Colloquium Prague v19

J. Heyrovsky Institute of Physical Chemistry, 24-25 October 2019

Neutrinoless Double Beta Decay Theory

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OUTLINE

I. *Introduction*

(Majorana ν's)

II. *The 0νββ-decay scenarios due neutrinos exchange*

(simpliest, sterile ν, LR-symmetric model)

III. *DBD NMEs – Current status*

(deformation, scaling relation?, exp. support, ab initio…)

IV. Quenching of g_A

(Ikeda sum rule, 2νββ-calc., novel approach for effective g_A)

V. *Looking for a signal of lepton number violation*

(LHC study, resonant 0νECEC …)

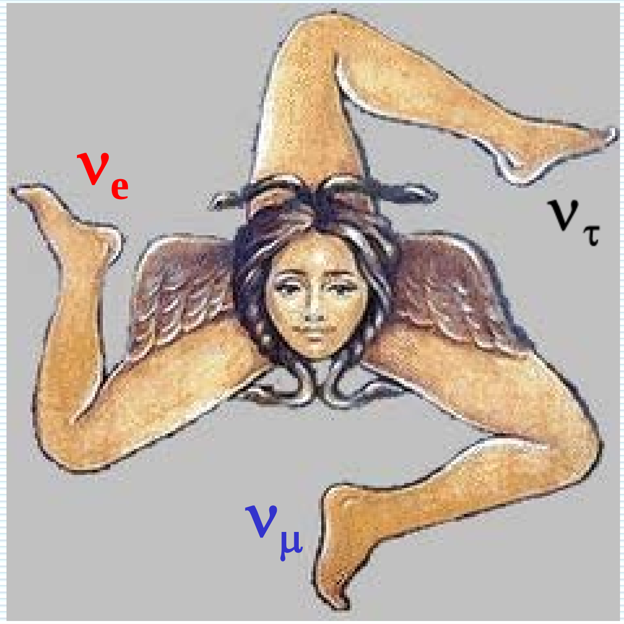
Acknowledgements: **A. Faessler (Tuebingen), P. Vogel (Caltech), S. Kovalenko (Valparaiso U.), M. Krivoruchenko (ITEP Moscow), D. Štefánik, R. Dvornický (Comenius U.), A. Babič, A. Smetana (IEAP CTU Prague), …**

After 89/63 years we know

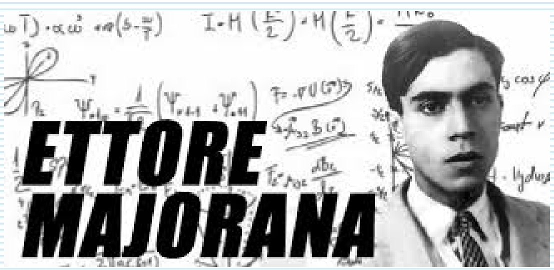
Fundamental ν properties

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)

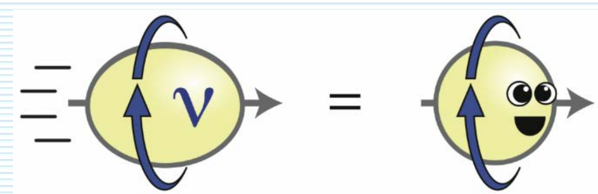


- Are ν Dirac or Majorana?
- Is there a CP violation in ν sector?
- Are neutrinos stable?
- What is the magnetic moment of ν?
- Sterile neutrinos?
- Statistical properties of ν? Fermionic or partly bosonic?



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

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 cosidetti « 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 accord ... isfacenti; sia perchè s ... trica, sia perchè la sir ... iante tali procedimenti ... che possibilmente dov ... uova via 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

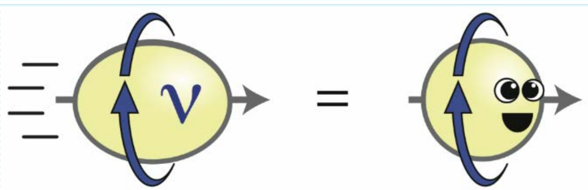
Submitted to JETP editor October 19, 1957

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

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

(neutrinos are Majorana particles)

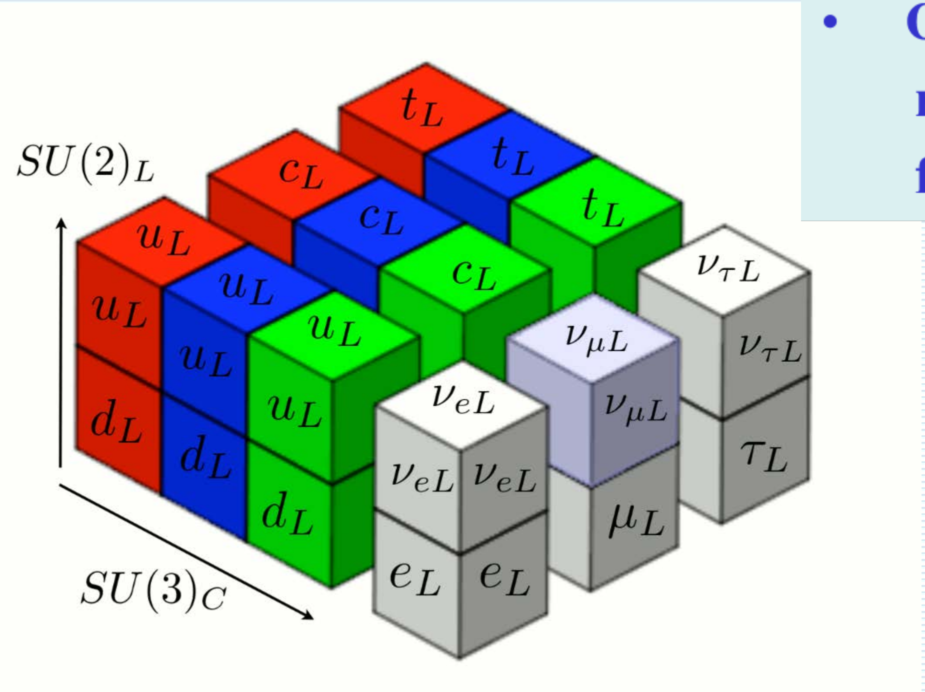
It follows from the above assumptions that in vacuum a neutrino can be transformed into an antineutrino and vice versa. This means that the neutrino and antineutrino are "mixed" particles, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 of different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



1968 Gribov, Pontecorvo [PLB 28(1969) 493]

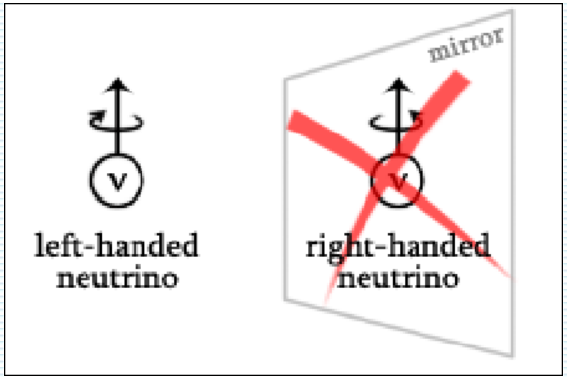
oscillations of neutrinos - a solution of deficit of solar neutrinos in Homestake exp.

Standard Model
(an astonishing successful theory, based on few principles)



Neutrino is a special particle in SM:

- **It is the only fermion that does not carry electric charge (like bosons γ, g, H^0) !**
- **In the SM, the only left-handed neutrinos ν_L appears in the theory.**
- **One cannot obtain a mass for ν_L with any renormalizable coupling with the Higgs fields through SSB.**



However, we know that ν's do have mass from the ν-oscillation experiments!
=> Thus the neutrino mass indicates that there is something new = BSM physics!

Majorana ν-mass => Lepton number violation

The absence of the RH ν fields in the SM is the simplest, most economical scenario. The ν-masses and mixing are generated by the L-number violating Majorana mass term coming from dimension-5 effective Weinberg operator:

$$L = \frac{\lambda (LH)(LH)}{\Lambda} + h.c.$$

(LH) is a SM singlet, Λ - mass scale, λ -dimensionless coupling. After SSB

$$L = \frac{\lambda v^2}{2\Lambda}(\nu_L \nu_L + h.c.)$$

The Majorana ν-mass term violates total lepton number

Make $\nu_L \to e^{i\phi}\nu_L$, L changes by $e^{2i\phi}$

Majorana Neutrinos

- LN violating
- $\nu = \nu^c$
- $\nu = \nu_L + (\nu_L)^c$

In the SM, The term like $\nu_L \nu_L$ is not allowed by SU(2)xU(1) => there is no natural Majorana mass term for the LH ν. However, dim-5 L-number non-conserving operator is allowed leading to a Majorana mass

$$m_M = \frac{\lambda v^2}{\Lambda}$$

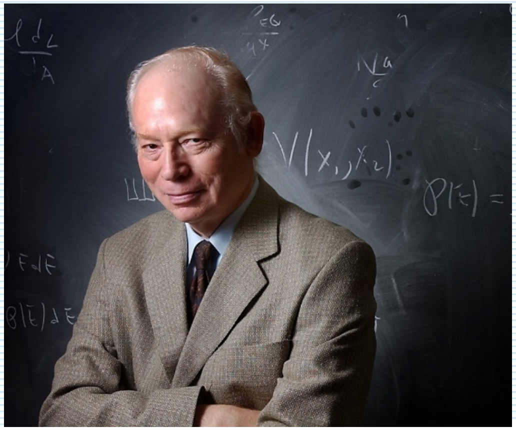
This is a seesaw formula, in the sense that small ν-mass can be understood when Λ is large. To get meV mass, we need

$$\Lambda = 10^{16} GeV \text{ (GUT scale)}$$

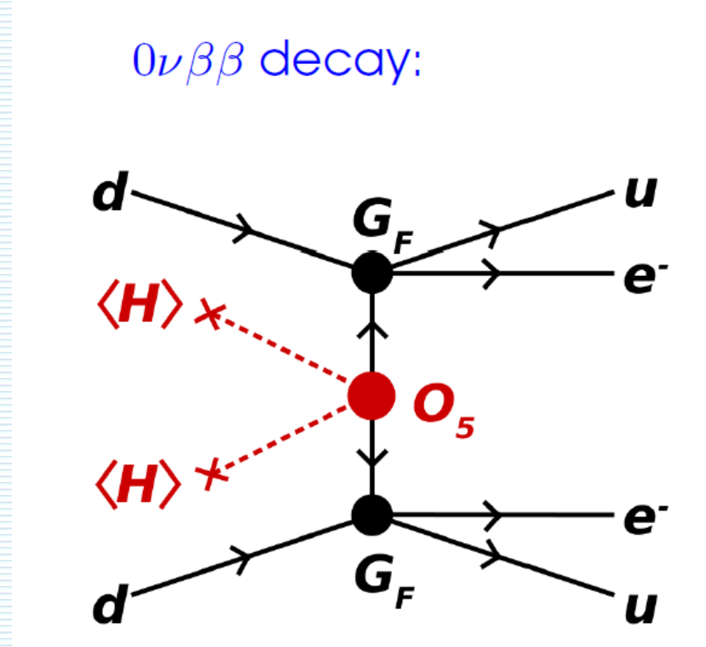
INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 57 NUMBER 9 NOVEMBER 2017



Weinberg, 1979: d=5

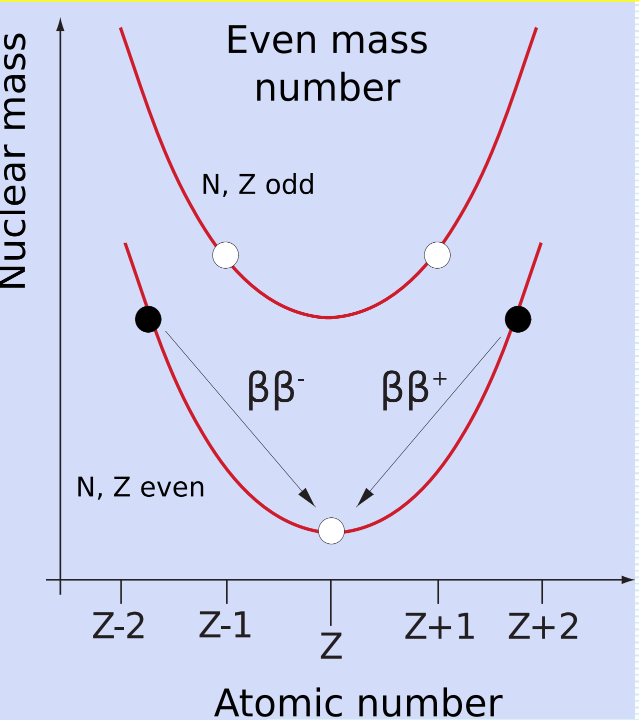


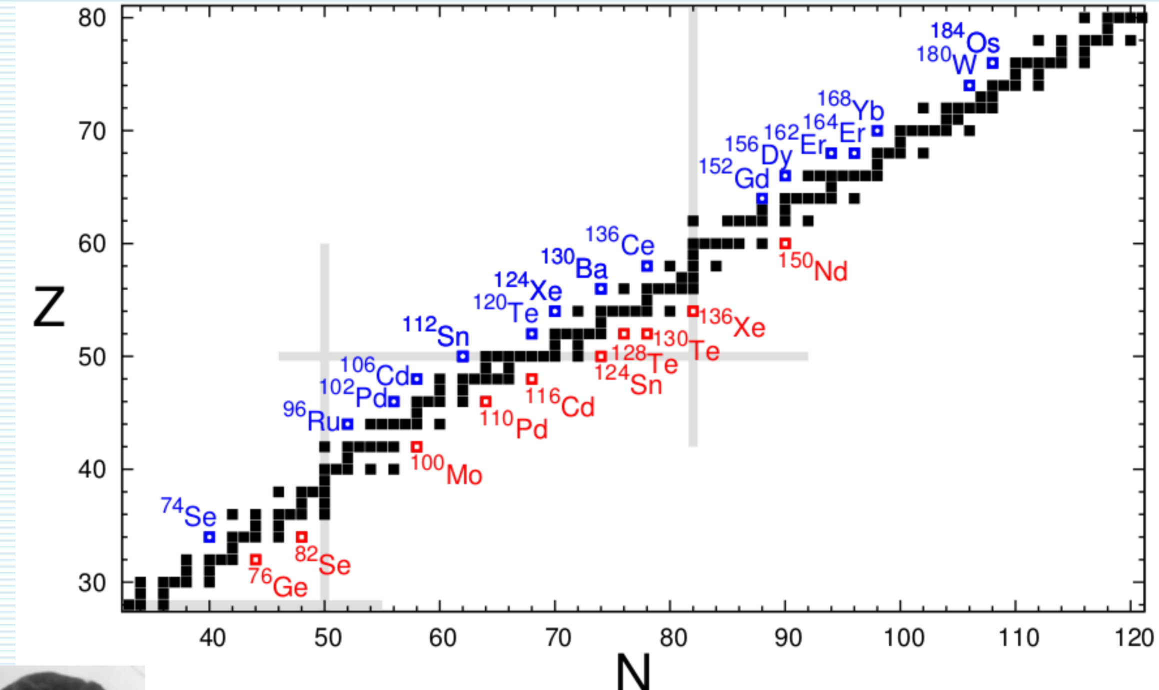
$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$

. 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."

II. The $0\nu\beta\beta$-decay scenarios

Nuclear double-β decay
(even-even nuclei, pairing int.)



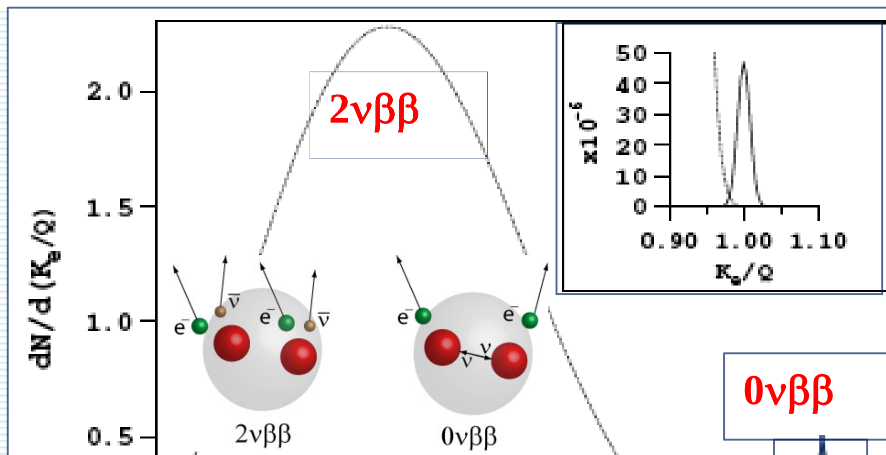


Phys. Rev. 48, 512 (1935)

Two-neutrino double-β decay – LN conserved

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

Goepert-Mayer – 1935. 1st observation in 1987



Nuovo Cim. 14, 322 (1937)

Phys. Rev. 56, 1184 (1939)

Neutrinoless double-β decay – LN violated

$$(A,Z) \rightarrow (A,Z+2) + e^- + e^- \quad \text{(Furry 1937)}$$

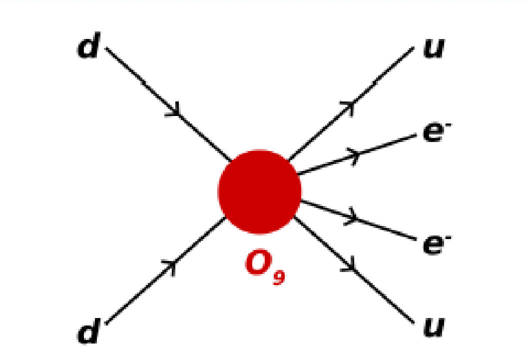
Not observed yet. Requires massive Majorana ν's

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact with active veto	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - III	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

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

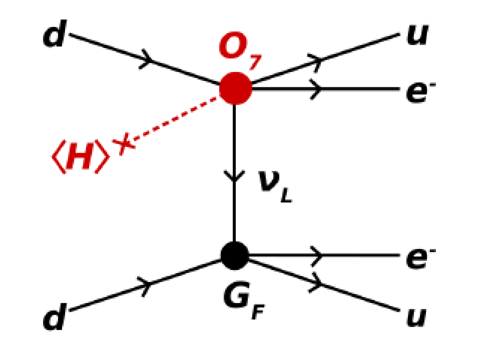
Beyond the SM physics

short range: d=9 (d=11)



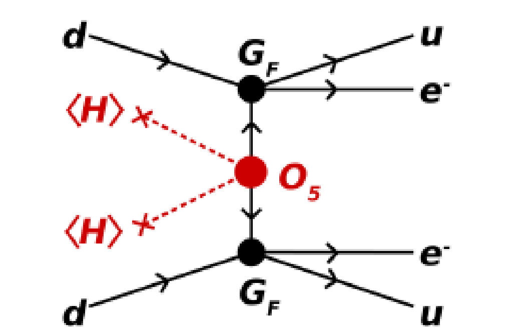
Amplitude for
(A,Z)→(A,Z+2)+2e⁻
can be divided into:

long range: d=7



mass mechanism: d=5

+



+

$\mathcal{O}_5 \propto LLQd^cHHH^\dagger$

$\mathcal{O}_6 \propto LL\bar{Q}\bar{u}^cHH^\dagger H$

$\mathcal{O}_7 \propto LQ\bar{e}^c\bar{Q}HHH^\dagger$

$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_iH)(L_jH)$

$\mathcal{O}_2 \propto LLLe^cH$

$\mathcal{O}_3 \propto LLQd^cH$

$\mathcal{O}_4 \propto LL\bar{Q}\bar{u}^cH$

$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^cd^cH$

$\mathcal{O}_9 \propto LLLe^cLe^c$

$\mathcal{O}_{10} \propto LLLe^cQd^c$

$\mathcal{O}_{11} \propto LLQd^cQd^c$

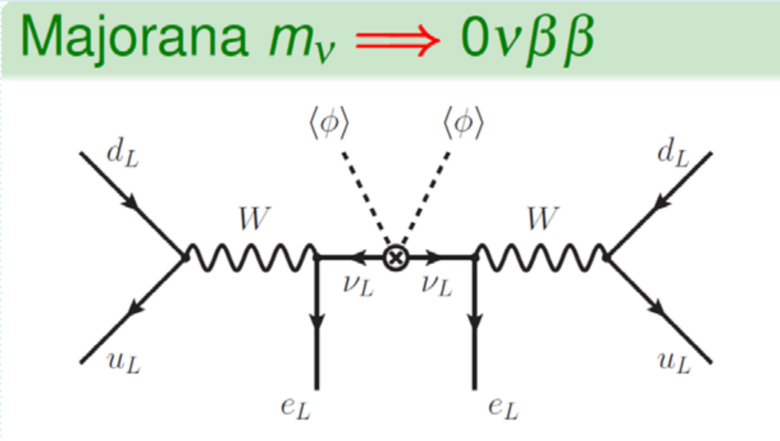
$\cdots\cdots$

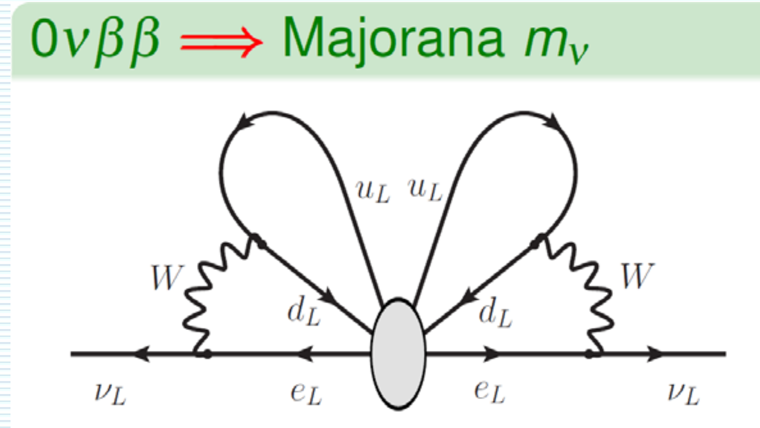
Valle

Weinberg, 1979

Babu, Leung: 2001
de Gouvea, Jenkins: 2007

If 0νββ is observed the ν is a Majorana particle

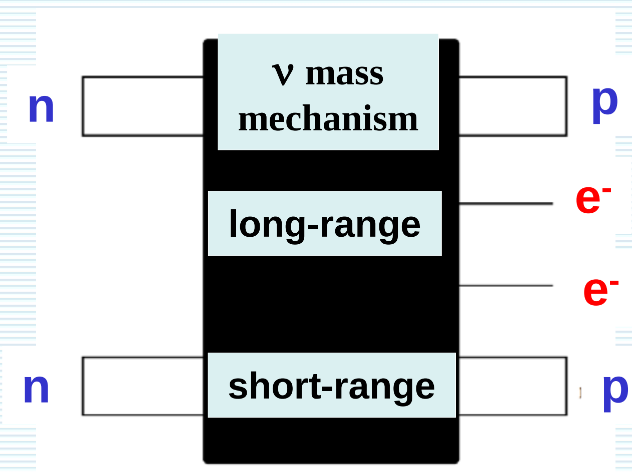




Schechter, Valle: PRD 1982

Different 0νββ-decay scenarios

Can we say something about content of the black box?

