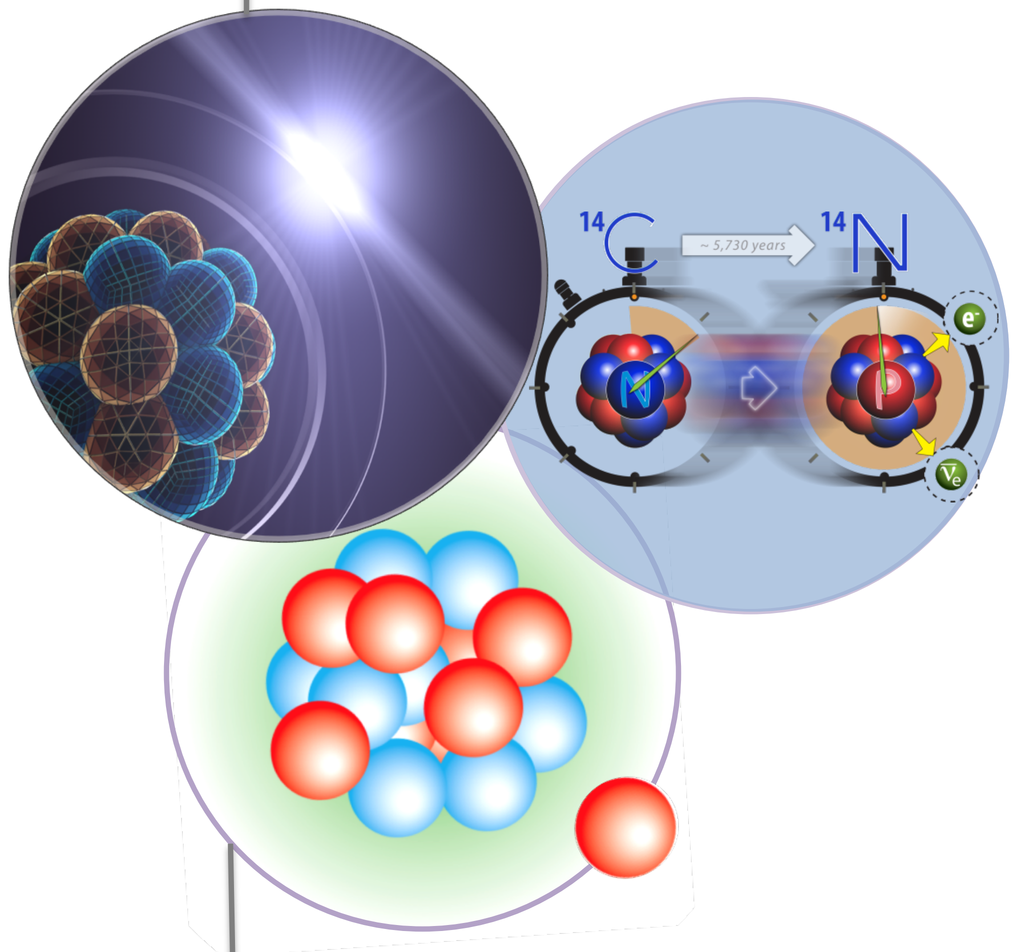
A solution to the quenching puzzle of beta-decays and 0vbb in ^{48}Ca



Gaute Hagen

Oak Ridge National Laboratory

Topical Collaboration Meeting

Chapel Hill, February 2nd, 2018

U.S. DEPARTMENT OF ENERGY

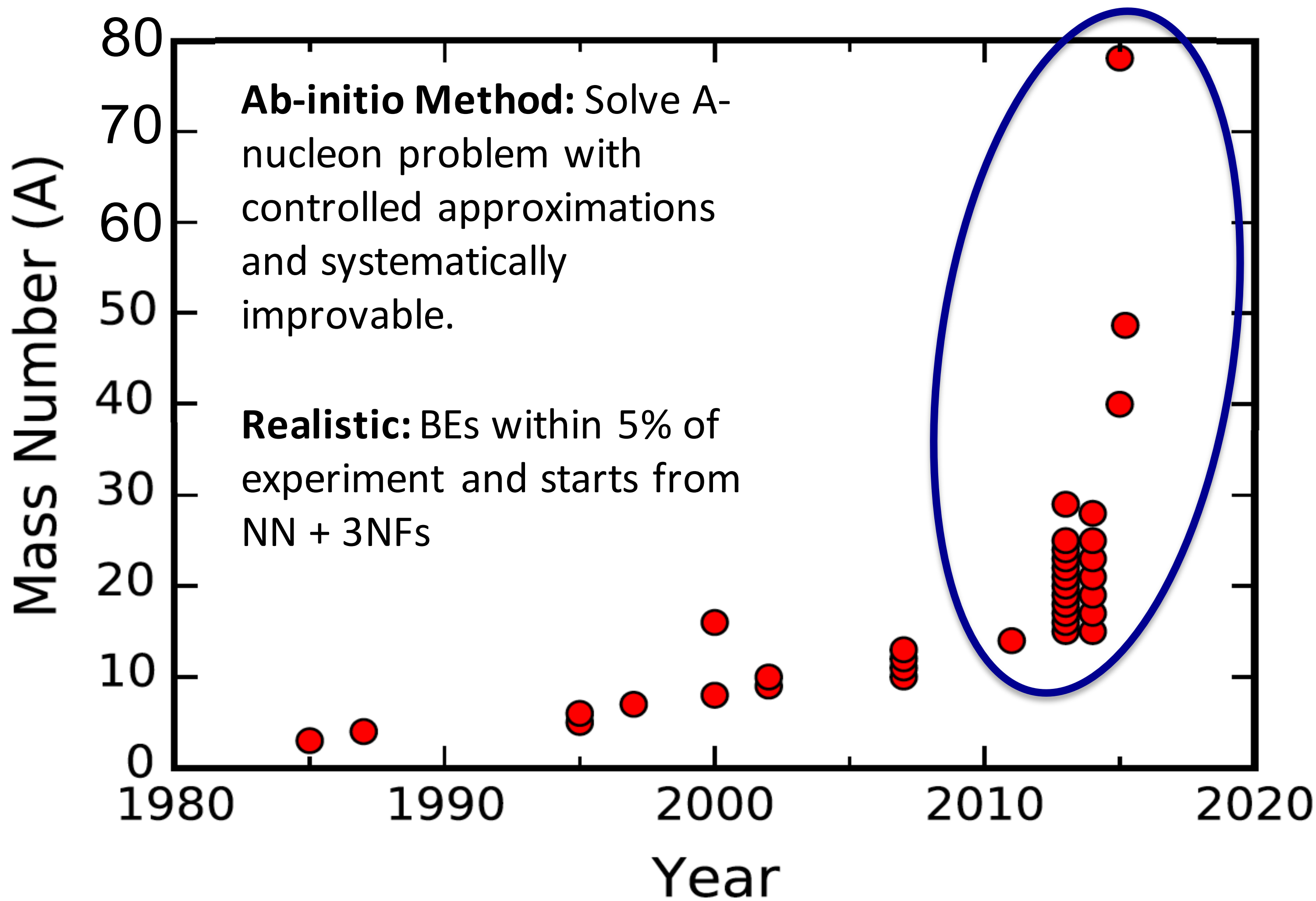
NUCLEI
Nuclear Computational Low-Energy Initiative

