Neutrinoless Double-Beta Decay

Insights from Electromagnetic Decays

Recommended Values for Neutrinoless Double-Beta Decay NMEs

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TRIUMF

OUTLINE

- **Introduction**
  - Double beta decay
  - Double gamma decay
- **Results**
  - Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs
  - Potential of measuring $\gamma\gamma$ & experimental prospects
  - Preparatory experiment @ IFJ-PAN
  - Correlation $2\nu\beta\beta$-$0\nu\beta\beta$ NMEs
- **Summary and outlook**

Introduction

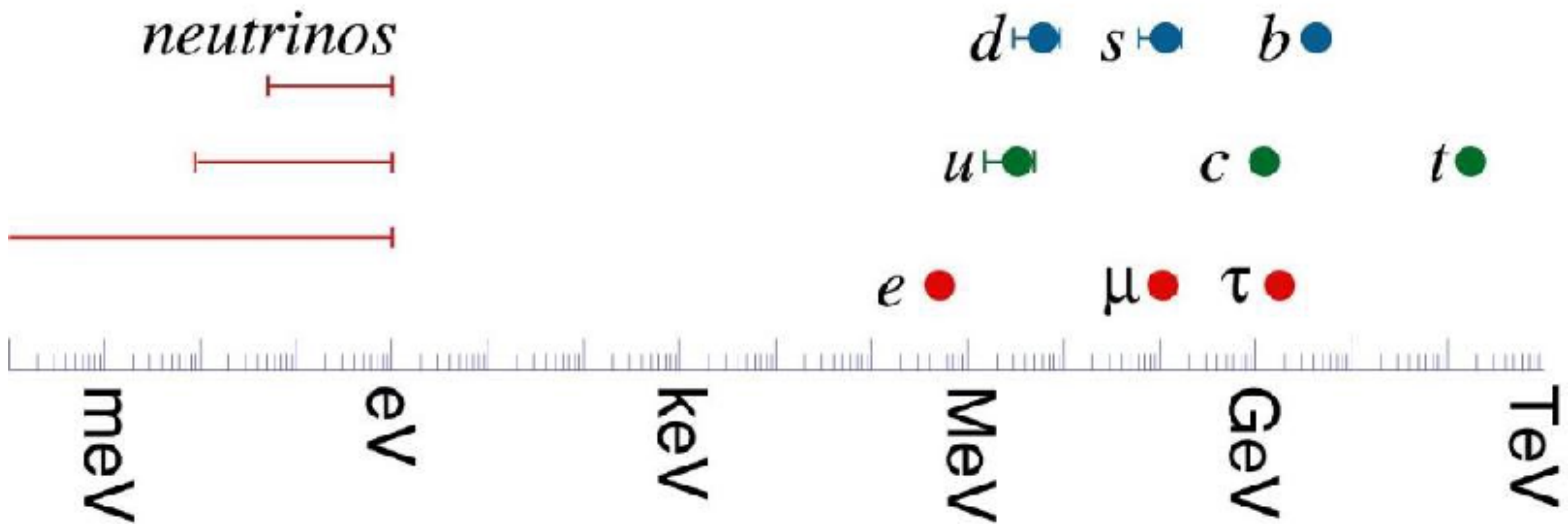
Standard Model open questions

The Standard Model (SM) describes many experimental observations with impressive accuracy, but there are yet **unsolved puzzles**

Most pressing shortcomings

- Missing dark-matter candidate
- Baryon asymmetry
- **Neutrino masses**

Why they are so small?



Intrinsically related with the **nature of neutrinos** (Dirac or Majorana)

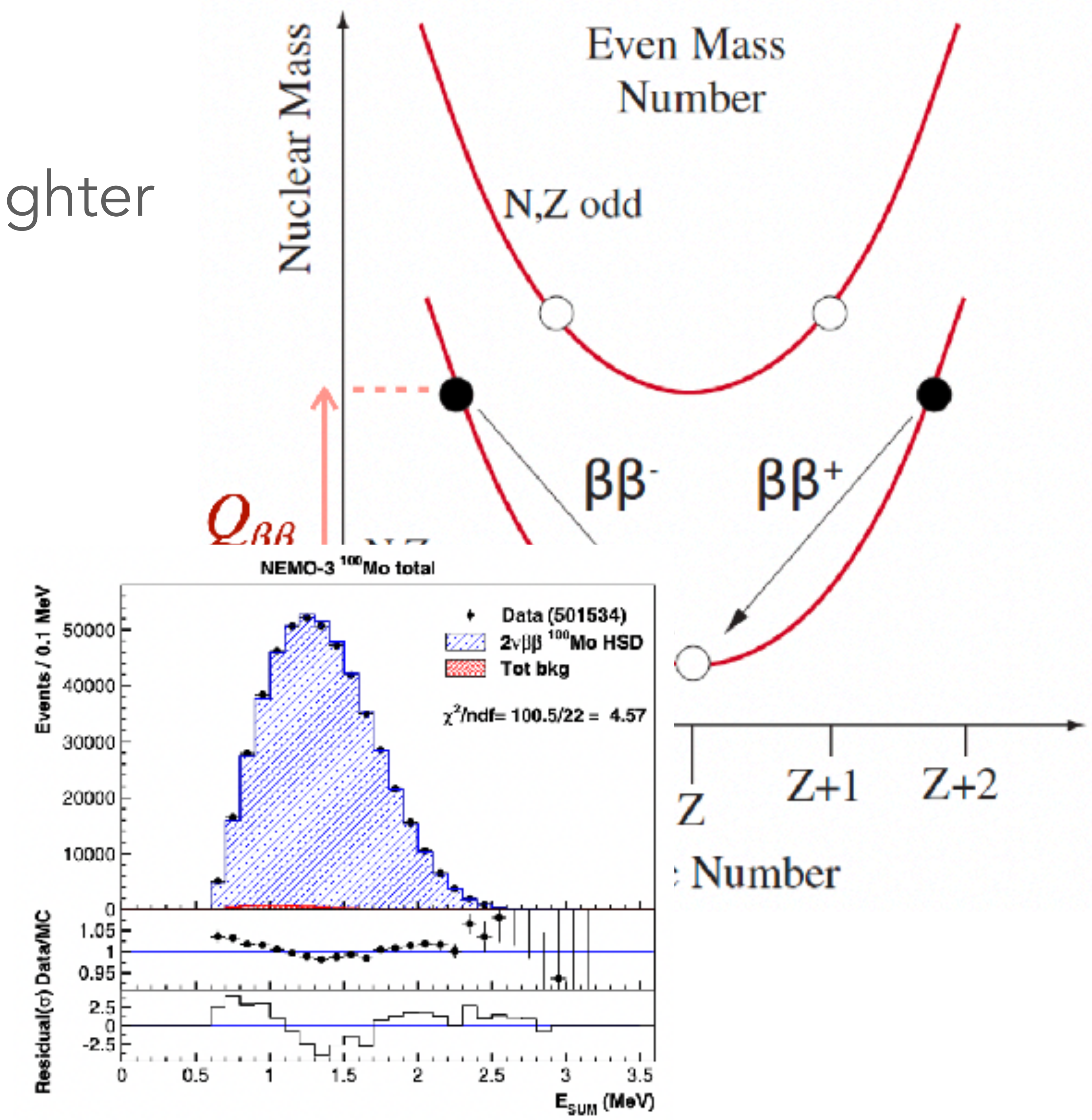
Majorana mass term violates lepton number (LNV) $\Delta L = 2$

The most feasible process to observe LNV and test Majorana nature of ν's is $0\nu\beta\beta$

Introduction

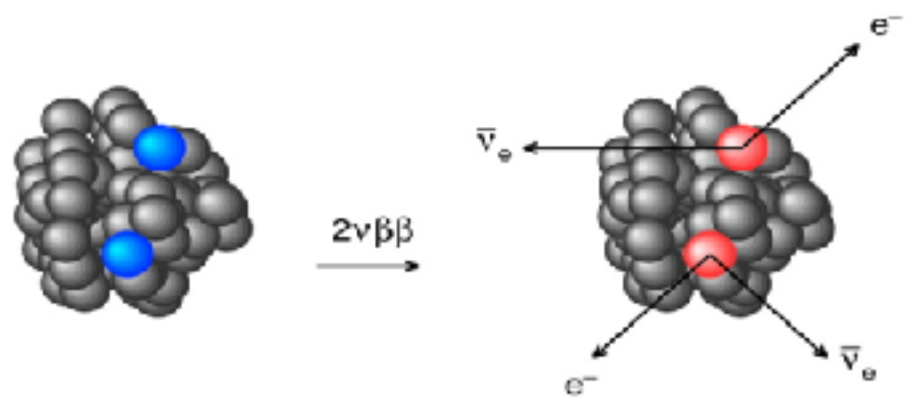
$2\nu\beta\beta$ & $0\nu\beta\beta$ decay modes

Candidate isotopes **even-even** nuclei which due to nuclear pairing force are lighter than the odd-odd (A,Z-1) nucleus (single beta decay kinematically forbidden)

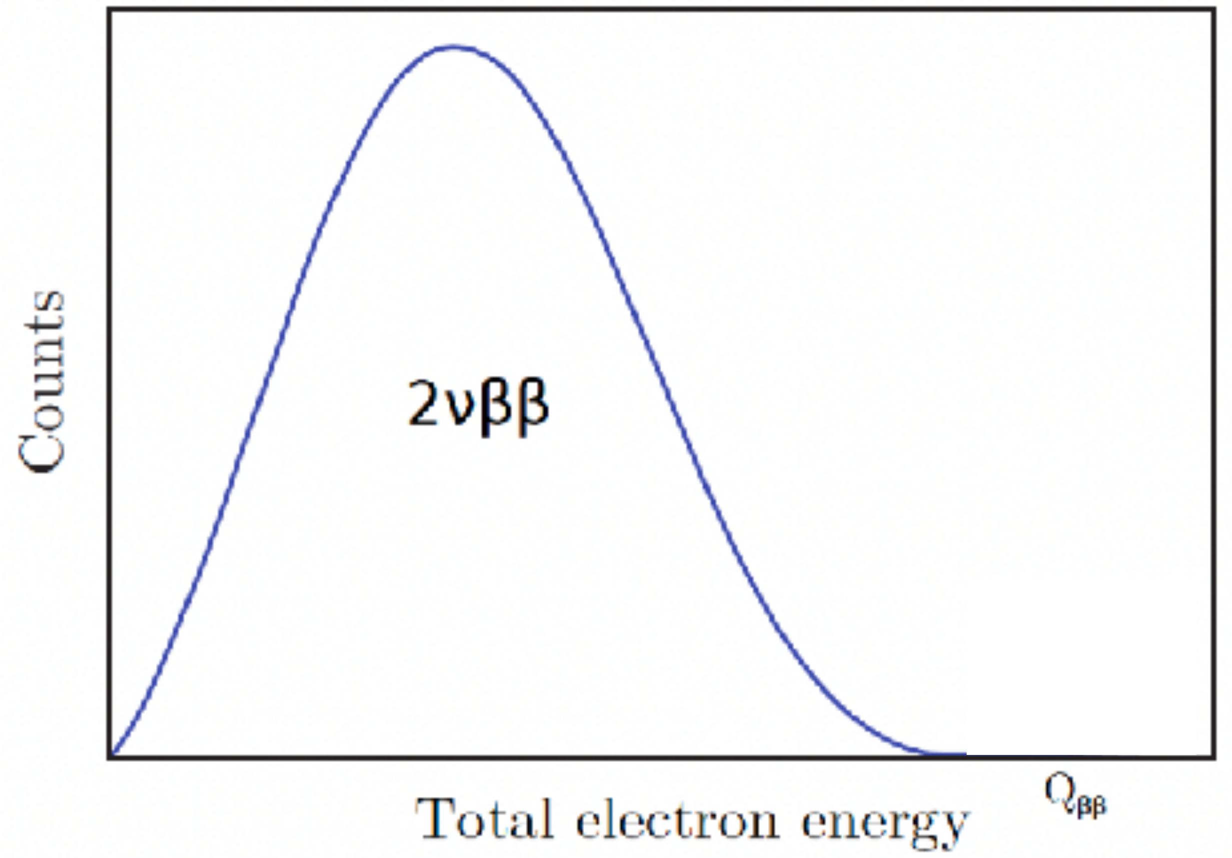


Possible for 35 nuclei

Standard $2\nu\beta\beta$-decay



(A,Z) $\quad$ $(A,Z+2)+2e^{-}+2\bar{\nu}_e$



- Allowed by Standard Model - Letpon number conserved
- Observed in 11 isotopes
- Half-lives $10^{18}-10^{21}y$
- Improved precision: test **nuclear structure** & **search new physics**

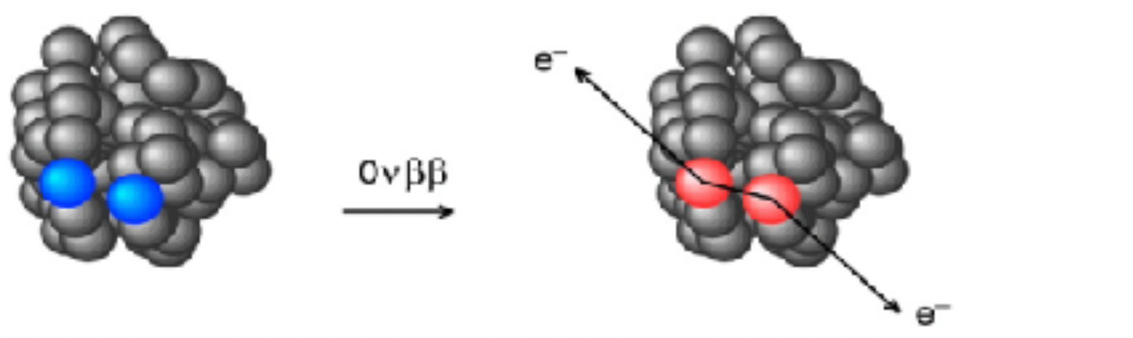
R Arnold *et. al.* Eur. Phys. J. C 79, 440 (2019)

$2\nu\beta\beta$ & $0\nu\beta\beta$ decay modes

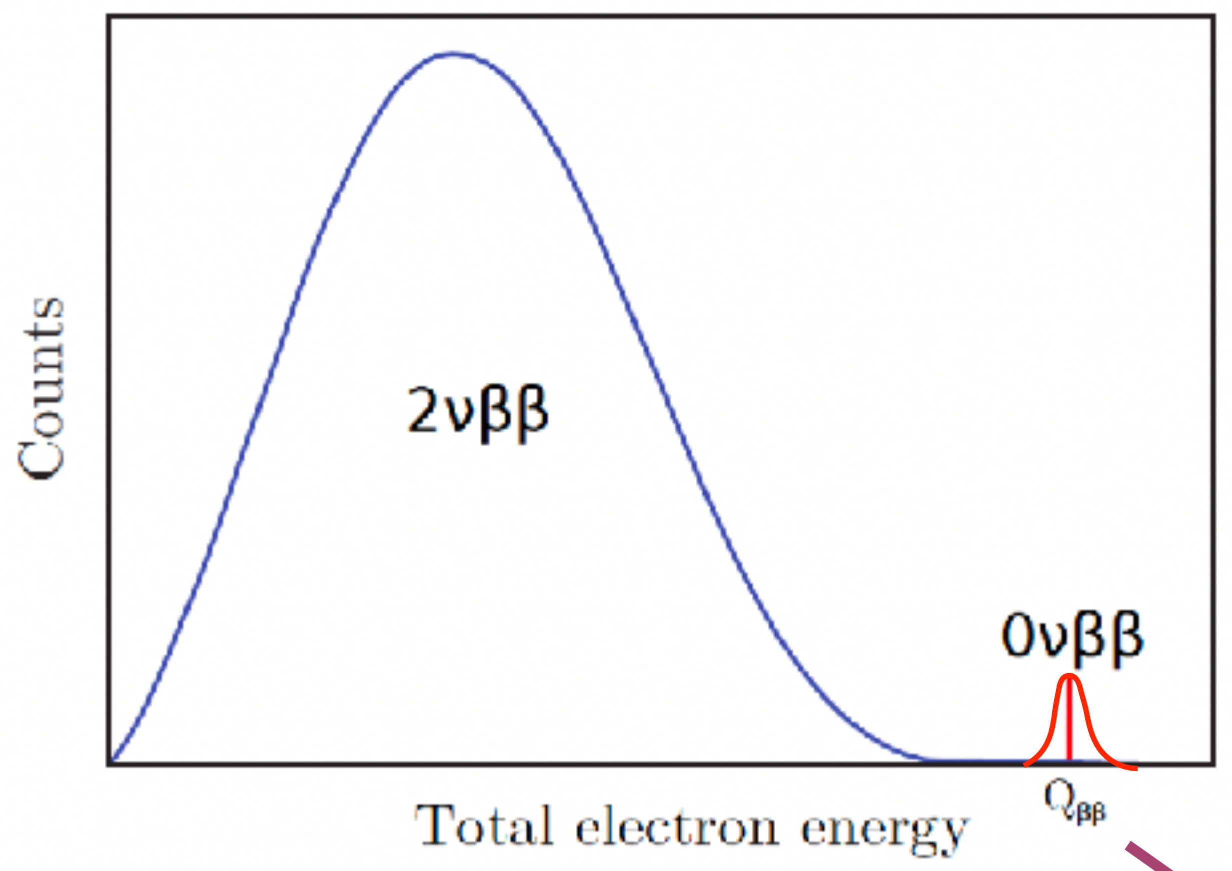
Candidate isotopes **even-even** nuclei which due to nuclear pairing force are lighter than the odd-odd (A,Z-1) nucleus (single beta decay kinematically forbidden)

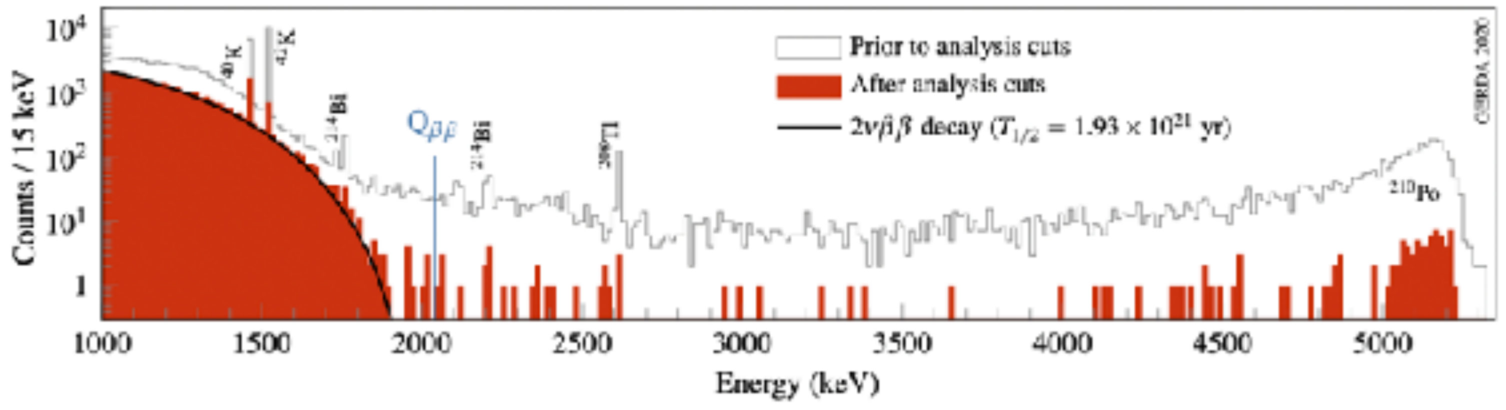
Possible for 35 nuclei

Beyond Standard Model $0\nu\beta\beta$-decay



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





^{76}Ge M Agostini Phys. Rev. Lett 125, 252502 (2020)

- Not allowed within Standard Model-**Letpon number violated**
- Immediately demonstrate **Majorana** nature of ν
- Current limits $> 10^{26}y \sim 10^{15}$ age of the universe!

necessary condition for discovery!

Introduction

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

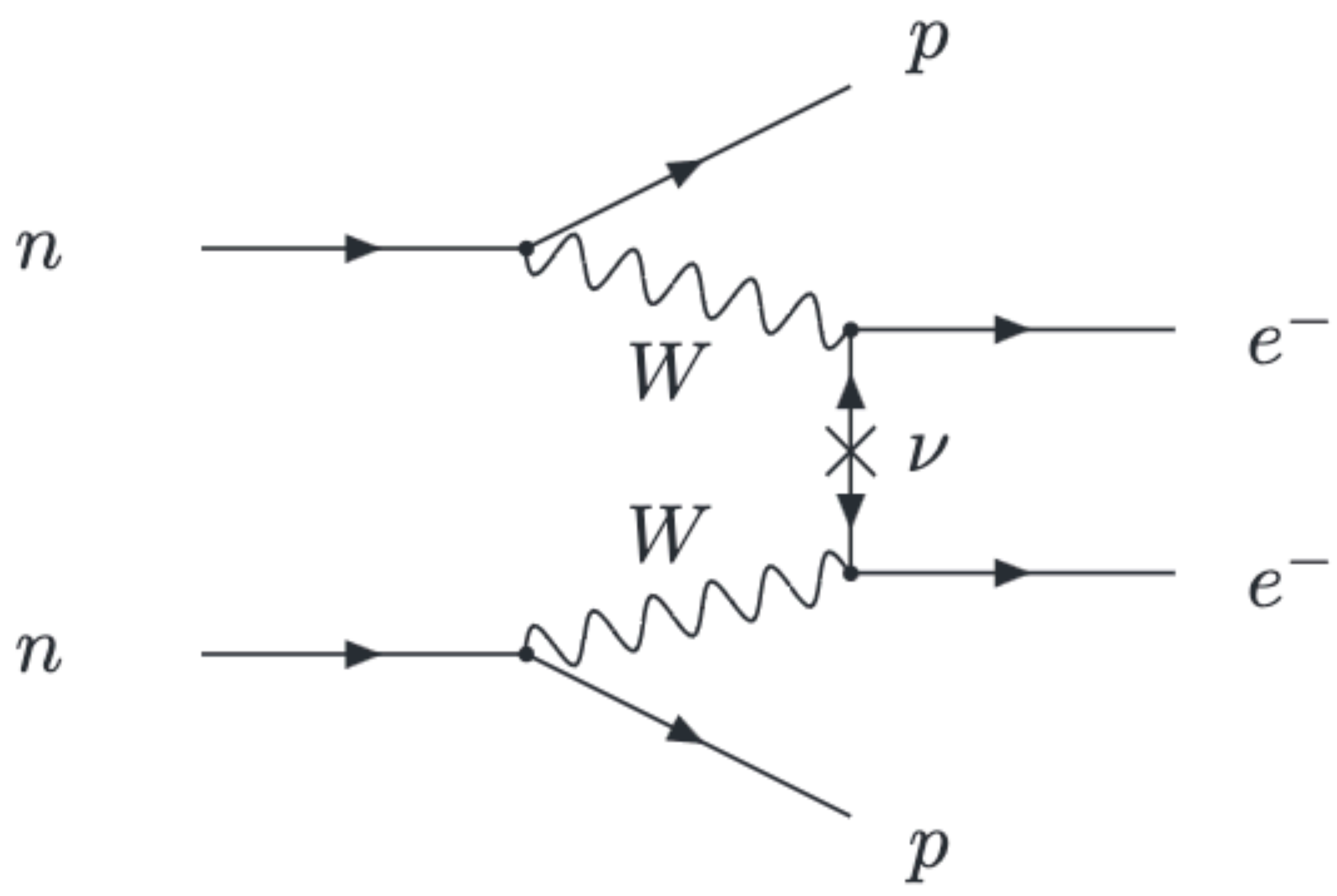
$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu}(Q,Z)(M^{0\nu})^2\phi^2$$

