Neutrinoless double-beta decay from an effective field theory for heavy nuclei

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European Research Council
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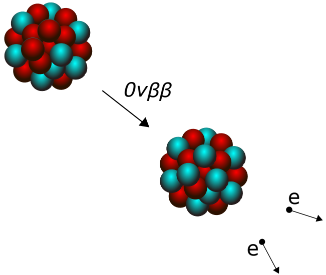
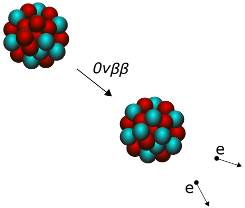


Wednesday 18th January, 2023

$0\nu\beta\beta$ decay

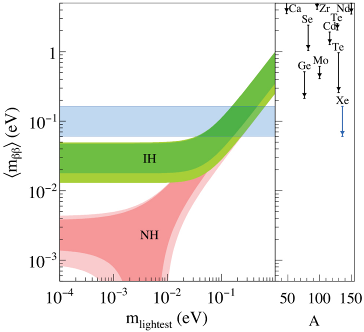


- lepton-number violation: no ν-emission
  $\rightarrow$ insights to matter and anti-matter asymmetry
- ν: neutral and massive
  $\rightarrow$ Majorana ($\nu = \overline{\nu}$) or Dirac ($\nu \neq \overline{\nu}$) particles?
- Standard Model: lepton-number conservation
  $\rightarrow$ BSM physics

open questions

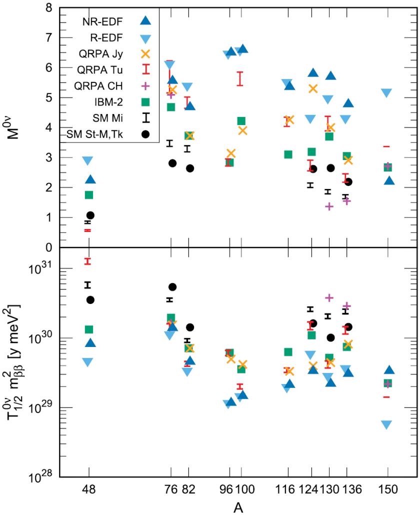
- mechanism(s) governing $0\nu\beta\beta$ decay
- mass hierarchy of neutrinos

answering these questions can be hindered by uncertainty of NMEs



Engel and Menéndez,
Rep. Prog. Phys. 80, 046301 (2017)

Motivation: experimental side



Engel and Menéndez, Rep. Prog. Phys. 80, 046301 (2017)

- phenomenological calculations for medium-mass or heavy nuclei
- top:
  deviation up to factor of three
- bottom - translation:
  up to an order of magnitude in half-life
- experiment:
  half-life $\sim$ required material

large NME uncertainty:

- severe consequences for planning experiments
- current uncertainty estimation:
  variation of model parameters

reliable uncertainty quantification $\rightarrow$ EFT for medium-mass and heavy nuclei

Effective Field Theory for heavy nuclei

Coello Pérez and Papenbrock Phys. Rev. C 92, 014323 (2015),
Coello Pérez and Papenbrock Phys. Rev. C 92, 064309 (2015),
Coello Pérez, Menéndez and Schwenk, Phys. Rev. C 98, 045501 (2018)

- phonon (quadrupole excitation) and fermion (neutron or proton) degrees of freedom

$$[d_\mu, d_\nu^\dagger] = \delta_{\mu\nu}\,, \quad \{n_\mu, n_\nu^\dagger\} = \delta_{\mu\nu}\,, \quad \{p_\mu, p_\nu^\dagger\} = \delta_{\mu\nu}$$

- reference state: ground state (gs) of spherical even-even core $|0\rangle$
- nucleus: reference state coupled to fermions and/or phonons

$$|J_f M_f; j_p, j_n\rangle = \left(n^\dagger \otimes p^\dagger\right)^{(J_f)} |0\rangle\,, \qquad \text{gs of odd-odd nucleus}$$

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- power counting: $Q^n = \left(\frac{\omega}{\Lambda}\right)^n$, n =number of phonons
  breakdown scale Λ at three-phonon level: $\Lambda = 3\omega \approx 2 - 3$ MeV
  $\rightarrow$ quantification of theoretical uncertainties

