**CONFERENCE ON NEUTRINO AND NUCLEAR PHYSICS**
**AFRICAN PRIDE ARABELLA HOTEL & SPA, 24 - 28 FEBRUARY 2020**

# Majorana neutrino mass generation, $0\nu\beta\beta$-decay and nuclear matrix elements


**Fedor Šimkovic**

# 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. Supporting nuclear physics experiments***
***(ChER, DCX, muon capture, 2νββ-decay )***
***V. 2νββ-decay and nuclear structure***
***(SSD/HSD, exotic contribution to 2νββ-decay rate)***
***V. Is there a relation between the 0νββ- and 2νββ-decay closure NMEs?***
***(a connection through 2n-exchange potential, anatomy of $C^{2\nu}_{GT}(r)$)***
***IV. Quenching of $g_A$***
***(theory and experimental indications, novel approach for effective $g_A$ )***

***Acknowledgements:*** **A. Faessler (Tuebingen), P. Vogel (Caltech), S. Kovalenko (Valparaiso U.), M. Krivoruchenko (ITEP Moscow), D. Štefánik, R. Dvornický (Comenius U.), A. Babič, A. Smetana (IEAP CTU Prague), F.F. Deppisch (Imperial College London), L. Graf (MPI Heidelberg ), …**

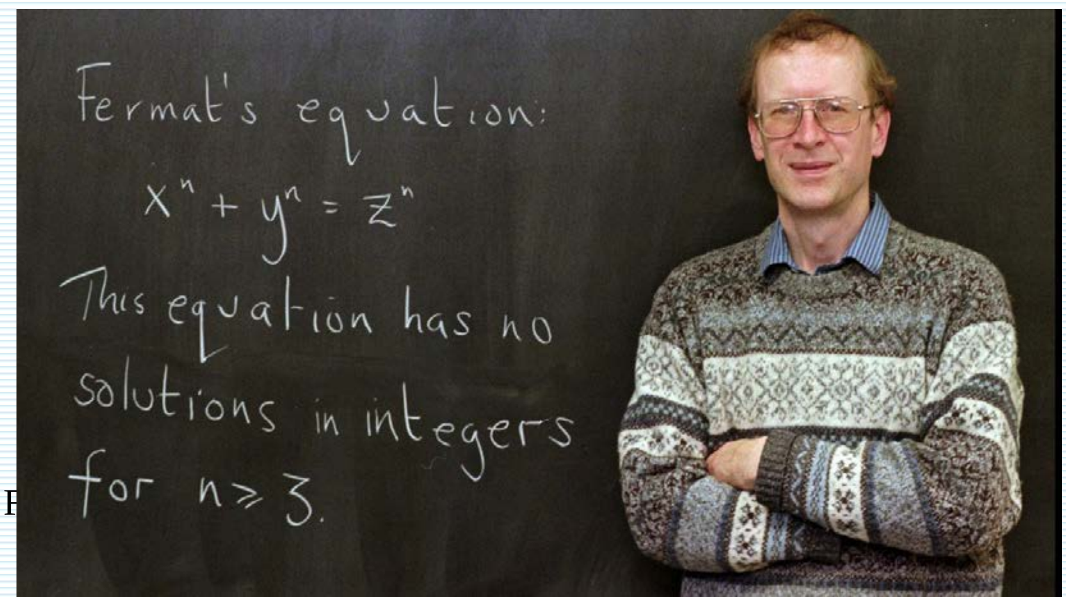

**Around 1637, Fermat wrote in the margin of a book that the more general equation**

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

**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.**



# Majorana fermion

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


CNNP 2018, Catania, October 15-21, 2018

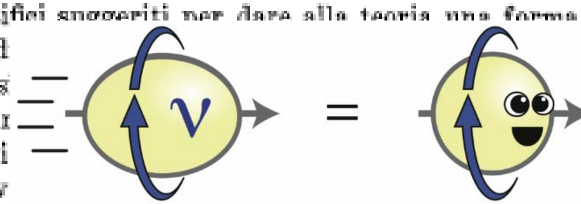
TEORIA SIMMETRICA DELL'ELETTRONE
E DEL POSITRONE

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.*

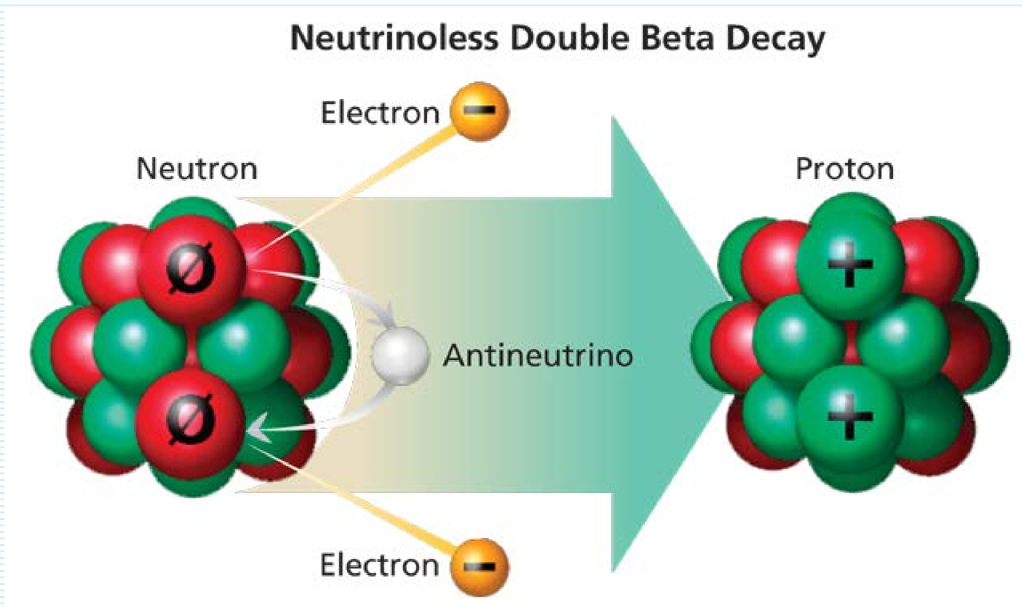
L'interpretazione dei cosidetti «stati di energia negativa» proposta da Dirac (¹) conduce, come è ben noto, a una descrizione sostanzialmente simmetrica degli elettroni e dei positroni. La sostanziale simmetria del formalismo consiste precisamente in questo, che fin dove è possibile applicare la teoria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

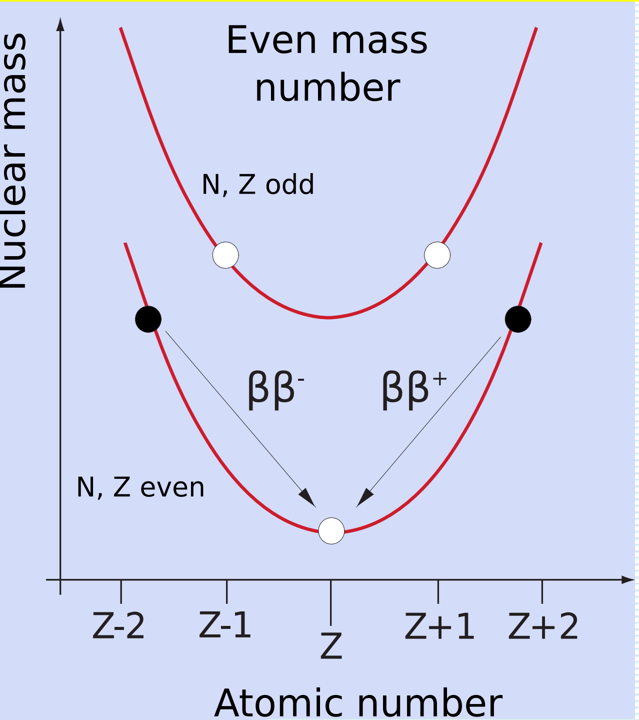
(¹) P. A. M. Dirac, «Proc. Camb. Phil. Soc.», **30**, 150, 1924. V. anche W. Heisenberg, «ZS. f. Phys.», **90**, 209, 1934.

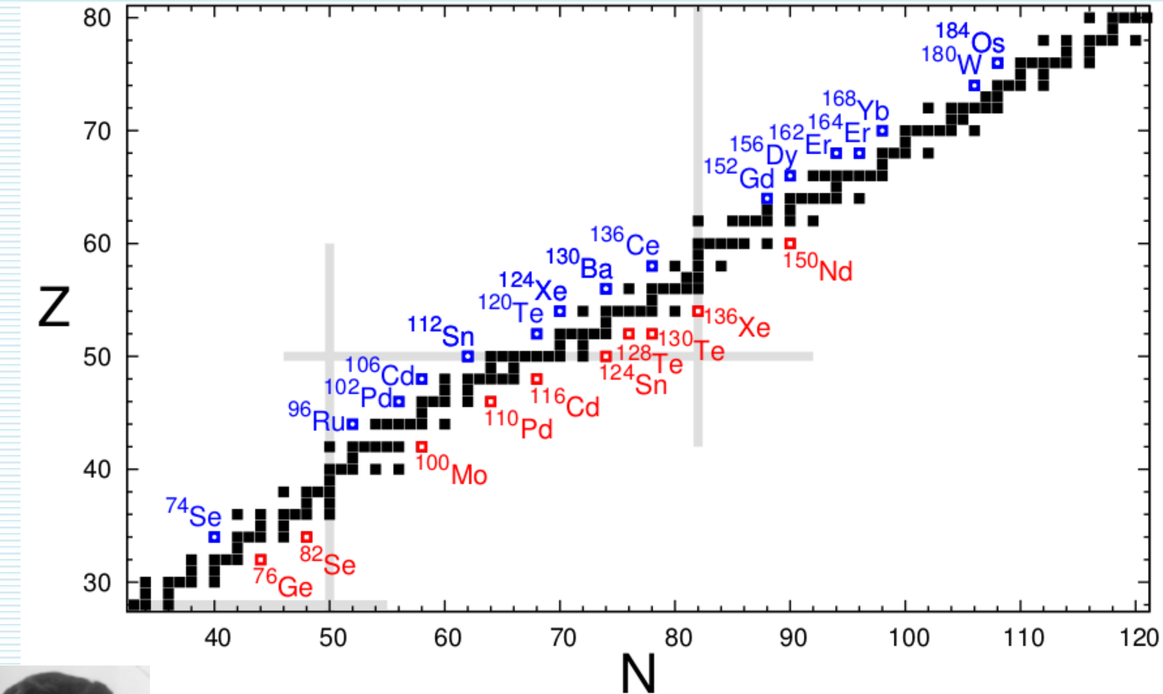

ARE NEUTRINOS
THEIR OWN
ANTIPARTICLES?


Neutrinoless Double Beta Decay
Electron
Neutron
Proton
Antineutrino
Electron

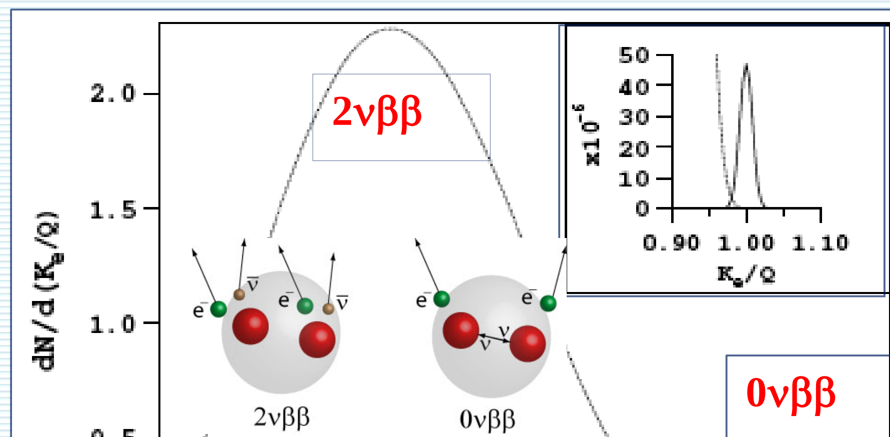
# Nuclear double-β decay

**(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 83 years …

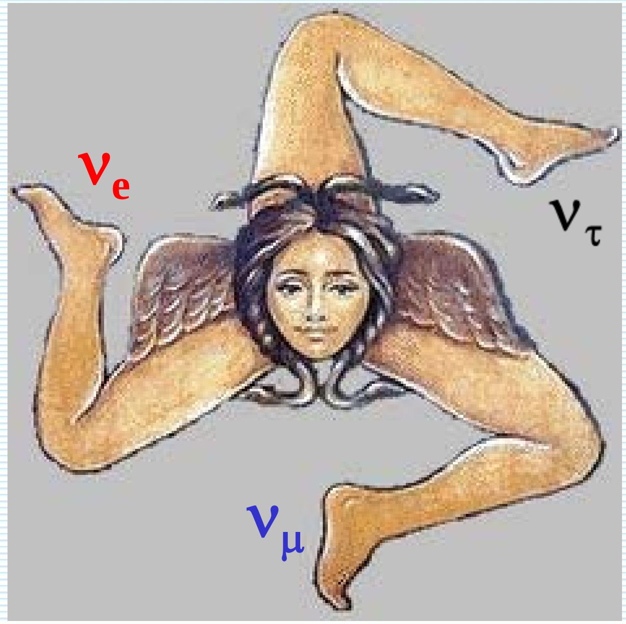
| Collaboration | Isotope | | mass ($0\nu\beta\beta$ isotope) | Status |
|---|---|---|---|---|
| CANDLES | Ca-48 | 305 kg $CaF_2$ crystals - liq. scint | 0.3 kg | Construction |
| CARVEL | Ca-48 | $^{48}CaWO_4$ crystal scint. | ~ ton | R&D |
| GERDA I | Ge-76 | Ge diodes in LAr | 15 kg | Complete |
| 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<br>Se-82 | Foils with tracking | 6.9 kg<br>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 |

After 90/64 years we know

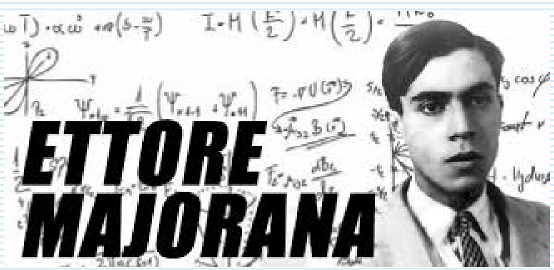
# Fundamental ν properties

No answer yet

- 3 families of light (V-A) neutrinos: $\nu_e, \nu_\mu, \nu_\tau$
- ν are massive: we know mass squared differences
- relation between flavor states and mass states (neutrino mixing)

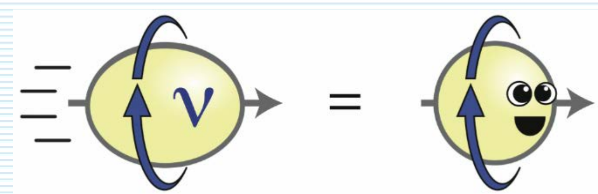



- Are ν Dirac or Majorana?
- Is there a CP violation in ν sector?
- Are neutrinos stable?
- What is the magnetic moment of ν?
- Sterile neutrinos?
- Statistical properties of ν? Fermionic or partly bosonic?




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)*

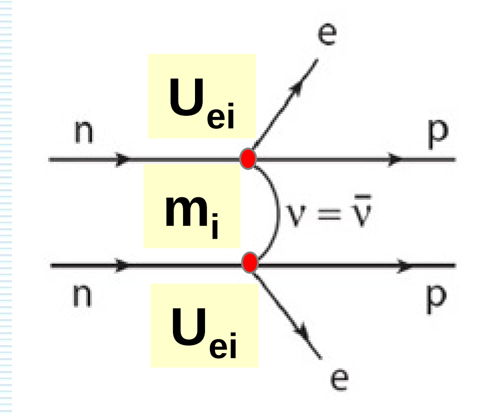
**(A,Z) → (A,Z+2) + e⁻ + e⁻**

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

?

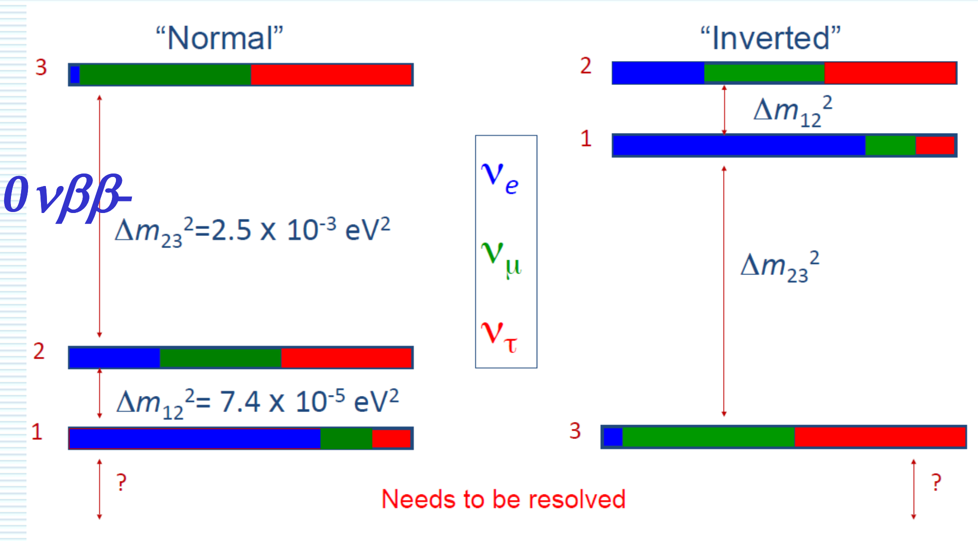
***Phase factor well understood***

***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***

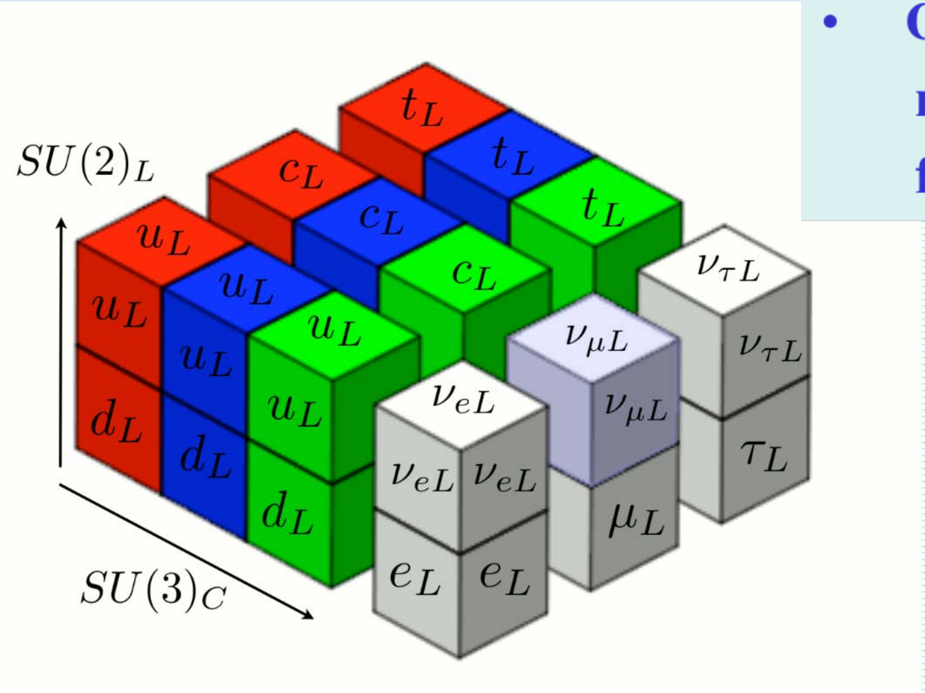
**$m_1, m_2, m_3, \theta_{12}, \theta_{13}, \alpha_1, \alpha_2$**

(3 unknown parameters: $m_1/m_3, \alpha_1, \alpha_2$)

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

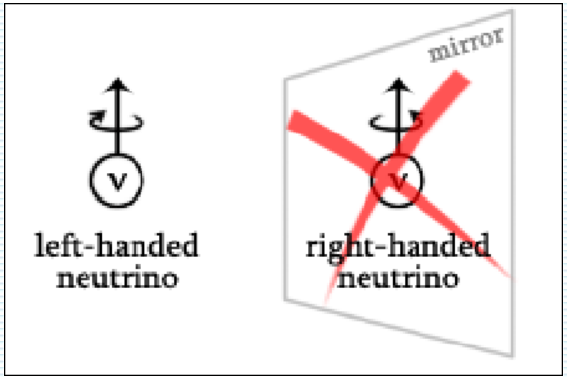
# *A generation of Majorana neutrino mass, $0\nu\beta\beta$-decay mechanisms*

**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 $\gamma, g, H^0$) !**
- **In the SM, the only left-handed neutrinos $\nu_L$ appears in the theory.**
- **One cannot obtain a mass for $\nu_L$ 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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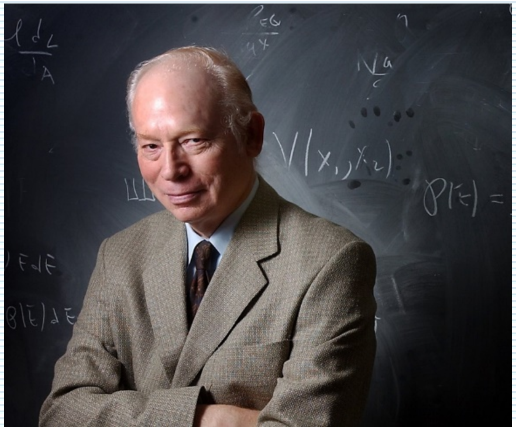
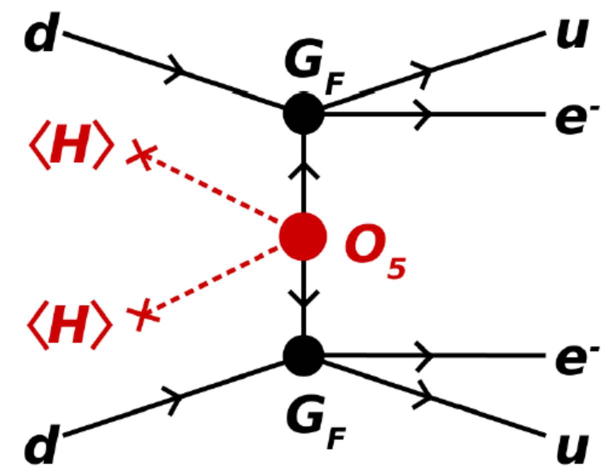


**Weinberg, 1979: d=5**

$0\nu\beta\beta$ decay:




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

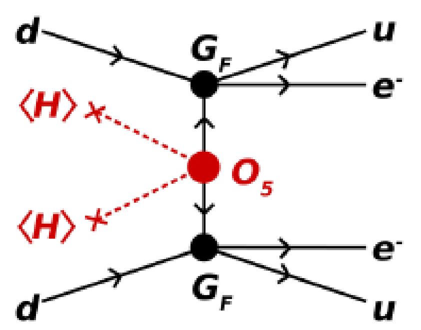
. Weinberg does not take credit for predicting neutrino masses, but he thinks it's the right interpretation. What's more, he says, the non-renormalisable interaction that produces the neutrino masses is probably also accompanied with non-renormalisable interactions that produce proton decay and other 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)→(A,Z+2)+2e⁻ can be divided into:**

**mass mechanism: d=5**

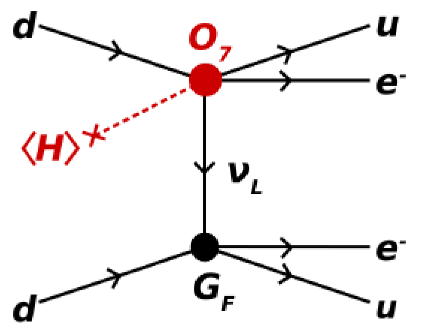



$$\mathcal{O}_W \propto \frac{c_{ij}}{\Lambda}(L_i H)(L_j H)$$

**Weinberg, 1979**

+

**long range: d=7**

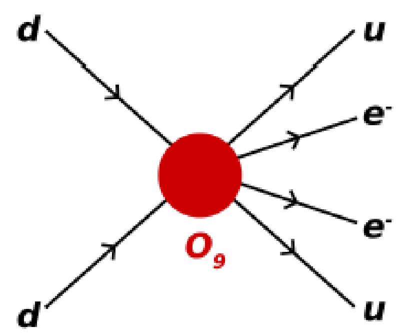



$$\mathcal{O}_2 \propto LLLe^cH$$
$$\mathcal{O}_3 \propto LLQd^cH$$
$$\mathcal{O}_4 \propto LL\bar{Q}\bar{u}^cH$$
$$\mathcal{O}_8 \propto L\bar{e}^c\bar{u}^cd^cH$$

**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

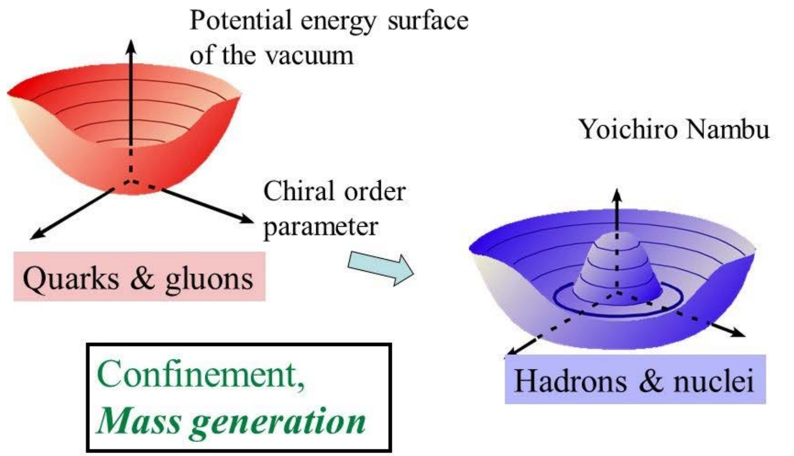
A. Babič, S. Kovalenko, M.I. Krivoruchenko , F.Š., arXive:1911.12189

**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 ($\chi$) symmetry***




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

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

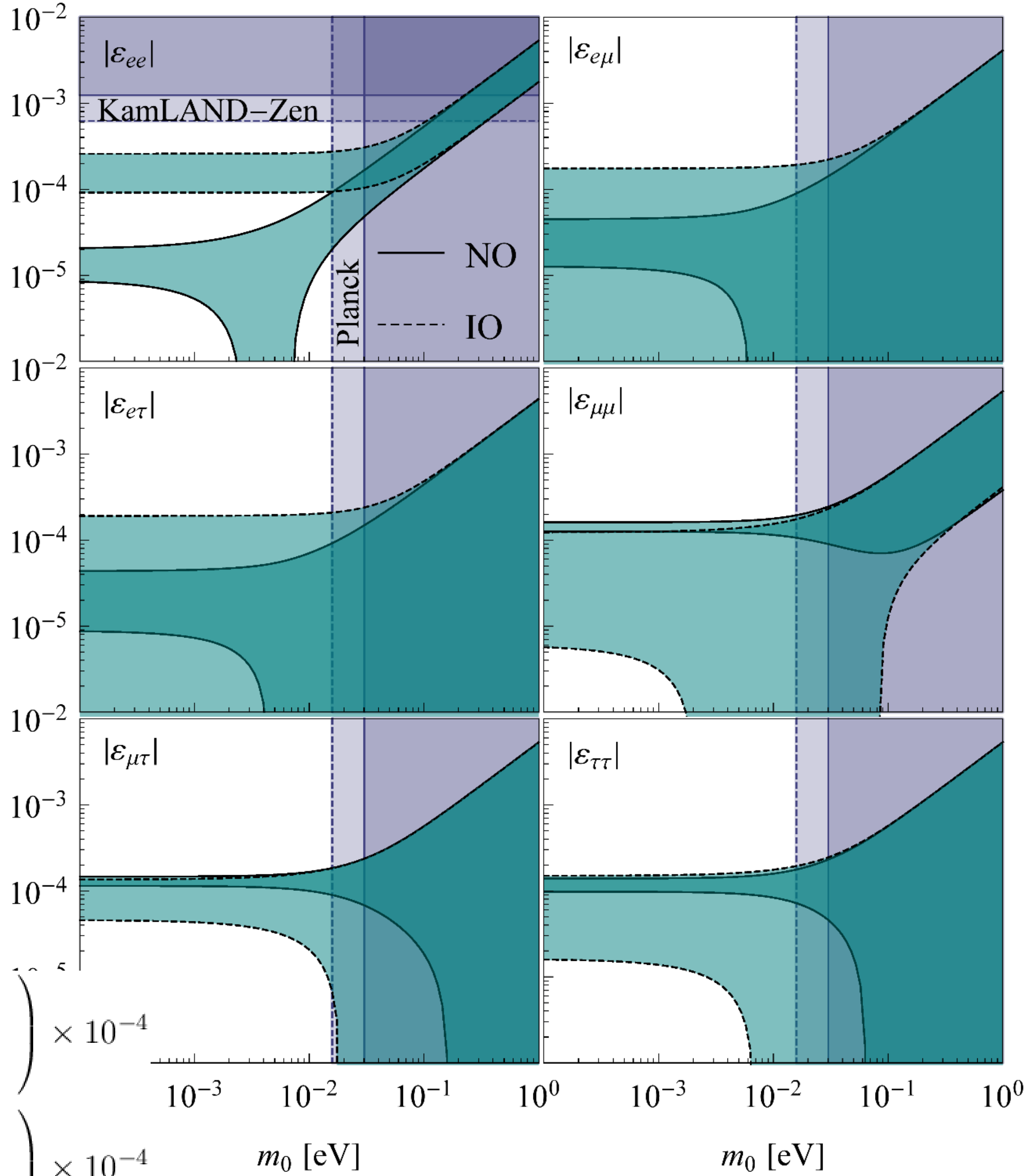
$$g_{\alpha\beta} = g^u_{\alpha\beta} + g^d_{\alpha\beta}, \quad v/\sqrt{2} = \langle H^0\rangle$$

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

**$\Lambda$ ~ 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


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




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

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

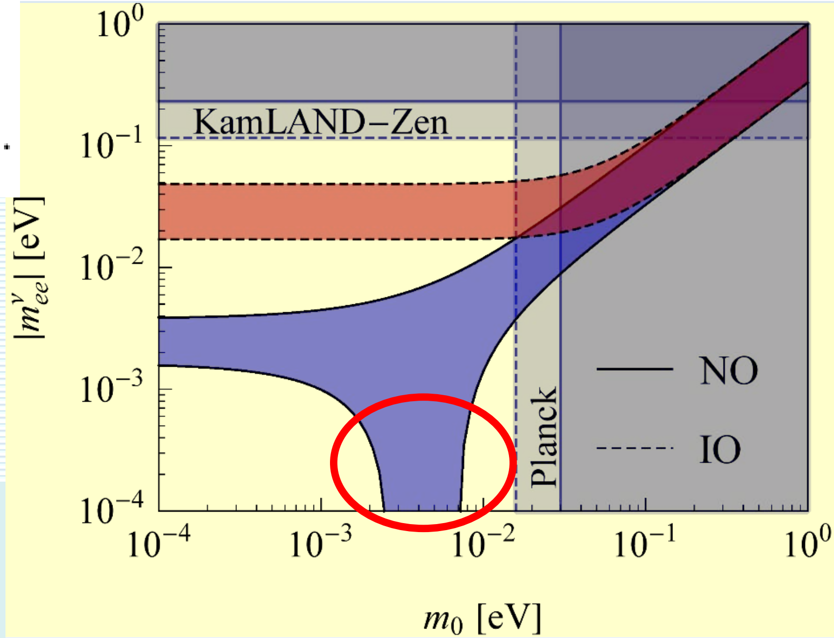
# The genuine QCSS scenario with no fine-tuning

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

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

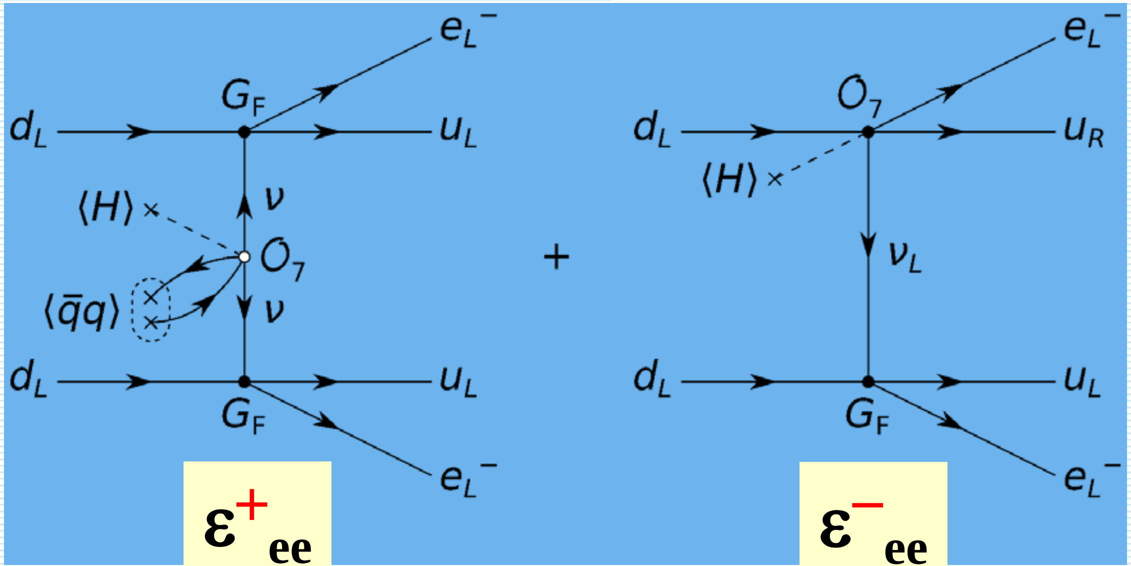
$$\varepsilon^{u,d}_{\alpha\beta} = \frac{g^{u,d}_{\alpha\beta} v/\Lambda^3}{G_F/\sqrt{2}}$$

$$\varepsilon^{\pm}_{\alpha\beta} = \varepsilon^{u}_{\alpha\beta} \pm \varepsilon^{d}_{\alpha\beta}$$




(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**

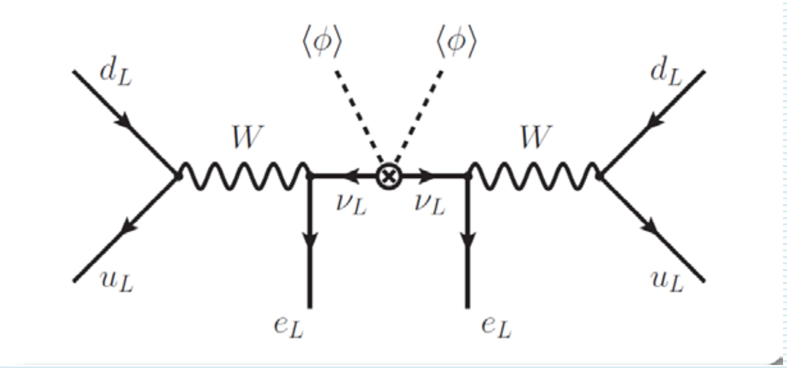
$9 \text{ meV} < m_\beta < 12 \text{ meV}$

**Prediction for cosmology**

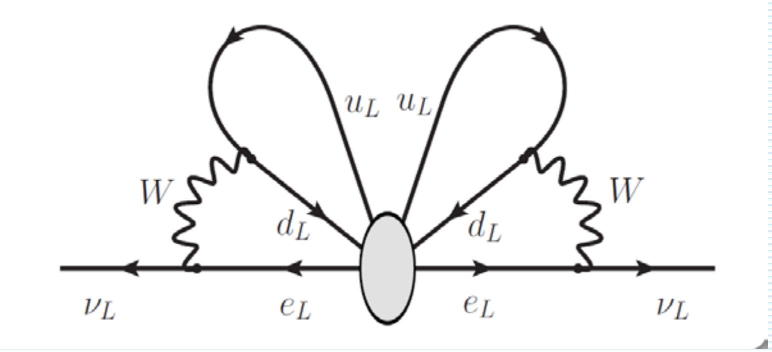
$62 \text{ meV} < m_1 + m_2 + m_3 < 69 \text{ meV}$

**If 0νββ is observed the ν is a Majorana particle**

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



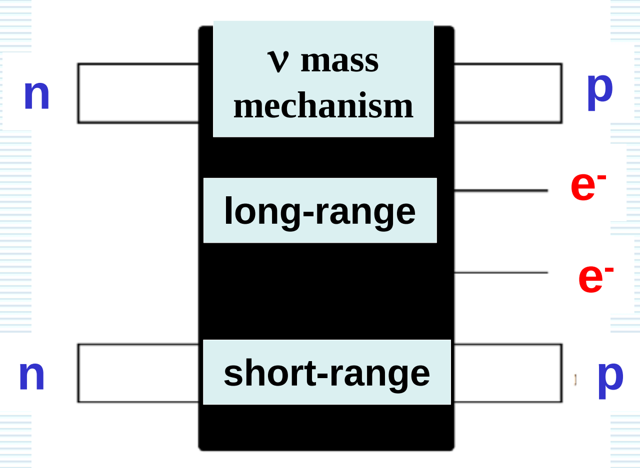

## $0\nu\beta\beta \Longrightarrow$ Majorana $m_\nu$




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. ....

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

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

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

**General case**

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

**light ν exchange**

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

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

**heavy ν exchange**

**Particular cases**

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

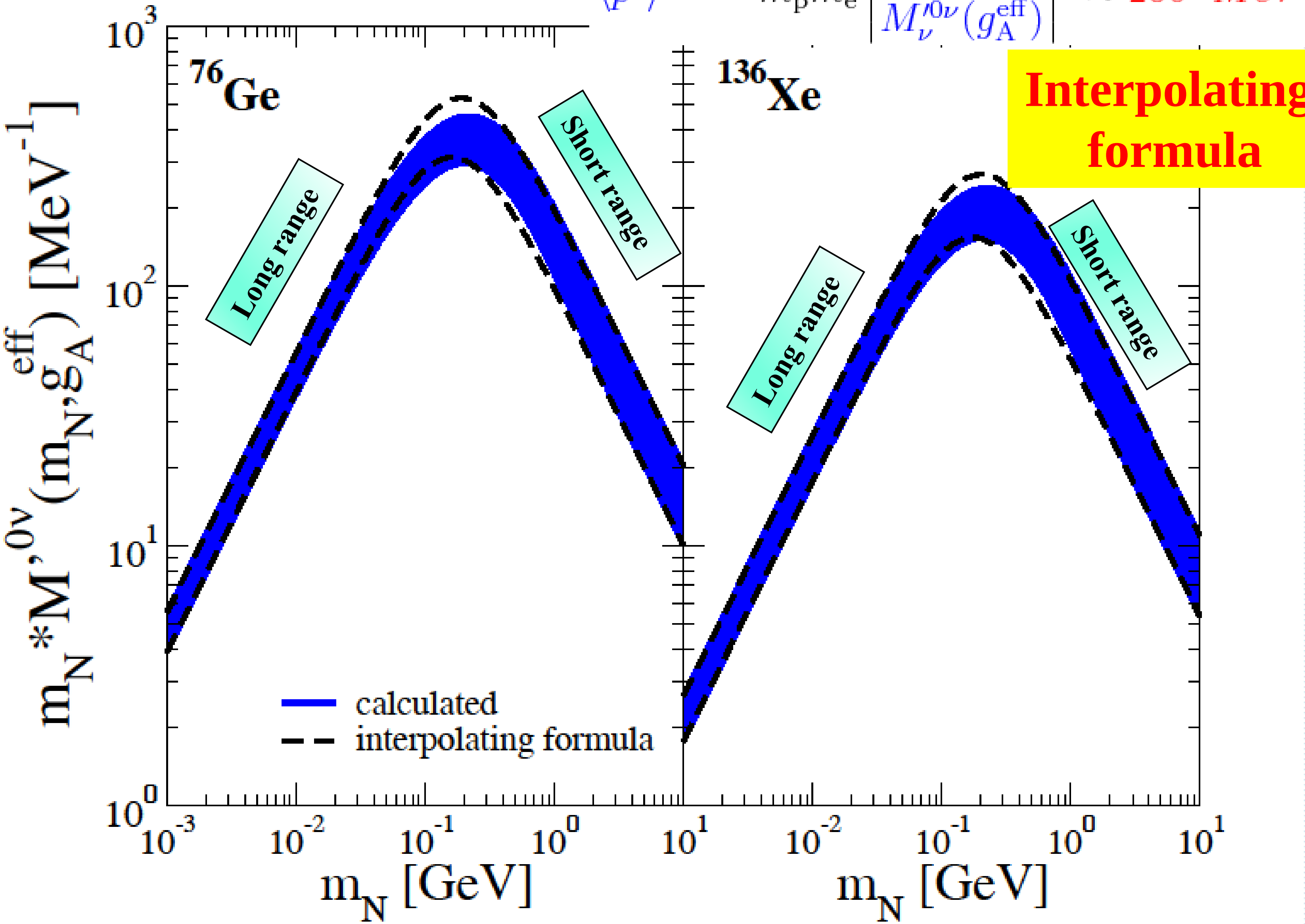
$$\langle m_\nu \rangle = \sum_N U^2_{eN} m_N$$

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

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

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

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



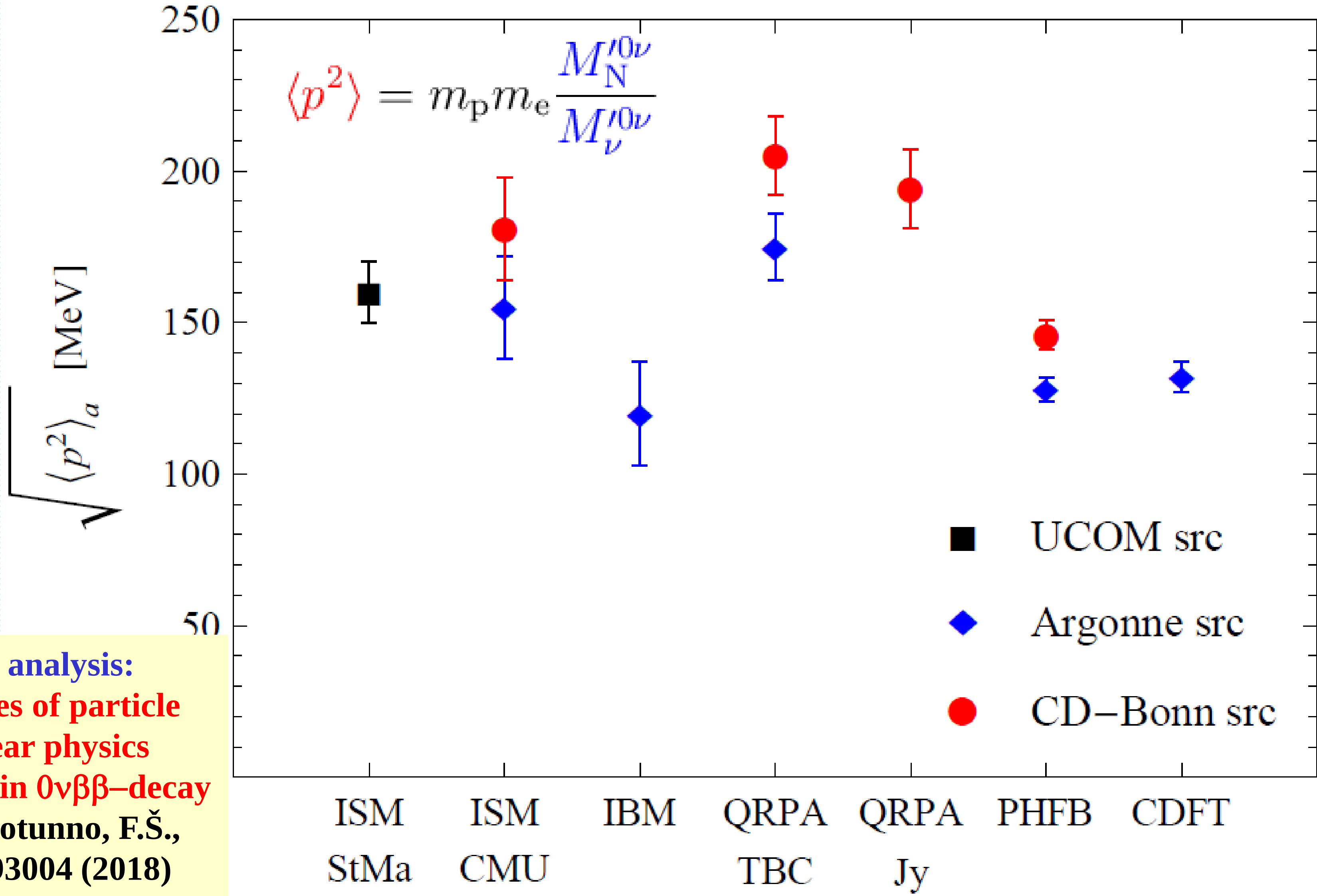



Faessler, Gonzales, Kovalenko, F. Š., PRD 90 (2014) 096010]

**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)

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




**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)**

$$[T^{0\nu}_{1/2}]^{-1} = \eta^2_{\nu N}\; C_{\nu N} \qquad C_{\nu N} = g_A^4\; \left|M'^{0\nu}_{\nu}\right|^2\; G^{0\nu}$$