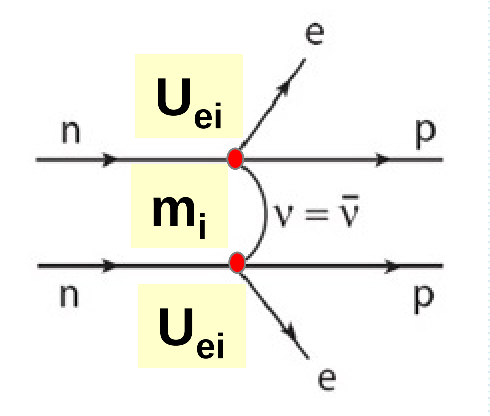


Considering

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

$0\nu\beta\beta$-decay *(V-A SM int., light ν-exchange)*

(A,Z) → (A,Z+2) + e⁻ + e⁻



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

?

Phase factor well understood

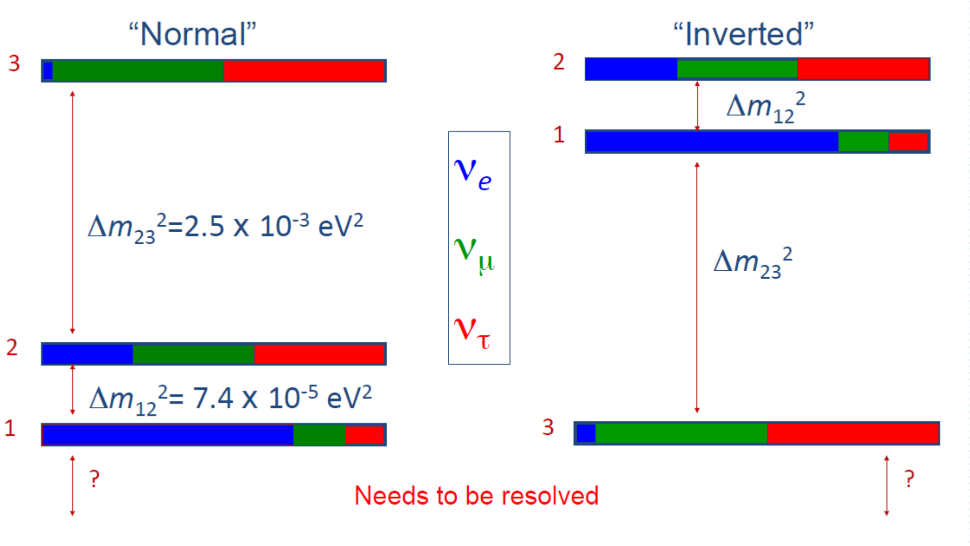
NME must be evaluated using tools of nuclear theory

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

Effective Majorana mass can be evaluated. It depends on

m_1, m_2, m_3, θ_{12}, θ_{13}, α_1, α_2

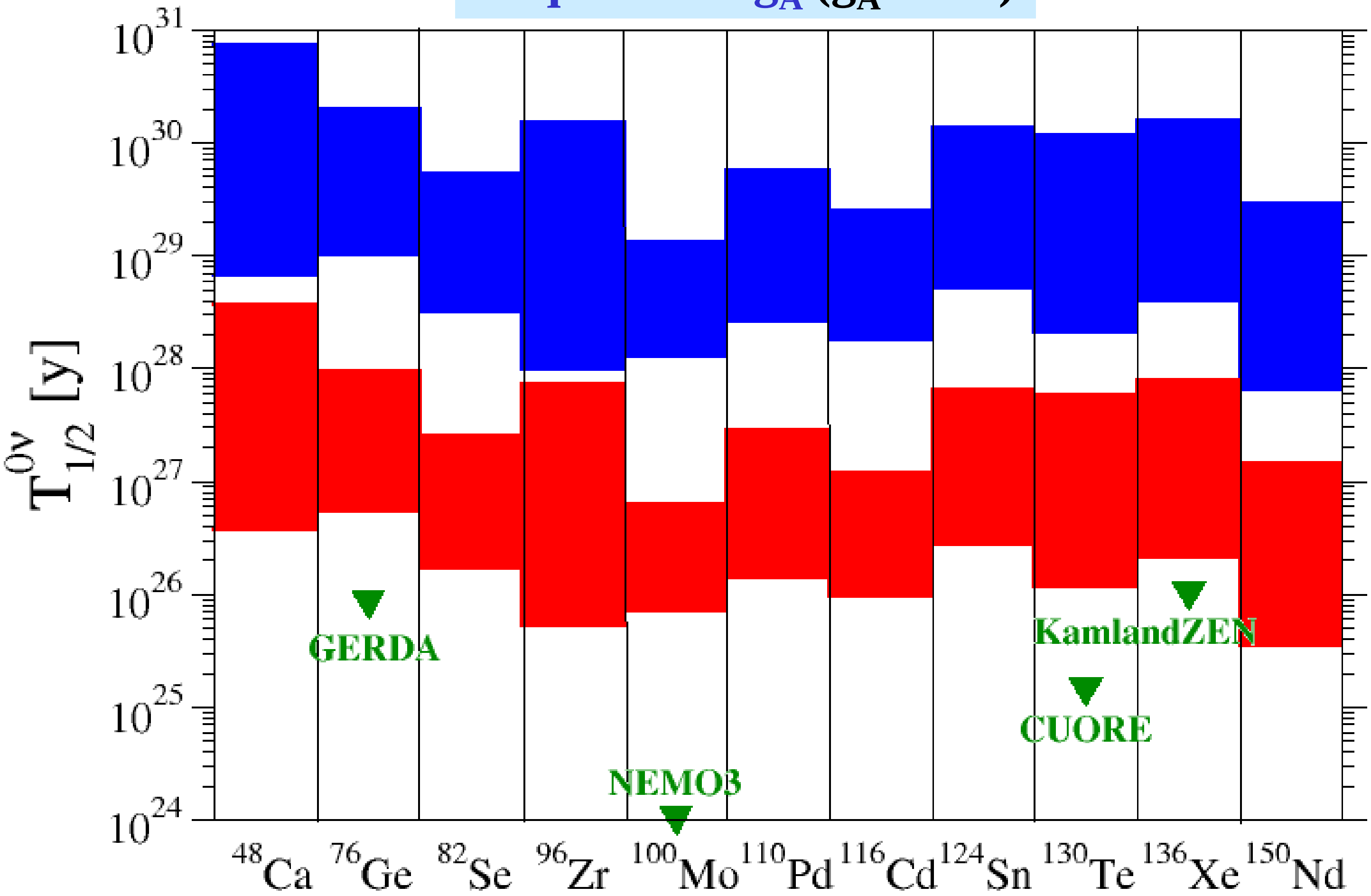
(3 unknown parameters: m_1/m_3, α_1, α_2)



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

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

unquenched g_A (g_A=1.27)



NH

IH

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

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

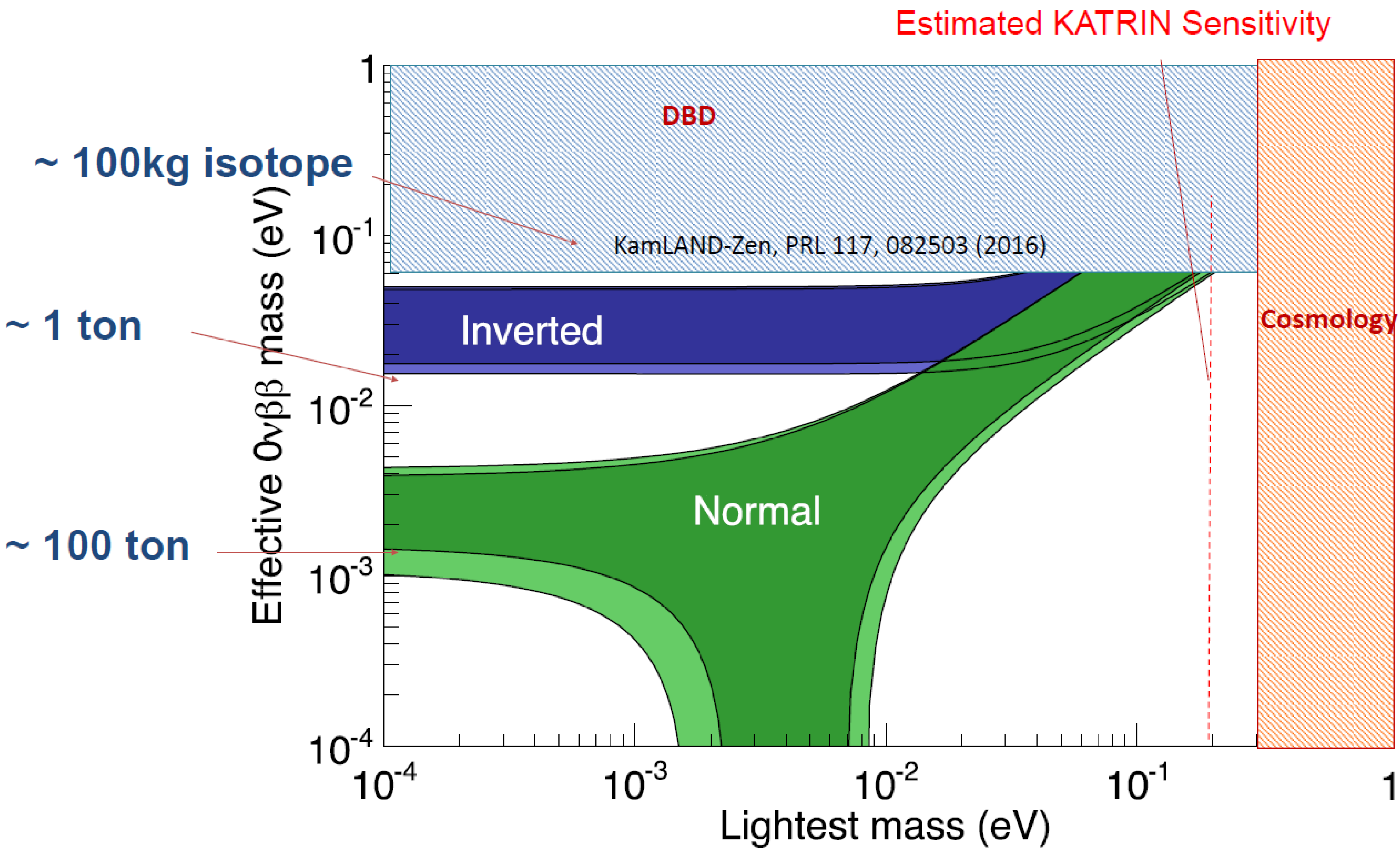
$1.4 \text{ meV} \le m_{\beta\beta} \le 3.6 \text{ meV}$

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

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

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

Lightest ν-mass equal to zero


Estimated KATRIN Sensitivity
~ 100kg isotope
~ 1 ton
~ 100 ton
DBD
KamLAND-Zen, PRL 117, 082503 (2016)
Inverted
Normal
Cosmology
Effective 0νββ mass (eV)
1
10-1
10-2
10-3
10-4
10-4
10-3
10-2
10-1
1
Lightest mass (eV)

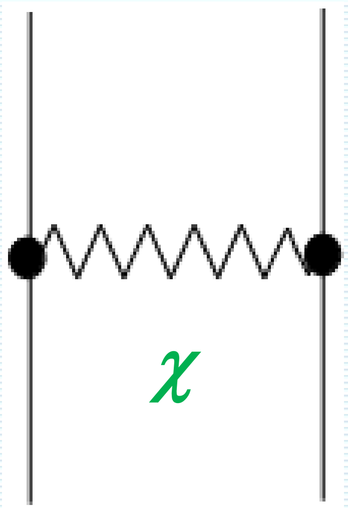
II.b Nuclear medium effect on the light neutrino mass exchange mechanism of the $0\nu\beta\beta$-decay

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

q

gO_A

q



ν

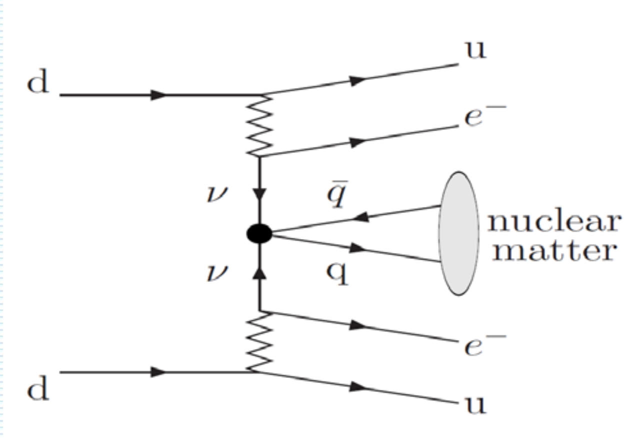
gO'_A

ν

χ

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

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

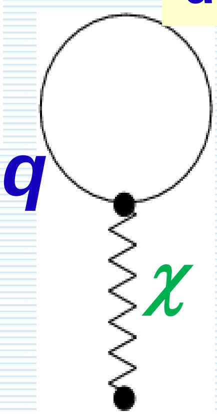


oscillation experiments, tritium β-decay

cosmology

$0\nu\beta\beta$-decay

density



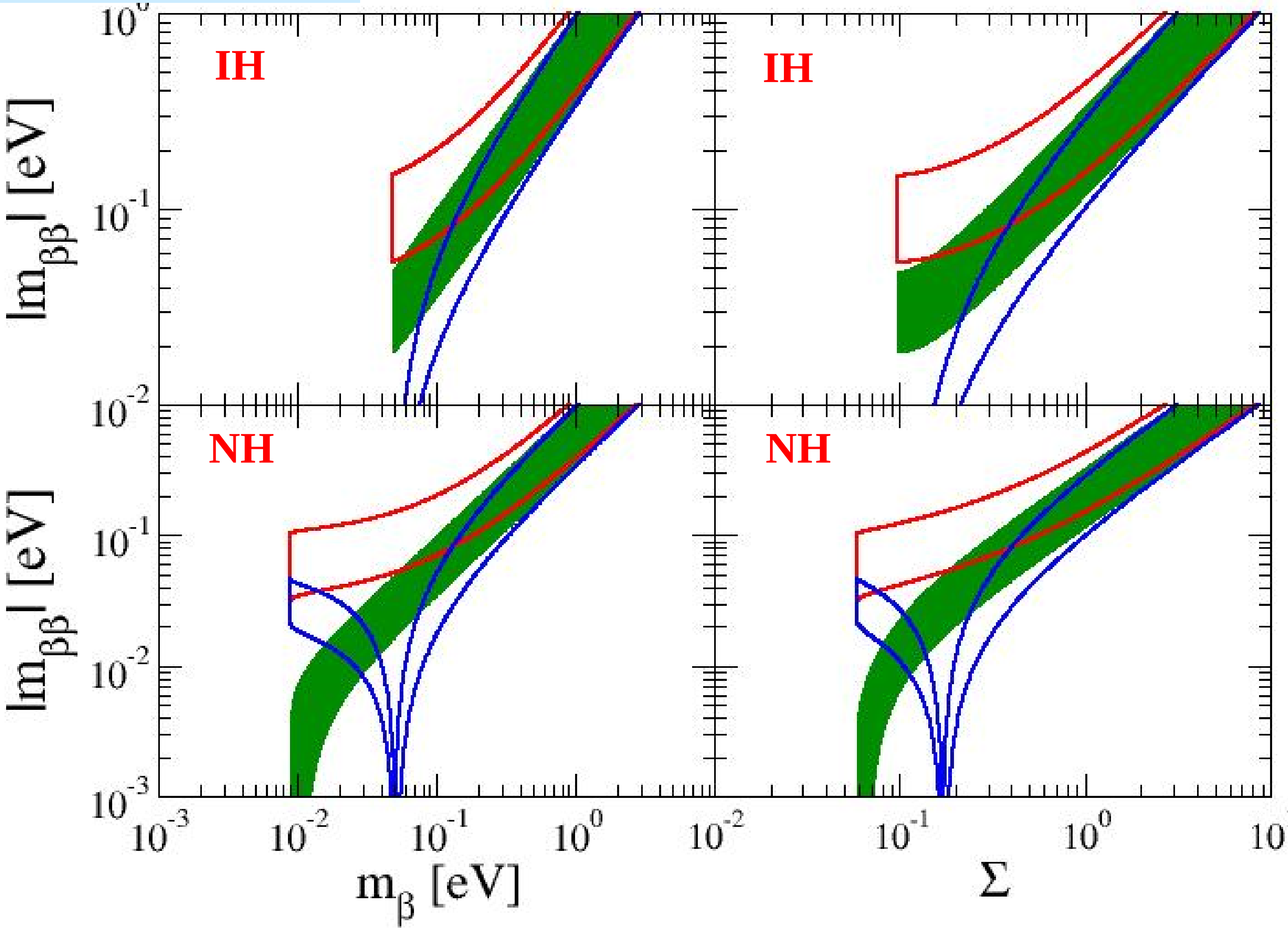
$$\Sigma_\nu^{\text{vac}} = \times , - - -$$

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

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

$$\langle\chi\rangle g^a_{ij} = -\frac{G_F}{\sqrt{2}}\langle\bar{q}q\rangle\varepsilon^a_{ij} \approx -25\,\varepsilon^a_{ij}\ \mathrm{eV}$$

$$\langle\chi\rangle = -\frac{g_\chi}{m_\chi^2}\langle\bar{q}q\rangle \qquad g^a_{ij} = \delta_{ij}g_a \qquad \varepsilon^a_{ij} = \delta_{ij}\varepsilon_a$$



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

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

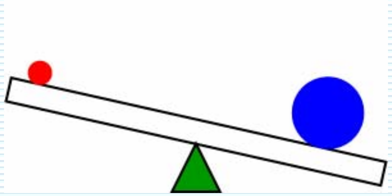
Dirac-Majorana mass term

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

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

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

Different motivations for the LNV scale Λ

eV	keV	Fermi	TeV	GUT	Planck
light sterile ν	hot DM		LHC		
10^{-6} GeV	10^{-6} GeV	10^{-6} GeV	10^{3} GeV	10^{16} GeV	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]

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

General case

light ν exchange

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

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

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

heavy ν exchange

Particular cases

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

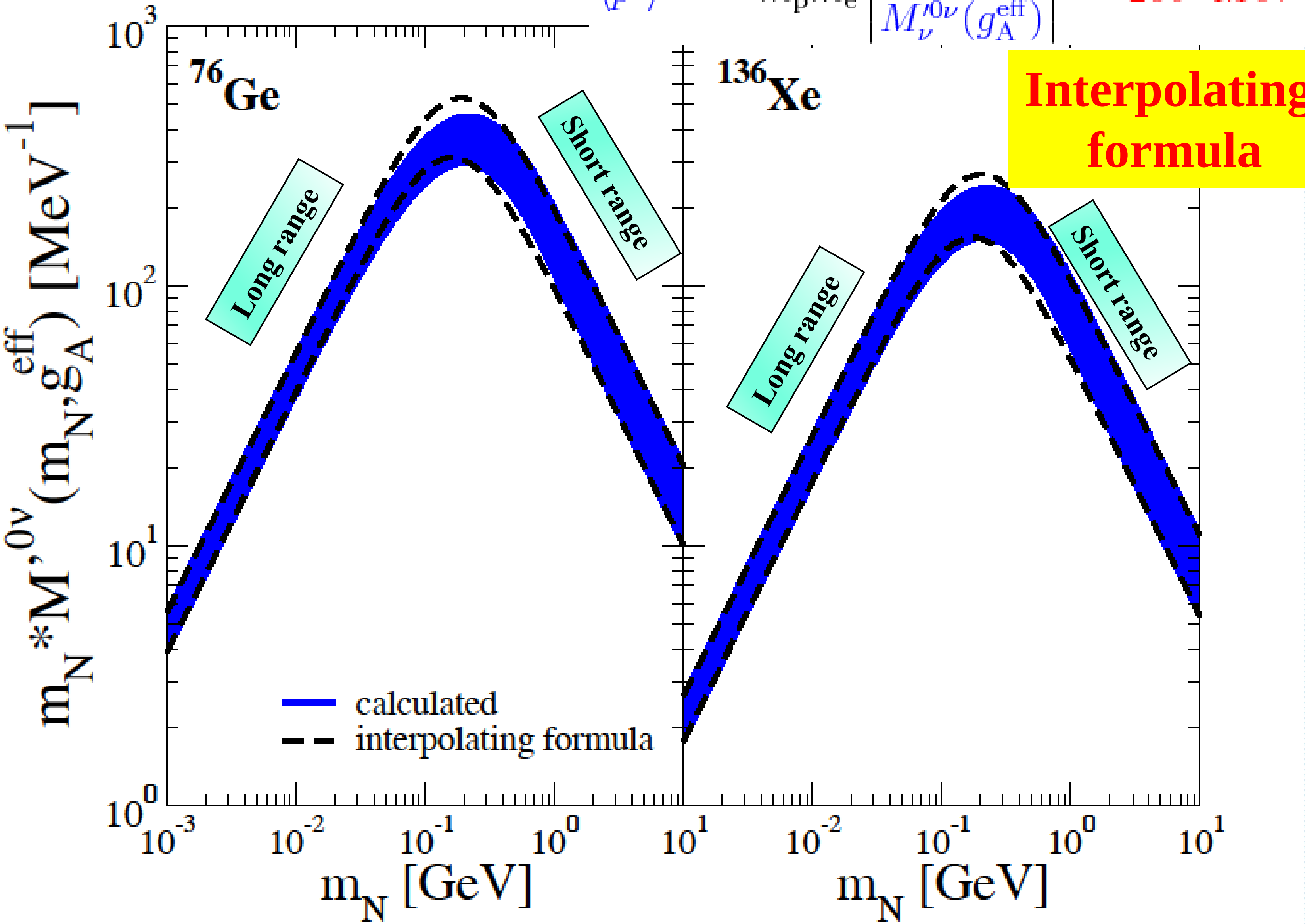
$$\langle m_\nu \rangle = \sum_N U^2_{eN} m_N$$

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

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A} \cdot \left| m_{\rm p} \sum_{\rm N} U^2_{e{\rm N}} \frac{m_{\rm N}}{\langle p^2 \rangle + m^2_{\rm N}} \right|^2 ,$$

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

$$\langle p^2 \rangle = m_{\rm p} m_{\rm e} \left| \frac{M'^{0\nu}_{\rm N}(g^{\rm eff}_{\rm A})}{M'^{0\nu}_{\nu}(g^{\rm eff}_{\rm A})} \right| \approx 200 \ \ MeV$$



