Topical Research Meeting: Prospects in Neutrino Physics
IOP, London, UK, December 19-20, 2013

Nuclear matrix elements for neutrinoless double-beta decays

Fedor Šimkovic

OUTLINE

$0\nu\beta\beta$ | $0\nu\varepsilon\varepsilon$ | $0\nu\varepsilon\beta$

$m_{\beta\beta}$

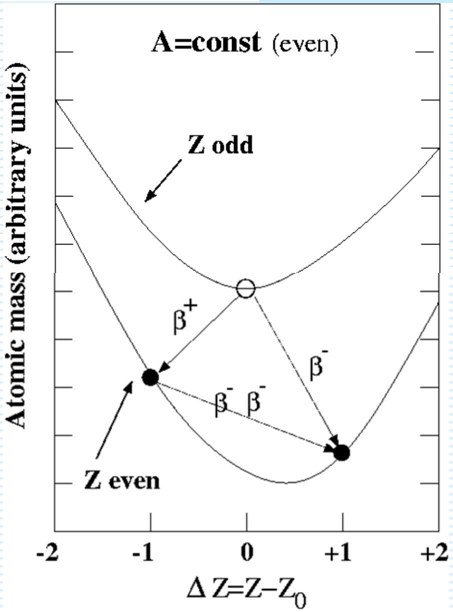
ν mass scale

CP-phases

Nuclear structure

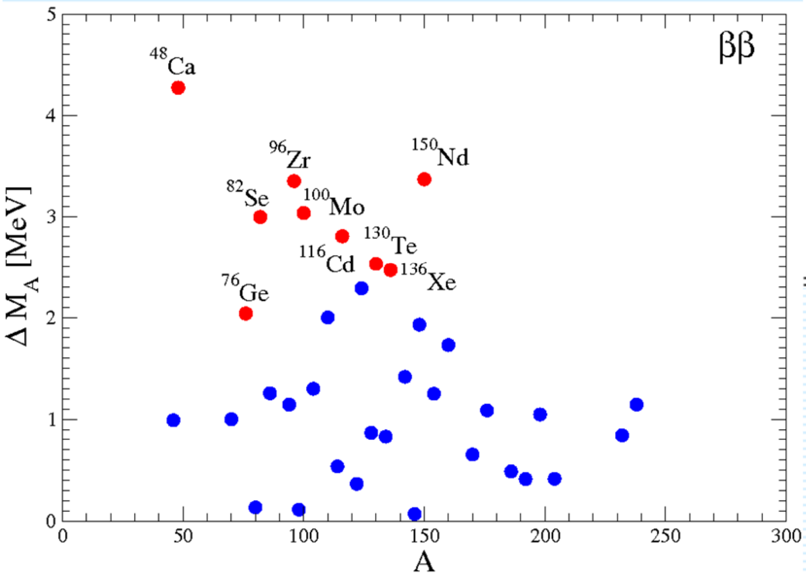
Neutrinoless Double-Beta Decay

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^-$$



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

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

Neutrinoless double beta decay of ^{110}Pd

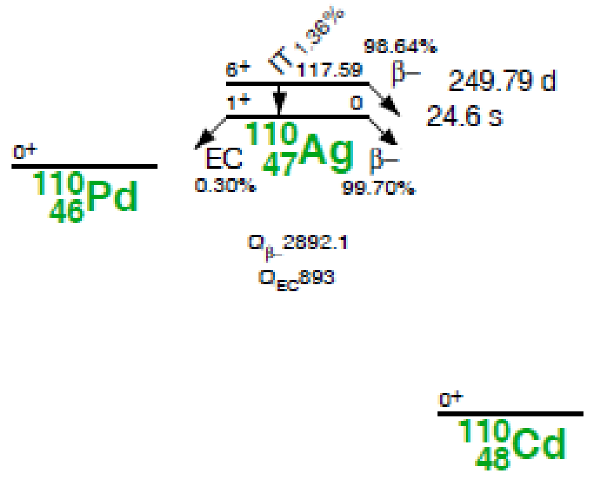
With its high natural abundance, the new results reveal ^{110}Pd to be an excellent candidate for double-β decay studies

Q-Value and Half-Lives for the Double-Beta-Decay Nuclide ^{110}Pd

D. Fink, et al.

Phys. Rev. Lett. 108 (2012) 062502.

	^{82}Se	^{110}Pd
Z	34	46
Abund. (%)	8.73	11.72
Q [keV]	2 995	2 017.8
$G^{0\nu}$ [10^{-15} yr^{-1}]	10.16	4.815
$0\nu\beta\beta$ NME	4.64	5.76
$T^{2\nu}_{1/2}$ [yr]	0.92 10^{20}	1.5(6) 10^{20}(SSD)



Effective Majorana neutrino mass

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

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

Absolute ν mass scale

Normal or inverted hierarchy of ν masses

CP-violating phases



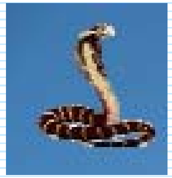
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

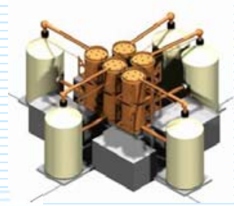
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

An accurate knowledge of the nuclear matrix elements, which is not available at present, is however a pre-requisite for exploring neutrino properties.

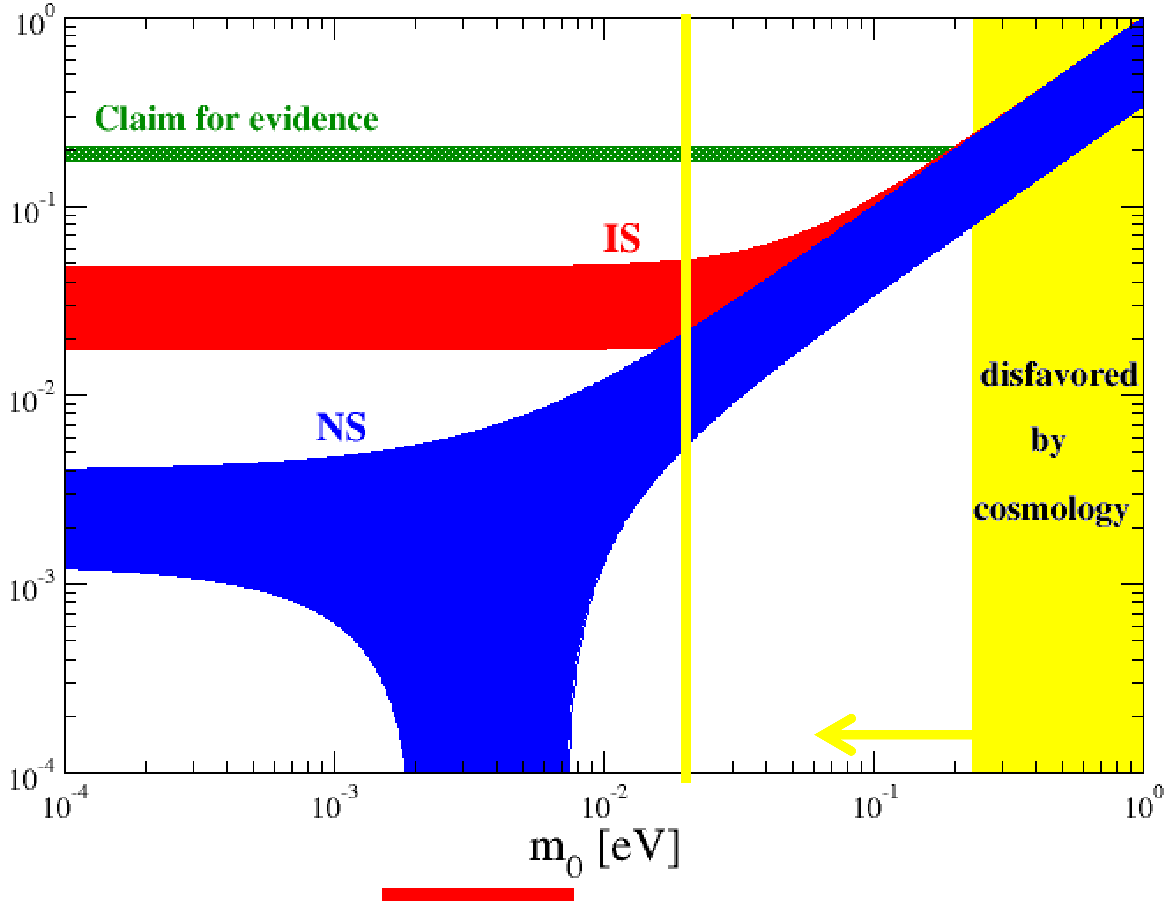
Daya Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$ (March 2012)

$$|m_{\beta\beta}^{(3\ \nu)}| = |c_{12}^2 c_{13}^2 e^{2i\alpha_1} m_1 + c_{13}^2 s_{12}^2 e^{2i\alpha_2} m_2 + s_{13}^2 m_3|$$





Issue: Lightest neutrino mass m_0



GUT's

(Rodejohann pres.)

On the possibility of measuring CP Majorana phases in the $0\nu\beta\beta$-decay

F.Š., S. Bilenky, A. Faessler, Th. Gutsche, Phys. Rev. D 87, 073002 (2013)

Majorana phases

$$P = diag(e^{-i\alpha_1/2}, e^{-i\alpha_2/2}, e^{-i\alpha_3/2})$$
$$\alpha_3/2 = \delta$$

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

Measured quantity

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

Normal hierarchy

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

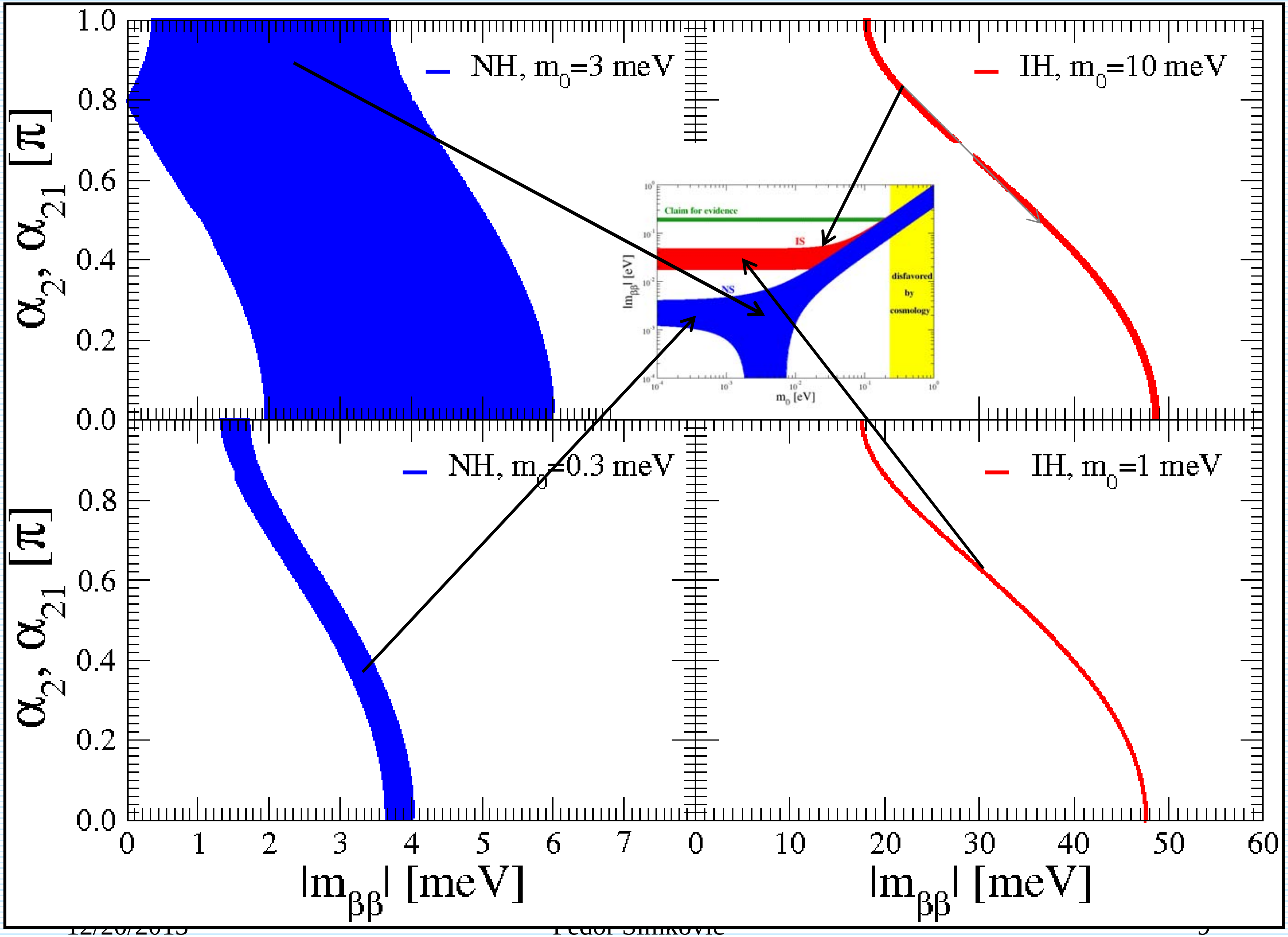
Inverted hierarchy

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

Assuming lightest neutrino mass to be zero

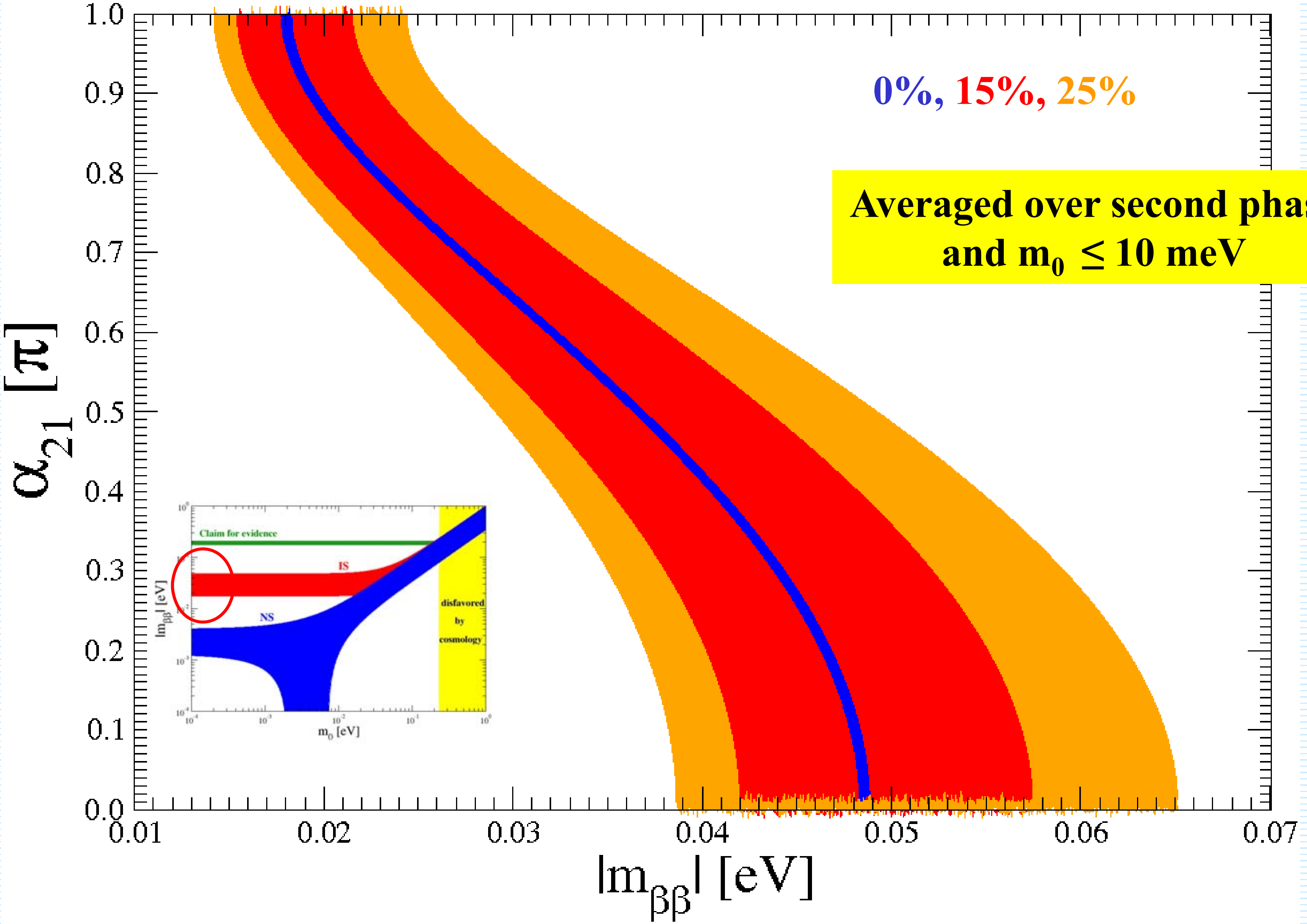
$$\cos\alpha_2 \simeq \frac{|m_{\beta\beta}|^2 - s_{12}^4 c_{13}^4 \Delta m^2_{\mathrm{SUN}} - s_{13}^4 \Delta m^2_{\mathrm{ATM}}}{2s_{12}^2 c_{13}^2 s_{13}^2 \sqrt{\Delta m^2_{\mathrm{SUN}} \Delta m^2_{\mathrm{ATM}}}}$$

$$\cos\alpha_{12} = \frac{|m_{\beta\beta}|^2 - c_{13}^4 (1 - 2s_{12}^2 c_{12}^2) \Delta m^2_{\mathrm{ATM}}}{2c_{12}^2 s_{12}^2 c_{13}^4 \Delta m^2_{\mathrm{ATM}}}$$