- low-energy constants (LECs):
  quenching, high-energy physics & microscopic information
  $\rightarrow$ fit to experimental data required

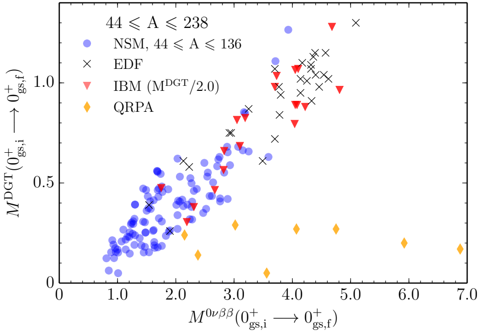
$0\nu\beta\beta$ not observed - how to fit low-energy constants?

- LECs: experimental data of GT transitions available
- correlation between DGT and $0\nu\beta\beta$ NMEs
  Shimizu *et al.*, Phys. Rev. Lett. 120 14, 142502 (2018),

strategy:

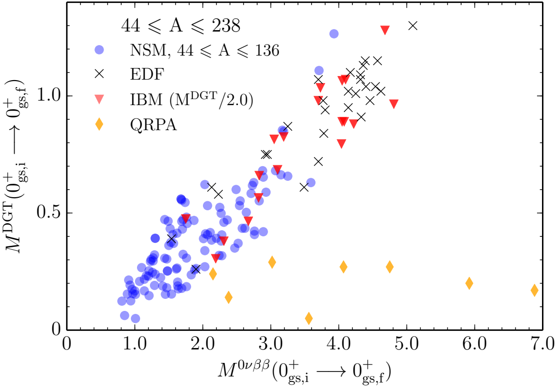
1. DGT NMEs within EFT
2. correlation + DGT NMEs

$\rightarrow$ EFT $0\nu\beta\beta$ NME prediction with systematic quantified uncertainties



but first: correlation

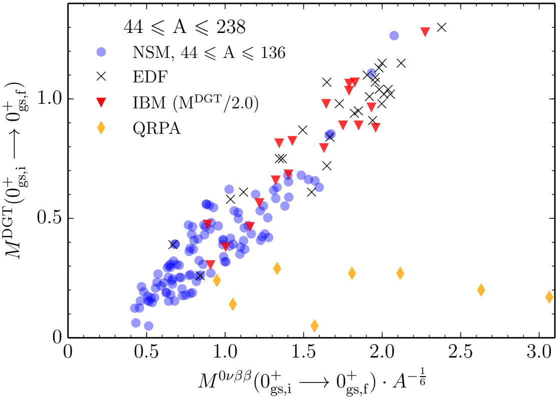
Correlation



- NSM, IBM and EDF results correlate very well
- QRPA results do not (see Javier's talk)

Variations of correlation

correlation		correlation coefficient r				
DGT	$0\nu\beta\beta$	NSM	EDF	IBM	QRPA	NSM, EDF, IBM
		0.83	0.91	0.88	−0.03	0.93
$\cdot R[\mathrm{fm}]$		0.64	0.85	0.66	−0.04	0.86
	$\cdot A^{-\frac{1}{6}}$	0.90	0.93	0.93	−0.03	0.95



CB, Menéndez, Coello Pérez and Schwenk PRC 106 (2022) 3, 034309

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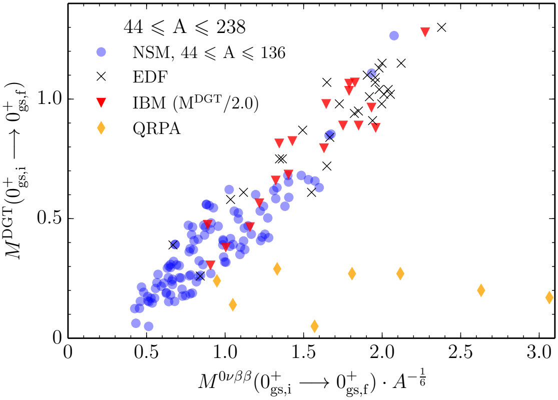

