Approaching neutrinoless double beta decay matrix elements via double gamma decay

B. Romeo Zaragozano | NME25 20th -21st January 2025

In collaboration with

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OUTLINE

- **Introduction**
  - Double beta decay
  - Double gamma decay
- **Results**
  - Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs
  - Potential of measuring $\gamma\gamma$
  - Experimental prospects
- **Summary**

Double beta decay

$0\nu\beta\beta$ nuclear matrix element

$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu}(Q,Z)g_A^4(M^{0\nu})^2\phi^2$$

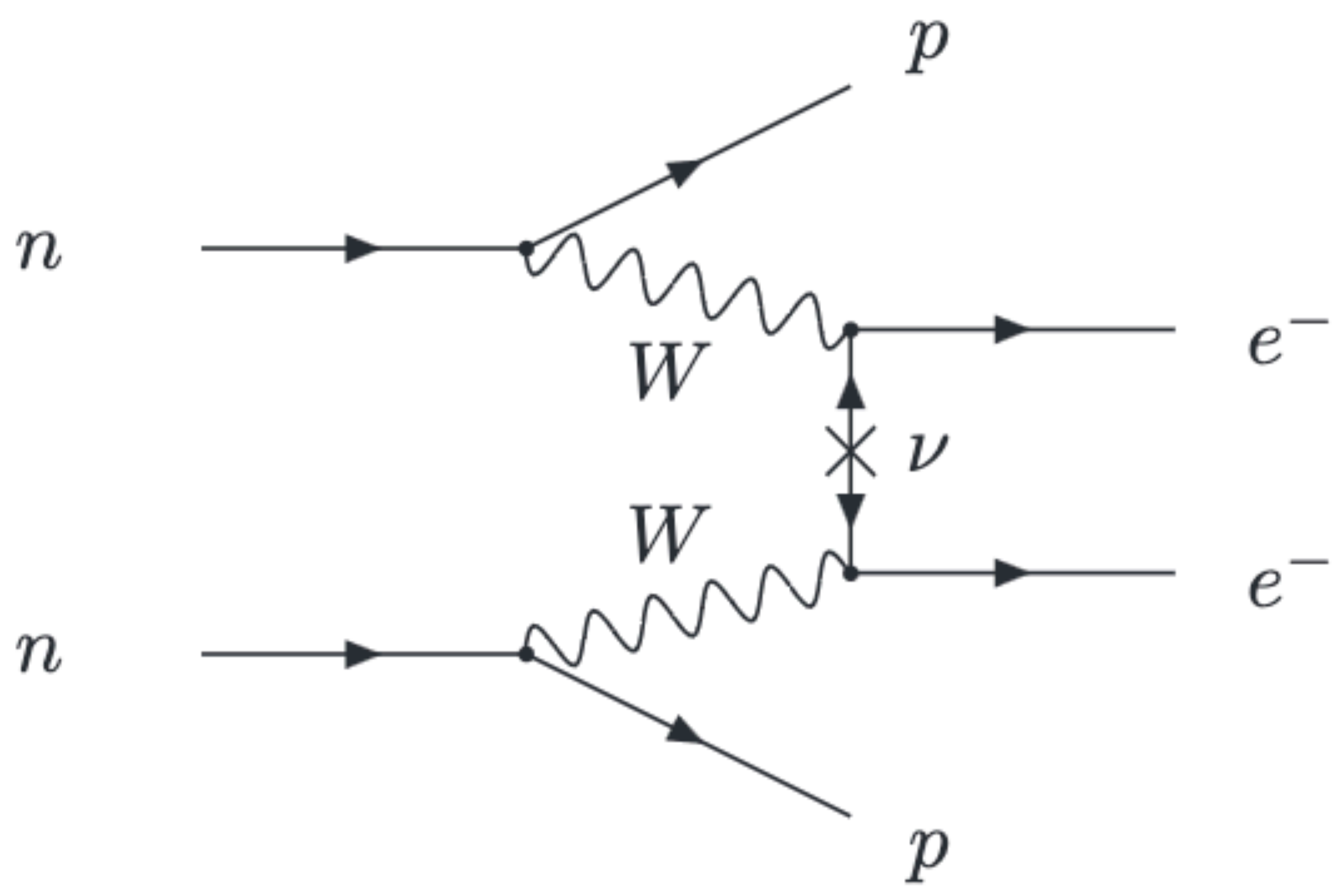
Phase Space Factor

New Physics parameter

$g_A^2 M^{0\nu}$ **Nuclear Matrix Element** (NME) a theoretical input, interpret **experimental results** demands the most **accurate evaluation NME**, essential to obtain predictions if a positive signal is observed

$$M_L^{0\nu} = M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2}M_F^{0\nu} + M_T^{0\nu}$$

Nuclear structure initial and final nuclei plays a relevant role in NMEs



Light neutrino exchange

(exactly those which oscillates)

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

Minimal extension Standard Model

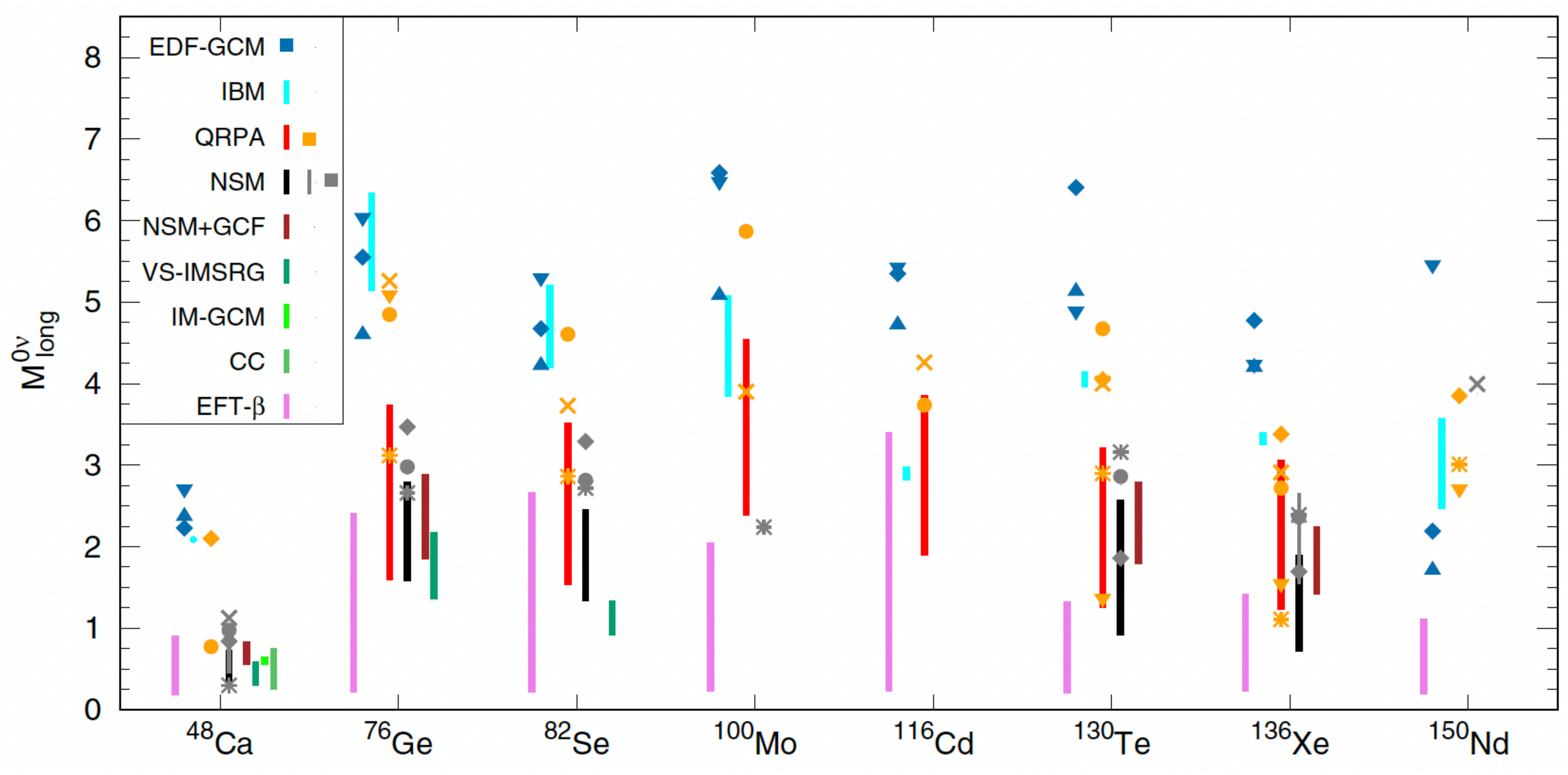
J. Engel, and J.Menéndez, Rep. Prog. Phys. 80 030301(2017)

Double beta decay

Discrepancy in the predicted NMEs

Improvement of the calculations of the NMEs important and challenging

Uncertainties introduced by approximate solution to the nuclear many-body problem

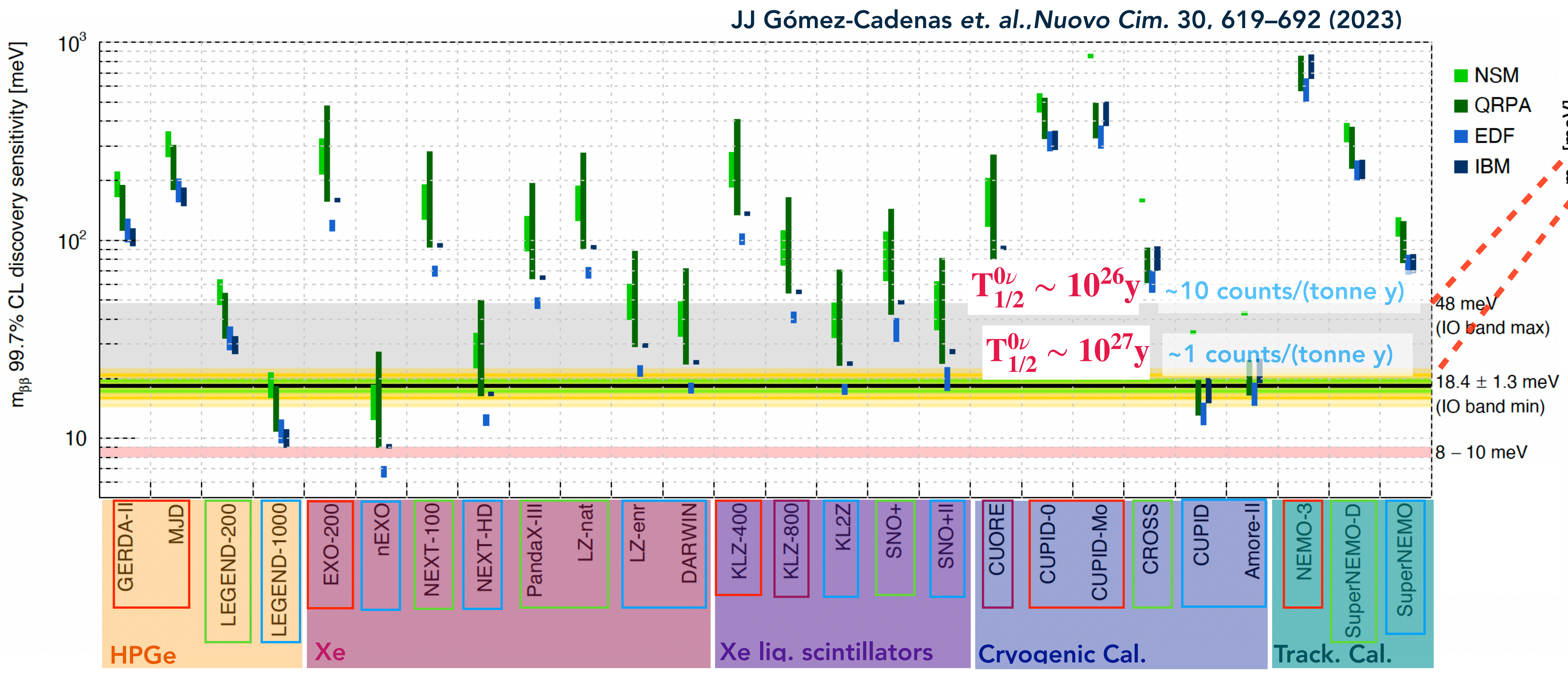


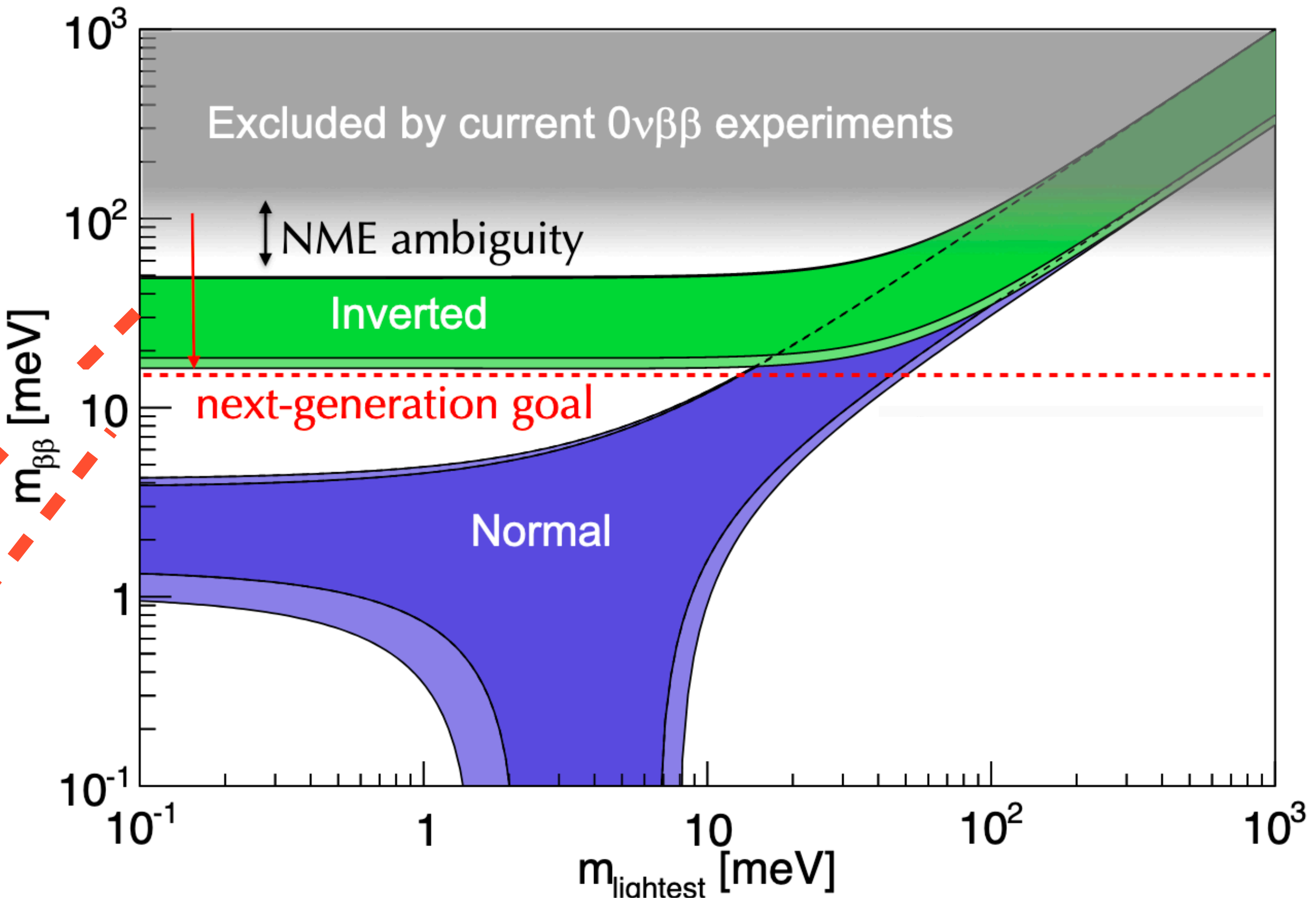
JJ Gómez-Cadenas *et. al.*, *Nuovo Cim.* 30, 619–692 (2023)