NH, m0=3 meV
IH, m0=10 meV
NH, m0=0.3 meV
IH, m0=1 meV
α2, α21 [π]
|mββ| [meV]
Claim for evidence
IS
NS
disfavored by cosmology
|mββ| [eV]
m0 [eV]

$$|m_{\beta\beta}| = \frac{1}{\sqrt{T_{1/2}^{0\nu} G^{0\nu}(Q_{\beta\beta}, Z)}\,|M'^{0\nu}|}$$

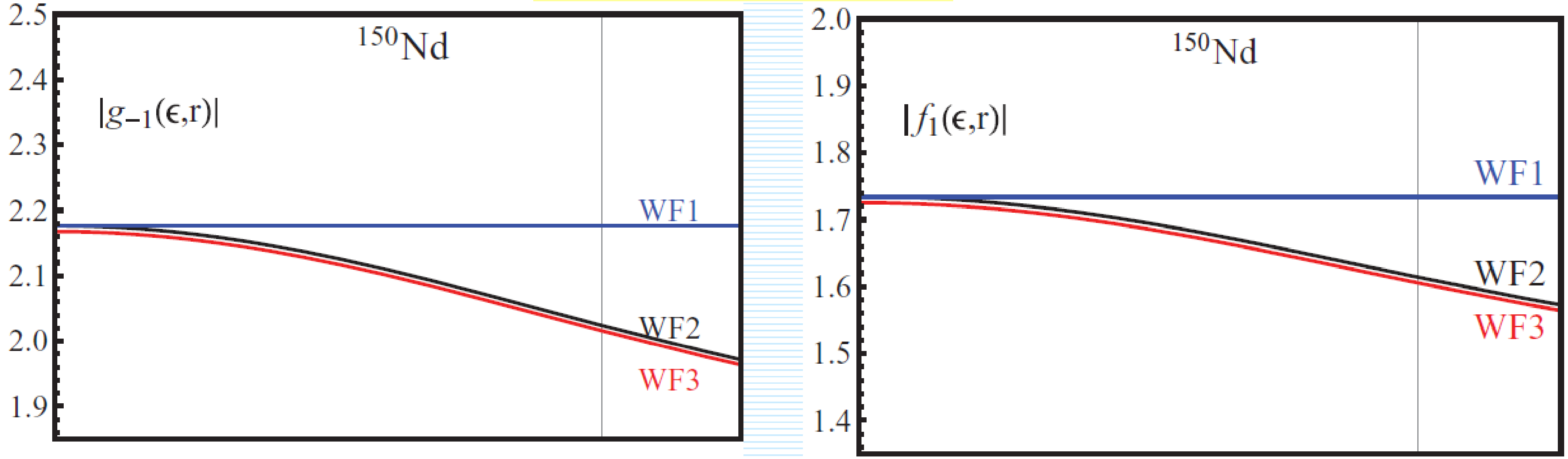
$$\frac{\sigma_{\beta\beta}}{|m_{\beta\beta}|^{obs}} = \sqrt{\frac{1}{4}\left(\frac{\sigma_{exp}}{T_{1/2}^{0\nu-obs}}\right)^2 + \left(\frac{\sigma_{th}}{|M'^{0\nu}|}\right)^2}$$



Phase-space factor

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

Electron w.f. at r=R



Dirac equations:

$$\psi_{\epsilon\kappa\mu}(\mathbf{r}) = \begin{pmatrix} g_\kappa(\epsilon,r)\chi^\mu_\kappa \\ i f_\kappa(\epsilon,r)\chi^\mu_{-\kappa}, \end{pmatrix}$$

$$\frac{dg_\kappa(\epsilon,r)}{dr} = -\frac{\kappa}{r} g_\kappa(\epsilon,r) + \frac{\epsilon - V + m_e c^2}{c\hbar} f_\kappa(\epsilon,r)$$

$$\frac{df_\kappa(\epsilon,r)}{dr} = -\frac{\epsilon - V - m_e c^2}{c\hbar} g_\kappa(\epsilon,r) + \frac{\kappa}{r} f_\kappa(\epsilon,r)$$

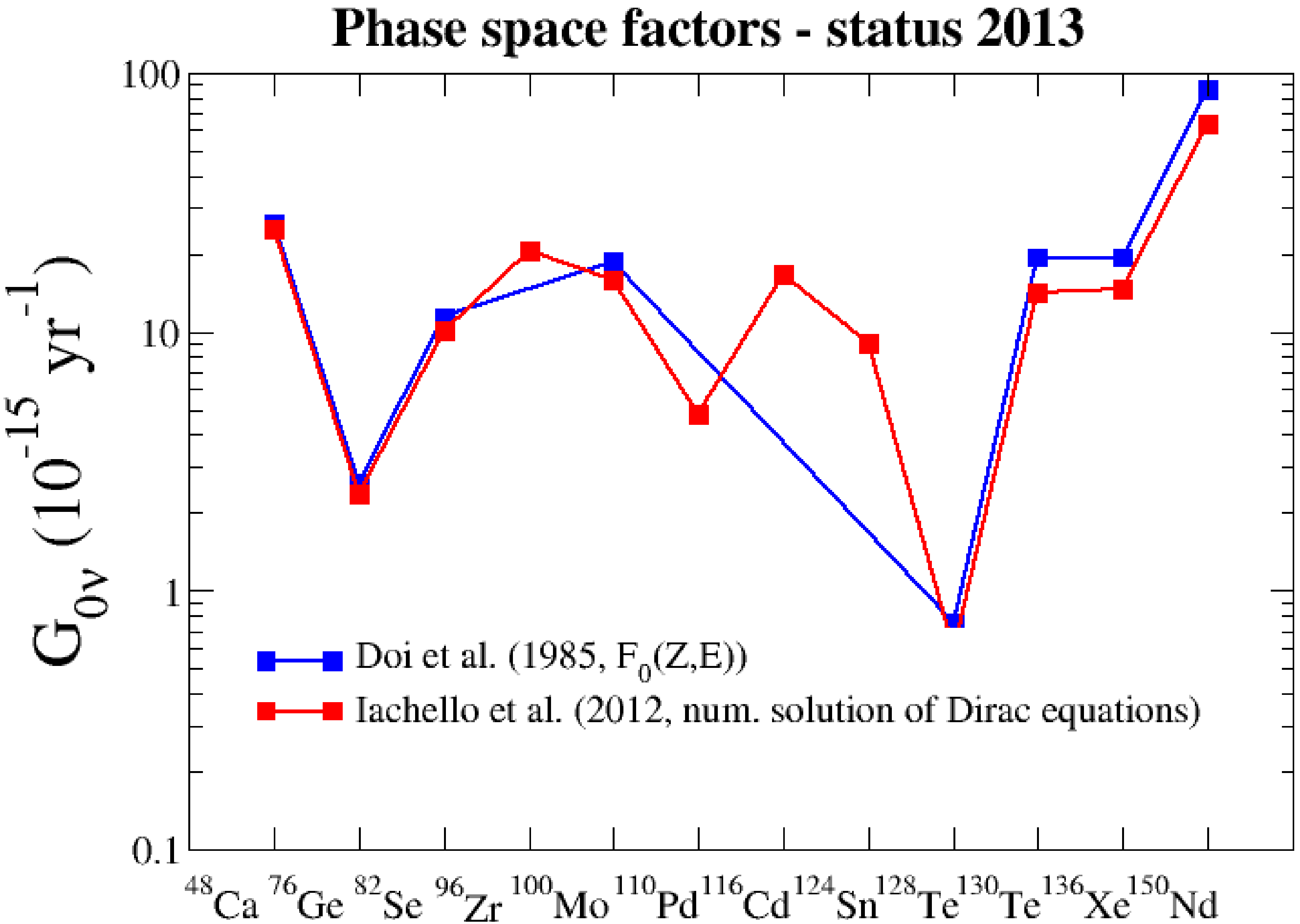
$s_{1/2}$ electron wave state

Finite nuclear size

$$e_s^{S_{1/2}}(\epsilon,\mathbf{r}) = \begin{pmatrix} g_{-1}(\epsilon,r)\chi_s \\ f_1(\epsilon,r)(\hat{\mathbf{p}}\cdot\vec{\sigma})\chi_s \end{pmatrix}$$

WF1: approx. sol. inside nucl. (M. Rose approach)
WF2: numerical solution of Dirac eq.
WF3: numerical solution of Dirac eq. with consideration of electron screening

Nucleus is considered to be spherical



Nuclear Matrix Elements (NMEs)

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

The $0\nu\beta\beta$-decay: A nuclear physics problem

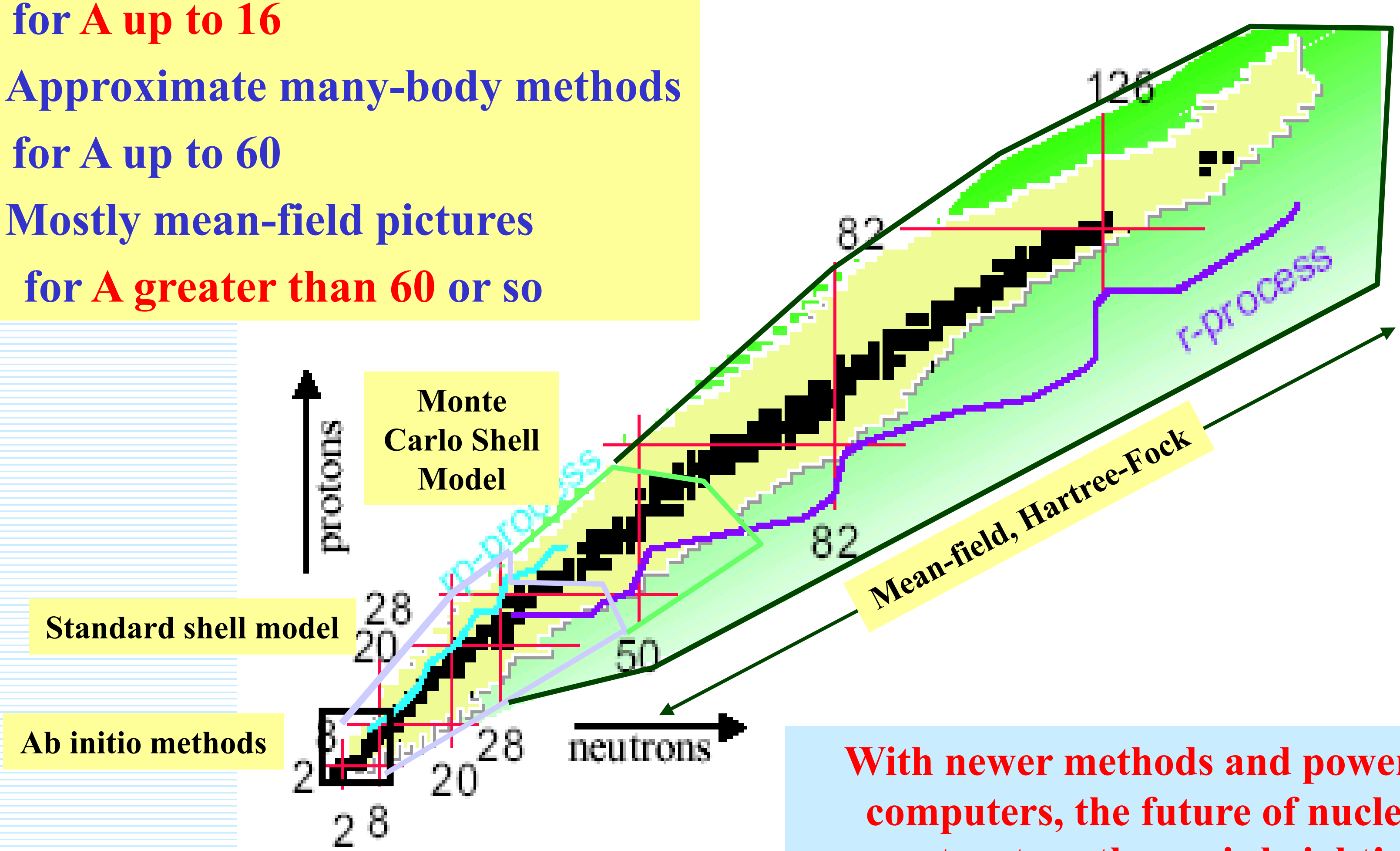
In double beta decay two neutrons bound in the ground state of an initial even-even nucleus are simultaneously transformed into two protons that are bound in the ground state or excited (0^+, 2^+) states of the final nucleus

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.

Nuclear Structure

- Exact methods exist up to **A=4**
- Computationally exact methods for **A up to 16**
- Approximate many-body methods for A up to 60
- Mostly mean-field pictures for **A greater than 60** or so

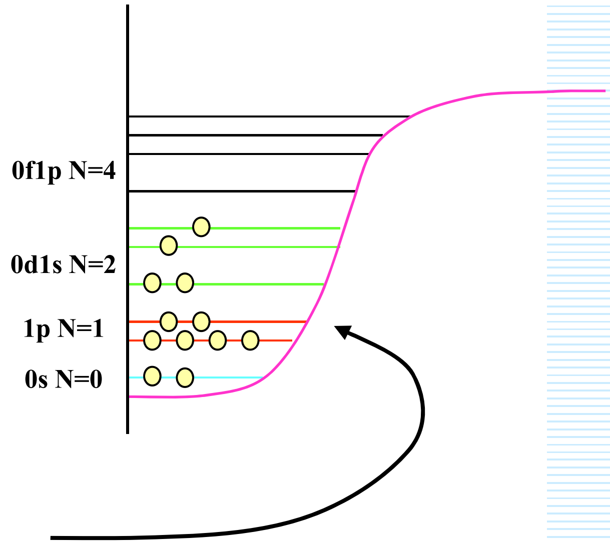


With newer methods and powerful computers, the future of nuclear structure theory is bright!

Many-body Hamiltonian

- **Start with the many-body Hamiltonian**

$$H = \sum_i \frac{\vec{p}_i^{\,2}}{2m} + \sum_{i<j} V_{NN}\left(\vec{r}_i - \vec{r}_j\right)$$



- **Introduce a mean-field U to yield basis**

$$H = \sum_i \left(\frac{\vec{p}_i^{\,2}}{2m} + U(r_i)\right) + \underbrace{\sum_{i<j} V_{NN}\left(\vec{r}_i - \vec{r}_j\right) - \sum_i U(r_i)}_{\text{Residual interaction}}$$

The success of any nuclear structure calculation depends on the choice of the mean-field basis and the residual interaction!

