Priority Issue 9
to be Tackled by Using Post K Computer
“Elucidation of the Fundamental Laws
and Evolution of the Universe”
KAKENHI grant 17K05433

RIKEN RIBF seminar
2018/07/10

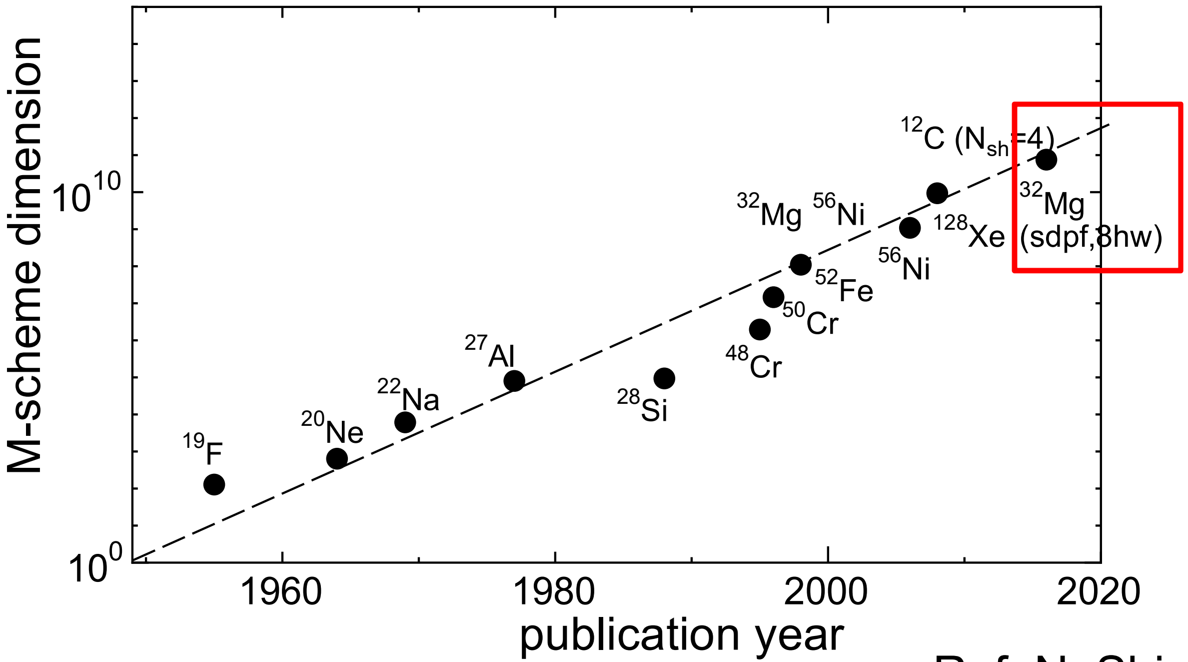
Double Gamow-Teller transitions and its relation to neutrinoless $\beta\beta$ decay

Noritaka Shimizu (CNS, U. Tokyo)

N. Shimizu, J. Menendez, and K. Yako,
Phys. Rev. Lett. **120**, 142502 (2018)

Shell model code "KSHELL"

- High-performance shell model code
- User-friendly interface, robust behavior
  - c.f. "OXBASH", "NuSHELL", "ANTOINE", …



~10^{11} dim. feasible by KSHELL code & K computer

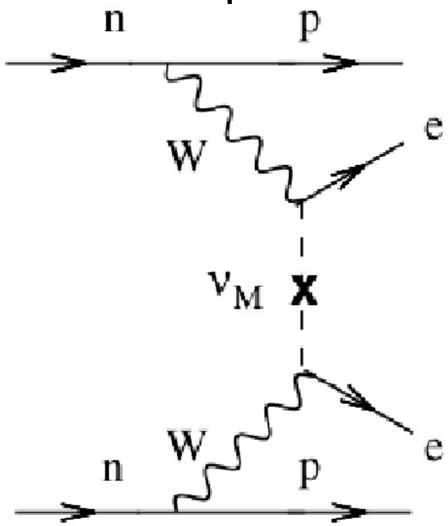
Ref. N. Shimizu, arXiv:1508.03683
https://sites.google.com/a/cns.s.u-tokyo.ac.jp/kshell/

Outline

- Current status and large-scale shell model (LSSM) studies of neutrinoless double beta decay nuclear matrix element ($0\nu\beta\beta$ NME)
- Double Gamow Teller Resonance and its relation to $0\nu\beta\beta$ NME of ^{48}Ca
- Relation between double Gamow Teller transition and $0\nu\beta\beta$ NME, systematic study

Status of neutrinoless double-beta decay experiments

Is neutrino Majorana particle or not?
neutrinoless double beta decay
lepton number violation

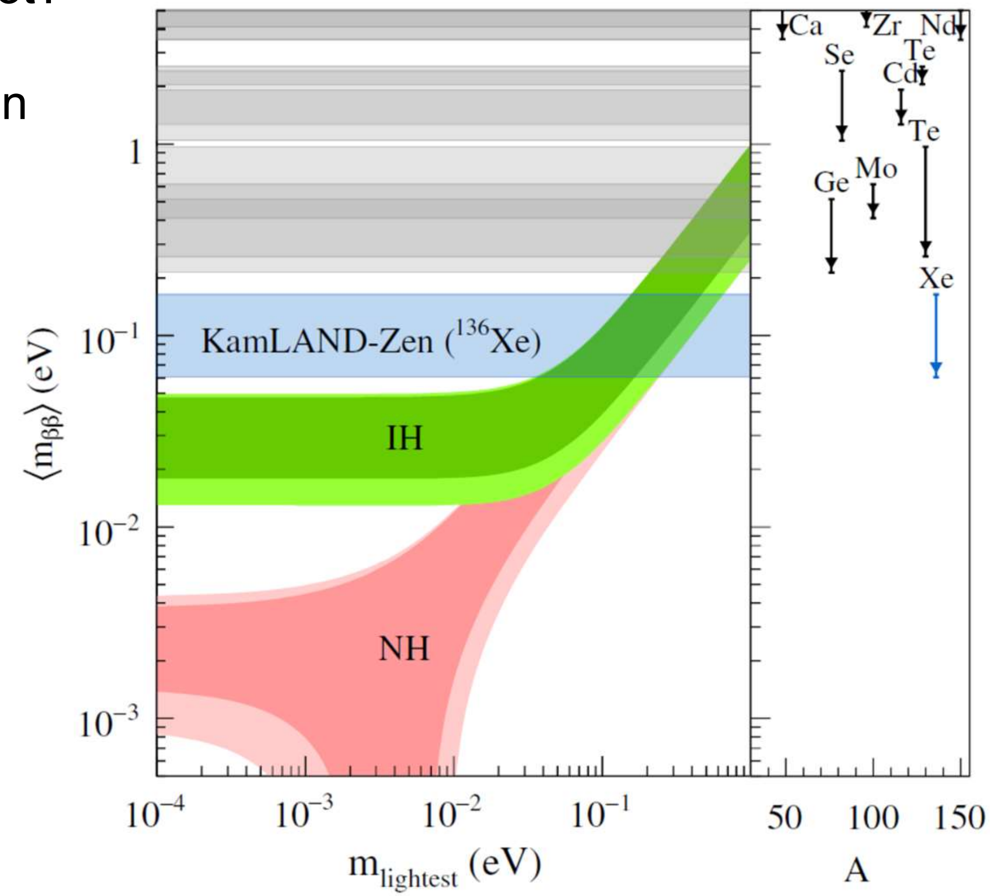


$2\nu\beta\beta$ decay

$$^{48}\text{Ca} \rightarrow {}^{48}\text{Ti} + 2e^- + 2\overline{\nu}_e$$

$0\nu\beta\beta$ decay

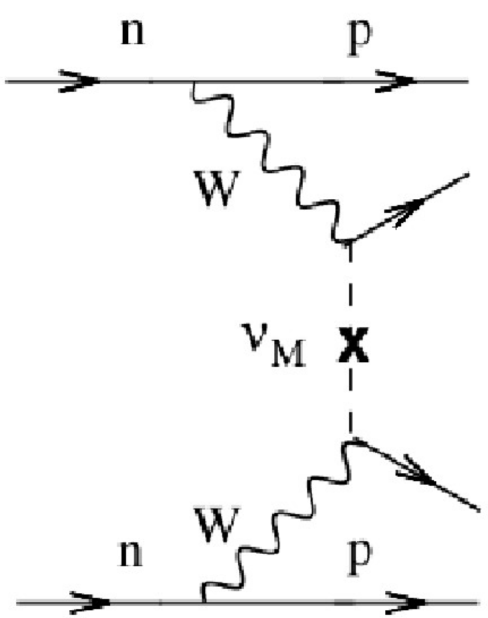
$$^{48}\text{Ca} \rightarrow {}^{48}\text{Ti} + 2e^-$$



Ref. A. Gando *et al.*, Phys. Rev. Lett. **117**, 082503 (2016)

Nuclear Matrix Element (NME) of neutrinoless double-beta decay

Is neutrino Majorana particle or not?
neutrinoless double beta decay



lepton number violation
(beyond the standard model)

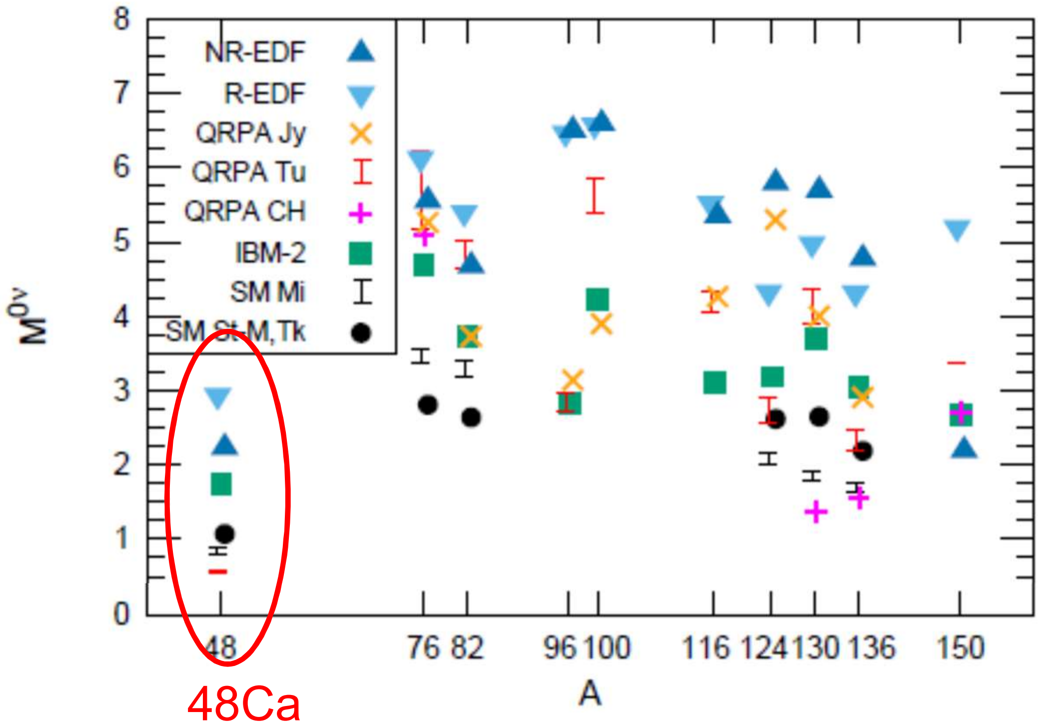
Theoretical prediction on the $0\nu\beta\beta$ NME varies depending on theoretical models.

$$[T_{1/2}^{0\nu}]^{-1} = G_1^{0\nu} |M^{0\nu}|^2 \left(\frac{<m_{\beta\beta}>}{m_e} \right)^2$$

Half life (exp.)

NME

effective neutrino mass



J. Engel and J. Menendez, Rep. Prog. Phys. **80**, 046301 (2017)

What is the origin of the spread predictions of $0\nu\beta\beta$ NMEs ?

