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Massive Neutrinos andNeutrinoless Double Beta Decay

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OUTLINE

I. *Introduction*
(Majorana ν's)
II. A *generation of neutrino mass, 0νββ-decay mechanisms*
(QCSS scenario, LR symmetric model)
III. The *0νββ-decay NMEs – Current status*
(deformation, SU(4) symmetry, ab initio…)
IV. *Quenching of g_A*
(theory and experimental indications, novel approach for effective g_A)
V. *Outlook*

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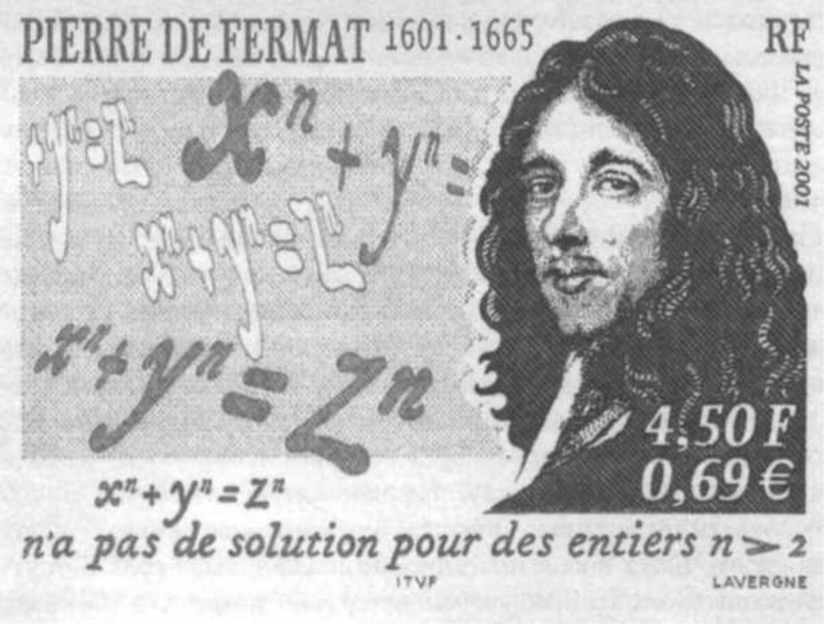


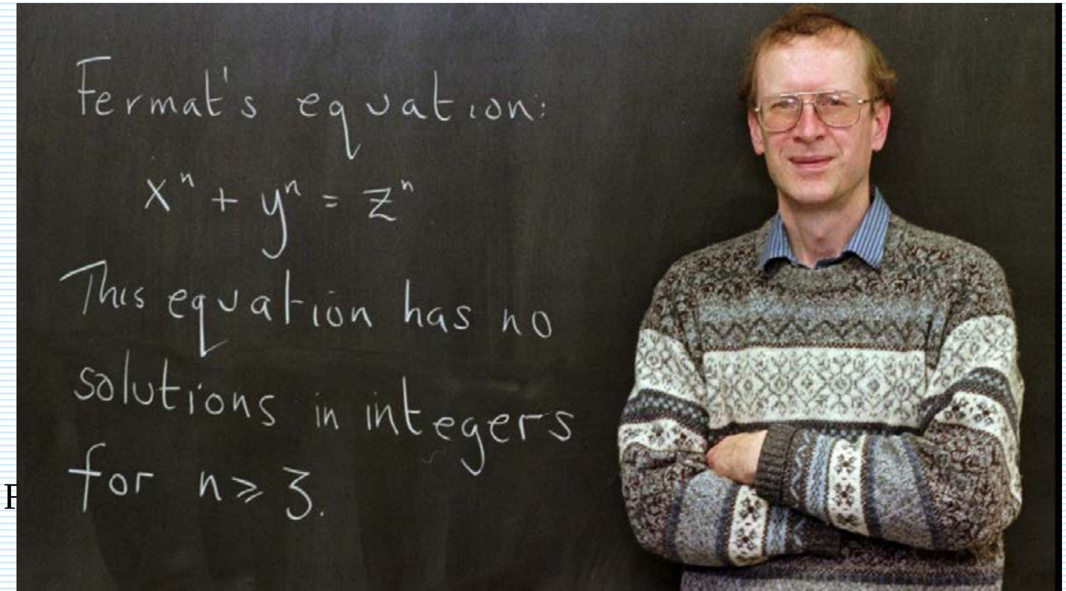
Around 1637, Fermat wrote in the margin of a book that the more general equation

$$a^n + b^n = c^n$$

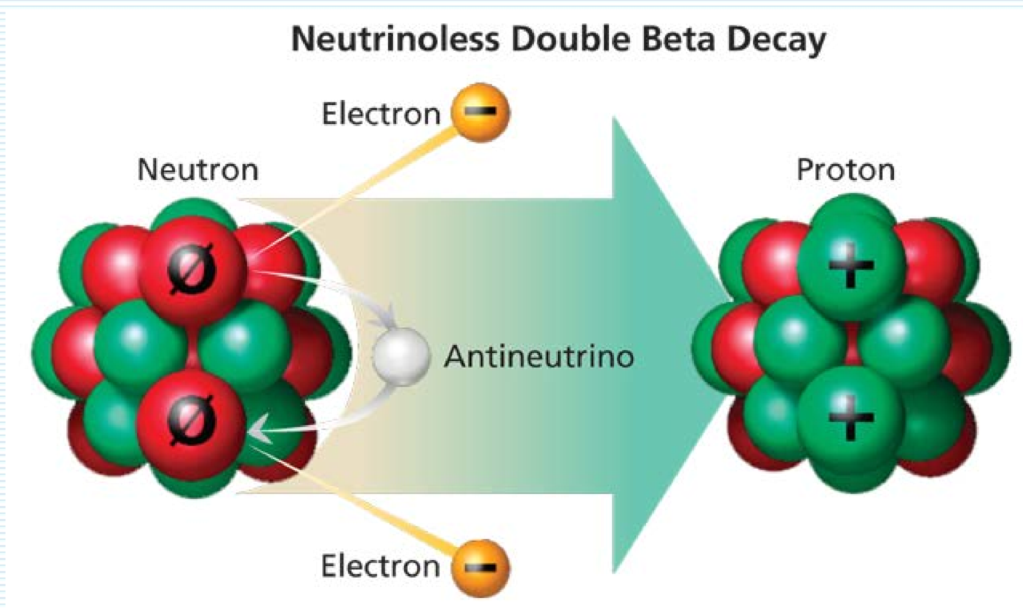
had no solutions in positive integers if *n* is an integer greater than 2.

After 358 years

The corrected proof was published by Andrew Wiles in 1995.




ARE NEUTRINOS THEIR OWN ANTIPARTICLES?


Neutrinoless Double Beta Decay
Electron
Neutron
Proton
Antineutrino
Electron

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

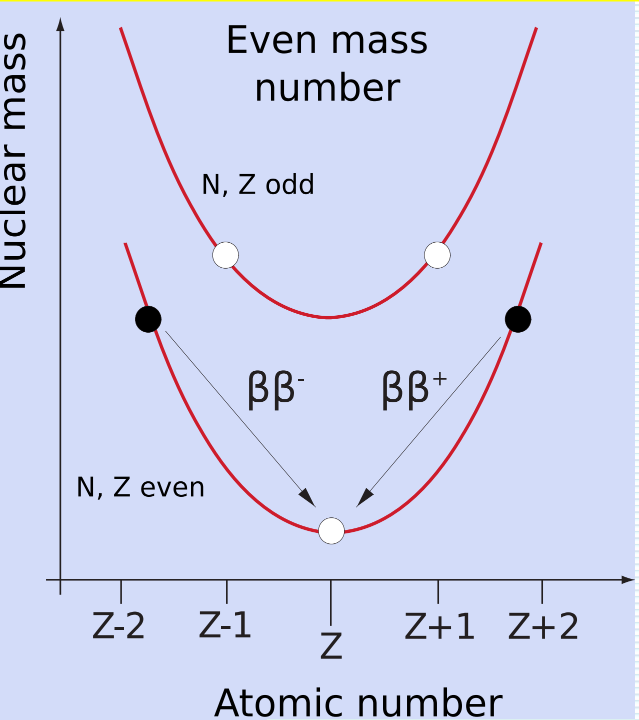
Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* Dirac *ne risulta alquanto modificato e non vi è più luogo a parlare di 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.*

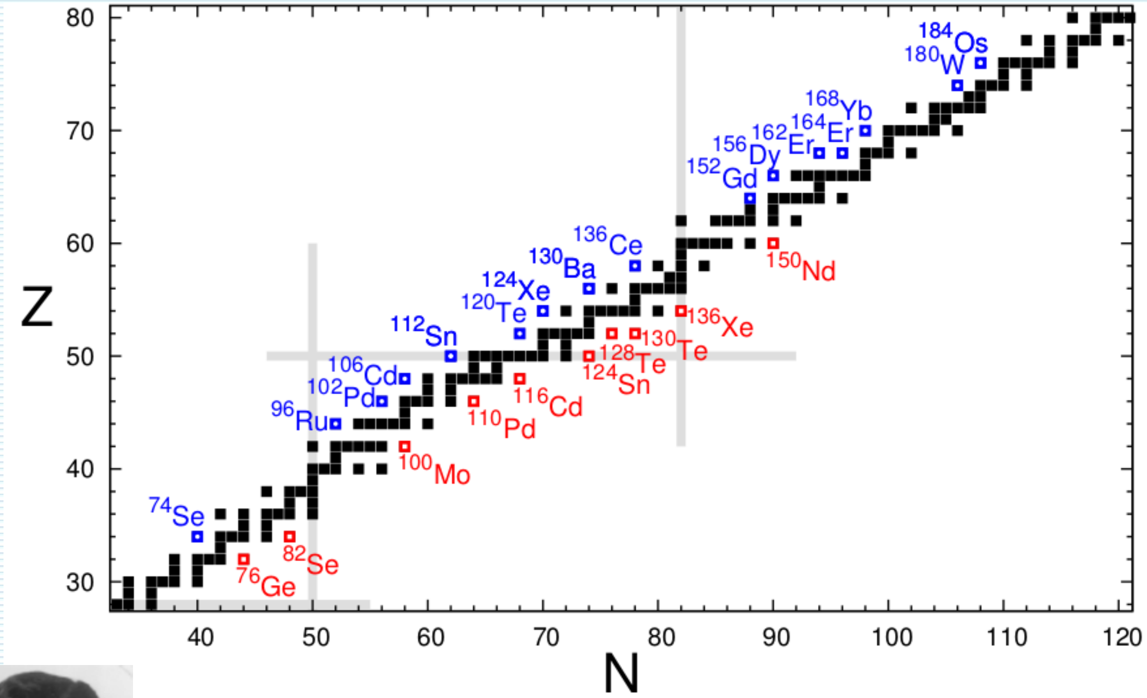
L'interpretazione dei cosidetti « stati di energia negativa » proposta da Dirac (1) conduce, come è ben noto, a una descrizione sostanzialmente simmetrica degli elettroni e dei positroni. La sostanziale simmetria del formalismo consiste precisamente in questo, che fin dove è possibile applicare la teoria 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 ... nuova 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.

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



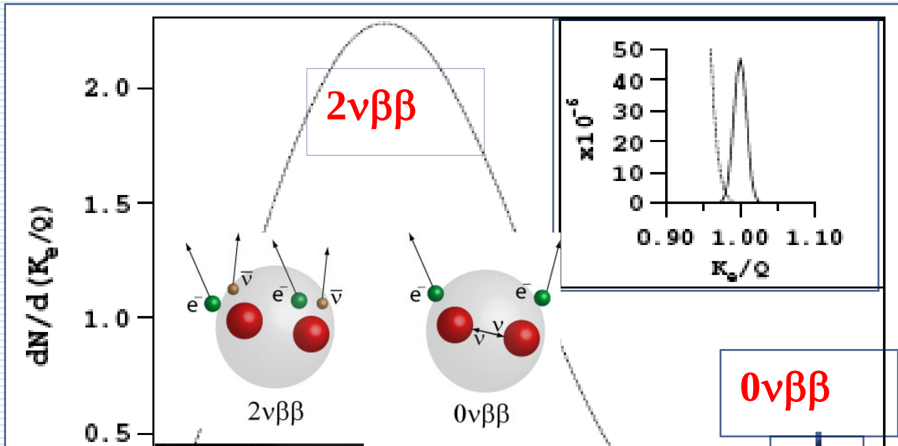


Phys. Rev. 48, 512 (1935)

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

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

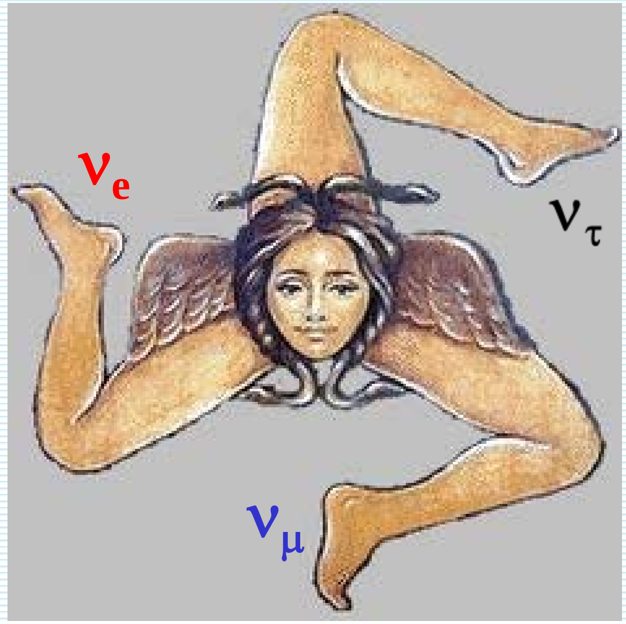
Not observed yet. Requires massive Majorana ν's

After **90/64** years we know

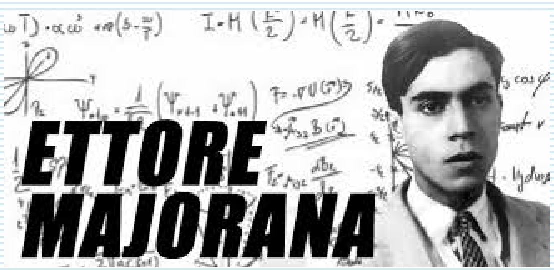
Fundamental ν properties

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)**

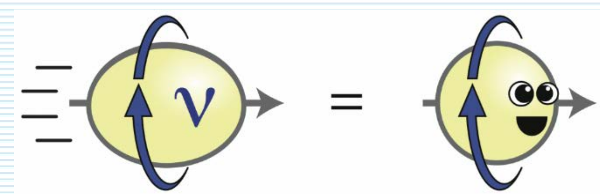


- Are ν Dirac or Majorana?
- Is there a CP violation in ν sector?
- Are neutrinos stable?
- What is the magnetic moment of ν?
- Sterile neutrinos?
- Statistical properties of ν? **Fermionic or partly bosonic?**



Currently main issue

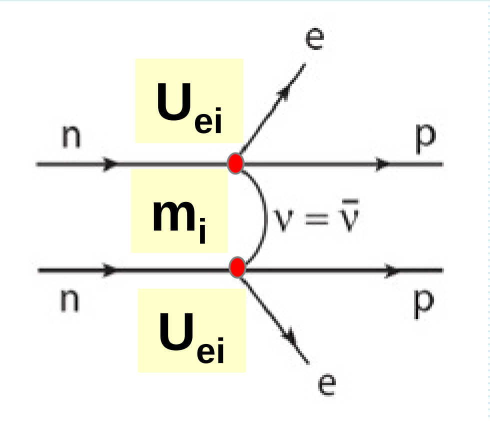
Nature, Mass hierarchy,
CP-properties, sterile ν



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

0νββ-decay *(traditional picture)*

(A,Z) → (A,Z+2) + e⁻ + e⁻



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

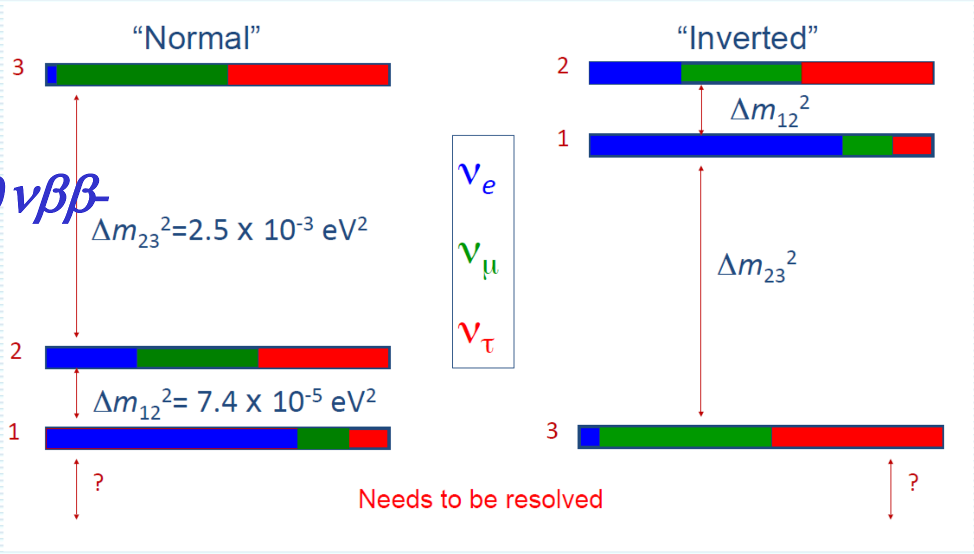
?

