Colloquium Prague ν15
Prague, Czech Republic
5- 6 November, 2015

Theory and phenomenology of the $0\nu\beta\beta$-decay

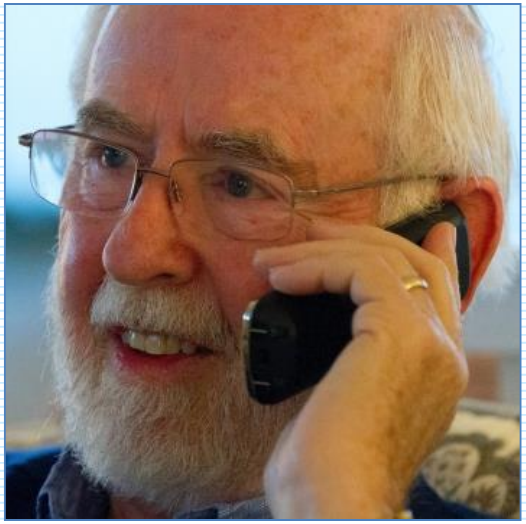
Fedor Šimkovic

OUTLINE

- *Introduction*
- *Bruno Pontecorvo and ν-oscillations*
- *$0\nu\beta\beta$-decay, effective Majorana neutrino mass in vacuum and nuclear matter*
- *$0\nu\beta\beta$-decay NMEs (uncertainty and quenching)*
- *$0\nu\beta\beta$-decay with emission of $p_{1/2}$-electrons*
- *Heavy/sterile neutrinos*
- *$0\nu\beta\beta$-decay with right-handed currents revisited*
- *Conclusions*

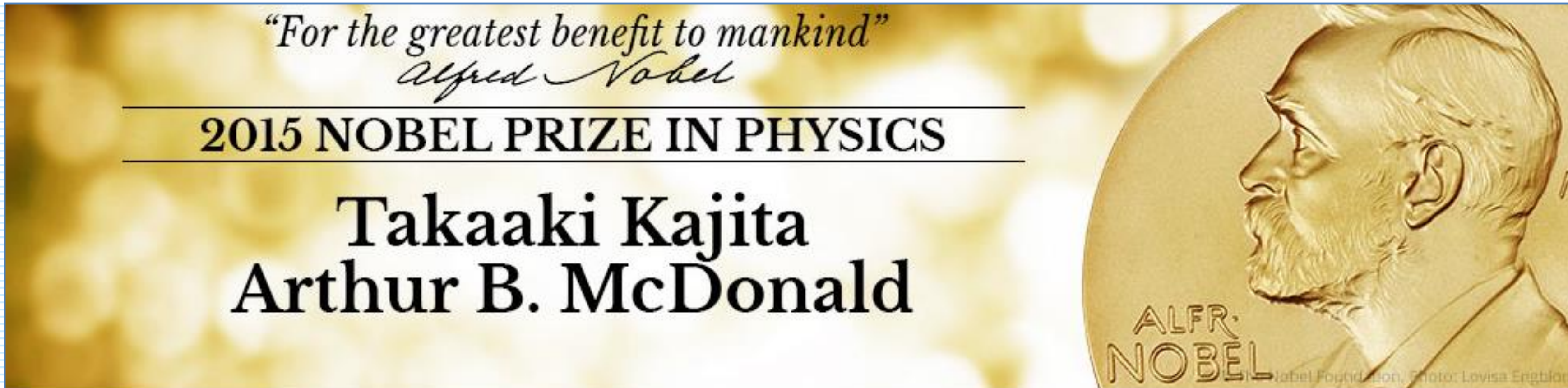
Amand Faesler, V. Rodin (U. Tuebingen), P. Vogel (Caltech), J. Engel (North Caroline U.), S. Kovalenko (Valparaiso U.), M. Krivoruchenko (ITEP Moscow), J. Vergados (U. Ioannina), S. Petcov (SISSA), D. Štefánik, R. Dvornický (Comenius U.), E. Lisi, G. Fogli (U. Bari) etc

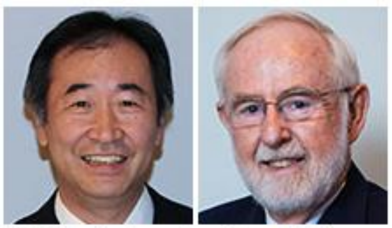
Nobel Laureates in Physics, 2015



Takaaki Kajita **Art McDonald**

Stockholm, October 6, 2015





2015 Physics Laureates: Takaaki Kajita, photo © Takaaki Kajita and Arthur B. McDonald, photo K. MacFarlane. Queen's Univ/SNOLAB

2015 Nobel Prize in Physics

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

They Solved the Neutrino Puzzle

Takaaki Kajita and Arthur B. McDonald solved the neutrino puzzle and opened a new realm in particle physics. They were key scientists of two large research groups, Super-Kamiokande and Sudbury Neutrino Observatory, which discovered the neutrinos mid-flight metamorphosis.

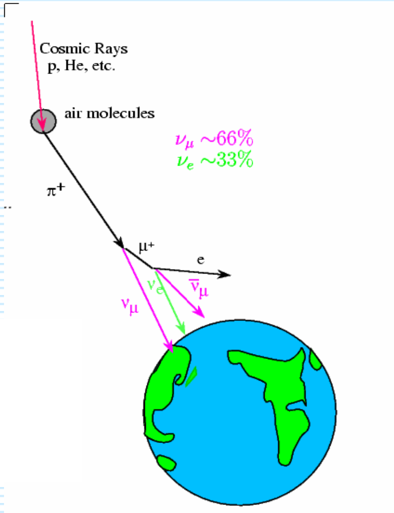
"I Gave My Wife a Hug!"

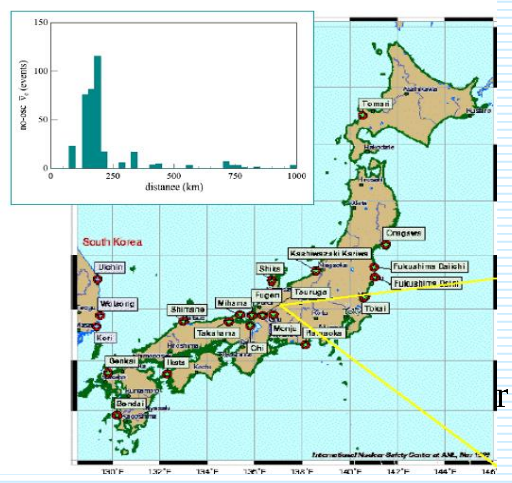
"It's ironic, in order to observe the sun you have to go kilometers under ground. That's not what you would expect." An interview with Arthur B. McDonald, awarded the 2015 Nobel Prize in Physics.

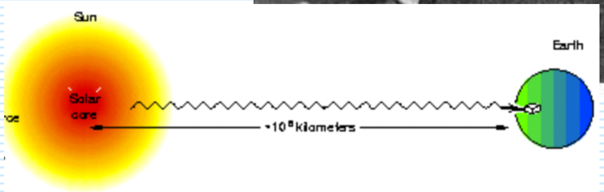
+ Transcript of the interview

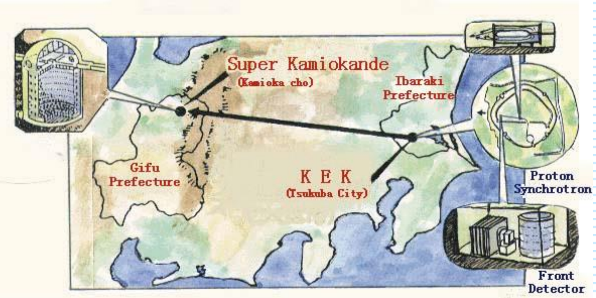
Neutrino oscillations

Let give credit to Bruno Pontecorvo Mr. Neutrino (22.8.1913-24.9.1993)

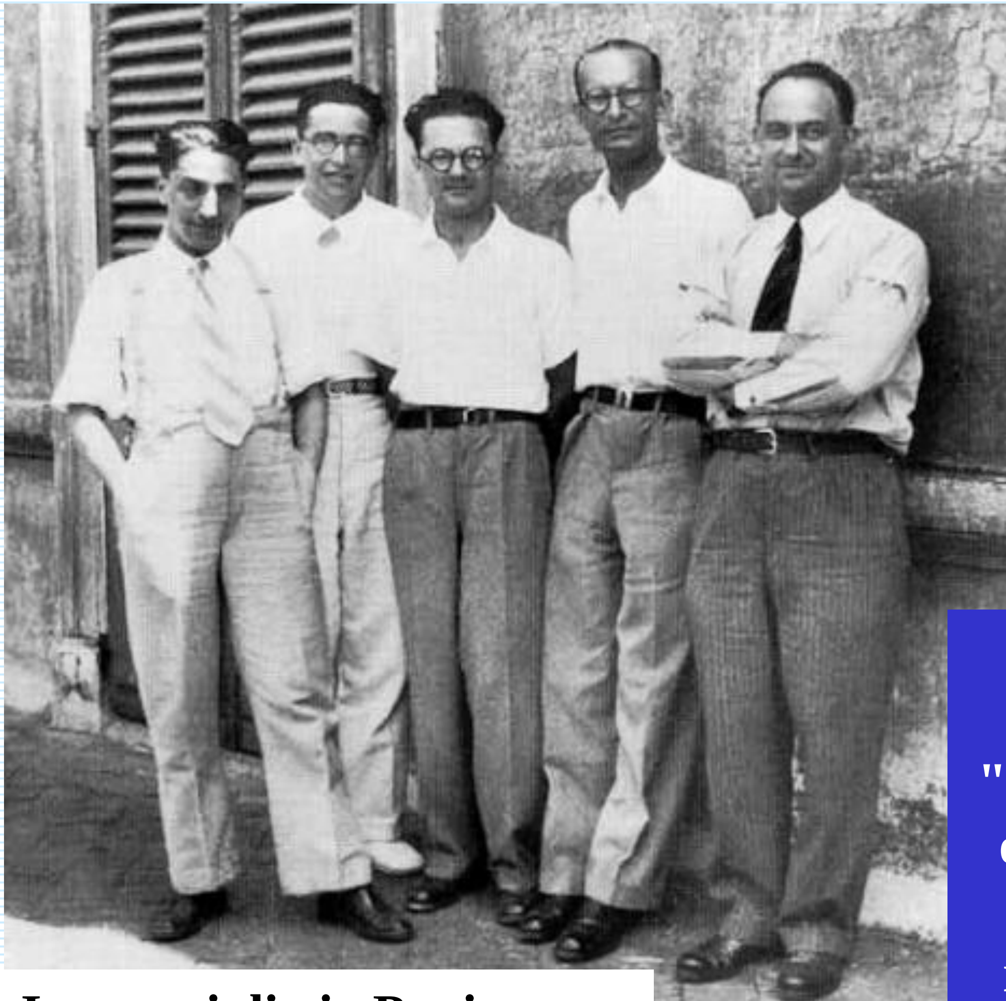








Enrico Fermi (far right) with the Via Panisperna boys. Enrico's team of student-colleagues is named for the lab in Rome where they carried out ground breaking research bombarding elements with slow neutrons, to learn about basic properties of matter. For this work, Enrico won the Nobel Prize in 1938.



I ragazzi di via Panisperna

Oscar D'Agostino
Emilio Segrè
Edoardo Amaldi
Franco Rasetti
Enrico Fermi

Where is
Bruno Pontecorvo?

The Nobel Prize in Physics 1938
Enrico Fermi
"for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons"

1946 Inverse β Process, Pontecorvo

NRC of Canada, DoAE, Chalk River Report Pd-205, 1946

Inverse β process as a tool for proof of the existence of neutrino. The radioactivity of the produced nucleus may be looked for as a proof of the inverse process. Examples:

$\nu + {}^{37}Cl \rightarrow \beta^- + {}^{37}Ar$, ${}^{37}Ar \rightarrow {}^{37}Cl$ (34 days, K-capture)

$\nu + {}^{79,81}Br \rightarrow \beta^- + {}^{79,81}Kr$, ${}^{79,81}Ar \rightarrow {}^{79,81}Cl$ (34 h, emission of positrons of 0.4 MeV)

Sources of neutrinos: 1. solar neutrinos, 2. reactor neutrinos, 3. accelerator neutrinos

It is the first neutrino programme

Ray Davis exploits the Pontecorvo reaction $\nu + {}^{37}Cl \rightarrow \beta^- + {}^{37}Ar$:

- **1955-58, antineutrinos from reactor (Brookhaven, Savannah River)**
  no signal => lepton number
- **1968, solar neutrinos detection**

1947 Nuclear capture of mesons and the meson decay, Pontecorvo

Phys. Rev. 72 (1947) 246

Experiment of Conversi, Pancini, Piccioni: Probability of capture of a meson by nuclei is much smaller that would be expected on the basis of Yukawa theory

$$\mu^- + (A,Z) \rightarrow \nu + (A,Z\text{-}1), \qquad \nu + (A,Z) \rightarrow \mu^- + (A,Z+1)$$

Pontecorvo: Process of nuclear absortion or production of a single meson should be accompanied by the emission of a neutrino

Bruno Pontecorvo: the idea of massive neutrino and oscillations – 1957 Dubna

The first idea of neutrino masses, mixing and oscillations was suggested by Bruno Pontecorvo.

- Inspired by the kaons oscillations (Gell-Man and Pais).
- Davis experiment with reactor antineutrinos. A rumour reached Pontecorvo that observed production of ^{37}Ar.
- He was thinking about antineutrino↔neutrino oscillations in vacuum as possible explanations
- He suggested "It will be extremely interesting to perform Cowan and Reines experiment at different distances from reactor"

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

Davis experiment finished with no production of ^{37}Ar found. Pontecorvo: Neutrino (antineutrino) could transfer into anti{ν_L} (ν_R), particles not participating in standard weak interaction. He introduced sterile neutrinos.

After ν_μ discovered in Brookhaven Pontecovo generalized his idea of neutrino oscillations for the case of two neutrinos: Zh.Exp.Teor.Fiz. 53 (1967) 1717

Different neutrino species exists (1962)

Second variety (or flavor) of neutrinos: $\nu_\mu \neq \nu_e$

1959 Pontecorvo raised the question whether ν from β-decay processes is identical with ν from pion decay (Sov. Phys. JETP 10 (1960) 1236)

1960 Pontecorvo and Schwartz (PRL 4 (1960) 306) suggested to study neutrino reactions with high energy muons coming from proton accelerator ($\pi \rightarrow \mu + \nu_\mu$ $K \rightarrow \mu + \nu_\mu$)

Lederman, Schwarz, Steinberger

First detection of CC ν_μ interactions

$$\nu_\mu + N \rightarrow \mu + X$$

BNLaccelerator experiment proves the existence of ν_μ by producing neutrinos from pion decays And determining the product of interaction to be muons (no electrons above background observed)

Nobel prize 1988

Lepton charge L_e, L_μ ... L_τ needed

First neutrino beam from an accelerators !

Same principle used today in conventional neutrino beams

1962-Two-neutrino mixing (Maki, Nakagawa, Sakata)

Nagoya model: i) In hadronic current enter fields of three fundamental baryons: p, n, Λ

ii) These particles were considered as bound states of leptons and boson B^+ : $p = \langle \nu B^+ \rangle$, $n = \langle e^- B^+ \rangle$, $\Lambda = \langle \mu^- B^+ \rangle$

(baryon-lepton symmetry)

There was indication from data of $\mu \to e\gamma$ experiment that ν_e and ν_μ are different particles

=> problem for Nagoya model: 4 leptons and 3 hadrons


Maki, Nakagawa,Sakata, Prog. Theor. Phys.28 (1962) 870

1. hadron-lepton sym, 2. Cabbibo angle hypothesis, 3. two types of neutrinos => neutrino mixing hypothesis

MNS proposed modified Nagoya model:

True (ν_1, ν_2) weak (ν_e, ν_μ) neutrinos

$$\nu_1 = +\nu_e \cos\delta + \nu_\mu \sin\delta$$
$$\nu_2 = -\nu_e \sin\delta + \nu_\mu \cos\delta$$

$$p = \langle \nu_1 B^+ \rangle, \quad n = \langle e^- B^+ \rangle, \Lambda = \langle \mu^{-+} B^+ \rangle$$

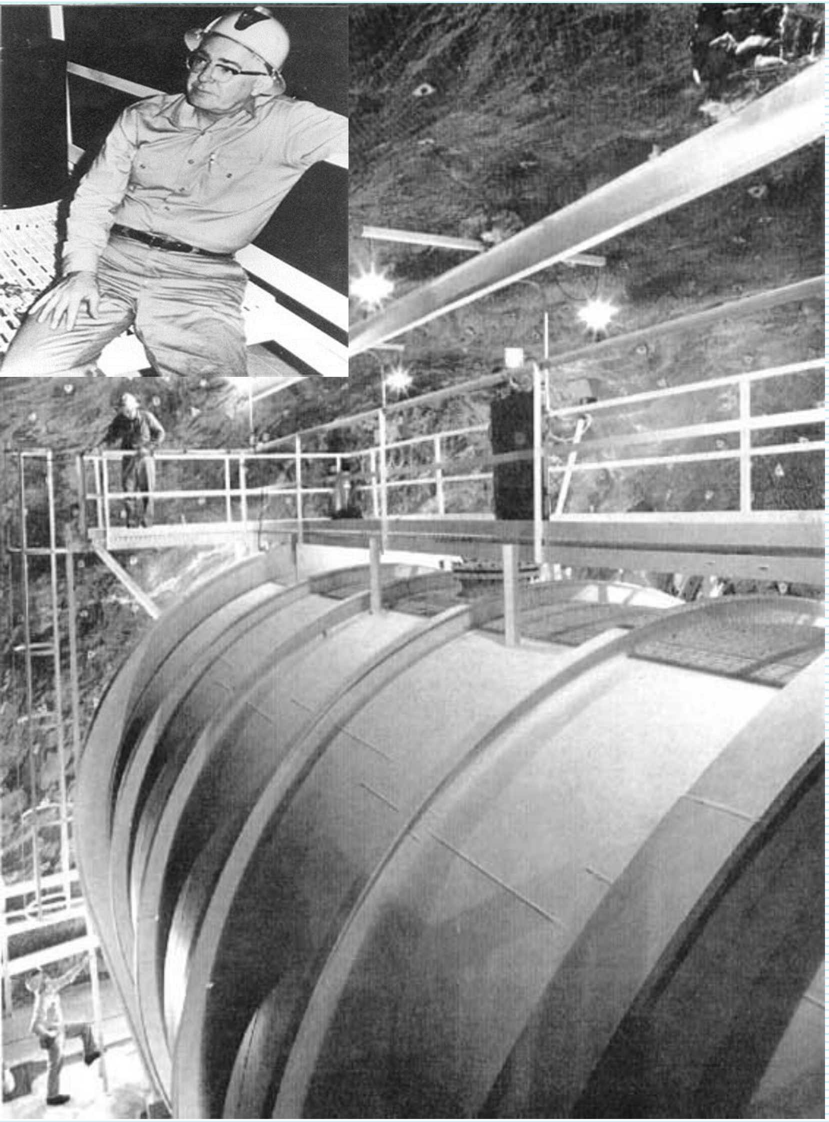
MNS assumed additional interaction with heavy boson X

$$L = g\, \nu_2\, \nu_2\, X^+ X$$

which provide difference of masses ν_1 and ν_2

1968 Homestake experiment

2002 Nobel prize



1964 John Bahcall and Ray Davis have idea to detect solar neutrinos using the reaction

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$

1967 Homestake experiment starts taking data

- 615 ton of cleaning fluid in a tank 4,100 mwe underground
- ^{37}Ar extracted chemically every few months (single atoms!)
- event rate: ~ 1 neutrino capture per day!