- LSSM : small $0\nu\beta\beta$ NMEs
  - small valence shell, full configuration mixing
- RPA, EDF : large $0\nu\beta\beta$ NMEs
  - large single-particle states, limited configurations

Let us see the effects of

- Single-particle space
- Configuration mixing
- Isoscalar pairing

LSSM calc. for nuclear matrix element (NME) of ^{48}Ca $0\nu\beta\beta$ decay

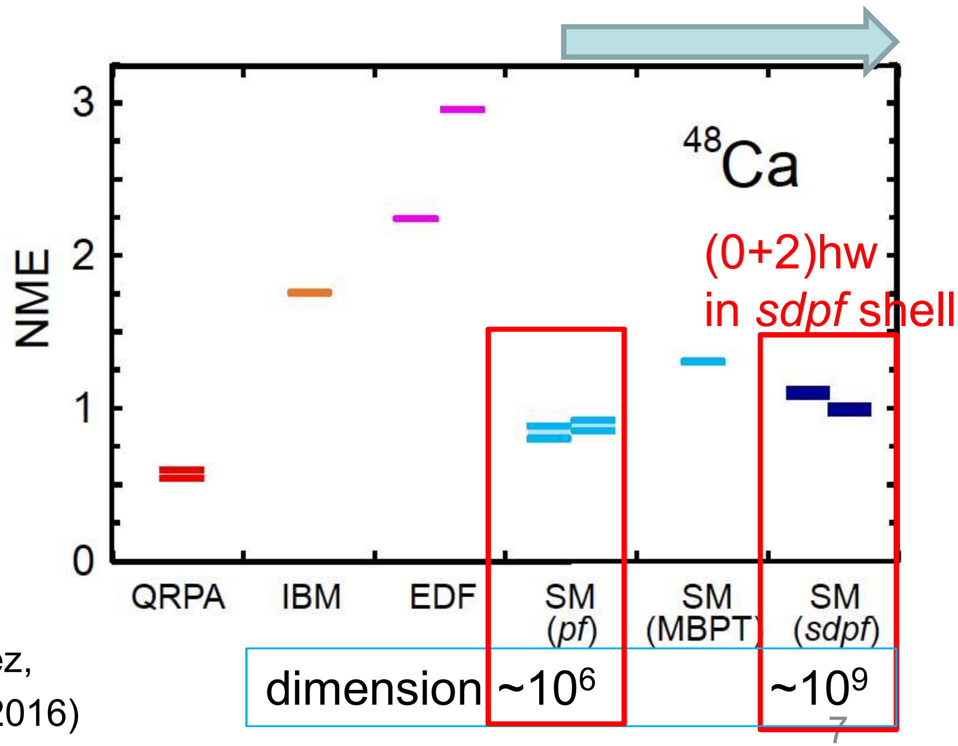
$2\nu\beta\beta$ decay

$$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Ti} + 2e^- + 2\overline{\nu}_e$$

$0\nu\beta\beta$ decay

$$^{48}\mathrm{Ca} \rightarrow {}^{48}\mathrm{Ti} + 2e^-$$

30% enhancement
by including *sd* shell



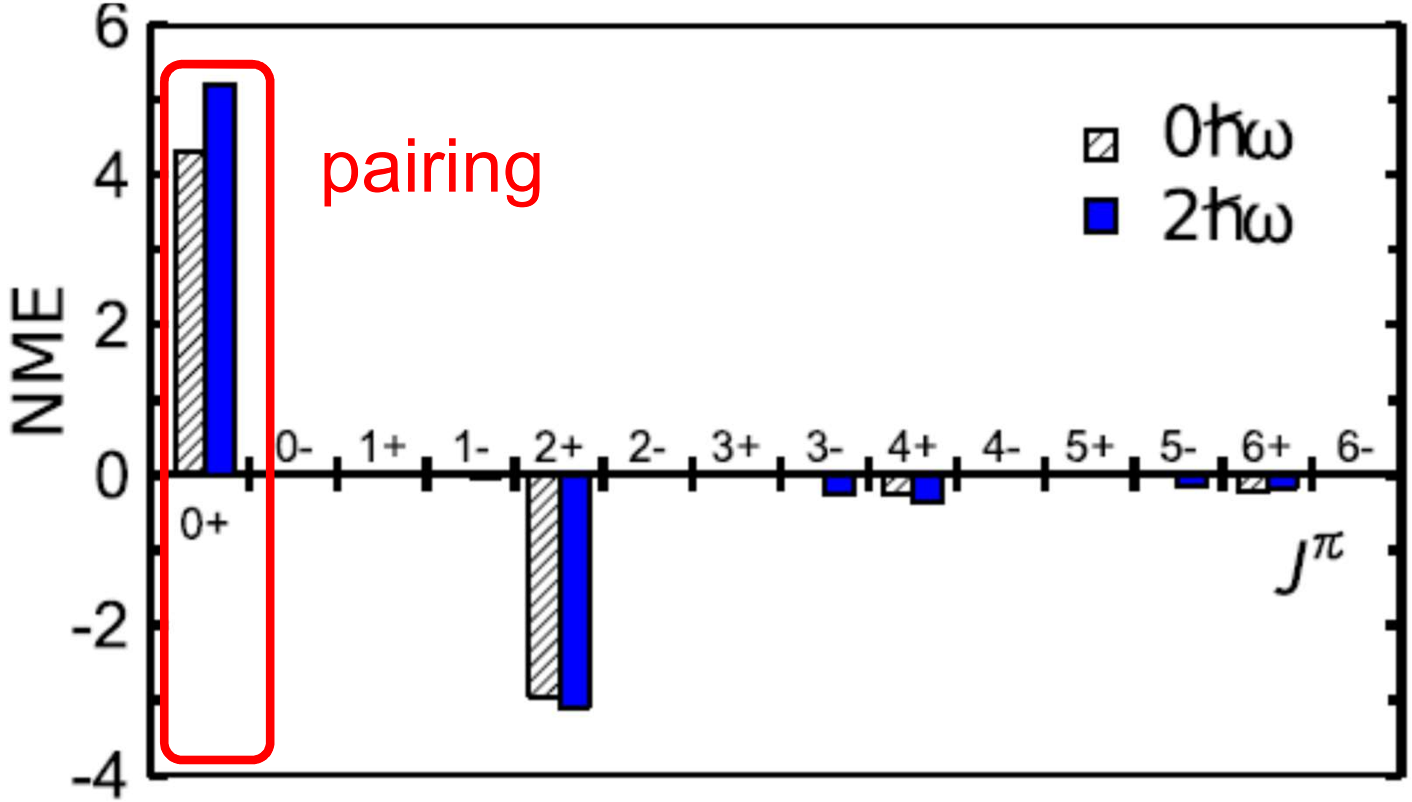
Large scale shell model calculation including 2hw excitation from *sd* shell
with closure approximation

Y. Iwata, N. Shimizu, T. Otsuka, Y. Utsuno, J. Menendez, M. Honma and T. Abe, Phys. Rev. Lett. **116**, 112502 (2016)

Why does the NME increases by extending the model space?

decompose this sum

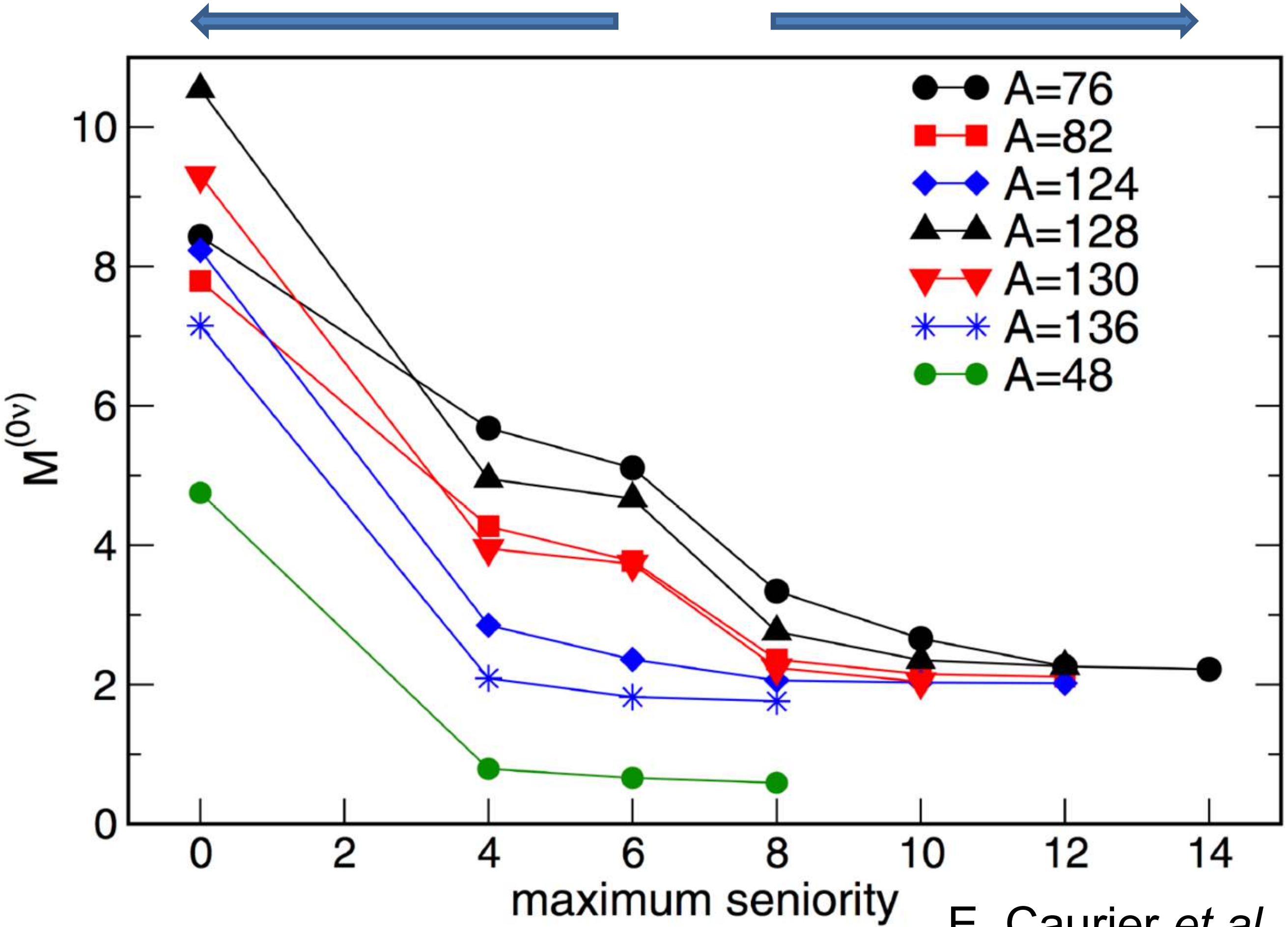
$$M^{0\nu} = \sum_J \langle 0_f^+ | \sum_{i\le j, k\le l} M_{ij,kl}^J [(\hat{a}_i^\dagger \hat{a}_j^\dagger)^J (\hat{a}_k \hat{a}_l)^J]^0 | 0_i^+ \rangle$$



Large cancellation is seen in general. It causes precise estimation difficult.