Phase factor well understood

NME must be evaluated using tools of nuclear theory

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

0νββ-



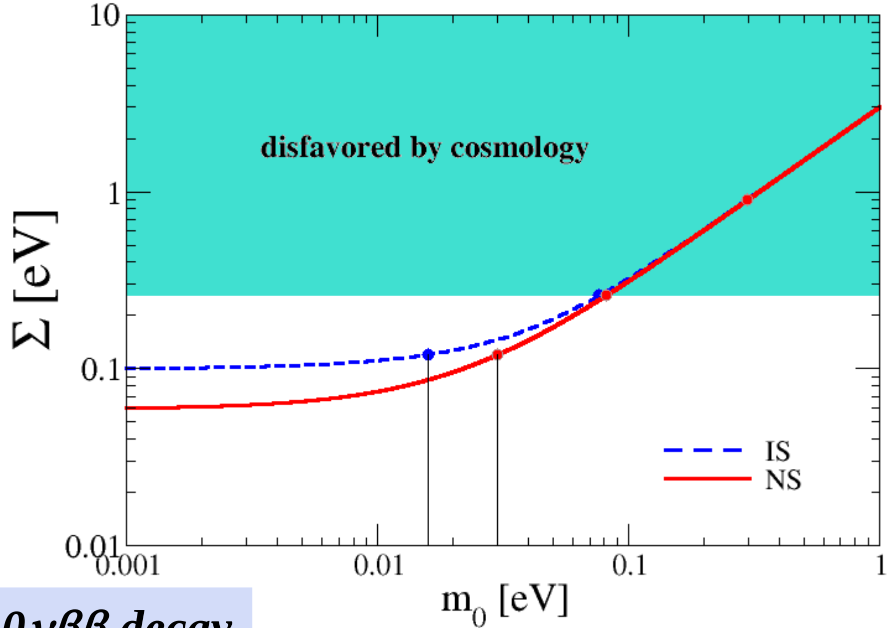
Effective Majorana mass can be evaluated. It depends on

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)

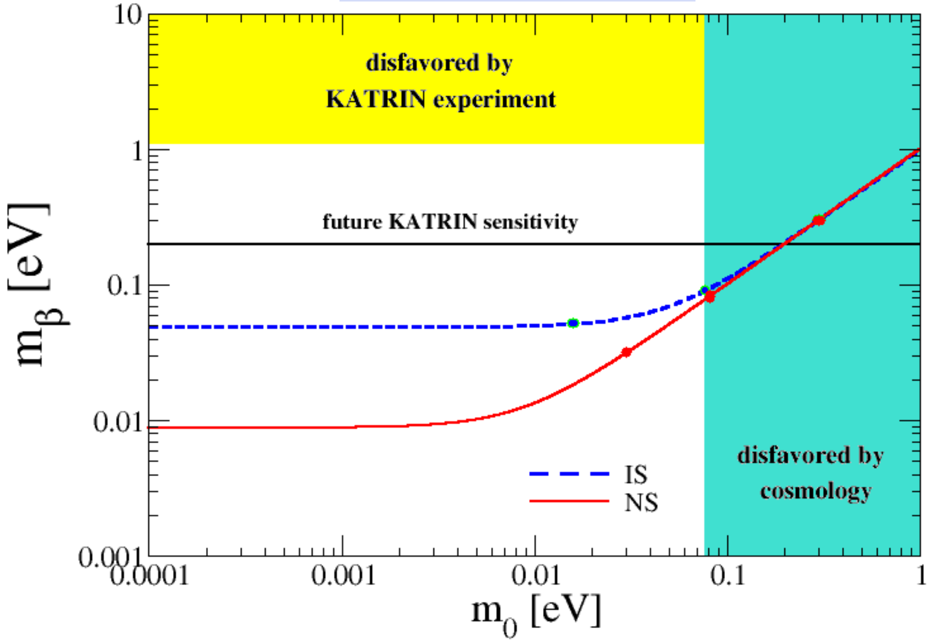
$$U^{PMNS} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -e^{i\delta}c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix}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

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



Σ < 0.90 eV
< 0.26 eV (Planck coll.)
< 0.12 eV

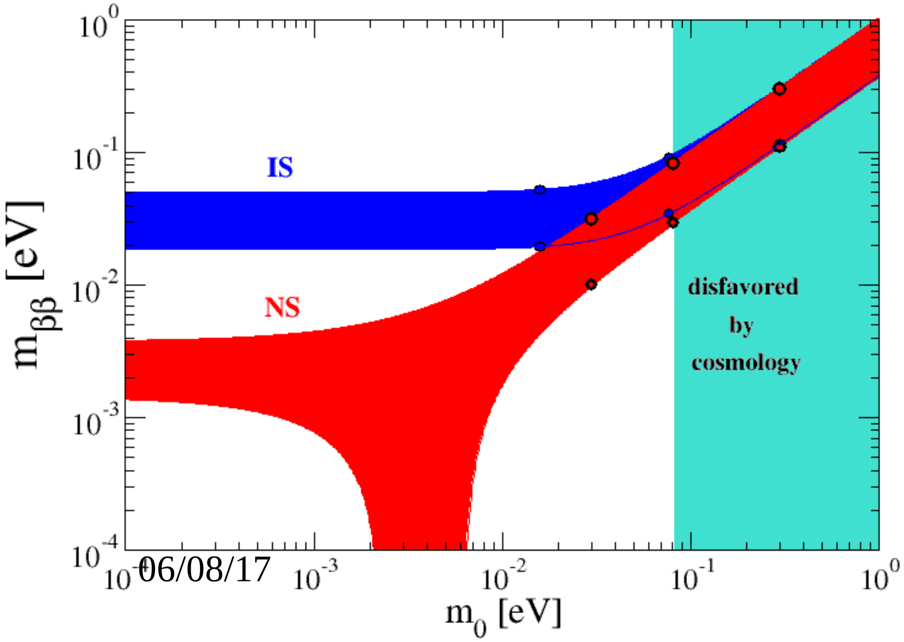
Tritium β-decay

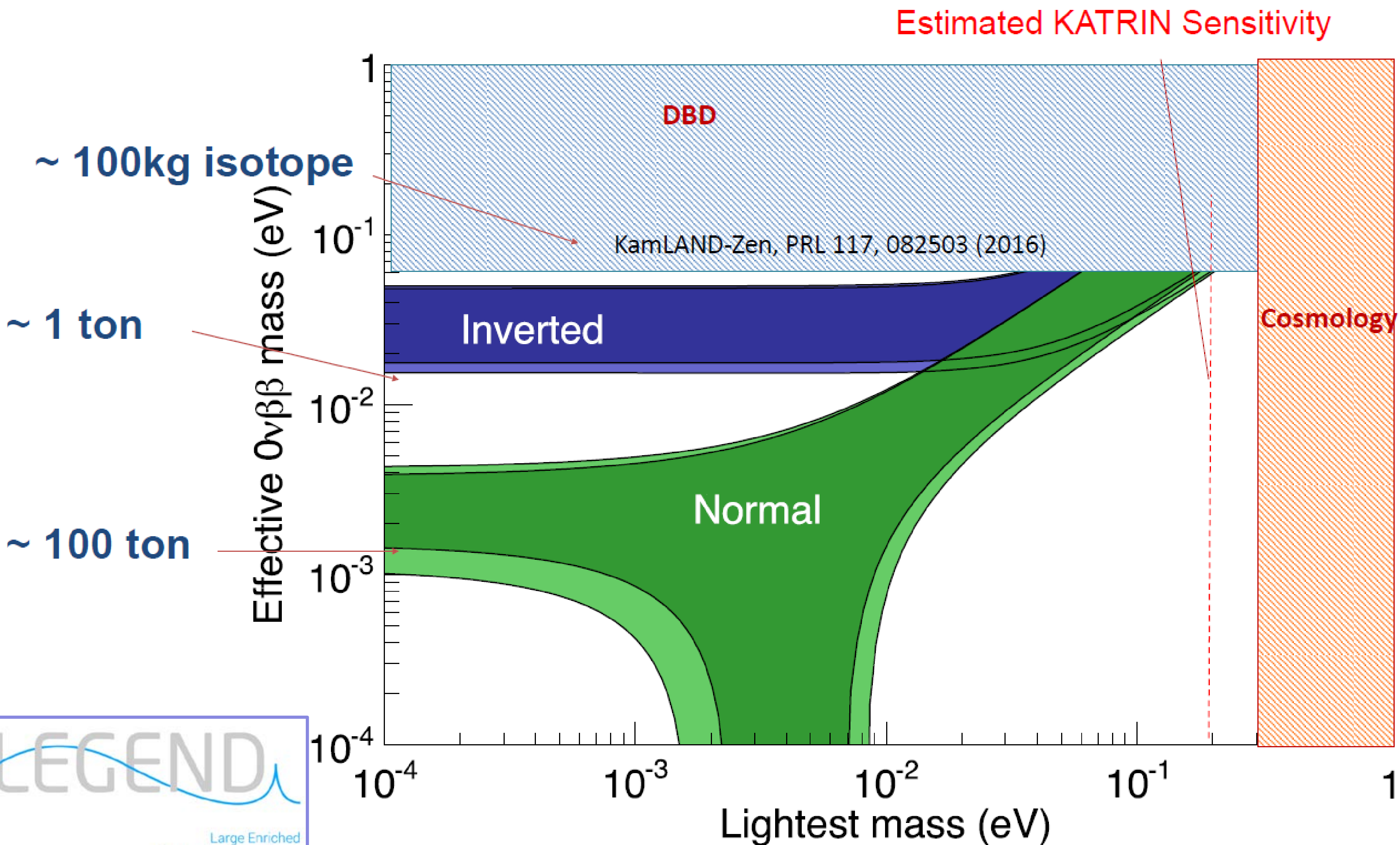


$$m_\beta = \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}$$

m_β < 1.1 eV (KATRIN)

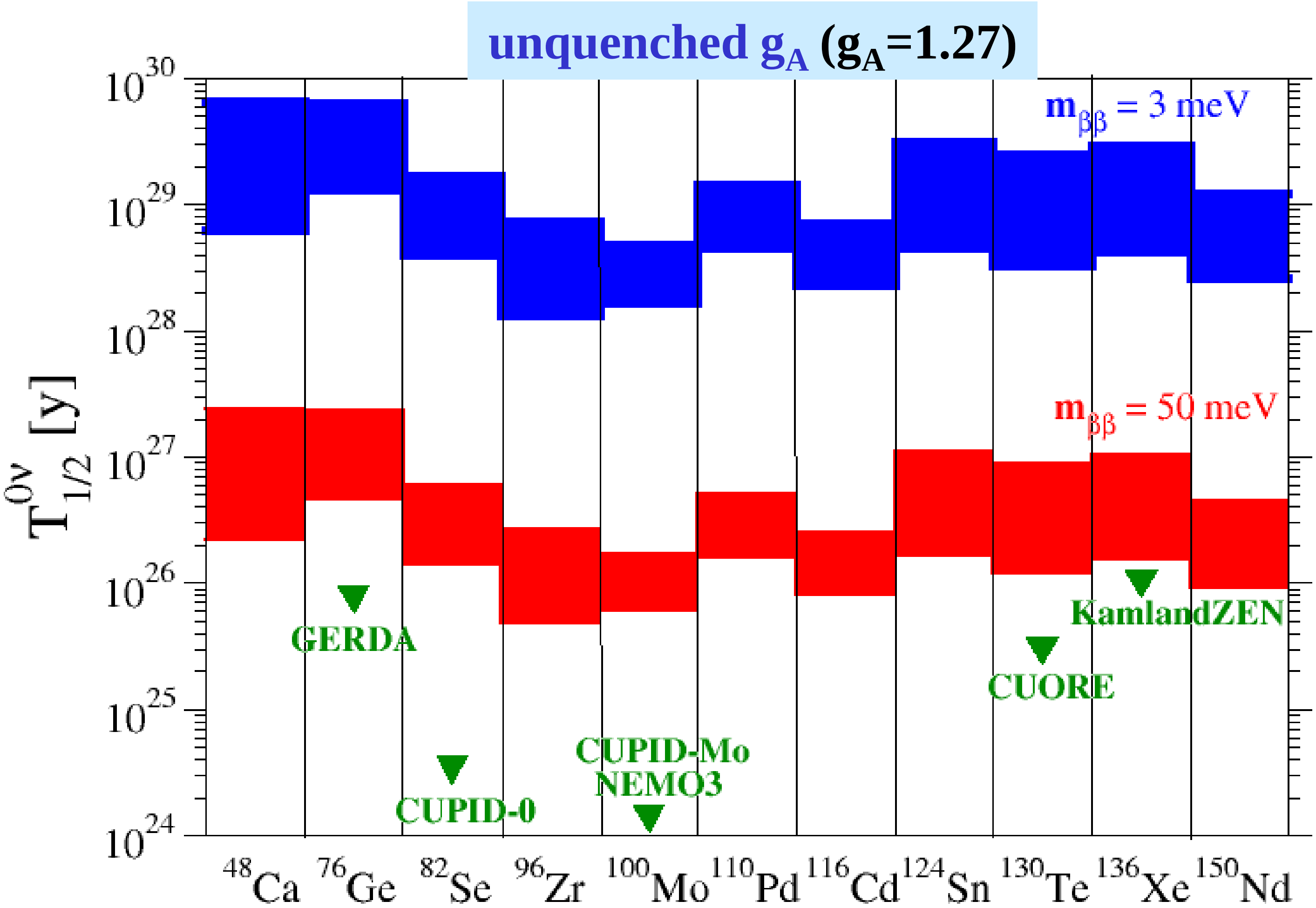
0νββ-decay





LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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



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

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

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

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

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

Lightest ν-mass equal to zero

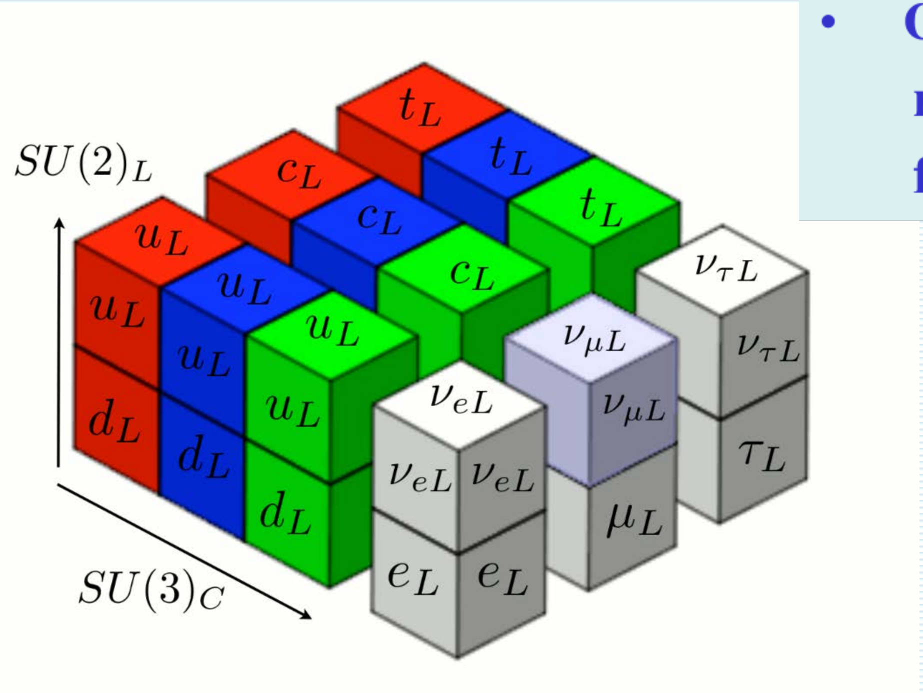
$20 \text{ meV} \leq m_{\beta\beta} \leq 49 \text{ meV}$

After 84 years …

Collaboration	Isotope		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

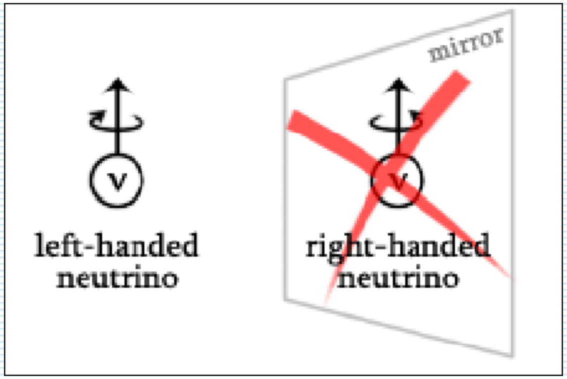
A generation of Majorana neutrino mass, $0\nu\beta\beta$-decay mechanisms

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!

