# Nuclear matrix elements for fundamental symmetries based on effective field theories

**Javier Menéndez**

**University of Barcelona**
**Institute of Cosmos Sciences**

Workshop XLIX on Gross Properties of Nuclei and Nuclear Excitations
Effective field theories for nuclei and nuclear matter

Hirschegg, 18th January 2023

UNIVERSITAT DE BARCELONA
MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA
Fondo Social Europeo
El FSE invierte en tu futuro
AGENCIA ESTATAL DE INVESTIGACIÓN
ICCUB

# Collaborators

| | |
|---|---|
| Universitat de Barcelona | J. P. Linares, **P. Soriano** |
| TRIUMF | **L. Jokiniemi** |
| LSC Laboratorio Subterráneo Canfranc | C. Peña-Garay, **B. Romeo** |
| | N. Shimizu |
| Los Alamos National Laboratory EST. 1943 | **R. Weiss** |
| Argonne National Laboratory | A. Lovato, B. Wiringa |
| Technische Universität Darmstadt | **C. Brase**, A. Schwenk |
| $u^b$ | M. Hoferichter, F. Noel |

# Nuclear matrix elements for new-physics searches

Neutrinos, dark matter studied in experiments using nuclei

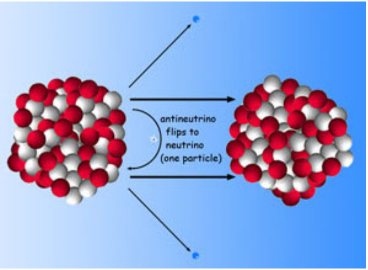
Nuclear structure physics
encoded in nuclear matrix elements
key to plan, fully exploit experiments

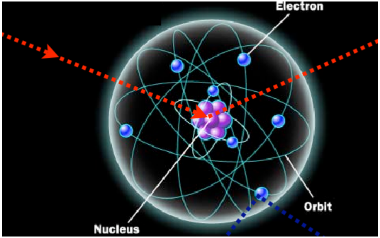
$$0\nu\beta\beta: \left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} \propto g_A^4 \left|M^{0\nu\beta\beta}\right|^2 m_{\beta\beta}^2$$

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

$$\text{CE}\nu\text{NS: } \frac{d\sigma_{\nu\mathcal{N}}}{d\boldsymbol{q}^2} \propto \left|\sum_i c_i\, \zeta_i\, \mathcal{F}_i\right|^2$$

$M^{0\nu\beta\beta}$: Nuclear matrix element
$\mathcal{F}_i$ : Nuclear structure factor



# Creation of matter in nuclei: $0\nu\beta\beta$ decay

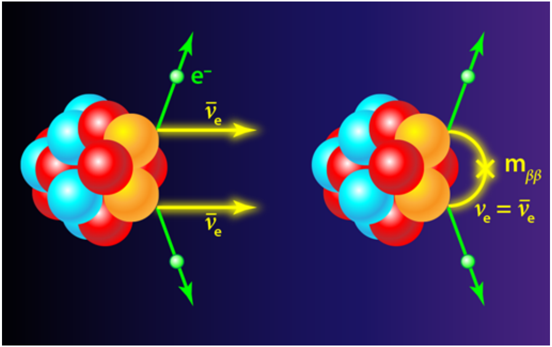
Lepton number is conserved
in all processes observed:

single $\beta$ decay,
$\beta\beta$ decay with neutrino emission...

Uncharged massive particles
like Majorana neutrinos ($\nu$)
allow lepton number violation:

neutrinoless $\beta\beta$ decay
two matter particles (electrons) created

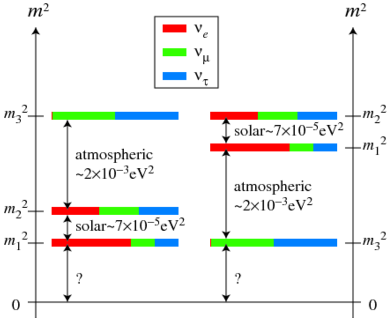
Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. in press, arXiv:2202.01787

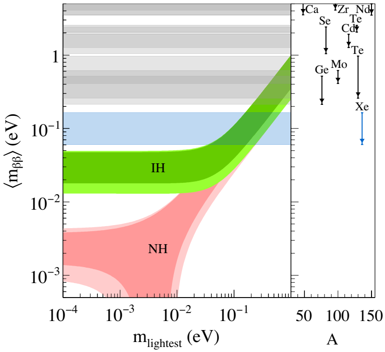



# Next generation experiments: inverted hierarchy

Decay rate sensitive to neutrino masses, hierarchy
$m_{\beta\beta} = \left|\sum U_{ek}^2 m_k\right|$

$$T_{1/2}^{0\nu\beta\beta}\left(0^+ \rightarrow 0^+\right)^{-1} = G_{0\nu}\, g_A^4 \left|M^{0\nu\beta\beta}\right|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

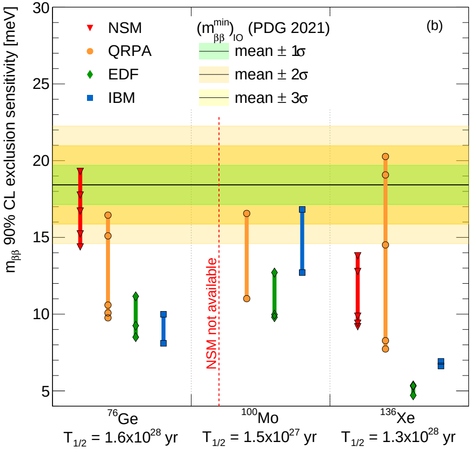



Matrix elements assess if next generation experiments fully explore "inverted hierarchy"