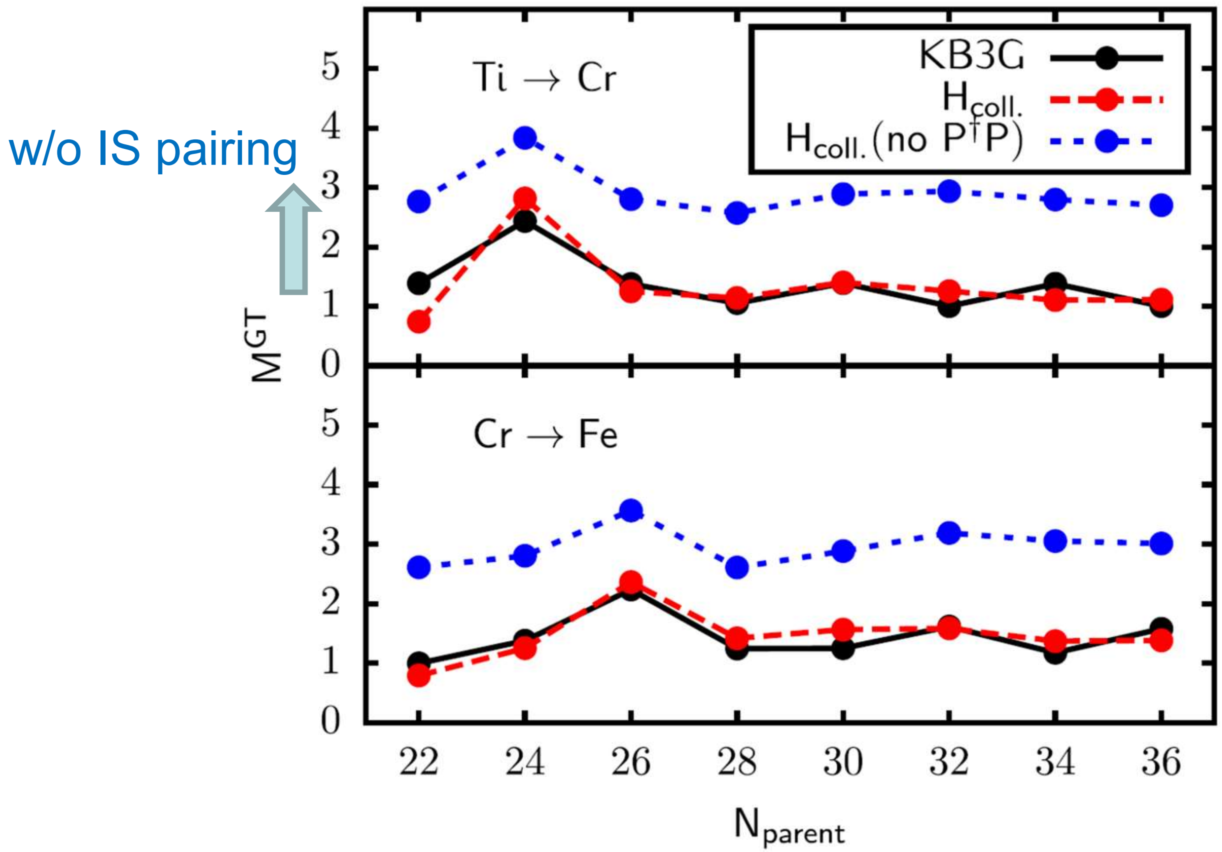
Configuration mixing: seniority truncation in LSSM

Isovector pairing correlation　　Full configuration mixing



E. Caurier *et al.*, Phys. Rev. Lett. 100, 052503 (2008)

A possible key to understand $0\nu\beta\beta$ NME: isoscalar pairing



- Isoscalar pairing suppress the GT-type $0\nu\beta\beta$ NME.

- c.f. QRPA calc.

  Strength of J=1 pn int. (g_{pp}) is scaled to reproduce $2\nu\beta\beta$ NME.

Ref. J. Menendez *et al.,* Phys. Rev. C **93**, 014305 (2016)

The NME is sensitive to the J=1 proton-neutron matrix element, or isoscalar pairing
Vogel (1986), Muto (1991), Rodin (2003) Menendez (2016), etc.

$0\nu\beta\beta$-decay NME

- $0\nu\beta\beta$-decay nuclear matrix element (NME) with closure approximation

$$M^{0\nu} = M^{0\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_F + M^{0\nu}_T$$

N.B. GT-type NME is dominant

$$\mathcal{O}_{GT} = \tau_{1-}\tau_{2-}\,(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)\, H_{GT}(r, E_\kappa),$$

$$\mathcal{O}_F = \tau_{1-}\tau_{2-}\, H_F(r, E_\kappa),$$

$$\mathcal{O}_T = \tau_{1-}\tau_{2-}\, S_{12}\, H_T(r, E_\kappa),$$

$$h_F(q^2) = \frac{g_V^2(q^2)}{g_V^2},$$

$$h_{GT}(q^2) = \frac{g_A^2(q^2)}{g_A^2}\left[1 - \frac{2}{3}\frac{q^2}{q^2+m_\pi^2} + \frac{1}{3}\left(\frac{q^2}{q^2+m_\pi^2}\right)^2\right] + \frac{2}{3}\frac{g_M^2(q^2)}{g_A^2}\frac{q^2}{4m_p^2},$$

$$h_T(q^2) = \frac{g_A^2(q^2)}{g_A^2}\left[\frac{2}{3}\frac{q^2}{q^2+m_\pi^2} - \frac{1}{3}\left(\frac{q^2}{q^2+m_\pi^2}\right)^2\right] + \frac{1}{3}\frac{g_M^2(q^2)}{g_A^2}\frac{q^2}{4m_p^2}.$$

neutrino potential
(Fourier transform of propagator)

$$H_\alpha(r, E_\kappa) = \frac{2R}{\pi}\int_0^\infty \frac{f_\alpha(qr)h_\alpha(q^2)q\,dq}{q + E_\kappa - (E_i + E_f)/2}$$

$$g_V(q^2) = \frac{g_V}{(1+q^2/\Lambda_V^2)^2},$$

$$g_M(q^2) = (\mu_p - \mu_n)g_V(q^2),$$

$$g_A(q^2) = \frac{g_A}{(1+q^2/\Lambda_A^2)^2},$$

$$f_{GT,F}(qr) = j_0(qr)$$

$$f_T(qr) = j_2(qr)$$

$0\nu\beta\beta$-decay NME and double Gamow-Teller (DGT) transition

- $0\nu\beta\beta$-decay nuclear matrix element (NME) with closure approximation

$$M^{0\nu} = M^{0\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_F + M^{0\nu}_T$$

N.B. GT-type NME is dominant

$$\mathcal{O}_{GT} = \tau_{1-}\tau_{2-}\ (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)\ H_{GT}(r, E_\kappa),$$

$$\mathcal{O}_F = \tau_{1-}\tau_{2-}\ H_F(r, E_\kappa),$$

$$\mathcal{O}_T = \tau_{1-}\tau_{2-}\ S_{12}\ H_T(r, E_\kappa),$$

- DGT transition

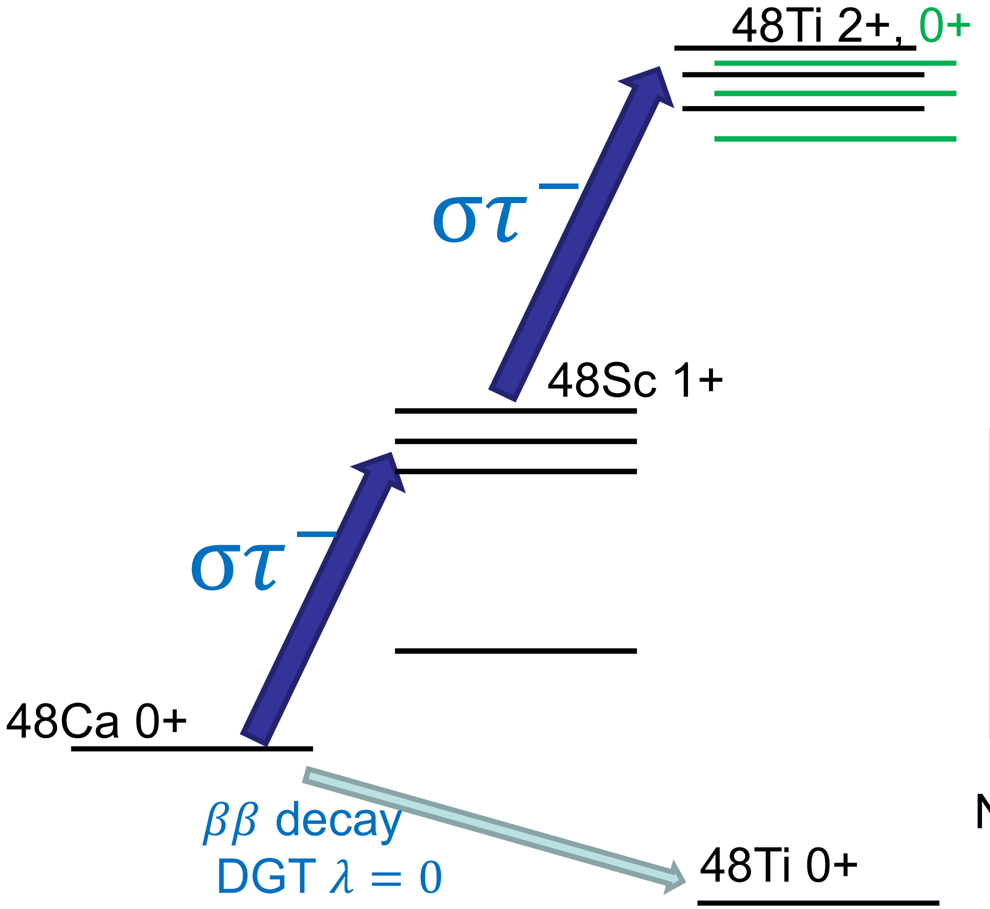
$$\mathcal{O}^{\pm} = [\sigma t^{\pm} \otimes \sigma t^{\pm}]^{(\lambda)} \quad \lambda = 0, 2$$

Double Gamow-Teller transition

- DGT transition probability
  - $B(DGT;\lambda) = \frac{1}{2J_i+1}\left\langle J_f \,||[\sigma t^- \otimes \sigma t^-]^{(\lambda)}\,|| J_i \right\rangle^2$

    Theory: Auerbach 1989, Zheng 1989, Muto 1981, Sagawa 2016
- DGTR itself attracts attention not only as an exotic collective motion, but also relevance to $0\nu\beta\beta$ NME
- Focus on ^{48}Ca
  - one of $\beta\beta$ decay nuclei with large Q value (CANDLES project)
  - shell model calc. is a suitable theoretical method (spin-orbit partners included)
  - DGT resonance (DGTR) was/will be measured experimentally

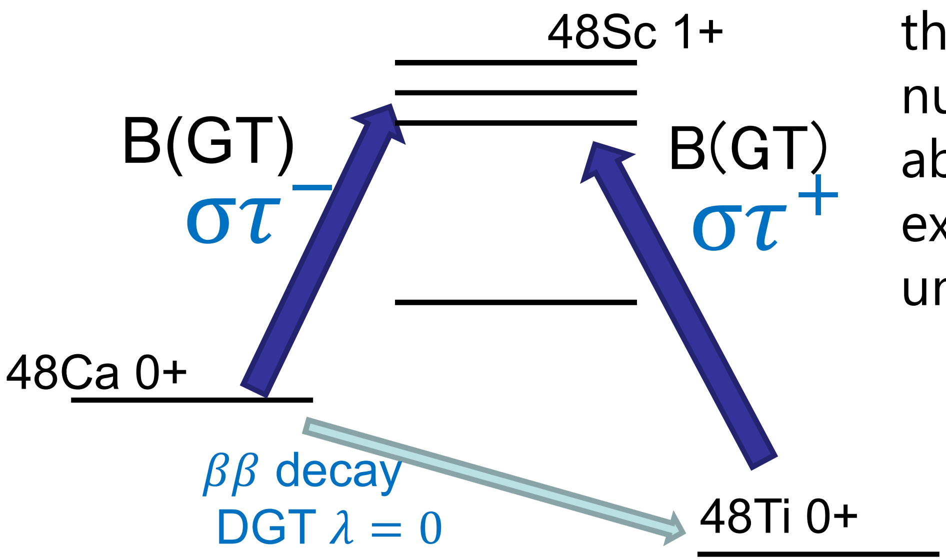
    Takaki at RCNP/Osaka, Uesaka at RIBF/RIKEN,
    Capuzzello NUMEN/Catania, …



By studying the stronger DGT transitions experimentally (...), theoretically, one may be able to "calibrate" the calculations of 2β-decay nuclear elements.