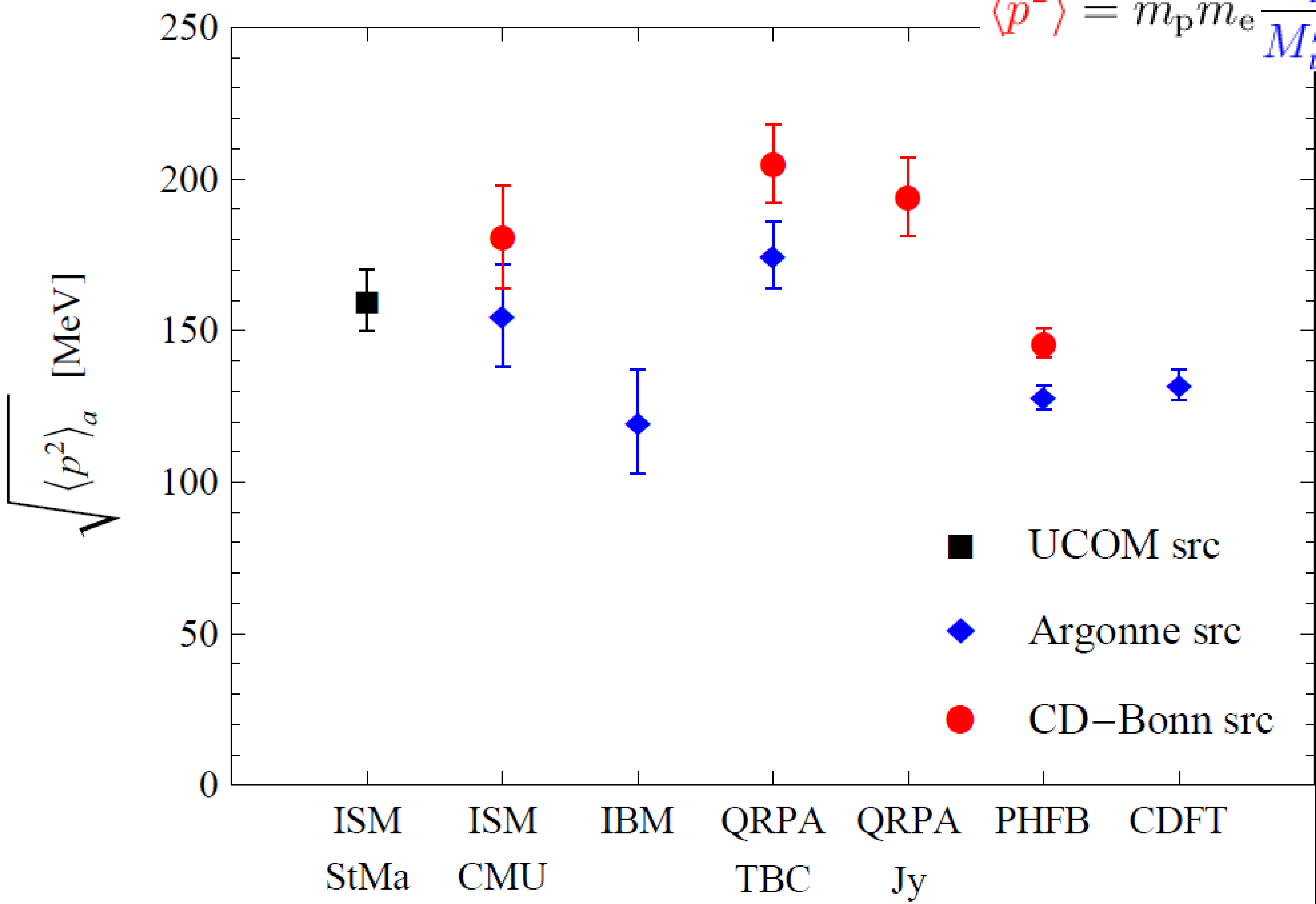
Faessler, Gonzales, Kovalenko, F. Š., PRD 90 (2014) 096010]

Interpolating formula is justified by practically no dependence <p²> on A

$$[T^{0\nu}_{1/2}]^{-1} = \mathcal{A}\cdot\left| m_{\rm p}\sum_{\rm N} U^2_{e\rm N}\frac{m_{\rm N}}{\langle p^2\rangle + m^2_{\rm N}}\right|^2,$$

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

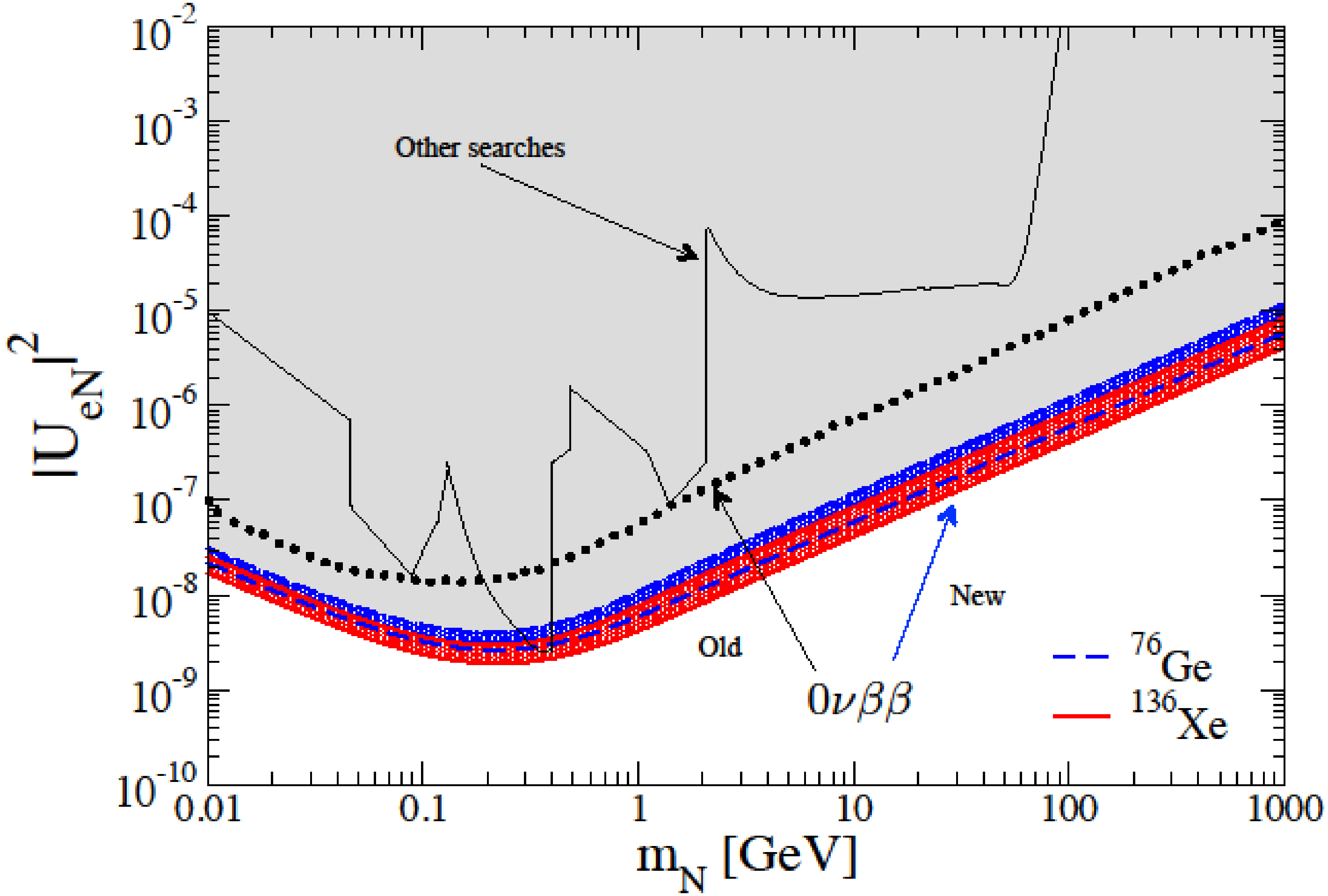
$$\langle p^2\rangle = m_{\rm p} m_{\rm e}\frac{M'^{0\nu}_{\rm N}}{M'^{0\nu}_{\nu}}$$



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

$T^{0\nu}_{1/2}(^{76}Ge) \geq 3.0\ 10^{25}$ yr $\Rightarrow$ **0.9 10^{26} yr**

$T^{0\nu}_{1/2}(^{136}Xe) \geq 3.4\ 10^{25}$ yr $\Rightarrow$ **1.1 10^{26} yr**



QRPA **(constrained Hamiltonian by 2νββ half-life, self-consistent treatment of src, restoration of isospin symmetry …)**

II.d. 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)

$$[T^{0\nu}_{1/2}]^{-1} = \eta^2_{\nu N}\ C_{\nu N}$$

$$C_{\nu N} = g^4_{\rm A}\ \left|M'^{0\nu}_{\nu}\right|^2\ G^{0\nu}$$

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 (due interpolating formula)

$$\eta^2_{\nu N} = \left|\sum_{j=1}^{3}\left(U^2_{ej}\ \frac{m_j}{m_e}\ +\ S^2_{ej}\ \frac{\langle p^2\rangle_a}{\langle p^2\rangle_a + M^2_j}\ \frac{M_j}{m_e}\right)\right|^2 + \lambda^2\left|\sum_{j=1}^{3}\left(T^2_{ej}\ \frac{m_j}{m_e}\ +\ V^2_{ej}\ \frac{\langle p^2\rangle_a}{\langle p^2\rangle_a + M^2_j}\ \frac{M_j}{m_e}\right)\right|^2$$

$$\langle p^2\rangle = m_{\rm p} m_{\rm e} \frac{M'^{0\nu}_{\rm N}}{M'^{0\nu}_{\nu}}$$

6x6 PMNS see-saw ν-mixing matrix
(the most economical one, prediction for mixing of heavy neutral leptons)

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

$$\mathcal{U}_{\rm PMNS} = \begin{pmatrix} U_{\rm PMNS} & \zeta\, 1 \\ -\zeta\, 1 & U^\dagger_{\rm PMNS} \end{pmatrix}$$

$$\mathcal{U}_{\rm PMNS}\, \mathcal{U}^\dagger_{\rm PMNS} = \mathcal{U}^\dagger_{\rm PMNS}\, \mathcal{U}_{\rm PMNS} = 1$$

see-saw parameter

$$\zeta = \frac{m_{\rm D}}{m_{\rm LNV}}$$

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

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

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

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

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

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

$$V_0 = U^\dagger_{\rm PMNS} =$$

$$\begin{pmatrix} c_{12}\, c_{13}\, e^{-i\alpha_1} & \left(-s_{12}\, c_{23} - c_{12}\, s_{13}\, s_{23}\, e^{-i\delta}\right) e^{-i\alpha_1} & \left(s_{12}\, s_{23} - c_{12}\, s_{13}\, c_{23}\, e^{-i\delta}\right) e^{-i\alpha_1} \\ s_{12}\, c_{13}\, e^{-i\alpha_2} & \left(c_{12}\, c_{23} - s_{12}\, s_{13}\, s_{23}\, e^{-i\delta}\right) e^{-i\alpha_2} & \left(-c_{12}\, s_{23} - s_{12}\, s_{13}\, c_{23}\, e^{-i\delta}\right) e^{-i\alpha_2} \\ s_{13}\, e^{i\delta} & c_{13}\, s_{23} & c_{13}\, c_{23} \end{pmatrix}$$

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

Inverse proportional

$$m_i M_i \simeq m_D^2$$

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

Proportional

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

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

$M^{R}_{\beta\beta}$ depends on "Dirac" CP phase δ unlike "Majorana" CP phases α_1 and α_2

Heavy Majorana mass $M^{R}_{\beta\beta}$ depends on the "Dirac" CP violating phase δ

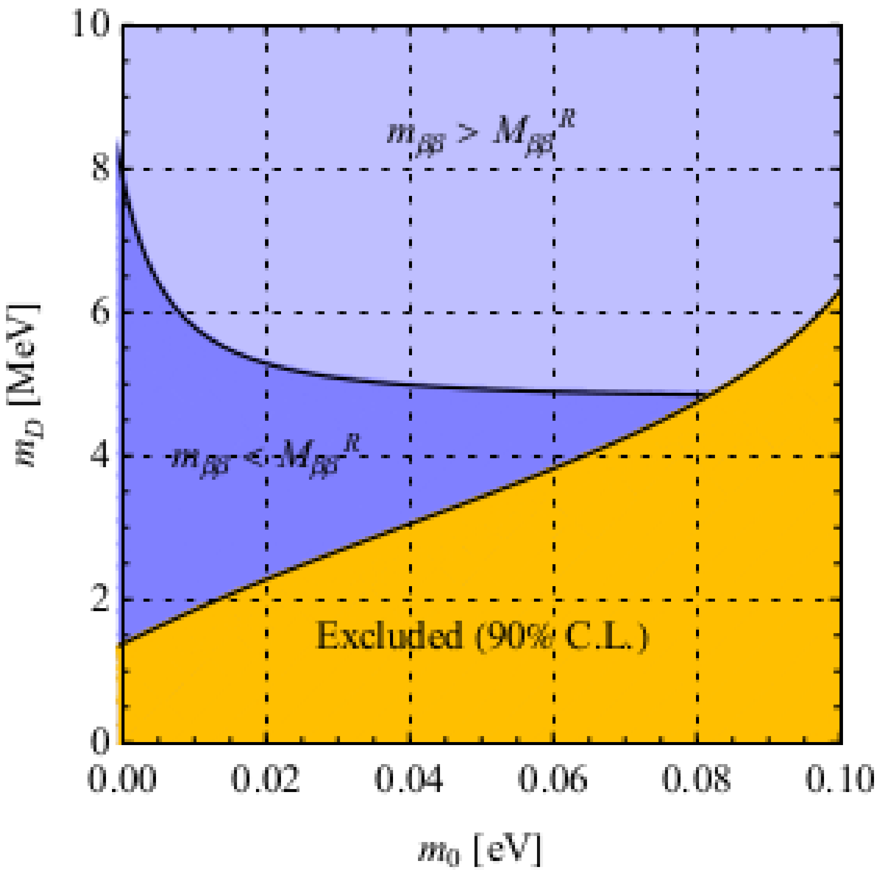
$$\eta_{\nu N}^2 = \frac{1}{m_e^2}\left(m_{\beta\beta}^2 + (M_{\beta\beta}^R)^2\right)$$

See-saw scenario

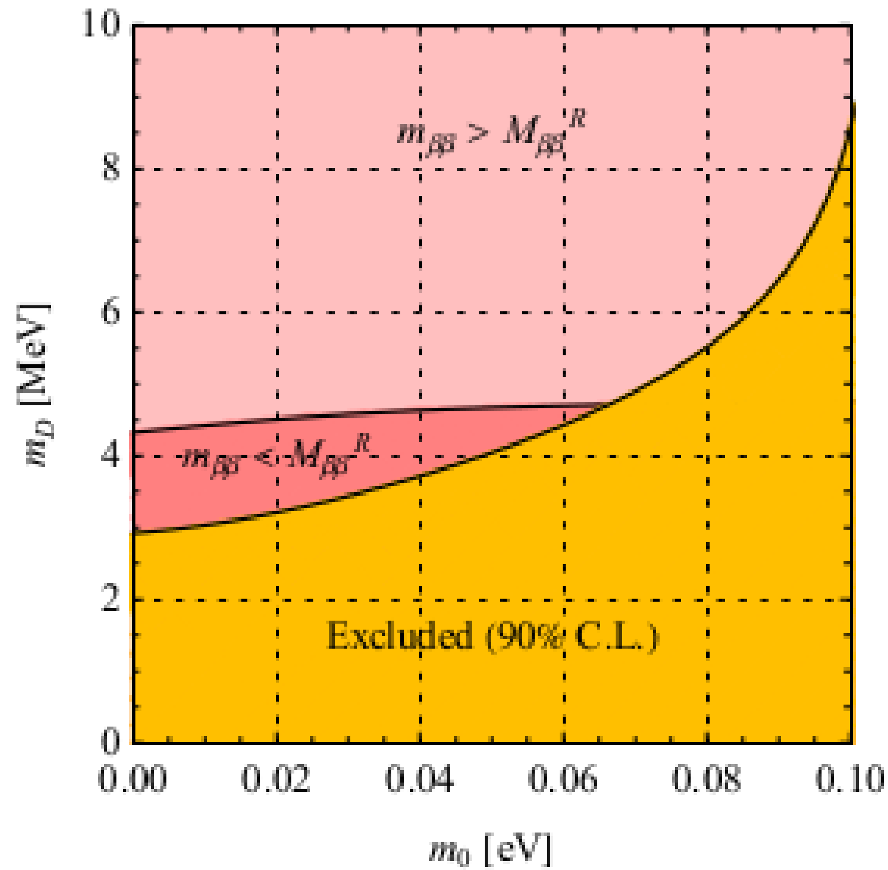
$$m_i M_i \simeq m_D^2$$

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

Normal spectrum



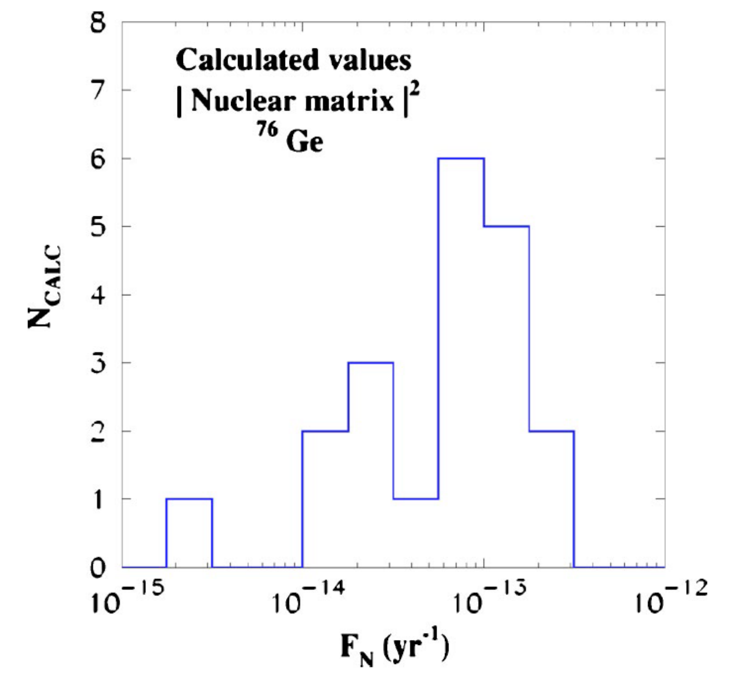
Inverted spectrum



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

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

2004 (factor 10)
few groups, 2 nuclear structure methods:
Nuclear Shell Model, QRPA



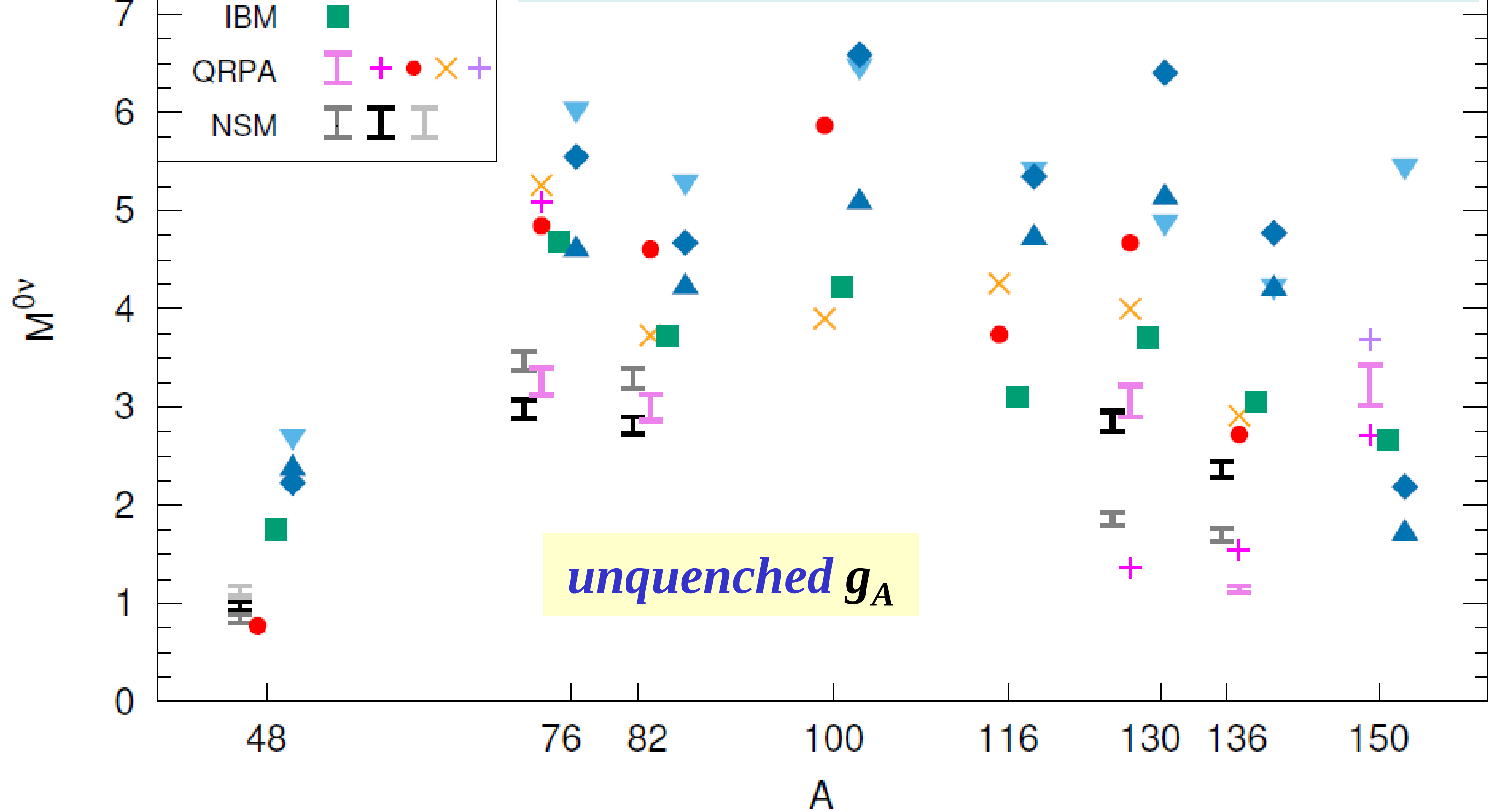
Bahcall, Maruyama, Pena-Garay, PRC 70, 033012 (2004)

2019 (factor 2-3)
many groups, many nuclear structure methods:
Nuclear Shell Model, QRPA, Interacting Boson Model, Energy Density Functional

Attempts (light nuclear systems):
Ab initio calculations by different approaches – No Core Shell Model, Green's Function Monte Carlo, Coupled Cluster Method, Lattice QCD

J. Engel, J. Menendez, Rept. Prog. Phys. 80, 046301 (2017)
(updated 2019)

$0\nu\beta\beta$-decay NME status 2019



All models missing essential physics

Impossible to assign rigorous uncertainties

Nuclear Shell Model **(Madrid-Strasbourg, Michigan, Tokyo): Relatively small model space (1 shell), all correlations included, solved by direct diagonalization**

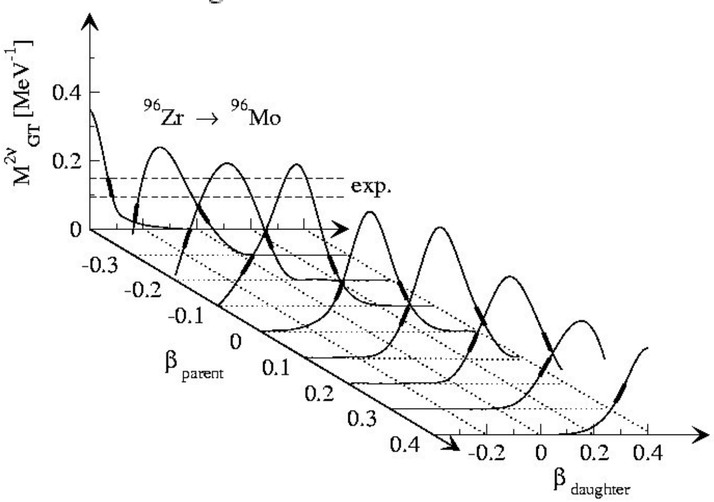
QRPA **(Tuebingen-Bratislava-Calltech, Jyvaskyla, Chapel Hill, Lanzhou, Prague): Several Shells, only simple correlations included**

