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Recent status of theoretical studies for neutrinoless double beta decay

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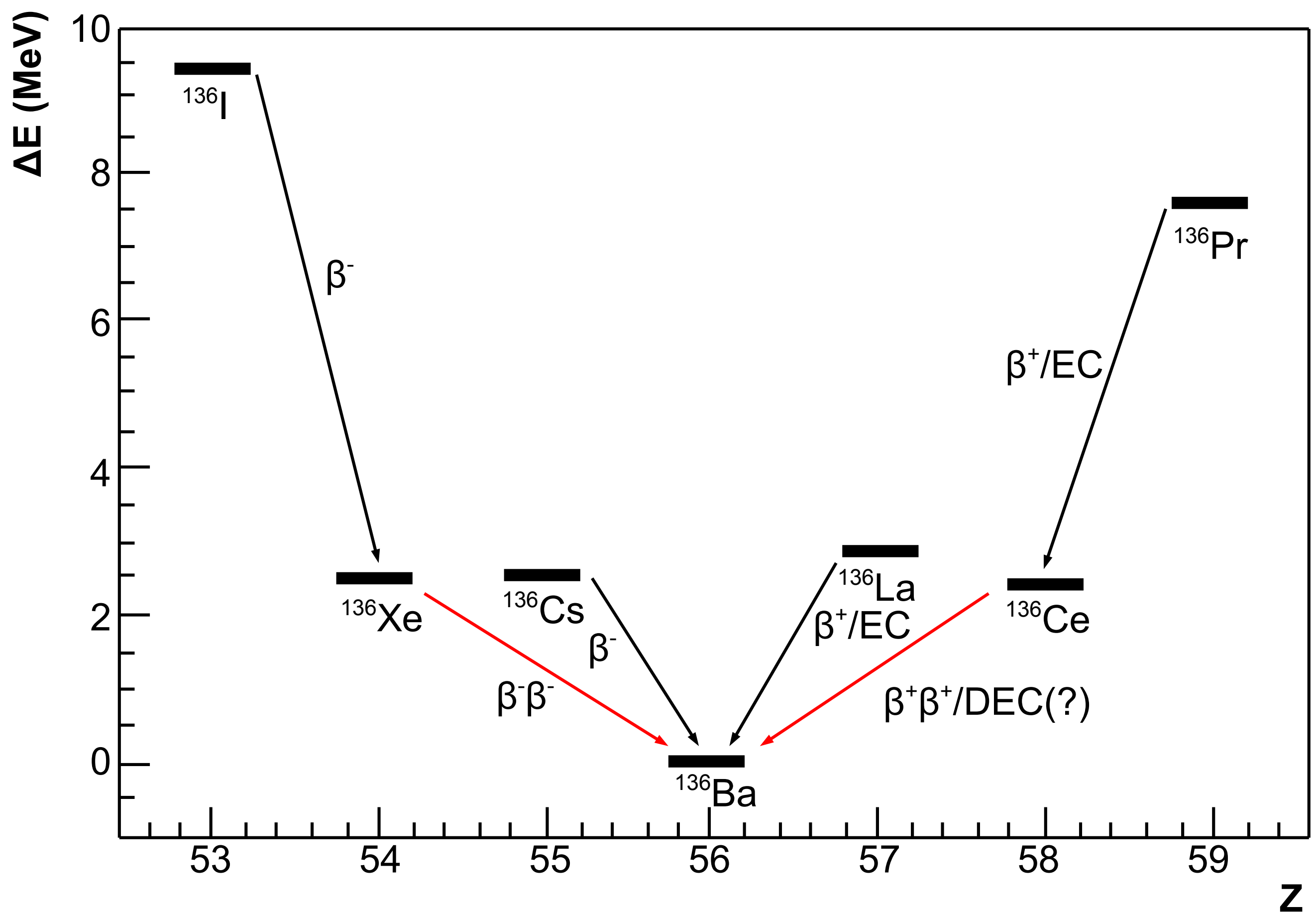
第二届地下和空间粒子物理与宇宙物理前沿问题研讨会

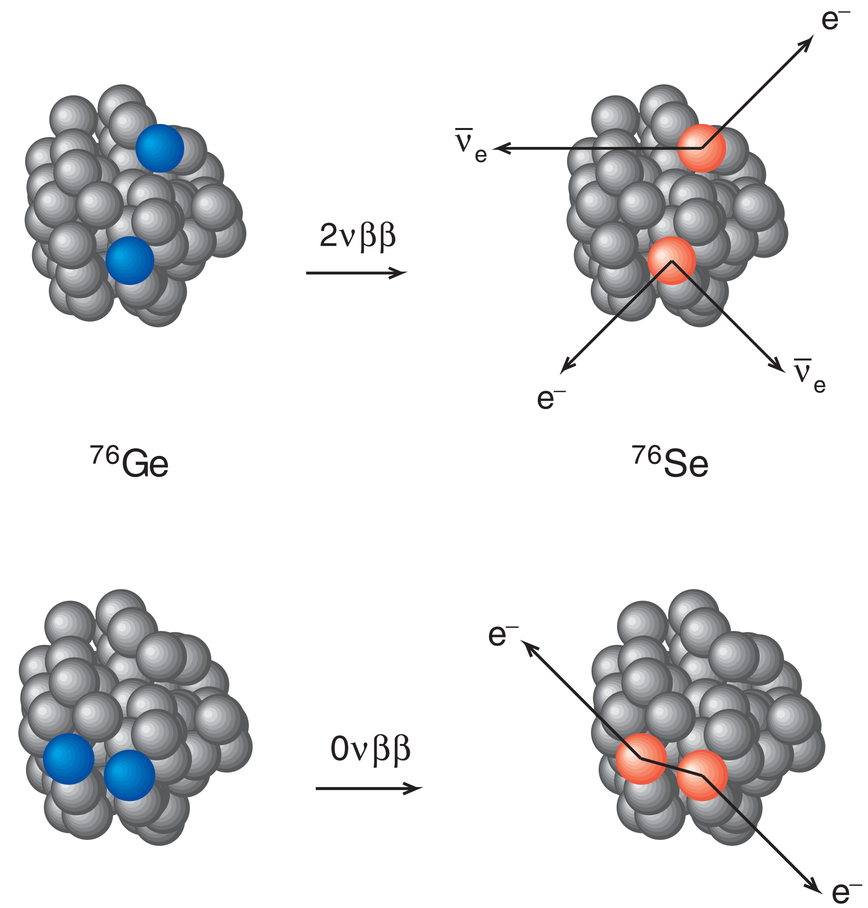
Outline

- Background
- Underlying new physics
- Mechanism at nucleon level
- NMEs from nuclear many-body calculations
- Attempts to measure the NME
- Conclusions and Outlook

Background

Background



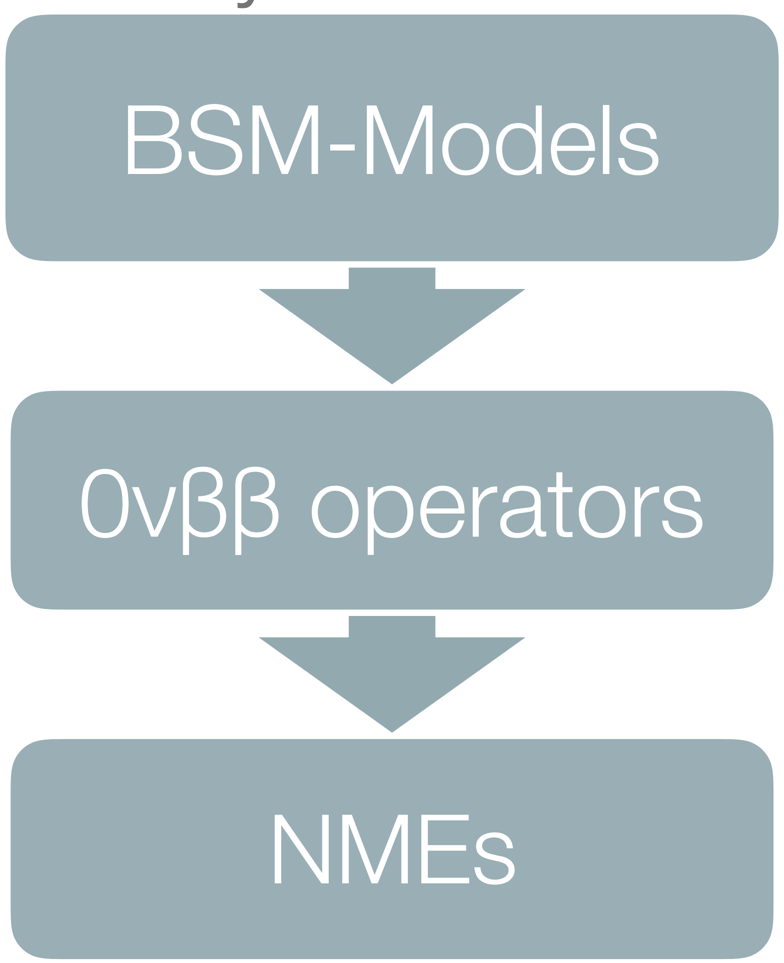


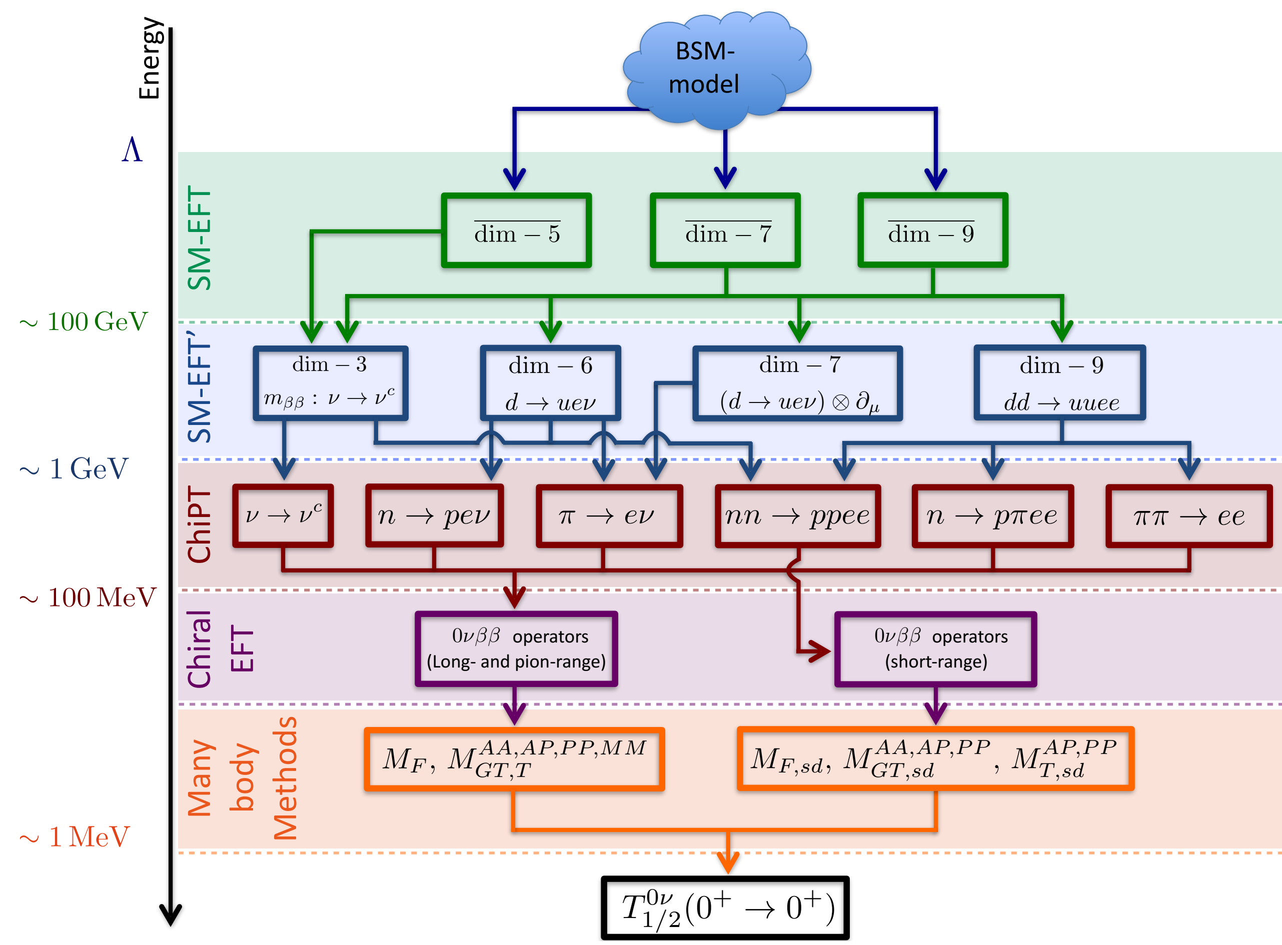
- Nuclear pairing induces double beta decay
- Neutrinoless double beta decay reveals Majorana nature of neutrino

Background

- A systematic way of describing neutrinoless double beta decay has been developed recently

Cirigliano 18'





- Advantages: better controlled errors and hierarchies

New Physics

Mechanisms

- Different new physics models with broken lepton-number conservation could lead to this decay mode
  - L-R symmetric models with see-saw

    Mohapatra 81'
  - R-parity violating SUSY

    Hirsh 95'
  - Extra dimension model

    Dienes 99'
  - ….