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CERN COURIER

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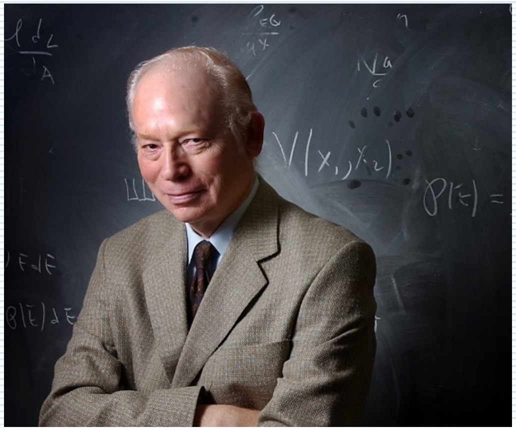
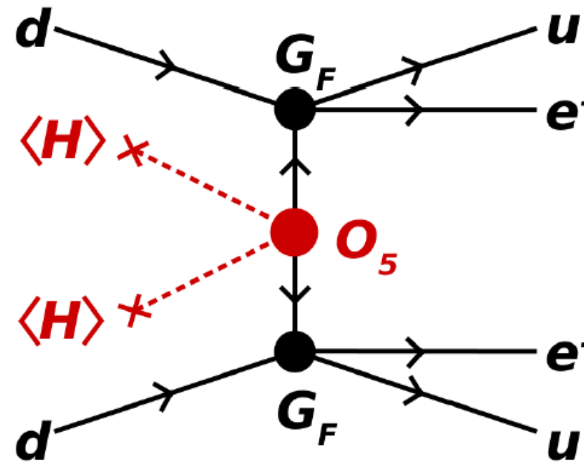


Weinberg, 1979: d=5

$0\nu\beta\beta$ decay:



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

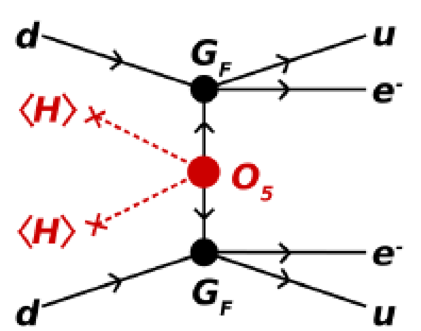
. Weinberg does not take credit for predicting neutrino masses, but he thinks it's the right interpretation. What's more, he says, the non-renormalisable interaction that produces the neutrino masses is probably also accompanied with non-renormalisable interactions that produce proton decay and other 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."

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

Beyond the SM physics

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

mass mechanism: d=5

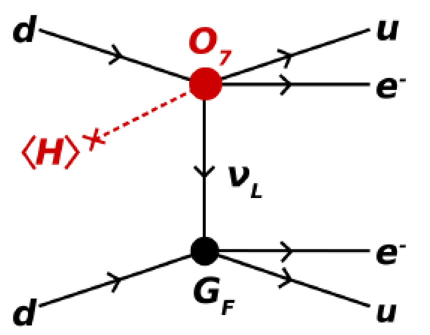


$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$

Weinberg, 1979

+

long range: d=7

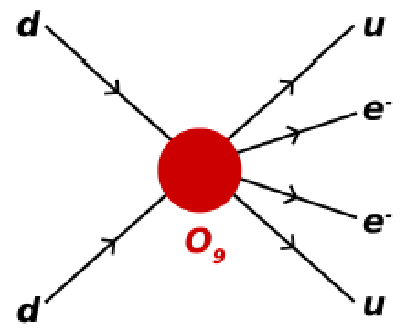


$$\mathcal{O}_2 \propto LLLe^cH$$
$$\mathcal{O}_3 \propto LLQd^cH$$
$$\mathcal{O}_4 \propto LL\bar{Q}\bar{u}^cH$$
$$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^cd^cH$$

Babu, Leung: 2001
de Gouvea, Jenkins: 2007

+

short range: d=9 (d=11)



$$\mathcal{O}_5 \propto LLQd^cHHH^\dagger$$
$$\mathcal{O}_6 \propto LL\bar{Q}\bar{u}^cHH^\dagger H$$
$$\mathcal{O}_7 \propto LQ\bar{e}^c\bar{Q}HHH^\dagger$$
$$\mathcal{O}_9 \propto LLLe^cLe^c$$
$$\mathcal{O}_{10} \propto LLLe^cQd^c$$
$$\mathcal{O}_{11} \propto LLQd^cQd^c$$
$$\cdots\cdots$$

Valle

Quark Condensate Seesaw Mechanism for Neutrino Mass

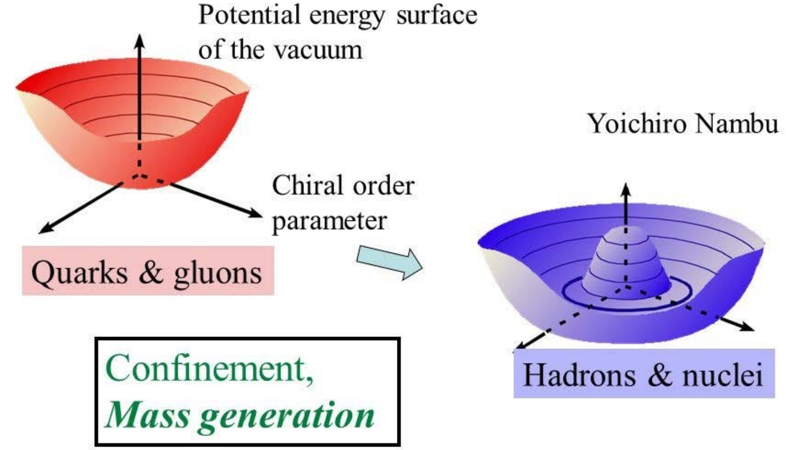
A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š., arXive:1911.12189

This operator contributes to the Majorana-neutrino mass matrix due to chiral symmetry breaking via the light-quark condensate.

The SM gauge-invariant effective operators

$$\mathcal{O}_7^{u,d} = \frac{\tilde{g}^{u,d}_{\alpha\beta}}{\Lambda^3}\, \overline{L^C_\alpha}\, L_\beta\, H \left\{ (\overline{Q}\, u_R),\ (\overline{d_R}\, Q) \right\}$$

Spontaneous breaking of
chiral (χ) symmetry



After the EWSB and ChSB one arrives at the Majorana mass matrix of active neutrinos

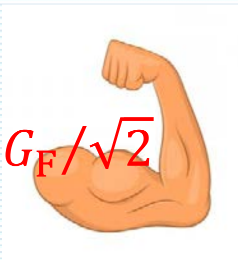
$$m_{\alpha\beta}{}^{\nu} = g_{\alpha\beta}\, v\, \frac{\langle \overline{q}q\rangle}{\Lambda^3} = g_{\alpha\beta}\, v \left(\frac{\omega}{\Lambda}\right)^3$$

$$g_{\alpha\beta} = g^u_{\alpha\beta} + g^d_{\alpha\beta}, \quad v/\sqrt{2} = \langle H^0 \rangle$$

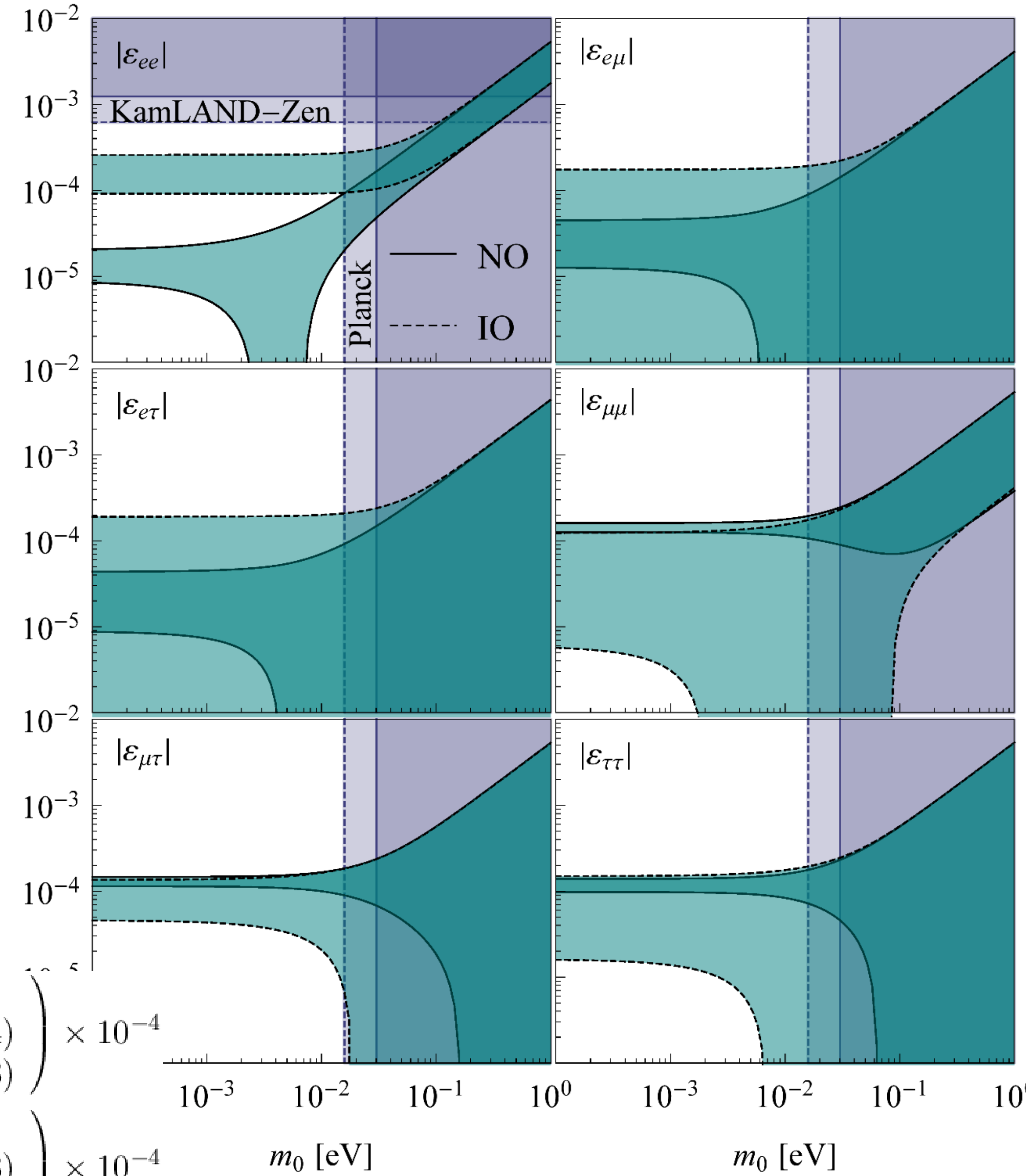
$$\omega = -\langle \overline{q}q\rangle^{1/3}, \quad \langle \overline{q}q\rangle^{1/3} \approx -283\ \text{MeV}$$

Λ ~ a few TeV
we get the neutrino mass in the sub-eV ballpark

The literature lacks the limits on this class of non-standard interactions



$$\varepsilon_{\alpha\beta} = \frac{g^2_{\alpha\beta}/\Lambda^2_{\rm LNV}}{G_F/\sqrt{2}} \approx \frac{M_{\alpha\beta}/\langle \bar{q}q\rangle_0}{G_F/\sqrt{2}}$$



$$|\varepsilon^{\rm NH}_{\alpha\beta}| = \begin{pmatrix} (0,\ 1.7) & (0,\ 1.3) & (0,\ 1.5) \\ & (0.9,\ 2.4) & (0.7,\ 2.4) \\ & & (0.5,\ 2.3) \end{pmatrix} \times 10^{-4}$$

$$|\varepsilon^{\rm NH}_{\alpha\beta}| = \begin{pmatrix} (0.9,\ 2.7) & (0,\ 1.9) & (0,\ 2.1) \\ & (0,\ 1.7) & (0.1,\ 1.8) \\ & & (0,\ 1.9) \end{pmatrix} \times 10^{-4}$$

The genuine QCSS scenario with no fine-tuning

A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š, arXiv: 1911.12189 [hep-ph]

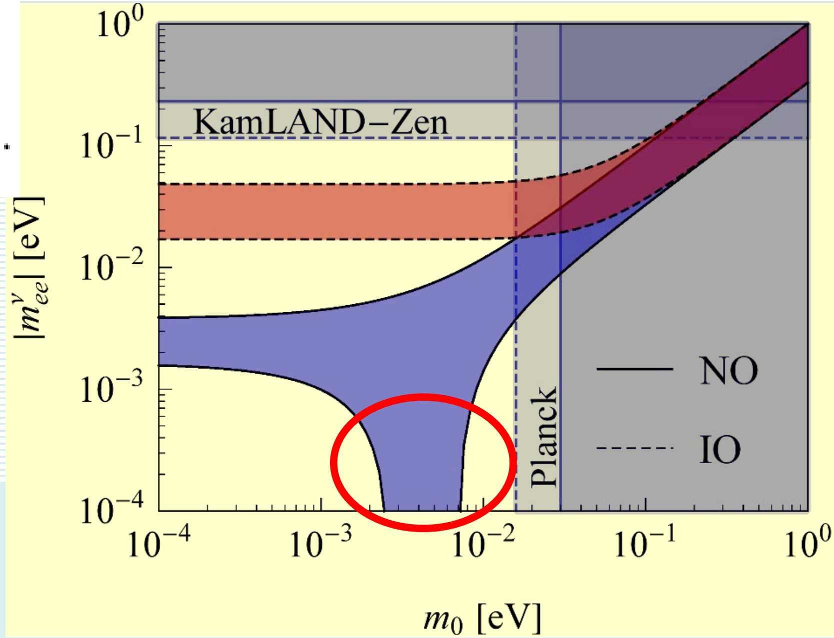
$$\mathcal{L}_7 = \frac{G_F}{\sqrt{2}} \overline{e_L} \nu_L^C \left(\varepsilon^u{}_{ee} \overline{u_R} d_L - \varepsilon^d{}_{ee} \overline{u_L} d_R \right) + \frac{G_F}{\sqrt{2}} \overline{\nu_L^C} \nu_L \left(\varepsilon^u{}_{ee} \overline{u_L} u_R + \varepsilon^d{}_{ee} \overline{d_R} d_L \right) + \text{H.c.}$$

