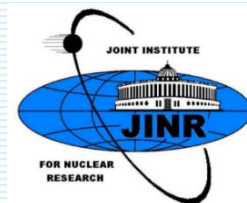


The Czech National Library of Technology
MEDEX'19-Matrix Elements for the Double beta decay EXperiments
Prague, May 27-31, 2019



Theory Challenges in Neutrinoless Double Beta Decay
Fedor Šimkovic



OUTLINE

I. Introduction

Majorana, Pontecorvo, Weinberg

II. The $0\nu\beta\beta$ -decay scenarios due neutrinos exchange

(simplest, sterile ν , LR-symmetric model, interpolating formula)

III. DBD NMEs – Current status

(deformed QRPA versus ISM, ...)

IV. Is there a proportionality between $0\nu\beta\beta$ and $2\nu\beta\beta$ -decay NMEs?

(role of SU(4) symmetry ...)

V. Quenching of g_A (Improved formalism of $2\nu\beta\beta$ -decay,

KamLAND-Zen constraining of g_A)

Acknowledgements: A. Faessler (Tuebingen), P. Vogel (Caltech), S. Kovalenko (Valparaiso U.), M. Krivoruchenko (ITEP Moscow), D. Štefánik, R. Dvornický (Comenius U.), A. Babič, A. Smetana (IEAP CTU Prague), ...

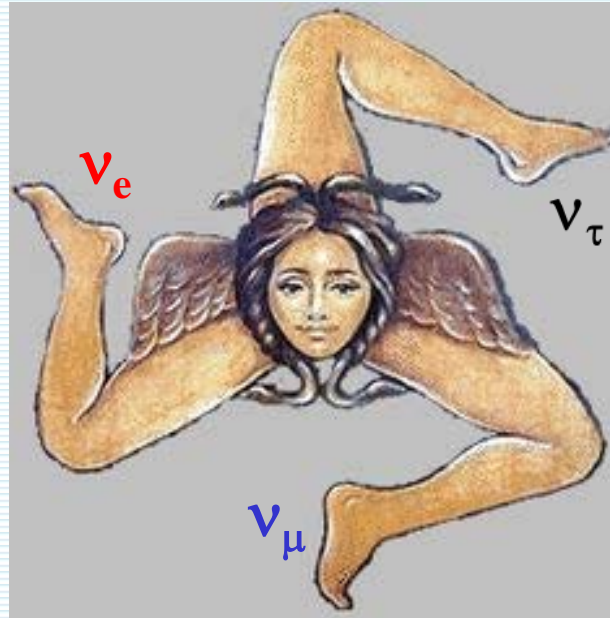
I. Introduction

After 62 years
we know

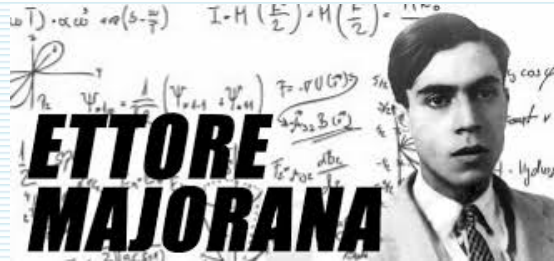
Fundamental ν properties

No answer yet

- 3 families of light (V-A) neutrinos:
 ν_e, ν_μ, ν_τ
- ν are massive:
we know mass squared differences
- relation between flavor states and mass states (neutrino mixing)

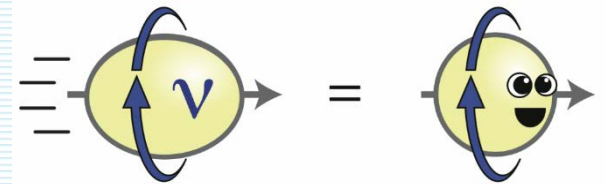


- Are ν Dirac or Majorana?
- Is there a CP violation in ν sector?
- Are neutrinos stable?
- What is the magnetic moment of ν ?
- **Sterile neutrinos?**
- Statistical properties of ν ? Fermionic or partly bosonic?



Currently main issue

Nature, Mass hierarchy, CP-properties, sterile ν



The observation of neutrino oscillations has opened a new excited era in neutrino physics and represents a big step forward in our knowledge of neutrino properties

Majorana fermion



https://en.wikipedia.org/wiki/File:Ettore_Majorana.jpg



CNNP 2018, Catania, October 15-21, 2018

5/27/2019

Fedor S

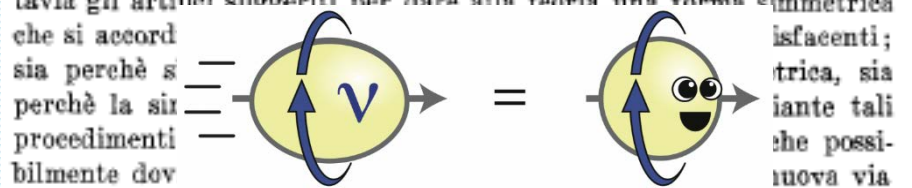
TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

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

Sunto. - Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di DIRAC ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.

L'interpretazione dei cosiddetti « stati di energia negativa » proposta da DIRAC ⁽¹⁾ conduce, come è ben noto, a una descrizione sostanzialmente simmetrica degli elettroni e dei positroni. La sostanziale simmetria del formalismo consiste precisamente in questo, che fin dove è possibile applicare la teoria girando le difficoltà di convergenza, essa fornisce realmente risultati del tutto simmetrici. Tuttavia gli artifici suggeriti per dare alla teoria una forma simmetrica che si accorda sia perchè sia perchè la sir procedimenti bilmente dov che conduce più direttamente alla meta.



Per quanto riguarda gli elettroni e i positroni, da essa si può veramente attendere soltanto un progresso formale; ma ci sembra importante, per le possibili estensioni analogiche, che venga a cadere la nozione stessa di stato di energia negativa. Vedremo infatti che è perfettamente possibile costruire, nella maniera più naturale, una teoria delle particelle neutre elementari senza stati negativi.

⁽¹⁾ P. A. M. DIRAC, « Proc. Camb. Phil. Soc. », **30**, 150, 1924. V. anche W. HEISENBERG, « ZS. f. Phys. », **90**, 209, 1934.



MESONIUM AND ANTIMESONIUM

B. PONTECORVO

Joint Institute for Nuclear Research

Submitted to JETP editor May 23, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 549-551 (August, 1957)

INVERSE BETA PROCESSES AND NONCONSERVATION OF LEPTON CHARGE

B. PONTECORVO

Joint Institute for Nuclear Research

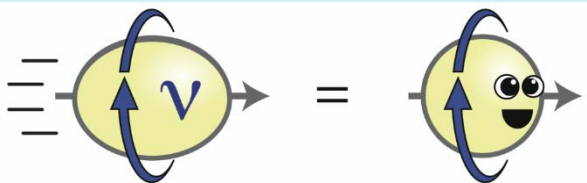
Submitted to JETP editor October 19, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 247-249 (January, 1958)



$\nu \leftrightarrow \bar{\nu}$ oscillation

(neutrinos are Majorana particles)



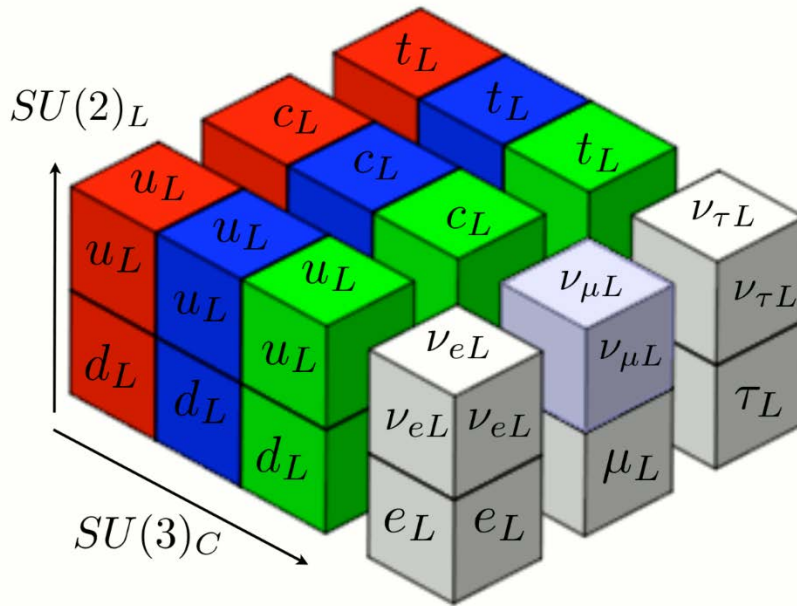
It follows from the above assumptions that in vacuum a neutrino can be transformed into an antineutrino and vice versa. This means that the neutrino and antineutrino are “mixed” particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 of different combined parity.⁵

1968 **Gribov, Pontecorvo** [PLB 28(1969) 493]
 oscillations of neutrinos - a solution
 of deficit of solar neutrinos in Homestake exp.



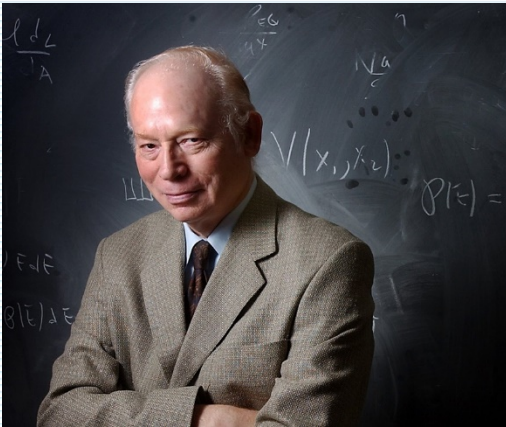


Beyond the Standard model physics (EFT scenario)



The **absence of the right-handed neutrino fields** in the SM 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**.

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda} \sum_i c_i^{(5)} \mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2} \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

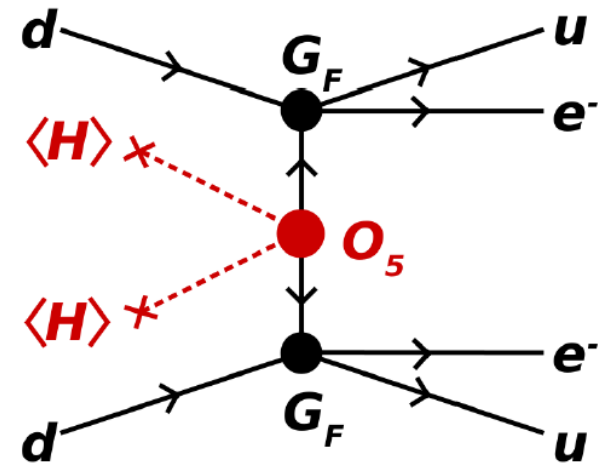


Weinberg, 1979: $d=5$

$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda} (L_i H)(L_j H)$$

Weinberg does not take credit for predicting neutrino masses, but he thinks it's the right interpretation. What's more, he says, the non-renormalisable interaction that produces the neutrino masses is probably also accompanied with non-renormalisable interactions that produce proton decay and other things that haven't been observed, such as violation of baryon-number conservations. "We don't know anything about the details of those terms, but I'll swear they are there."

$0\nu\beta\beta$ decay:

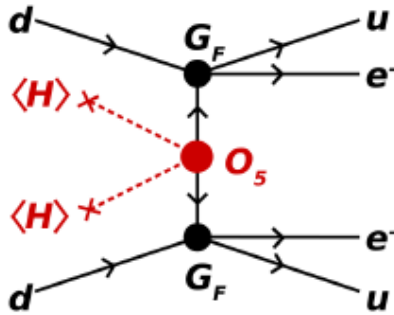


II. The $0\nu\beta\beta$ -decay scenarios due neutrinos exchange

**Amplitude for $(A,Z) \rightarrow (A,Z+2) + 2e^-$
can be divided into:**

M. Hirsch, Pontecorvo school 2015

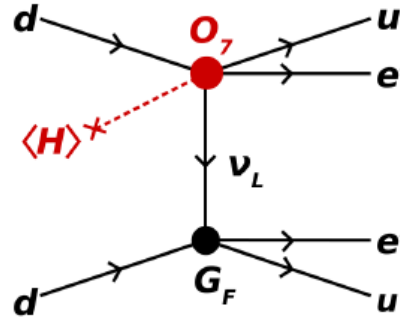
mass mechanism: $d=5$



$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda} (L_i H)(L_j H)$$

Weinberg, 1979

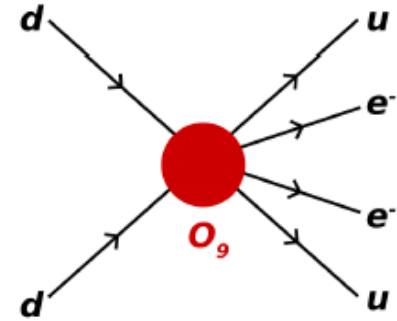
long range: $d=7$



$$\begin{aligned} \mathcal{O}_2 &\propto LLLe^c H \\ \mathcal{O}_3 &\propto LLQd^c H \\ \mathcal{O}_4 &\propto LL\bar{Q}\bar{u}^c H \\ \mathcal{O}_8 &\propto L\bar{e}^c \bar{u}^c d^c H \end{aligned}$$

**Babu, Leung: 2001
de Gouvea, Jenkins: 2007**

short range: $d=9$ ($d=11$)

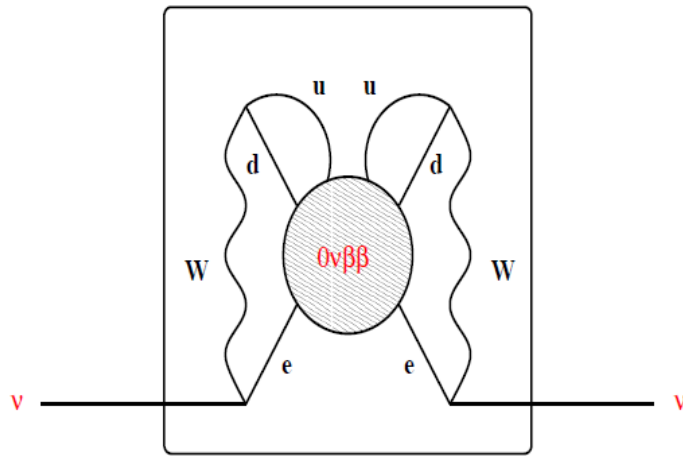


$$\begin{aligned} \mathcal{O}_5 &\propto LLQd^c HHH^\dagger \\ \mathcal{O}_6 &\propto LL\bar{Q}\bar{u}^c HHH^\dagger H \\ \mathcal{O}_7 &\propto LQ\bar{e}^c \bar{Q}HHH^\dagger \end{aligned}$$

$$\begin{aligned} \mathcal{O}_9 &\propto LLLe^c Le^c \\ \mathcal{O}_{10} &\propto LLLe^c Qd^c \\ \mathcal{O}_{11} &\propto LLQd^c Qd^c \end{aligned}$$

.....

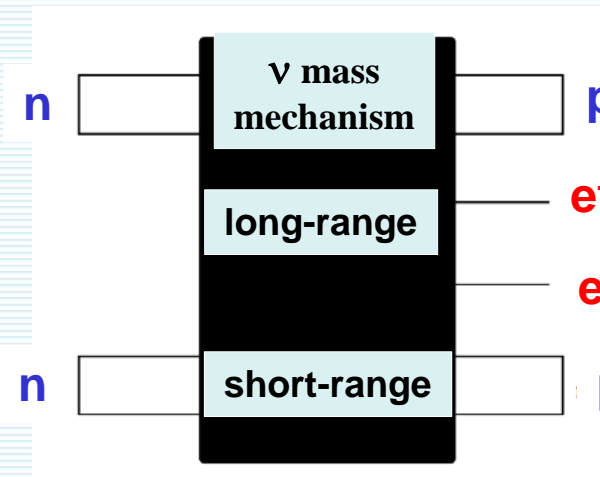
**Physics at LHC
(Jose Valle talk)**



If $0\nu\beta\beta$ is observed the ν is
a Majorana particle

Different $0\nu\beta\beta$ -decay scenarios

Can we say
something about
content
of the black box?



Considering

- i. Sterile ν
- ii. Different LNV scales
- iii. Right-handed currents
- iv. Non-standard ν -interactions

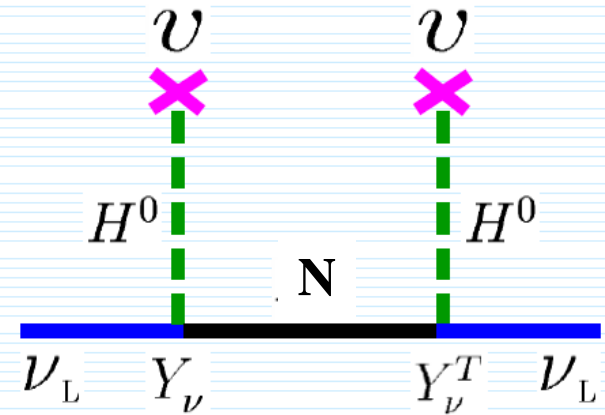
II.a. *The simplest $0\nu\beta\beta$ -decay scenario: LHC & LNV scale Λ is too large*

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

Heavy Majorana leptons N_i ($N_i = N_i^c$)
singlet of $SU(2)_L \times U(1)_Y$ group
Yukawa lepton number violating int.

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

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



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

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

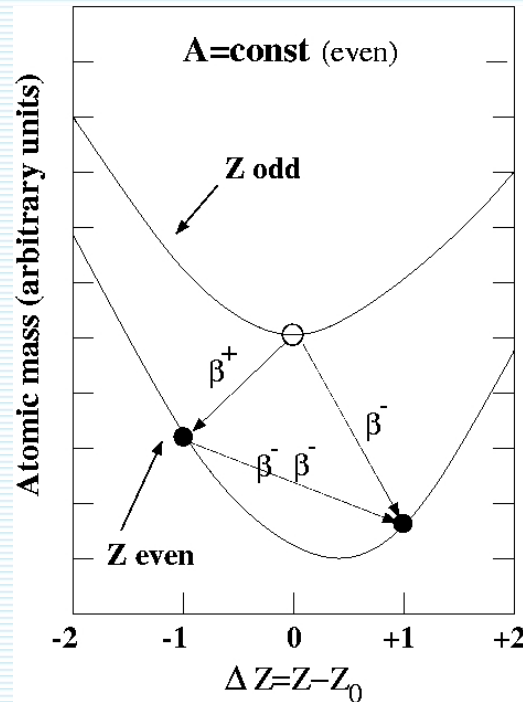
The discovery of the $\beta\beta$ -decay and absence of transitions of flavor neutrinos into sterile states would be evidence in favor of this minimal scenario.



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

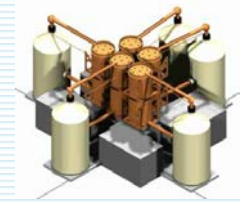
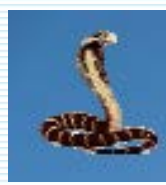
$$m_{\beta\beta} =$$

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



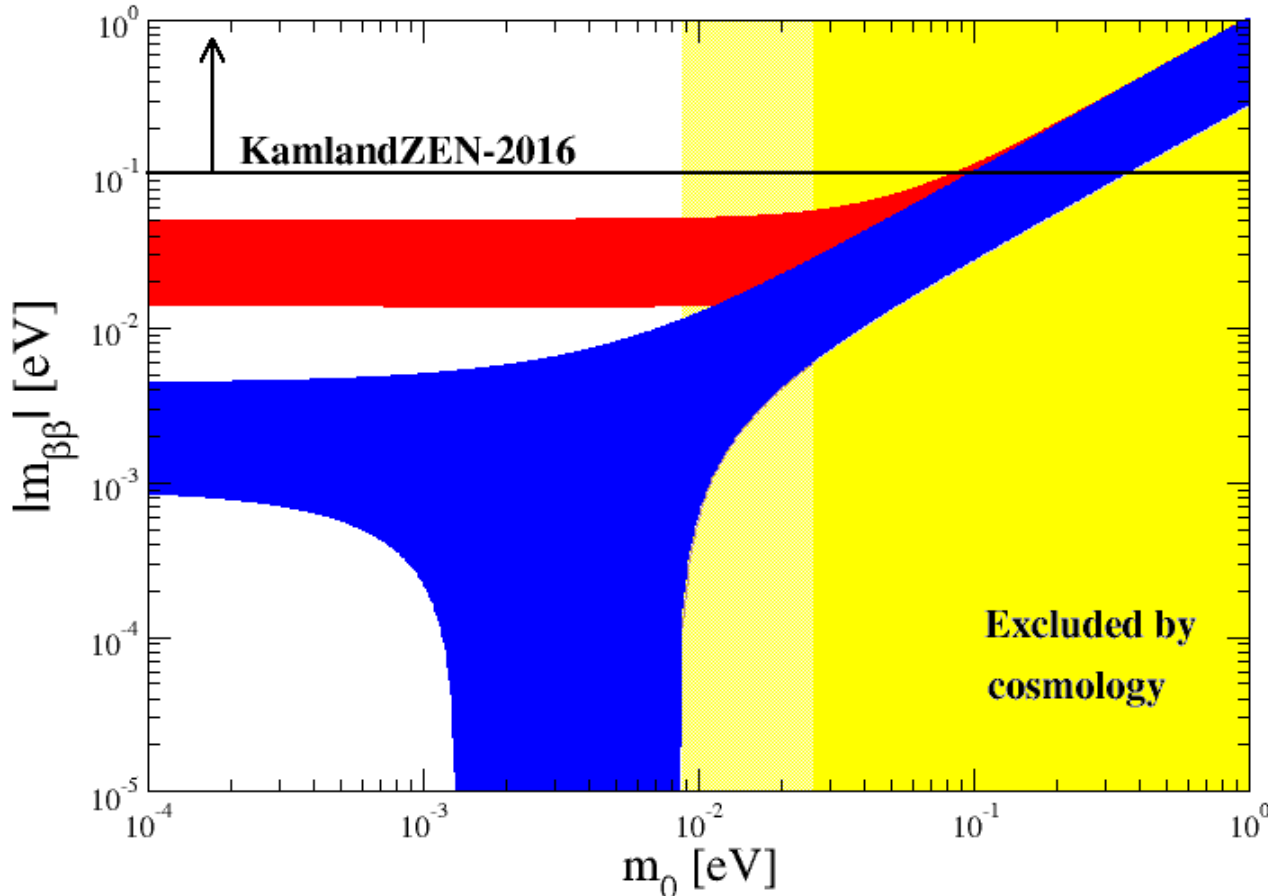
transition	$G^{01}(E_0, Z)$ $\times 10^{14} y$	$Q_{\beta\beta}$ [MeV]	Abund. (%)	$ M^{0\nu} ^2$
$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$	26.9	3.667	6	?
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	8.04	4.271	0.2	?
$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$	7.37	3.350	3	?
$^{116}\text{Cd} \rightarrow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

The NMEs for $0\nu\beta\beta$ -decay must be evaluated using tools of nuclear theory



Effective mass of Majorana neutrinos

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



β -decay (Mainz, Troitsk)

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

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

Cosmology (Planck)

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

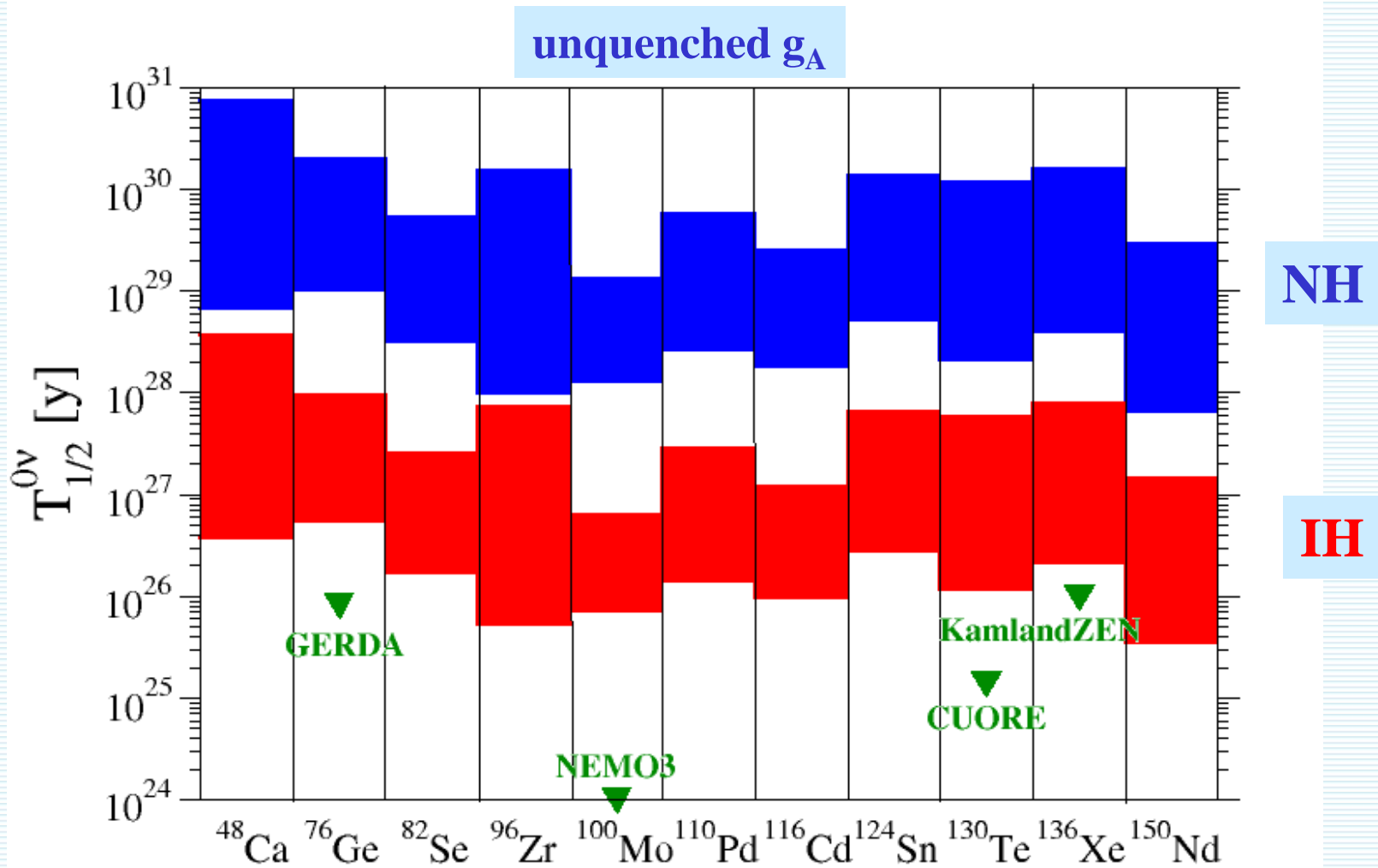
$m_0 > 26 \text{ meV (NS)}$
 87 meV (IS)