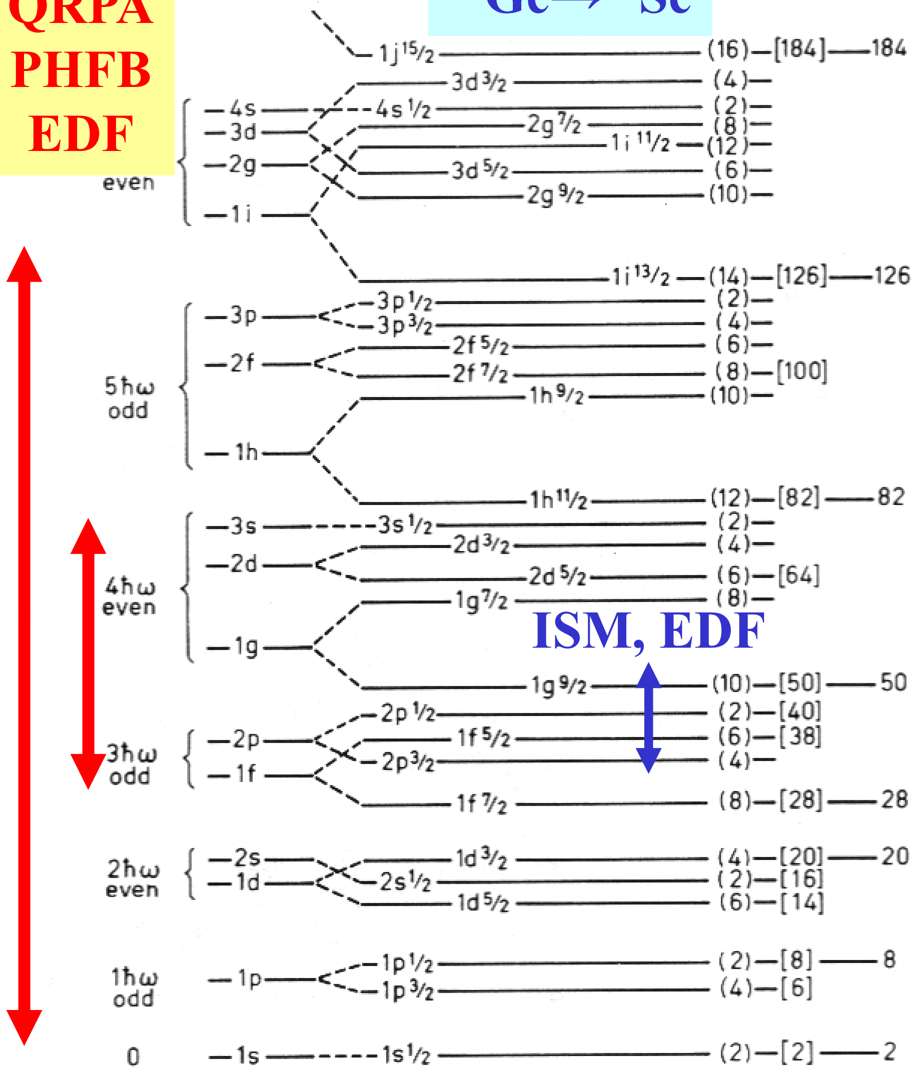
- **The mean field determines the shell structure**
- **In effect, nuclear-structure calculations rely on perturbation theory**

Nuclear structure approaches

In QRPA a large valence space is used, but only a class of configurations is included. Describe collective states, but not details of dominantly few particle states. Relative simple, thus more 0nbb-decay calculations.

QRPA
PHFB
EDF

$^{76}Ge \rightarrow {}^{76}Se$



In ISM a limited valence space is used but all configurations of valence nucleons are included. Describes well properties of low-lying nuclear states.

IBM: The low-lying states of the nucleus Are modeled in terms of L=0,2 bosons. They Interact through one-body and two-body Forces giving rise to bosonic wave functions

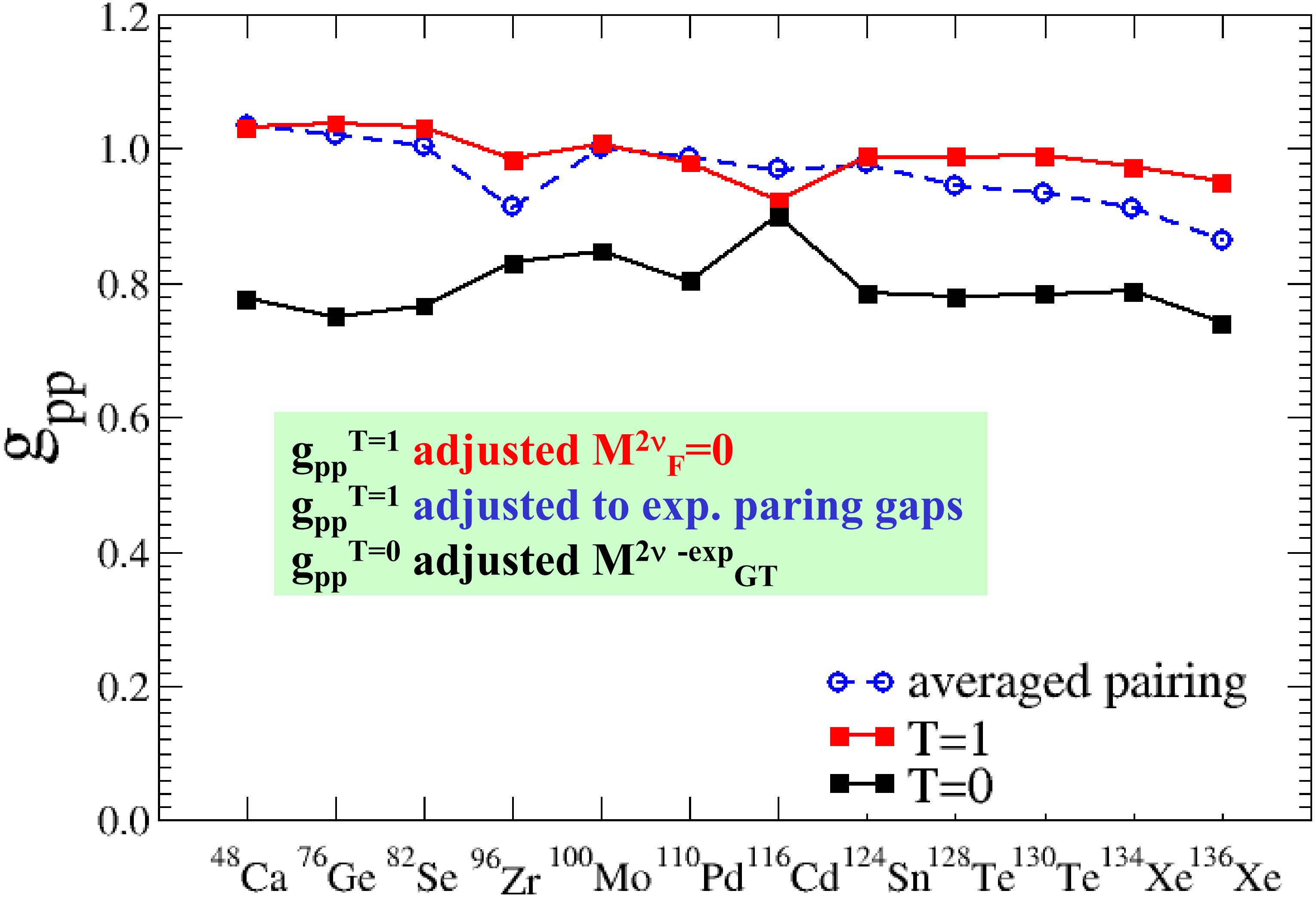
PHFB: Mean field approach based on the Bogoliubov-Hartree-Fock method and Projection. States have good angular momentum due projection.

EDF: Beyond mean field effects are incl. within generating coordinate method with particle and angular projections

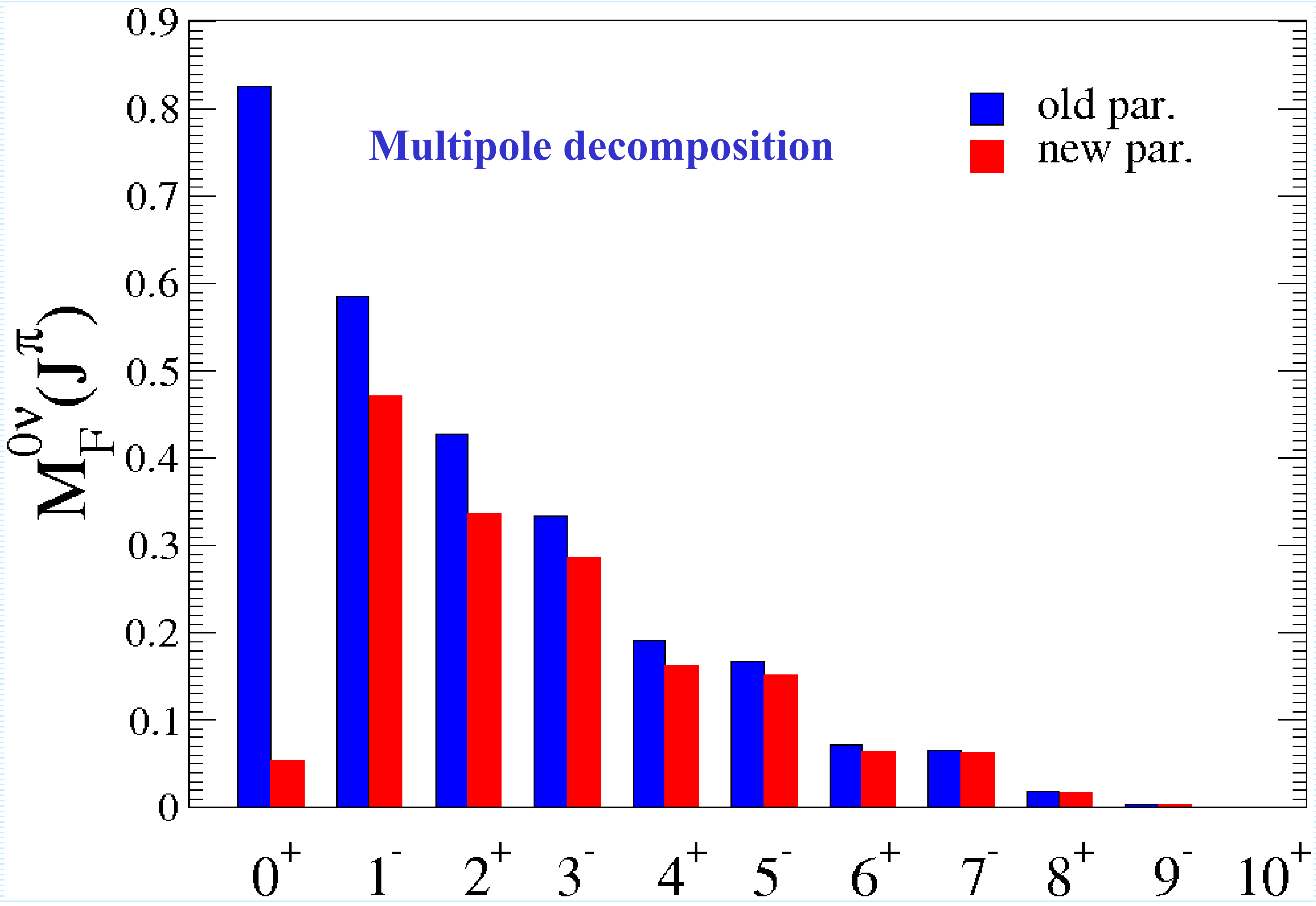
QRPA and isospin symmetry restoration

F.Š., V. Rodin, A. Faessler, and P. Vogel
PRC 87, 045501 (2013)

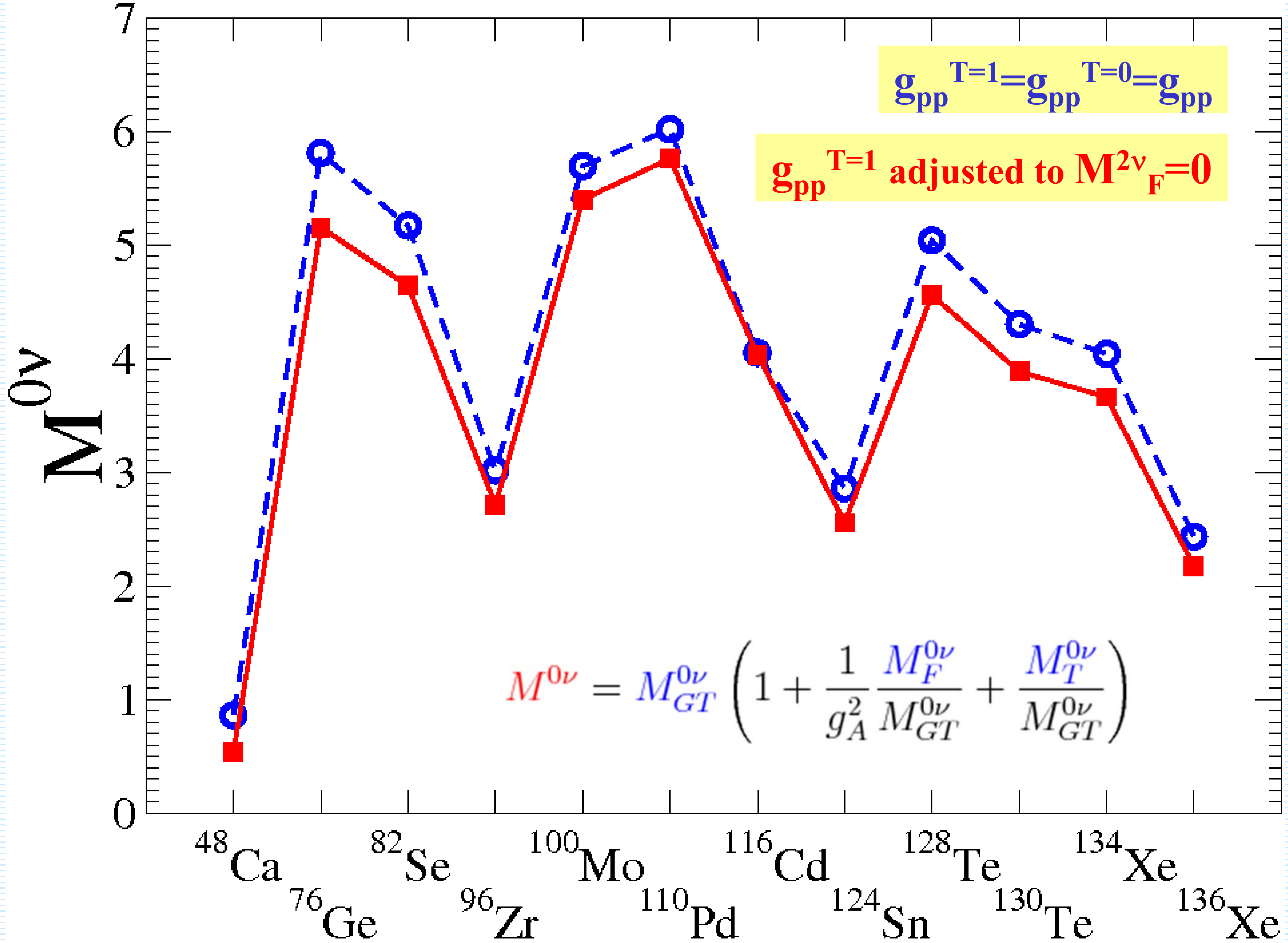
Close values ■ and ■ => no new parameter