New Physics

Cirigliano 18'

EFT is a useful tool to provide more complete description

- Dim-5 operator

$$\epsilon_{kl}\epsilon_{mn}(L_k^T\,\mathcal{C}^{(5)}\,CL_m)H_lH_n$$

- Dim-7 operators

Class 5	$\psi^4 D$
$\mathcal{O}^{(1)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L_i^T C(D^\mu L)_j)$
Class 6	$\psi^4 H$
$\mathcal{O}_{LL\bar{e}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{e}L_i)(L_j^T CL_m)H_n$
$\mathcal{O}^{(1)}_{LLQ\bar{d}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{d}L_i)(Q_j^T CL_m)H_n$
$\mathcal{O}^{(2)}_{LLQ\bar{d}H}$	$\epsilon_{im}\epsilon_{jn}(\bar{d}L_i)(Q_j^T CL_m)H_n$
$\mathcal{O}_{LL\bar{Q}uH}$	$\epsilon_{ij}(\bar{Q}_m u)(L_m^T CL_i)H_j$
$\mathcal{O}_{Leu\bar{d}H}$	$\epsilon_{ij}(L_i^T C\gamma_\mu e)(\bar{d}\gamma^\mu u)H_j$

- Dim-3 operator: mass

- Dim-6 operators

$$\frac{2G_F}{\sqrt{2}}\Big(C^{(6)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j}$$
$$+C^{(6)}_{\mathrm{SR},ij}\,\bar{u}_L d_R\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{SL},ij}\,\bar{u}_R d_L\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j}$$
$$+C^{(6)}_{\mathrm{T},ij}\,\bar{u}_L\sigma^{\mu\nu}d_R\,\bar{e}_{L,i}\sigma_{\mu\nu}\,C\bar{\nu}^T_{L,j}\Big) + \mathrm{h.c.}$$

- Dim-7 operators

$$\frac{2G_F}{\sqrt{2}v}\Big(C^{(7)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{L,i}\,C\,i\overleftrightarrow{\partial}_\mu\bar{\nu}^T_{L,j} + C^{(7)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{L,i}\,Ci\overleftrightarrow{\partial}_\mu\bar{\nu}^T_{L,j}\Big) + \mathrm{h.c.}$$

- Dim-9 operator

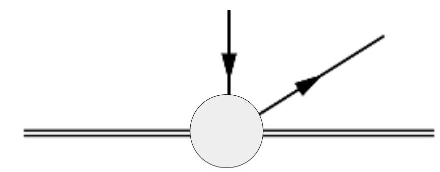
$$\frac{1}{v^5}\sum_i\Big[\Big(C^{(9)}_{i\,\mathrm{R}}\,\bar{e}_R C\bar{e}_R^T + C^{(9)}_{i\,\mathrm{L}}\,\bar{e}_L C\bar{e}_L^T\Big)\,O_i + C^{(9)}_i\bar{e}\gamma_\mu\gamma_5 C\bar{e}^T\,O_i^\mu\Big]$$

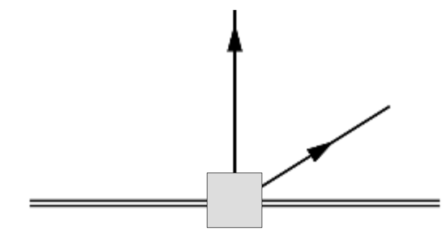
Matching at nucleon level

Operators for free nucleons

Cirigliano 18'

$$\bar{N}\tau^+\left[\frac{l_\mu + r_\mu}{2}J_V^\mu + \frac{l_\mu - r_\mu}{2}J_A^\mu - s\,J_S + ip\,J_P + t_{R\,\mu\nu}\,J_T^{\mu\nu}\right]N$$





- Matching following χEFT technique for dim-6,7 operator

$$\begin{aligned}
J_V^\mu &= g_V(\mathbf{q}^2)\left(v^\mu + \frac{p^\mu + p'^\mu}{2m_N}\right) + \frac{i g_M(\mathbf{q}^2)}{m_N}\varepsilon^{\mu\nu\alpha\beta}v_\alpha S_\beta q_\nu\,,\\
J_A^\mu &= -g_A(\mathbf{q}^2)\left(2S^\mu - \frac{v^\mu}{2m_N}\,2S\cdot(p+p')\right) + \frac{g_P(\mathbf{q}^2)}{2m_N}2q^\mu\,S\cdot q\,,\\
J_S &= g_S(\mathbf{q}^2)\,,\\
J_P &= B\frac{g_P(\mathbf{q}^2)}{m_N}S\cdot q\,,\\
J_T^{\mu\nu} &= -2g_T(\mathbf{q}^2)\varepsilon^{\mu\nu\alpha\beta}\left(v_\alpha + \frac{p_\alpha + p'_\alpha}{2m_N}\right)S_\beta - i\frac{g'_T(\mathbf{q}^2)}{2m_N}(v^\mu q^\nu - v^\nu q^\mu)\,.
\end{aligned}$$

$$\begin{aligned}
s + ip &= -\frac{2G_F}{\sqrt{2}}\left[C_{\rm SL}^{(6)}\,(\tau^+)\,\bar{e}_L C\bar{\nu}_L^T + C_{\rm SR}^{(6)*}\,(\tau^-)\,\nu_L^T C e_L\right],\\
s - ip &= -\frac{2G_F}{\sqrt{2}}\left[C_{\rm SR}^{(6)}\,(\tau^+)\,\bar{e}_L C\bar{\nu}_L^T + C_{\rm SL}^{(6)*}\,(\tau^-)\,\nu_L^T C e_L\right],\\
l_\mu &= \frac{2G_F}{\sqrt{2}v}(\tau^+)\left[-2vV_{ud}\bar{e}_L\gamma_\mu\nu_L + v\,C_{\rm VL}^{(6)}\,\bar{e}_R\gamma_\mu C\bar{\nu}_L^T + C_{\rm VL}^{(7)}\,\bar{e}_L\,Ci\overleftrightarrow{\partial}_\mu\bar{\nu}_L^T\right] + \text{h.c.}\\
r_\mu &= \frac{2G_F}{\sqrt{2}v}(\tau^+)\left[v\,C_{\rm VR}^{(6)}\,\bar{e}_R\gamma_\mu C\bar{\nu}_L^T + C_{\rm VR}^{(7)}\,\bar{e}_L\,Ci\overleftrightarrow{\partial}_\mu\bar{\nu}_L^T\right] + \text{h.c.}\,,\\
t_R^{\mu\nu} &= \frac{2G_F}{\sqrt{2}}(\tau^+)C_T^{(6)}\bar{e}_L\sigma^{\mu\nu}C\bar{\nu}_L^T\,,
\end{aligned}$$

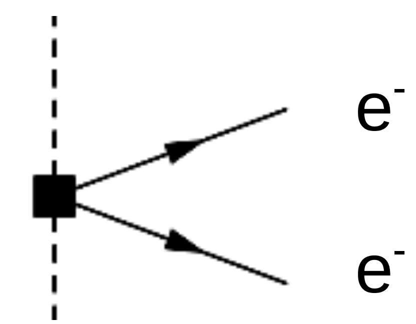
- Lepton parts are treated as external currents

Operators for free nucleons

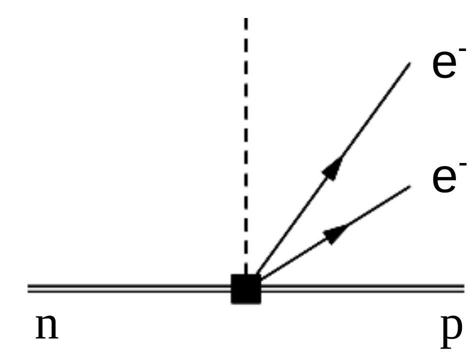
Cirigliano 18'

- For dim-9 operator

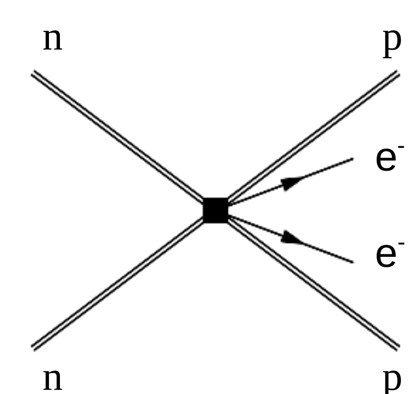
$$\frac{F_0^4}{4}\left[\frac{5}{3}g_1^{\pi\pi}C_{1\mathrm{L}}^{(9)}L_{21}^{\mu}L_{21\,\mu}+\left(g_2^{\pi\pi}C_{2\mathrm{L}}^{(9)}+g_3^{\pi\pi}C_{3\mathrm{L}}^{(9)}\right)\mathrm{Tr}\left(U\tau^+U\tau^+\right)\right.$$
$$\left.+\left(g_4^{\pi\pi}C_{4\mathrm{L}}^{(9)}+g_5^{\pi\pi}C_{5\mathrm{L}}^{(9)}\right)\mathrm{Tr}\left(U\tau^+U^\dagger\tau^+\right)\right]\frac{\bar{e}_L C\bar{e}_L^T}{v^5}+(L\leftrightarrow R)$$



$$g_A g_1^{\pi N}C_{1\mathrm{L}}^{(9)}F_0^2\left[\bar{N}S^\mu u^\dagger\tau^+uN\,\mathrm{Tr}\left(u_\mu u^\dagger\tau^+u\right)\right]\frac{\bar{e}_L C\bar{e}_L^T}{v^5}$$



$$g_1^{NN}C_{1\mathrm{L}}^{(9)}\,(\bar{N}u^\dagger\tau^+uN)(\bar{N}u^\dagger\tau^+uN)\,\frac{\bar{e}_L C\bar{e}_L^T}{v^5}$$
$$+\left(g_2^{NN}C_{2\mathrm{L}}^{(9)}+g_3^{NN}C_{3\mathrm{L}}^{(9)}\right)\,(\bar{N}u^\dagger\tau^+u^\dagger N)(\bar{N}u^\dagger\tau^+u^\dagger N)\,\frac{\bar{e}_L C\bar{e}_L^T}{v^5}$$
$$+\left(g_4^{NN}C_{4\mathrm{L}}^{(9)}+g_5^{NN}C_{5\mathrm{L}}^{(9)}\right)\,(\bar{N}u^\dagger\tau^+uN)(\bar{N}u\tau^+u^\dagger N)\,\frac{\bar{e}_L C\bar{e}_L^T}{v^5}+(L\leftrightarrow R)$$