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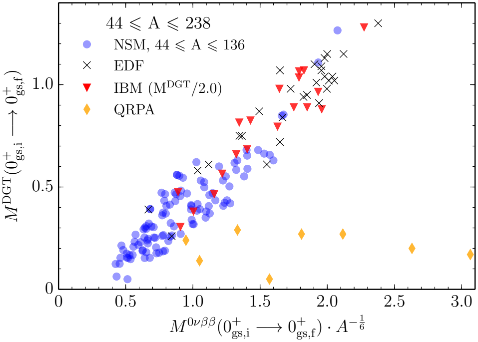
Correlation - motivation of factor



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$M^{0\nu\beta\beta}_{\mathrm{NSM/IBM}}$ implicit dependence on

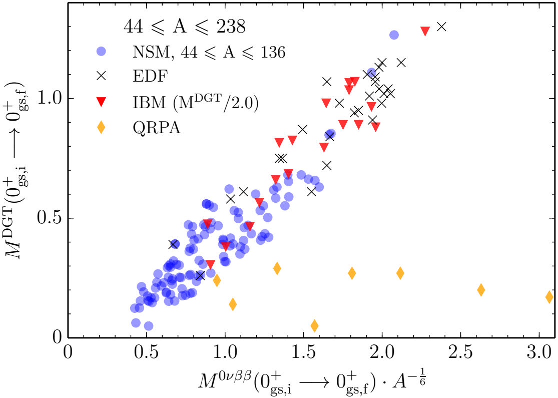
- harmonic oscillator length $b \sim A^{1/6}$
- inverse radius $1/R$ with $R \sim A^{1/3}$

best fit accounts for implicit dependence $\rightarrow b/R \sim A^{-1/6}$

Correlation - linear fit of band

- application of correlation → band
- fit of three linear functions to NSM data:

$$m \cdot \left(M^{0\nu\beta\beta} \cdot A^{-1/6}\right) + n = M^{\mathrm{DGT}}$$



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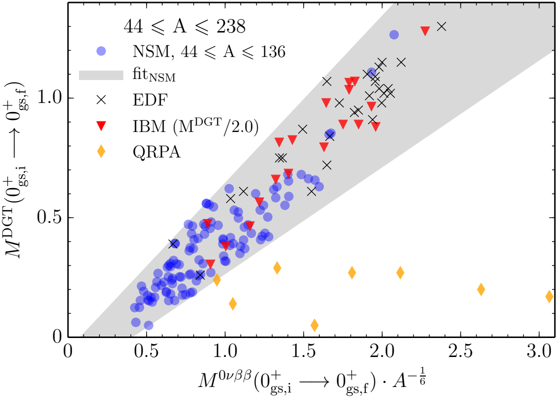

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- EDF and IBM enclosed by $\mathrm{fit}_{\mathrm{NSM}}$
- impressive mass range across nuclear chart (close to valley of stability)

Double Gamow-Teller transitions within EFT

- effective double GT operator between even-even states

$$\hat{O}_{\mathrm{DGT}} = \left(\hat{O}_{\mathrm{GT}} \otimes \hat{O}_{\mathrm{GT}}\right)^{(0)} = \underbrace{\overline{C}_{\beta}^{2} \left((\tilde{p} \otimes \tilde{n})^{(1)} \otimes (\tilde{p} \otimes \tilde{n})^{(1)} \right)^{(0)}}_{\mathrm{LO}} + \ldots$$

- define spherical-tensor annihilation operator: $\tilde{a}_{\mu} = (-1)^{j_a+\mu} a_{-\mu}$

- higher-order terms not considered $\rightarrow$ uncertainty

$$\delta \sim \sum_{n=1}^{\infty} \left(\frac{\omega}{\Lambda}\right)^{n} = 0.5$$

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- multifermion excitation of reference state

$$|0^{+}_{\mathrm{gs}}\rangle = \frac{1}{2} \left(\left(n^{\dagger} \otimes n^{\dagger}\right)^{(0)} \otimes \left(p^{\dagger} \otimes p^{\dagger}\right)^{(0)} \right)^{(0)} |0\rangle$$

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- final even-even nucleus $\rightarrow$ reference state $|0\rangle$

LO nuclear matrix element

$$M_{\mathrm{EFT}}^{\mathrm{DGT}} = \sqrt{\frac{4}{3(2j_n+1)(2j_p+1)}} \overline{C}_{\beta}^{2}$$