5/27/2019

GUT's

$m_1, m_2, m_3, \theta_{12}, \theta_{13}, \alpha_1, \alpha_2$
 (3 unknown parameters)

$0\nu\beta\beta$ –half lives for NH and IH with included uncertainties in NMEe



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

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

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

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

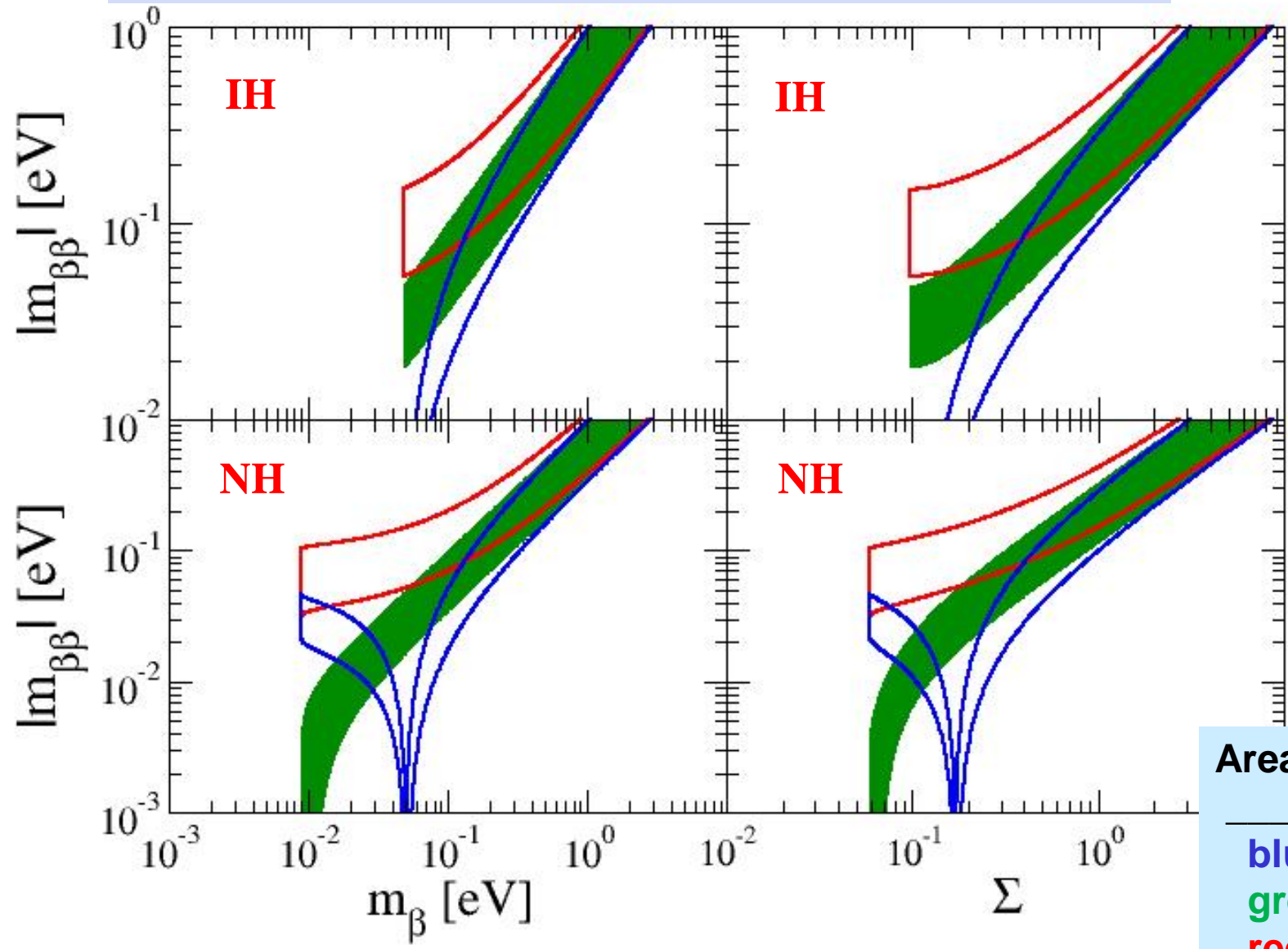
$1.4 \text{ meV} \leq m_{\beta\beta} \leq 3.6 \text{ meV}$

Lightest ν -mass equal to zero

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

Complementarity between β -decay, $0\nu\beta\beta$ -decay and cosmological measurements might be spoiled, e.g., by nonstandard ν -int.

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



On the Generation of Majorana Neutrino Mass via Quark Condensate
 Andrej Babič
 Presentation
 MEDEX 2019
 Thursday
 30.05.2019

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

II.b. *The sterile ν mechanism of the $0\nu\beta\beta$ -decay* *(D-M mass term, V-A, SM int.)*

Interpolating formula

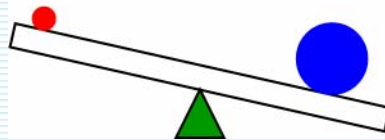
Dirac-Majorana
mass term

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

Mixing of
active-sterile
neutrinos

small ν masses due to see-saw mechanism

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



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

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

Different motivations for the LNV scale Λ

Talk of
Carlo Giunti

eV
light sterile ν
 10^{-6} GeV

keV
hot DM
 10^{-6} GeV

Fermi
 10^{-6} GeV or Si

TeV
LHC
 10^3 GeV

GUT
 10^{16} GeV

Planck
 10^{19} GeV

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

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

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} g_A^4 \left| \sum_N (U_{eN}^2 m_N) m_p M'^{0\nu}(m_N, g_A^{\text{eff}}) \right|^2$$

General case

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

$$M'^{0\nu}(m_N \rightarrow \infty, g_A^{\text{eff}}) = \frac{1}{m_N^2} M_N'^{0\nu}(g_A^{\text{eff}})$$

light ν exchange

heavy ν exchange

Particular cases

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} g_A^4 \times \begin{cases} \left| \frac{\langle m_\nu \rangle}{m_e} \right|^2 \left| M_\nu'^{0\nu}(g_A^{\text{eff}}) \right|^2 & \text{for } m_N \ll p_F \\ \left| \langle \frac{1}{m_N} \rangle m_p \right|^2 \left| M_N'^{0\nu}(g_A^{\text{eff}}) \right|^2 & \text{for } m_N \gg p_F \end{cases}$$

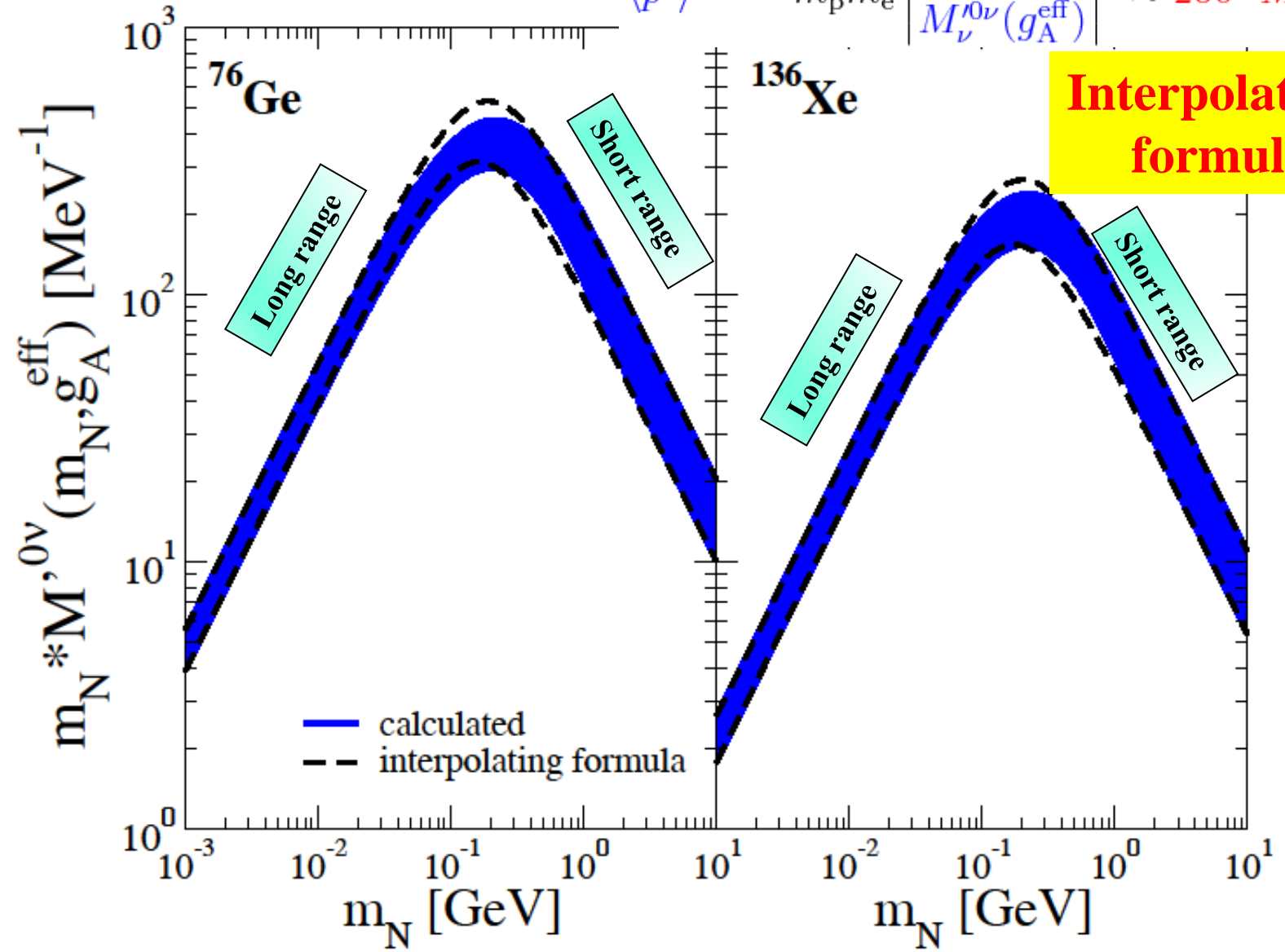
$$\langle m_\nu \rangle = \sum_N U_{eN}^2 m_N$$

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

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

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

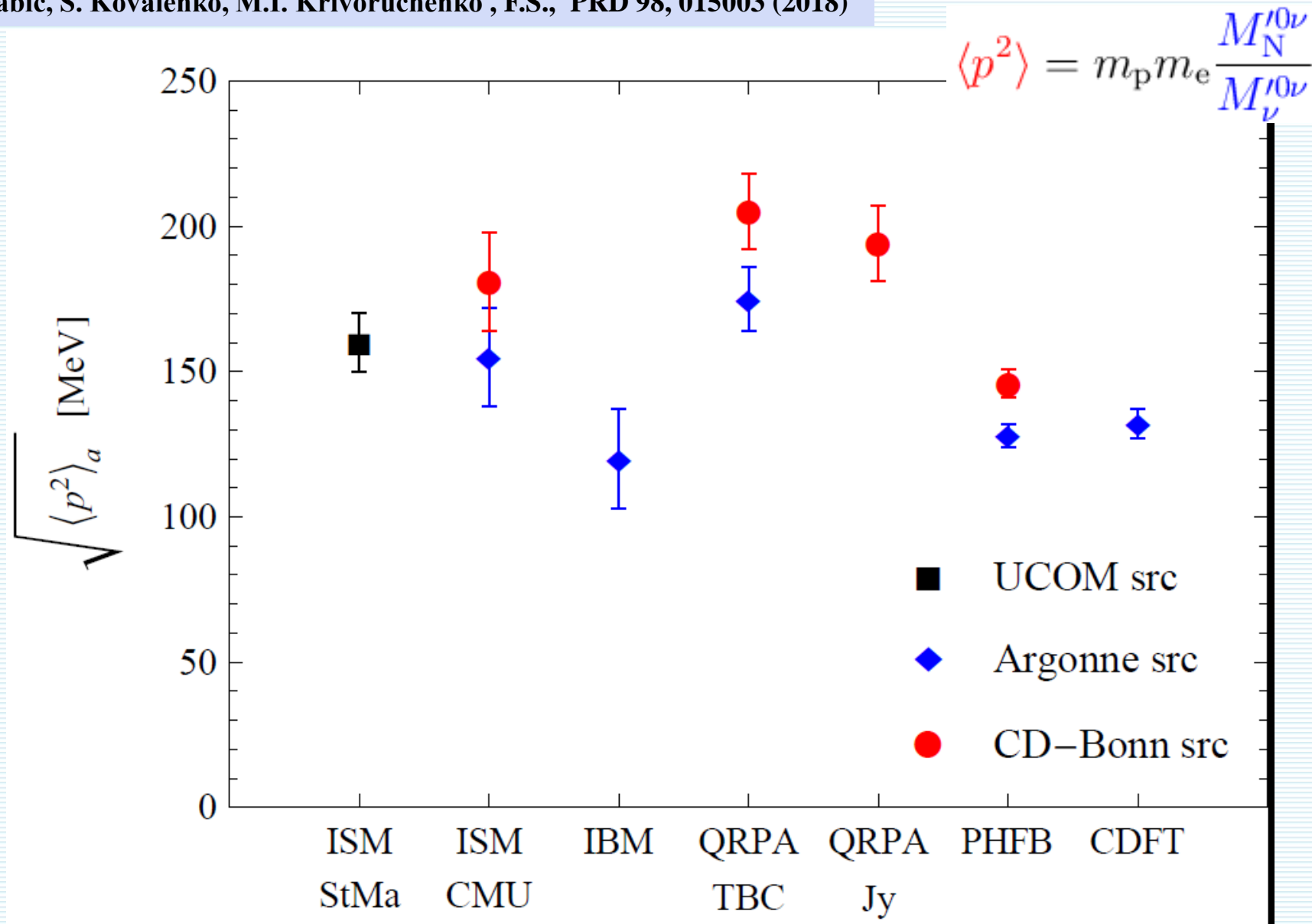
$$\langle p^2 \rangle = m_p m_e \left| \frac{M_N^{0\nu}(g_A^{\text{eff}})}{M_\nu^{0\nu}(g_A^{\text{eff}})} \right| \approx 200 \text{ MeV}$$



**Interpolating formula is justified
by practically no dependence $\langle p^2 \rangle$ on A**

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

A. Babič, S. Kovalenko, M.I. Krivoruchenko, F.Š., PRD 98, 015003 (2018)



II.c. *The $0\nu\beta\beta$ -decay within L-R symmetric theories*

(interpolating formula)

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

A. Babič, S. Kovalenko, M.I. Krivoruchenko, F.Š., PRD 98, 015003 (2018)

$$[T_{1/2}^{0\nu}]^{-1} = \eta_{\nu N}^2 C_{\nu N}$$

$$C_{\nu N} = g_A^4 \left| M_{\nu}^{\prime 0\nu} \right|^2 G^{0\nu}$$

Mixing of light and heavy neutrinos

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

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

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

Effective LNV parameter within LRS model

$$\eta_{\nu N}^2 = \left| \sum_{j=1}^3 \left(U_{ej}^2 \frac{m_j}{m_e} + S_{ej}^2 \frac{\langle p^2 \rangle_a}{\langle p^2 \rangle_a + M_j^2} \frac{M_j}{m_e} \right) \right|^2 + \lambda^2 \left| \sum_{j=1}^3 \left(T_{ej}^2 \frac{m_j}{m_e} + V_{ej}^2 \frac{\langle p^2 \rangle_a}{\langle p^2 \rangle_a + M_j^2} \frac{M_j}{m_e} \right) \right|^2$$

$$\langle p^2 \rangle = m_p m_e \frac{M_N^{\prime 0\nu}}{M_{\nu}^{\prime 0\nu}}$$

6x6 PMNS see-saw ν -mixing matrix

(the most economical one)

6x6 neutrino mass matrix

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

Basis

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

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

6x6 matrix: 15 angles, 10+5 CP phases

3x3 matrix: 3 angles, 1+2 CP phases

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

Assumptions:

i) the see-saw structure

ii) mixing between different generations is neglected

$$U_{\text{PMNS}} = \begin{pmatrix} U_{\text{PMNS}} & \zeta \mathbf{1} \\ -\zeta \mathbf{1} & U_{\text{PMNS}}^\dagger \end{pmatrix} \quad U_{\text{PMNS}} U_{\text{PMNS}}^\dagger = U_{\text{PMNS}}^\dagger U_{\text{PMNS}} = \mathbf{1}$$

see-saw
parameter

$$\zeta = \frac{m_D}{m_{\text{LNV}}}$$

6x6 matrix: 3 angles, 1+2 CP phases, 1 see-saw par.

6x6 PMNS see-saw ν -mixing matrix (the most economical one)

$$\mathcal{U} = \begin{pmatrix} U_0 & \zeta \mathbf{1} \\ -\zeta \mathbf{1} & V_0 \end{pmatrix}$$

$$U_0 = U_{\text{PMNS}}$$

A. Babič, S. Kovalenko, M.I. Krivoruchenko, F.Š., PRD 98, 015003 (2018)

$$V_0 = U_{\text{PMNS}}^\dagger = \begin{pmatrix} c_{12} c_{13} e^{-i\alpha_1} & (-s_{12} c_{23} - c_{12} s_{13} s_{23} e^{-i\delta}) e^{-i\alpha_1} & (s_{12} s_{23} - c_{12} s_{13} c_{23} e^{-i\delta}) e^{-i\alpha_1} \\ s_{12} c_{13} e^{-i\alpha_2} & (c_{12} c_{23} - s_{12} s_{13} s_{23} e^{-i\delta}) e^{-i\alpha_2} & (-c_{12} s_{23} - s_{12} s_{13} c_{23} e^{-i\delta}) e^{-i\alpha_2} \\ s_{13} e^{i\delta} & c_{13} s_{23} & c_{13} c_{23} \end{pmatrix}$$

Assumption about heavy neutrino masses M_i (by assuming see-saw)

Inverse
proportional

$$m_i M_i \simeq m_D^2$$

$$M_{\beta\beta}^{\text{R}} = \lambda \frac{\langle p^2 \rangle_a}{m_D^2} \left| \sum_{j=1}^3 (U_0^\dagger)_{ej}^2 m_j \right|$$

$$m_i \simeq \zeta^2 M_i$$

$$M_{\beta\beta}^{\text{R}} = \lambda \zeta^2 \left| \sum_{j=1}^3 (U_0^\dagger)_{ej}^2 \frac{\langle p^2 \rangle_a}{m_j} \right|$$

Proportional

$M_{\beta\beta}^{\text{R}}$ depends on
“Dirac” CP phase δ
unlike “Majorana”
CP phases α_1 and α_2

Heavy Majorana mass $M_{\beta\beta}^{\text{R}}$ depends on the “Dirac” CP violating phase δ 3

Contribution from exchange of heavy neutrino to $0\nu\beta\beta$ -decay rate might be large

Inverse proportional

$$m_i M_i \simeq m_D^2$$

$$M_{\beta\beta}^R = \lambda \frac{\langle p^2 \rangle_a}{m_D^2} \left| \sum_{j=1}^3 (U_0^\dagger)_{ej}^2 m_j \right|$$

$$V_0 = U_{PMNS}^\dagger$$

$$M_i = m_D^2 / m_i \quad m_D \simeq 5 \text{ MeV}$$

$$\lambda = 7.7 \times 10^{-4}$$

Proportional

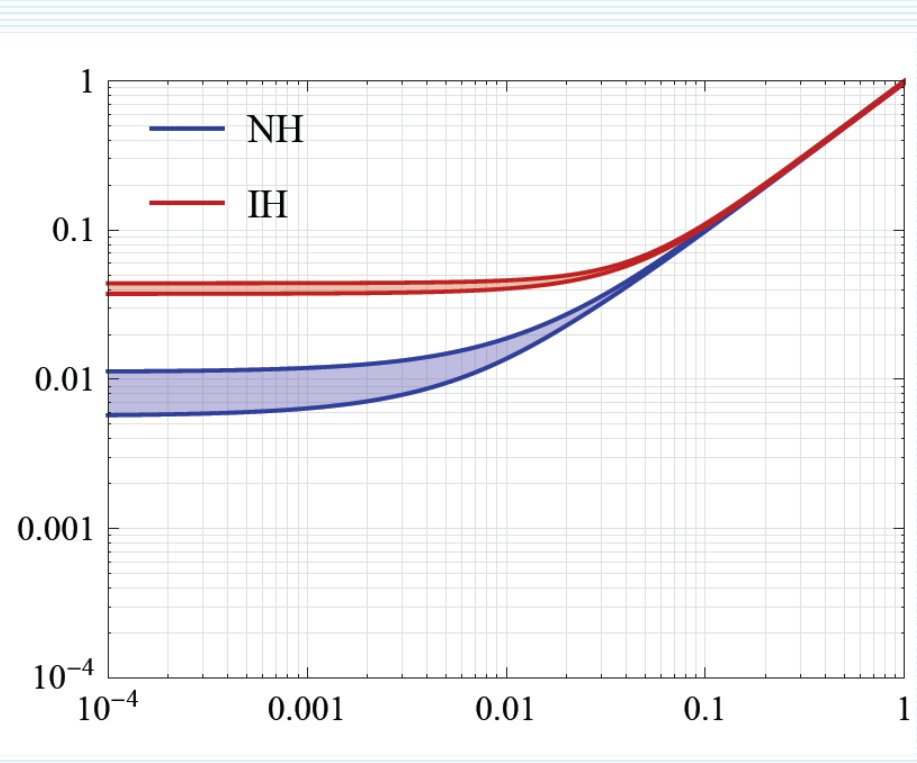
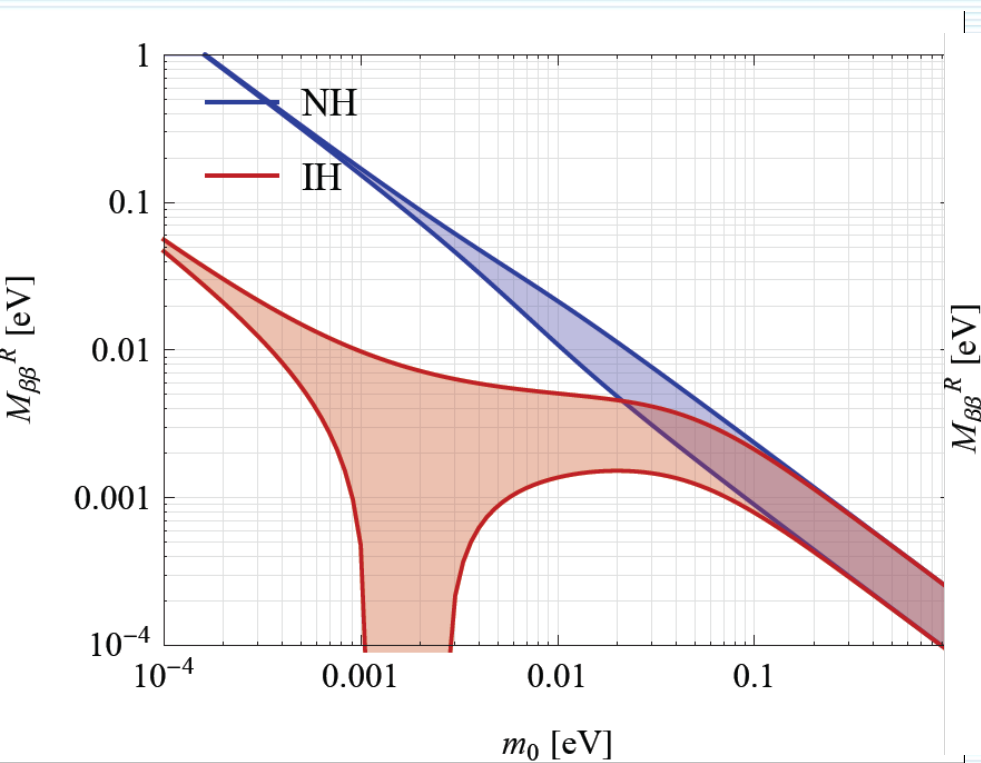
$$m_i \simeq \zeta^2 M_i$$