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Trend in realistic ab-initio calculations

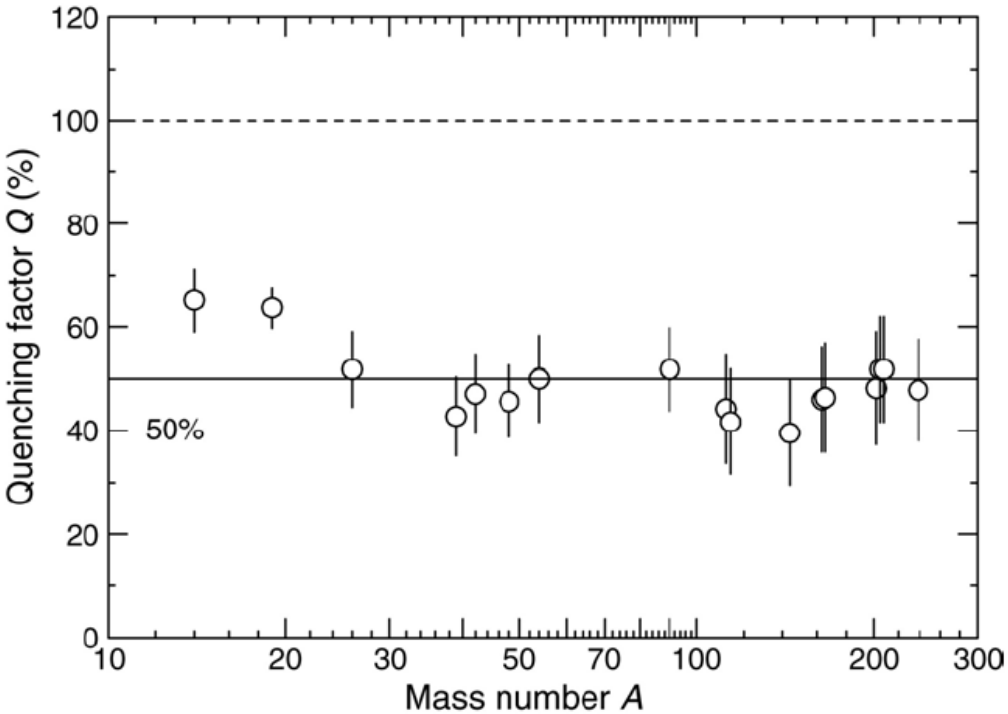
Explosion of many-body methods (Coupled clusters, Green's function Monte Carlo, In-Medium SRG, Lattice EFT, MCSM, No-Core Shell Model, Self-Consistent Green's Function, UMOA, …)

Application of ideas from EFT and renormalization group (V_{low-k}, Similarity Renormalization Group, …)



The puzzle of quenched of beta decays

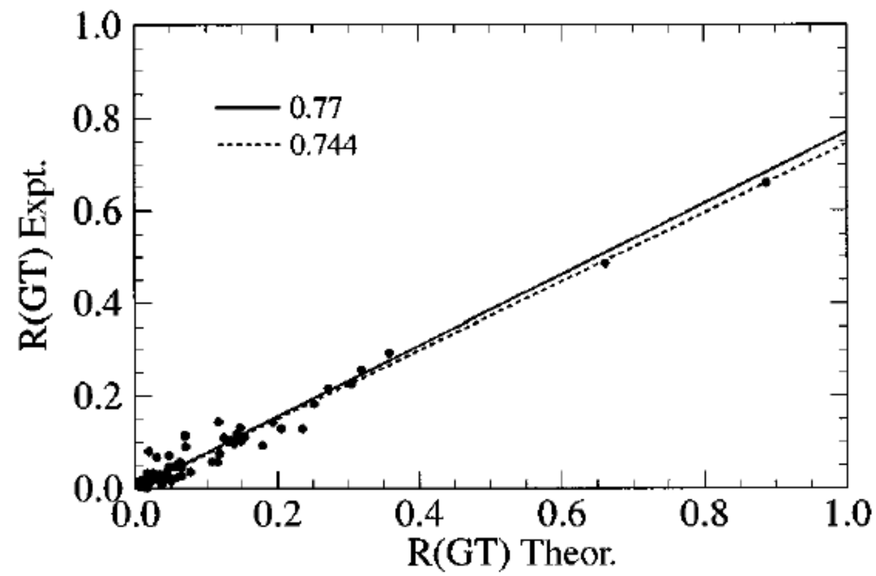
Long-standing problem: Experimental beta-decay strengths quenched compared to theoretical results.



- Renormalizations of the Gamow-Teller operator?
- Missing correlations in nuclear wave functions?
- Model-space truncations?
- Two-body currents (2BCs)?