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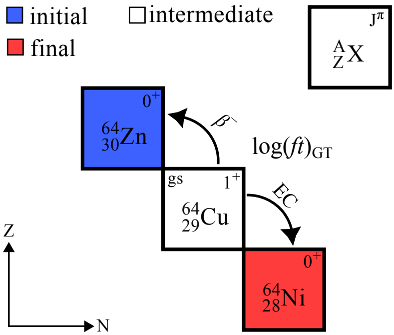
$\overline{C}_{\beta}^2$ fit to GT data: $\bar{C}_{\beta}^2 = C_{\beta 1} C_{\beta 2}$

Coello Pérez, Menéndez, and Schwenk, Phys. Lett. B 797, 134885 (2019)

- GT transition selection rule:

  $\triangle J_{\mathrm{GT}} = 1 \quad \triangle \pi_{\mathrm{GT}} = +$

- log(ft)-values of GT decays
- GT strengths from charge-exchange reactions



https://www.nndc.bnl.gov/ensdf/ ,
Grewe *et al.*, Phys. Rev. C 76, 054307 (2007), Thies *et al.*, Phys. Rev. C 86, 014304 (2012)
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Puppe *et al.*, Phys. Rev. C 86, 044603 (2012), Puppe *et al.*, Phys. Rev. C 84, 051305 (2011)
Guess *et al.*, Phys. Rev. C 83, 064318 (2011)

LO nuclear matrix element - Low-energy constant

$$M^{\mathrm{DGT}}_{\mathrm{EFT}} = \sqrt{\frac{4}{3(2j_n+1)(2j_p+1)}}\,\overline{C}_\beta^2$$

$\overline{C}_\beta^2$ fit to GT data: $\bar{C}_\beta^2 = C_{\beta 1} C_{\beta 2}$

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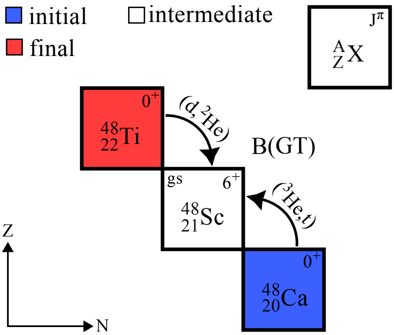

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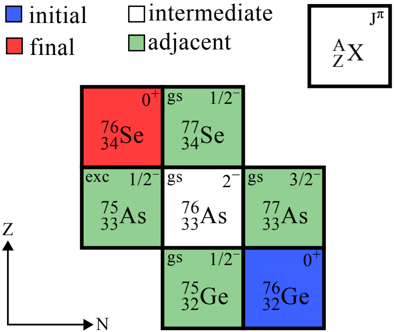
$$M^{\mathrm{DGT}}_{\mathrm{EFT}} = \sqrt{\frac{4}{3(2j_n+1)(2j_p+1)}}\,\overline{C}^2_\beta$$

- idea: nucleon orbitals from adjacent odd-mass nuclei
- dominant orbitals:
  ground or low-lying single-particle excited states

- $j_\mathrm{n} = \frac{1}{2}$
- $j_\mathrm{p} = \frac{3}{2}$ or $j_\mathrm{p} = \frac{1}{2}$



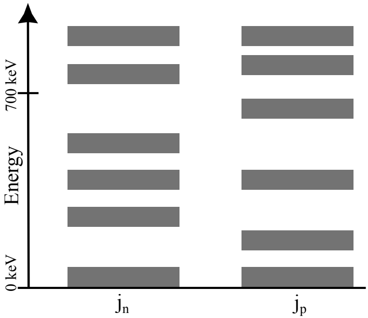
CB, Menéndez, Coello Pérez and Schwenk
PRC 106 (2022) 3, 034309

Nucleon orbitals

conditions:

- physically motivated thresholds
  - $E \leqslant 700$ keV (dominance)
  - $T_{1/2} \geqslant 0.1$ ns (single particle)
- GT transition selection rules
  - $|j_\mathrm{n} - j_\mathrm{p}| \leqslant 1 \leqslant |j_\mathrm{n} + j_\mathrm{p}|$
  - $\pi_\mathrm{n} \cdot \pi_\mathrm{p} = +$
- additional restrictions from
  - NSM: collective/not dominant

spectra of adjacent odd-mass nuclei



experimental data of odd-mass adjacent nuclei, https://www.nndc.bnl.gov/ensdf/

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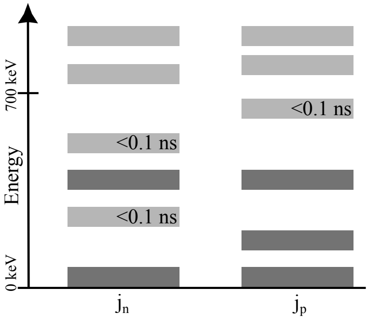

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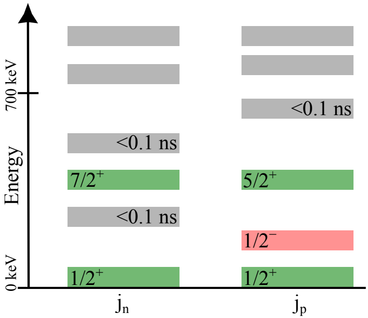

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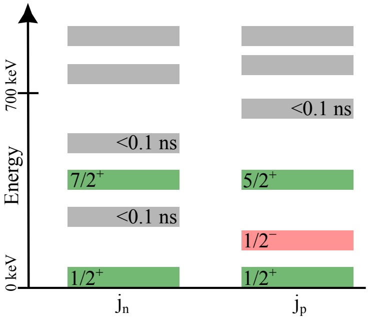
spectra of adjacent odd-mass nuclei



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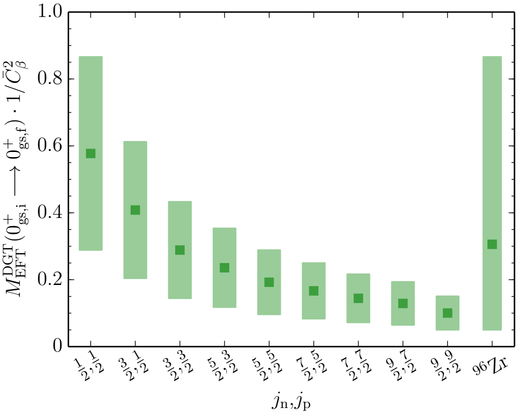
Nucleon orbitals contributions



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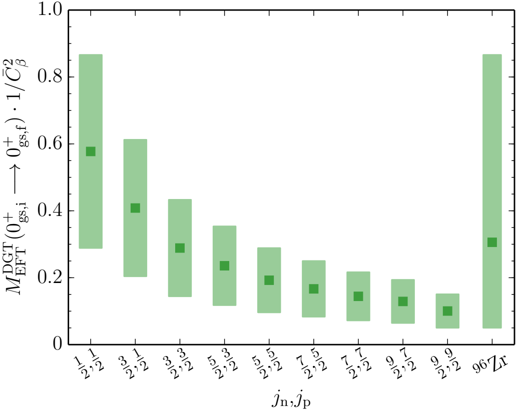
- truncation uncertainty: 50%
- ^{96}Zr central value: average of EFT DGT NME central values
- ^{96}Zr uncertainty: complete uncertainty range

Nucleon orbitals contributions



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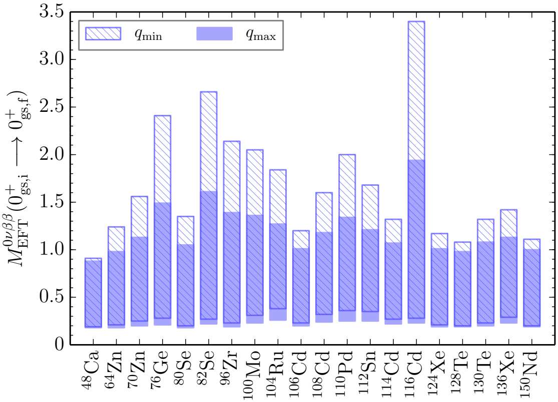
DGT NME + correlation band $\rightarrow$ $0\nu\beta\beta$ NME