Phase Space Factor

New Physics parameter

$M^{0\nu}$ **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

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

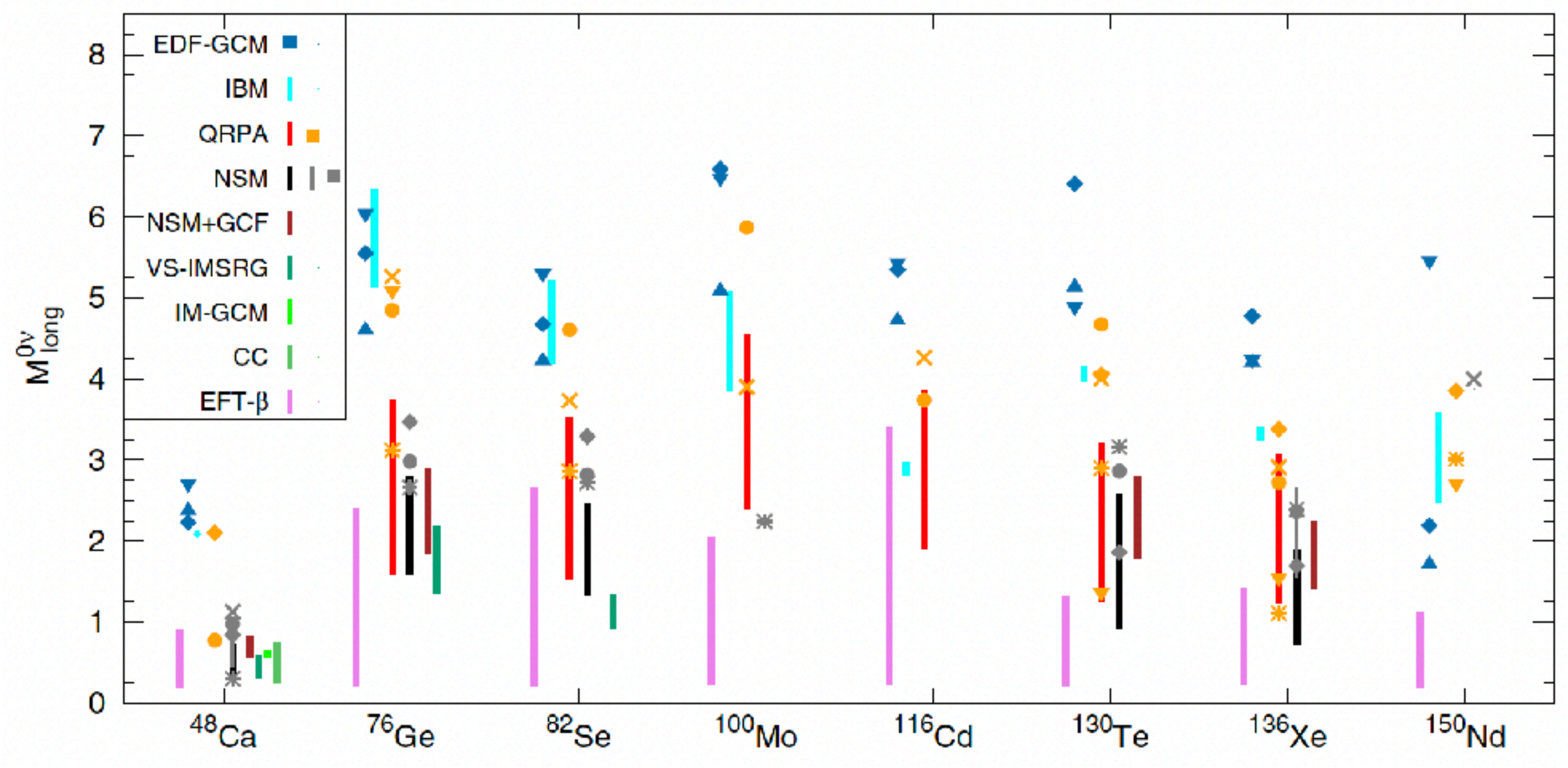
J. Engel, and J.Menéndez, Rep. Prog. Phys. 80 045301(2017)

Introduction

Discrepancy in the predicted NMEs

NMEs are an input that must be calculated within a nuclear structure model

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



JJ Gómez-Cadenas *et. al.*,*Nuovo Cim.* 45, 619–692 (2023)

Phenomenological character of most calculations prevent reliable uncertainty estimation

To take advantage of $0\nu\beta\beta$ experiments to **test theoretical models**, need **accurate** predictions of the **NME** with **controlled uncertainties**

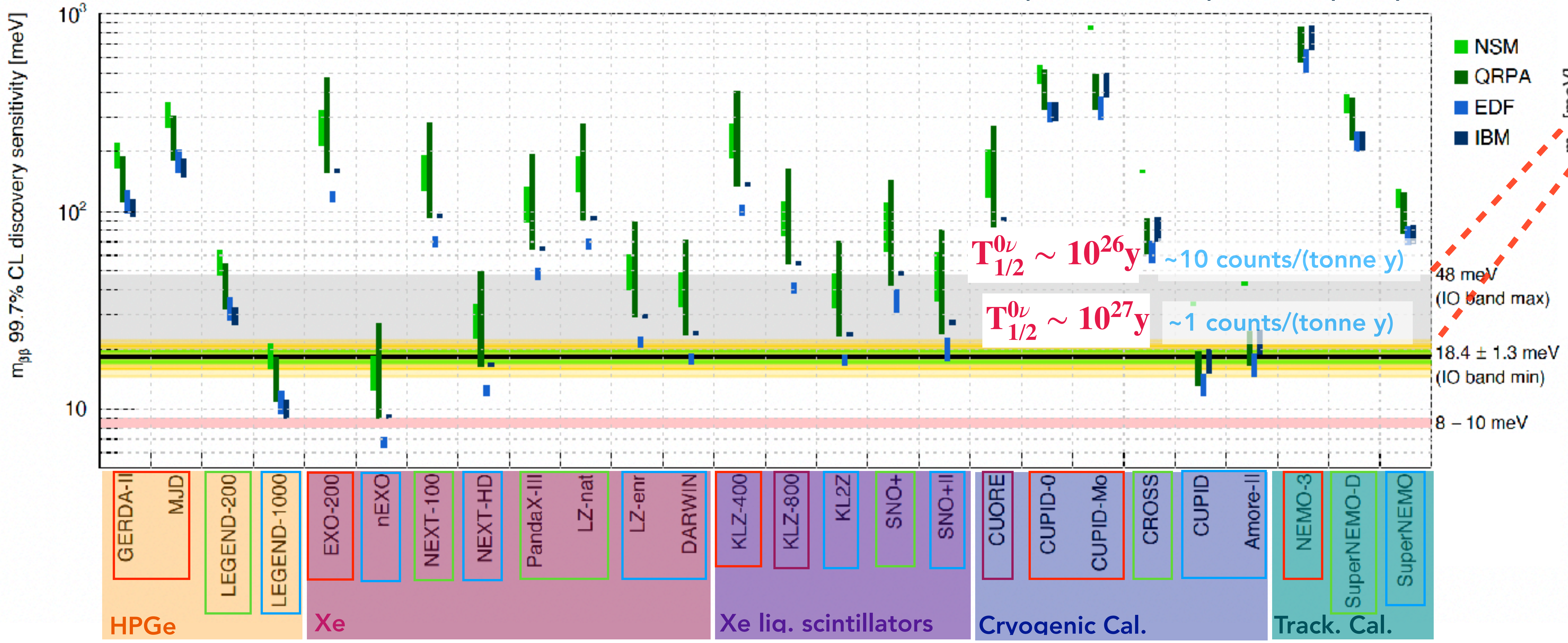
Also experimentalist need them to **plan** their **physics reach**

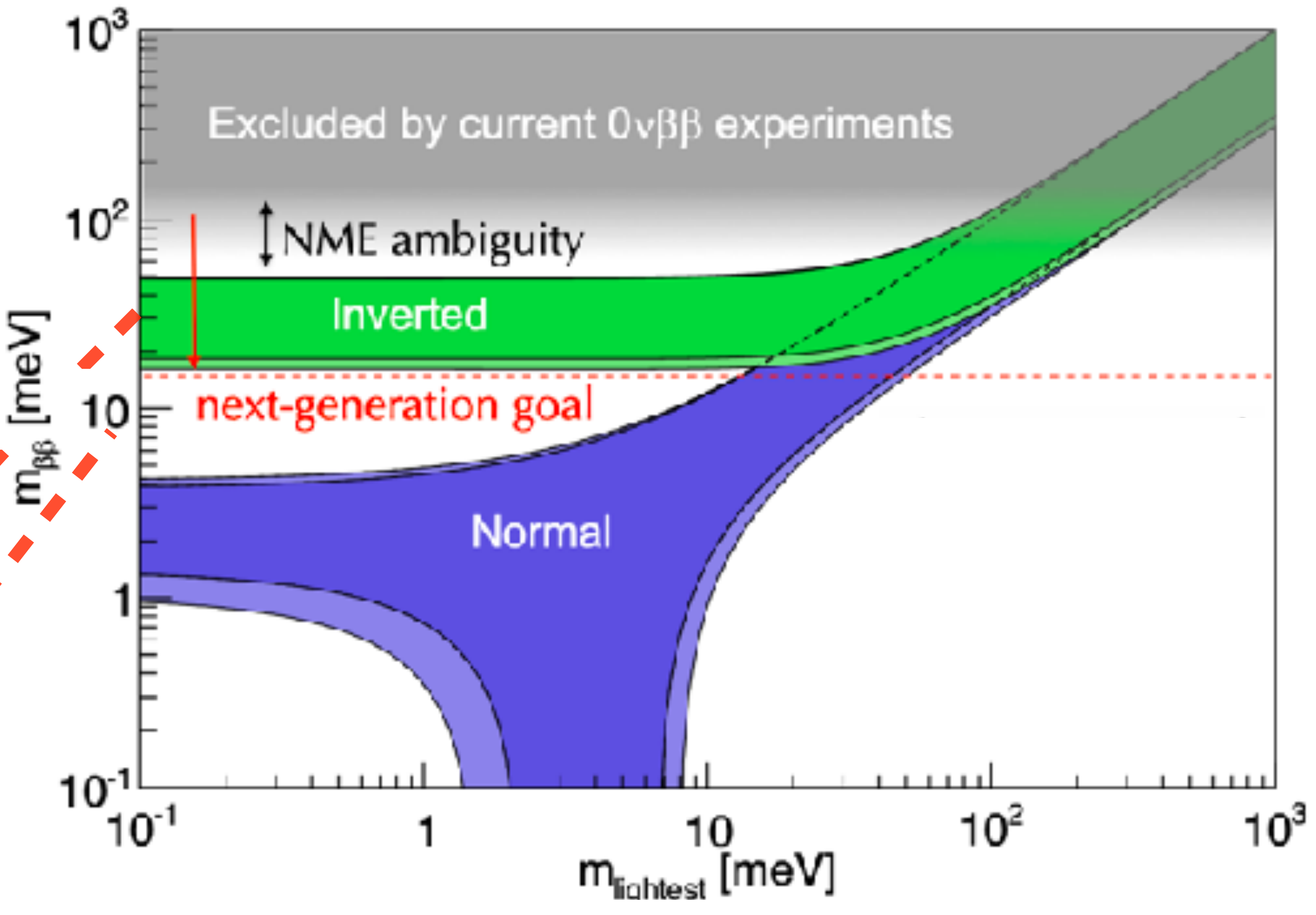
Introduction

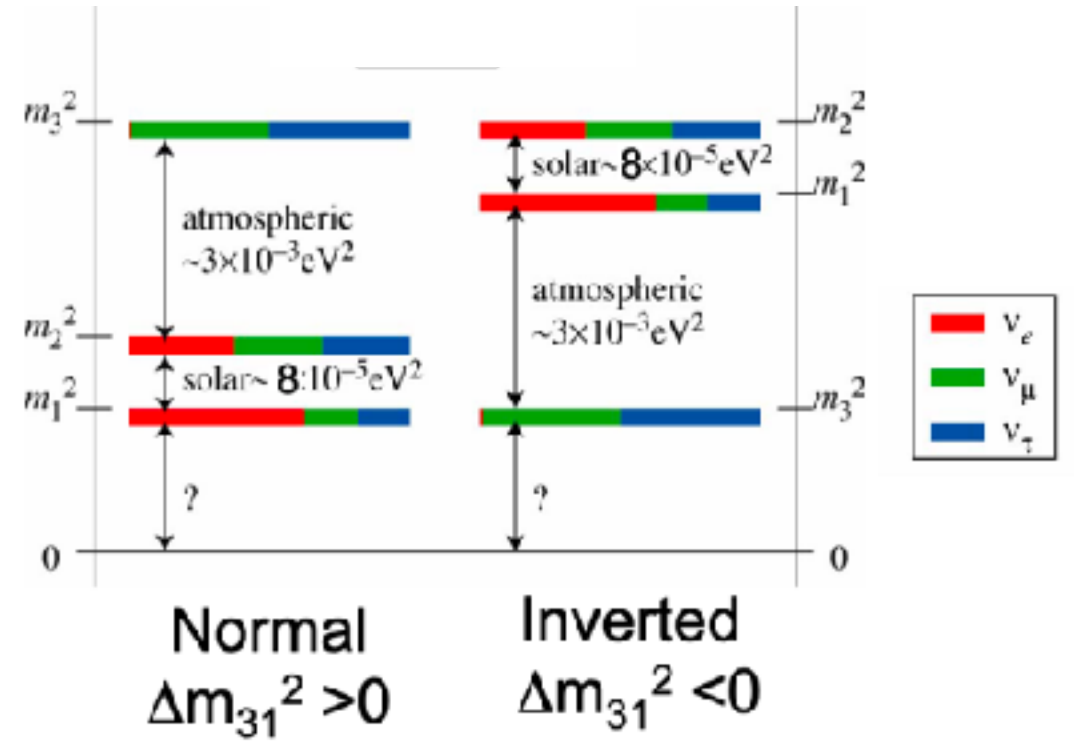
Motivation of neutrinoless double beta decay - $0\nu\beta\beta$

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

JJ Gómez-Cadenas *et. al.*,*Nuovo Cim.* 45, 619–692 (2023)







Take advantage of $0\nu\beta\beta$ experiments **test theoretical models**, **accurate** predictions of the **NME** with **controlled uncertainties**

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

Approach to constrain $0\nu\beta\beta$ NMEs

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

Double charge-exchange reactions, nuclear transitions where $|i\rangle$ and $|f\rangle$ are the same as in $0\nu\beta\beta$, **transition operators similar** ($\sim\sigma\tau$)

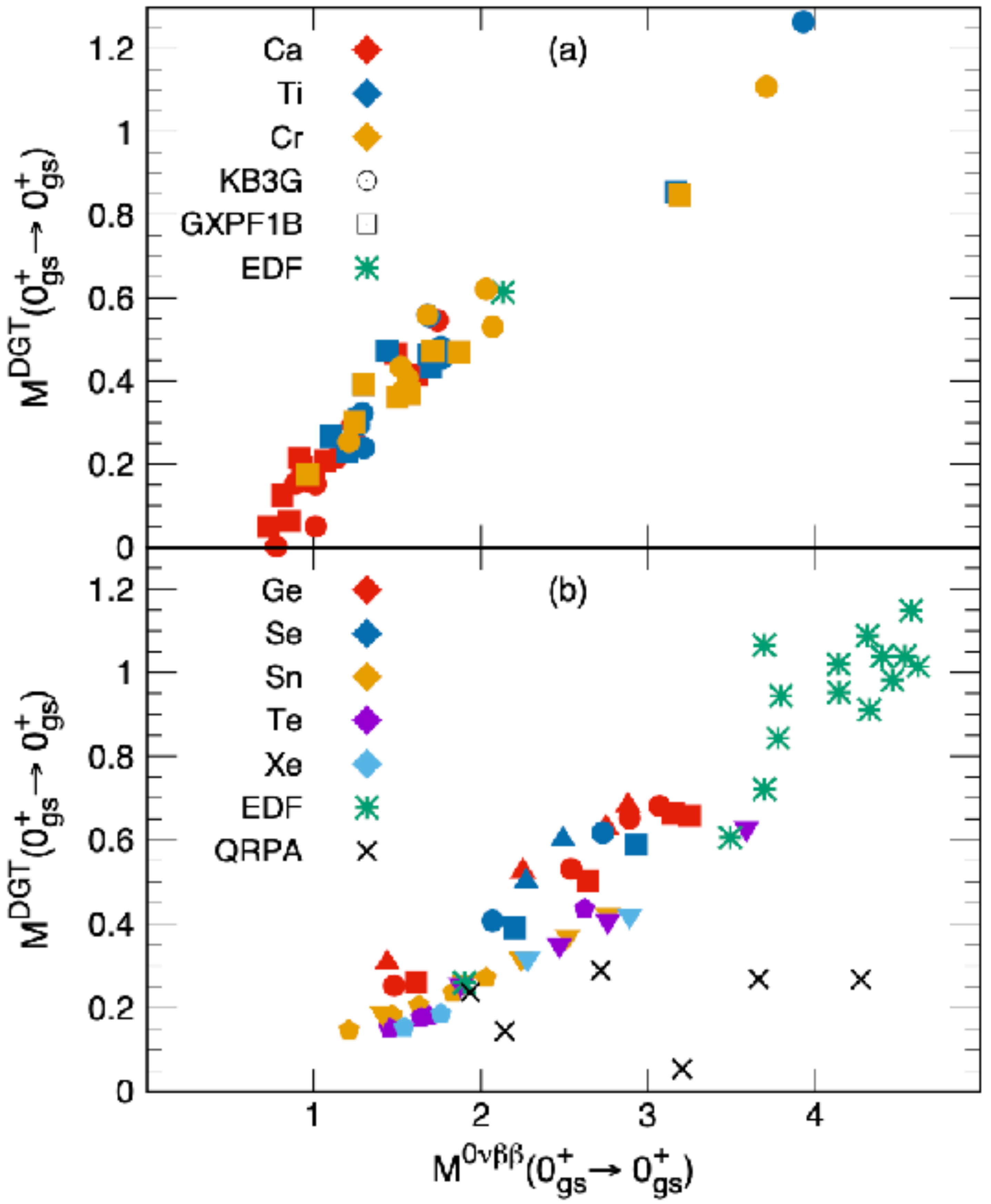
$^{130}Te(^{20}Ne,^{20}O)^{130}Xe$: nn $\longrightarrow$ pp | pp $\longrightarrow$ nn

NUMEN (INFN-Laboratori Nazionali del Sud) accessing $0\nu\beta\beta$ NMEs, measuring the cross sections of DCE reactions

Encouraged by 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** (small fraction total strength, tiny cross section)



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

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

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

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

Electromagnetic transitions **powerful** nuclear spectroscopic tool

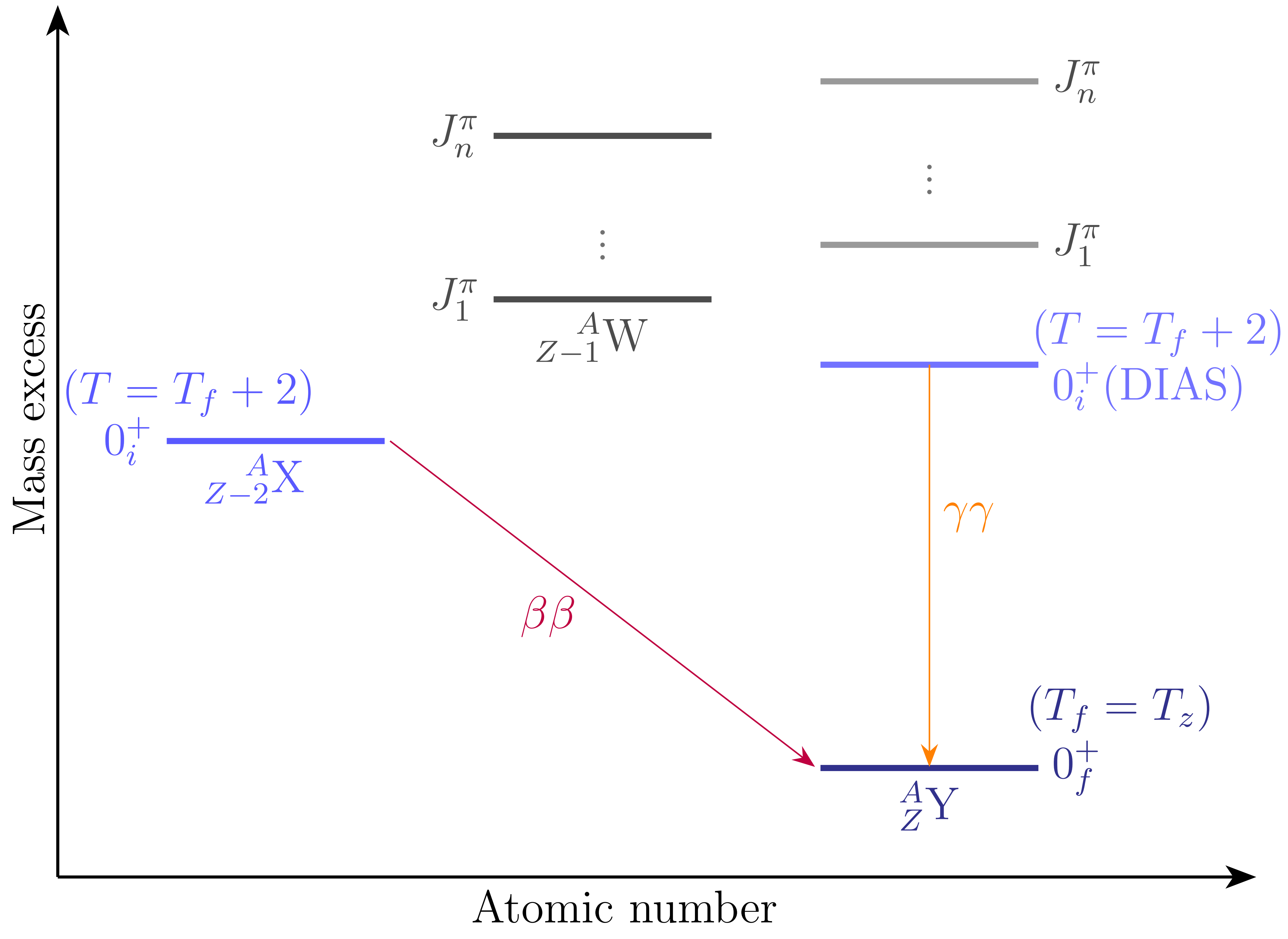
$\gamma\gamma$ and $\beta\beta$ nuclear states relation

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

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

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 $0\nu\beta\beta$



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

$\gamma\gamma$ 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)

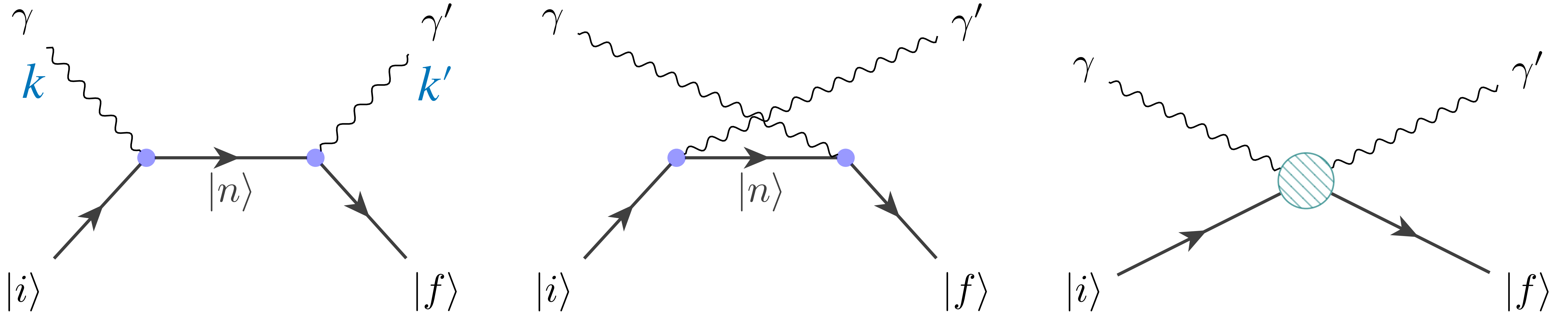
Transition amplitude

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

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

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

Subleading



(a) (b) (c)

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

$\gamma\gamma$ decay transition amplitude

Transition amplitude is proportional to

$$P^{LL'(2)} \sim \sum_{n,J_n} \left[\frac{\langle J_f || \mathcal{O}(SL,k_0) || J_n \rangle \langle J_n || \mathcal{O}(S'L',k_0') || J_i \rangle}{E_n - E_i + k_0'} + (-1)^{J-L-L'} (S,L,k_0 \leftrightarrow S',L',k_0') \right]$$

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

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

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

Electric (EL) and magnetic (ML) multipoles

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

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

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

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

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

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

$\longrightarrow$ **MLML** or **ELEL**

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

$$\mathbf{M1} \sim (g^l \mathbf{l} + g^s \frac{1}{2}\boldsymbol{\sigma}) \qquad \textbf{GT} \sim \sigma \cdot \tau$$