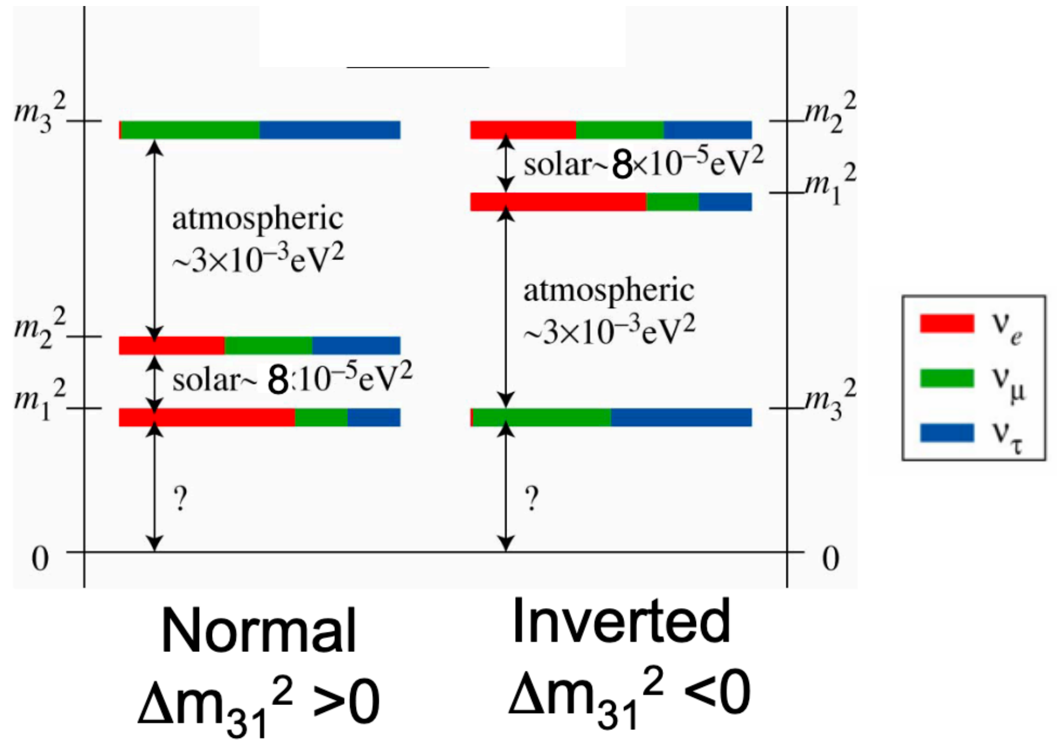
Double beta decay

Motivation of neutrinoless double beta decay - $0\nu\beta\beta$

Strong **physics potential**: Majorana nature of ν, lepton number violation, absolute ν mass







Lively experimental program that has been for a long time and it is underway, and also the huge effort made by the nuclear community to quantify the uncertainties

Double gamma decay

Approach to address uncertainty quantification of $0\nu\beta\beta$ NMEs

Search of **observables** that are **linked** to $0\nu\beta\beta$ even not mediated by same interaction

Good linear correlation **Double Gamow-Teller**(DGT) and the $0\nu\beta\beta$ NMEs

$$M^{DGT} = \langle 0^+_{gs,f} || \sum_{j,k} [\sigma_j \tau_j^- \times \sigma_k \tau_k^-]^0 || 0^+_{gs,i} \rangle$$

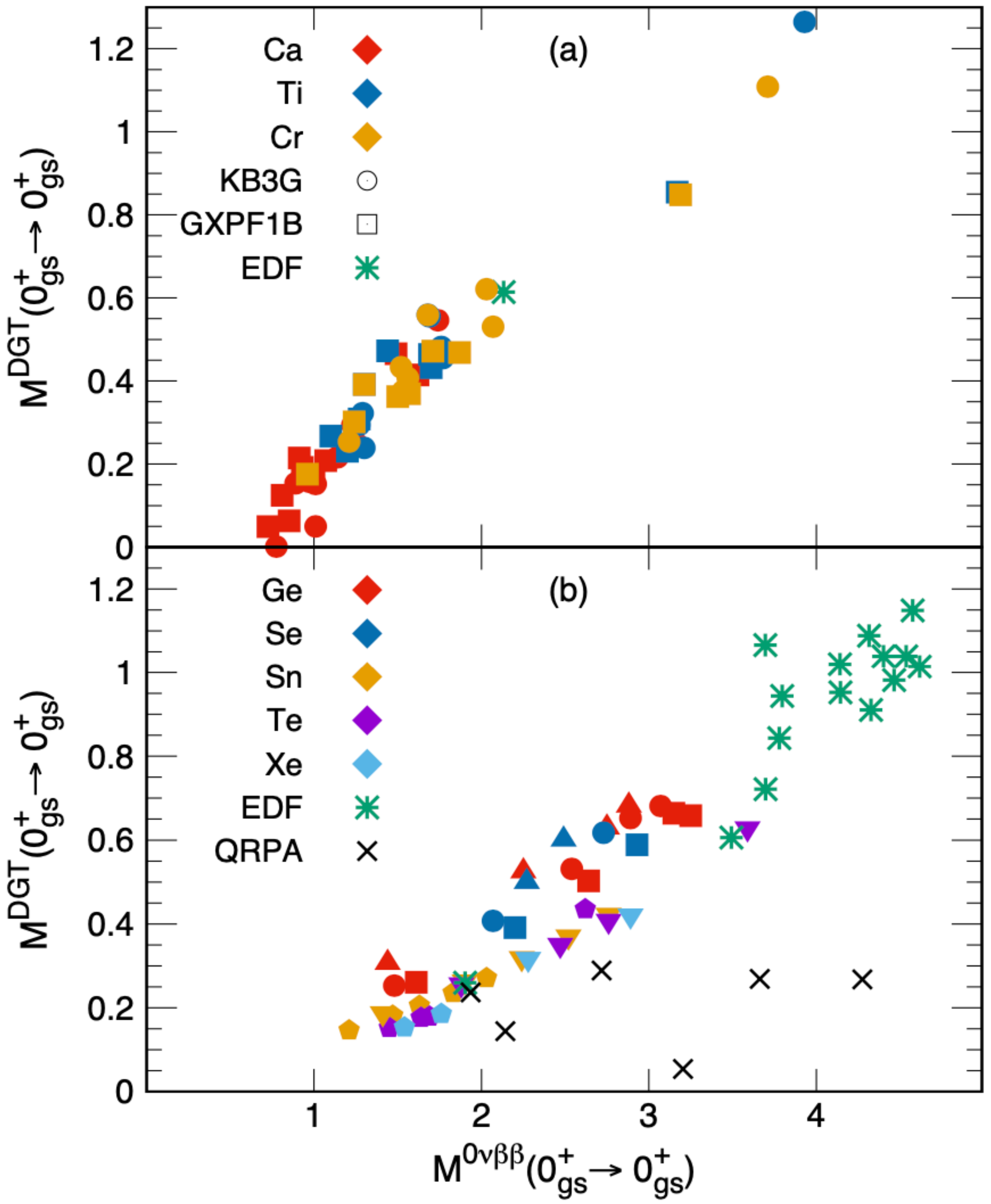
Measure M^{DGT} is challenging

Key: look for more accessible experiments and try to measure giving valuable information for $0\nu\beta\beta$ NME

Electromagnetic transitions powerful nuclear spectroscopic tool

γ decay from IAS were proposed to inform of electroweak transitions

H. Ejiri *et al.*, Phys. Rev. Lett. 21 (1968) 373 $\gamma(E1) \leftrightarrow \beta$



N. Shimizu *et. al.*, Phys. Rev. Lett 120, 142502 (2018)-NSM

JM. Yao *et. al.*, Phys. Rev. C 106, 014315 (2022)-IMSRG

L. Jokiniemi *et. al.*, Phys. Rev. C 107, 044316 (2023)-QRPA

Double gamma decay

$\gamma\gamma$ decay: correlations with $0\nu\beta\beta$ NMEs

Second order electromagnetic transitions, expect experimental measurement **more accessible** than $0\nu\beta\beta$

Double magnetic dipole (M1M1) $\gamma\gamma$-transition operator similar to **DGT** (same isovector $\sigma\tau$ term)

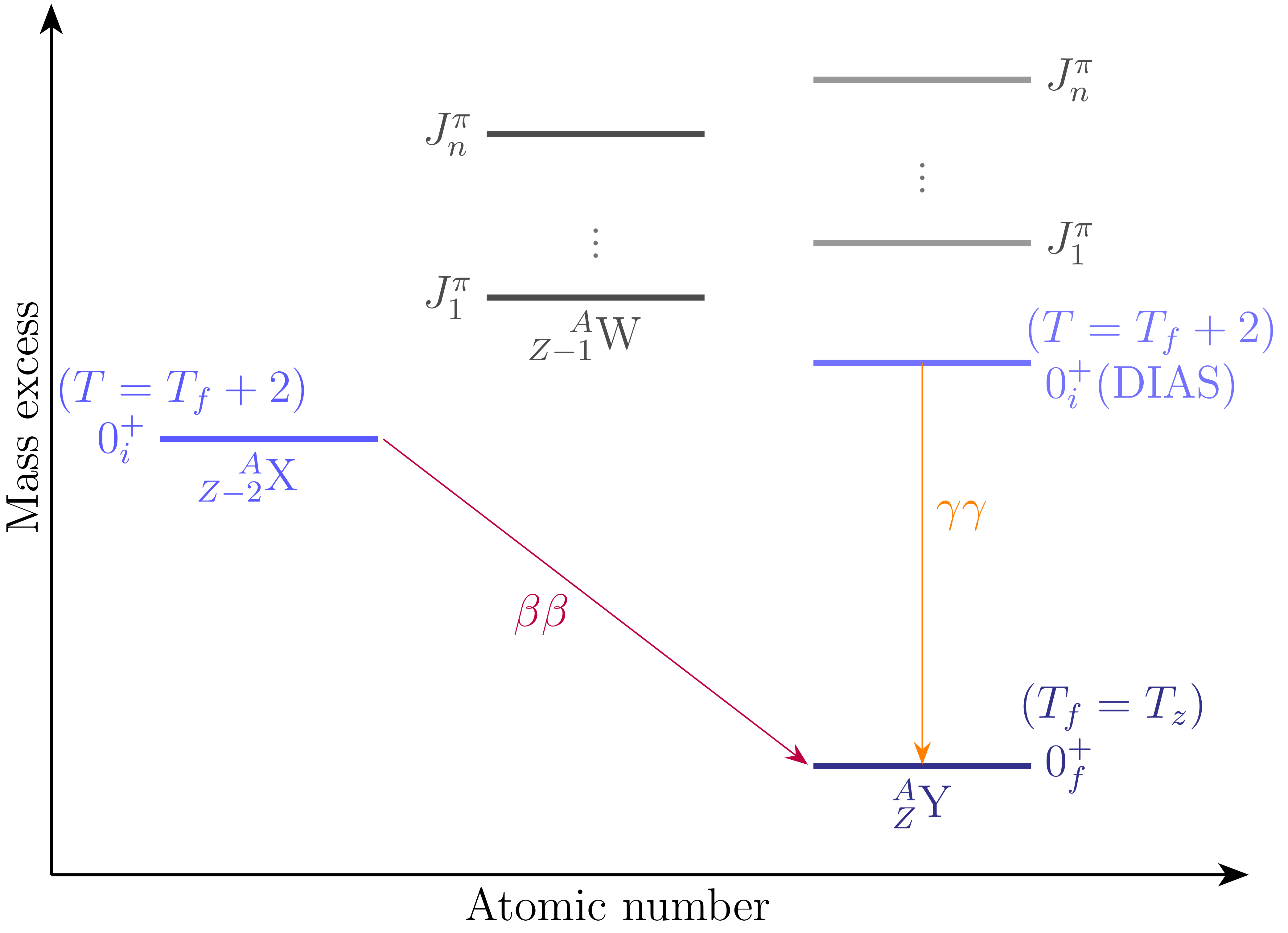
$\gamma\gamma$ and $\beta\beta$ nuclear states relation

$$|0_i^+\rangle_{\gamma\gamma} \equiv |0_i^+\rangle_{\beta\beta}(DIAS) = \frac{T\_T\_}{N_f}|0_i^+\rangle_{\beta\beta}$$

$$|0_f^+\rangle_{\gamma\gamma} \equiv |0_f^+\rangle_{\beta\beta}$$

Isospin lowering operator $T^- = \sum_i^A \tau_i^-$ N_f normalization factor

Isospin symmetry holds very well in nuclei: nuclear structure of **double isobaric analog state (DIAS)** in $\gamma\gamma$ is similar to the initial state of $0\nu\beta\beta$



Double gamma decay

$\gamma\gamma$ decay transition amplitude

$${}^{A}_{Z}X^{*} \longrightarrow {}^{A}_{Z}X + 2\gamma$$

simultaneous emission of 2γ!

Interaction Hamiltonian

$$\hat{H}_I = \int d^4x \hat{J}_\mu(x) A^\mu(x) + \frac{1}{2}\int d^4x d^4y \hat{B}_{\mu\nu}(x,y) A^\mu(x) A^\nu(y)$$

$\hat{J}_\mu(x)$ hadronic current operator
$\hat{B}_{\mu\nu}(x)$ two photon operator
$A_\mu(x)$ photon op

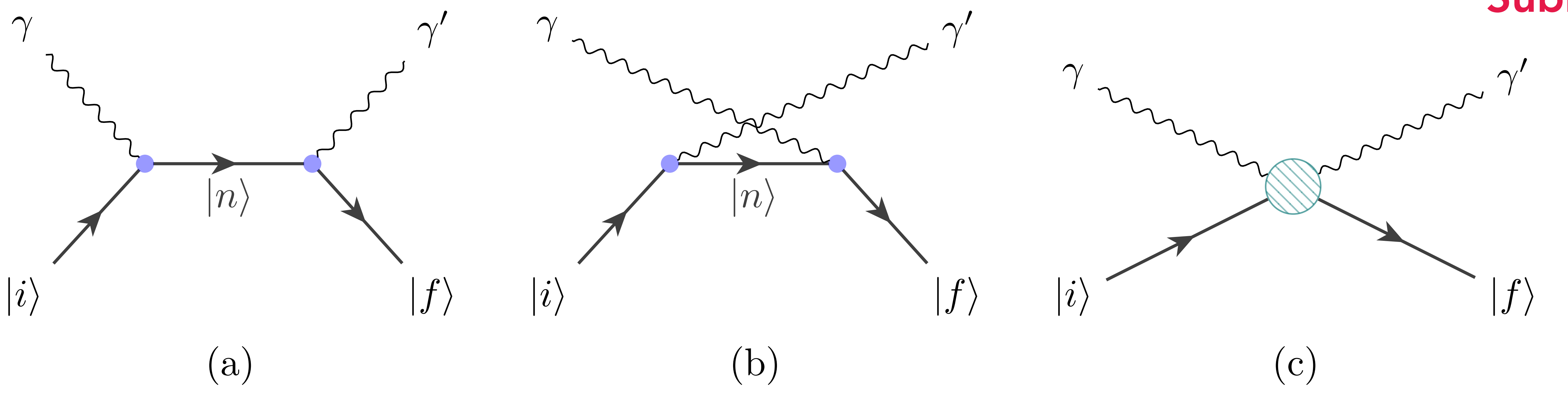
J.L.Friar, Ann. of Phys 95, 170 (1975)

Transition amplitude

$$\mathcal{M}^{(i)}_{\text{fi}}(k',k) \sim l^{\mu\nu}(k,k') \int d^4x d^4y e^{-i(k'x+ky)} N^{(i)}_{\mu\nu}(x,y)$$

$$N^{(2)}_{\mu\nu}(x,y) = \langle \xi_f J_f M_f | T[J_\mu(x) J_\nu(y)] | \xi_i J_i M_i \rangle \qquad N^{(1)}_{\mu\nu}(x,y) = \langle \xi_f J_f M_f | B_{\mu\nu}(x,y) | \xi_i J_i M_i \rangle$$

Subleading



Double gamma decay

$\gamma\gamma$ decay transition amplitude

Transition amplitude is proportional to

$$P_J^{LL'(2)}(k_0, k_0') = (2\pi)(-1)^{J_f+J_i}\hat{L}\hat{L}'\sum_{n,J_n}\left[\begin{Bmatrix} L & L' & J \\ J_i & J_f & J_n \end{Bmatrix}\frac{\langle J_f||\mathcal{O}(SL,k_0)||J_n\rangle\langle J_n||\mathcal{O}(S'L',k_0')||J_i\rangle}{E_n - E_i + k_0'} + (-1)^{J-L-L'}(S,L,k_0 \leftrightarrow S',L',k_0')\right]$$