N. Auerbach, L. Zamick and D.C.Zheng
Ann. Phys. **192**, 197 (1989)

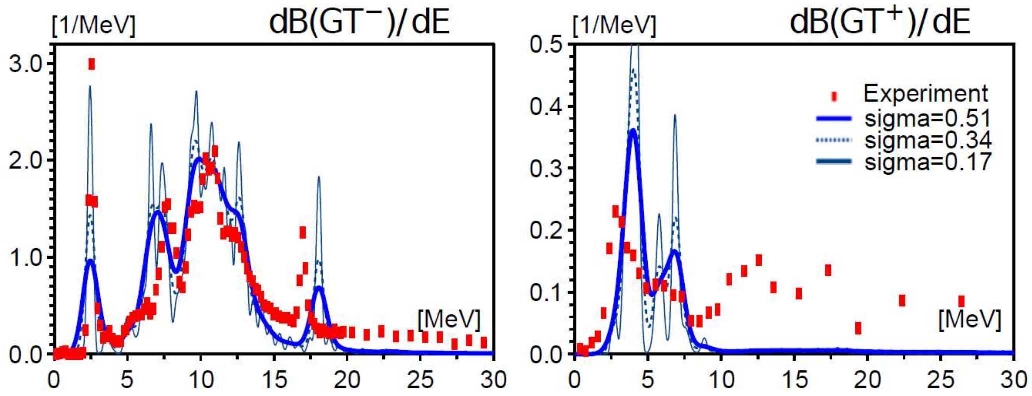
"smearing" the Fermi surface. The matrix element, however, still remains very small and accounts for only a 10^{-4} to 10^{-3} fraction of the total DGT sum rule [13]. A precise calculation of such hindered transitions is, of course, very difficult and is inherently a subject of large percent uncertainties. At the present there is no direct way to "calibrate" such complicated nuclear structure calculations involving miniature fractions of the two-body DGT transitions. By studying the stronger DGT transitions and, in particular, the giant DGT states experimentally and as we do here, theoretically, one may be able to "calibrate" the calculations of 2β-decay nuclear elements.



Both sides of the Gamow-Teller transitions are also useful for the "calibration" of the $\beta\beta$-decay nuclear elements. However only absolute values can be measured experimentally. (relative phase unknown)

$$M^{2\nu} = \sum_m \frac{\langle 0^f_{\mathrm{g.s.}} || O_{\mathrm{GT}^-} || 1^+_m \rangle \langle 1^+_m || O_{\mathrm{GT}^-} || 0^i_{\mathrm{g.s.}} \rangle}{E_m - E_0 + Q_{\beta\beta}/2}$$

$$M^{2\nu}_+ \equiv \sum_m \frac{\sqrt{B(\mathrm{GT}^-; m)}\sqrt{B(\mathrm{GT}^+; m)}}{E_m - E_0 + Q_{\beta\beta}/2}$$

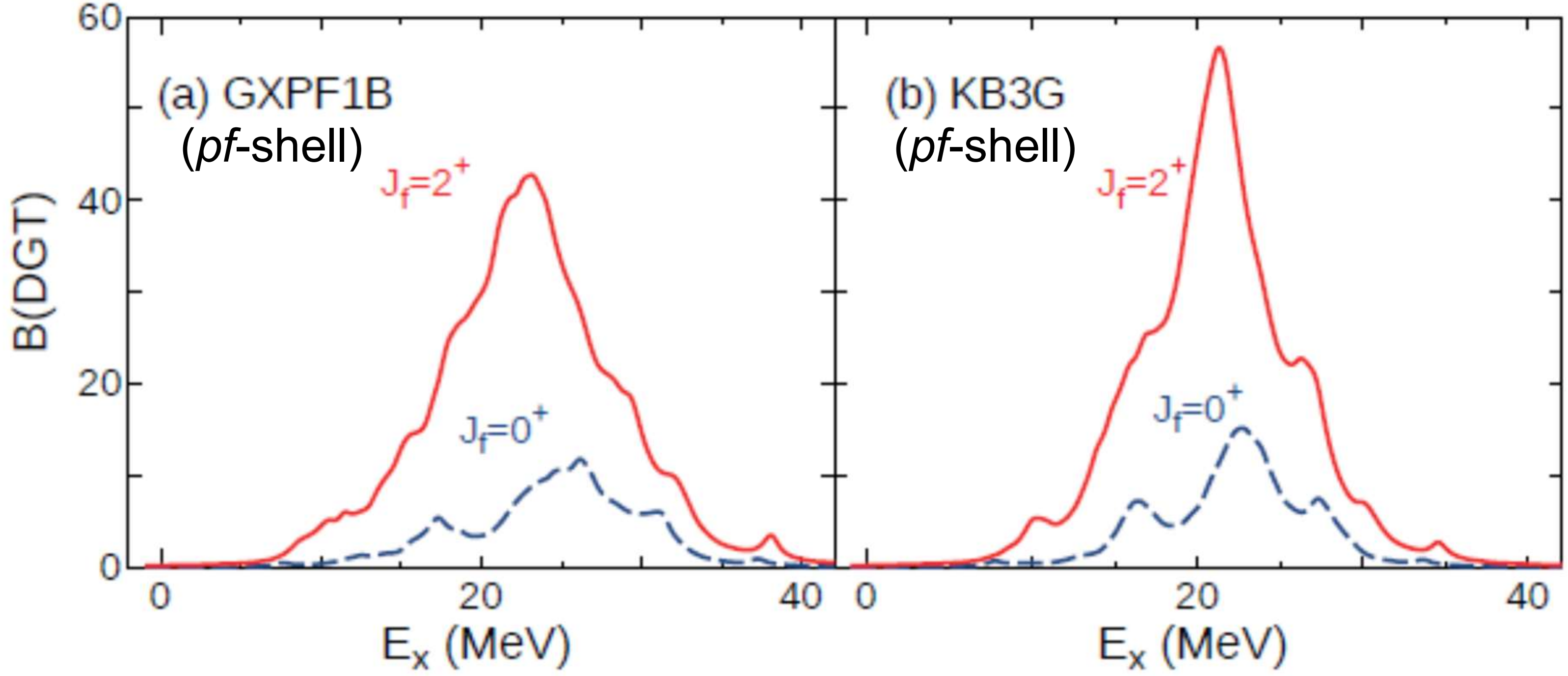


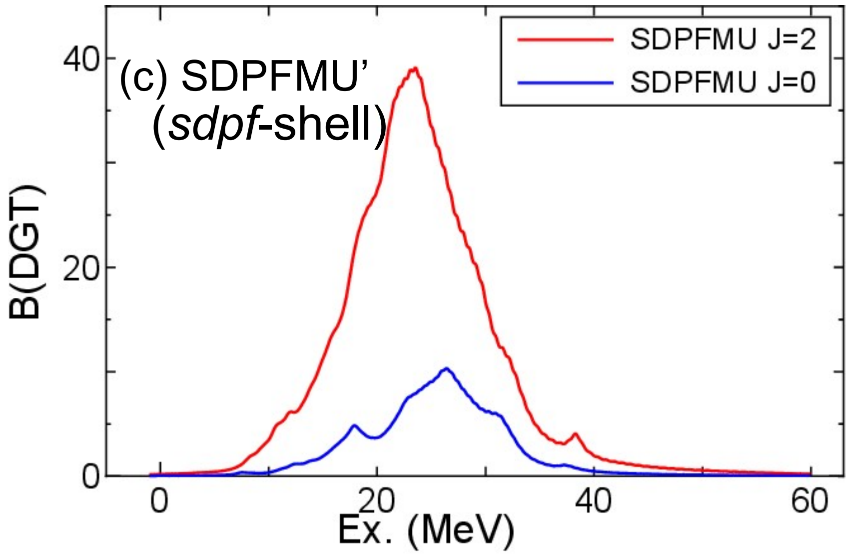
Red symbol : exp.
Blue line: shell-model calc.

Y. Iwata *et al*., JPS Conf. Proc. **6**, 030057 (2015)
Exp. K. Yako *et al*., Phys. Rev. Lett. **103**, 012503 (2009).

Double Gamow-Teller Resonance in ^{48}Ca by shell-model calculations

DGTR strength of ^{48}Ca by shell-model calc.





Lanczos strength function
smeared out by Lorentzian $\Gamma = 1$ MeV

focus on GXPF1B and *pf* shell hereafter

- What information is extracted from DGT resonance? Relation to the neutrinoless double-beta-decay nuclear matrix element ($0\nu\beta\beta$ NME)?

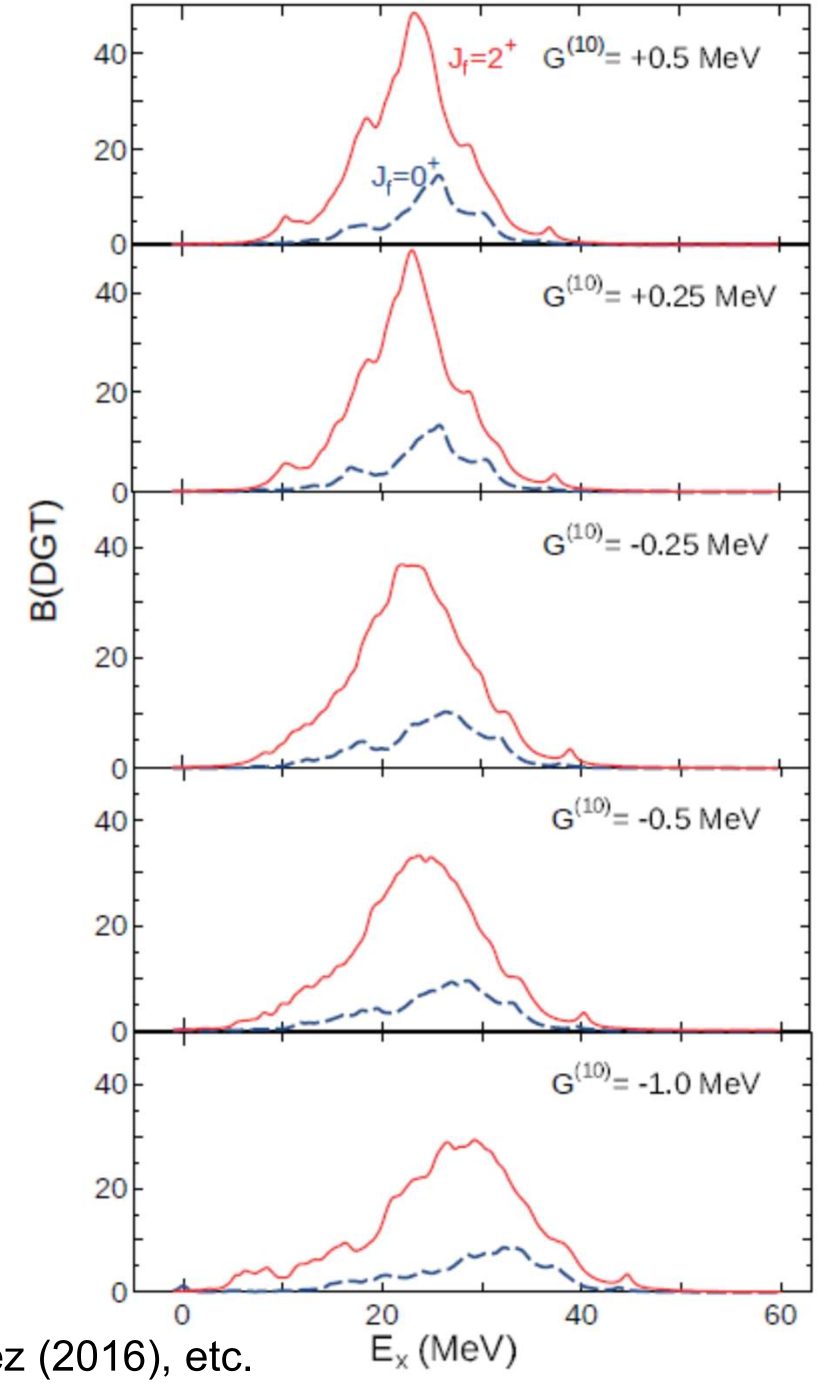
- Play by modifying the shell-model interaction

Dependence of isoscalar pairing

We artificially add
the isoscalar pairing interaction

$$H' = H + G^{10} P^{J=1,T=0}$$

GXPF1B Isoscalar pairing int.