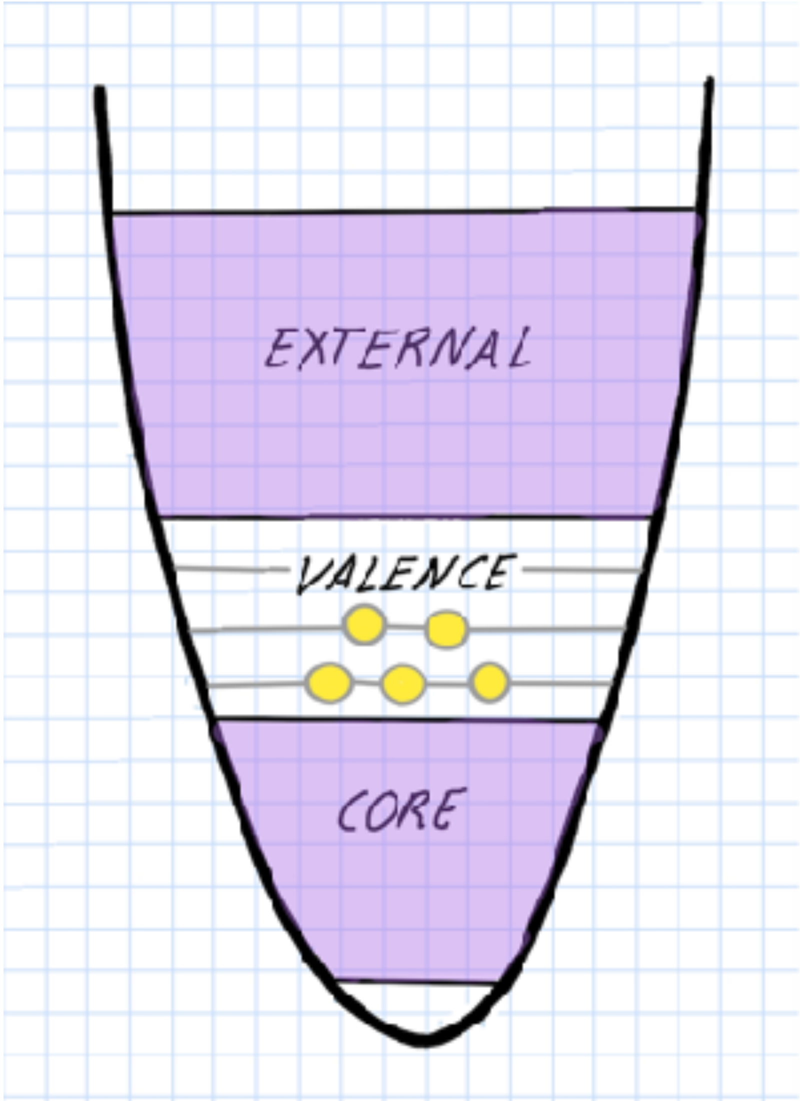
$P_0 \sim (k_0 k_0')^L$ statistically photons have the same energy

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

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

Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs
The nuclear shell model

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



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

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

$|\Psi_i^{\text{eff}}\rangle = \sum_{k=1}^{d} a_{ij}|\Phi_j\rangle$ a_{ij} obtained from diagonalising H_{eff}

$|\Phi_\alpha\rangle = \prod_{\alpha_i=(n_i,l_i,j_i,m_i,m_{t_i})}^{A} c^\dagger_{\alpha_i}|0\rangle$ Slater determinant

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

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

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

Nuclear interactions and configuration spaces

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

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

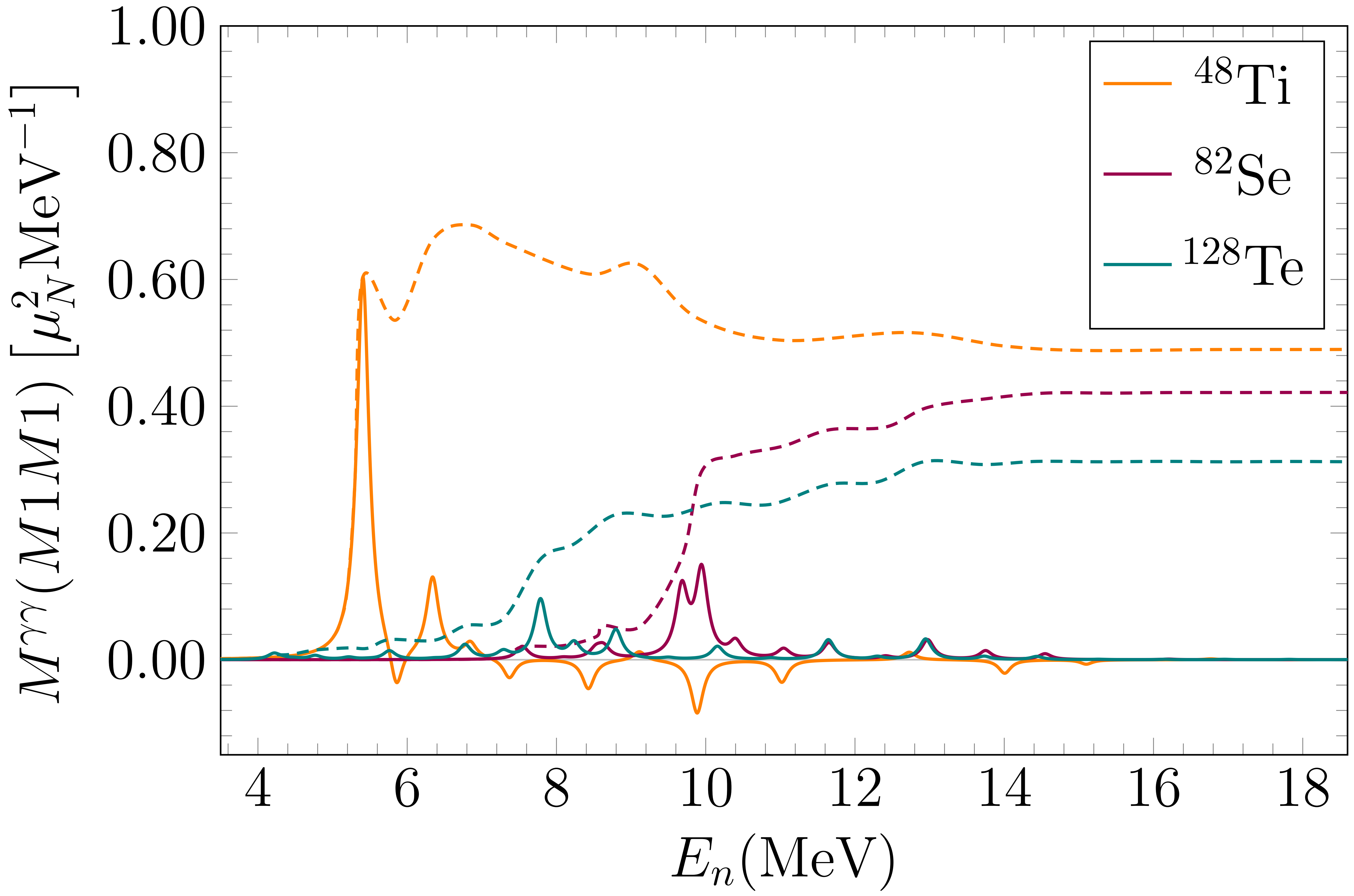
Double gamma decay matrix elements

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

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

Few states contribute to the total matrix element

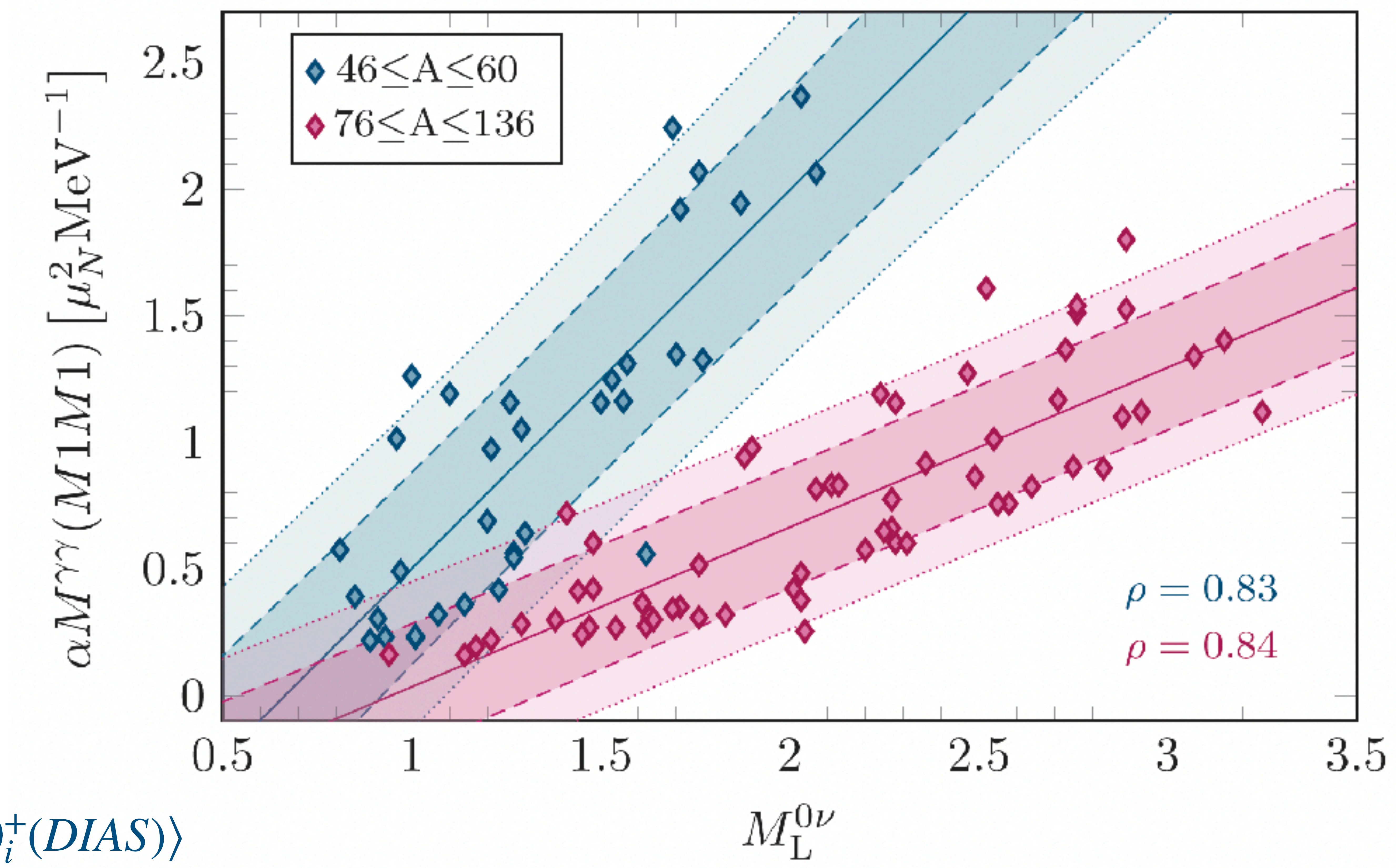
Energies of dominant states different for medium and heavier mass nuclei



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,JUN45,GCN2850,QX, GCN5082

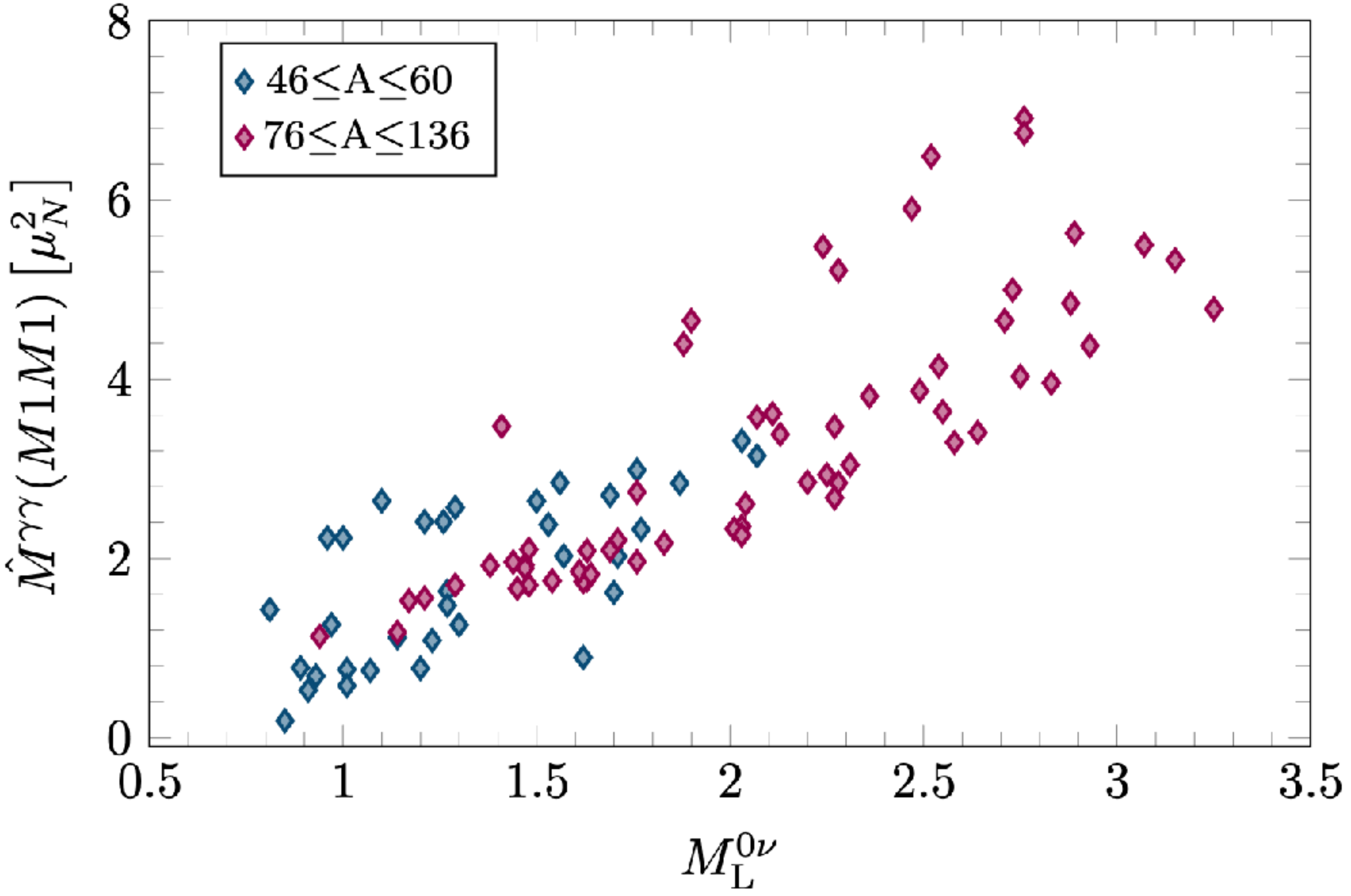


$$M^{\gamma\gamma}(M1M1) = \sum_n \frac{\langle 0^+_{gs} || \mathbf{M1} || 1^+_n(IAS)\rangle \langle 1^+_n(IAS) || \mathbf{M1} || 0^+_i(DIAS)\rangle}{E_n - \frac{1}{2}(E_i + E_f)}$$

BR, J.Menéndez and C. Peña-Garay, Phys. Lett. B 827, 136965 (2022)
$M_L^{0\nu}$ from N. Shimizu *et. al.* Phys. Rev. Lett 120, 142502 (2018)

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

Effect of intermediate states energies



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

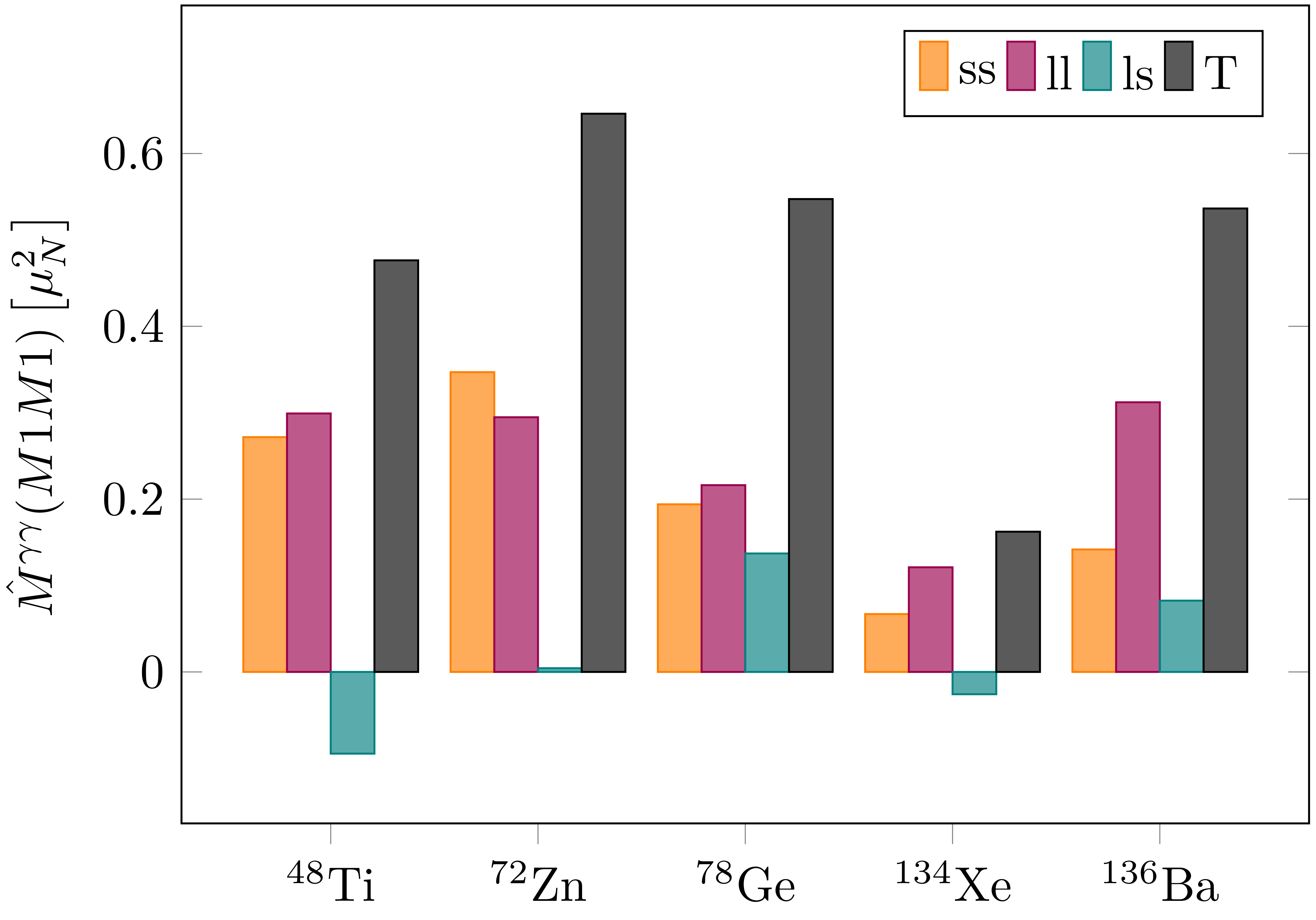
$$\hat{M}^{\gamma\gamma} = \hat{M}^{\gamma\gamma}_{\rm ss} + \hat{M}^{\gamma\gamma}_{\rm ll} + \hat{M}^{\gamma\gamma}_{\rm ls}$$

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

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

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

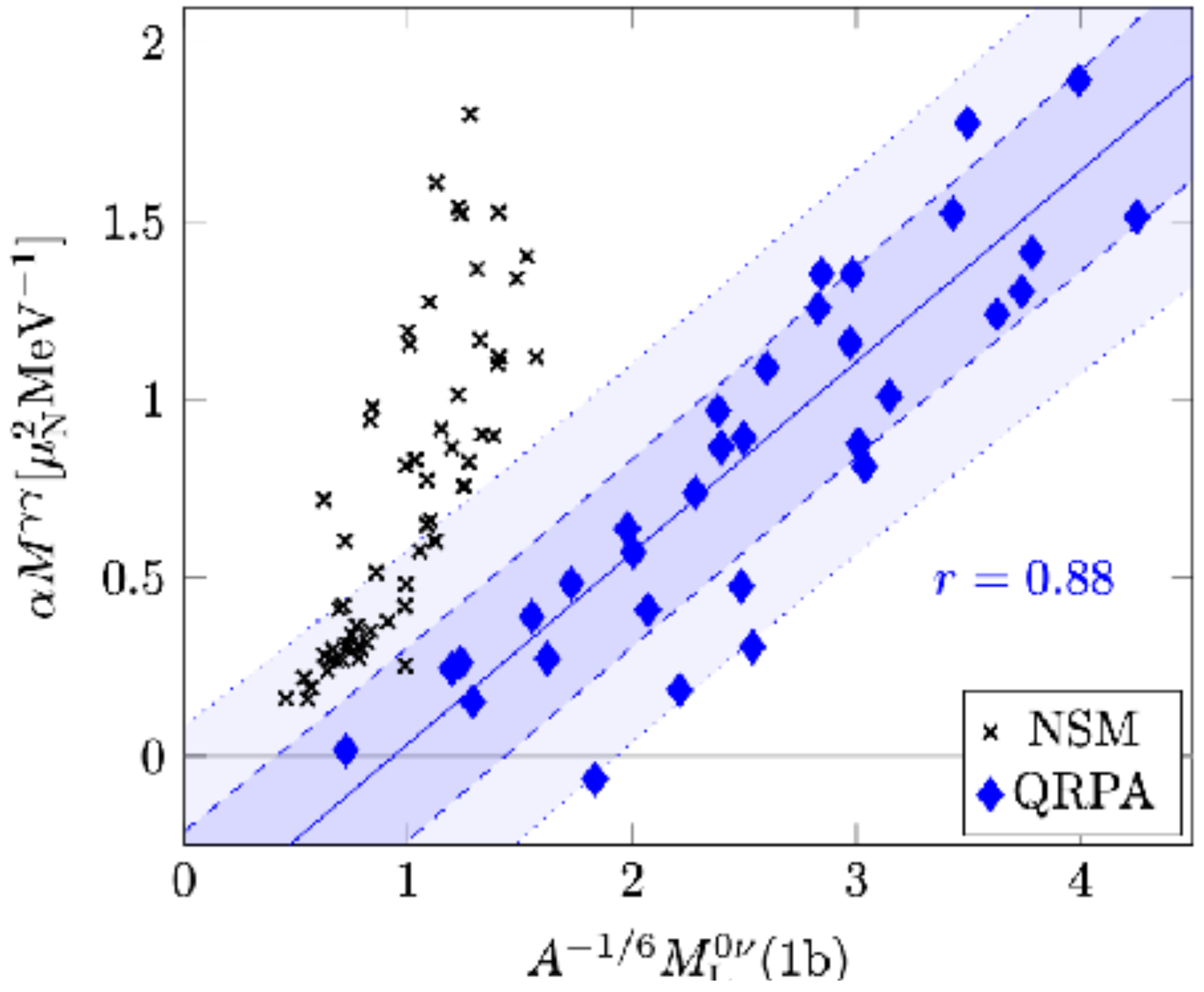
This behaviour is systematic in other nuclei

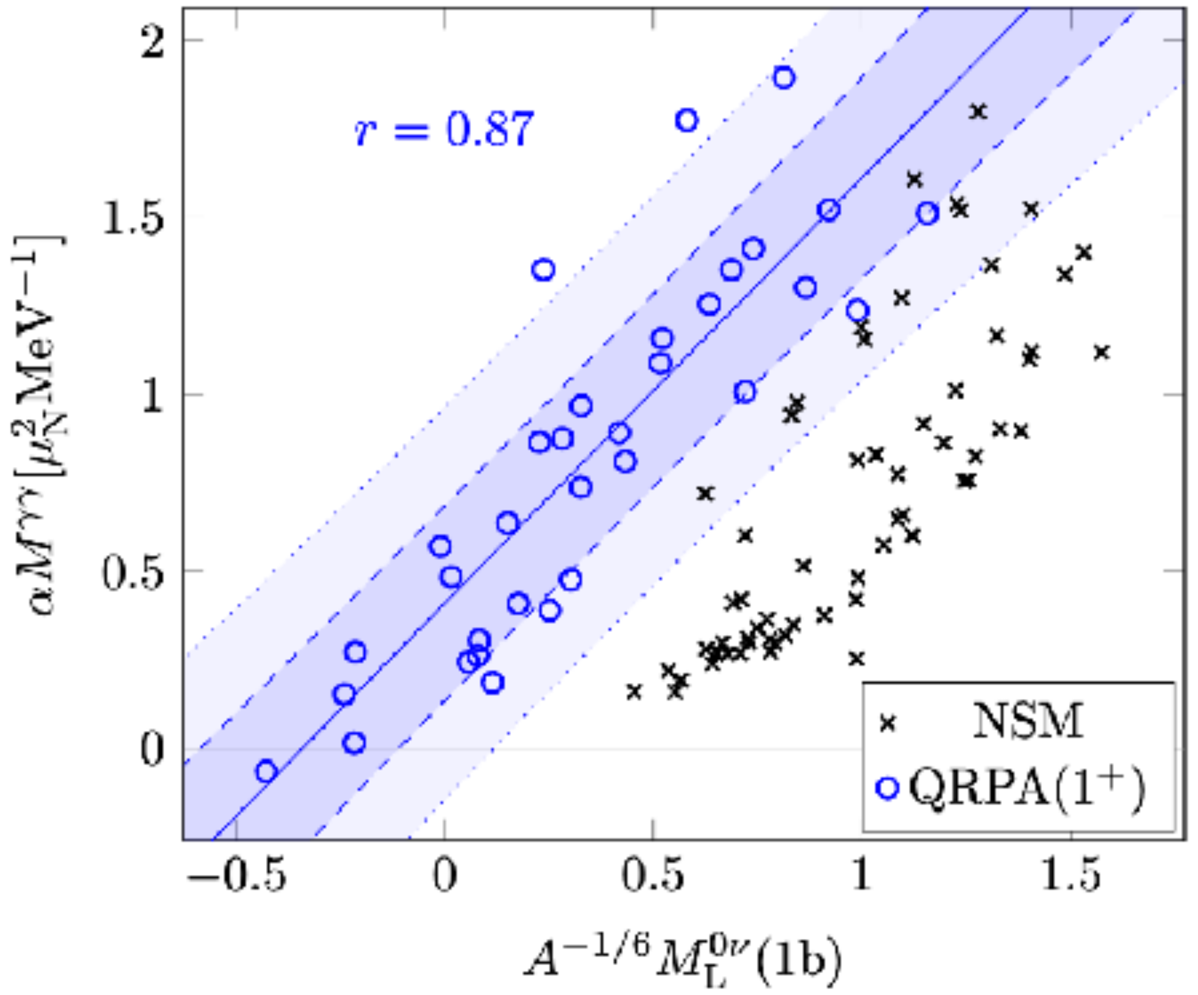


Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs

$\gamma\gamma$-M1M1 decay in spherical pnQRPA

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





A good correlation $R^2 = 0.88$ in spherical pnQRPA

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

Since isospin is not a good quantum number in QRPA, not able to describe DIAS

$\gamma\gamma$-M1M1 decay is calculated as charge-changing transitions between the different isotopes (between the initial/final even-even nucleus and the intermediate odd-odd nucleus of the double-beta-decay triplet)