Interacting Boson Method **(Yale-Concepcion): Small space, important proton-neutron Pairing correlations missing**

Energy Density Functional theory **(Madrid, Beijing): >10 shells, important proton-neutron pairing missing**

Suppression of the ββ-decay NMEs due to different deformation of initial and final nuclei

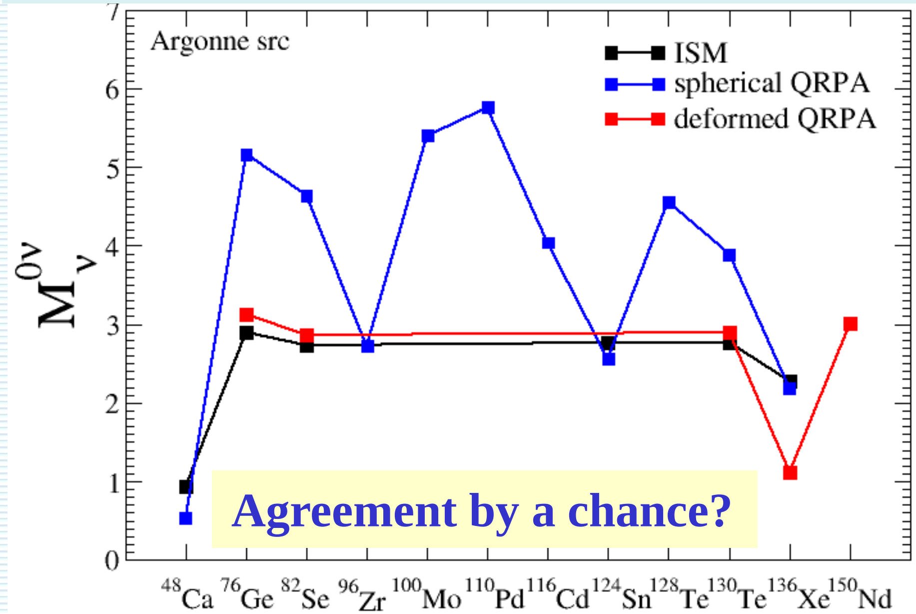
$$\beta = \sqrt{\frac{\pi}{5}} \frac{Q_p}{Z r_c^2}$$



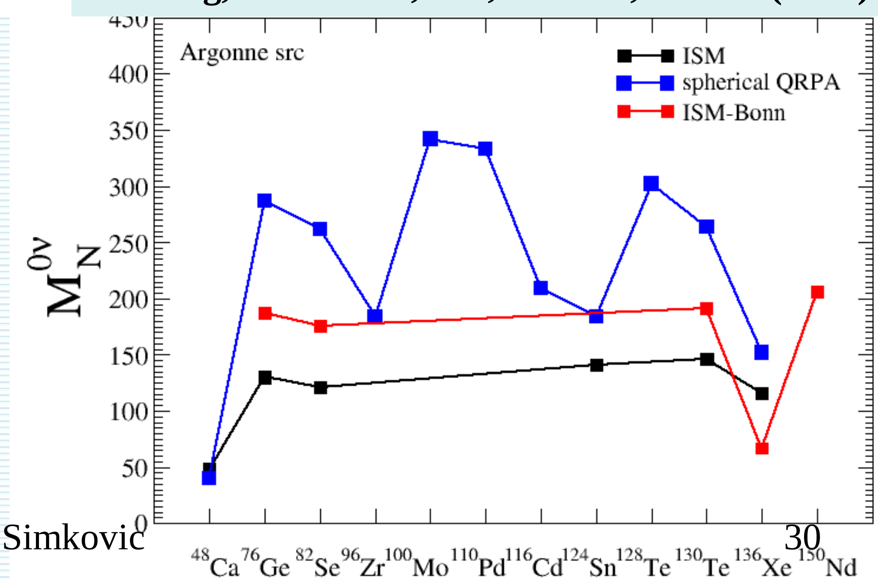
Systematic study of the deformation effect on the 2νββ-decay NME Within deformed QRPA

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

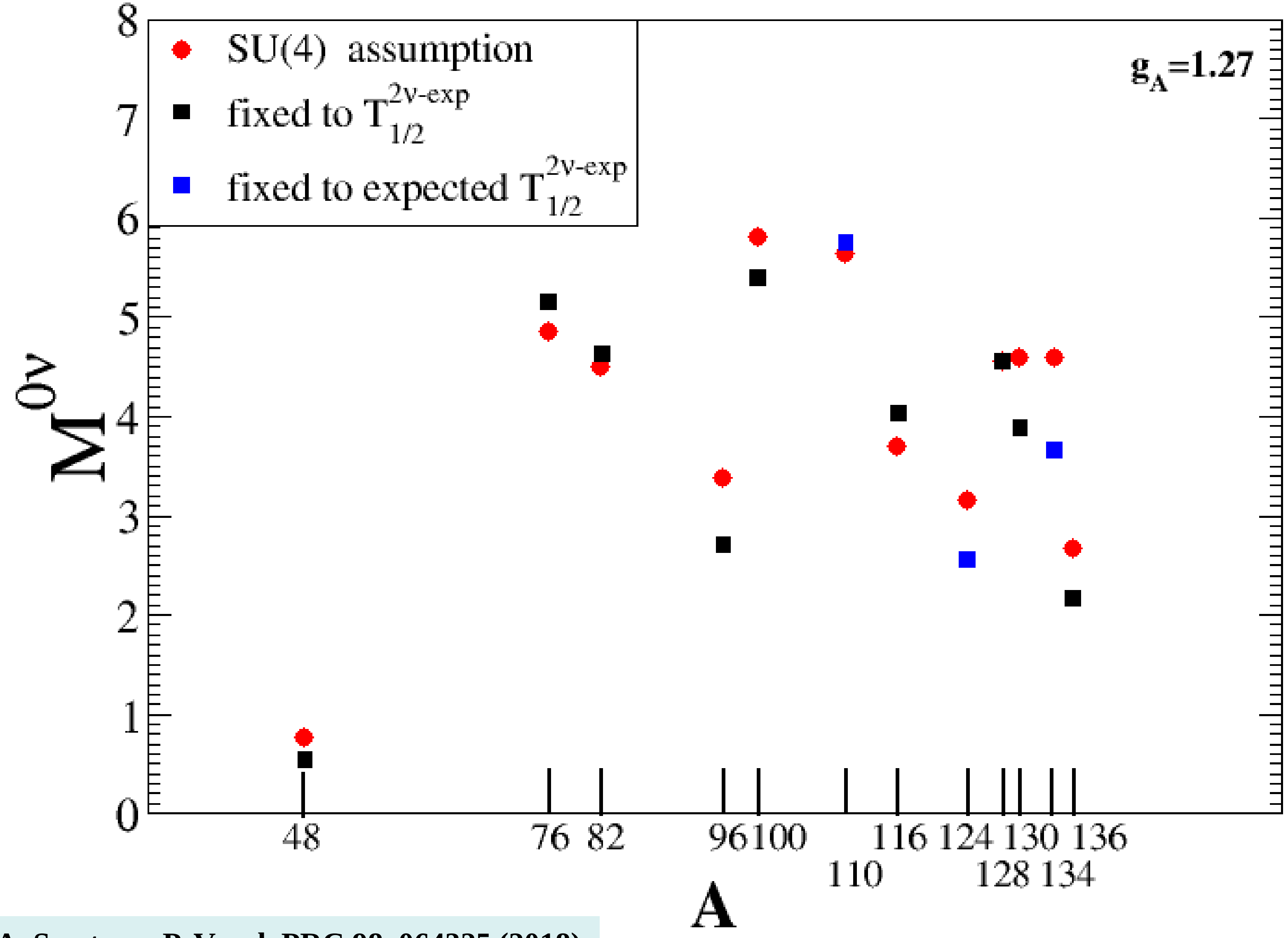
0νββ-decay NMEs within deformed QRPA with partial restoration of isospin symmetry



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



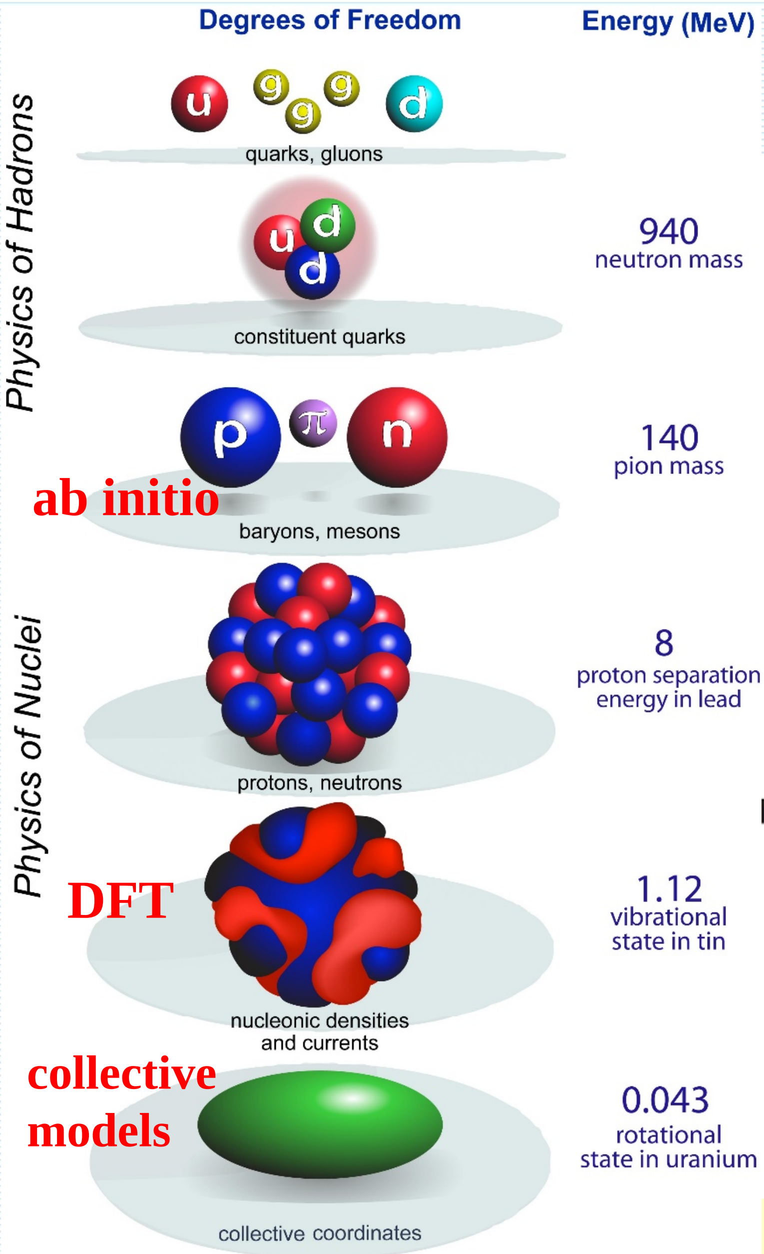
New QRPA calculations based on restoration of the SU(4) symmetry ($M^{2\nu}_{GT-cl}=0$)



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

Ab Initio Nuclear Structure
(Often starts with chiral effective-field theory)

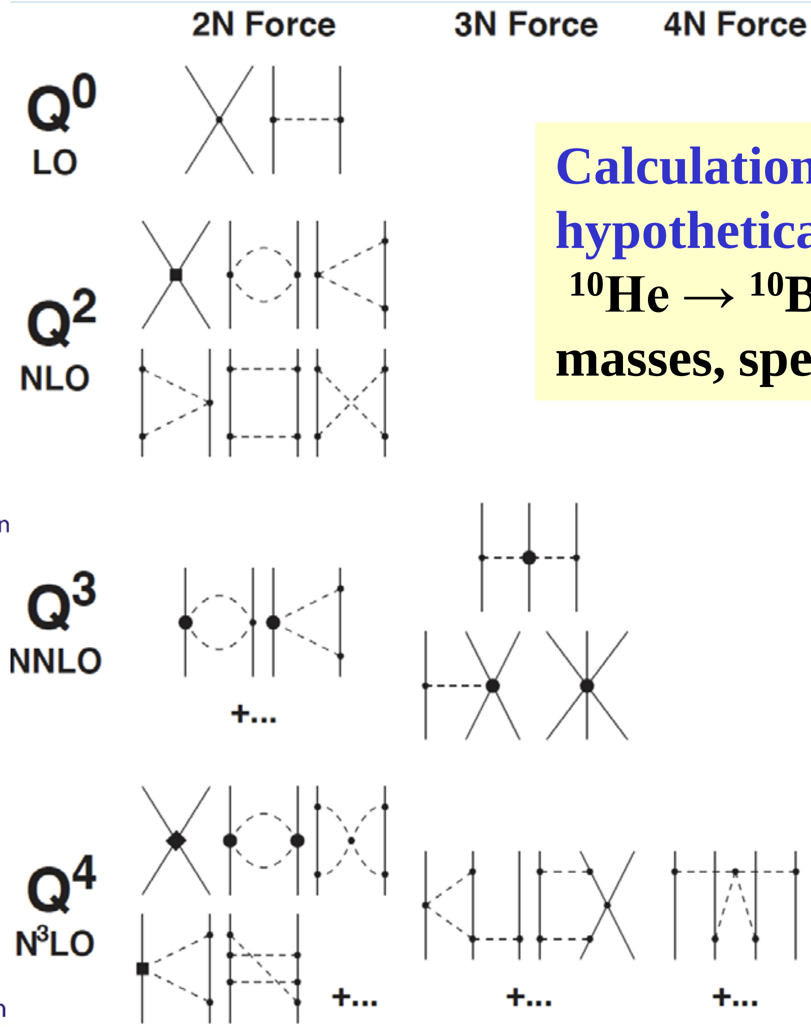
Nucleons, pions. Sufficient below chiral symmetry breaking scale. Expansion of operators in power of Q/Λ_χ. $Q=m_\pi$ or typical nucleon momentum.



ab initio

DFT

collective models

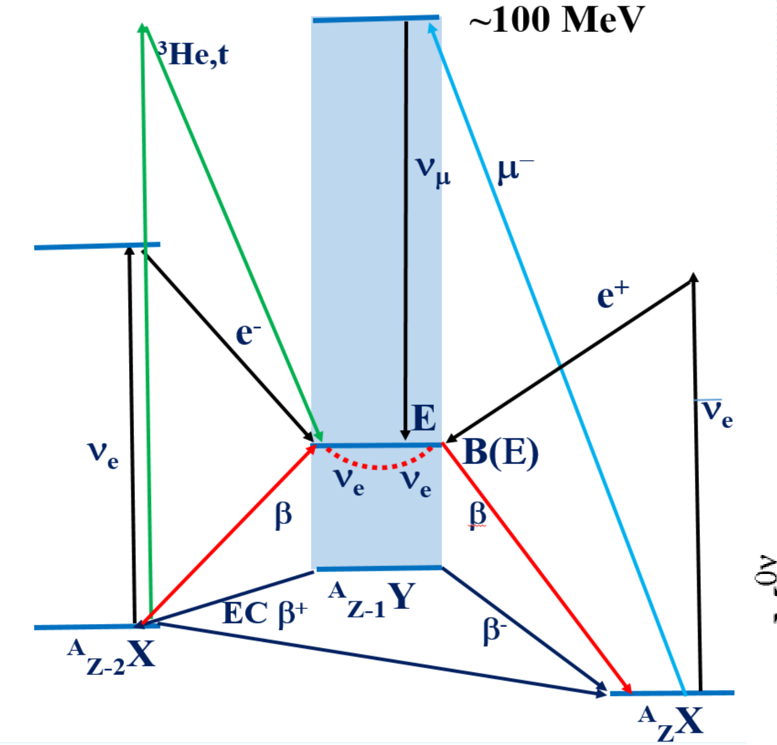


Calculation for the hypothetical 0νββ decay:
^{10}He → ^{10}Be + e$^-$ + e-
masses, spectra

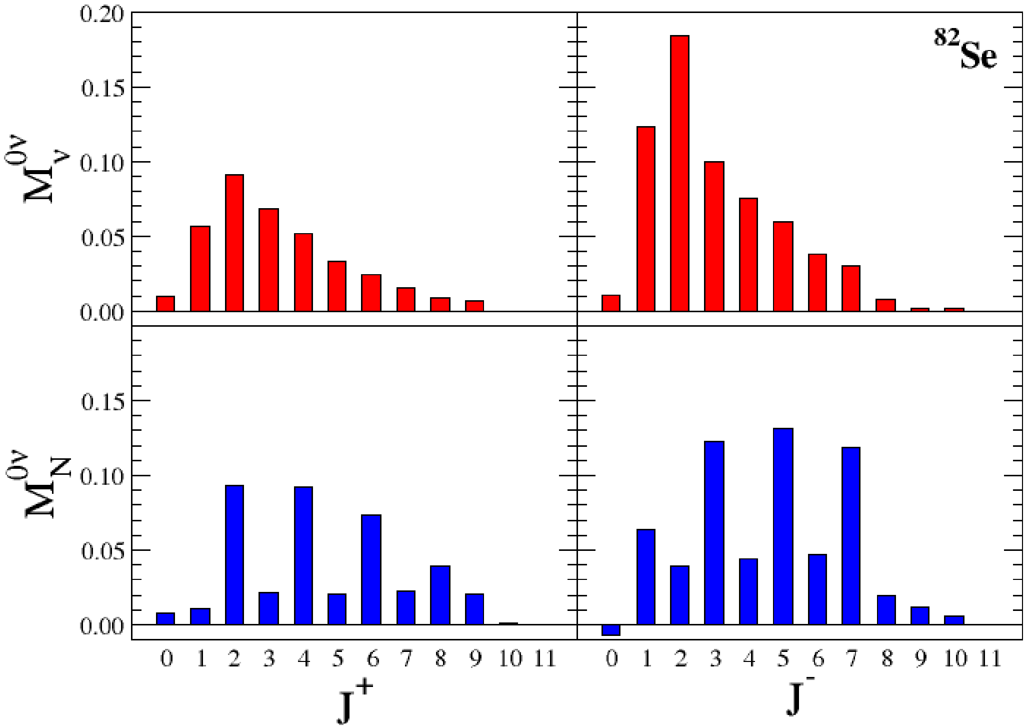
A. Schwenk, P. Navratil, J. Engel, J. Menendez

Moore's law: exponential growth in computing power

Exploiting charge-exchange reactions (^{3}He,t) and μ-capture to constrain 0νββ–decay NMEs (presentation by Hiro Ejiri)



Multipole decomposition of light and heavy 0νββ-decay NMEs normalized to unity

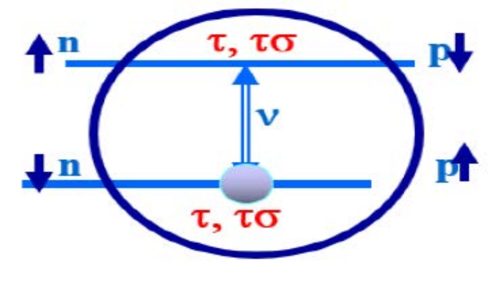


Higher multiploles are populated mostly due large ν-momenta transfer

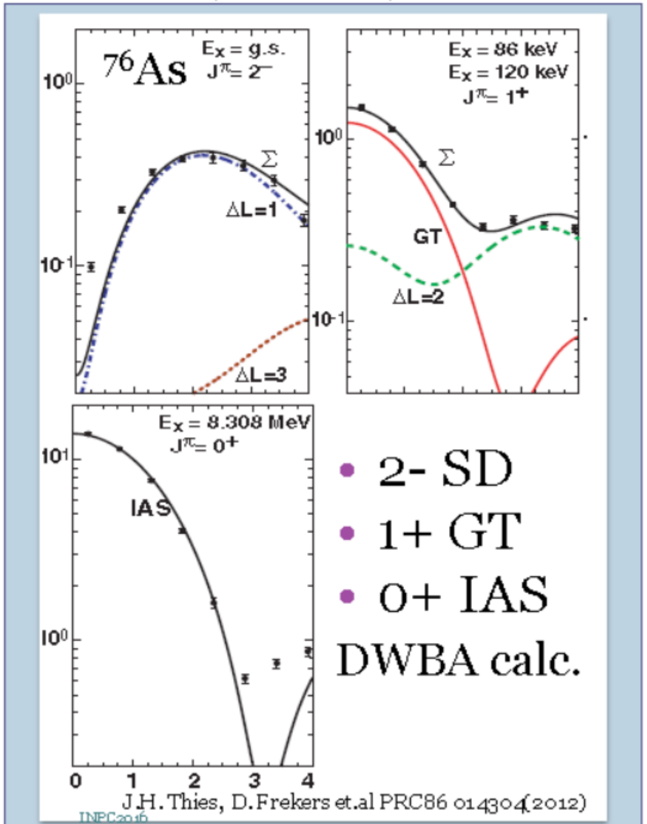
RCNP Osaka p,He

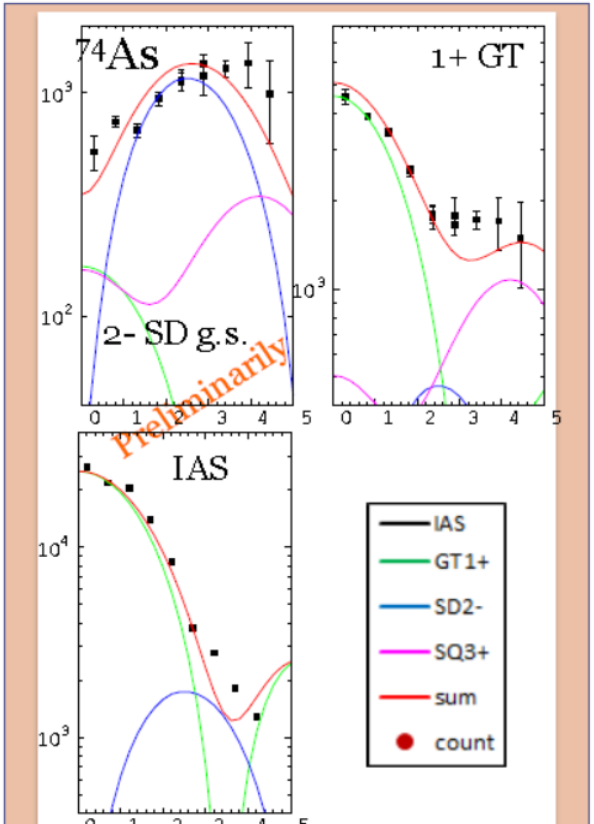
Measuring of GT-like (2^-, 3^+) strengths distribution for ^{74,76}Ge → ^{74,76}As with (^{3}He,t) reactions