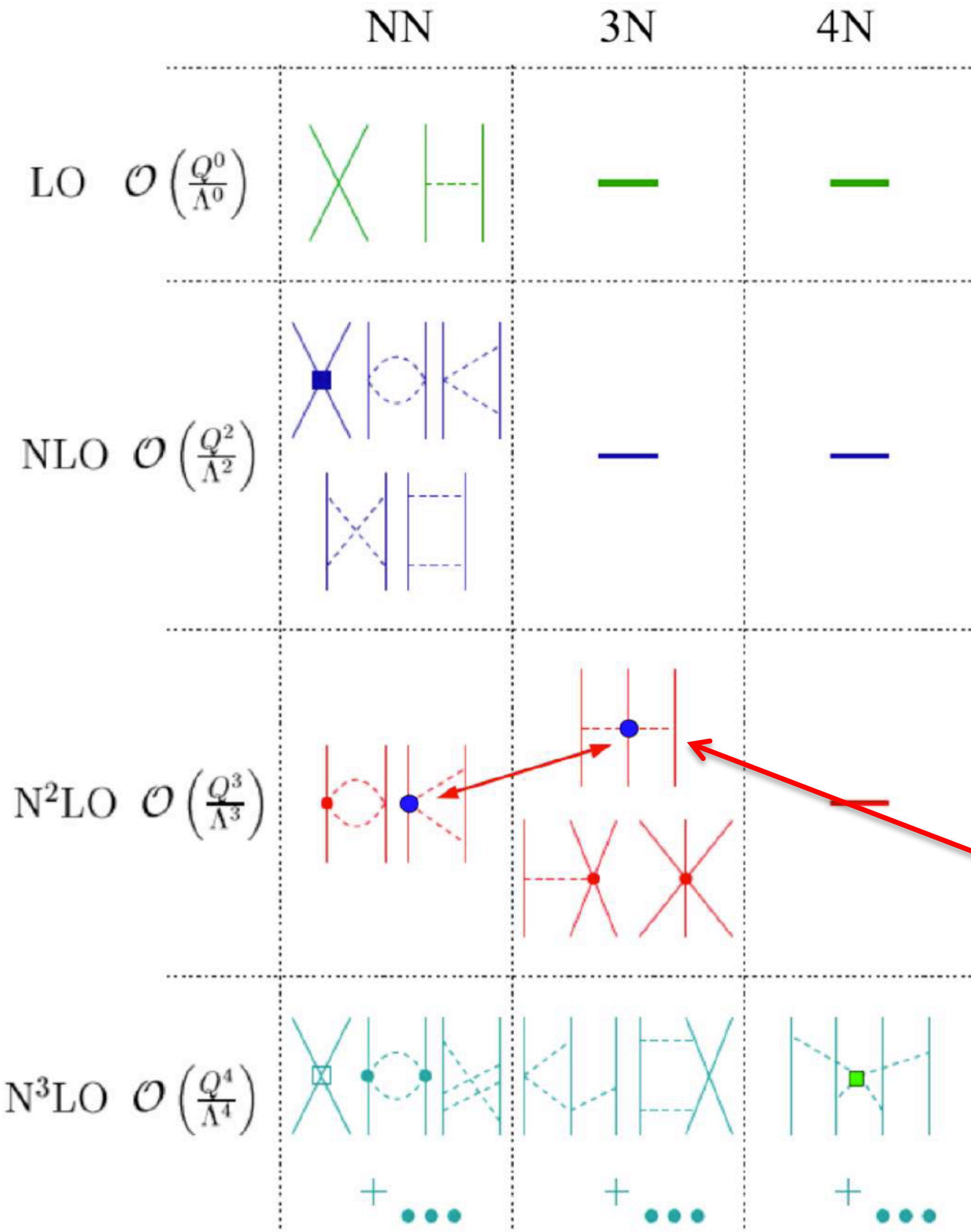
Quenching obtained from charge-exchange (*p,n*) experiments. (Gaarde 1983).

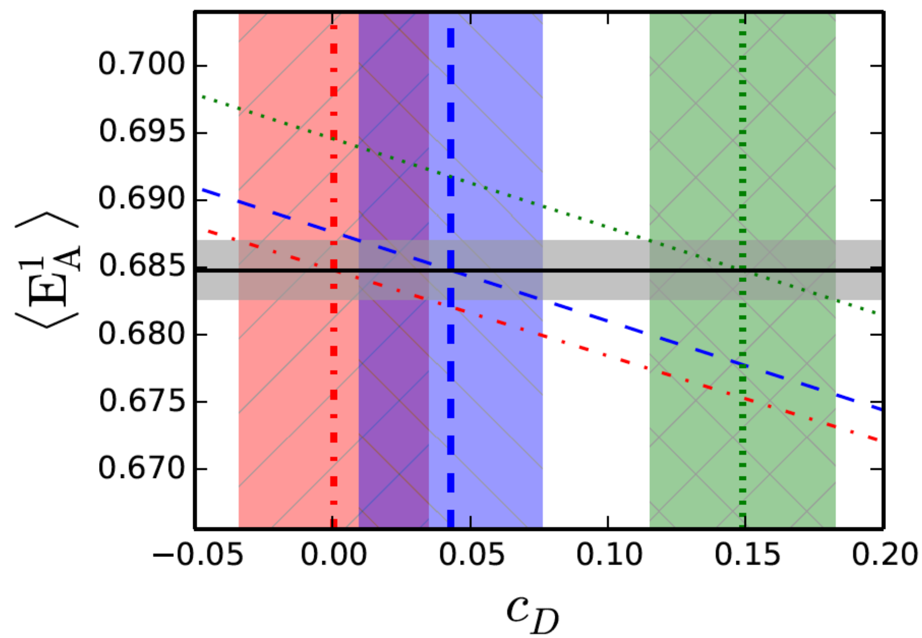
G. Martinez-Pinedo et al, PRC **53**, R2602 (1996)