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

$\gamma\gamma$-M1M1 decay in VS-IMSRG(2)

Study of $\gamma\gamma$(M1M1) within VS-IMSRG(2), starts from **NN** and **3N** interactions based on chiral effective field theory

$\gamma\gamma$(M1M1) NME from $0^+_{\mathrm{DIAS}} \longrightarrow 0^+_{\mathrm{gs}}$ ***sd*-shell**

$^{20-28}\mathrm{Ne}$ $^{22-26,30}\mathrm{Mg}$ $^{24-32}\mathrm{Si}$ $^{32-34}\mathrm{S}$ $^{34-36}\mathrm{Ar}$

Worst convergence of $M^{\gamma\gamma}$ as the isospin of 0^+_{DIAS} is higher

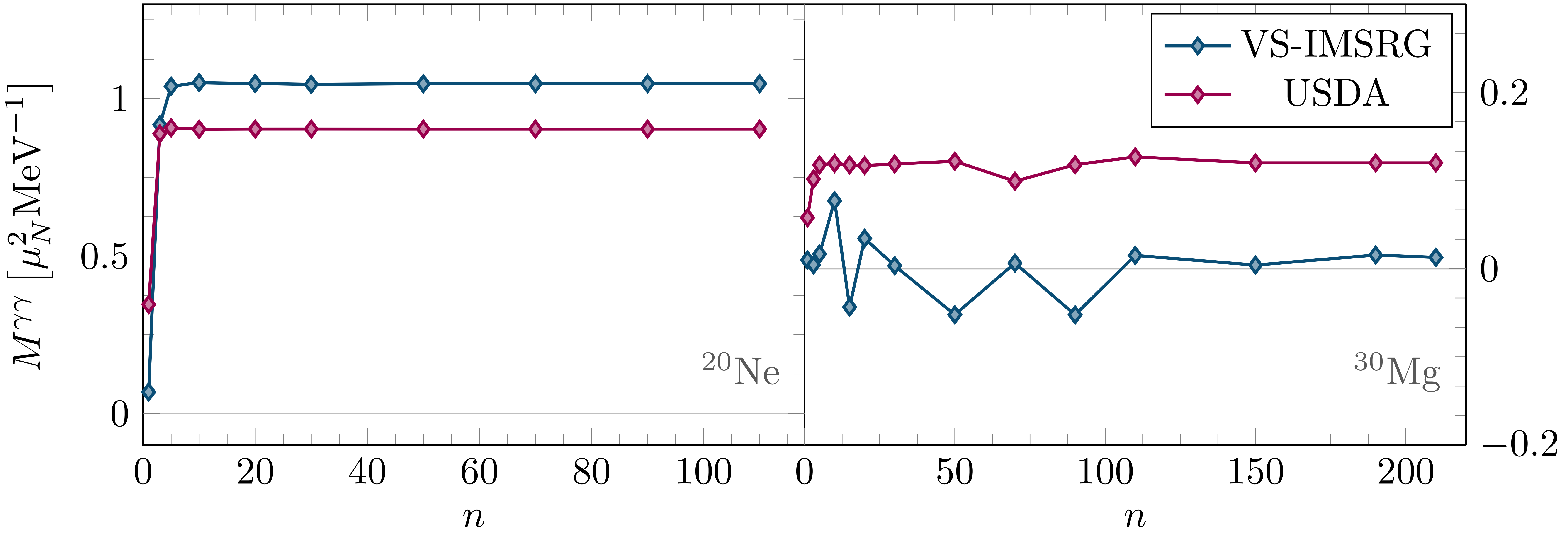
Chiral NN+3N EM1.8/2.0 interaction **isospin symmetry is slightly broken** → study of isospin mixing

State	Nuclei	1.8/2.0 EM	USDA	USDB	Exp.
0^+_{DIAS}	$^{20}\mathrm{Ne}$	16.60	16.96	16.84	16.73
1^+_{IAS}	$^{20}\mathrm{Ne}$	10.47	11.19	11.17	11.26
0^+_{DIAS}	$^{24}\mathrm{Mg}$	16.22	15.35	15.38	15.44
1^+_{IAS}	$^{24}\mathrm{Mg}$	11.00	9.85	9.94	9.97
0^+_{DIAS}	$^{28}\mathrm{Si}$	16.48	15.52	15.36	15.23
0^+_{DIAS}	$^{32}\mathrm{S}$	13.16	11.91	11.93	12.05
1^+_{IAS}	$^{32}\mathrm{S}$	8.58	6.78	6.84	7.00
0^+_{DIAS}	$^{36}\mathrm{Ar}$	12.97	10.88	10.86	10.85

Energies of **IAS, DIAS states**

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

$\gamma\gamma$-M1M1 decay in VS-IMSRG(2)



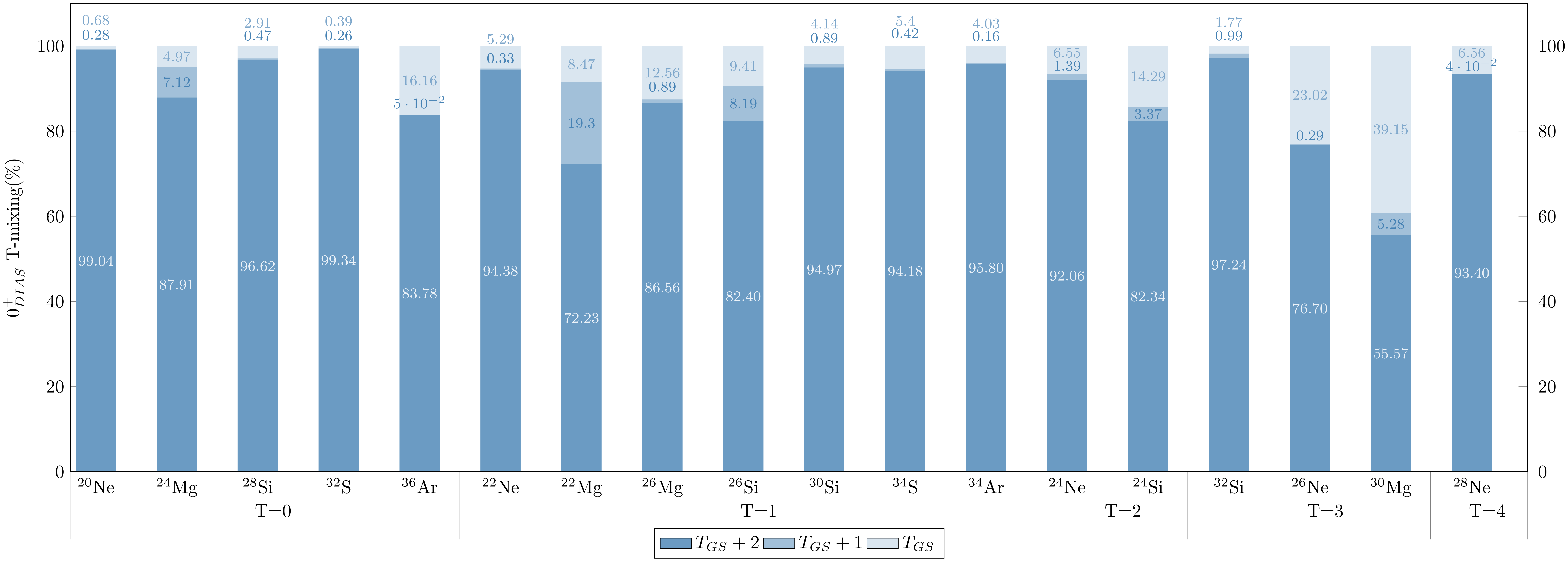
In general worst convergence as the isospin of 0^+_{DIAS} is higher, this might be because of isospin mixing with T_{gs} and $T_{gs}+1$

Since in chiral NN+3N EM1.8/2.0 interaction isospin symmetry is slightly broken

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

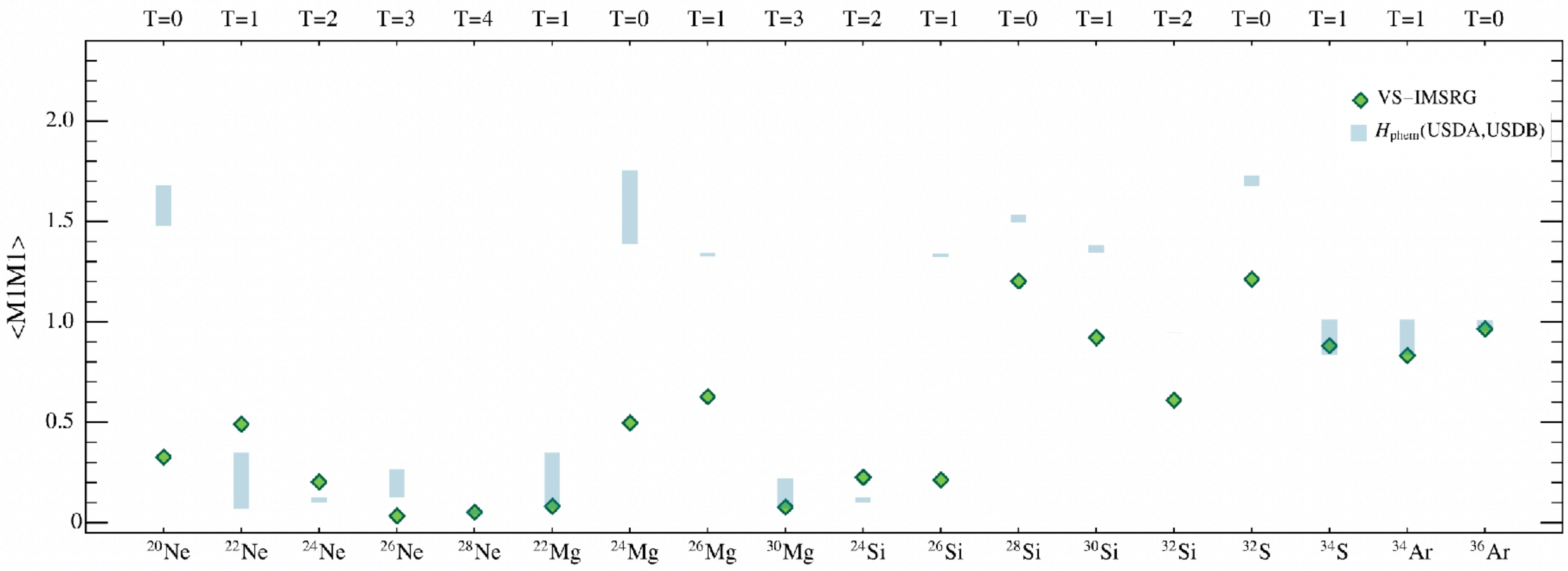
Ab initio study for $\gamma\gamma$ from $0^+_{\rm DIAS}$ & isospin mixing

Isospin mixing of $0^+_{\rm DIAS}$ $\quad |0^+_{\rm DIAS}\rangle = \alpha_{T_f+2}|0^+, T_f+2\rangle + \alpha_{T_f+1}|0^+, T_f+1\rangle + \alpha_{T_f}|0^+, T_f\rangle$



Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs
$\gamma\gamma$-M1M1 decay in VS-IMSRG(2)

M1M1: VS-IMSRG comparison with phenomenological interactions USDA and USDB



OUTLINE

- Introduction
  - Double beta decay
  - Double gamma decay
- **Results**
  - Correlation $\gamma\gamma$-$0\nu\beta\beta$ NMEs
  - Potential of measuring $\gamma\gamma$ & experimental prospects
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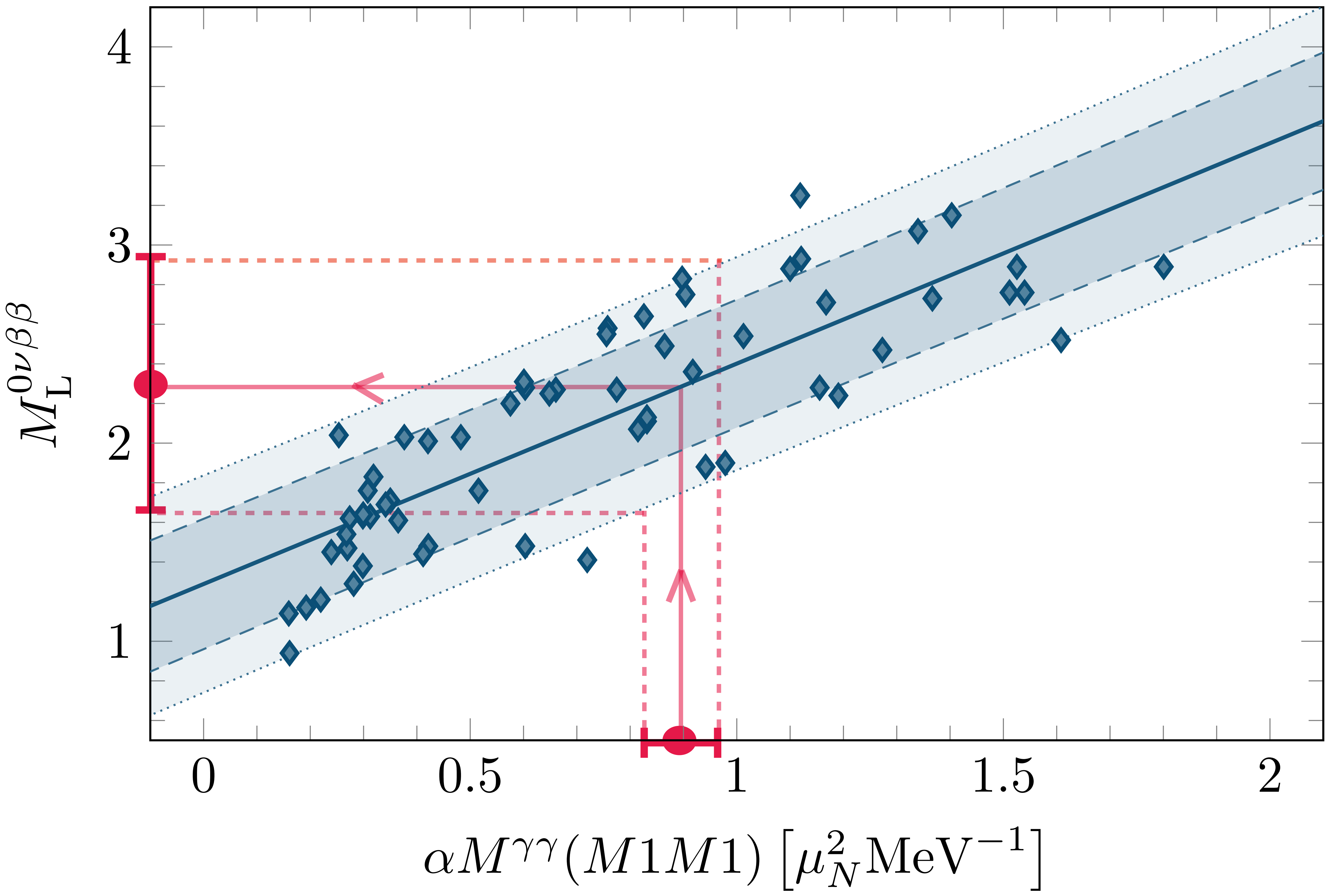
  - Correlation $2\nu\beta\beta$-$0\nu\beta\beta$ NMEs
- Summary and outlook

Potential of measuring $\gamma\gamma$

$0\nu\beta\beta$-decay NMEs from $\gamma\gamma$-M1M1 data

Using $M^{0\nu} = a + bM^{\gamma\gamma}$ and prediction bands: predict $0\nu\beta\beta$ NMEs from a measurement of $\gamma\gamma(M1M1)$

Constrains on single estimated NMEs, estimate what we would expect from single measure of $0\nu\beta\beta$

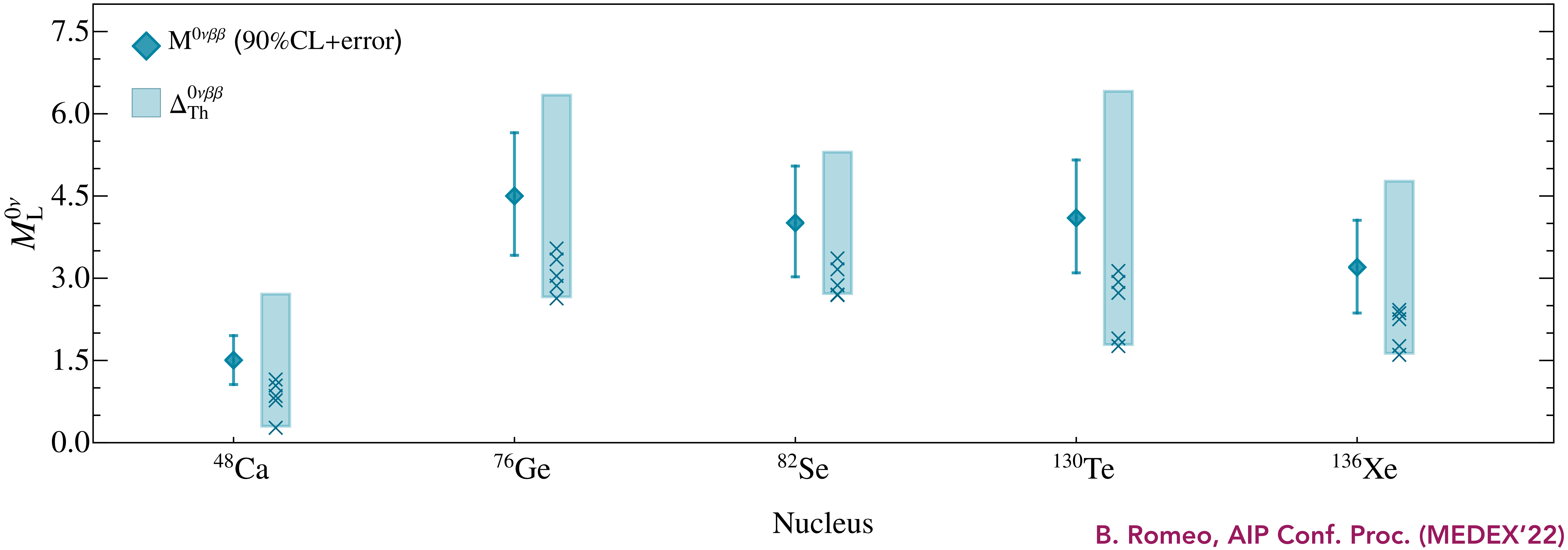


Potential of measuring $\gamma\gamma$

$0\nu\beta\beta$-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 $\gamma\gamma$

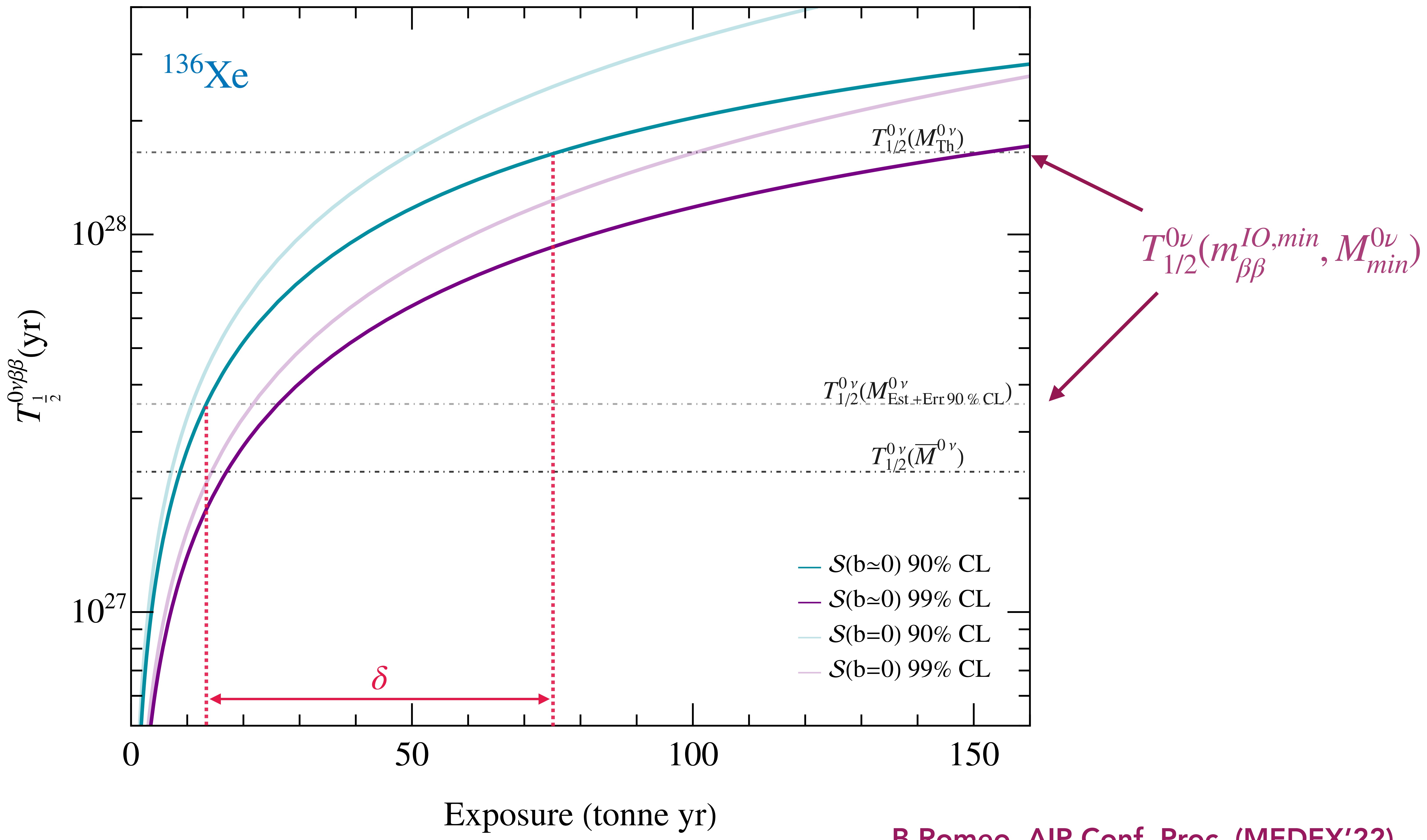
$T_{1/2}^{0\nu\beta\beta}$ sensitivity

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

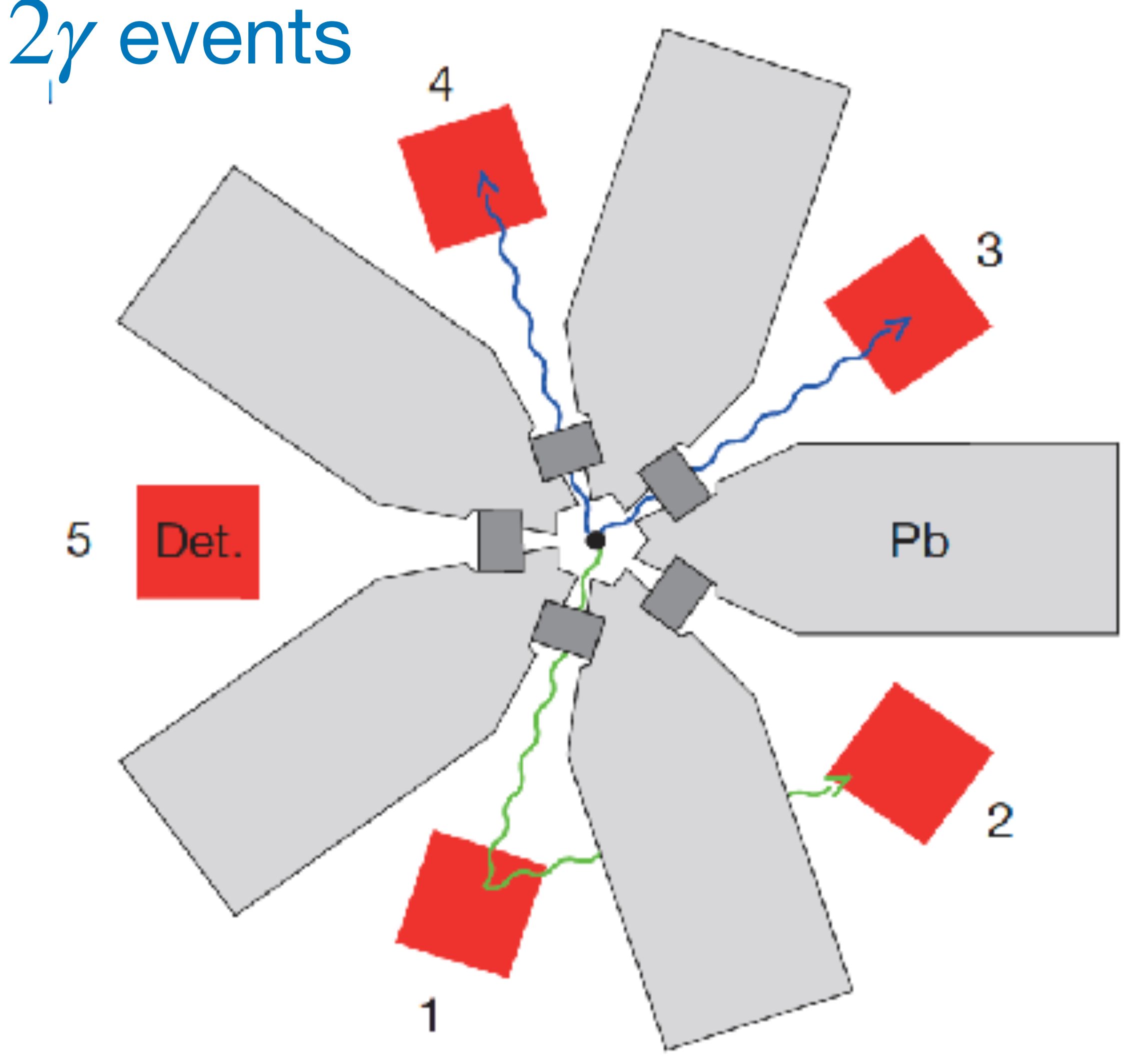


B.Romeo, AIP Conf. Proc. (MEDEX'22)