Expressions for nuclei

Decay rate

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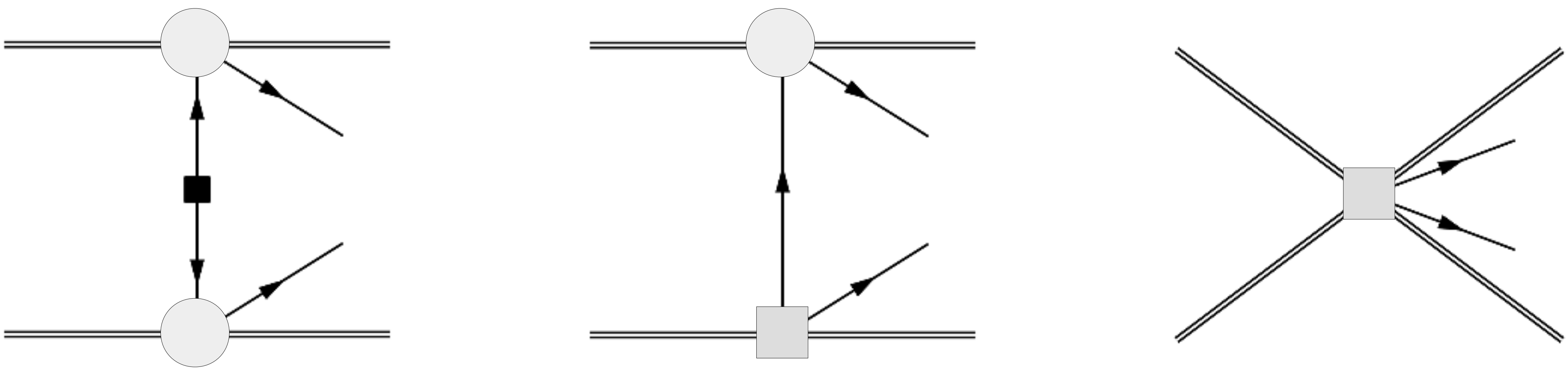


- The master formula for decay width ($0^+ \longrightarrow 0^+$):

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \Big\{ G_{01}\ \left(|\mathcal{A}_\nu|^2 + |\mathcal{A}_R|^2\right) - 2(G_{01} - G_{04})\mathrm{Re}\mathcal{A}_\nu^* \mathcal{A}_R + 4G_{02}\,|\mathcal{A}_E|^2$$
$$+2G_{04}\left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re}\left(\mathcal{A}_{m_e}^*(\mathcal{A}_\nu + \mathcal{A}_R)\right)\right]$$
$$-2G_{03}\,\mathrm{Re}\left[(\mathcal{A}_\nu + \mathcal{A}_R)\mathcal{A}_E^* + 2\mathcal{A}_{m_e}\mathcal{A}_E^*\right]$$
$$+G_{09}\,|\mathcal{A}_M|^2 + G_{06}\,\mathrm{Re}\left[(\mathcal{A}_\nu - \mathcal{A}_R)\mathcal{A}_M^*\right] \Big\} .$$

Decay rate

$$\mathcal{A}_\nu = \frac{m_{\beta\beta}}{m_e}\mathcal{M}_\nu^{(3)} + \frac{m_N}{m_e}\mathcal{M}_\nu^{(6)} + \frac{m_N^2}{m_e v}\mathcal{M}_\nu^{(9)} \quad \mathcal{A}_M = \frac{m_N}{m_e}\mathcal{M}_M^{(6)} + \frac{m_N^2}{m_e v}\mathcal{M}_M^{(9)}$$

$$\mathcal{A}_E = \mathcal{M}_{E,L}^{(6)} + \mathcal{M}_{E,R}^{(6)} \quad \mathcal{A}_{m_e} = \mathcal{M}_{m_e,L}^{(6)} + \mathcal{M}_{m_e,R}^{(6)} \quad \mathcal{A}_R = \frac{m_N^2}{m_e v}\mathcal{M}_R^{(9)}$$

- M's here are the combinations of NMEs, for the neutrino mass mechanism, we have M_F, M_{GT} and M_T

$$\mathcal{M}_\nu^{(3)} = -V_{ud}^2\left(-\frac{1}{g_A^2}M_F + \mathcal{M}_{GT} + \mathcal{M}_T + 2\frac{m_\pi^2\, g_\nu^{NN}}{g_A^2}M_{F,\,sd}\right), \quad \mathcal{M}_R^{(9)} = \mathcal{M}_\nu^{(9)}\big|_{L\to R}$$

$$\mathcal{M}_\nu^{(9)} = -\frac{1}{2m_N^2}C_{\pi\pi\,\mathrm{L}}^{(9)}\left(\frac{1}{2}M_{GT,sd}^{AP} + M_{GT,sd}^{PP} + \frac{1}{2}M_{T,sd}^{AP} + M_{T,sd}^{PP}\right)$$
$$+\frac{m_\pi^2}{2m_N^2}C_{\pi N\,\mathrm{L}}^{(9)}\left(M_{GT,sd}^{AP} + M_{T,sd}^{AP}\right) - \frac{2}{g_A^2}\frac{m_\pi^2}{m_N^2}C_{NN\,\mathrm{L}}^{(9)}M_{F,\,sd}\,,$$

- Many approximations are used here

Decay rate

- M_F, M_{GT} and M_T are the long range Fermi, Gamow-Teller and tensor parts we are familiar with

$$\mathcal{M}_{GT} = M_{GT}^{AA} + M_{GT}^{AP} + M_{GT}^{PP} + M_{GT}^{MM} \qquad \mathcal{M}_{T} = M_{T}^{AP} + M_{T}^{PP} + M_{T}^{MM}$$

- Where $$M_I^K = \langle f | \frac{2R}{\pi} \int h_I^K(q) j_I(qr) \frac{q dq}{q + E_N} \mathcal{O}_I | i \rangle$$

- Short range NMEs are similar $$M_{I,sd}^K = \langle f | \frac{2R}{\pi} \int h_I^K(q) j_I(qr) \frac{q^2 dq}{q + E_N} \mathcal{O}_I | i \rangle$$

- All these *M*'s can then be expressed in 15 NMEs

$$M_F \quad M_{GT}^{AA} \quad M_{GT}^{AP} \quad M_{GT}^{PP} \quad M_{GT}^{MM} \quad M_{T}^{AA} \quad M_{T}^{AP} \quad M_{T}^{PP} \quad M_{T}^{MM}$$

$$M_{F,sd} \quad M_{GT,sd}^{AA} \quad M_{GT,sd}^{AP} \quad M_{GT,sd}^{PP} \quad M_{T,sd}^{AP} \quad M_{T,sd}^{PP}$$

Decay rate

Stefanik 18'

- A comparison with LR symmetric model in traditional treatment where left- and right-handed neutrino are treated equally (short range mechanism neglected)

$$[T^{0\nu}_{1/2}]^{-1} = g_A^4 |M_{GT}|^2 \Big\{ C_{mm} \left(\frac{|m_{\beta\beta}|}{m_e}\right)^2 + C_{m\lambda} \frac{|m_{\beta\beta}|}{m_e} \langle\lambda\rangle \cos\psi_1 + C_{m\eta} \frac{|m_{\beta\beta}|}{m_e} \langle\eta\rangle \cos\psi_2 + C_{\lambda\lambda}\langle\lambda\rangle^2 + C_{\eta\eta}\langle\eta\rangle^2 + C_{\lambda\eta}\langle\lambda\rangle\langle\eta\rangle \cos(\psi_1 - \psi_2) \Big\}$$

- Where

$$C_{mm} = (1 - \chi_F + \chi_T)^2 G_{01},$$

$$C_{m\lambda} = -(1 - \chi_F + \chi_T)[\chi_{2-} G_{03} - \chi_{1+} G_{04}],$$

$$C_{m\eta} = (1 - \chi_F + \chi_T)[\chi_{2+} G_{03} - \chi_{1-} G_{04} - \chi_P G_{05} + \chi_R G_{06}],$$

$$C_{\lambda\lambda} = \chi_{2-}^2 G_{02} + \tfrac{1}{9}\chi_{1+}^2 G_{011} - \tfrac{2}{9}\chi_{1+}\chi_{2-} G_{010},$$

$$C_{\eta\eta} = \chi_{2+}^2 G_{02} + \tfrac{1}{9}\chi_{1-}^2 G_{011} - \tfrac{2}{9}\chi_{1-}\chi_{2+} G_{010} + \chi_P^2 G_{08} - \chi_P \chi_R G_{07} + \chi_R^2 G_{09},$$

$$C_{\lambda\eta} = -2\big[\chi_{2-}\chi_{2+} G_{02} - \tfrac{1}{9}(\chi_{1+}\chi_{2+} + \chi_{2-}\chi_{1-}) G_{010} + \tfrac{1}{9}\chi_{1+}\chi_{1-} G_{011}\big].$$

Decay

- The rich structures for these NMEs are presented

$$\chi_{1\pm} = \chi_{qGT} - 6\chi_{qT} \pm 3\chi_{qF}, \quad \chi_{2\pm} = \chi_{GT\omega} + \chi_{T\omega} \pm \chi_{F\omega} - \frac{1}{9}\chi_{1\mp}.$$

- These are terms from the helicity exchange terms in neutrino propagator

$$M_{\omega F,\omega GT,\omega T} = \sum \langle A_f \| h_{\omega F,\omega GT,\omega T}(r_-)\mathcal{O}_{F,GT,T} \| A_i \rangle$$

$$M_{qF,qGT,qT} = \sum \langle A_f \| h_{qF,qGT,qT}(r_-)\mathcal{O}_{F,GT,T} \| A_i \rangle$$

- And also time-space components and recoil terms

$$M_P = \sum i \langle A_f \| h_P(r_-)\tau_r^+ \tau_s^+ \frac{(\mathbf{r}_- \times \mathbf{r}_+)}{R^2} \cdot \vec{\sigma}_r \| A_i \rangle$$

$$M_R = \sum \langle A_f \| [h_{RG}(r_-)\mathcal{O}_{GT} + h_{RT}(r_-)\mathcal{O}_T] \| A_i \rangle$$

Decay rate

Stefanik 18'

- A comparison with LR symmetric model in traditional treatment where left- and right-handed neutrino are treated equally

$$
\begin{aligned}
\left[T_{1/2}^{0\nu}\right]^{-1} &= g_A^4 |M_{GT}|^2 \Bigg\{ C_{mm} \left(\frac{|m_{\beta\beta}|}{m_e}\right)^2 + C_{m\lambda} \frac{|m_{\beta\beta}|}{m_e} \langle\lambda\rangle \cos\psi_1 \\
&+ C_{m\eta} \frac{|m_{\beta\beta}|}{m_e} \langle\eta\rangle \cos\psi_2 + C_{\lambda\lambda} \langle\lambda\rangle^2 + C_{\eta\eta} \langle\eta\rangle^2 + C_{\lambda\eta} \langle\lambda\rangle\langle\eta\rangle \cos(\psi_1 - \psi_2) \Bigg\}
\end{aligned}
$$

- A direct comparison with SMEFT haven't been done

$$
\begin{aligned}
\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \Big\{ & G_{01} \left(|\mathcal{A}_\nu|^2 + |\mathcal{A}_R|^2\right) - 2(G_{01} - G_{04}) \mathrm{Re} \mathcal{A}_\nu^* \mathcal{A}_R + 4 G_{02} |\mathcal{A}_E|^2 \\
& + 2 G_{04} \left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re}\left(\mathcal{A}_{m_e}^* (\mathcal{A}_\nu + \mathcal{A}_R)\right) \right] \\
& - 2 G_{03} \, \mathrm{Re}\left[(\mathcal{A}_\nu + \mathcal{A}_R) \mathcal{A}_E^* + 2 \mathcal{A}_{m_e} \mathcal{A}_E^* \right] \\
& + G_{09} |\mathcal{A}_M|^2 + G_{06} \, \mathrm{Re}\left[(\mathcal{A}_\nu - \mathcal{A}_R) \mathcal{A}_M^* \right] \Big\} .
\end{aligned}
$$