Generalized polarizability

Transition operators:

$$\mathcal{O}_M(SL,k_0) = \int d^3\mathbf{x}(-1)^{\Delta_{\mu 0}}J_\mu(\mathbf{x})A^\mu_{LM}(S,k_0,\mathbf{x})$$

non null components

$A^0_{L,M}(E,k_0,\mathbf{x})$ $\mathbf{A}_{L,M}(M,k_0,\mathbf{x})$

Nucleus as a collection of non-relativistic point nucleons with charge and magnetic moments

Electric (EL) and magnetic (ML) multipoles

$$\mathcal{O}_M(EL,k_0) = k_0^L\alpha(L)\sum_{i=1}^{A} e(i)r_i^L Y_{LM}(\Omega_i)$$

$$\mathcal{O}_M(ML,k_0) = i\alpha(L)\frac{\mu_N k_0^L}{\hbar c}\left[\sum_{i=1}^{A}\left(\frac{2}{L+1}g_l^{(i)}\mathbf{l}_i + g_s^{(i)}\mathbf{s}_i\right)\cdot\nabla_i\left(r_i^L Y_{LM}(\Omega_i)\right)\right]$$

Double gamma decay

$\gamma\gamma$ $0_i^+ \longrightarrow 0_f^+$ parity and angular momentum selection rules

$$\pi_i \pi_f = \pi_{\gamma\gamma} = (-1)^{L+S+L'+S'}$$

$$J_i = J_f = 0 \Rightarrow J = 0,\, L = L'$$

→ **MLML** or **ELEL**

Leading contributions E1E1 and M1M1, but **only M1** similar to **Gamow-Teller**

$$\mathbf{M1} = \mu_N \sqrt{\frac{3}{4\pi}} \sum_{i=1}^{A} (g_i^l \mathbf{l}_i + g_i^s \frac{1}{2} \sigma_i)$$

GT $\sim \sigma \cdot \tau$

$P_0 \sim (k_0 k_0')^L$ most probable case photons have the same energy

Assume: $k_0 \simeq k_0' \simeq Q_{\gamma\gamma}/2$

$$M^{\gamma\gamma}(M1M1) = \sum_n \frac{\langle 0_{gs}^+ || \mathbf{M1} || 1_n^+ \rangle \langle 1_n^+ || \mathbf{M1} || 0_i^+(DIAS) \rangle}{E_n - \frac{1}{2}(E_{DIAS} + E_{GS})}$$

Double gamma decay

$\gamma\gamma$(M1M1) NMEs

$$|0_i^+\rangle_{\gamma\gamma} \equiv |0_i^+\rangle_{\beta\beta}(DIAS) = \frac{T^-T^-}{K^{1/2}}|0_i^+\rangle_{\beta\beta}$$

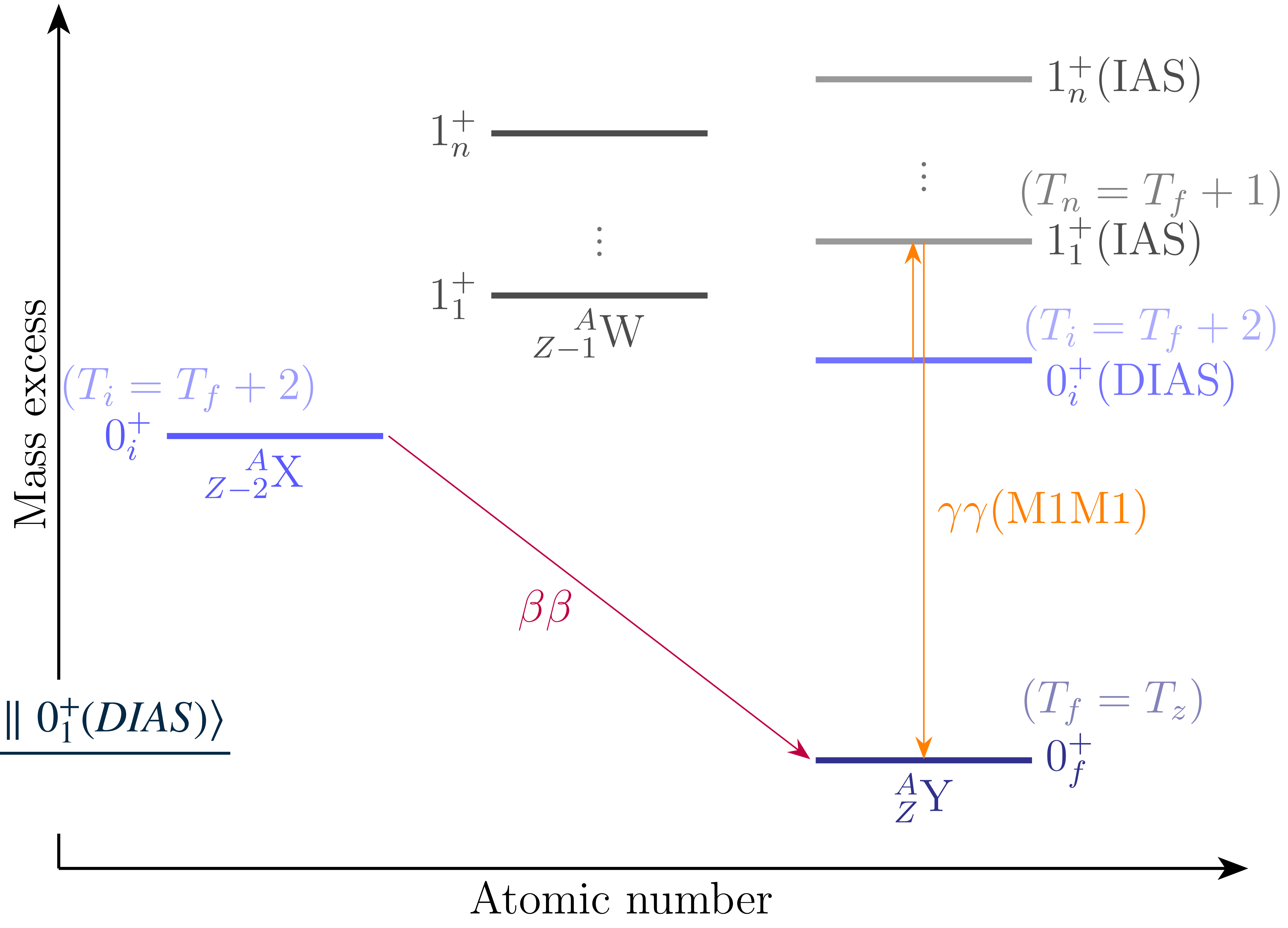
$$|0_f^+\rangle_{\gamma\gamma} \equiv |0_f^+\rangle_{\beta\beta}$$

Isovector component

M1 $\Delta T = 0, 1$ $\quad |1_n^+\rangle \equiv |1_n^+(IAS)\rangle$

$$M^{\gamma\gamma}(M1M1) = \sum_n \frac{\langle 0_{GS}^+ \| \mathbf{M1} \| 1_n^+(IAS)\rangle\langle 1_n^+(IAS) \| \mathbf{M1} \| 0_1^+(DIAS)\rangle}{E_n - \frac{1}{2}(E_{DIAS}+E_{GS})}$$

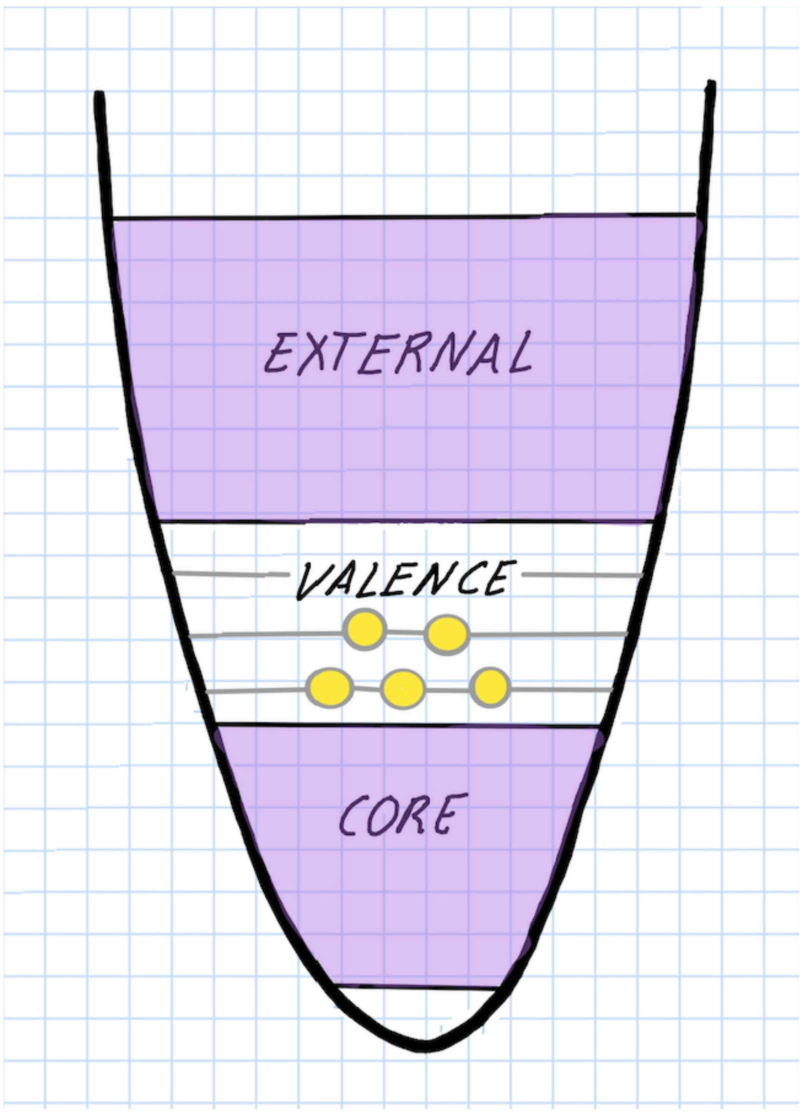
$$\mathbf{M1} = \mu_N\sqrt{\frac{3}{4\pi}}\sum_{i=1}^{A}(g_i^l \mathbf{l}_i + g_i^s \frac{1}{2}\sigma_i)$$



Double gamma decay

The nuclear shell model

Microscopic treatment of the nucleus requires to solve $H|\Psi_i\rangle = E_i|\Psi_i\rangle$



Nuclear shell model $H_{eff}|\Psi_i^{\mathrm{eff}}\rangle = E_i|\Psi_i^{\mathrm{eff}}\rangle$

$|\Psi_i^{\mathrm{eff}}\rangle$ configuration (valence) space wave function

$$|\Psi_i^{\mathrm{eff}}\rangle = \sum_{k=1}^{d} a_{ij}|\Phi_j\rangle$$

a_{ij} obtained from diagonalising H_{eff}

$$|\Phi_\alpha\rangle = \prod_{\alpha_i=(n_i,l_i,j_i,m_i,m_{t_i})}^{A} c^\dagger_{\alpha_i}|\phi_0\rangle$$

Slater determinant

ANTOINE (Caurier and Nowacki,1999) **E Caurier *et. al.*, Rev. Mod. Phys. 77, 427 (2005)**

KSHELL (N. Shimizu et. al.),Python library (T. Miyagi) **Comp. Phys. Comm. 244, 372 (2019)**

m-scheme shell code, Slater determinants with definite M_J and M_T but not **J** and **T**

^{76}Se d=3.8 10^8 (M_J=0)

Matrix size maximal but sparse and easy to compute ⟶ **Diagonalization** using **Lanczos** method

Nuclear interactions and configuration spaces

Valence space		H_{eff}
pf-shell	[^{40}Ca CORE] $0f_{7/2}1p_{3/2}1p_{1/2}0f_{5/2}$	KB3G A. Poves *et. al.*, Nucl. Phys. A 649, 157(2001)
$\gamma\gamma$ decay in	$^{46-58}Ti$ $^{50-60}Cr$ $^{54-60}Fe$	GXPF1B M. Honma *et. al.*, RIKEN Accelerator. Progr. Rep. 41,32(2008)
	$0\nu\beta\beta$ in ^{48}Ca	
pfg-shell	[^{56}Ni CORE] $1p_{3/2}1p_{1/2}0f_{5/2}0g_{9/2}$	GCN2850 E. Caurier et. al., Phys. Rev. Lett 100, 052 503 (2008)
$\gamma\gamma$ decay in	$^{72-78}Zn$ $^{74-80}Ge$ $^{76-82}Se$ $^{82-84}Kr$	JUN45 M. Honma et al., Phys. Rev. C80,064323 (2009)
	$0\nu\beta\beta$ in ^{76}Ge	JJ44B B.A. Brown and A.F. Lisetskiy, Private communication
gdsh-shell	[^{100}Sn CORE] $0g_{7/2}1d_{5/2}1d_{3/2}1s_{1/2}0h_{11/2}$	GCN5082 E. Caurier et. al., Phys. Rev. Lett 100, 052 503 (2008)
$\gamma\gamma$ decay in	$^{124-132}Te$ $^{130-134}Xe$ $^{134-136}Ba$	QX C. Qi and Z.X. Xu, Phys. Rev. C 86, 044323 (2012)
	$0\nu\beta\beta$ in ^{136}Xe	

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Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs

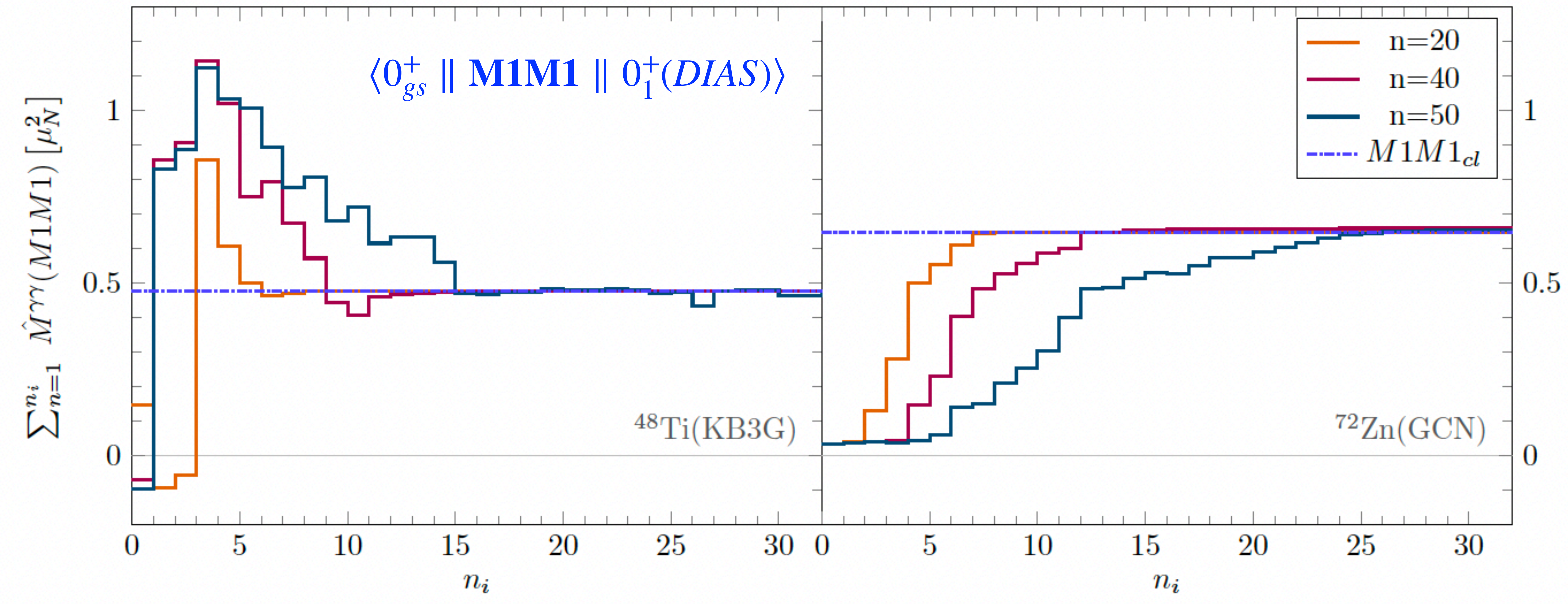
Double gamma decay matrix elements

Running sum NMEs with the number of intermediate states (n_i) in Lanczos strength function

$$\hat{M}^{\gamma\gamma}(M1M1) = \sum_n \langle 0^+_{gs} \parallel \mathbf{M1} \parallel 1^+_n(IAS)\rangle\langle 1^+_n(IAS) \parallel \mathbf{M1} \parallel 0^+_1(DIAS)\rangle$$