$$M_{\beta\beta}^R = \lambda \zeta^2 \left| \sum_{j=1}^3 (U_0^\dagger)_{ej}^2 \frac{\langle p^2 \rangle_a}{m_j} \right|$$

$$V_0 = U_{PMNS}^\dagger$$

$$\zeta = m_i / M_i \quad \zeta^2 \simeq 5 \times 10^{-17}$$

$$\lambda = 7.7 \times 10^{-4}$$



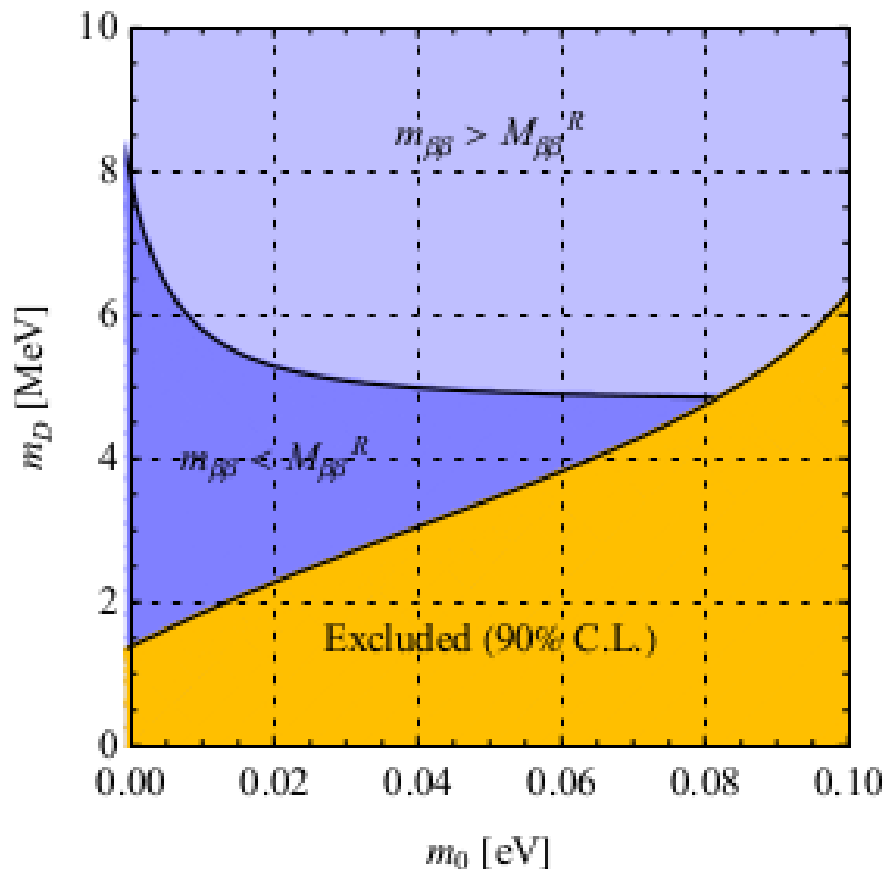
See-saw scenario

$$m_i M_i \simeq m_D^2$$

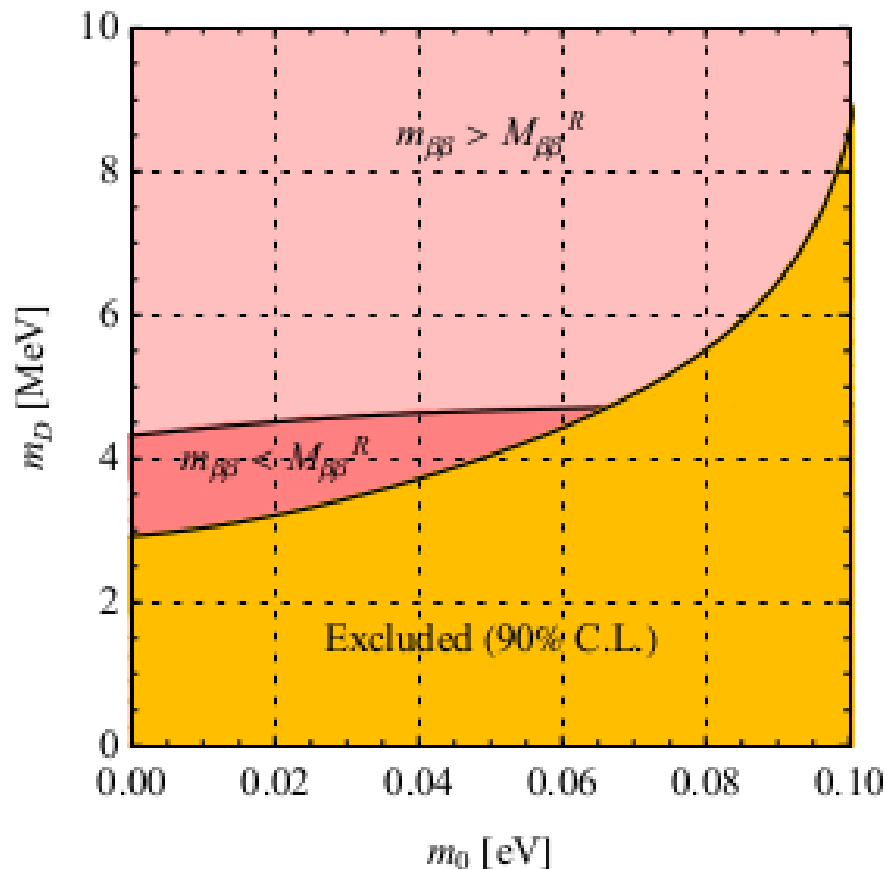
$$M_{\beta\beta}^R = \lambda \frac{\langle p^2 \rangle_a}{m_D^2} \left| \sum_{j=1}^3 (U_0^\dagger)_{ej}^2 m_j \right|$$

$$\eta_{\nu N}^2 = \frac{1}{m_e^2} \left(m_{\beta\beta}^2 + (M_{\beta\beta}^R)^2 \right)$$

Normal spectrum



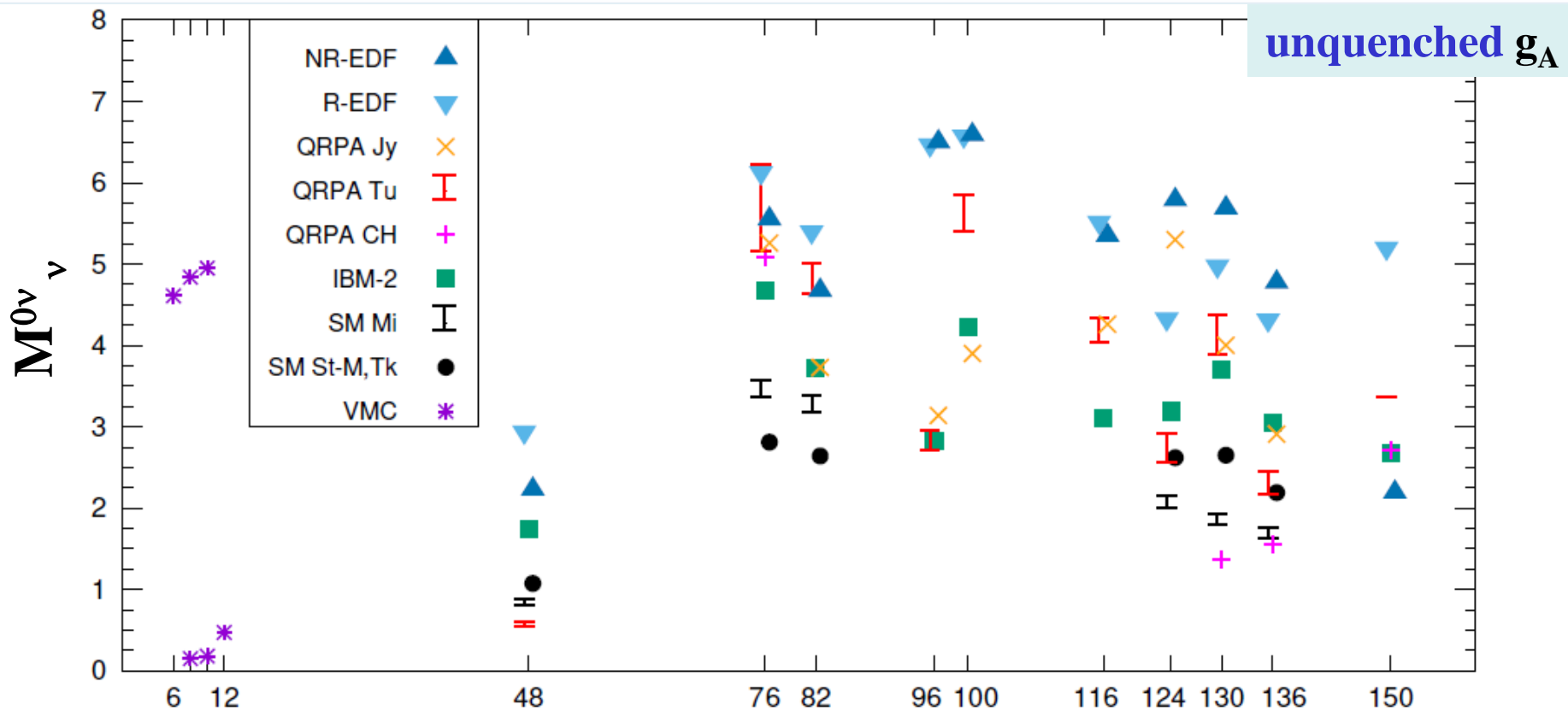
Inverted spectrum



III. $0\nu\beta\beta$ decay NMEs

0νββ-decay NME (light ν mass) – status 2017

J. Engel, J. Menendez, Rept. Prog. Phys. 80, 046301 (2017)



A

mean field meth.

ISM

IBM

QRPA

Large model space

yes

no

no

yes

Constr. Intern. States

no

yes

no

yes

Nucl. Correlations

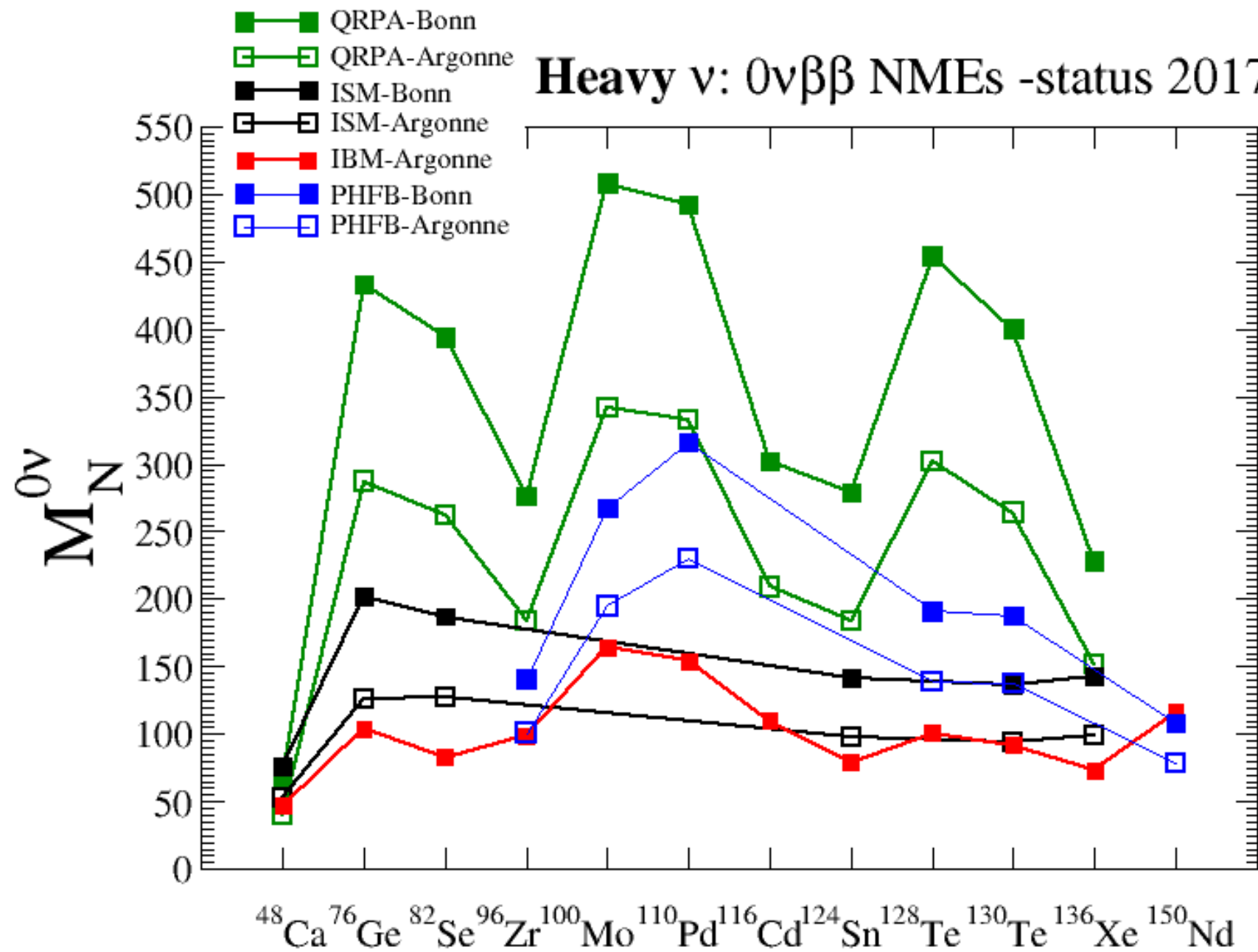
limited

all

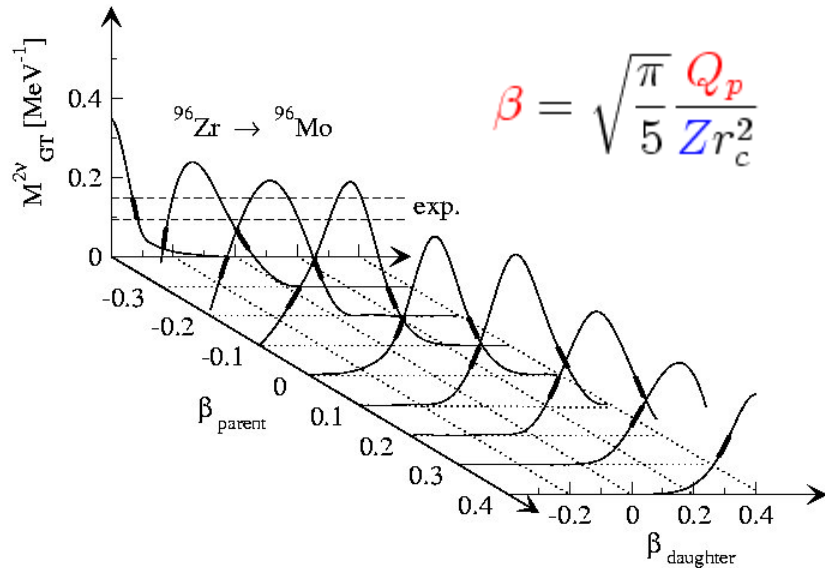
restricted

restricted

Heavy ν : $0\nu\beta\beta$ NMEs -status 2017



Suppression of the $0\nu\beta\beta$ -decay NMEs due to different deformation of initial and final nuclei

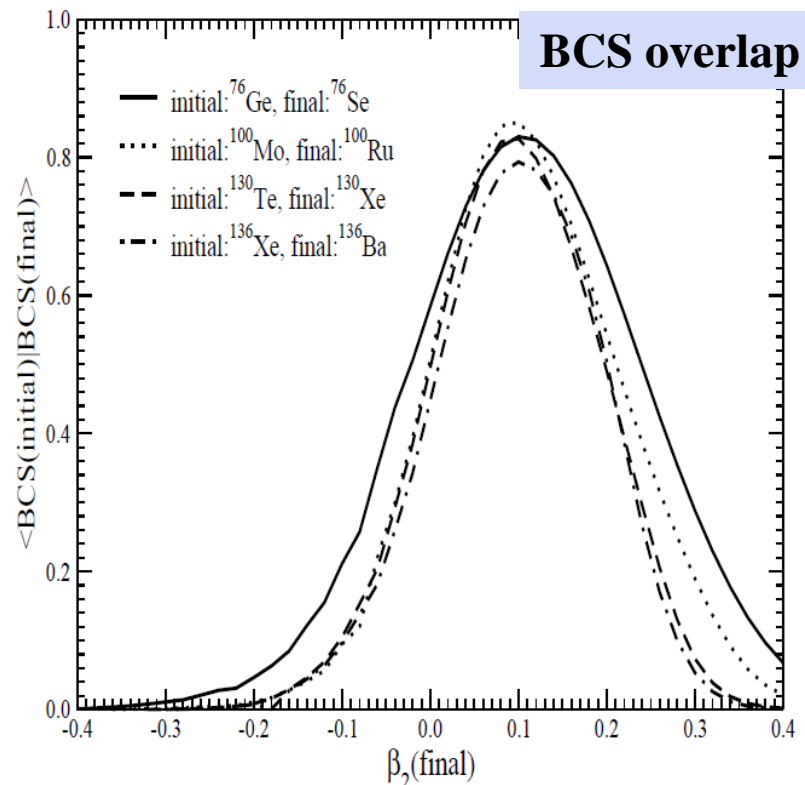


**The suppression of the NME depends
on the relative deformation
of initial and final nuclei**

F.Š., Pacearescu, Faessler, NPA 733 (2004) 321

**Systematic study of the deformation
effect on the $2\nu\beta\beta$ -decay NME within
deformed QRPA**

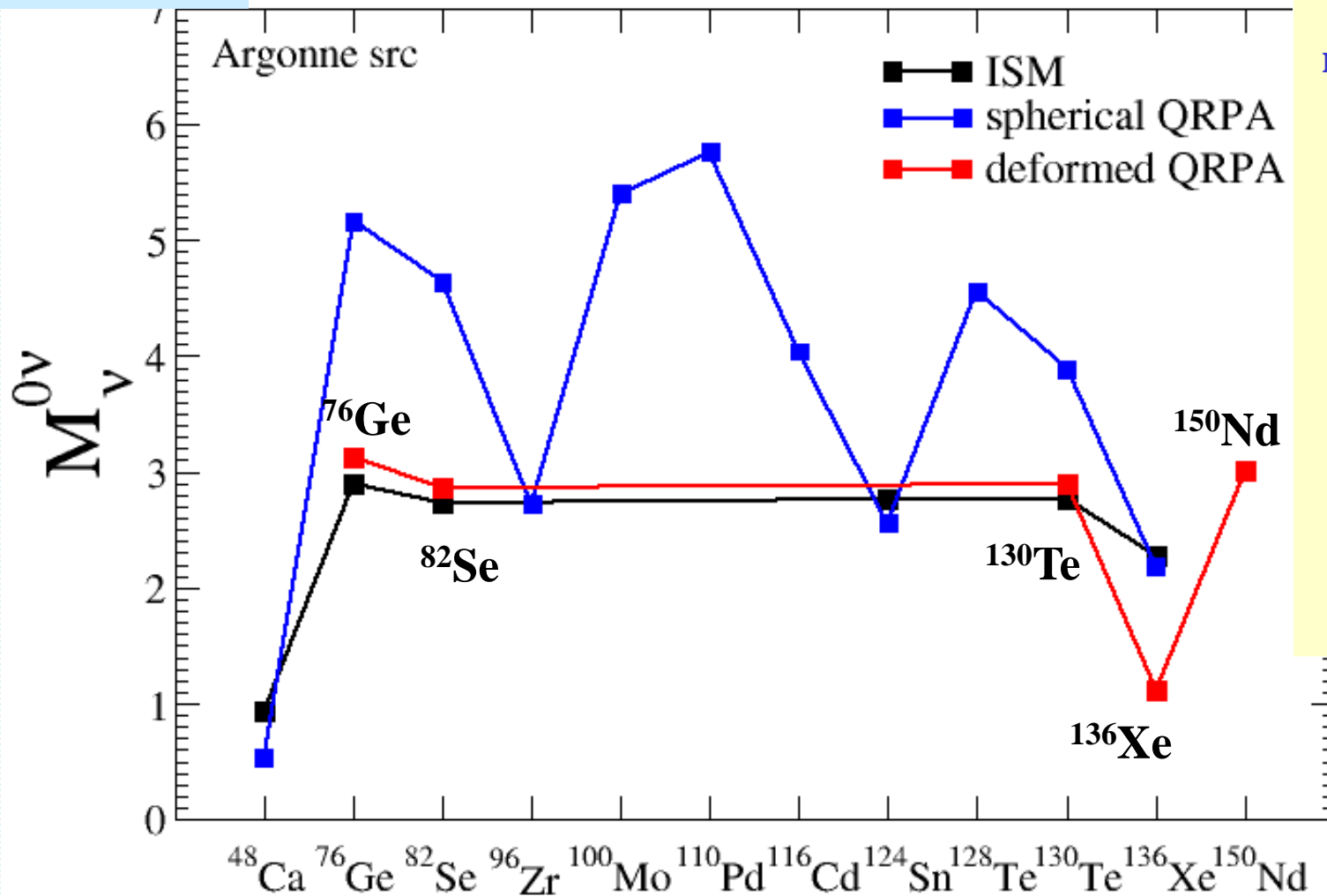
Alvarez, Sarriguren, Moya, Pacearescu,
Faessler, F.Š., Phys. Rev. C 70 (2004) 321



$0\nu\beta\beta$ -decay NMEs within deformed QRPA with partial restoration of isospin symmetry (light neutrino exchange)

Agreement
by a chance?

