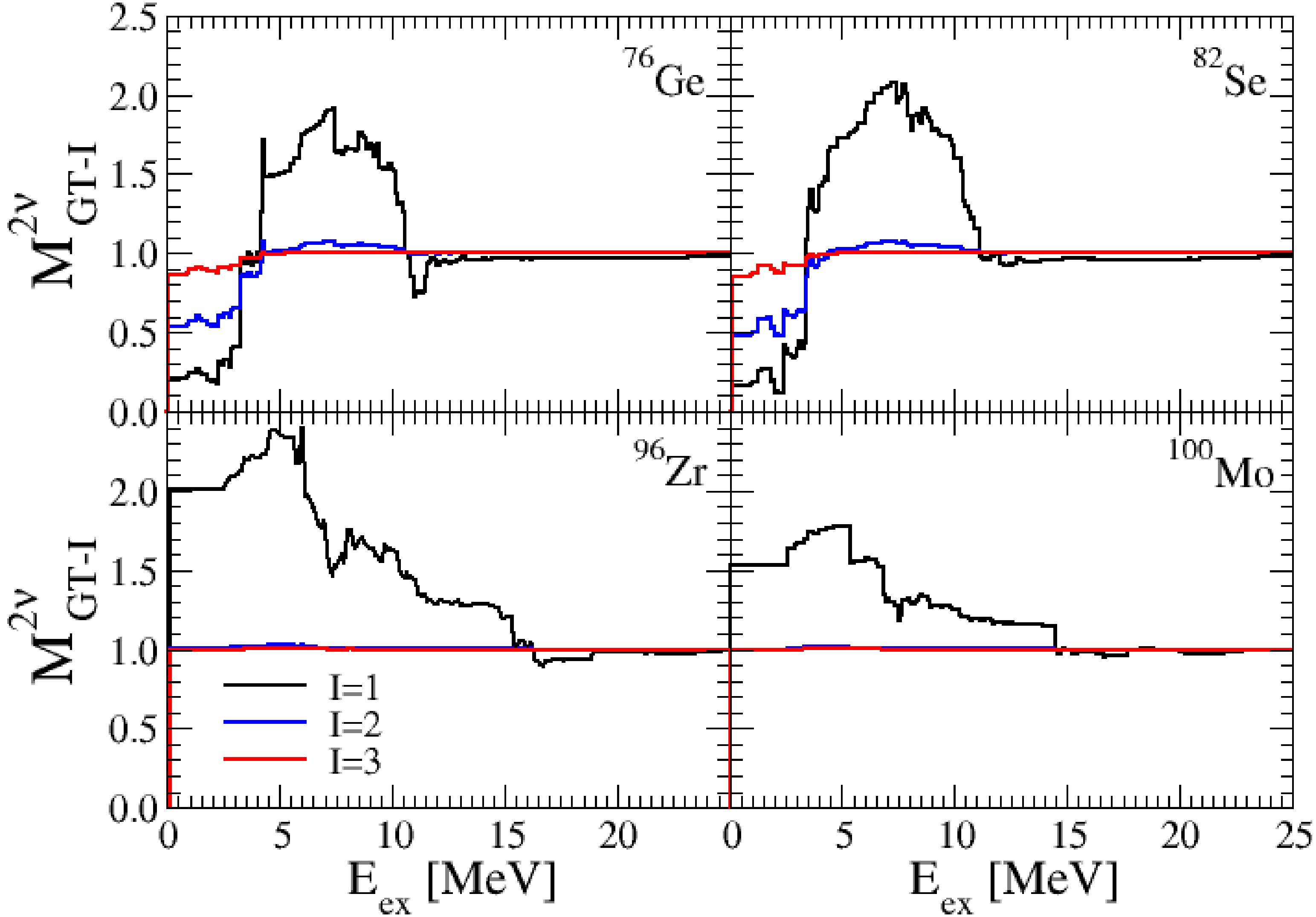
The half-life expressed with only one ratio of NMEs