**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)**

$$\langle p^2\rangle = m_p m_e \frac{M'^{0\nu}_N}{M'^{0\nu}_\nu}$$

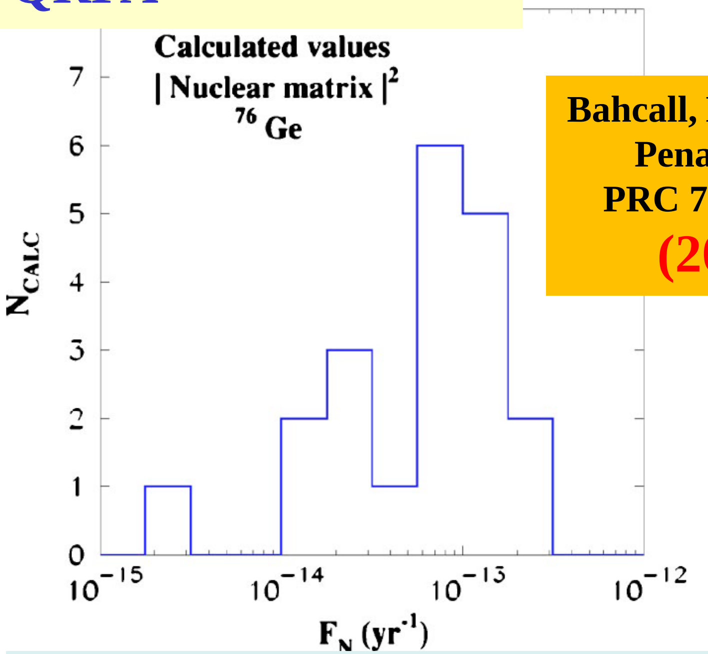
$$\eta^2_{\nu N} = \left|\sum_{j=1}^{3}\left(U^2_{ej}\,\frac{m_j}{m_e} + S^2_{ej}\,\frac{\langle p^2\rangle_a}{\langle p^2\rangle_a + M_j^2}\,\frac{M_j}{m_e}\right)\right|^2 + \lambda^2\left|\sum_{j=1}^{3}\left(T^2_{ej}\,\frac{m_j}{m_e} + V^2_{ej}\,\frac{\langle p^2\rangle_a}{\langle p^2\rangle_a + M_j^2}\,\frac{M_j}{m_e}\right)\right|^2$$

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

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

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

## *0νββ 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**

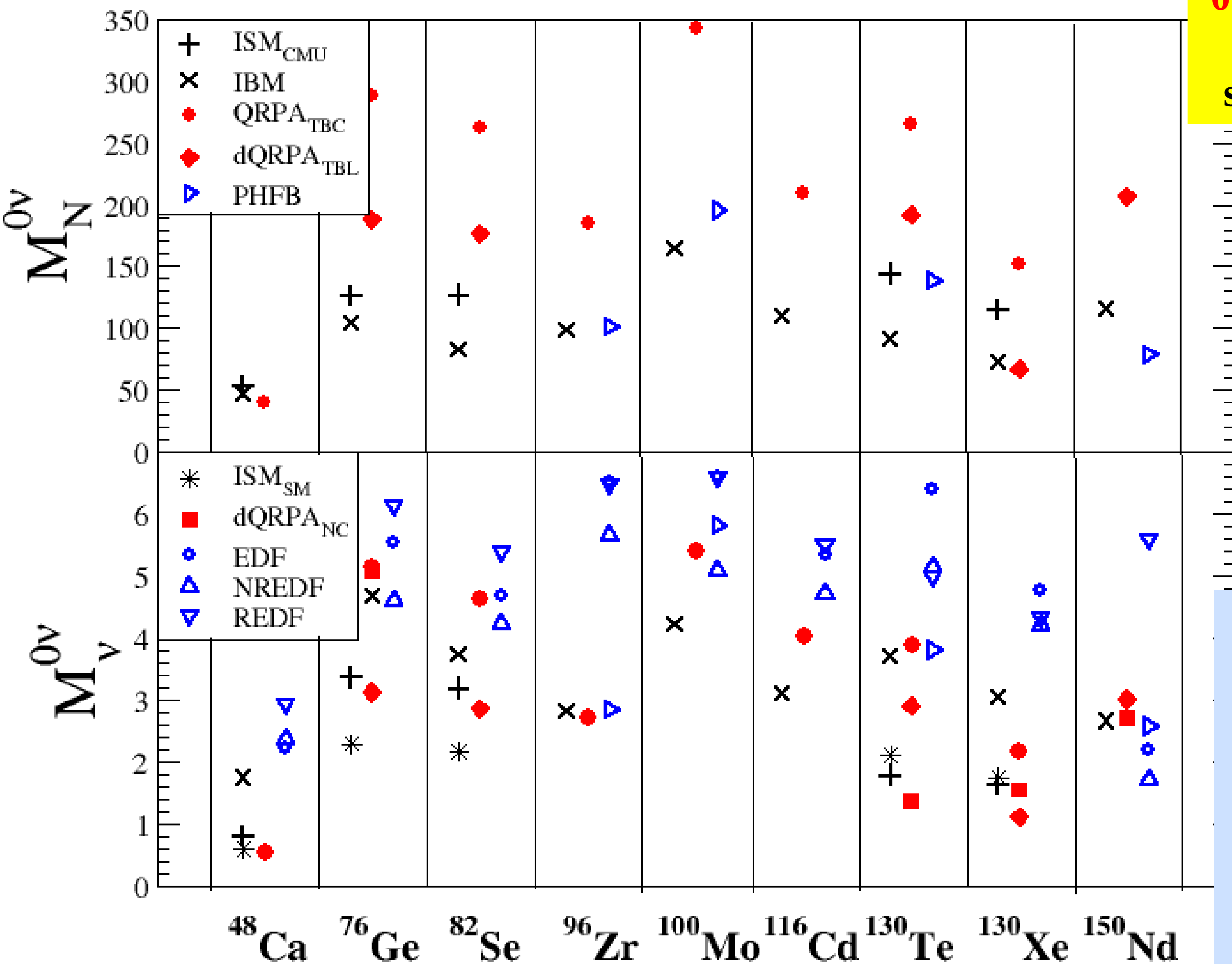
***Nuclear Shell Model*** **(Madrid-Strasbourg, Michigan, Tokyo): Relatively small model space (1 shell), all correlations included, solved by direct diagonalization**

***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**

**0νββ-decay NME status 2019**



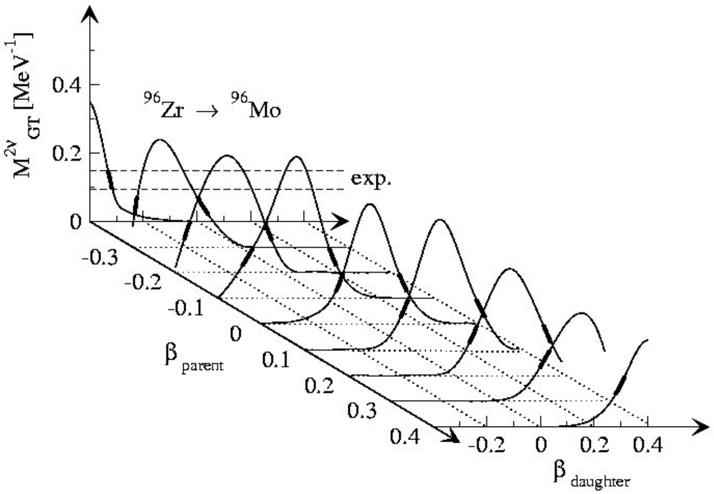

*unquenched $g_A$*

*All models missing essential physics*

*Impossible to assign rigorous uncertainties*

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

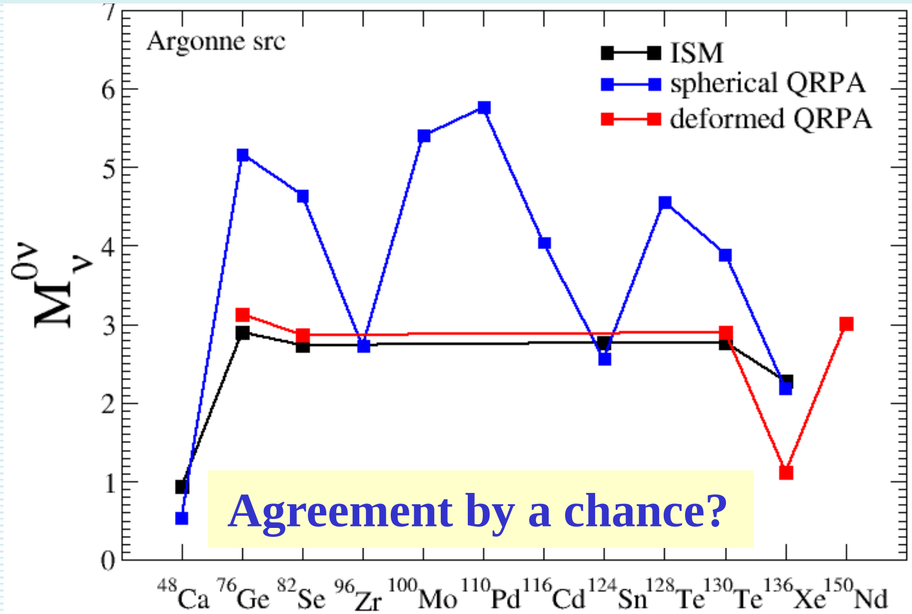
$$\beta = \sqrt{\frac{\pi}{5}}\frac{Q_p}{Zr_c^2}$$



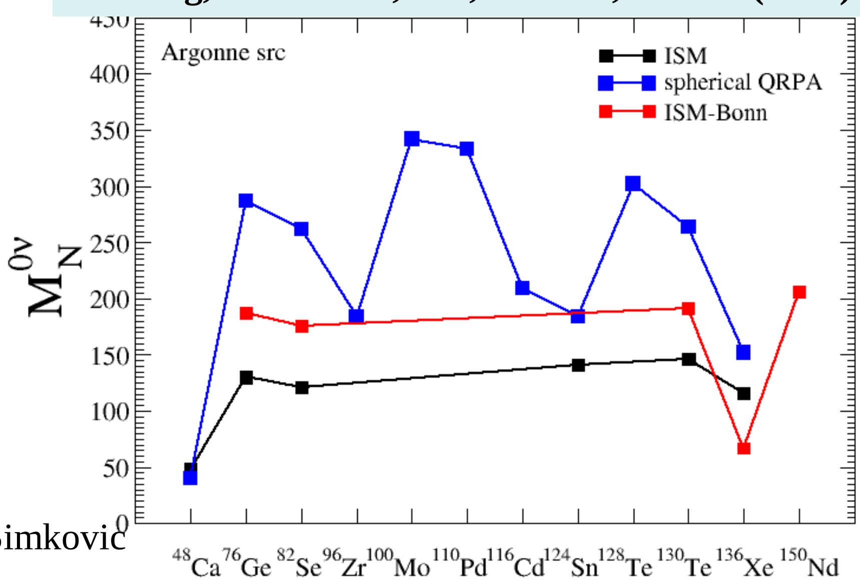

**Systematic study of the deformation effect on the 2νββ-decay NME Within deformed QRPA**

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)



$M^{2\nu}_{F\text{-}cl} = 0$

# *The DBD Nuclear Matrix Elements and the SU(4) symmetry*

D. Štefánik, F.Š., A. Faessler, PRC 91, 064311 (2015)

$M^{2\nu}_{GT\text{-}cl} = 0$

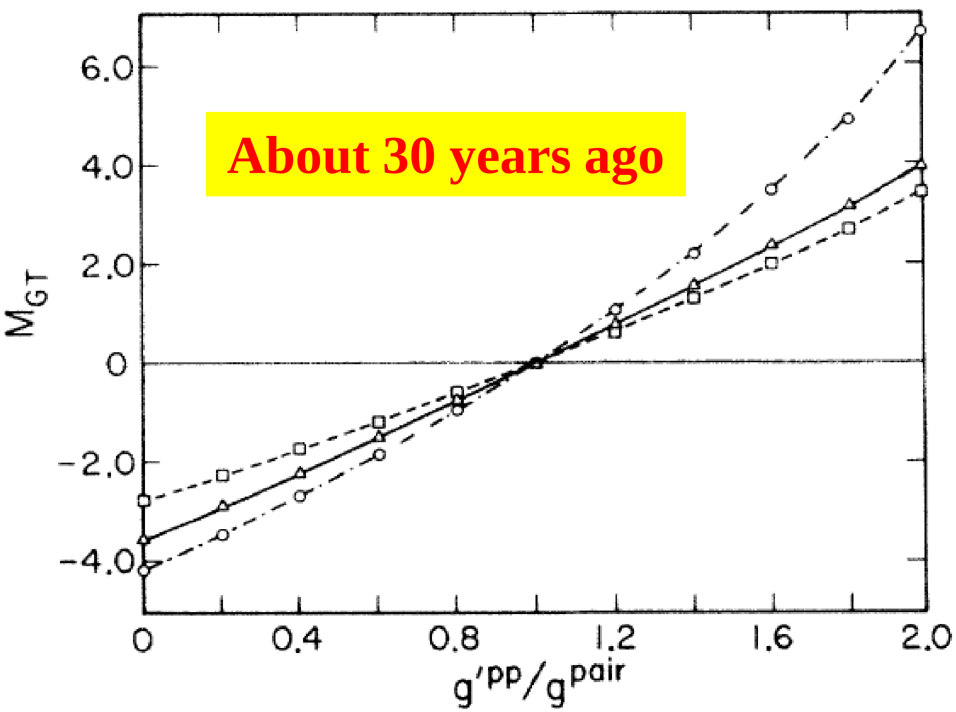
## Suppression of the Two Neutrino Double Beta Decay by Nuclear Structure Effects

P. Vogel, M.R. Zirnbauer, PRL (1986) 3148

O. Civitarese, A. Faessler, T. Tomoda, PLB 194 (1987) 11

E. Bender, K. Muto, H.V. Klapdor, PLB 208 (1988) 53

…



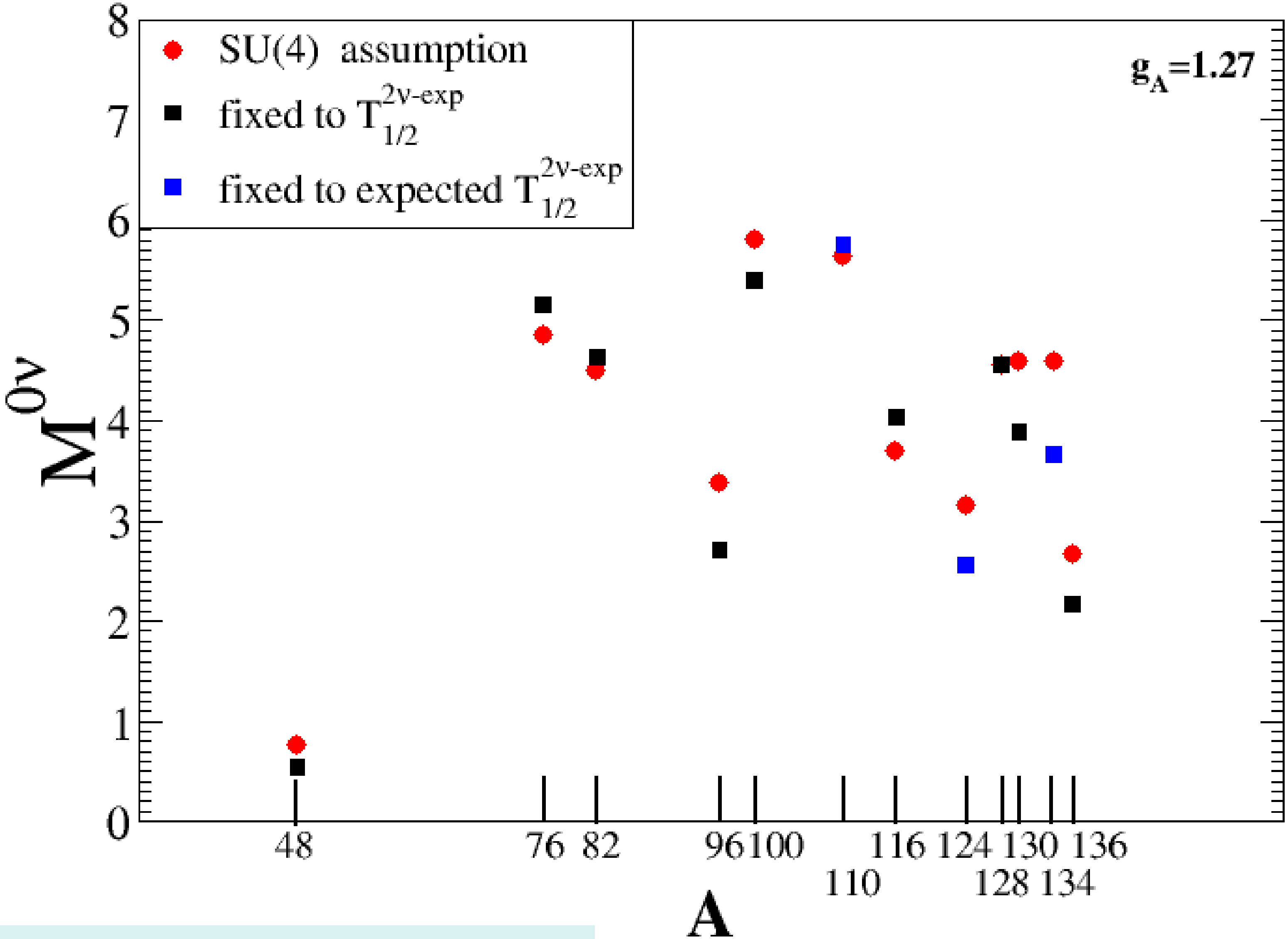

**The isospin is known to be a good approximation in nuclei**

**In heavy nuclei the SU(4) symmetry is strongly broken by the spin-orbit splitting.**



**What is beyond this behavior? Is it an artifact of the QRPA?**

## 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)

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

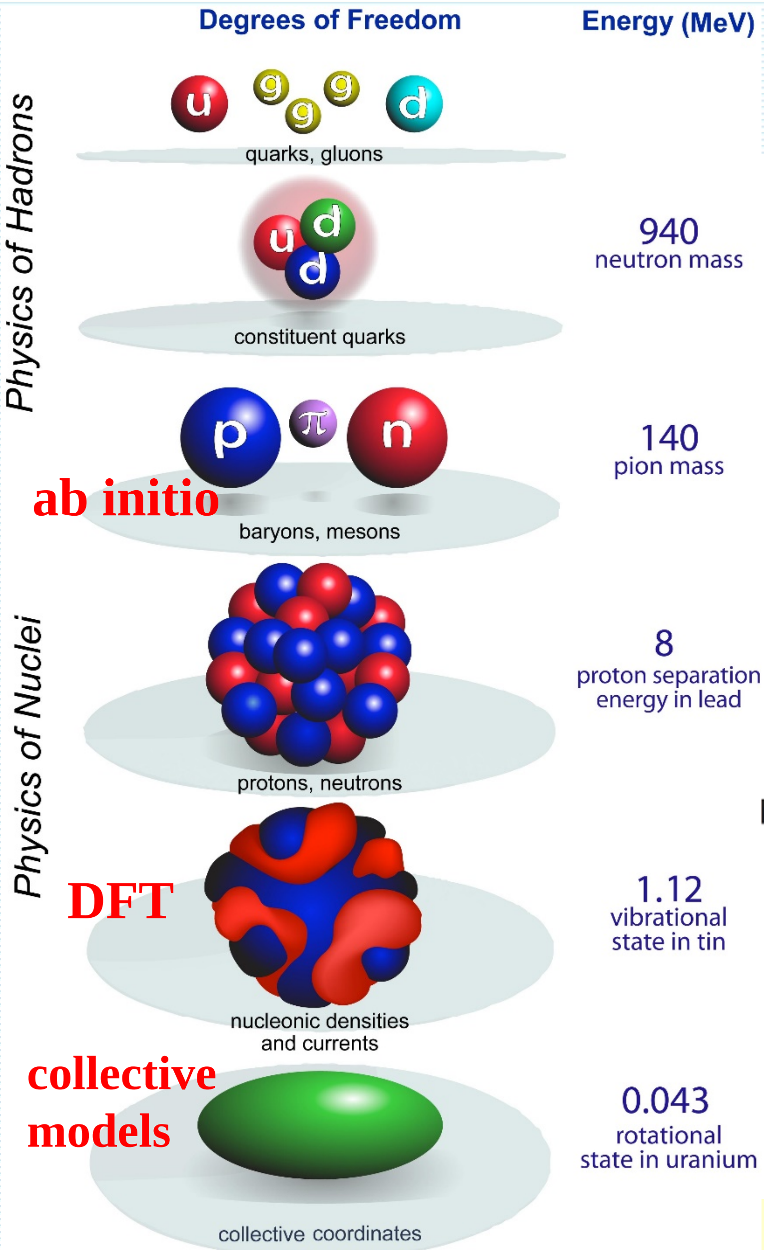
$$g_A^{\rm eff} = q \times g_A^{\rm free} = 0.901$$
$$g_A^{\rm free} = 1.269, \qquad q = 0.710$$

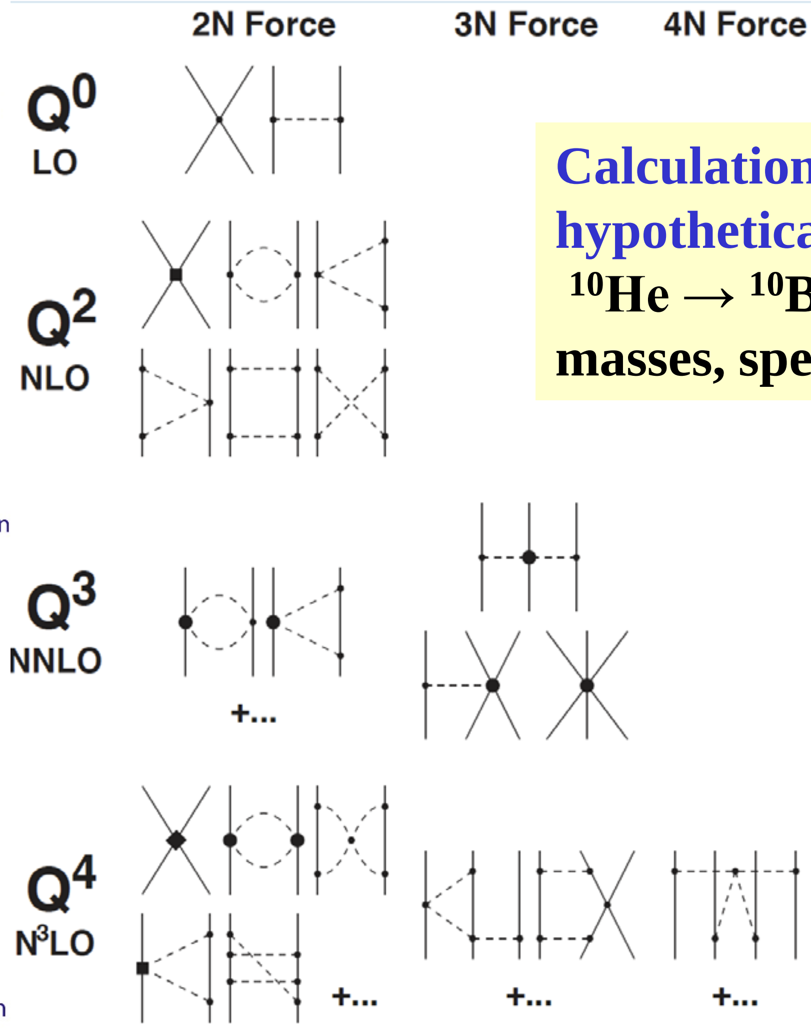
| Nucleus | $d^i_{pp}$ | $d^f_{pp}$ | $d^i_{nn}$ | $d^f_{nn}$ | $g^{T=1}_{pp}$ | $g^{T=0}_{pp}$ | $M^{2\nu}_F$ [MeV$^{-1}$] | $M^{2\nu}_{GT} \times q^2$ [MeV$^{-1}$] | $M^{2\nu}_{exp}$ [MeV$^{-1}$] |
|---|---|---|---|---|---|---|---|---|---|
| $^{48}$Ca | - | 1.069 | - | 0.982 | 1.028 | 0.745 | -0.003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