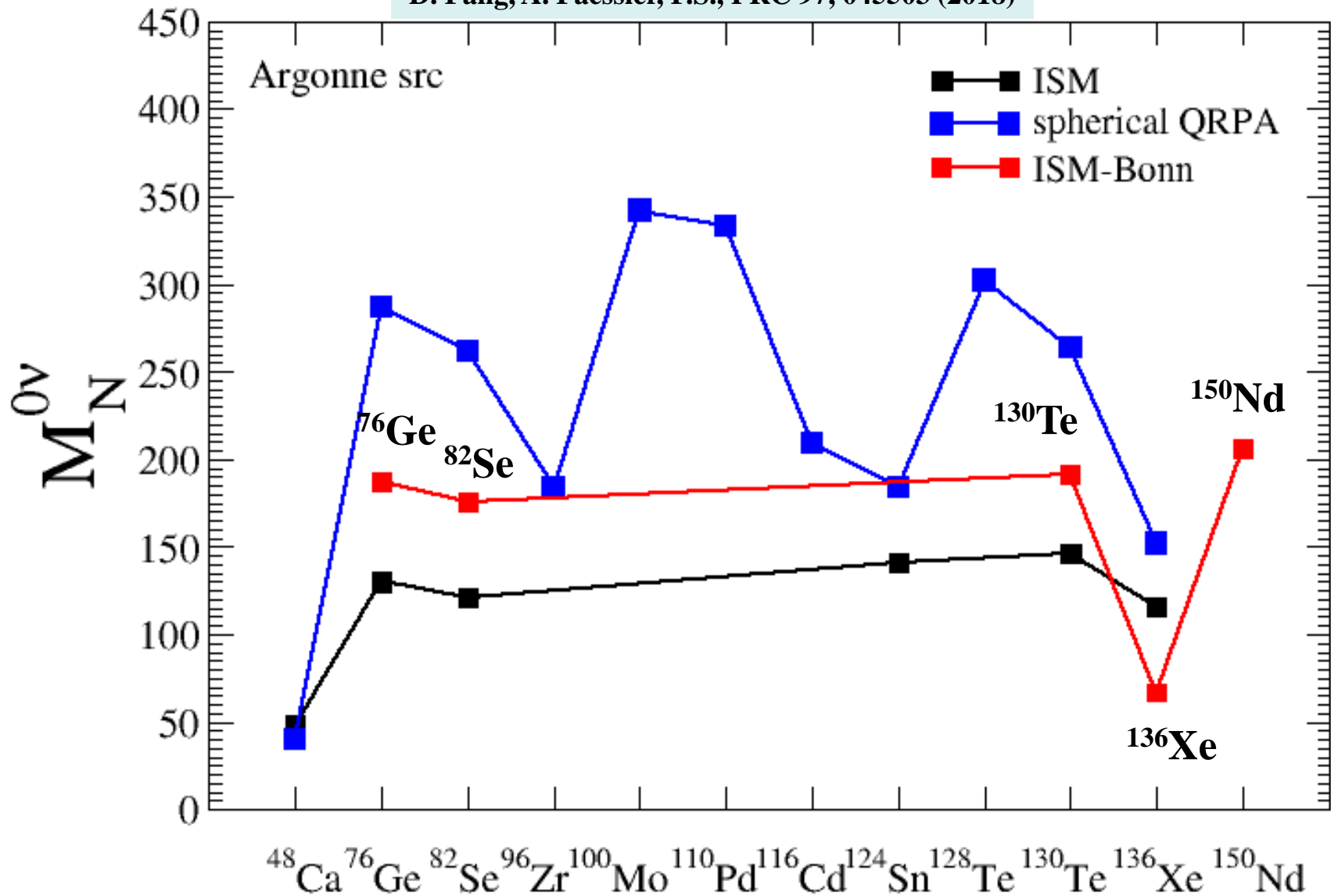
D. Fang, A. Faessler, F.Š., PRC 97, 045503 (2018)



Double beta
decay nuclear
matrix elements
from deformed
QRPA
calculations
with
realistic forces
**Dong-Liang
Fang**
Presentation
MEDEX 2019
Wednesday
29.05.2019

$0\nu\beta\beta$ -decay NMEs within deformed QRPA with partial restoration of isospin symmetry (heavy neutrino exchange, Argonne src)

D. Fang, A. Faessler, F.Š., PRC 97, 045503 (2018)



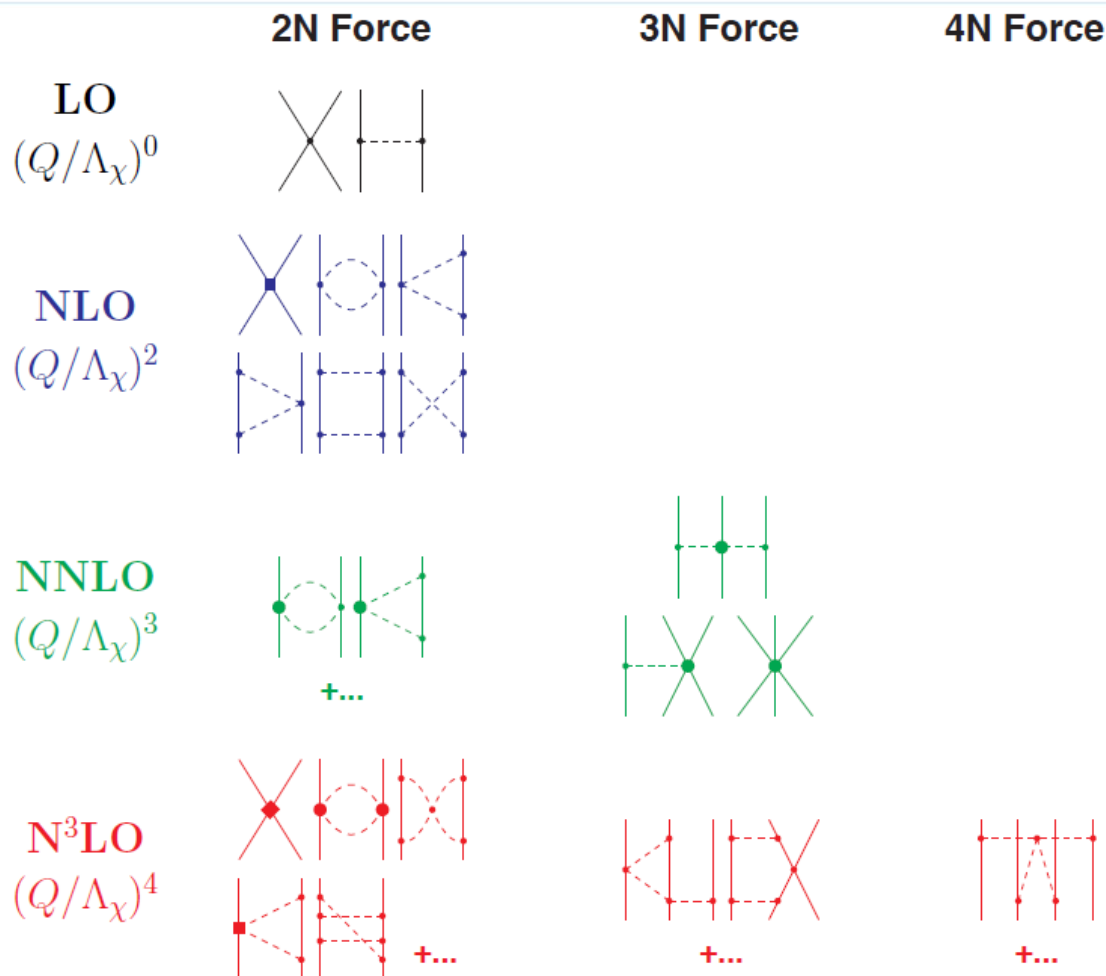
Ab Initio Nuclear Structure

(Often starts with chiral effective-field theory)

Nucleons, pions sufficient below chiral symmetry breaking scale.
 Expansion of operators in power of Q/Λ_χ . $Q=m_\pi$ or typical nucleon momentum.

A. Schwenk (Darmstadt U.)
 P. Navratil (TRIUMPH)
 J. Engel (North Carolina U.)
 J. Menendez (Tokyo U.)

Calculation for the
 hypothetical $0\nu\beta\beta$ decay
 of ^{10}He :
 $^{10}\text{He} \rightarrow ^{10}\text{Be} + e^- + e^-$
 masses, spectra

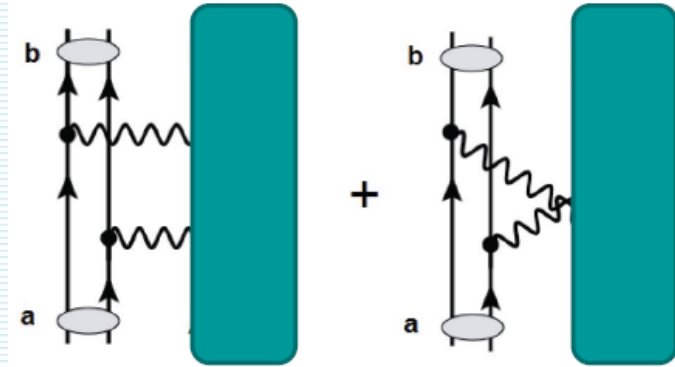
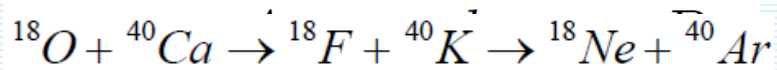


Supporting nuclear physics experiments

($2\nu\beta\beta$ -decay ChER, pion and heavy ion DCX, nucleon transfer reactions etc)

40	C	41	Ca	42	Ca
39	K	41	K	41	K
38	Ar	39	Ar	40	Ar

$(18O, 18F) \rightarrow$ (arrow from C to K)
 $(18F, 18Ne) \rightarrow$ (arrow from K to Ar)



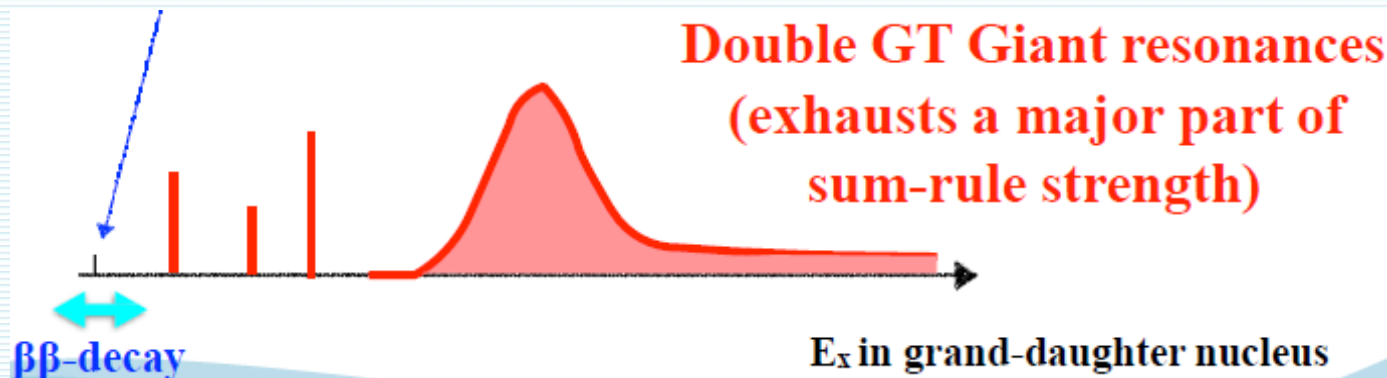
H. Lenske group

Theory of heavy ion DCX and
Connection to DBD NMEs

Heavy ion DCX:

NUMEN (LNC-INFN),

HIDCX (RCNP/RIKEN)



IV. Is there a proportionality between $0\nu\beta\beta$ and $2\nu\beta\beta$ -decay NMEs?

Understanding of the $2\nu\beta\beta$ -decay NMEs is of crucial importance for correct evaluation of the $0\nu\beta\beta$ -decay NMEs



*Both $2\nu\beta\beta$ and $0\nu\beta\beta$ operators connect the same states.
Both change two neutrons into two protons.*

Explaining $2\nu\beta\beta$ -decay is necessary but not sufficient

There is no reliable calculation of the $2\nu\beta\beta$ -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

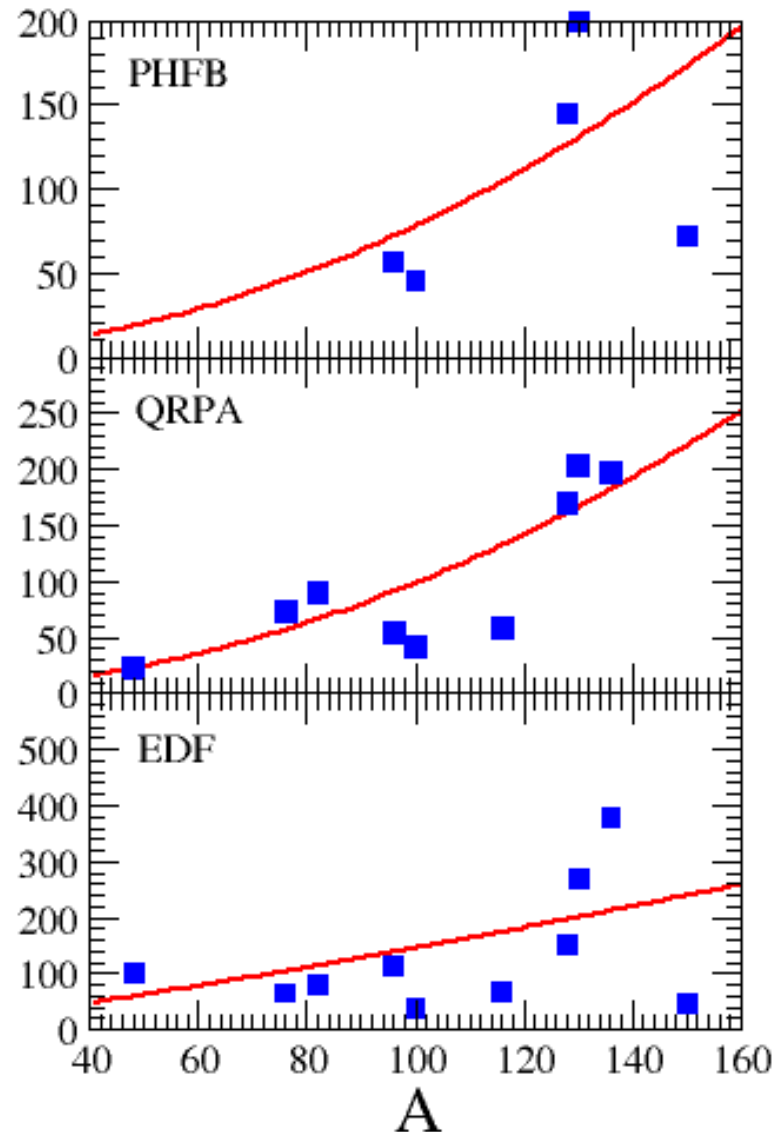
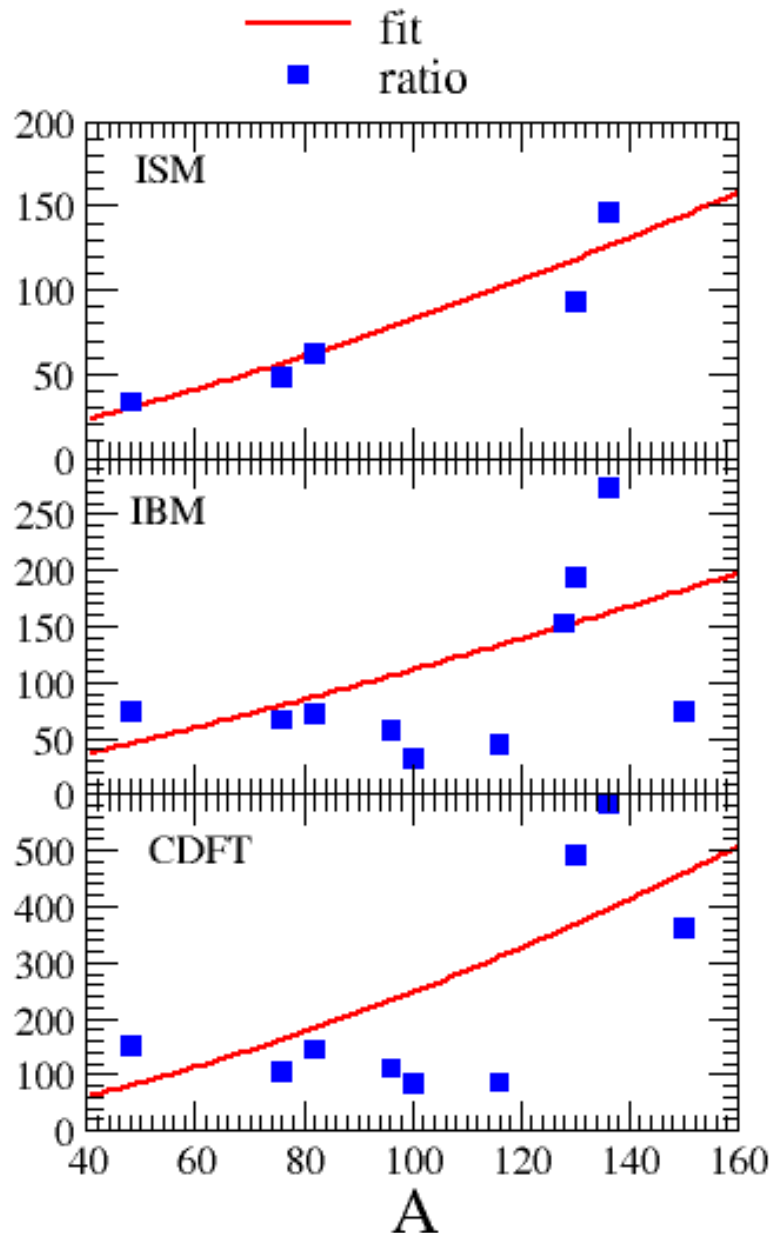
No calculation: EDF

Is there a proportionality between $0\nu\beta\beta$ - and $2\nu\beta\beta$ -decay NMEs?

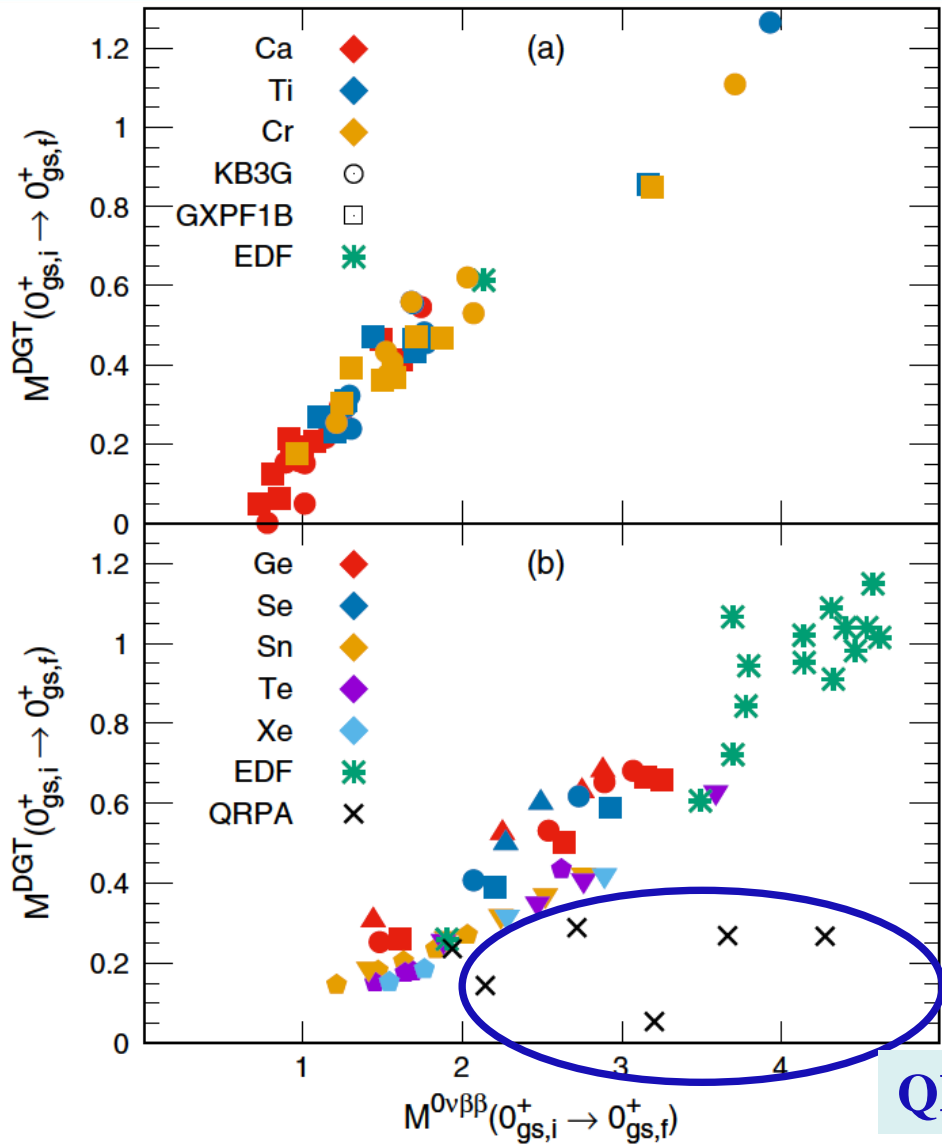
Known
from
measured
 $2\nu\beta\beta$ -
decay
half-life

$$M_V^{0\nu} / (m_e M^{2\nu\text{-exp}})$$

Calc.
within
nuclear
model



$$M^{0\nu} \propto M^{2\nu}_{GT-cl} : \text{ISM, EDF}$$



QRPA?

$$M^{DGT} = M^{2\nu}_{GT}$$

SSD ChER

^{48}Ca		0.22
^{76}Ge		0.52
^{96}Zr		0.22
^{100}Mo	0.35	
^{116}Cd	0.35	0.30
^{128}Te	0.41	

EDF: 0.6 → 1.2

ISM: 0.1 → 0.7

IBM: 1.6 → 4.4

QRPA: |0.1| → |0.7|

IBM: J. Barea, J. Kotila, F. Iachello,
PRC 91, 034304 (2015)

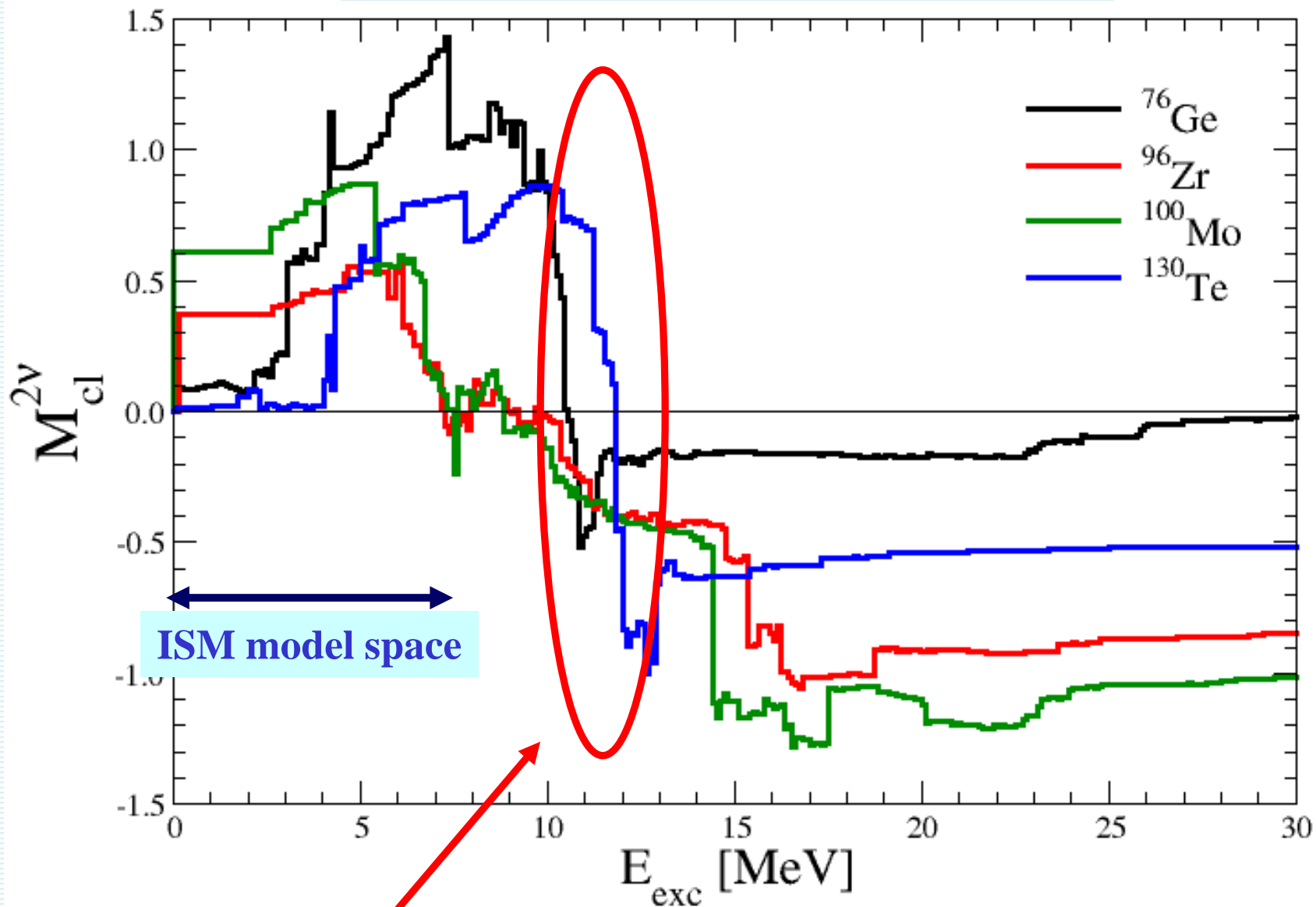
QRPA: F.Š., R. Hodák, A. Faessler, P. Vogel,
PRC 83, 015502 (2011)

ISM: N. Shimizu, J. Menendez, K. Yako, Fedor Simkovic
PRL 120, 142502 (2018)

M^{DGT} – only 1^+
 $M^{0\nu}$ - contribution
from many J^π (!)