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \simeq \left(g_A^{\rm eff}\right)^4 \left|M_{GT-3}^{2\nu}\right|^2 \frac{1}{\left|\xi_{13}^{2\nu}\right|^2} \left(G_0^{2\nu} + \xi_{13}^{2\nu} G_2^{2\nu}\right)$$

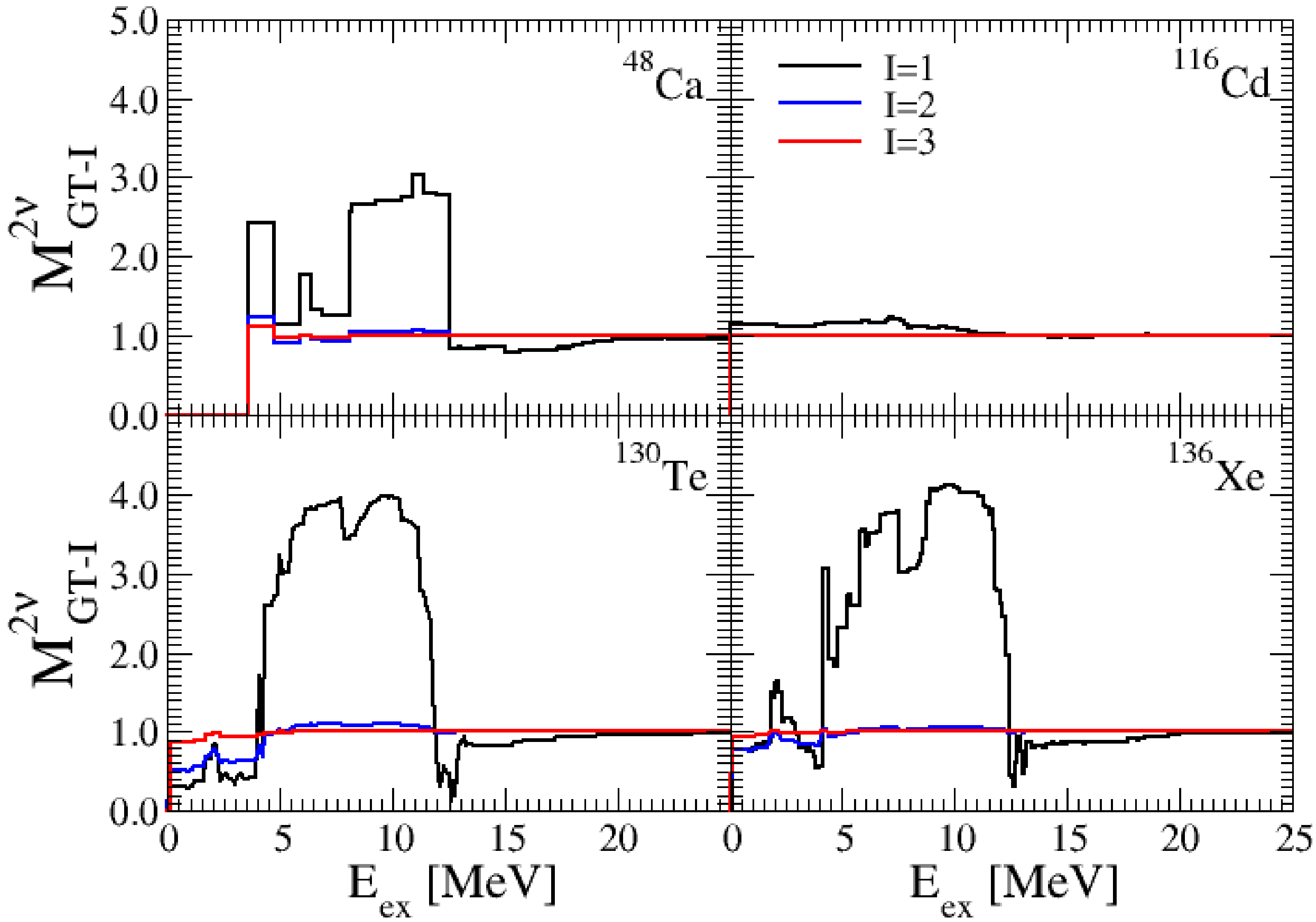
The g_A^{eff} can be deterimed with measured half-life and ratio of NMEs and calculated NME dominated by transitions through low lying states of the intermediate nucleus (ISM?)