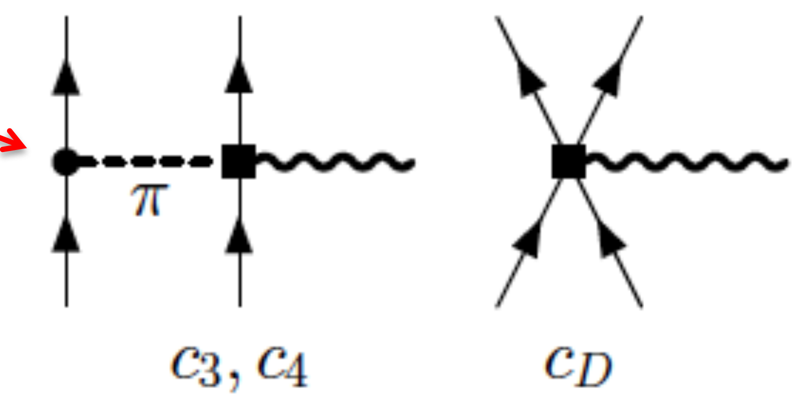


Nuclear forces from chiral effective field theory

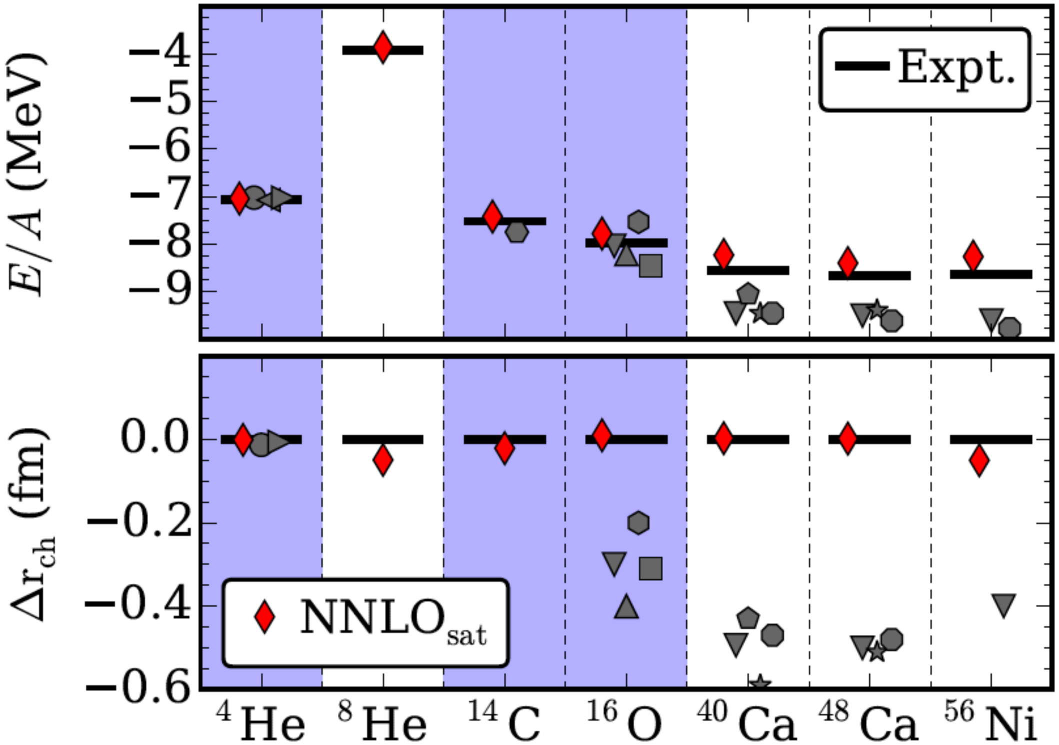
[Weinberg; van Kolck; Epelbaum *et al.*; Entem & Machleidt; …]







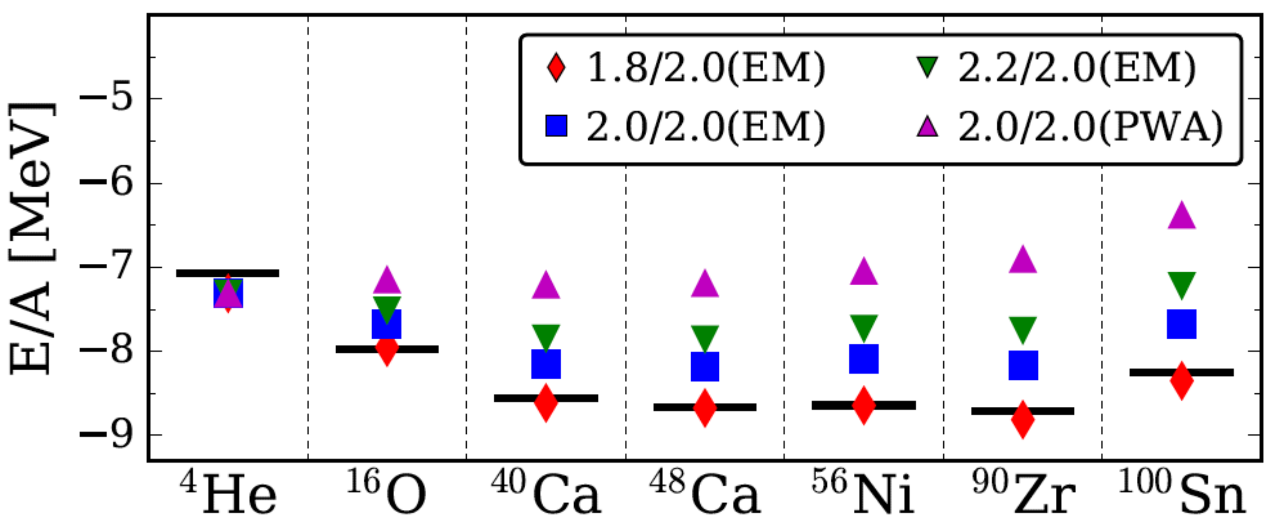
Two interactions from chiral EFT: $NNLO_{sat}$ & 1.8/2.0 (EM)



$NNLO_{sat}$: Accurate radii and BEs

- Simultaneous optimization of NN and 3NFs
- Include charge radii and binding energies of ^{3}H, $^{3,4}He$, ^{14}C, ^{16}O in the optimization
- Harder interaction: difficult to converge beyond ^{56}Ni