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

Previous experimental measurements $\gamma\gamma$

True 2γ events



Measurements of second order electromagnetic decays difficult, but have been done for $0^+_2 \longrightarrow 0^+_1$ in double magic nuclei ${}^{16}O, {}^{40}Ca, {}^{90}Zr$

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

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

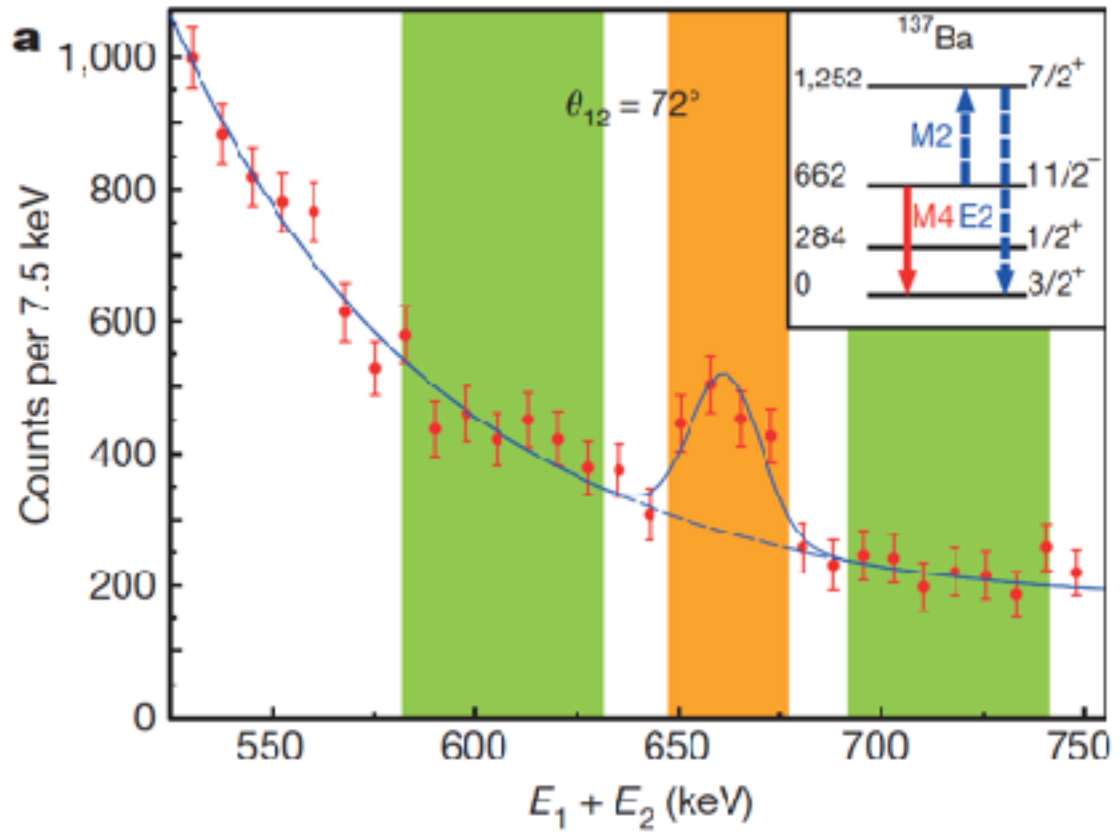
A.C. Hayes et al., Phys. Rev. C 41, 1727 (1990)
J. Schirmer et. al.,Phys. Rev. Lett. 53, 1897 (1984)

Background 2γ events

Faster crystal detectors allowed measurement of competitive $\gamma\gamma/\gamma$ decay in ${}^{137}Ba$ 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 $0^+_{\rm DIAS}$

Competition with γ decay

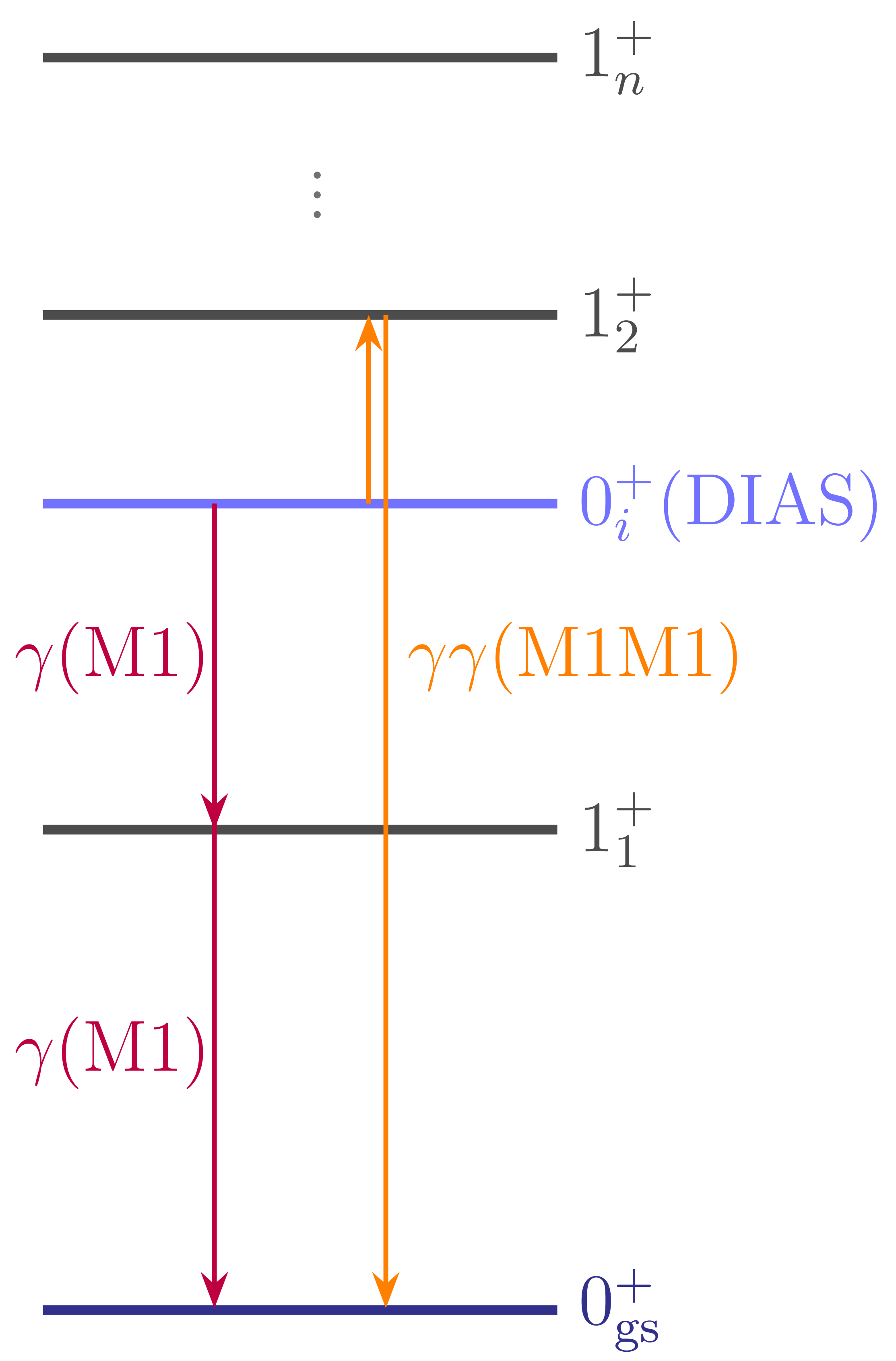
- New avenue to constrain $0\nu\beta\beta$ NMEs if $\gamma\gamma(M1M1)$ from DIAS to ground state can be measured
- $\gamma\gamma$ from DIAS to ground state never been observed
- Challenge: populate DIAS & small BRs involved!

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

γ-E1s hard to compute, γ-E2s small compared with γ-M1s

$$\Gamma_\gamma \sim \text{eV while } \Gamma_{\gamma\gamma} \sim 10^{-6} - 10^{-8}\text{eV}$$

$$\boxed{\Gamma_{\gamma\gamma}/\Gamma_\gamma \sim 10^{-6} - 10^{-8}}$$



BR, D. Stramaccioni, J. Menéndez, and J. J. Valiente-Dobón, Phys Lett B 860 (2025)

Experimental prospects of $\gamma\gamma$ from 0^+_{DIAS}
Competition with single proton emission

$0^+(\mathrm{DIAS})$ **high energy states** particle branch open!

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

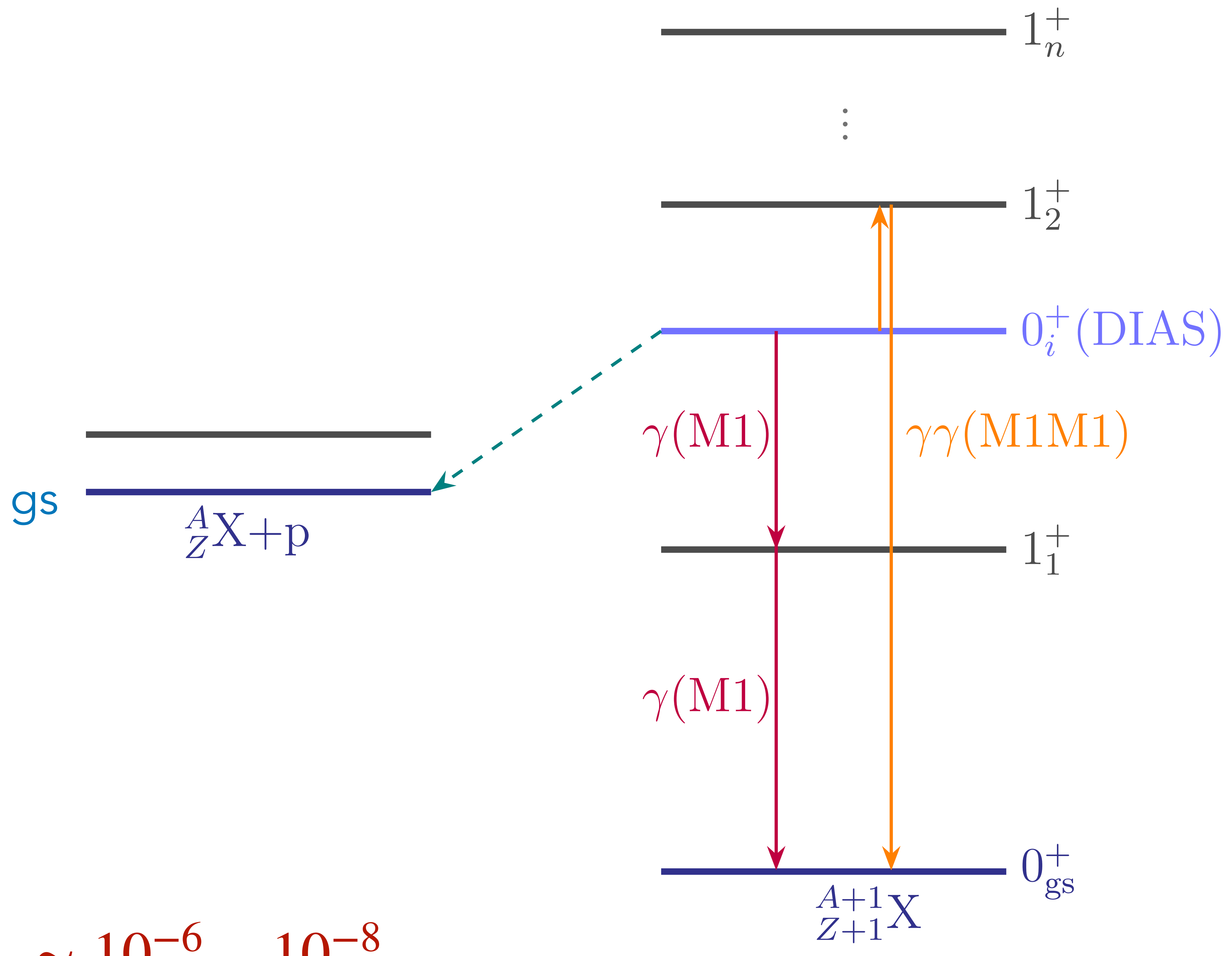
${}^{A+1}_{Z+1}X^*$ excited state with $T_i = T_{gs} + 2$

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

Isospin forbidden decay
highly suppressed

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

$\Gamma_{\gamma\gamma}/\Gamma_p \sim 10^{-8} - 10^{-9}$ $\Gamma_{\gamma\gamma}/\Gamma_\gamma \sim 10^{-6} - 10^{-8}$



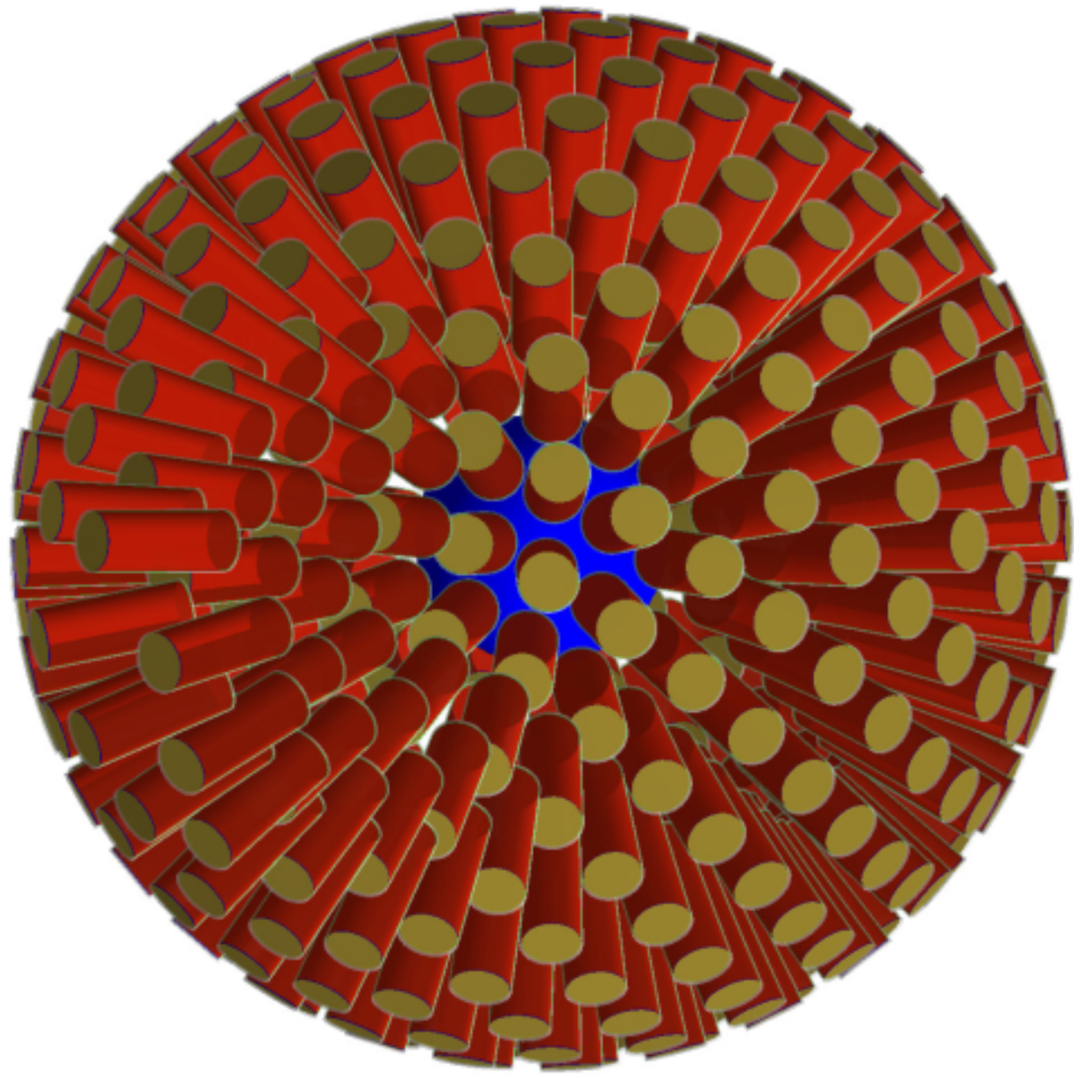
Experimental prospects of $\gamma\gamma$ from 0^+_{DIAS}

The experimental challenge

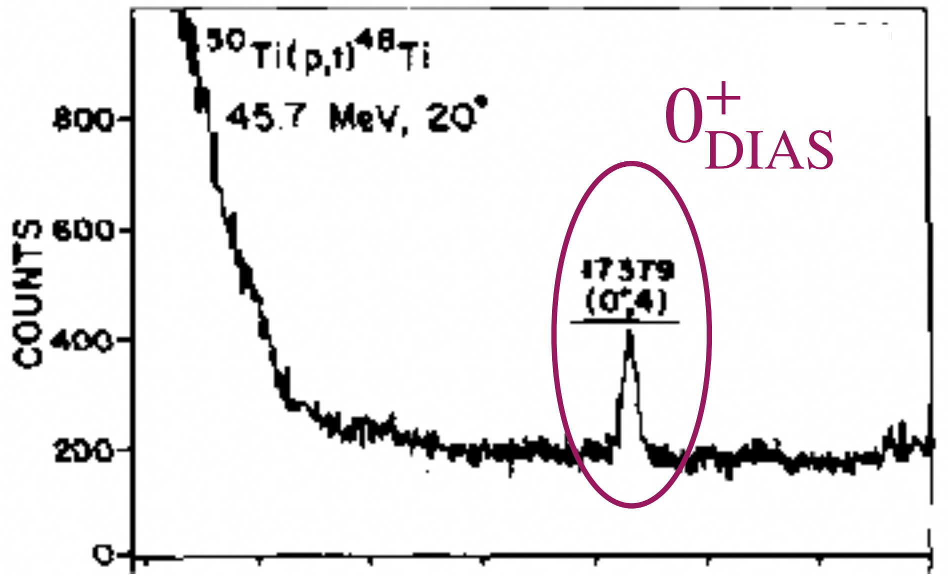
New avenue to quantify $0\nu\beta\beta$ NMEs uncertainties if $\gamma\gamma(M1M1)$ from DIAS to ground state can be measured

Nucleus	$\Gamma_{\gamma\gamma}/\Gamma_\gamma$	$\Gamma_{\gamma\gamma}/\Gamma_p$	$\Gamma_{\gamma\gamma}/\Gamma_{\mathrm{IC}}$	$\Gamma_{\gamma\gamma}/\Gamma_{\mathrm{IPC}}$
^{48}Ti	2×10^{-8}	7×10^{-10}	3×10^{-5}	0.5
^{76}Se	5×10^{-7}	$<2\times10^{-8}$	7×10^{-6}	0.07
^{82}Kr	5×10^{-7}	$<4\times10^{-8}$	2×10^{-6}	0.03
^{130}Xe	8×10^{-8}	$<4\times10^{-9}$	10^{-7}	2×10^{-4}
^{136}Ba	1×10^{-7}	$<1\times10^{-8}$	6×10^{-7}	0.001

Challenge: extremely small decay width, difficult to populate 0^+_{DIAS}; ^{48}Ti(0^+_{DIAS}) it lies at 17.4MeV



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



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

BR, D. Stramaccioni, J. Menéndez, and J. J. Valiente-Dobón, Phys Lett B 860 (2025)

D. Stramaccioni Master Thesis

Key setup requirements:

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

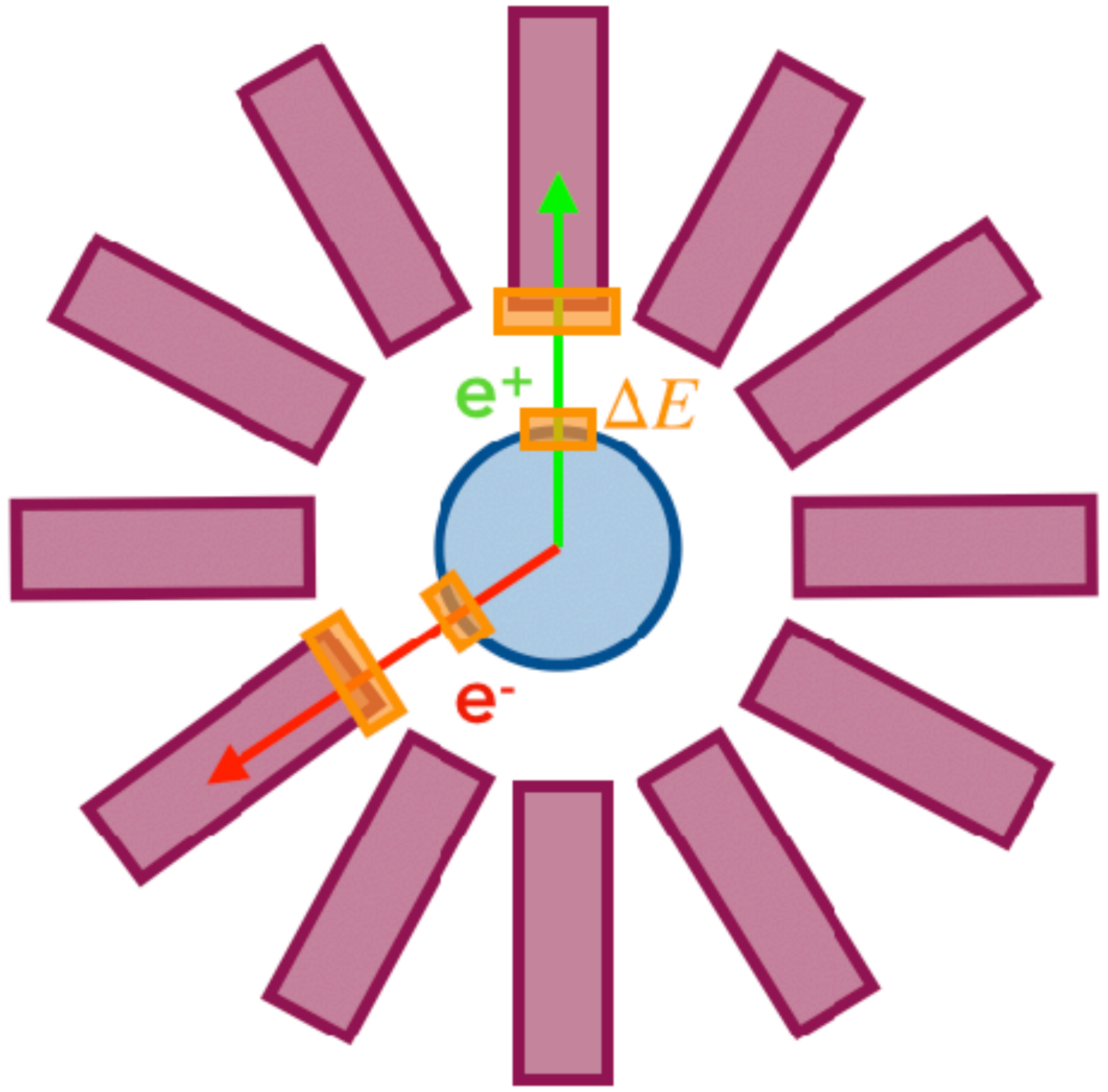
- $\gamma\gamma$-decay in **^{48}Ti**
- **302**, 3.5″x8″ cylindrical **$\mathrm{LaBr_3}$** detectors
- $\Delta t = 800\mathrm{ps}$
- Reaction chamber (Al, 17cm, 2mm thick)