NME

Cirigliano 17', Hyvarinen15', Barea 15', Horoi 18'

- NME correspondence in different references

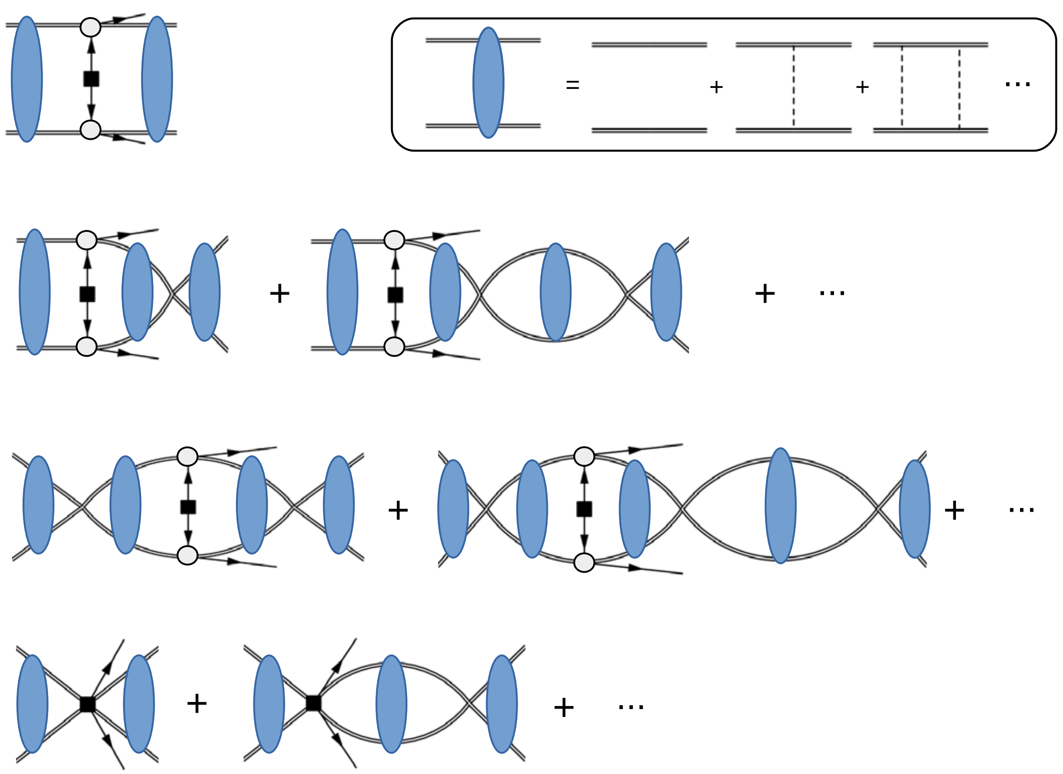
NMEs	Ref. [76, 84, 85]	Ref. [83]	Ref. [32]
M_F	M_F	M_F	$M_{F,F\omega,Fq}$
M_{GT}^{AA}	M_{GT}^{AA}	M_{GT}^{AA}	$M_{GT\omega,GTq}$
M_{GT}^{AP}	M_{GT}^{AP}	M_{GT}^{AP}	$4\frac{m_e}{B}M_{GT\pi\nu}+\frac{1}{3}M_{GT2\pi}$
M_{GT}^{PP}	M_{GT}^{PP}	M_{GT}^{PP}	$-\frac{1}{6}M_{GT2\pi}$
M_{GT}^{MM}	$r_M^2 M_{GT}^{MM}$	M_{GT}^{MM}	$r_M\frac{g_M}{2g_Ag_VR_Am_N}M_R=\frac{g_M^2}{6g_A^2R_Am_N}M_{GT'}$
M_T^{AA}	✗	✗	✗
M_T^{AP}	M_T^{AP}	M_T^{AP}	$4\frac{m_e}{B}M_{T\pi\nu}+\frac{1}{3}M_{T2\pi}$
M_T^{PP}	M_T^{PP}	M_T^{PP}	$-\frac{1}{6}M_{T2\pi}$
M_T^{MM}	$r_M^2 M_T^{MM}$	M_T^{MM}	$-\frac{g_M^2}{12g_A^2R_Am_N}M'_T$
$M_{F,sd}$	$\frac{m_em_N}{m_\pi^2}M_{F,sd}$	$\frac{m_em_N}{m_\pi^2}M_{F,sd}$	$\frac{m_em_N}{m_\pi^2}M_{FN}=\frac{m_N}{R_Am_\pi^2}M'_F$
$M_{GT,sd}^{AA}$	$\frac{m_em_N}{m_\pi^2}M_{GT,sd}^{AA}$	$\frac{m_em_N}{m_\pi^2}M_{GT,sd}^{AA}$	$\frac{m_em_N}{m_\pi^2}M_{GTN}=\frac{m_N}{R_Am_\pi^2}M'_{GT}$
$M_{GT,sd}^{AP}$	$\frac{m_em_N}{m_\pi^2}M_{GT,sd}^{AP}$	$\frac{m_em_N}{m_\pi^2}M_{GT,sd}^{AP}$	$\frac{2}{3}M_{GT1\pi}$
$M_{GT,sd}^{PP}$	$\frac{m_em_N}{m_\pi^2}M_{GT,sd}^{PP}$	$\frac{m_em_N}{m_\pi^2}M_{GT,sd}^{PP}$	$\frac{1}{6}(M_{GT2\pi}-2M_{GT1\pi})$
$M_{T,sd}^{AP}$	$\frac{m_em_N}{m_\pi^2}M_{T,sd}^{AP}$	$\frac{m_em_N}{m_\pi^2}M_{T,sd}^{AP}$	$\frac{2}{3}M_{T1\pi}$
$M_{T,sd}^{PP}$	$\frac{m_em_N}{m_\pi^2}M_{T,sd}^{PP}$	$\frac{m_em_N}{m_\pi^2}M_{T,sd}^{PP}$	$\frac{1}{6}(M_{T2\pi}-2M_{T1\pi})$

New Contributions

Cirigliano 18'

- The requirement of renormalizablility of χEFT

- A contact operator need to be prompted to LO to cancel the divergence



- The operator is actually with a simple form

$$V_{\nu,CT} = -2g_{\nu}^{\mathrm{NN}}\tau^{(1)+}\tau^{(2)+}$$

- The LEC needs to be determined

NMEs

Approaches

- Modern nuclear structure calculations relay on our understanding of nuclear force and many-body correlations

- For the nuclear force used in many-body approaches:

  - Realistic nuclear force — derived from bare nucleon force and softened by certain methods (*ab initio*)

    IMSRG, ab initio CC, VSIMSRG+NSM, …

  - Phenomenological force — starting with certain symmetries and the parameters are fitted by nuclear properties

Approaches

- Most traditional methods used in double beta decay calculations are based on phenomenological forces
  - Shell Model (configuration interaction)
  - DFT based on relativistic and non-relativistic mean-field
  - GCM based on DFT
  - QRPA based on DFT or phenomenological mean-field
- Geometric models without explicit inclusions of nuclear forces: pSU(3), IBM etc.

Results

- The light neutrino mass mechanism has been in last decade well investigated although the new LO terms haven’t been included

- It is impossible to give a complete list

    - NSM: renormalization of operator; larger model space

Caurier 12’, Horoi 13’, Menendez 14’, Iwata 16’, Menendez 18’, Coraggio 20’

    - QRPA: isospin symmetry restoration

Mustonen 13’, Simkovic13’, Hyvarinen 15’, Fang 18’ , Lv22’

    - IBM: ISR

Barea 13’, Barea15’

    - PHFB

Sahu 15’, Rath 19’, Wang 21’

    - DFT(+GCM): relativistic

Vaquero 13’, Song14’, Yao 15’, Song17’, Jiao 17’, Wang 23’

Results

- Compared to light neutrino mass mechanism, there are less on heavy neutrino mass

  - SM: renormalization of operator; larger model space

Horoi 13', Menendez 18'

  - QRPA: isospin symmetry restoration

Hyvarinen 15', Fang 18'

  - IBM: ISR

Barea15'

  - PHFB

Rath 19'