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

# 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 $Q/\Lambda_\chi$. $Q=m_\pi$ or typical nucleon momentum.*




**Calculation for the hypothetical 0νββ decay:**

**$^{10}He \rightarrow {}^{10}Be + e^- + e^-$**

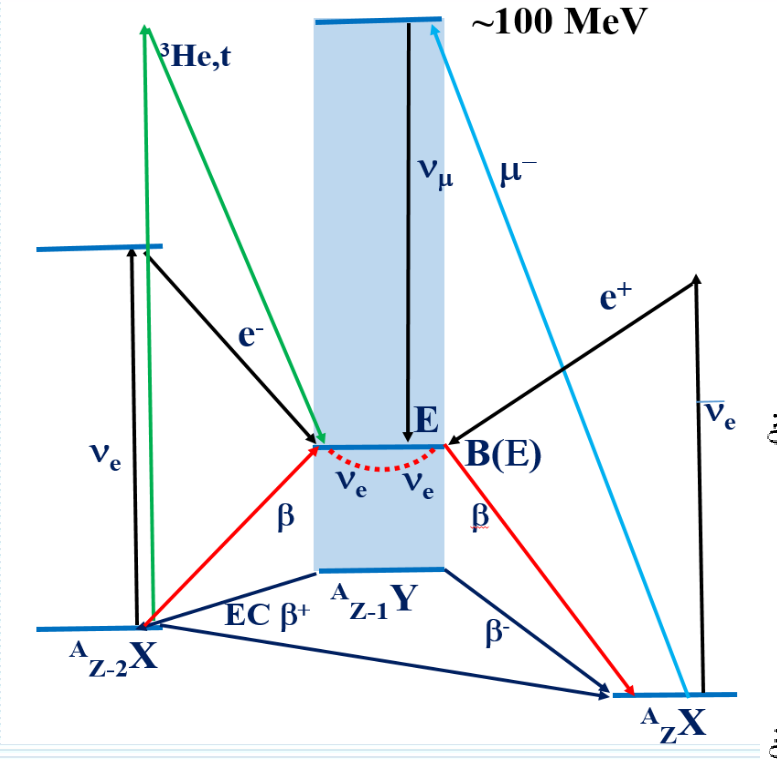
**masses, spectra**

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

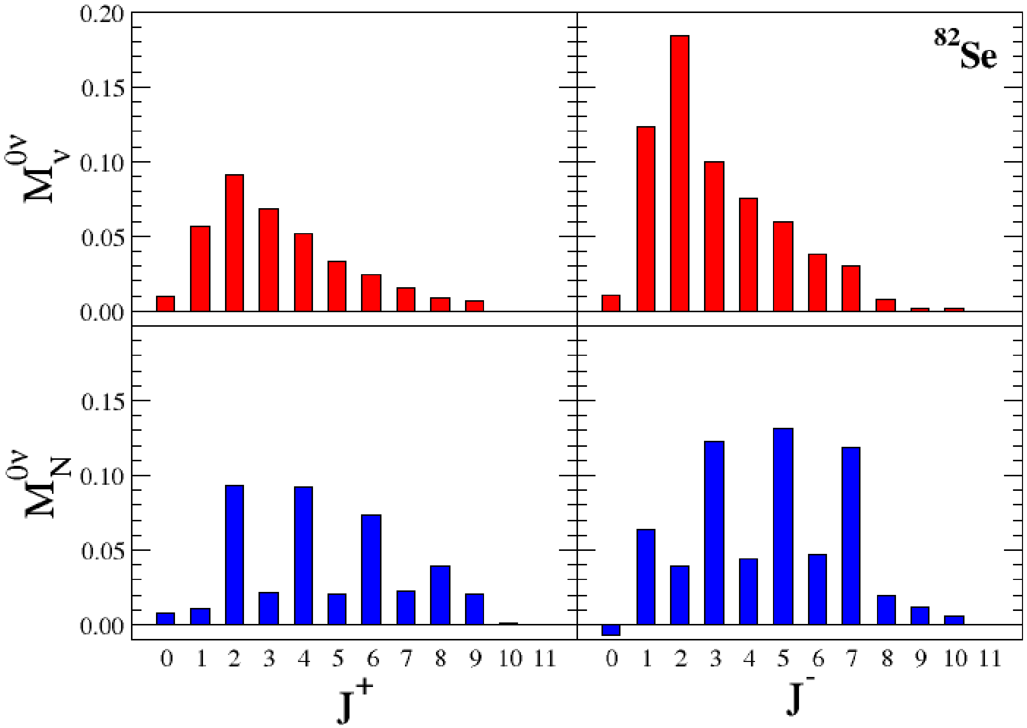
**Moore's law: exponential growth in computing power**

## ***Supporting nuclear physics experiments***

# Exploiting charge-exchange reactions ($^3$He,t) and μ-capture to constrain 0νββ–decay NMEs




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

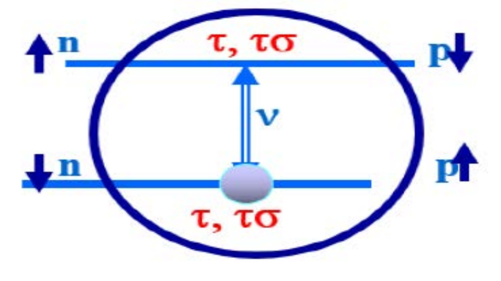



*Higher multiploles are populated mostly due large ν-momenta transfer*

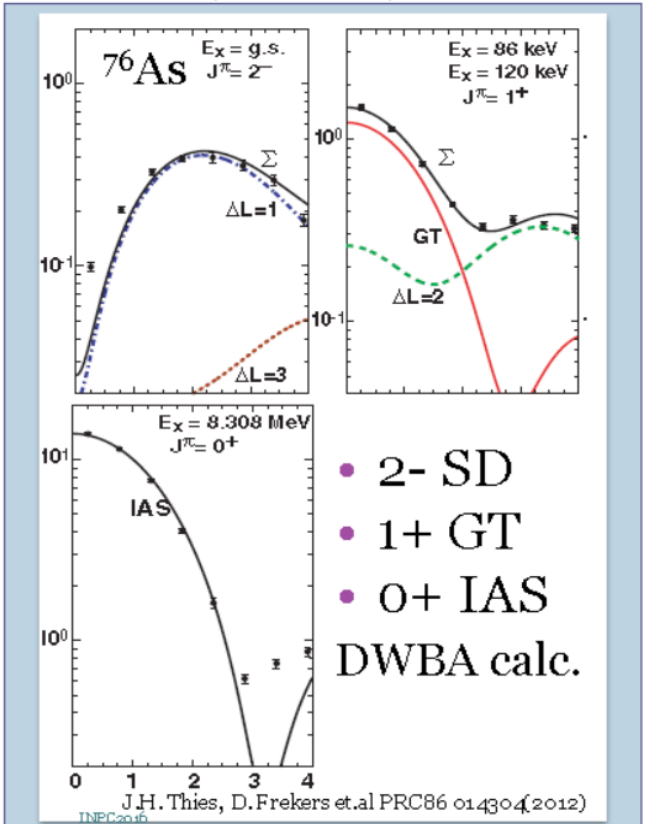
## RCNP Osaka p,He

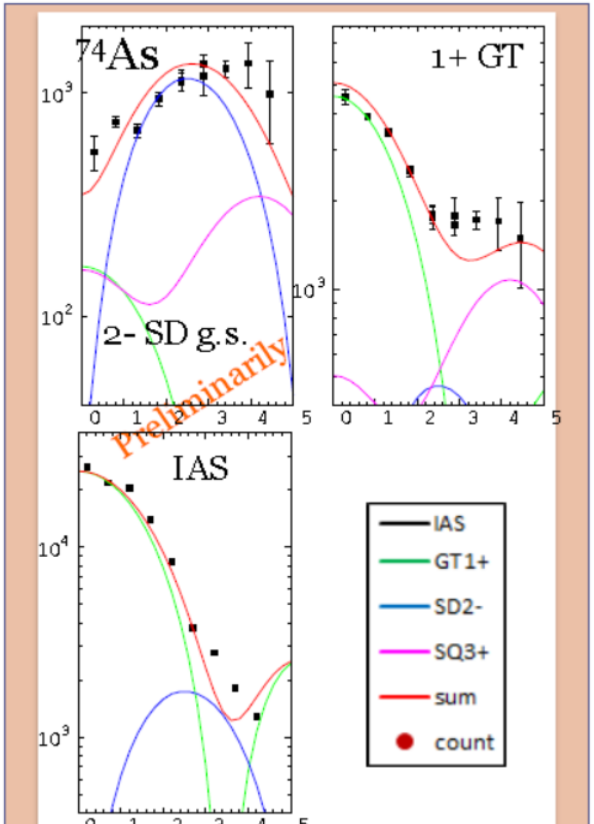
# Measuring of GT-like ($1^+$, $2^-$, $3^+$) strengths distribution for $^{74,76}Ge \rightarrow ^{74,76}As$ with ($^3He$,t) reactions

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



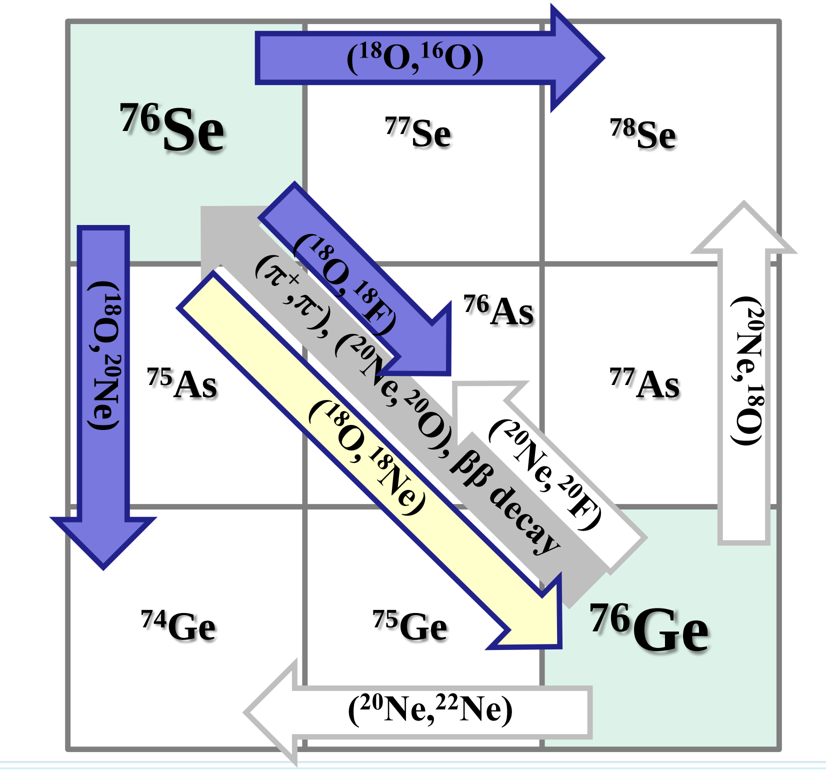

## $^{74,76}Ge(^3He,t)^{74,76}As$ Angular distribution

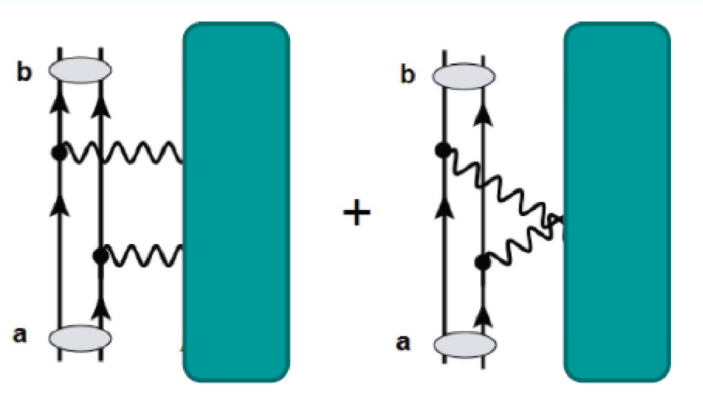


# Supporting nuclear physics experiments

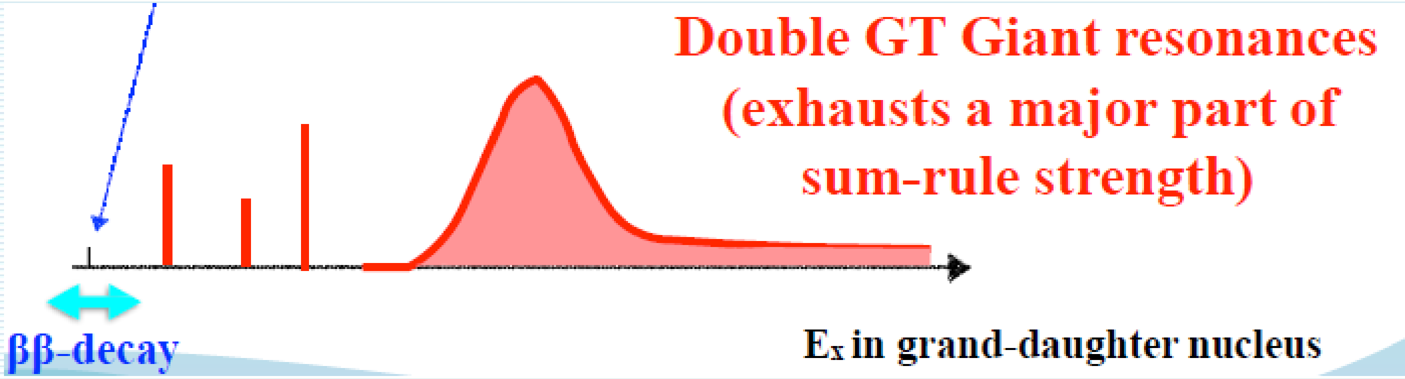
(2νββ-decay, μ-capture ChER, pion and heavy ion DCX, nucleon transfer reactions etc)




*H. Lenske group*
*Theory of heavy ion DCX and connection to DBD NMEs*

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



## 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

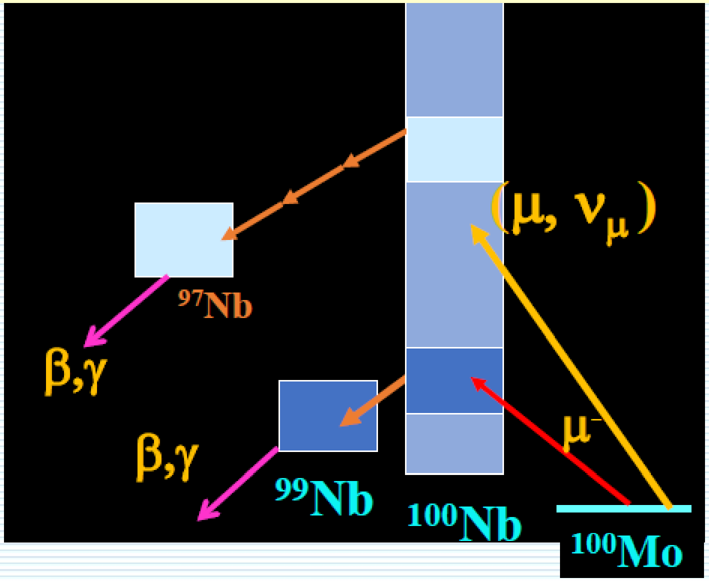
**Contradicting results:**

- **Strong quenching**

Jokiniemi, Suhonen, PRC 100, 014619 (2019)