KamLAND-Zen, PRL117 082503(2016)

# Uncertainty in physics reach of $0\nu\beta\beta$ experiments




Agostini, Benato, Detwiler, JM, Vissani
Phys. Rev. C 104 L042501 (2021)

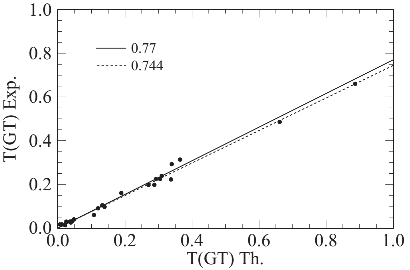
Nuclear matrix element theoretical uncertainty critical to anticipate $m_{\beta\beta}$ sensitivity of future experiments

Current uncertainty in $m_{\beta\beta}$ prevents to foresee if next-generation experiments will fully cover parameter space of “inverted” neutrino mass hierarchy

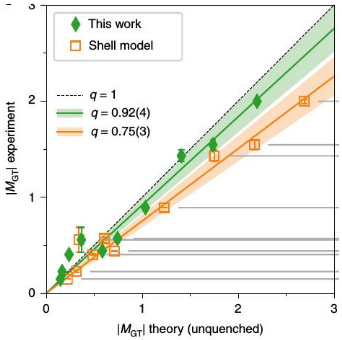
Uncertainty needs to be reduced!

# $\beta$–decay Gamow-Teller transitions: "quenching"

## $\beta$ decays ($e^-$ capture): phenomenology vs ab initio




Martinez-Pinedo et al. PRC53 2602(1996)




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

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

Standard shell model needs $\boldsymbol{\sigma}_i \tau$ "quenching"

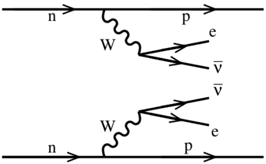
Ab initio calculations including meson-exchange currents and additional nuclear correlations do not need any "quenching"

# Two-neutrino $\beta\beta$ decay, $2\nu$ECEC

$2\nu\beta\beta$ decay same initial, final states , similar operator $(\sigma\tau)$ as $0\nu\beta\beta$
Comparison of predicted $2\nu\beta\beta$ decay vs data

Shell model reproduce $2\nu\beta\beta$ data including "quenching"

Prediction previous to $^{48}$Ca measurement!
Caurier, Poves, Zuker
PLB 252 13(1990)



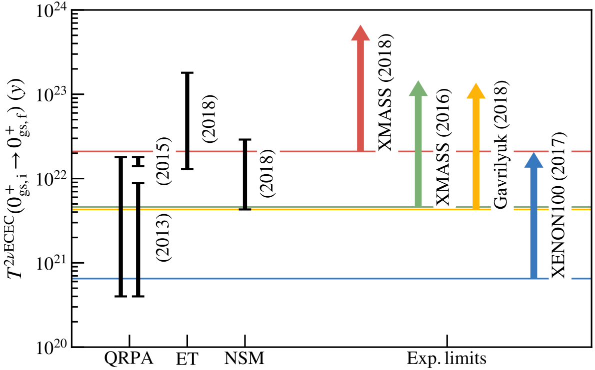

$$M^{2\nu\beta\beta} = \sum_k \frac{\langle 0_f^+ | \sum_n \sigma_n \tau_n^- \; |1_k^+\rangle \langle 1_k^+ | \sum_m \sigma_m \tau_m^- \; |0_i^+\rangle}{E_k - (M_i + M_f)/2}$$

**Table 2**
The ISM predictions for the matrix element of several $2\nu$ double beta decays (in MeV$^{-1}$). See text for the definitions of the valence spaces and interactions.

| | $M^{2\nu}$(exp) | $q$ | $M^{2\nu}$(th) | INT |
|---|---|---|---|---|
| $^{48}Ca \to {}^{48}Ti$ | $0.047 \pm 0.003$ | 0.74 | 0.047 | kb3 |
| $^{48}Ca \to {}^{48}Ti$ | $0.047 \pm 0.003$ | 0.74 | 0.048 | kb3g |
| $^{48}Ca \to {}^{48}Ti$ | $0.047 \pm 0.003$ | 0.74 | 0.065 | gxpf1 |
| $^{76}Ge \to {}^{76}Se$ | $0.140 \pm 0.005$ | 0.60 | 0.116 | gcn28:50 |
| $^{76}Ge \to {}^{76}Se$ | $0.140 \pm 0.005$ | 0.60 | 0.120 | jun45 |
| $^{82}Se \to {}^{82}Kr$ | $0.098 \pm 0.004$ | 0.60 | 0.126 | gcn28:50 |
| $^{82}Se \to {}^{82}Kr$ | $0.098 \pm 0.004$ | 0.60 | 0.124 | jun45 |
| $^{128}Te \to {}^{128}Xe$ | $0.049 \pm 0.006$ | 0.57 | 0.059 | gcn50:82 |
| $^{130}Te \to {}^{130}Xe$ | $0.034 \pm 0.003$ | 0.57 | 0.043 | gcn50:82 |
| $^{136}Xe \to {}^{136}Ba$ | $0.019 \pm 0.002$ | 0.45 | 0.025 | gcn50:82 |

Caurier, Nowacki, Poves, PLB 711 62 (2012)

Predicted $2\nu$ECEC half-life:
shell model error bar largely dominated by “quenching” uncertainty




Suhonen
JPG 40 075102 (2013)