Separation of g_{pp} into $g_{pp}^{T=0}$ and $g_{pp}^{T=1}$

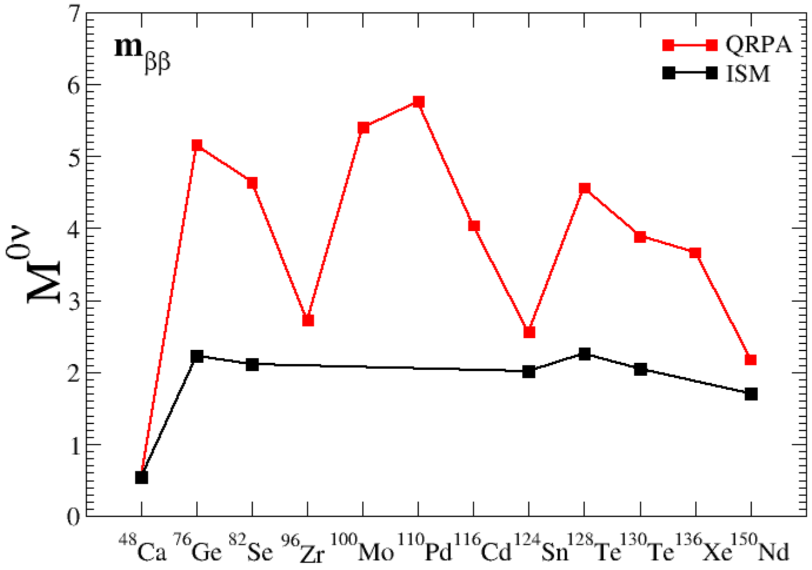


Multipole decomposition
old par.
new par.
$M_F^{0\nu}(J^\pi)$
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0^+ 1^- 2^+ 3^- 4^+ 5^- 6^+ 7^- 8^+ 9^- 10^+

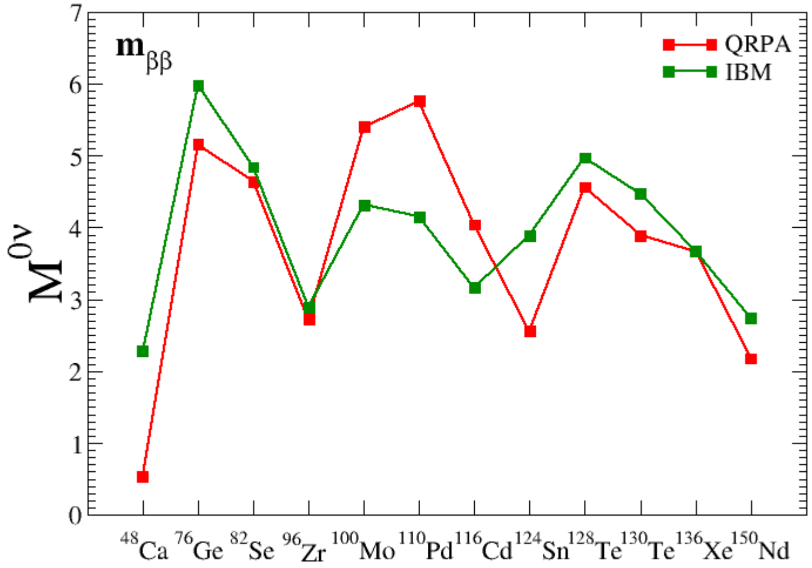


$g_{pp}^{T=1}=g_{pp}^{T=0}=g_{pp}$
$g_{pp}^{T=1}$ adjusted to $M^{2\nu}_{F}=0$
$M^{0\nu}$
$M^{0\nu} = M^{0\nu}_{GT}\left(1+\frac{1}{g_A^2}\frac{M^{0\nu}_{F}}{M^{0\nu}_{GT}}+\frac{M^{0\nu}_{T}}{M^{0\nu}_{GT}}\right)$
0
1
2
3
4
5
6
7
^{48}Ca
^{76}Ge
^{82}Se
^{96}Zr
^{100}Mo
^{110}Pd
^{116}Cd
^{124}Sn
^{128}Te
^{130}Te
^{134}Xe
^{136}Xe

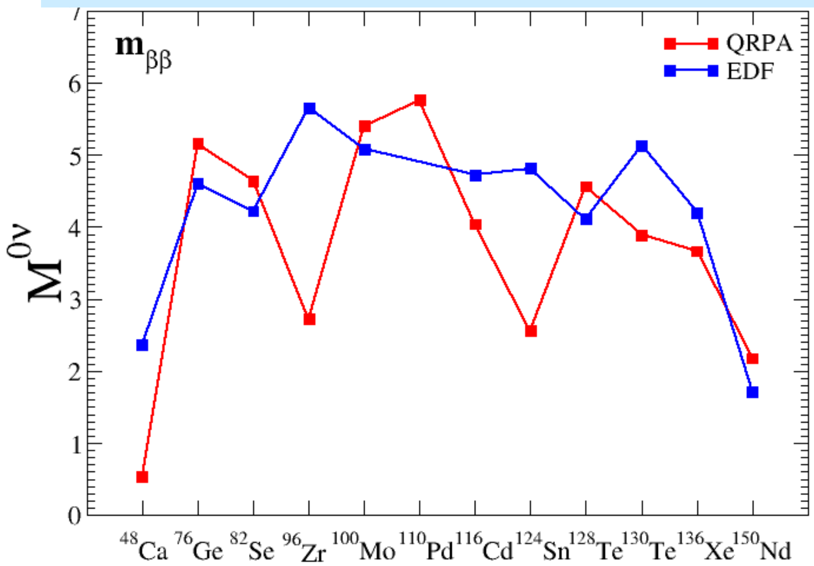
ISM: Menendez et al. NPA 818 (2009) 139



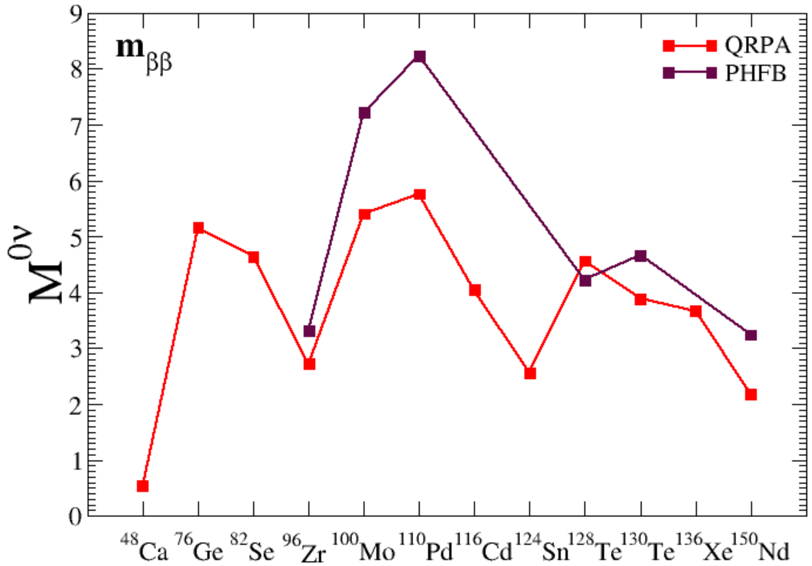
IBM: Barea, Kotila, Iachello, PRC (2013) 014315



EDF: Rodrigez, Martinez-Pinedo, PRL (2010) 105



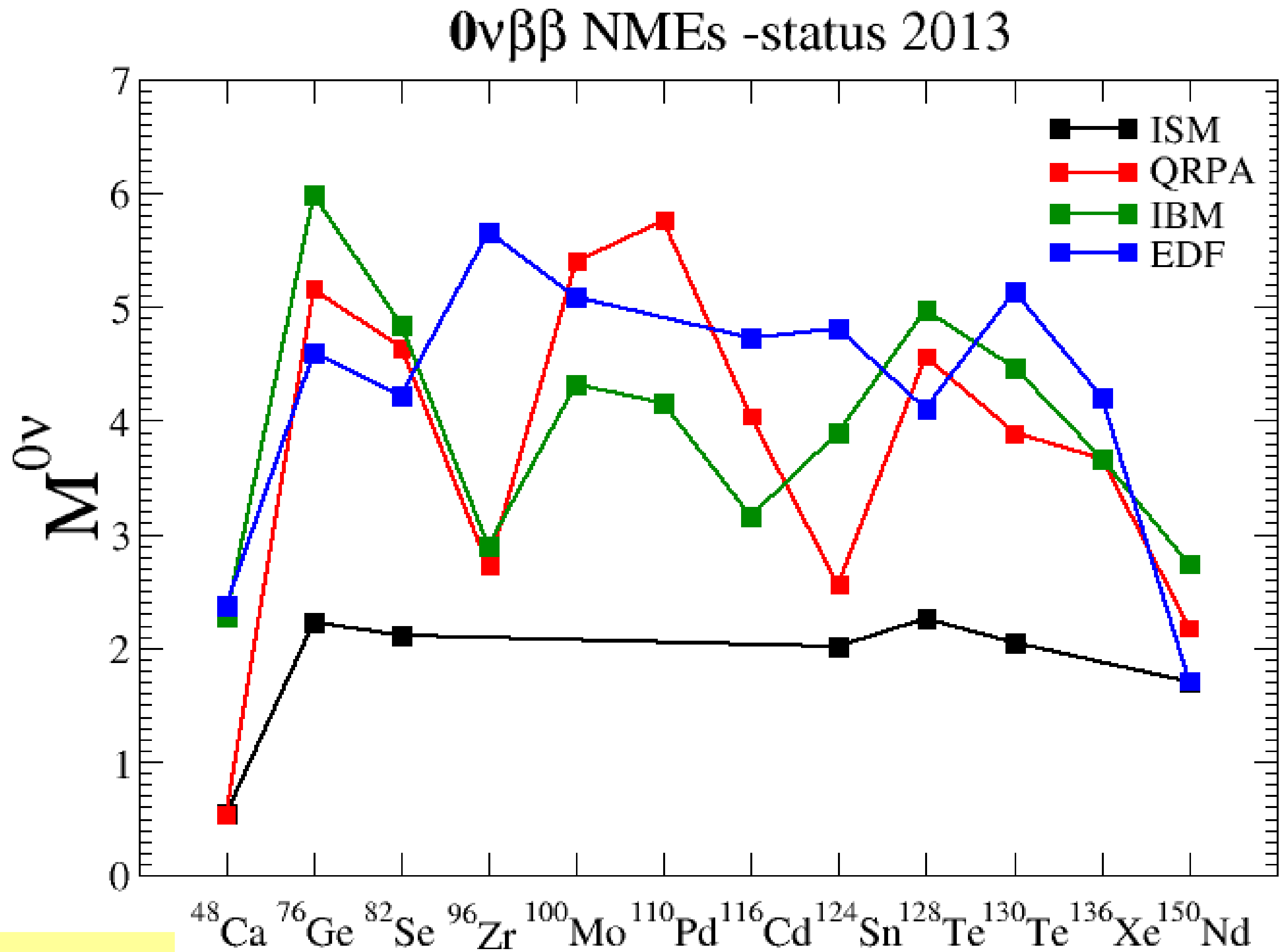
PHFB: K. Rath et al., PRC 85 (2012) 014308



***Differences:** mean field; residual int.; size of the m.s.; many-body appr.*

The 0νββ-decay NMEs (Status:2013)

Nobody is perfect:



g_A=1.25(7), CCm or UCOM s.r.c., r_0=1.20 fm

Differences:

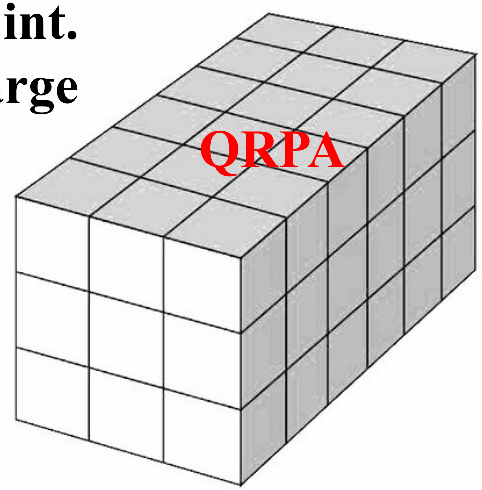
i) mean field;
ii) residual int.;
iii) size of the m.s.
iv) many-body appr.

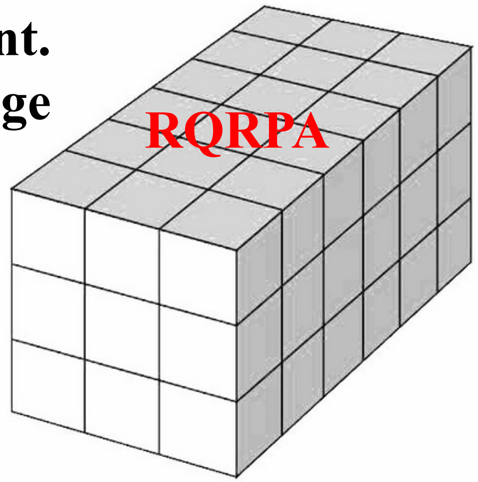
LSSM (small m.s., negative parity states)
PHFB (GT force neglected)
IBM (Hamiltonian truncated)
(R)QRPA (g.s. correlations not accurate enough)

QRPA uncertainties and their correlations in the analysis of $0\nu\beta\beta$ decay

A. Faessler, G.L. Fogli, E. Lisi, V. Rodin, A. M. Rotunno,F.Š.,
PRD 87, 053002 (2013)

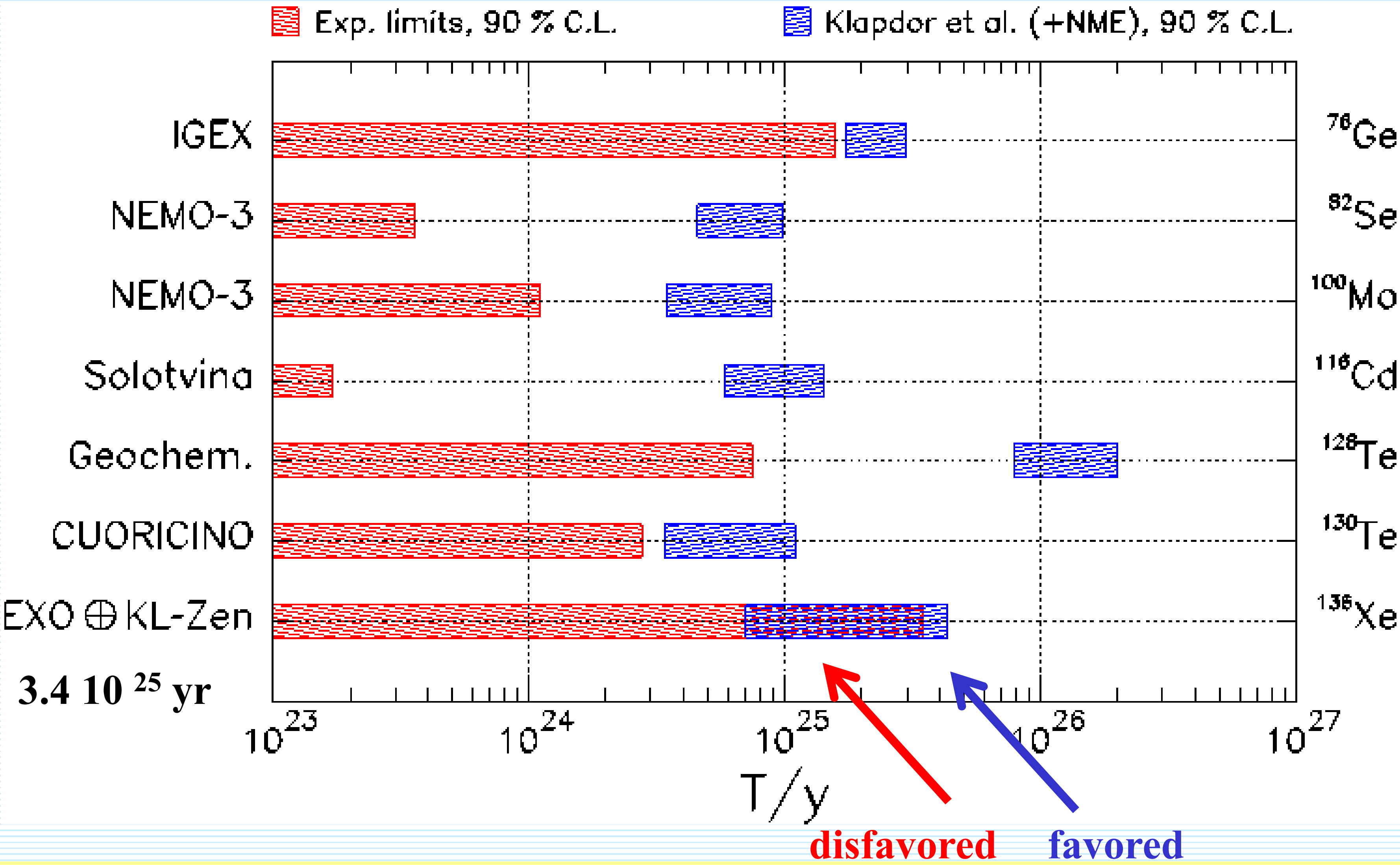
Effects of isospin restoration not included yet.