1968 First results: only 34% of predicted neutrino flux

Experiment observed: 2.56±0.23 SNU
SSM prediction: 7.7 ±1.2 SNU
1 SNU = 10^{-36} interactions/(target atom)/ s

1968 Gribov, Pontecorvo [PLB 28(1969) 493]
proposed neutrino oscillations as a solution

Next 20 years no other solar neutrino experiment

Davis, Harmer and Hoffman, Phys. Rev. Lett. 20 (1968) 1205

The Nobel Prize in Physics 1988

Leon M. Lederman, Melvin Schwartz and Jack Steinberger

"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"

ν_μ

The Nobel Prize in Physics 1995

"for pioneering experimental contributions to lepton physics"

Martin L. Perl

"for the discovery of the tau lepton"

Frederick Reines

"for the detection of the neutrino"

ν_e

The Nobel Prize in Physics 2002

ν_e

Raymond Davis Jr. and Masatoshi Koshiba

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

The Nobel Prize in Physics 2015

ν_e, ν_μ θ_{12}, θ_{23}

Takaaki Kajita and Arthur B. McDonald

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

The Nobel Prize in Physics 1957
Chen Ning Yang and **Tsung-Dao (T.D.) Lee**
"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

The Nobel Prize in Physics 1967
Hans Albrecht Bethe
"for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"

The Nobel Prize in Physics 1979
Sheldon Lee Glashow, **Abdus Salam** and **Steven Weinberg**
"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"

The Nobel Prize in Physics 1980
James Watson Cronin and **Val Logsdon Fitch**
"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

After 59 years we know

- **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)**

No answer yet

- **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

$0\nu\beta\beta$-decay: 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

The observed small neutrino masses have profound implications for our understanding of the Universe and are now a major focus in astro, particle and nuclear physics and in cosmology.

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

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

- **3 neutrino mixing angles are measured and non-zero**
- **Large θ_{13} opens door for searching of CP-violation in lepton sector**
- **Large θ_{13} gives good chances for measurement of mass hierarchy (MH) and CP violation in neutrino oscillations using present neutrino beams and detectors**
- **Time to start MH and δ measurements**

The size of θ_{13} $\rightarrow$ Future Program of neutrino physics

Nσ ranges for single parameters (all data included):

[F. Capozzi, G.L. Fogli, E. Lisi, D. Montanino, A. Marrone, and A. Palazzo, arXiv:1312.2878]

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi^2_{\mathrm{I-N}} = +0.3$).

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.44	2.38 – 2.52	2.30 – 2.59	2.22 – 2.66
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.40	2.33 – 2.47	2.25 – 2.54	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.16 – 2.56	1.97 – 2.76	1.77 – 2.97
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.39	2.18 – 2.60	1.98 – 2.80	1.78 – 3.00
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.25	3.98 – 4.54	3.76 – 5.06	3.57 – 6.41
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.37	4.08 – 4.96 $\oplus$ 5.31 – 6.10	3.84 – 6.37	3.63 – 6.59
δ/π (NH)	1.39	1.12 – 1.72	0.00 – 0.11 $\oplus$ 0.88 – 2.00	—
δ/π (IH)	1.35	0.96 – 1.59	0.00 – 0.04 $\oplus$ 0.65 – 2.00	—

Fractional uncertainties (defined as 1/6 of 3σ ranges):

δm^2	=	Δm^2_{21}
$\theta_{12}, \theta_{23}, \theta_{13}, \delta$	=	as in PDB
δ range	=	$[0, 2\pi]$ (others prefer $[-\pi, +\pi]$)
Δm^2	=	$(\Delta m^2_{31} + \Delta m^2_{32})/2$

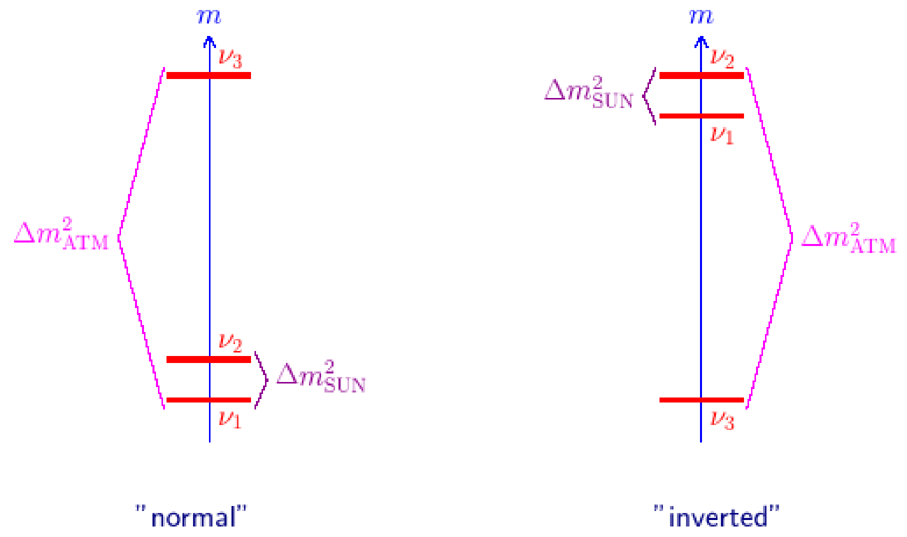
δm^2	2.6 %
Δm^2	3.0 %
$\sin^2\theta_{12}$	5.4 %
$\sin^2\theta_{13}$	8.5 %
$\sin^2\theta_{23}$	~ 11 %

An indication of CP violation in neutrino sector

Neutrinos mass spectrum

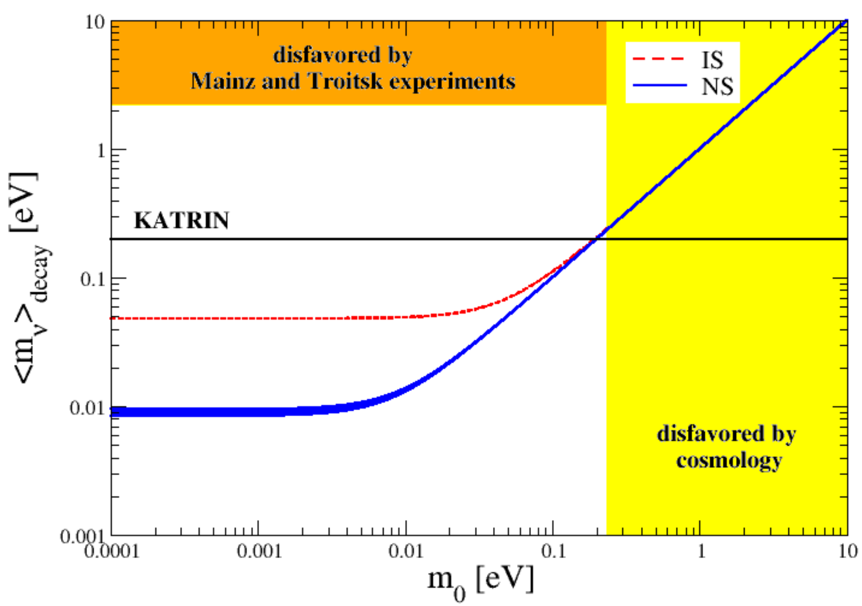
0νββ Measurements

$$\langle m^2_{\beta\beta}\rangle = \Big|\sum_i^{n_\nu} U^2_{ei} m_{\nu,i}\Big|^2$$



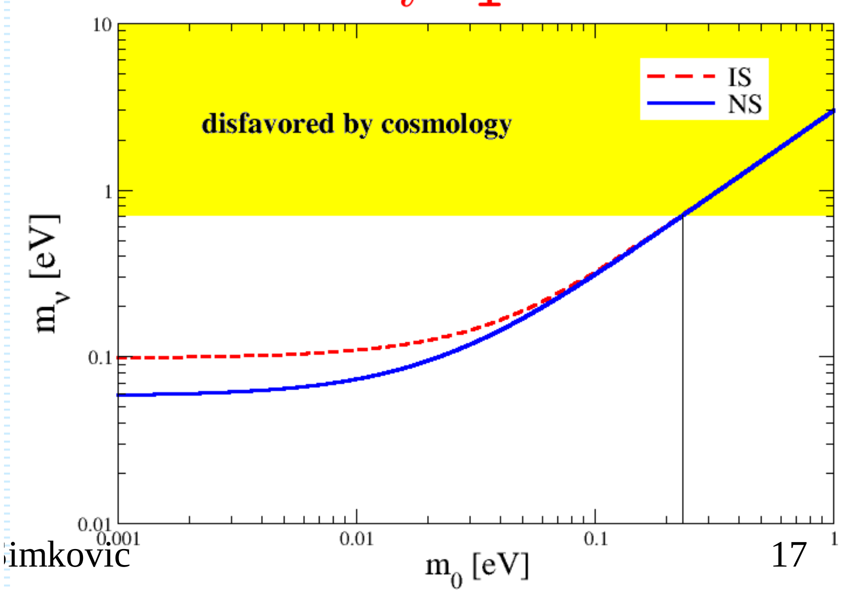
Beta Decay Measurements

$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \; m_i^2}$$



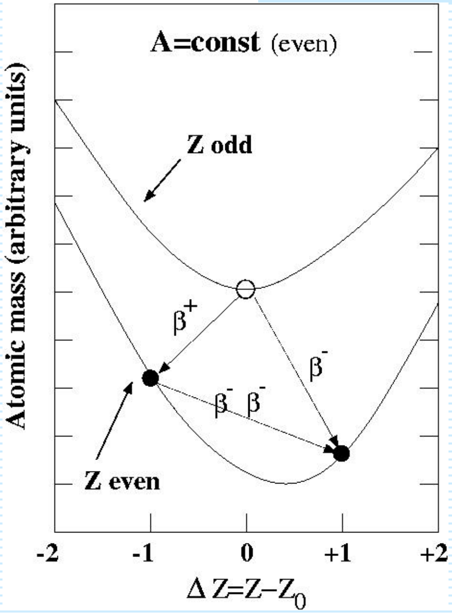
Cosmological Measurements

$$\sum_{i=1}^{3} m_i$$



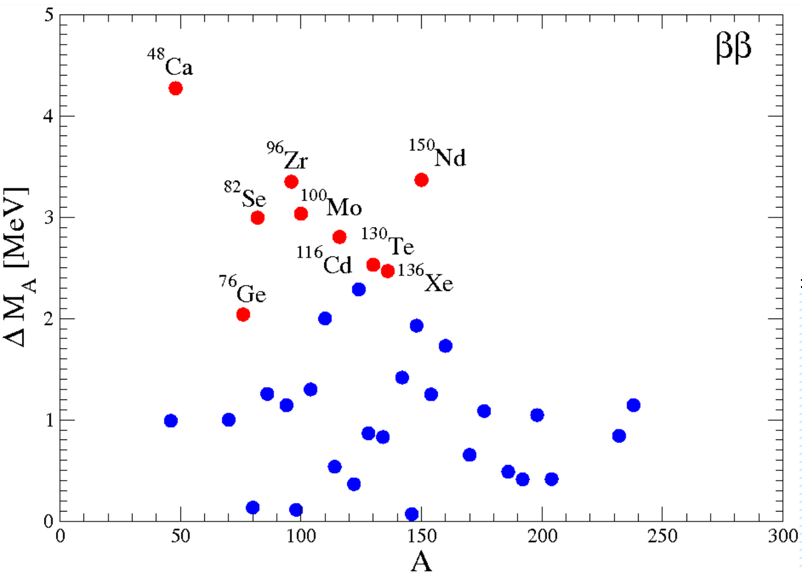
Neutrinoless Double-Beta Decay

(A,Z) → (A,Z+2) + e⁻ + e⁻



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

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



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

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.

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

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.

Effective mass of Majorana neutrinos

$$m_{\beta\beta}^{\rm vac} = \sum_i (U^L_{ei})^2 m_i$$

Majorana phases

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

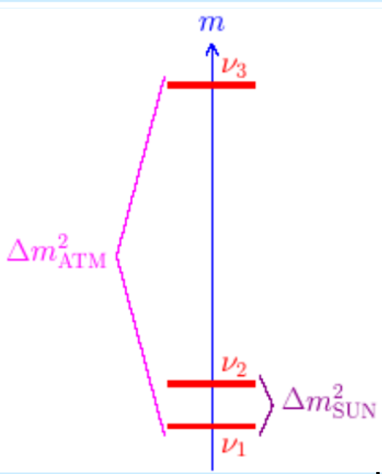
$$\begin{aligned} |m_{\beta\beta}| &= |c^2_{12}c^2_{13}e^{i\alpha_1}m_1 \\ &\quad + s^2_{12}c^2_{13}e^{i\alpha_2}m_2 + s^2_{13}m_3| \end{aligned}$$

Measured quantity

$$\begin{aligned} |m_{\beta\beta}|^2 &= c^4_{12}c^4_{13}m^2_1 + s^4_{12}c^4_{13}m^2_2 + s^4_{13}m^2_3 \\ &\quad + 2c^2_{12}s^2_{12}c^4_{13}m_1m_2\cos(\alpha_1-\alpha_2) \\ &\quad + 2c^2_{12}c^2_{13}s^2_{13}m_1m_3\cos\alpha_1 + 2s^2_{12}c^2_{13}s^2_{13}m_2m_3\cos\alpha_2. \end{aligned}$$

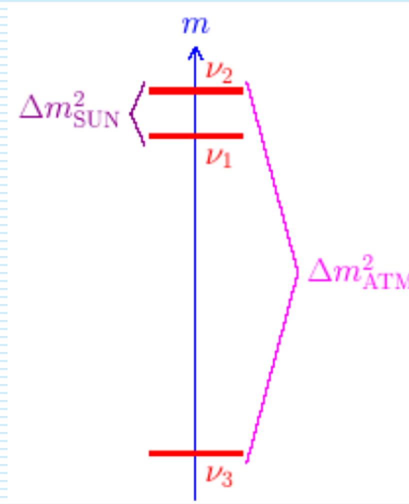
Normal hierarchy

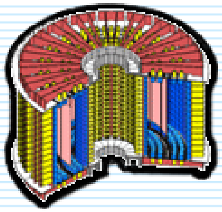
$$\begin{aligned} m_1 &\ll \sqrt{\Delta m^2_{\rm SUN}} \\ m_2 &\simeq \sqrt{\Delta m^2_{\rm SUN}} \\ m_3 &\simeq \sqrt{\Delta m^2_{\rm ATM}} \end{aligned}$$

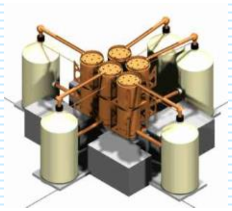


Inverted hierarchy

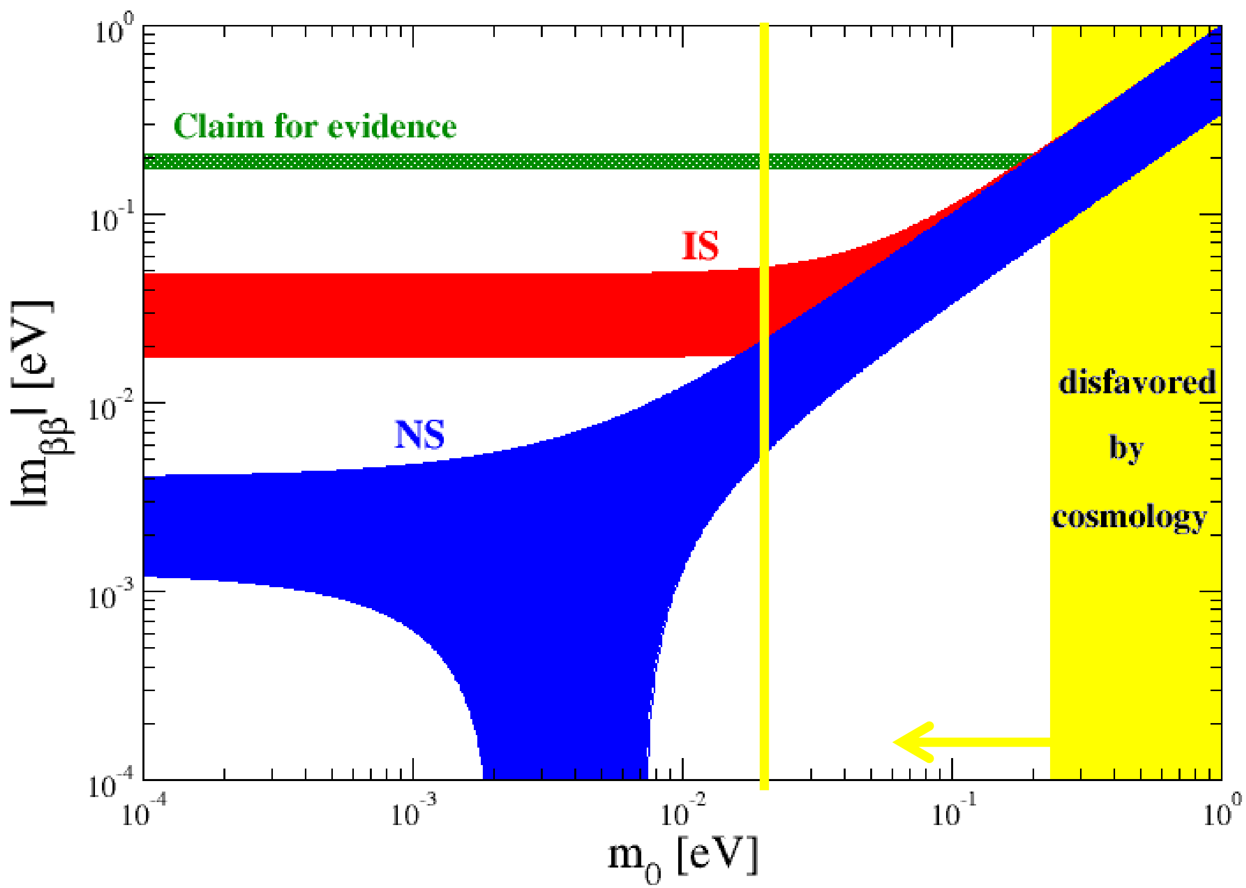
$$\begin{aligned} m_3 &\ll \sqrt{\Delta m^2_{\rm ATM}} \\ m_1 &\simeq m_2 \simeq \sqrt{\Delta m^2_{\rm ATM}} \end{aligned}$$