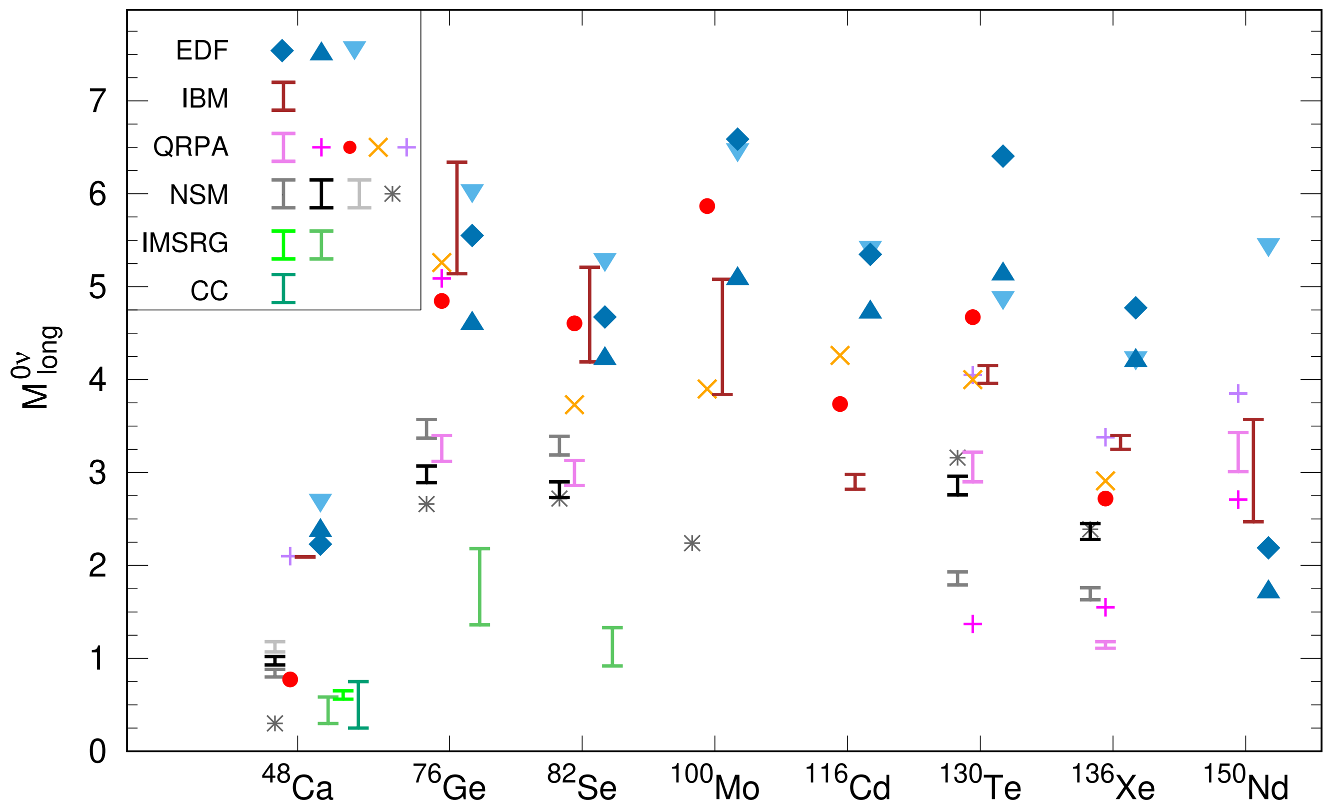
  - DFT+GCM: relativity

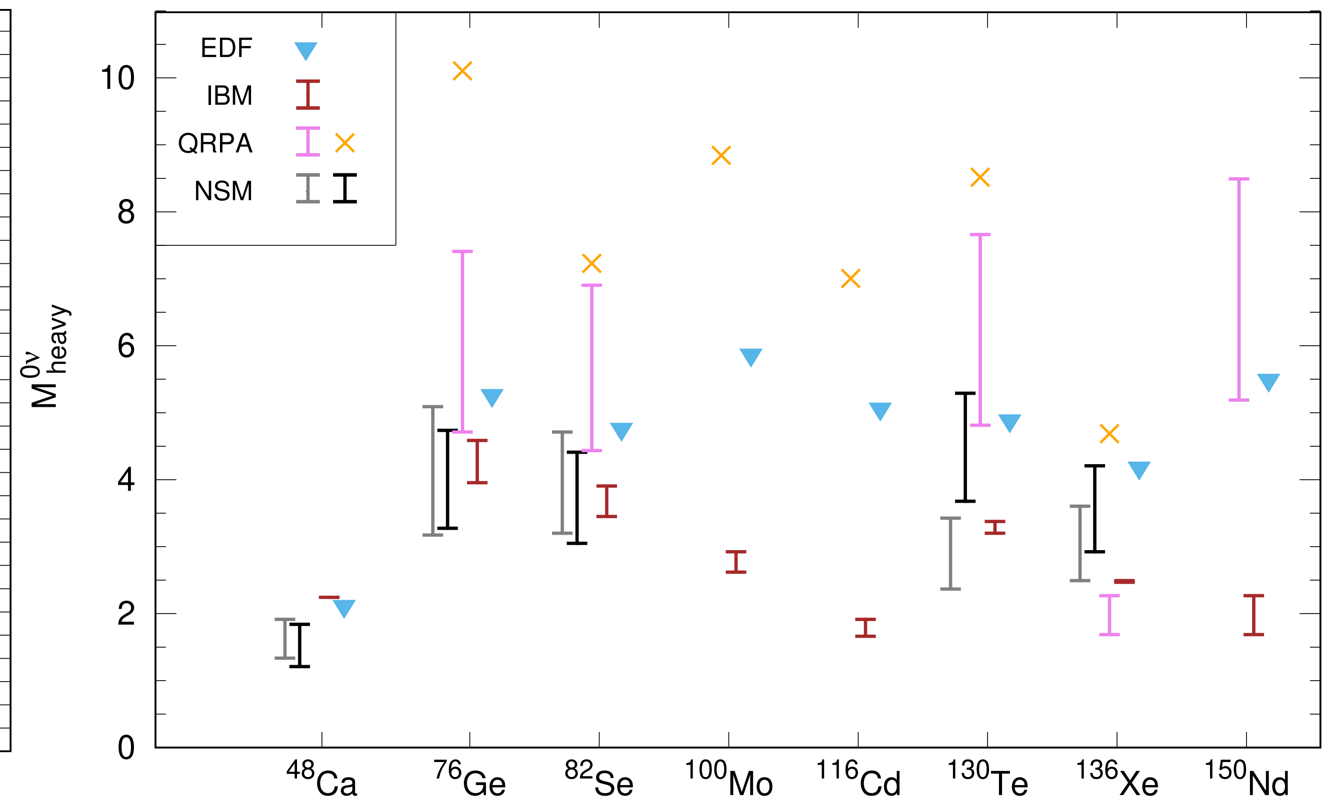
Song17'

Results

- Deviations from different methods

Agostini 22'



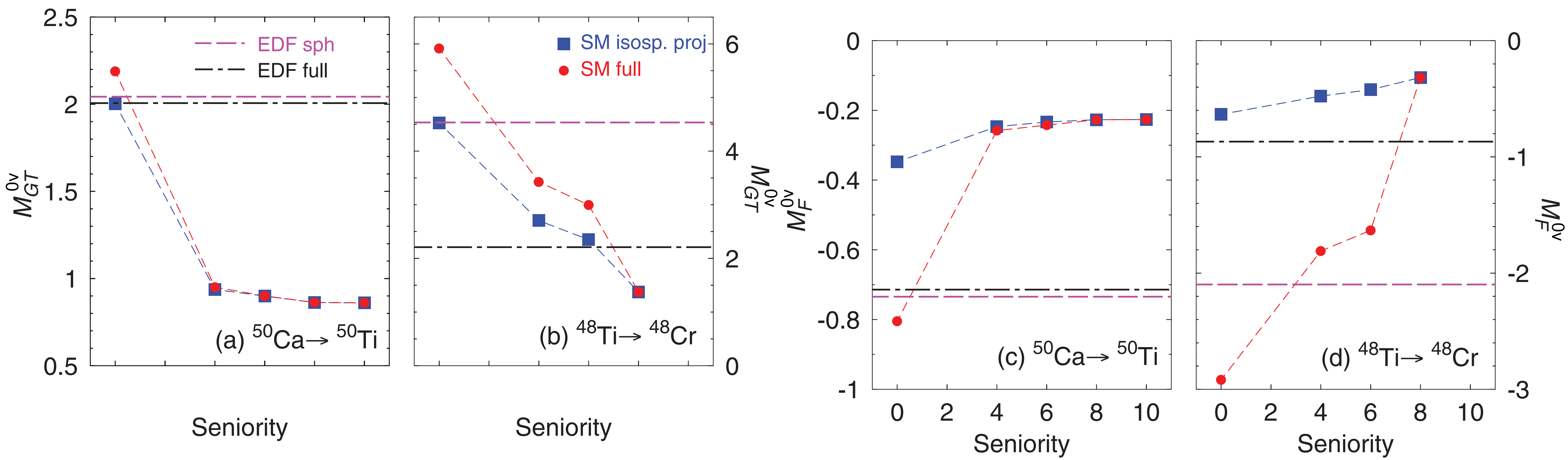


- Different mechanisms have different deviation
- Originating from various sources

Results

- Comparative studies between SM and EDF

Menendez 14'



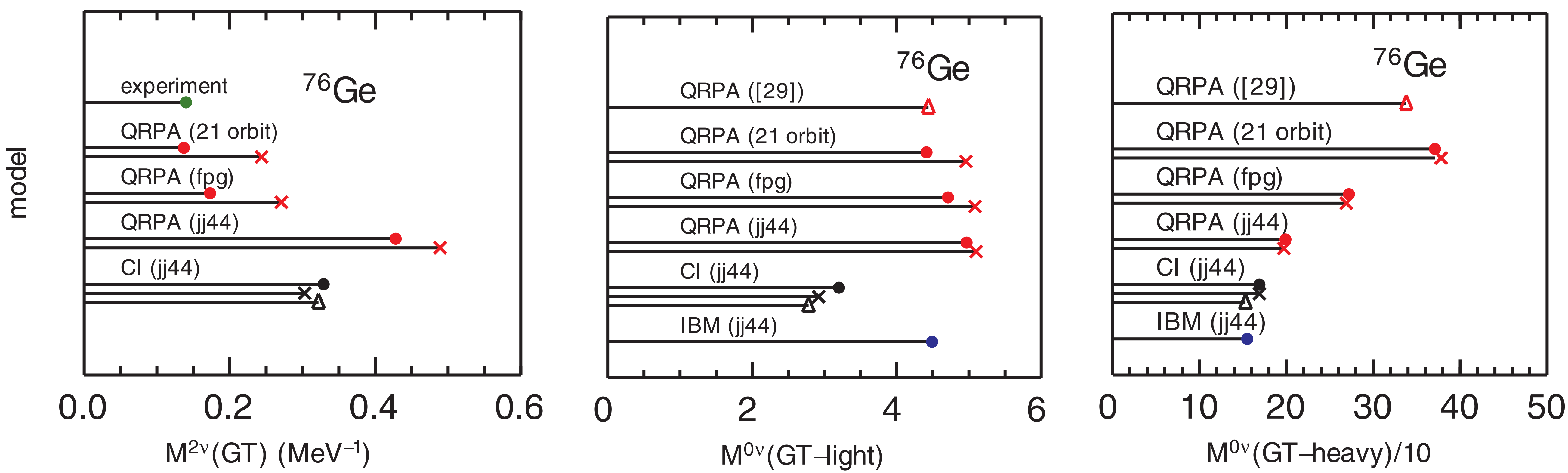
- They come out with the conclusion, SM and EDF are similar at some level when seniority is 0 for SM and only spherical shape are assumed for EDF

Results

Brown 15'

$$M^{0\nu} = [3.0(3)][1.2(2)][0.97(3)][1.12(7)] = 3.9(8)$$

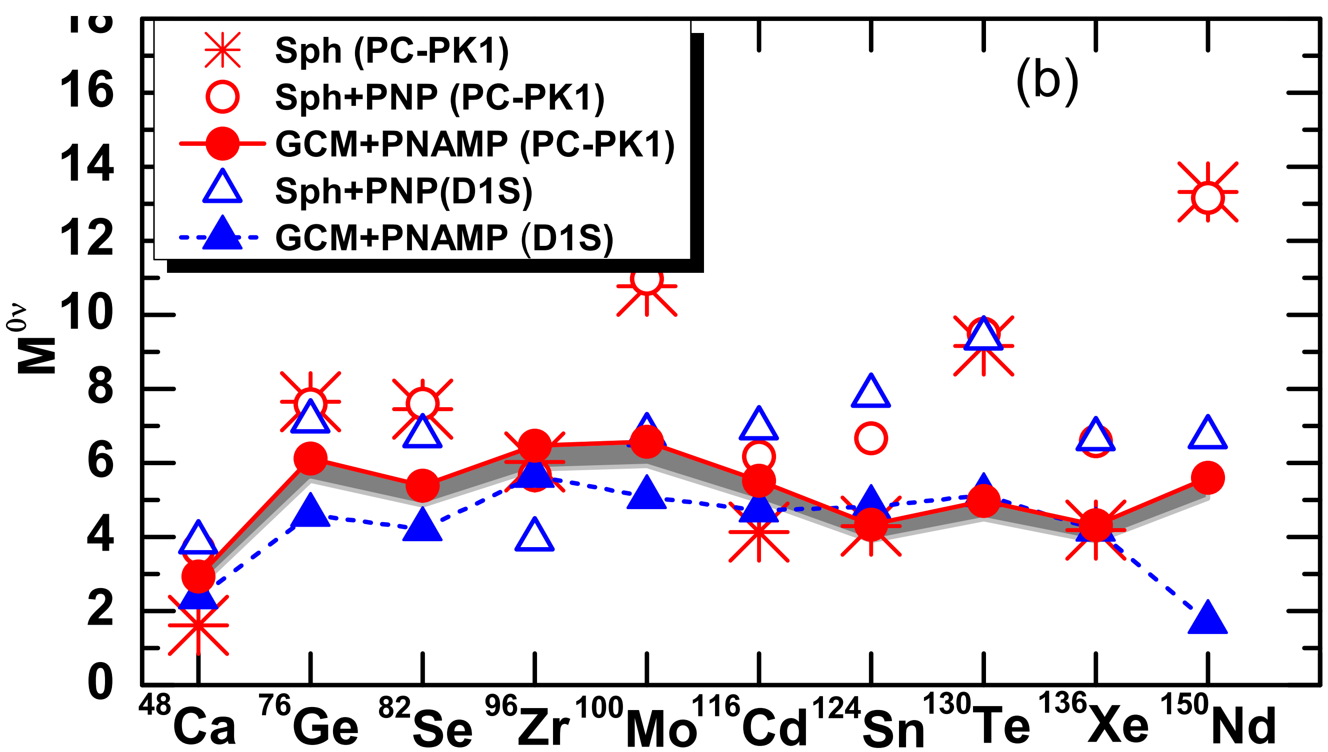
$$M^{0N} = [155(10)][1.65(25)][0.80(20)][1.13(13)] = 232(80)$$