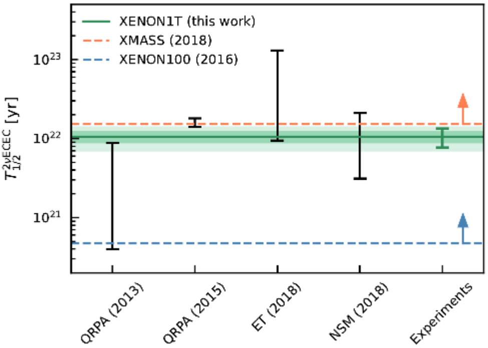
Pirinen, Suhonen
PRC 91, 054309 (2015)

Coello Pérez, JM, Schwenk
PLB 797 134885 (2019)

Shell model, QRPA and Effective theory (ET) predictions
suggest experimental detection close to XMASS 2018 limit

# Two-neutrino ECEC of $^{124}$Xe

Predicted $2\nu$ECEC 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)

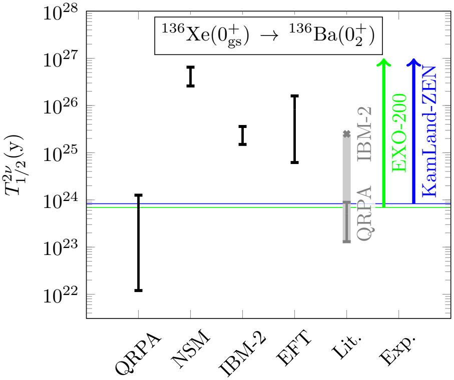
XENON1T
Nature 568 532 (2019)
PRC106, 024328 (2022)

Shell model, QRPA and Effective theory (ET) predictions
good agreement with XENON1T measurement of $2\nu$ECEC!

# $2\nu\beta\beta$ decay of $^{136}$Xe to $^{136}$Ba $0_2^+$

Current experiments sensitive to two-neutrino $\beta\beta$ of $^{136}$Xe to $^{136}$Ba $0_2^+$

EXO-200, KamLAND-Zen




Nuclear shell model
QRPA, EFT and IBM
very different predictions!

Barea et al.
PRC 91 034304 (2015)

Pirinen, Suhonen
PRC 91, 054309 (2015)

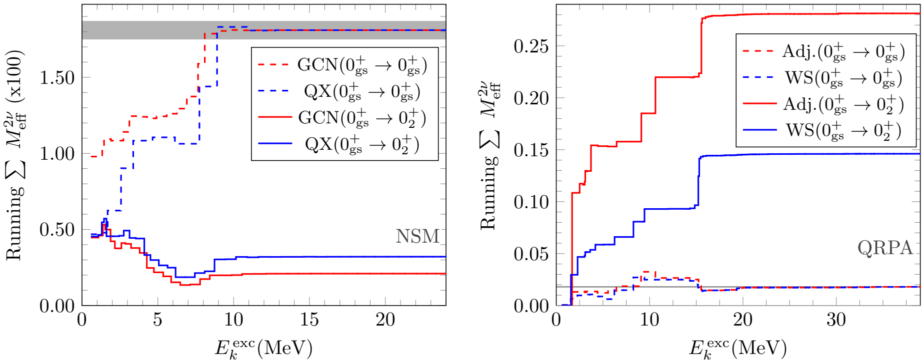
Jokiniemi, Romeo, Brase, Kotila et al.
PLB in press, arXiv:2211.03764

Very good test of theoretical calculations!

**See Catharina Brase's talk for EFT for $2\nu\beta\beta$**

# $^{136}Xe \longrightarrow {}^{136}Ba\ 0_2^+$ running sums

Subtle cancellation NME running sum, depends on many-body method



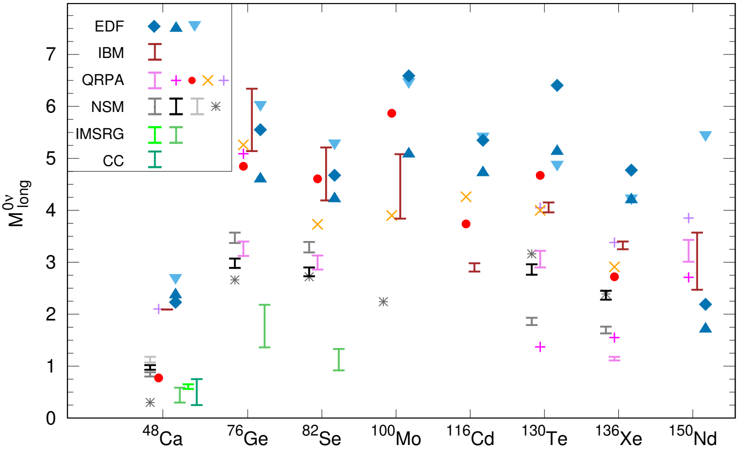

Shell-model running sum shows cancellations in decay to ground state

QRPA running sum shows cancellations in decay to excited state

Since ground-state decay fitted to data, very different decay to excited state

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

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




Agostini, Benato, Detwiler, JM, Vissani, Rev. Mod. Phys. in press, arXiv:2202.01787

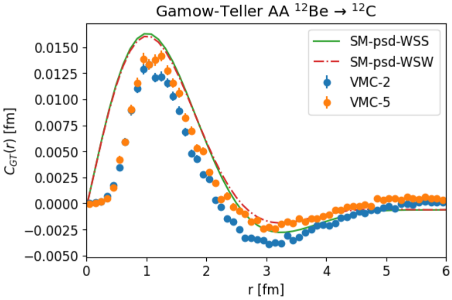
# Shell model vs quantum Monte Carlo: correlations

