

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

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Catharina Bräse

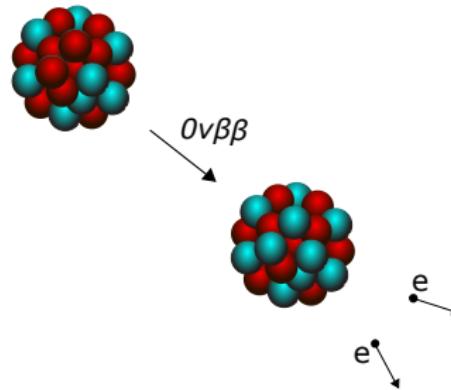
Institut für Kernphysik, TU Darmstadt

in collaboration with J. Menéndez, E. A. Coello Pérez and A. Schwenk

Workshop on Progress in *Ab Initio* Nuclear Theory

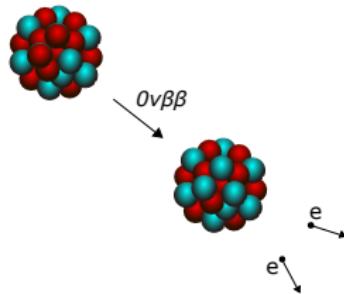


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Wednesday 1<sup>st</sup> March, 2023

# $0\nu\beta\beta$ decay

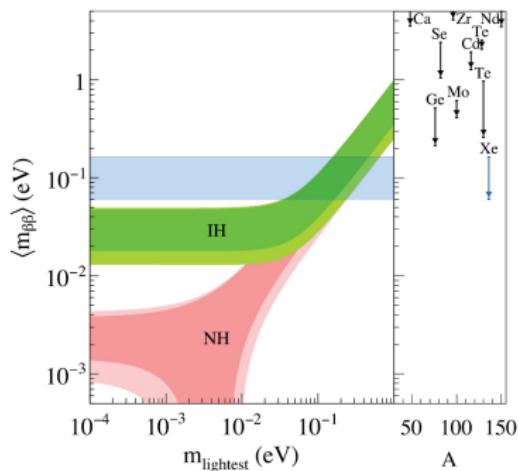


- ✚ lepton-number violation: no  $\nu$ -emission  
→ insights to matter and anti-matter asymmetry  
→ BSM physics
- ✚  $\nu$ : neutral and massive  
→ Majorana ( $\nu = \bar{\nu}$ ) or Dirac ( $\nu \neq \bar{\nu}$ ) particles?

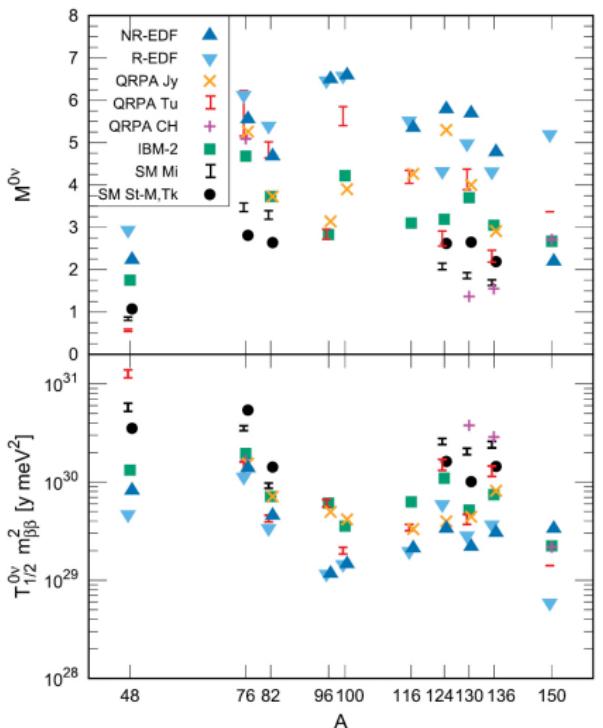
## open questions

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

answering these questions can be hindered  
by uncertainty of NMEs



# Motivation



- 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:**  
current uncertainty estimation  
 $\rightarrow$  variation of model parameters

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

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

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

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- ⊕ power counting:  $Q^n = \left(\frac{\omega}{\Lambda}\right)^n$ ,  $n$  = number of phonons  
breakdown scale  $\Lambda$  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