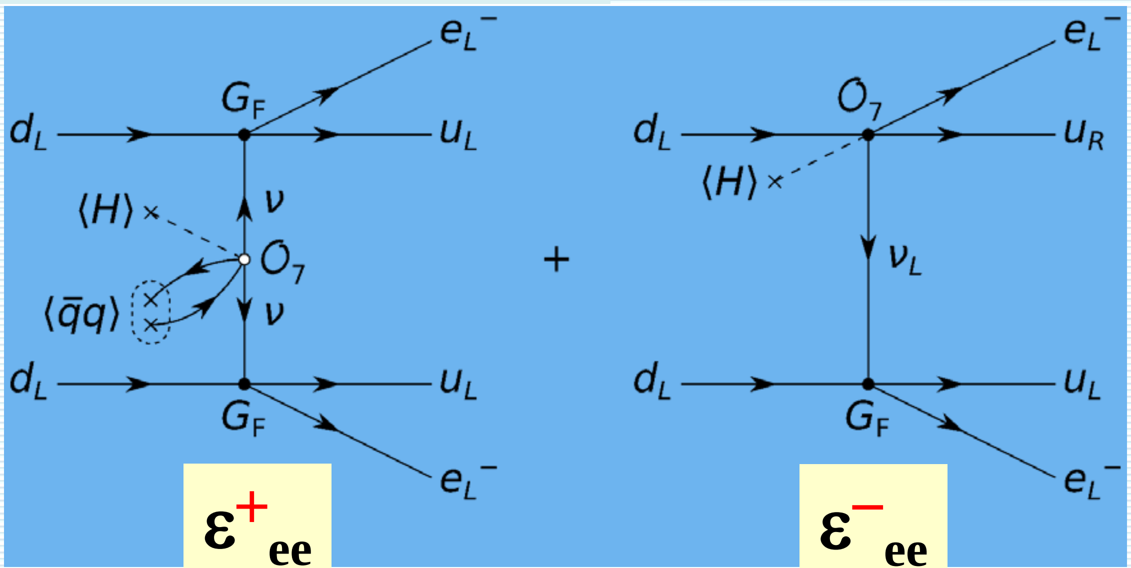
$$\varepsilon^{u,d}_{\alpha\beta} = \frac{g^{u,d}_{\alpha\beta} v / \Lambda^3}{G_F/\sqrt{2}}$$

$$\varepsilon^{\pm}_{\alpha\beta} = \varepsilon^u_{\alpha\beta} \pm \varepsilon^d_{\alpha\beta}$$

(a) discussed earlier in S.Kovalenko, M.I. Krivoruchenko, F.Š., PRL 112, 142503 (2014).

(b) discussed earlier in H. Päs, M. Hirsch, S. Kovalenko PLB 453, 194 (1999).





New features:

IH excluded, limits $\varepsilon < 10^{-8}$

Neutrino spectrum

$2 \text{ meV} < m_1 < 7 \text{ meV}$

$9 \text{ meV} < m_2 < 11 \text{ meV}$

$50 \text{ meV} < m_2 < 51 \text{ meV}$

Prediction for Kathrin

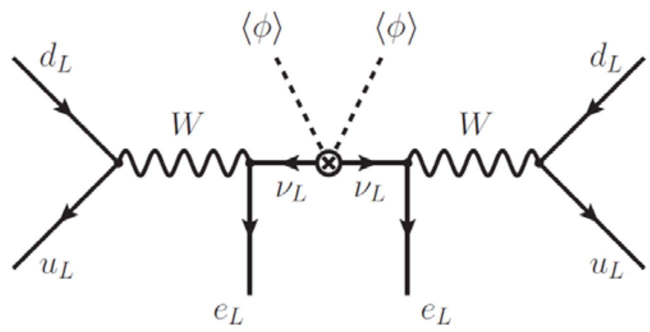
$9 \text{ meV} < m_\beta < 12 \text{ meV}$

Prediction for cosmology

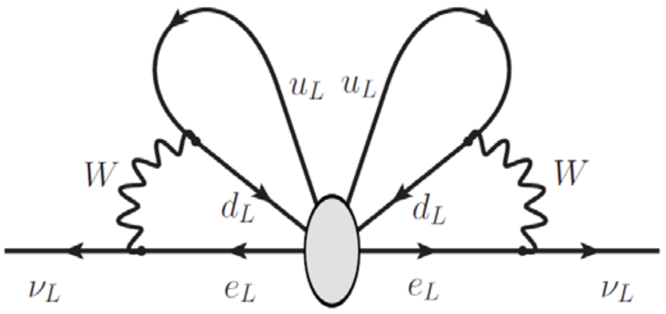
$62 \text{ meV} < m_1 + m_2 + m_3 < 69 \text{ meV}$

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

Majorana $m_\nu \Longrightarrow 0\nu\beta\beta$



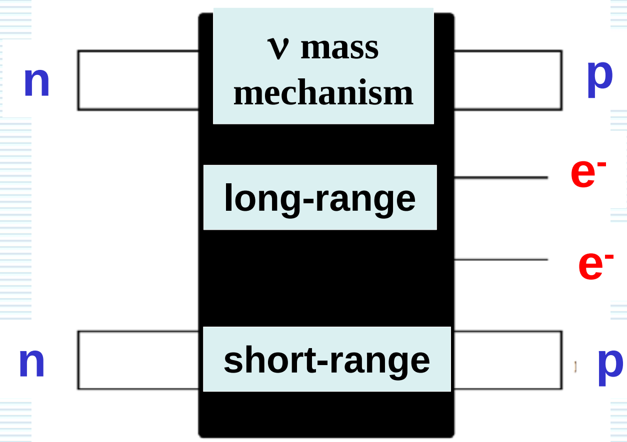
$0\nu\beta\beta \Longrightarrow$ Majorana m_ν



Schechter, Valle: PRD 1982

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

Can we say something about content of the black box?



Considering

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

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

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

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

General case

$$M'^{0\nu}(m_{\rm N}, g_{\rm A}^{\rm eff}) = \frac{1}{m_{\rm p} m_{\rm e}} \frac{R}{2\pi^2 g_A^2} \sum_n \int d^3x\, d^3y\, d^3p$$

$$\times e^{i\mathbf{p}\cdot(\mathbf{x}-\mathbf{y})} \frac{\langle 0_F^+ | J^{\mu\dagger}(\mathbf{x}) | n\rangle \langle n | J^\dagger_\mu(\mathbf{y}) | 0_I^+\rangle}{\sqrt{p^2 + m_N{}^2}\left(\sqrt{p^2 + m_N{}^2} + E_n - \frac{E_I - E_F}{2}\right)}$$

light ν exchange

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

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

heavy ν exchange

Particular cases

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu} g_{\rm A}^4 \times$$

$$\times \begin{cases} \left|\frac{\langle m_\nu\rangle}{m_e}\right|^2 \left| M'^{0\nu}_\nu(g_{\rm A}^{\rm eff})\right|^2 & \text{for } m_{\rm N} \ll p_{\rm F} \\ \left|\langle \frac{1}{m_{\rm N}}\rangle m_{\rm p}\right|^2 \left| M'^{0\nu}_{\rm N}(g_{\rm A}^{\rm eff})\right|^2 & \text{for } m_{\rm N} \gg p_{\rm F} \end{cases}$$

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

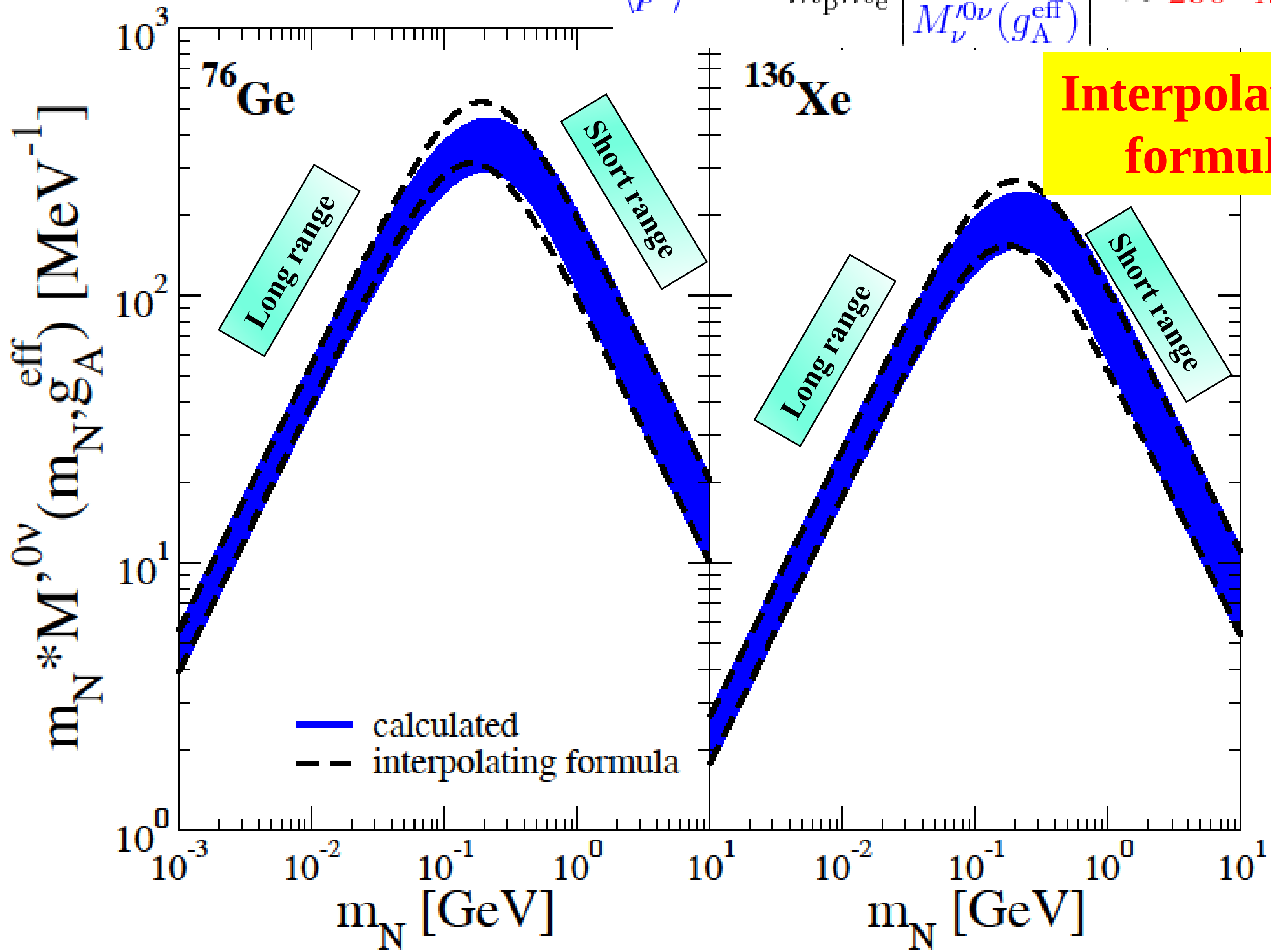
$$\left\langle \frac{1}{m_{\rm N}} \right\rangle = \sum_{\rm N} \frac{U^2_{e\rm N}}{m_{\rm N}}$$

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

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

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

Interpolating formula

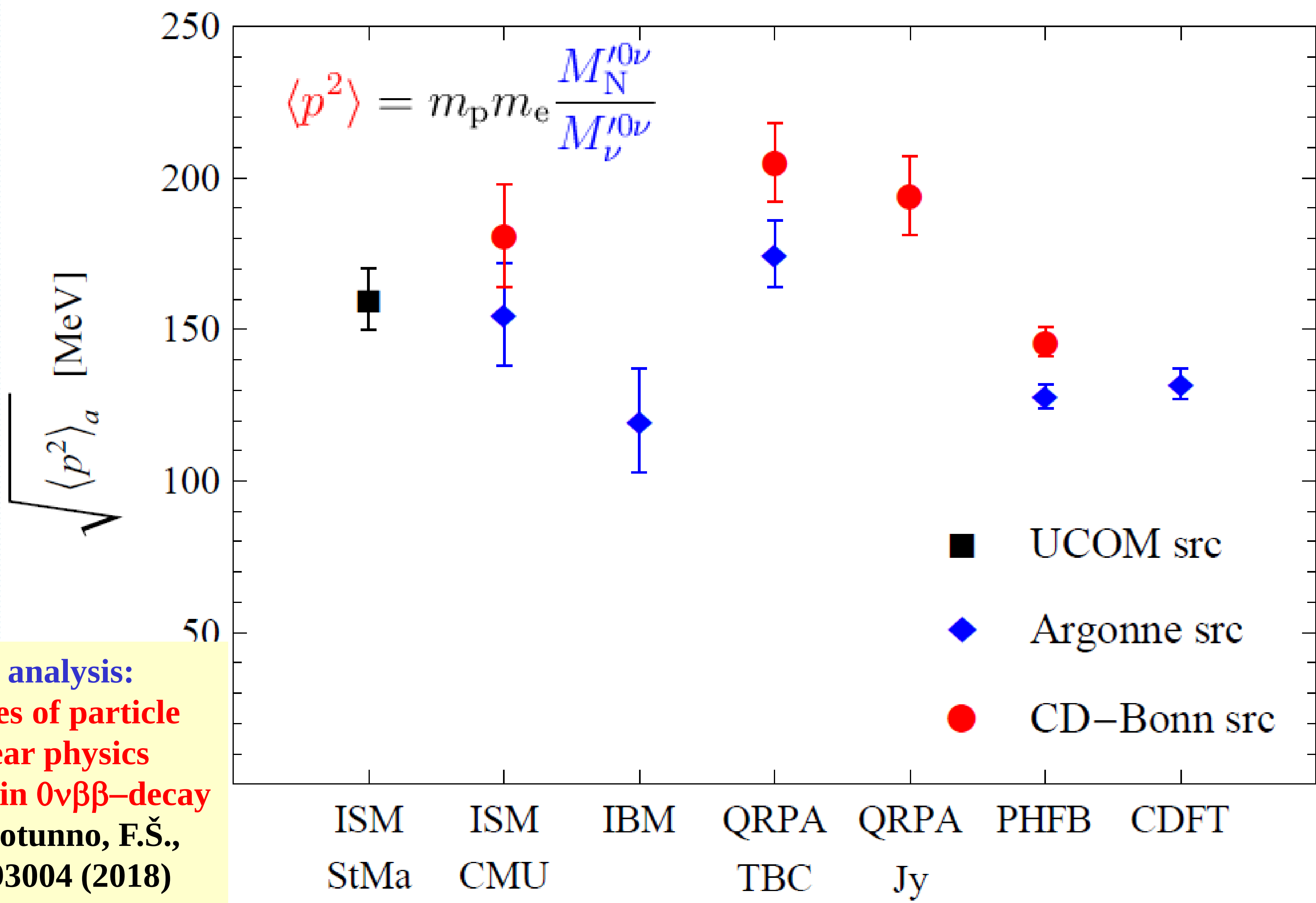


Faessler, Gonzales, Kovalenko, F. Š., PRD 90 (2014) 096010]

Interpolating formula is justified by practically no dependence <p^2> on A

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

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



Detailed analysis:
Degeneracies of particle and nuclear physics uncertainties in 0νββ–decay
E. Lisi, A. Rotunno, F.Š., PRD 92, 093004 (2018)

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)

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

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

The dominance of light and heavy ν-mass contributions to 0nbb-decay rate can not be established by observing this process at different nuclei.