Compare $\beta\beta$ transition densities in
nuclear shell model and quantum Monte Carlo calculations in light nuclei

$$4\pi r^2 \rho_{GT}(r) = \langle \Psi_f | \sum_{a<b} \delta(r - r_{ab}) \sigma_{ab} \, \tau_a^+ \tau_b^+ | \Psi_i \rangle \,,$$

$$M_{GT}^{0\nu} = \int_0^\infty dr \, C_{GT}^{0\nu} \,,$$

Agreement at long distances, missing short-range correlations in shell model




Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)

Similar findings in Wang et al. PLB 798 134974 (2019)

# Generalized contact formalism (GCF)

Generalized contact formalism Weiss, Bazak, Barnea PRL 114 012501 (2015)

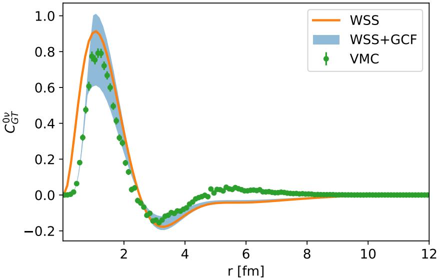
Separation of scales: wf, transition density factorize for two nearby nucleons

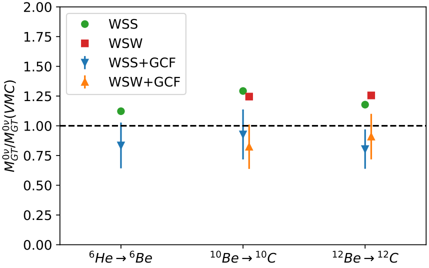
$$\Psi \xrightarrow[r_{ij}\to 0]{} \sum_{\alpha} \varphi^{\alpha}(\boldsymbol{r}_{ij}) A^{\alpha}(\boldsymbol{R}_{ij}, \{\boldsymbol{r}_k\}_{k\neq i,j}), \quad \rho_{GT}(r) \xrightarrow[r\to 0]{} -3|\varphi^0(r)|^2 C^0_{pp,nn}(f,i)$$

with $\varphi(r)$ the solution of the two-nucleon Schrödinger equation

The contact $C^0(f,i) = \frac{A(A-1)}{2}\langle A^{\alpha}(f)|A^{\beta}(i)\rangle$ is model dependent

Replace shell-model by QMC contact
to improve transition density and nuclear matrix element

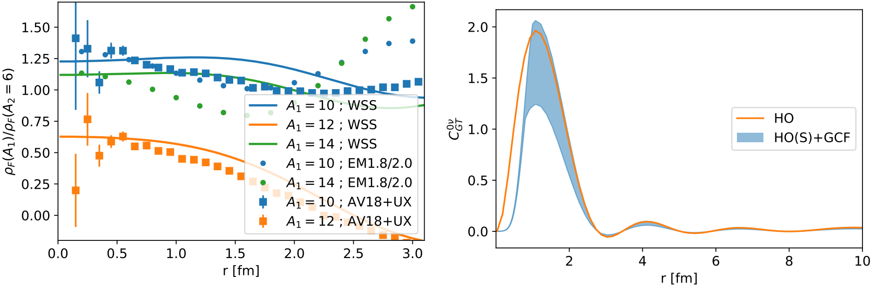


# GCF: model independence of ratios

Generalized contact formalism Weiss, Bazak, Barnea PRL 114 012501 (2015)

The contact $C^0(f,i) = \frac{A(A-1)}{2}\langle A^\alpha(f)|A^\beta(i)\rangle$ is model dependent
(shell model, quantum Monte Carlo, no-core shell model...)
but for two nuclei the ratio $C^0_{pp,nn}(X)/C^0_{pp,nn}(Y)$ relatively model independent:
combine QMC calculation in light nuclei with two shell model calculations:

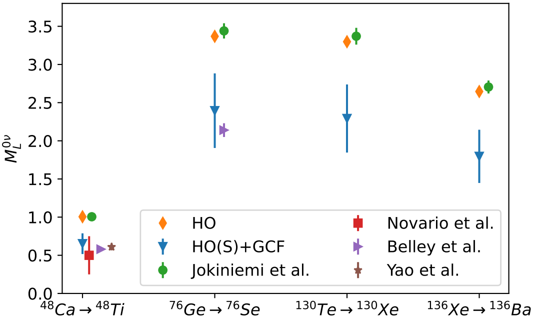



Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)

# Shell model + Generalized contact formalism: NMEs

GCF builds QMC short-range correlations to shell model transitions densities can be extended to heavy nuclei where shell model calculations are possible

Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)




Short-range correlations included by GCF reduce $0\nu\beta\beta$ NMEs moderately

$\sim$ 30% reduction in general consistent with ab initio NMEs in $^{48}$Ca, $^{76}$Ge

Good agreement in benchmark NMEs in light nuclei with ab initio calculations

# Light-neutrino exchange: contact operator

Contact operator suggested to contribute to light-neutrino exchange
to absorb cutoff dependence of two-nucleon decay amplitude

Contribution of high-energy neutrinos

$$T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M_{\text{long}}^{0\nu} + M_{\text{short}}^{0\nu}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2},$$

Cirigliano et al. PRL120 202001(2018)

$$M_{\text{short}}^{0\nu} \equiv \frac{1.2 A^{1/3}\,\text{fm}}{g_A^2} \langle 0_f^+ | \sum_{n.m} \tau_m^- \tau_n^- \,\mathbb{1} \left[\frac{2}{\pi} \int j_0(qr)\, 2 g_\nu^{\text{NN}}\, g(p/\Lambda)\, p^2 dp\right] |0_i^+\rangle,$$

$$M_{\text{GT}}^{0\nu} \simeq \frac{1.2 A^{1/3}\,\text{fm}}{g_A^2} \langle 0_f^+ | \sum_{n.m} \tau_m^- \tau_n^- \,\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \left[\frac{2}{\pi} \int j_0(qr)\, \frac{1}{p^2}\, g_A^2\, f^2(p/\Lambda_A)\, p^2 dp\right] |0_i^+\rangle$$

Unknown value (and sign) of the hadronic coupling $g_\nu^{\text{NN}}$!