Pivot

$|v_1\rangle \simeq M1_{IV}|0^+_{GS}\rangle$



The value of the exact closure NME has been used as a **criteria** of good convergence (errors $\sim 1\,\%$)

Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs

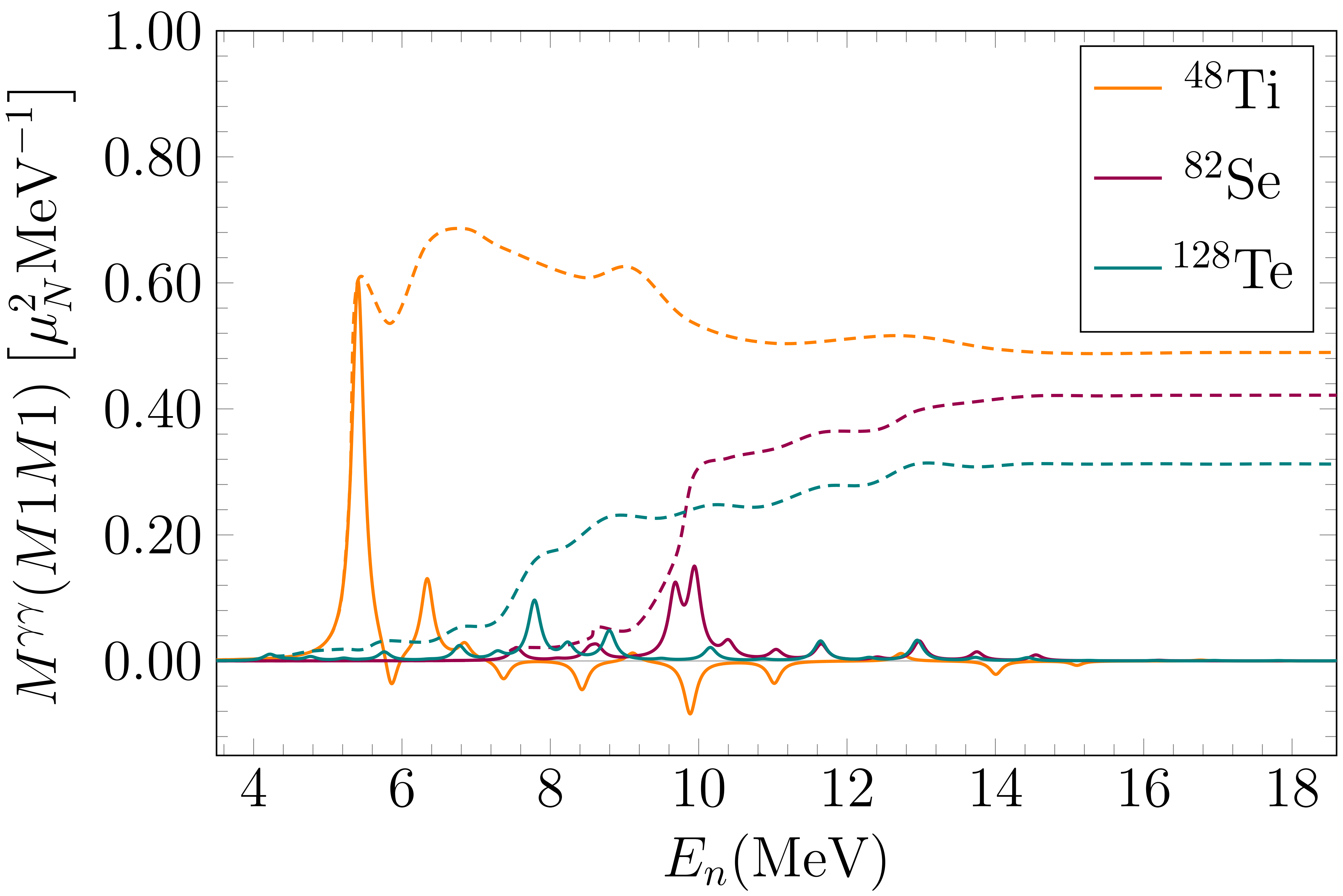
Double gamma decay matrix elements

$$M^{\gamma\gamma}(M1M1) = \sum_n \frac{\langle 0^+_{GS} \parallel \mathbf{M1} \parallel 1^+_n \rangle \langle 1^+_n \parallel \mathbf{M1} \parallel 0^+_1(DIAS) \rangle}{E_n - \frac{1}{2}(E_{DIAS} + E_{GS})}$$

$M^{\gamma\gamma}(M1M1)$ as a function of energy of the intermediate state (solid lines), accumulated value (dashed lines)

Few states contribute to the total matrix element

Energies of dominant states different for medium and heavier mass nuclei



Energy of the denominator has been evaluated using experimental energies when data is available, $M^{\gamma\gamma}(M1M1)$ modified less than 5% when compared to calculated energies

Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs

Double gamma decay correlation

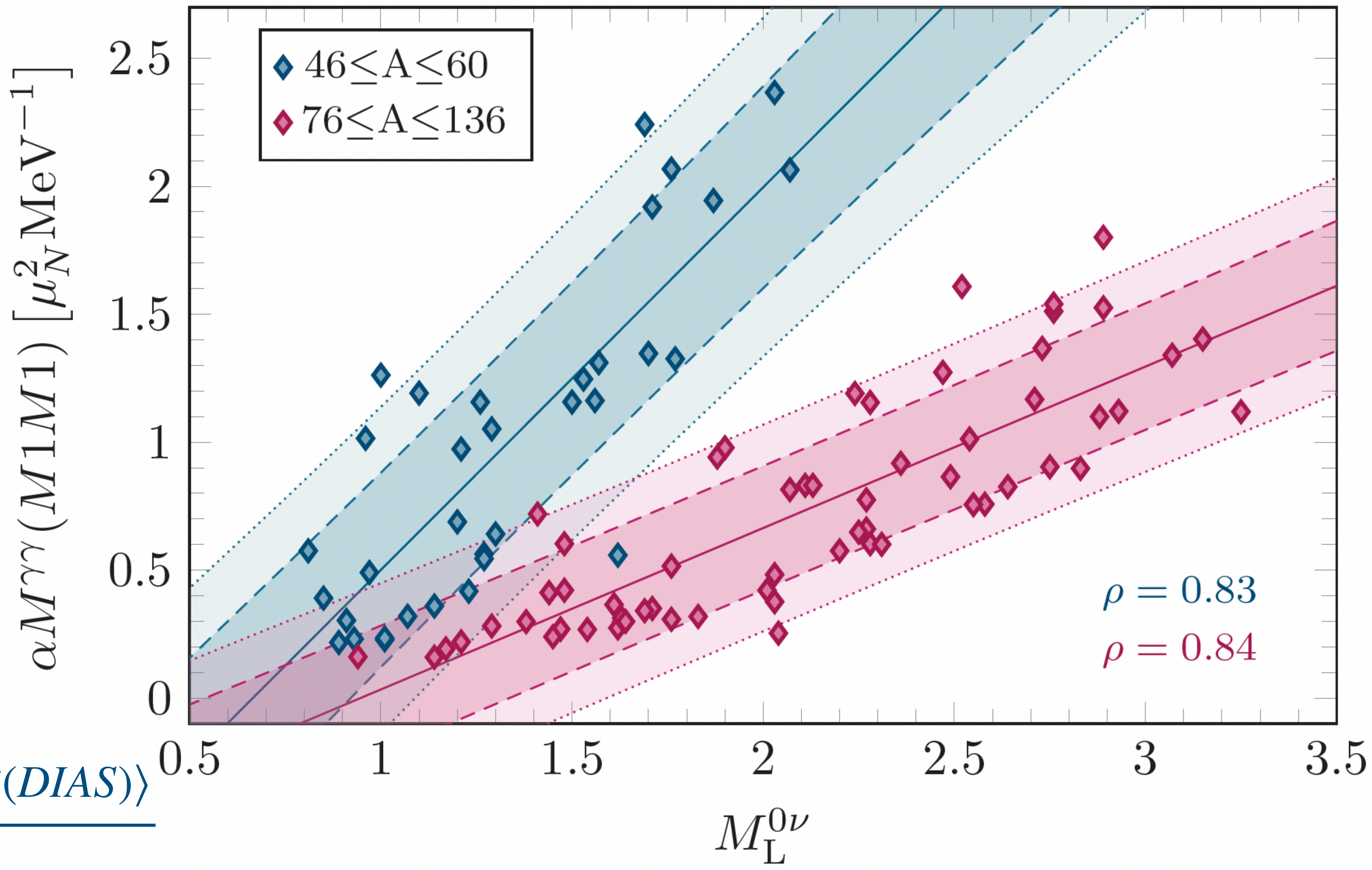
19 nuclei **Ti,Cr,Fe** in region $46 \leq A \leq 60$
GXPF1, KB3G

25 nuclei **Zn, Se, Kr, Te, Xe, Ba** in $72 \leq A \leq 136$
JJ44B,JUN30,GCN2850,QX, GCN5082

α from Wigner-Eckart Th. to isospin space

***Good* correlation** coefficients

$$M^{\gamma\gamma}(M1M1) = \sum_n \frac{\langle 0^+_{gs}||\mathbf{M1}||1^+_n(IAS)\rangle\langle 1^+_n(IAS)||\mathbf{M1}||0^+_i(DIAS)\rangle}{E_n - \frac{1}{2}(E_{GS}+E_{DIAS})}$$



B. Romeo, J.Menéndez and C. Peña-Garay, Phys. Lett. B 827, 136965 (2022)

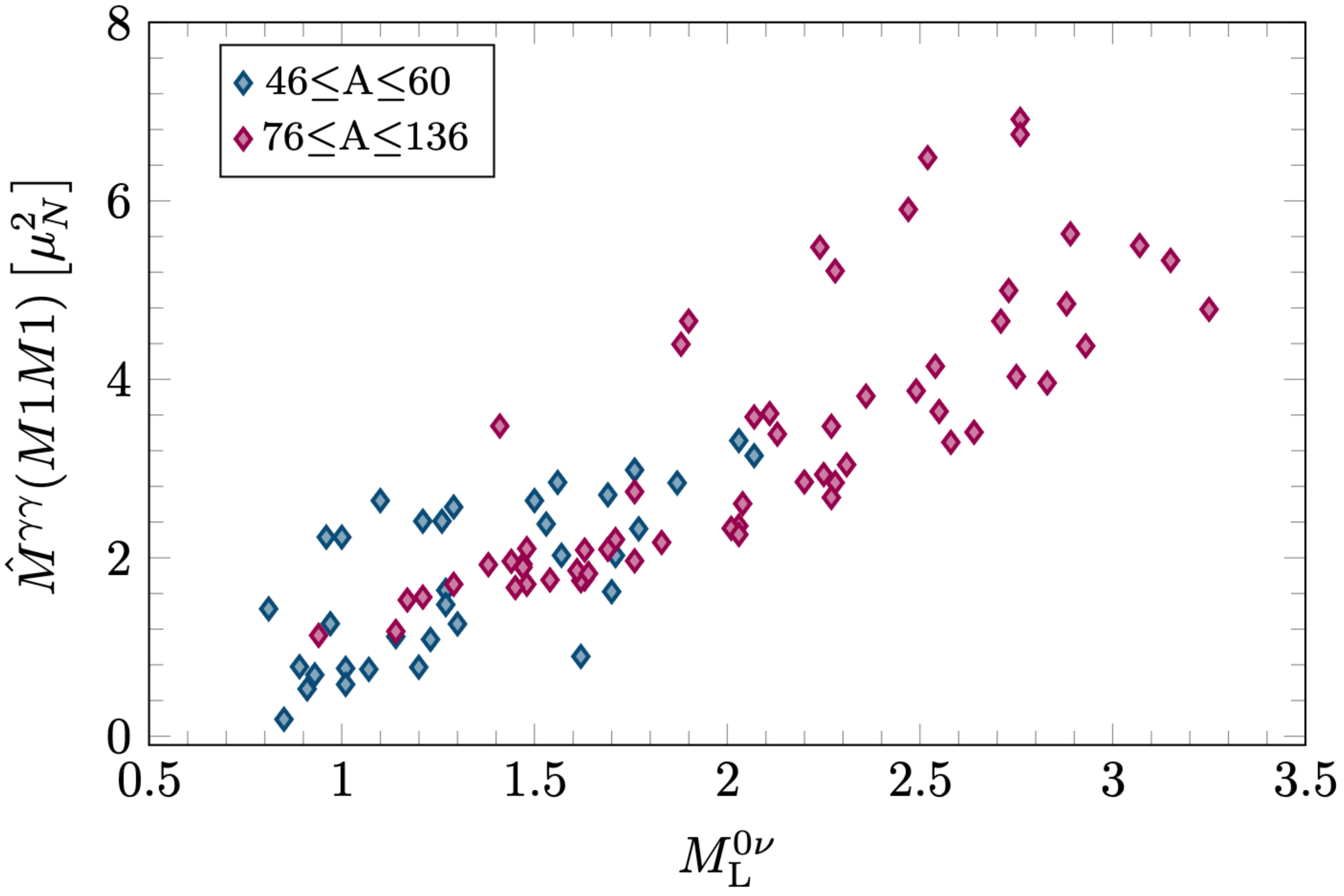
$M^{0\nu}_L$ from N. Shimizu *et. al.* Phys. Rev. Lett 120, 142502 (2018)

Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs

Effect of intermediate states energies

Different slopes due to **energy denominator**

$$\hat{M}^{\gamma\gamma}(M1M1) \equiv \sum_{1_n^+} \langle 0_f^+ \parallel \mathbf{M1} \parallel 1_n^+ \rangle \langle 1_n^+ \parallel \mathbf{M1} \parallel 0_i'^+ \rangle$$



Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs

Spin, orbital and interference contributions

Decomposing $\gamma\gamma$-M1M1 into **spin**(ss), **orbital**(ll) and **interference** (ls) parts

$$\mathbf{M1} = \mu_N \sqrt{\frac{3}{4\pi}} \sum_{i=1}^{A} (g_i^l \mathbf{l}_i + g_i^s \frac{1}{2}\sigma_i)$$

Focusing in $\gamma\gamma$-M1M1 numerator

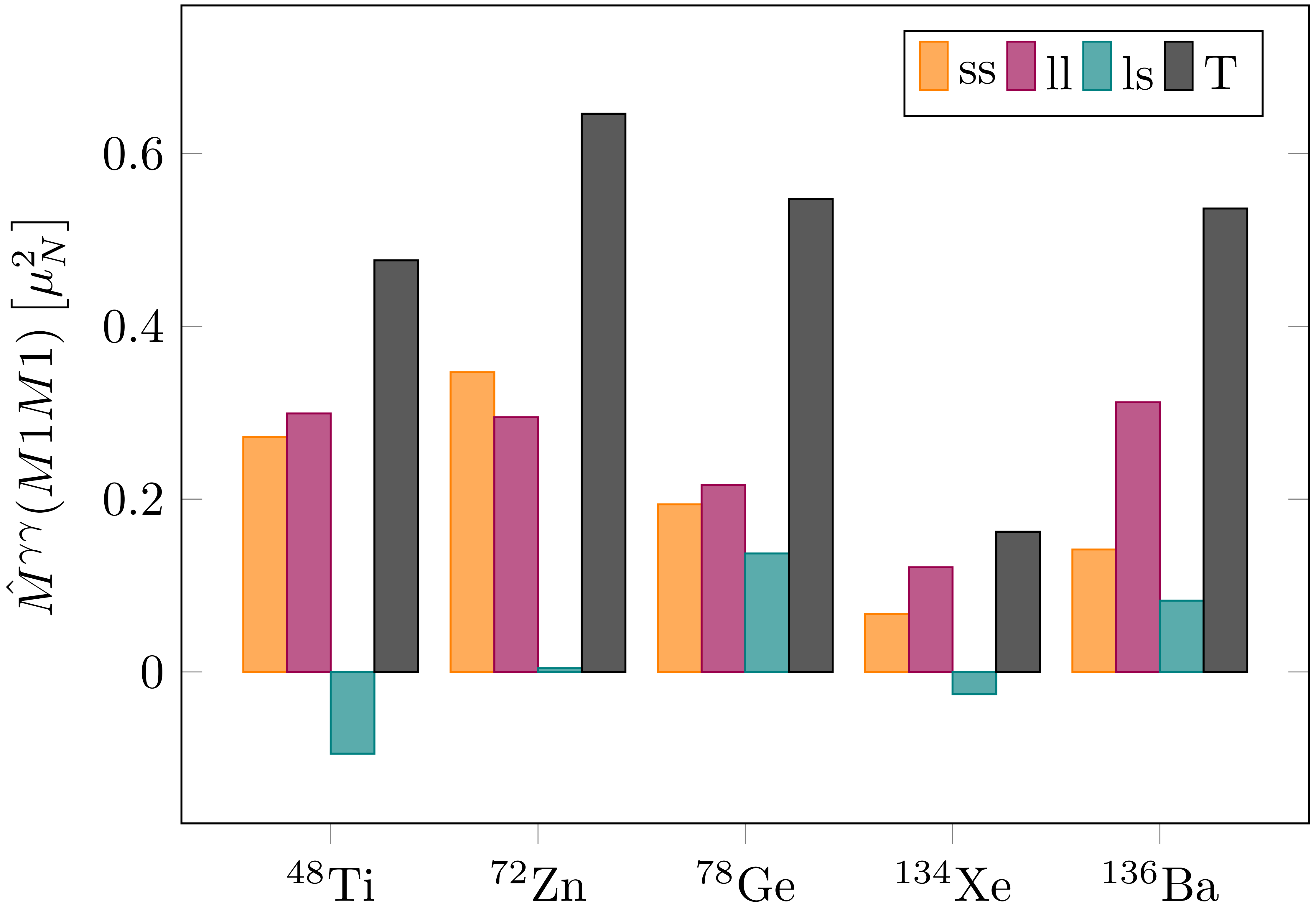
$$\hat{M}^{\gamma\gamma} = \hat{M}^{\gamma\gamma}_{\mathrm{ss}} + \hat{M}^{\gamma\gamma}_{\mathrm{ll}} + \hat{M}^{\gamma\gamma}_{\mathrm{ls}}$$