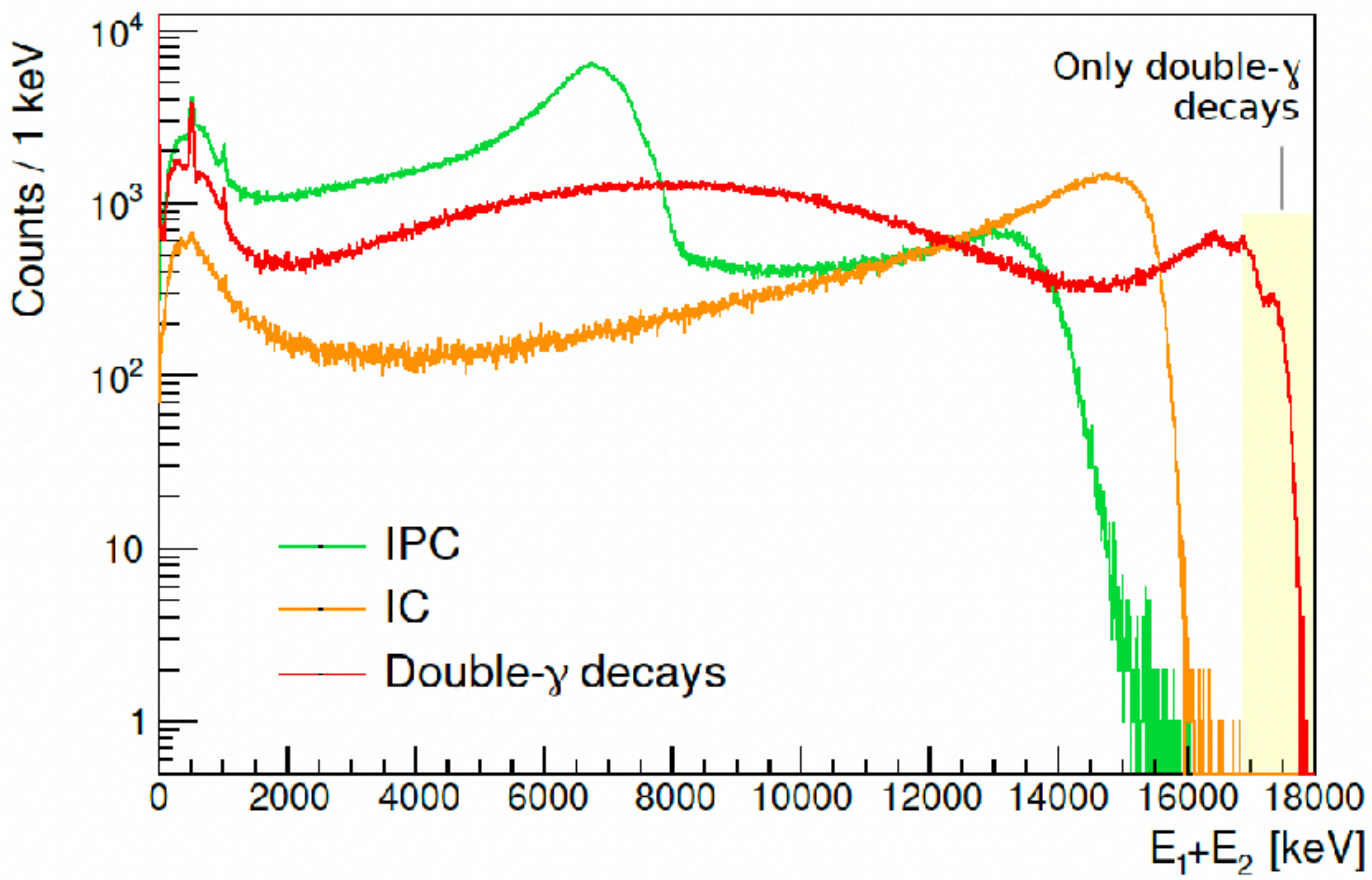
Experimental prospects of $\gamma\gamma$ from 0^+_{DIAS}

Discrimination of competing processes

Neglecting ^{48}Ti recoil energy, IC e- carries the total energy, while shared by e$^+$ - e$^-$ pair in IPC

Energy loss $\Delta E \simeq 2\mathrm{MeV}$





Remove IC&IPC events with an energy threshold **E1+E2>15MeV**

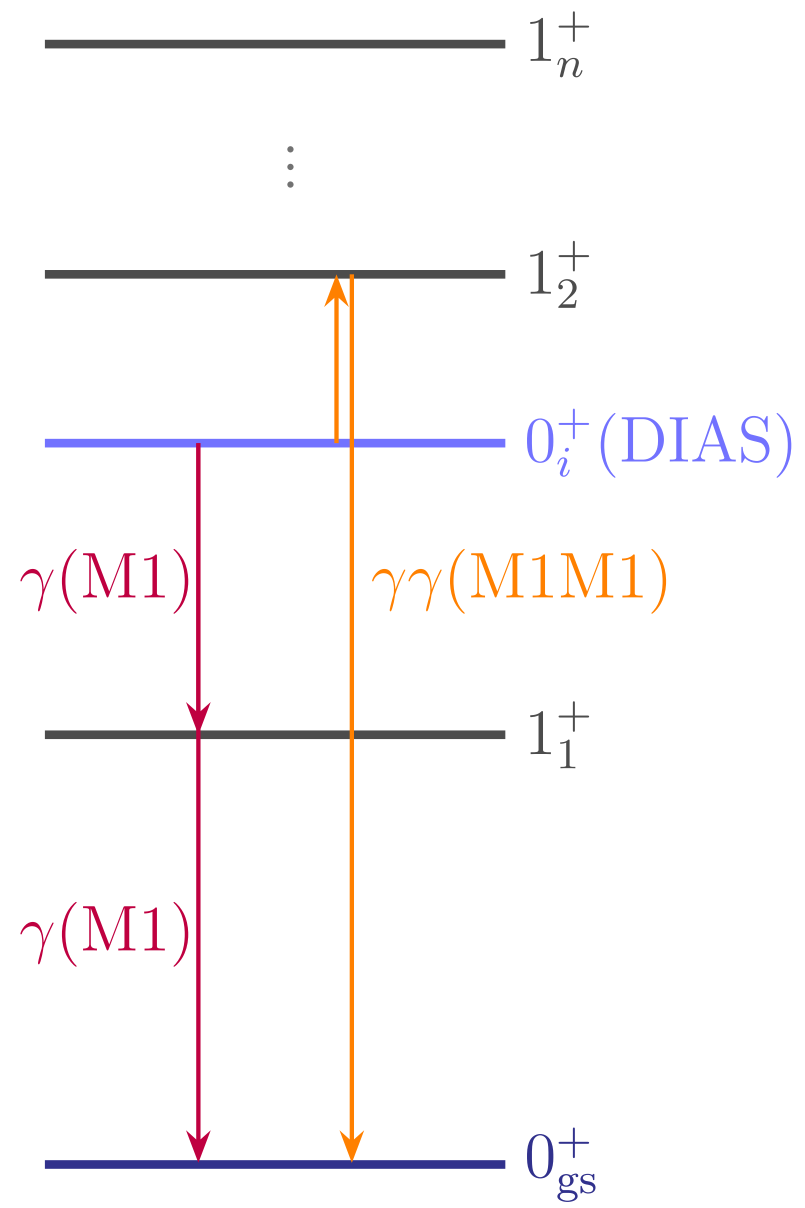
Experimental prospects of $\gamma\gamma$ from 0^+_{DIAS}

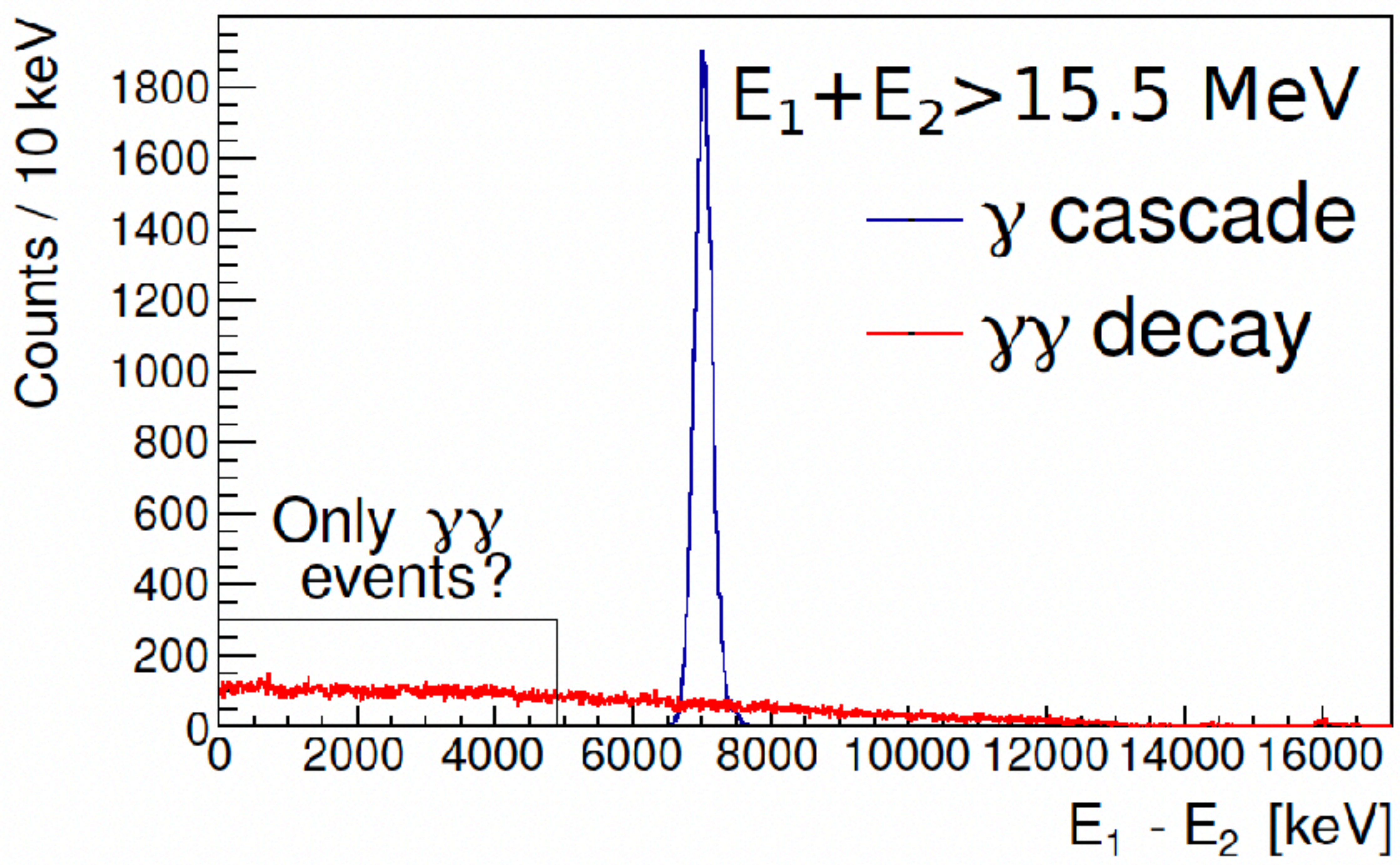
Discrimination of competing processes

De-excitation through an intermediate state, 2γ cascade $\Gamma_{\gamma\gamma}/\Gamma_\gamma \sim 10^{-8}$

Main difference: continuous vs discrete spectrum

Natural to chose the energy difference between two hits



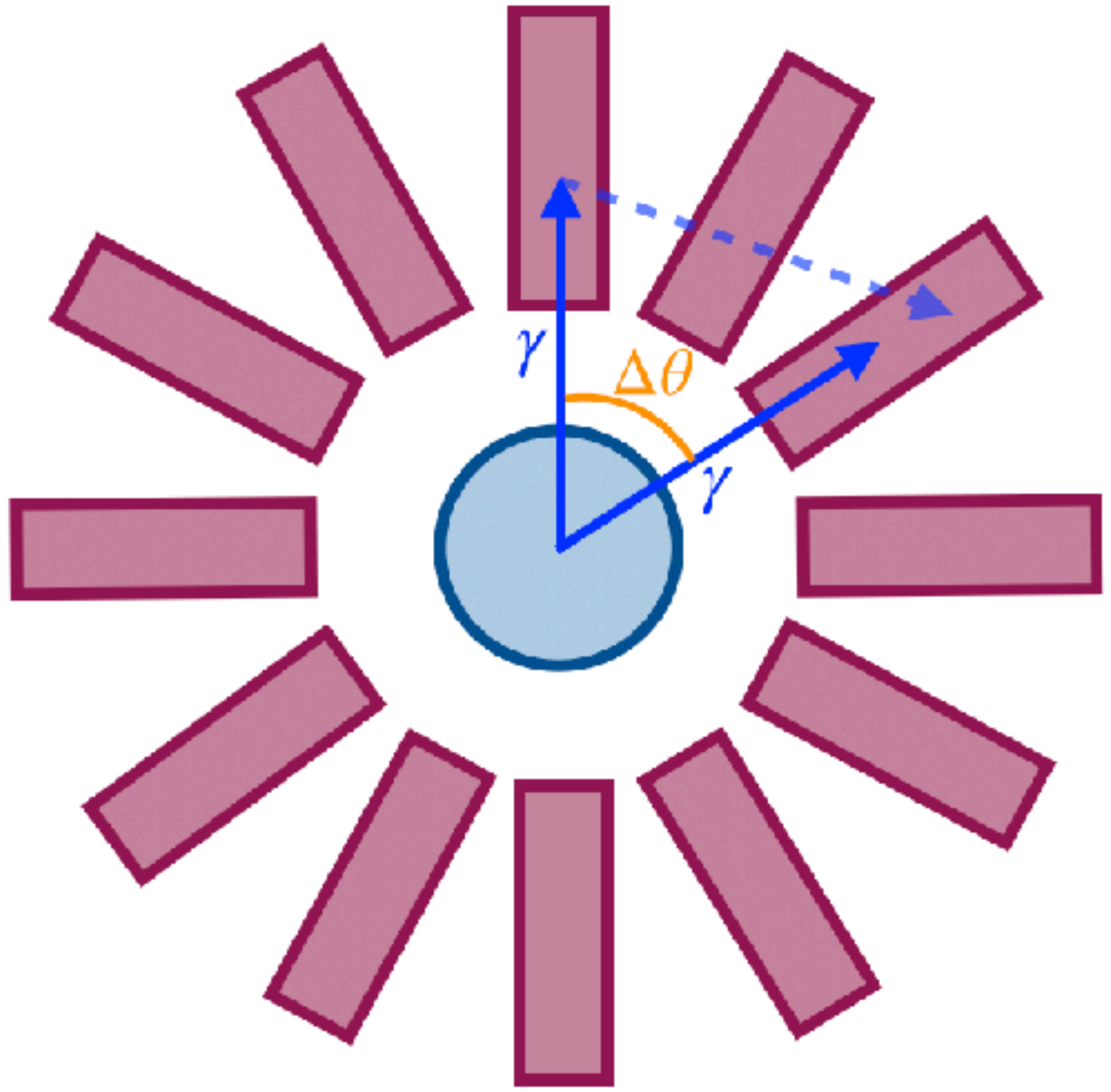


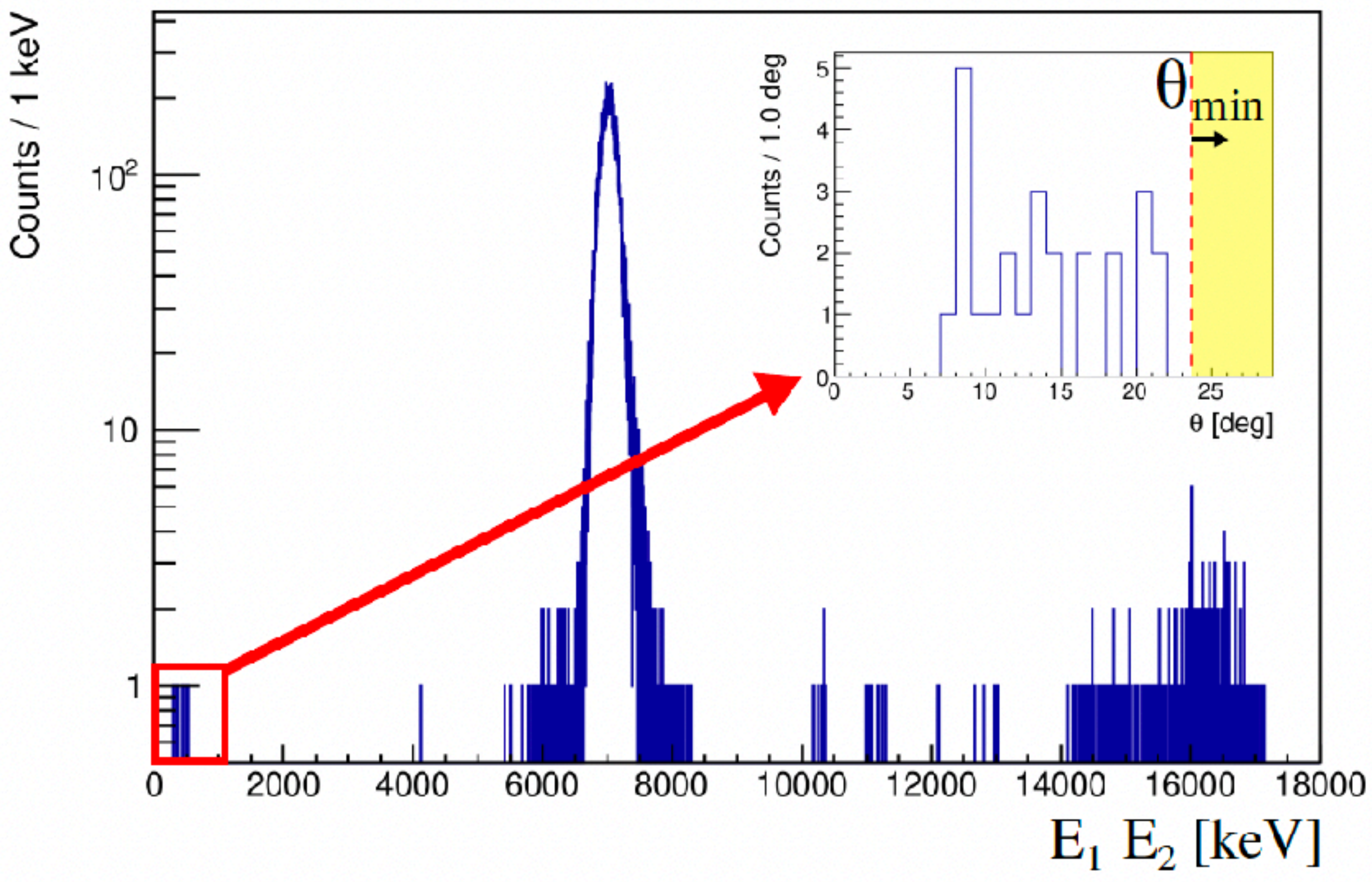
Experimental prospects of $\gamma\gamma$ from $0^+_{\rm DIAS}$

The experimental challenge

A few counts lie in the region $|E_1-E_2|<1$MeV

γs partial deposit only 8.5MeV in one detector, scatter on it and deposit the rest where the other gamma hit





We can remove these events setting a limit angle $\theta > 25^\circ$

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Preparatory experiment @ IFJ-PAN

Double gamma spectroscopy in ^{48}Ti

First steps done!

- A **method to isolate** and measure 2γ-decay BR

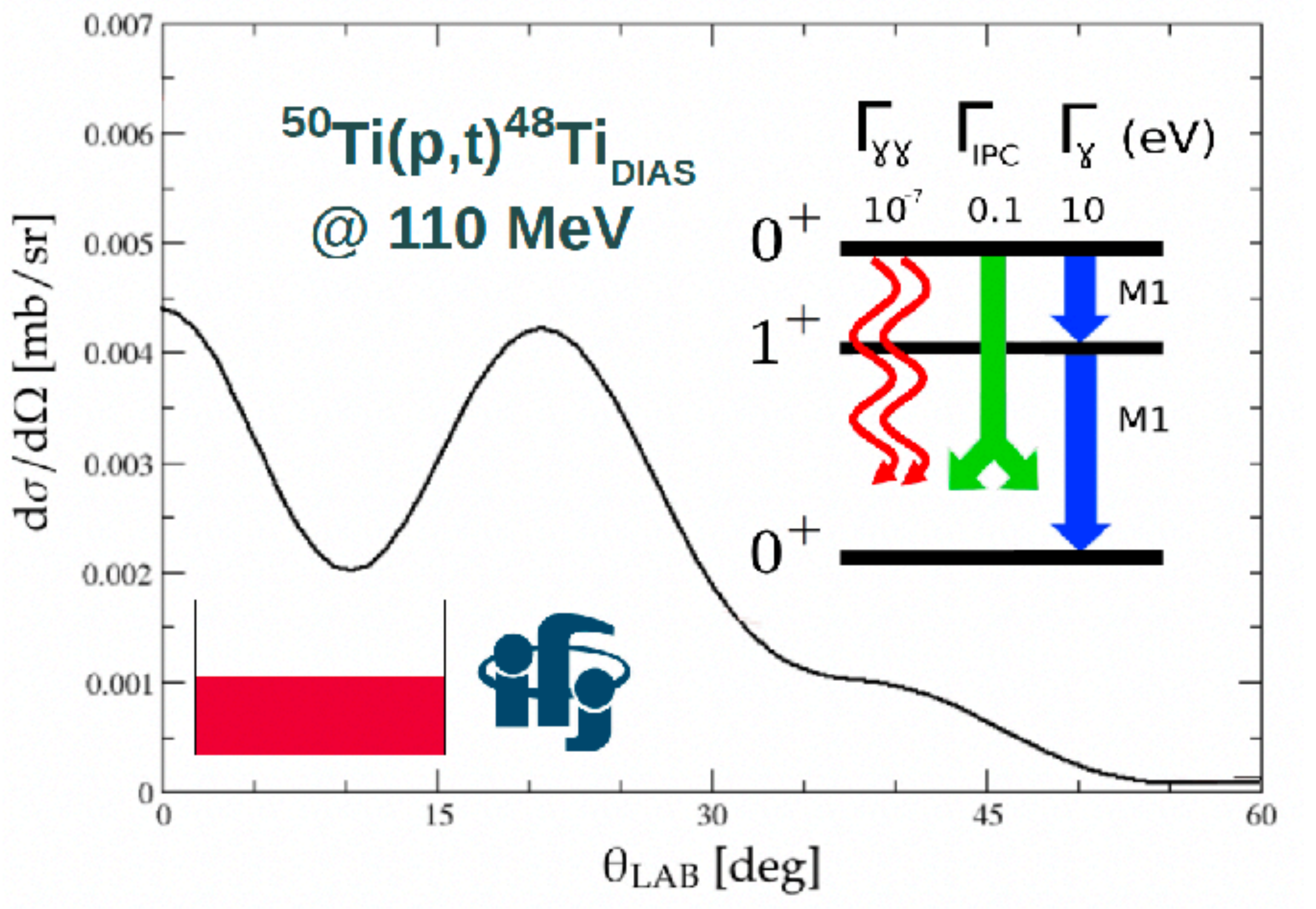
But there is still work to be done before real 2γ (M1M1)-decay measurement

- Perform the **preparatory experiment** to characterize ^{48}Ti (DIAS)
- Main goals: determine **cross section** to populate DIAS and measure **dominant** competing process: **γ-decay BR**
- Proposed at **Cyclotron Centre Bronowice** (CCB), part of the Institute of Nuclear Physics of the Polish Academy of Sciences (**IFJ PAN**) in Kraków

Gamma decay study of the Double Isobaric Analog State in ^{48}Ti.

Spokepersons: D. Stramaccioni, M. Balogh, J.J. Valiente-Dobón

G. Andreetta, F. Angelini, M. Balogh, D. Brugnara, G. de Angelis, A. Goasduff, B. Gongora, A. Gottardo, R. Nicolás del Álamo, S. Pigliapoco, E. Pilotto, D. Stramaccioni, J.J. Valiente-Dobón, L. Zago
INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy.