A. Ekström *et al*, Phys. Rev. C **91**, 051301(R) (2015).

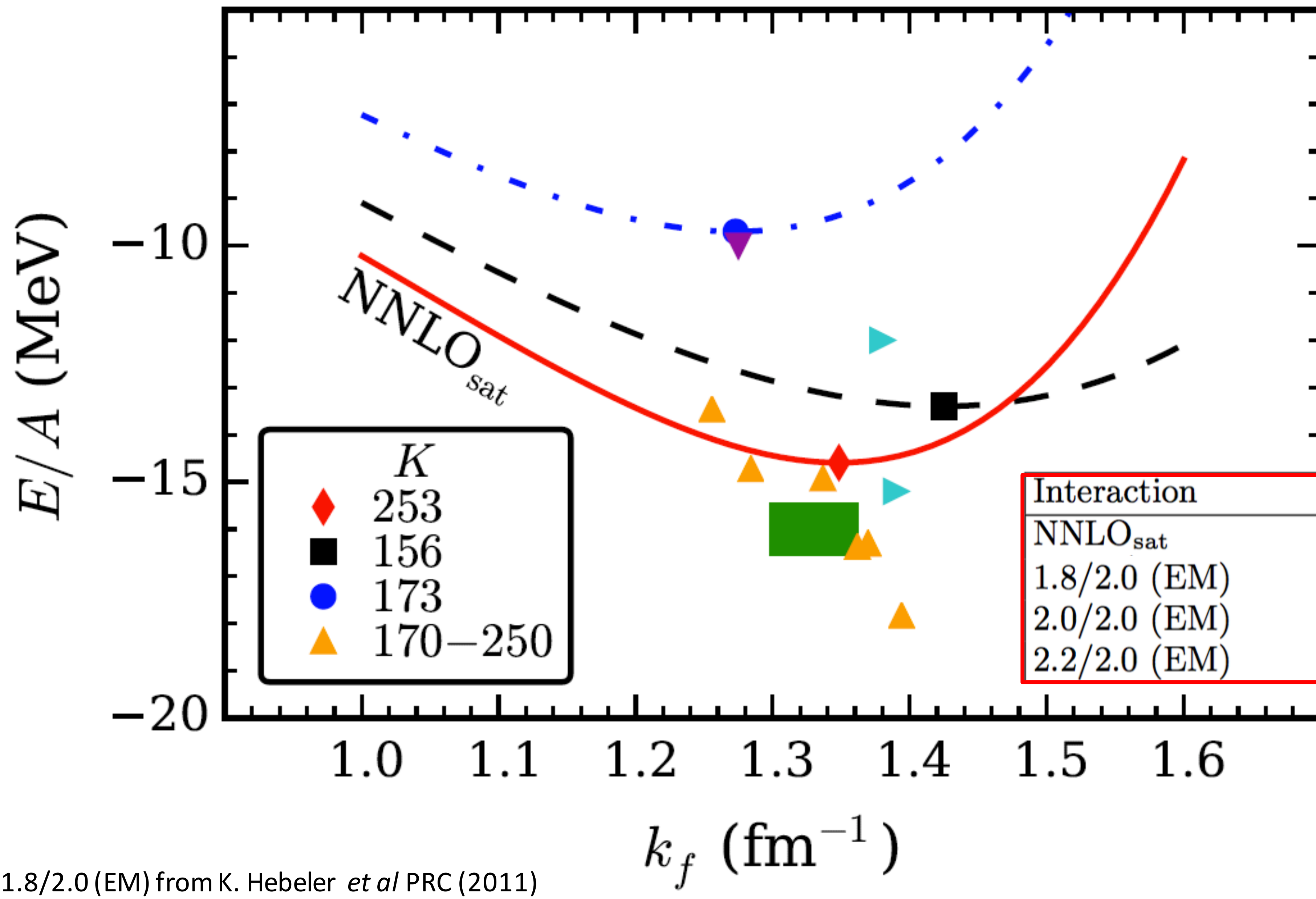


1.8/2.0(EM): Accurate BEs

Soft interaction: SRG NN from Entem & Machleidt with 3NF from chiral EFT

K. Hebeler *et al* PRC (2011).
T. Morris *et al*, arXiv:1709.02786 (2017).

Saturation in nuclear matter from chiral interactions



Interaction	c_D
NNLO$_{sat}$	0.817
1.8/2.0 (EM)	1.264
2.0/2.0 (EM)	1.271
2.2/2.0 (EM)	1.214

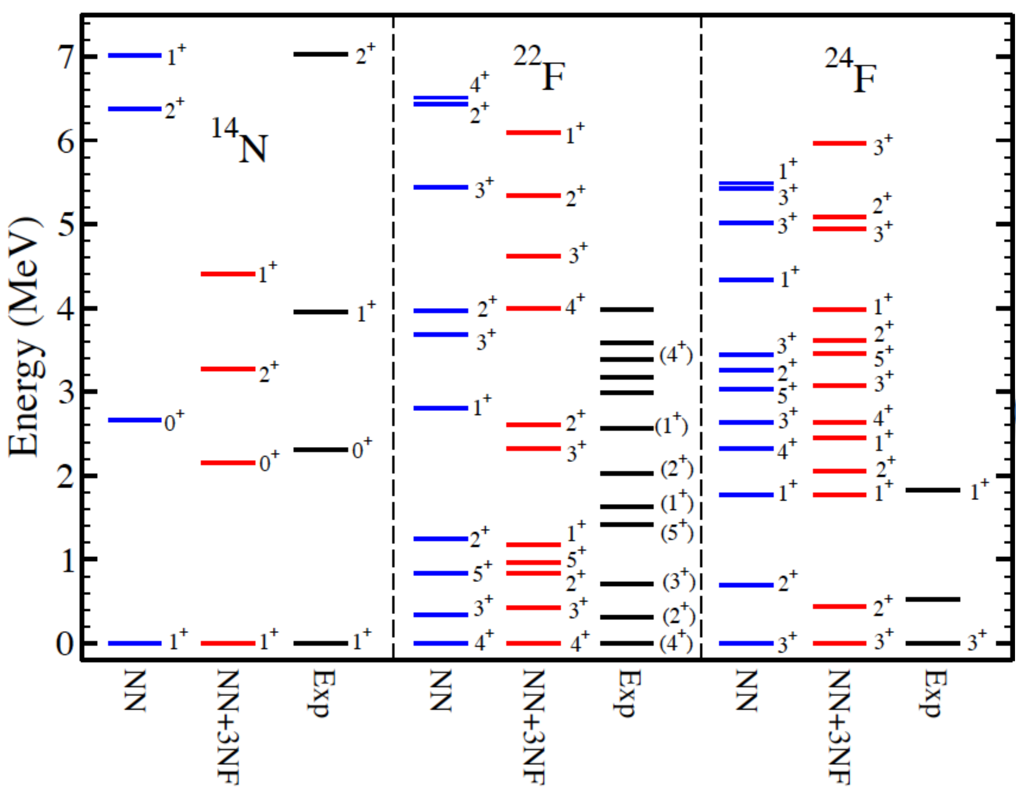
1.8/2.0 (EM) from K. Hebeler *et al* PRC (2011)

The other chiral NN + 3NFs are from Binder et al, PLB (2014)

Charge exchange EOM-CCSDT-1

$$\bar{H}_{CCSDT-1} = \begin{bmatrix} \langle S|\bar{H}|S\rangle & \langle D|\bar{H}|S\rangle & \langle T|\bar{H}|S\rangle \\ \langle S|\bar{H}|D\rangle & \langle D|\bar{H}|D\rangle & \langle T|V|D\rangle \\ \langle S|V|T\rangle & \langle D|V|T\rangle & \langle T|F|T\rangle \end{bmatrix}$$

$$R_\nu = \sum r_i^a \, p_a^\dagger n_i + \frac{1}{4}\sum r_{ij}^{ab} \, p_a^\dagger N_b^\dagger N_j n_i + \frac{1}{36}\sum r_{ijk}^{abc} \, p_a^\dagger N_b^\dagger N_c^\dagger N_k N_j n_i$$



r_{ijk}^{abc} has massive requirements for realistic calcs

A. Ekström, G. Jansen, K. Wendt et al, PRL 113 262504 (2014)

Charge exchange EOM-CCSDT-1

$$\bar{H}_{CCSDT-1} = \begin{bmatrix} \langle S|\bar{H}|S\rangle & \langle D|\bar{H}|S\rangle & \langle T|\bar{H}|S\rangle \\ \langle S|\bar{H}|D\rangle & \langle D|\bar{H}|D\rangle & \langle T|V|D\rangle \\ \langle S|V|T\rangle & \langle D|V|T\rangle & \langle T|F|T\rangle \end{bmatrix}$$