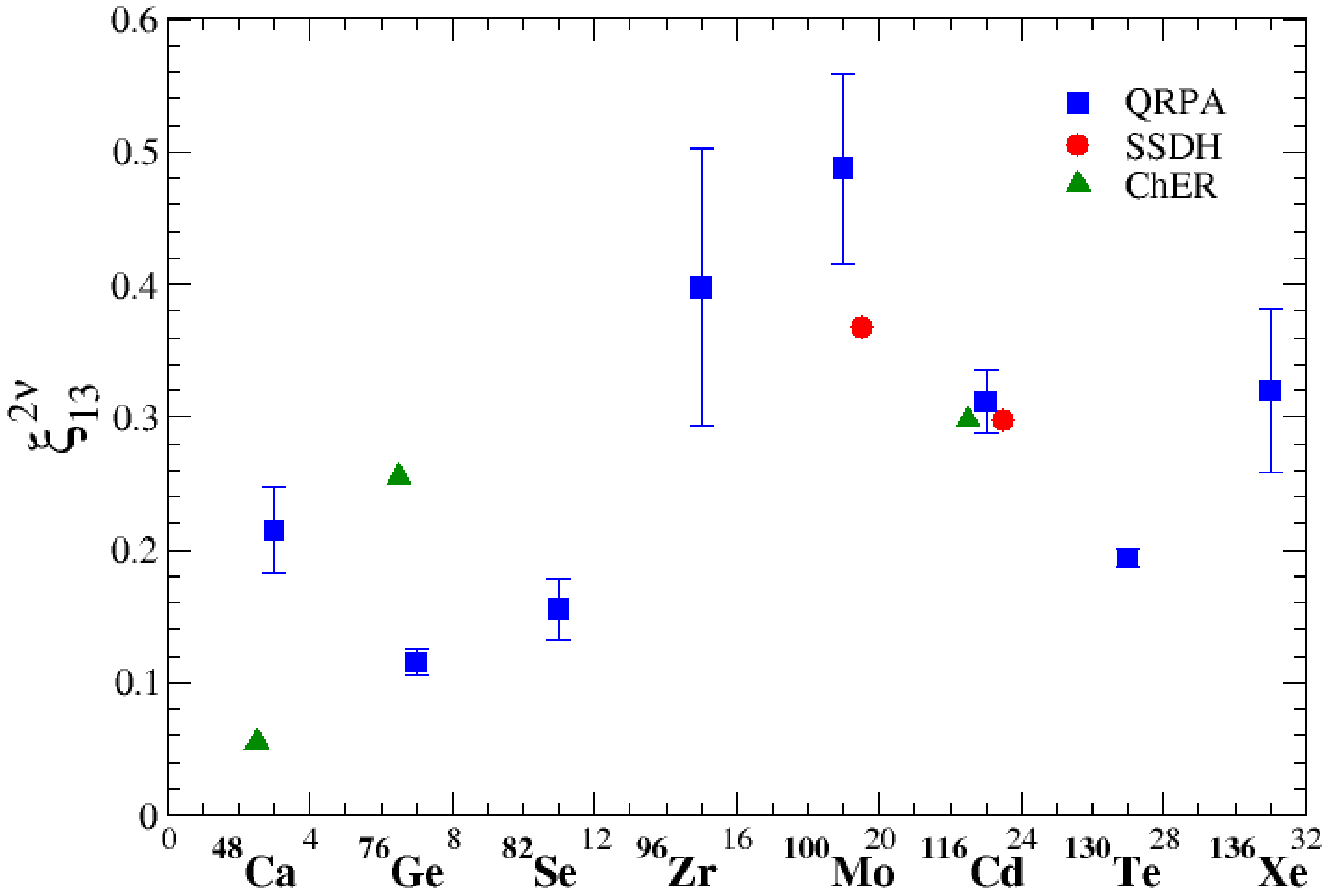
$$\left(g_A^{\rm eff}\right)^2 = \frac{1}{\left|M_{GT-3}^{2\nu}\right|} \frac{\left|\xi_{13}^{2\nu}\right|}{\sqrt{T_{1/2}^{2\nu-exp}\left(G_0^{2\nu} + \xi_{13}^{2\nu} G_2^{2\nu}\right)}}$$