Lattice QCD calculations can obtain value of $g_\nu^{\text{NN}}$
Davoudi, Kadam, Phys. Rev. Lett. 126, 152003 (2021), PRD105 094502('22)
or match $nn \to pp + ee$ amplitude calculated with approximate QCD methods
Cirigliano et al. PRL126 172002 (2021), JHEP 05 289 (2021)

# Short-range NME: relative impact

Modified decay rate: $T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M_{\rm long}^{0\nu} + M_{\rm short}^{0\nu}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$

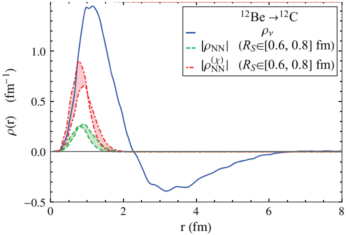
Assume $g_\nu^{\rm NN} \sim 1{\rm fm}^2$

Cirigliano et al.
PRC100 055504 (2019)

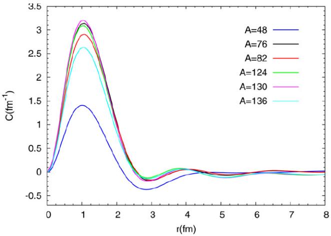
TABLE II. Values of $\mathcal{C}_1 + \mathcal{C}_2$ obtained from the CIB contact interactions in various chiral potentials.

| Model | Ref. | $R_S$ (fm) | $C_0^{\rm IT}$ (fm$^2$) | $(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm$^2$) | Model | Ref. | $\Lambda$ (MeV) | $(\mathcal{C}_1+\mathcal{C}_2)/2$ (fm$^2$) |
|---|---|---|---|---|---|---|---|---|
| NV-Ia* | [38] | 0.8 | 0.0158 | −1.03 | Entem-Machleidt | [34] | 500 | −0.47 |
| NV-IIa* | [38] | 0.8 | 0.0219 | −1.44 | Entem-Machleidt | [34] | 600 | −0.14 |
| NV-Ic | [38] | 0.6 | 0.0219 | −1.44 | Reinert *et al.* | [39] | 450 | −0.67 |
| NV-IIc | [38] | 0.6 | 0.0139 | −0.91 | Reinert *et al.* | [39] | 550 | −1.01 |
| | | | | | $\rm NNLO_{sat}$ | [37] | 450 | −0.39 |

$\sim$ 75% correction for QMC $^{12}$Be NME
In heavy nuclei, less severe cancellation of dominant $M^{0\nu}$?




Cirigliano et al. PRL120 202001(2018)



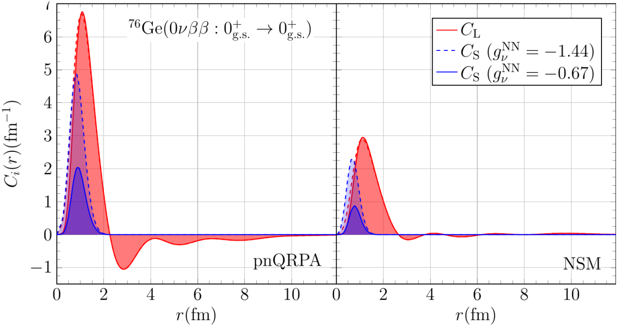

JM et al. NPA818 139 (2009)

# Long and short-range NME in heavy nuclei

Relatively stable contribution of new term $M_S/M_L$:

20% – 50% impact of short-range NME in shell model
30% – 70% impact of short-range NME in QRPA

consistent with 43% effect in IM-GCM for $^{48}$Ca
using synthetic data on $nn \to pp + ee$ decay Wirth et al. PRL127 242502 (2021)




Jokiniemi, Soriano, JM, Phys. Lett. B 823 136720 (2021)

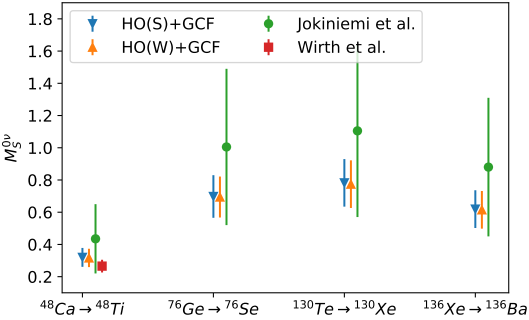
Uncertainty dominated by coupling $g_\nu^{NN}$

# Short-range NME: GCF + shell model

Shell model with short-range correlations from QMC using the GCF give consistent contribution of new term $M_S$

$\sim$ 25% impact of short-range NME in GCF + shell model obtained with $g_\nu^{\rm NN}$ from AV18 CIB term

consistent with 43% effect in IM-GCM for $^{48}$Ca using synthetic data on $nn \to pp + ee$ decay Wirth et al. PRL127 242502 (2021)




Weiss, Soriano, Lovato, JM, Wiringa, PRC106 065501 (2022)

# Double Gamow-Teller strengths and $\beta\beta$ decay

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

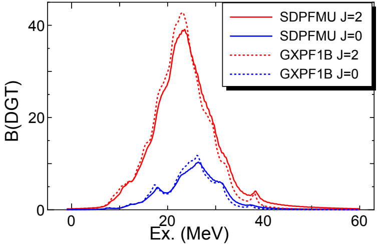
Takaki et al. JPS Conf. Proc. 6 020038 (2015)