$\hat{M}^{\gamma\gamma}_{\mathrm{ll}}$: same size and sign as the spin part

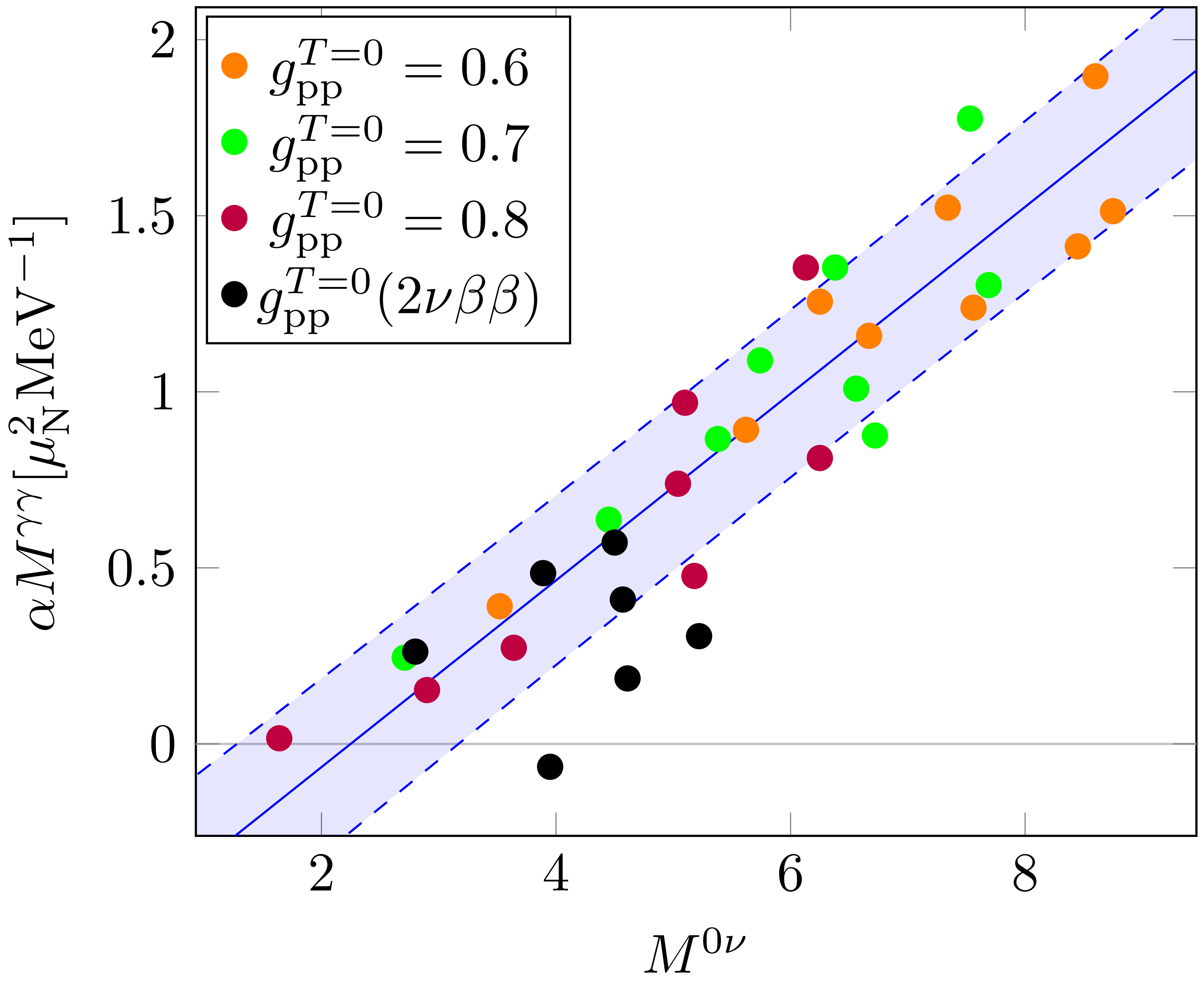
Xe, Ba: $\hat{M}^{\gamma\gamma}_{\mathrm{ll}}$ dominates but same correlation

correlation with $0\nu\beta\beta$ not limited to operators driven by **spin**

This behaviour is systematic in other nuclei



Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs
$0\nu\beta\beta$-$\gamma\gamma$ correlation in QRPA



L. Jokiniemi and J. Menéndez, Phys. Rev. C 107, 044316 (2023)

L. Jokiniemi has found also a very good correlation $R^2 = 0.80$ in spherical pnQRPA

Use different values of particle-particle parameter $g_{pp}^{T=0}$ for A=76,82,116,128,130 and 136

Different linear correlation

It could be due to the different role of 1^+ and other multipoles in both methods

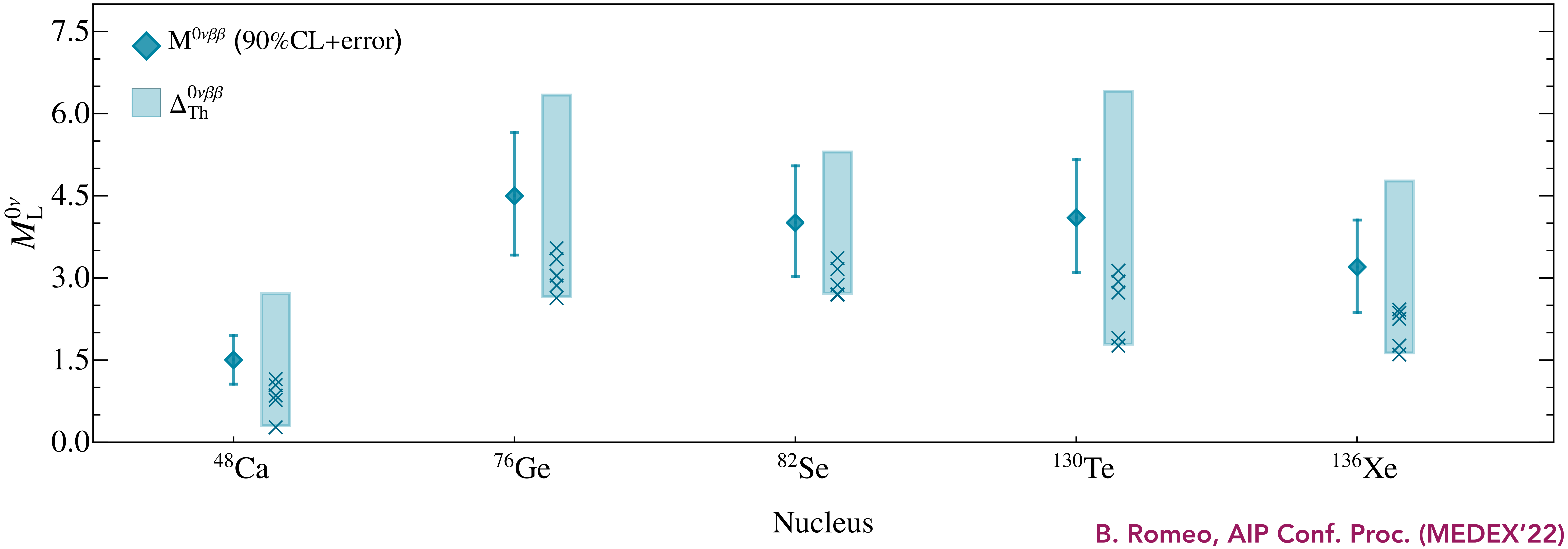
May change if deformation is included into the pnQRPA calculations

Potential of measuring $\gamma\gamma$

$0\nu\beta\beta$-decay NMEs from $\gamma\gamma$-M1M1 hypothetical measurement

"×" Shell model NMEs literature **M Agostini *et. al.*, Rev. Mod. Phys. 95, 025002 (2023)**

Shaded bands represent combined calculated NME with other methods



B. Romeo, AIP Conf. Proc. (MEDEX'22)

$M^{0\nu}$ from correlation and $\gamma\gamma$-hypothetical measurement includes information from systematic calculations tens of nuclei, different interactions, less model dependent

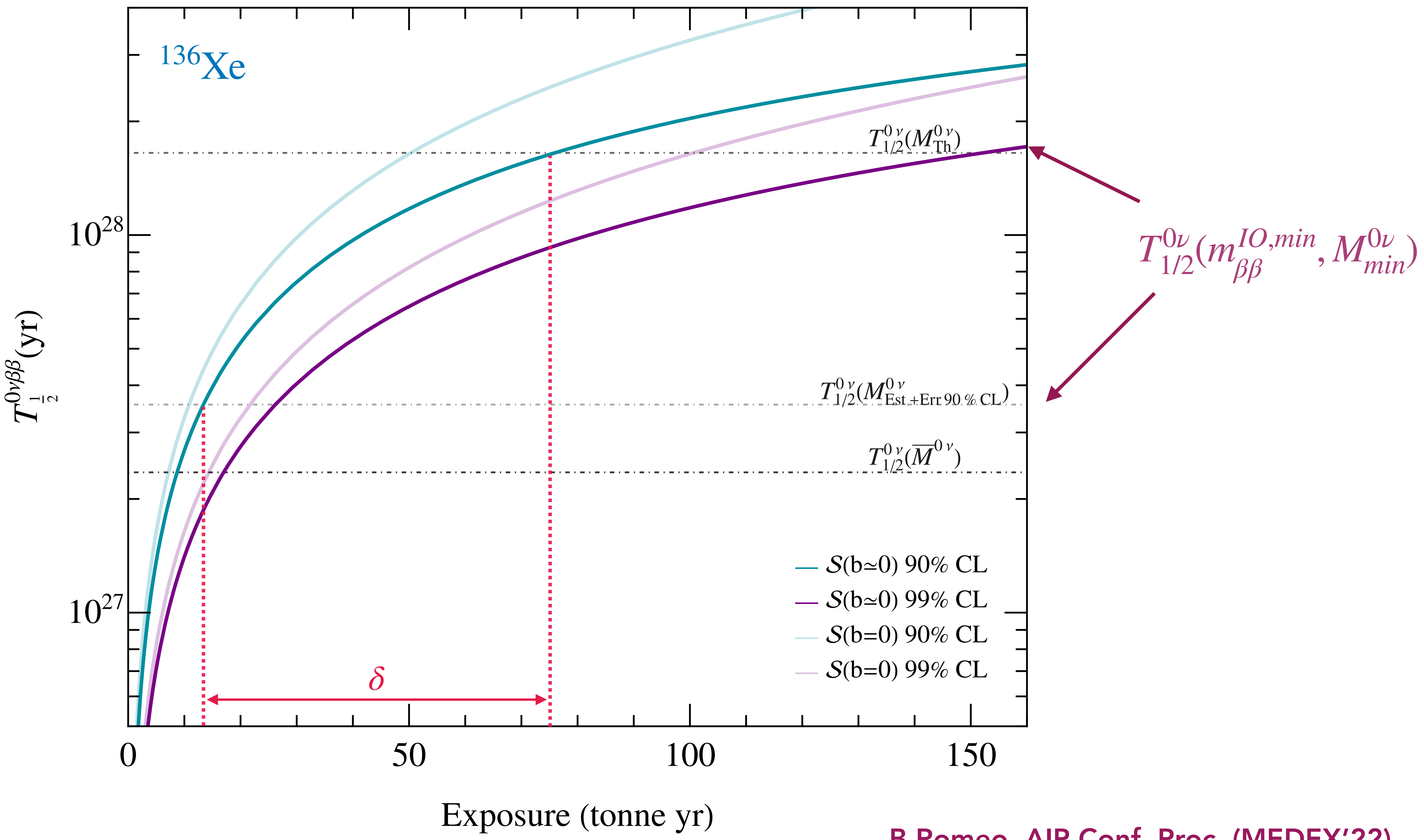
Potential of measuring $\gamma\gamma$
$m_{\beta\beta}$ & $T_{1/2}^{0\nu\beta\beta}$ sensitivity

A reduction of the current spread in $M^{0\nu}$ values important consequences for $0\nu\beta\beta$ experiments and their limits

Data for ^{136}Xe high pressure time projection chamber (NEXT experiment)

NEXT Collaboration: C. Adams et. al., arXiv:2005.06467 (2020)

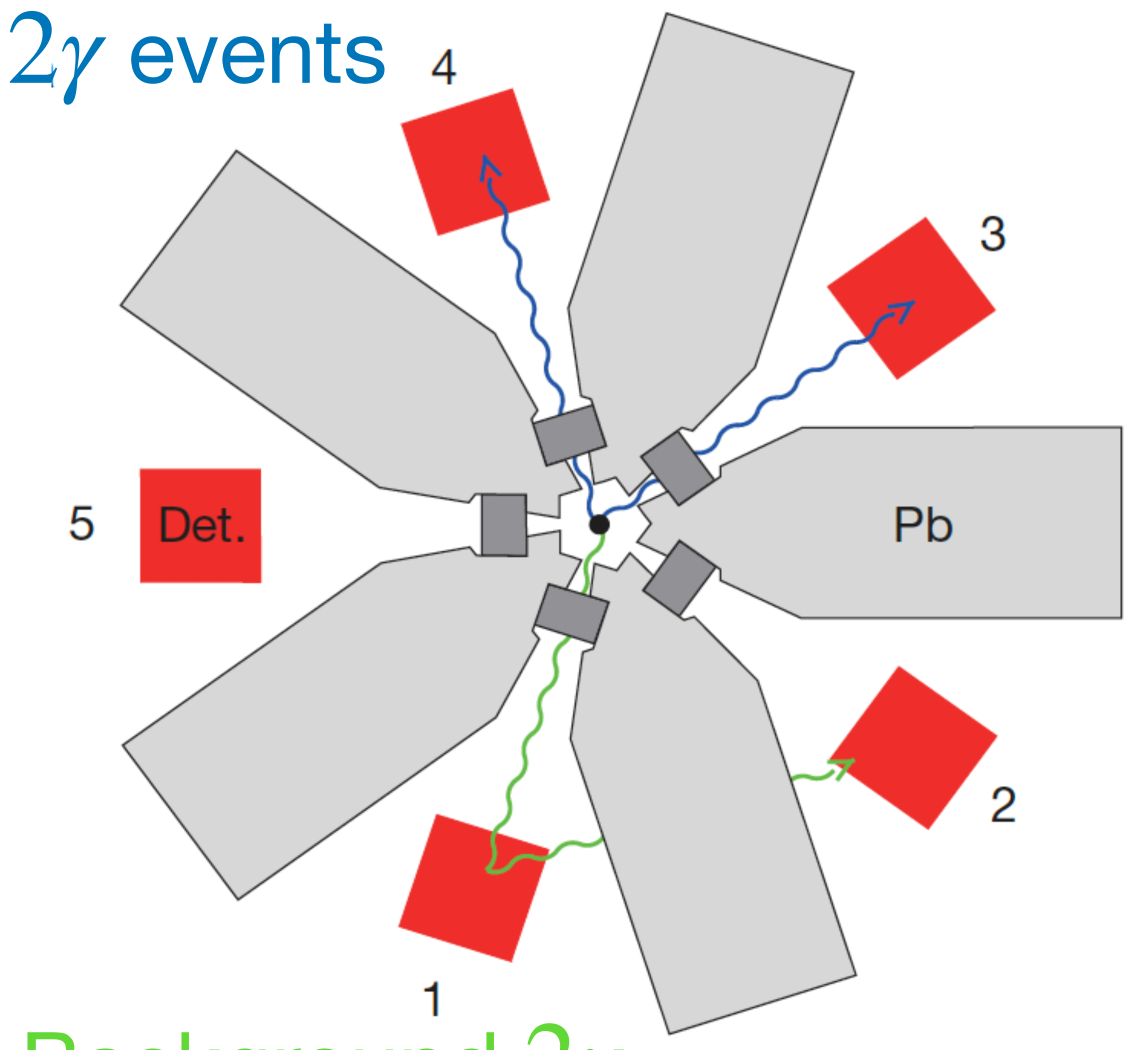
Considerable reduction (δ) in the exposure necessary to reach the bottom of the inverted mass ordering