The running sum of the 2νββ–decay NMEs



The running sum of the 2νββ–decay NMEs





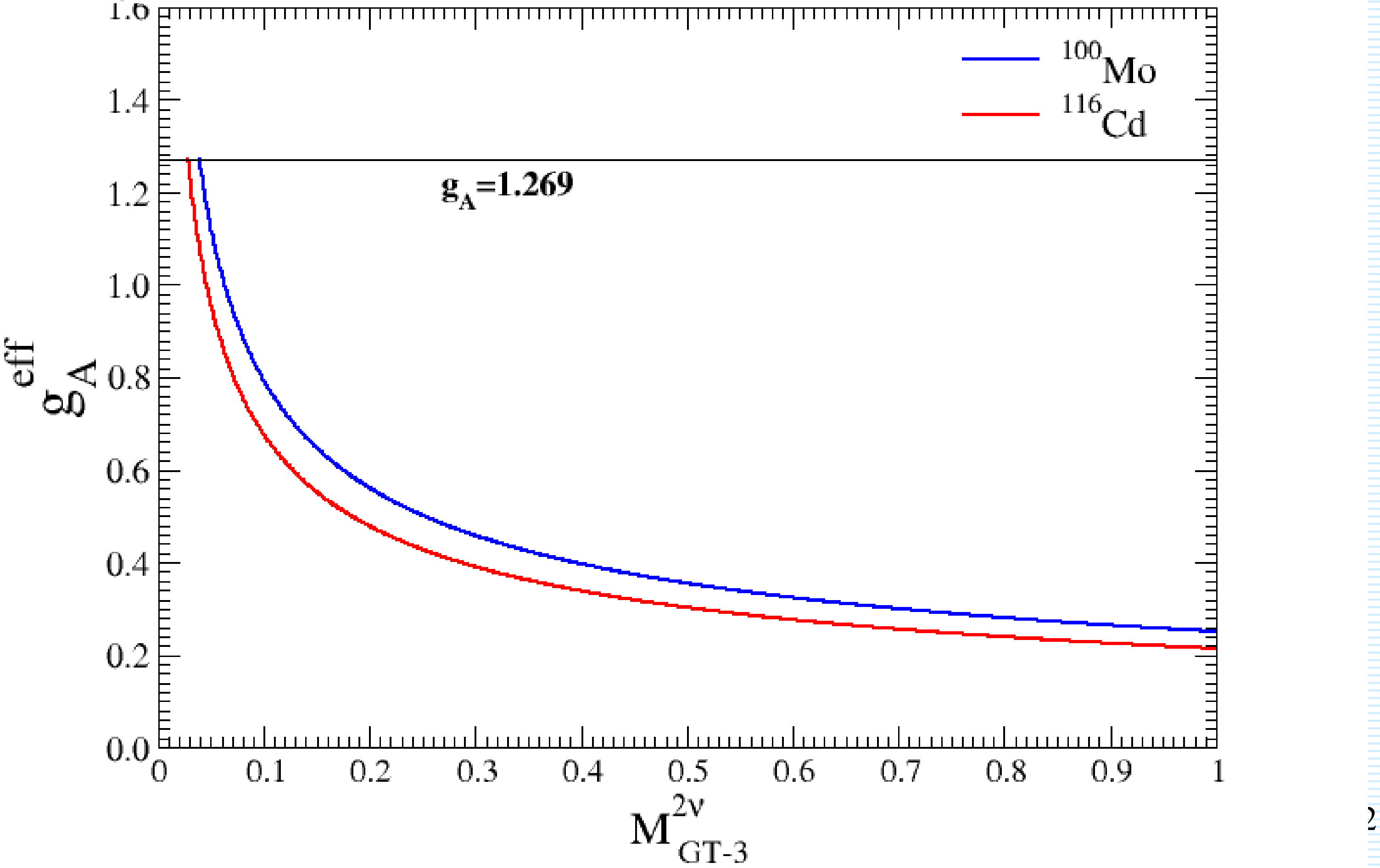
$\xi_{13}^{2\nu}$
0.6
0.5
0.4
0.3
0.2
0.1
0
0
4
8
12
16
20
24
28
32
^{48}Ca
^{76}Ge
^{82}Se
^{96}Zr
^{100}Mo
^{116}Cd
^{130}Te
^{136}Xe
QRPA
SSDH
ChER