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

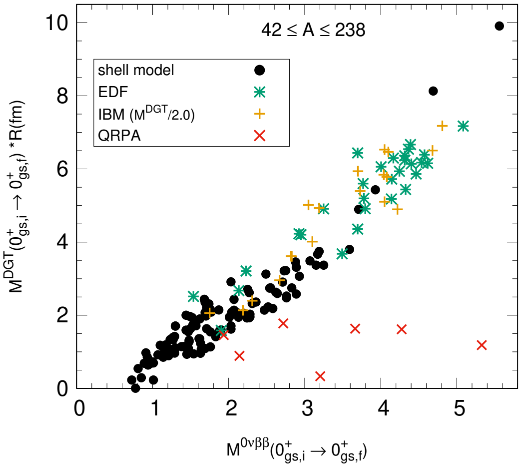
Shimizu, JM, Yako, PRL120 142502 (2018)




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

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

Double GT transition to ground state
good linear correlation with $0\nu\beta\beta$ decay NMEs




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

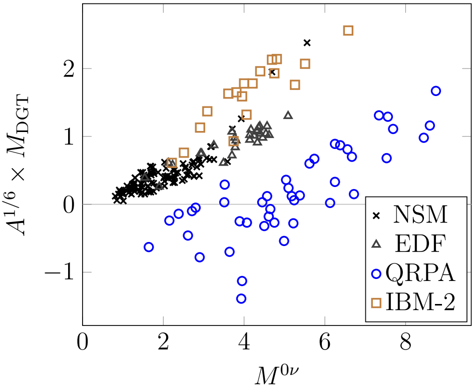
Also correlation in VS-IMSRG (but weaker)

Yao et al. PRC106 014315(2022)

Experiments at RIKEN, INFN, RCNP? access DGT transitions

# Correlation of $0\nu\beta\beta$ decay to DGT in QRPA

In QRPA, $g_{pp}$ parameter
typically fitted to reproduce $2\nu\beta\beta$ half-life of measured transitions
but actually some tension between $g_{pp}$ values to reproduce single-$\beta$ decays
Faessler et al., J. Phys. G 35, 075104 (2008)




Jokiniemi, JM, in preparation

Perform QRPA calculations with range of $g_{pp} = (0.6 - 0.9)$

Correlation between DGT and $0\nu\beta\beta$ NMEs! but different than for other many-body methods

Partially caused by relevance of $J > 1$ intermediate states in QRPA compared to eg shell model
Ejiri et al. Phys. Rept. 797 1 (2019)
Horoi et al, PRC 93, 044334 (2016)

# $\beta$ decays and $\gamma$ transitions from IAS

The relation between electromagnetic decays from IAS and weak ones has been used and tested many times

Ejiri, Suhonen, Zuber, Phys. Rept. 797 1 (2019)

Fujita, Rubio, Gelletly, Prog. Part. Nucl. Phys.66, 549 (2011)

And it is certainly not a novel idea...

ELECTRIC DIPOLE TRANSITION FROM THE $2f_{7/2}$ ISOBARIC ANALOG R
TO THE $2d_{5/2}$ GROUND STATE IN $^{141}$Pr †

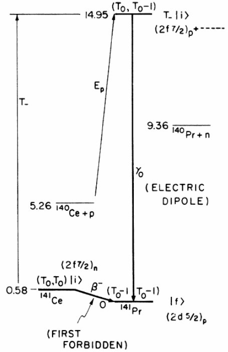
H. Ejiri,* P. Richard, S. Ferguson, R. Heffner, and D. Perry
Department of Physics, University of Washington, Seattle, Washingtor

(Received 19 April 1968)

Electric dipole $\gamma$ rays from the $2f_{7/2}$ isobaric analog state $(2T_0)^{-1/2}T_-|i\rangle$ to t ground state $|f\rangle$ in $^{141}$Pr were measured with a Ge(Li) crystal. The matrix ele the $E1$ $\gamma$ transition, $|\langle f|m_\gamma T_-(2T_0)^{-1/2}|i\rangle|$, and that of the analogous first for transition, $|\langle f|m_\beta|i\rangle|$, were obtained.

PRL 21 373 (1968)

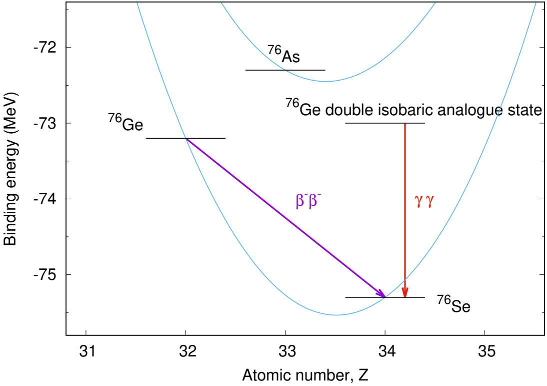
VOLUME 21, NUMBER 6 PHYSICAL RE



# $\gamma\gamma$ decay of the DIAS of the initial $\beta\beta$ nucleus

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

$$M^{\gamma\gamma}_{M1\,M1} = \sum_k \frac{\langle 0_f^+ | \sum_n (g_n^l \boldsymbol{l}_n + g_n^s \boldsymbol{\sigma}_n)^{IV} | 1_k^+(\mathrm{IAS})\rangle \langle 1_k^+(\mathrm{IAS}) | \sum_m (g_m^l \boldsymbol{l}_m + g_m^s \boldsymbol{\sigma}_m)^{IV} | 0_i^+(\mathrm{DIAS})\rangle}{E_k - (E_i + E_f)/2}$$