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

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

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

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

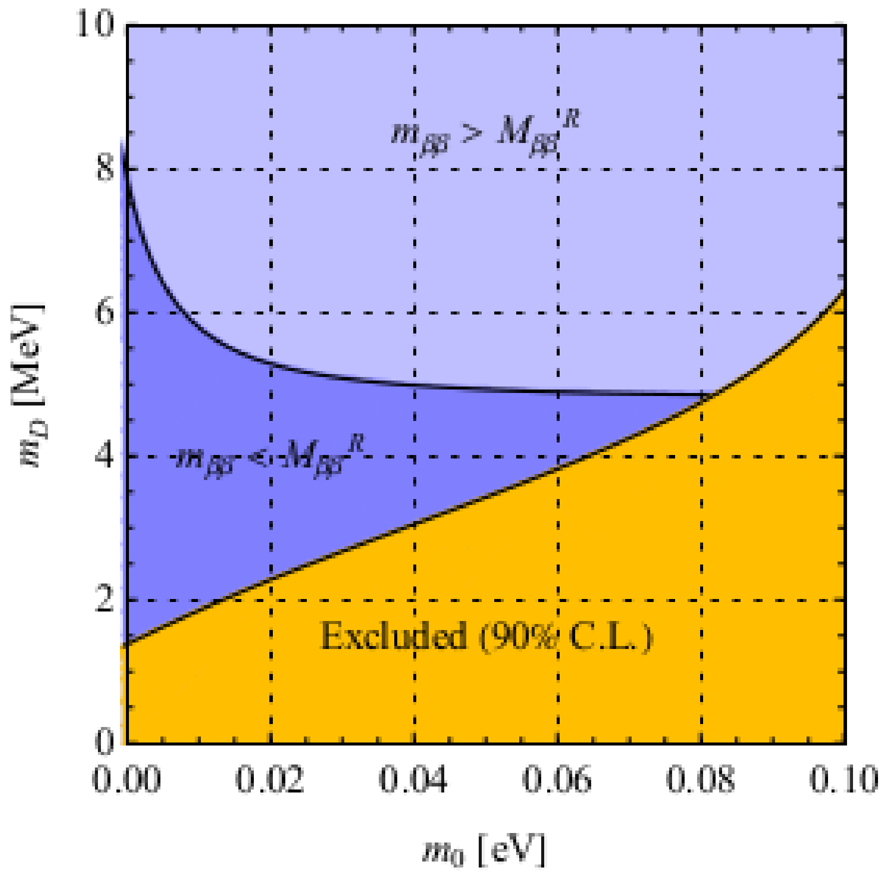
$$\eta^2_{\nu N} = \frac{1}{m_e^2}\left(m_{\beta\beta}^2 + (M^R_{\beta\beta})^2\right)$$

See-saw scenario

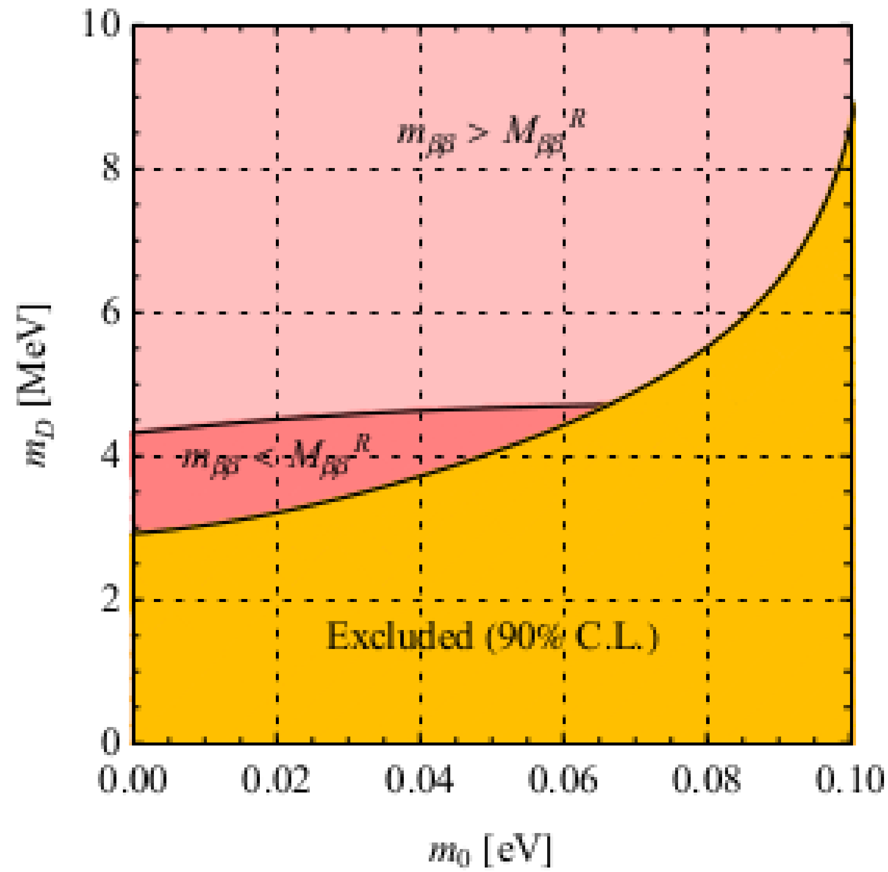
$$m_i M_i \simeq m_D^2$$

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

Normal spectrum



Inverted spectrum

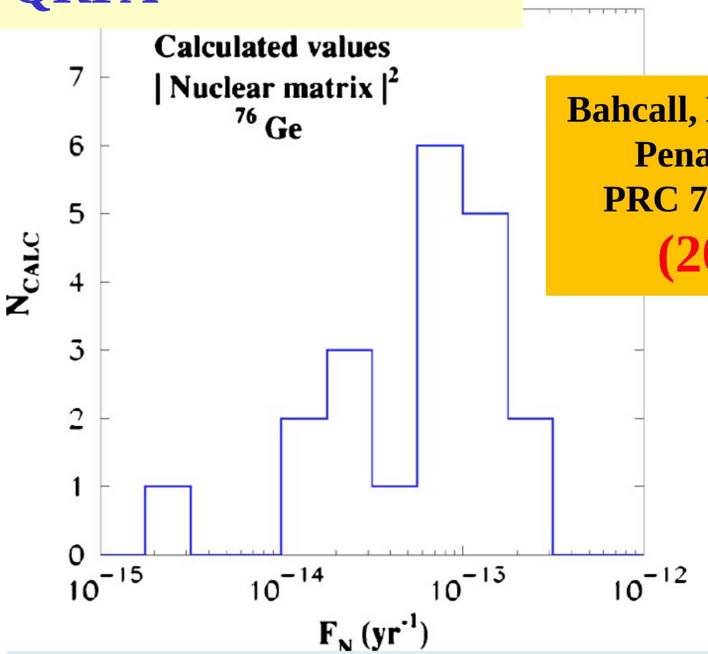


A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š., PRD 98, 015003 (2018)

The $0\nu\beta\beta$-decay NMEs – current status

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

$0\nu\beta\beta$ decay NMEs



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

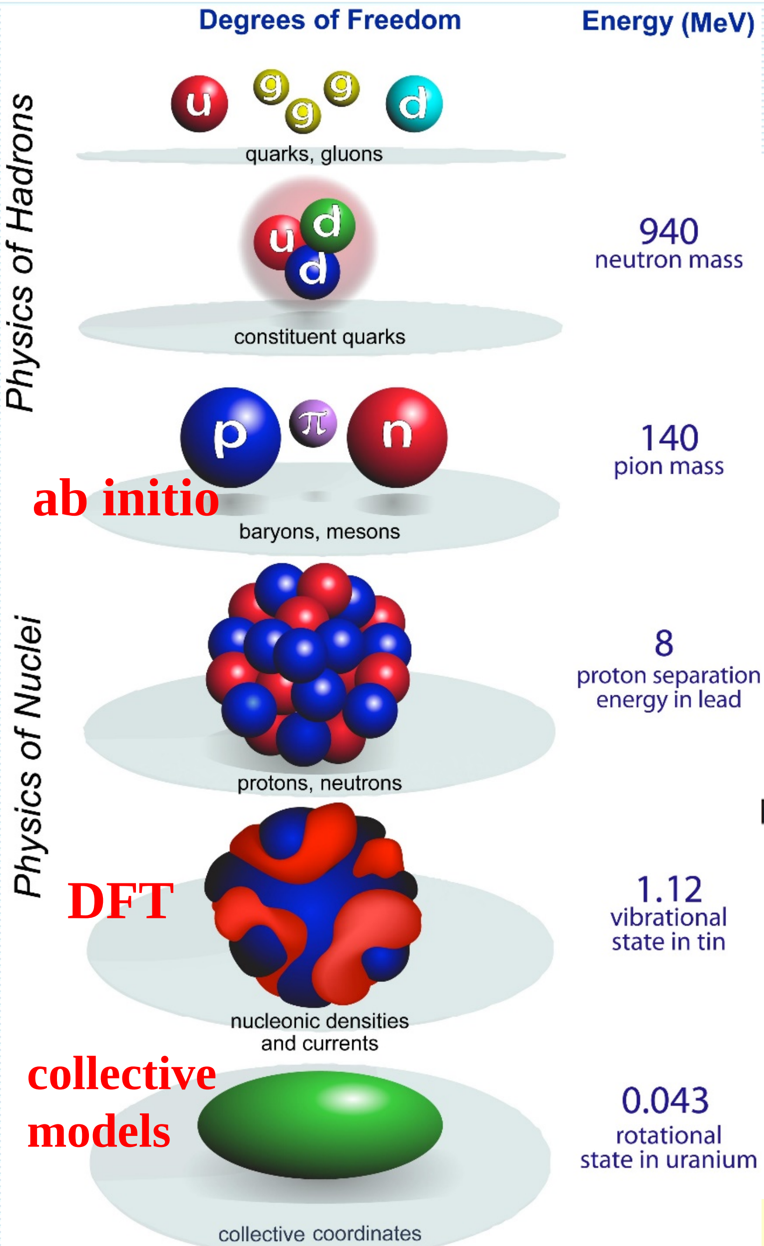
2019 (factor 2-3)
many groups, many nuclear structure methods:
Nuclear Shell Model, QRPA, Interacting Boson Model, Energy Density Functional

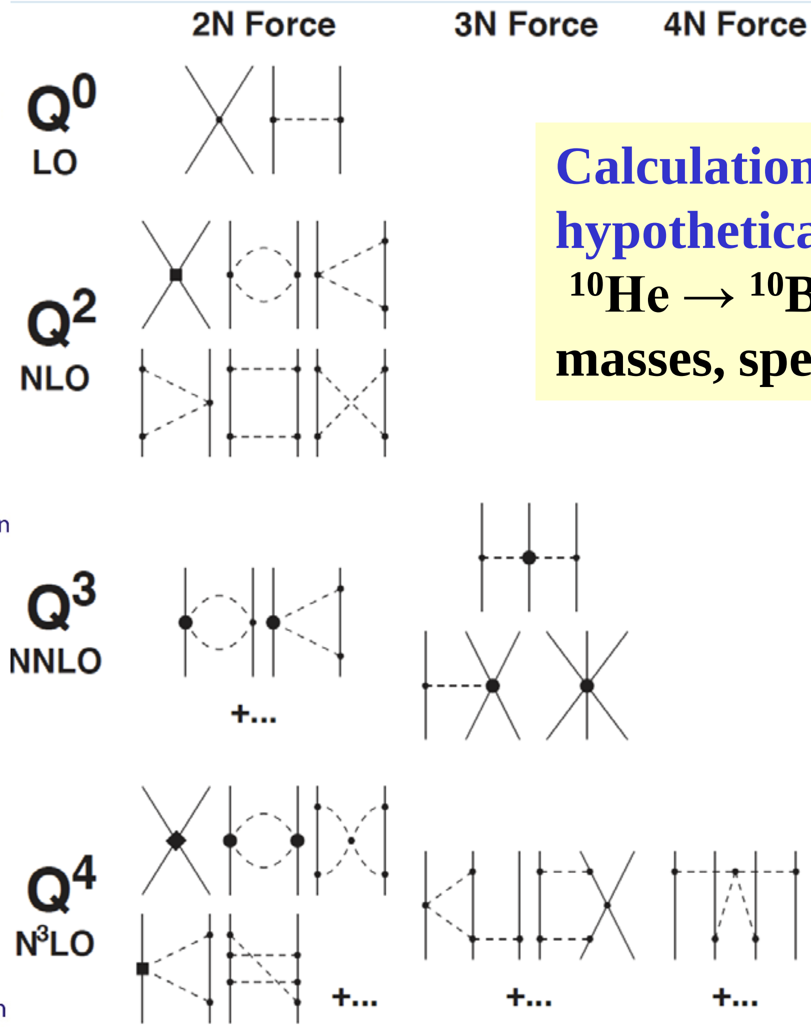
Attempts (light nuclear systems):
Ab initio calculations by different approaches – No Core Shell Model, Green's Function Monte Carlo, Coupled Cluster Method, Lattice QCD

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**

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.

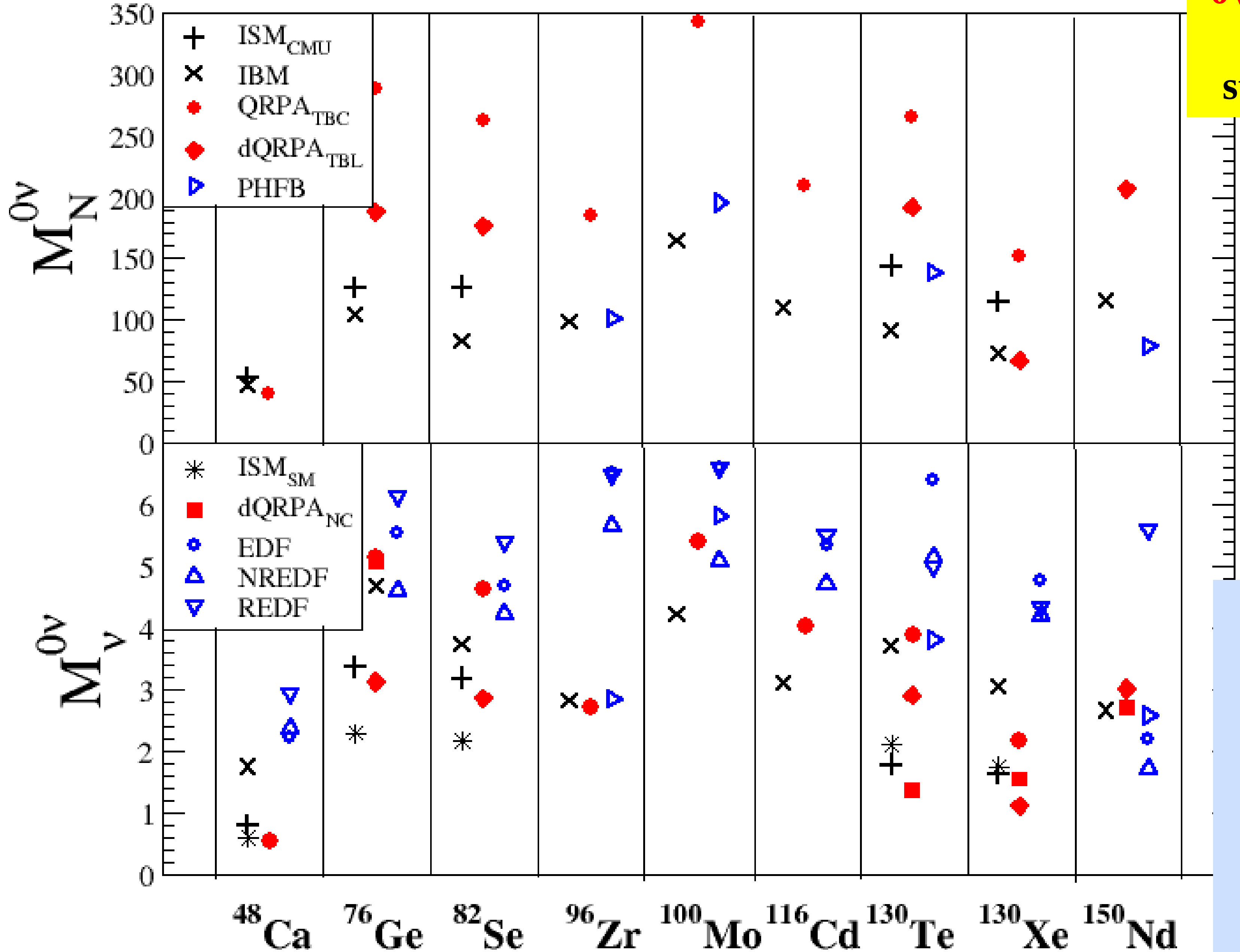




Calculation for the hypothetical 0νββ decay:
$^{10}He \rightarrow {}^{10}Be + e^- + e^-$
masses, spectra