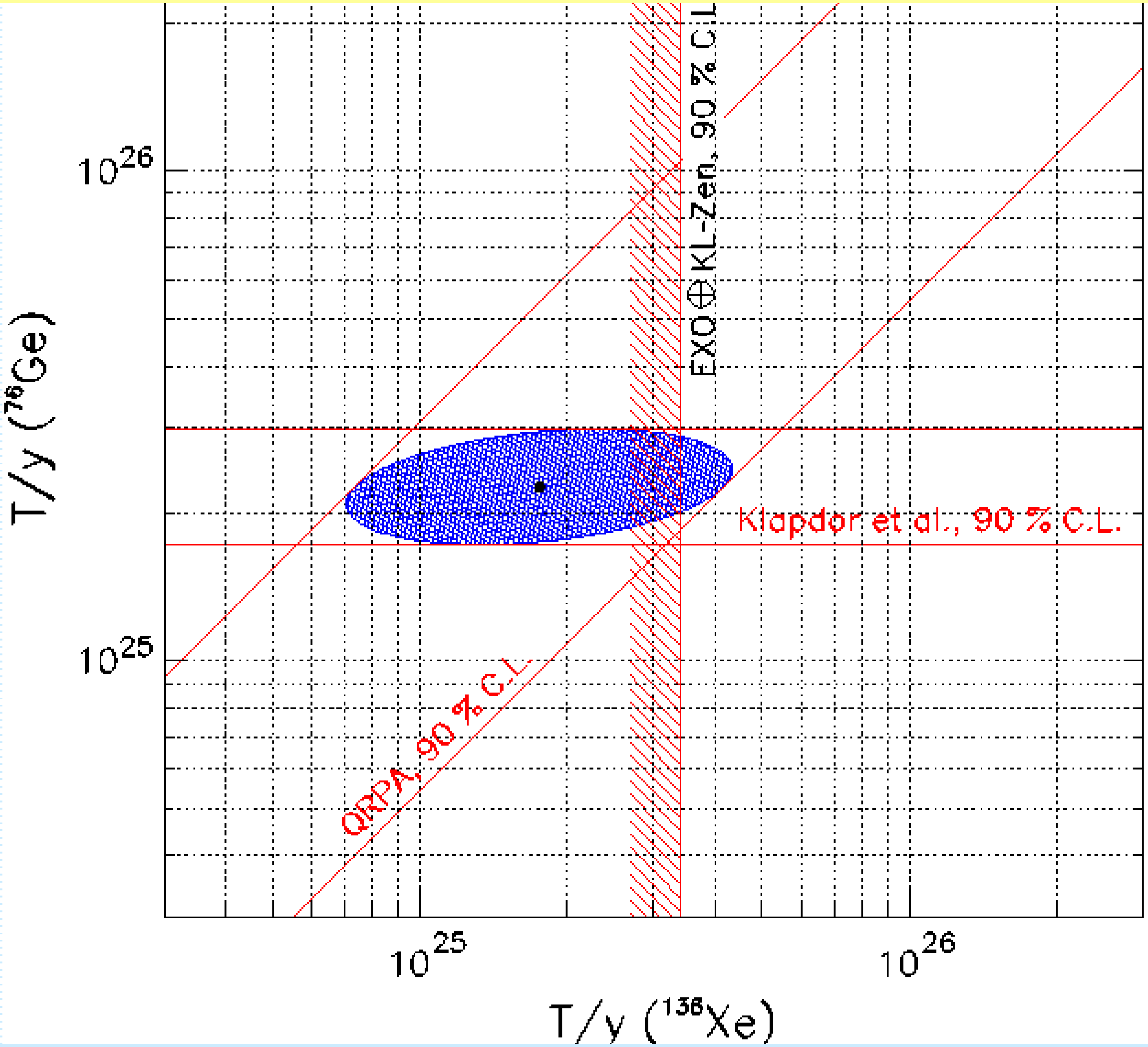
For each nucleus 2x2x2x3=24 NMEs

Range of half-lives preferred at 90% C.L. by the 0νββ claim of evidence compared with the 90% exclusion limits placed by other experiments.



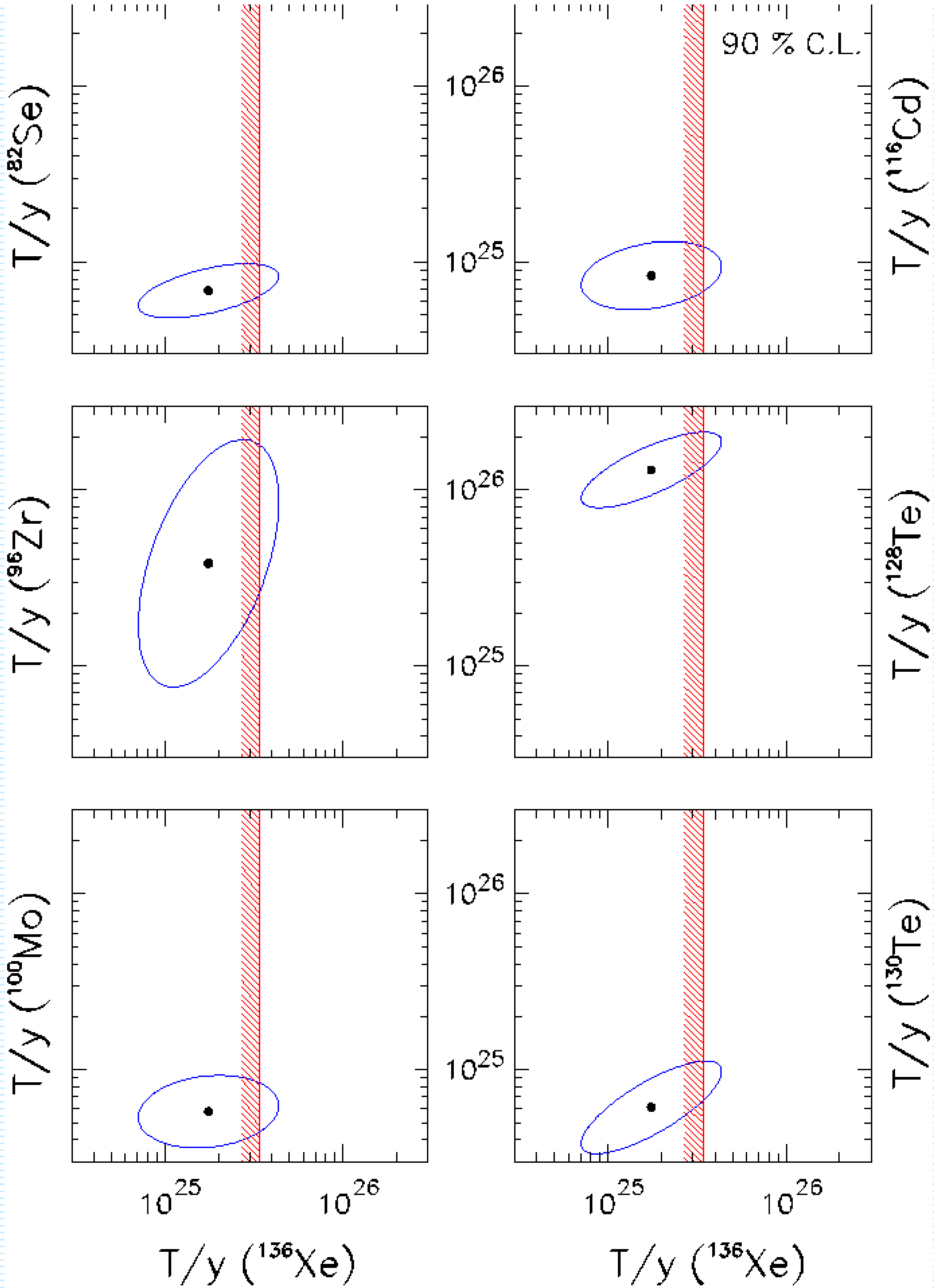
The comparison involves the NME and their errors as well as their correlations

Theoretical and expperimental constraints in the plane charted by the $0\nu\beta\beta$ half-lives of ^{76}Ge and ^{136}Xe.



Horizontal band:range prefered by claim. Slanted band: constraint place by our QRPA estimates. The combination provides the shaded ellipse, whose projection on the abscissa gives the range preferred at 90% C.L. for the ^{136}Xe half-life.

Allowed regions (ellipses) as derived from Klapdor's claim in the plane charted by the half-lives of ^{136}Xe and each of six nuclei



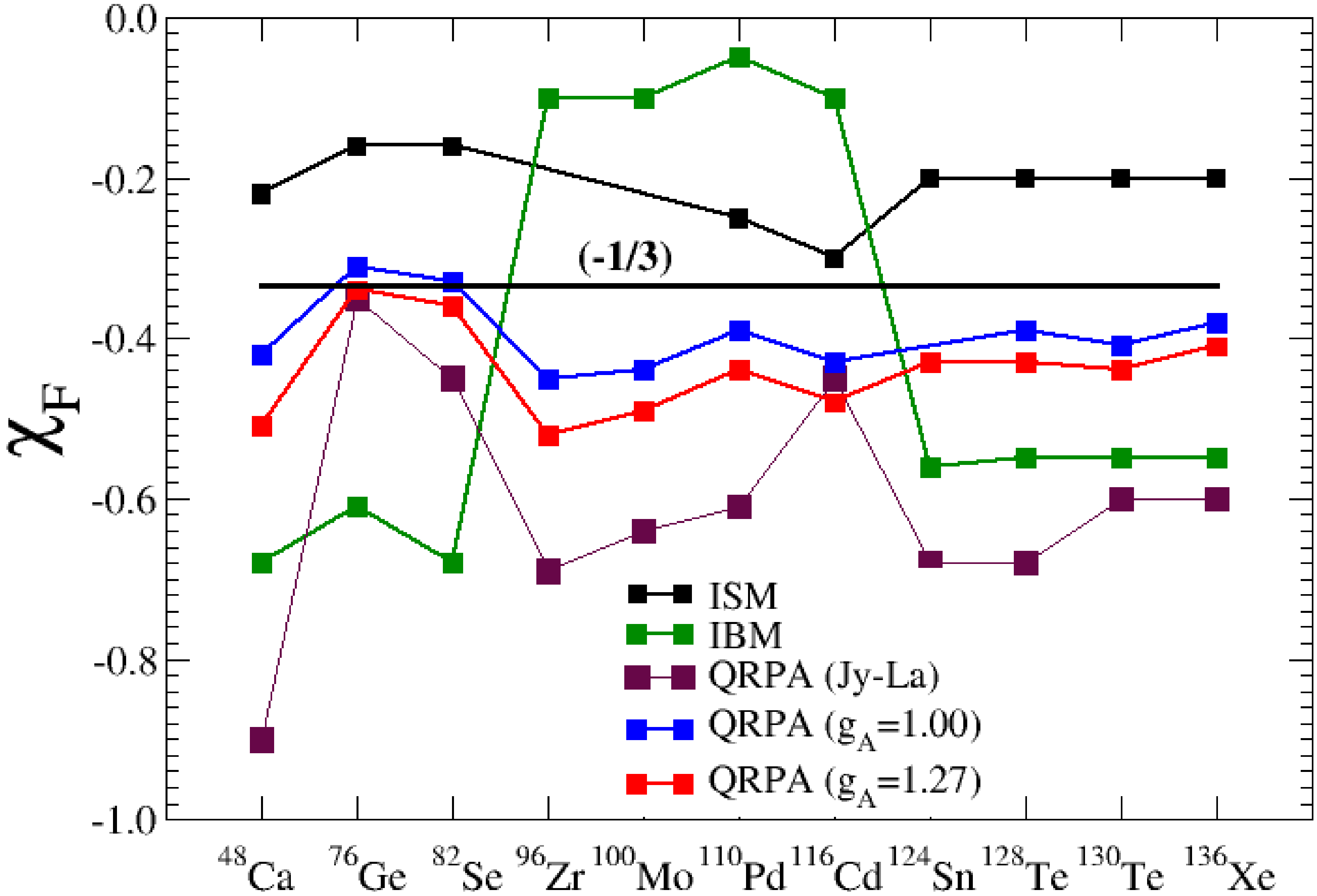
A large fraction of each ellipse Is excluded by the combined EXO & KL-Zen results. (All bounds are at 90% C.L. on one variable)

Some notes about the 0νββ-decay NMEs

$\chi_F = M^{0\nu}_F / M^{0\nu}_{GT} \approx -1/3$

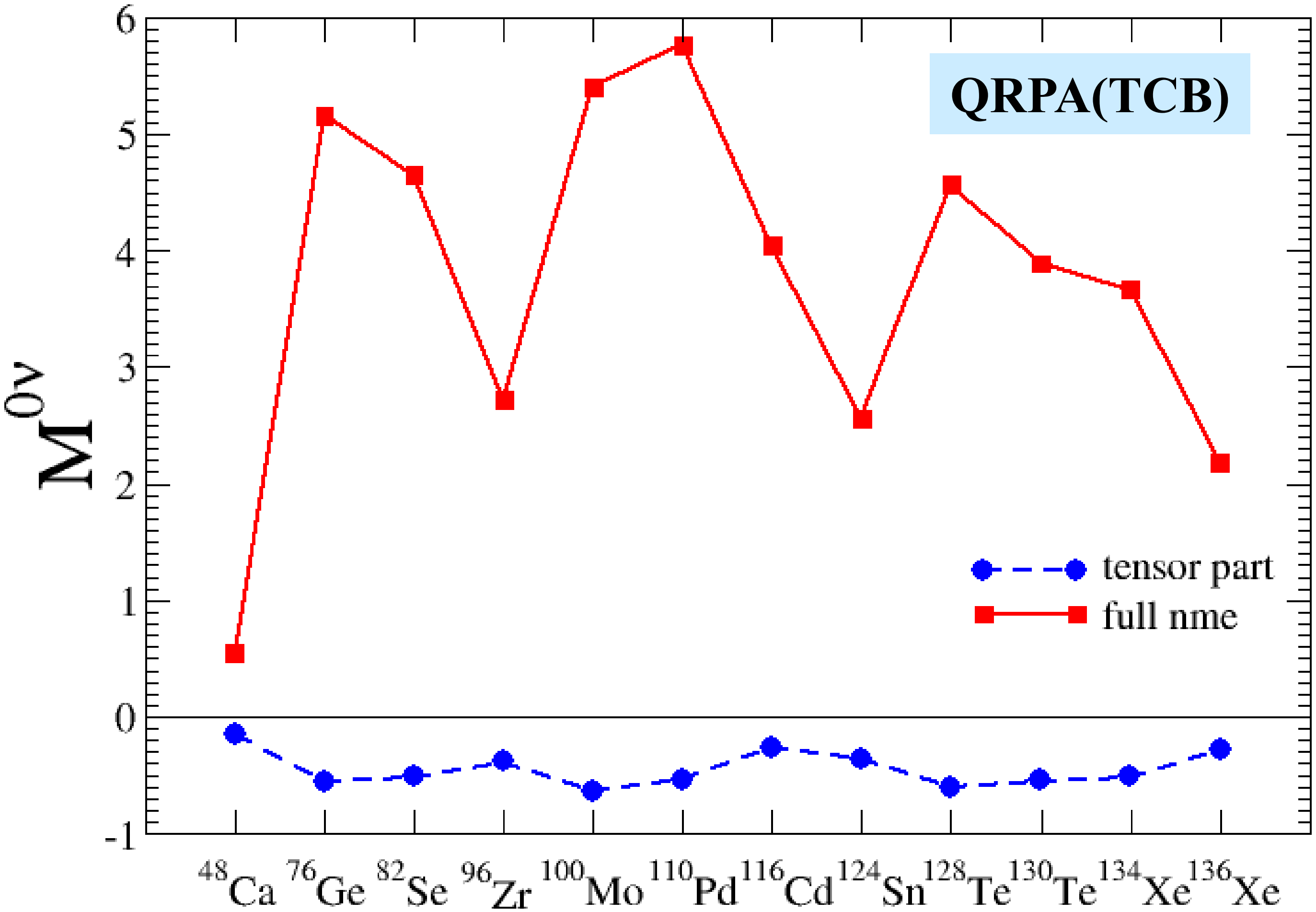
Fermi : $1 = \Omega(S=0) + \Omega(S=1)$

Gamow-Teller: $\sigma.\sigma = -3\,\Omega(S=0) + \Omega(S=1)$



Tensor part of the $0\nu\beta\beta$ NME

(some disagreement)