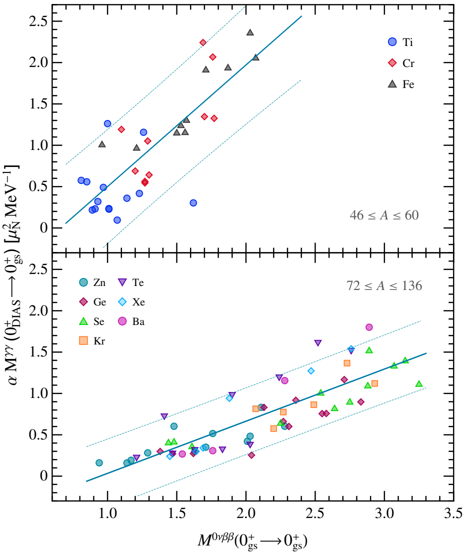

Similar initial and final states
but both in same nucleus
for electromagnetic transition

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

Different energy denominator

Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

# Correlation between $M1M1$ and $0\nu\beta\beta$ NMEs




Good correlation between $M1M1$ same-energy photons and shell-model $0\nu\beta\beta$ NMEs
A dependence: energy denom.

$\gamma\gamma$ decays observed recently in competition with $\gamma$ decays

Waltz et al. Nature 526, 406 (2015)

Soderstrom et al. Nat.Comm.11 3242('20)

Particle emission, $M1$, $E1$: $10^{-7} - 10^{-8}$ BR

Experimental proposal for $^{48}$Ti by Valiente-Dobón et al.

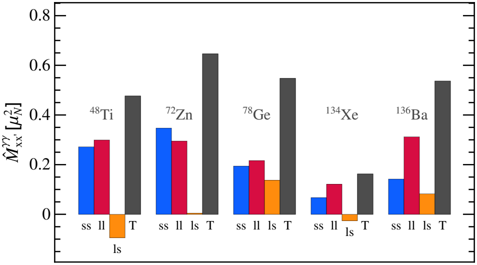
Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

# Spin, angular momentum decomposition

The numerator NME can be decomposed into

$$\hat{M}_{ss} + \hat{M}_{ll} + \hat{M}_{ls}$$

spin, angular momentum and interference components




Spin, angular momentum terms
strikingly similar,
always carry same sign

Interference term
can cancel the other two
but always much smaller

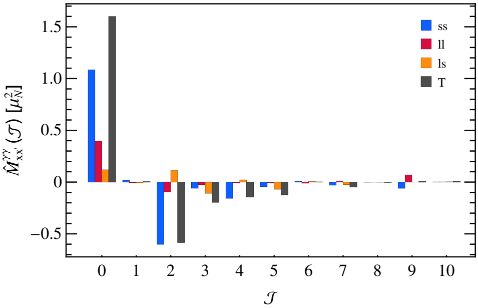
Romeo, JM, Peña-Garay
PLB 827 136965 (2022)

# Total angular momentum decomposition

The numerator NME can be decomposed into

$$\hat{M}_{ss}(\mathcal{J}) + \hat{M}_{ll}(\mathcal{J}) + \hat{M}_{ls}(\mathcal{J})$$

spin, angular momentum and interference components
and total angular momentum of the nucleons involved in the transition




Dominance of $\mathcal{J} = 0$ terms
for spin and orbital contributions
just like in $0\nu\beta\beta$ decay

Cancellation from $\mathcal{J} > 0$ terms
less pronounced in orbital part

Explains similar behaviour of spin
and orbital components:

$$s_1\, s_2 = \mathcal{S}^2 - 3/2 < 0$$

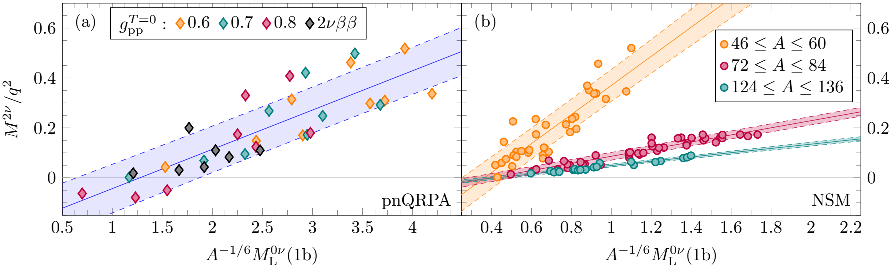
$$l_1\, l_2 = \mathcal{L}^2 - l_1^2 - l_2^2 < 0$$

Romeo et al. PLB 827 136965 (2022)

# Correlation of $0\nu\beta\beta$ decay and $2\nu\beta\beta$ decay

Good correlation between $2\nu$ and $0\nu$ modes of $\beta\beta$ decay
in nuclear shell model (systematic calculations of different nuclei)
and QRPA calculations (decays of $\beta\beta$ emitters with different $g_{pp}$ values)

Similar but not common correlation, depends on mass for shell model
$0\nu\beta\beta - 2\nu\beta\beta$ correlation also observed in $^{48}$Ca Horoi et al. arXiv:2203.10577




Jokiniemi, Romeo, Soriano, JM, arXiv:2207.05108

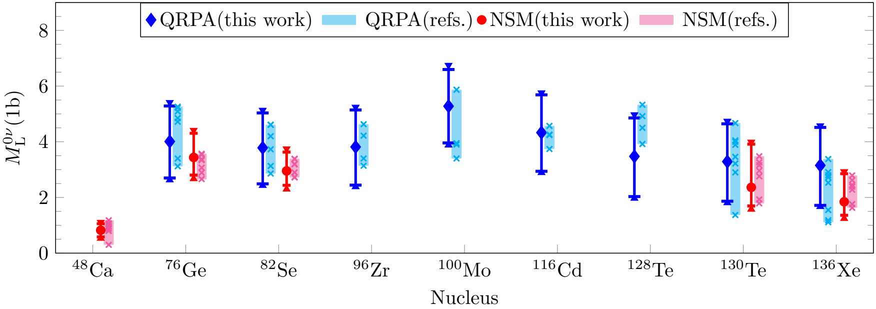
Use $2\nu\beta\beta$ data to predict $0\nu\beta\beta$ NMEs!