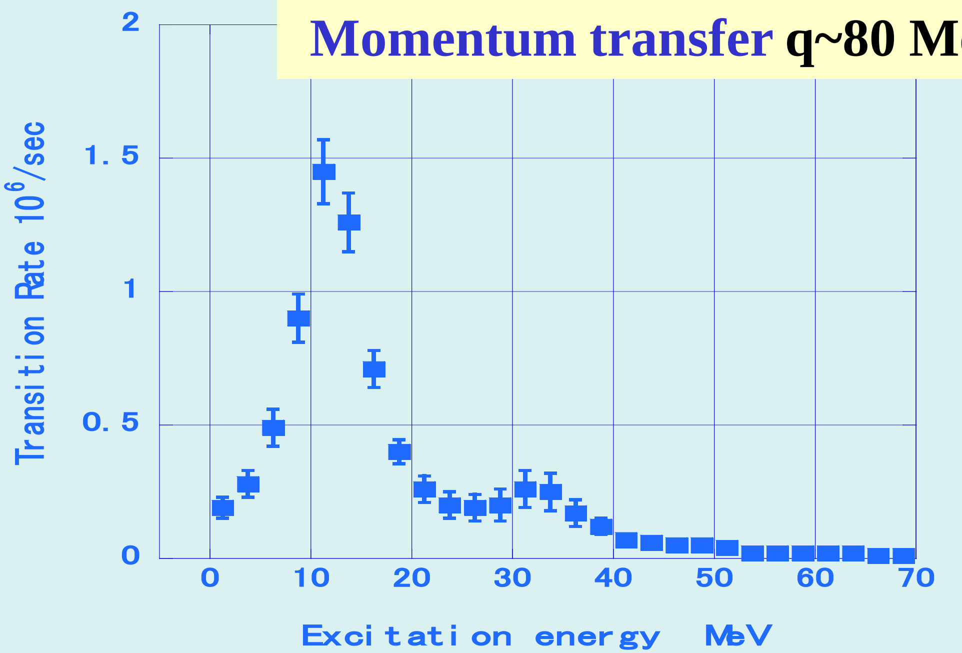
- **Weak quenching**

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



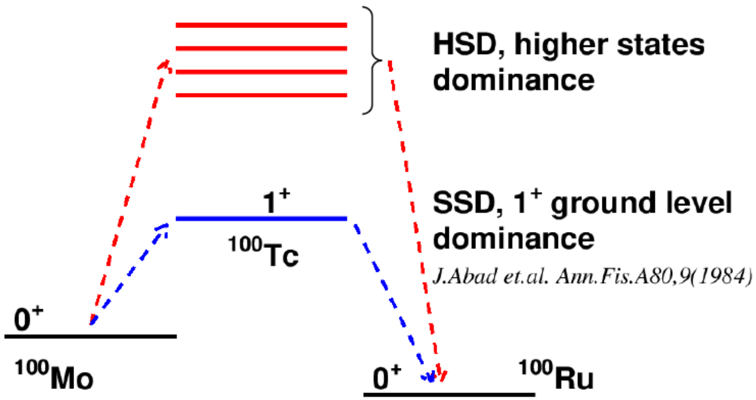

I. Hashim H. Ejiri , MXG16, PR C 97 2018

**Momentum transfer q~80 MeV**




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

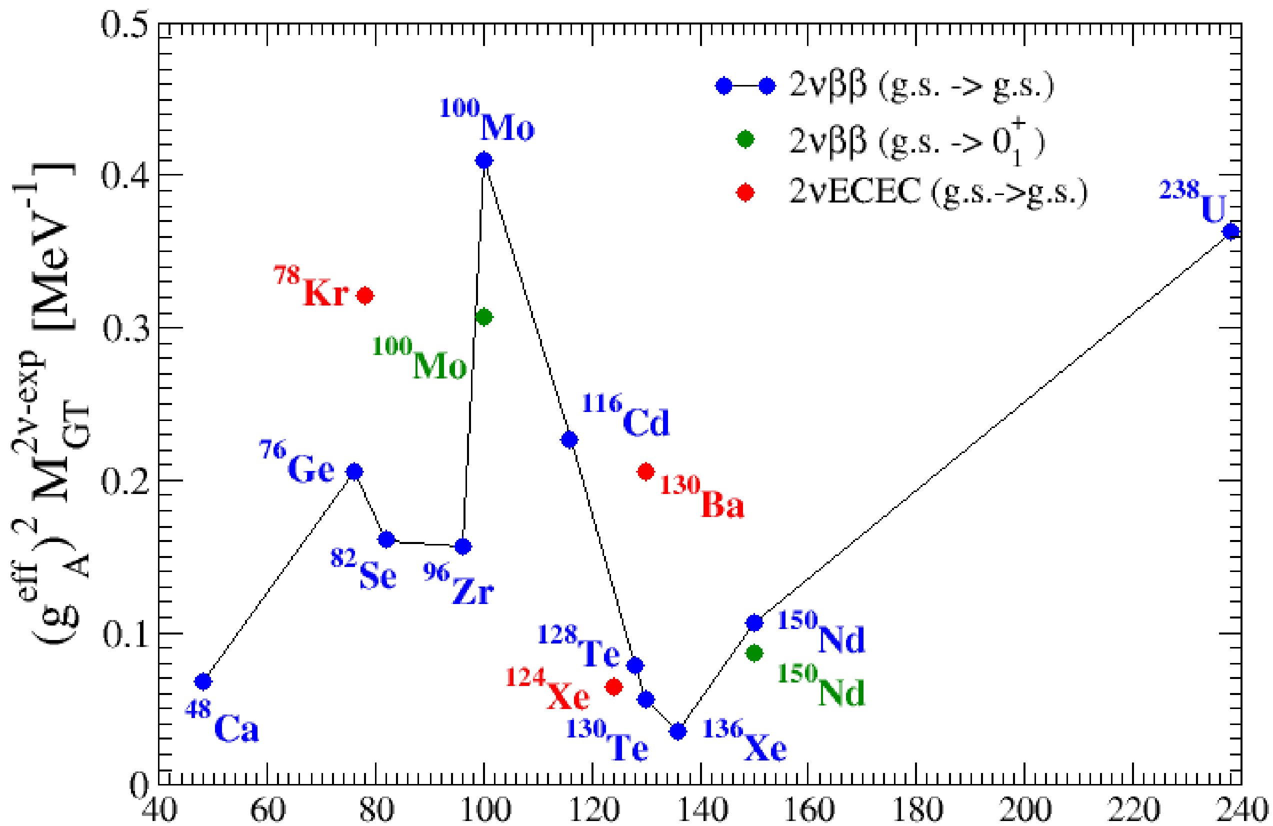
## *The 2νββ-decay*




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

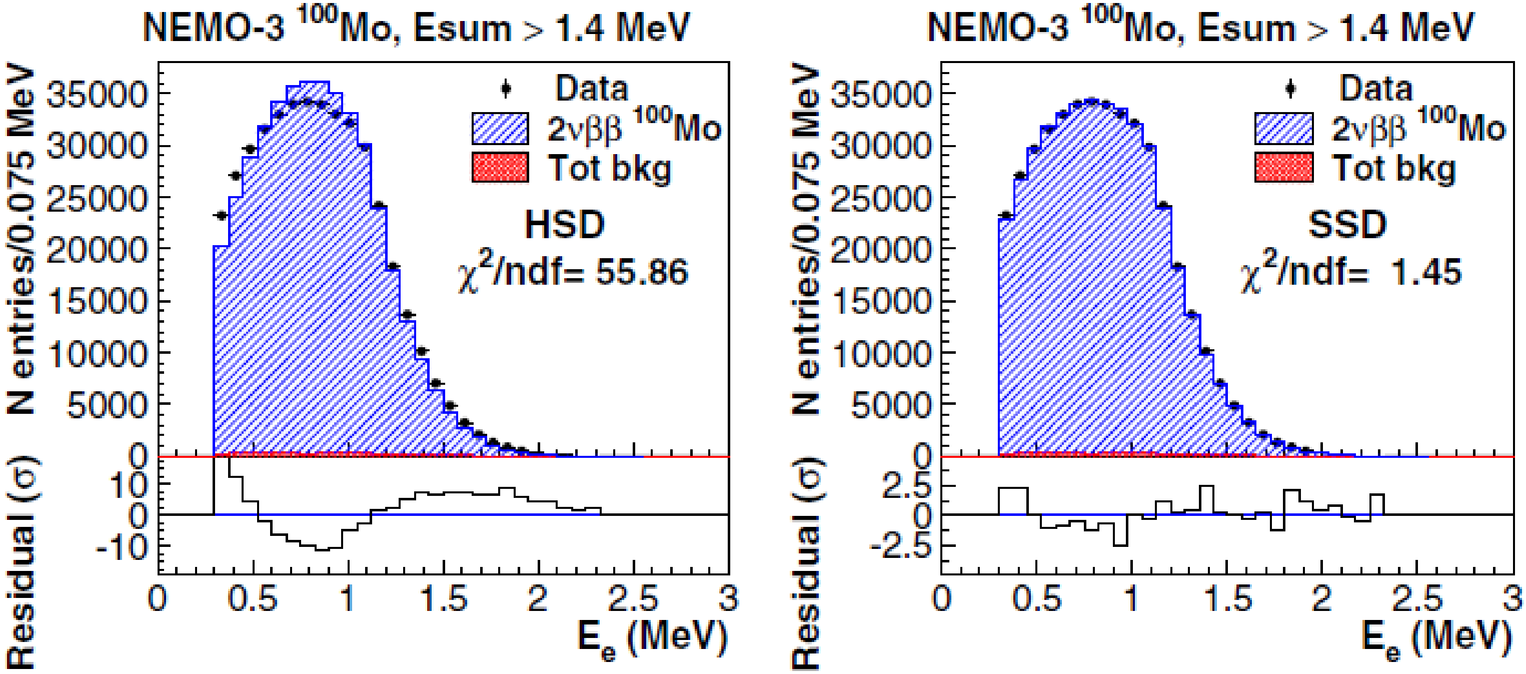
$$M^{2\nu}_{GT} = \sum_m \frac{< 0^+_f||\tau^+\sigma||1^+_m >< 1^+_m||\tau^+\sigma||0^+_i >}{E_m - E_i + \Delta}$$

**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***

# Looking for SSD/HSD effect



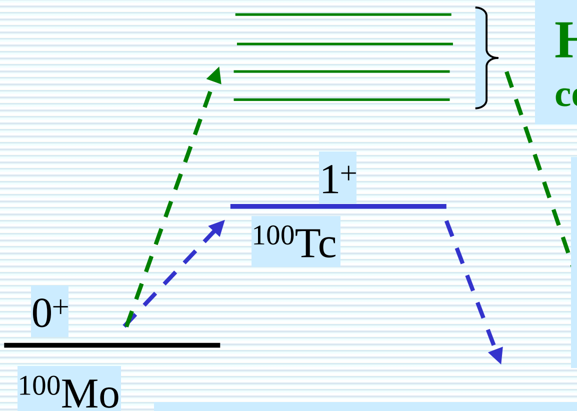

NEMO3 Collaboration, Eur. Phys. J. C79, 440 (2019)

**SSD favored**

⇒

**Strong trans. through low lying states of (A,Z+1);**

$M_F^{2\nu} \approx 0$




**HSD, higher levels contribute to the decay**

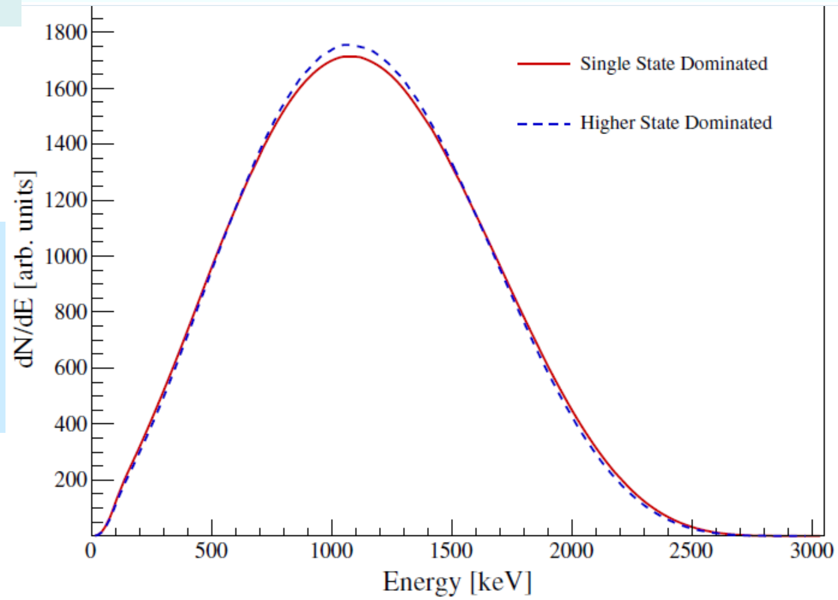
**SSD, 1+ level dominates in the decay**

(Abad et al., 1984, Ann. Fis. A 80, 9)

**Look at energy distributions**

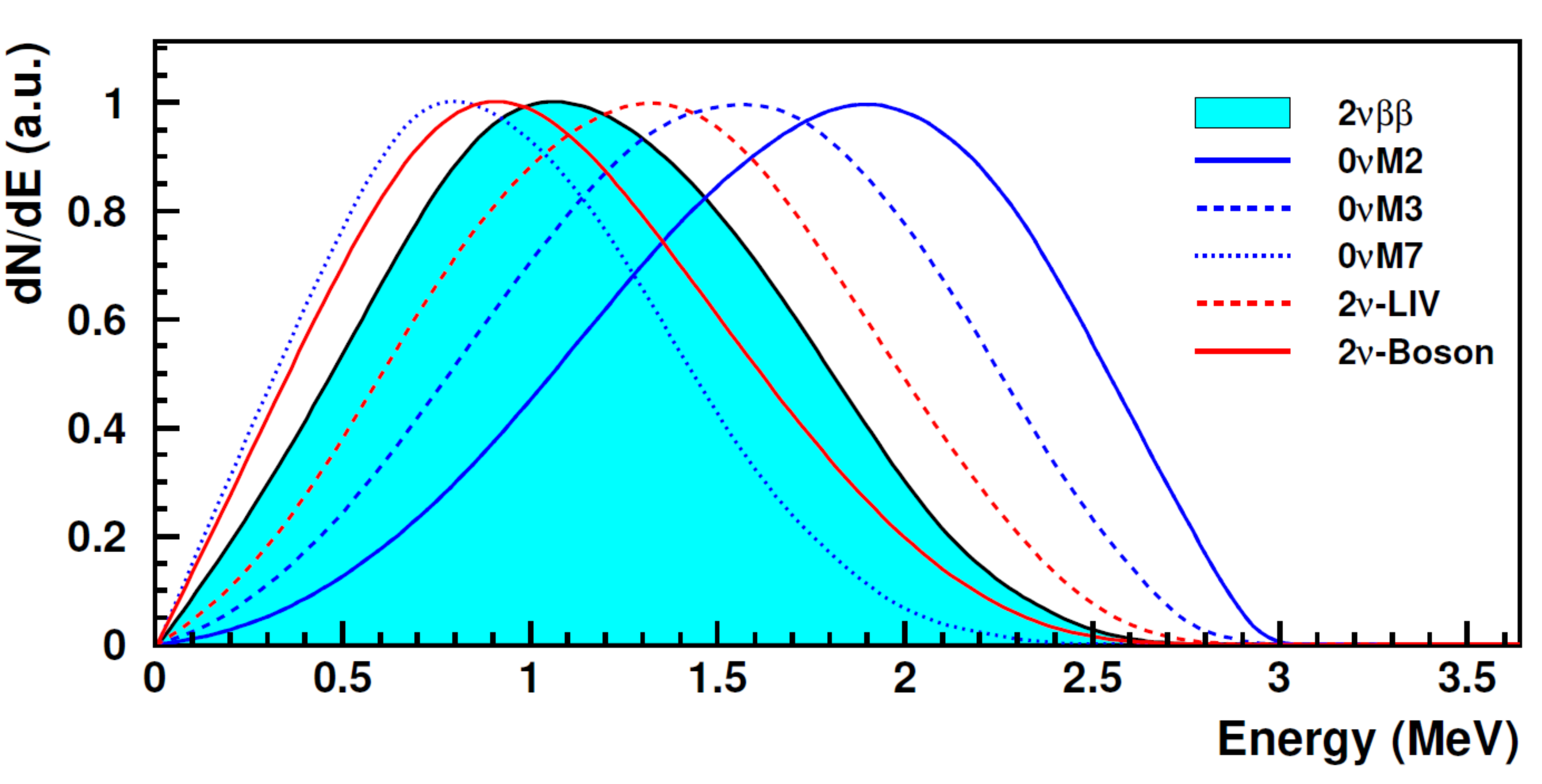
**F. Š., Šmotlák, Semenov**

**J. Phys. G, 27, 2233, 2001**




CUPID-0 Coll., PRL 123, 262501 (2019

# Looking for a new physics with differential characteristics




**Spectral index n**

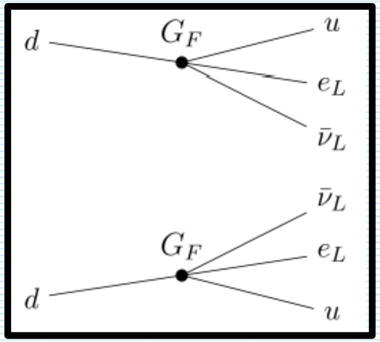
$$\frac{d\Gamma}{d\varepsilon_1 d\varepsilon_2} = C(Q - \varepsilon_1 - \varepsilon_2)^n \; [p_1 \varepsilon_1 F(\varepsilon_1)] \; [p_2 \varepsilon_2 F(\varepsilon_2)]$$

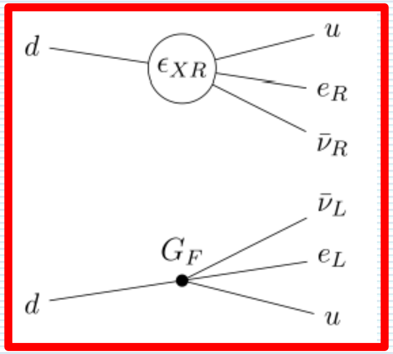
# Searching for New Physics in the 2νββ-Decay

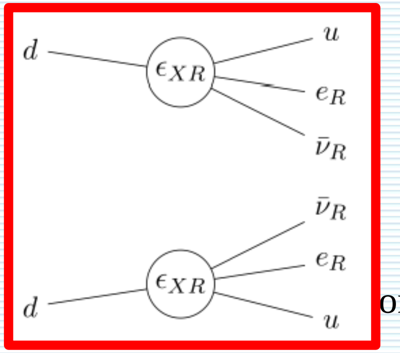
**F.F. Deppisch, L. Graf, F. Š., to be submitted**

$$\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \left( (1+\epsilon_{LL}) j_L^{\mu} J_{L\mu} + \epsilon_{LR} j_R^{\mu} J_{L\mu} + \epsilon_{RR} j_R^{\mu} J_{R\mu} \right) + \text{h.c.}$$

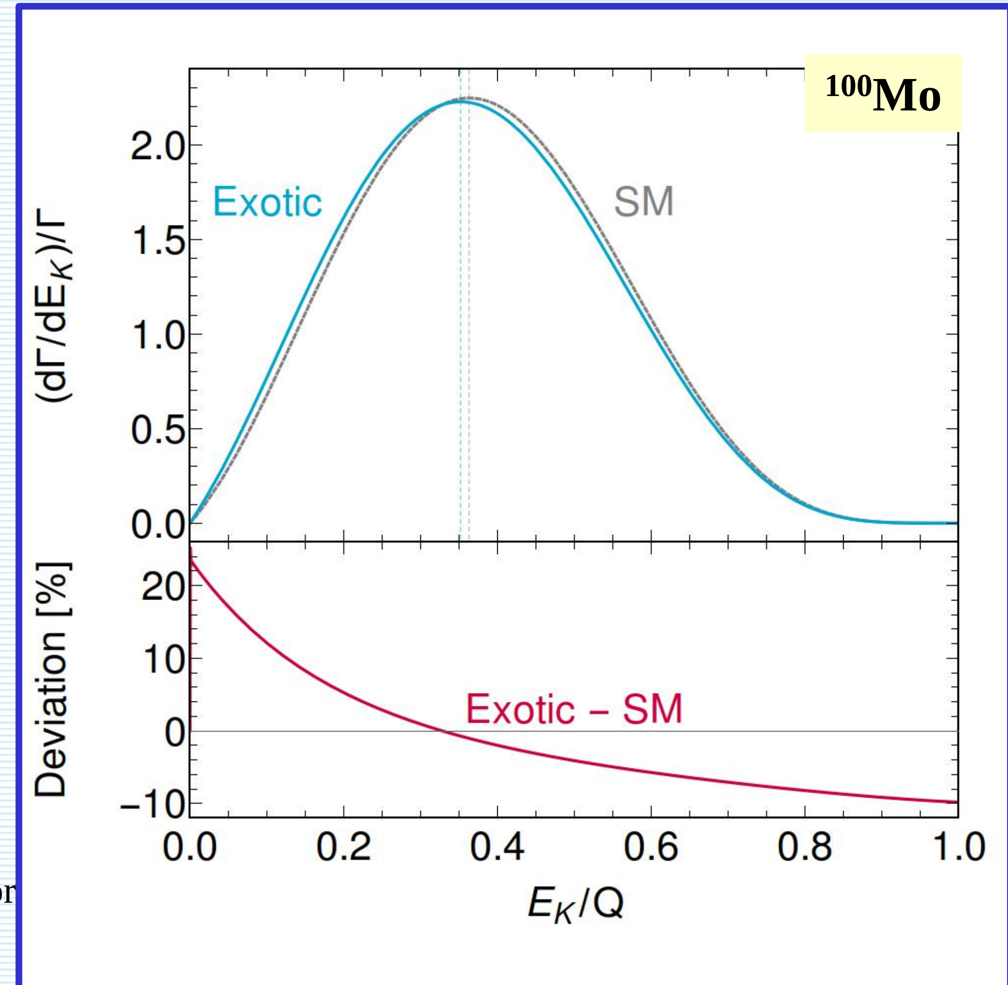
$$|\mathcal{M}^{2\nu}| = |\mathcal{M}_0^{2\nu}| + |\epsilon_{XR}|^2 |\mathcal{M}_{\epsilon\epsilon}^{2\nu}|^2$$



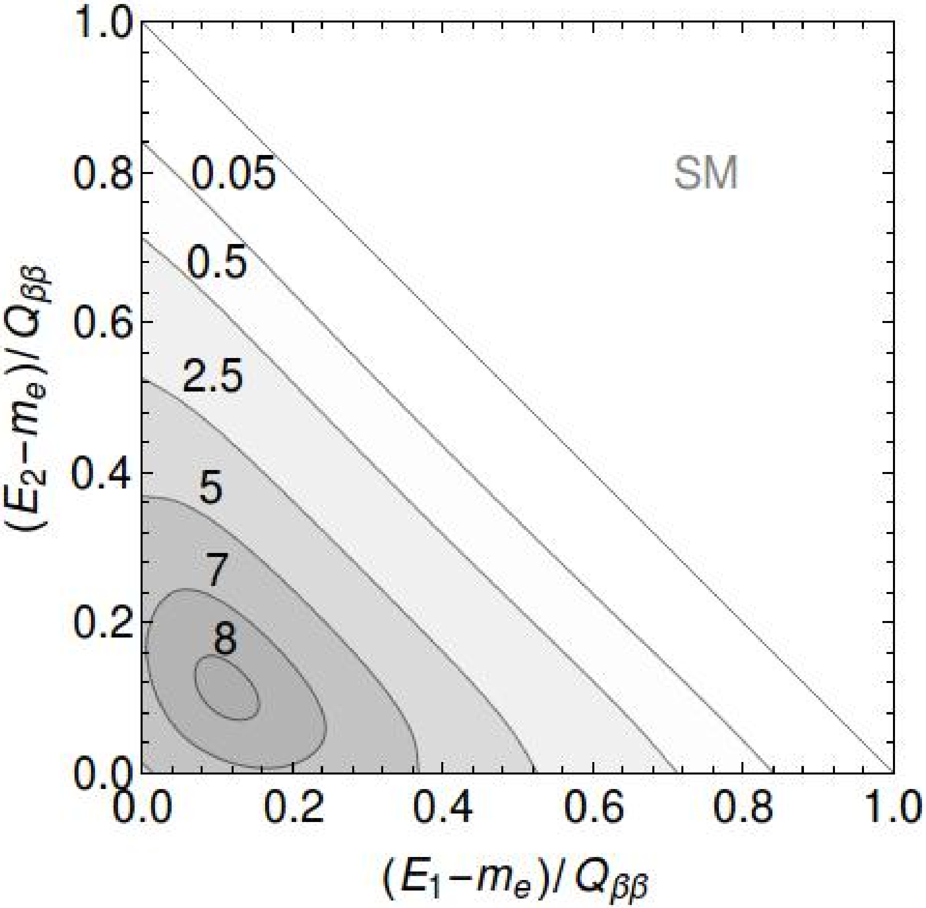




or

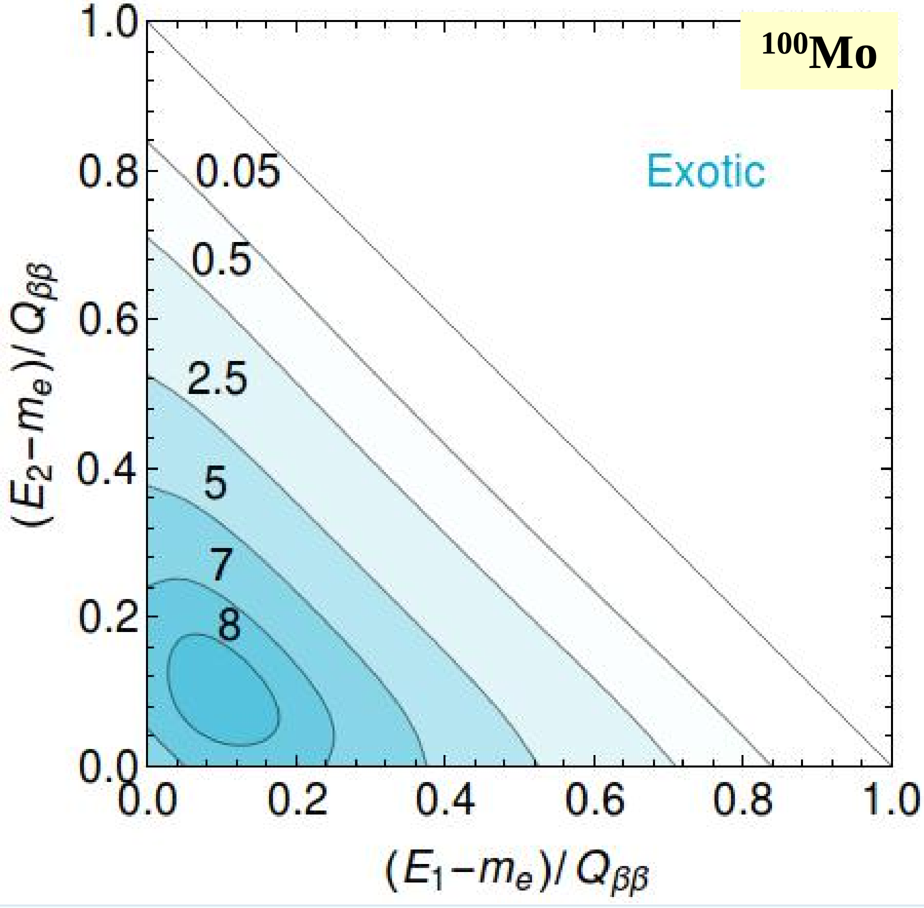


# Double energy distributions of the emitted electrons in dependence on their kinetic energies for the $2\nu\beta\beta$-decay of $^{100}$Mo

$$\frac{d\Gamma^{2\nu}}{dE_{e_1} dE_{e_2} d\cos\theta} = \frac{\Gamma^{2\nu}}{2} \frac{d\Gamma^{2\nu}_{\rm norm}}{dE_{e_1} dE_{e_2}} \left(1 + \alpha(E_{e_1}, E_{e_2}) \cos\theta\right)$$




Sim



# Angular correlation of the emitted electrons in dependence on their kinetic energies for the $2\nu\beta\beta$-decay of $^{100}$Mo