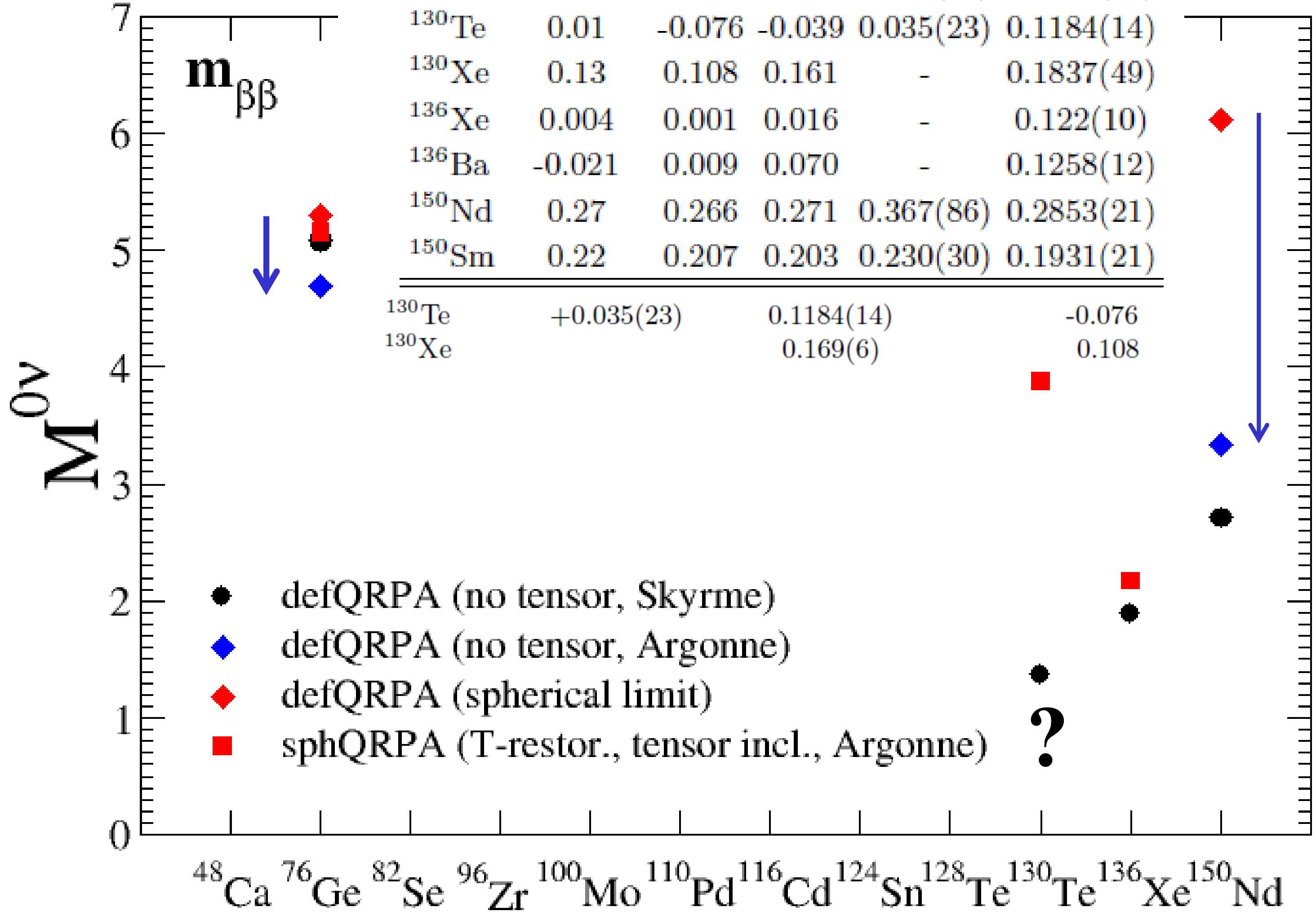


ISM: effect is small, QRPA(J): negligable; PHFB, EDF: not calculated; QRPA(TBC), IBM: up to 10%

Deformed QRPA

	this work	Ref. [24] Sk3	Ref. [24] SG2	Exp. Ref. [25]	Exp. Ref. [26]
^{76}Ge	0.184[a]	0.161	0.157	0.095(30)	0.2623(9)
^{76}Se	-0.018	-0.181	-0.191	0.163(33)	0.3090(37)
^{130}Te	0.01	-0.076	-0.039	0.035(23)	0.1184(14)
^{130}Xe	0.13	0.108	0.161	-	0.1837(49)
^{136}Xe	0.004	0.001	0.016	-	0.122(10)
^{136}Ba	-0.021	0.009	0.070	-	0.1258(12)
^{150}Nd	0.27	0.266	0.271	0.367(86)	0.2853(21)
^{150}Sm	0.22	0.207	0.203	0.230(30)	0.1931(21)

^{130}Te	+0.035(23)	0.1184(14)	-0.076
^{130}Xe		0.169(6)	0.108



Skyrme int: Mustonen, Engel, arXiv:1301.6997 [nucl-th]

Argonn int: Fang, Faessler, Rodin, F.Š. , PRC 83 (2011) 034320

Quenching of g_A and two-body currents

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

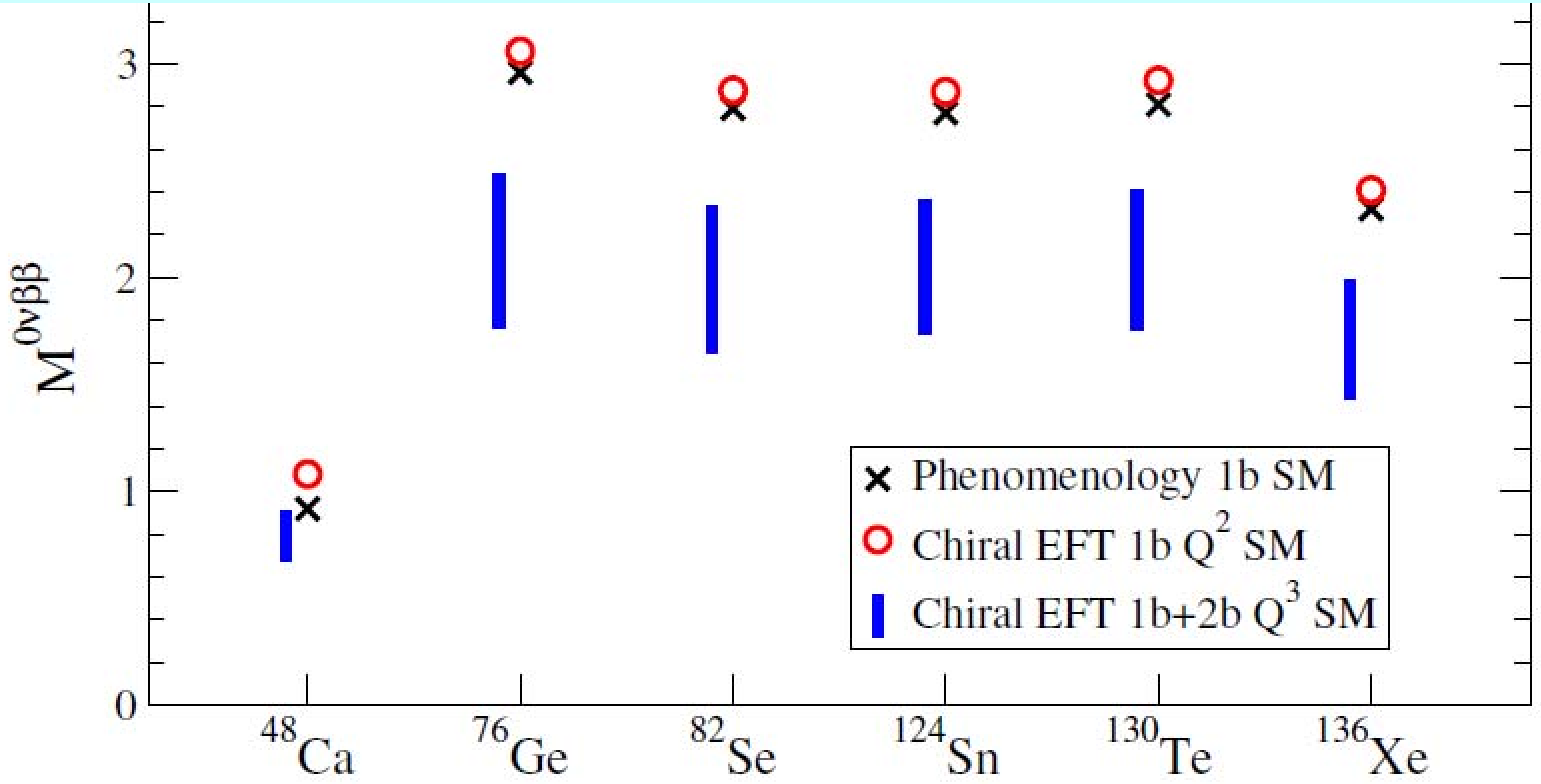
$g_A = 1.269$
$g^{eff}_A = 0.75\, g_A$

$(1.269)^4 = 2.6$

Strength of GT trans. has to be quenched to reproduce experiment

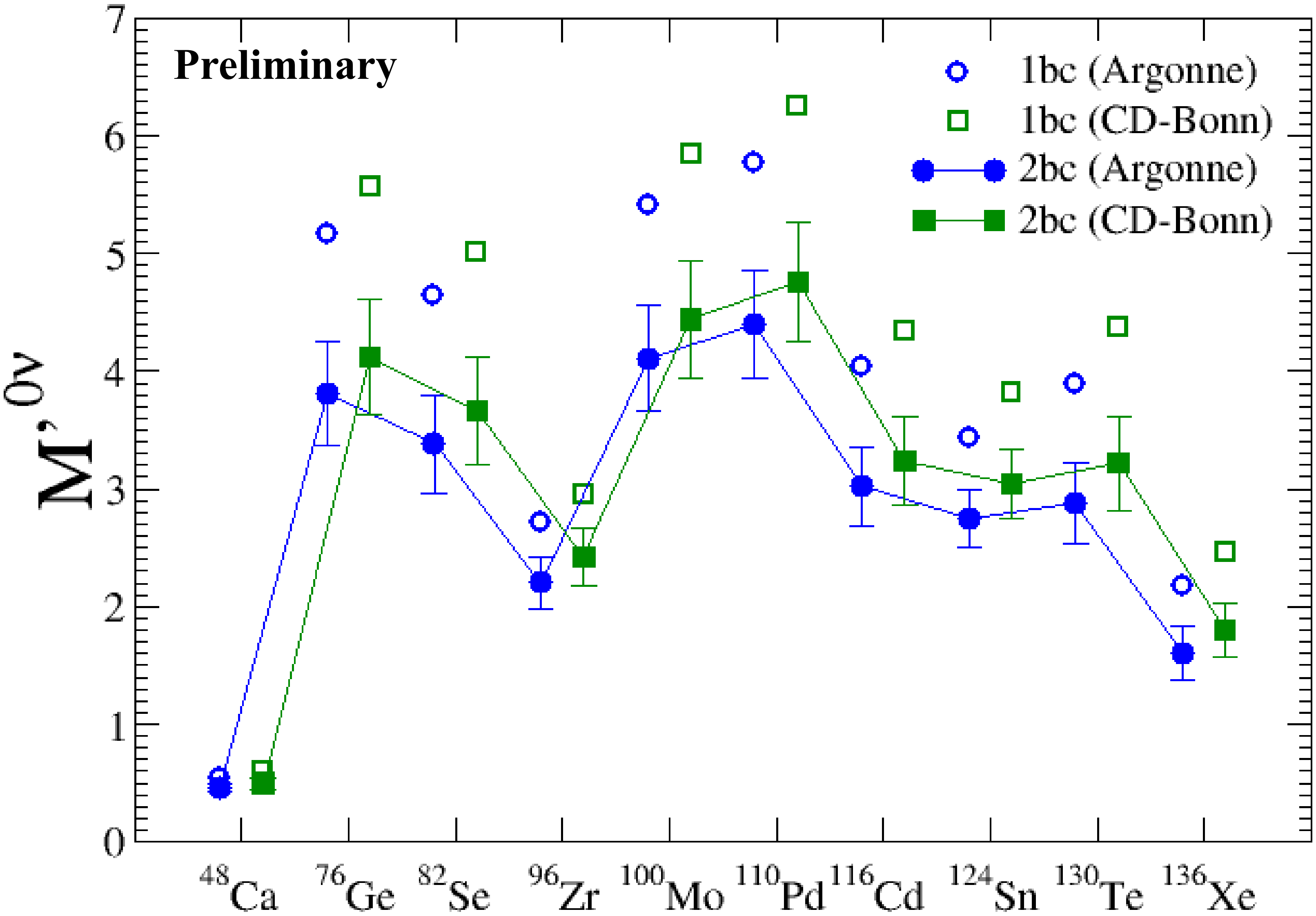
$$\mathbf{J}^{\mathrm{eff}}_{i,2b} = -g_A \boldsymbol{\sigma}_i \tau_i^- \frac{\rho}{F_\pi^2}\left[\frac{2}{3} c_3 \frac{p^2}{4m_\pi^2 + p^2} + I(\rho, P)\left(\frac{1}{3}(2c_4 - c_3) + \frac{1}{6m}\right)\right] = -g_A \delta(p) \boldsymbol{\sigma}_i \tau_i^-$$

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 about 20-30%)