Issue: Lightest neutrino mass m_0



GUT's

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

β-decay (Mainz, Troitsk)

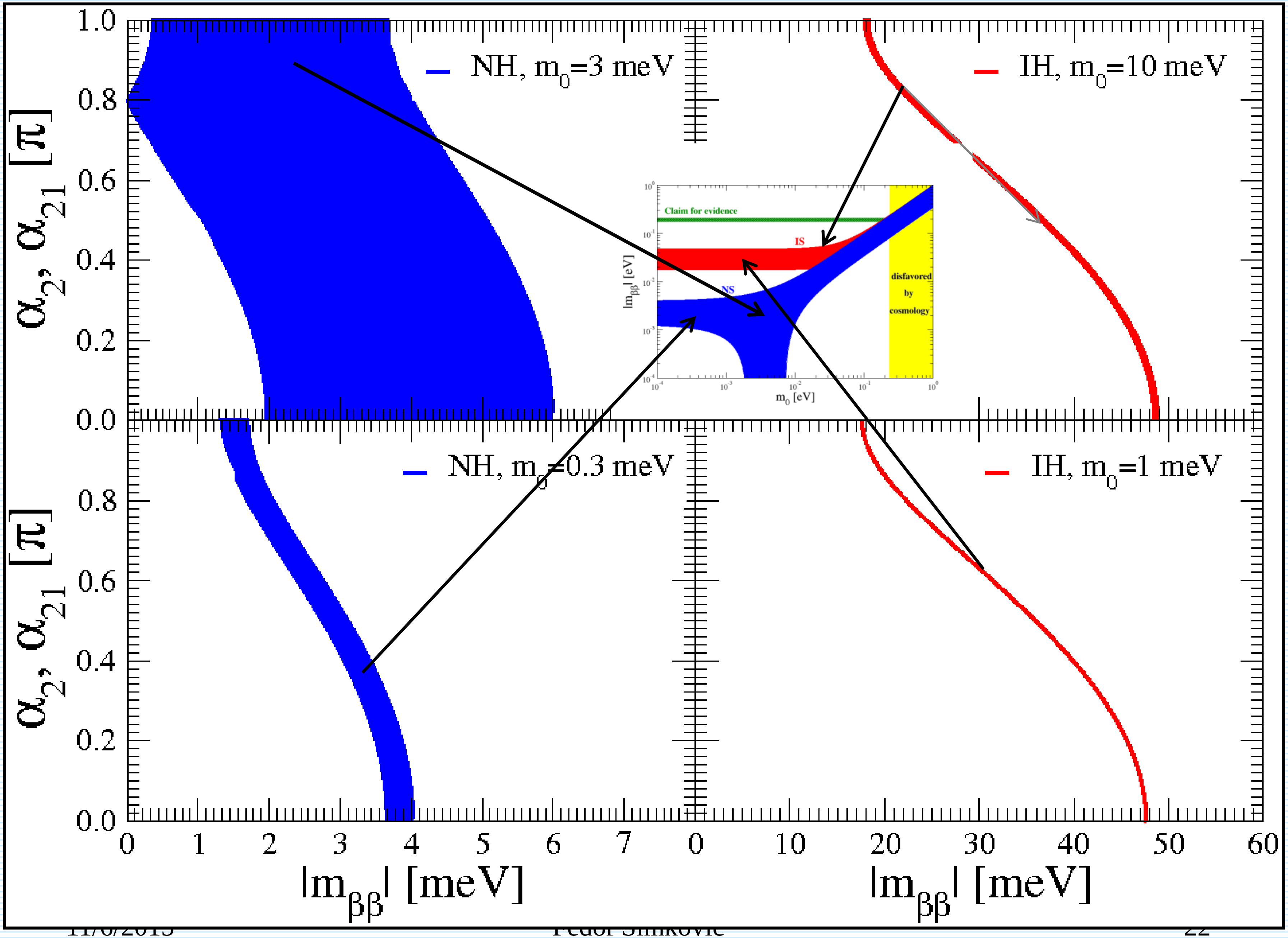
$$m_\beta^2 = \sum_i |U_{ei}^L|^2 m_i^2 \leq (2.2\ \mathrm{eV})^2$$

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

Cosmology (Planck)

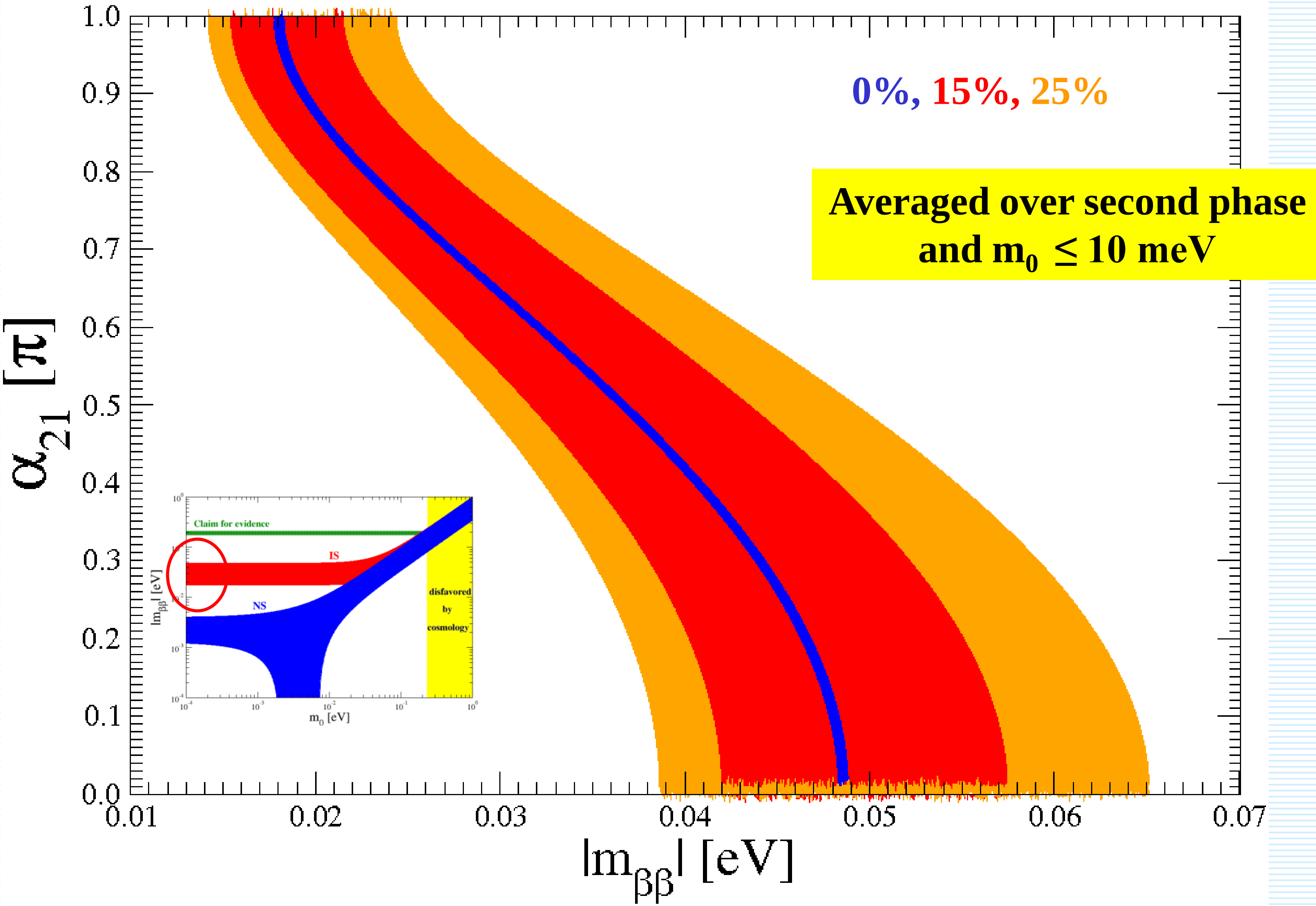
$$\sum_i m_i \leq 0.23\text{–}1.08\ \mathrm{eV}$$

$$m_0 \leq 0.07\ \mathrm{eV}$$


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]

$$|m_{\beta\beta}| = \frac{1}{\sqrt{T^{0\nu}_{1/2} G^{0\nu}(Q_{\beta\beta}, Z)}\,|M'^{0\nu}|}$$

$$\frac{\sigma_{\beta\beta}}{|m_{\beta\beta}|^{obs}} = \sqrt{\frac{1}{4}\left(\frac{\sigma_{exp}}{T^{0\nu-obs}_{1/2}}\right)^{2} + \left(\frac{\sigma_{th}}{|M'^{0\nu}|}\right)^{2}}$$



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

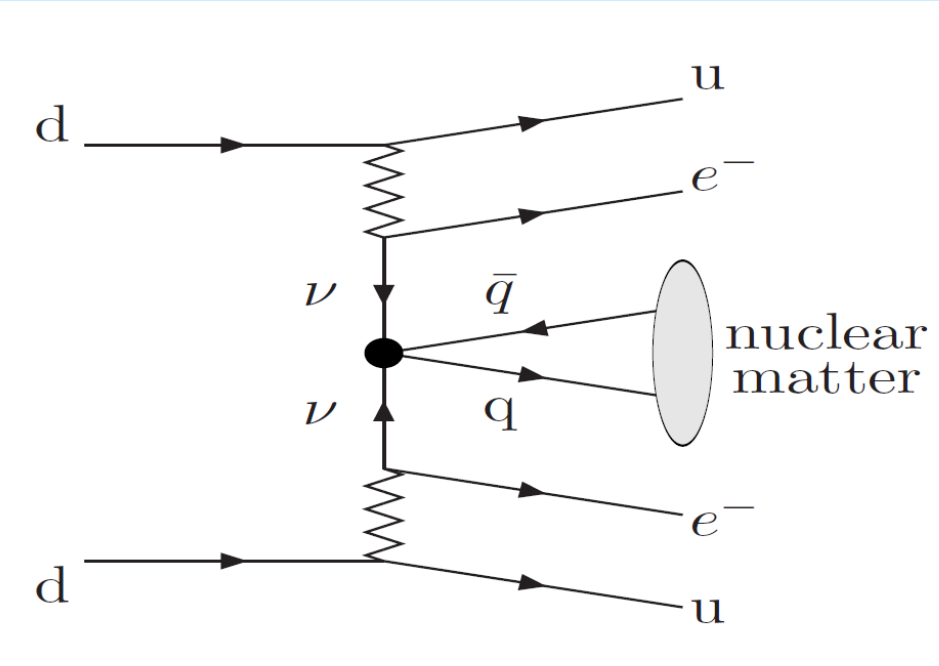
S.G. Kovalenko, M.I. Krivoruchenko, F. Š., Phys. Rev. Lett. 112 (2014) 142503

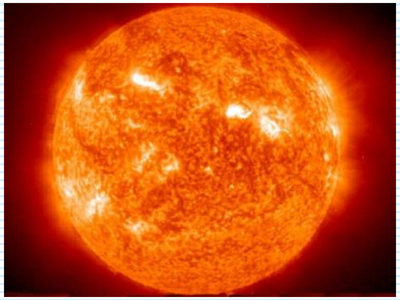
A novel effect in $0\nu\beta\beta$ decay related with the fact, that its underlying mechanisms take place in the nuclear matter environment:

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

+ In-medium Majorana mass of neutrino

+ $0\nu\beta\beta$ constraints on the universal scalar couplings





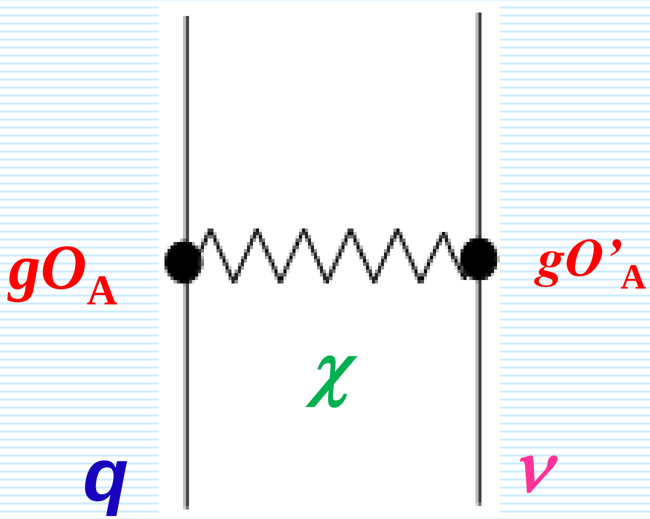
Non-standard ν–int. discussed e.g., in the context of ν–osc. at Sun

$\rho_{\mathrm{Sun}} = 1.4\ \mathrm{g/cm^3}$

$\rho_{\mathrm{Earth}} = 5.5\ \mathrm{g/cm^3}$

$\rho_{\mathrm{nucleus}} = 2.3\ 10^{14}\ \mathrm{g/cm^3}$

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



➡

Low energy 4-fermion
ΔL ≠ 0 Lagrangian

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

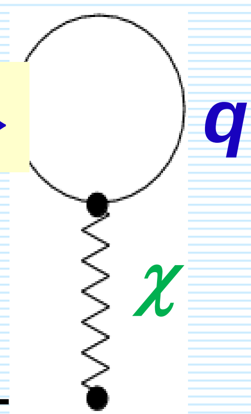
$$m_\chi \gtrsim M_W.$$

0νββ-decay

density →

oscillation experiments
tritium β-decay, cosmology

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



Classification of the vertices gO_A and gO'_A

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

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

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

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

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

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

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

Mean field approximation

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

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

To compare with weak interaction: $\frac{g_\chi g_{ij}^a}{m_\chi^2} = \frac{G_F}{\sqrt{2}} \varepsilon_{ij}^a$

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

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

In-medium Lagrangian of Majorana ν

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

where

$$Z_{ij}=\delta_{ij}-\langle\chi\rangle g^4_{ij}, \qquad Z'_{ij}=-\langle\chi\rangle g^6_{ij}$$
$$M_{ij}=m_i\delta_{ij}+\langle\chi\rangle g^1_{ij}, \quad M'_{ij}=\langle\chi\rangle g^2_{ij}.$$