QRPA: There is no proportionality between $0\nu\beta\beta$ -decay and $2\nu\beta\beta$ -decay NMEs

F.Š., R. Hodák, A. Faessler, P. Vogel, PRC 83, 015502 (2011)



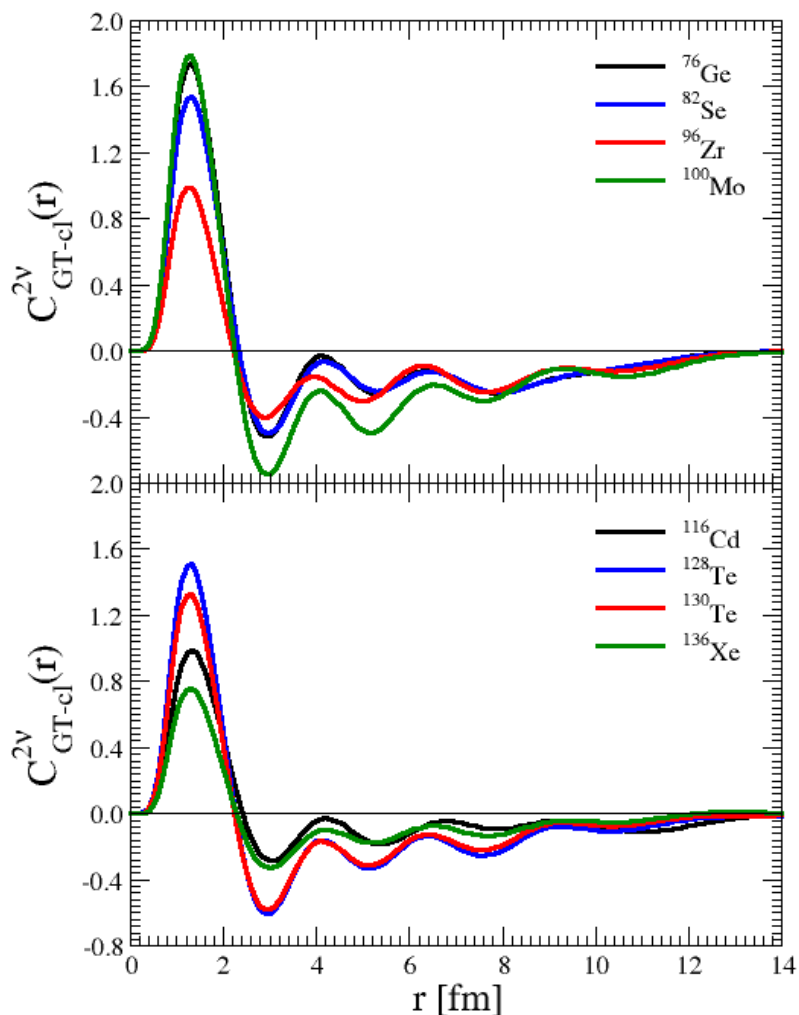
Region of GT resonance

A connection between closure $2\nu\beta\beta$ and $0\nu\beta\beta$ GT NMEs

F.Š., R. Hodák, A. Faessler, P. Vogel,
PRC 83, 015502 (2011)

Going to
relative
coordinates:

$$M_{GT-cl}^{2\nu} = \int_0^\infty C_{GT-cl}^{2\nu}(r) dr$$

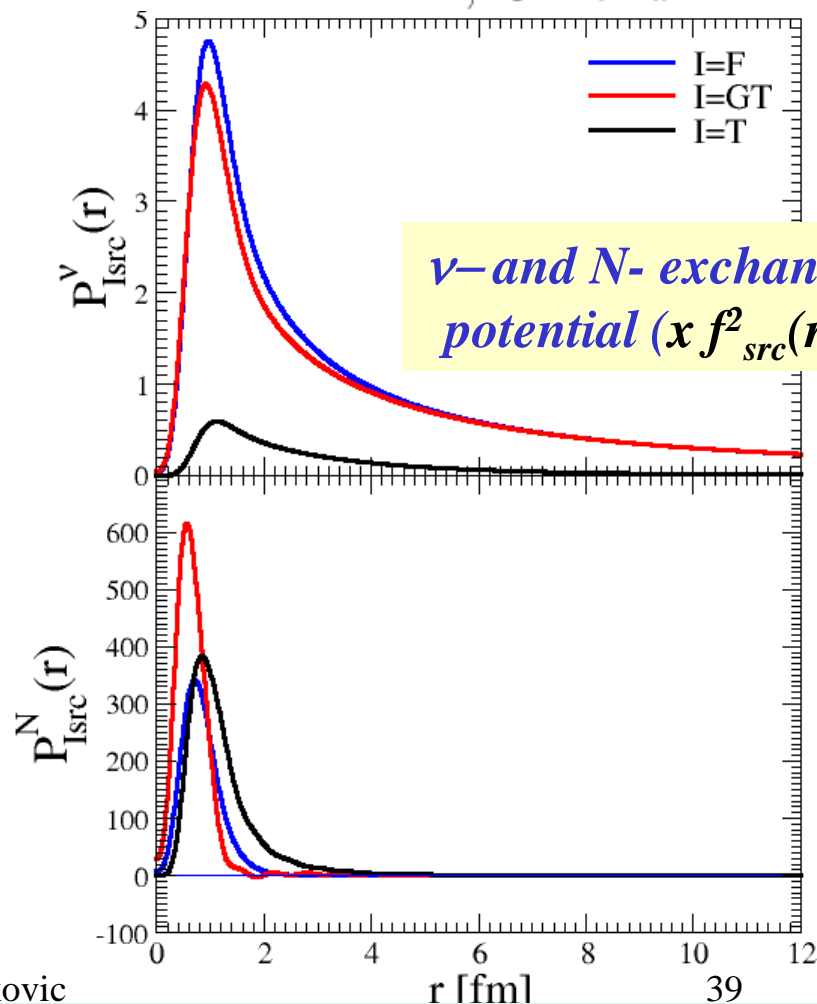


r - relative distance of two decaying nucleons

$$M_{\nu,N-I}^{0\nu} = \int_0^\infty P_{I-src}^{\nu,N}(r) C_{I-cl}^{2\nu}(r) dr$$

$$= \int_0^\infty f_{src}^2(r) P_I^{\nu,N}(r) C_{I-cl}^{2\nu}(r) dr$$

$I = F, GT \text{ and } T$



ν - and N - exchange
potential ($\propto f_{src}^2(r)$)

Simkovic

Neutrino potential prefers short distances

39

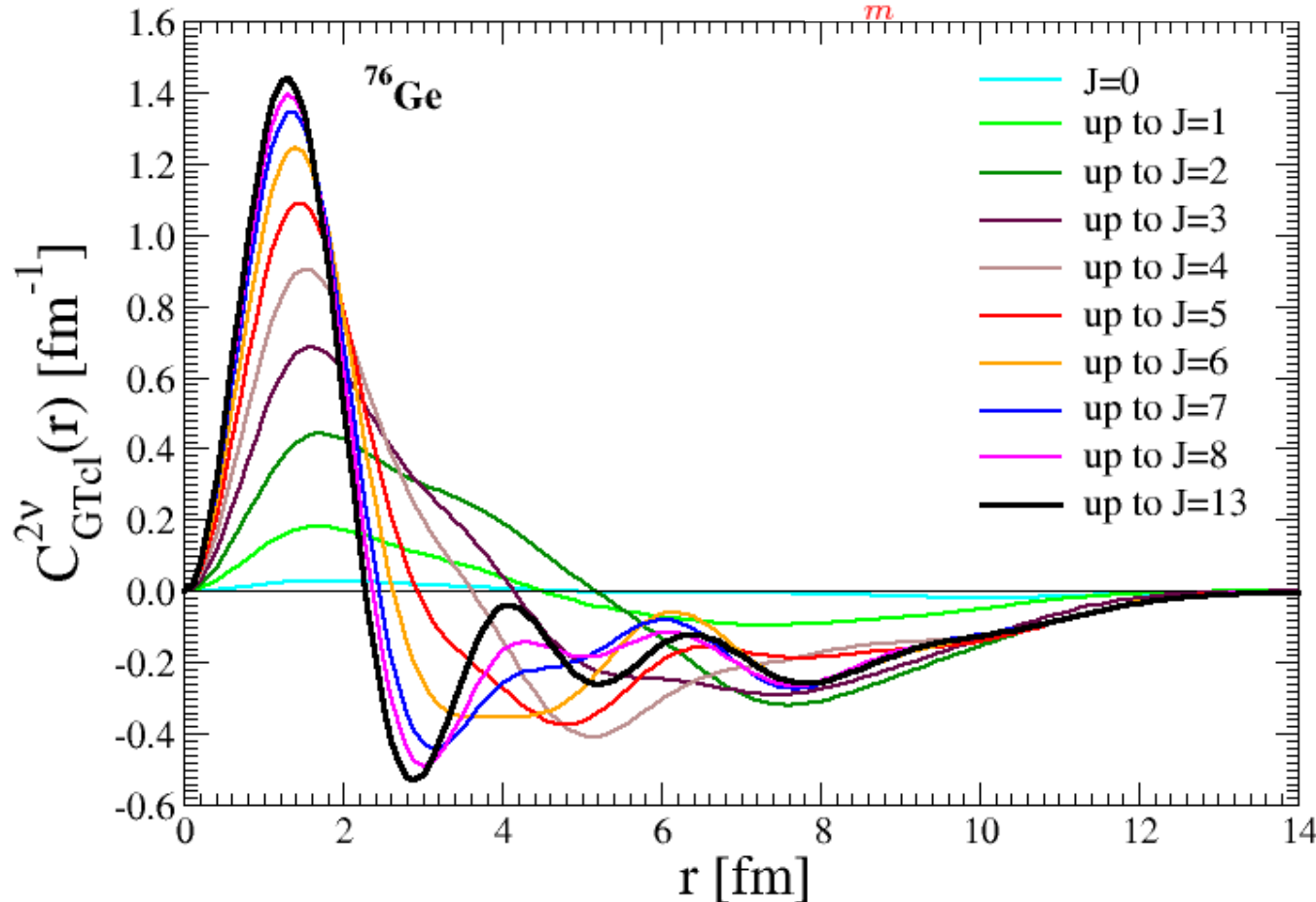
Closure $2\nu\beta\beta$ GT NME

The only non-zero contribution from $J^\pi=1^+$

$$M_{GT-cl}^{2\nu} = \sum_{J^\pi} \int_0^\infty C_{GT-J^\pi}^{2\nu}(r) dr$$

$$M_{GT-cl}^{2\nu} = \sum_{J^\pi, m} \langle 0_f^+ | \tau^+ \vec{\sigma} | J^\pi, m \rangle \cdot \langle J^\pi, m | \tau^+ \vec{\sigma} | 0_i^+ \rangle$$

$$M_{GT-cl}^{2\nu} = \sum_m \langle 0_f^+ | \tau^+ \vec{\sigma} | 1^+, m \rangle \cdot \langle 1^+, m | \tau^+ \vec{\sigma} | 0_i^+ \rangle$$

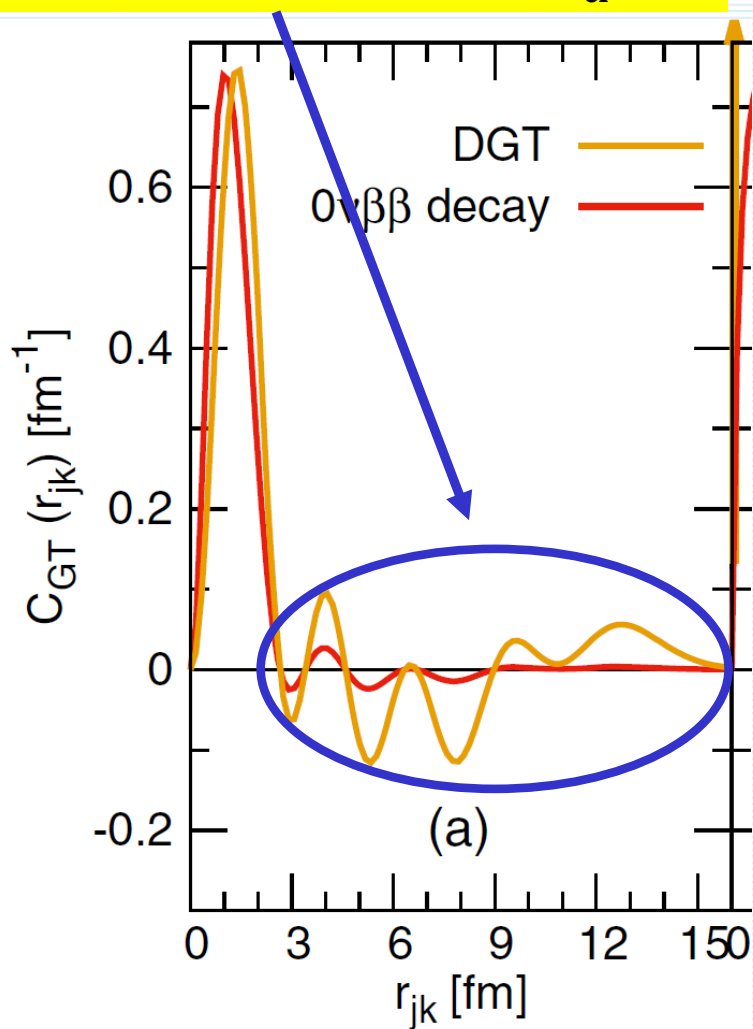


Many multipole contributions not included within the ISM due to truncation of the model space

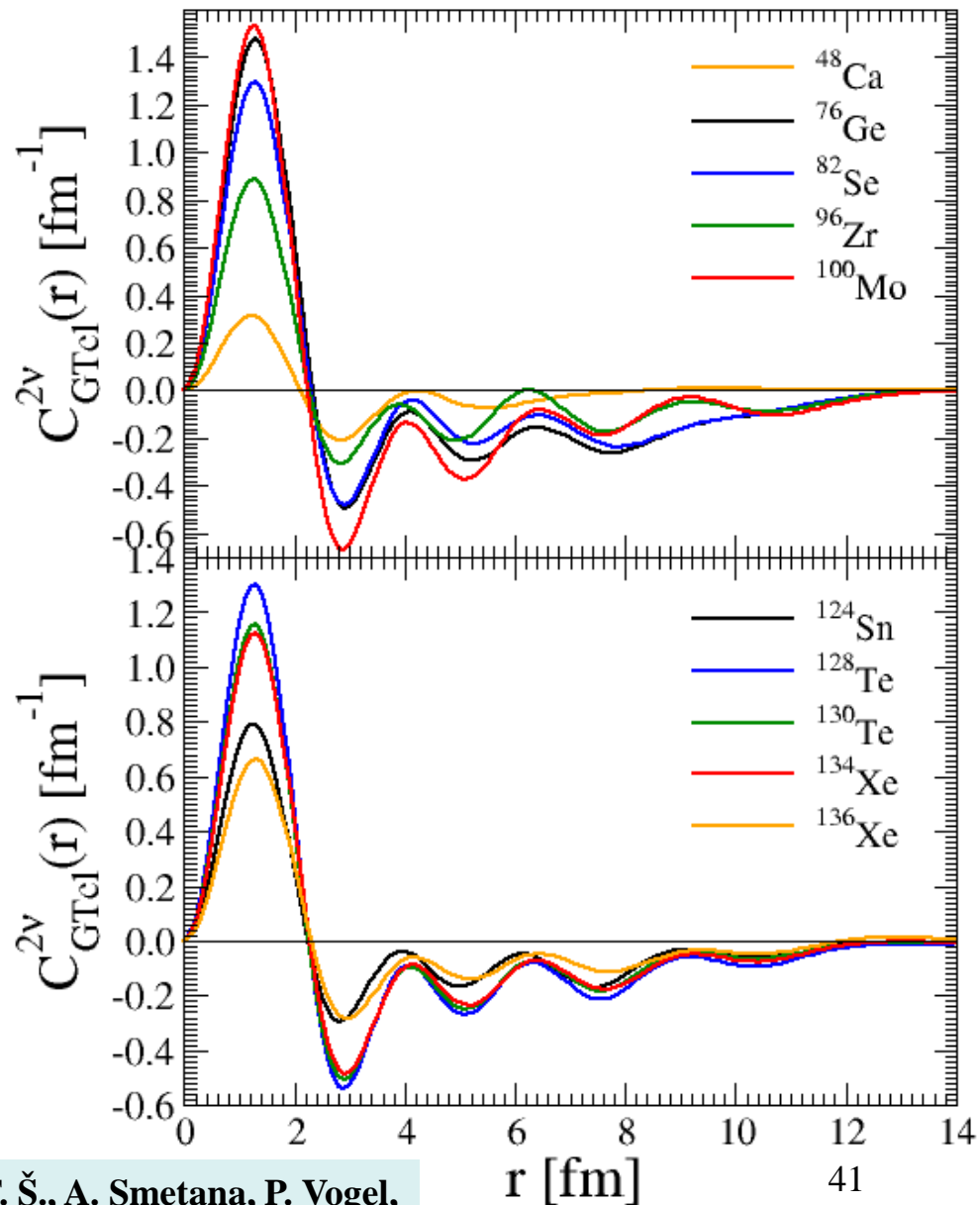
QRPA: Bump \approx - Tail $\Rightarrow M^{2\nu}_{cl} \approx 0$

**Close to restoration of the SU(4) symmetry
of residual Hamiltonian**

ISM: Tail ≈ 0 (!) $\Rightarrow M^{2\nu}_{cl} \gg 0$



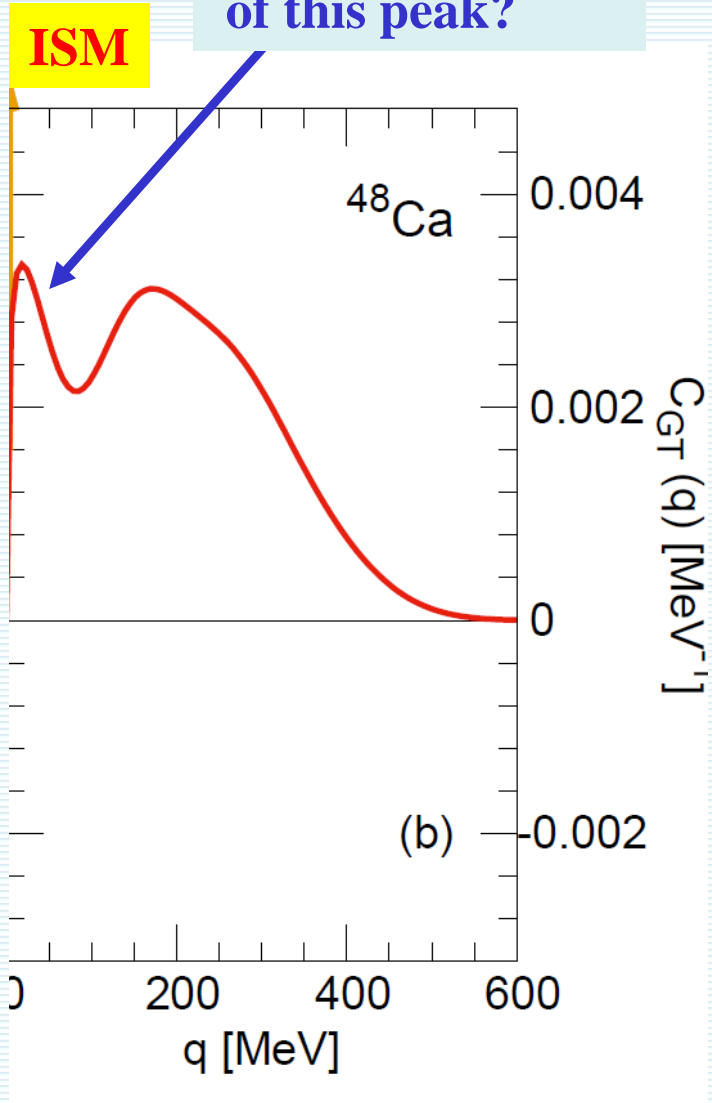
N. Shimizu, J. Menendez, K. Yako,
PRL 120, 142502 (2018)



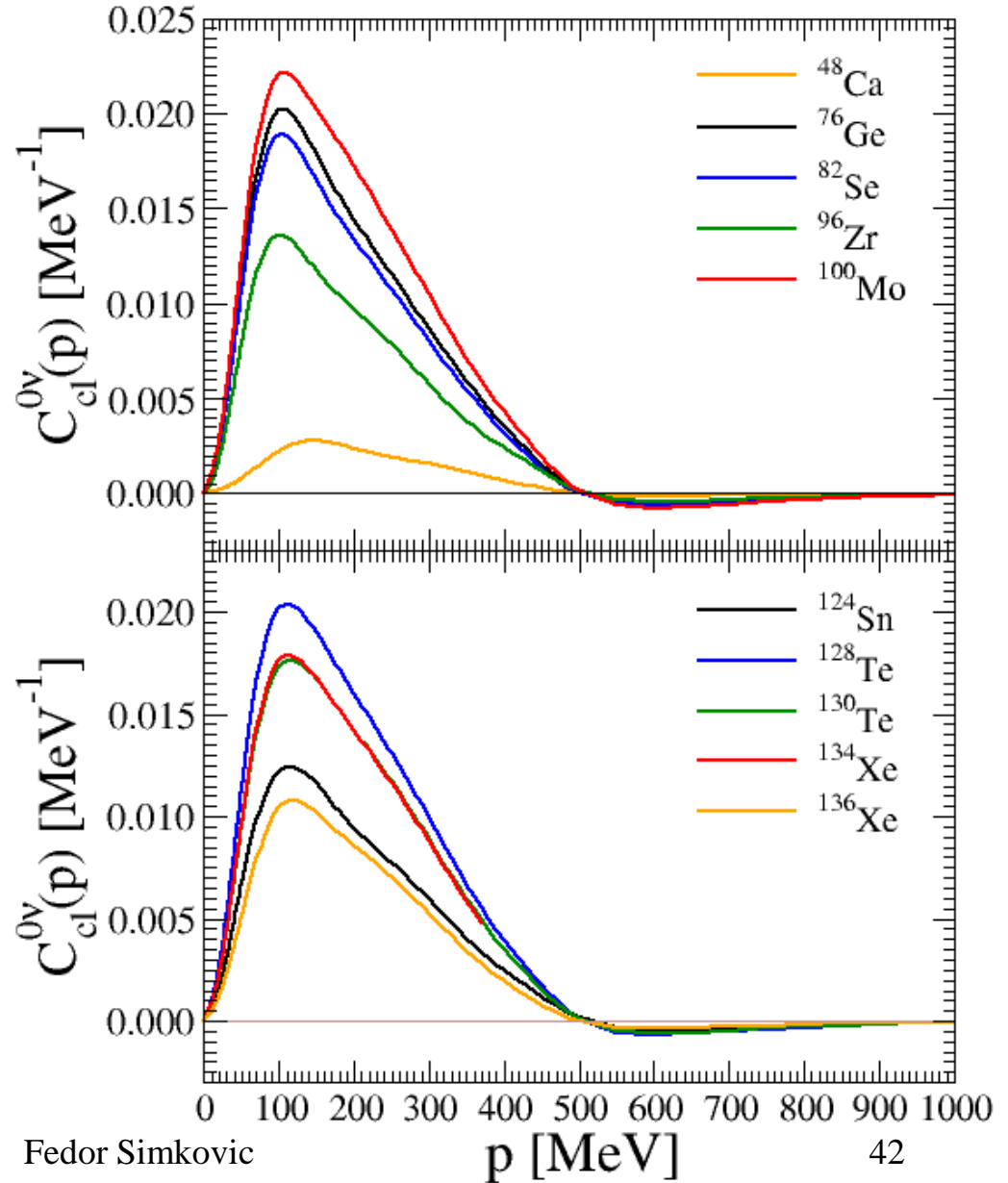
F. Š., A. Smetana, P. Vogel,
PRC 98, 064325 (2018)

QRPA

What is the origin
 of this peak?