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



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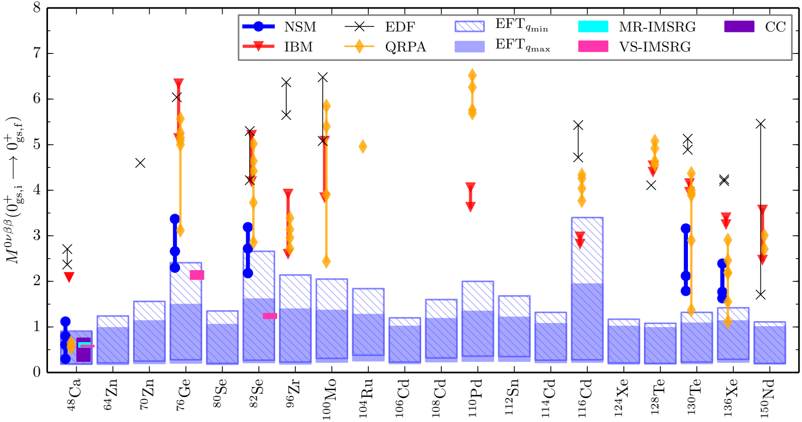
- include quenching uncertainty from NSM GT transition
- $A > 48$: $q_{\rm min} = 0.42$ and $q_{\rm max} = 0.65$
- $A = 48$: $q_{\rm min} = 0.70$ and $q_{\rm max} = 0.80$
- range: $0.18 \leqslant M^{0\nu\beta\beta}_{\rm EFT} \leqslant 3.40$

Predictions in comparison

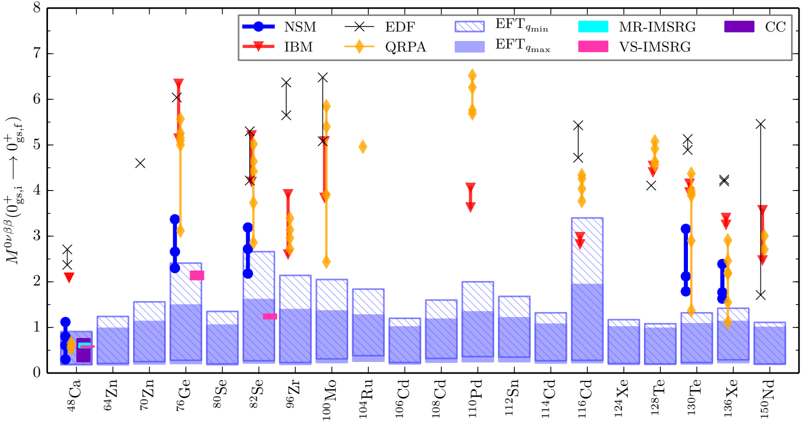
CB, Menéndez, Coello Pérez and Schwenk PRC 106 (2022) 3, 034309



Menéndez *et al.*, Nucl. Phys. A 818, 139 (2009), Horoi *et al.*, Phys. Rev. C 101, 044315 (2020), Iwata *et al.*, Phys. Rev. Lett. 116, 112502 (2016), Rodríguez *et al.*, Phys. Rev. Lett. 105, 252503 (2010), Song *et al.*, Phys. Rev. C 95, 024305 (2017), Šimkovic *et al.*, Phys. Rev. C 87, 045501 (2013), Fang *et al.*, Phys. Rev. C 97, 045503 (2018), Hyvärinen and Suhonen, Phys. Rev. C 91, 024613 (2015), Mustonen and Engel, Phys. Rev. C 87, 064302 (2013), Šimkovic *et al.*, Phys. Rev. C 98, 064325 (2018), Barea *et al.*, Phys. Rev. C 91, 034304 (2015), Yao *et al.*, Phys. Rev. Lett. 124, 232501 (2020), Belley *et al.*, Phys. Rev. Lett. 126, 042502 (2021), Novario *et al.*, Phys. Rev. Lett. 126, 182502 (2021)