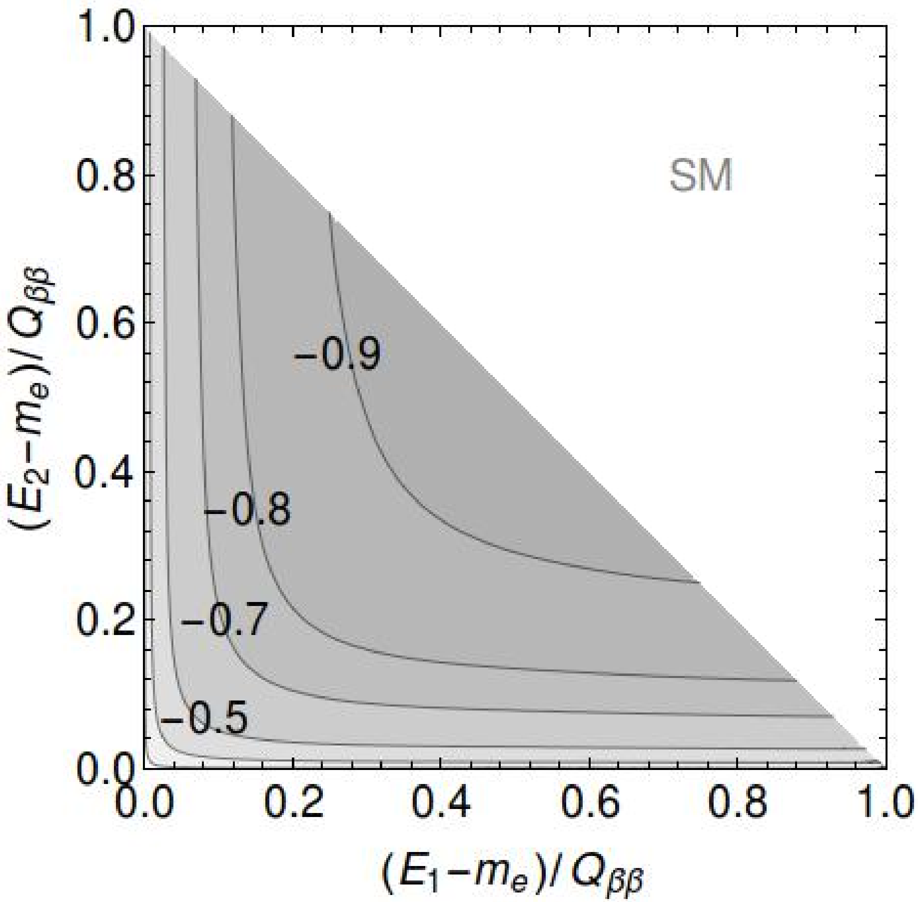
$$\frac{d\Gamma^{2\nu}}{d\cos\theta} = \frac{\Gamma^{2\nu}}{2}\left(1 + K^{2\nu}\cos\theta\right)$$

$$K^{2\nu} \approx -0.63 + \kappa\,\epsilon^2_{XR}$$

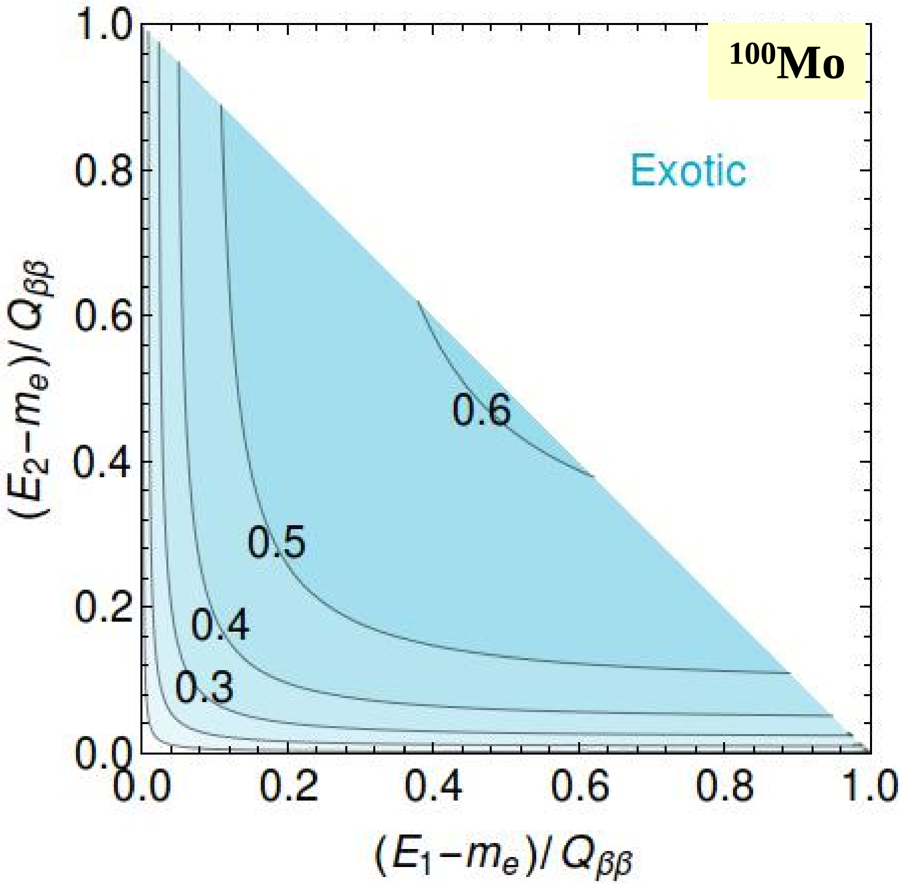
$$K^{2\nu}_0 = -0.63$$

$$K^{2\nu}_{\epsilon\epsilon} = +0.37$$

$$\frac{d\Gamma^{2\nu}}{dE_{e_1}dE_{e_2}d\cos\theta} = \frac{\Gamma^{2\nu}}{2}\frac{d\Gamma^{2\nu}_{\rm norm}}{dE_{e_1}dE_{e_2}}\left(1 + \alpha(E_{e_1}, E_{e_2})\cos\theta\right)$$



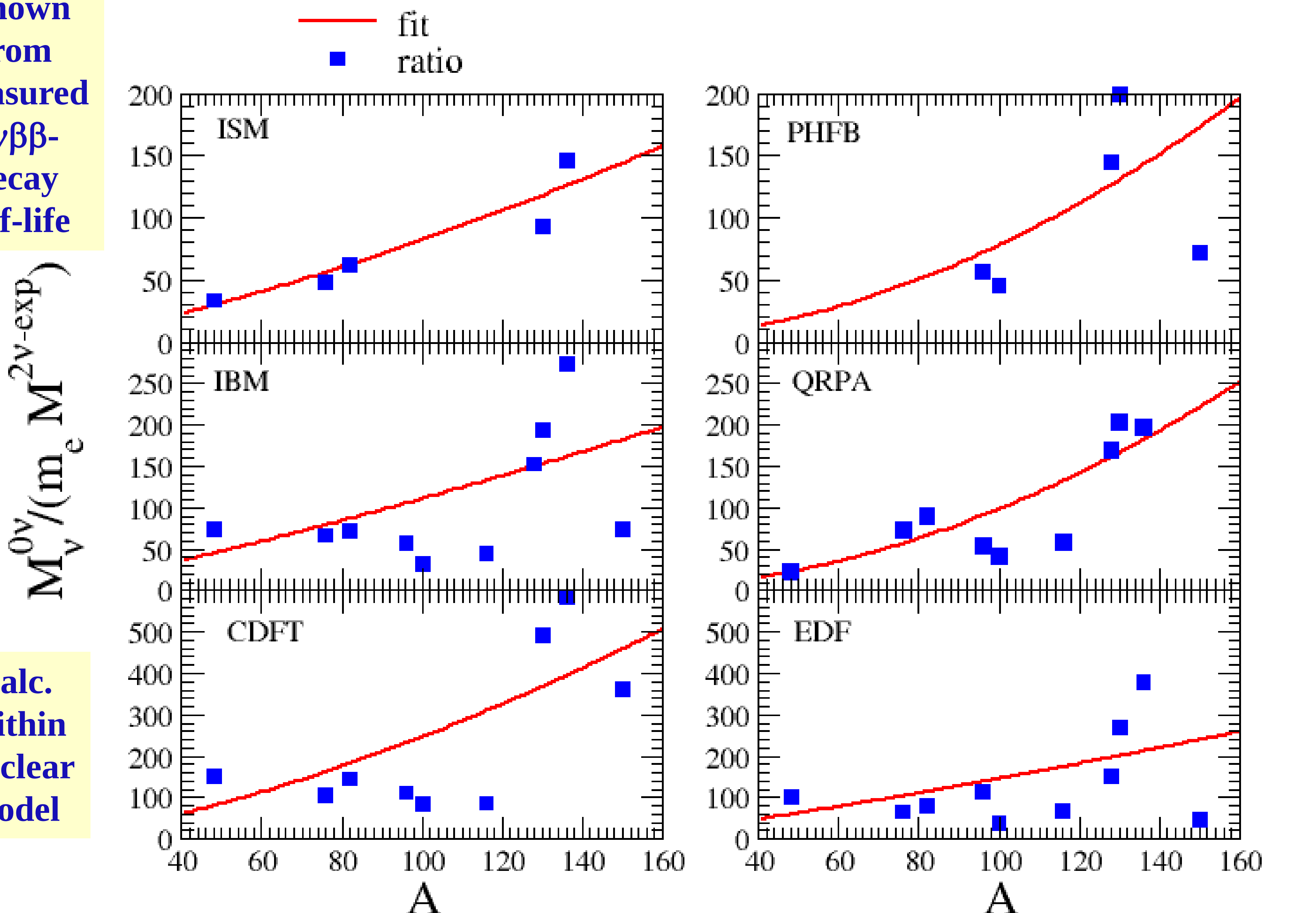

Si



***Is there a relation between the $2\nu\beta\beta$- and $0\nu\beta\beta$-decay NMEs?***

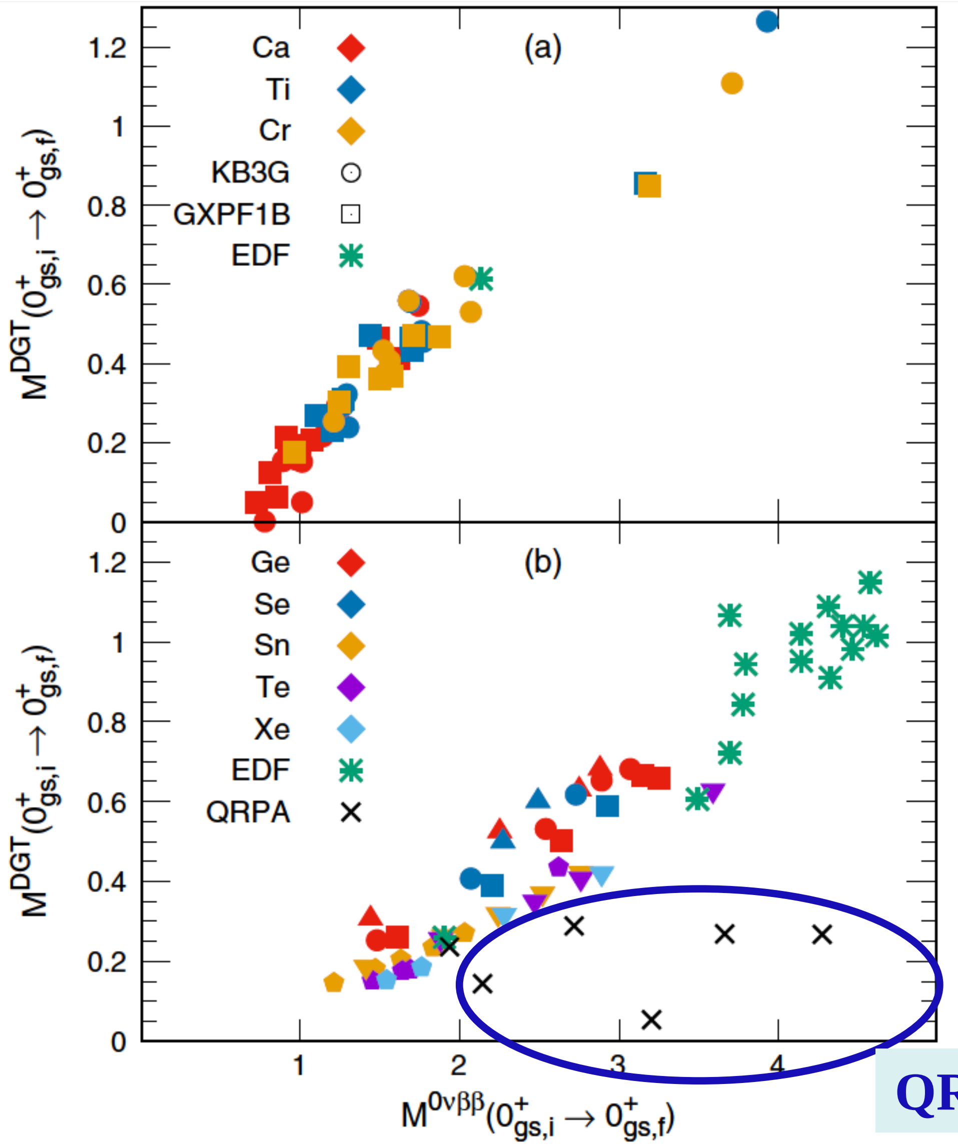
# Is there a proportionality between 0νββ- and 2νββ-decay NMEs?

**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:** $0.6 \rightarrow 1.2$

**ISM:** $0.1 \rightarrow 0.7$

**IBM:** $1.6 \rightarrow 4.4$

**QRPA:** $|0.1| \rightarrow |0.7|$

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

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

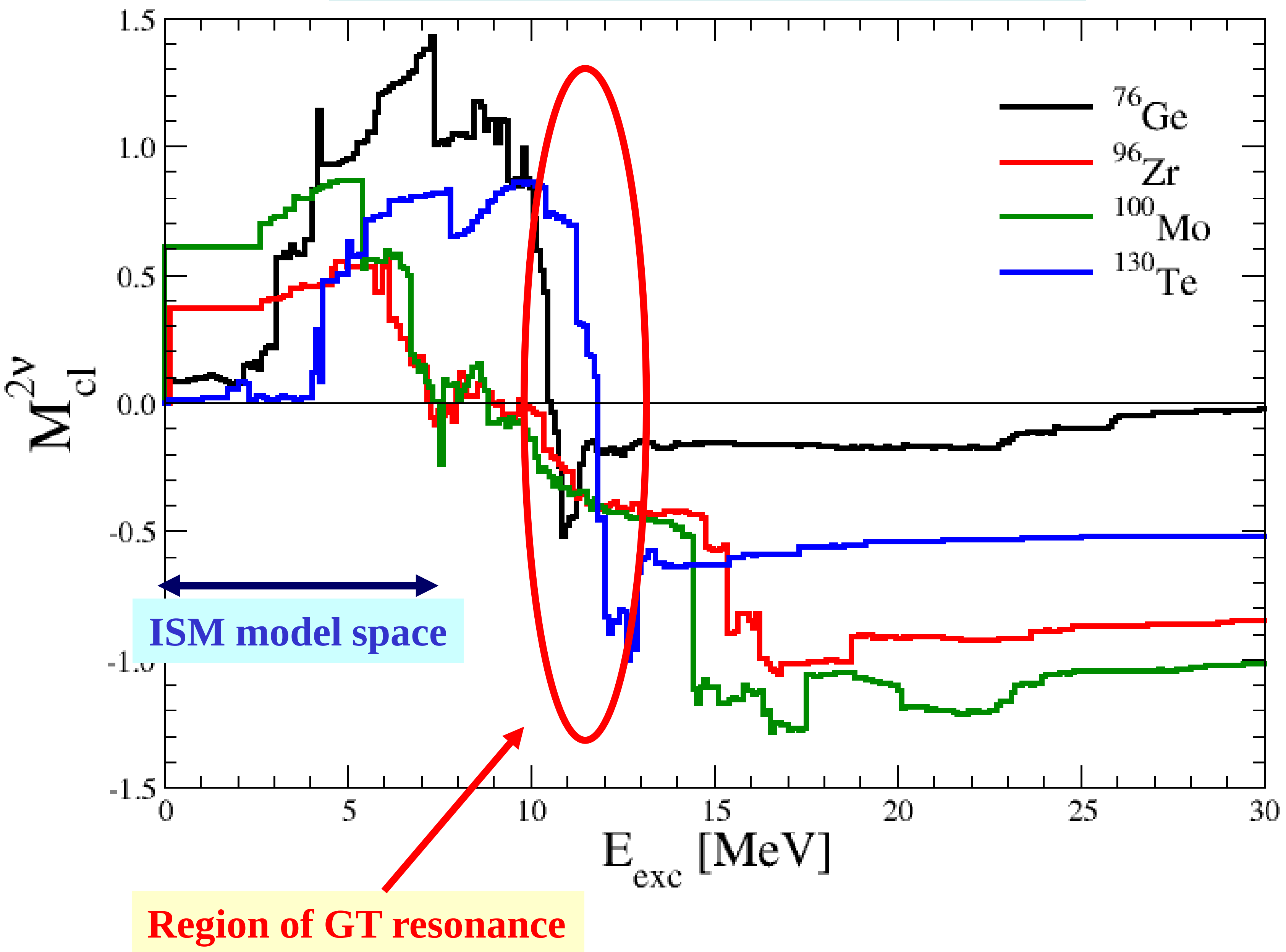
**ISM:** N. Shimizu, J. Menendez, K. Yako, PRL 120, 142502 (2018)

Fedor Simkovic

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

# QRPA: There is no proportionality between 0νββ-decay and 2νββ-decay NMEs

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



# 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:***

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

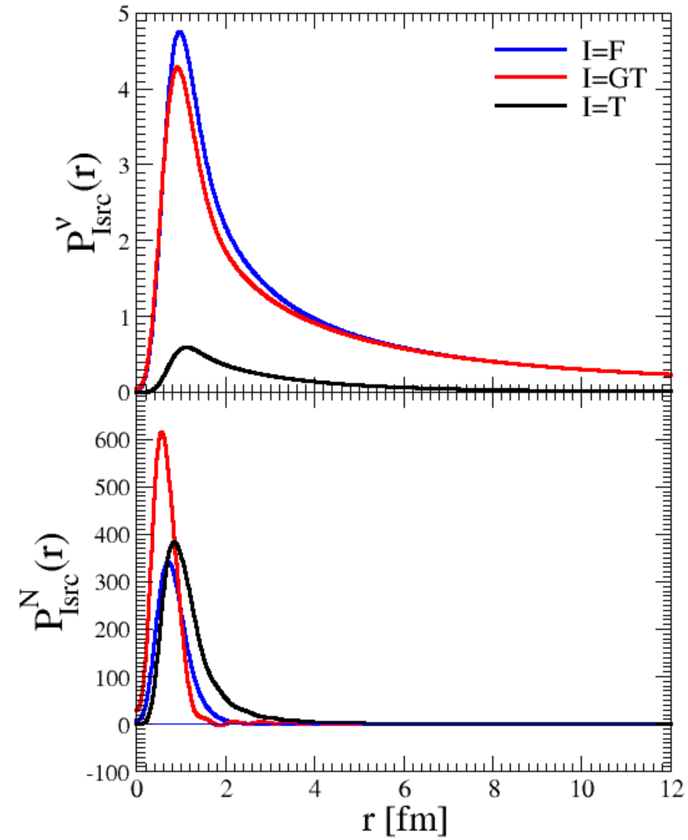
***r- relative distance of two decaying nucleons***

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

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

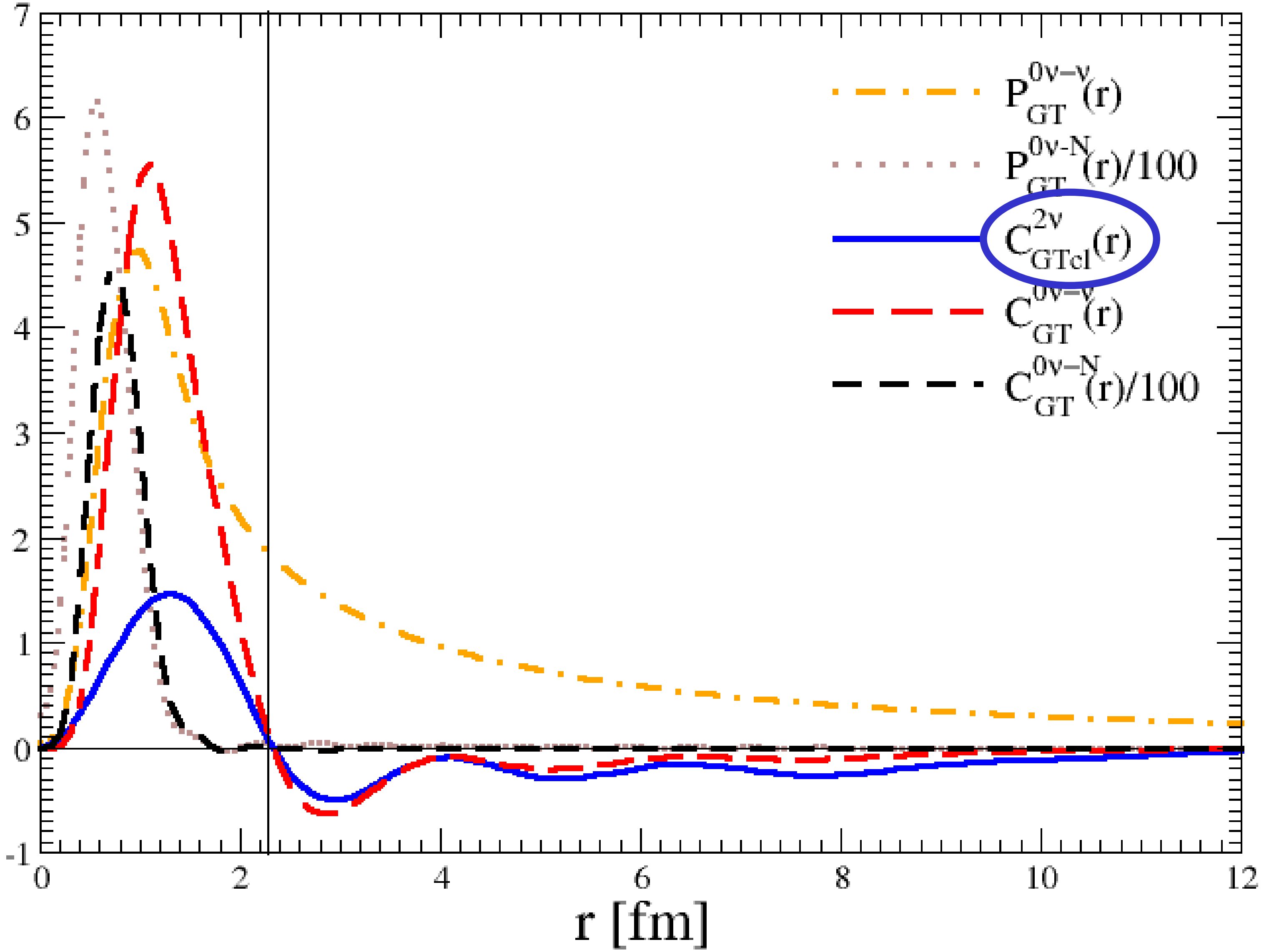
imkov

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




***Neutrino potential prefers short distances***

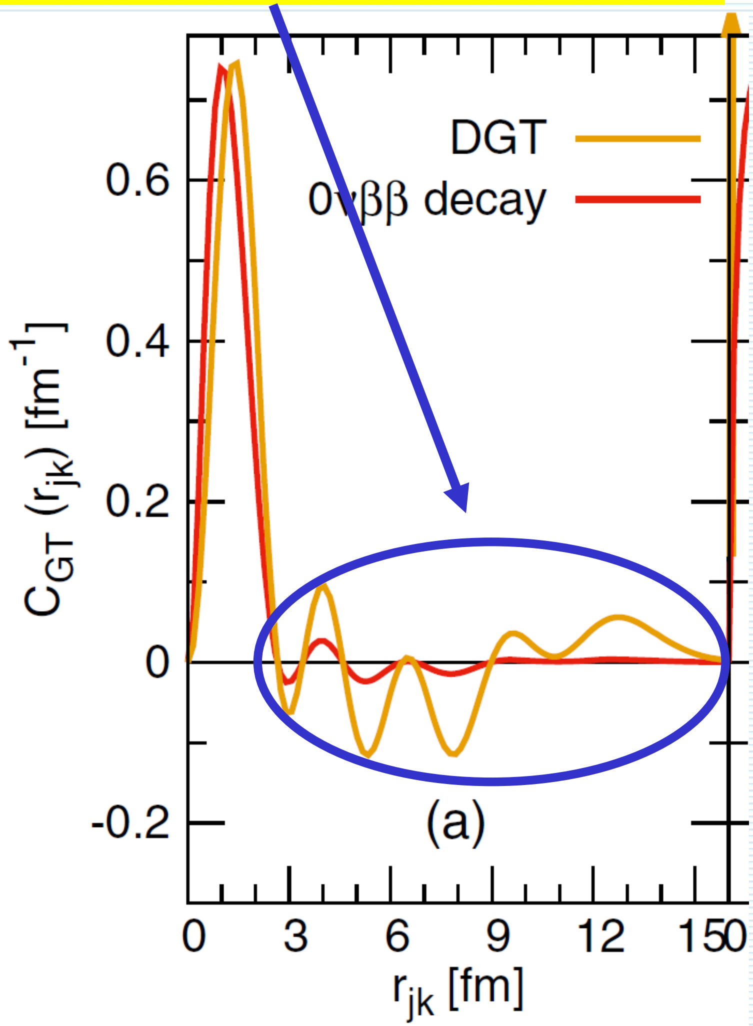
**It is enough to know $C^{2\nu}_{GTcl}(r)$ and two-nucleon exchange potential P(r)**