Charge exchange EOM-CCSDT-1

P-space

$$\bar{H}_{CCSDT-1} = \begin{bmatrix} \langle S|\bar{H}|S\rangle & \langle D|\bar{H}|S\rangle & \langle T|\bar{H}|S\rangle \\ \langle S|\bar{H}|D\rangle & \langle D|\bar{H}|D\rangle & \langle T|V|D\rangle \\ \langle S|V|T\rangle & \langle D|V|T\rangle & \langle T|F|T\rangle \end{bmatrix}$$

Q-space

Charge exchange EOM-CCSDT-1

P-space

$$\bar{H}_{CCSDT-1} = \begin{bmatrix} \langle S|\bar{H}|S\rangle & \langle D|\bar{H}|S\rangle & \langle T|\bar{H}|S\rangle \\ \langle S|\bar{H}|D\rangle & \langle D|\bar{H}|D\rangle & \langle T|V|D\rangle \\ \langle S|V|T\rangle & \langle D|V|T\rangle & \langle T|F|T\rangle \end{bmatrix}$$

Q-space

- Fock matrix, F, is invertible in any of the blocks.
- Bloch-Horrowitz is exact; iterative solution poss.

$$\overline{H}_{PP}R_P + \overline{H}_{PQ}(\omega - \overline{H}_{QQ})^{-1}\overline{H}_{QP}R_P = \omega R_P$$

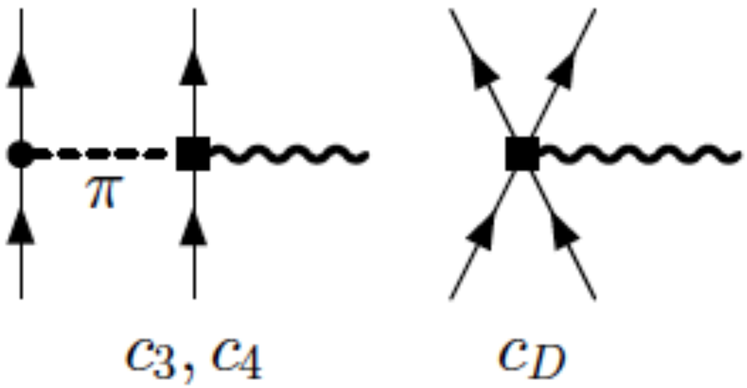
- No large memory for mult R_3 lanczos vectors
- Can only solve for one state at a time

W. C. Haxton and C.-L. Song Phys. Rev. Lett. **84** (2000)
W. C. Haxton Phys. Rev. C **77**, 034005 (2008)
C. E. Smith, J. Chem. Phys. **122**, 054110 (2005)

Normal ordered one- and two-body current

Gamow-Teller matrix element:

$$\hat{O}_{\rm GT} \equiv \hat{O}^{(1)}_{\rm GT} + \hat{O}^{(2)}_{\rm GT} \equiv g_A^{-1}\sqrt{3\pi}E_1^A$$



Normal ordered operator:

$$\hat{O}_{\rm GT} = O_N^0 + O_N^1 + O_N^2$$

$$O_N^0 = \sum_{i\leq E_f}\langle i|O^{(1)}|i\rangle + \frac{1}{2}\sum_{i,j\leq E_f}\langle ij|O^{(2)}|ij\rangle$$

$$O_N^1 = \sum_{pq}\langle p|O^{(1)}|q\rangle\{p^\dagger q\} + \sum_{pq}\sum_{i\leq E_f}\langle pi|O^{(2)}|qi\rangle\{p^\dagger q\}$$

$$O_N^2 = \frac{1}{4}\sum_{pqrs}\langle pq|O^{(2)}|rs\rangle\{p^\dagger q^\dagger sr\}$$