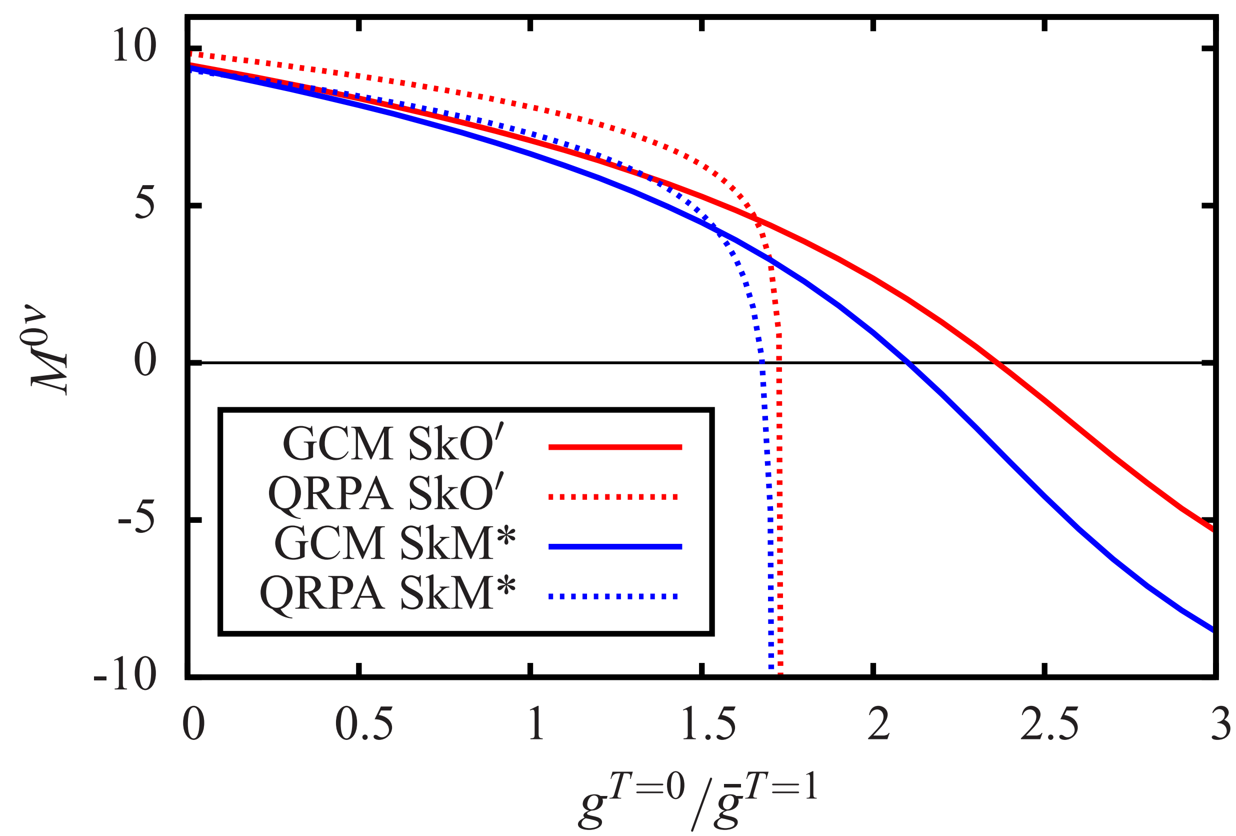


- comparative studies between SM and QRPA and estimations of errors

Results

Yao 15', Hinohara 14'

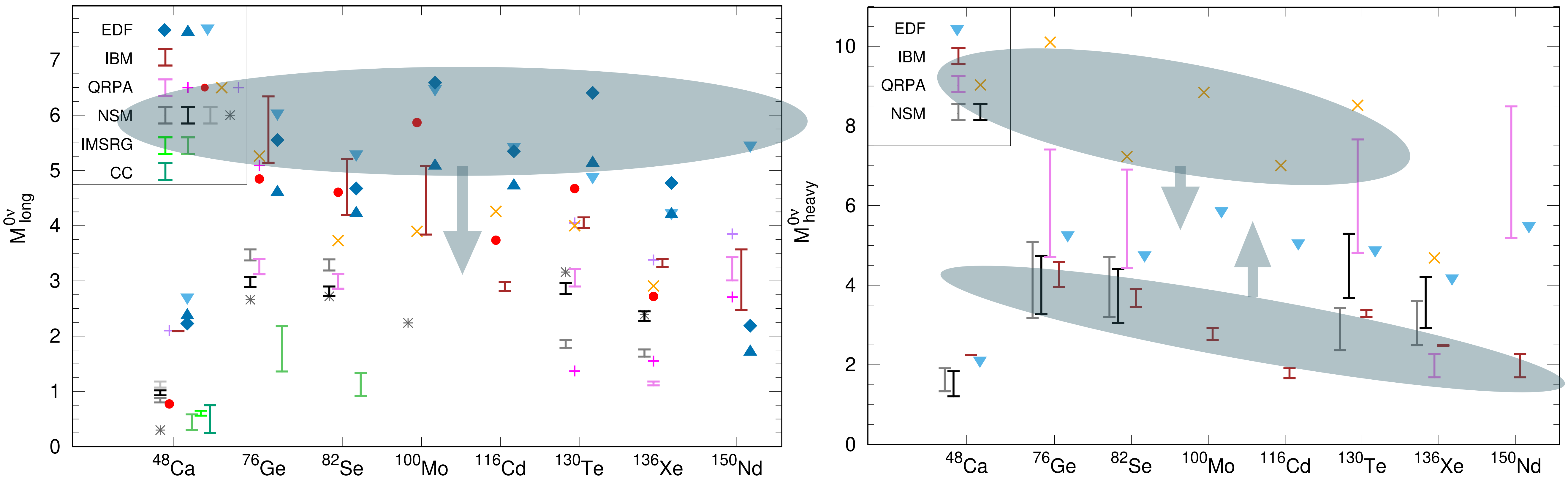




- Experience from DFT+GCM

Results

Agostini 22'



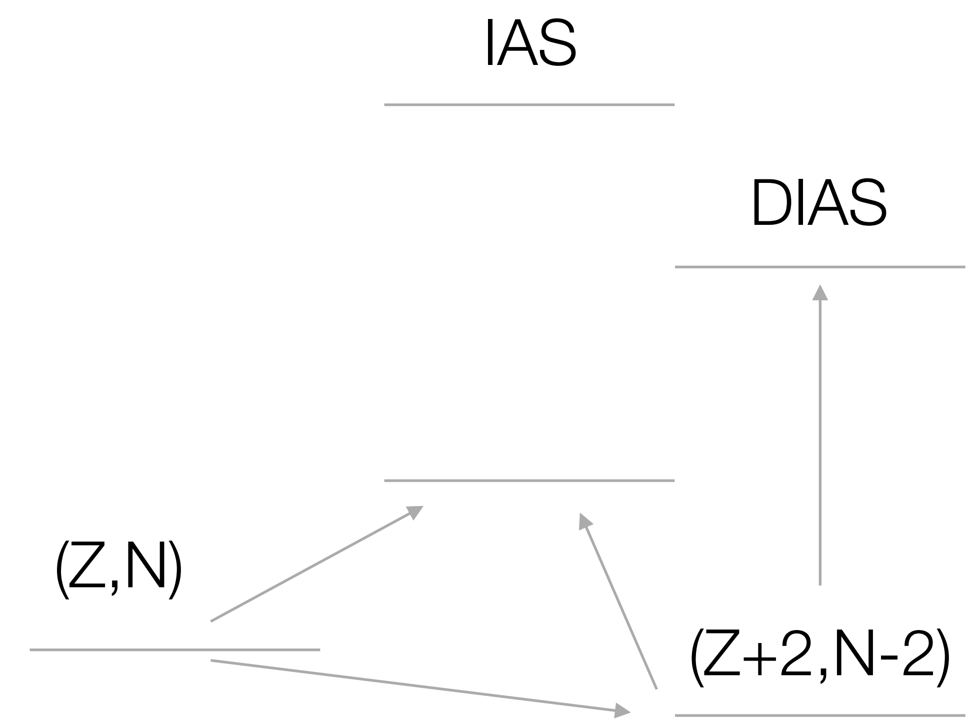
- Converged results are expected

Measuring NME

NME from experiments

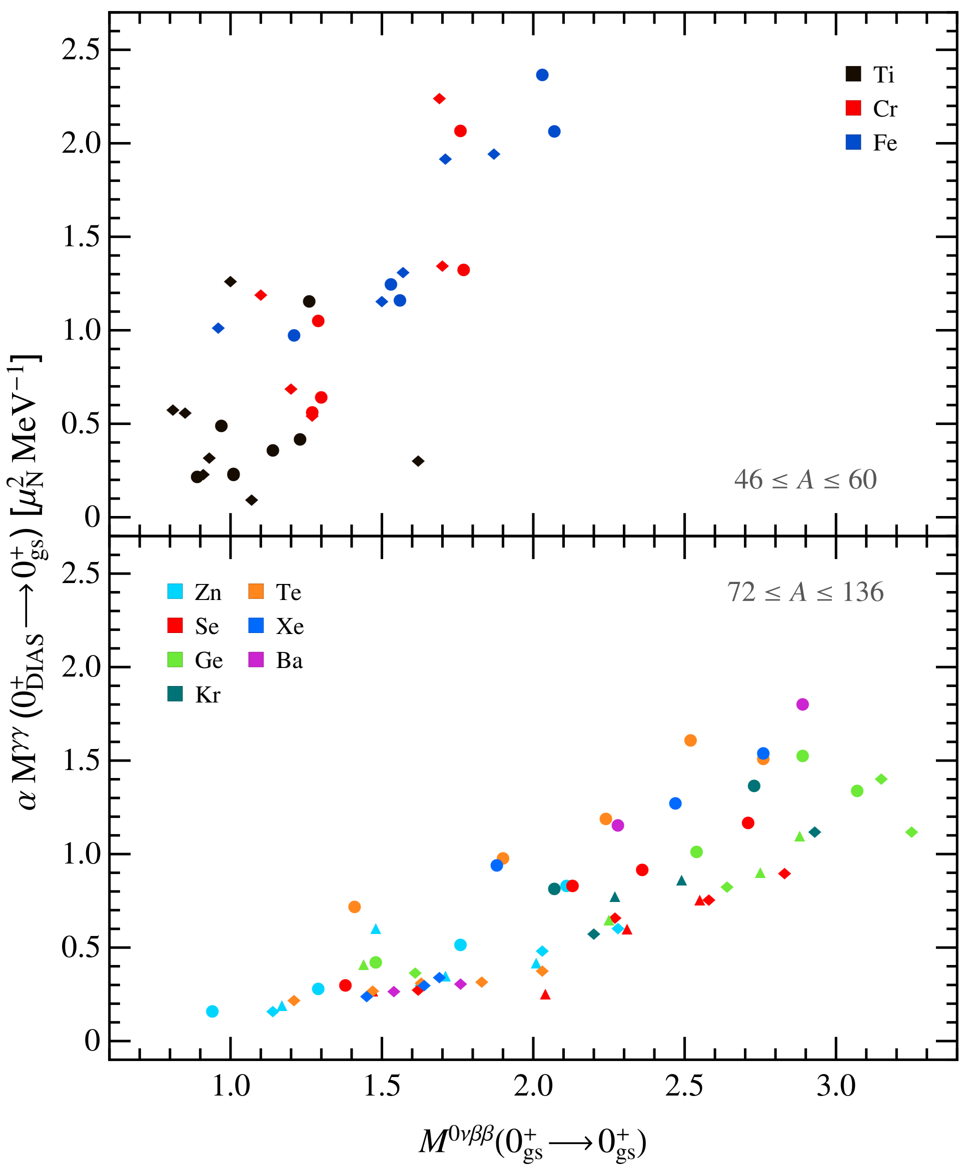
- Are there any observables which can be related to the NMEs?
- Early attempts are to relate the Fermi NME with double Fermi transition or coulomb excitations
- $$M_F^{0\nu} \approx -\frac{2}{e^2}\,\bar{\omega}_{\mathrm{IAS}}\langle 0_f|\hat{T}^-|\mathrm{IAS}\rangle\langle \mathrm{IAS}|\hat{T}^-|0_i\rangle$$

