Double-beta decay nuclear matrix elements

Javier Menéndez

University of Barcelona

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ICCUB

Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

Nuclear structure physics encoded in nuclear matrix elements key to plan, fully exploit experiments

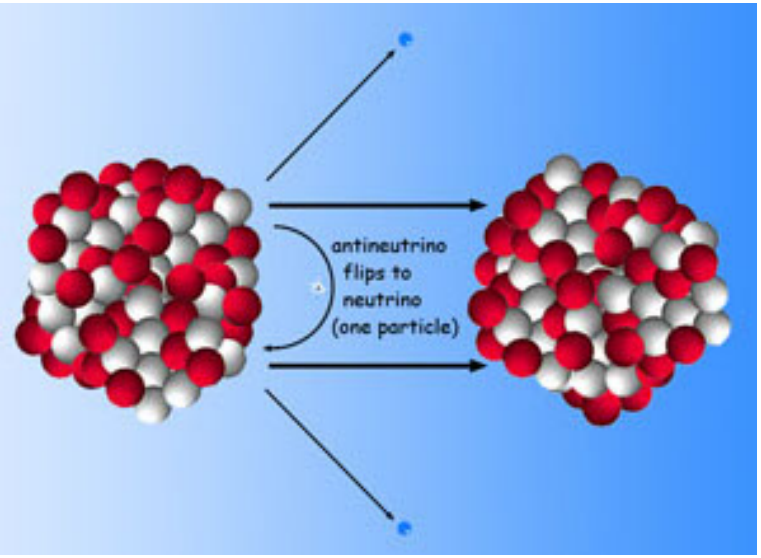
$0\nu\beta\beta$: $\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$

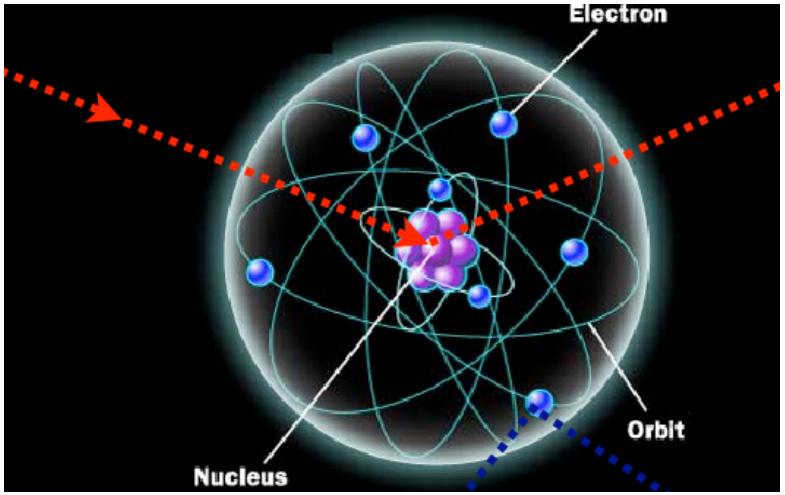
Dark matter: $\dfrac{\mathrm{d}\sigma_{\chi\mathcal{N}}}{\mathrm{d}\boldsymbol{q}^2} \propto \left|\sum_i c_i\,\zeta_i\,\mathcal{F}_i\right|^2$

CEνNS: $\dfrac{\mathrm{d}\sigma_{\nu\mathcal{N}}}{\mathrm{d}\boldsymbol{q}^2} \propto \left|\sum_i c_i\,\zeta_i\,\mathcal{F}_i\right|^2$

$M^{0\nu\beta\beta}$: Nuclear matrix element

$\mathcal{F}_i$: Nuclear structure factor



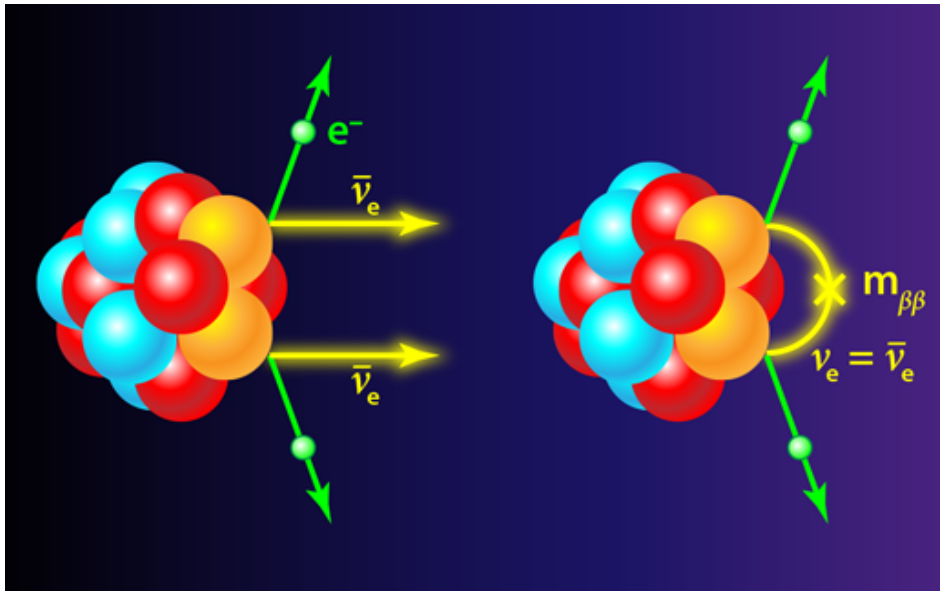


Calculating nuclear matrix elements

Nuclear matrix elements needed in low-energy new physics searches

$$\langle \text{Final} | \mathcal{L}_{\text{leptons}-\text{nucleons}} | \text{Initial} \rangle = \langle \text{Final} | \int dx\, j^{\mu}(x) J_{\mu}(x) | \text{Initial} \rangle$$

- Nuclear structure calculation of the initial and final states:
  Shell model, QRPA, IBM,
  Energy-density functional
  Ab initio many-body theory
  GFMC, Coupled-cluster, IMSRG...
- Lepton-nucleus interaction:
  Hadronic current in nucleus:
  phenomenological,
  effective theory of QCD



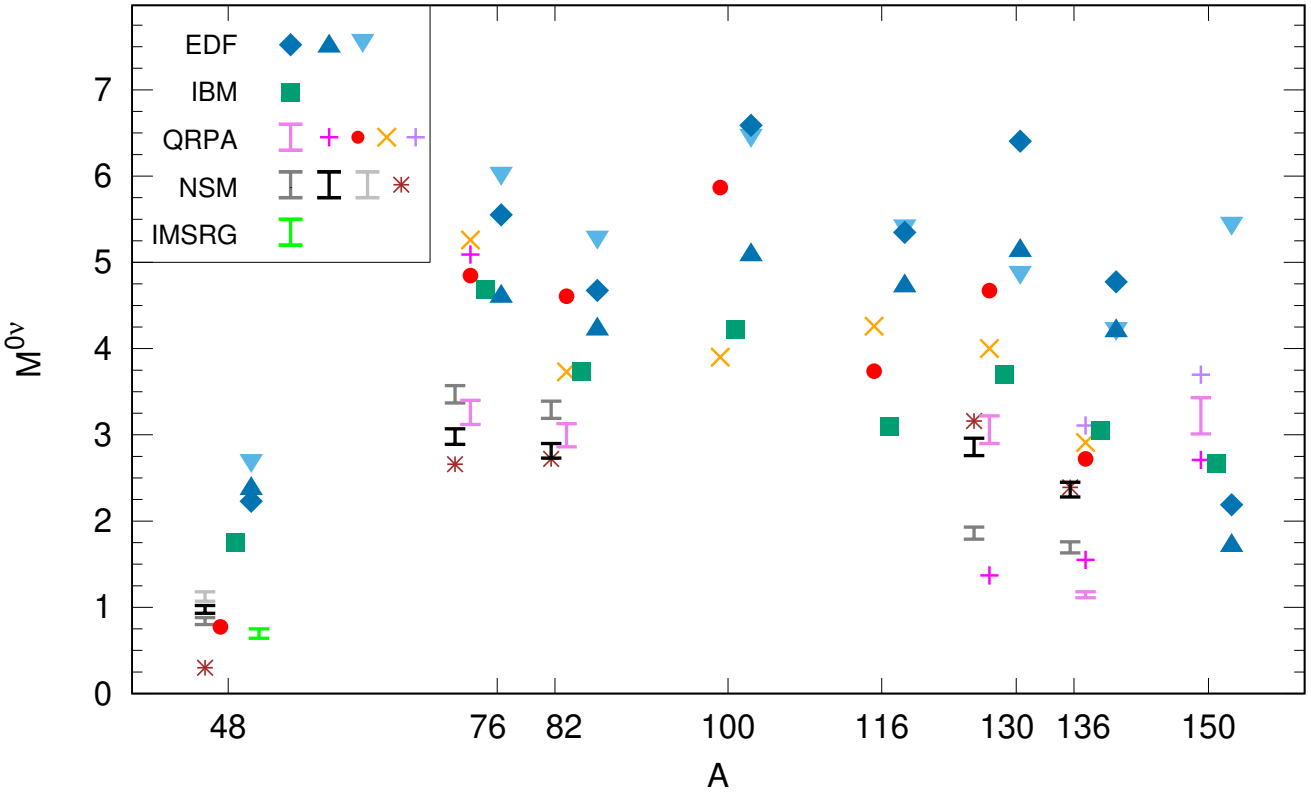
$0\nu\beta\beta$ decay nuclear matrix elements