One- and two-body currents and normal ordering in Coupled-Cluster

CCSD similarity transformed normal-ordered current operator: $T = T_1 + T_2$

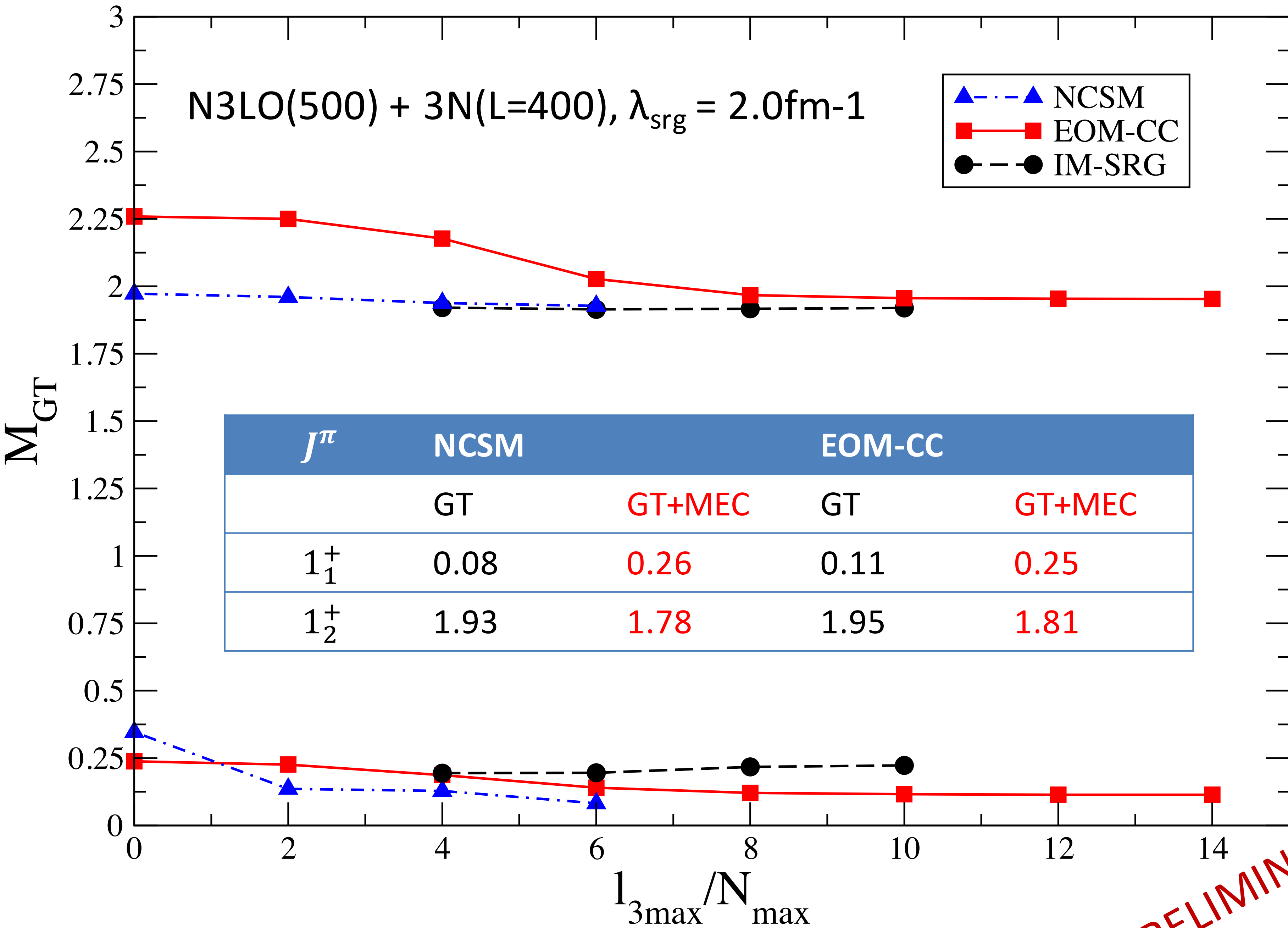
3-body terms

6-body terms

$$\overline{O_{\mathrm{GT}}} = e^{-T} O_N e^{T} = e^{-T} O_N^1 e^{T} + e^{-T} O_N^2 e^{T}$$

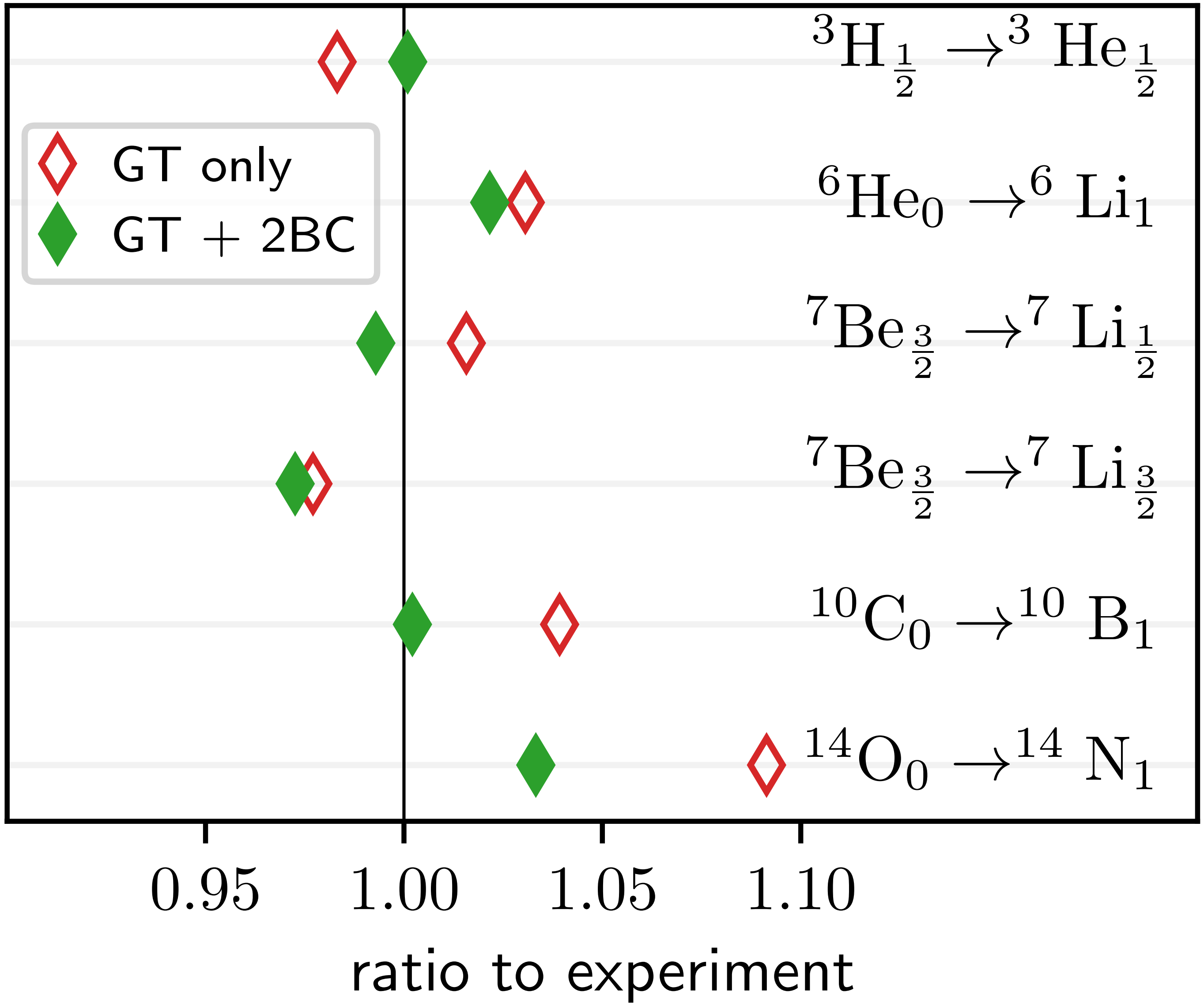
Normal-ordered 1-body approximation

Benchmarks for Gamow-Teller transitions in ^{14}C



J^π	NCSM		EOM-CC	
	GT	GT+MEC	GT	GT+MEC
1^+_1	0.08	0.26	0.11	0.25
1^+_2	1.93	1.78	1.95	1.81

Theory to experiment ratios for beta decays in light nuclei from NCSM



Role of 2BC in light nuclei small except for the large transition in ^{14}O

NN at N4LO
Entem, Machleidt, Nosyk, Phys. Rev. C 96, 024004 (2017)

3NF at N2LO (local non-local regulated)