Predictions in comparison

CB, Menéndez, Coello Pérez and Schwenk PRC 106 (2022) 3, 034309



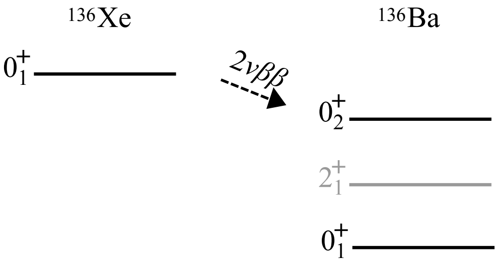
- range: $M^{0\nu\beta\beta}_{\mathrm{EFT}} \leqslant 3.40$ vs. $M^{0\nu\beta\beta}_{\mathrm{other}} \leqslant 6.5$ $\rightarrow$ EFT smaller predictions
- **(almost) overlap: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd and ^{136}Xe**
- combined unc. from other models larger than EFT unc.
- **consistent with *ab initio* predictions** (MR-/VS-IMSRG & CC)

$^{136}\text{Xe}(0^+_{\text{gs}}) \xrightarrow{2\nu\beta\beta} {}^{136}\text{Ba}(0^+_2)$

Jokiniemi, Romeo, CB, Kotila, Soriano, Schwenk and Menéndez

arXiv:2211.03764 in press at PLB

Motivation - $^{136}\mathbf{Xe}(\mathrm{gs}, 0_1^+) \xrightarrow{2\nu\beta\beta} {}^{136}\mathbf{Ba}(\mathrm{exc}, 0_2^+)$



- test of predictions from different nuclear many body calculations
- useful, because applying these same methods for $0\nu\beta\beta$
- ongoing search for this decay at KamLAND-Zen and nEXO
  K. Asakura, et al., Nucl. Phys. A 946 (2016) 171,
  G. Adhikari, et al, J. Phys. G: Nucl. Part. Phys. 49 015104 (2022)

EFT for $2\nu\beta\beta$ decay

- fit LECs to data from β decay or from charge-exchange reaction (GT-strength)
  $\longrightarrow$ predict $2\nu\beta\beta$ decay from gs to gs $M^{2\nu}_{\mathrm{EFT}}(0^+_{\mathrm{gs}} \to 0^+_{\mathrm{gs}})$ with single state dominance (SSD) approximation

$$M^{2\nu}_{\mathrm{GT}} \sim \langle f || \hat{O}_{\mathrm{GT}} || 1^+_1 \rangle \langle 1^+_1 || \hat{O}_{\mathrm{GT}} || i \rangle$$

- uncertainty associated to SSD approximation can be explicitly included

  Coello Pérez, Menéndez and Schwenk, PRC 98, 045501 (2018)

- subsequently decay to first excited 0^+_2 can be predicted

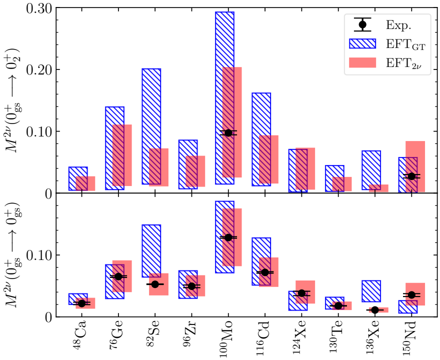
  Coello Pérez, Menéndez and Schwenk, PRC 98, 045501 (2018)

$$M^{2\nu}_{\mathrm{EFT}}(0^+_{\mathrm{gs}} \to 0^+_2) \approx \left(1 + \frac{D_{10^+_2}}{D_{20^+_2}} + \frac{D_{10^+_2}}{D_{30^+_2}}\right) \frac{D_{10^+_{\mathrm{gs}}}}{D_{10^+_2}} \frac{\sqrt{2}}{3} M^{2\nu}_{\mathrm{EFT}}(0^+_{\mathrm{gs}} \to 0^+_{\mathrm{gs}})$$

$$\delta(\mathrm{gs} \to 0^+_2) = \frac{\omega}{\Lambda}\left(\frac{D_{10^+_2}}{D_{20^+_2}} + \frac{D_{10^+_2}}{D_{30^+_2}}\right) + \frac{D_{10^+_2}}{\Lambda}\phi\left(\frac{\omega}{\Lambda}, 1, \frac{D_{30^+_2} + \omega}{\omega}\right)$$

fit to GT data

- EFT works very well for gs to gs and for gs to exc(0_2^+)
- but for ^{136}Xe gs to gs not consistent with experiment