The NME is sensitive to the J=1
proton-neutron matrix element, or isoscalar pairing
Vogel (1986), Muto (1991), Rodin (2003) Menendez (2016), etc.

Isoscalar pairing dependence: $0\nu\beta\beta$ decay NME and DGT

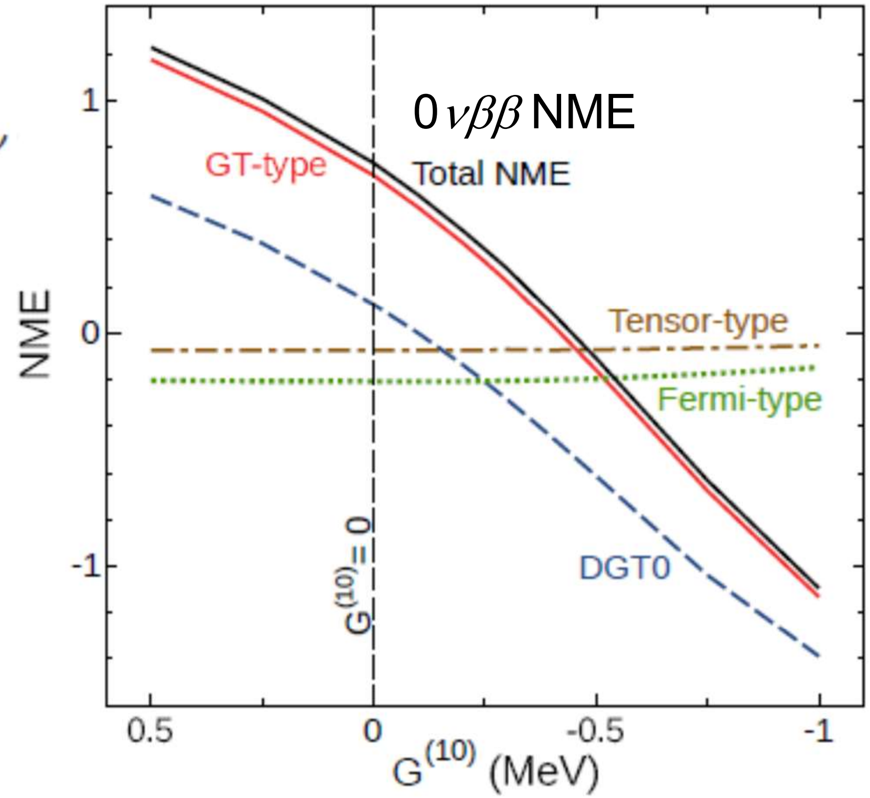
Total
$$M^{0\nu} = M^{0\nu}_{GT} - \left(\frac{g_V}{g_A}\right)^2 M^{0\nu}_{F} + M^{0\nu}_{T}$$

GT-type
$$M^{0\nu}_{GT} = \langle f | \sum_{jk} \tau_j \sigma_j \tau_k \sigma_k V_{GT}(r_{jk}) | i \rangle$$

Fermi-type
$$M^{0\nu}_{F} = \langle f | \sum_{jk} \tau_j \tau_k V_{F}(r_{jk}) | i \rangle$$

tensor-type
$$M^{0\nu}_{T} = \langle f | \sum_{jk} \tau_j \tau_k S_{jk} V_{T}(r_{jk}) | i \rangle,$$

DGT0
$$M^{DGT} = -\langle {}^{48}\mathrm{Ti}, 0^+_1 || \mathcal{O}^{(\lambda=0)}_{-} || {}^{48}\mathrm{Ca}, 0^+_1 \rangle$$



isoscalar pairing strength

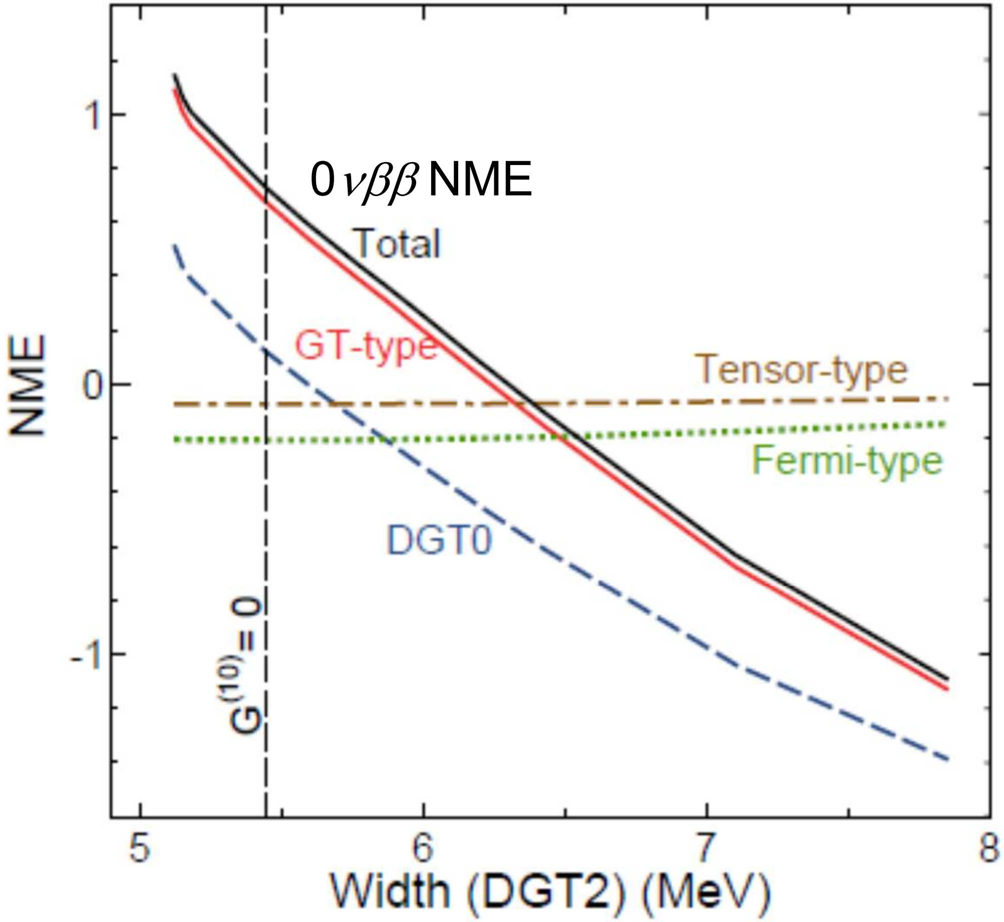
The NME is sensitive to the J=1 proton-neutron matrix element, or isoscalar pairing

Vogel (1986), Muto (1991), Rodin (2003) Menendez (2016), etc.