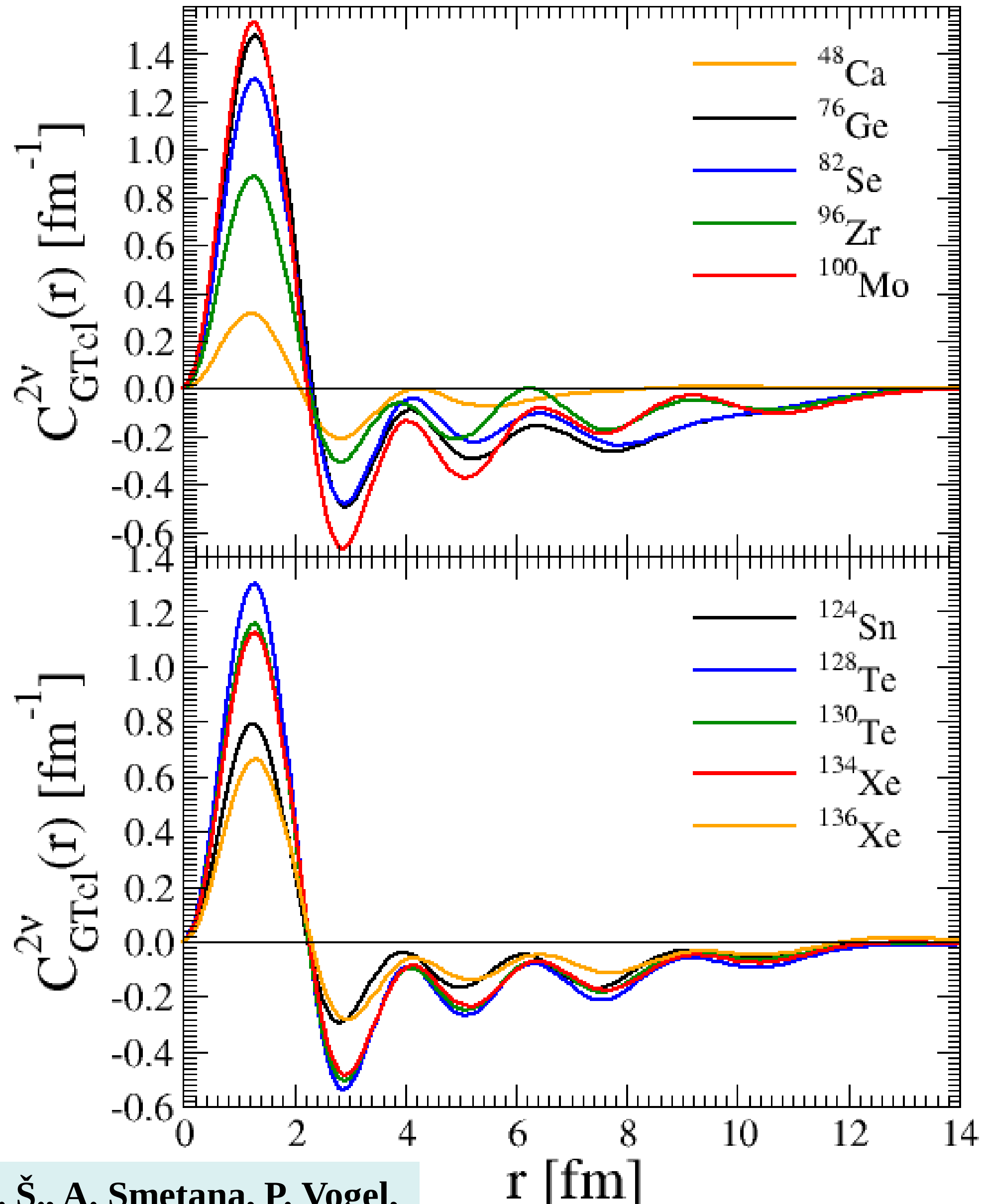
**QRPA: Bump ≈ - Tail => $M^{2\nu}_{cl} \approx 0$**

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

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



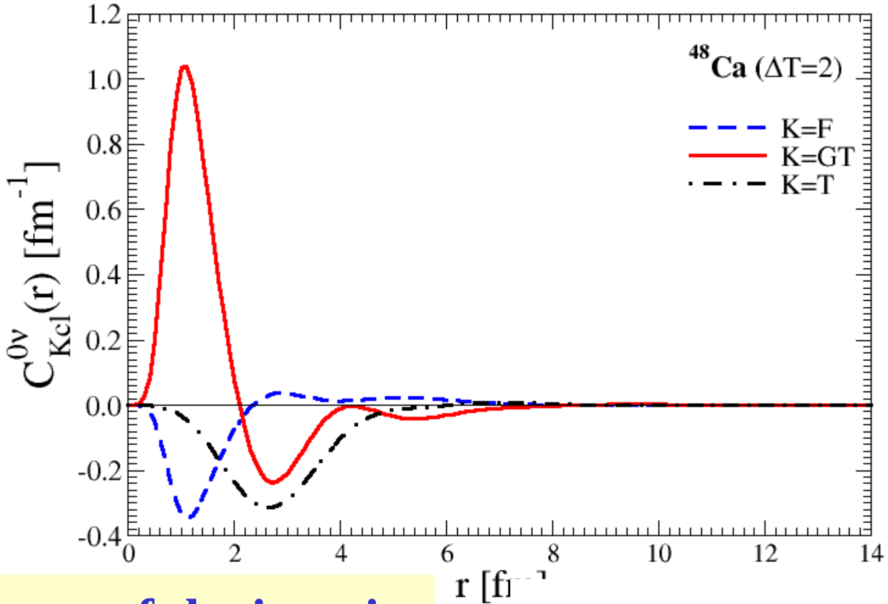

N. Shimizu, J. Menendez, K. Yako, PRL 120, 142502 (2018)



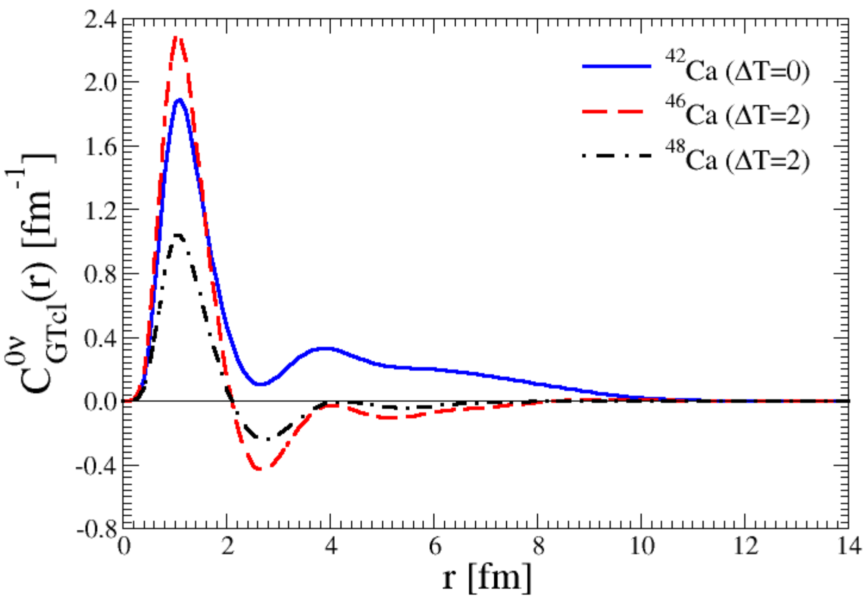

F. Š., A. Smetana, P. Vogel, PRC 98, 064325 (2018)

# QRPA

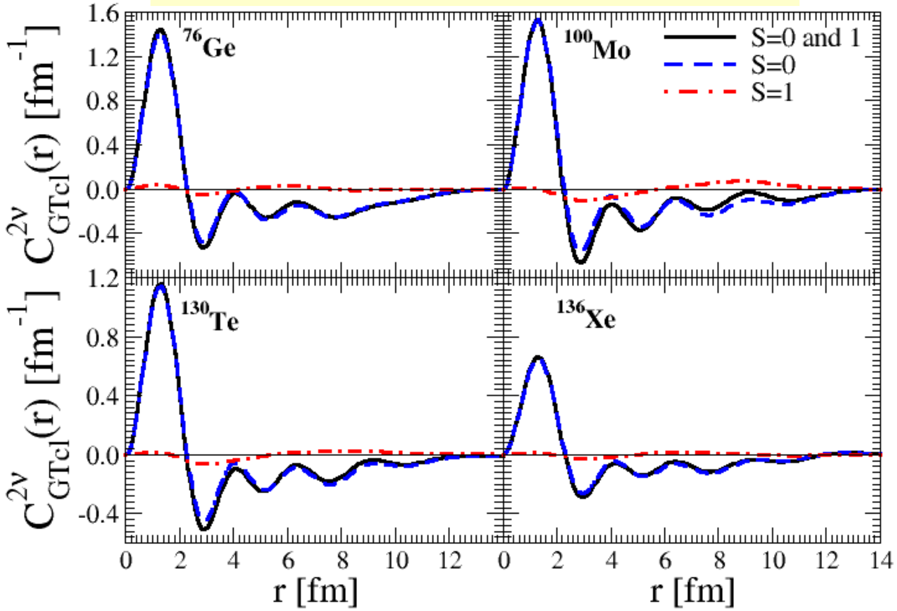
## Fermi, Gamow-Teller and tensor




## Role of the change of the isospin



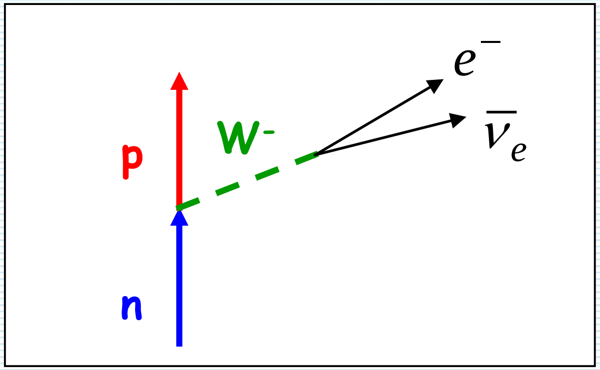

## S=0 and S=1 contributions

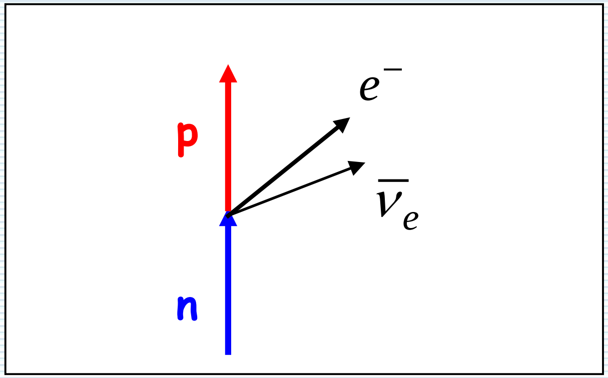


# V. *Quenching of $g_A$* ($q = g^{eff}_A / g^{free}_A$)

**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).**

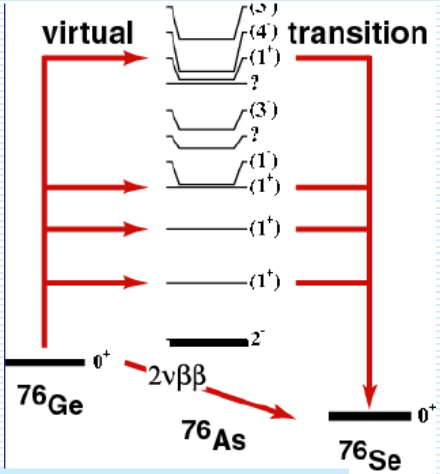
$g_A^4 = (1.269)^4 = 2.6$

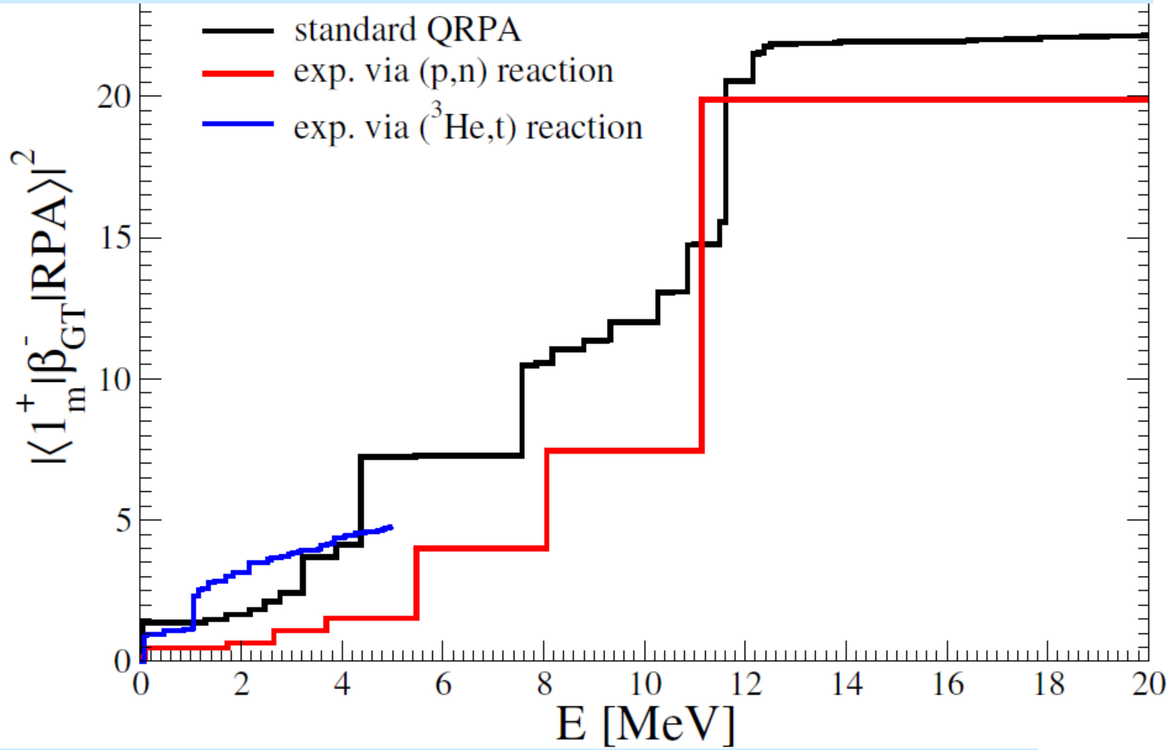
# Quenching of $g_A$ (from exp.: $T_{1/2}^{0\nu}$ up 2.5 x larger)

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

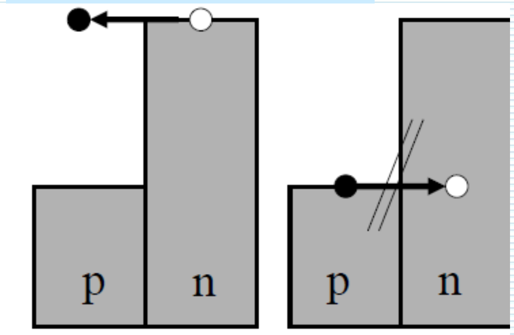
**Strength of GT trans. (approx. given by Ikeda sum rule =3(N-Z)) has to be quenched to reproduce experiment.**
**Using $g_A^{\rm eff} \approx 0.77 \times g_A^{\rm free}$ agrees with data**

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




**Pauli blocking**




**Cross-section for charge exchange reaction:**

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

$q = 0!!$

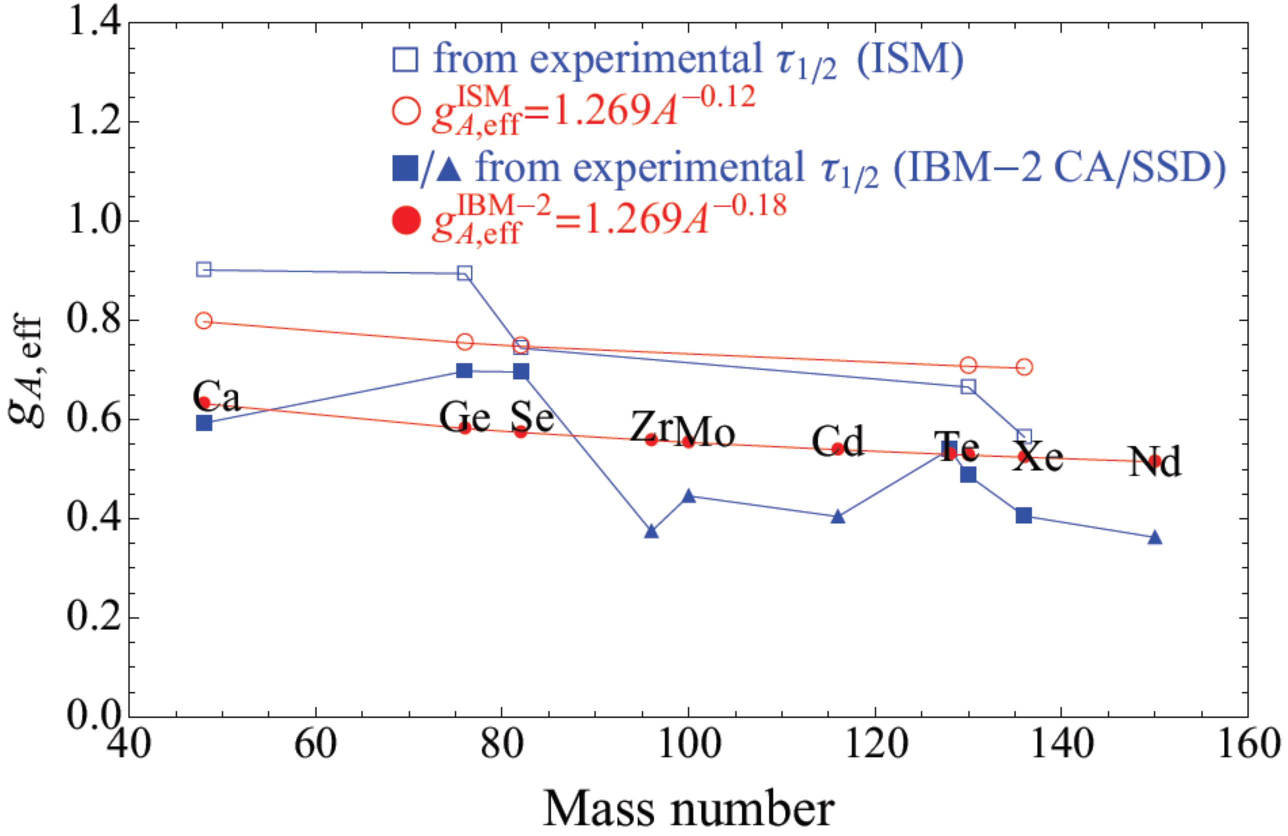
largest at 100 - 200 MeV/A

# *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.**

From F. Iachello

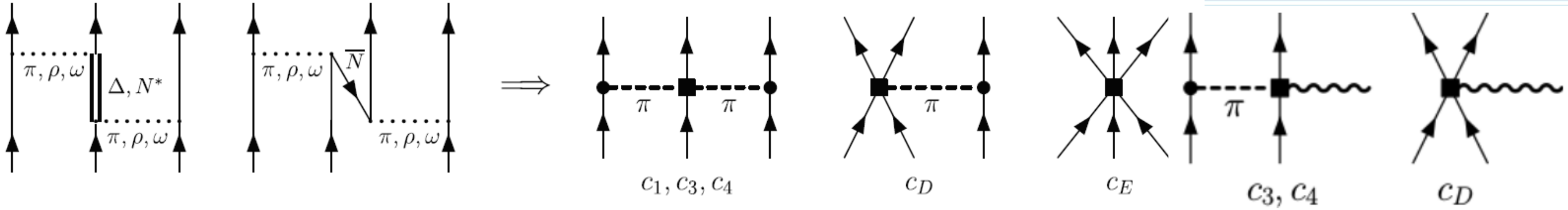


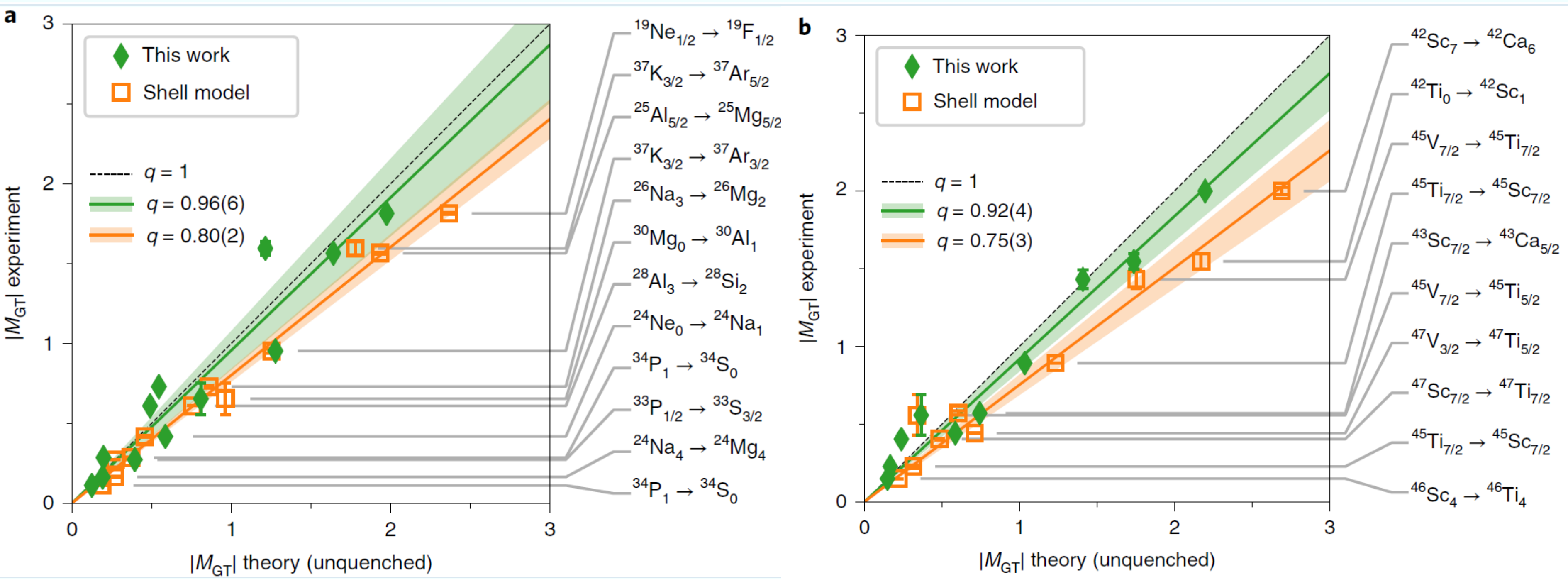

J. Barea, J. Kotila, F. Iachello, PRC 87, 014315 (2013).

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 $g_A^{\text{eff}}$)