Large difference in nuclear matrix element calculations: factor $\sim 2-3$

$$\left\langle 0_f^+ \middle| \sum_{n,m} \tau_n^- \tau_m^- \sum_x H^x(r)\,\Omega^x \middle| 0_i^+ \right\rangle$$

Ω^x = Fermi ($\mathbb{1}$), GT ($\sigma_n \sigma_m$),Tensor

$H(r)$ = neutrino potential



EDF: large NMEs

QRPA: wider range

NSM: small NMEs

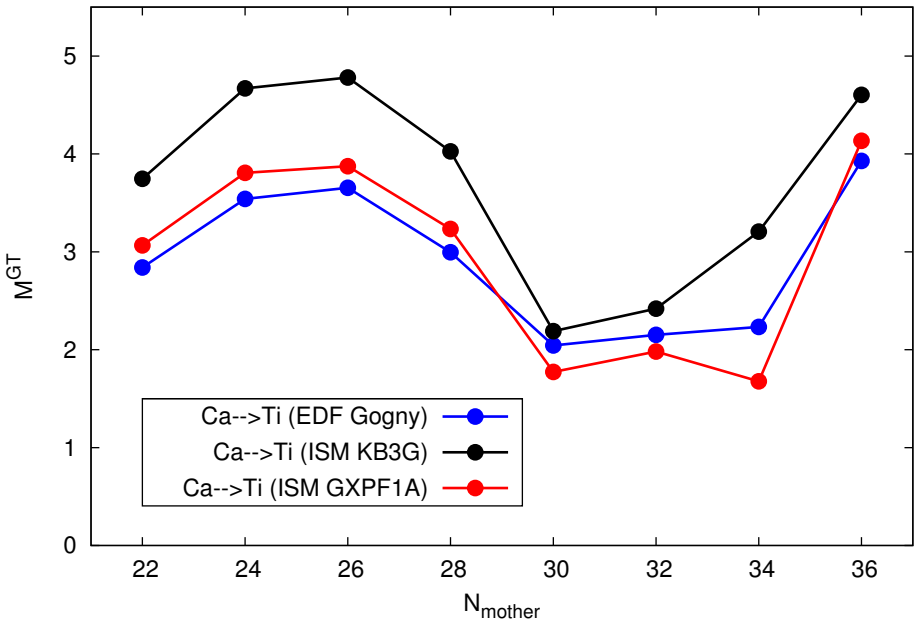
IMSRG ab initio
^{48}Ca NME: quite small
(no 2b currents)

M. Agostini, G. Benato, J. Detwiler, JM, F. Vissani, in preparation

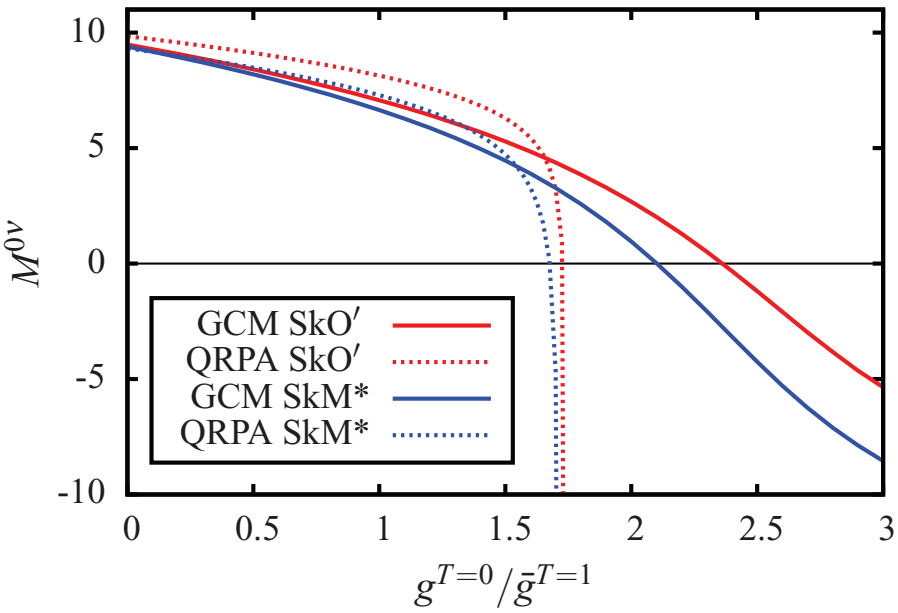
Correlations: proton-neutron pairing

$0\nu\beta\beta$ NMEs agree without nuclear correlations (very simplistic nuclei)

NMEs too large if proton-neutron pairing correlations are neglected



JM et al. PRC90 024311(2014)



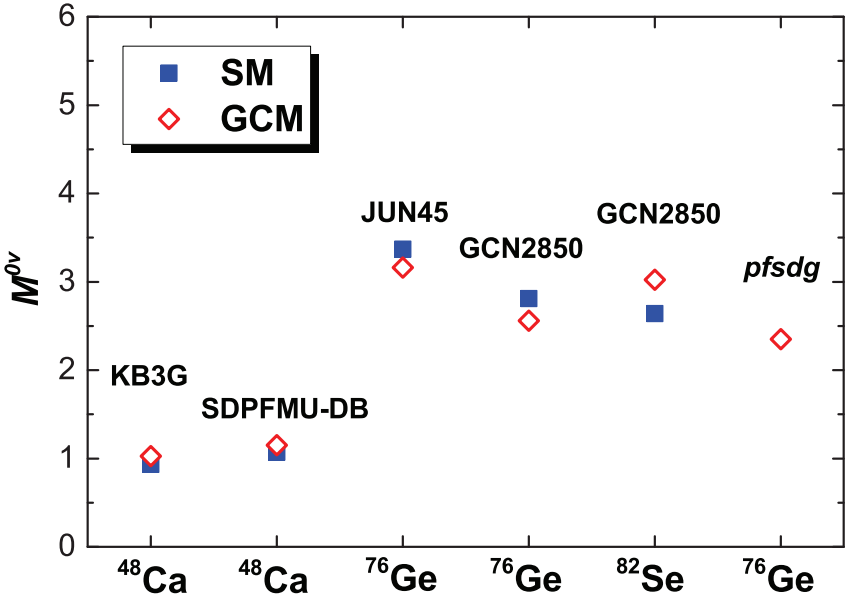
Hinohara, Engel PRC90 031301 (2014)

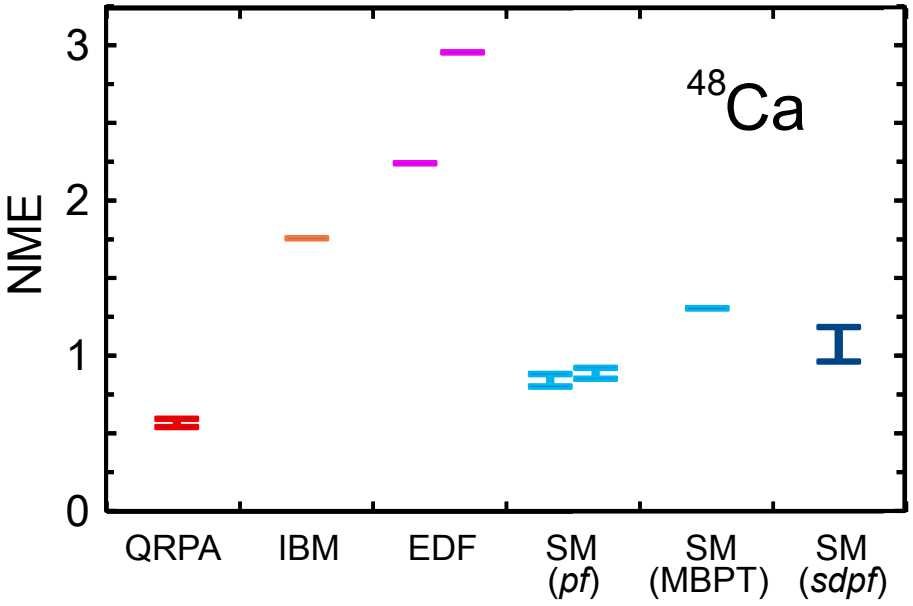
Related to approximate $SU(4)$ symmetry of the $\sum H(r)\boldsymbol{\sigma}_i\boldsymbol{\sigma}_j\tau_i\tau_j$ operator

Correlations: large configuration space

^{48}Ca extended configuration space from *pf* to *sdpf*, 4 to 7 orbitals dimension 10^5 to 10^9
^{48}Ca 0_2^+ state lowered by 1.3 MeV
nuclear matrix elements enhanced only moderately 30%

Iwata et al. PRL116 112502 (2016)





Also small effect of large space with perturbative calculation

Coraggio et al. PRC 101 044315 (2020)

Likewise, very mild effect found in ^{76}Ge GCM calculations

Jiao et al. PRC96 054310 (2017)