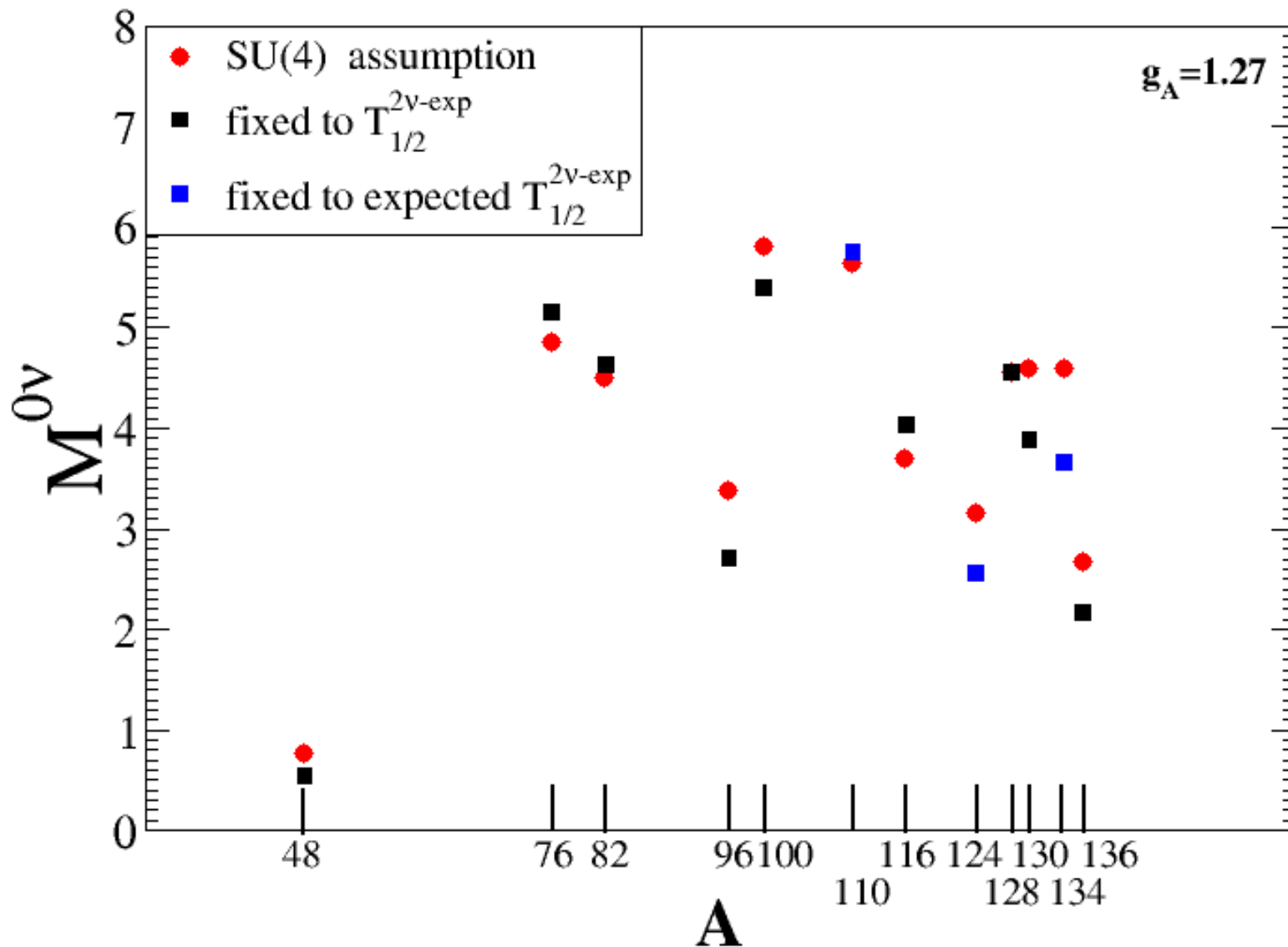


N. Shimizu, J. Menendez, K. Yako,
 Phys. Rev. Lett. 120, 14502 (2018)



QRPA – SU(4) parametrization

F. Š., A. Smetana, P. Vogel,
PRC 98, 064325 (2018)



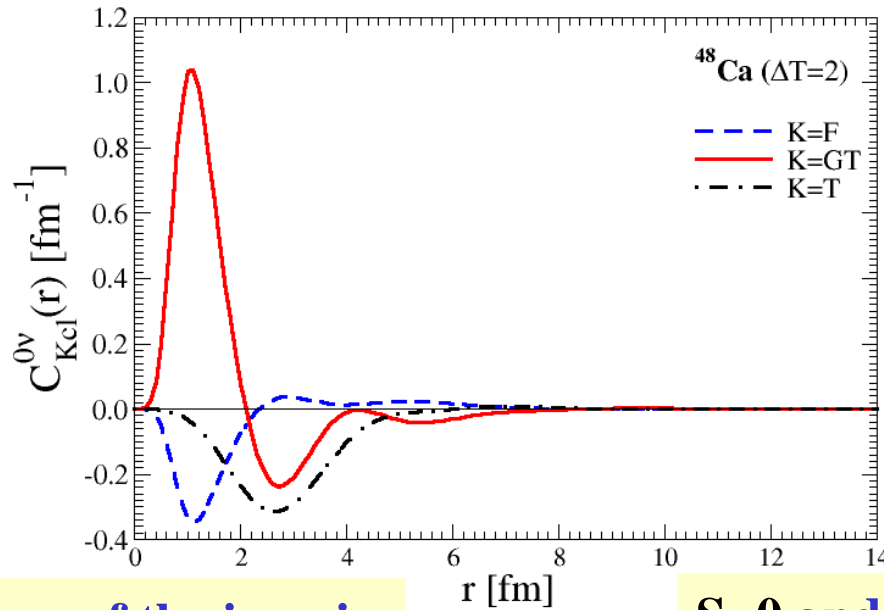
2νββ–decay within the QRPA

(restoration of the SU(4) symmetry – $M^{2\nu}_{cl} = 0$)

$$\begin{aligned}
 g_A^{\text{eff}} &= q \times g_A^{\text{free}} = 0.901 \\
 g_A^{\text{free}} &= 1.269, \quad q = 0.710
 \end{aligned}$$

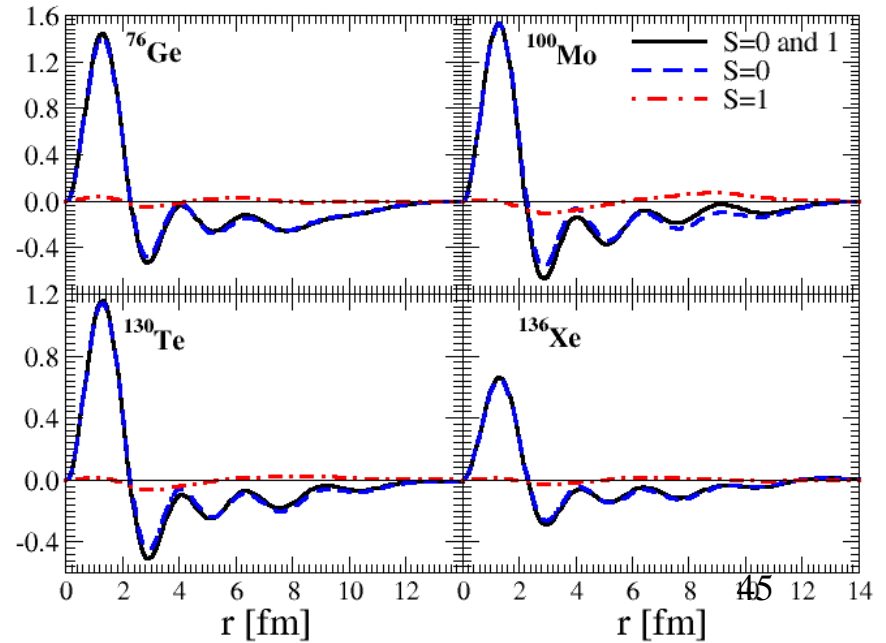
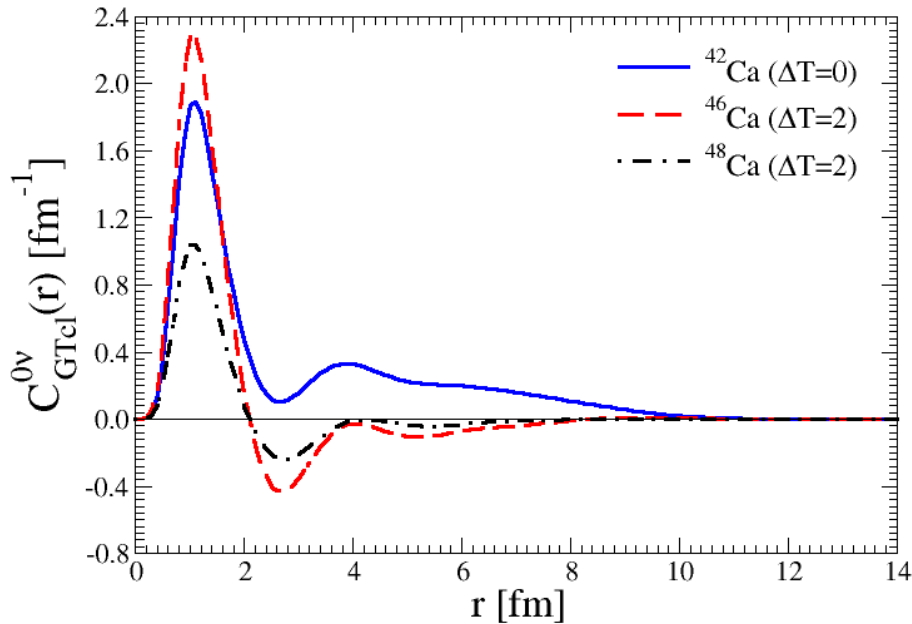
Nucleus	d_{pp}^i	d_{pp}^f	d_{nn}^i	d_{nn}^f	$g_{pp}^{T=1}$	$g_{pp}^{T=0}$	$M_F^{2\nu}$ [MeV ⁻¹]	$M_{GT}^{2\nu} \times q^2$ [MeV ⁻¹]	$M_{exp}^{2\nu}$ [MeV ⁻¹]
⁴⁸ Ca	-	1.069	-	0.982	1.028	0.745	-0.003	0.037	0.046
⁷⁶ Ge	0.922	0.960	1.053	1.085	1.021	0.733	0.003	0.076	0.136
⁸² Se	0.861	0.921	1.063	1.108	1.016	0.737	0.001	0.070	0.100
⁹⁶ Zr	0.910	0.984	0.752	0.938	0.961	0.739	0.001	0.161	0.097
¹⁰⁰ Mo	1.000	1.021	0.926	0.953	0.985	0.799	-0.001	0.304	0.251
¹¹⁶ Cd	0.998	-	0.934	0.890	0.892	0.877	-0.000	0.059	0.136
¹²⁸ Te	0.816	0.857	0.889	0.918	0.965	0.741	0.017	0.075	0.052
¹³⁰ Te	0.847	0.922	0.971	1.011	0.963	0.737	0.016	0.064	0.037
¹³⁶ Xe	0.782	0.885	-	0.926	0.910	0.685	0.014	0.039	0.022

F. Š., A. Smetana, P. Vogel, PRC 98, 064325 (2018)



Role of the change of the isospin

S=0 and S=1 contributions

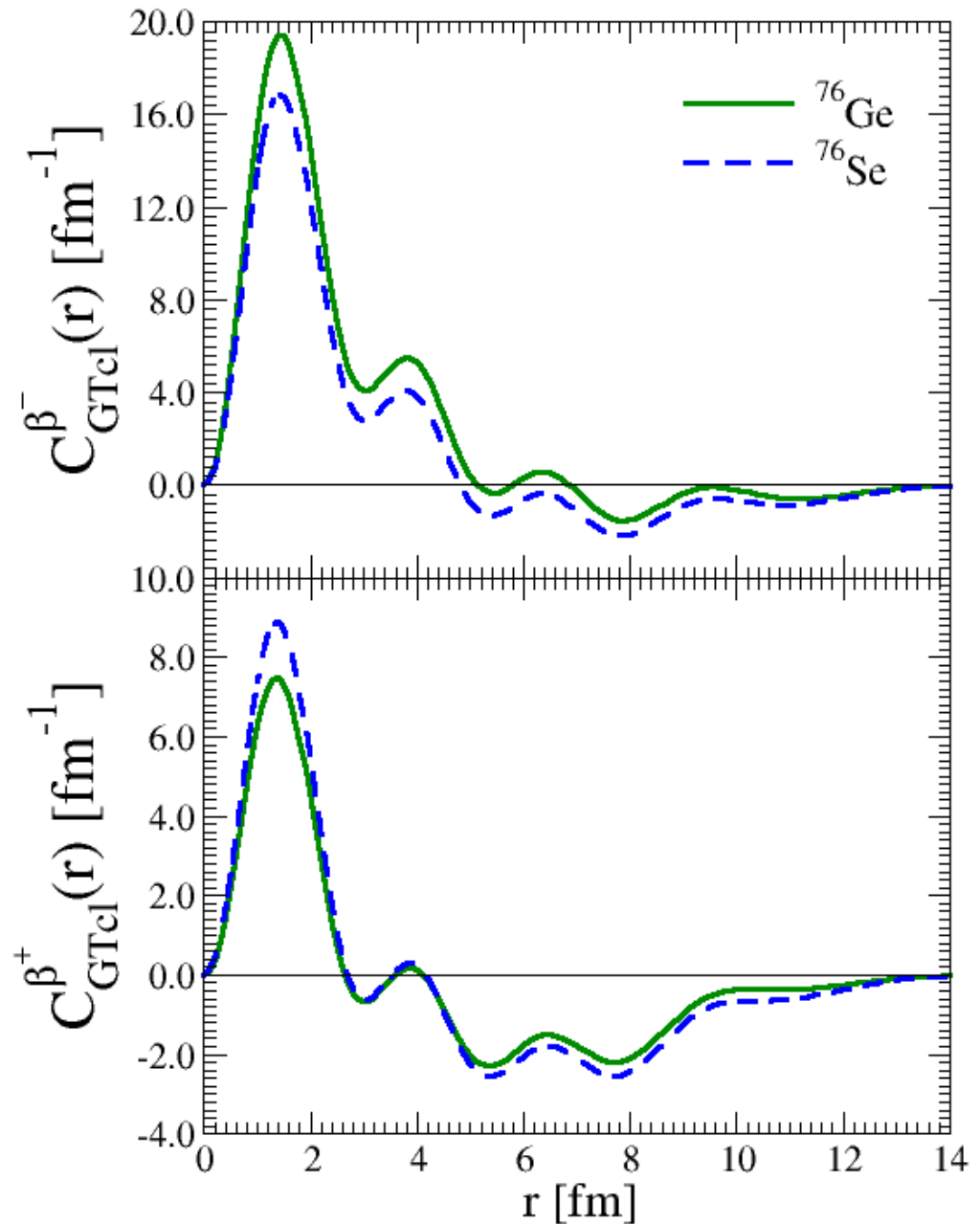


S(β^-) and S(β^+) total strengths
QRPA

(restoration of the SU(4)
symmetry $\longrightarrow M^{2\nu}_{cl} = 0$)

$^{76}\text{Ge} \longrightarrow ^{76}\text{Se} (\Delta T=2)$

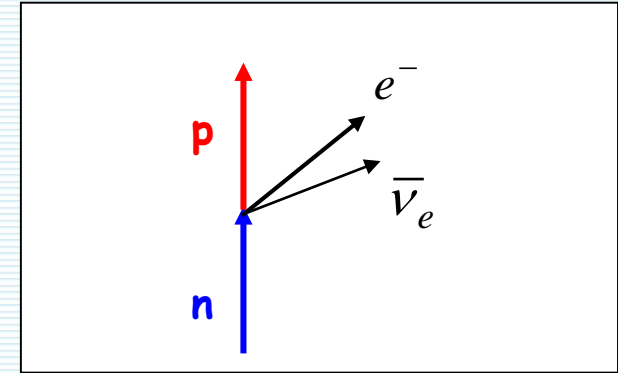
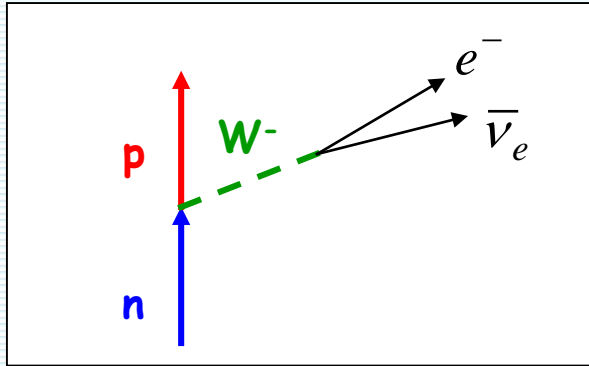
F. Š., A. Smetana, P. Vogel,
PRC 98, 064325 (2018)



V. Quenching of g_A

Quenching in nuclear matter: $g_A^{\text{eff}} = q g_A^{\text{free}}$

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



$$\mathcal{L} = -\frac{G_\beta}{\sqrt{2}} [\bar{u}\gamma^\alpha(1-\gamma^5)d] [\bar{e}\gamma^\alpha(1-\gamma^5)\nu_e]$$

$$\mathcal{L} = -\frac{G_\beta}{\sqrt{2}} [\bar{p}\gamma^\alpha(g_V - g_A\gamma^5)n] [\bar{e}\gamma^\alpha(1-\gamma^5)\nu_e]$$

CVC hypothesis

$g_V = 1$ at the quark level

$g_V = 1$ at the nucleon level

$g_V = 1$ inside nuclei

Quenching of g_A

$g_A = 1$ at the quark level

$g_A^{\text{free}} = 1.27$ at the nucleon level

$g_A^{\text{eff}} = ?$ inside nuclei

ISM: $(g_A^{\text{eff}})^4 \simeq 0.66$ (^{48}Ca), 0.66 (^{76}Ge), 0.30 (^{76}Se), 0.20 (^{130}Te) and 0.11 (^{136}Xe)

IBM: $(g_A^{\text{eff}})^4 \simeq (1.269 A^{-0.18})^4 = 0.063$

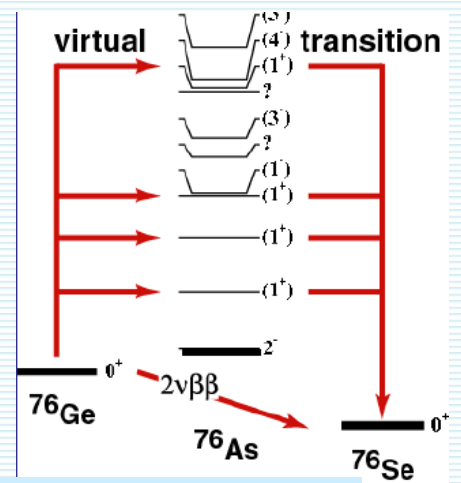
QRPA: $(g_A^{\text{eff}})^4 = 0.30$ and 0.50 for ^{100}Mo and ^{116}Cd

$g_A^4 = (1.269)^4 = 2.6$ **Quenching of g_A** (from exp.: $T_{1/2}^{0\nu}$ up 2.5 x larger)

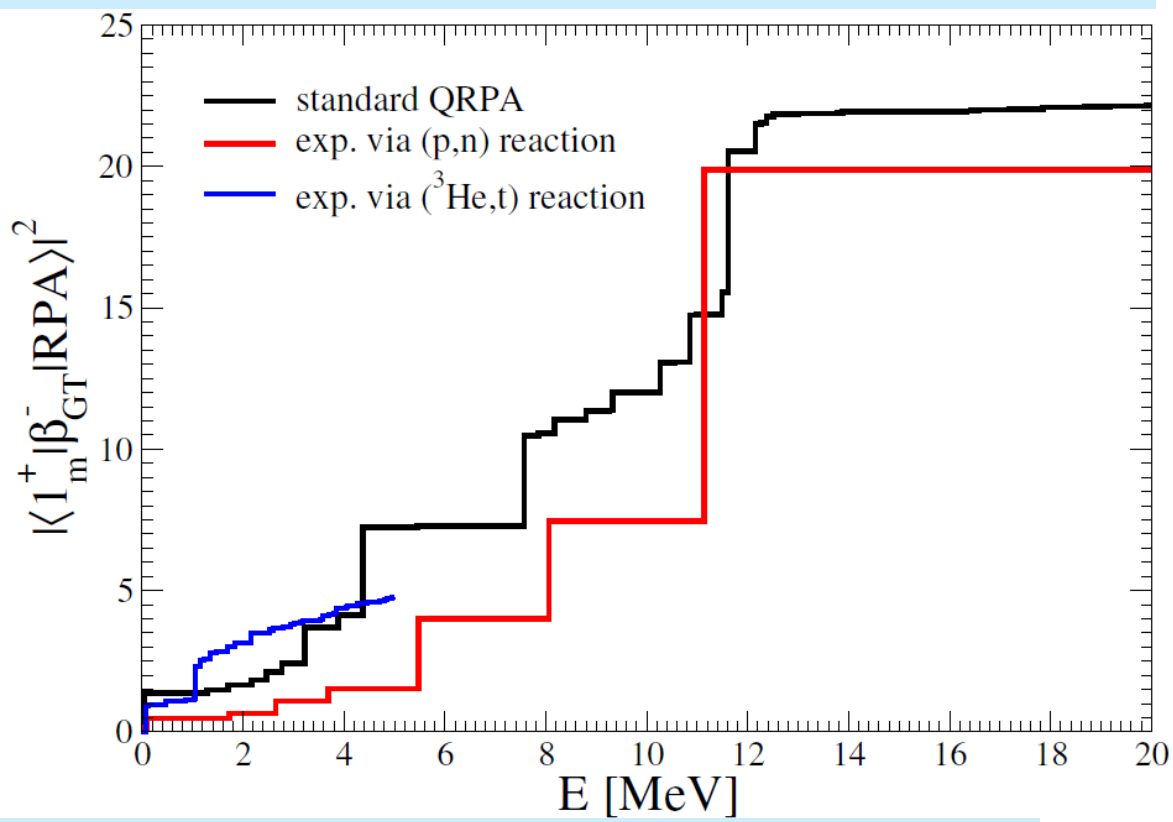
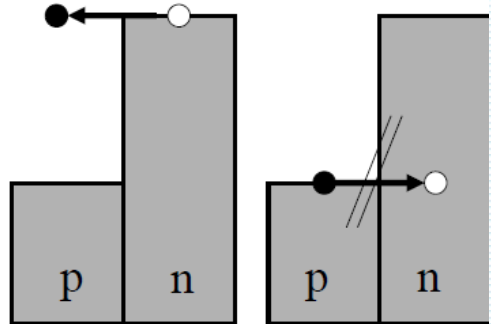
$(g_A^{\text{eff}})^4 = 1.0$

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

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



Pauli blocking



Cross-section for charge exchange reaction:

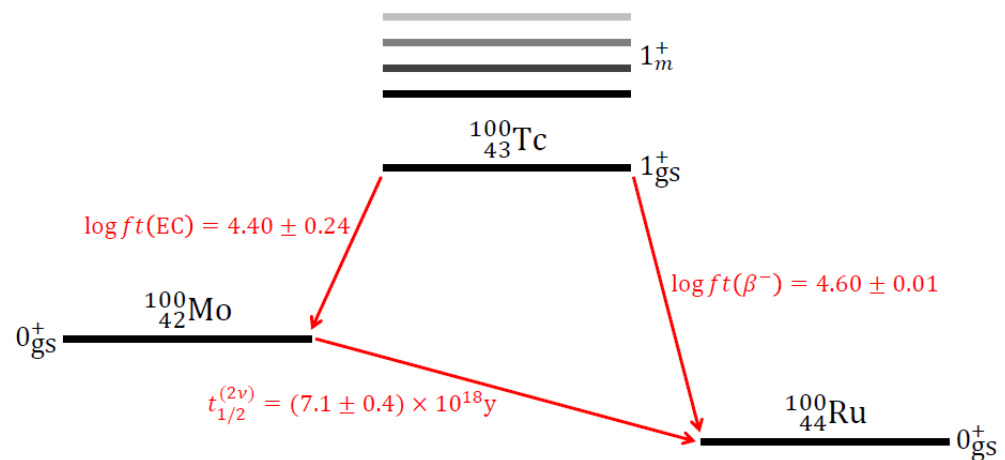
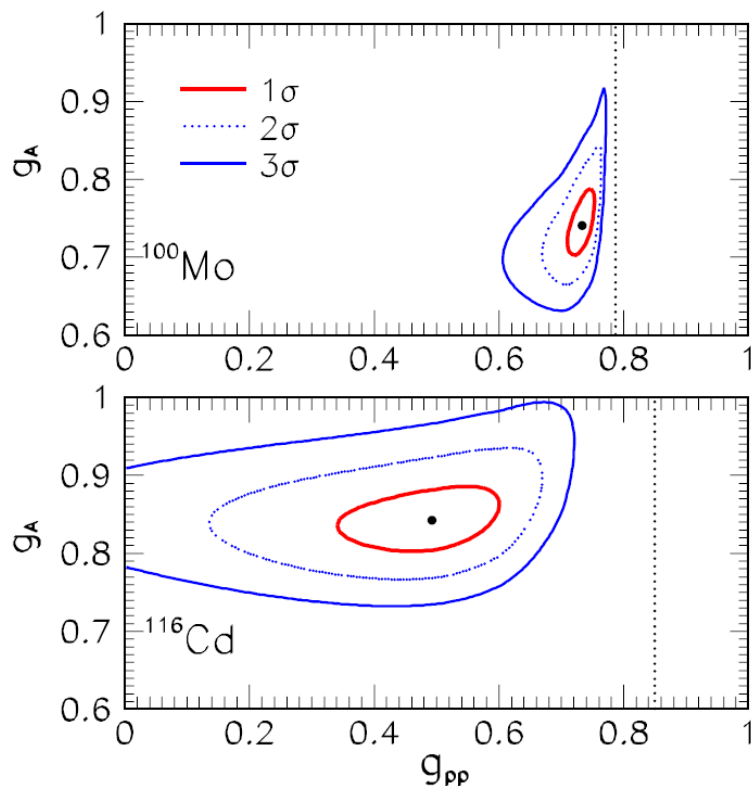
$$\left[\frac{d\sigma}{d\Omega} \right] = \left[\frac{\mu}{\pi\hbar} \right]^2 \frac{k_f}{k_i} N_d |v_{\sigma\tau}|^2 |\langle f | \sigma\tau | i \rangle|^2$$

$q = 0!!$

largest at 100 - 200 MeV/A

$(g_A^{\text{eff}})^4 = 0.30$ and 0.50 for ^{100}Mo and ^{116}Cd , respectively (**The QRPA prediction**). g_A^{eff} was treated as a completely free parameter alongside g_{pp} (used to renormalize particle-particle interaction) by performing calculations within the QRPA and RQRPA. It was found that a least-squares fit of g_A^{eff} 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_A^{eff} of about **0.7** or **0.8**.