H. Akimune, H. Ejiri, RCNP, Catania, KVI , Munster・・



^{74,76}Ge (^{3}He,t)^{74,76}As Angular distribution





Measurement of GT strength via μ-capture

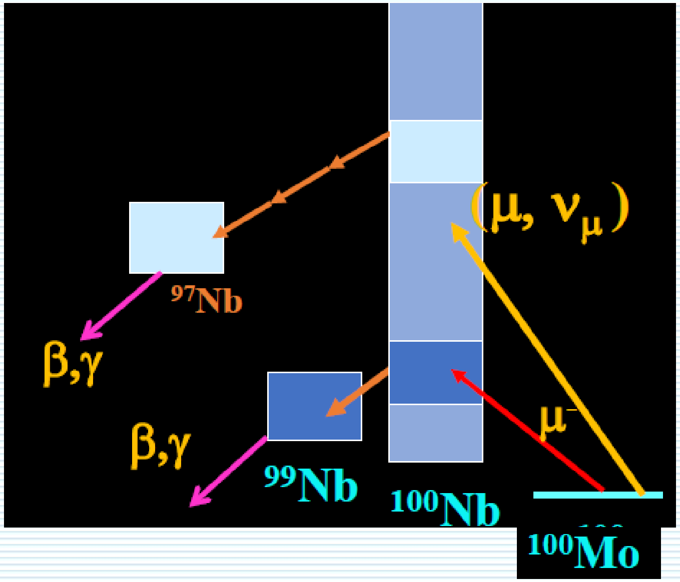
$\mu^-_b + (A,Z) \rightarrow (A,Z-1) + \nu_\mu$

J-PARC 3-50 GeV p, ν, μ

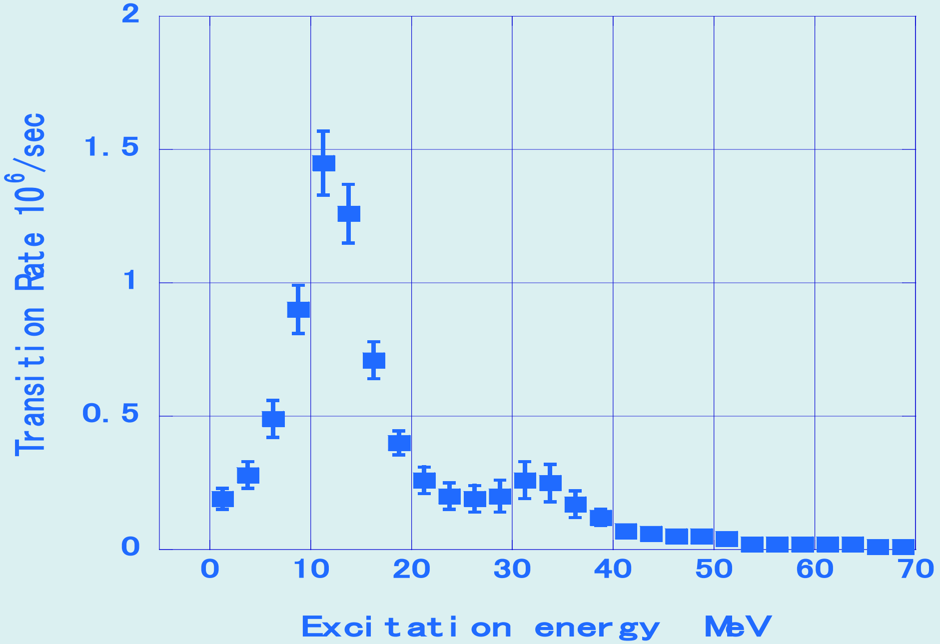
CER $(\mu,\nu_\mu, xn\ \gamma)$ $\nu-\beta^+$

Responses q~80 MeV

2^- 3^+ **multipoles**



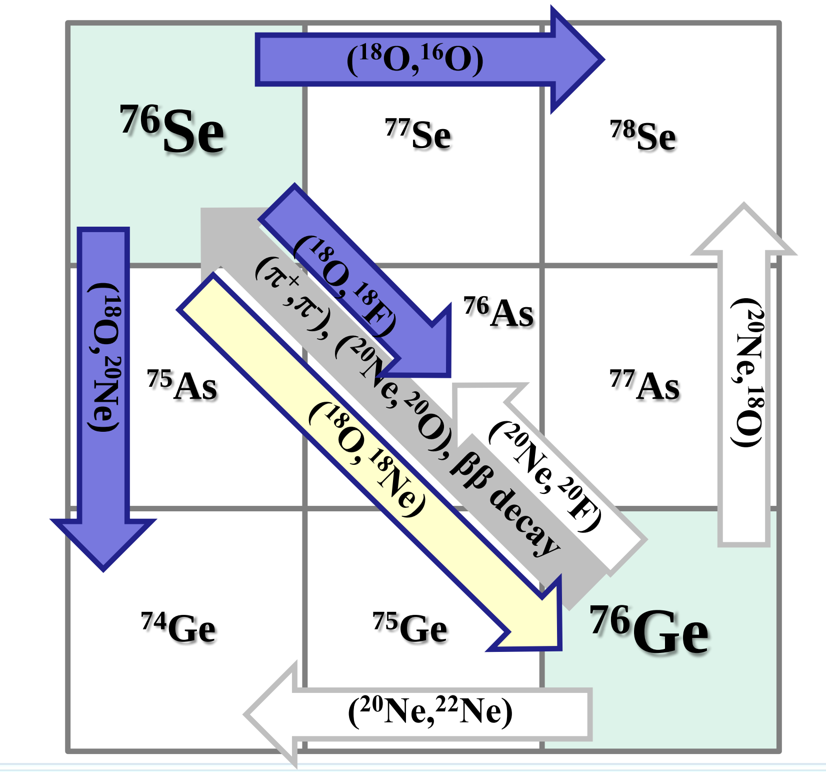
I. Hashim H. Ejiri , MXG16, PR C 97 2018

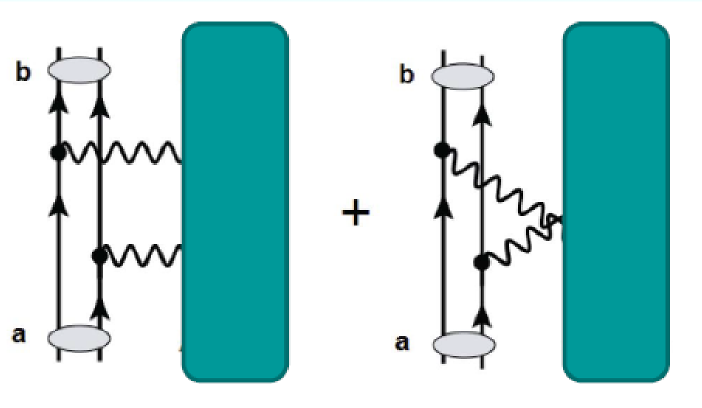


⇒ **Small basis nuclear structure calculations (NSM, IBM) are disfavored.** ⇒

Supporting nuclear physics experiments

(2νββ-decay, μ-capture ChER, pion and heavy ion DCX, nucleon transfer reactions etc)

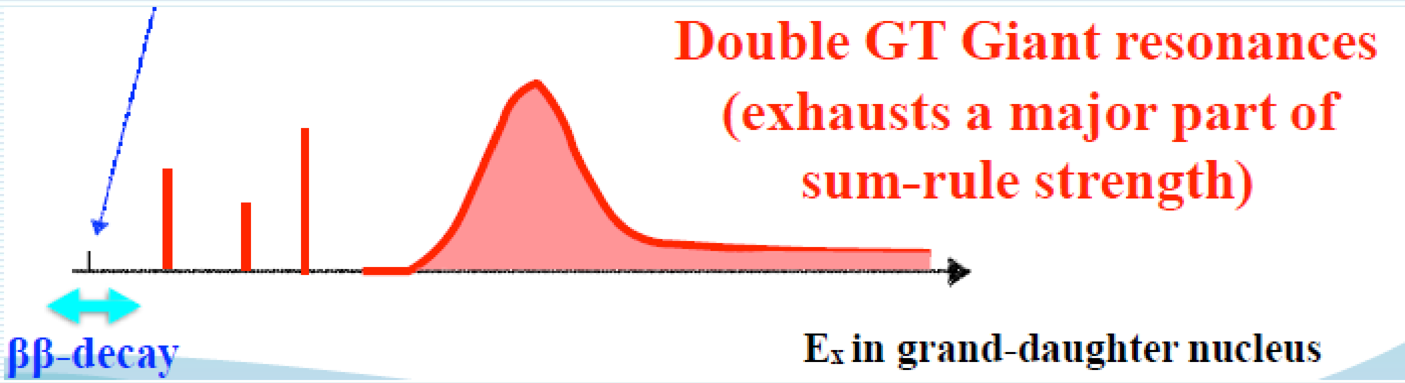


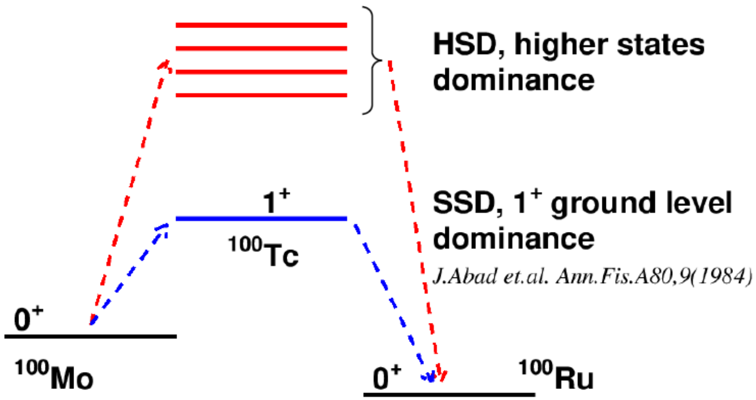


H. Lenske group

Theory of heavy ion DCX and connection to DBD NMEs

Heavy ion DCX: NUMEN (LNC-INFN), HIDCX (RCNP/RIKEN)

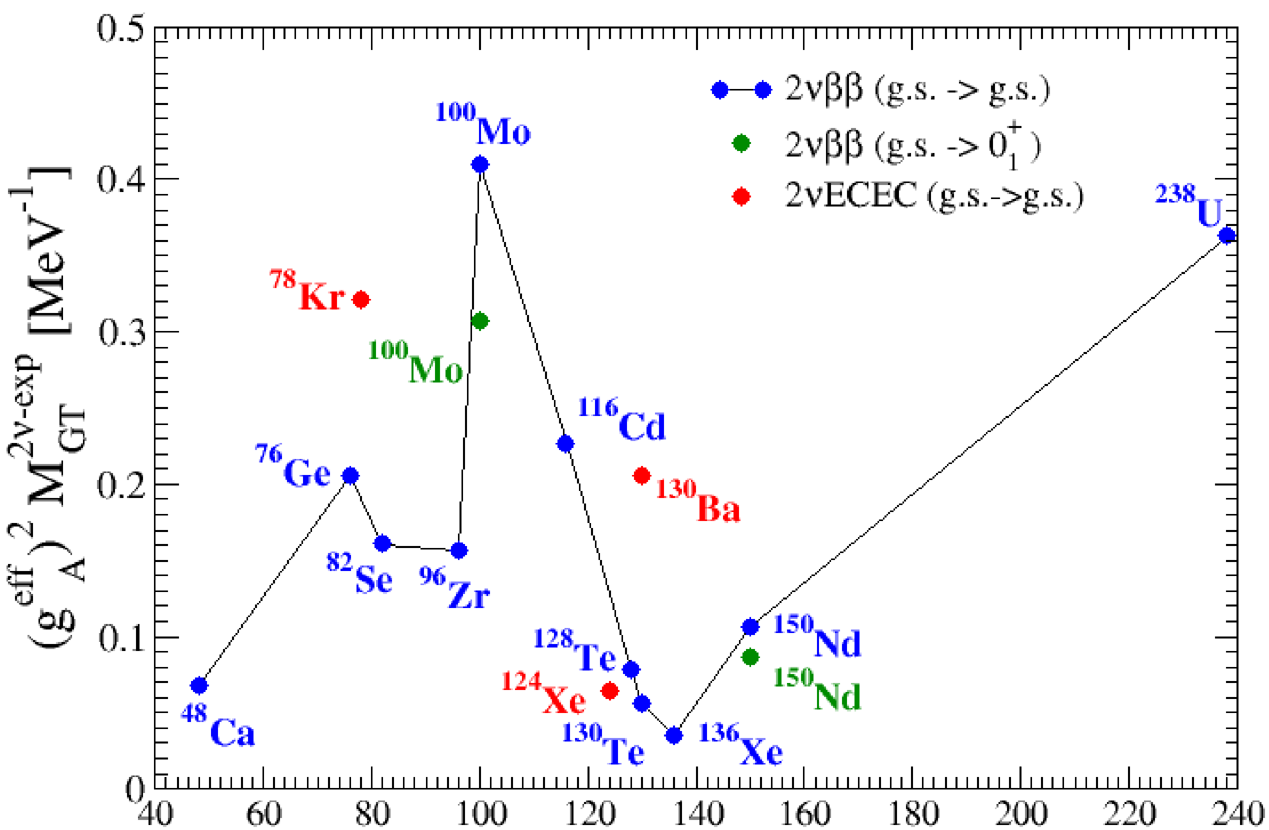




Understanding of the 2νββ-decay NMEs is of crucial importance for correct evaluation of the 0νββ-decay NMEs

$$M^{2\nu}_{GT} = \sum_m \frac{< 0^+_f||\tau^+\sigma||1^+_m >< 1^+_m||\tau^+\sigma||0^+_i >}{E_m - E_i + \Delta}$$

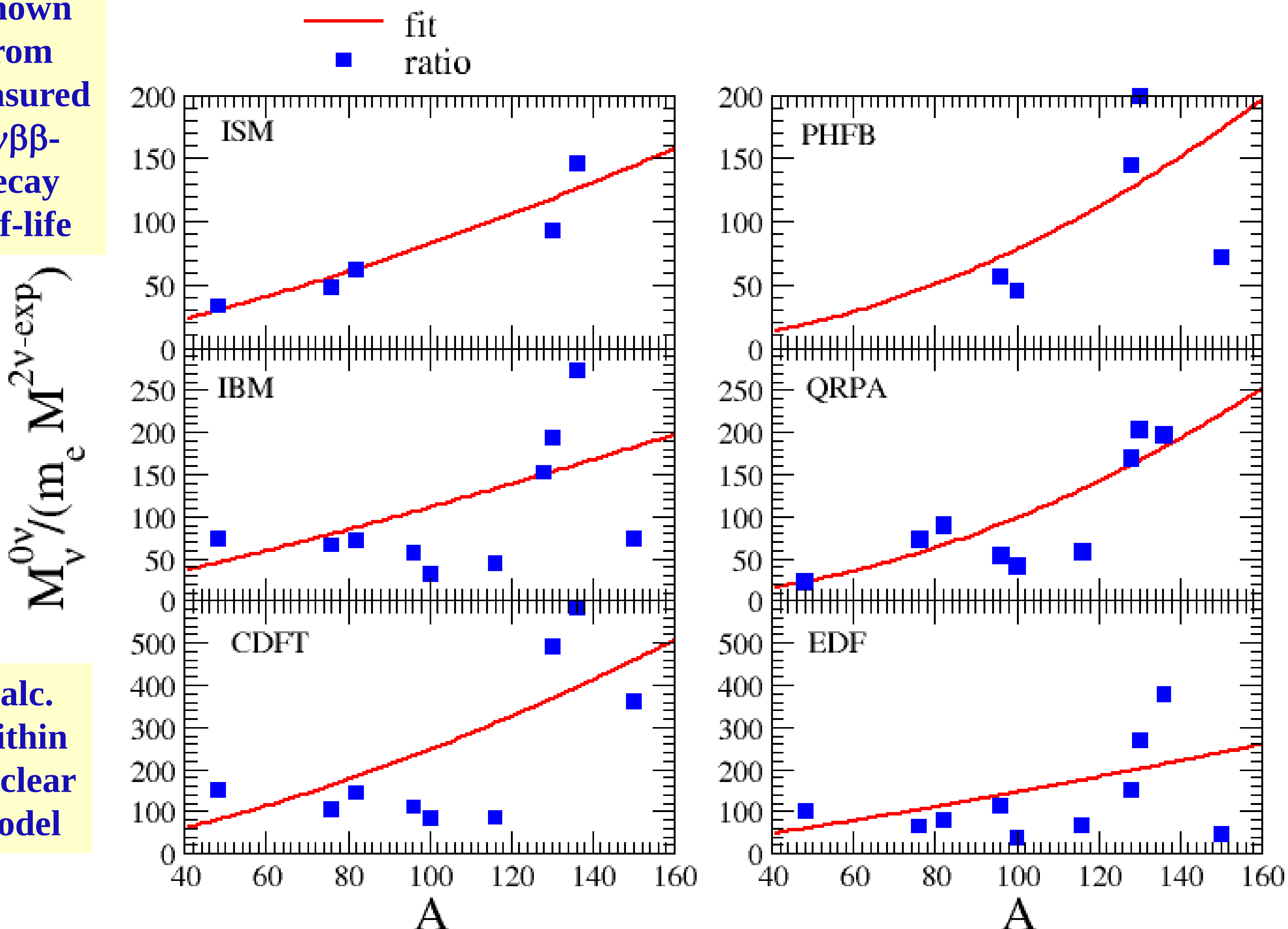
There is no reliable calculation of the *2νββ-decay NMEs yet*



Both 2νββ and 0νββ operators connect the same states. Both change two neutrons into two protons. Explaining 2νββ-decay is necessary but not sufficient

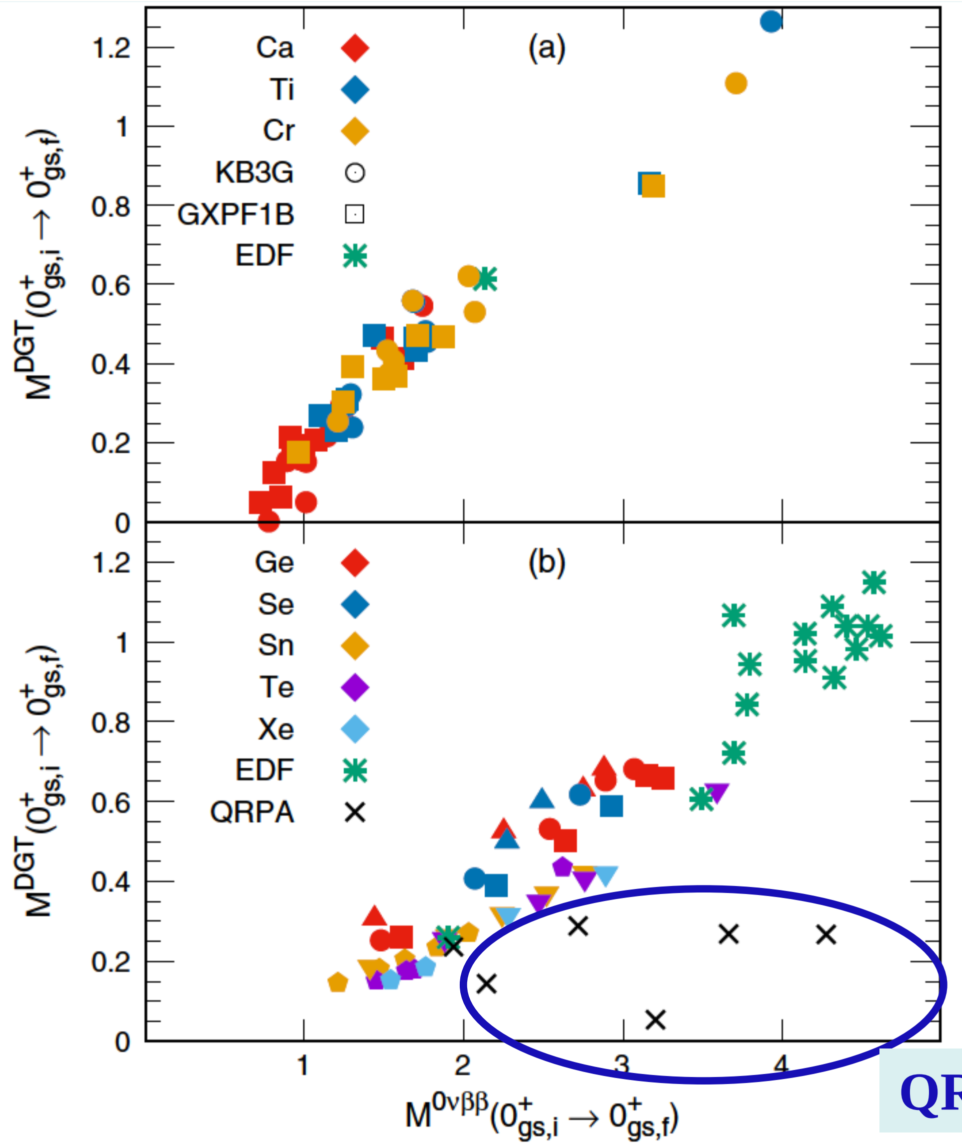
Is there a proportionality between 0νββ- and 2νββ-decay NMEs?

Known krom measured 2νββ-decay half-life



Calc. within nuclear model

$M^{0\nu} \propto M^{2\nu}_{GT\text{-}cl}$: 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, PRL 120, 142502 (2018)

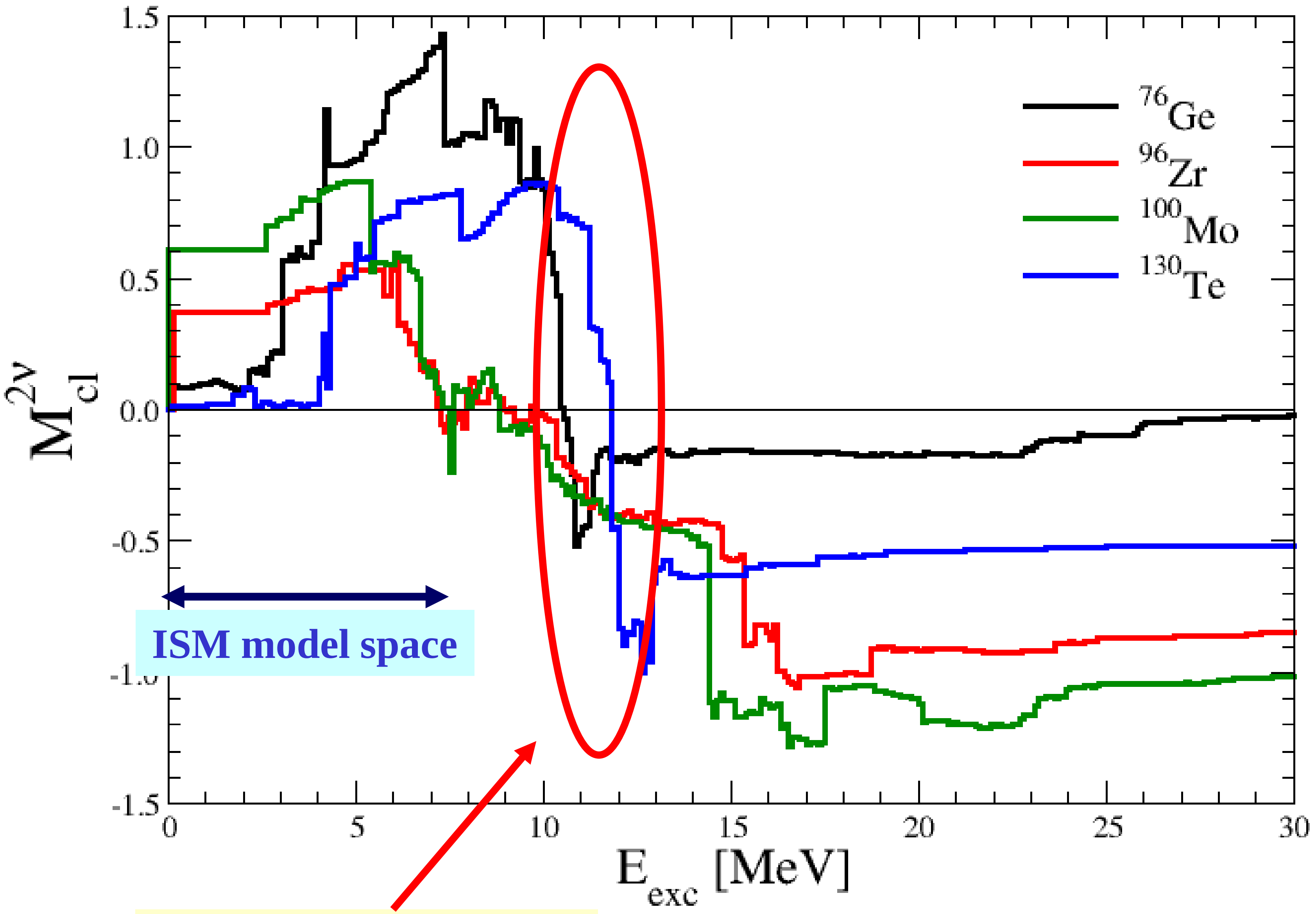
Fedor Simkovic

M^{DGT} – only 1^+

$M^{0\nu}$ - contribution from many J^π (!)