Solution: NEMO3/Supernemo measurement of ξ and calculation of M_{GT-3}

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \simeq \left(g_A^{\rm eff}\right)^4 \left|M_{GT-3}^{2\nu}\right|^2 \frac{1}{\left|\xi_{13}^{2\nu}\right|^2}\left(G_0^{2\nu} + \xi_{13}^{2\nu} G_2^{2\nu}\right)$$

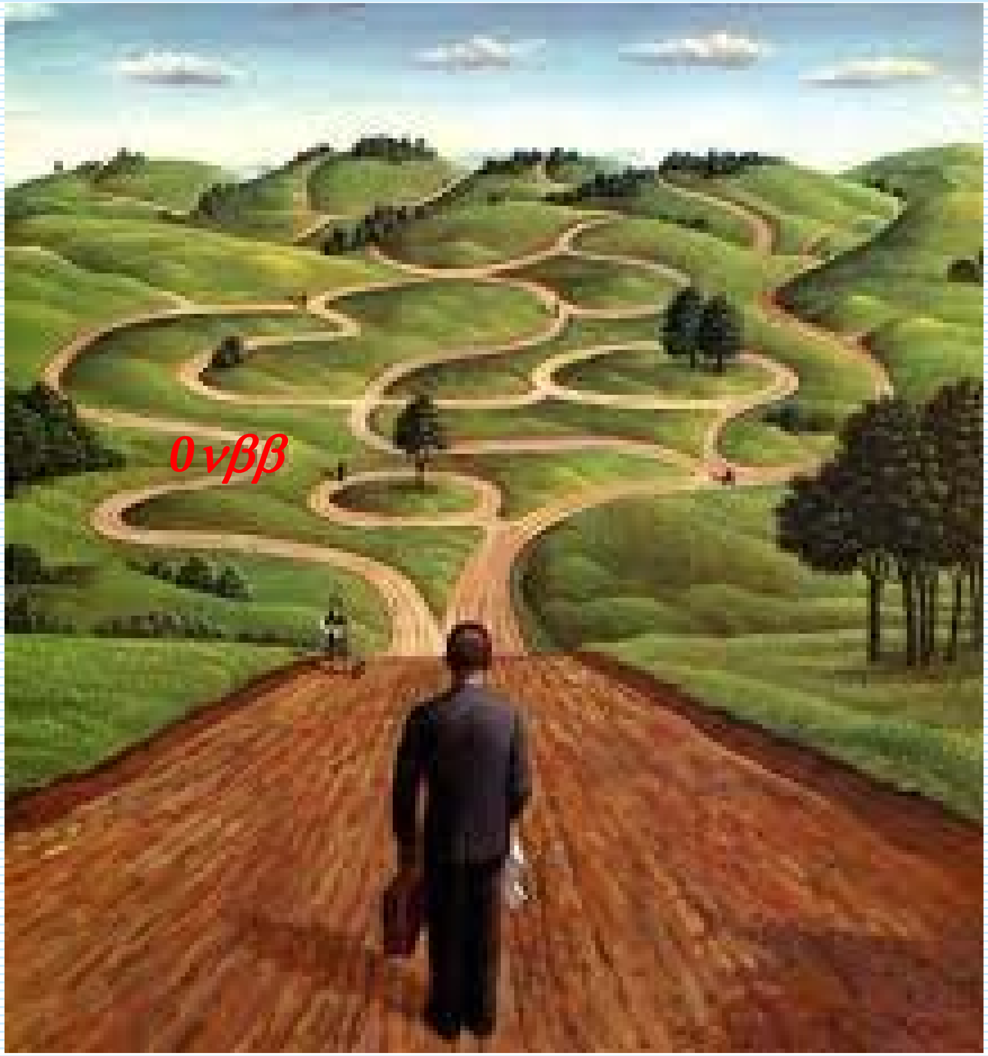
$$g_A^{\rm eff}(^{100}{\rm Mo}) = \frac{0.251}{\sqrt{M_{GT-3}^{2\nu}}}$$