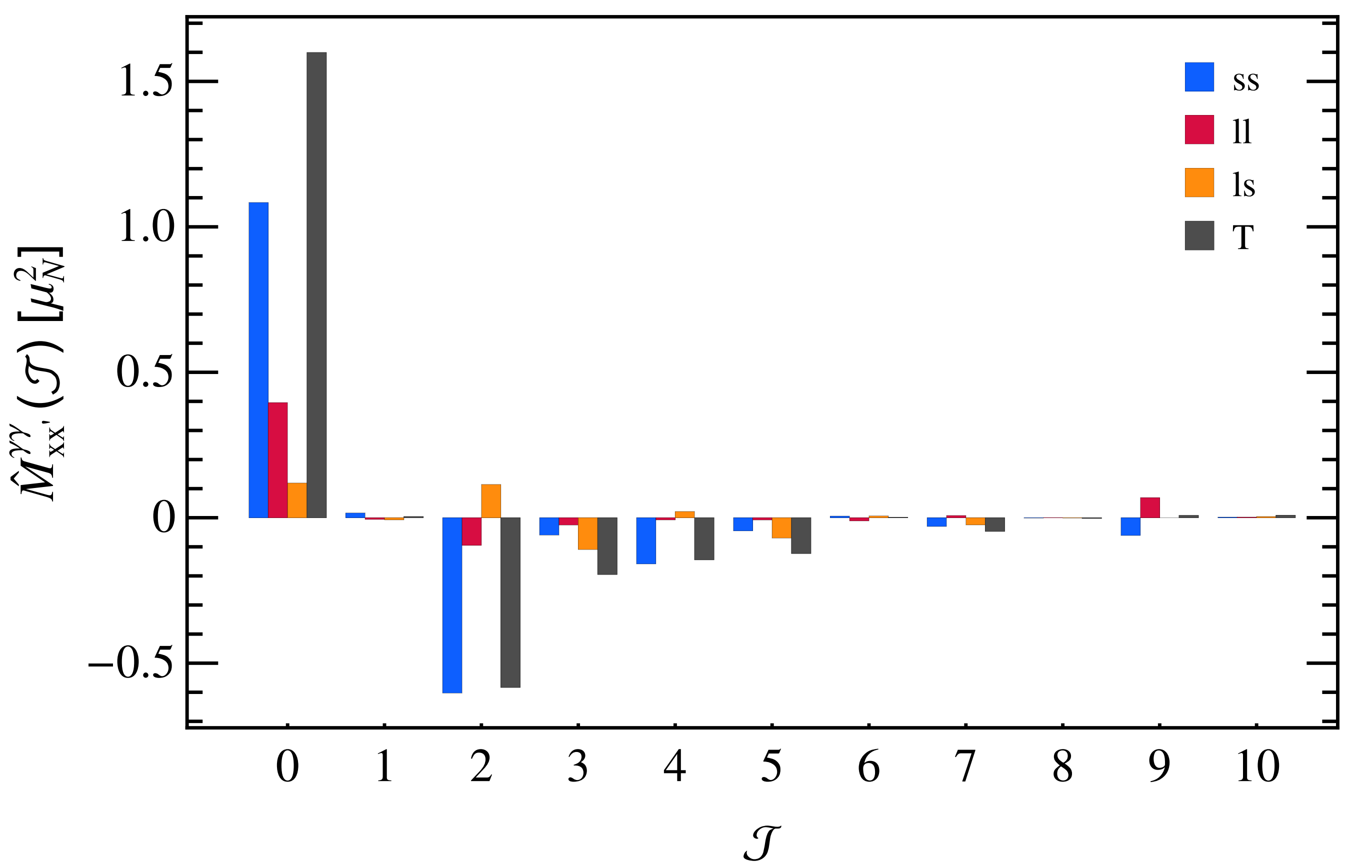
Rodin 09'



NME from experiments

- The idea of EM transitions from DIAS to ground states has been formulated with shell model recently **Romeo 21'**

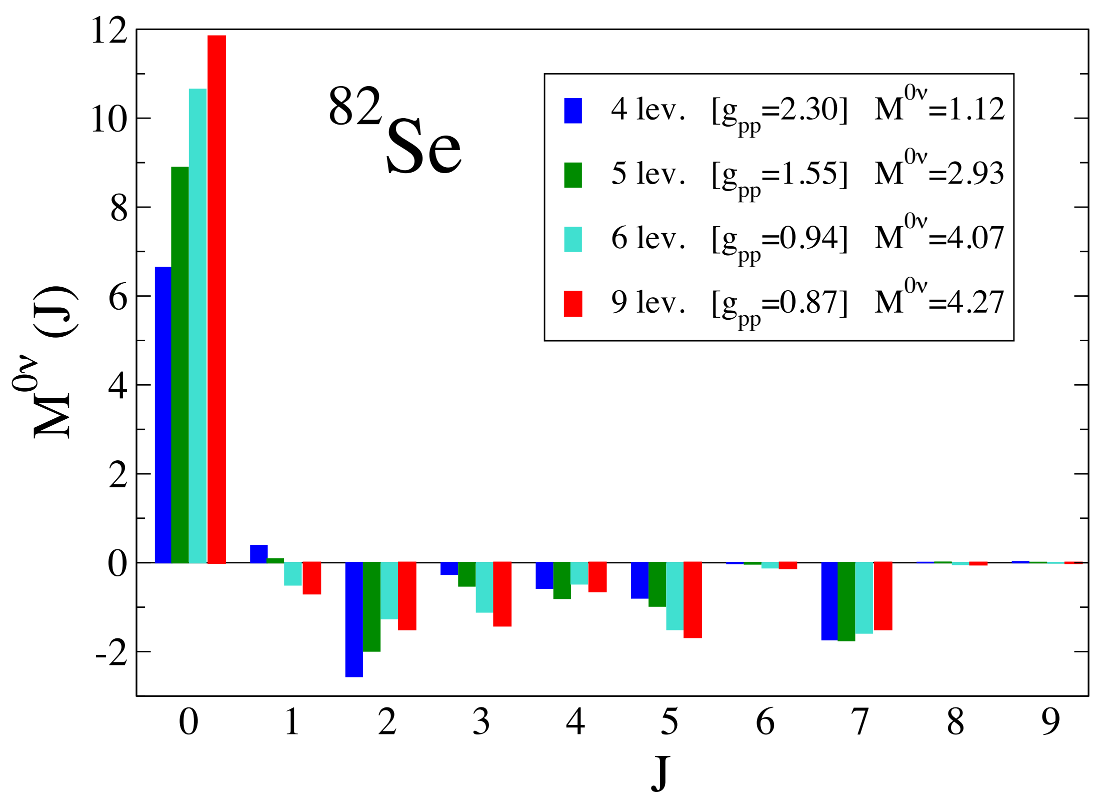


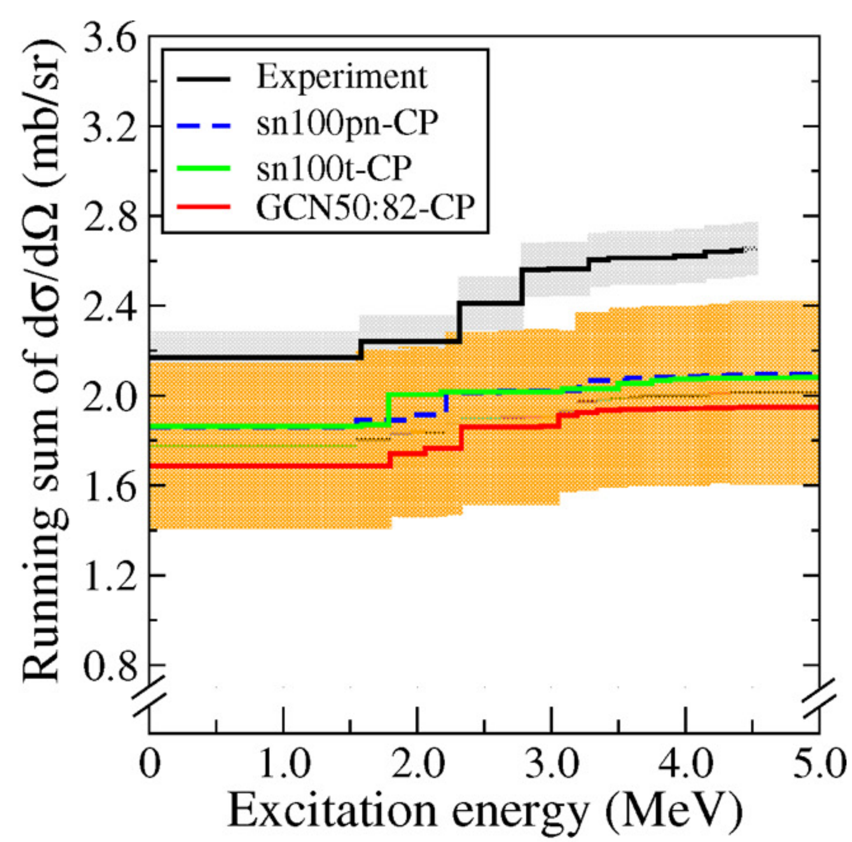


NME from experiments

- Above results has a similar nucleon pair structure as double beta decay

Rebeiro 20'