Universal scalar interaction

$$g^a_{ij}=\delta_{ij}g_a \quad \varepsilon^a_{ij}=\delta_{ij}\varepsilon_a$$

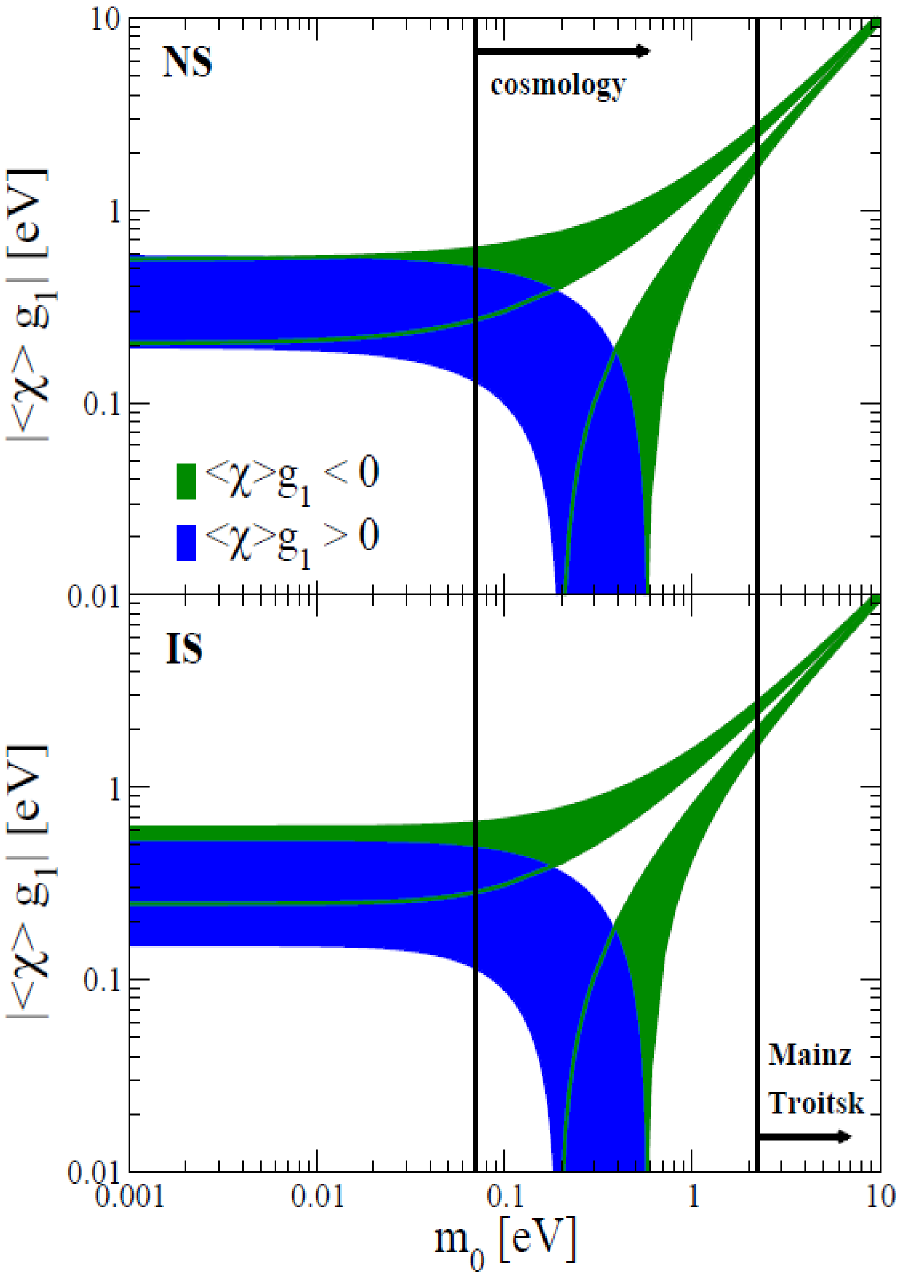
In medium ν mass

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

In medium effective Majorana ν mass

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

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



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

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

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

$$\varepsilon_{ij} \leq 0.02 \text{ (Planck)}, 0.1 \text{ (Tritium)}$$

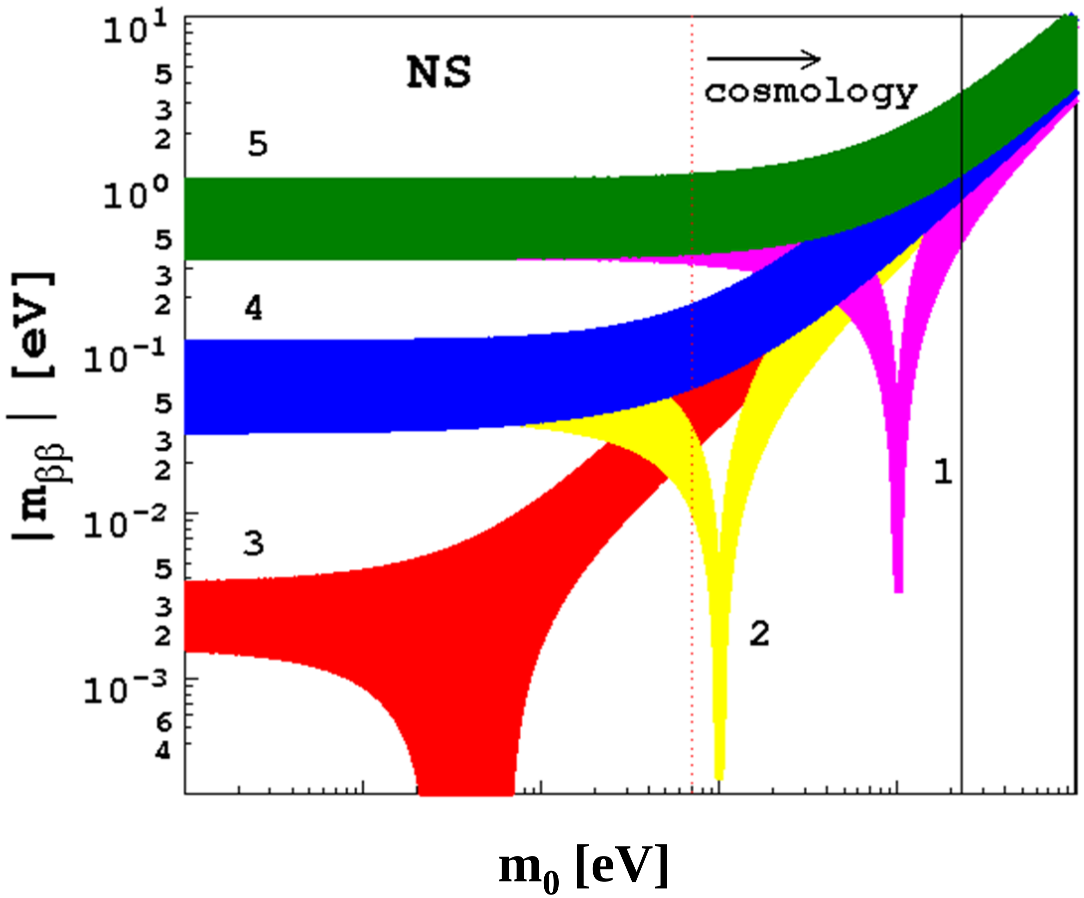
Using experimental data on the 0νββ decay in combination with β-decay and cosmological data we evaluated the characteristic scales of 4-fermion neutrino-quark operators, which is Λ_{LNV} > 2.4 TeV.

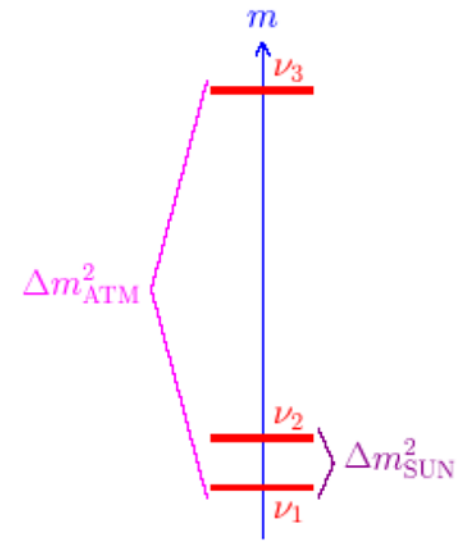
Pion decay: BR($\pi^0 \to \nu\nu$) ≤ 2.7 10^{-7}

$$\Lambda_{LNV} \geq 560 \text{ GeV}$$

The normal neutrino mass spectrum (NS)

$$m_1 < m_2 < m_3$$





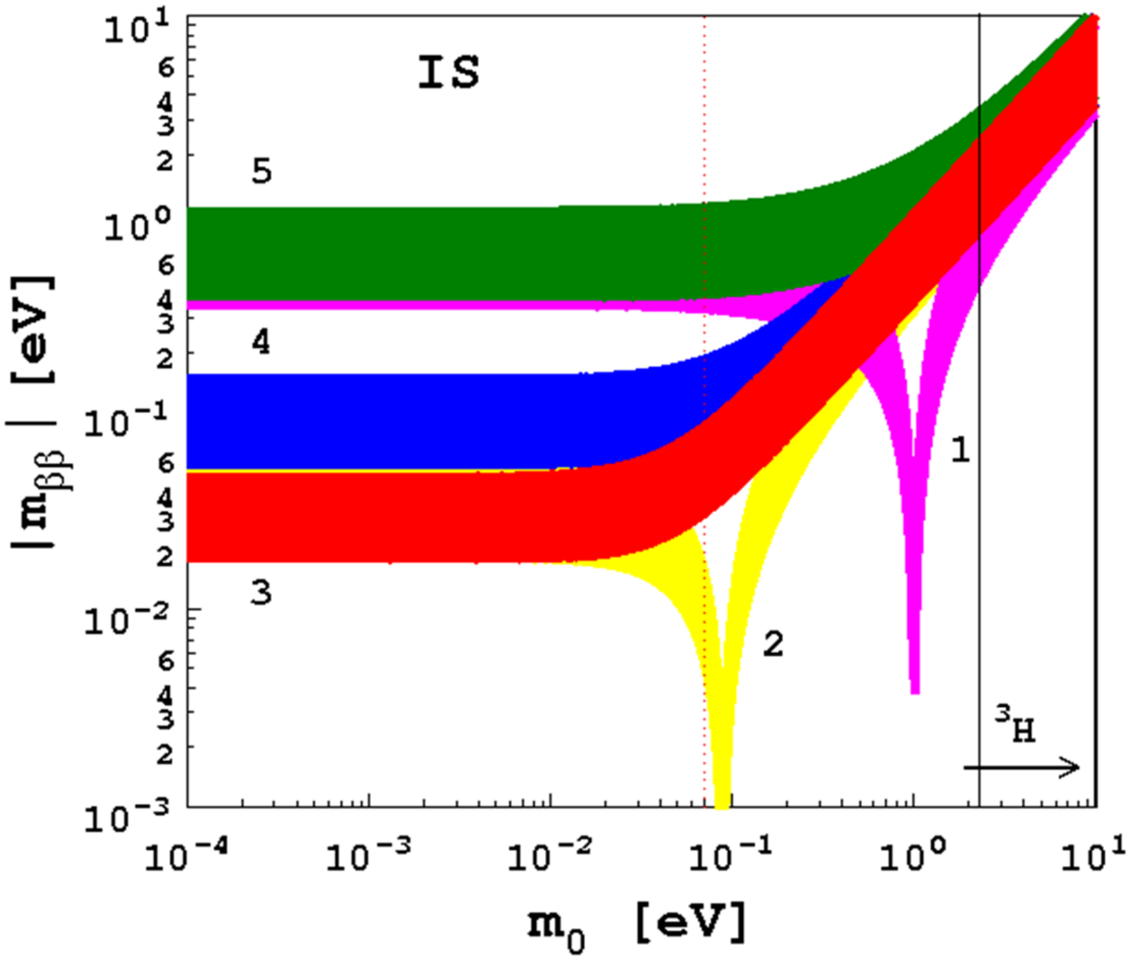
Area	$\langle\chi\rangle g_1$ [eV]
1	-1
2	-0.1
3	0
4	0.1
5	1

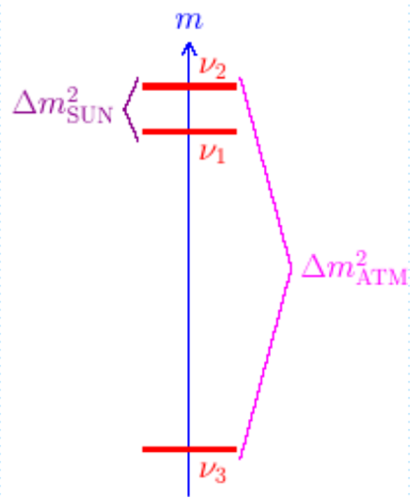
$$g_2 = g_4 = 0$$

No possibility to conclude about hierarchy

The inverted neutrino mass spectrum (IS)

$$m_3 < m_1 < m_2$$



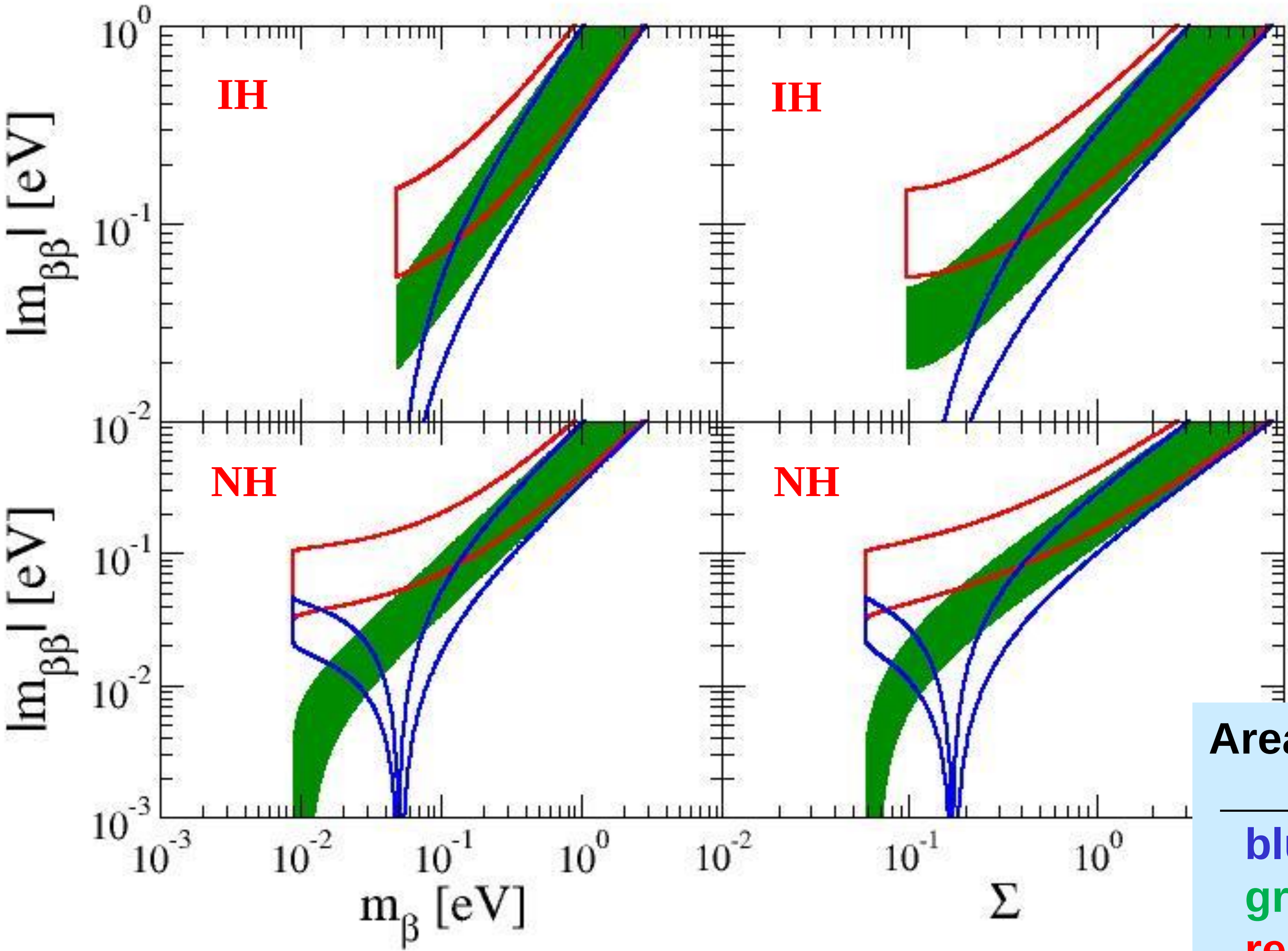


Area	$\langle\chi\rangle g_1$ [eV]
1	-1
2	-0.1
3	0
4	0.1
5	1

$$g_2 = g_4 = 0$$

No possibility to conclude about hierarchy

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



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

The 0νββ-decay Nuclear Matrix Elements

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

QRPA and isospin symmetry restoration

F.Š., V. Rodin, A. Faessler, and P. Vogel

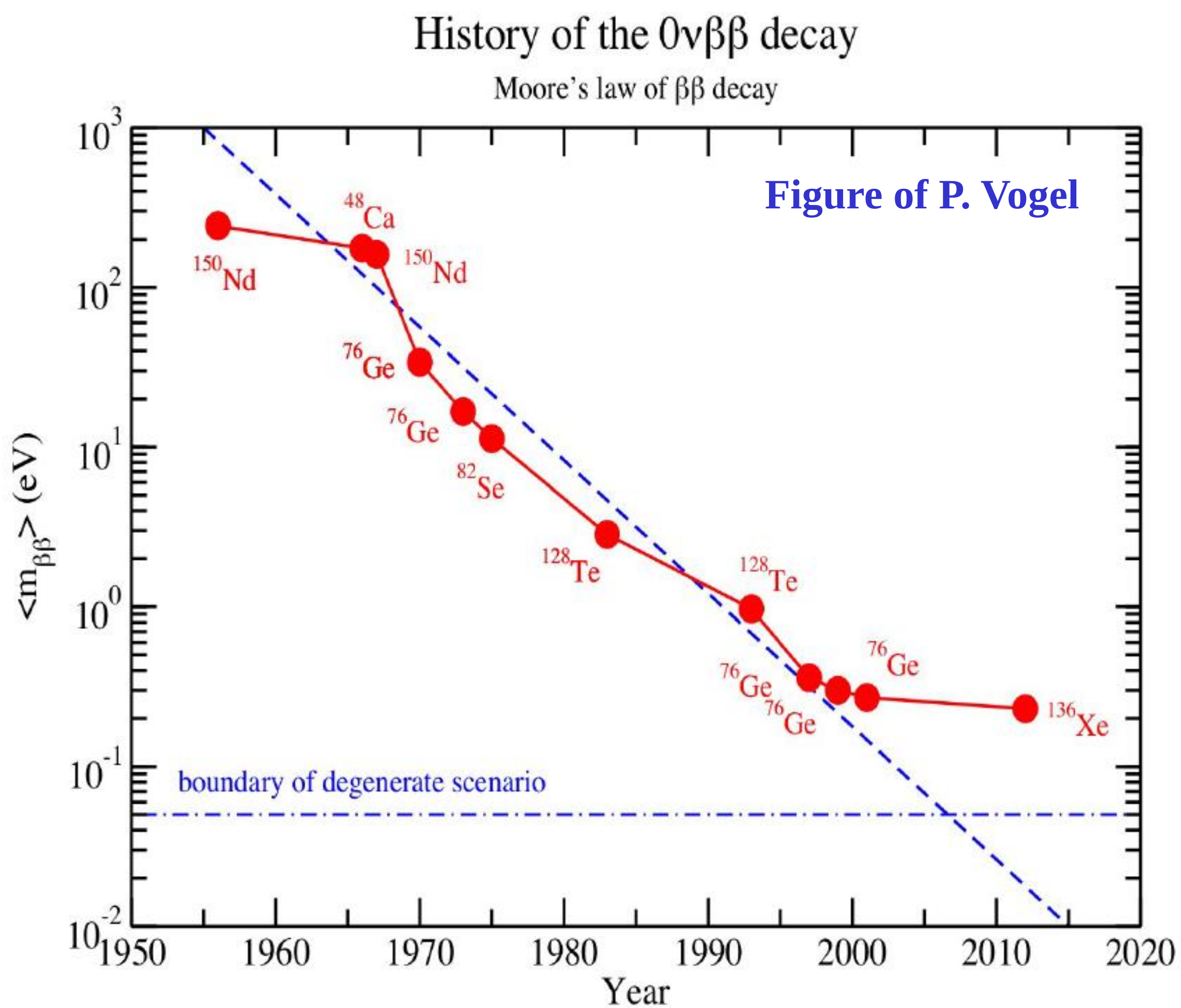
PRC 87, 045501 (2013)

If (or when) the $0\nu\beta\beta$ decay is observed two theoretical problems must be resolved

How to relate the observed decay rate to the fundamental parameters, i.e., what is the value of the corresponding nuclear matrix elements.