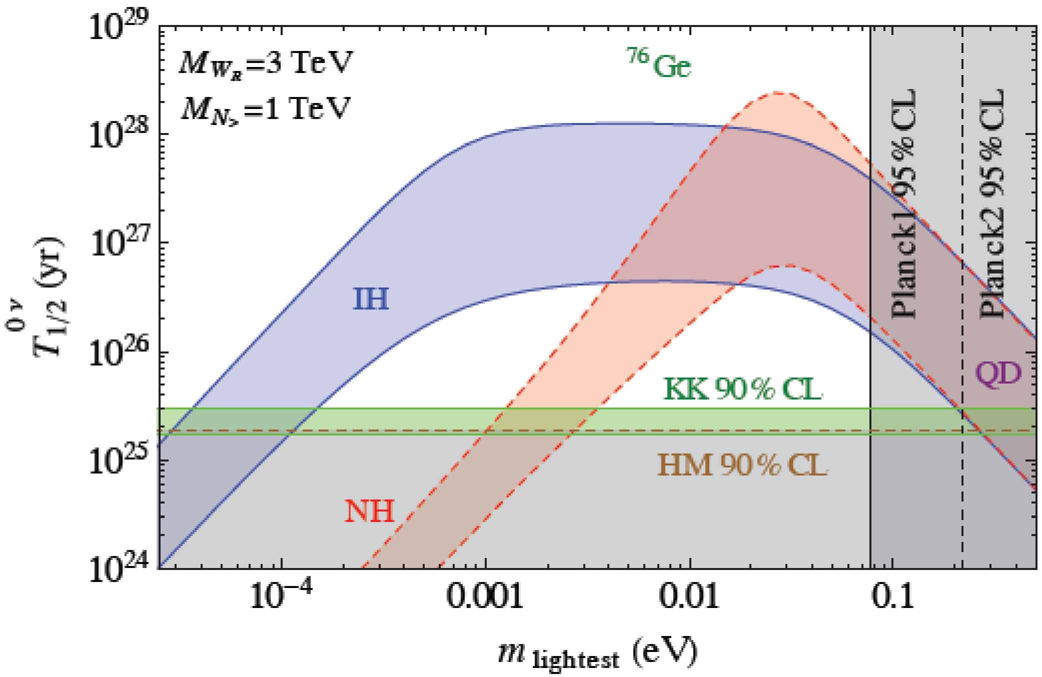


Engel, Vogel, Faessler, F.Š., to be submitted

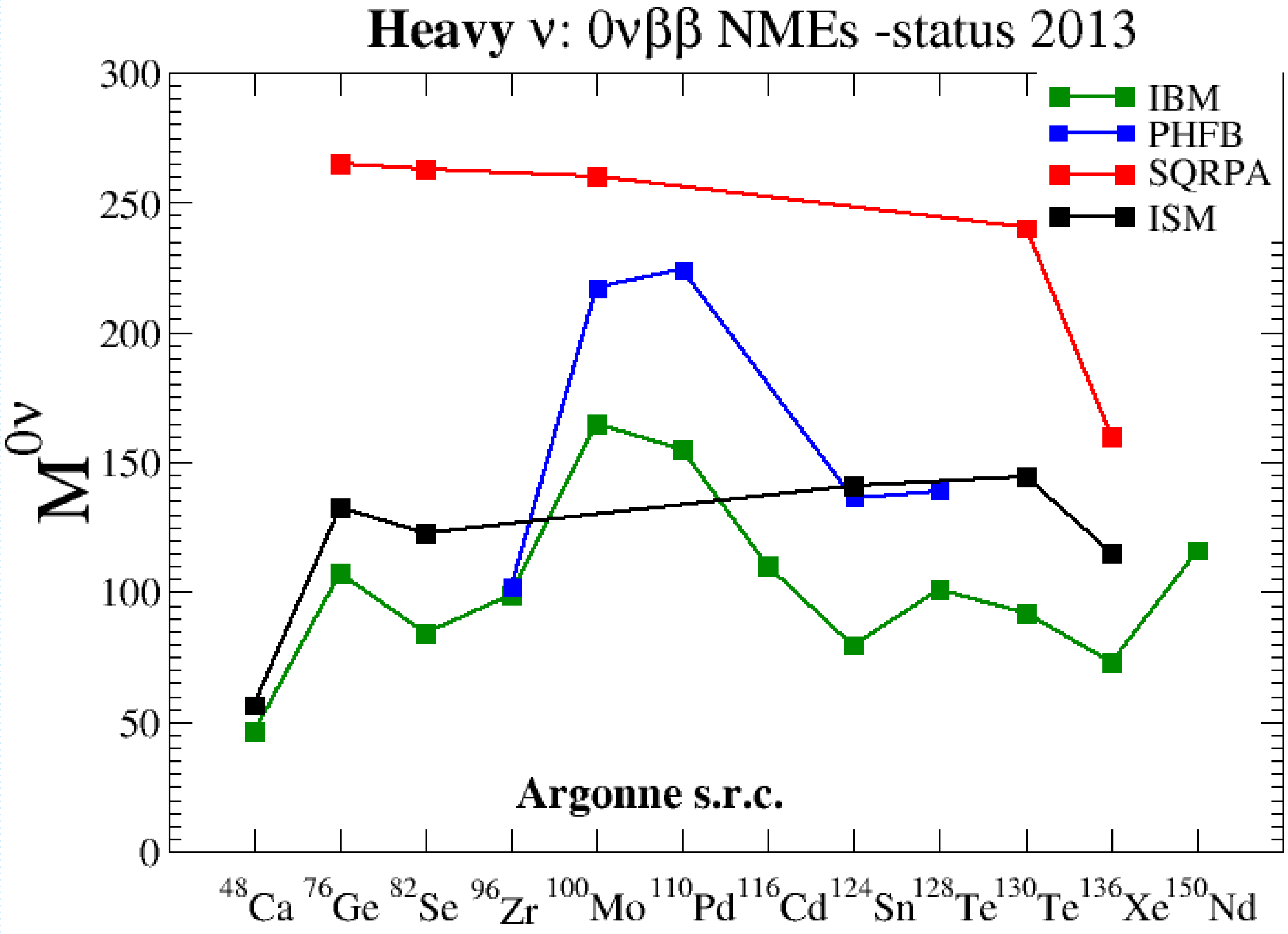
Heavy ν 0νββ-decay NMEs (type II see-saw)

LHC (scale!?) and L-R symmetric models

Discrete LR symmetry to parity (U=V)



Presentation of W. Rodejohann at TAUP13



PHFB: K. Rath et al., PRC 85 (2012) 014308
IBM: Barea, Kotila, Iachello, PRC (2013) 014315

SQRPA: Vergados, Ejiri, F. Š., RPP 75 (2012) 106301
ISM: Menendez, privite communications

Co-existence of few mechanisms of the $0\nu\beta\beta$-decay

It may happen that in year 201? (or 2???) the $0\nu\beta\beta$-decay will be detected for 2-3 or more isotopes …

(If there will be enough money for enrichment of isotopes!?)

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

$$T^{0\nu}_{1/2}(^{76}Ge) \geq 1.9\times10^{25}y, \qquad T^{0\nu}_{1/2}(^{76}Ge) = 2.23^{+0.44}_{-0.31}\times10^{25}y$$

$$5.8\times10^{23}y \leq T^{0\nu}_{1/2}(^{100}Mo) \leq 5.8\times10^{24}y, \qquad 3.0\times10^{24}y \leq T^{0\nu}_{1/2}(^{130}Te) \leq 3.0\times10^{25}y$$

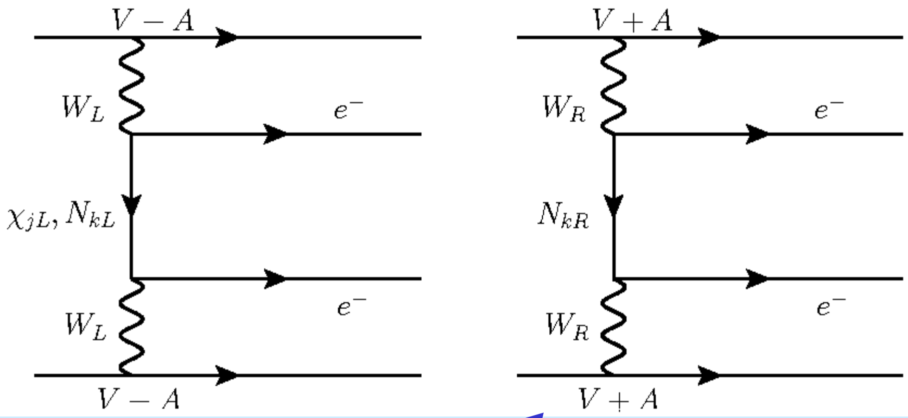
Half-life:

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

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

Set of equations:

$$\begin{aligned}\frac{1}{T_1G_1} &= |\eta_\nu|^2|M'^{0\nu}_{1,\nu}|^2 + |\eta_R|^2|M'^{0\nu}_{1,N}|^2\\ \frac{1}{T_2G_2} &= |\eta_\nu|^2|M'^{0\nu}_{2,\nu}|^2 + |\eta_R|^2|M'^{0\nu}_{2,N}|^2\end{aligned}$$



Solutions:

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

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

A. Faessler, A. Meroni, S.T. Petcov, F. Š., J.D. Vergados,
B. 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)

The positivity condition:

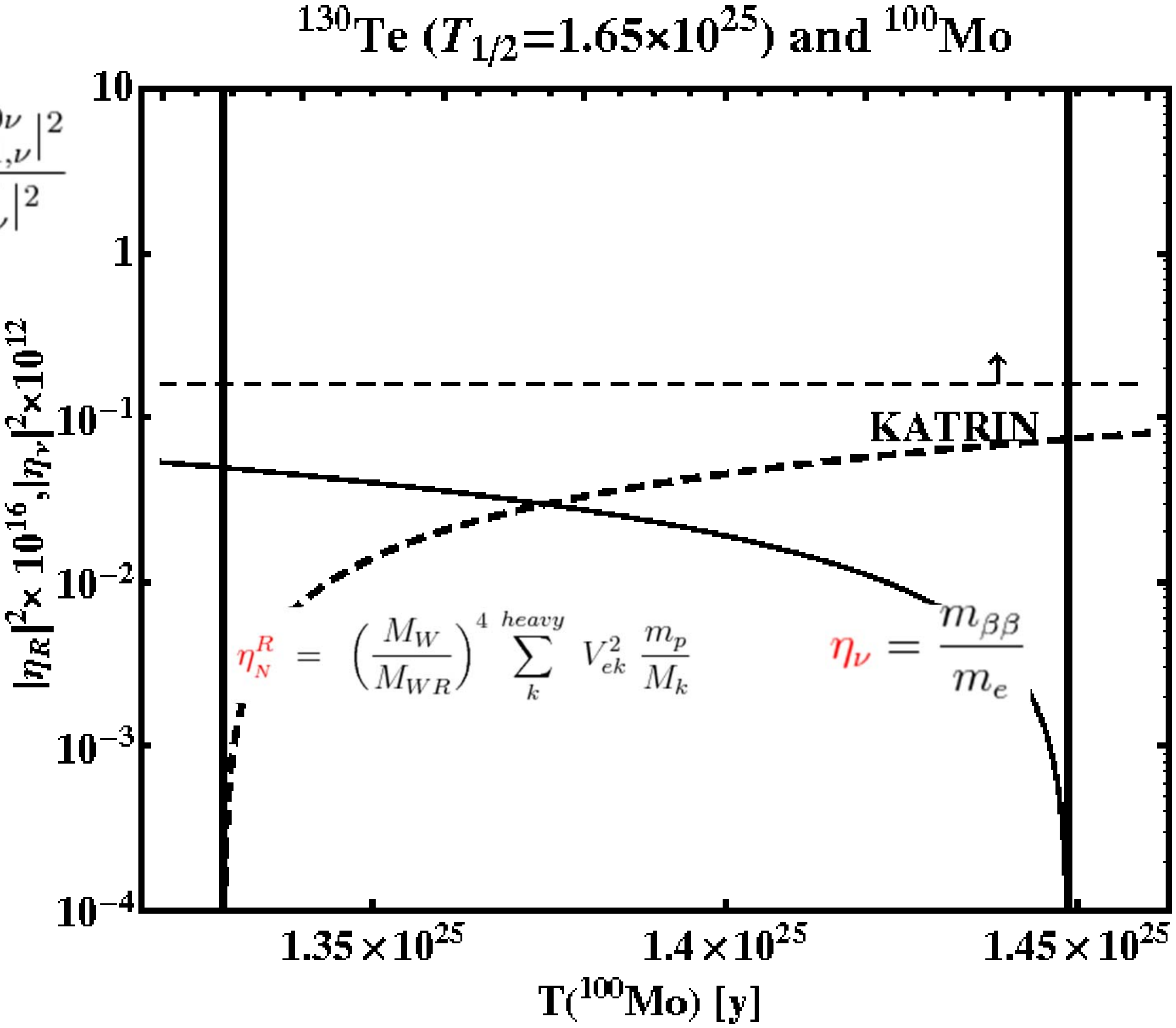
$$\frac{T_1 G_1 |M'^{0\nu}_{1,N}|^2}{G_2 |M'^{0\nu}_{2,N}|^2} \leq T_2 \leq \frac{T_1 G_1 |M'^{0\nu}_{1,\nu}|^2}{G_2 |M'^{0\nu}_{2,\nu}|^2}$$

Very narrow ranges!

$$0.15 \leq \frac{T^{0\nu}_{1/2}(^{100}Mo)}{T^{0\nu}_{1/2}(^{76}Ge)} \leq 0.18$$

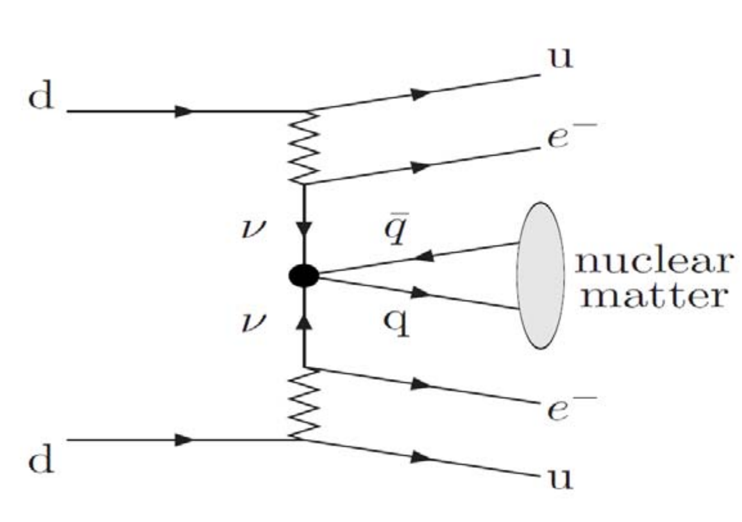
$$0.17 \leq \frac{T^{0\nu}_{1/2}(^{130}Te)}{T^{0\nu}_{1/2}(^{76}Ge)} \leq 0.22$$

$$1.14 \leq \frac{T^{0\nu}_{1/2}(^{130}Te)}{T^{0\nu}_{1/2}(^{100}Mo)} \leq 1.24$$



Neutrino propagation in nuclear medium and neutrinoless double-beta decay

S.G. Kovalenko, M.I.Krivoruchenko., F. Š., e-print arXiv:1311.4200[hep-ph]

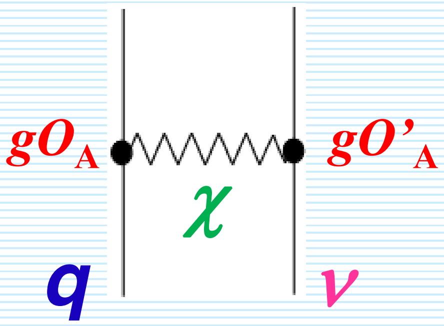


$\rho_{Sun} = 1.4\ g/cm^3$
$\rho_{Earth} = 5.5\ g/cm^3$
$\rho_{nucleus} = 2.3\ 10^{14}\ g/cm^3$

A novel effect in $0\nu\beta\beta$ decay related with the fact, that its underlying mechanisms take place in the nuclear matter environment, is discussed
+ 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

For the LNV scale we have LNV $\geq$ 2.4 TeV

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



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

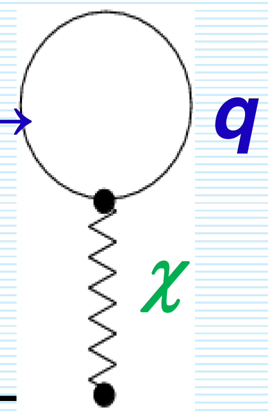
$$m_\chi \gtrsim M_W.$$

0νββ-decay

oscillation experiments

tritium β-decay

density →



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

Classification of the vertices gO_A and gO'_A

In nuclei, mean fields are created by scalar and vector currents.
Vector currents do not flip spin for 0νββ decay.