# $0\nu\beta\beta$ NMEs from $2\nu\beta\beta - 0\nu\beta\beta$ correlation

NMEs consistent with previous nuclear shell model, QRPA results

Theoretical uncertainty involves
systematic calculations covering dozens of nuclei and interactions
error of each calculation (eg quenching) and experimental $2\nu\beta\beta$ error

Previous theoretical uncertainty mostly ignored: collection of calculations




Jokiniemi, Romeo, Soriano, JM, arXiv:2207.05108

# 2b currents in $0\nu\beta\beta$ 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 normal ordering with respect to a Fermi gas

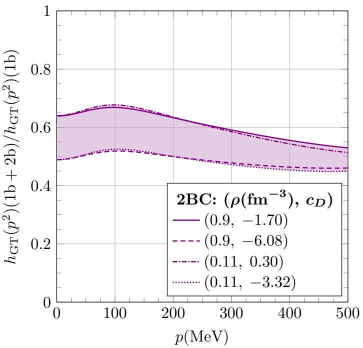
JM, Gazit, Schwenk, PRL107 062501(2011)

Normal-odering approximation works remarkably well for $\beta$ decay ($q = 0$)

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

Some reduction of quenching due to 2b currents at $p \sim m_\pi$ relevant for $0\nu\beta\beta$ decay

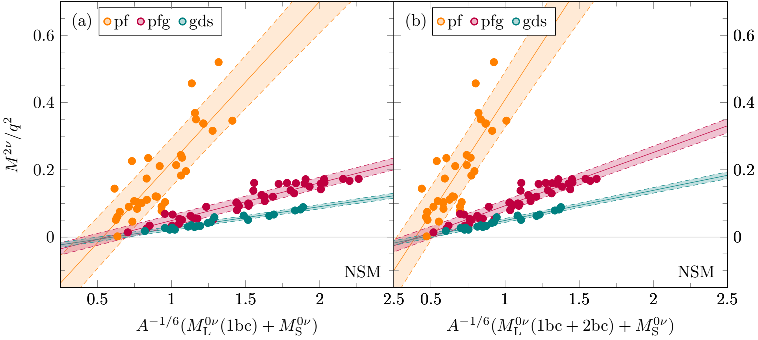
Hoferichter, JM, Schwenk PRD102 074018 (2020)




Jokiniemi, Romeo, Soriano, JM, arXiv:2207.05108

# Correlation of $0\nu\beta\beta$ decay to $2\nu\beta\beta$: general case

A good correlation between $2\nu\beta\beta$ and $0\nu\beta\beta$
also appears when we include to the calculation of $0\nu\beta\beta$ NMEs
2b currents and the short-range nuclear matrix element




Jokiniemi, Romeo, Soriano, JM, arXiv:2207.05108

Use $2\nu\beta\beta$ data to predict $0\nu\beta\beta$ NMEs with 2b currents, short-range NME

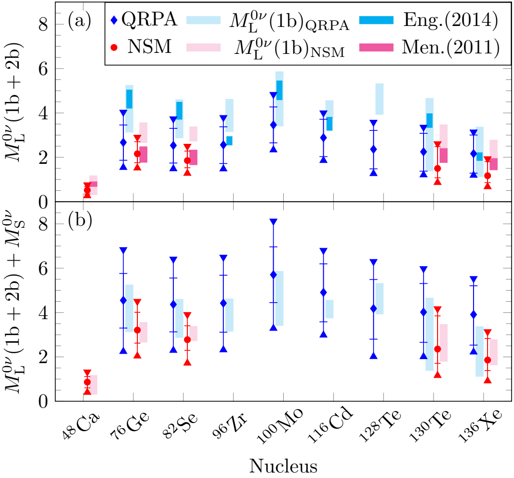
# $0\nu\beta\beta$ NMEs from correlation: 2bc, short-range

$0\nu\beta\beta$ NMEs including 2b currents and short-range NME obtained from $0\nu\beta\beta - 2\nu\beta\beta$ correlation and $2\nu\beta\beta$ data

Theoretical uncertainty due to correlation, calculation uncertainties: quenching, 2bc, short-range NME coupling (dominant uncertainty)

First complete estimation of $0\nu\beta\beta$ nuclear matrix elements with theoretical uncertainties

Jokiniemi, Romeo, Soriano, JM, arXiv:2207.05108



# Summary

Calculations of $0\nu\beta\beta$ NMEs
challenge nuclear many-body methods,
searches demand reliable NMEs

Ab initio results suggest reduced NMEs
due to nuclear correlations (eg via GCF)
and two-body currents
Likely enhancement by short-range NME

Double Gamow-Teller transitions,
electromagnetic $M1M1$ decay of DIAS
good correlation with $0\nu\beta\beta$ NMEs

Good $0\nu\beta\beta - 2\nu\beta\beta$ correlation
exploit $2\nu\beta\beta$ data to obtain $0\nu\beta\beta$ NMEs
with theoretical uncertainties