Correlations: ab initio IMSRG NME for ^{48}Ca

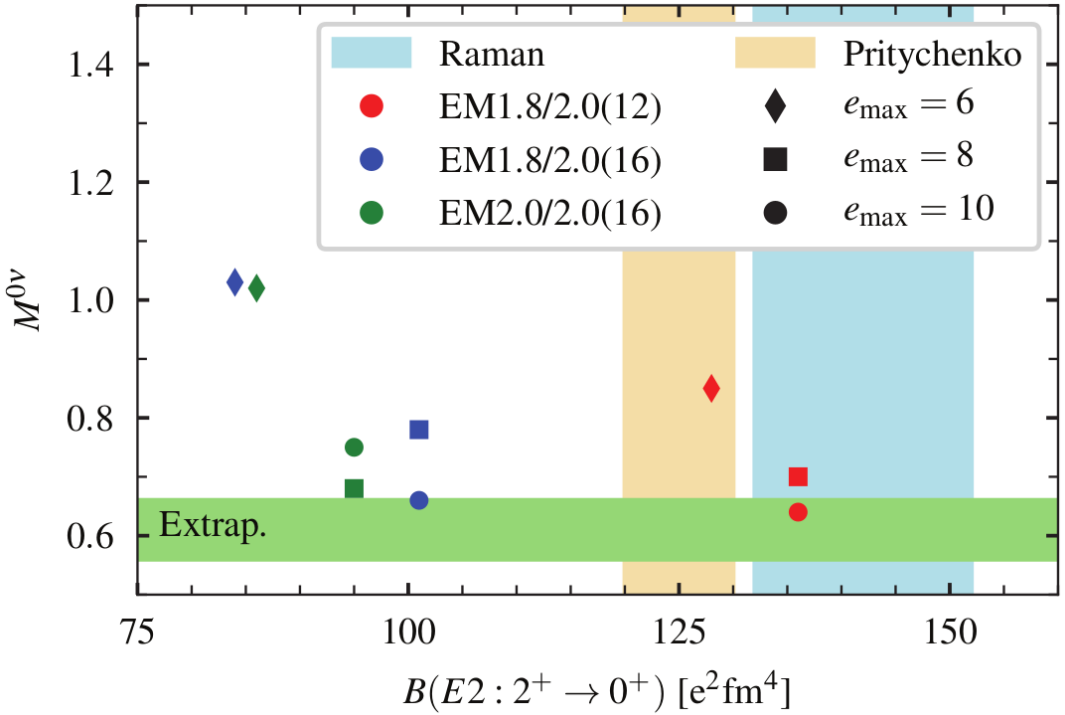
Complete nuclear correlations included in ab initio calculations
IMSRG (in-medium similarity renormalization group) for ^{48}Ca NME

Correlations systematically built on collective reference state
Generator coordinate method: deformation, isoscalar pairing

Best calculation reproduces electromagnetic transitions in ^{48}Ti

NME $\sim$ 0.4/30% smaller than nuclear shell model

Yao et al.
PRL 124 232501 (2020)



Ab initio many-body methods

Oxygen dripline using chiral NN+3N forces correctly reproduced
ab-initio calculations treating explicitly all nucleons
excellent agreement between different approaches

No-core shell model
(Importance-truncated)

In-medium SRG

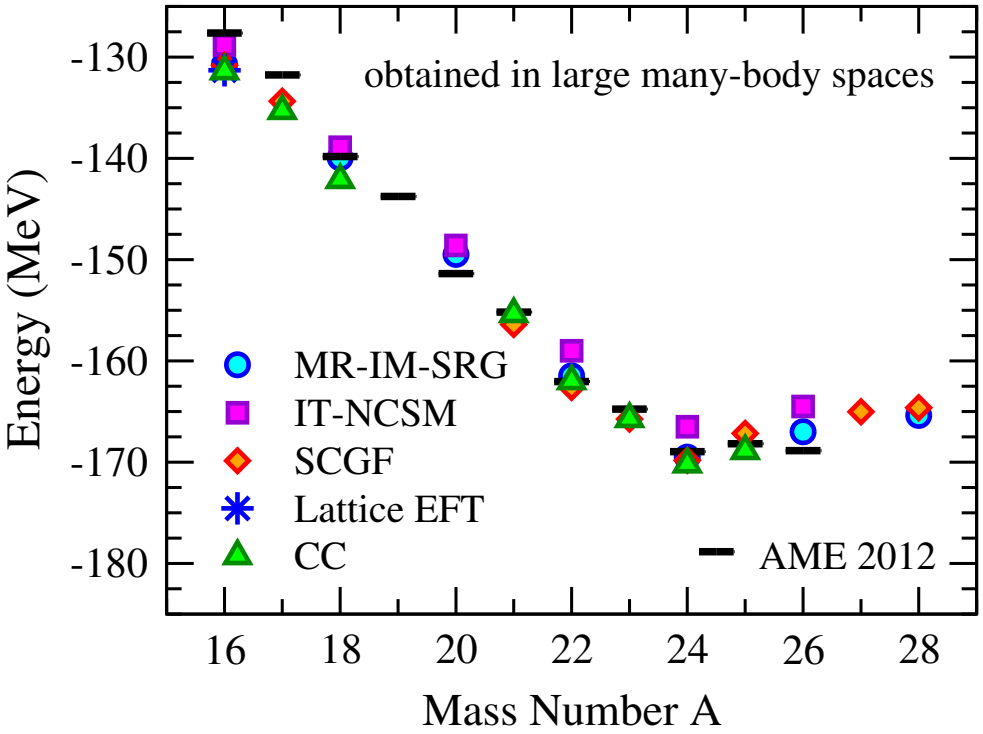
Hergert et al. PRL110 242501(2013)

Self-consistent Green's function

Cipollone et al. PRL111 062501(2013)

Coupled-clusters

Jansen et al. PRL113 142502(2014)