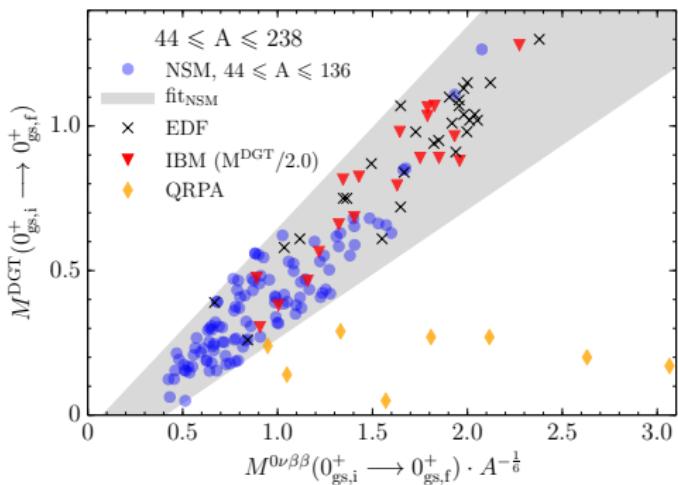
# $0\nu\beta\beta$ not observed - how to fit low-energy constants?

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



## LO nuclear matrix element

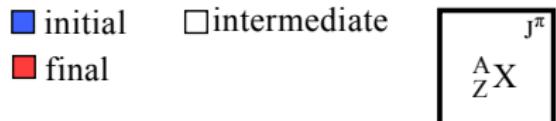
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$$M_{\text{EFT}}^{\text{DGT}} = \sqrt{\frac{4}{3(2j_n + 1)(2j_p + 1)}} \overline{\mathcal{C}}_{\beta}^2$$

# LO nuclear matrix element - Low-energy constant

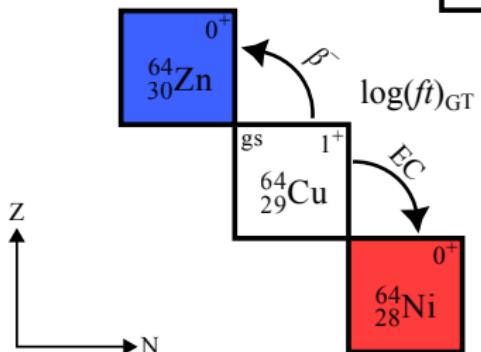
$$M_{\text{EFT}}^{\text{DGT}} = \sqrt{\frac{4}{3(2j_n + 1)(2j_p + 1)}} \bar{C}_{\beta}^2$$

$\bar{C}_{\beta}^2$  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:  
 $\Delta J_{\text{GT}} = 1$     $\Delta \pi_{\text{GT}} = +$

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



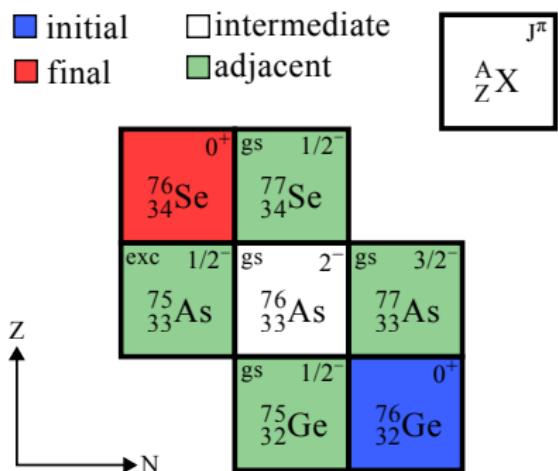
<https://www.nndc.bnl.gov/ensdf/>,

Grawe et al., Phys. Rev. C 76, 054307 (2007), Thies et al., Phys. Rev. C 86, 014304 (2012)  
 Frekers et al., Phys. Rev. C 94, 014614 (2016), Thies et al., Phys. Rev. C 86, 054323 (2012)  
 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)

# Nucleon orbitals

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

- \* idea: nucleon orbitals from adjacent odd-mass nuclei
- \* dominant orbitals:  
ground or low-lying single-particle excited states
- \*  $j_n = \frac{1}{2}$
- \*  $j_p = \frac{3}{2}$  or  $j_p = \frac{1}{2}$