Courtesy of D. Stramaccioni

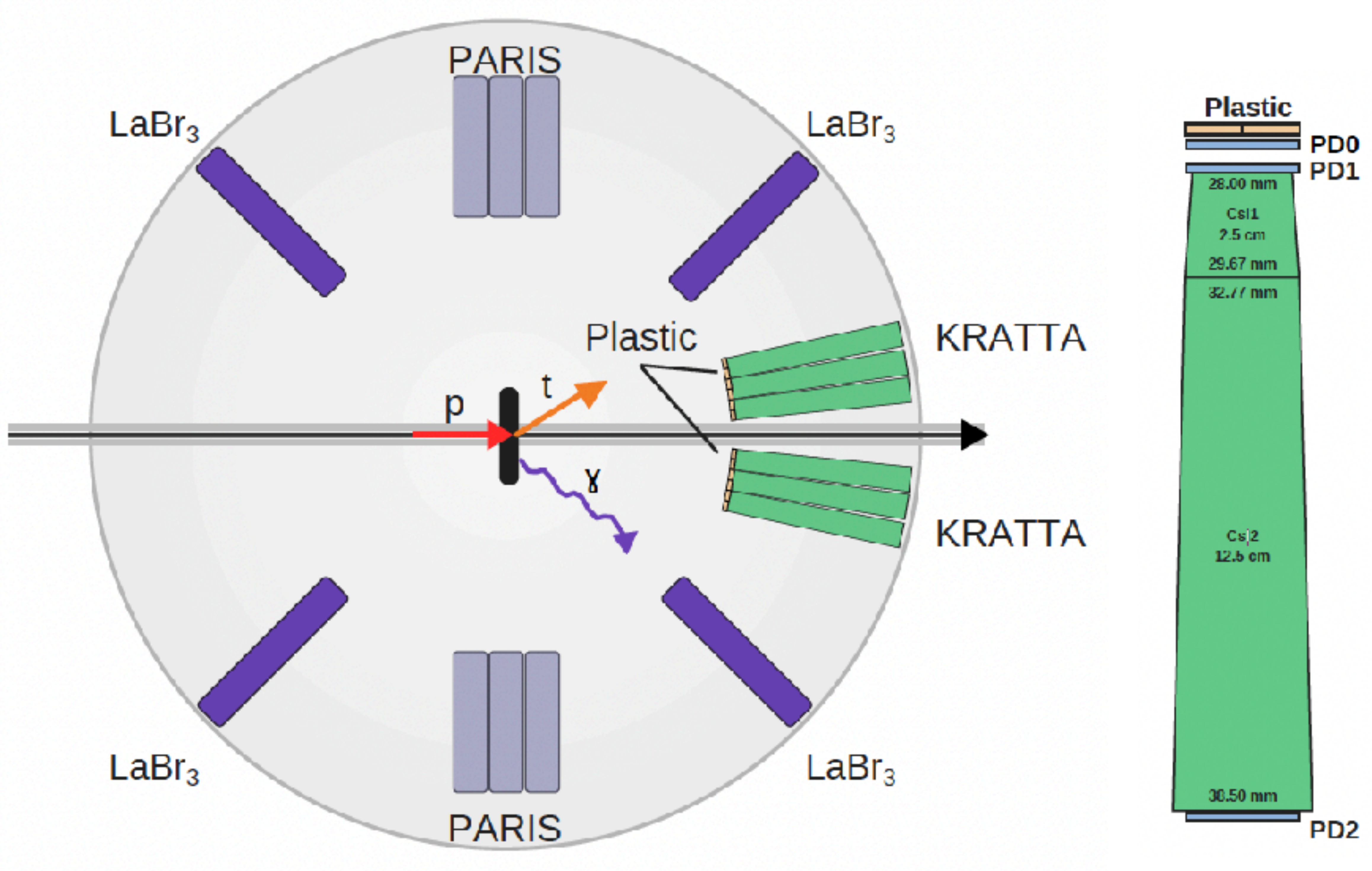
Preparatory experiment @ IFJ-PAN

Double gamma spectroscopy in ^{48}Ti

^{50}Ti(p,t)^{48}Ti @ 110MeV

Main limitation of (p,t) transfer reaction to populate DIAS is kinematics: DIAS at high excitation energy

- High energetic proton beam E_p=100 MeV
- Charge detection system capable of measuring low-yield tritons at forward angles
- Bean currents compatible with simultaneous detection of high-energy γ rays



Courtesy of D. Stramaccioni

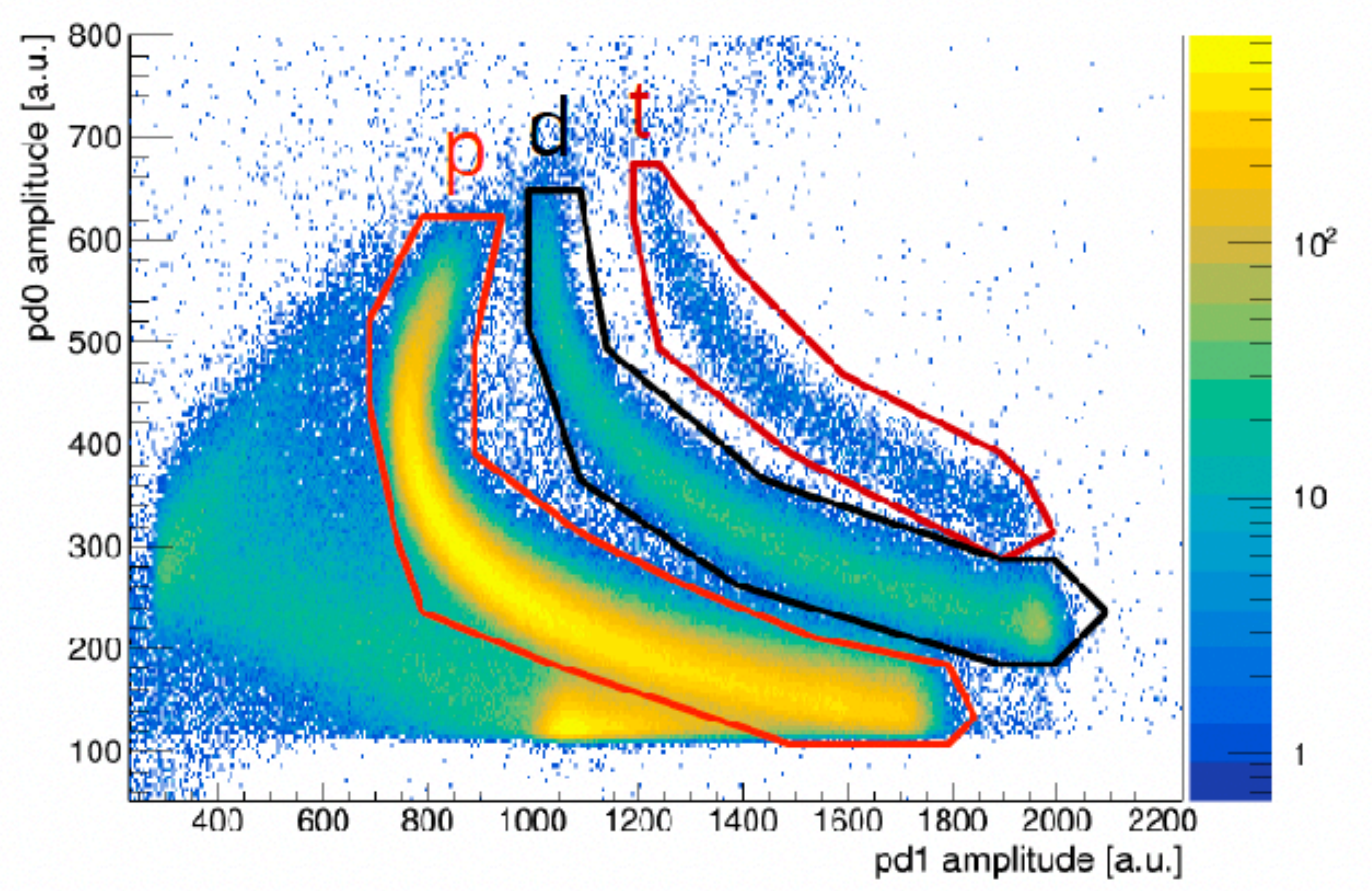
Experimental set up

- 32 **KRATTA telescopes** (plastic scintillator in front, PIN photodiodes PD0,1, CsTl crystals) 6 columns at forward angles → **Scattered tritons**
- 4 large volume **$LaBr_3$ detectors** and 26 PARIS modules for high energy γ rays → **γ rays**

Double gamma spectroscopy in ^{48}Ti

Data from three months ago, online analysis looks promising

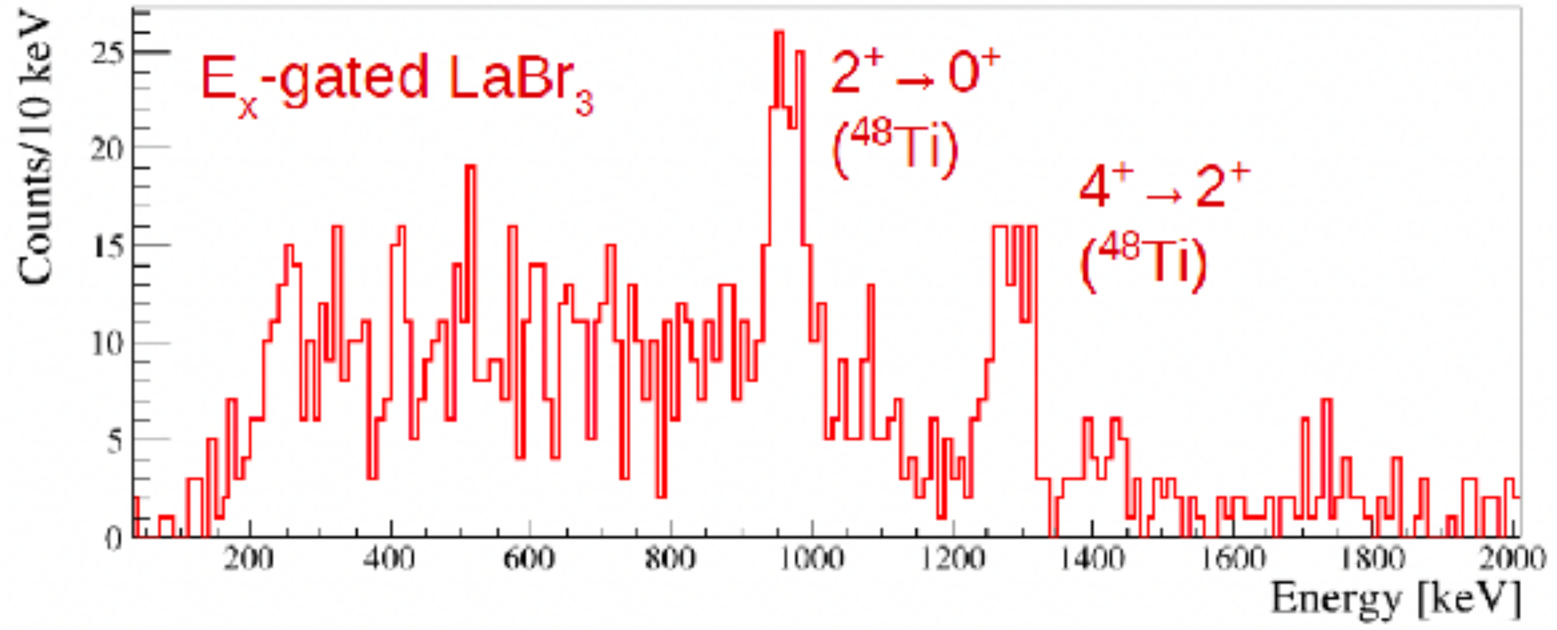
Particle identification matrix



To discriminate between the different light charged particles produced in the reaction, the correlation in the energy released in PD0 and PD1 is used

This allows to make a cut to select triton events and reconstruct the residual nucleus excitation spectrum

Preliminary γ-ray spectrum measured in coincidence with tritons selected



With **good PD1 calibration** it is expected to measure

σ_{DIAS} **and** γ**-BR**

And **assess** $\gamma\gamma$**-experimental program feasibility**

Courtesy of D. Stramaccioni

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Correlation $2\nu\beta\beta$-$0\nu\beta\beta$ NMEs

$2\nu\beta\beta - 0\nu\beta\beta$ NMEs

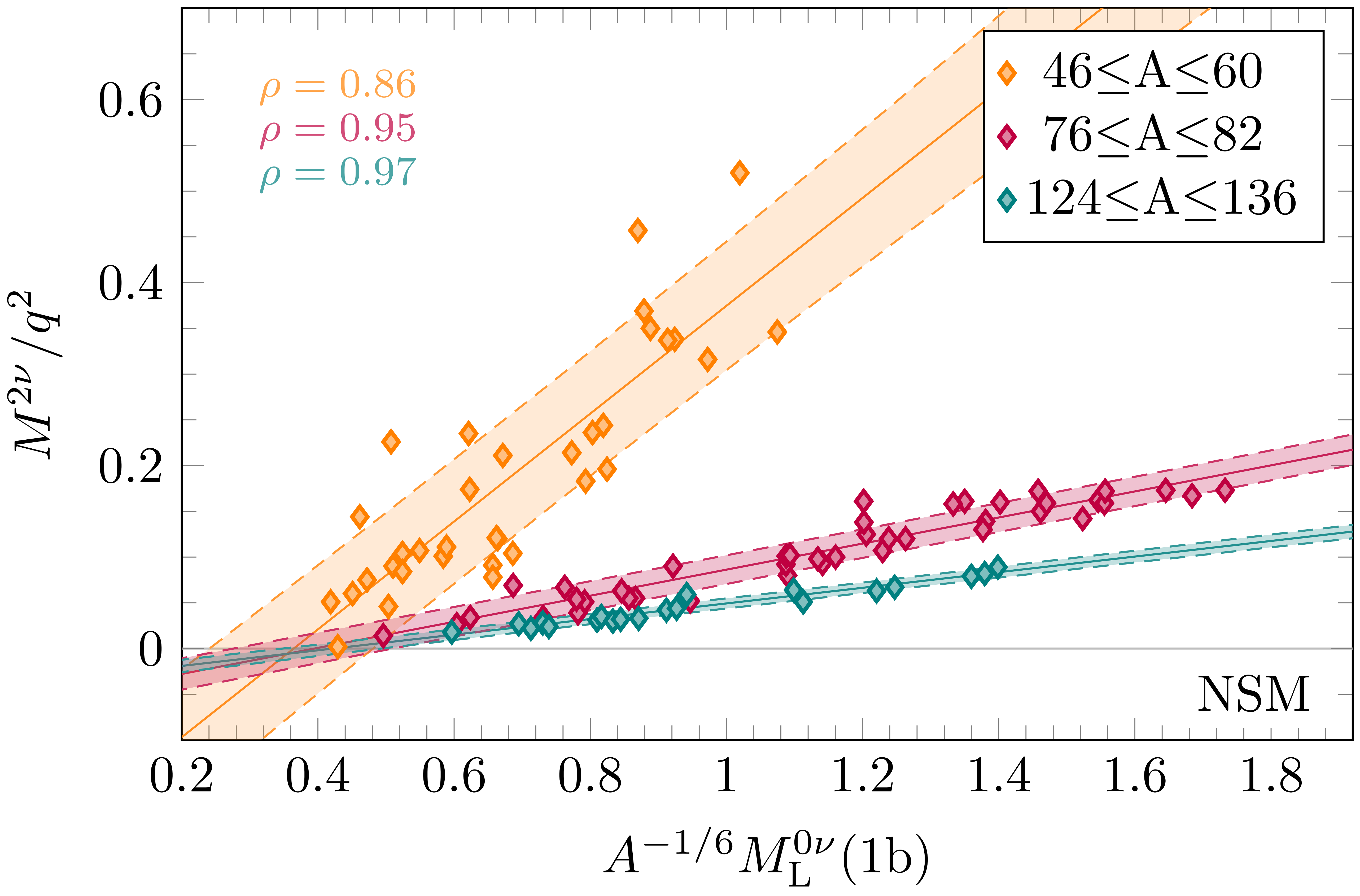
Same systematic analysis but for the $M^{2\nu}$ & $M^{0\nu}$ advantage $T^{2\nu}_{1/2}$ data

Same systematic analysis but for the $M^{2\nu}$

$$M^{2\nu} = m_e \sum_k \frac{(0_f^+ || \sum_a \tau_a^- \boldsymbol{\sigma}_a || 1_k^+)(1_k^+ || \sum_b \tau_b^- \boldsymbol{\sigma}_b || 0_i^+)}{E_k - \frac{1}{2}(E_i + E_f)}$$

Correct for the overestimation of the 2vββ-decay calculations by quenching

<u>q from β- & $\beta\beta$-decay</u>
0.65-0.77 pf
0.55-64 pfg
0.42-0.72 gdsh

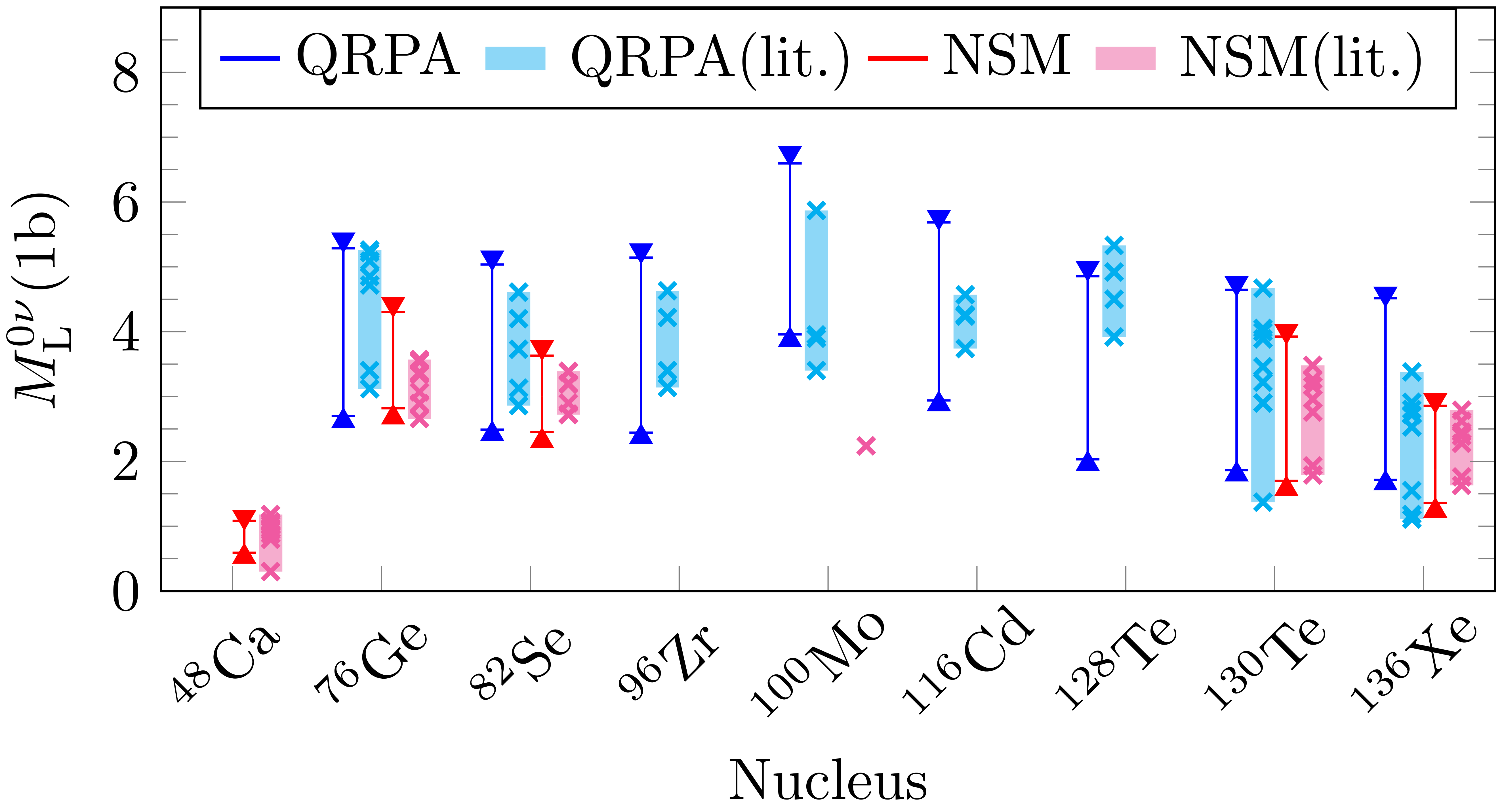


L. Jokiniemi, B. Romeo, P. Soriano, and J. Menéndez, Phys. Rev. C 107, 044305 (2023)

Correlation $2\nu\beta\beta$-$0\nu\beta\beta$ NMEs

$2\nu\beta\beta - 0\nu\beta\beta$ NMEs

Predictions on $M^{0\nu}$ with an uncertainty from $2\nu\beta\beta$ data, less model dependent



L. Jokiniemi, B. Romeo, P. Soriano, and J. Menéndez, Phys. Rev. C 107, 044305 (2023)

Although uncertainties are comparable to the band obtained from literature values, it includes information from systematic calculations in tens of nuclei using several H_{eff}

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Summary and Outlook

$0\nu\beta\beta$ decay: Insights from Electromagnetic Decays

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

- The connection between $2\nu\beta\beta$ and $0\nu\beta\beta$ has been used to **predict 0vββ-decay NMEs** from **2vββ data**, with **uncertainties** which is based on many systematic calculations, results are consistent considering uncertainties

- $\gamma\gamma$(M1M1) decay in VS-IMSRG, and study the effect of **two-body currents** in M1M1

- The experimental feasibility of measuring $\gamma\gamma(M1M1)$ in the final nuclei of **ββ** measured decays has been addressed

- Discuss possible **strategy for the measurement** of this γγ-decay

- **Started!** initial experiment aiming to measure γ-decay from ^{48}Ti(T=4,0^{+}) and cross section using **proton beam** from **Cyclotron Centre Bronowice** in Krakow (D. Stramaccioni, M. Balogh, J.J. Valiente-Dobón)

Thank you!