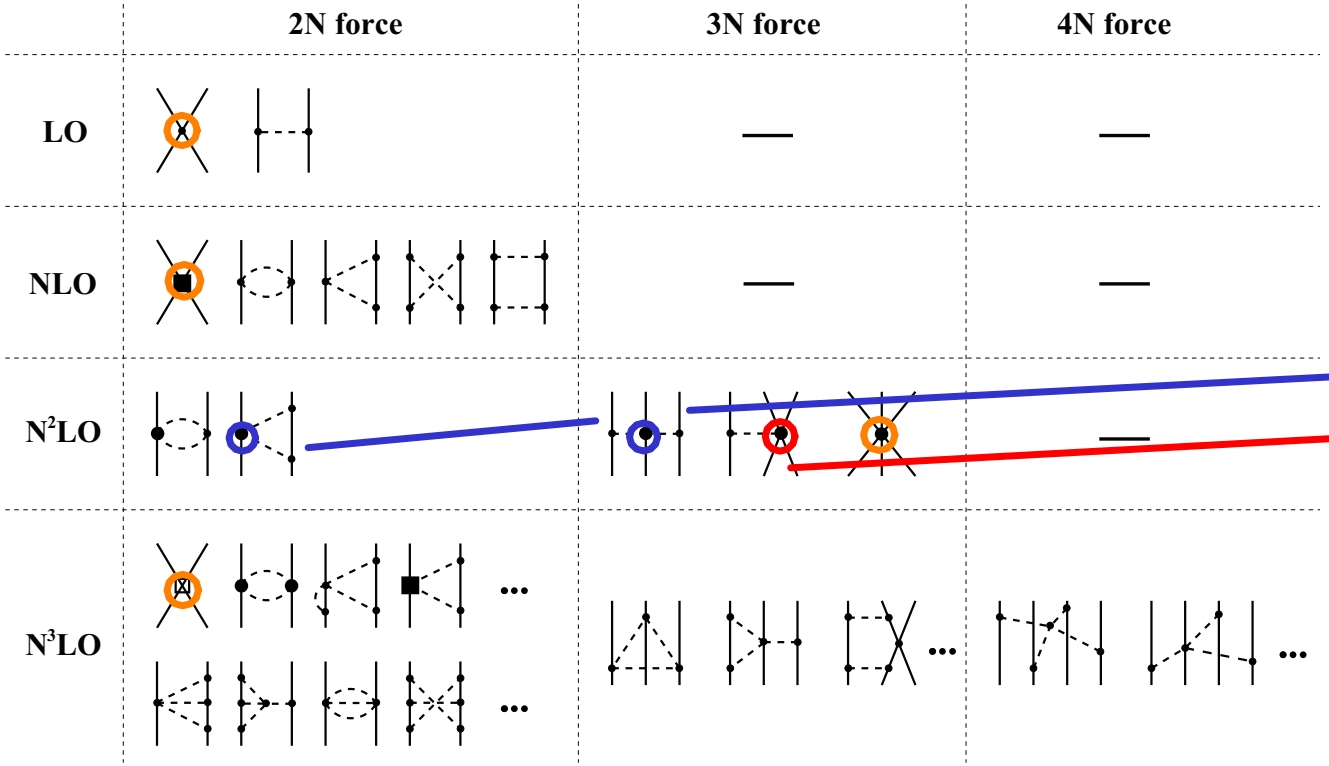


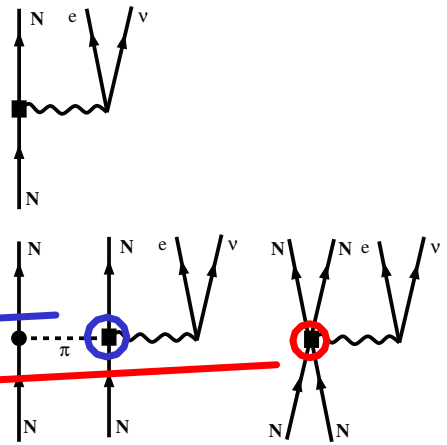
Chiral effective field theory

Chiral EFT: low energy approach to QCD, nuclear structure energies

Approximate chiral symmetry: pion exchanges, contact interactions

Systematic expansion: nuclear forces and electroweak currents





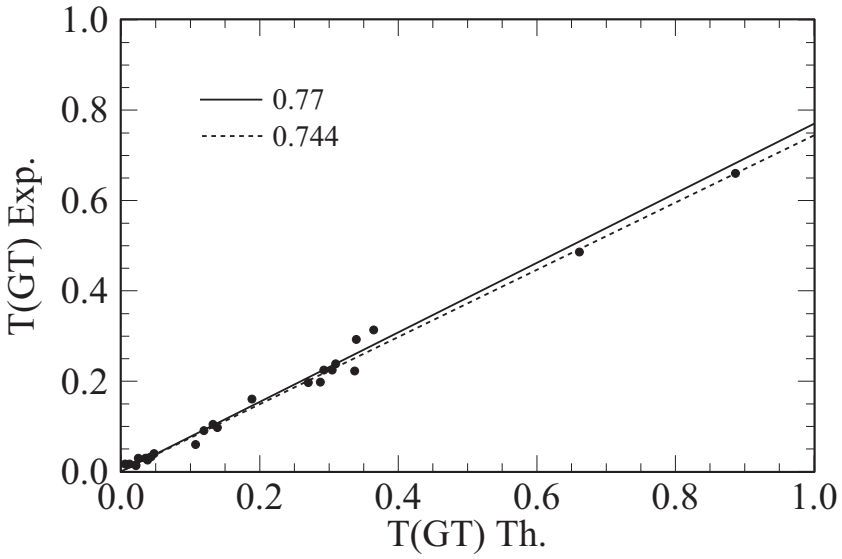
Park, Baroni, Krebs...

2b currents applied to νd scattering (SNO), ^{3}H β-decay, μ moment...

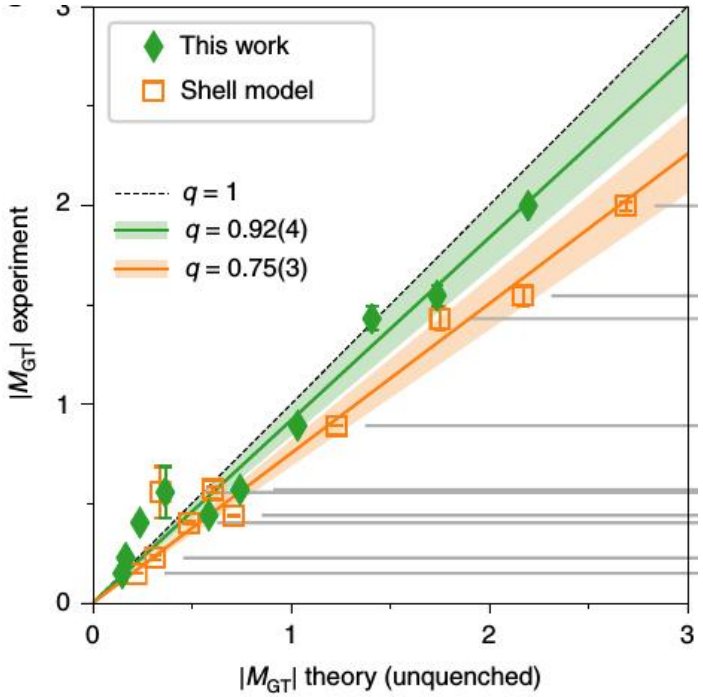
Weinberg, van Kolck, Kaplan, Savage, Wise, Meißner, Epelbaum...

Solution of the "g_A quenching" puzzle

β decays (e^- capture) challenge for nuclear theory



Martinez-Pinedo et al. PRC53 2602(1996)



Gysbers et al. Nature Phys. 15 428 (2019)

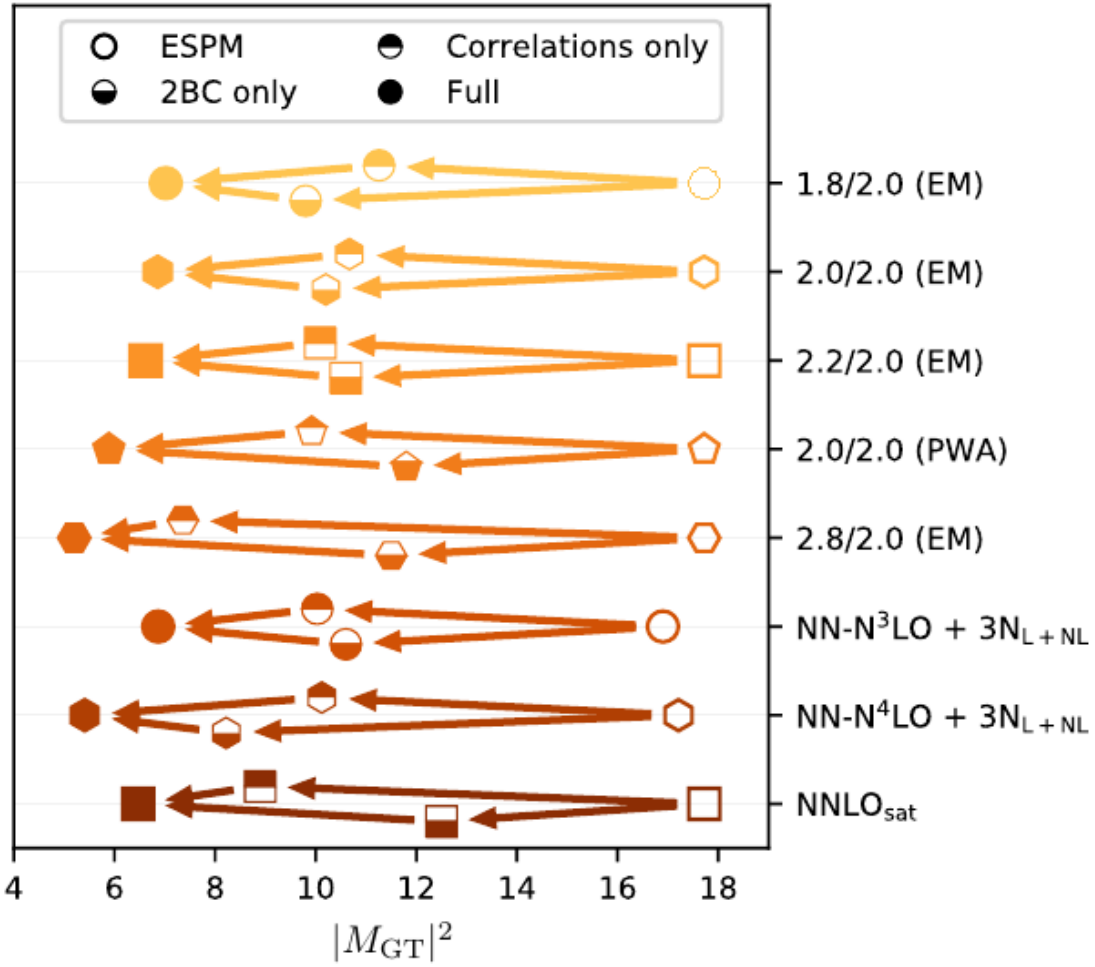
$$\langle F| \sum_i [g_A\, \boldsymbol{\sigma}_i \tau_i^-]^{\text{eff}} |I\rangle\,, \quad [\boldsymbol{\sigma}_i \tau]^{\text{eff}} \approx 0.7 \boldsymbol{\sigma}_i \tau$$

Phenomenological models need $\boldsymbol{\sigma}_i \tau$ "quenching"

Ab initio calculations including two-body/meson-exchange currents and additional nuclear correlations do not need any "quenching"

Origin of β decay "quenching"

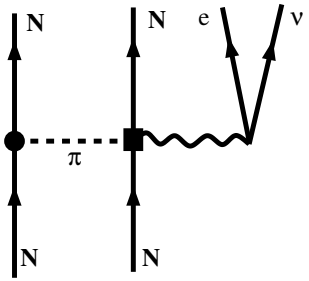
Which are main effects missing in conventional β-decay calculations?