QRPA: There is no proportionality between 0νββ-decay and 2νββ-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)
F. Š., A. Smetana, P. Vogel, PRC 98, 064325 (2018)

Going to relative coordinates:

$$M^{0\nu}_{\nu,N-I} = \int_0^\infty P^{\nu,N}_{I-src}(r)\ C^{2\nu}_{I-cl}(r)\ dr$$
$$= \int_0^\infty f^2_{src}(r)\ P^{\nu,N}_{I}(r)\ C^{2\nu}_{I-cl}(r)\ dr$$
$$I = F,\ GT \text{ and } T$$

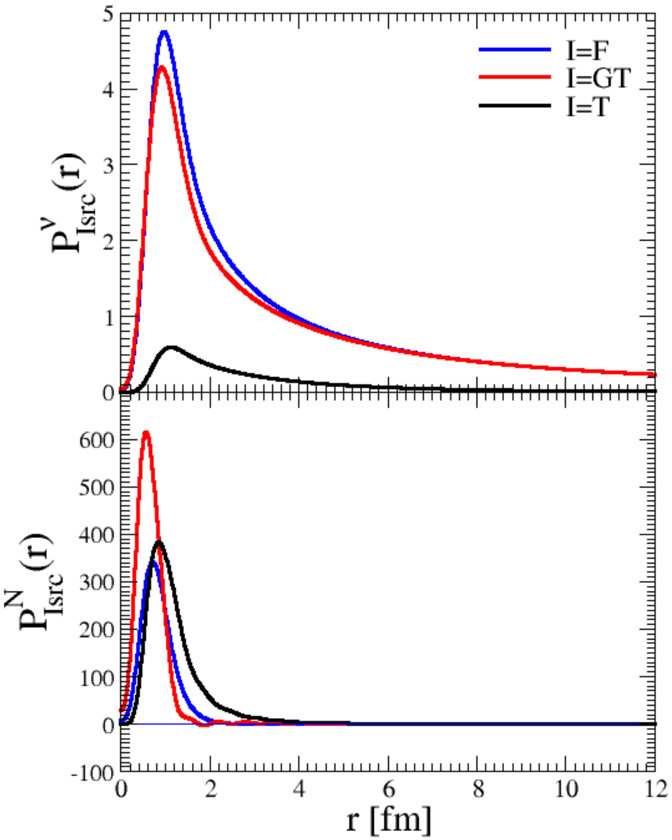
r- relative distance of two decaying nucleons

$$M^{2\nu}_{GT-cl} = \int_0^\infty C^{2\nu}_{GT-cl}(r)\,dr$$

$$M^{2\nu}_{GT-cl} =$$
$$\sum_{J^\pi,m} < 0^+_f|\tau^+\vec{\sigma}|J^\pi,m > \cdot < J^\pi,m|\tau^+\vec{\sigma}|0^+_i >$$
$$\sum_{m} < 0^+_f|\tau^+\vec{\sigma}|1^+,m > \cdot < 1^+,m|\tau^+\vec{\sigma}|0^+_i >$$

imkov

ν– and N- exchange potential (x $f^2_{src}(r)$)

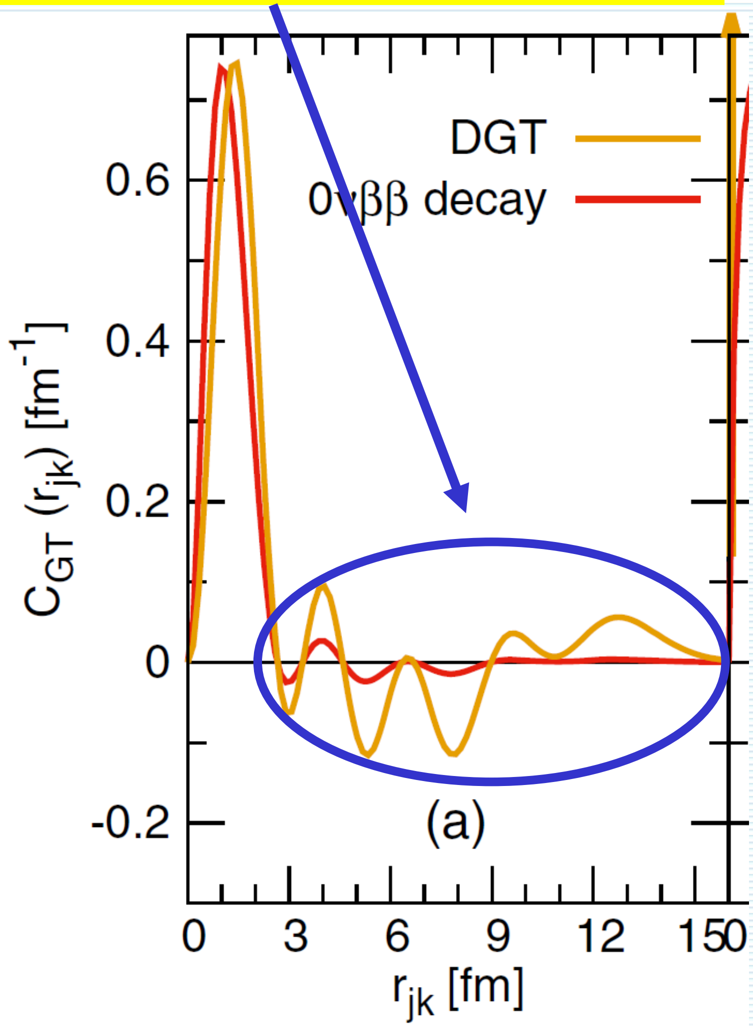


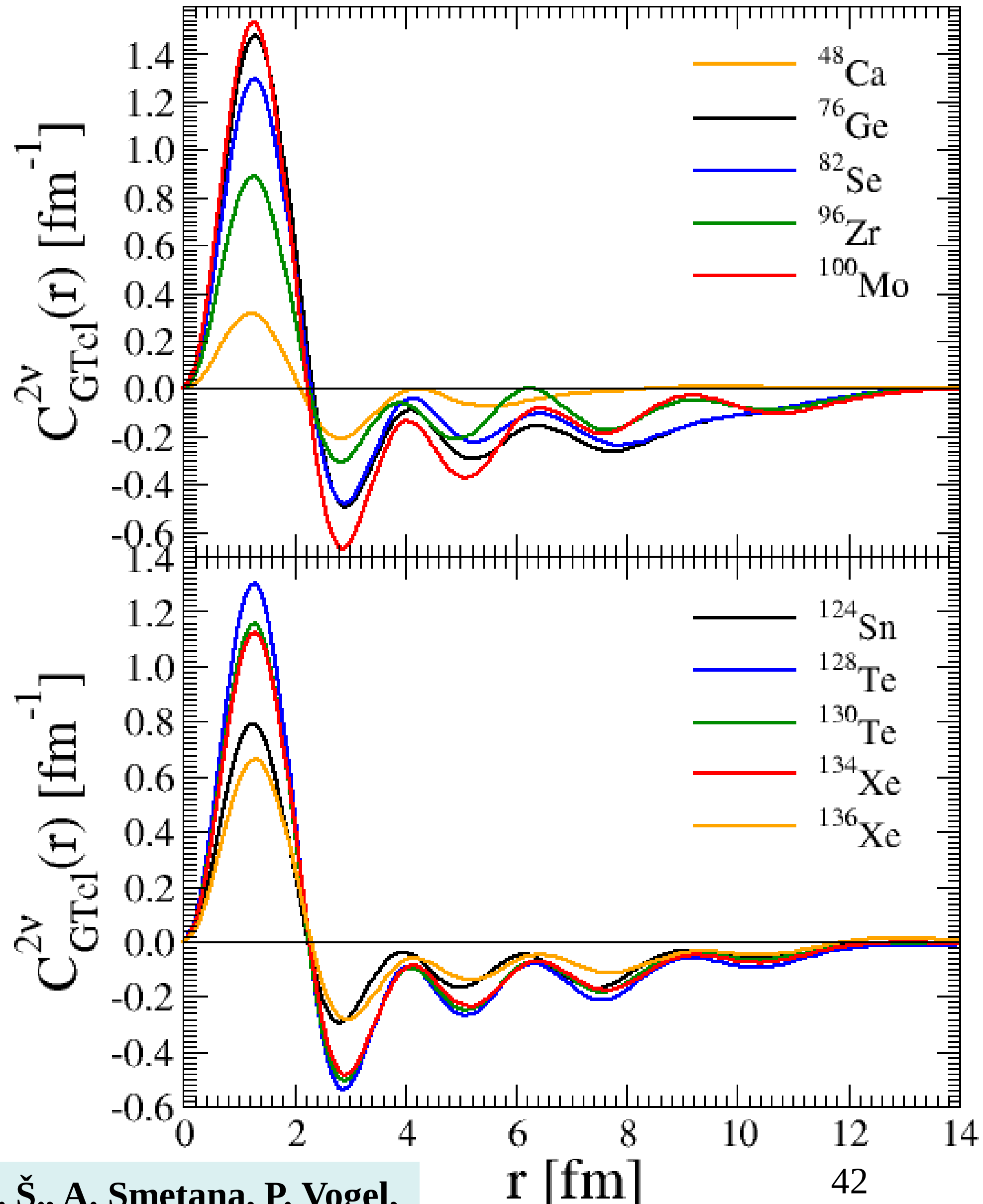
Neutrino potential prefers short distances

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

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

ISM: Tail ≈ 0 (?!) => $M^{2\nu}_{cl}$ » 0



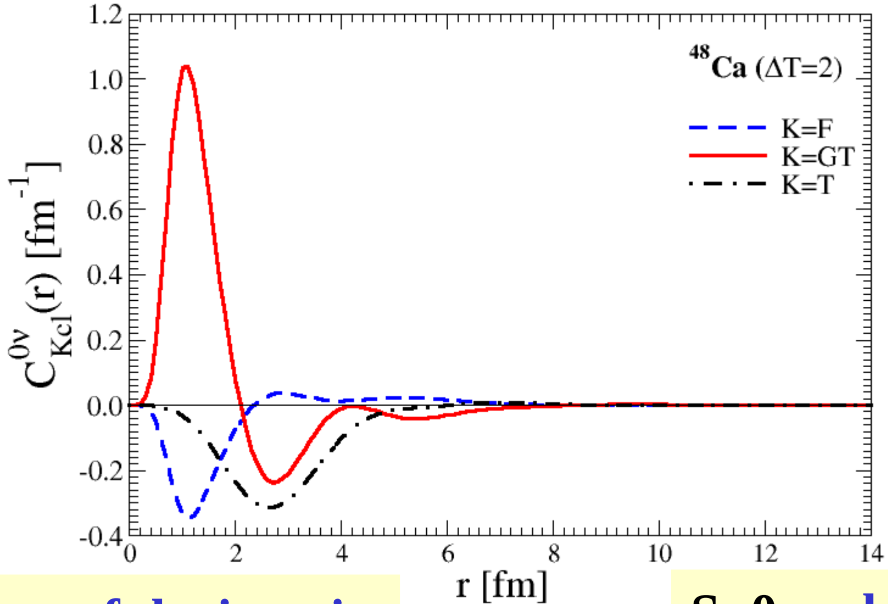


N. Shimizu, J. Menendez, K. Yako, PRL 120, 142502 (2018)

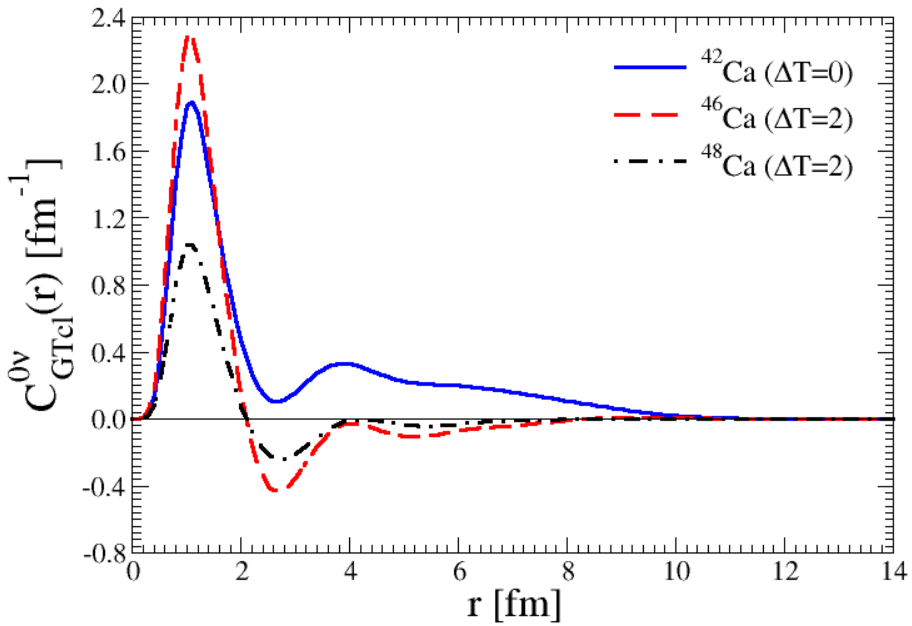
F. Š., A. Smetana, P. Vogel, PRC 98, 064325 (2018)

QRPA

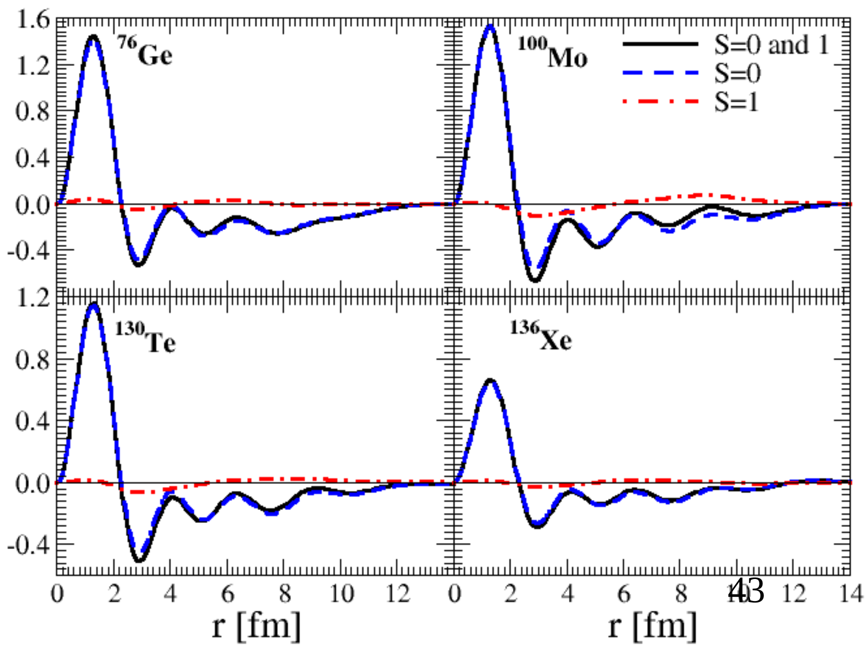
Fermi, Gamow-Teller and tensor



Role of the change of the isospin



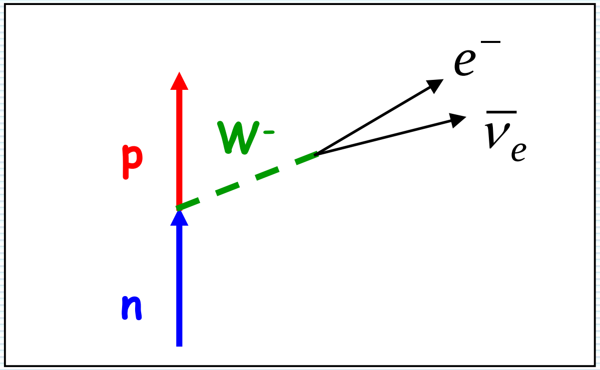
S=0 and S=1 contributions



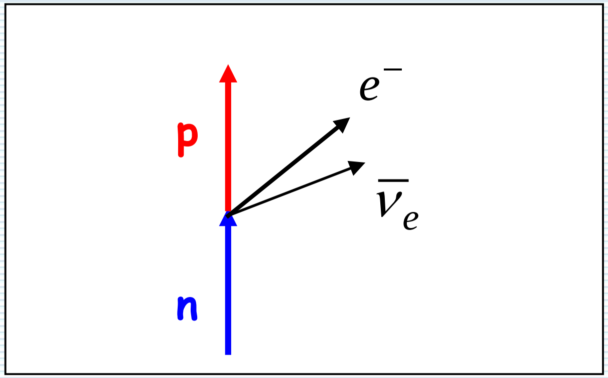
V. *Quenching of g_A* $(q = g^{eff}_A / g^{free}_A)$

Should g_A be quenched in medium?
Missing wave-function correlations
Renormalized operator?
Neglected two-body currents?
Model-space truncations?

Quenching in nuclear matter: $g^{eff}_A = q\, g^{free}_A$



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



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

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^{free}_A =1.27 at the nucleon level

g^{eff}_A = ? inside nuclei

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

QRPA: $(g^{eff}_A)^4 = 0.30$ and 0.50 for ^{100}Mo and ^{116}Cd

IBM: $(g^{eff}_A)^4 \simeq (1.269\, A^{-0.18})^4 = 0.063$

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

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

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

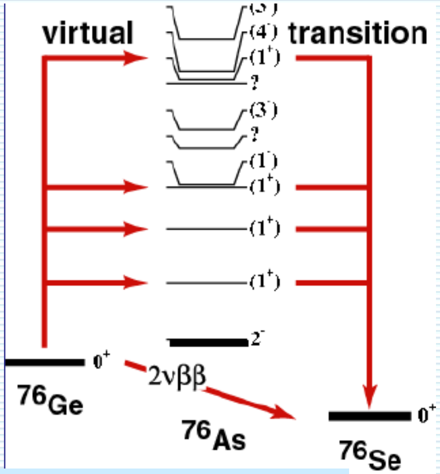
$(g^{eff}_A)^4 = 1.0$

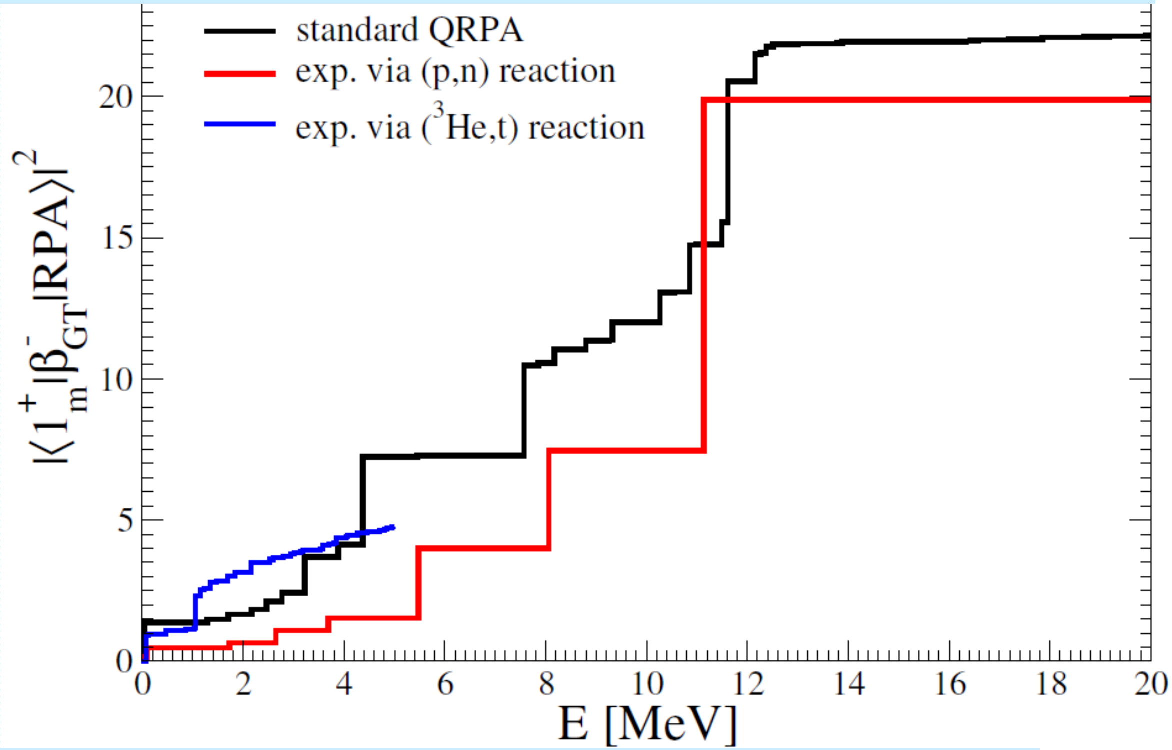
Strength of GT trans. (approx. given by Ikeda sum rule =3(N-Z)) has to be quenched to reproduce experiment.