(g_{pp}, g_A) allowed regions



Extended calculation also for neighbor isotopes performed by

F.F. Depisch and J. Suhonen, PRC 94, 055501 (2016)

or Simkovic

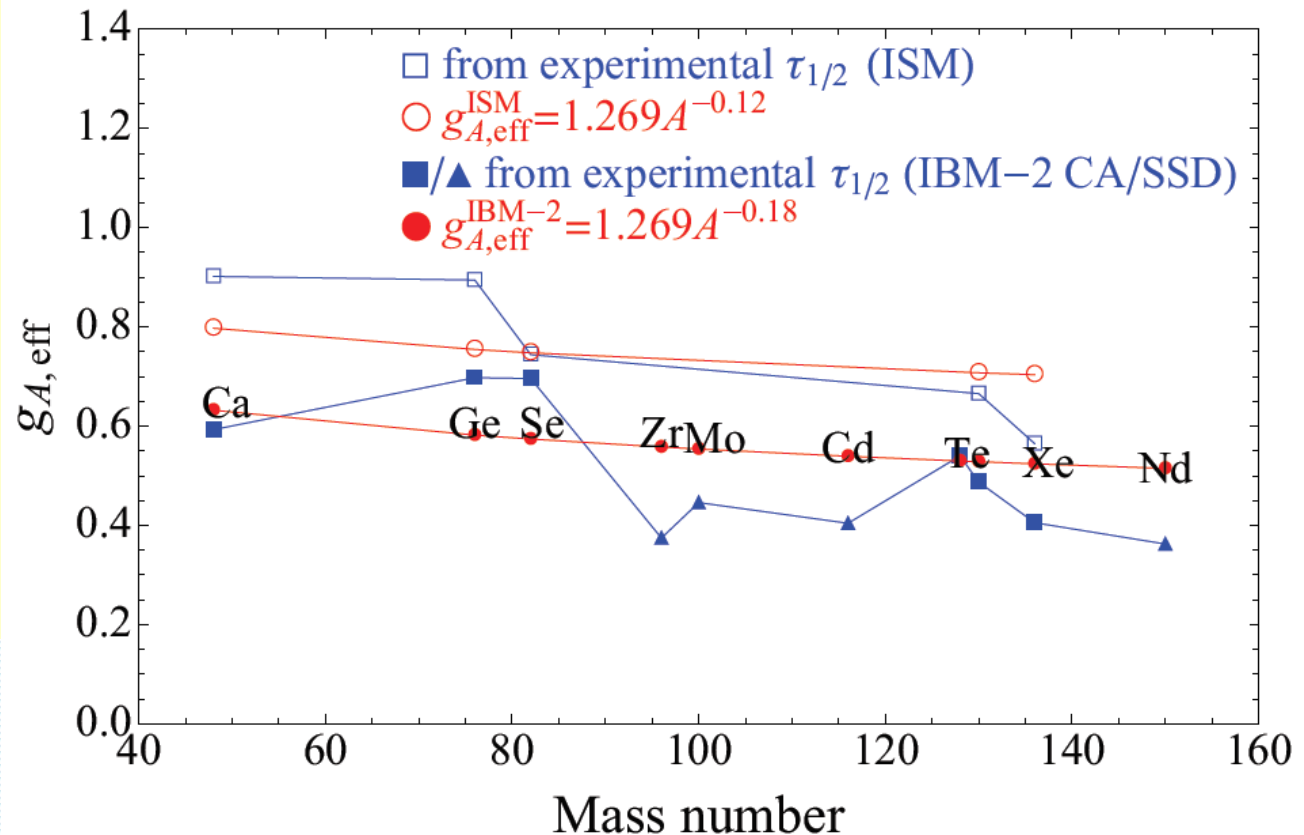
Dependence of g_A^{eff} on A was not established.

Quenching of g_A -IBM ($T_{1/2}^{0\nu}$ suppressed up to factor 50)

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

It has been determined by theoretical prediction for the $2\nu\beta\beta$ -decay half-lives, which were based on within closure approximation calculated Corresponding NMEs, with the measured half-lives.

From F. Iachello



5/27/2019

Improved description of the $0\nu\beta\beta$ -decay rate (and novel approach of fixing g_A^{eff})

F. Š, R. Dvornický, D. Štefánik, A. Faessler, PRC 97, 034315 (2018).

Let perform
Taylor expansion

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

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

$$\epsilon_K = (E_{e_2} + E_{\nu_2} - E_{e_1} - E_{\nu_1})/2$$

$$\epsilon_L = (E_{e_1} + E_{\nu_2} - E_{e_2} - E_{\nu_1})/2$$

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

We get

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

$$M_{GT-1}^{2\nu} = \sum_n M_n \frac{1}{(E_n - (E_i + E_f)/2)}$$

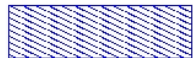
$$M_{GT-3}^{2\nu} = \sum_n M_n \frac{4 m_e^3}{(E_n - (E_i + E_f)/2)^3}$$

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

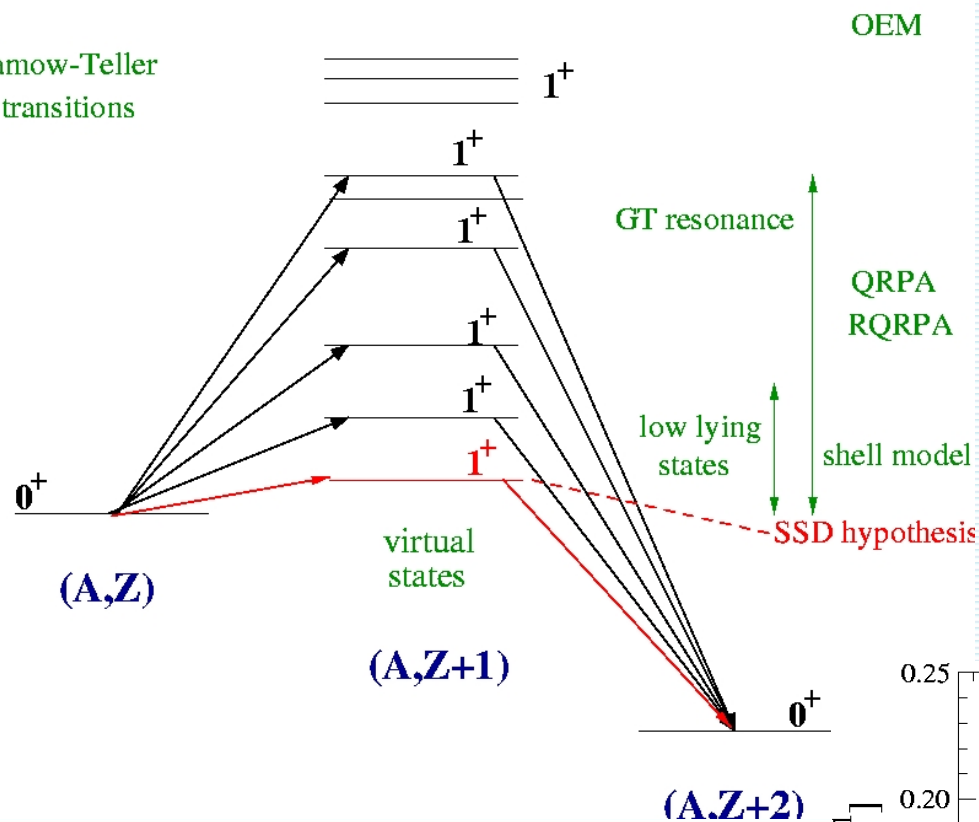
The g_A^{eff} can be determined **with measured half-life and ratio of NMEs** and calculated NME dominated by transitions through low lying states of the intermediate nucleus (ISM?)

2νββ-decay

Gamow-Teller transitions



Continuum states

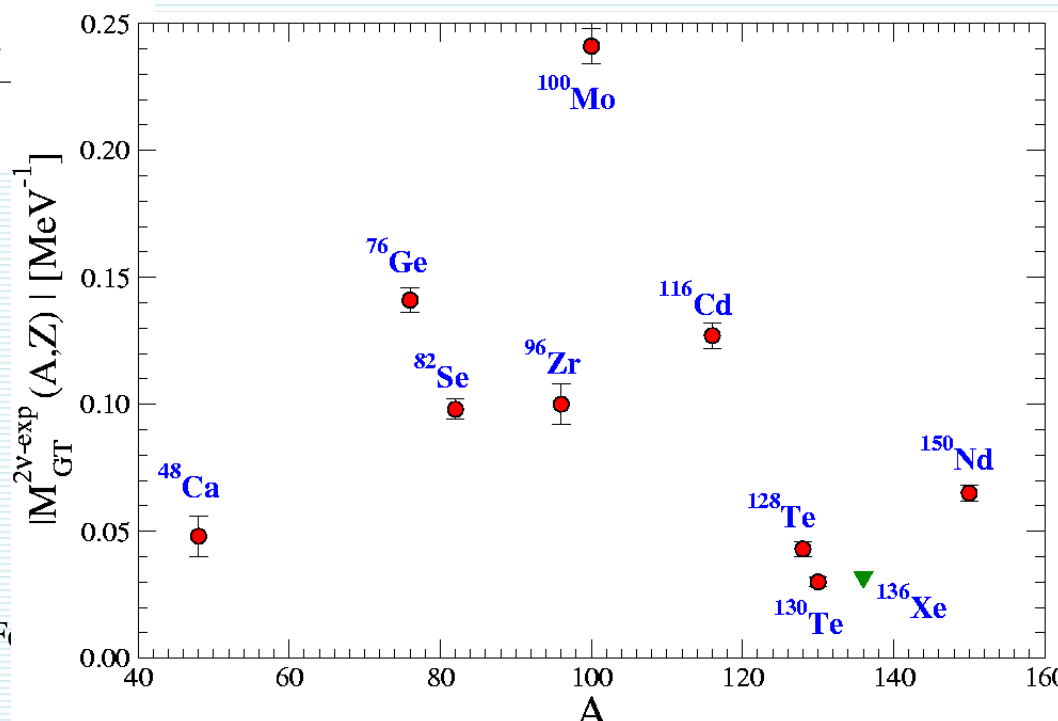


2νββ-decay nuclear matrix elements

$$(T_{1/2}^{2\nu})^{-1} = G^{2\nu} |M_{GT}^{2\nu}|^2$$

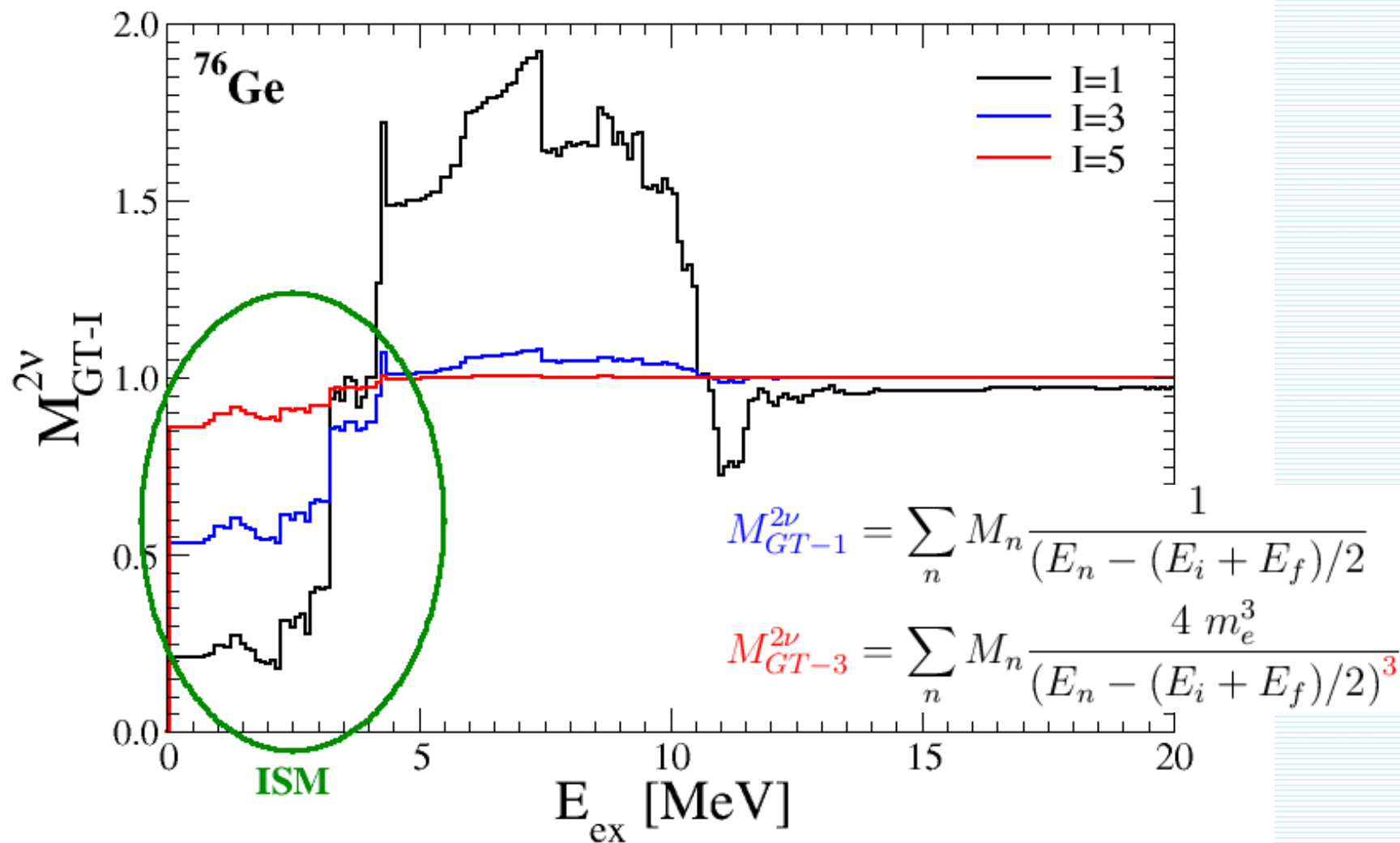
Deduced from measured $T_{1/2}^{2\nu}$

$$M_{GT}^{2\nu} = \sum_m \frac{\langle 0_f^+ || \tau^+ \sigma || 1_m^+ \rangle \langle 1_m^+ || \tau^+ \sigma || 0_i^+ \rangle}{E_m - E_i + \Delta}$$



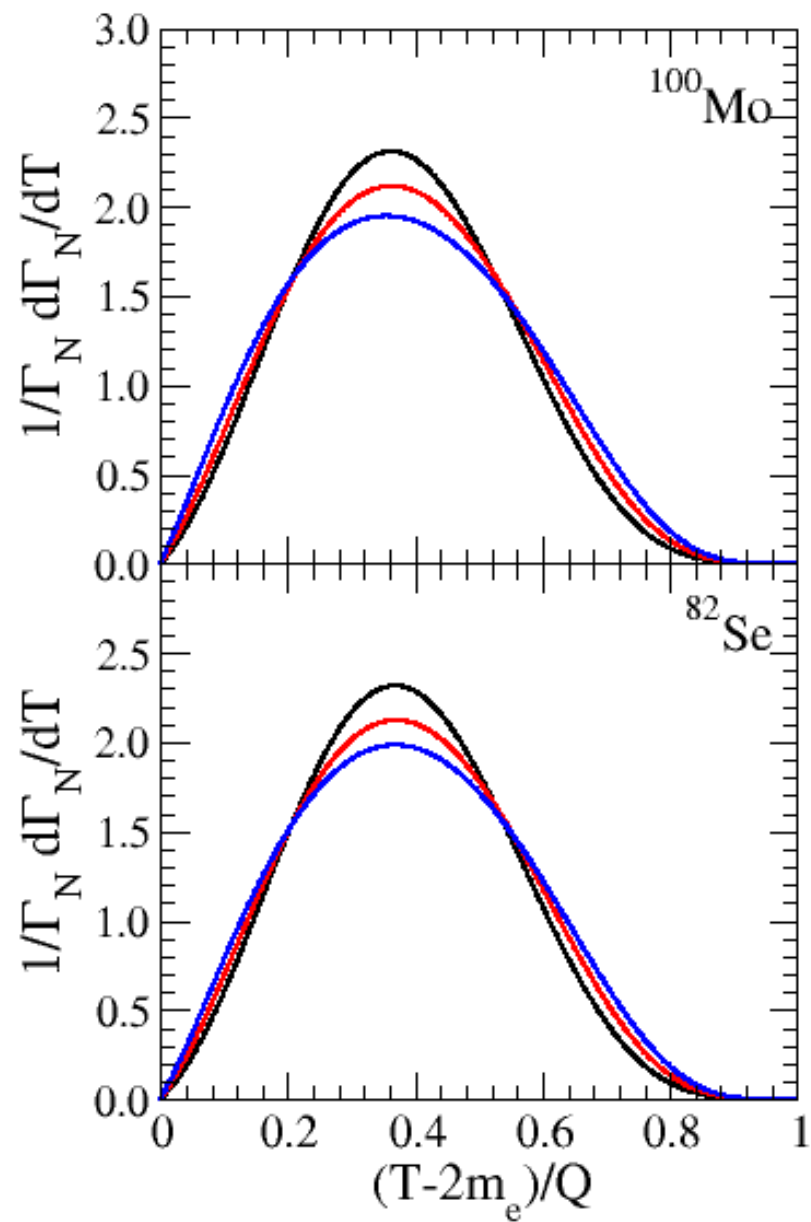
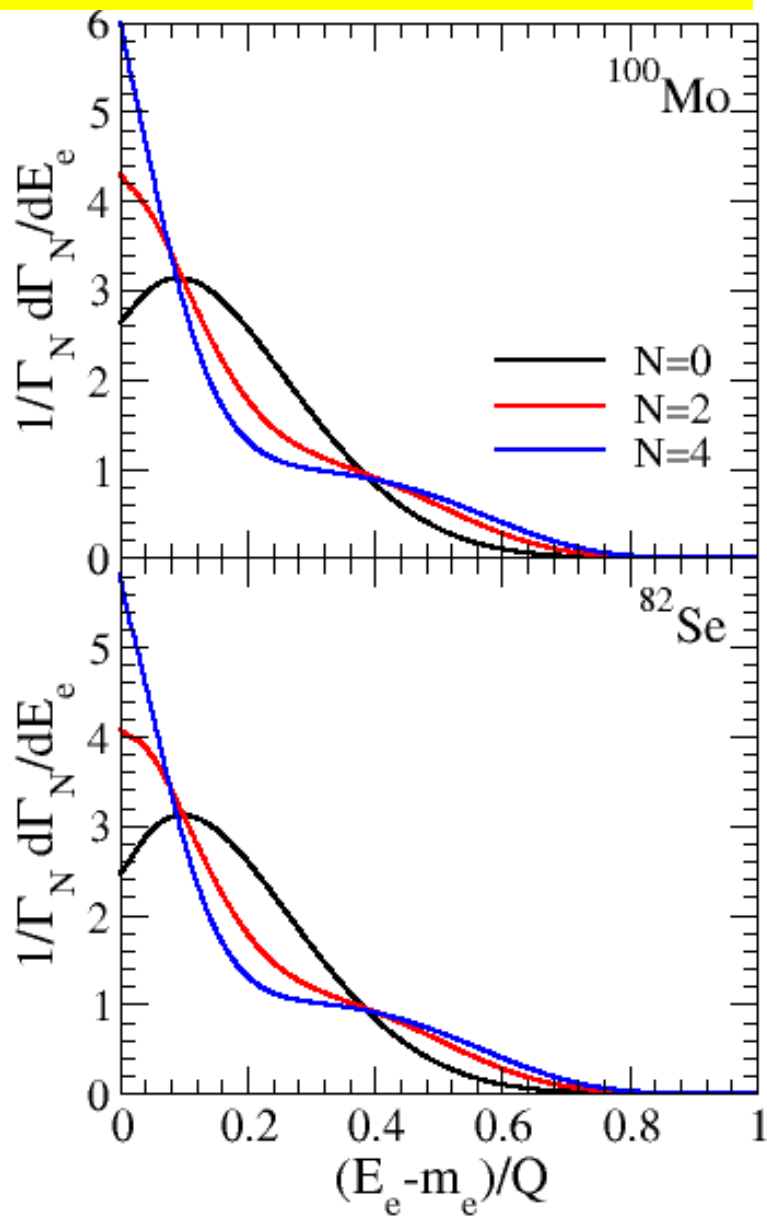
Differences in NME: by factor ~ 10

The running sum of the $2\nu\beta\beta$ -decay NMEs (QRPA)



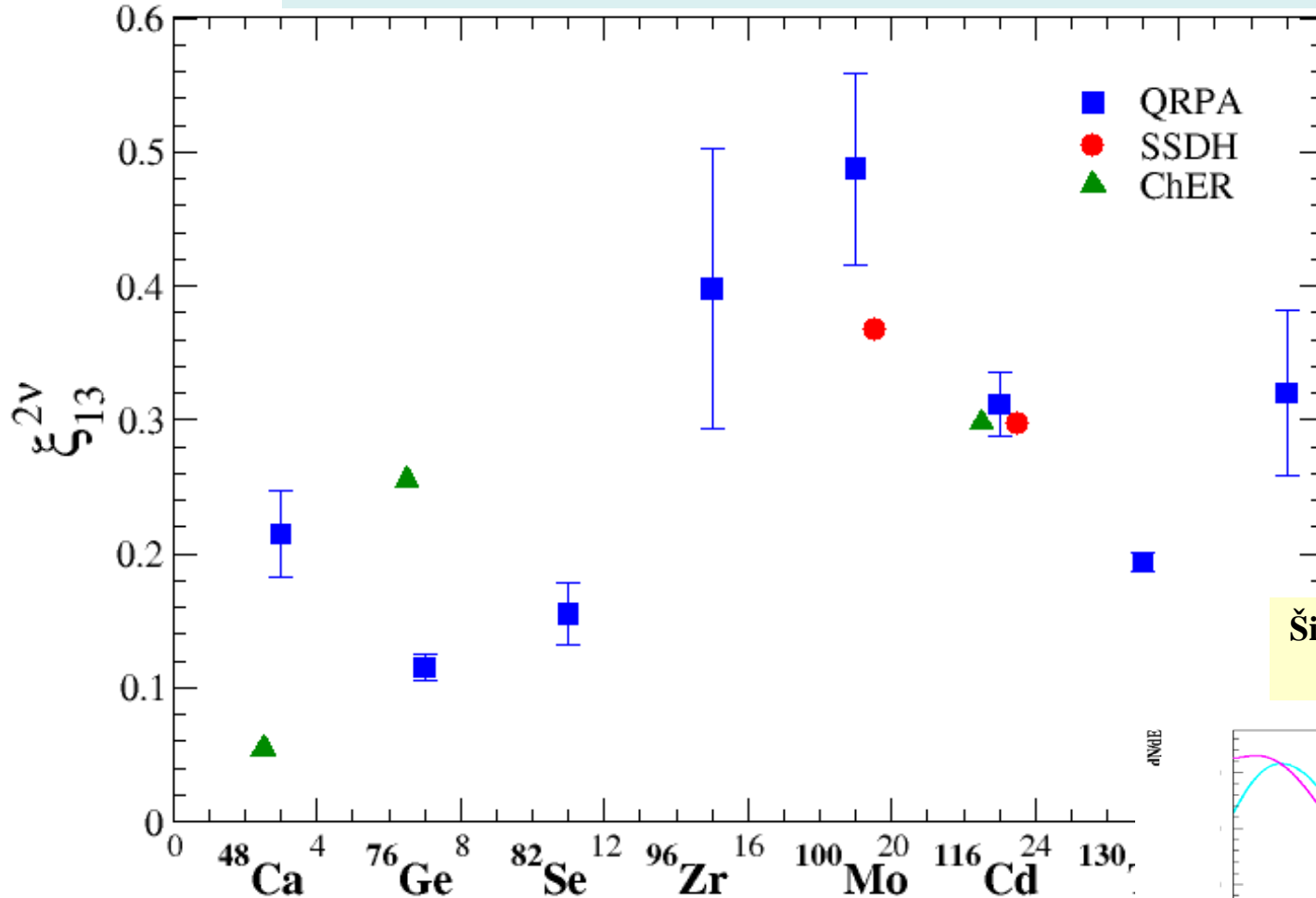
**Normalized to unity
different partial energy distributions**

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



ξ_{13} tell us about importance of higher lying states of int. nucl.

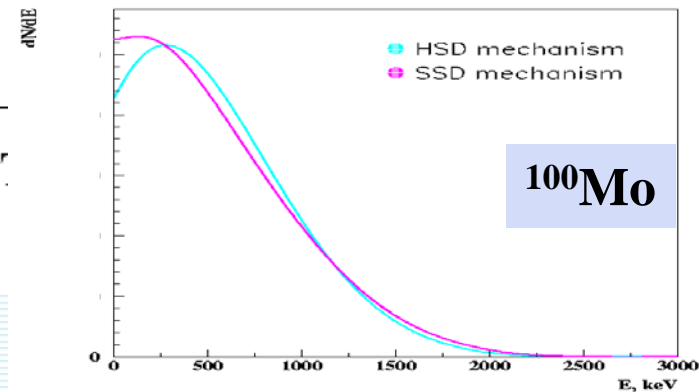
F. Š, R. Dvornický, D. Štefánik, A. Faessler, PRC 97, 034315 (2018).