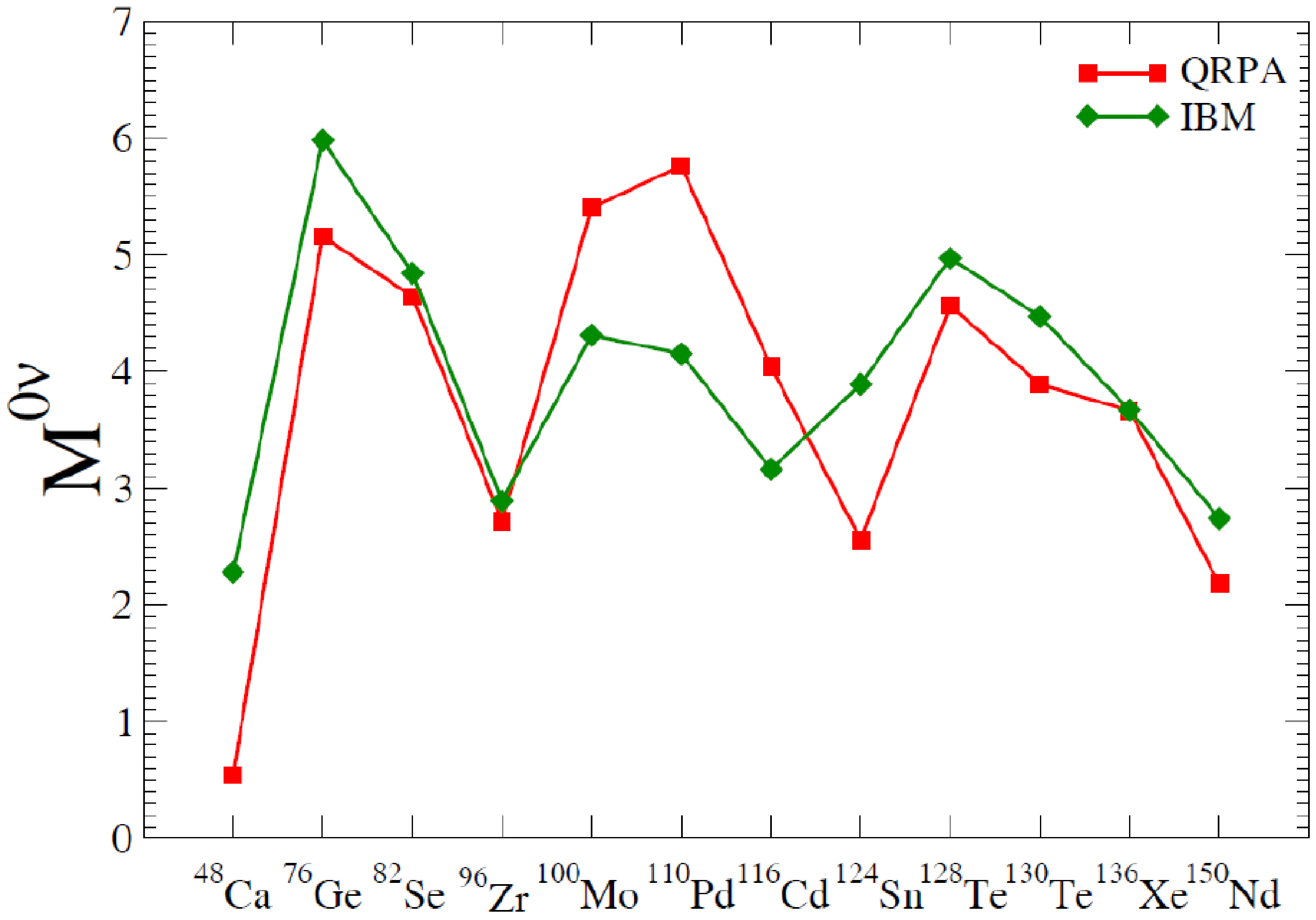
What is the mechanism of the decay, i.e., what kind of virtual particle is exchanged between the affected nucleons (quarks).

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



During the last decade the complexity and costs of $0\nu\beta\beta$-decay experiments increased dramatically

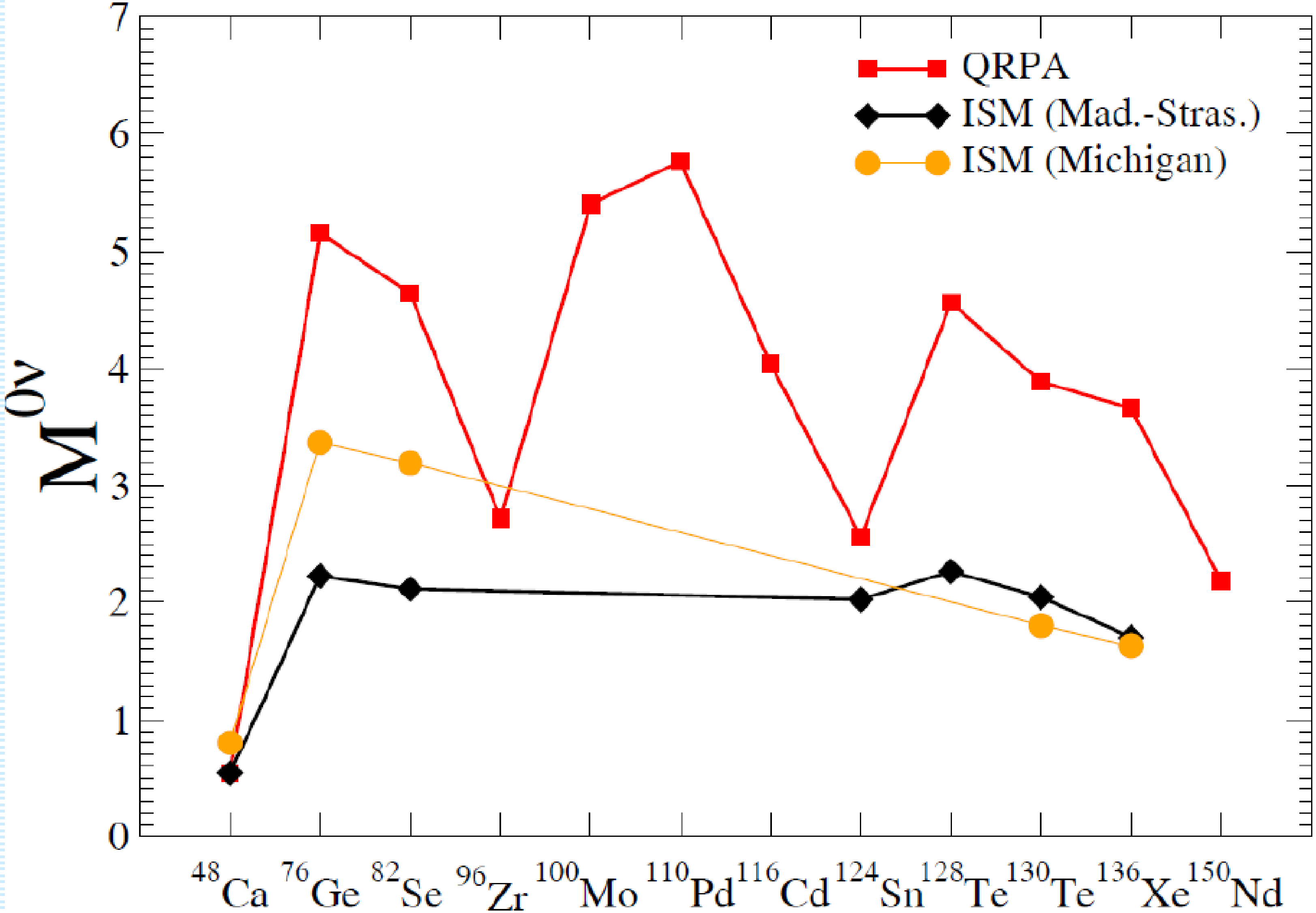
QRPA versus IBM



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

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

QRPA versus Interacting Shell Model



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

ISM: Brown, Horoi etc., Phys.Rev.Lett. 113 (2014) 262501 …

Quenching of g_A (systematic error)

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

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

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

$g_A = 1.269 \Rightarrow g^{eff}_A = 0.75\, g_A \approx 1$

$(g^{eff}_A)^4 = (0.8)^4 = 0.41$

$(g^{eff}_A)^4 = (0.7)^4 = 0.24$

In QRPA g^{eff}_A and isoscalar force were fitted to reproduce the $2\nu\beta\beta$-decay half-life, β^- decay rate and β^+/EC rate
$\Rightarrow g^{eff}_A$ is smaller than unity.

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

$g_A^{eff\text{-}ISM} = 0.57\text{-}0.90$

$g_A^{eff\text{-}IBM} = 0.35\text{-}0.71$

g_A^{eff} is highly dependent on the model calculations and assumptions made

Barea, Kotila, Iachello, PRC 87, 014315 (2013)

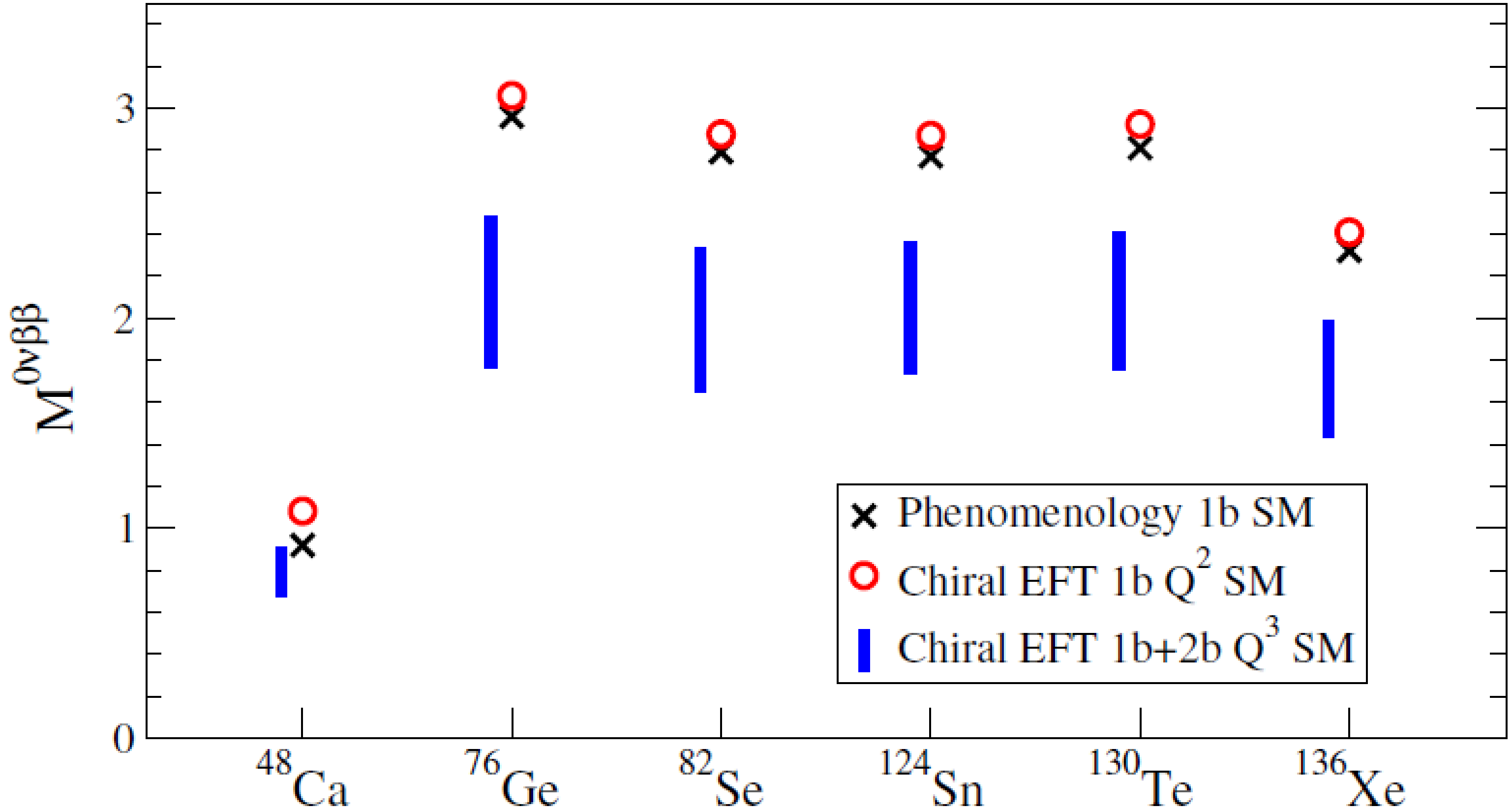
Is g_A^{eff} different for different (A,Z) and different spin-dependent transition operators?

Quenching of g_A and two-body currents

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

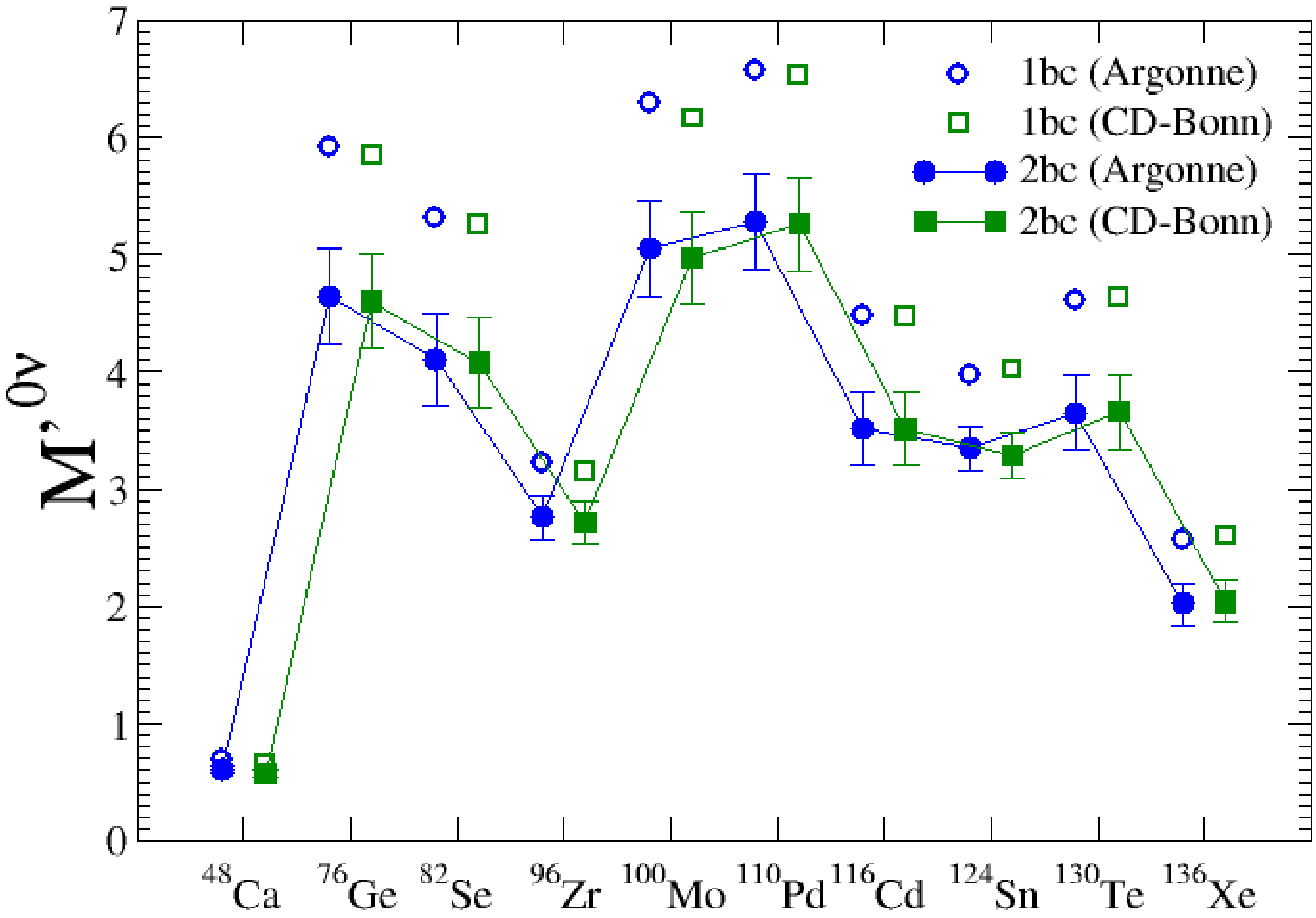
$$\mathbf{J}^{\mathrm{eff}}_{i,2b} = -g_A \boldsymbol{\sigma}_i \tau_i^- \frac{\rho}{F_\pi^2}\left[\frac{2}{3}c_3\frac{p^2}{4m_\pi^2+p^2} + I(\rho,P)\left(\frac{1}{3}(2c_4-c_3)+\frac{1}{6m}\right)\right] = -g_A \delta(p) \boldsymbol{\sigma}_i \tau_i^-$$

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

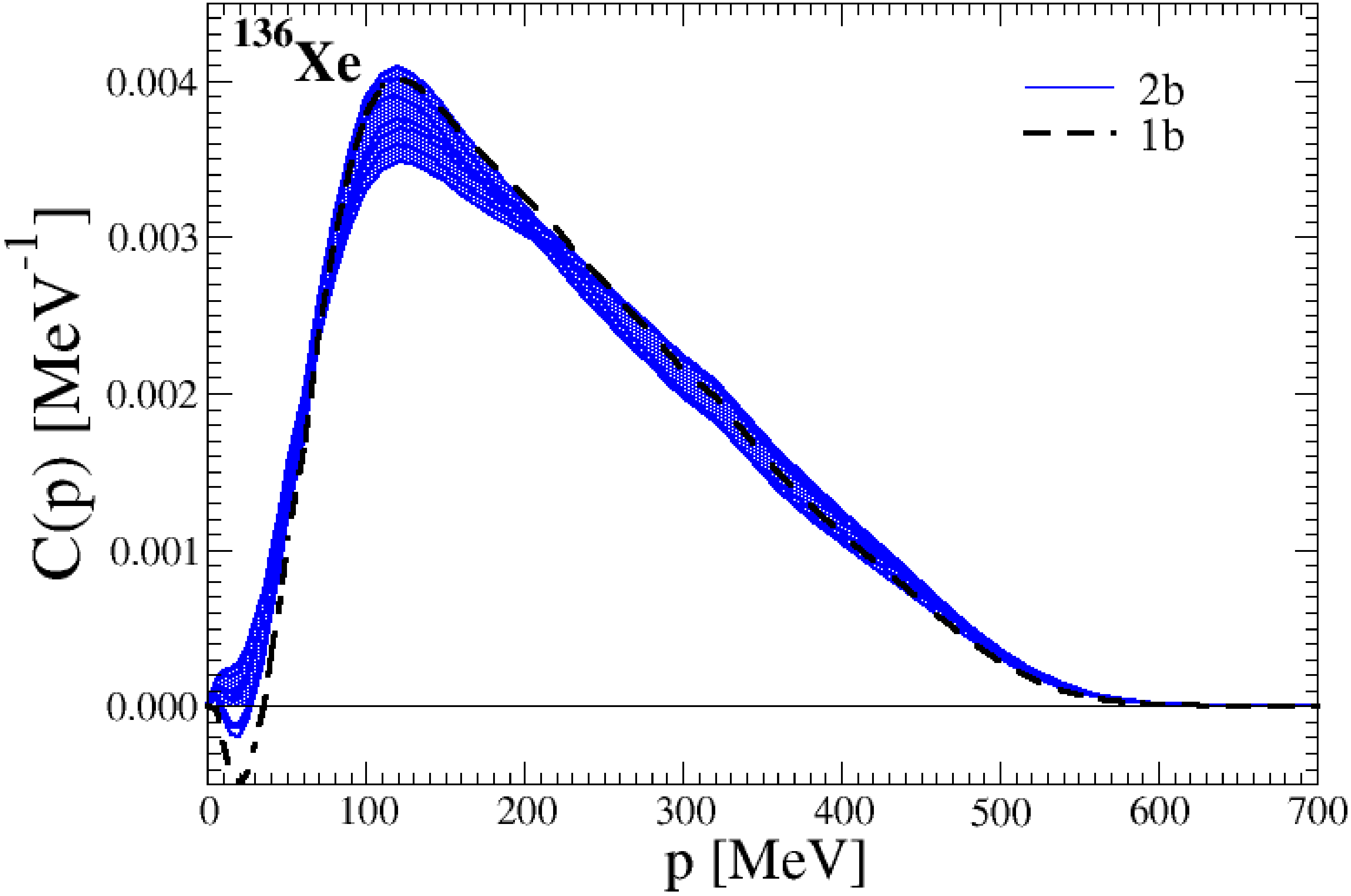
(Suppression of about 20%)