Relatively similar and complementary impact of

- nuclear correlations
- meson-exchange currents

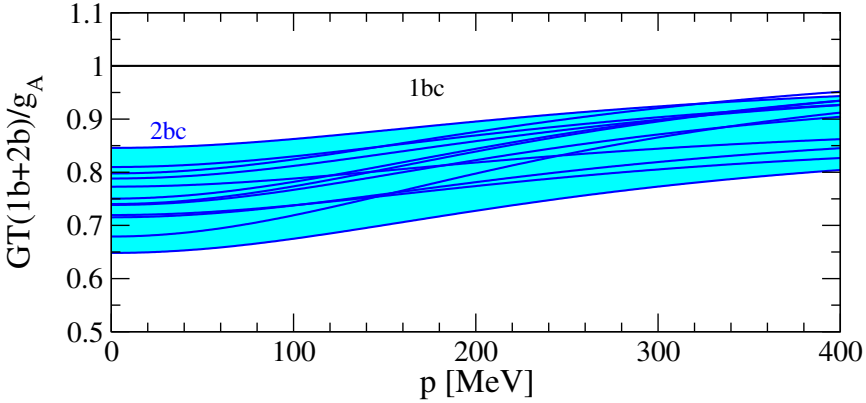
Gysbers et al.
Nature Phys. 15 428 (2019)



2b currents in $\beta\beta$ decay

In $0\nu\beta\beta$ decay, two weak currents lead to four-body operator when including the product of two 2b currents: computational challenge

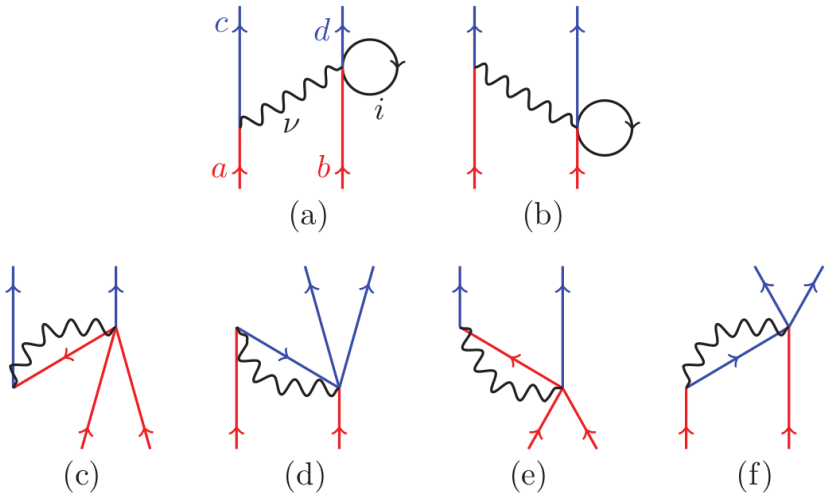
Approximate 2b current as effective 1b current



Quenching reduced to $\sim 20\%$ at $p \sim m_\pi$ for $0\nu\beta\beta$ decay

JM et al. PRL107 062501(2011)

Approximate 4b operator as effective 3b operator



Estimated effect $\sim 10\%$

Wang et al. PRC98 031301 (2018)

Estimations suggest that 2b currents smaller in $0\nu\beta\beta$ than β decay

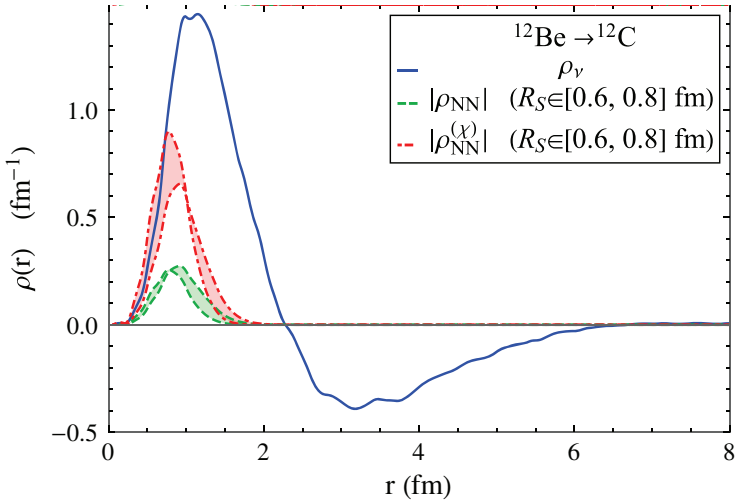
Light neutrino exchange: new contact operator

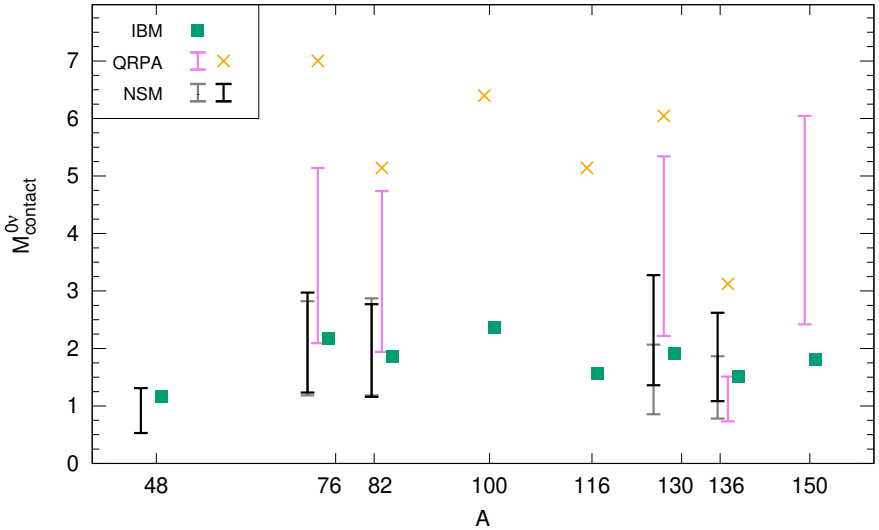
Contact operator suggested to contribute to light-neutrino exchange

Cirigliano et al. PRL120 202001(2018)

$$T_{1/2}^{-1} = G_{01}\left(g_A^2 M^{0\nu} + g_\nu^{\mathrm{NN}} m_\pi^2 M_{\mathrm{cont}}^{0\nu}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

Unknown value of the hadronic coupling g_ν^{NN}!
to be determined experimentally or Lattice QCD calculations ($\sim g_A$)





Short-range operator similar disagreement than standard NME
larger error bars because uncertainty in short-range dynamics

$0\nu\beta\beta$ mediated by BSM heavy particles

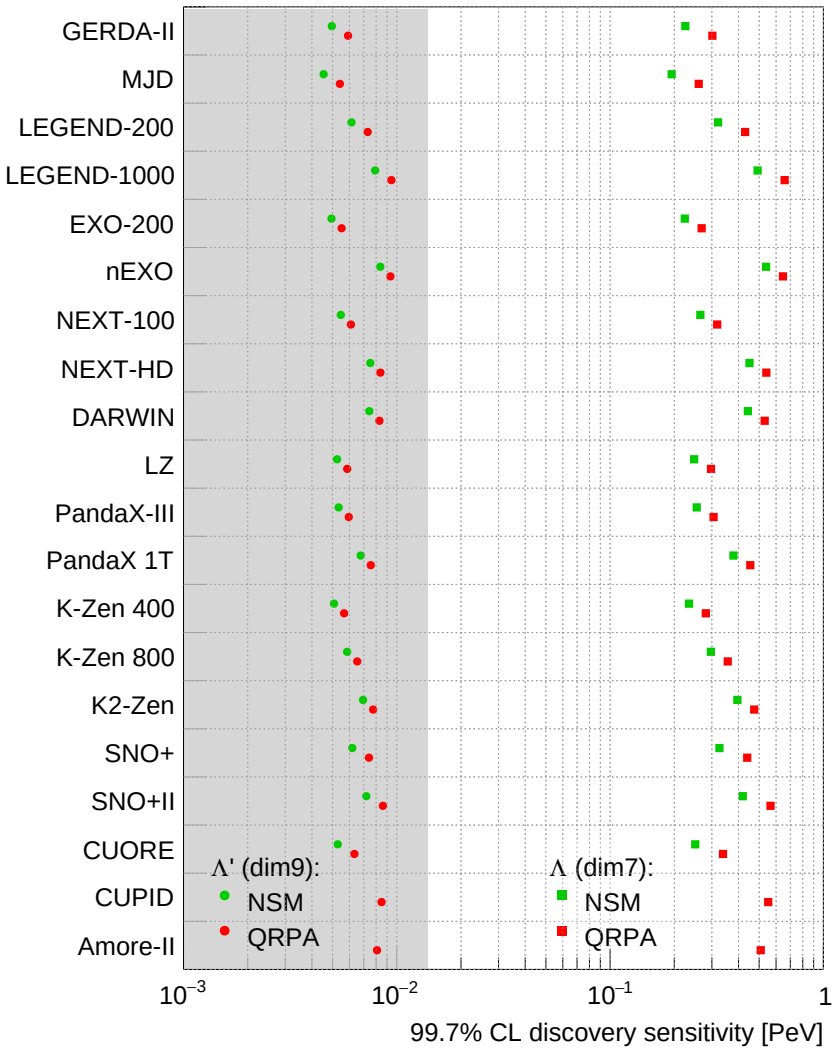
Standard Model extensions trigger $0\nu\beta\beta$ (heavy ν, M_R...)