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

Moore's law: exponential growth in computing power



0νββ-decay NME status 2019

All models missing essential physics

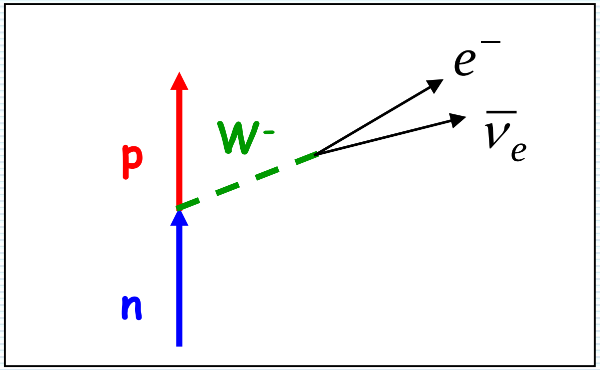
Impossible to assign rigorous uncertainties

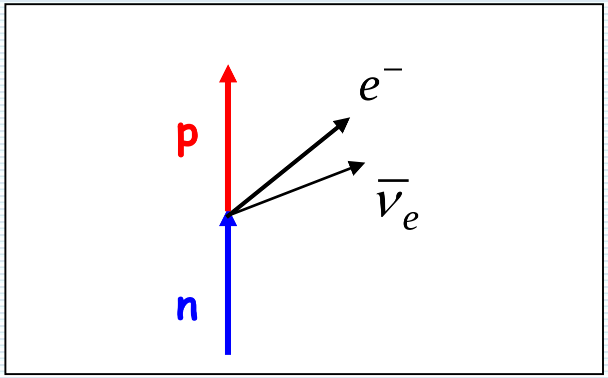
unquenched g_A

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).

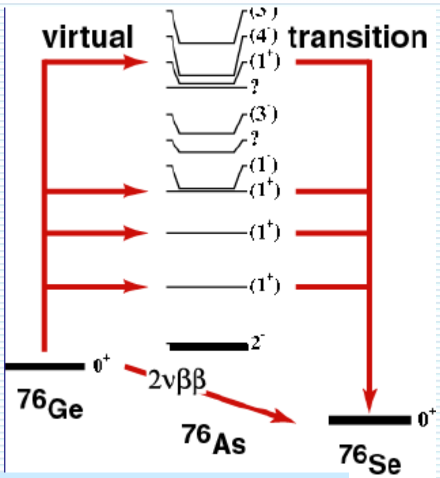
$g_A^4 = (1.269)^4 = 2.6$

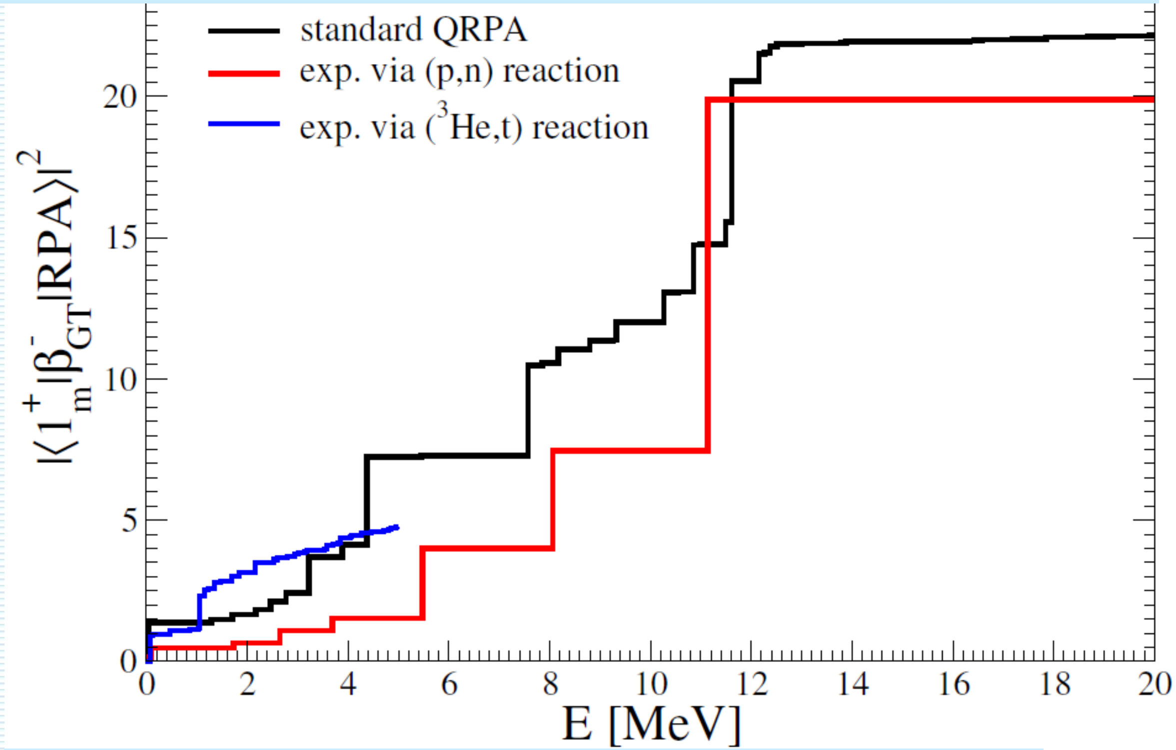
Quenching of g_A (from exp.: $T_{1/2}^{0\nu}$ up 2.5 x larger)

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

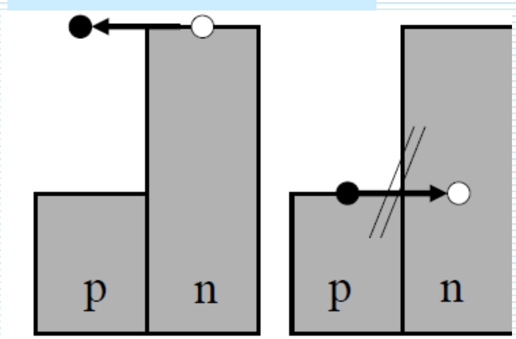
Strength of GT trans. (approx. given by **Ikeda sum rule** =3(N-Z)) has to be quenched to reproduce experiment.
Using $g_A^{\rm eff} \approx 0.77 \times g_A^{\rm free}$ agrees with data

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





Pauli blocking



Cross-section for charge exchange reaction:

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

$q = 0!!$

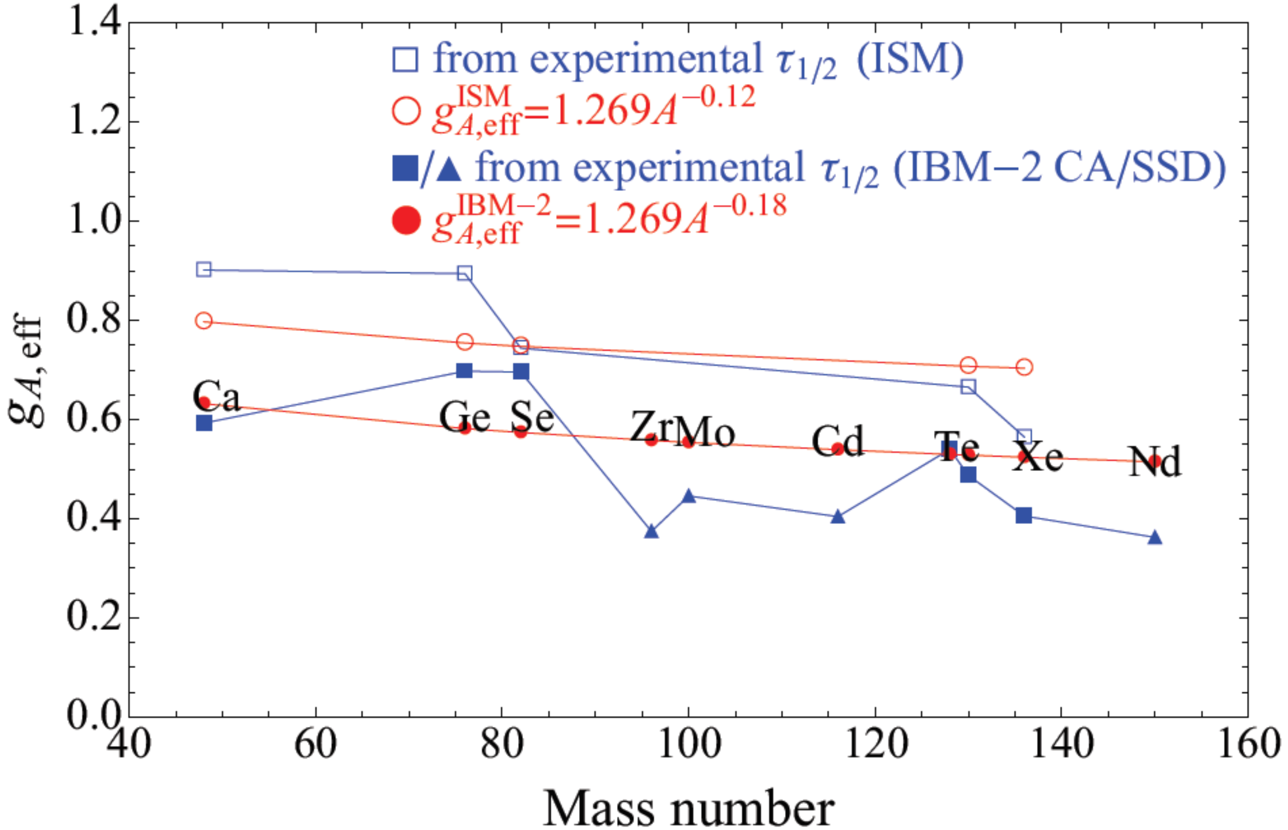
largest at 100 - 200 MeV/A

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.

From F. Iachello

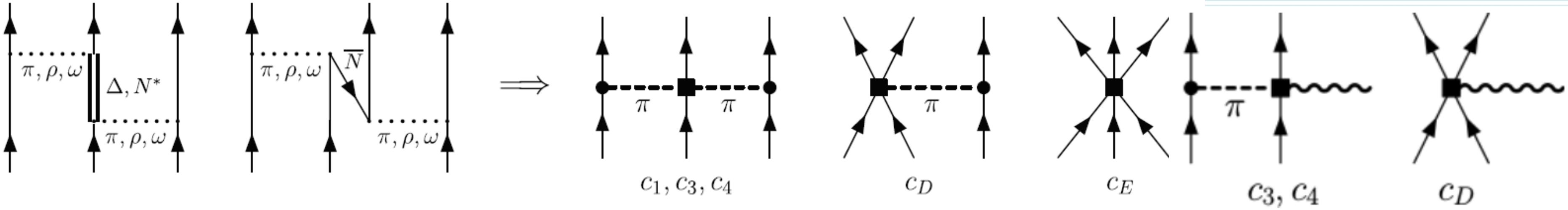


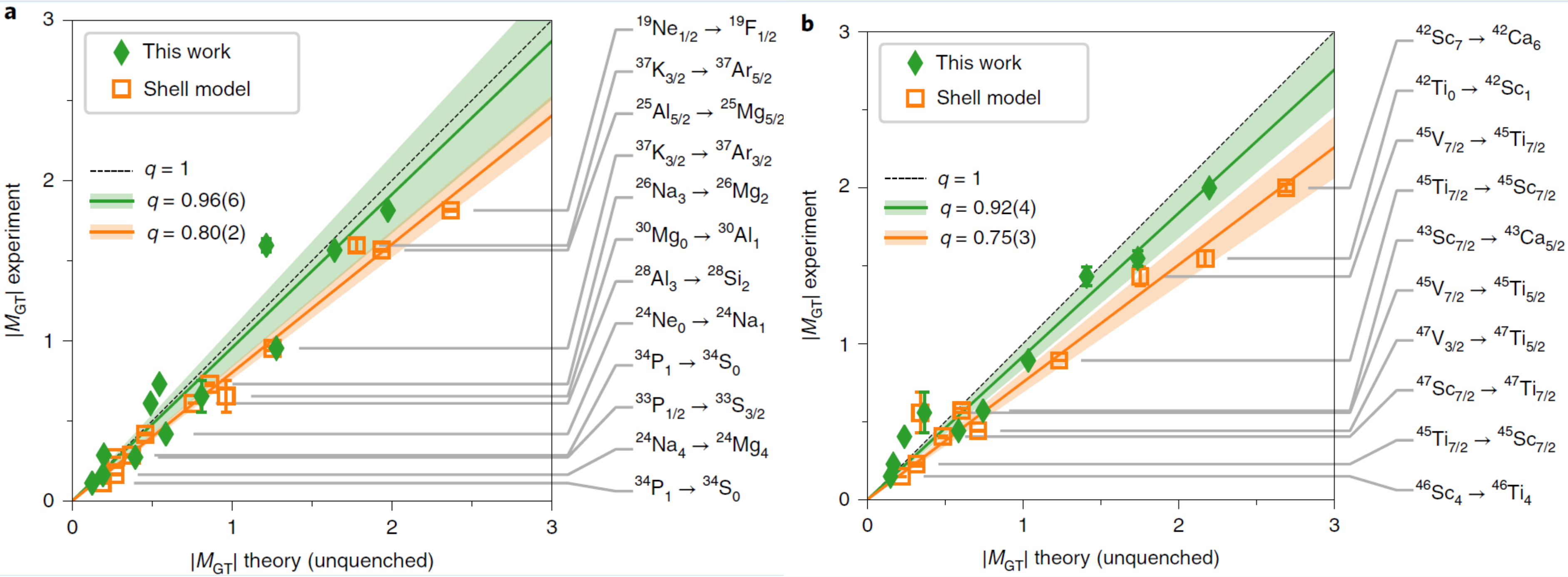
J. Barea, J. Kotila, F. Iachello, PRC 87, 014315 (2013).