$$g_A^{\rm eff}(^{100}{\rm Cd}) = \frac{0.214}{\sqrt{M_{GT-3}^{2\nu}}}$$



Instead of Conclusions

Progress in nuclear structure calculations is highly required



We are at the beginning of the BSM Road…

VII International Pontecorvo Neutrino Physics School 2017

http://theor.jinr.ru/~neutrino17

August 20 – September 1, 2017

Prague, Czech Republic

Introduction to ν-physics
Theory of ν-masses and mixing
ν-oscillation phenomenology
Solar ν-experiments and theory
Accelerator ν-experiments
Reactor ν-experiments
Measurement of ν-mass

$0\nu\beta\beta$-decay experiments
$0\nu\beta\beta$-decay nuclear matrix elements
ν-nucleus interactions
Sterile neutrinos

Leptogenesis
ν-astronomy
ν-telescopes
ν-cosmology
Dark matter experiments
Observation of gravitational waves
Neutrino physics at CERN
Future colliders
Statistics for Nucl. and Particle Phys.

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Kutná Hora

Nucleus	SSD $(g_A^{\rm eff})^2 M^{2\nu}_{GT-1}$	SSD $(g_A^{\rm eff})^2 M^{2\nu}_{GT-3}$	SSD $(g_A^{\rm eff})^2 M^{2\nu}_{GT-5}$	SSD $\xi^{2\nu}_{13}$	SSD $\xi^{2\nu}_{15}$	ChER $M^{2\nu}_{GT-1}$	ChER $M^{2\nu}_{GT-3}$	ChER $M^{2\nu}_{GT-5}$	ChER $\xi^{2\nu}_{13}$	ChER $\xi^{2\nu}_{15}$
^{48}Ca	-	-	-	-	-	$4.25\ 10^{-2}$	$2.31\ 10^{-3}$	$1.26\ 10^{-4}$	$5.44\ 10^{-2}$	$2.96\ 10^{-3}$
^{76}Ge	-	-	-	-	-	$8.61\ 10^{-2}$	$2.20\ 10^{-2}$	$5.61\ 10^{-3}$	$2.55\ 10^{-1}$	$6.52\ 10^{-2}$
^{100}Mo	$1.71\ 10^{-1}$	$6.29\ 10^{-2}$	$2.31\ 10^{-2}$	$3.68\ 10^{-1}$	$1.35\ 10^{-1}$	-	-	-	-	-
^{116}Cd	$1.53\ 10^{-1}$	$4.57\ 10^{-2}$	$1.36\ 10^{-2}$	$2.98\ 10^{-1}$	$8.87\ 10^{-2}$	$5.88\ 10^{-2}$	$1.75\ 10^{-2}$	$5.22\ 10^{-3}$	$2.98\ 10^{-1}$	$8.87\ 10^{-2}$
^{128}Te	$1.60\ 10^{-2}$	$5.87\ 10^{-3}$	$2.16\ 10^{-3}$	$3.67\ 10^{-1}$	$1.35\ 10^{-1}$	-	-	-	-	-