Effective field theory master formula

Cirigliano et al JHEP 12 097 (2018)

$$T_{1/2}^{-1} = G_{01}\left(g_A^2\, M^{0\nu} + g_\nu^{\mathrm{NN}}\, m_\pi^2\, M_{\mathrm{cont}}^{0\nu}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2} + \frac{m_N^2}{m_e^2}\tilde{G}\,\tilde{g}^4\,\tilde{M}^2\left(\frac{v}{\Lambda}\right)^6 + \frac{m_N^4}{m_e^2\, v^2}\tilde{G}'\,\tilde{g}'^4\,\tilde{M}'^2\left(\frac{v}{\Lambda'}\right)^{10} + \cdots,$$

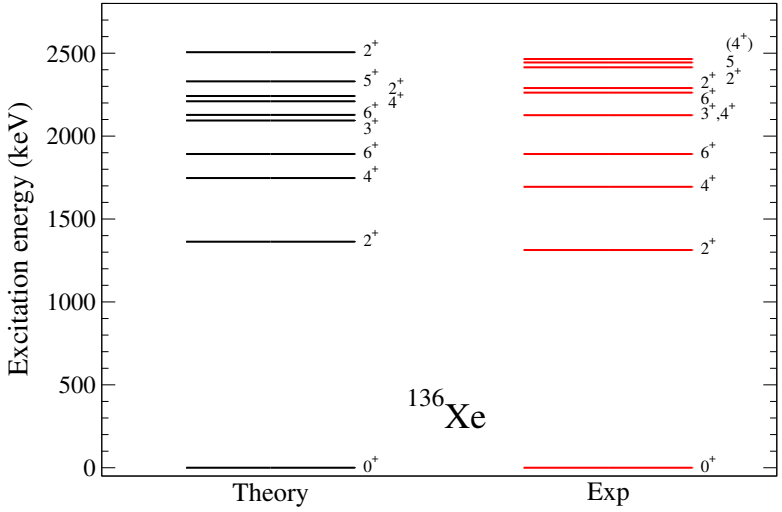
Current constraints on dim-7 ($\sim 1/\Lambda^3$), dim-9 ($\sim 1/\Lambda^5$) operators: $\Lambda \gtrsim 250$ / 5 TeV

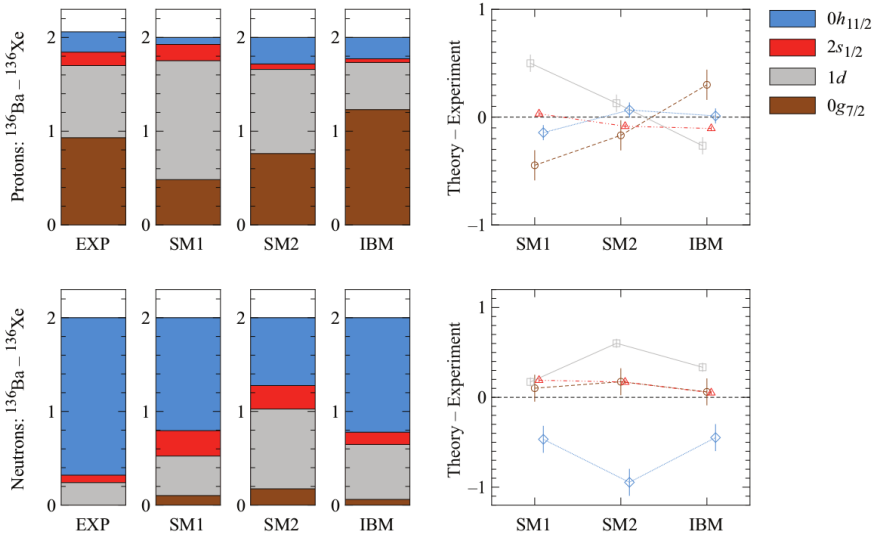


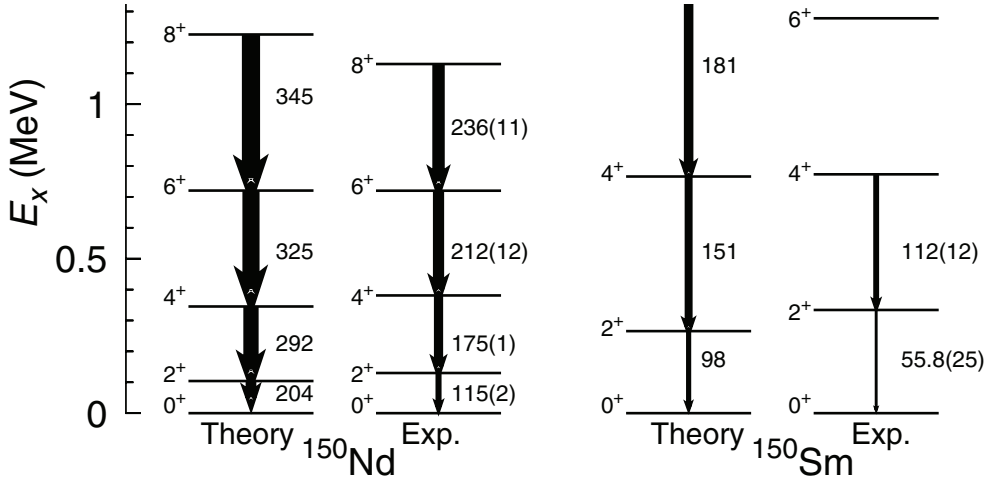
Agostini, Benato, Detwiler, JM, Vissani, in prep.

Tests of nuclear structure

Spectroscopy well described: masses, spectra, transitions, knockout...







Schiffer et al. PRL100 112501(2009)

Kay et al. PRC79 021301(2009)

...

Szwec et al., PRC94 054314 (2016)

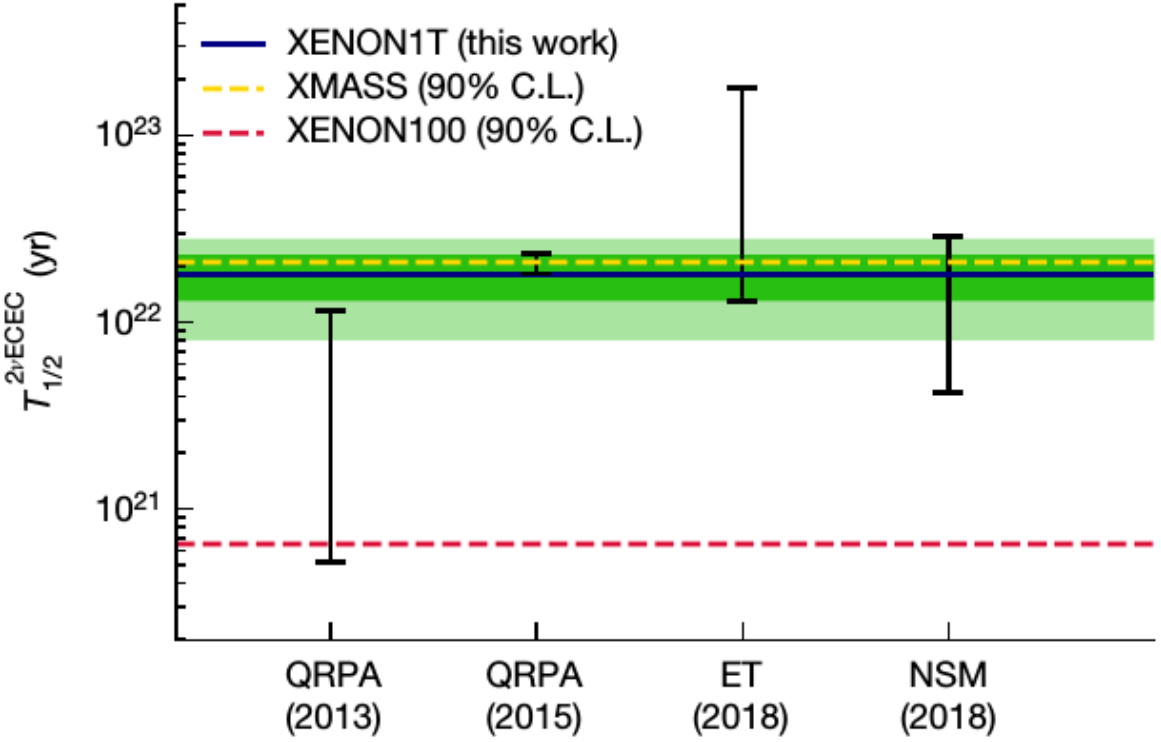
Rodríguez et al. PRL105 252503 (2010)

...