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"





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

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

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

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

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

We get

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

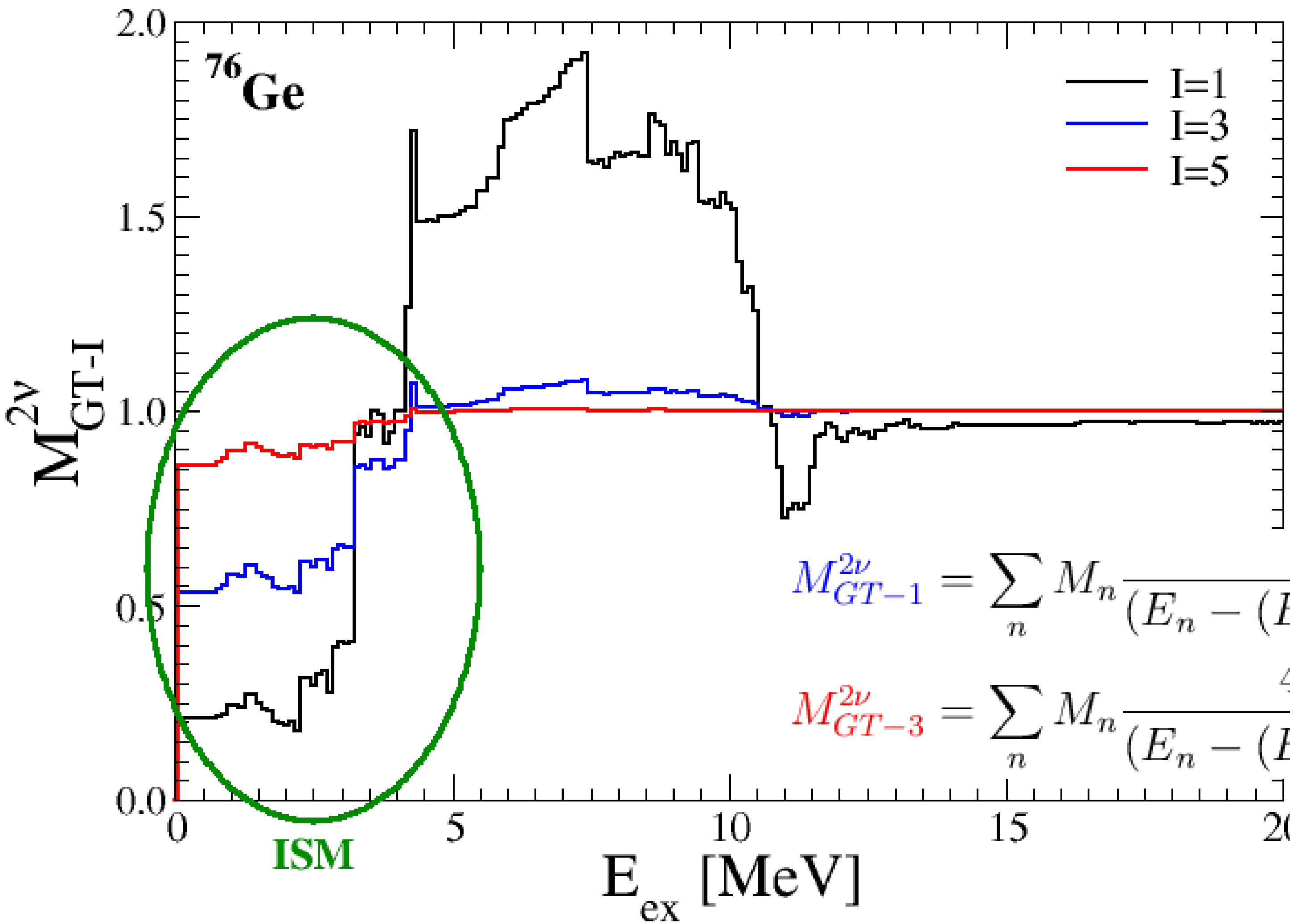
$$M_{GT-1}^{2\nu} = \sum_n M_n \frac{1}{(E_n - (E_i + E_f)/2}$$

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

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

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)

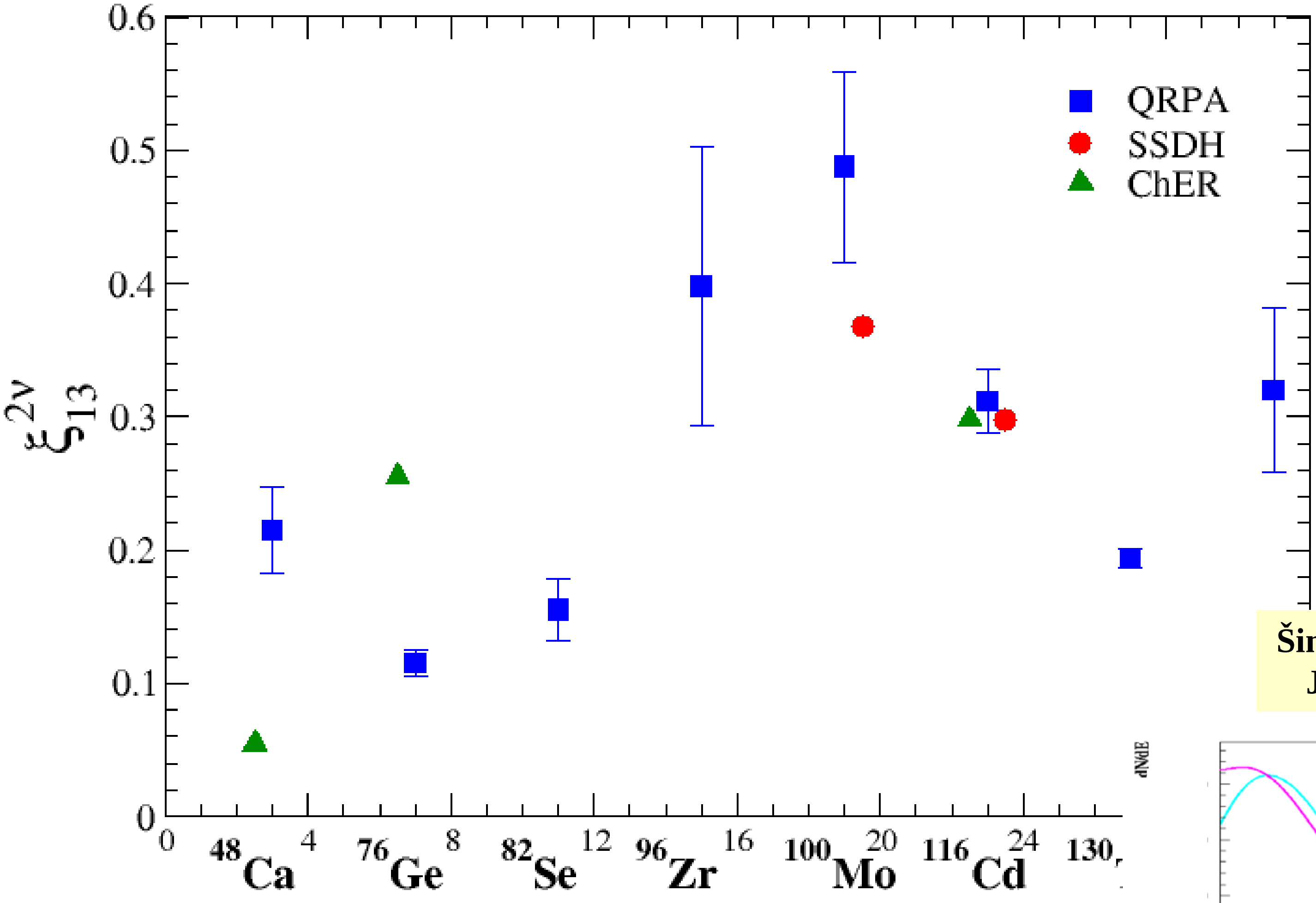
The running sum of the 2νββ–decay NMEs (QRPA)



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

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

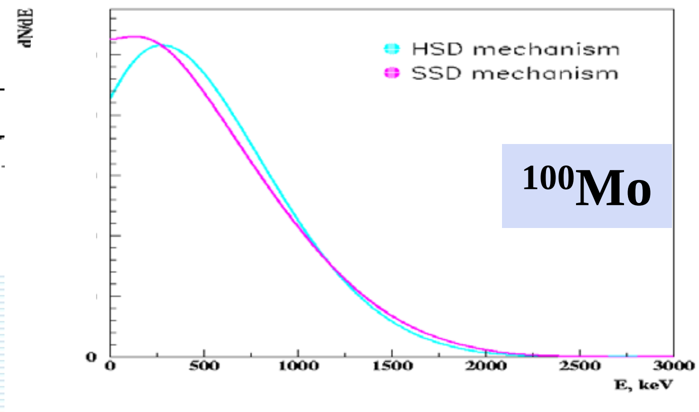
ξ_{13} tell us about importance of higher lying states of int. nucl.



HSD: ξ_{13}=0

$\xi_{13}\approx$1 (large)
Possible due to a large cancellation of contributions through lower and higher lying states of (A,Z+1).

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

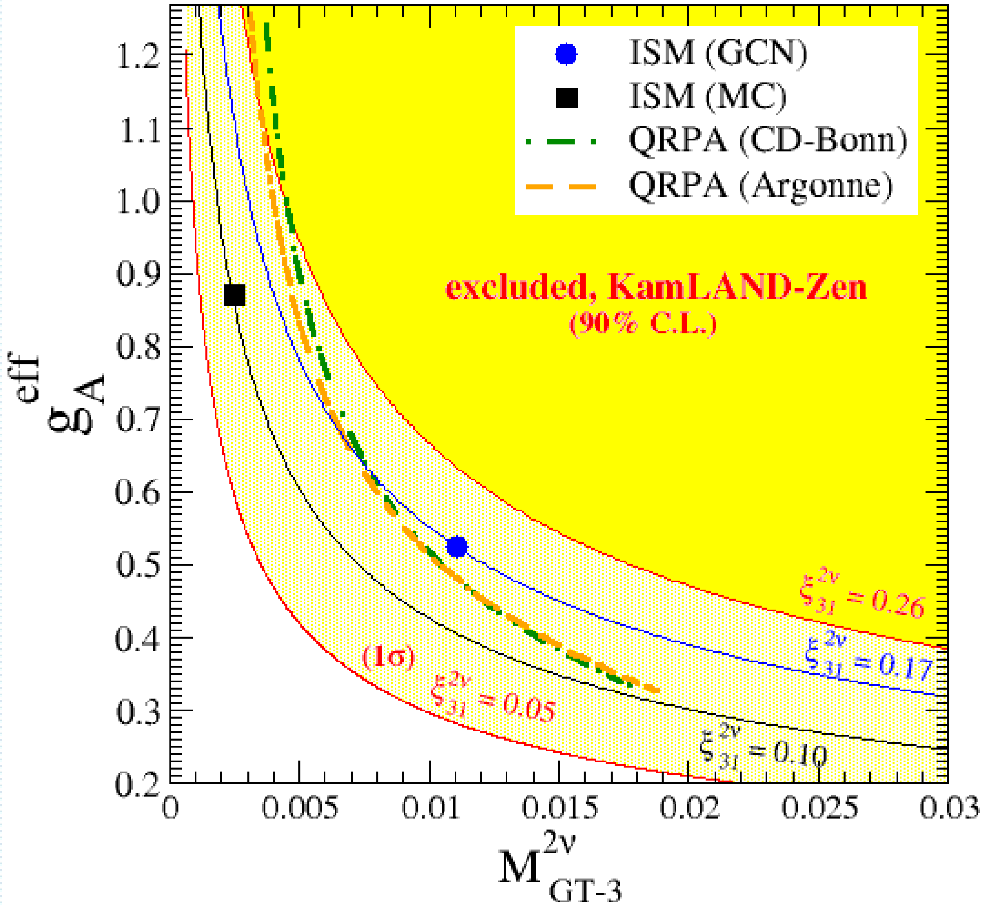


ξ_{13} can be determined phenomenologically from the shape of energy distributions of emitted electrons

The g_A^{eff} can be 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)

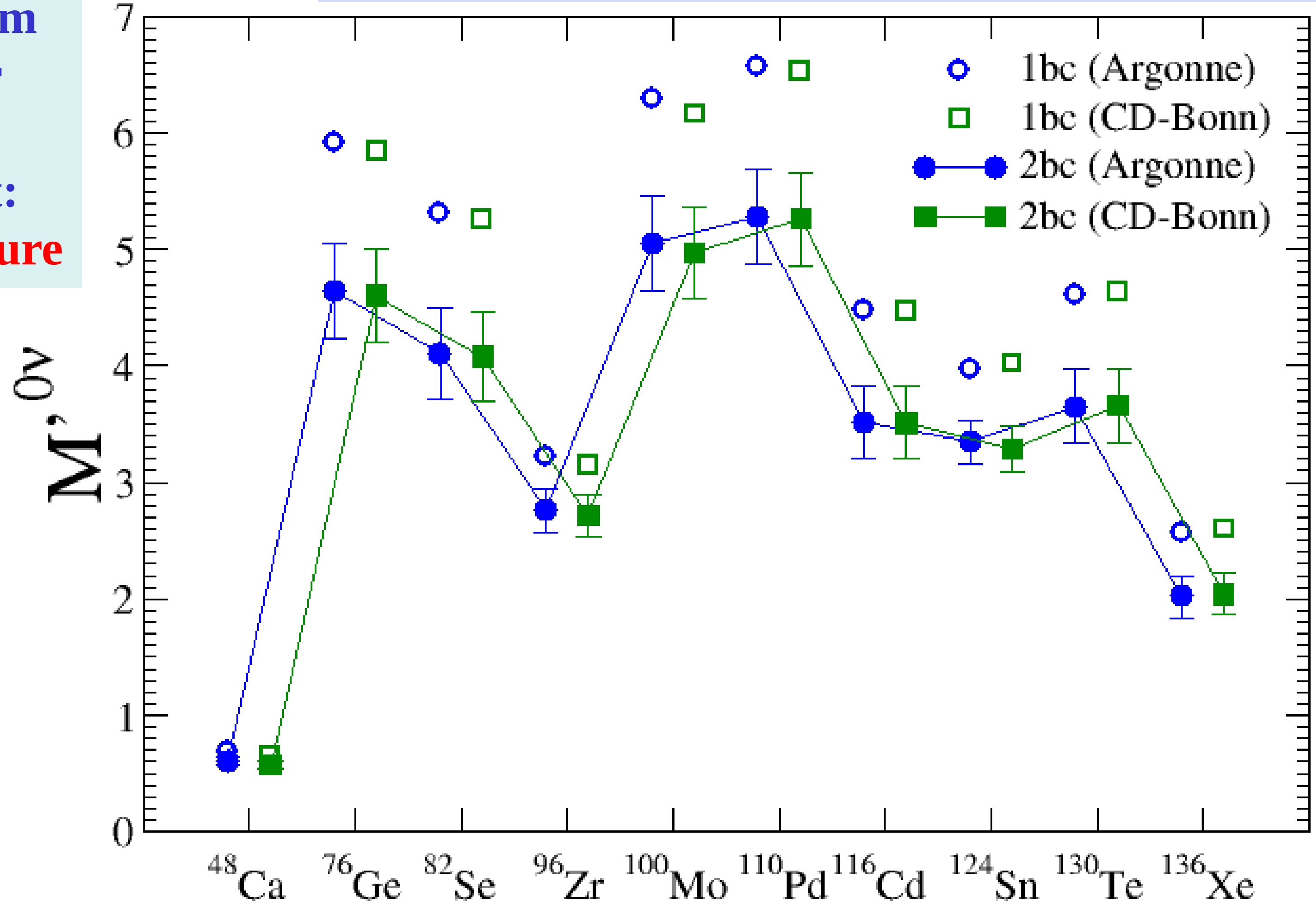
Quenching of g_A, two-body currents and QRPA

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

Engel, Vogel, Faessler, F.Š., PRC 89 (2014) 064308
See also: Menendez, Gazit, Schwenk, PRL 107 (2011) 062501

Effect of momentum transfer

Relevant: muon capture



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

Muon capture rates evaluated within QRPA

F. Š, R. Dvornický, P. Vogel, PRC 102, 034301 (2020).

TABLE I. The coefficients C_F, C_{GT}, and C_T [see Eq. (23)] calculated within the present approach [see Eq. (18)] and in the Fujii-Primakoff approximation [see Eq. (19)].