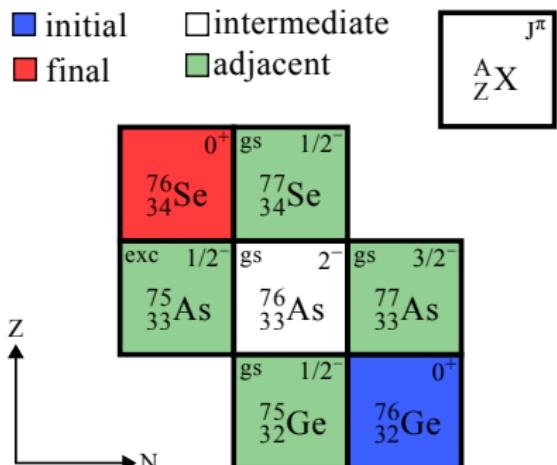


CB, Menéndez, Coello Pérez and Schwenk  
PRC 106 (2022) 3, 034309

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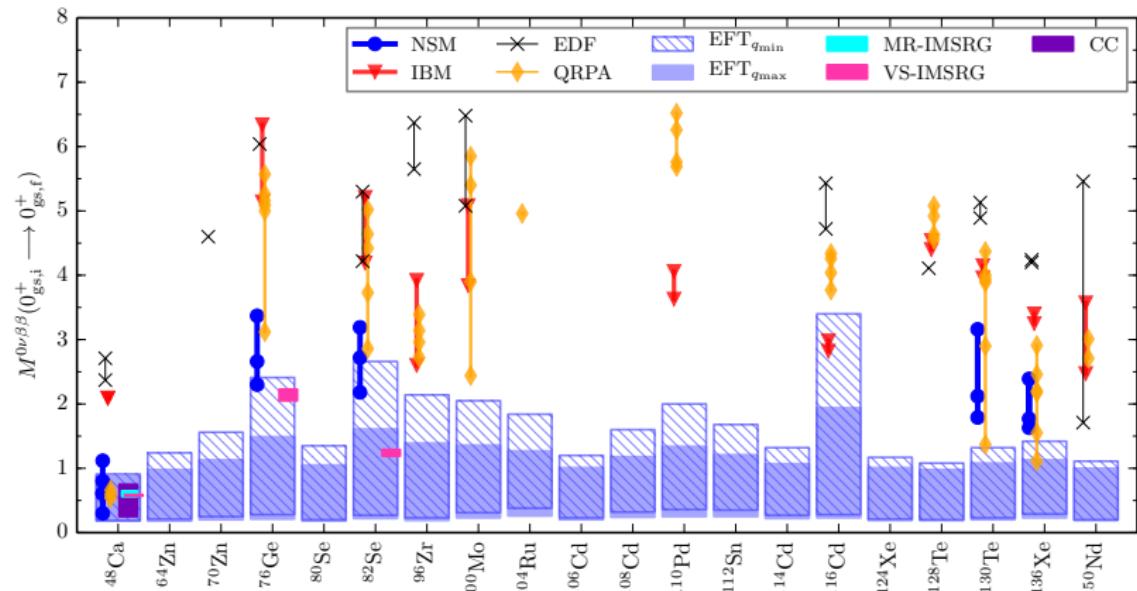


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DGT NME + correlation band  $\rightarrow 0\nu\beta\beta$  NME

# Predictions in comparison

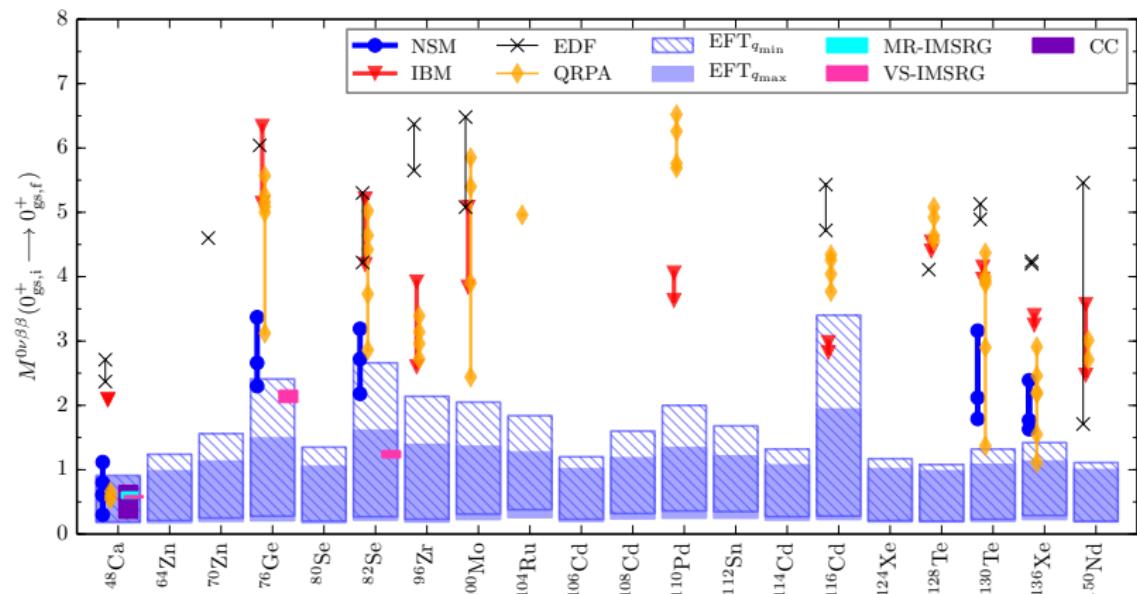
CB, Menéndez, Coello Pérez and Schwenk PRC 106 (2022) 3, 034309