Vietze et al. PRD91 043520 (2015)

Two-neutrino ECEC of ^{124}Xe

Predicted 2νECEC half-life:
shell model error bar largely dominated by “quenching” uncertainty



Suhonen
JPG 40 075102 (2013)

Pirinen, Suhonen
PRC 91, 054309 (2015)

Coello Pérez, JM, Schwenk

PLB 797 134885 (2019)

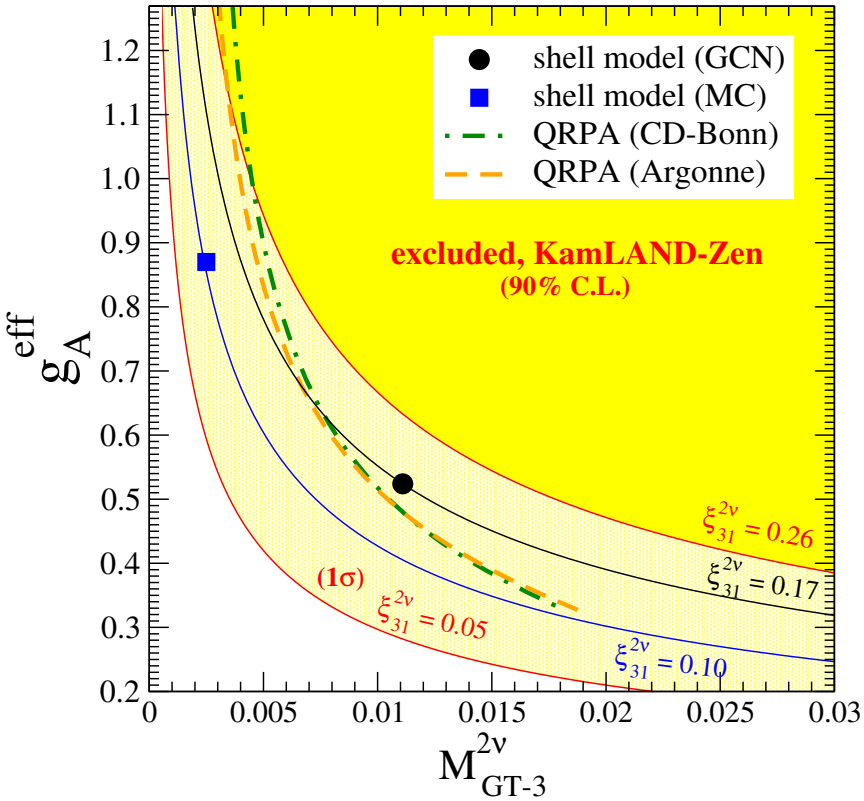
XENON1T

Nature 568 532 (2019)

Shell model, QRPA and Effective theory (ET) predictions
good agreement with XENON1T measurement of 2νECEC!

Tests of $2\nu\beta\beta$ electron spectrum

Shape of $\beta\beta$ spectrum constrains matrix element ratio $\xi_{31}^{2\nu} = M_{GT-3}^{2\nu}/M_{GT}^{2\nu}$



Theory deficiencies in $M_{GT}^{2\nu}$ fixed adjusting g_A ("queching")

$\xi_{31}^{2\nu}$ measurement test theoretical models KamLAND-Zen coll. in ^{136}Xe

Shell model, most QRPA $\xi_{31}^{2\nu}$ predictions consistent with 90% confidence limit

KamLAND-Zen et al. PRL122 192501 (2019)

Similar study in ^{82}Se by CUPID-0: $2\nu\beta\beta$ single-state dominance only lowest-lying intermediate ^{82}Br 1^+ state, not predicted by theory!

CUPID-0, PRL123 262501 (2019)

Double Gamow-Teller strength distribution

Measurement of Double Gamow-Teller (DGT) resonance
in double charge-exchange reactions ^{48}Ca(pp,nn)^{48}Ti proposed in 80's

Auerbach, Muto, Vogel... 1980's, 90's

Recent experimental plans in RCNP, RIKEN (^{48}Ca), INFN Catania

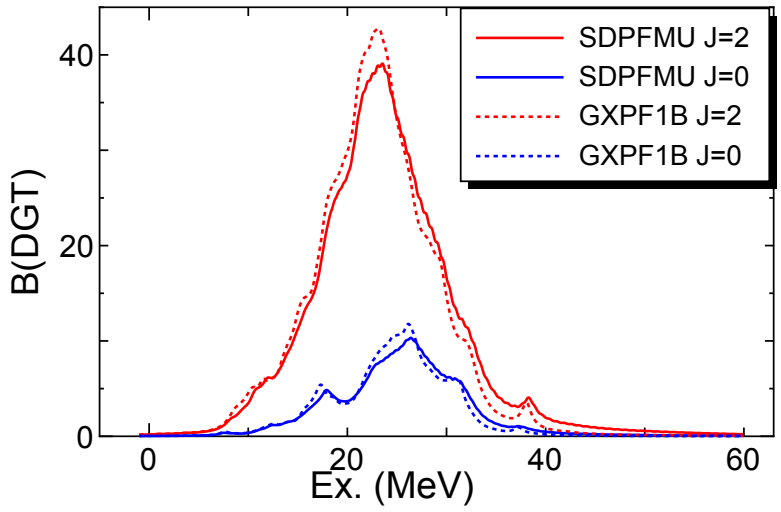
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

Capuzzello et al. EPJA 51 145 (2015), Takahisa, Ejiri et al. arXiv:1703.08264

Promising connection to $\beta\beta$ decay,
two-particle-exchange process,
especially the (tiny) transition
to ground state of final state

Shell model calculation

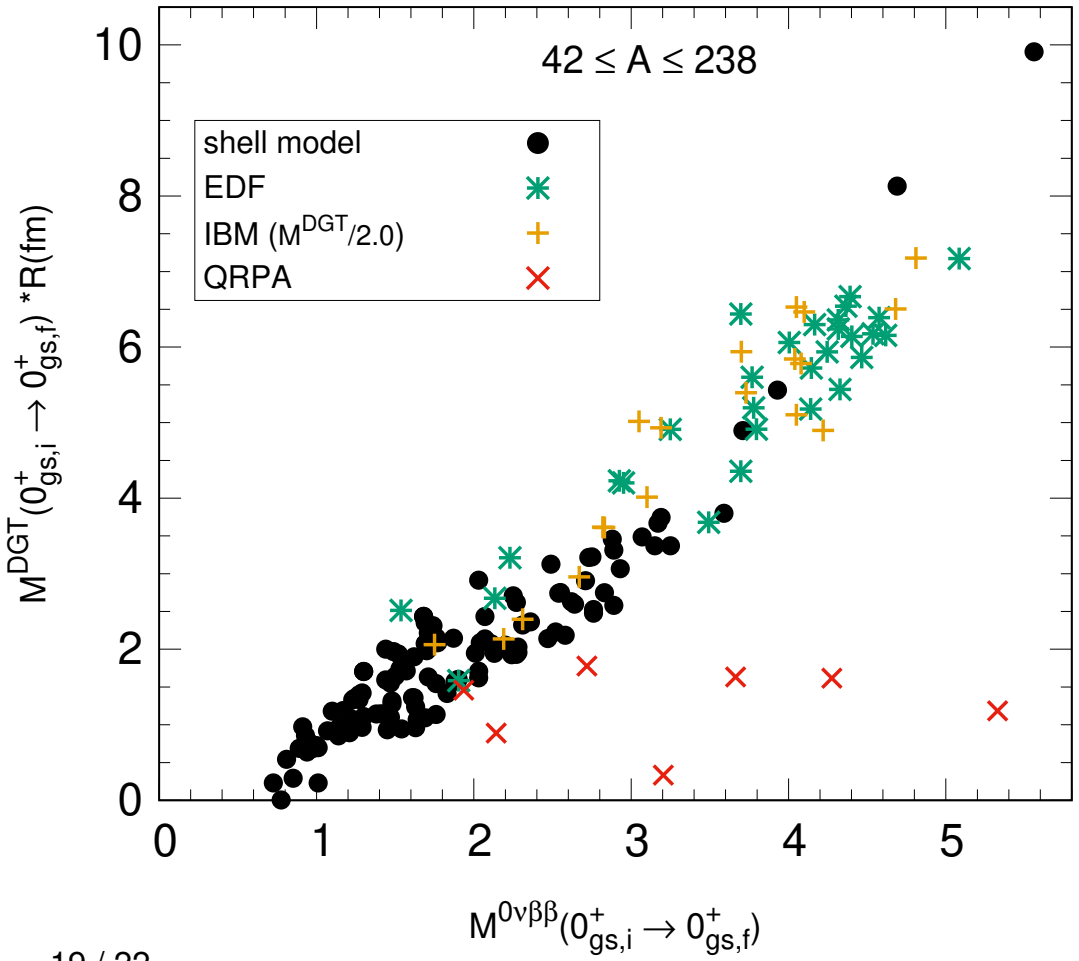
Shimizu, JM, Yako, PRL120 142502 (2018)



$$B(DGT^-;\lambda;i\to f)=\frac{1}{2J_i+1}\left|\left\langle {}^{48}\mathrm{Ti}\left\|\left[\sum_i \boldsymbol{\sigma}_i\tau_i^- \times \sum_j \boldsymbol{\sigma}_j\tau_j^-\right]^{(\lambda)}\right\|{}^{48}\mathrm{Ca}_{gs}\right\rangle\right|^2$$

Correlation of $0\nu\beta\beta$ decay to DGT transitions

Double GT transition to ground state $M^{\mathrm{DGT}} = \langle \mathrm{F_{gs}} || [\sum_i \boldsymbol{\sigma}_i \tau_i^- \times \sum_j \boldsymbol{\sigma}_j \tau_j^-]^0 || \mathrm{I_{gs}} \rangle |^2$
very good linear correlation with $0\nu\beta\beta$ decay nuclear matrix elements