E_ν (MeV)	$g_A^{\rm eff}$	present approach C_F	C_{GT}	C_T	Fujii-Primakoff C_F	C_{GT}	C_T
75	0.80	0.976	0.797	−0.241	1.054	1.165	−0.333
	1.00	0.976	0.821	−0.197	1.054	1.091	−0.296
	1.27	0.976	0.847	−0.158	1.054	1.030	−0.265
85	0.80	0.965	0.805	−0.239	1.052	1.203	−0.359
	1.00	0.965	0.823	−0.197	1.052	1.117	−0.317
	1.27	0.965	0.844	−0.159	1.052	1.048	−0.282
95	0.80	0.955	0.818	−0.234	1.051	1.241	−0.385
	1.00	0.955	0.828	−0.195	1.051	1.145	−0.337
	1.27	0.955	0.844	−0.159	1.051	1.067	−0.298

New formalism (derivation as by 0νββ-decay

$$\Gamma = m_\mu \frac{\left(G_\beta m_\mu^2\right)^2}{2\pi} \times \left(g_A^{\rm eff}\right)^2 \left(C_F \frac{B_{\Phi F}}{(g_A^{\rm eff})^2} + C_{GT} B_{\Phi GT} + C_T B_{\Phi T}\right)$$

$$B^k_{\Phi K}(p_{\nu_k}) = \frac{1}{\hat{J}_i} \sum_{M_i M_k} \int \frac{d\Omega_\nu}{4\pi} \times |\langle J_k M_k| \sum_{j=1}^{A} \tau_j^- e^{i\mathbf{p}_{\nu_k}\cdot\mathbf{r}_i} O_K \frac{\Phi_g(r_i)}{m_\mu^{3/2}} |J_i M_i\rangle|^2$$

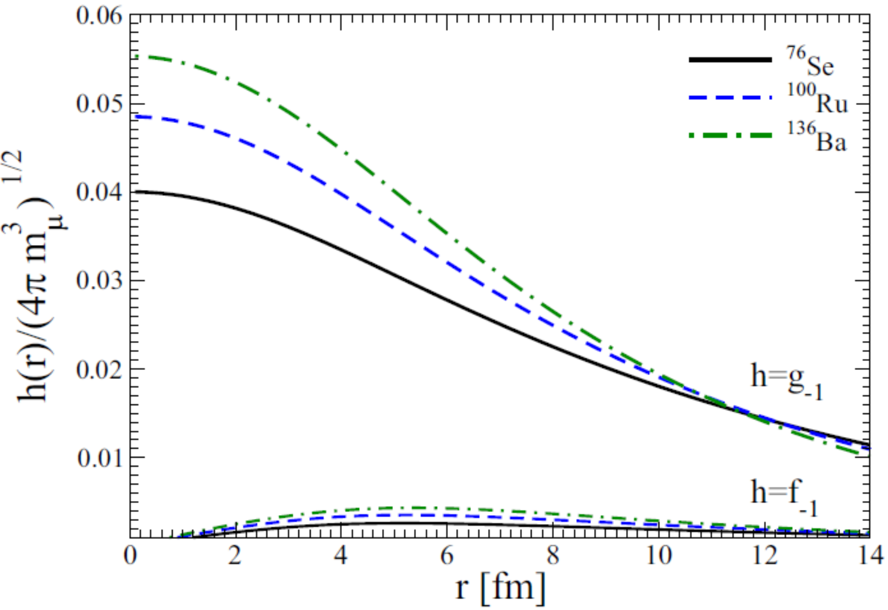
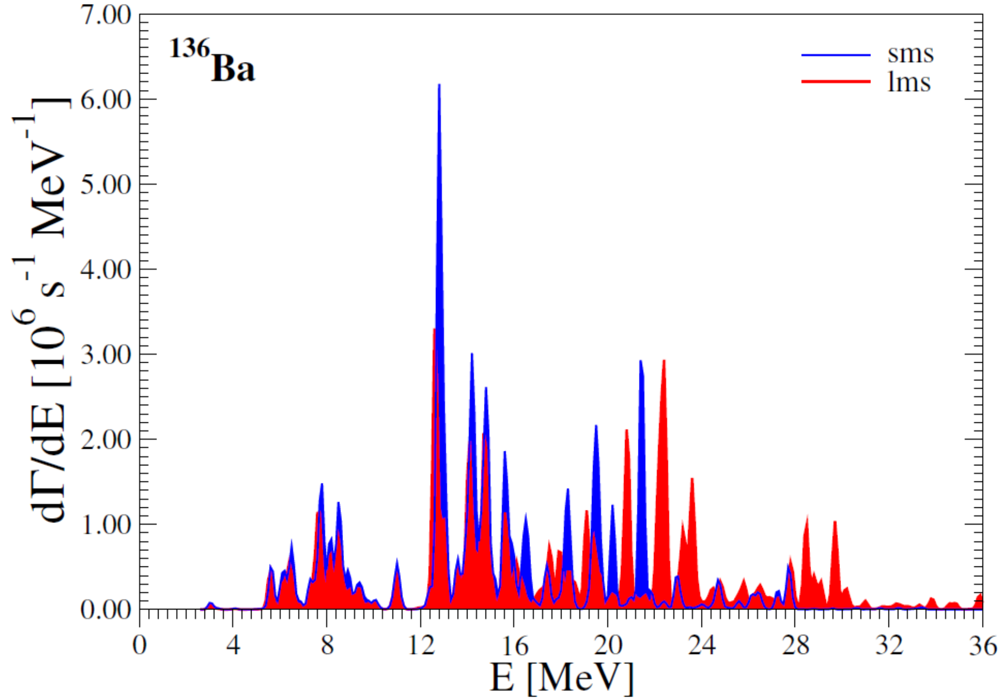
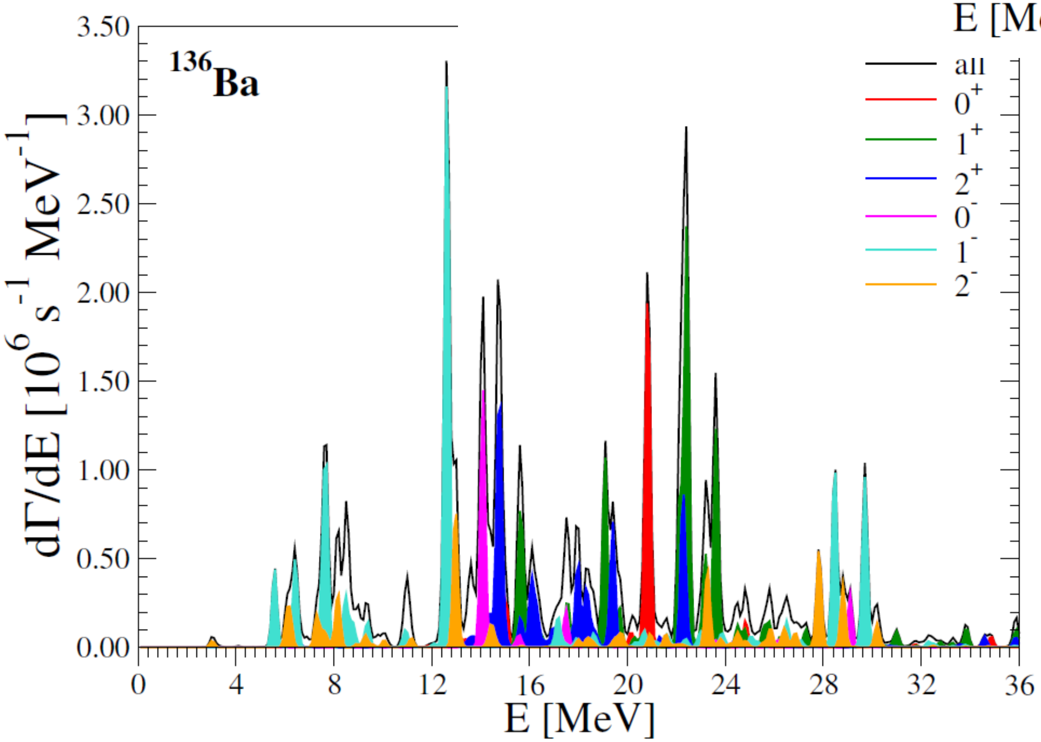
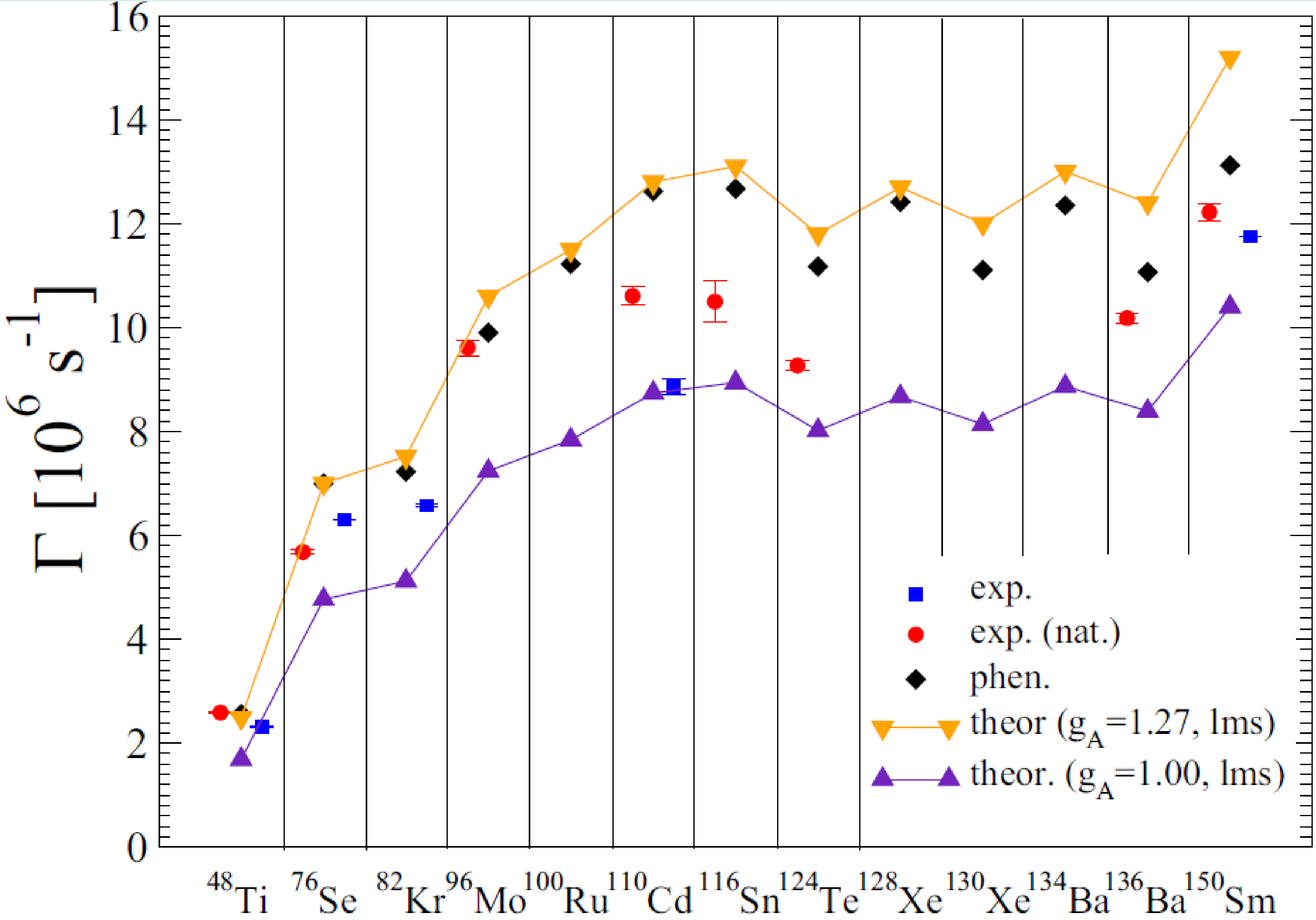


FIG. 1. The radial dependen
tions $g_{-1}(r)$ and $f_{-1}(r)$ for ^{76}Se,





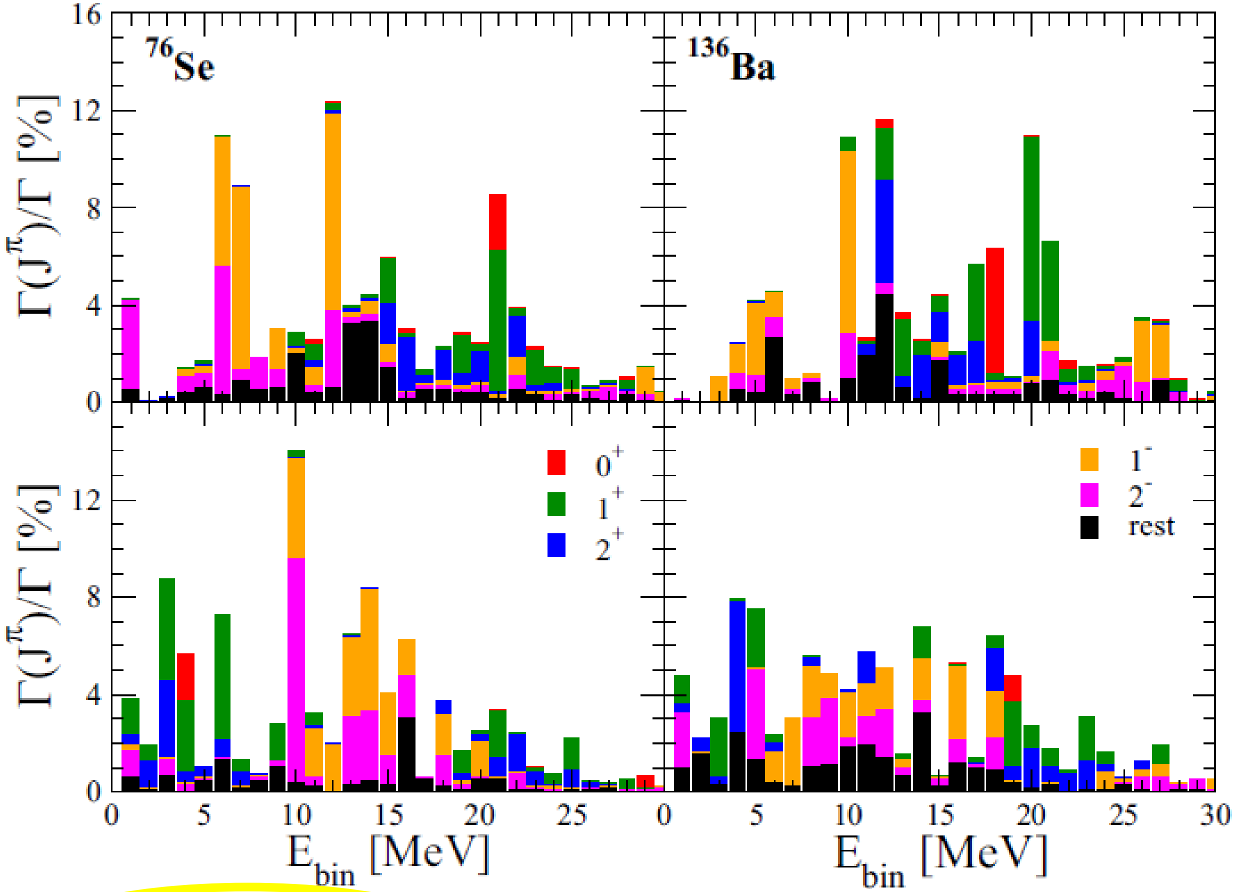


In agreement with soft quenching

Zinner, Langanke, Vogel PRC 74, 024326 (2006)
Marketin, Paar, Niksic, Vretenar PRC 79, 054323 (2009)

F.S., Dvornicky, Vogel
PRC 100, 014619 (2019)

Jokiniemi, Suhonen,
PRC 100, 014619 (2019)
(Strong quenching needed)



nucleus	Γ_{GP}	Γ_{QRPA}	Γ_{pres}	Γ_{FP}
^{76}Se	7.00	16.4	3.50	4.66
^{82}Kr	7.22	16.5	3.76	5.00
^{96}Mo	9.90	20.4	5.32	7.06
^{100}Ru	11.2	16.7	5.77	7.65
^{116}Sn	12.7	15.7	6.61	8.73
^{128}Xe	12.4	21.2	6.37	8.39
^{130}Xe	11.1	23.6	5.97	7.87
^{136}Ba	11.1	21.1	7.61	10.0

Contradicting results:
Strong quenching
Jokiniemi, Suhonen,
PRC 100, 014619 (2019)

Thank You!

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)