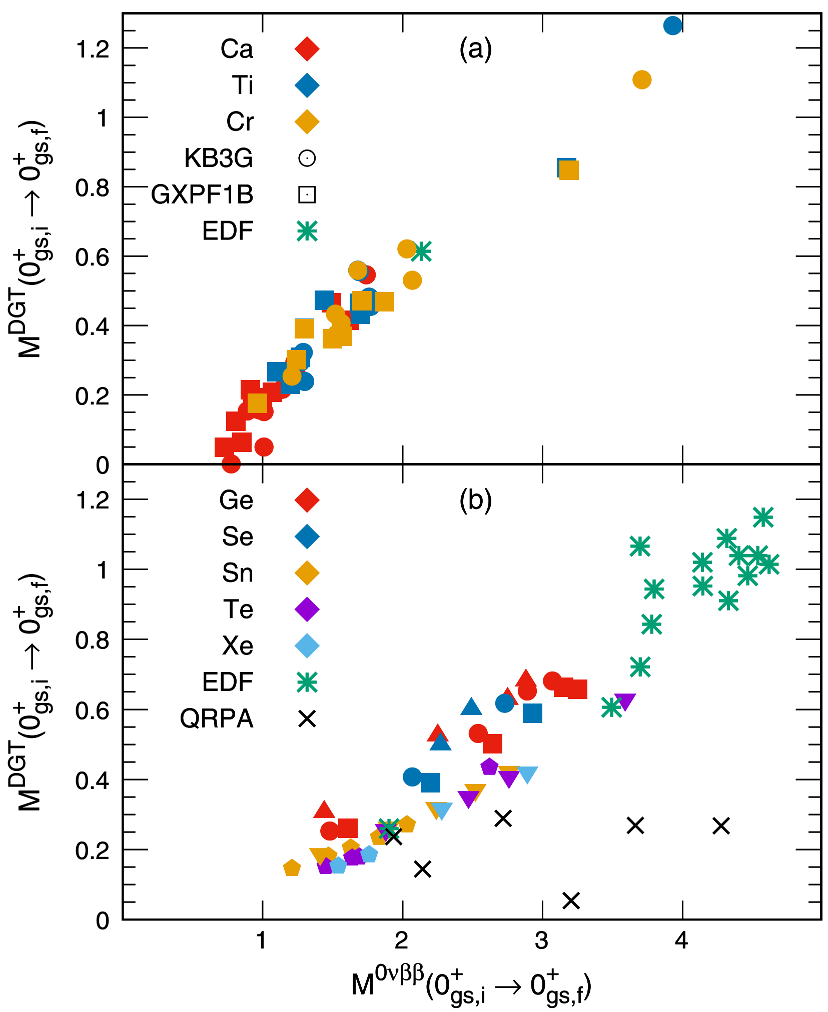




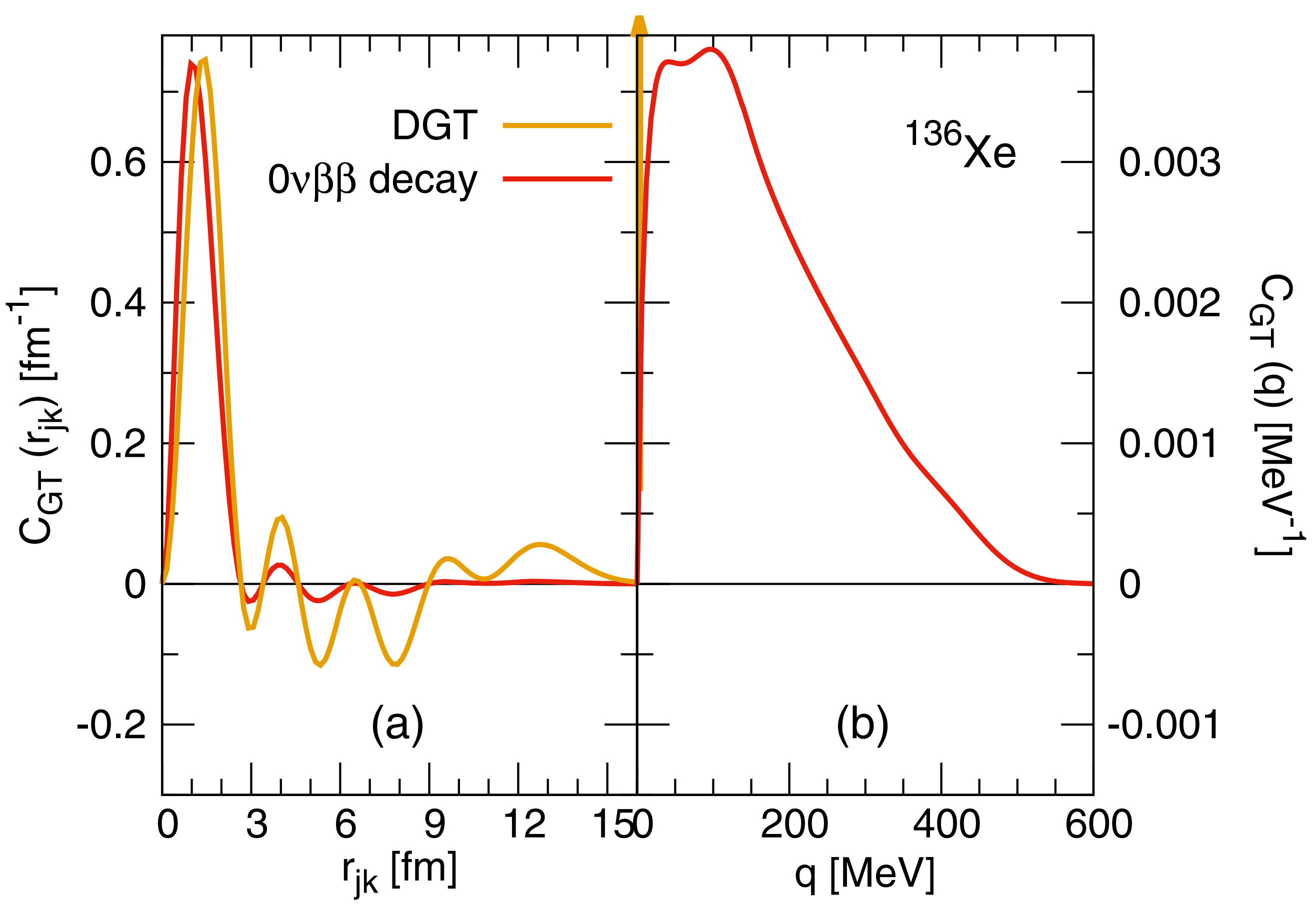
- Two nucleon removal amplitude constrained with charge changing (p,t) reactions

NME from experiments

- Recently, the measurement of DGT for determinations of double beta decay matrix elements are proposed



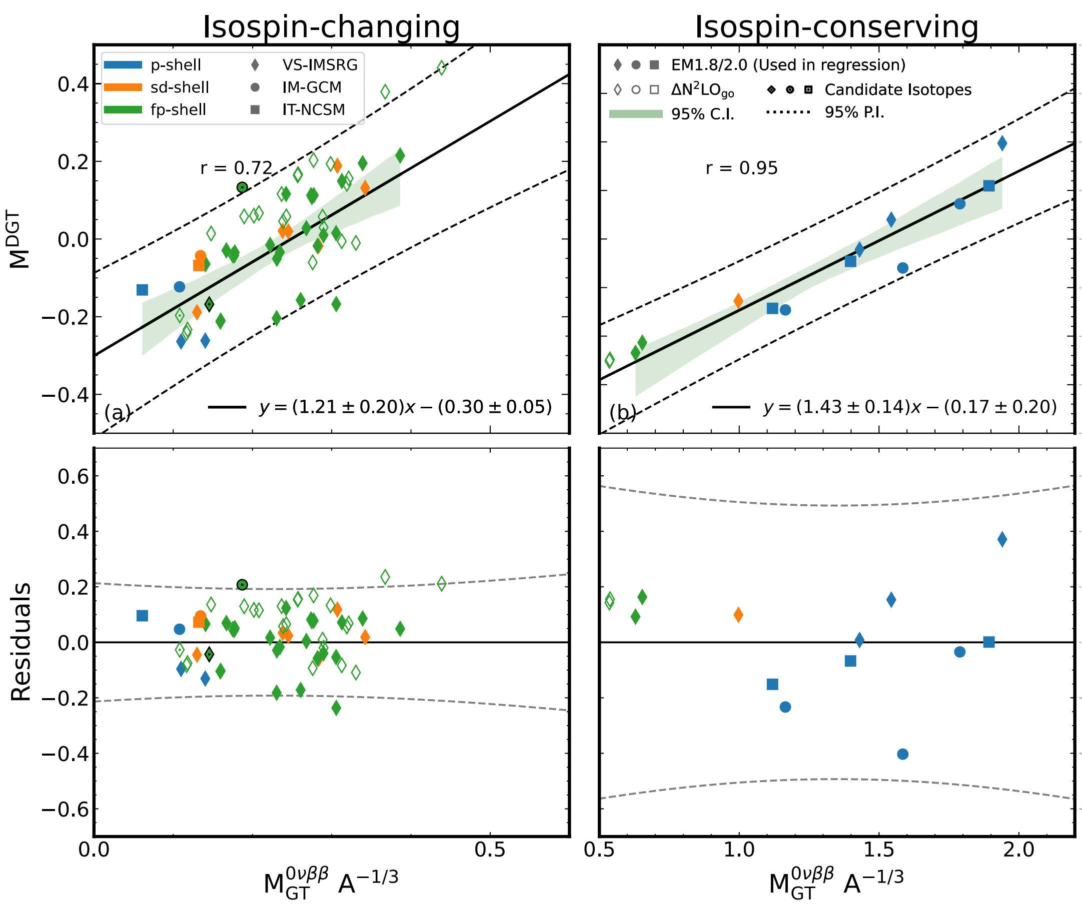
Shimizu 18'

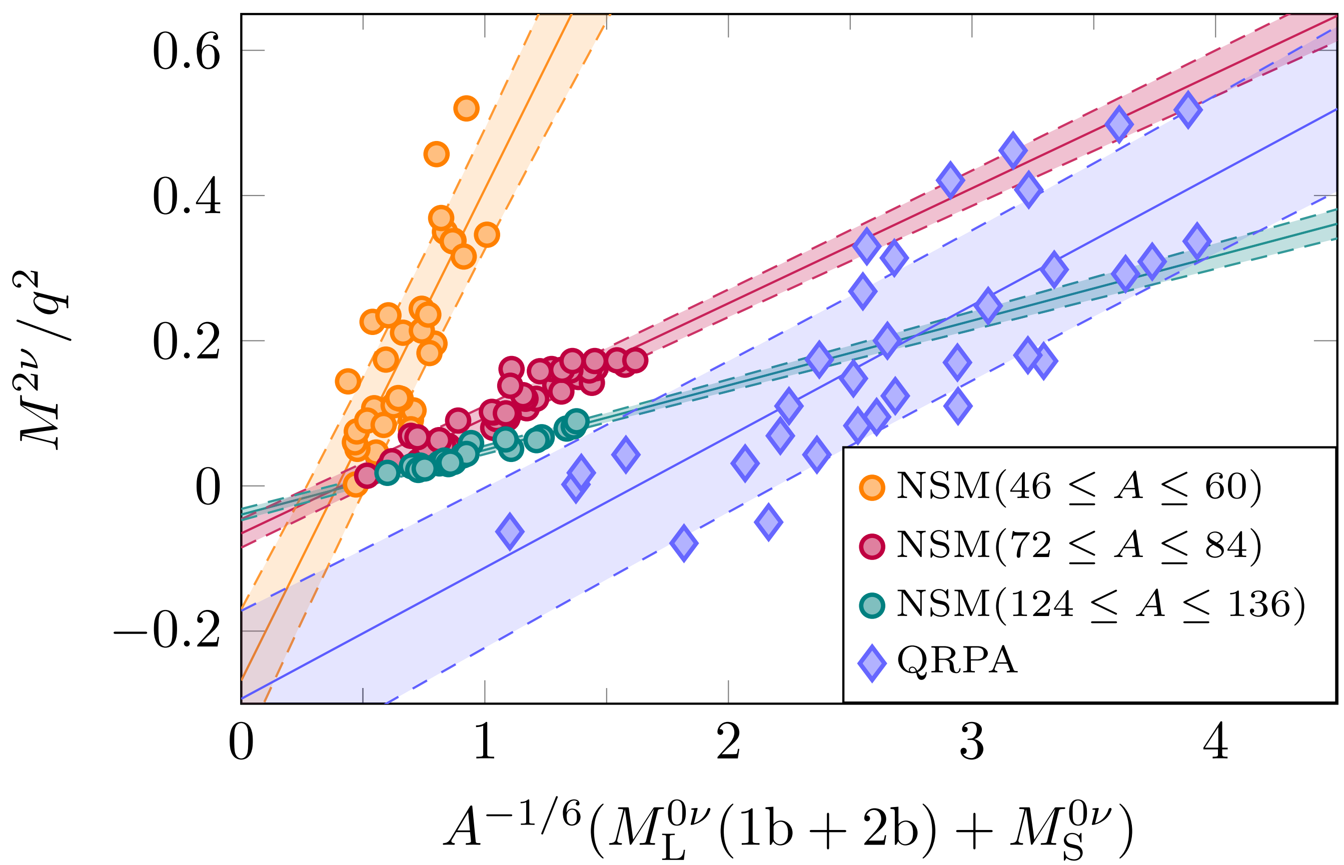


- What they found in shell model calculations,

NME from experiments

Yao 22', Jokiniemi 23'





- Some claim a strong correlation between DGT or 2νββ and 0νββ, while others doubt

Conclusion

- New formalism of double beta decay based on SMEFT frame has been proposed
- But deviations are still presented
- Deviations among traditional many-body approaches are large and we are trying to understand the reason
- There are also efforts of constraining the NMEs from experiment side

Outlook

- A more complete expression is needed for non-standard mechanisms
- With more powerful HPCs, we are confident that the calculations will be more precise
- More measurements will help determine the NMEs

Thanks for your attention