HSD: $\xi_{13}=0$

Šimkovic, Šmotlák, Semenov
J. Phys. G, 27, 2233, 2001

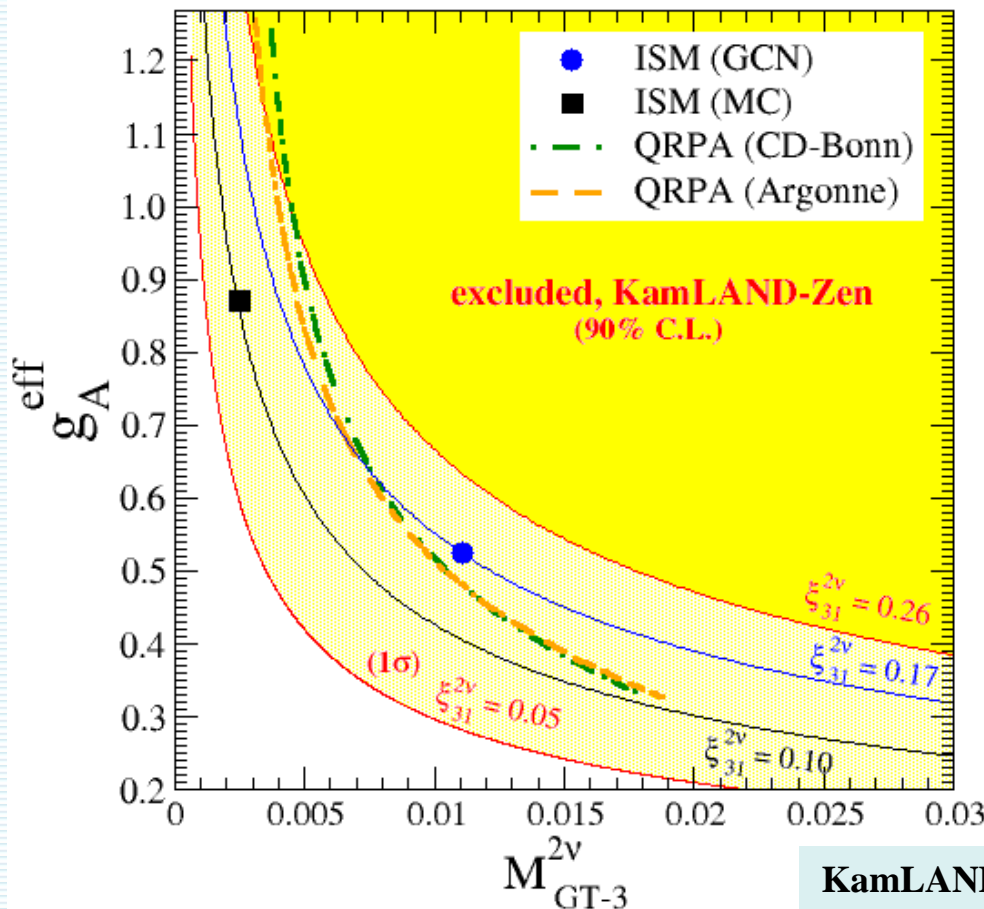
ξ_{13} can be determined phenomenologically from the shape of energy distributions of emitted electrons



The g_A^{eff} can be determined with measured half-life and ratio of NMEs $\xi_{31}^{2\nu}$ and calculated NME dominated by transitions through low lying states of the intermediate nucleus.

M_{GT-3} have to be calculated by nuclear theory - ISM

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



$$M_{GT-1}^{2\nu} = \sum_n M_n \frac{1}{(E_n - (E_i + E_f)/2)}$$

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

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

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

F. Š., R. Dvornický, D. Štefánik, A. Faessler, PRC 97, 034315 (2018)

KamLAND-Zen Coll. (+J. Menendez, F.Š.), PRL 122, 192501 (2019)

NEMO3 analysis of ξ_{13} in progress

If measured ξ_{13} is larger than ξ_{13} within SSD it follows that there is a mutual cancellation of contributions through the 1st and excited states of the intermediate nucleus in M_{GT-1}

SSD: $g_A^2 M_{GT-3} = 0.063$

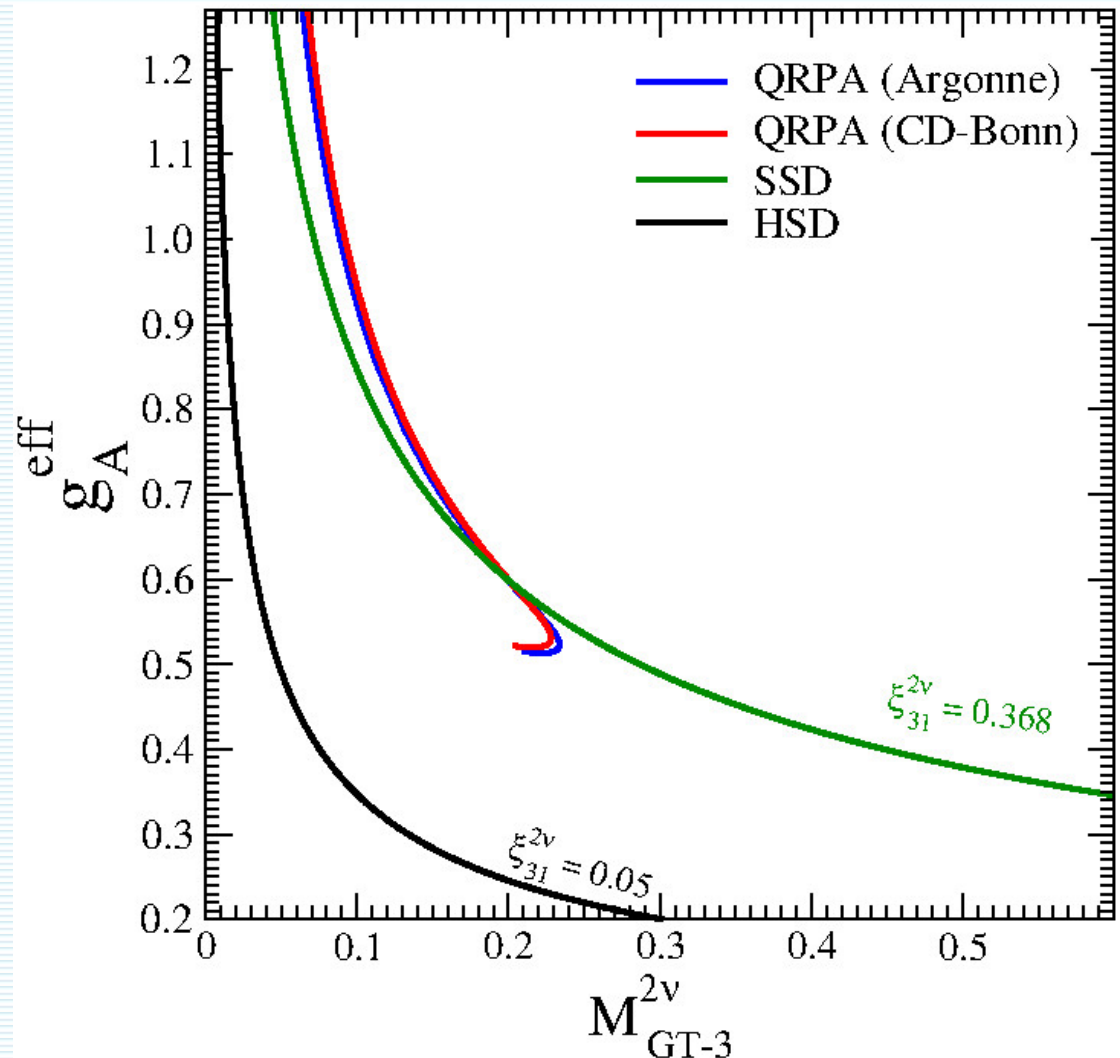
$g_A^{\text{eff}} = 1.0 \Rightarrow M_{GT-3} = 0.06$

$g_A^{\text{eff}} = 0.8 \Rightarrow M_{GT-3} = 0.10$

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

$$M_{GT-1}^{2\nu} = \sum_n M_n \frac{1}{(E_n - (E_i + E_f)/2)}$$

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

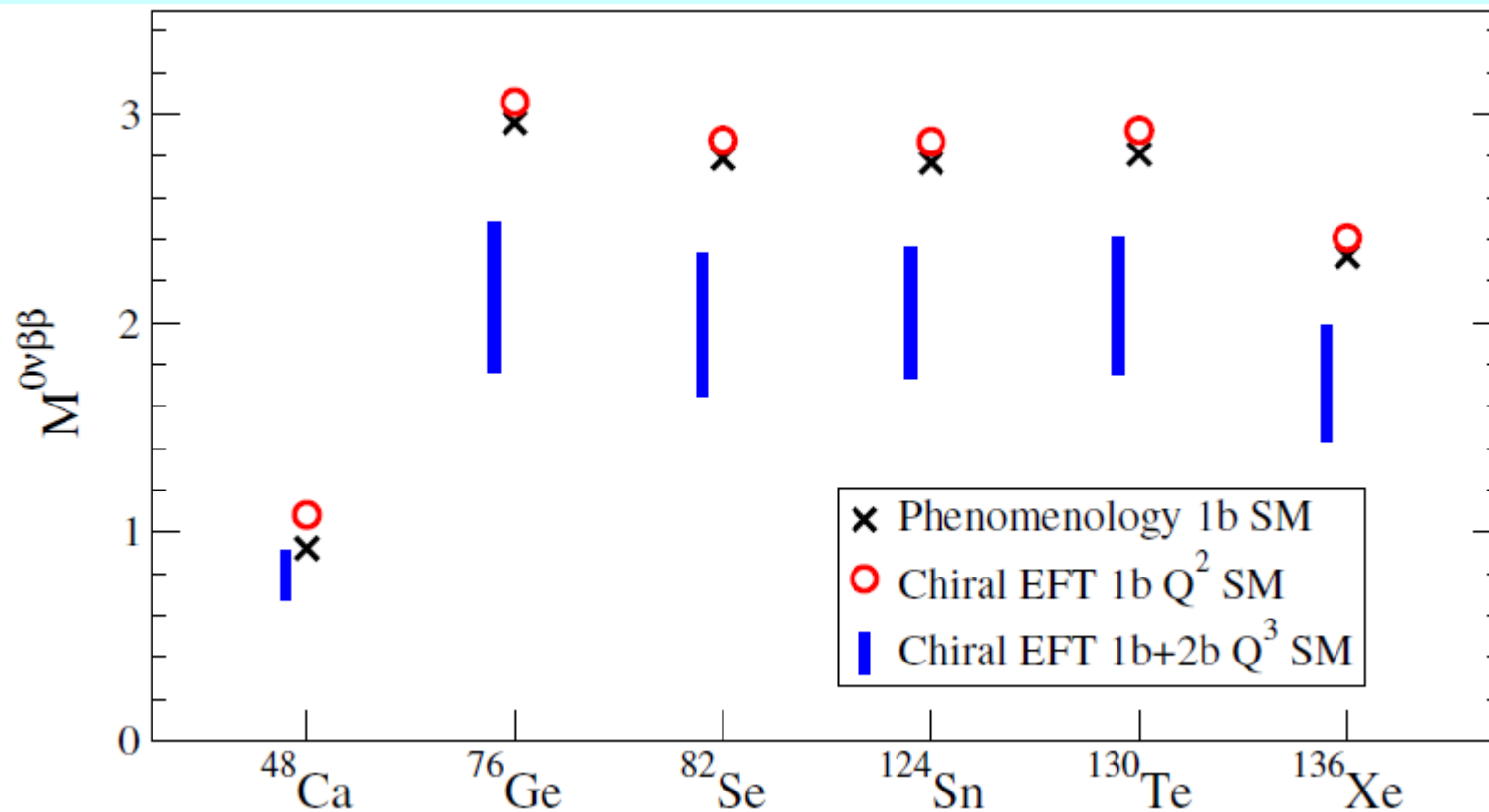


Quenching of g_A and two-body currents

Menendez, Gazit, Schwenk, PRL 107, 062501 (2011)

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

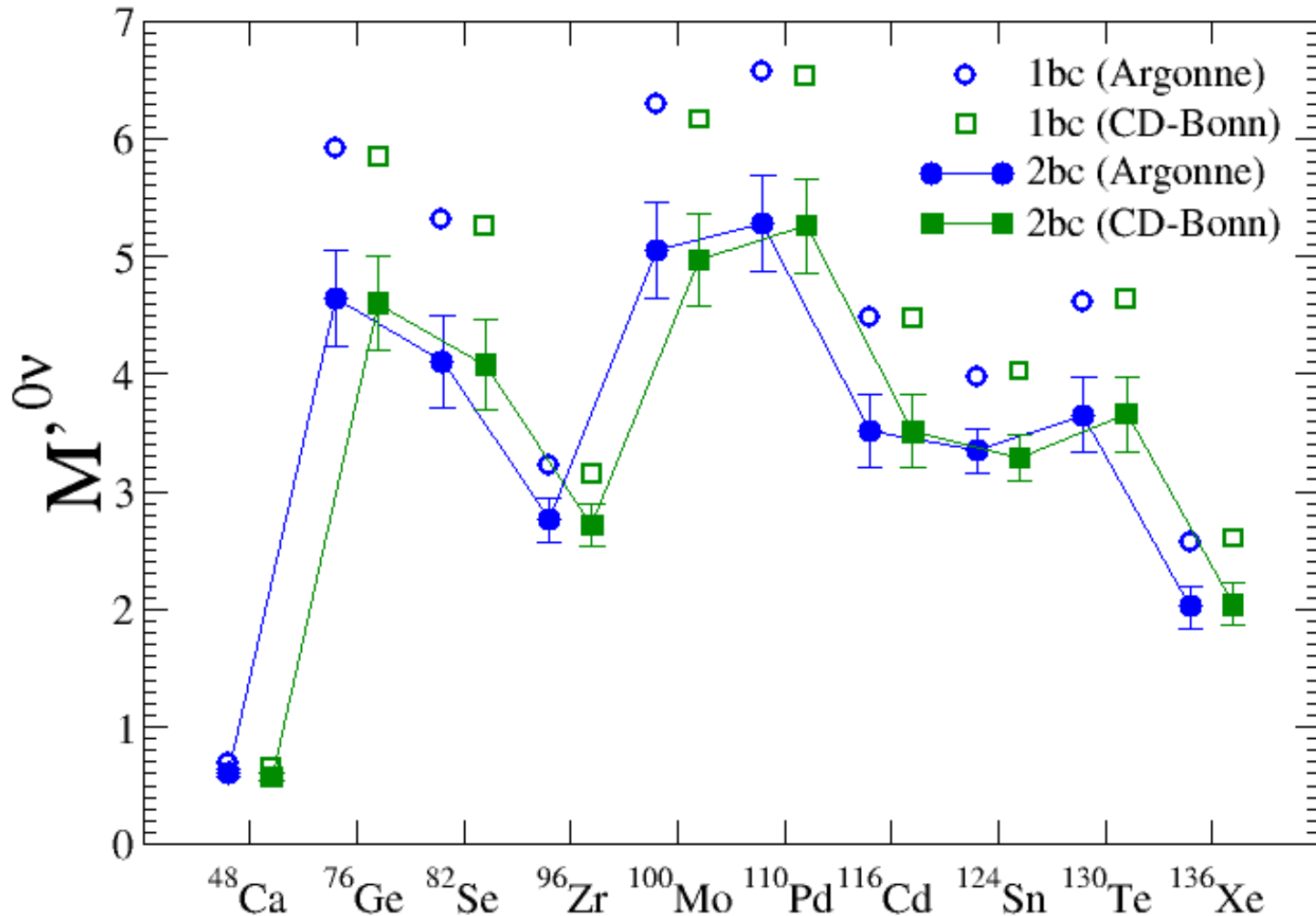
The $0\nu\beta\beta$ operator calculated within effective field theory. Corrections appear as 2-body current predicted by EFT. The 2-body current contributions are related to the quenching of Gamow-Teller transitions found in nuclear structure calc.



Quenching of g_A , two-body currents and QRPA

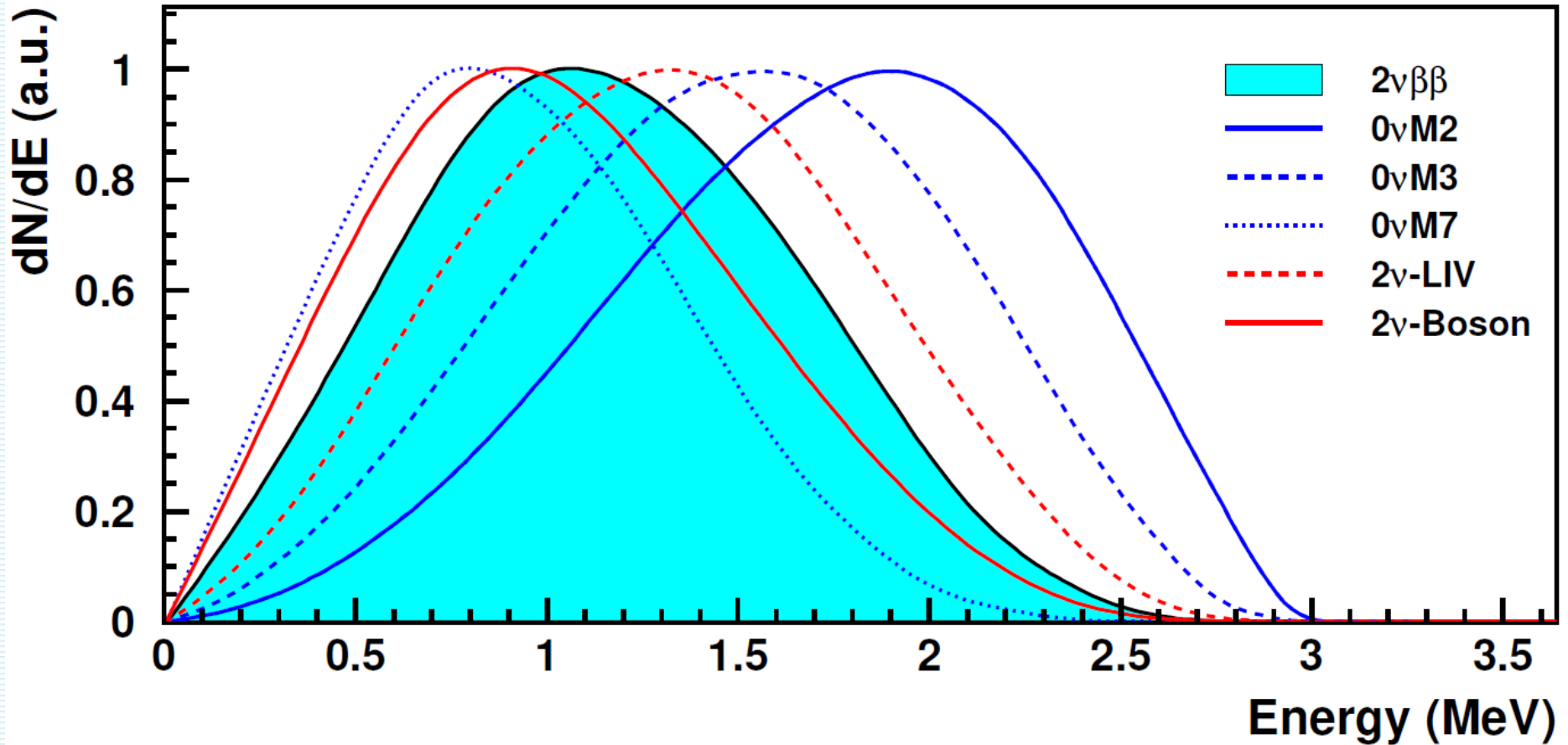
(Suppression of the $0\nu\beta\beta$ -decay NME of about 20%)

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



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

Looking for a new physics with differential characteristics



Spectral index n

$$\frac{d\Gamma}{d\varepsilon_1 d\varepsilon_2} = C(Q - \varepsilon_1 - \varepsilon_2)^n [p_1 \varepsilon_1 F(\varepsilon_1)] [p_2 \varepsilon_2 F(\varepsilon_2)]$$

Instead of Conclusions

LHC physics

$$\frac{1}{\Lambda^2} \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + O\left(\frac{1}{\Lambda^3}\right)$$

Neutrino physics

$$\frac{1}{\Lambda} \sum_i c_i^{(5)} \mathcal{O}_i^{(5)}$$

$0\nu\beta\beta$

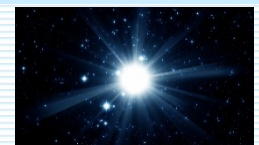


Progress in nuclear structure calculations is highly required

We are at the beginning of the **Beyond Standard Model Road...**



The future of neutrino physics is bright





Organizing Committee:

Chairman: **V.A. Matveev** (JINR)

Scientific program: **S.M. Bilenky** (JINR)

Vice-chairmen:

A.G. Olshevskiy (JINR)

S. Stoica (CIFRA, Bucharest)

I. Stekl (CTU Prague)

F. Simkovic (Comenius U./JINR)

Members:

V.A. Bednyakov (JINR)

R. Leitner (Charles U. Prague)

C. Giunti (Univ. Torino)

V.B. Brudanin (JINR)

E.A. Kolganova (JINR)

Secretaries:

A. Babic (JINR)

O. Nimescu (CIFRA, Bucharest)

J. Mansour (CIFRA, Bucharest)

VII Pontecorvo Neutrino Physics School

Sinaia, Romania, September 1-10, 2019

Lectures at the School

Introduction to ν -physics

Theory of ν -masses and mixing

ν -oscillation phenomenology

ν -oscillation experiment:

Solar ν -experiments

Atmospheric ν -experiments

Accelerator ν -experiments

Reactor ν -experiments

Spectra of ν 's from reactor

Light sterile neutrinos:

theory

experiments

Heavy sterile neutrinos

Measurement of ν -mass

$0\nu\beta\beta$ -decay experiments

$0\nu\beta\beta$ -decay nuclear matrix elements

Coherent scattering of neutrinos

ν -nucleus interactions

Leptogenesis

ν -telescopes

ν -properties from cosmology

Dark matter experiments

Physics of gravitational waves

Everything about Higgs boson

Statistics for ν -experiments

Samoil Bilenky (JINR Dubna)

Alexei Smirnov (MPI Heidelberg)

Boris Kayser (Fermilab)

Oleg Smirnov (JINR Dubna)

Juan Pablo Yanez (Univ. of Alberta)

Maury Goodman (Argonne National Laboratory)

Yifang Wang (IHEP)

Anna Hayes (Los Alamos National Lab)

Carlo Giunti (INFN Torino)

Vyacheslav Egorov (JINR Dubna)

Dmitry Gorbunov (INR RAS Moscow)

Kathrin Valerius (KIT in Karlsruhe)

Andrea Giuliani (CSNSM in Paris)

Javier Menendez (Univ. of Tokyo)

Henry Wong (Academia Sinica, Taipei)

Jan Sobczyk (Wroclaw University)

Pascuale DiBari (Univ. of Southampton)

Nathan Whitehorn (Univ. of California)

Richard Battye (University of Manchester)

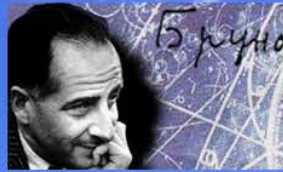
Nicolao Fornengo (INFN Torino)

Imre Bartos (Univ. of Florida)

Guenakh Mitselmakher (Univ. of Florida)

Thomas Schwetz (KIT in Karlsruhe)

VIII International Pontecorvo Neutrino Physics School



September 1 – September 10, 2019
Sinaia, Romania



ν_3

<http://theor.jinr.ru/~neutrino19/>

ν_2

Organizing Committee:

Members:

V. A. Matveev	- chairman	V.A. Bednyakov
S. M. Bilenky	- scientific program	V.B. Brudanin
A.G. Olshevskiy	- vice-chairman	C. Giunti
S. Stoica	- vice-chairman	E.A. Kolganova
F. Šimkovic	- vice-chairman	R. Leitner
I. Štekl	- vice-chairman	

ν_1

Secretaries:

A. Babič, J. Mansour, O. Nitescu

Introduction to ν -physics
Theory of ν -masses and mixing
 ν -oscillation phenomenology
 ν -oscillations experiments:
Solar ν -experiments
Atmospheric ν -experiments
Accelerator ν -experiments
Reactor ν -experiments
Spectra of ν 's from reactor
Light sterile neutrinos
theory -
experiments -
Heavy sterile neutrinos

Samoil Bilenky (JINR Dubna)
Alexei Smirnov (MPI Heidelberg)
Boris Kayser (Fermilab)
Oleg Smirnov (JINR Dubna)
Juan Pablo Yanez (Univ. of Alberta)
Maury Goodman (Argonne National Lab)
Yifang Wang (IHEP)
Anna Hayes (Los Alamos National Lab)
Carlo Giunti (INFN)
Vyacheslav Egor (JINR Dubna)
Dmitry Gorbunov (INR RAS Moscow)

Measurement of ν -mass
 $0\nu\beta\beta$ -decay experiments
 $0\nu\beta\beta$ -decay NMEs
Coherent scattering of ν 's
 ν -nucleus interactions
Leptogenesis
 ν -telescopes
 ν -properties from cosmology
Dark matter searches
Physics of gravitational waves
Everything about Higgs boson
Statistics for ν -experiments

Kathrin Valerius (KIT in Karlsruhe)
Andrea Giuliani (CSNSM in Paris)
Javier Menendez (Univ. of Tokyo)
Henry Wong (Academia Sinica, Taipei)
Jan Sobczyk (Univ. of Wrocław)
Pascuale DiBari (Univ. of Southampton)
Nathan Whitehorn (Univ. of California)
Richard Battye (Univ. of Manchester)
Nicolaio Fornengo (INFN Torino)
Imre Bartos (Univ. of Florida)
Guenakh Mitselmakher* (Univ. of Florida)
Thomas Schwetz (KIT in Karlsruhe)