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

Momentum distribution of NME normalized to unity

<p> ≈ 230 MeV, sqrt(<p^2>) ≈ 250 MeV

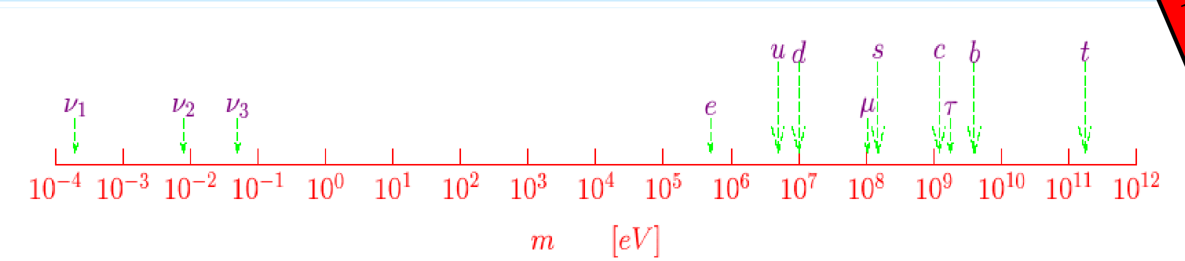


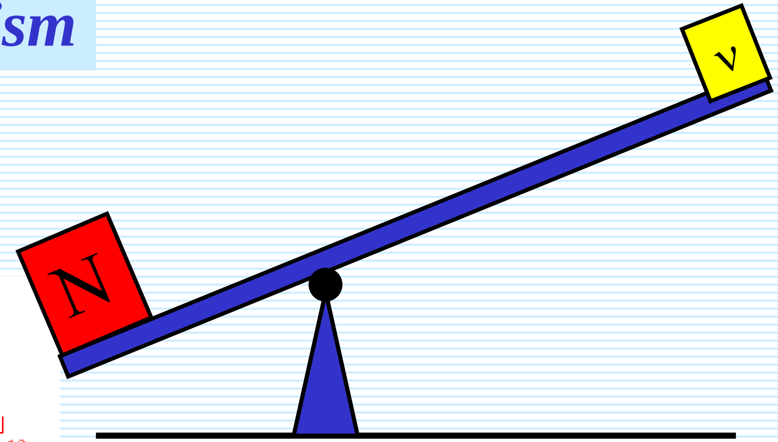
The $0\nu\beta\beta$-decay mechanisms with light and heavy neutrinos

Assumption $M_R \gg m_D$

See-Saw mechanism

$$\begin{pmatrix} \overline{\nu}_L & \overline{(\nu_R)^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ \nu_R \end{pmatrix}$$





Left-right symmetric models SO(10)

$$\nu_{eL} = \sum_{i=1}^{light} U_{ei}\chi_{iL} + \sum_{i=1}^{heavy} U_{ei}N_{iL}$$

large **small**

$$(\nu_{eR})^c = \sum_{i=1}^{light} V_{ei}\chi_{iL} + \sum_{i=1}^{heavy} V_{ei}N_{iL}$$

small **large**

Probability of Neutrino Oscillations

As N increases, the formalism gets rapidly more complicated!

N	Δm_{ij}^2	θ_{ij}	CP
2	1	1	0+1
3	2	3	1+2
6	5	15	10+5

Why TeV Seesaws?

Is the seesaw scale very close to a fundamental physics scale?

How heavy are the heavy Majorana neutrinos or the Higgs triplet?

10^{19} GeV — **Planck**

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]

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

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

General case

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

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

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

Particular cases

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

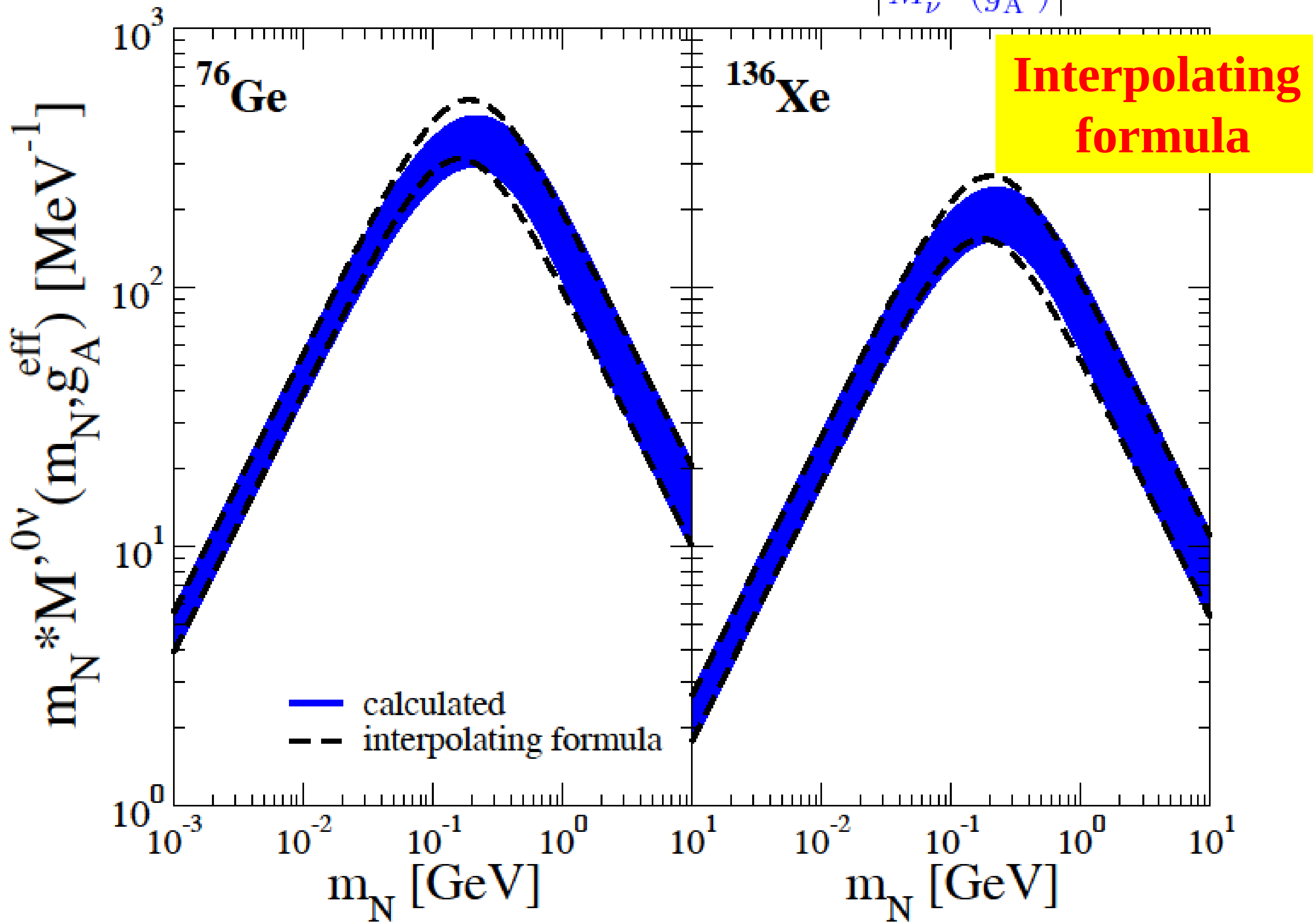
$$\langle m_\nu \rangle = \sum_N U^2_{eN} m_N$$

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

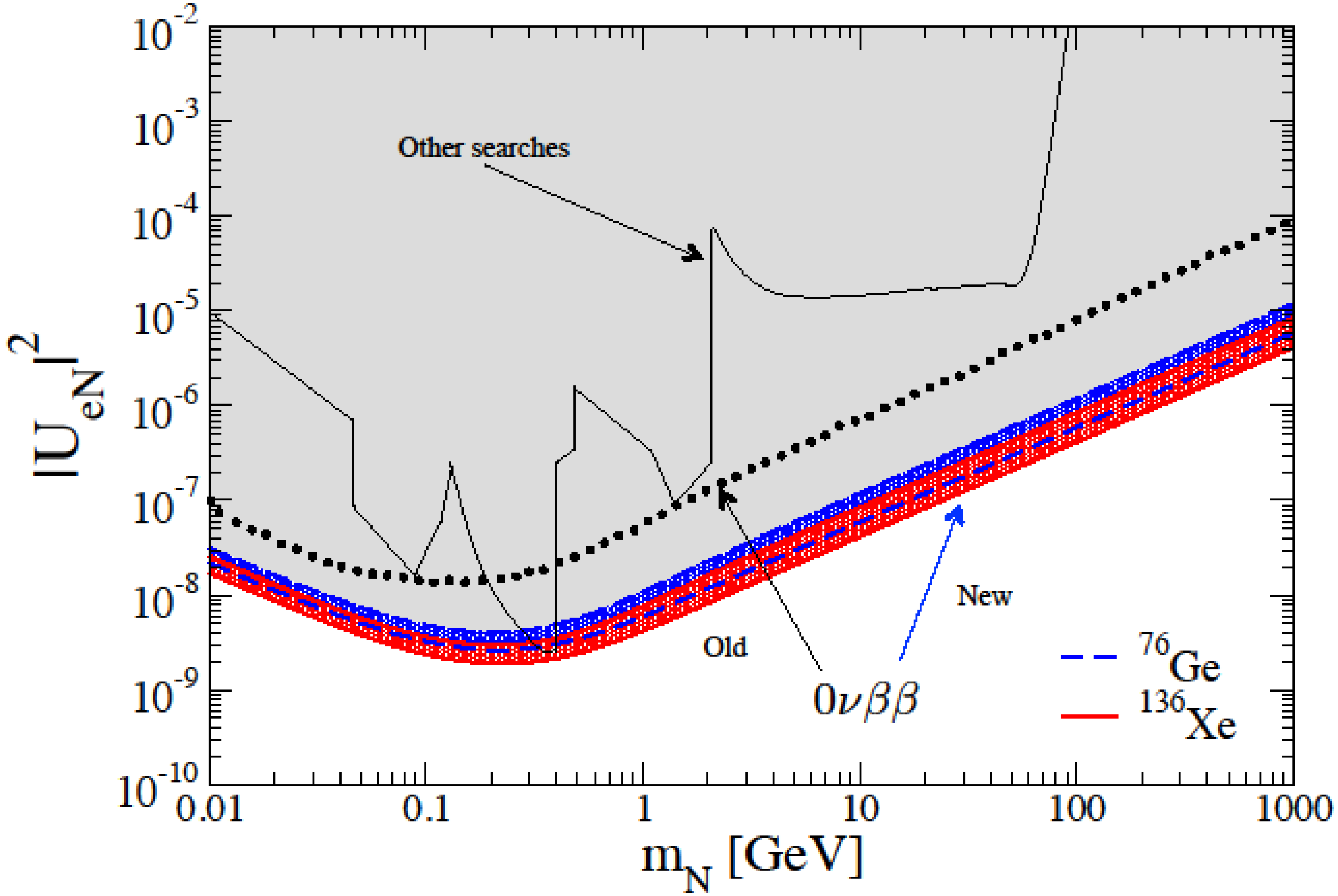
$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A} \cdot \left| m_p \sum_N U^2_{eN} \frac{m_N}{\langle p^2 \rangle + m_N^2} \right|^2 ,$$

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

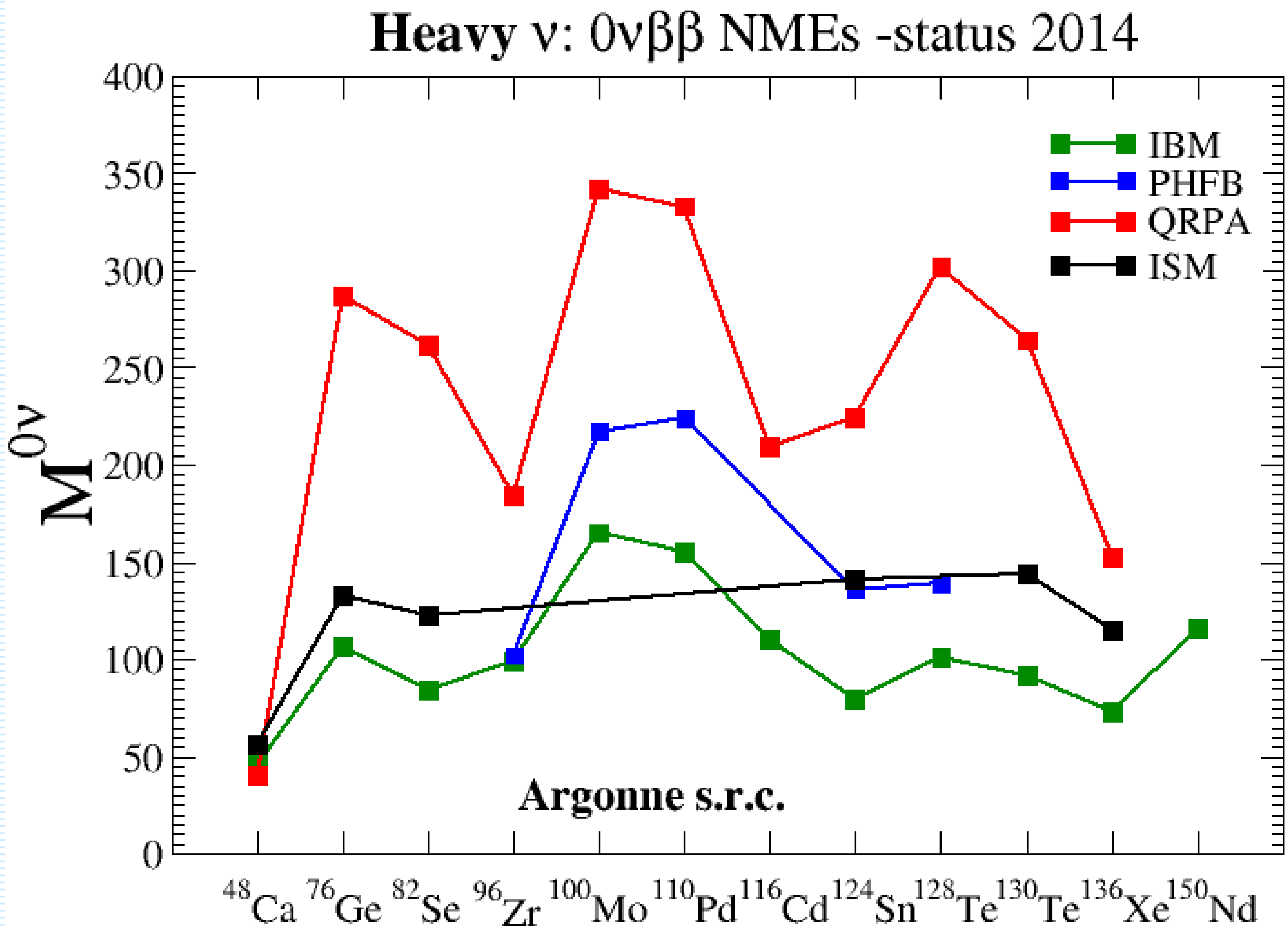
$$\langle p^2 \rangle = m_p m_e \left| \frac{M'^{0\nu}_N (g_A^{\rm eff})}{M'^{0\nu}_\nu (g_A^{\rm eff})} \right|^{\cancel{2}} \approx 200 \quad MeV$$



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



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

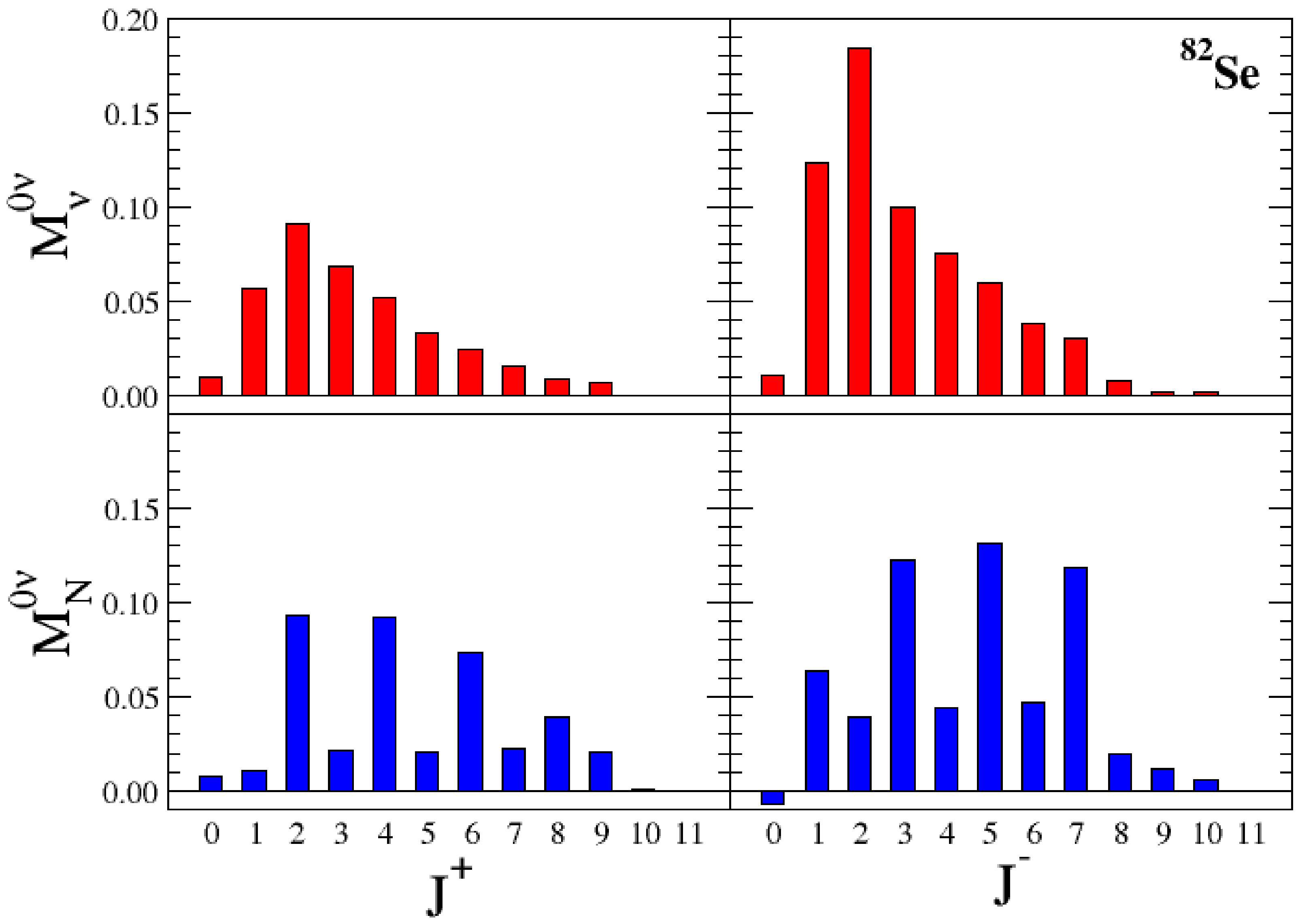


PHFB: **K. Rath et al., PRC 85 (2012) 014308**
IBM: **Barea, Kotila, Iachello, PRC (2013) 014315**