Using $g_A^{\rm eff} \approx 0.77 \times g_A^{\rm free}$ agrees with data

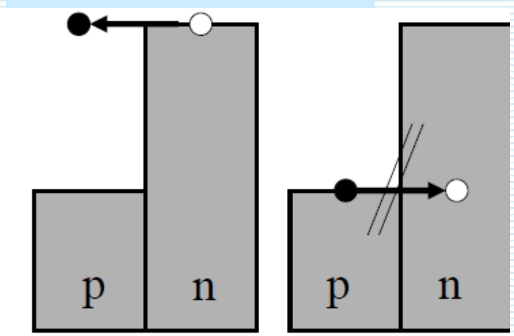
$^{76}_{32}Ge_{44} \Rightarrow$

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





Pauli blocking



Cross-section for charge exchange reaction:

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

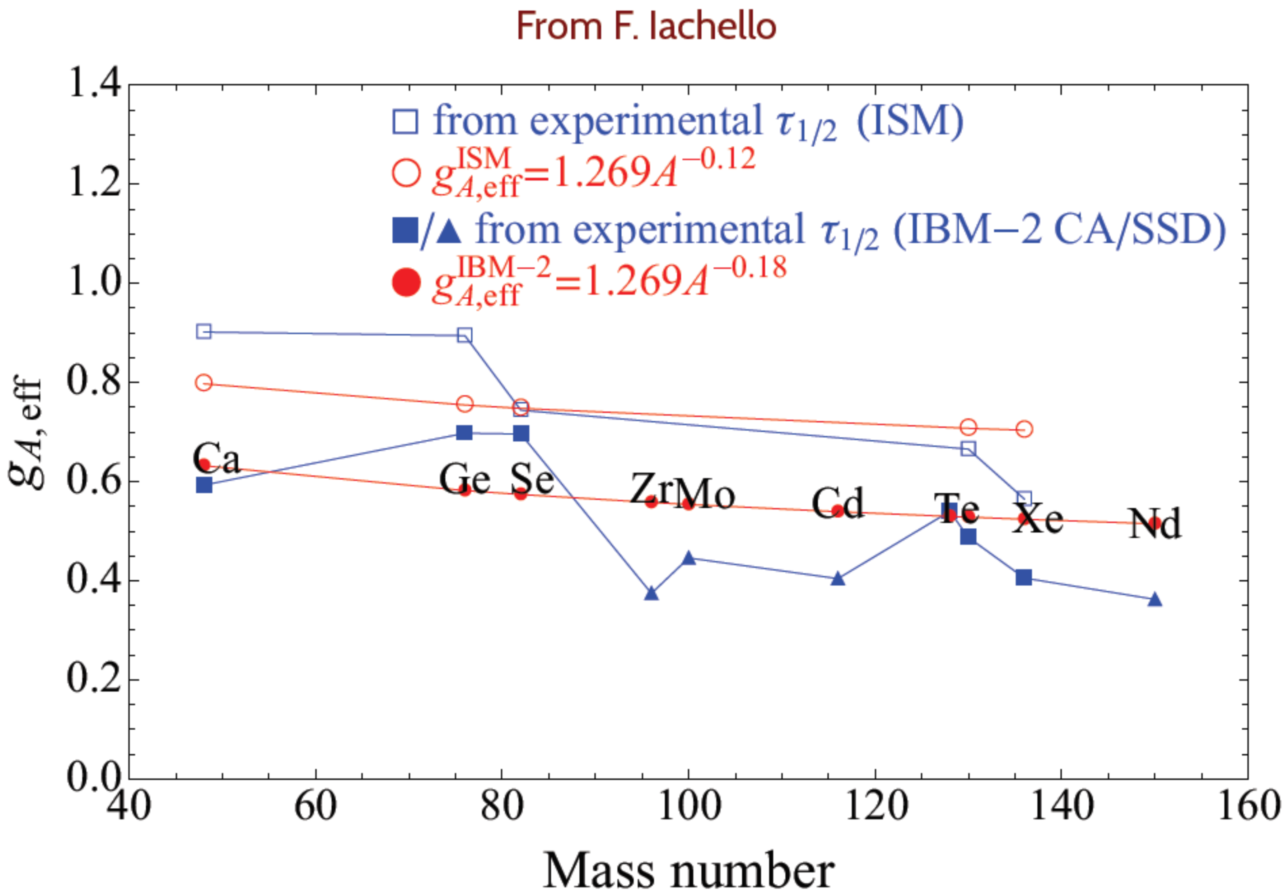
$q = 0!!$

largest at 100 - 200 MeV/A

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

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

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



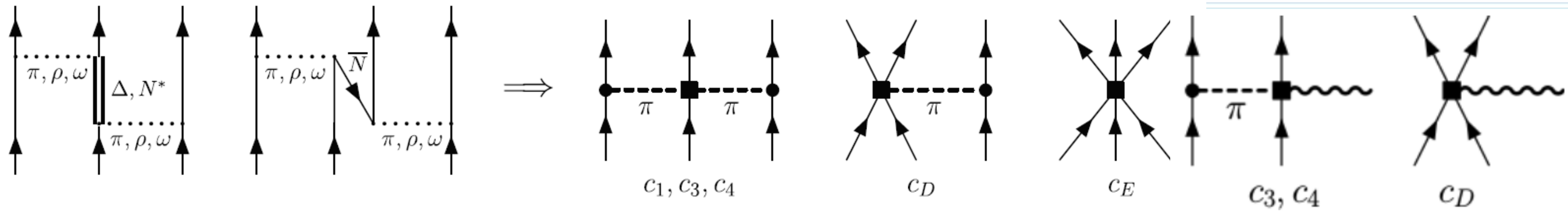
10/24/2019

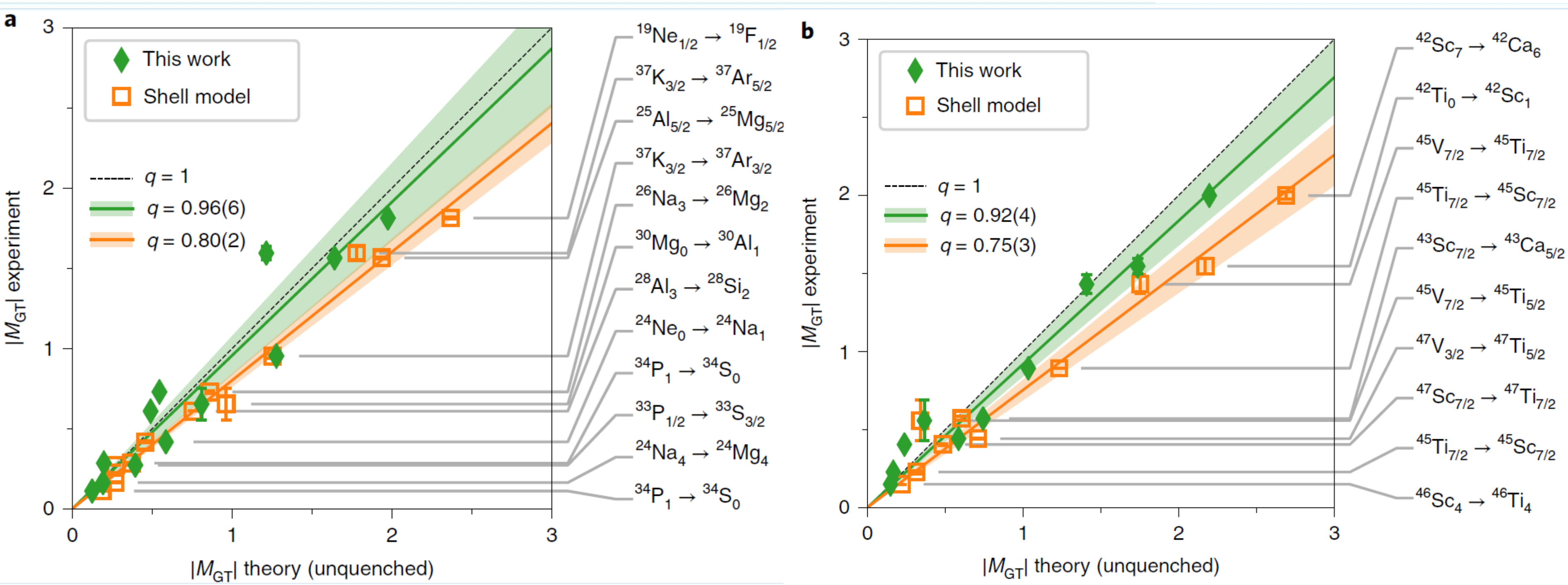
J. Barea, J. Kotila, F. Iachello, PRC 87, 014315 (2013).

LETTERS
https://doi.org/10.1038/s41567-019-0450-7
nature physics

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

Ab initio calculations (light nuclear systems) including meson-exchange currents do not need any "quenching"



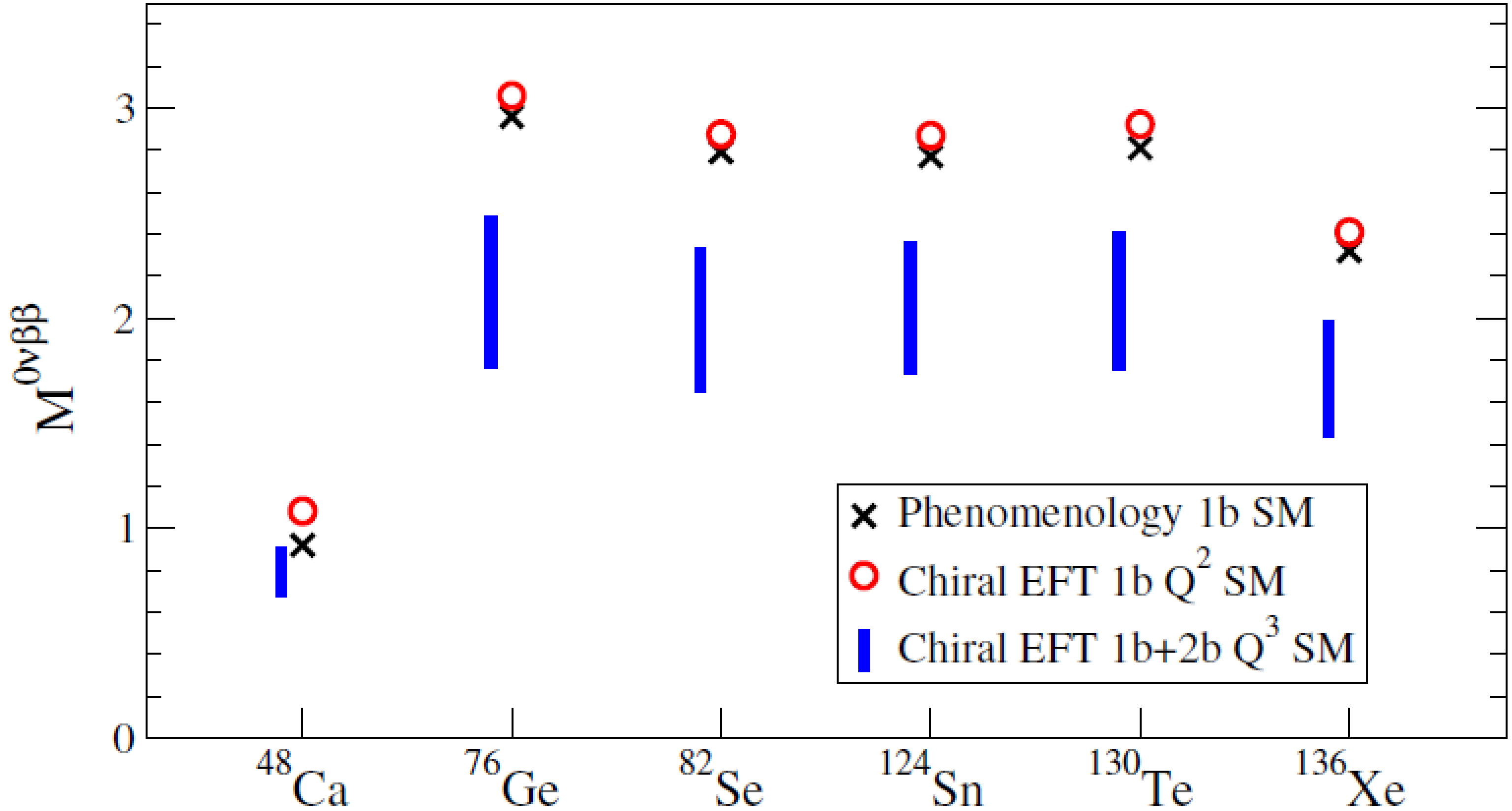


Quenching of g_A and two-body currents

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

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

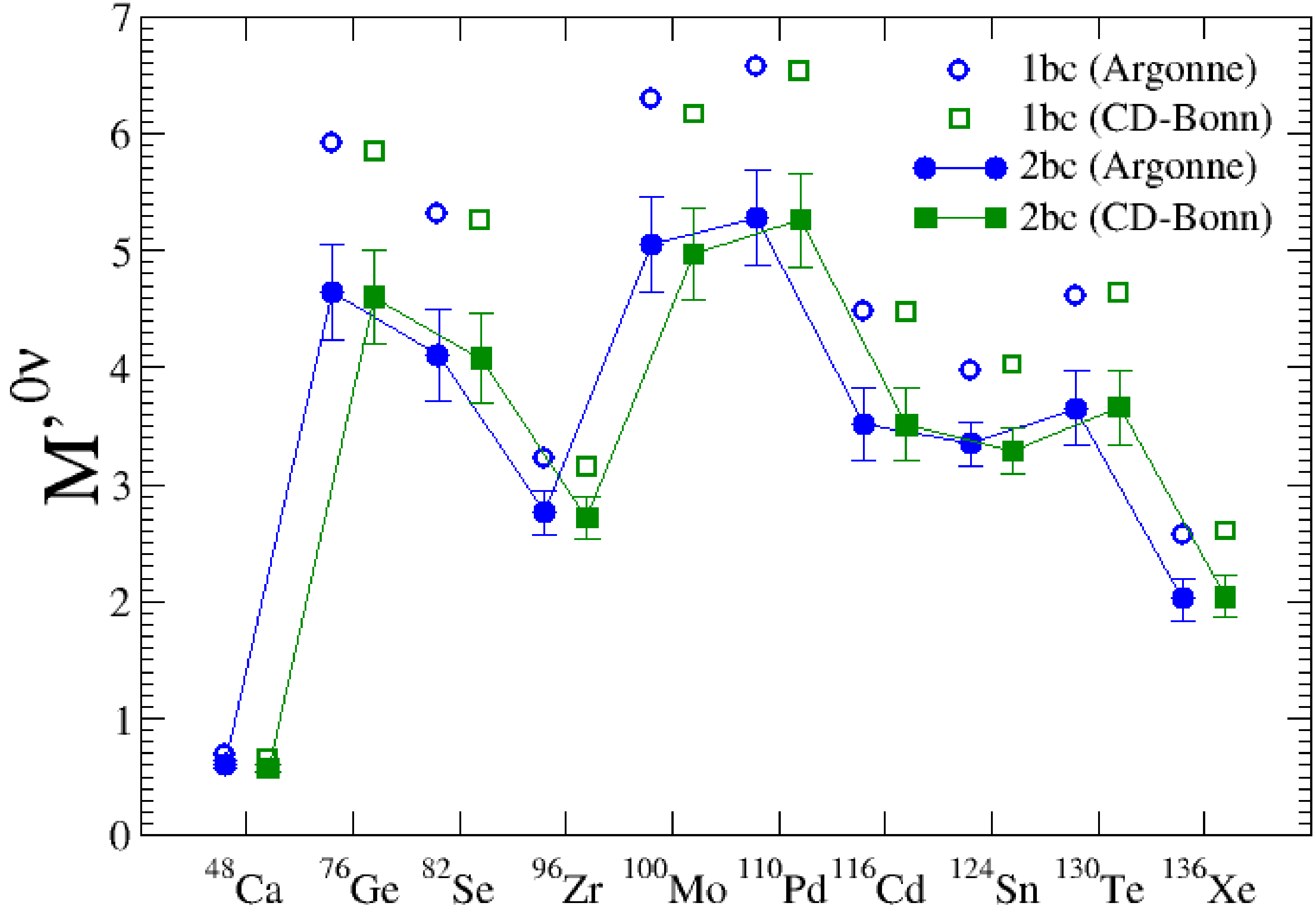
The $0\nu\beta\beta$ operator calculated within effective field theory. Corrections appear as 2-body current predicted by EFT. The 2-body current contributions are related to the quenching of Gamow-Teller transitions found in nuclear structure calc.



Quenching of g_A, two-body currents and QRPA

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

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



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

Improved description of the 0νββ–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

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

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

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

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

We get

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

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

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

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

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

The g_A^{eff} can be deterimed with measured half-life and ratio of NMEs ξ_{31} and calculated NME dominated by transitions through low lying states of the intermediate nucleus.

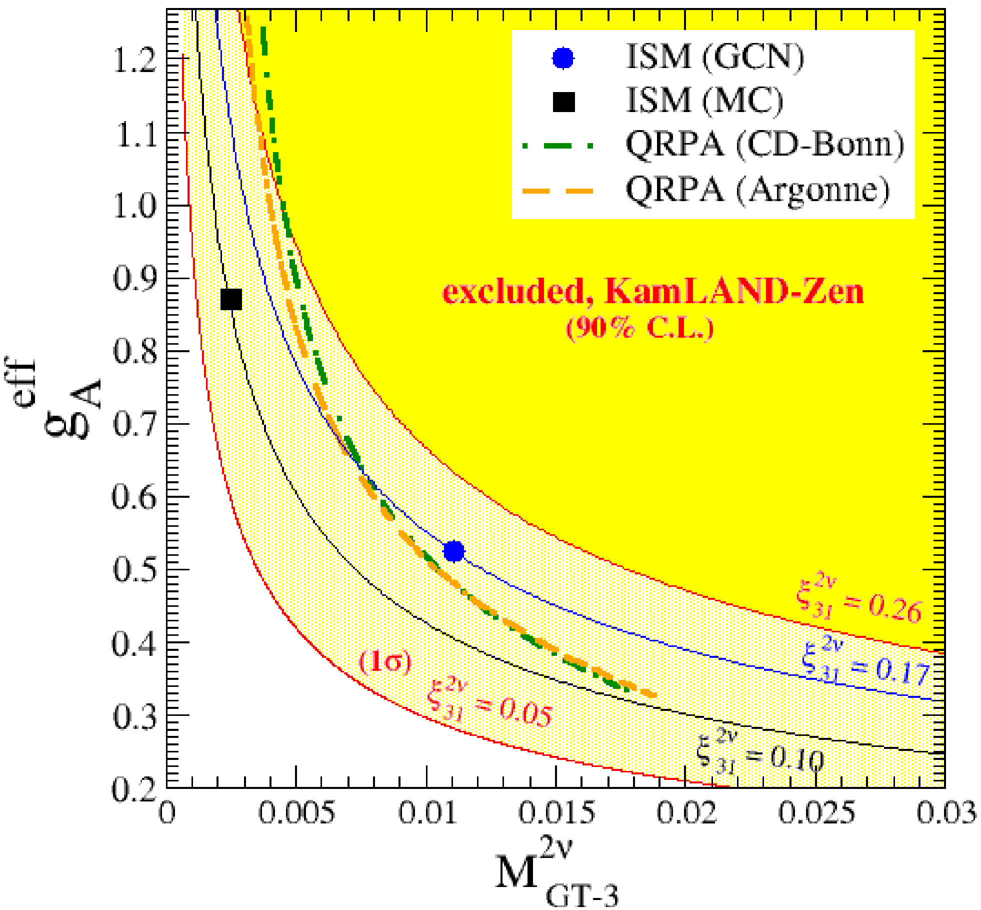
M_{GT-3} have to be calculated by nuclear theory - ISM

$$\left(g_A^{\rm eff}\right)^2 = \frac{1}{\left|M^{2\nu}_{GT-3}\right|}\frac{\left|\xi^{2\nu}_{13}\right|}{\sqrt{T^{2\nu-exp}_{1/2}\left(G^{2\nu}_0 + \xi^{2\nu}_{13} G^{2\nu}_2\right)}}$$

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

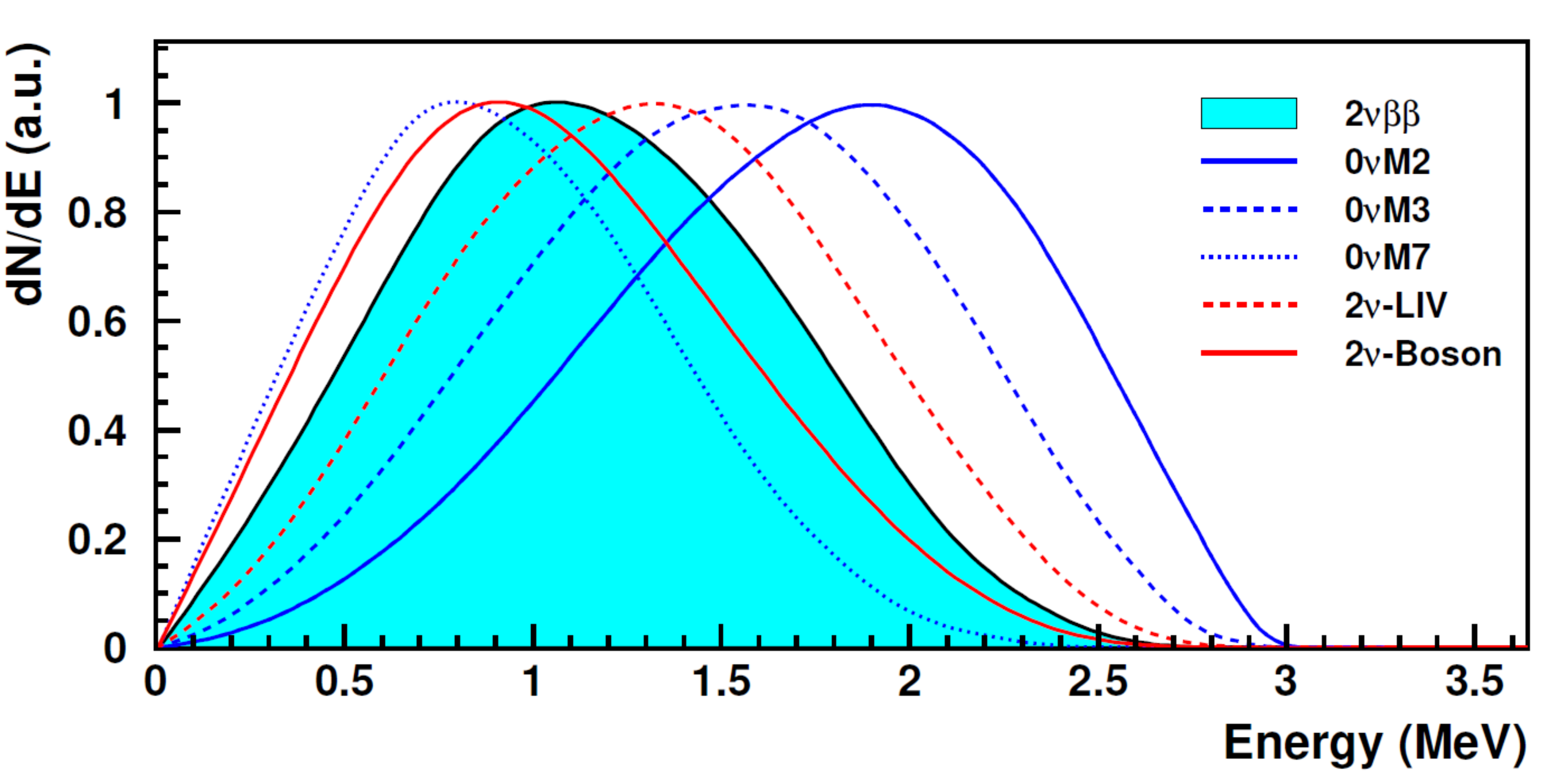
$$M^{2\nu}_{GT-3} = \sum_n M_n \frac{4\ m_e^3}{(E_n - (E_i + E_f)/2)^3}$$

$$\xi^{2\nu}_{13} = \frac{M^{2\nu}_{GT-3}}{M^{2\nu}_{GT-1}}$$



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

Looking for a new physics with differential characteristics



Spectral index n

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

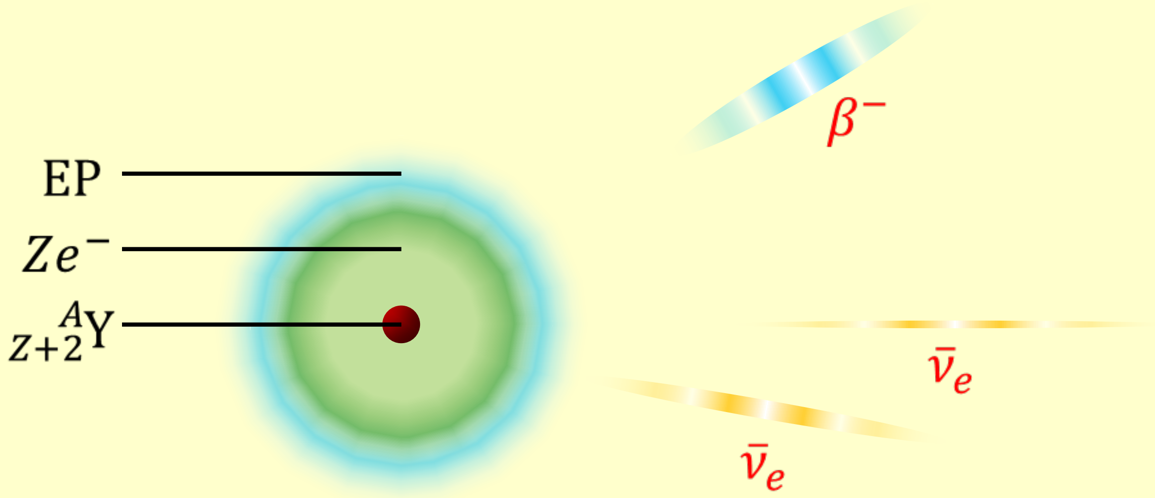
Double Beta Decay with emission of a single electron