- 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)

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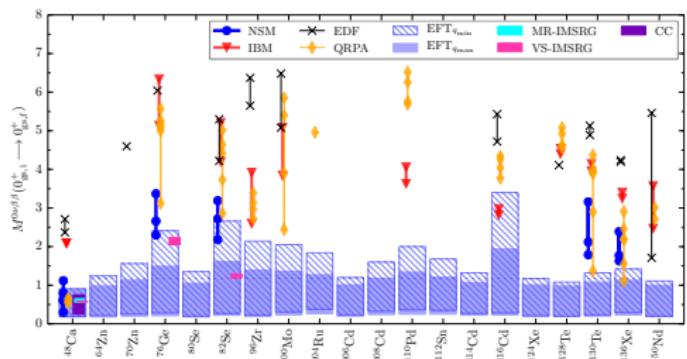
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- ✚ range:  $M_{\text{EFT}}^{0\nu\beta\beta} \leqslant 3.40$  vs.  $M_{\text{other}}^{0\nu\beta\beta} \leqslant 6.5$   $\rightarrow$  EFT smaller predictions
- ✚ (almost) overlap:  ${}^{48}\text{Ca}$ ,  ${}^{76}\text{Ge}$ ,  ${}^{82}\text{Se}$ ,  ${}^{100}\text{Mo}$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

# Summary

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

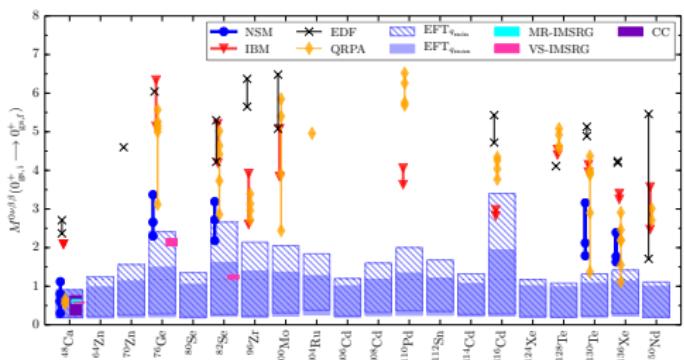


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PRC 106 (2022) 3, 034309

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

C. Brauer<sup>1,2</sup>, J. Mekhora<sup>3</sup>, E. A. Coello Pérez<sup>4</sup>, and A. Scherck<sup>2</sup>

PRC 104, 032409 (2022)

**1. Motivation**

- Motivation for neutrino mass bounds from EFT: Majorana exchange in a 2x2 [1]
- EFT provides SM-like predictions for neutrino masses [2]
- good fit: NMBS from an EFT with quantized uncertainties for heavy nuclei

**2. Correlation**

unpredicted vs EFT: EFT low energy constants not directly predictable via EFT

**3. Effective Field Theory**

- degrees of freedom and fermion renormalizations [3]
- power counting in number of pion exchanges [3] ( $|\mathcal{L}| \sim \Lambda^{-2}$ )
- initial state spherical wave function to nucleons and nucleon holes
- effective leading order (ELO) parameters
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**4. Nuclear matrix element**

$M_{\alpha\beta} = \sum_{\text{pions}} \bar{\psi}_{\alpha}(p) \mathcal{O}_{\text{NMBS}}(p) \psi_{\beta}(p)$

CST 2022 uncertainty as power counting in number of pion exchanges

$\Delta M_{\alpha\beta} / M_{\alpha\beta} \sim (\Lambda^{-1})^{n_{\text{pions}}} \sim \Lambda^{-n_{\text{pions}}}$

+ additional sources of uncertainty for  $n_{\text{pions}} > 1$ : effective nucleon orbital contributions

**5. EFT input**

$\ln(\lambda/\Lambda) = \ln(\Lambda/\Lambda_0) + \ln(\mu/\Lambda_0)$

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**6. Results**

- EFT results in general nuclear
- (dashed) overlap with lower NMBS and QPNS results
- comparison with EFT at tree-level results
- determination of uncertainty of accuracy:

  - width of total fit
  - several effective nucleon orbital contributions
  - in comparison with EFT input uncertainty smaller effect

- in general: EFT results are comparable with combined uncertainty of all models

Thank you!!