Fedo

QRPA: **Faessler, Gonzales, , F. Š., Kovalenko, PRD 90 (2014) 096010 ``Vergados, Ejiri, F. Š., RPP 75 (2012) 106301**
ISM: Menendez, privite communications

Multipole decomposition of NMEs normalized to unity

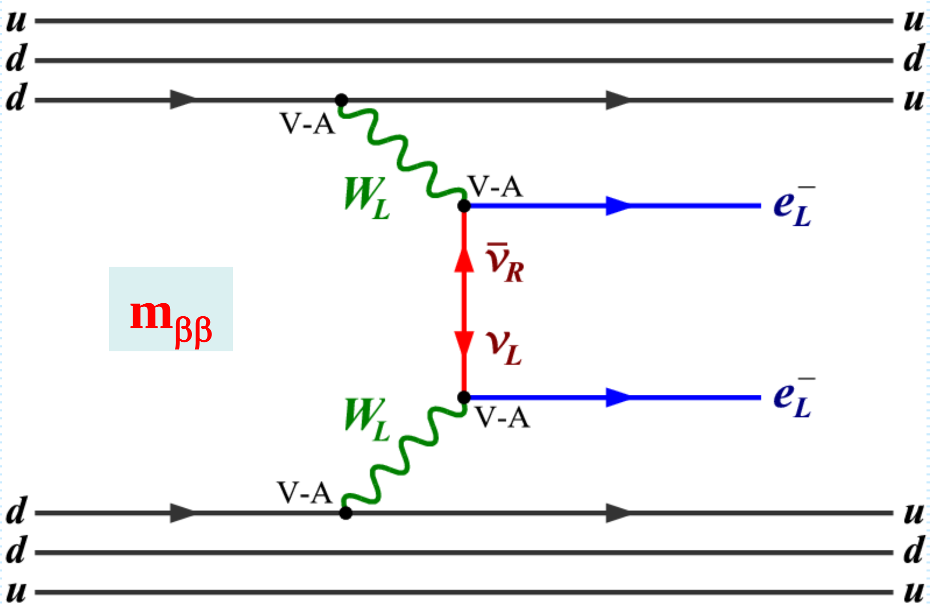


The $0\nu\beta\beta$-decay with right-handed currents revisited (exchange of light neutrinos)

D. Štefánik, R. Dvornický, F.Š., P. Vogel, arXiv:1506.07145 [hep-ph], accepted in PRC

Which of the mechanisms is the most important?

$m_{\beta\beta} = \Sigma_j U_{ej} U_{ej} m_j$	**Majorana neutrino mass**
$\langle\eta\rangle = \eta \Sigma_j U_{ej} V_{ej}$	W_L-W_R **mixing**
$\langle\lambda\rangle = \lambda \Sigma_j U_{ej} V_{ej}$	W_L-W_R **exchange**



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

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

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

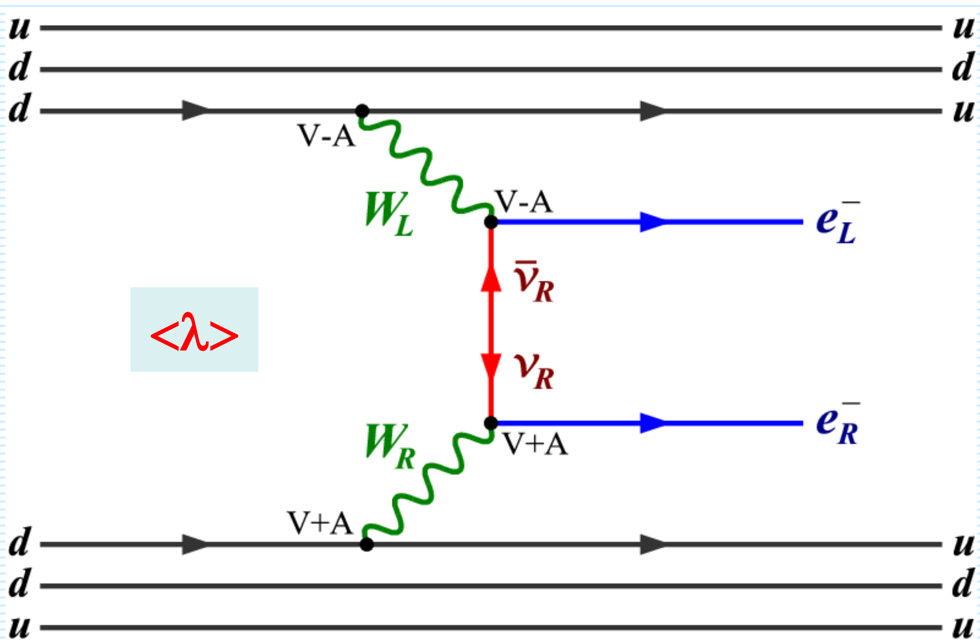
$$j_R^{\ \rho} = \bar{e}\gamma_\rho(1+\gamma_5)\nu_{eR}$$

Left-right symmetric models SO(10)

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

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

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



Fedor

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

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

Basis

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

6x6 neutrino mass matrix

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

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

15 angles, 10+5 phases

Decomposition

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

Type seesaw I

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

Approximation

$$U_0 \simeq V_0$$

LNV parameters

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

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

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

The 0νββ-decay rate with right-handed currents

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

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

The induced pseudoscalar term included

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

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

Different types of electron wave functions

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

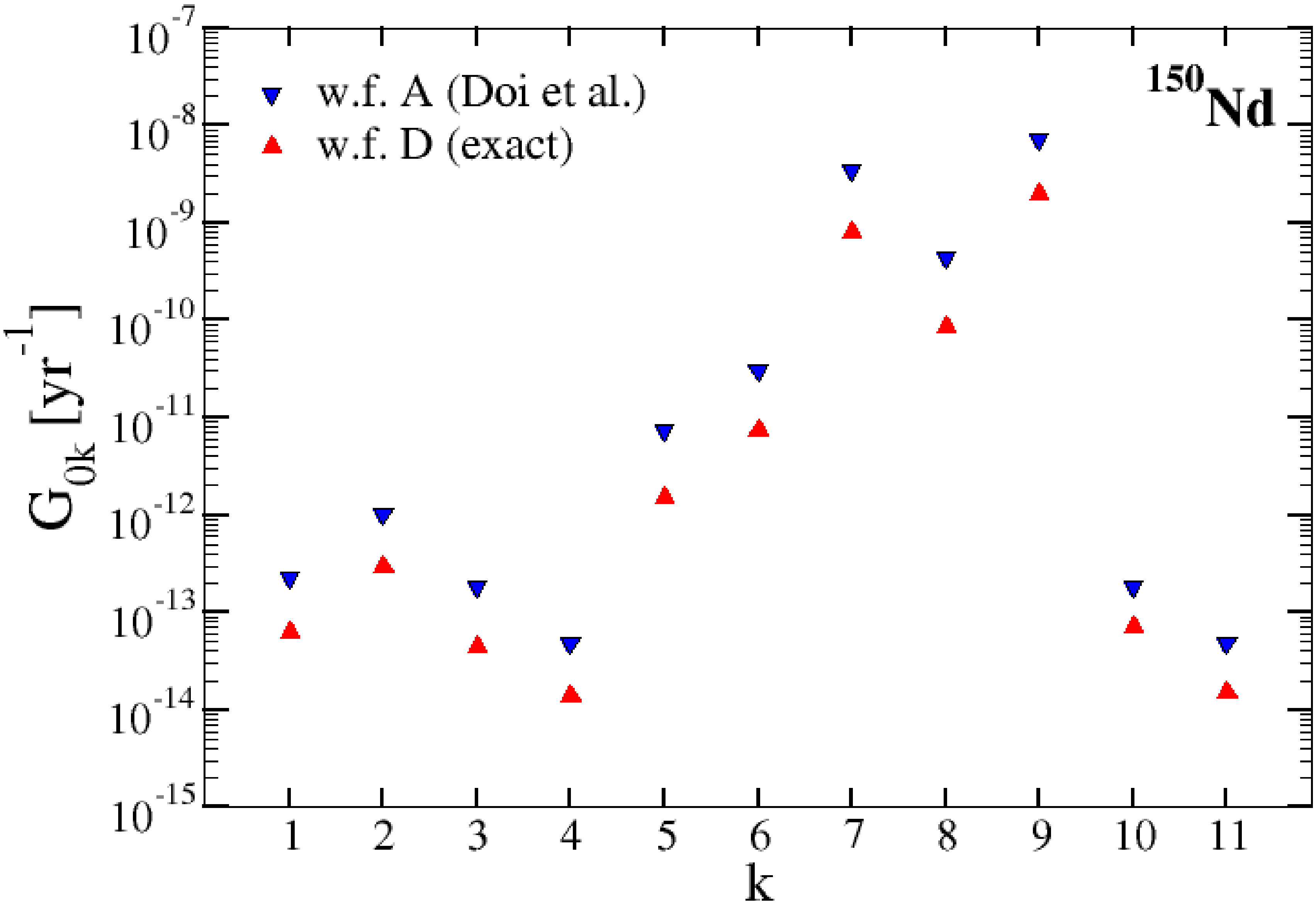
w.f. A (Doi et al.), uniform charge distribution, only the lowest term in expansion r/R

$$\begin{pmatrix} g_{-1}(\varepsilon,r) \\ f_{+1}(\varepsilon,r) \end{pmatrix} \approx \sqrt{F_0(Z_f,\varepsilon)} \begin{pmatrix} \sqrt{\frac{\varepsilon+m_e}{2\varepsilon}} \\ \sqrt{\frac{\varepsilon-m_e}{2\varepsilon}} \end{pmatrix}$$

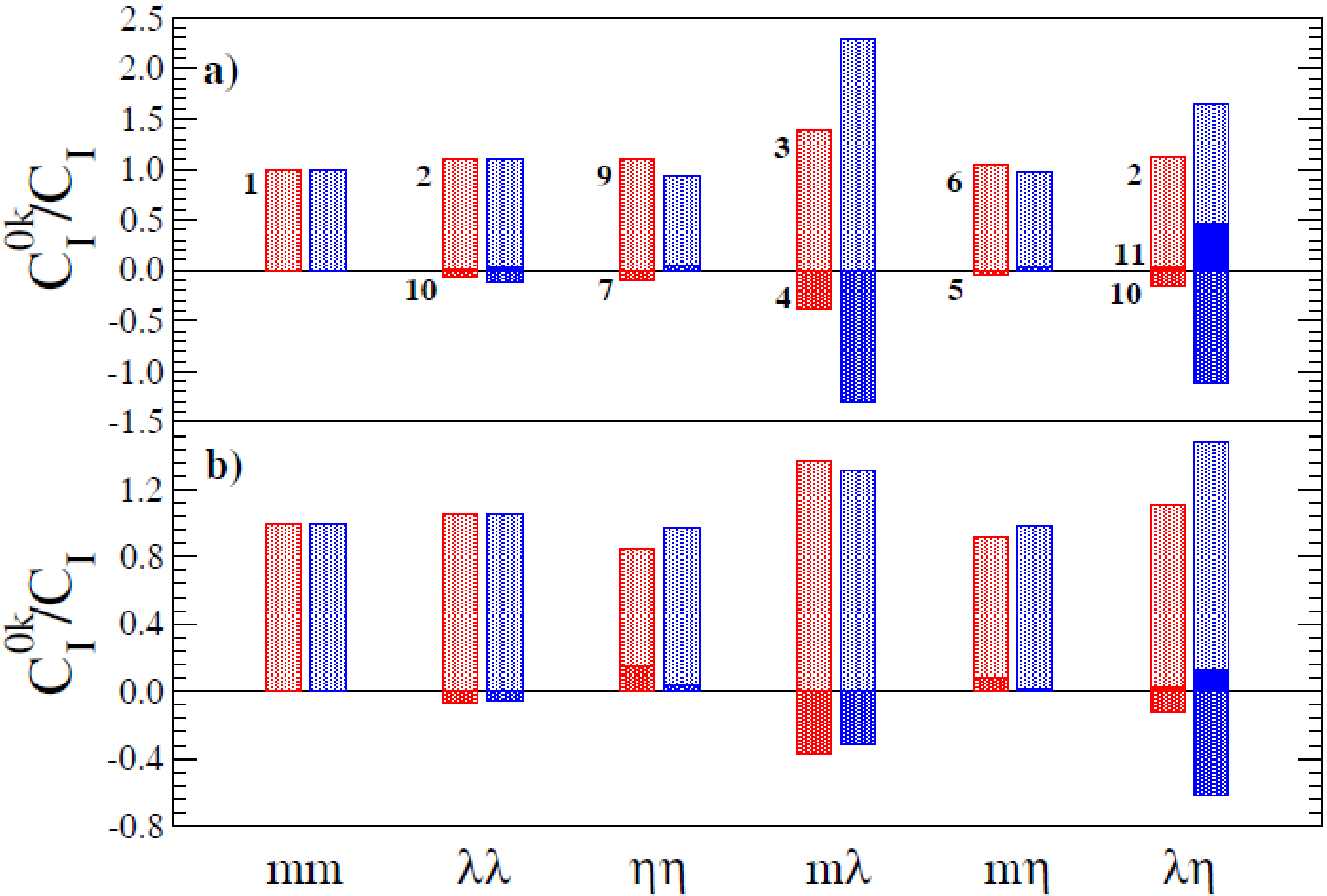
$$\begin{pmatrix} g_{+1}(\varepsilon,r) \\ f_{-1}(\varepsilon,r) \end{pmatrix} \approx \sqrt{F_0(Z_f,\varepsilon} \begin{pmatrix} \sqrt{\frac{\varepsilon-m_e}{2\varepsilon}}[\alpha Z_f/2 + (\varepsilon+m_e)r/3] \\ -\sqrt{\frac{\varepsilon+m_e}{2\varepsilon}}[\alpha Z_f/2 + (\varepsilon-m_e)r/3] \end{pmatrix}$$

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

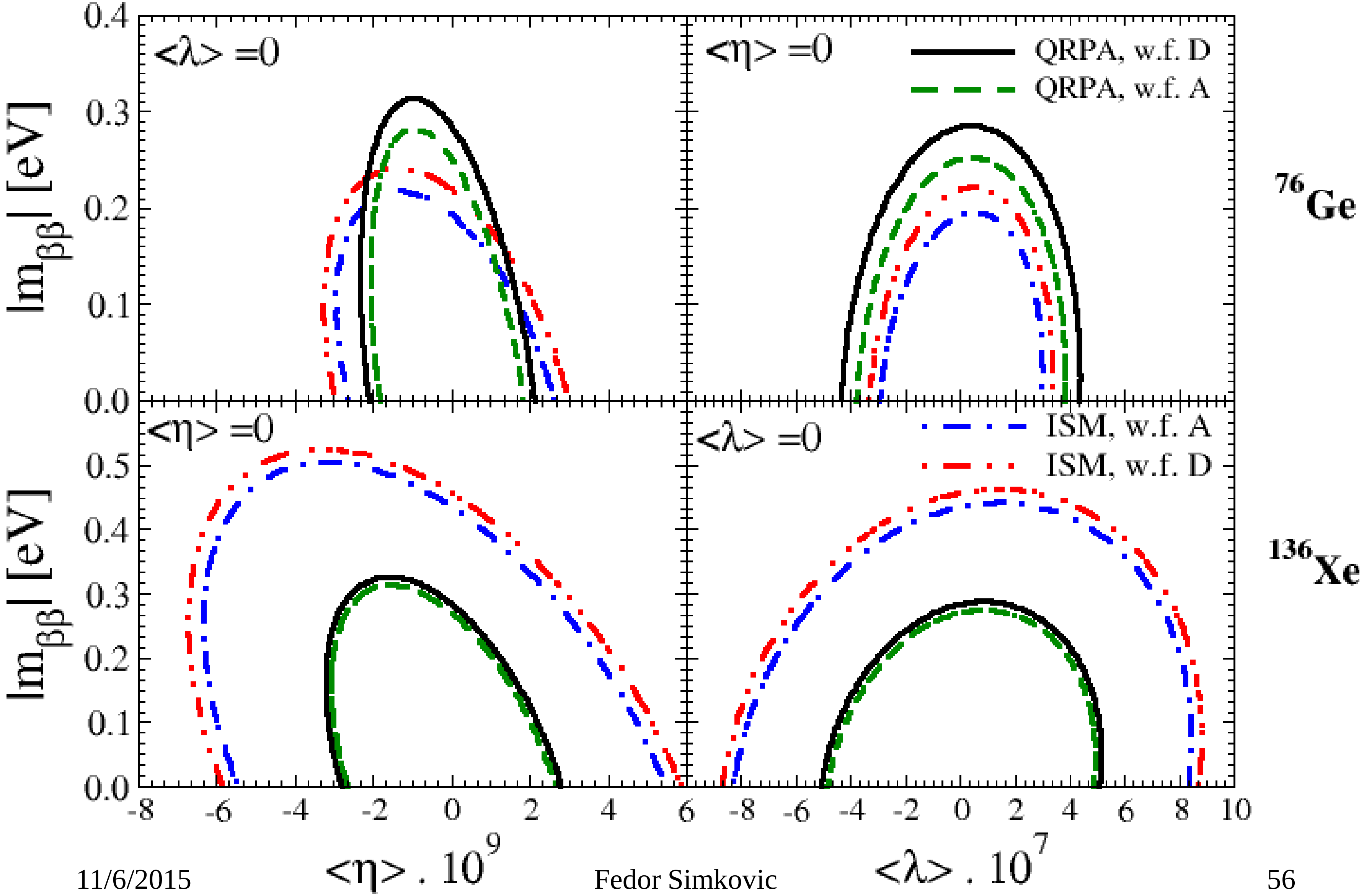
Phase-space factors for ^{150}Nd



Importance of contribution associated with G_{0k} for a given mechanism



Constraints on LNV mechanisms from the GERDA and EXO+KamLAND-Zen half-life limits