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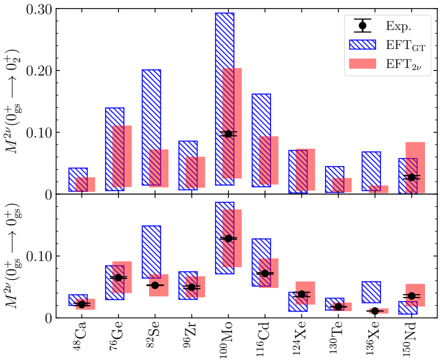

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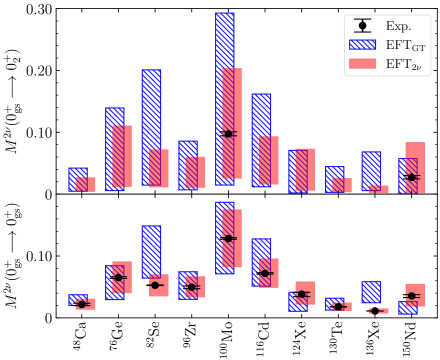

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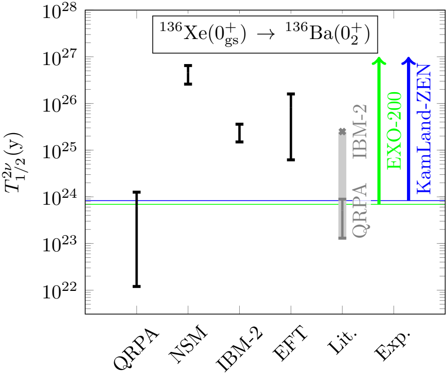
comparison

- fit to $2\nu\beta\beta$: NMEs generally smaller
- overlap of fitting strategies: smallest for ^{136}Xe

half-lives!

- EFT advantage: systematic theoretical uncertainties
- QRPA only small overlap with lower limits
- NSM, IBM-2 and EFT in complete agreement with exp. lower limit
- IBM-2 and EFT consistent



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So I am excited about future experimental measurements

Summary

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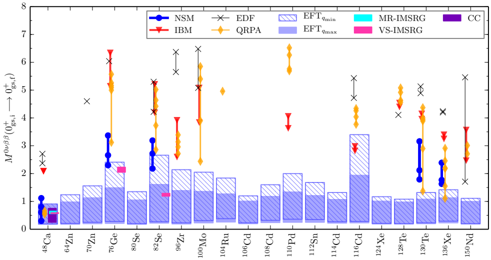
- rare decays within EFT for heavy nuclei at LO
- in general: $0\nu\beta\beta$ EFT NMEs smaller in comparison
- consistent with *ab initio* calculations



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PRC 106 (2022) 3, 034309

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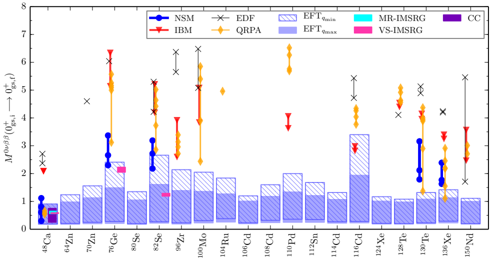

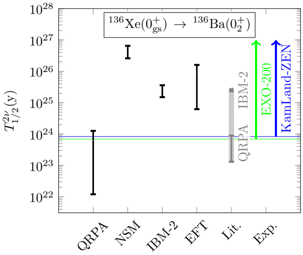

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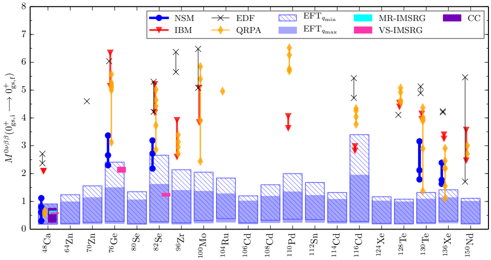

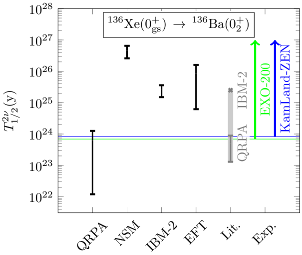

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Thank you!!