B.Romeo, AIP Conf. Proc. (MEDEX'22)

Previous experimental measurements $\gamma\gamma$

Measurements of second order electromagnetic decays rare, but have been done for $0^+ \longrightarrow 0^+$ in double magic nuclei $^{16}\mathrm{O}, ^{40}\mathrm{Ca}, ^{90}\mathrm{Zr}$



First excited state 0^+
γ decay forbidden
competing internal conversion

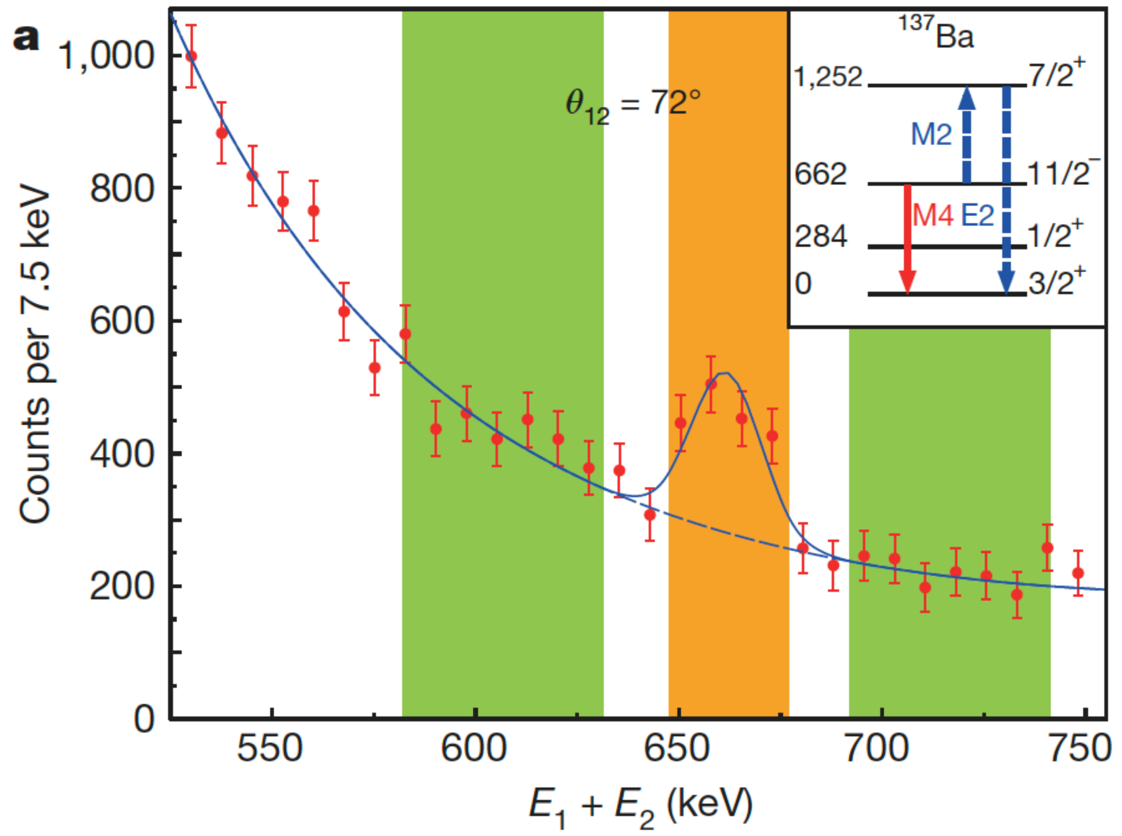
$$\Gamma_{\gamma\gamma}/\Gamma \simeq 10^{-4}$$

B. A. Watson et. al, Phys. Rev. Lett. 35, 1333 (1975)
A.C. Hayes et al., Phys. Rev. C 41, 1727 (1990)
J. Schirmer et. al.,Phys. Rev. Lett. 53, 1897 (1984)

Faster crystal detectors allowed measurement of competitive $\gamma\gamma/\gamma$ decay in $^{137}\mathrm{Ba}$ for $11^+/2 \longrightarrow 3^+/2$

$$\Gamma_{\gamma\gamma}/\Gamma_{\gamma} \simeq 10^{-6}$$

C. Walz et. al., Nat. 526, 406–409 (2015)
P.A. Söderström et. al., Nat. Commun. 11, 3242 (2020)



Recently the first $0^+ \longrightarrow 0^+$ $\gamma\gamma$ decay in $^{72}\mathrm{Ge}^{32+}$

D. Freire-Fernández et. al., arXiv:2312.11313

Experimental prospects of $\gamma\gamma$ from $0^+_{\rm DIAS}$

$\gamma\gamma$(M1M1) from DIAS

- Exploring DIAS and isovector electromagnetic transitions opens new paths to investigate isospin-breaking phenomena and rare decays
- $\gamma\gamma$ from DIAS to ground state never been observed
- Challenge: populate DIAS & small BRs involved!

Relevant $\beta\beta$ nuclei: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{130}Te and ^{136}Xe

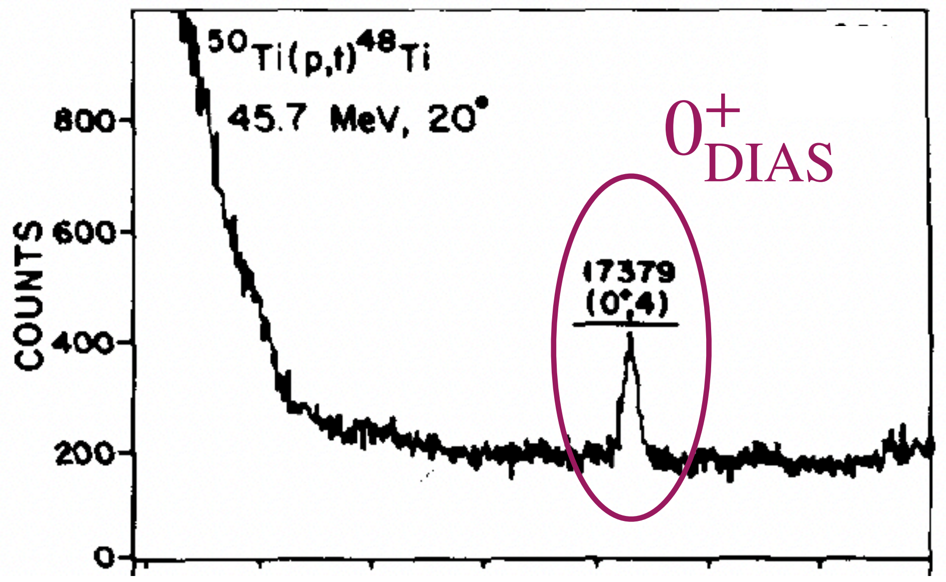
$$^{A}_{Z}X^{DIAS} \longrightarrow ^{A}_{Z}X + 2\gamma$$

$$E_\gamma \simeq E_{DIAS}/2$$

Nucleus	$H_{\rm eff}$	$E_{\rm DIAS}$ (MeV)	$\Gamma_{\gamma\gamma}(\times 10^{-7}$ eV)
^{48}Ti	KB3G	16.1	2.0
^{48}Ti	GXPF1B	17.3	0.55
^{76}Se	GCN2850	19.2	8.7
^{76}Se	JUN45	21.2	15
^{76}Se	JJ44B	23.6	32
^{82}Kr	GCN2850	21.6	12
^{82}Kr	JUN45	22.9	12
^{82}Kr	JJ44B	26.6	27
^{130}Xe	GCN5082	27.7	2.2
^{136}Ba	GCN5082	29.1	17

B.Romeo, D. Stramaccioni, J. J. Valiente Dobón, and J. Menéndez; Phys. Lett. B 860 (2025) 139186

^{50}Ti(p,t)^{48}Ti



R. Kouzes *et. al.*, *Nuc. Phys. A*, 309, 329–343 (1978)

Experimental prospects of $\gamma\gamma$ from 0^+_{DIAS}

Competition channels: IC, IPC, γ-decay and p-emission

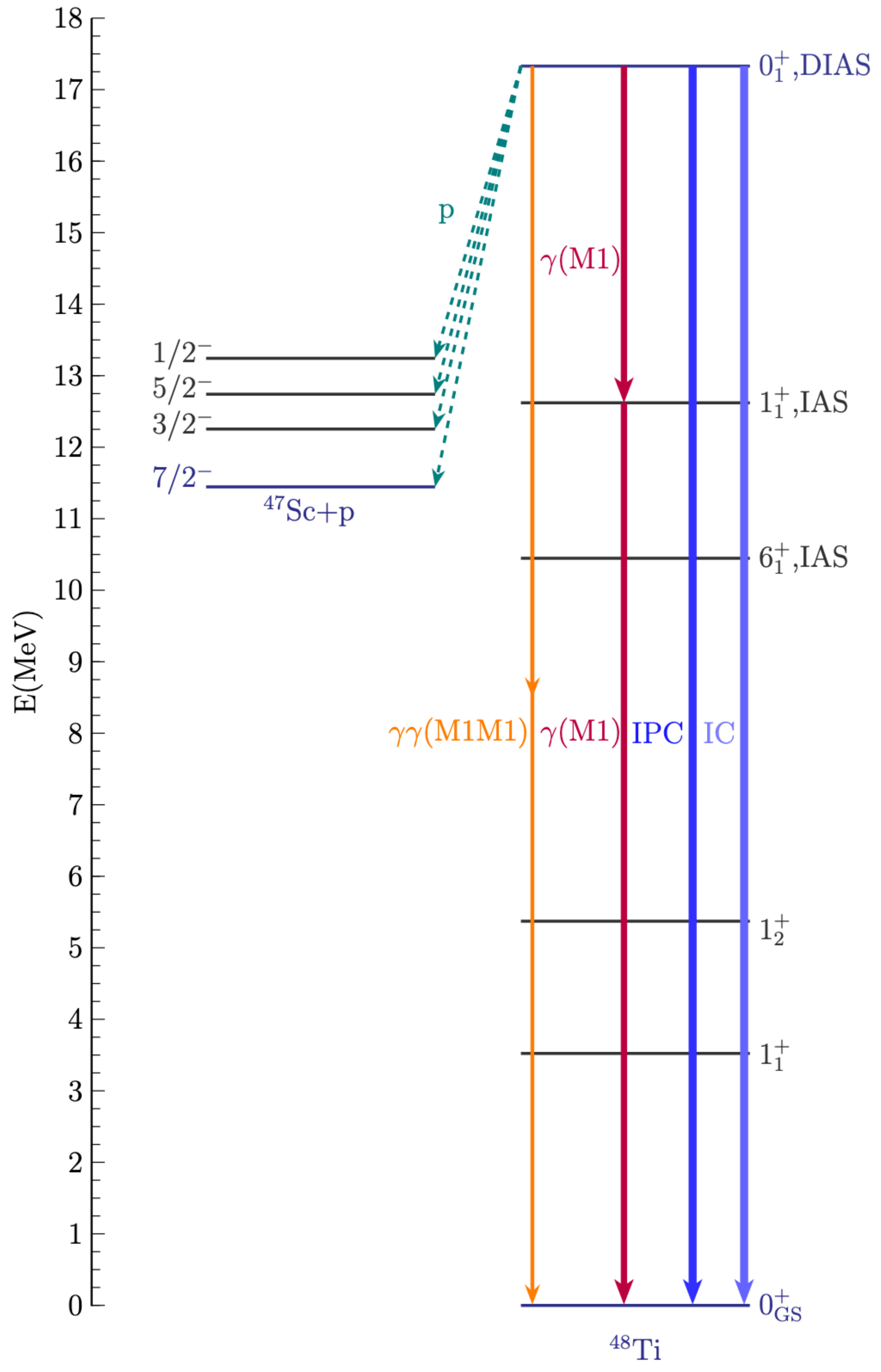
$\Gamma_{\gamma\gamma} \sim 10^{-6} - 10^{-8}\text{eV}$ demands careful study of competing channels

In 0+ excited states, IC and IPC are competing channels with $\gamma\gamma$ decay, and relevant branches for DIAS

$$\Gamma_{IC} \sim 10^{-3} - 10^{-6}\ \text{eV} \qquad \Gamma_{IPC} \sim 10^{-2} - 1\ \text{eV}$$

γ-E1 decays are expected to be dominant, hard to compute in a reliable way within our model, γ-E2s small compared with γ-M1s

$$\Gamma_{\gamma} \sim 0.1 - 10\ \text{eV}$$



B.Romeo, D. Stramaccioni, J. J. Valiente Dobón, and J. Menéndez; Phys. Lett. B 860 (2025) 139186

Experimental prospects of $\gamma\gamma$ from 0^+_{DIAS}

Competition channels: IC, IPC, γ-decay and p-emission

0^+(DIAS) **high energy states** particle branch open!

$${}^{A+1}_{Z+1}X^* \longrightarrow {}^{A}_{Z}X + p$$

${}^{A+1}_{Z+1}X^*$ excited state with $T_i = T_{gs} + 2$

While $T_f = T_{gs} + \frac{1}{2}$ $\longrightarrow$ $\Delta T = \frac{3}{2}$

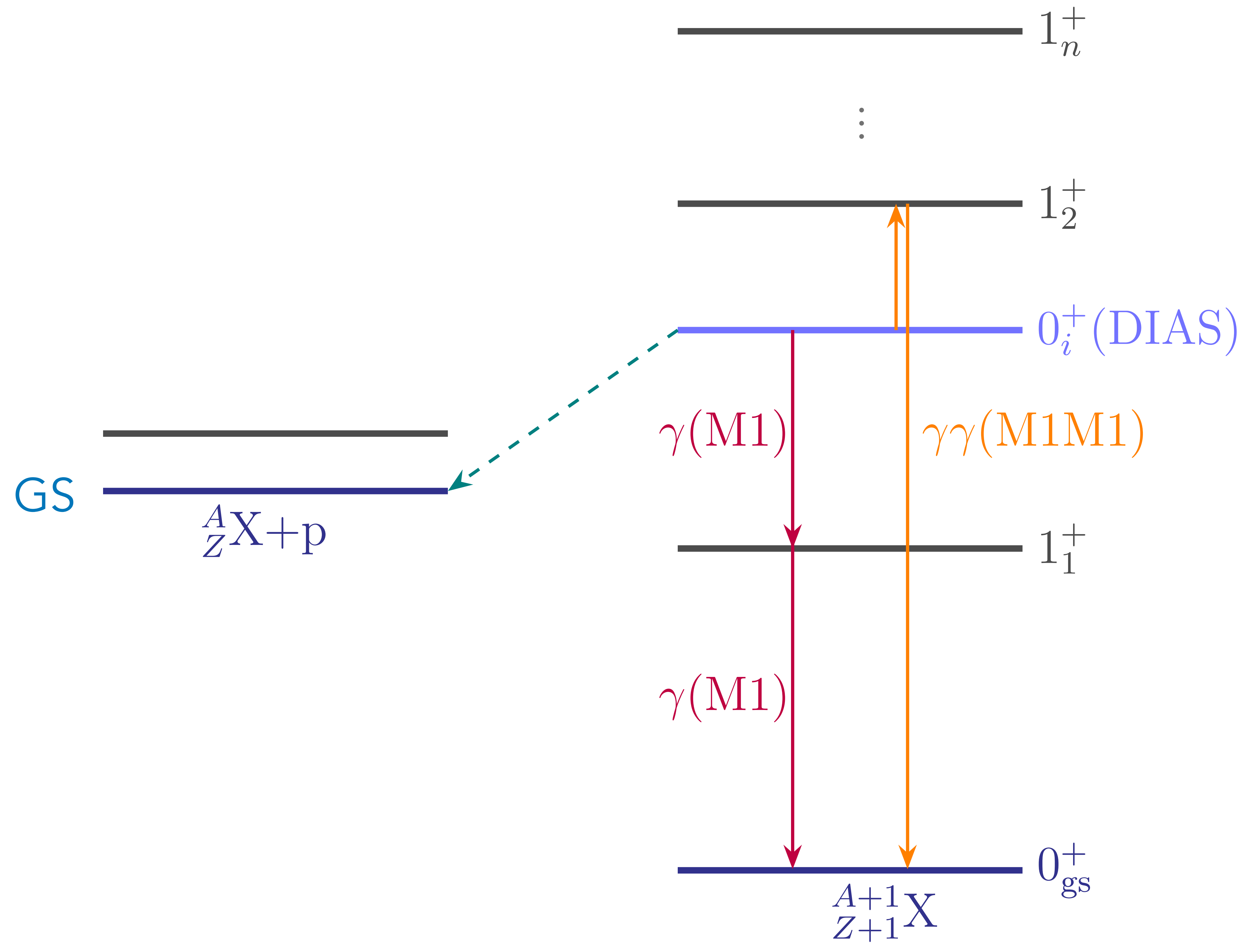
Isospin forbidden decay

highly suppressed

γ **branch** starts to be **competitive** $\Gamma_\gamma \sim \Gamma_p$

$$\Gamma_p = S\Gamma_{sp}$$

S spectroscopic factor, Γ_{sp} single particle width



Experimental prospects of $\gamma\gamma$ from 0^+_{DIAS}

Competition with single proton emission

Shell-model interactions used are isospin symmetric, the corresponding spectroscopic factor for the $\Delta T = 3/2$ proton emission vanishes

$$S^{emp} = 3.7 \times 10^{-5} \qquad S^{Coul} = 6.5 \times 10^{-5} \qquad S^{\chi} = 6.3 \times 10^{-5}$$

imsrg++ code (R. Stroberg)

$$^{32}S(DIAS) \longrightarrow ^{31}P + p$$

S. Triambak *et al.*, Phys. Rev. C 73 (5 2006)

$$^{48}Ti \longrightarrow ^{47}Sc + p$$

The same semi empirical spectroscopic factor is employed in the calculation of the Γ_p for heavier nuclei