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

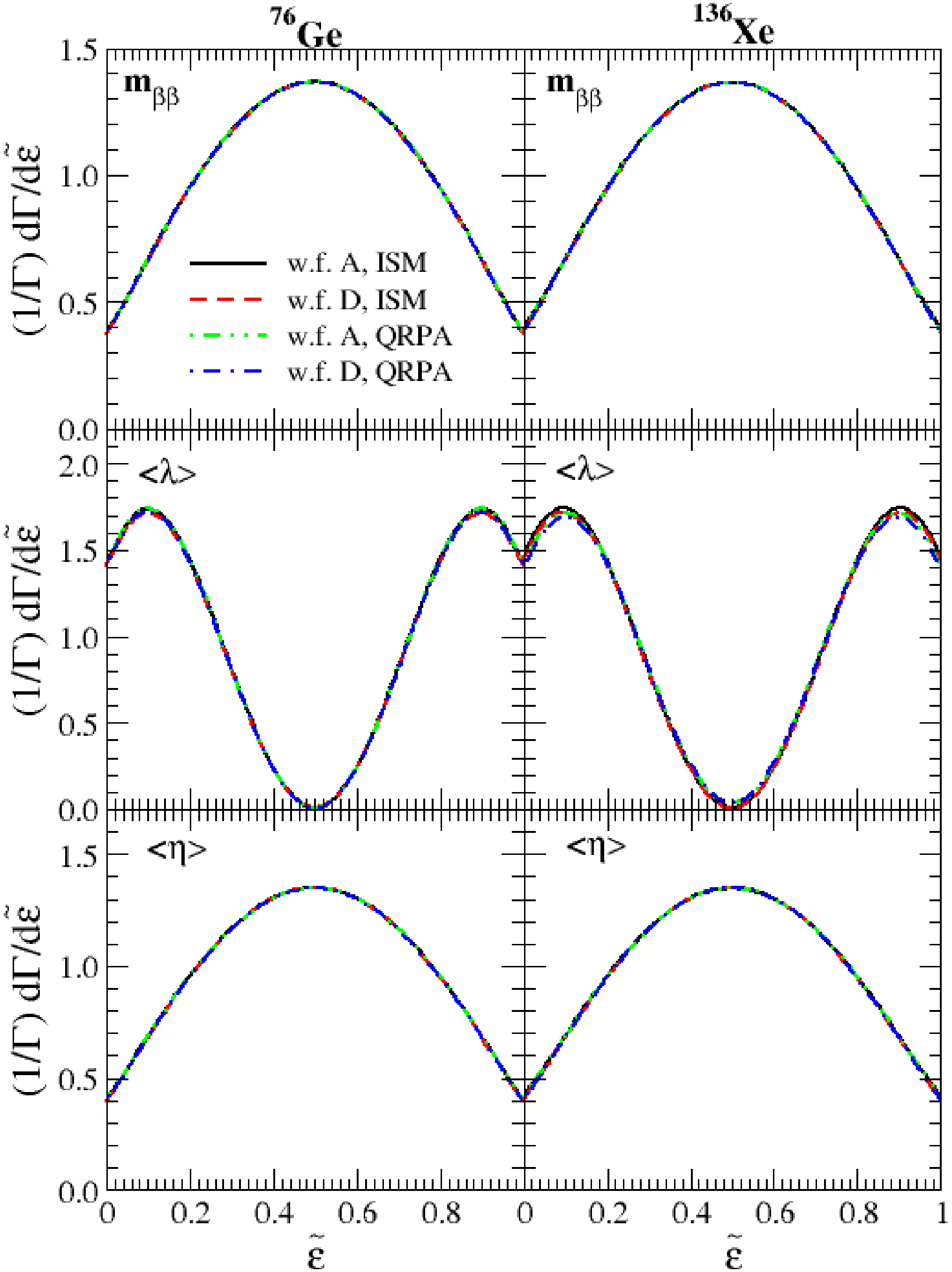
	^{76}Ge		^{136}Xe	
w.f.	A	D	A	D
		QRPA		
$\lvert m_{\beta\beta}\rvert$ [eV]	0.321	0.333	0.285	0.315
$\lvert m_{\beta\beta}\rvert$ [eV] (for $\langle\eta\rangle = \langle\eta\rangle = 0$)	0.271	0.284	0.251	0.285
$\langle\eta\rangle \times 10^{-9}$	3.093	3.239	2.077	2.337
$\langle\lambda\rangle \times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

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

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

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

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



SuperNEMO experiment could see it

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

Results do not depend on isotope, NME and type of w.f.

i) Case $m_{\beta\beta} \neq 0$

$(\langle\lambda\rangle = 0$ and $\langle\eta\rangle = 0)$

ii) Case $\langle\lambda\rangle \neq 0$

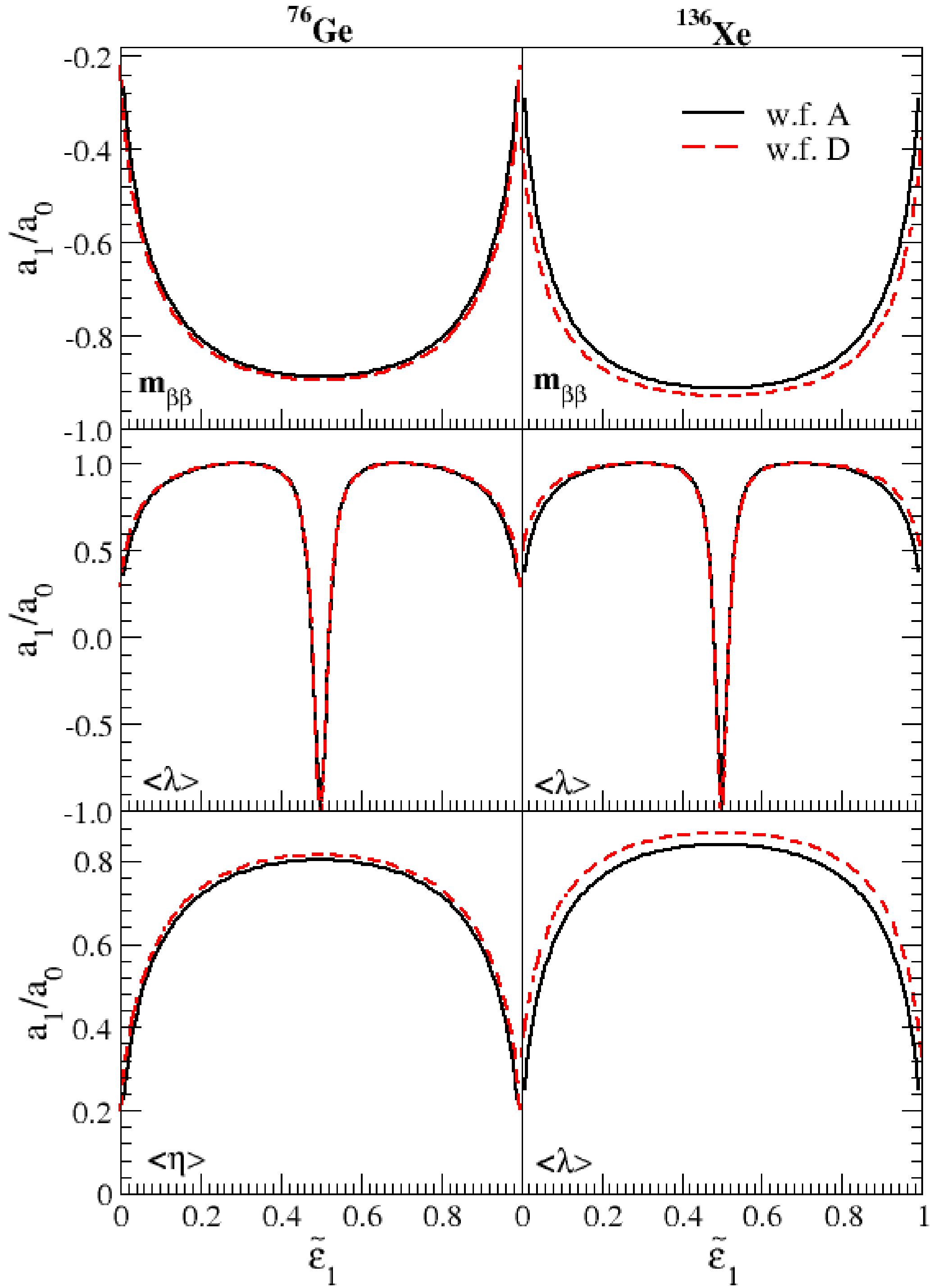
$(m_{\beta\beta} = 0$ and $\langle\eta\rangle = 0)$

iii) Case $\langle\eta\rangle \neq 0$

$(m_{\beta\beta} = 0$ and $\langle\lambda\rangle = 0)$

$$\varepsilon_1 = \tilde{\varepsilon}_1 Q_{\beta\beta} + m_e$$

$$\varepsilon_2 = Q_{\beta\beta} + 2m_e - \varepsilon_1)$$



Angular correlation factor as function of electron energy

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

SuperNEMO experiment could see it

Neutrinoless Double-Electron Capture

$$(A,Z) \to (A,Z-2)^{**}$$

Additional modes of the 0νECEC-decay:

$$
\begin{aligned}
e_b + e_b + (A,Z) \to (A,Z-2) &+ \gamma \\
&+ 2\gamma \\
&+ e^+e^- \\
&+ M
\end{aligned}
$$

Neutrinoless double electron capture (resonance transitions)

$(A,Z)\rightarrow(A,Z\text{-}2)^{*HH'}$

J. Bernabeu, A. DeRujula, C. Jarlskog, Nucl. Phys. B 223, 15 (1983)

Atom mixing amplitude
ΔM

$$E \simeq E^{*} + E_{\mathrm{H}} + E_{\mathrm{H}'},$$

$$\Gamma \simeq \Gamma^{*} + \Gamma_{\mathrm{H}} + \Gamma_{\mathrm{H}'}.$$

Decay rate

$$\frac{1}{\tau} \simeq \frac{(\Delta M)^2}{(Q-E)^2 + \frac{1}{4}\Gamma^2}\Gamma,$$

2νECEC-background depends strongly on Q-value

DEC transitions, abundance, daughter nuclear excitation, atomic vacancies and figure of merit of some isotopes [10]

Transition $Z \rightarrow Z-2$	Z-natural abundance in %	Nuclear excitation E^* (in MeV), J^P	Atomic vacancies H, H′	Figure of merit $Q-E$ (in keV)
${}^{74}_{34}\mathrm{Se} \rightarrow {}^{74}_{32}\mathrm{Ge}$	0.87	1.204 (2^+)	2S(P), 2S(P)	2 ± 3
${}^{78}_{36}\mathrm{Kr} \rightarrow {}^{78}_{34}\mathrm{Se}$	0.36	2.839 (2^+) 2.864 (?)	1S, 1S	${}^{19}_{-6} \pm 10$
${}^{102}_{46}\mathrm{Pd} \rightarrow {}^{102}_{44}\mathrm{Ru}$	1	1.103 (2^+) 1.107 (4^+)	1S, 1S	${}^{29}_{25} \pm 9$
${}^{106}_{48}\mathrm{Cd} \rightarrow {}^{106}_{46}\mathrm{Pd}$	1.25	2.741 (?)	1S, 1S	-8 ± 10
${}^{112}_{50}\mathrm{Sn} \rightarrow {}^{112}_{48}\mathrm{Cd}$	1.01	1.871 (0^+)	1S, 1S	-3 ± 10
${}^{130}_{56}\mathrm{Ba} \rightarrow {}^{130}_{54}\mathrm{Xe}$	0.11	2.502 (?) 2.544 (?)	1S, 1S 1S, 2S(P)	${}^{8}_{-6} \pm 13$
${}^{152}_{64}\mathrm{Gd} \rightarrow {}^{152}_{62}\mathrm{Sm}$	0.20	0 (0^+)	1S, 2S	4 ± 4
${}^{162}_{68}\mathrm{Er} \rightarrow {}^{162}_{66}\mathrm{Dy}$	0.14	1.783 (2^+)	1S, 2S	1 ± 6
${}^{164}_{68}\mathrm{Er} \rightarrow {}^{164}_{66}\mathrm{Dy}$	1.56	0 (0^+)	2S, 2S	9 ± 5
${}^{168}_{70}\mathrm{Yb} \rightarrow {}^{168}_{68}\mathrm{Er}$	0.14	1.355 (1^-) 1.393 (?)	1S, 2S 2S, 2S	${}^{-1}_{8} \pm 4$
${}^{180}_{74}\mathrm{W} \rightarrow {}^{180}_{72}\mathrm{Hf}$	0.13	0 (0^+) 0.093 (2^+)	1S, 1S 1S, 3S	${}^{26}_{-4} \pm 17$
${}^{196}_{80}\mathrm{Hg} \rightarrow {}^{186}_{78}\mathrm{Pt}$	0.15	0.689 (2^+)	1S, 2S	26 ± 9

Oscillations of atoms

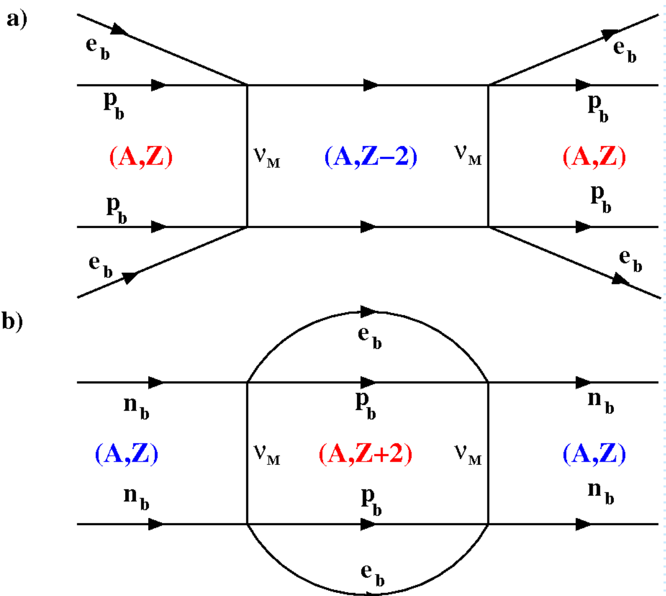
$$H^{atom}_{eff} = \begin{pmatrix} M_i & V^{LNV} \\ V^{LNV} & M_f - \frac{i}{2}\Gamma \end{pmatrix}$$

Oscillation of atoms
(lepton number violation)

F.Š., M. Krivoruchenko, Phys.Part.Nucl.Lett. 6 (2009) 485.

In analogy with oscillations of
n-anti{n} (baryon number violation)

$$H^{n\bar{n}}_{eff} = \begin{pmatrix} M & V^{BNV} \\ V^{BNV} & M - \frac{i}{2}\Gamma \end{pmatrix}$$



Oscillations of stable atoms **(Γ=0)**

$$|<f|e^{-iH_{eff}t}|i>|^2 = \frac{4V^2}{(M_i - M_f)^2}\sin^2\left[t\,(M_i - M_f)/2\right]$$

$${}^{164}_{68}Er \rightarrow {}^{164}_{66}Dy$$
$$(M_i - M_f) = 24.1\ keV$$

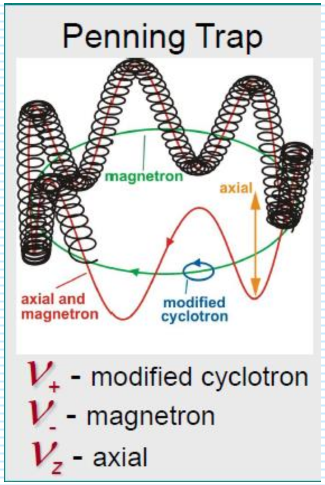
$$|<f|e^{-iH_{eff}t}|i>|^2 \leq 3\ 10^{-55}$$

Oscillations of unstable atoms **(Γ≠0)**

Double electron capture
(resonant enhancement)

Improved Q-value measurements
Klaus Blaum (MPI Heidelberg)

nucl. tr.	Q_{old}	$E = B + E_\gamma$	Orbit.	$\Delta = Q(old) - E$	Q_{new}	$\Delta = Q(new) - E$
$^{112}Sn \to ^{112}Cd$	1919.5(4.8)	1901.7	KL_1	17.8(4.8)	1919.82(16)	18.12(16)
		1924.4	KK	-4.9(4.8)		-4.56(16)
$^{152}Gd \to ^{152}Sm$	54.6(3.5)	54.79+0	KL_1	-0.19(3.50)	55.70(18)	0.91(18)
$^{164}Er \to ^{164}Dy$	23.3(3.9)	18.09	l_1L_1	5.21(3.90)		



$^{152}Gd \to ^{152}Sm$ **(Eliseev, et al., F.Š, M. Krivoruchenko, PRL 106, 052504 (2011))**
(F.Š., Krivoruchenko, Faessler, PPNP 66, 446 (2011)

$$T^{0\nu}_{1/2} = 4 \times 10^{26} \left(\frac{1\ \mathrm{eV}}{m_{\beta\beta}}\right)^2 \ \text{years.}$$

Remeasured Q-value: **^{112}Sn, ^{74}Se, ^{136}Ce, ^{96}Ru, ^{152}Gd, ^{162}Er, ^{168}Yb, ^{106}Cd, ^{156}Dy, ^{180}W, ^{124}Xe, ^{130}Ba, ^{184}Os, ^{190}Pt**

A comparison

Resonance enhancement of neutrinoless double electron capture
M.I. Krivoruchenko, F. Š., D. Frekers, and A. Faessler,
Nucl. Phys. A 859, 140-171 (2011)

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

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

Perturbation theory

$$\frac{1}{T^{0\nu}_{1/2}} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 \; G^{01}(E_0,Z) \; \left|M^{0\nu}\right|^2$$

- 2νββ-decay background can be a problem
- Uncertainty in NMEs factor ~2, 3
- $0^+ \rightarrow 0^+, 2^+$ transitions
- Large Q-value
- ^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe …
- Many exp. in construction, potential for observation in the case of inverted hierarchy (2020)

Breit-Wigner form

$$\Gamma^{0\nu ECEC}(J^\pi) = \frac{|V_{\alpha\beta}(J^\pi)|^2}{(M_i - M_f)^2 + \Gamma^2_{\alpha\beta}/4}\,\Gamma_{\alpha\beta}$$

- 2νεε-decay strongly suppressed
- NMEs need to be calculated
- $0^+ \rightarrow 0^+, 0^-, 1^+, 1^-$ transitions
- Small Q-value
- Q-value needs to be measured at least with 100 eV accuracy
- ^{152}Gd, looking for additional
- small experiments yet

Instead of Conclusions

We are at the beginning of the Road…

The future of neutrino physics is bright.