DGTR width vs NME

$$\sigma = \sqrt{\sum_f (E_f - E_c)^2 B(DGT2, f) / \sum_f B(DGT2, f)}$$

$$E_c = \sum_f E_f B(DGT2, f) / \sum_f B(DGT2, f).$$

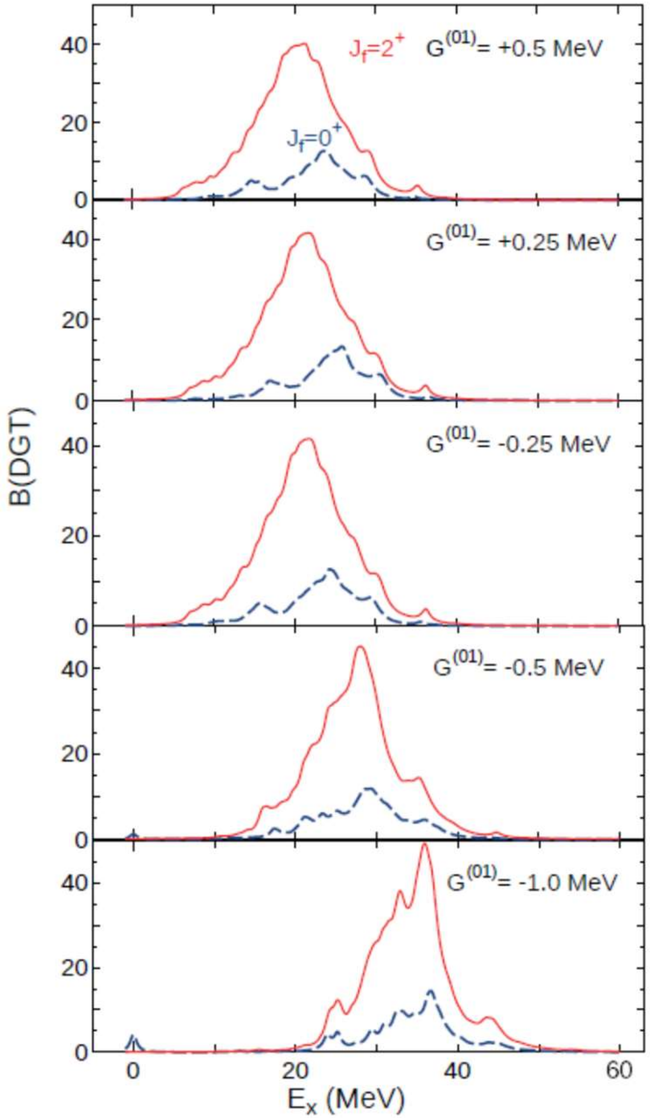


N. B. width is independent
of quenching factor.

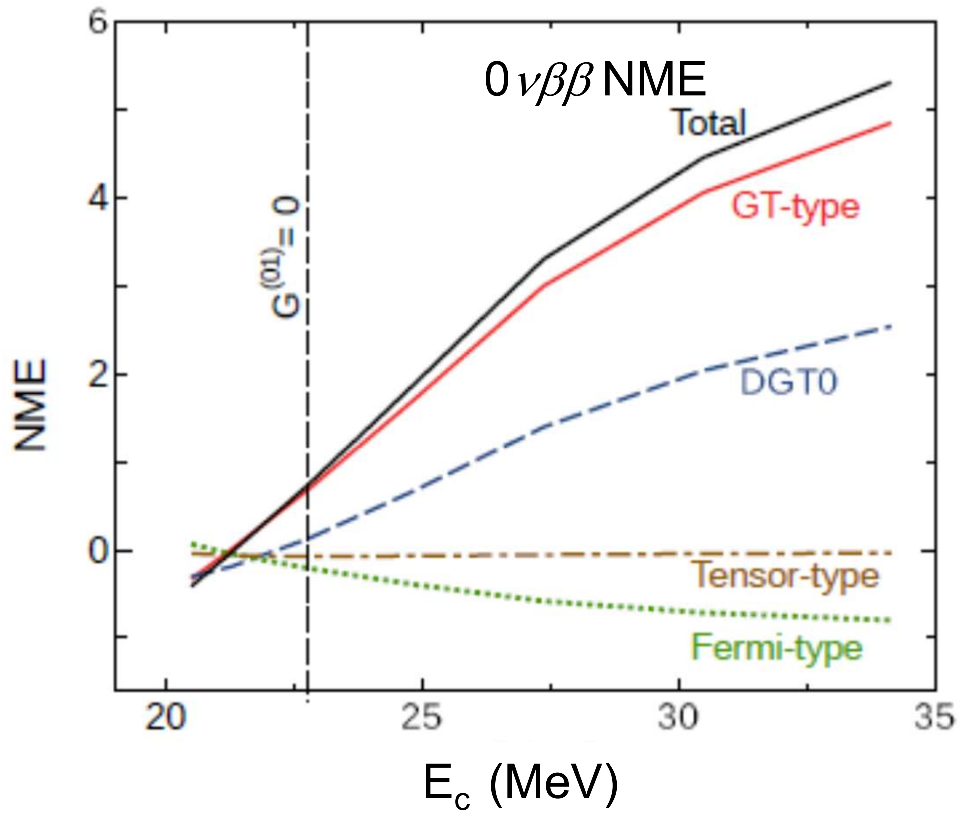
DGTR and Isovector pairing

$$H' = H + G^{01} P^{J=0,T=1}$$

$$E_c = \sum_f E_f B(DGT2, f) / \sum_f B(DGT2, f).$$

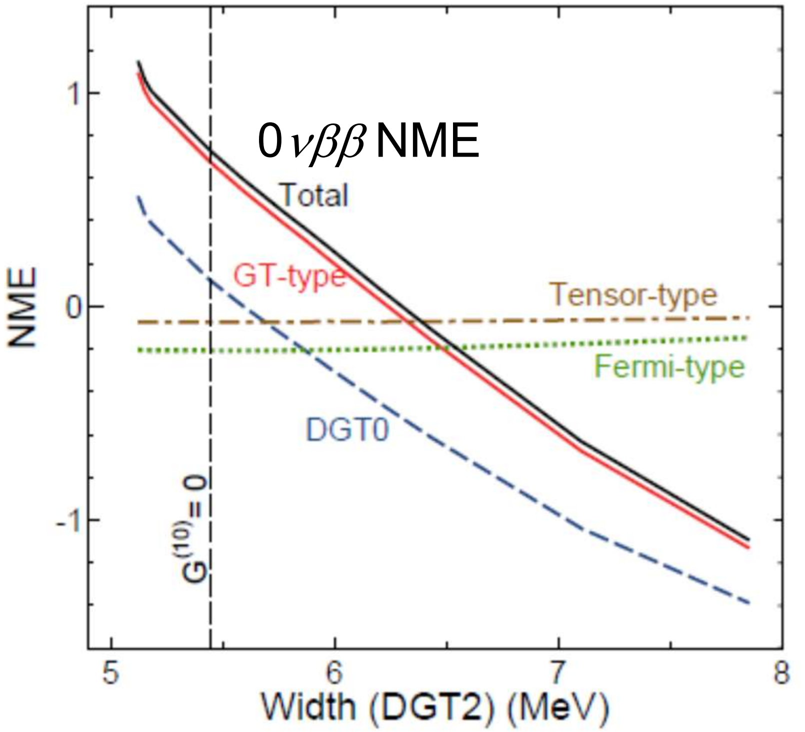


DGTR centroid energy vs. NME

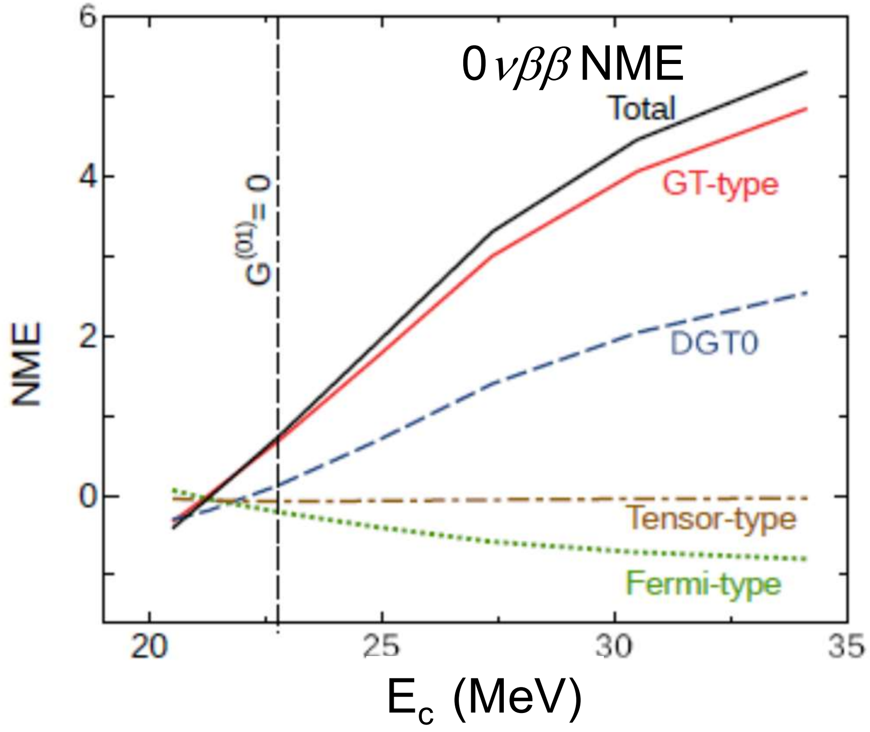


Summary :
Pairing – DGTR – $0\nu\beta\beta$ NME

varying isoscalar pairing

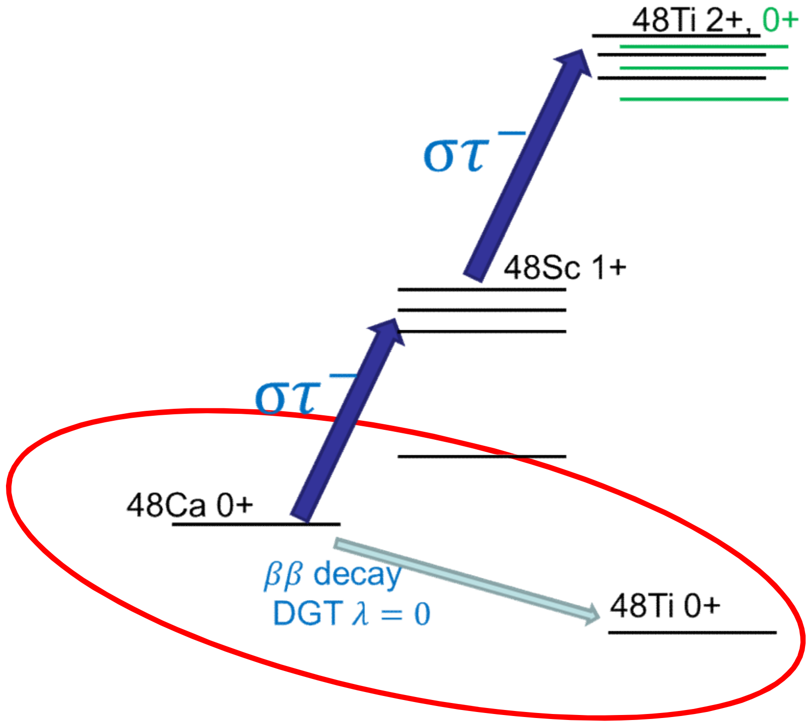


varying isovector pairing

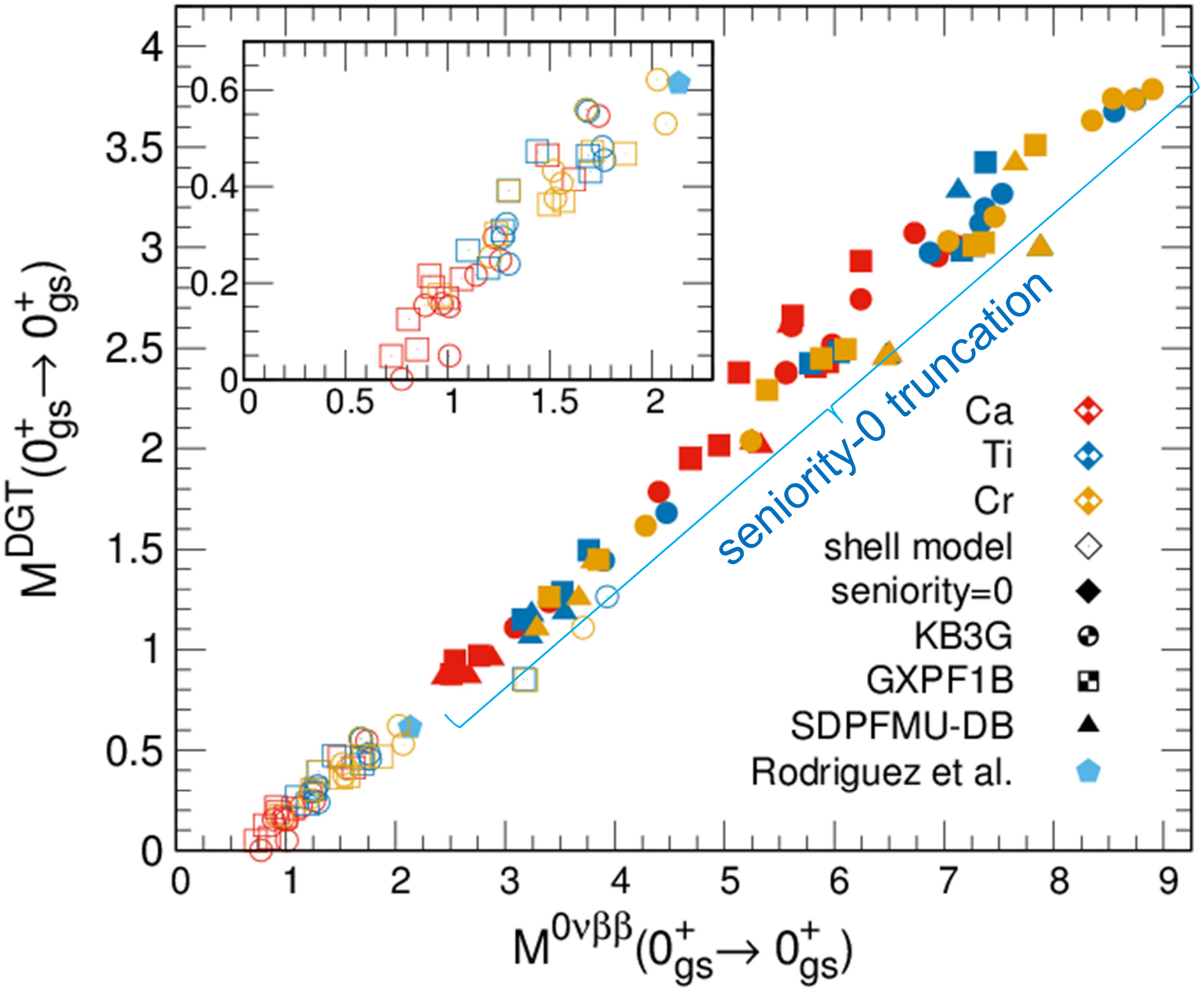


DGT transition between the ground states

See the relation between DGT($\lambda = 0$) and $0\nu\beta\beta$ NME (initial and final states are common)