Double Gamow-Teller correlation with $0\nu\beta\beta$ decay holds across nuclear chart

Shimizu, JM, Yako

PRL120 142502 (2018)

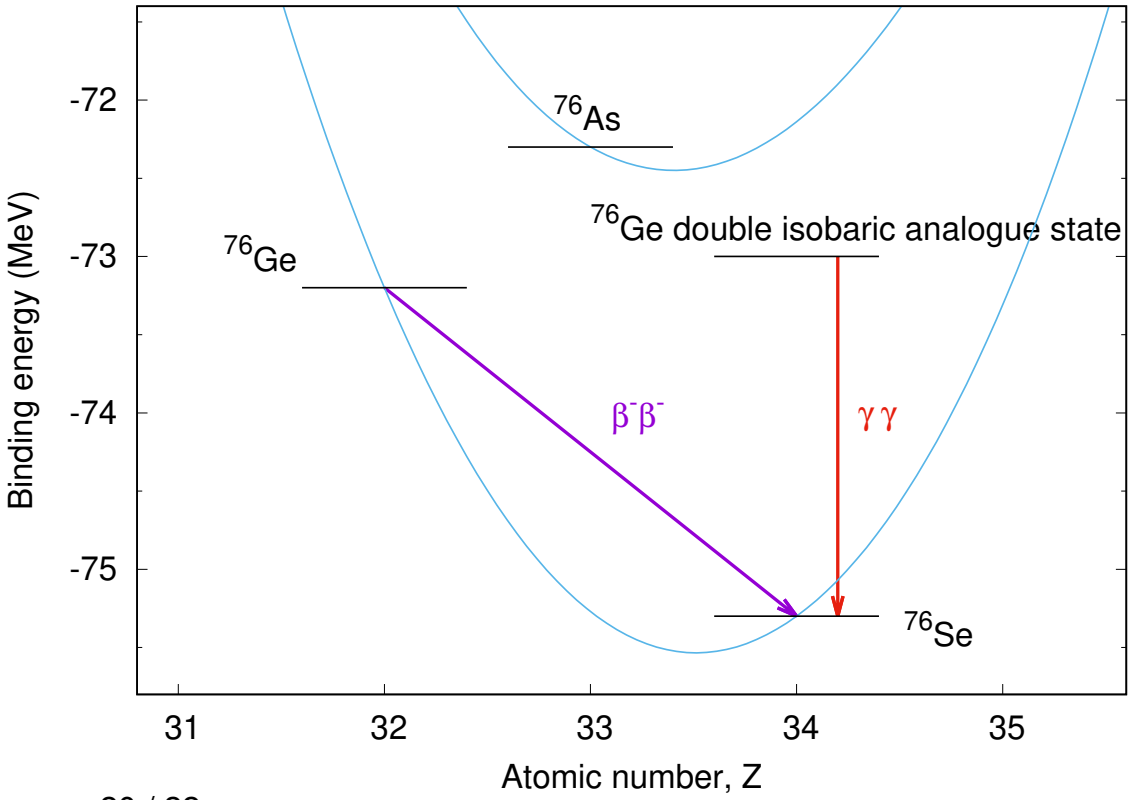
Common to shell model energy-density functionals interacting boson model, disagreement to QRPA

Experiments at RIKEN, INFN Catania may access DGT transitions

Similar $0\nu\beta\beta$ and $\gamma\gamma$ decays?

Explore correlation between $0\nu\beta\beta$ and $\gamma\gamma$ decays,
focused on double-M1 transitions

$$M^{\gamma\gamma}_{M1\,M1} = \sum_k \frac{\langle 0^+_f | \sum_n (g^l_n \boldsymbol{l}_n + g^s_n \boldsymbol{\sigma}_n)^{IV} | 1^+_k(\mathrm{IAS}) \rangle \langle 1^+_k(\mathrm{IAS}) | \sum_m (g^l_m \boldsymbol{l}_m + g^s_m \boldsymbol{\sigma}_m)^{IV} | 0^+_i(\mathrm{DIAS}) \rangle}{E_k - (M_i + M_f)/2}$$



Similar initial and final states but both in same nucleus for electromagnetic transition

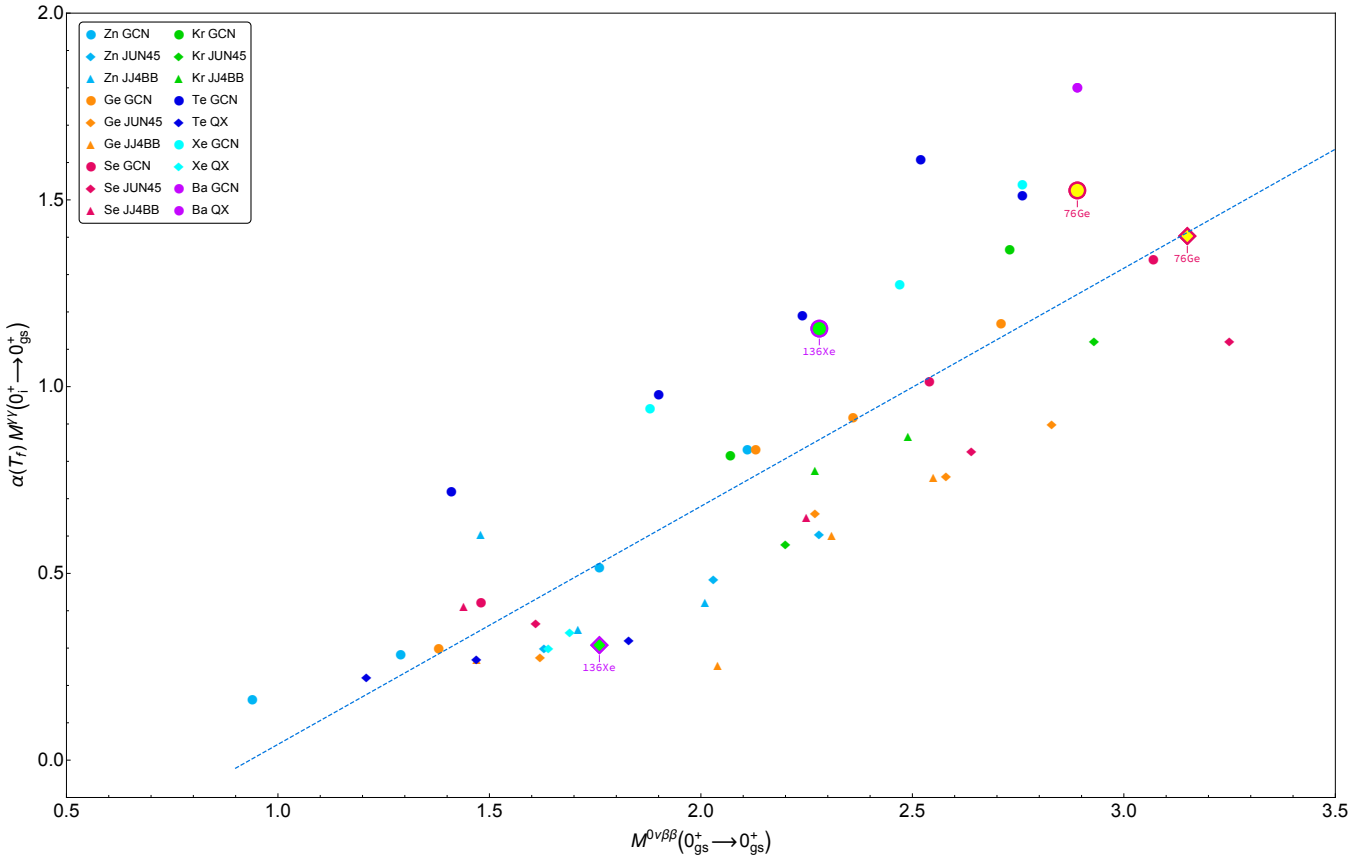
M1 and GT operators similar, physics of spin operator
M1 also angular momentum

Different energy denominator

Romeo, JM, Peña-Garay, in progress

Correlation of $0\nu\beta\beta$ decay to $\gamma\gamma$ transitions

Good linear correlation between $\gamma\gamma$ M1M1 and $0\nu\beta\beta$ decays obtained with nuclear shell model, holds for nuclei with $A \sim 60 - 140$



Includes $\beta\beta$ nuclei: ^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe

Romeo, JM, Peña-Garay, in progress

Measurements of $\gamma\gamma$ M1M1 decays could inform $0\nu\beta\beta$ NMEs!

Summary

Nuclear matrix elements key
for the design of next-generation tonne-scale $0\nu\beta\beta$ decay experiments

- Present nuclear matrix element calculations still disagree by factor $2-3$
- Ab initio calculations
  solve much of β decay "quenching" problem,
  ab initio ^{48}Ca NME quite small
  extension to heavier $\beta\beta$ nuclei soon
- Tests to $2\nu\beta\beta$ lifetimes, electron spectra
  promising correlations of $0\nu\beta\beta$
  with double-GT and $\gamma\gamma$ transitions
- Similar uncertainties in NMEs
  for BSM exchange of heavy particles