Backup

Valence space-in medium similarity renormalization group (VS-IMSRG)

Basic idea **similarity renormalization group**: perform unitary transformation U on the H (other operators) resulting nuclear wave functions simpler

Transform H, to block- or band-diagonal form by a sequence of unitary transformation U(s)

$$H(s) = U(s)H(0)U^{\dagger}(s)$$

$$H(s) = H^{d}(s) + H^{od}(s)$$

$$U(s)\,|\,s \to \infty \qquad H^{d}(s) \longrightarrow H^{d}(s),\ \ H^{od}(s) \longrightarrow 0$$

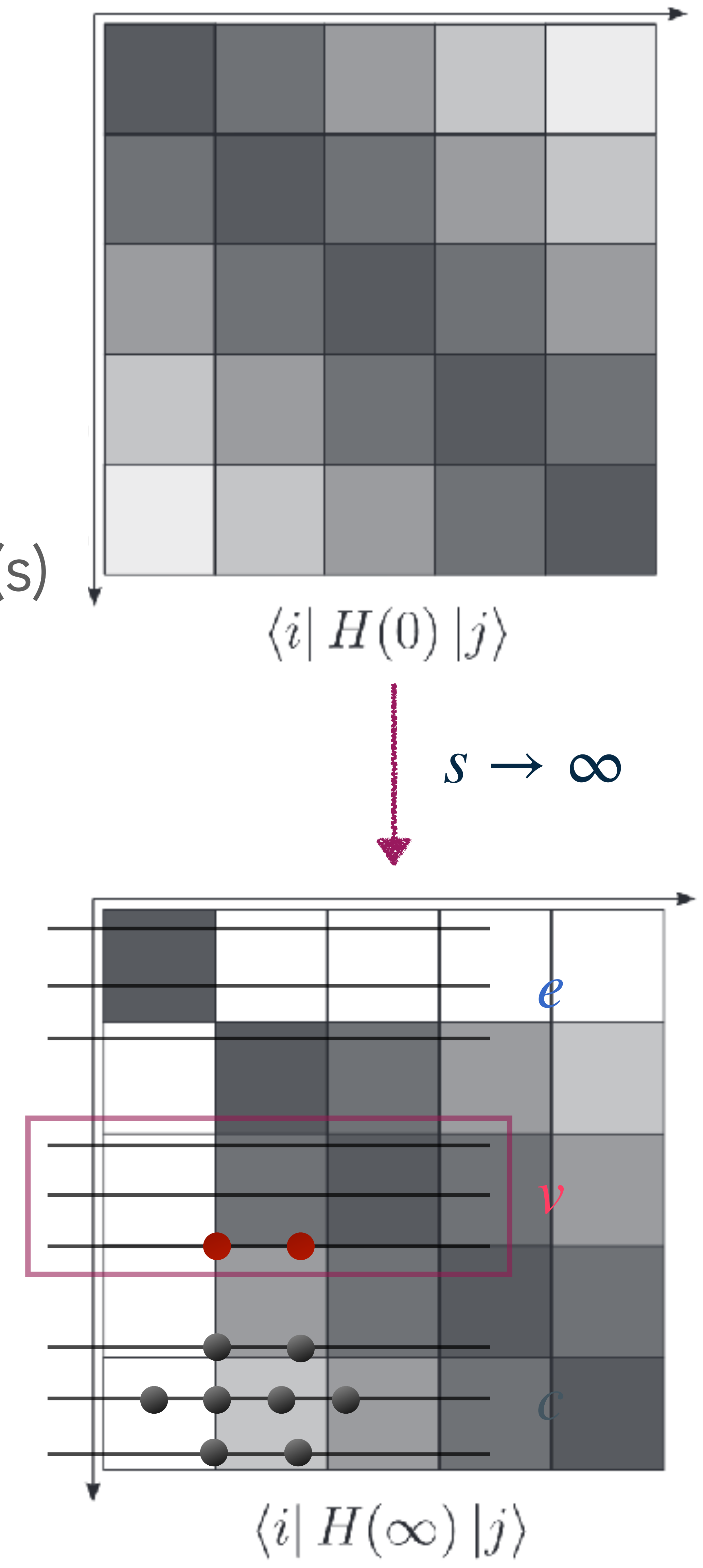
In the VS formulation $H^{\mathrm{od}} \equiv H^{\mathrm{exc}}$, all terms connecting valence configurations to non-valence configurations

0

$$\begin{aligned} H^{od} \equiv\, & \langle v|H|c\rangle + \langle e|H|c\rangle + \langle e|H|v\rangle + \\ & +\langle vv|H|cc\rangle + \langle ev|H|cc\rangle + \langle ee|H|cc\rangle + \langle vv|H|vc\rangle \\ & +\langle ev|H|vc\rangle + \langle ee|H|vc\rangle + \langle ev|H|vv\rangle + \langle ee|H|vv\rangle \end{aligned}$$

VS effective interaction

$$\langle v|H|v\rangle + \langle vv|H|vv\rangle$$



H Hergert *et. al.*, Phys. Rep. 621, 165–222 (2016)

Backup

VS-IMSRG method

Way in which U changes given by the action of an operator called the **generator** η

$$\frac{dU(s)}{ds} = \eta(s)U(s)$$

Flow equation for H

$$\boxed{\frac{dH(s)}{ds} = [\eta(s), H(s)]}$$

Example $\eta(s) = \frac{H_{ij}^{\mathrm{od}}}{E_i - E_j}$

Consistent transformation of observables

$$H(s) = U(s)H(0)U^{\dagger}(s) \implies O(s) = U(s)O(0)U^{\dagger}(s)$$

$$\frac{dH(s)}{ds} = [\eta(s), H(s)] \implies \boxed{\frac{dO(s)}{ds} = [\eta(s), O(s)]}$$

IMSRG evolution of H(s) and M1(s) is done with **`imsrg++`** code (R. Stroberg), **KSHELL** (arXiv:1310.5431) for NMEs calculations

Backup

Ab initio study for $\gamma\gamma$ from $0^+_{\rm DIAS}$

Study of $\gamma\gamma$(M1M1) within VS-IMSRG(2), starts from **NN** and **3N** interactions based on chiral effective field theory

$\gamma\gamma$(M1M1) NME from $0^+_{\rm DIAS} \longrightarrow 0^+_{\rm gs}$ ***sd*-shell**

$^{20-28}$Ne $^{22-26,30}$Mg $^{24-32}$Si $^{32-34}$S $^{34-36}$Ar

Worst convergence of $M^{\gamma\gamma}$ as the isospin of $0^+_{\rm DIAS}$ is higher

Chiral NN+3N EM1.8/2.0 interaction **isospin symmetry is slightly broken** → study of isospin mixing

State	Nuclei	1.8/2.0 EM	USDA	USDB	Exp.
$0^+_{\rm DIAS}$	^{20}Ne	16.60	16.96	16.84	16.73
$1^+_{\rm IAS}$	^{20}Ne	10.47	11.19	11.17	11.26
$0^+_{\rm DIAS}$	^{24}Mg	16.22	15.35	15.38	15.44
$1^+_{\rm IAS}$	^{24}Mg	11.00	9.85	9.94	9.97
$0^+_{\rm DIAS}$	^{28}Si	16.48	15.52	15.36	15.23
$0^+_{\rm DIAS}$	^{32}S	13.16	11.91	11.93	12.05
$1^+_{\rm IAS}$	^{32}S	8.58	6.78	6.84	7.00
$0^+_{\rm DIAS}$	^{36}Ar	12.97	10.88	10.86	10.85

Energies of **IAS, DIAS states**

Backup

Double gamma decay contact amplitude

The contact amplitude is proportional to

$$P_J^{sg}(S'L'SL, k_0, k_0') = (2\pi)(-1)^J \frac{\hat{L}\hat{L}'}{\hat{J}} \langle J_f || \int d^3\mathbf{x} d^3\mathbf{y} (-1)^{\Delta_{\mu 0}+\Delta_{\nu 0}} \hat{B}_{\mu\nu}(\mathbf{x},\mathbf{y}) \left[\widetilde{A}^{\mu}_{L'} \times \widetilde{A}^{\nu}_{L} \right]_J || J_i \rangle$$

Point-like nucleons, absence of exchange currents

$$B_{\mu\nu}(\mathbf{x},\mathbf{y}) = \frac{\delta_{\mu\nu}}{m} \sum_{i=1}^{A} e^2(i) \delta^{(3)}(\mathbf{x}-\mathbf{x}_i)(\mathbf{x},\mathbf{y}) \delta^{(3)}(\mathbf{y}-\mathbf{x}_i) \longrightarrow P_J^{sg}(ML'ML, k_0, k_0') = O(k_0, k_0', L, L', J) \langle J_f || \underbrace{\sum_{i=1}^{A} \frac{e^2(i)}{m} r_i^{L+L'} Y_J(\Omega_i)}_{O^{SG}_{LL'J}} || J_i \rangle$$

$$\delta_{00} = \delta_{0k} = 0$$

$B_{ij}(\mathbf{x},\mathbf{y}) \rightarrow$ Only magnetic multipoles contribute

$$\widetilde{\mathbf{A}}_{L,M}(E, k_0, \mathbf{x}) = 0 \qquad \widetilde{\mathbf{A}}_{L,M}(M, k_0, \mathbf{x}) \neq 0$$

Backup

Double gamma decay contact amplitude

Steps followed to obtain $M_{sg}^{\gamma\gamma}(M1M1)$

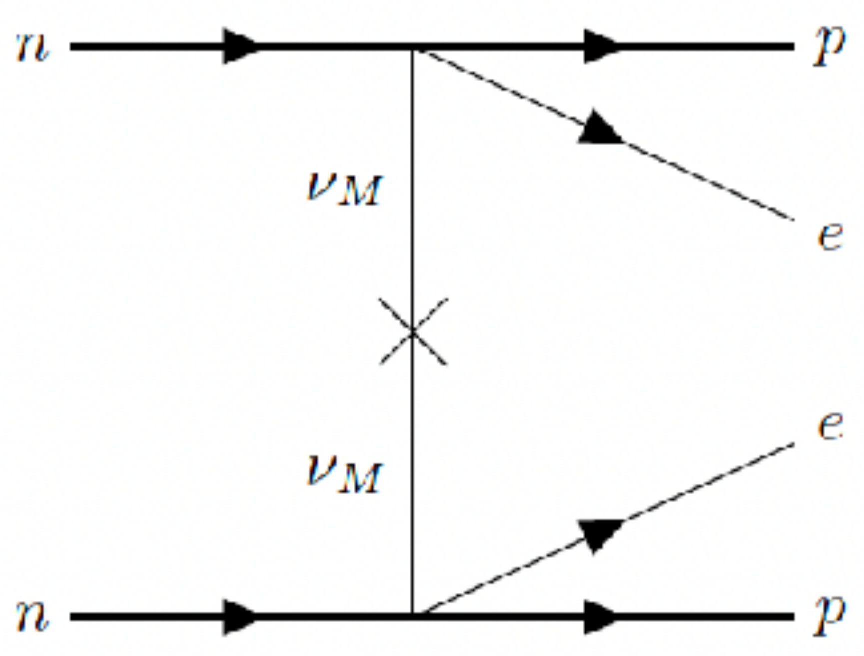
$$M_{sg}^{\gamma\gamma}(2M1) = \sum_{a,b} (a \parallel \mathbf{O}_{\mathbf{1}}^{\mathbf{sg}} \parallel b)\langle 0_f^+ \parallel [c_\alpha^\dagger \tilde{c}_\beta]_0 \parallel 0_i^+(DIAS)\rangle$$

The steps would be the same but without obtaining intermediate estates

However the isospin tensor structure makes not possible to connect $|0_i^+(DIAS)\rangle$ and $|0_f^+\rangle \longrightarrow M_{sg}^{\gamma\gamma}(M1M1) \ll 1$

Backup

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



Lepton and hadron currents

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

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

Long range part (closure app.)

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

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

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

Spin-space operators

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

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

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

Backup

Light neutrino $M_S^{0\nu}$ term

Short range operator

$$M_{\mathrm{S}}^{0\nu} = \frac{2R}{\pi g_A^2}\langle 0_f^+ || \sum_{ij} \tau_i^- \tau_j^- \int j_0(qr_{ij}) h_{\mathrm{S}}(q^2) q^2 dq || 0_i^+ \rangle$$

with the neutrino potential $h_{\mathrm{S}}(q^2) = 2g_\nu^{NN} e^{-q^2/(2\Lambda_{\mathrm{S}})}$

Backup

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

Extend the standard model adding right-handed neutrinos ν_R not participating in weak interactions

Dirac mass term $\mathscr{L}_D = -\frac{1}{2} m_D(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L) \longrightarrow m_D = \frac{y^\nu v}{\sqrt{2}}$ $y_\nu \sim 10^{-12} \ll y_l$

But for neutral particles

Majorana condition $\nu^c = \nu$ $\nu^c = C\bar{\nu}^T$ is the CP conjugate of ν and $\nu_R = (\nu_L)^c$

Majorana mass term $\mathscr{L}_L = -\frac{1}{2} m_L(\overline{\nu_L}\nu_L^c + \overline{(\nu_L^c)}\nu_L) \longrightarrow m_L = \frac{v^2}{2\Lambda}$ $\Lambda \sim 10^{15}\mathrm{GeV}$ new physics scale

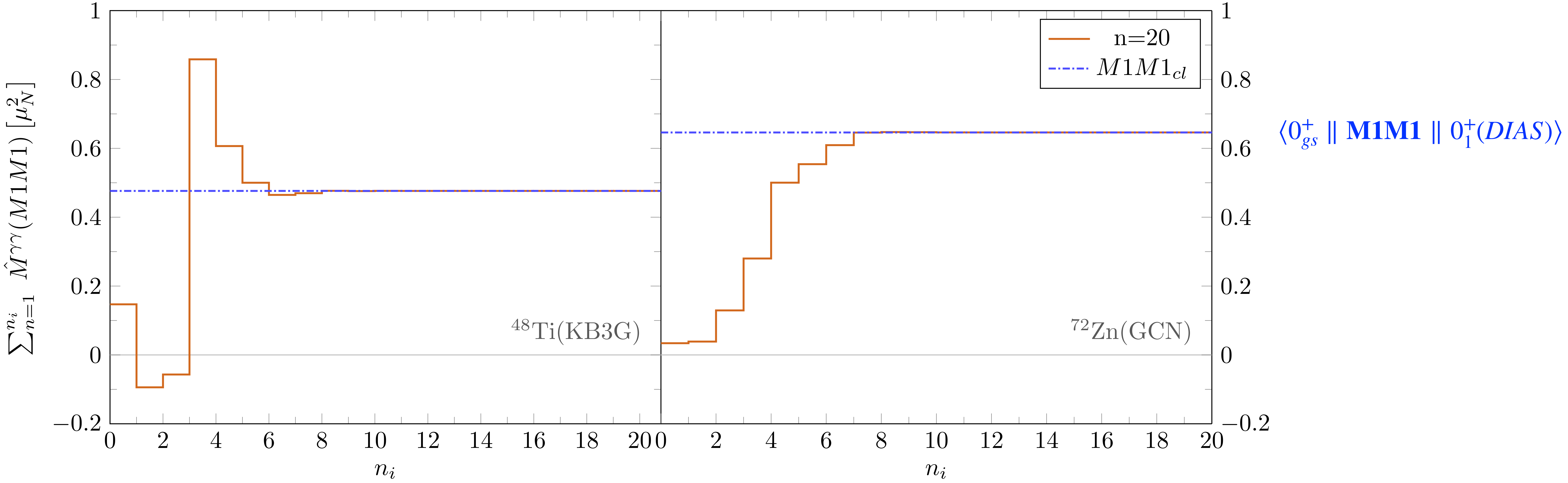
Violates lepton number (LNV) $\Delta L = 2$ and converts particles into their antiparticles

Most feasible process to **observe LNV in laboratory is** $0\nu\beta\beta$, help to **understand mater-antimatter asymmetry** in the universe

M1M1 convergence

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

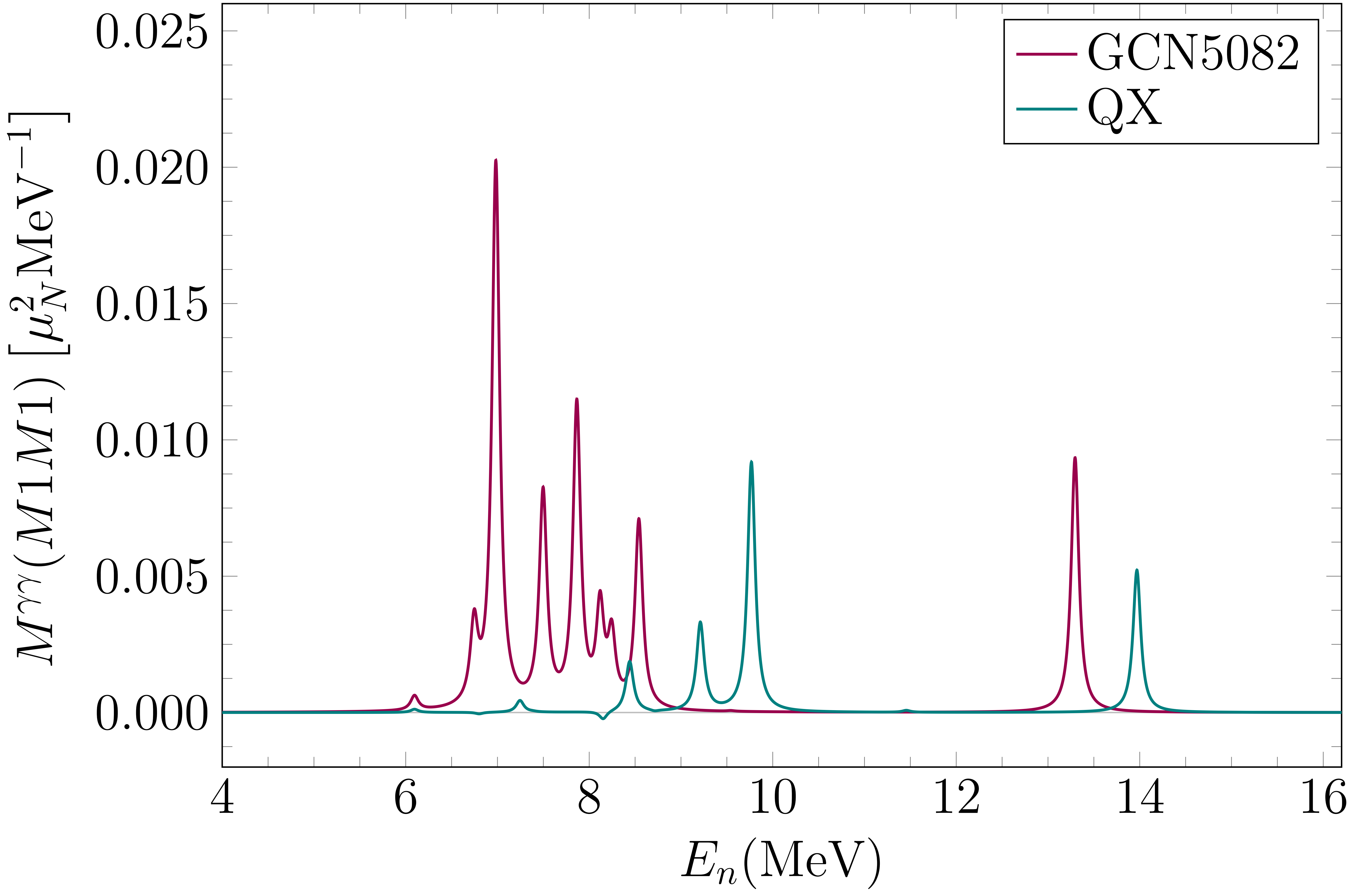
$$\hat{M}^{\gamma\gamma}(M1M1) = \sum_n \langle 0^+_{gs} \parallel \mathbf{M1} \parallel 1^+_n(IAS)\rangle\langle 1^+_n(IAS) \parallel \mathbf{M1} \parallel 0^+_1(DIAS)\rangle$$



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

Backup

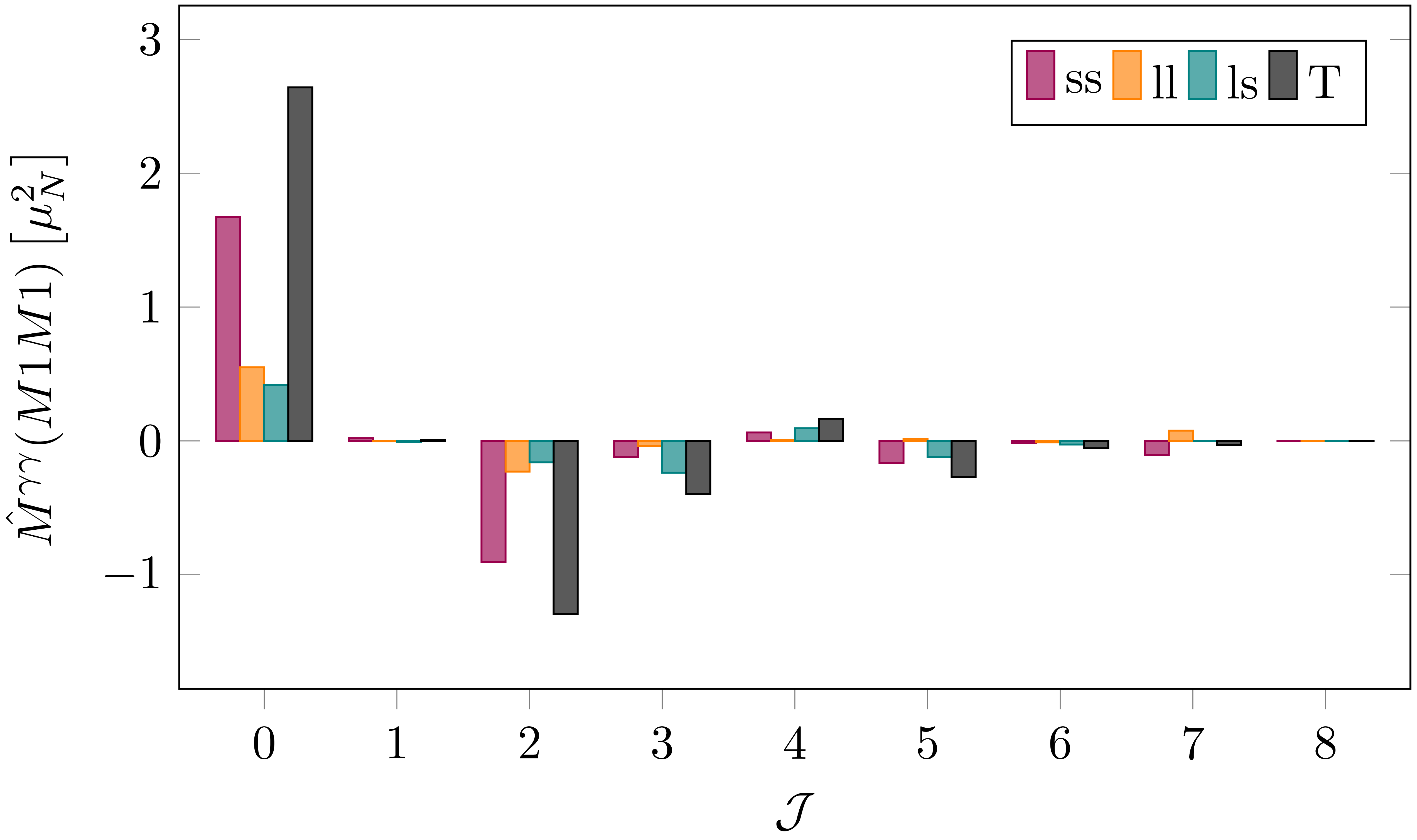
Effective interaction effect in sdhg configuration space

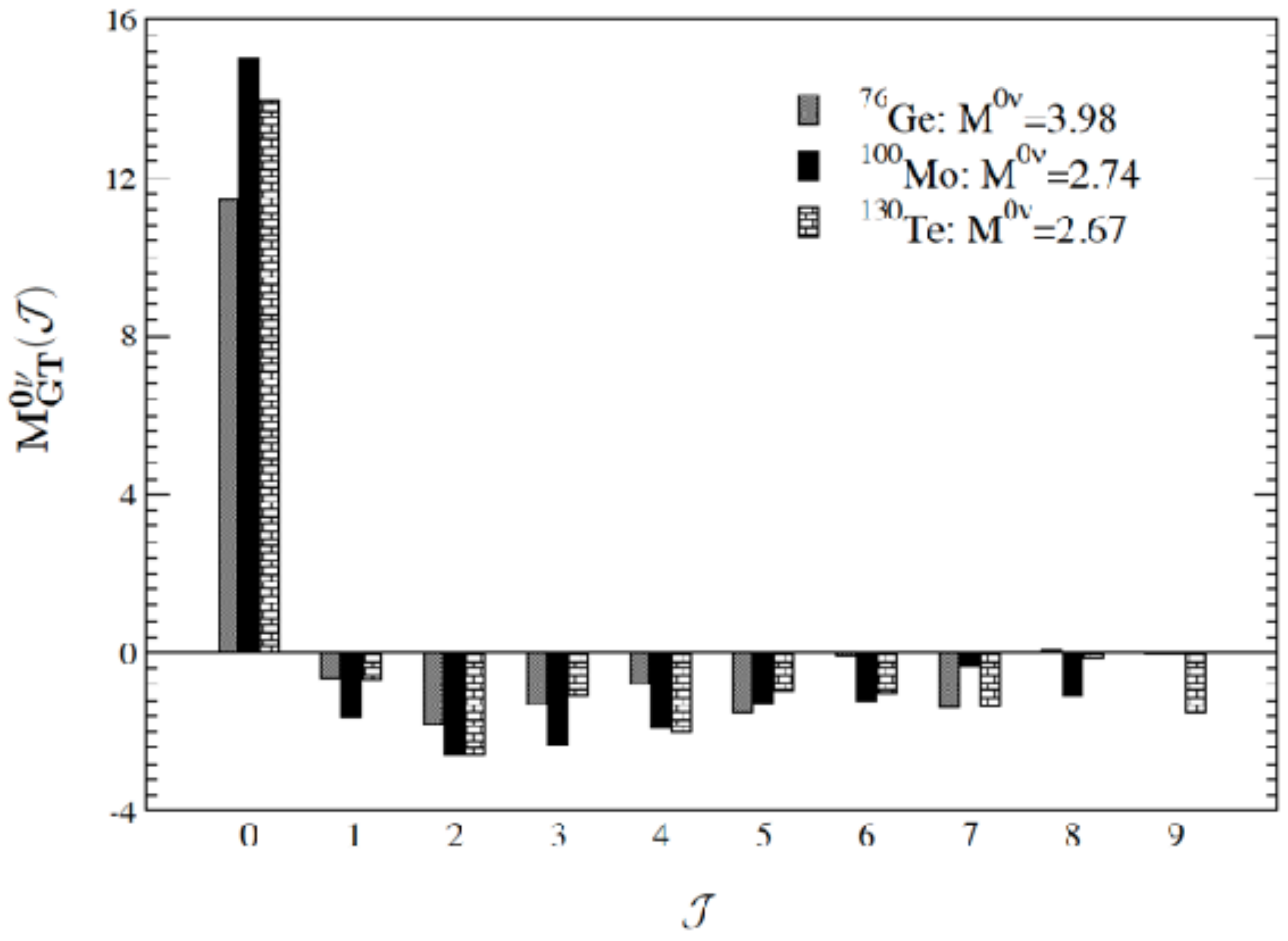


Backup

Spin Orbital and Interference contributions

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





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

But also it is where the strongest cancellation is observed