A. Babič, M.I. Krivoruchenko, F.Š., PRC 98, 065501 (2018)

[Jung *et al.* (GSI), 1992] observed beta decay of $^{163}_{66}\mathrm{Dy}^{66+}$ ions with Electron Production (EP) in K or L shells: $T_{1/2}^{\mathrm{EP}} = 47\ \mathrm{d}$

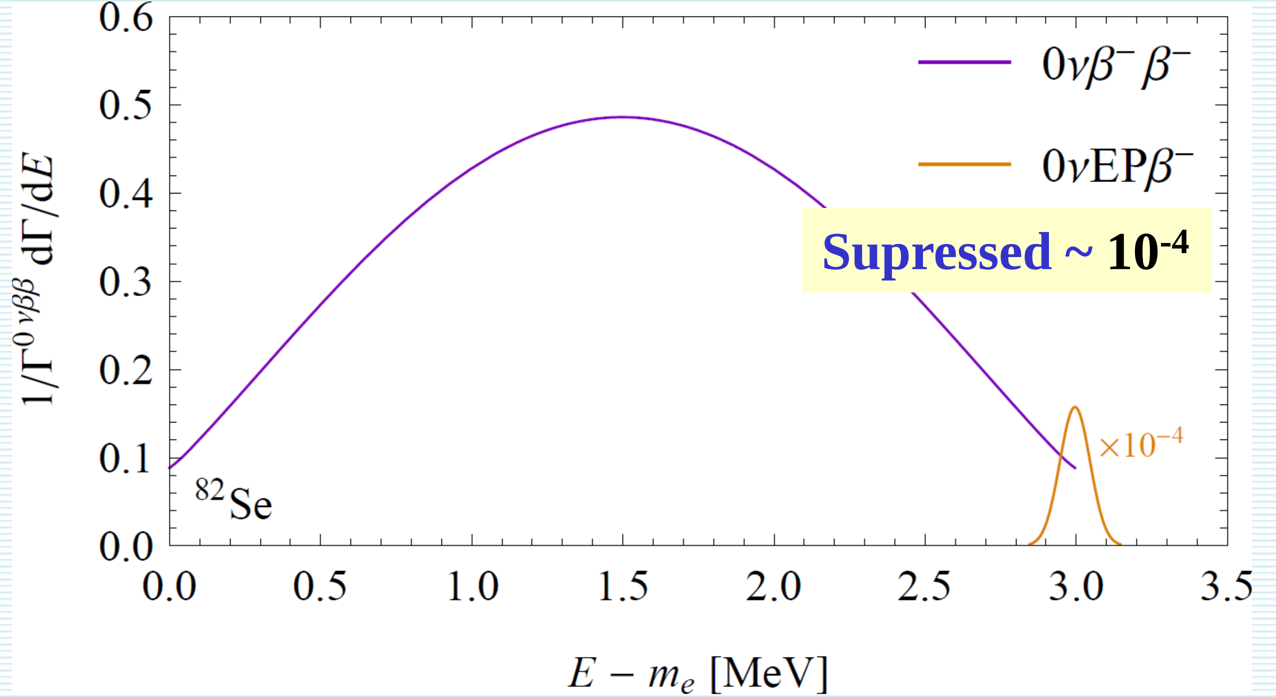
Bound-state double-beta decay $0\nu\mathrm{EP}\beta^-$ $(2\nu\mathrm{EP}\beta^-)$ **with EP in available** $\mathrm{s}_{1/2}$ **or** $\mathrm{p}_{1/2}$ **subshell of daughter 2+ ion:**

$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+2}\mathrm{Y} + e_{\mathrm{b}}^{-} + e^{-} + (\bar{\nu}_e + \bar{\nu}_e)$$

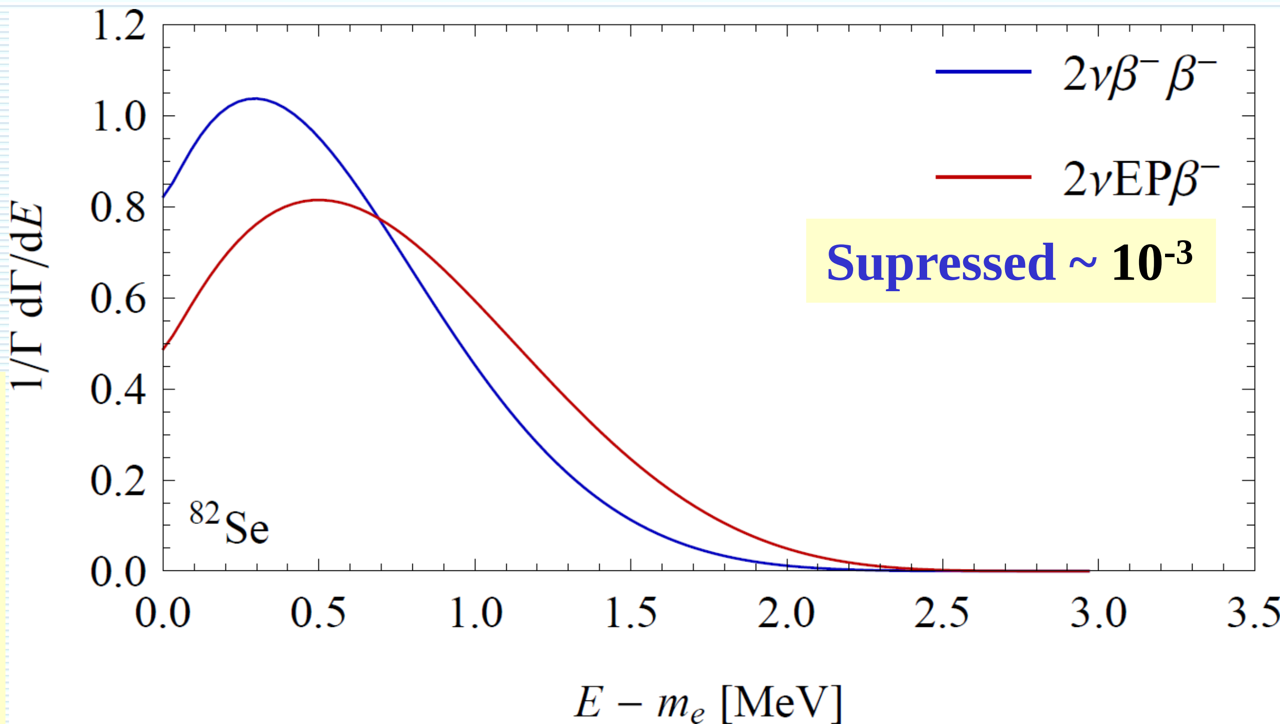


Search for possible manifestation in single-electron spectra…

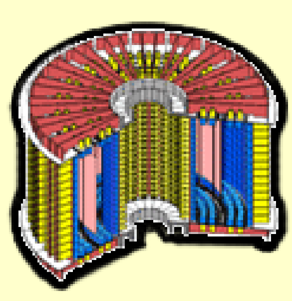
Energy distribution of a single electron



0νEPβ strongly suppresed

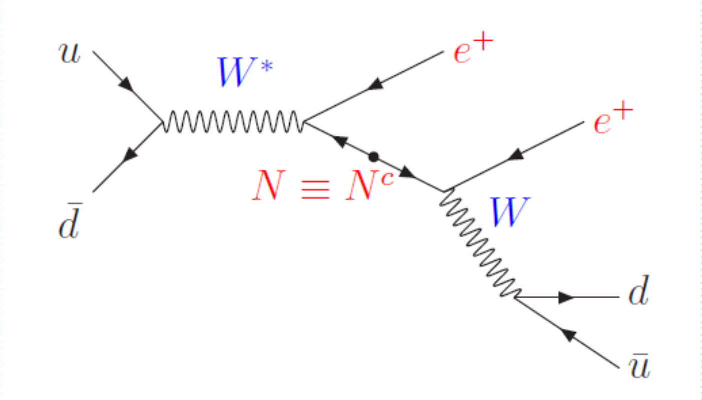


2νEPβ could be detected
Half-life predictions independent n gA and value of 2nbb NME

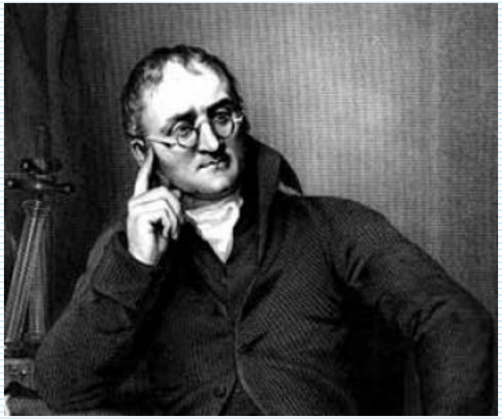


V. On the search for the signal of the total LNV

a resonance production of heavy **N**



0νββ
Avogadro number is large …



Collider: $pp \to l^+l^+ + jj$

$\mu^- + (A,Z) \to (A,Z\text{-}2) + e^+$

$\mu^- + (A,Z) \to (A,Z\text{-}2) + \mu^+$

Mesons decays

… many others

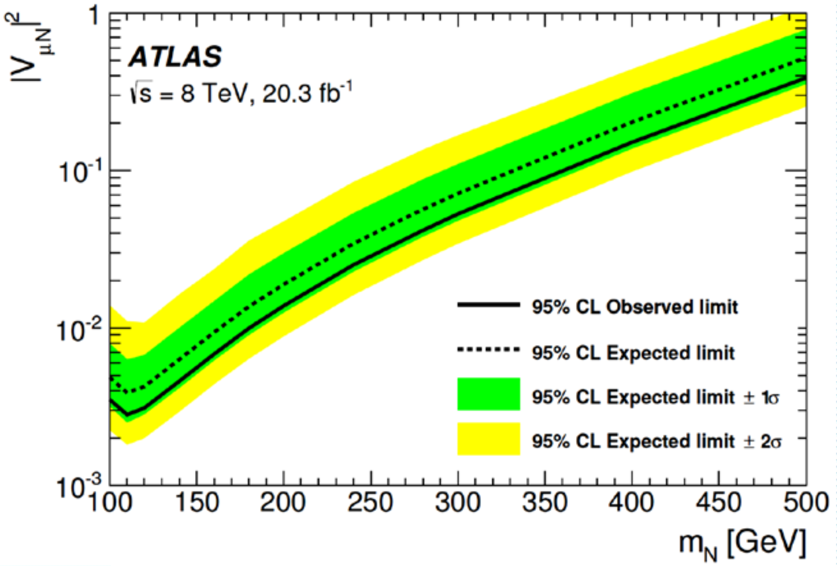
restictions for future:
Solar neutrinos, 2νββ background

=>

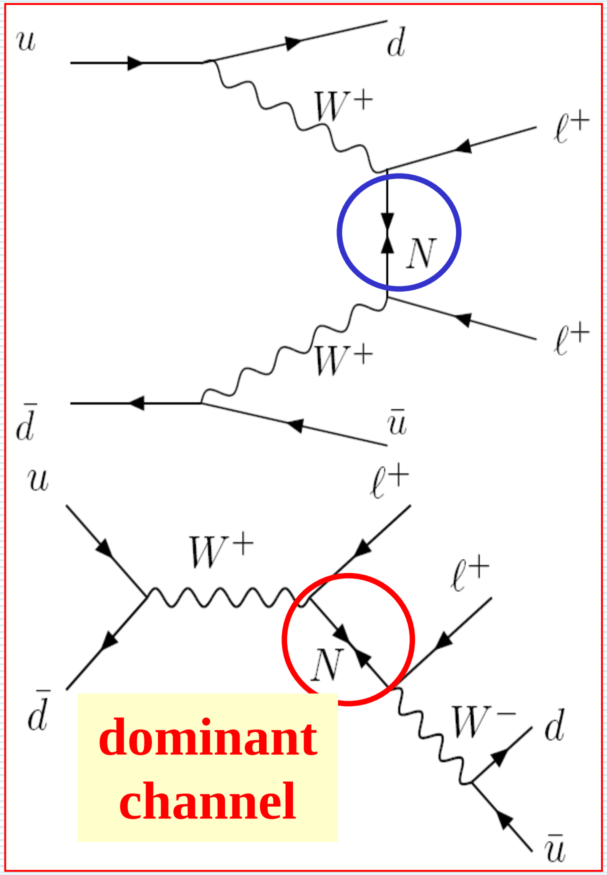
Solution?
resonant neutrinoless double electron capture

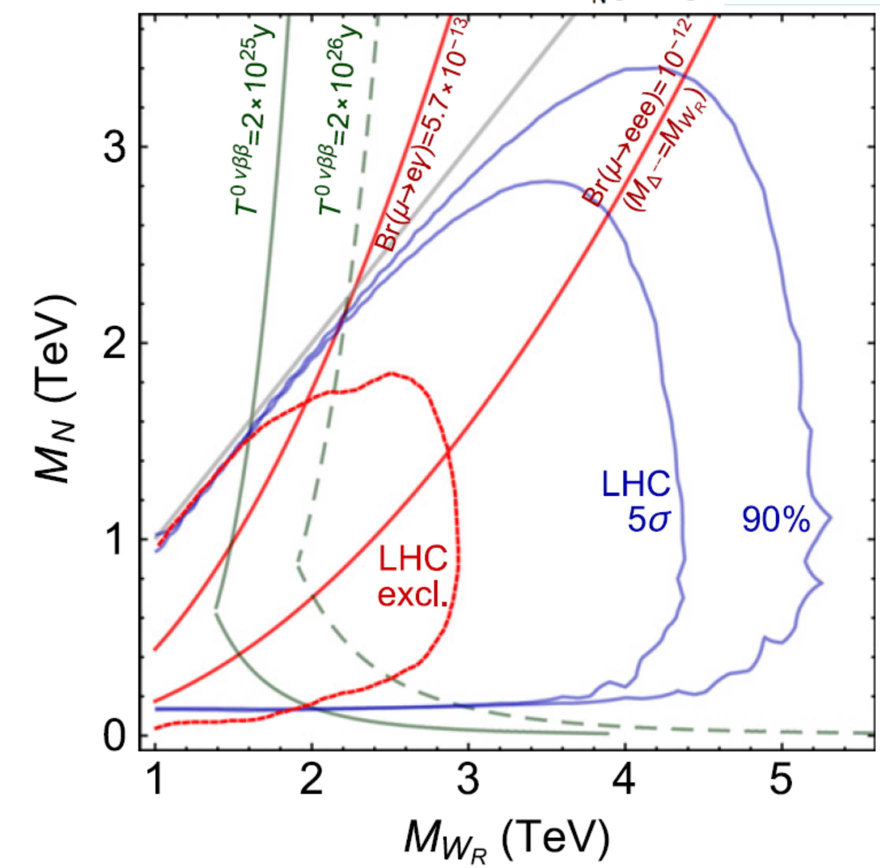
Direct searches for heavy ν's at LHC => TeV mass limit

$$pp \to l^+ l^+ + jj$$



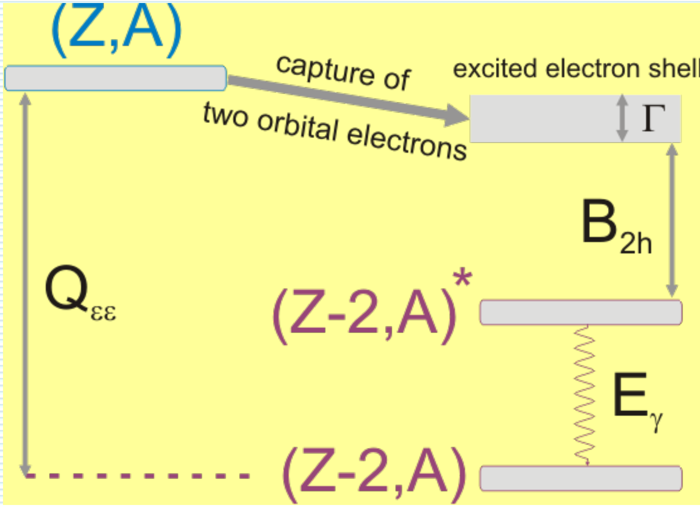
collider analogue to 0νββ decay



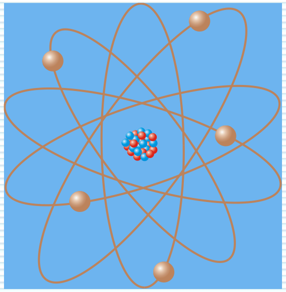


Deppisch, Dev, Pilaftis, New J. Phys. 17, 075019 (2018)

***N* can be produced on resonance**



Resonant neutrinoless double-electron capture

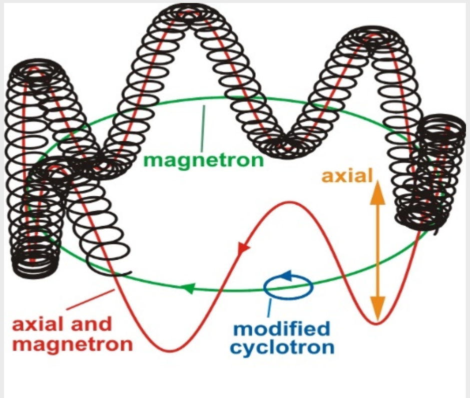


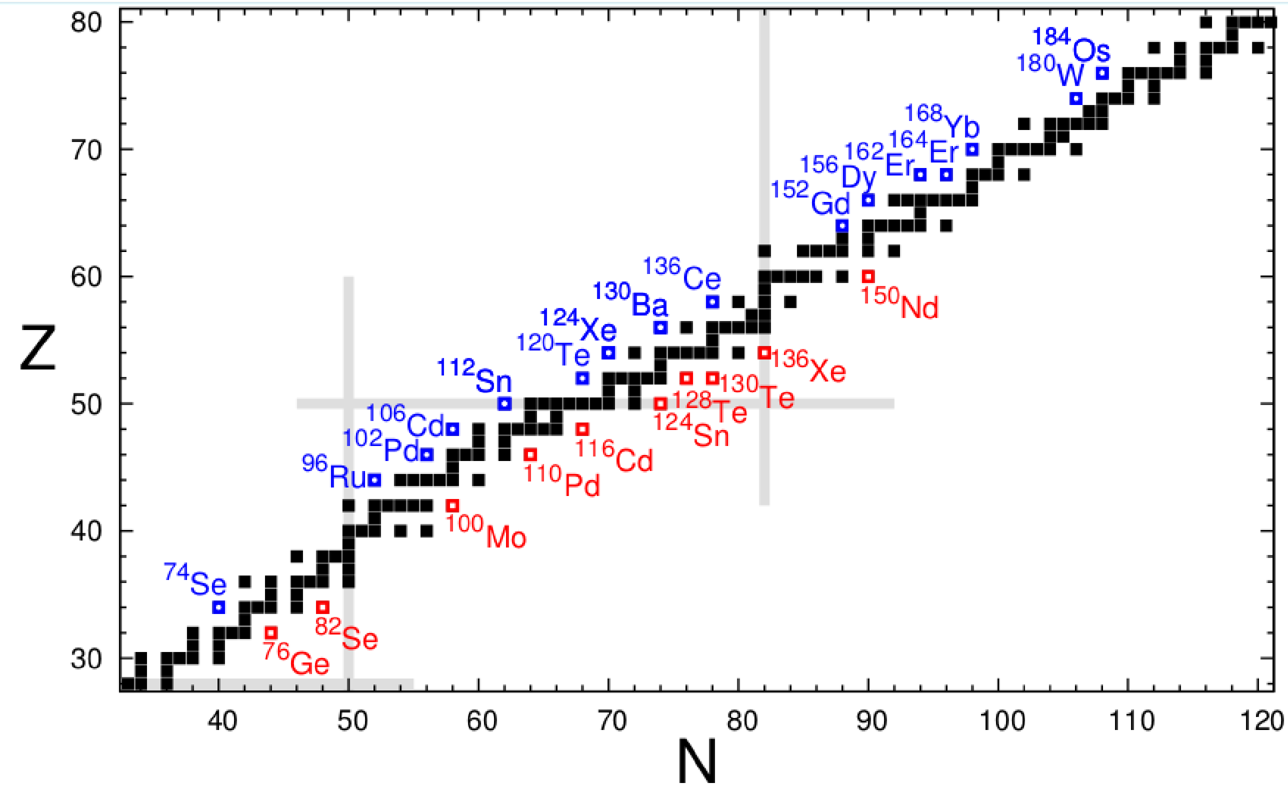
$$e^- + e^- + (A,Z) \rightarrow (A,Z\text{-}2)^{**}$$

$$\frac{1}{T_{1/2}} = A \cdot |\psi_{1e}|^2 \cdot |\psi_{2e}|^2 \cdot \frac{\Gamma}{(Q - B_{2h} - E_\gamma)^2 + \frac{1}{4}\Gamma^2}$$

$^{152}Gd^+$: ΔM=100 eV

Penning Trap





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 and solar ν's can be a problem
- $0^+ \rightarrow 0^+, 2^+$ 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 (2022)

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
- No background from solar ν's
- $0^+ \rightarrow 0^+, 0^-, 1^+, 1^-$ transitions
- Small Q-value
- Q-value measured with below 1 keV accuracy
- ^{152}Gd → ^{152}Sm (sensitivity to $m_{\beta\beta}$ by factor ~10 worser as by 0νββ)
- small experiments yet
- Can we manipulate atomic structure ….

Conclusions and Outlook

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

***ν's*, the Standard Model misfits**

WE are at the beginning of the Beyond Standard Model Road…

people often overestimate what will happen in the next two years and underestimate what will happen in ten (Bill Gates)