Nucleus	$\Gamma_{\gamma\gamma}/\Gamma_\gamma$	$\Gamma_{\gamma\gamma}/\Gamma_p$	$\Gamma_{\gamma\gamma}/\Gamma_{\text{IPC}}$	$\Gamma_{\gamma\gamma}/\Gamma_{\text{IC}}$
^{48}Ti	2×10^{-8}	7×10^{-10}	3×10^{-6}	0.06
^{76}Se	5×10^{-7}	$< 4 \times 10^{-9}$	7×10^{-6}	0.07
^{82}Kr	7×10^{-7}	$< 7 \times 10^{-9}$	3×10^{-6}	0.03
^{130}Xe	8×10^{-8}	$< 6 \times 10^{-9}$	1×10^{-7}	0.0002
^{136}Ba	1×10^{-7}	$< 3 \times 10^{-9}$	6×10^{-7}	0.001

B.Romeo, D. Stramaccioni, J. J. Valiente Dobón, and J. Menéndez; Phys. Lett. B 860 (2025) 139186

Challenge: extremely small decay width, difficult to populate 0^+_{DIAS}

- Good efficiency (small BRs, little statistics)
- Good time resolution (distinguising $\gamma\gamma$)

See J.J. Valiente talk

OUTLINE

- Introduction
  - Double beta decay
  - Double gamma decay
- Results
  - Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs
  - Potential of measuring $\gamma\gamma$
  - Experimental prospects
- **Summary**

Summary

- A **good correlation** has been found between $\gamma\gamma(M1M1)$ and $0\nu\beta\beta$-decay nuclear matrix elements within the nuclear shell model, for 19 nuclei comprising Ti, Cr and Fe ($46 \leq A \leq 60$) and 25 heavier nuclei including Zn, Ge, Se, Kr, Te, Xe and Ba ($72 \leq A \leq 136$), with several effective interactions

- The connection between $\gamma\gamma(M1M1)$ and $0\nu\beta\beta$ suggests a new avenue to **predict 0vββ-decay NMEs** from a **measurement** of $\gamma\gamma(M1M1)$ decay from $0^{+}(DIAS)$, providing an **uncertainty** based on many systematic calculations, less model dependent

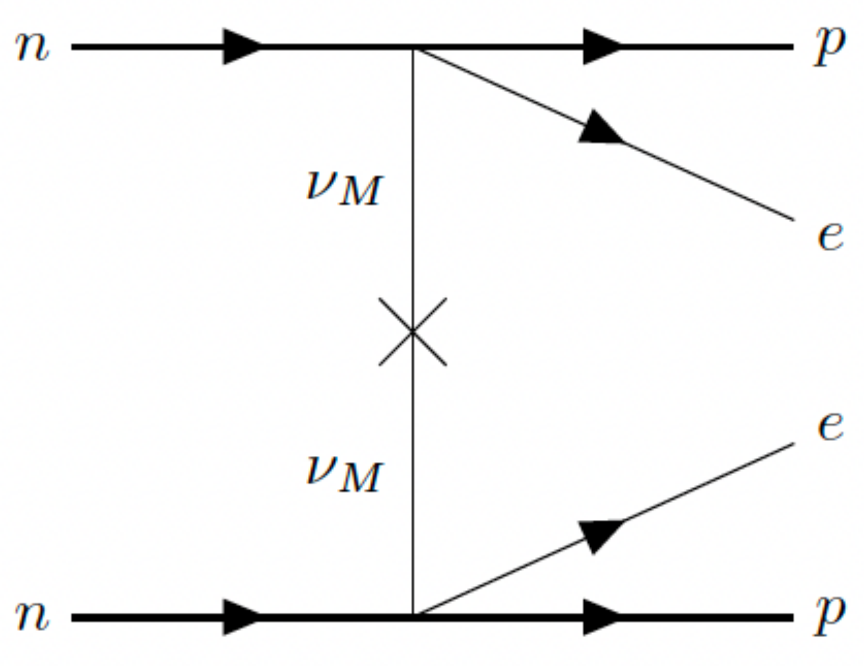
- Study of the implications to the sensitivity analysis of current and future $0\nu\beta\beta$ experiments has been performed

- Calculated branching ratios of the dominant competing decay channels: IC, IPC, **γ-decay**, and **proton emission**

- An **initial experiment** aiming to measure **γ-decay from ^{48}Ti(T=4,0^{+})** and cross section to populate it (D. Stramaccioni, M. Balogh, J.J. Valiente-Dobón) is underway

Thank you!

Light neutrino $M_L^{0\nu}$ in closure approximation



Lepton and hadron currents

$$j_{L\mu} = \bar{e}(x)\gamma_\mu(1-\gamma_5)\nu_{eL} \qquad \nu_{eL} = \sum_i U_{ei}\nu_{iL}$$

$$J_L^{\mu\dagger} = \langle p \,|\, \tau^-[g_V(p^2)\gamma^\mu + i g_M(p^2)\frac{\sigma^{\mu\nu}}{2m_N}p_\nu - g_A(p^2)\gamma^\mu\gamma_5 - g_P(p^2)p^\mu\gamma_5]\,|\, n\rangle$$

Long range part (closure app.)

$$M_{L,\alpha}^{0\nu} = \sum_{ij} \langle 0_f^+ \,||\, \mathcal{O}_{ij}^\alpha t_i^- t_j^- H_\alpha(r_{ij}) f_{\mathrm{SRC}}^2(r_{ij}) \,||\, 0_i^+ \rangle$$

Spin-space operators

$$\mathcal{O}_{ij}^F = \mathbb{1}, \quad \mathcal{O}_{ij}^{\mathrm{GT}} = \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j, \quad \mathcal{O}_{ij}^{\mathrm{T}} = 3(\boldsymbol{\sigma}_i \cdot \hat{\mathbf{r}}_{ij})(\boldsymbol{\sigma}_j \cdot \hat{\mathbf{r}}_{ij}) - \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$$

$f_{\mathrm{SRC}}(r_{ij})$ short-range correlations

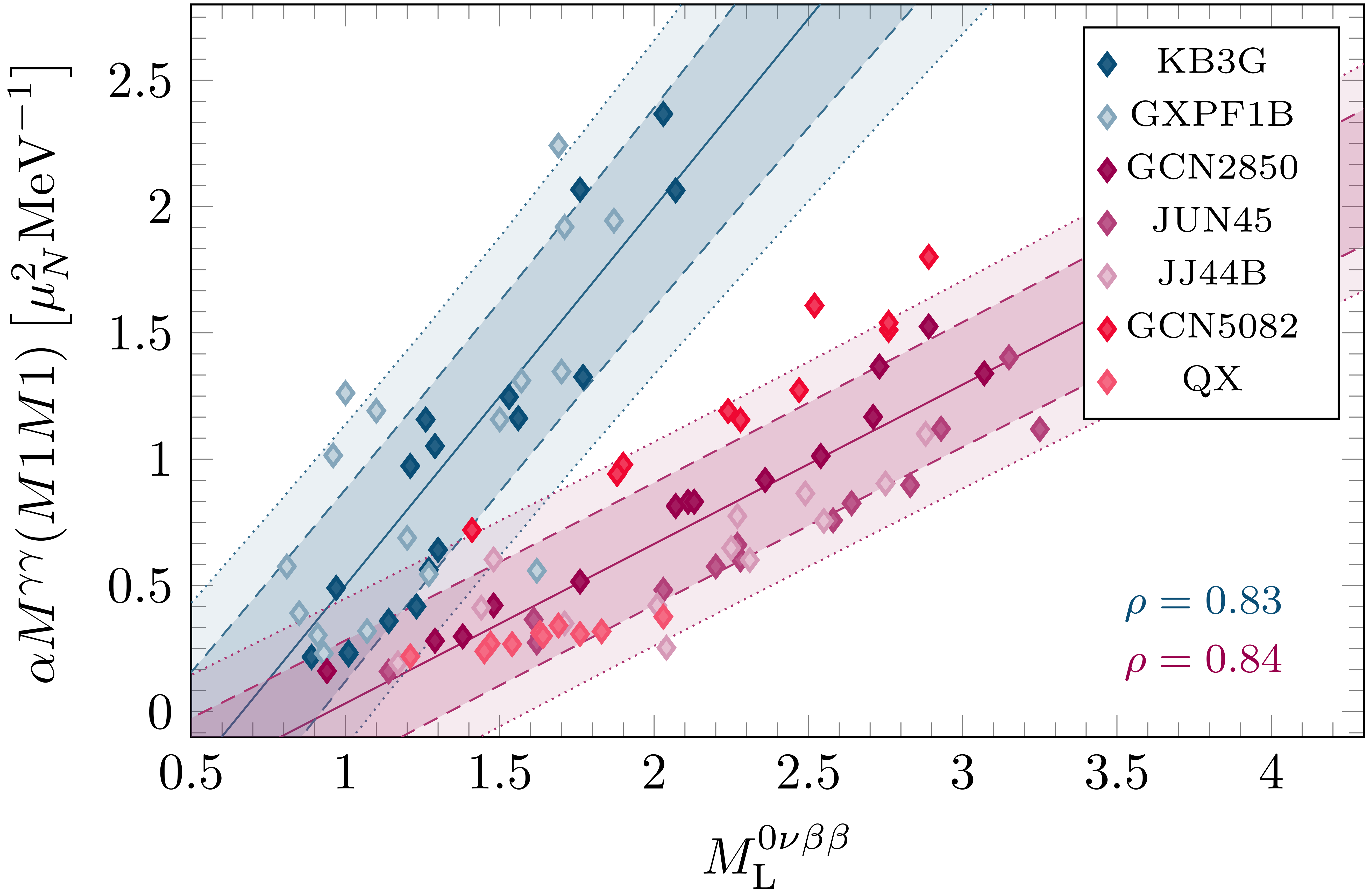
$$f_{\mathrm{SRC}}(r_{ij}) = 1 - c e^{-ar^2}(1 - br^2)$$

Neutrino potentials $E_k + \frac{1}{2}(E_i + E_f) \longrightarrow E_{cl}$

$$H_\alpha(r_{ij}, E_k) = \frac{2R}{\pi}\int_0^\infty dq \frac{q^2 j_\lambda(q r_{ij}) h_\alpha(q^2)}{q(q + E_k + (E_i + E_f)/2)} \longrightarrow H(r_{ij})$$

Backup

Double gamma decay correlation



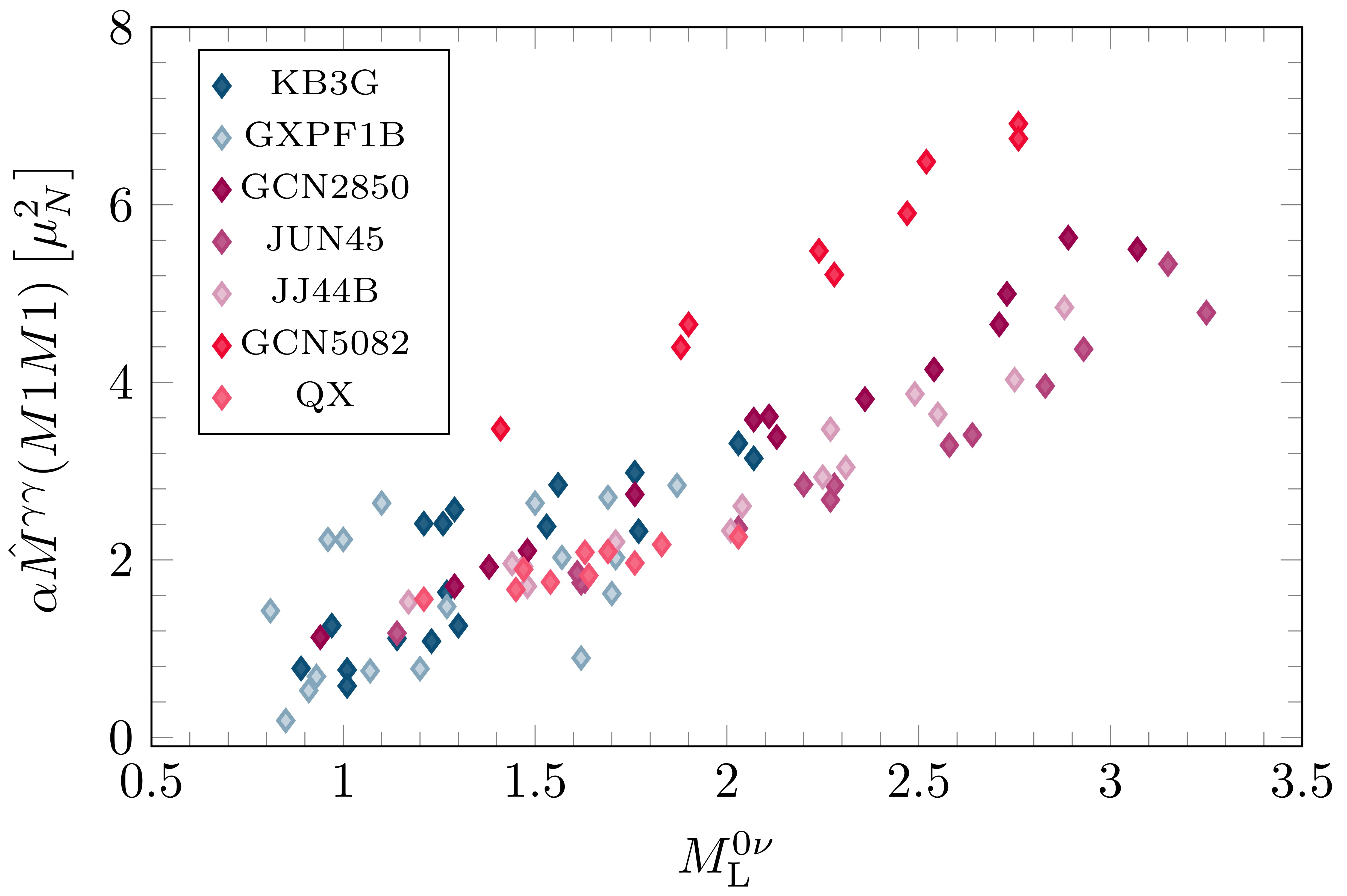
Phys. Lett. B 827, 136965 (2022)