Of all the expressions we choose the scalar combinations:

TABLE II: Symmetric (S) and antisymmetric (A) scalar neutrino currents J^a_{ij}.

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

Classification of the vertices gO_A and gO'_A

with Majorana neutrinos:

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

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

g^a_{ij} are real symmetric for $a = 1,2,3,4$
and imaginary antisymmetric for $a = 5,6$.

In-medium Majorana mass of neutrino

The effect depends on the product $\langle \chi \rangle g_{ij}^{a}$.

Typical scale:

$$\langle \chi \rangle g_{ij}^{a} = -\frac{G_F}{\sqrt{2}} \langle \bar{q} q \rangle \varepsilon_{ij}^{a} \approx -25 \varepsilon_{ij}^{a} \text{ eV}$$

We expect

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

In the limit of *R* = ∞, the currents *a* = 3,5 vanish.

In-medium Majorana mass of neutrino

LAGRANGIAN:

$$\Delta\mathcal{L} = \frac{1}{4}\sum_{ij}\bar{\nu}_i(Z_{ij}+\gamma_5 Z'_{ij})i\gamma^\mu \overleftrightarrow{\partial}_\mu \nu_j - \frac{1}{2}\sum_{ij}\bar{\nu}_i(M_{ij}+i\gamma_5 M'_{ij})\nu_j,$$

where

$$Z_{ij} = \delta_{ij} - \langle\chi\rangle g^4_{ij}, \qquad Z'_{ij} = -\langle\chi\rangle g^6_{ij},$$

$$M_{ij} = m_i\delta_{ij} + \langle\chi\rangle g^1_{ij}, \quad M'_{ij} = \langle\chi\rangle g^2_{ij}.$$

In-medium Majorana mass of neutrino

After the diagonalization

$$\nu_L = (V\lambda^{-1/2})_{kinetic} (W^L)_{mass} \nu'_L$$

with $V, W^L \in U(n) \wedge \lambda = \mathrm{diag}(\lambda_1, \ldots, \lambda_n)$

the in-medium Lagrangian takes the free form

$$\Delta L = \frac{1}{4}\sum_i \bar{\nu}'_i i\gamma^\mu \overleftrightarrow{\partial}_\mu \nu'_i - \frac{1}{2}\sum_i \mu_i \bar{\nu}'_i \nu'_i .$$

The effective Majorana mass in the 0νββ

$$m_{\beta\beta} = \sum_i (U^{\text{eff}}_{ei})^2 \mu_i \qquad U^{\text{eff}}_{ei} = \sum_{kj} U^L_{ek} V_{kj} \lambda_j^{-1/2} W^L_{ji}$$

Universal scalar interaction

$$g_{ij}^a = \delta_{ij} g_a \ \left(\varepsilon_{ij}^a = \delta_{ij}\varepsilon_a\right)$$

The effective Lagrangian is taken to the free form with

$$V_{ij} = \delta_{ij}, \ \ \lambda_i = 1 - \langle\chi\rangle g_4, \ \ W_{ij} = \delta_{ij} e^{i\gamma_5 \phi_i/2}$$

where

$$\tan\phi_i = \frac{\langle\chi\rangle g_2}{m_i + \langle\chi\rangle g_1}.$$

The in-medium neutrino masses

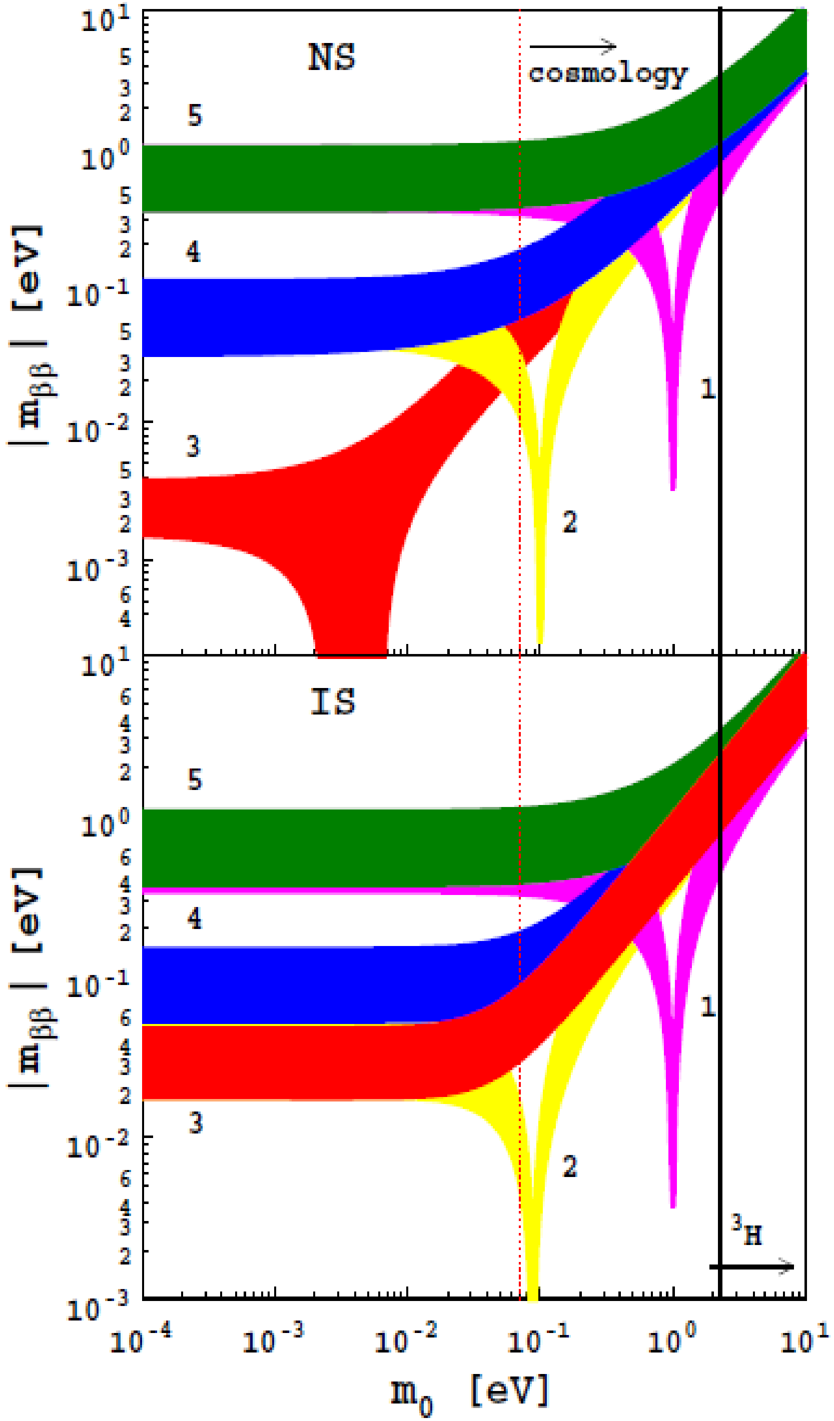
$$\mu_i = \frac{\sqrt{(m_i + \langle\chi\rangle g_1)^2 + (\langle\chi\rangle g_2)^2}}{\lambda_i}.$$

Universal scalar interaction

The effect of $g_1 \neq 0$ is studied numerically

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

NB: The signs of the Majorana masses are no longer absorbed by the CP violating phases

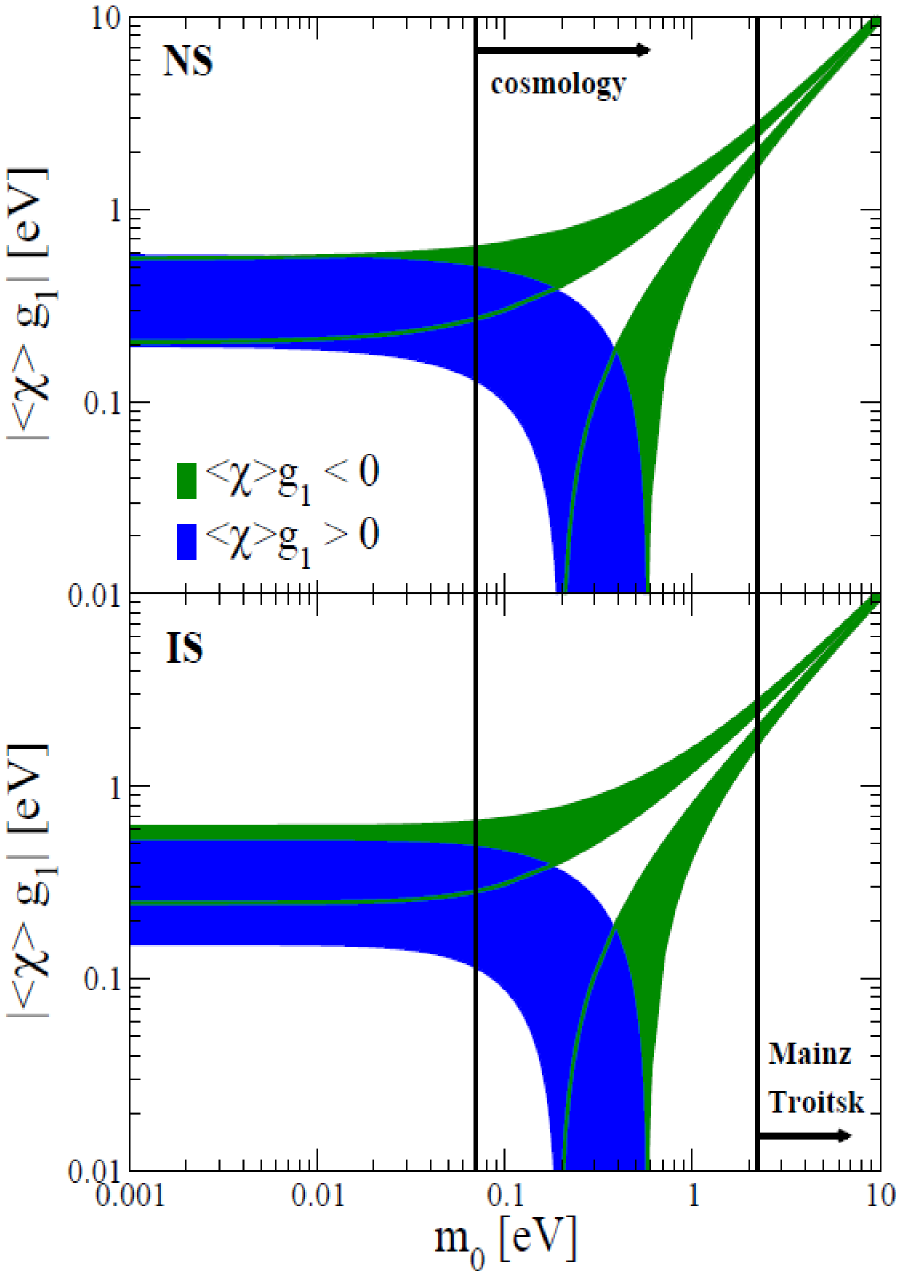


Area	$\langle\chi\rangle g_1$ [eV]
1	-1
2	-0.1
3	0
4	0.1
5	1

&

$$g_2 = g_4 = 0$$

Regions of admisible values of $\langle\chi\rangle g_1$ and m_0 ($m_{\beta\beta}$=0.2 eV)



$$\langle\chi\rangle = 0.17\ fm^{-3} = \frac{0.17}{(5.07)^3} GeV^3$$

$$\Lambda_{LNV} \geq 2.4\ \mathrm{TeV\ (Planck)}$$

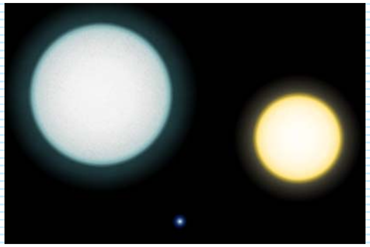
$$1.1\ \mathrm{TeV\ (Tritium)}$$

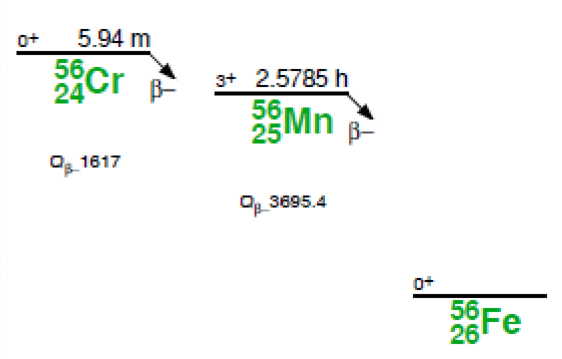
What is today exotic tomorrow is standard!!

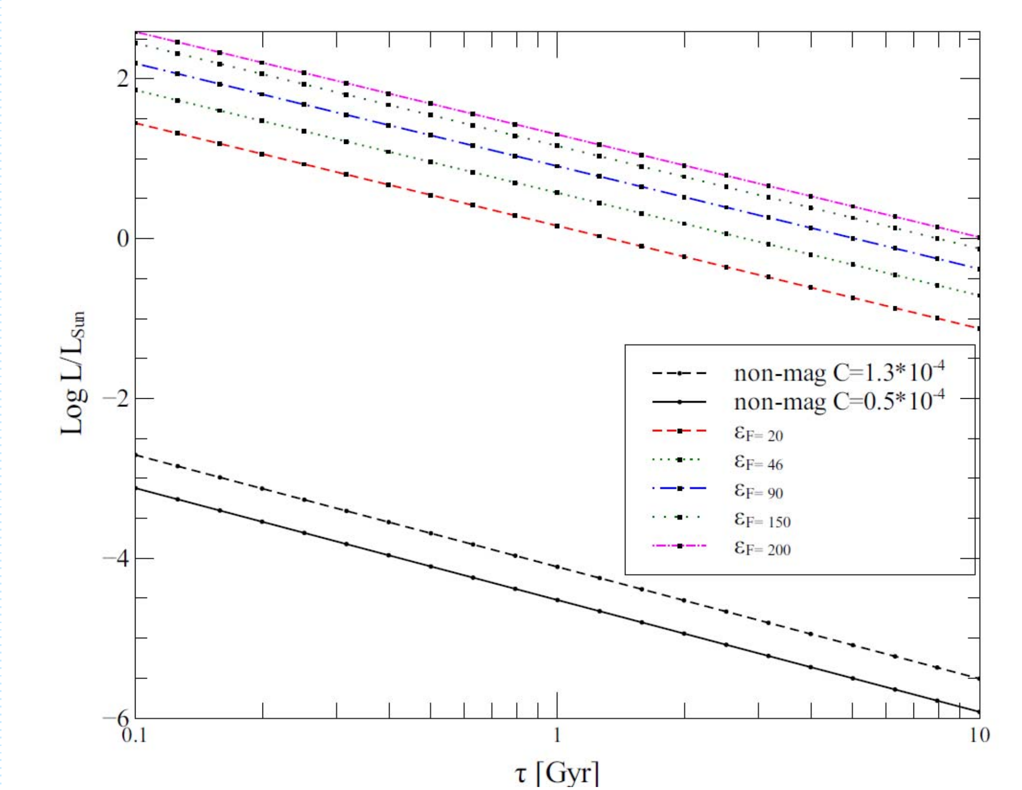
Universe as a laboratory to study LN violation

Belyaev, Ricci, Simkovic, Truhlik, arXiv: 1212.3155, Truhlik, MEDEX13 presentation

Cooling of strongly magnetized iron White dwarfs







$e^- + {}^{56}Fe \rightarrow {}^{56}Cr + e^+$

$e^- + e^- + {}^{56}Fe \rightarrow {}^{56}Cr$

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?

$\nu \quad \Rightarrow$

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

OUTLOOK

(slide of P. Vogel at Indian summer school, Prague, 2012)

Historically, there are > 100 experimental limits on $T_{1/2}$ of the $0\nu\beta\beta$ decay.

However, during the last decade the complexity and cost of such experiments increased dramatically The constant slope is no longer maintained.