DGT($\lambda = 0$) transition vs. $0\nu\beta\beta$ decay NME



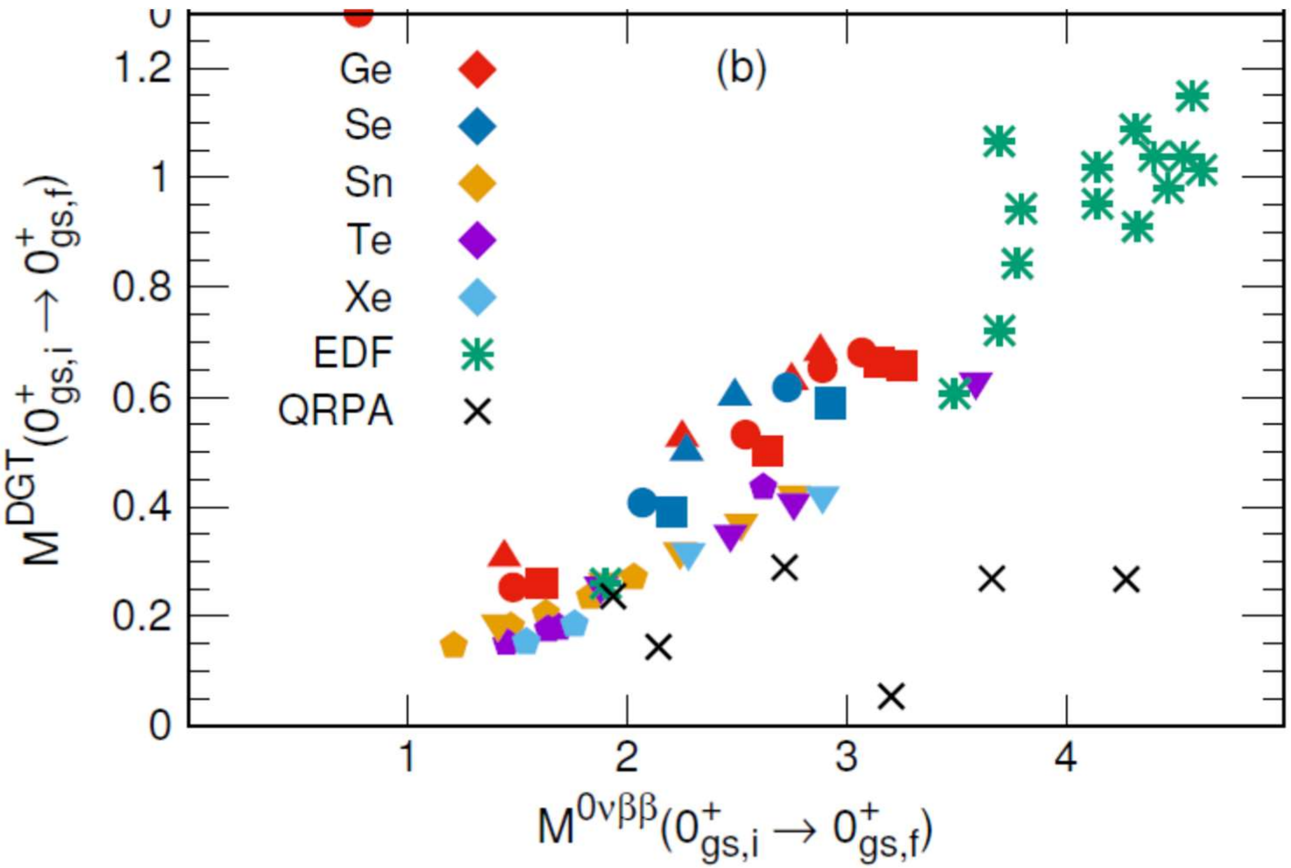
Ca, Ti, Cr isotopes
(N=22, 24, ..., 36)

SM: KB3G, GXPF1B,
SDPFMU-DB
interactions

filled symbol: SM w/
seniority-zero
approximation

EDF: ^{48}Ca Gogny+GCM
Rodriguez *et al.*,
PLB719 174 (2013)

DGT transition vs 0vbb decay NME



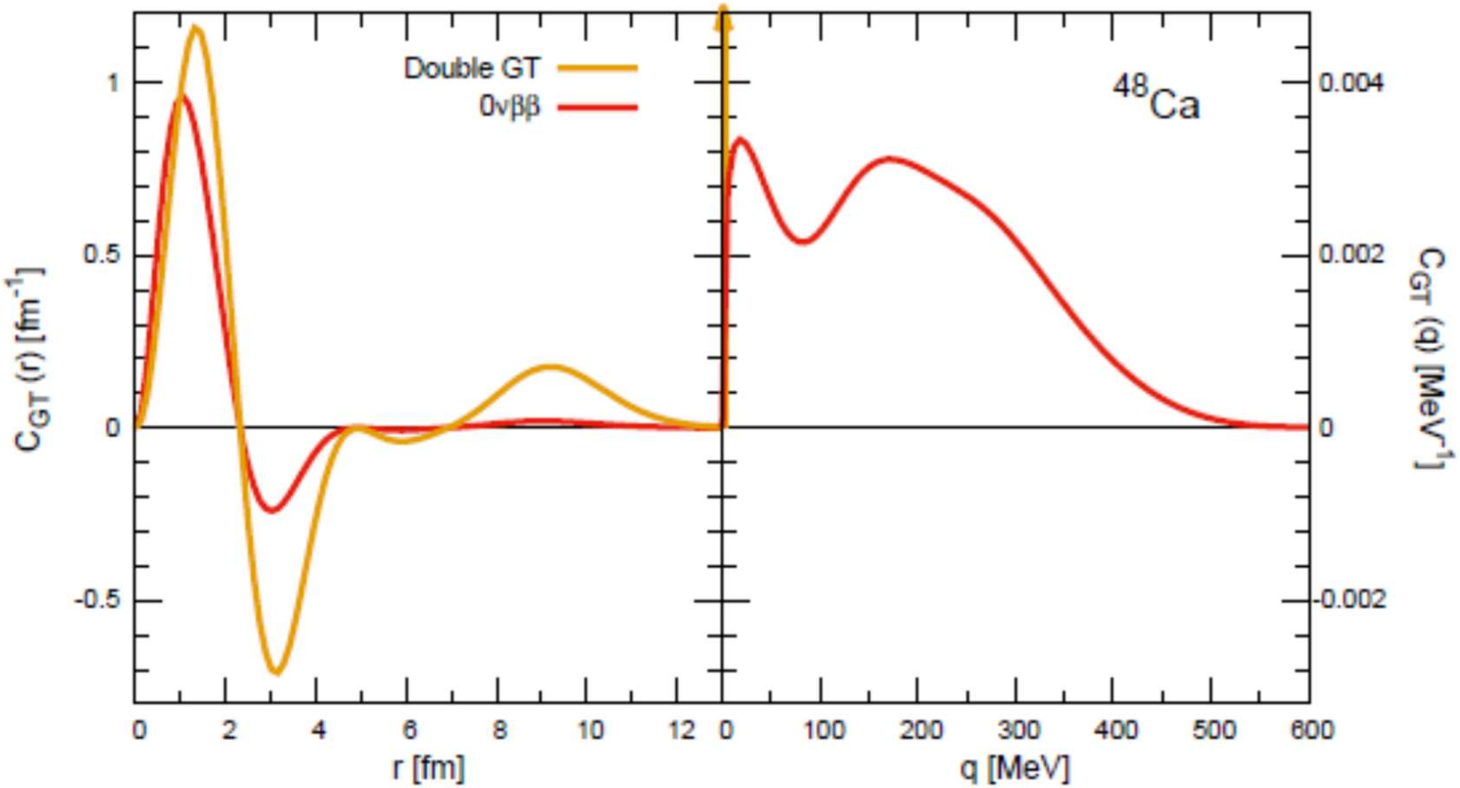
$^{74\text{-}82}$Se, ^{74,76}Ge, $^{124\text{-}132}$Sn, $^{128\text{-}130}$Te, ^{134,136}Xe

SM: shell model
GCN2850, jj44b,
JUN45,
GCN5082,QX

EDF: Gogny+GCM
Rodriguez *et al.*,
PLB719 174 (2013)

QRPA: AV18+G-matrix
F. Simkovic *et al.*,
PRC83, 015502 (2011).

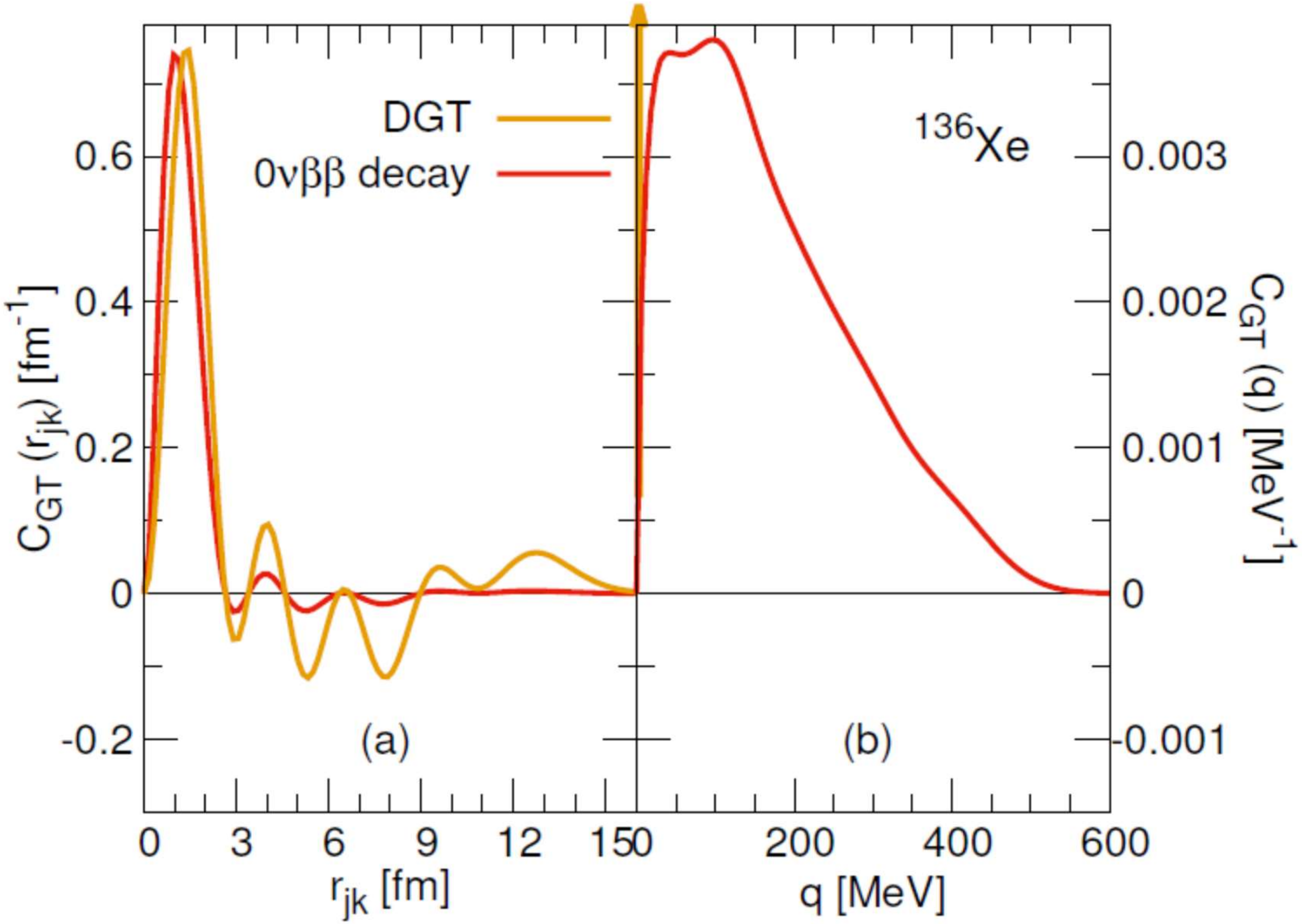
DGT and $0\nu\beta\beta$ NMEs: distance and momentum dependences : ^{48}Ca