Backup

Intermediate states energies effect

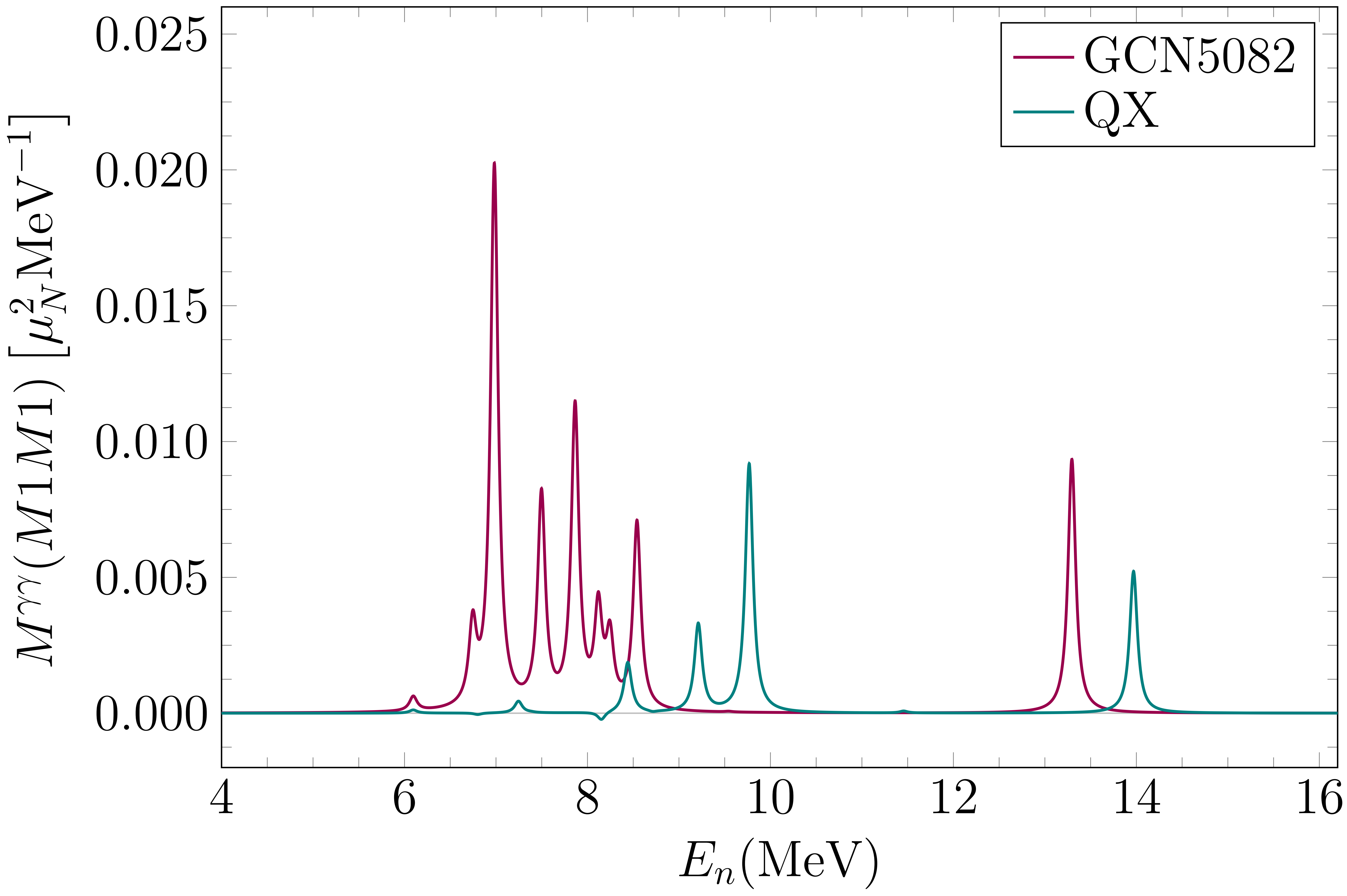
Behind this different slope it is the **energy denominator**

$$\hat{M}^{\gamma\gamma}(M1M1) \equiv \sum_{1_n} \langle 0_f^+ \parallel \mathbf{M1} \parallel 1_n^+ \rangle \langle 1_n^+ \parallel \mathbf{M1} \parallel 0_i'^+ \rangle$$



Backup

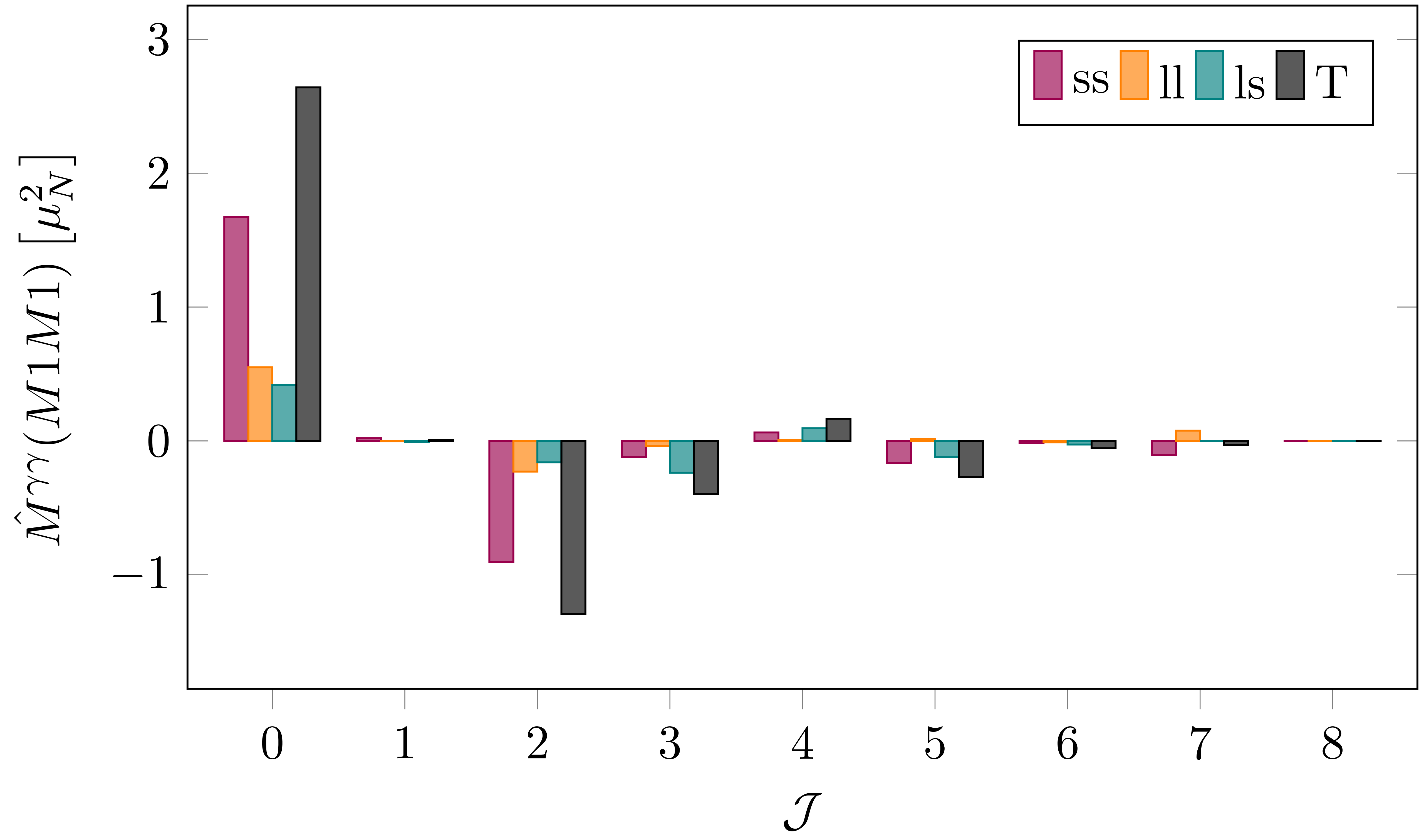
Effective interaction effect in sdhg configuration space

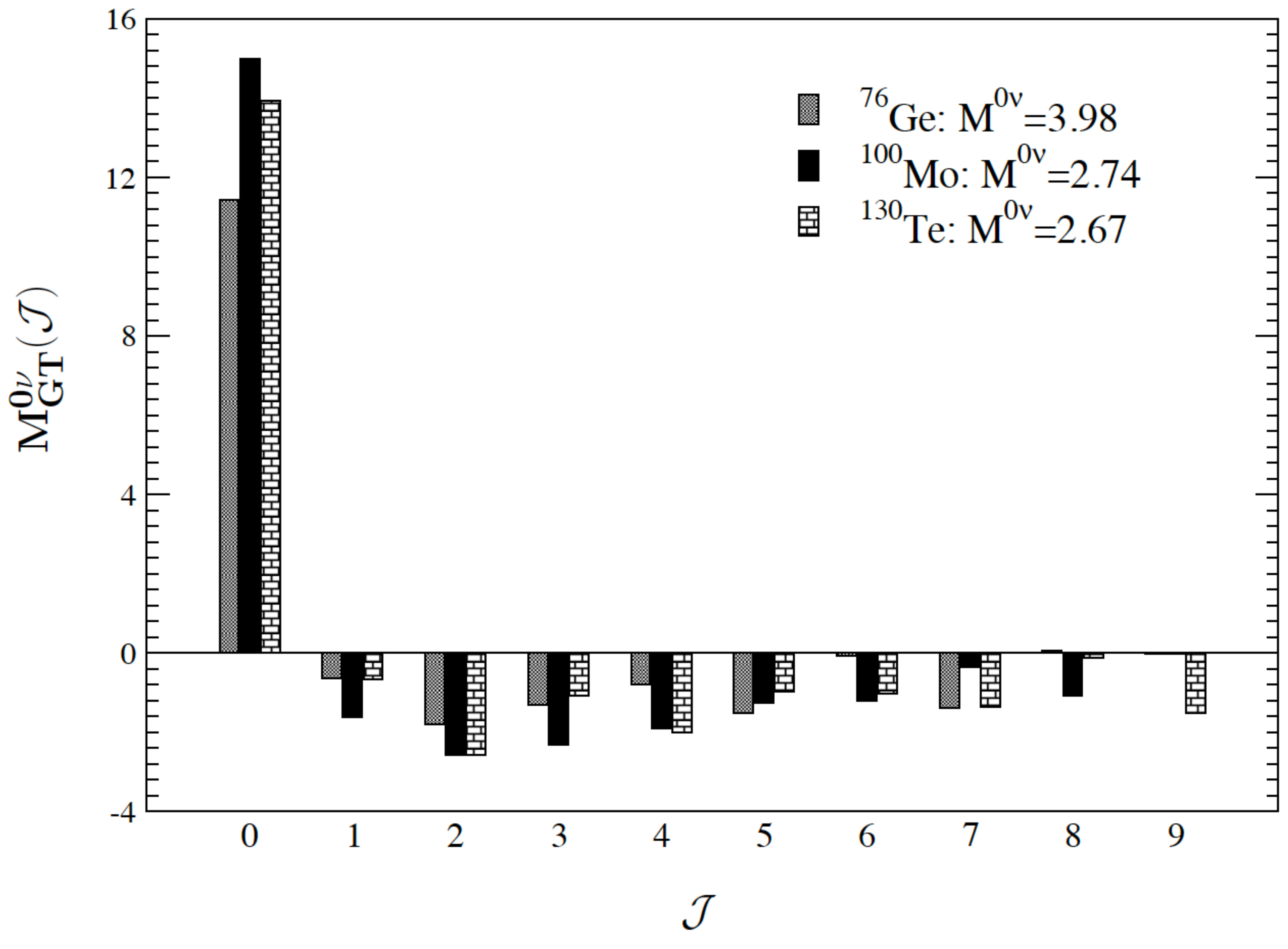


Backup

Spin Orbital and Interference contributions

For $M^{0\nu\beta\beta}$ is revealing the J^P decomposition, nn and pp coupled to J^P





Phys. Rev. Lett. 117, 179902 (2016)

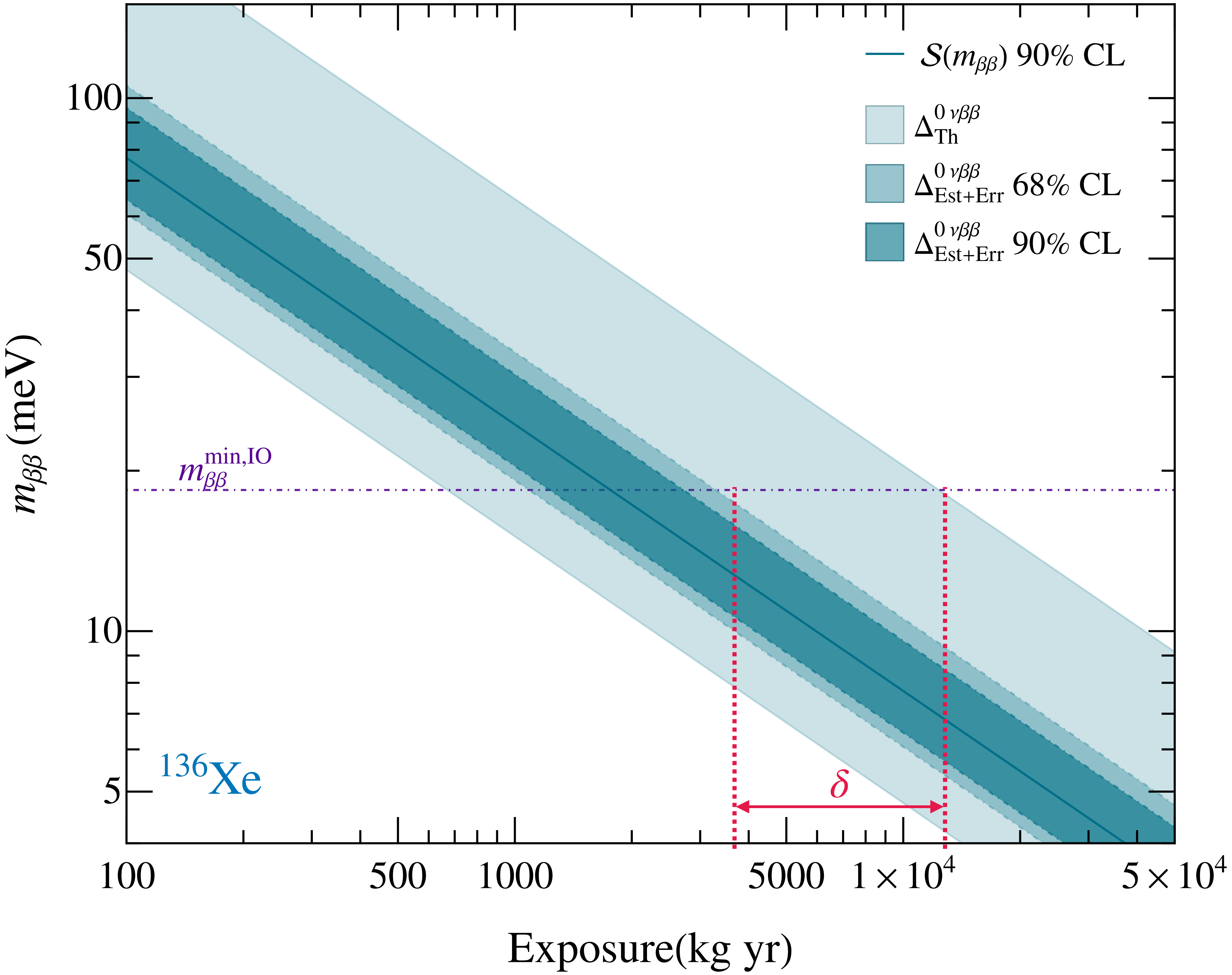
The spin component is the dominant contribution for J=0,2

But also it is where the strongest cancellation is observed

Backup

$m_{\beta\beta}$ sensitivity

Quantitative reduction δ in the exposure to completely cover the inverted ordering region



B.Romeo, AIP Conf. Proc. (MEDEX'22)

Backup

$m_{\beta\beta}$ sensitivity

Horizontal dashed lines show 90%CL current upper limits from $0\nu\beta\beta$ searches

Tightest and loosest limits among those reported in the literature, most stringent from KamLAND-Zen (with largest NMEs) and less stringent from CUORE (with lowest NMEs)

Orange lightest shaded area: uncertainity current calculations

Orange darker shaded areas: uncertainty estimated from correlation at 68(90)%CL