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**

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

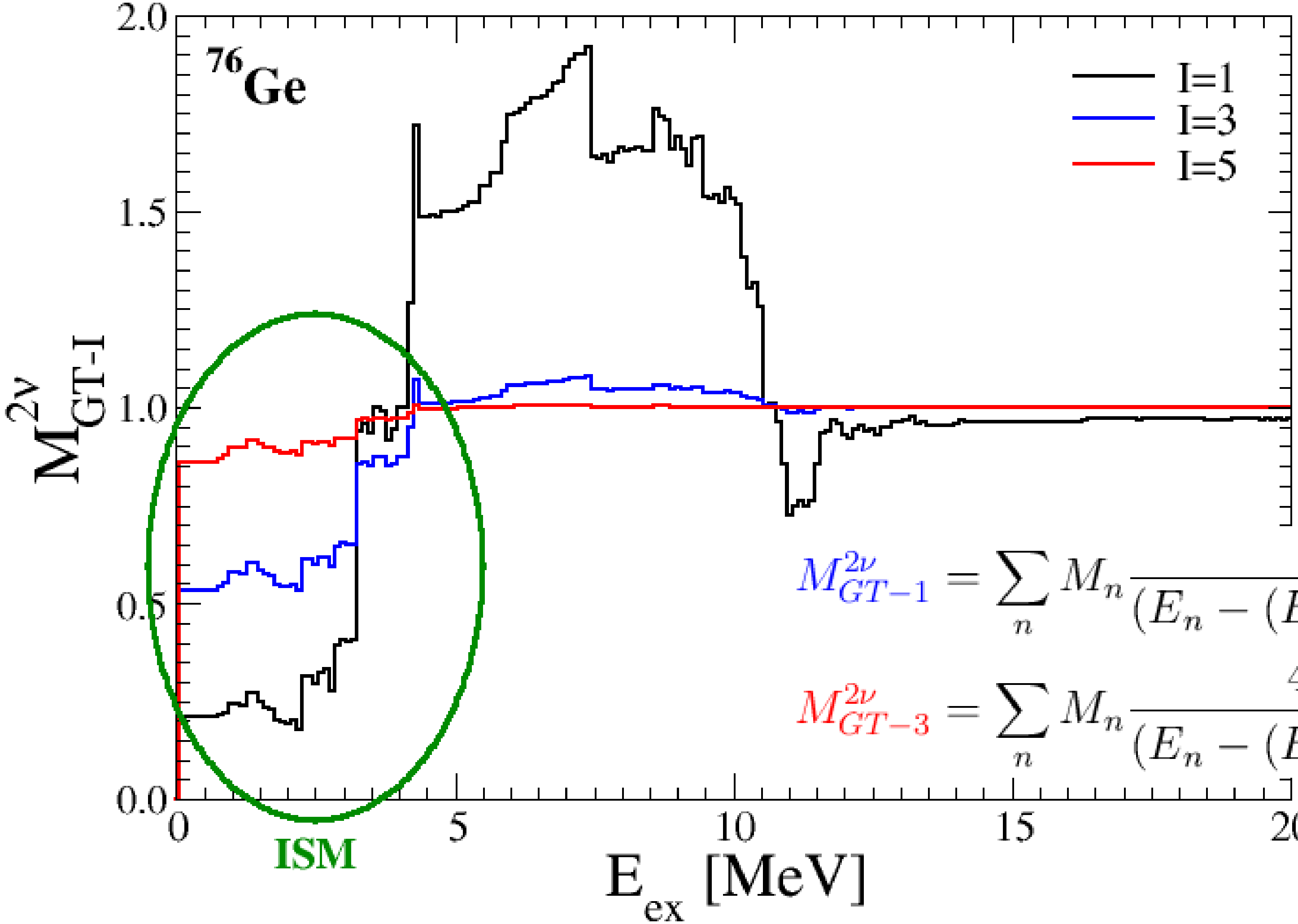
$$M_{GT-1}^{2\nu} = \sum_n M_n \frac{1}{(E_n - (E_i+E_f)/2}$$

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

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

*The $g_A^{\text{eff}}$ 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)***

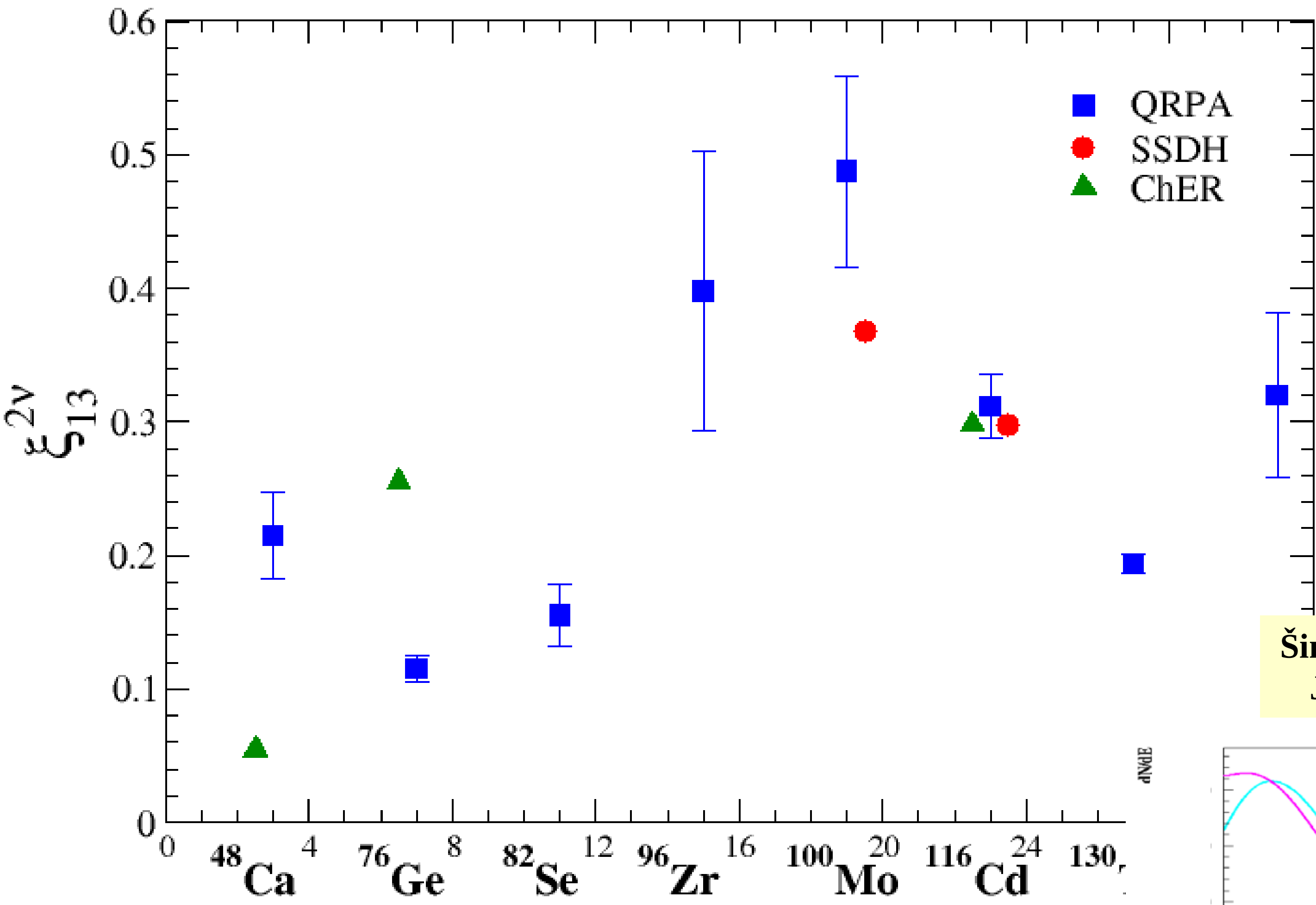
# The running sum of the 2νββ–decay NMEs (QRPA)




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

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

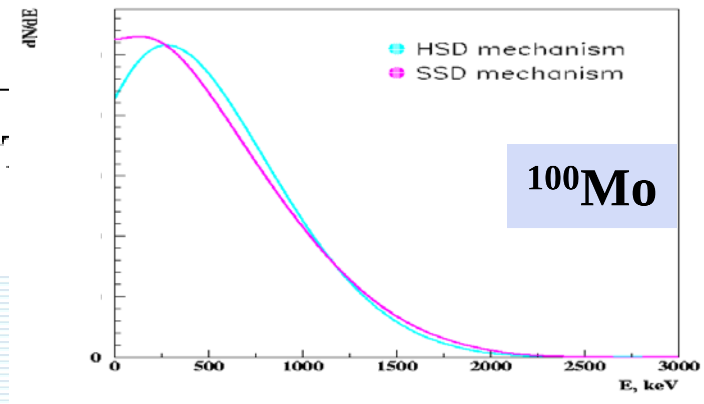
# $\xi_{13}$ tell us about importance of higher lying states of int. nucl.




**HSD: $\xi_{13}$=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**

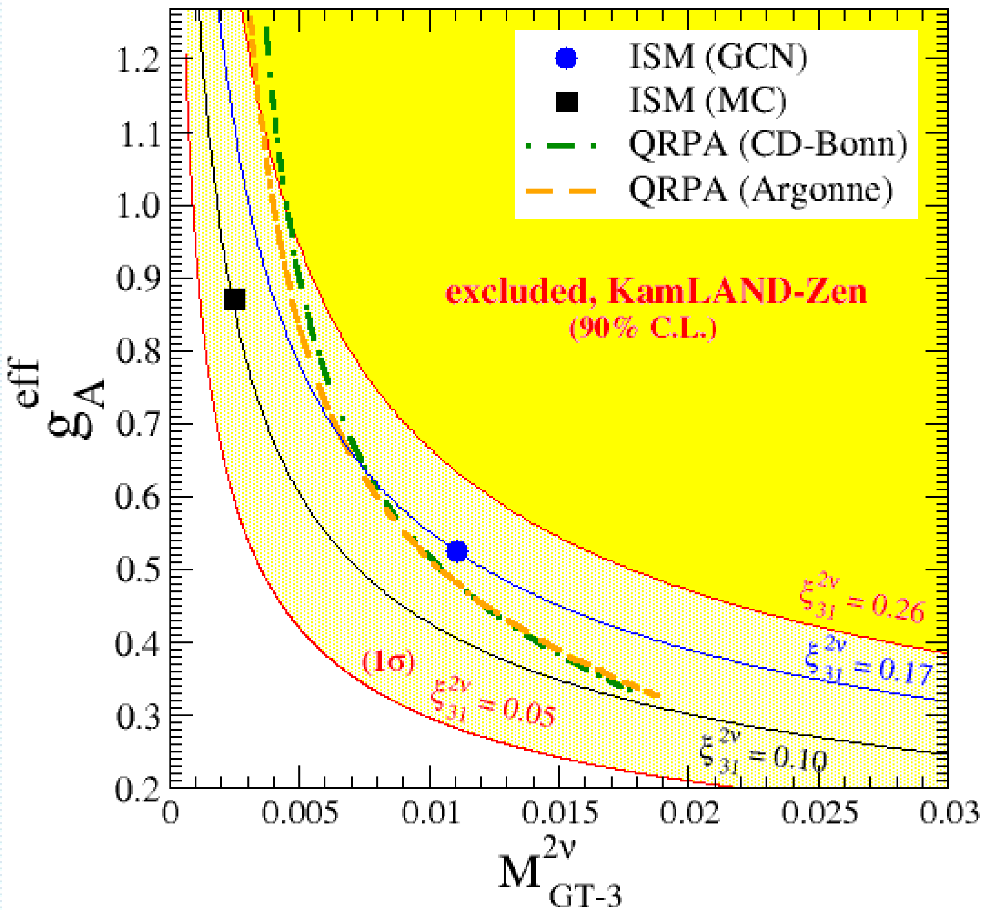



**$\xi_{13}$ can be determined phenomenologically from the shape of energy distributions of emitted electrons**

**The $g_A^{eff}$ can be deterimed with measured half-life and ratio of NMEs $\xi_{31}$ 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)**

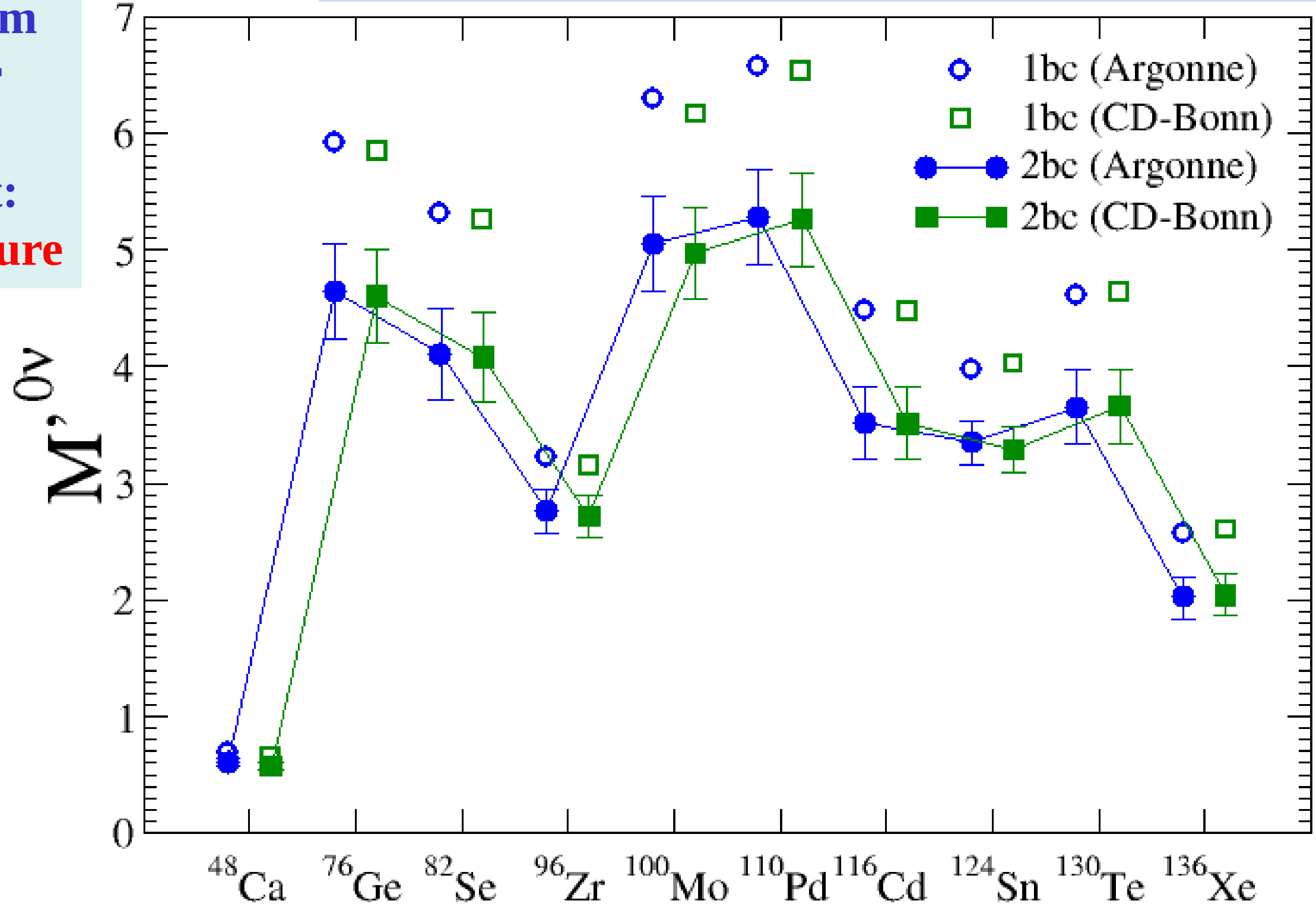
## *Quenching of $g_A$, two-body currents and QRPA*

***(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, ($g_A^{eff} = g_A\delta(p=0) = 0.7\text{-}1.0$)**

# Thank You!

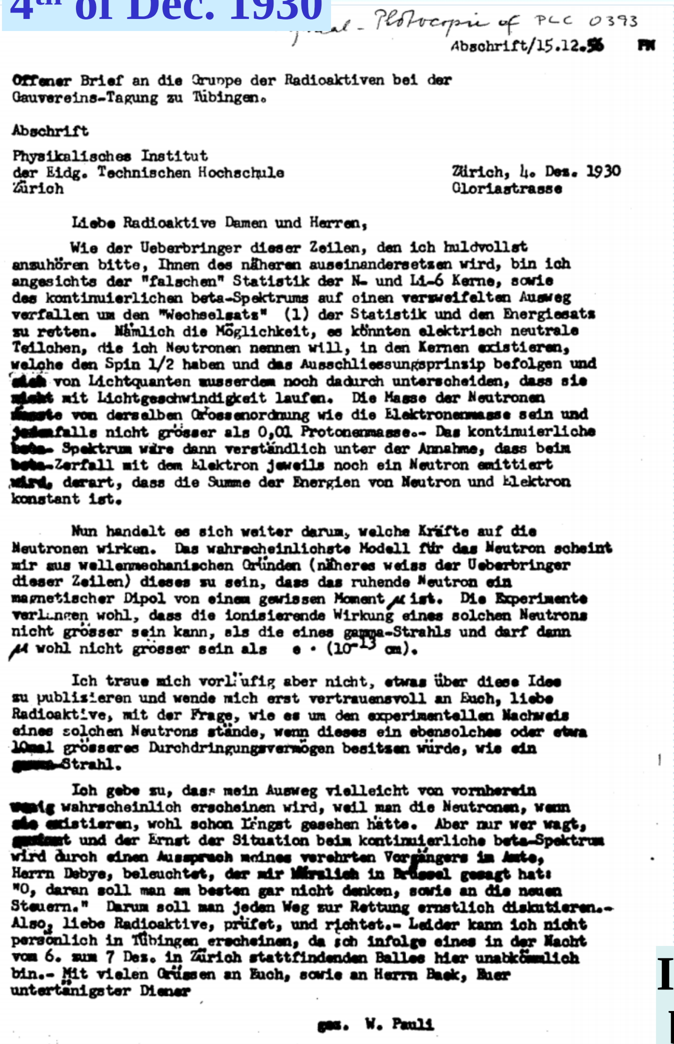
*ν's*, the Standard Model misfits


*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)*


$\nu_e$ $\nu_\mu$ $\nu_\tau$

**4th of Dec. 1930**



Photocopie of PLC 0393

Abschrift/15.12.56 FM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

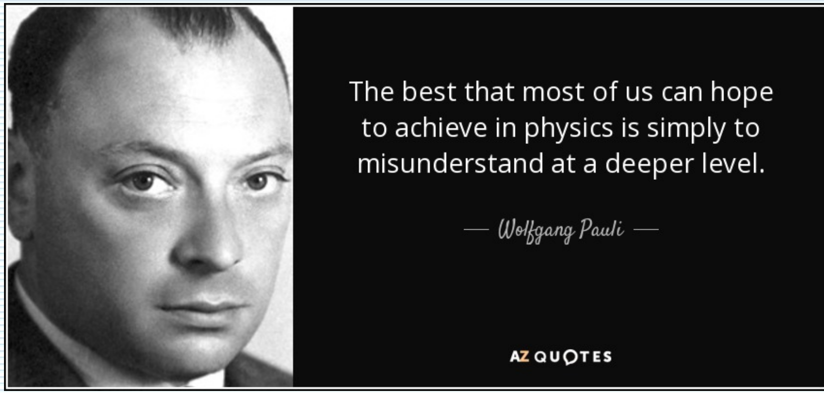
Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment $\mu$ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann $\mu$ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

**90 years of $\nu$-physics!**




**I have done a terrible thing. I invented a particle that cannot be detected. Wolfgang Pauli**