$M = \int C(r_{ab}) dr_{ab}$ internucleon distance

$M = \int C(|\boldsymbol{q}|) d|\boldsymbol{q}|$ momentum transfer

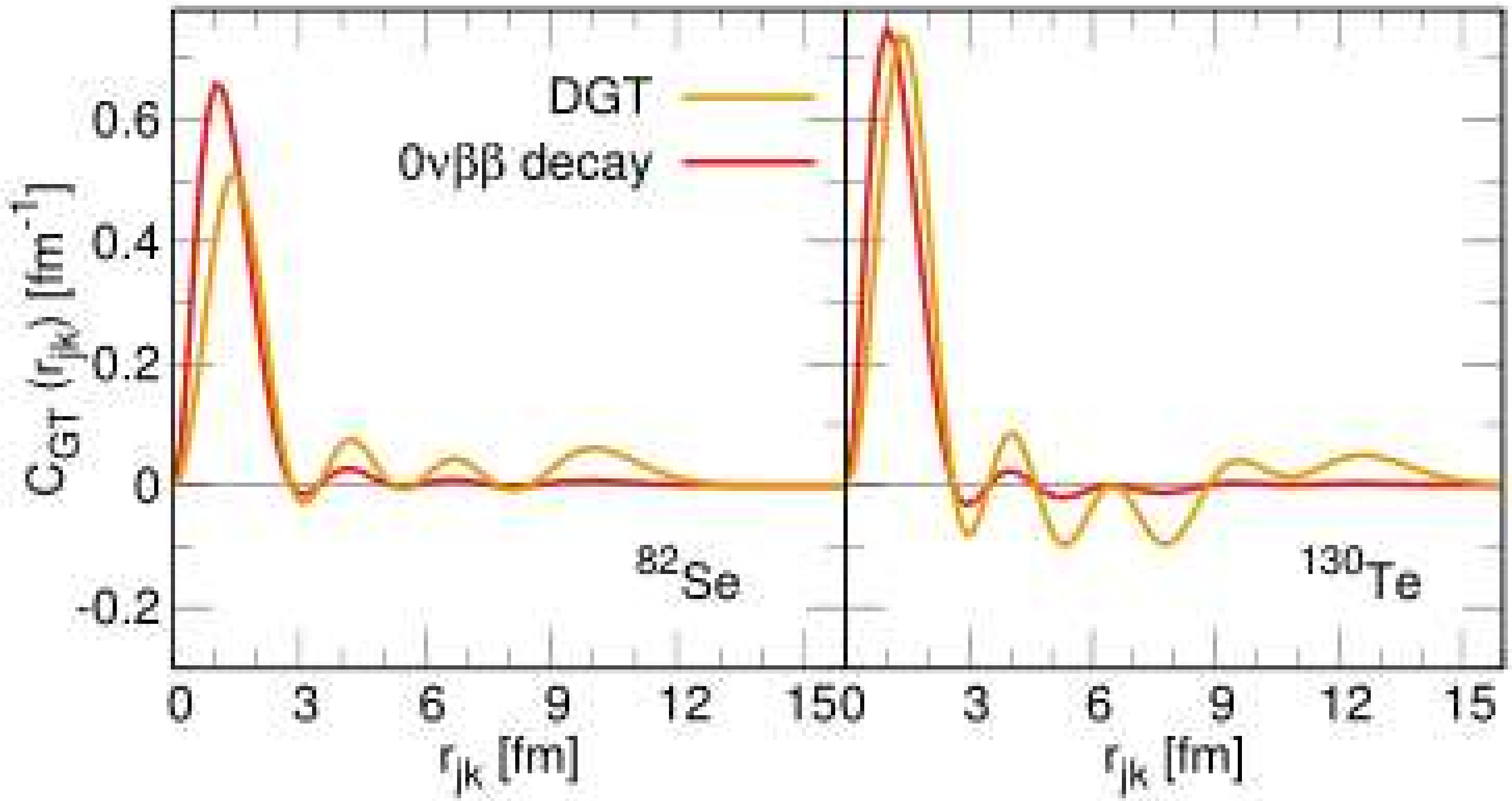
DGT and $0\nu\beta\beta$ NMEs: distance and momentum dependences : ^{136}Xe



$$M = \int C(r_{ab}) dr_{ab}$$

$$M = \int C(|\boldsymbol{q}|) d|\boldsymbol{q}|$$

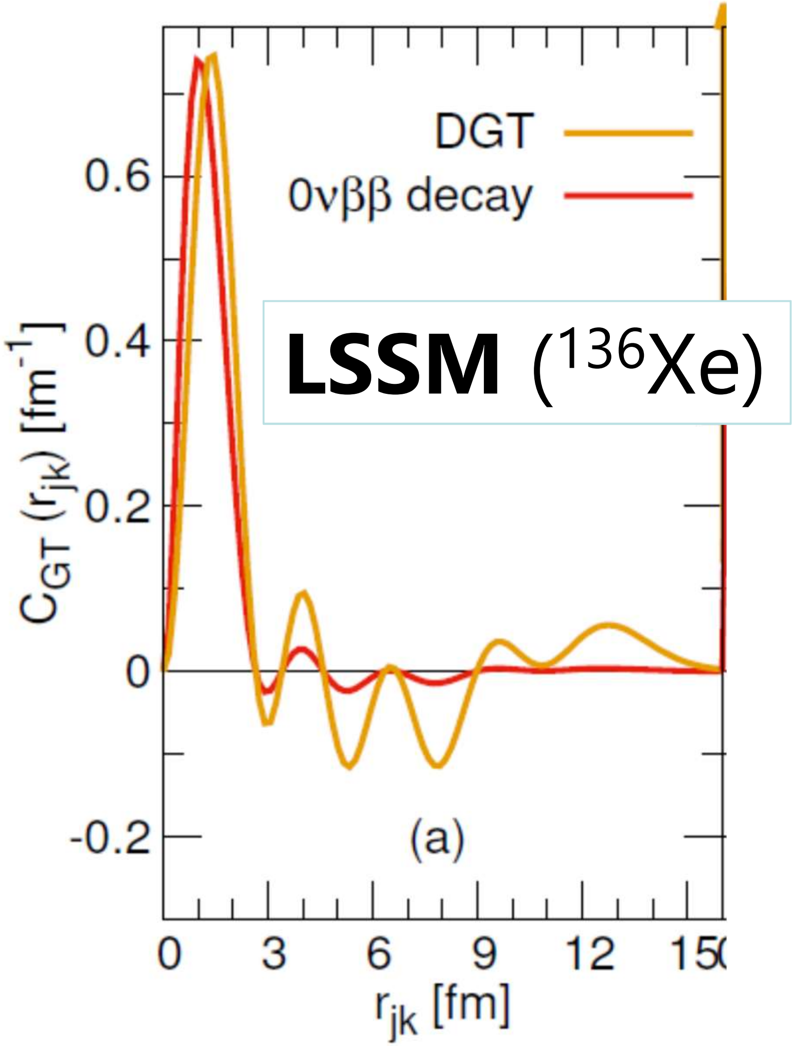
DGT and $0\nu\beta\beta$ NMEs: distance dependences : ^{82}Se and ^{136}Xe

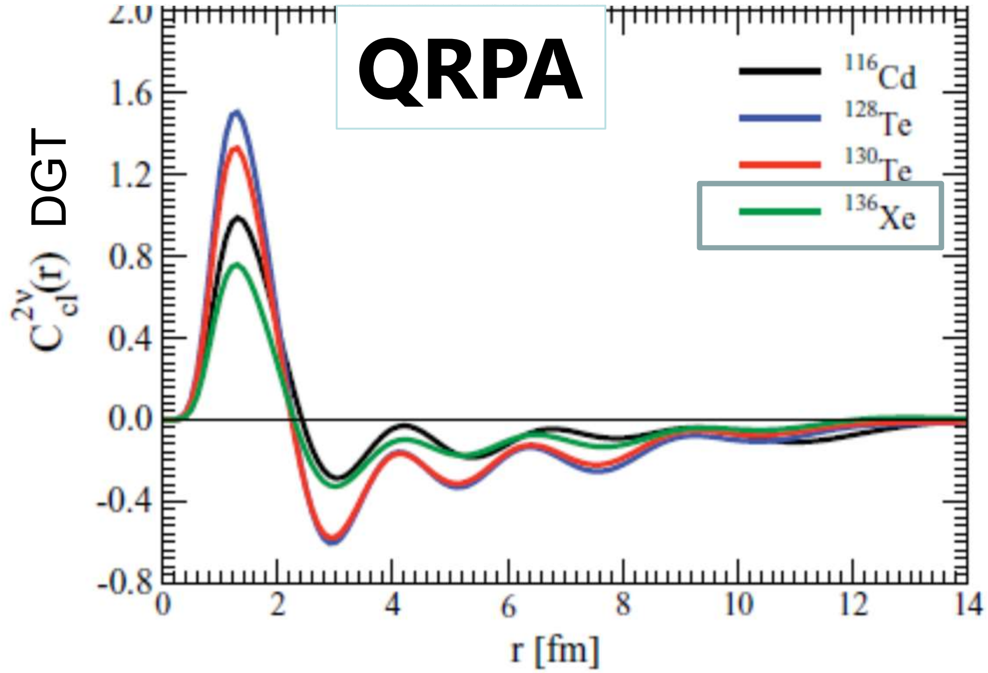


Why linear correlation between DGT and $0\nu\beta\beta$ NMEs?

- Similar behaviour in distance dependence, contrary to momentum dependence
- Intermediate and long-range parts show cancellation, resulting small contribution to the NME. The short-range character dominates

- factorization: short-distance details decouple from long-distance dynamics
  - E. R. Anderson, S. K. Bogner, R. J. Furnstahl, and R. J. Perry, Phys. Rev. C **82**, 054001 (2010)
  - S. K. Bogner and D. Roscher, Phys. Rev. C **86**, 064304 (2012).





NO cancellation
⇒ small M(DGT)

F. Simkovic *et al.*, PRC 83 015502 (2012)

Reaction theory for DCX reaction

E. Santopinto *et al.,* arXiv:1806.03069 [nucl-th]

- Eikonal approximation
  - DGT is dominant at $\theta = 0°$
  - Linear relation between $0\nu\beta\beta$ NME and DGT NME extracted from DCE reaction cross section

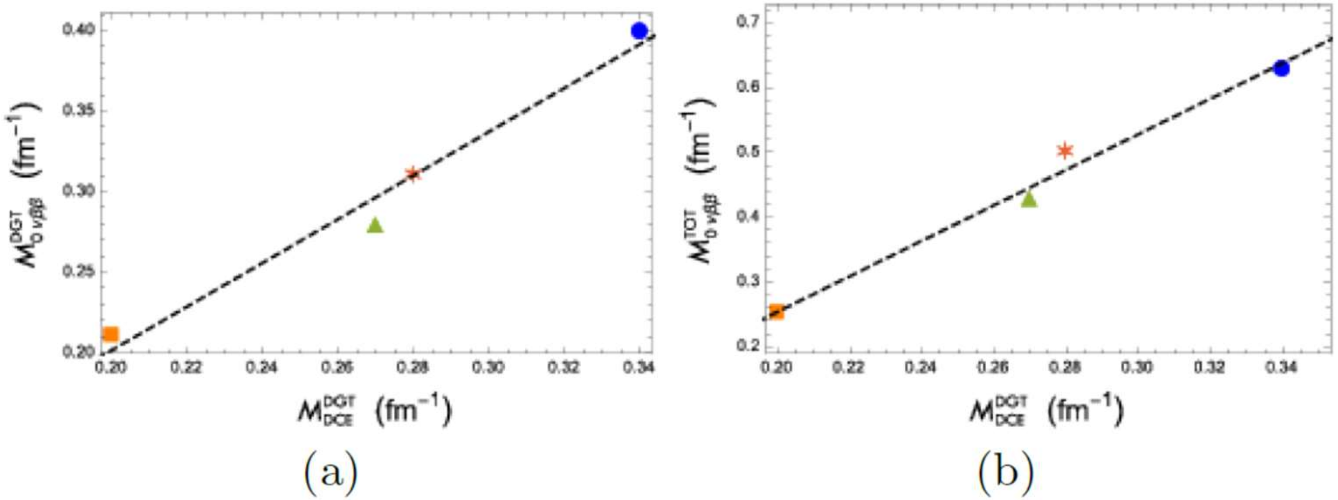


FIG. 3: Correlation between our calculated DCE-DGT NMEs and (a) $0\nu\beta\beta$-DGT NMEs [59] and (b) $0\nu\beta\beta$-total NMEs [59]. The orange squares, green triangles, red stars and blue circles stand for ^{116}Cd $\rightarrow$ ^{116}Sn, ^{128}Te $\rightarrow$ ^{128}Xe, ^{82}Se$\rightarrow$ ^{82}Kr and ^{76}Ge $\rightarrow$ ^{76}Se data.

Summary

- Using the shell-model calculations, $0\nu\beta\beta$ NME and double Gamow-Teller Resonance of ^{48}Ca are studied.
  - DGTR is correlated to the $0\nu\beta\beta$ NME via isovector and isoscalar pairing correlations.
- DGT and $0\nu\beta\beta$ NMEs show clear linear correlation. They are dominated by the short-range character.
- The HIDCX reaction may be useful to "calibrate" theoretical studies of $0\nu\beta\beta$ NME.
- Reaction theory of HIDCX, …