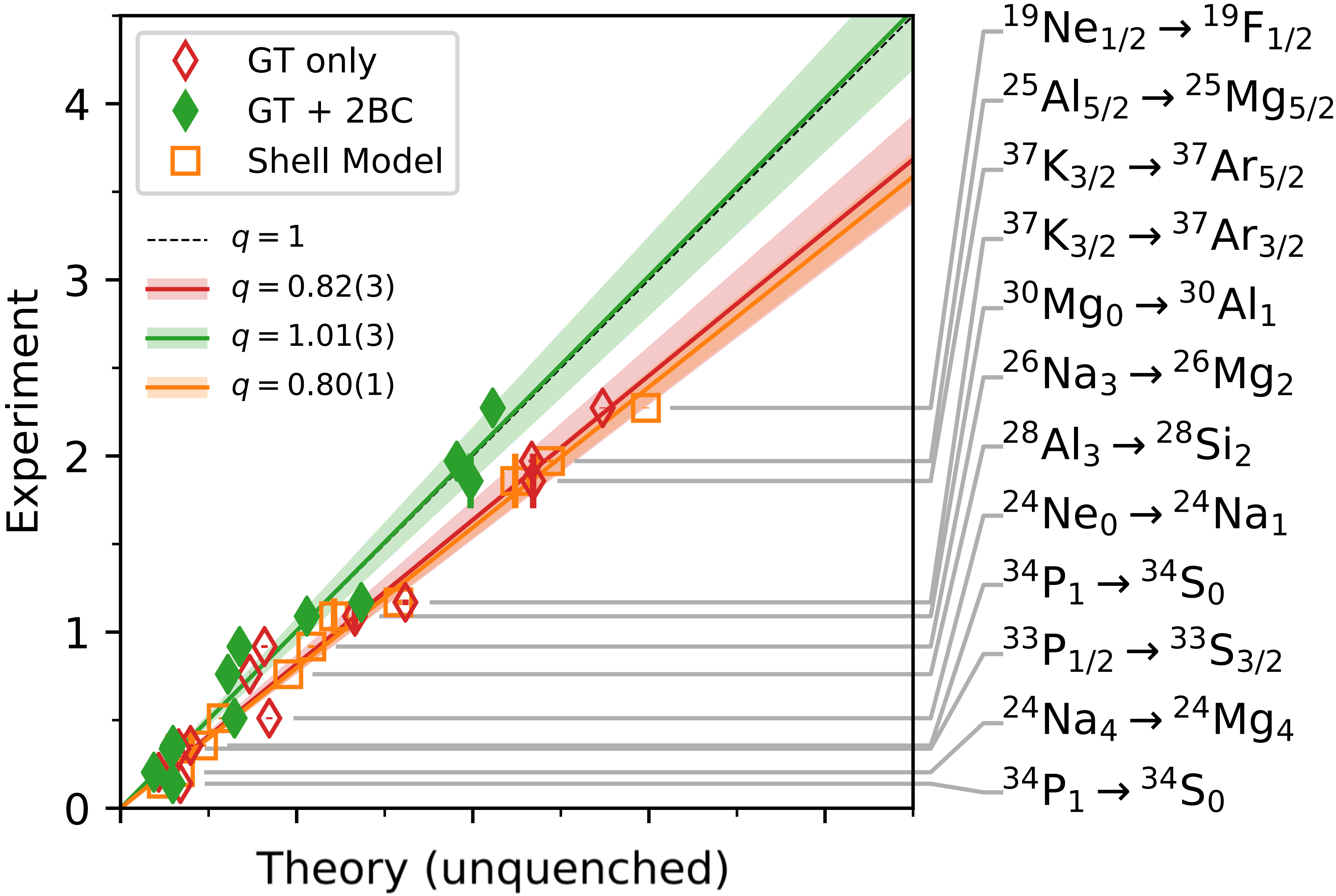
2BC fit to triton half-life (cD = 0.45)

Consistently SRG-evolved to 2.0fm^{-1}

See Sofia's talk for details

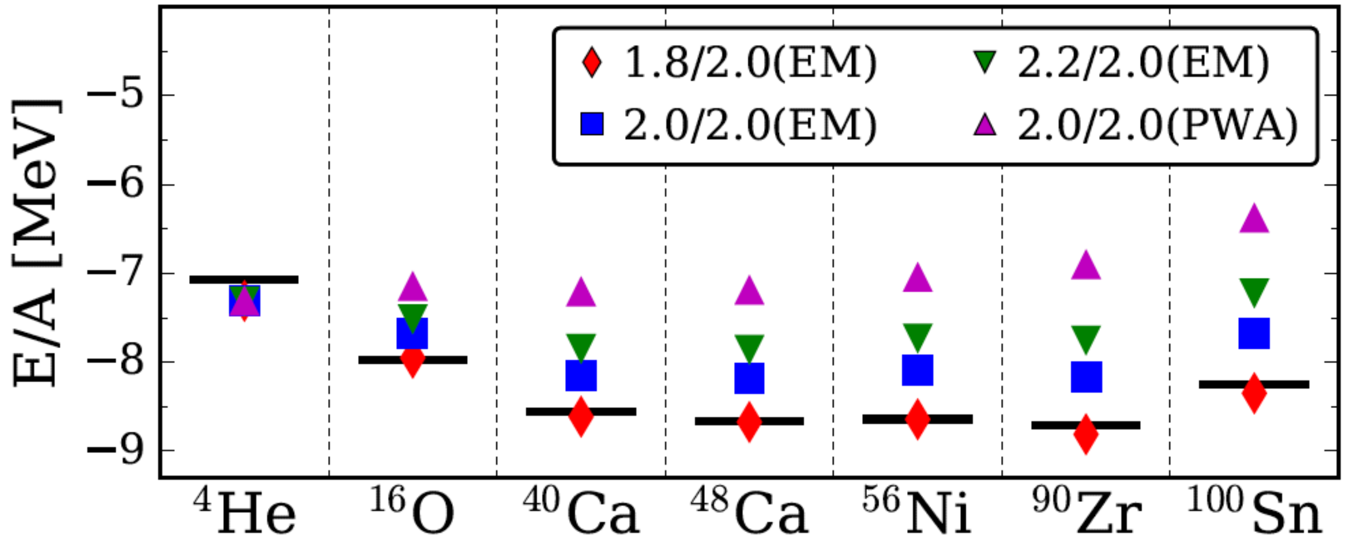
The role of 2BC in sd-shell nuclei

See Jason Holt's talk

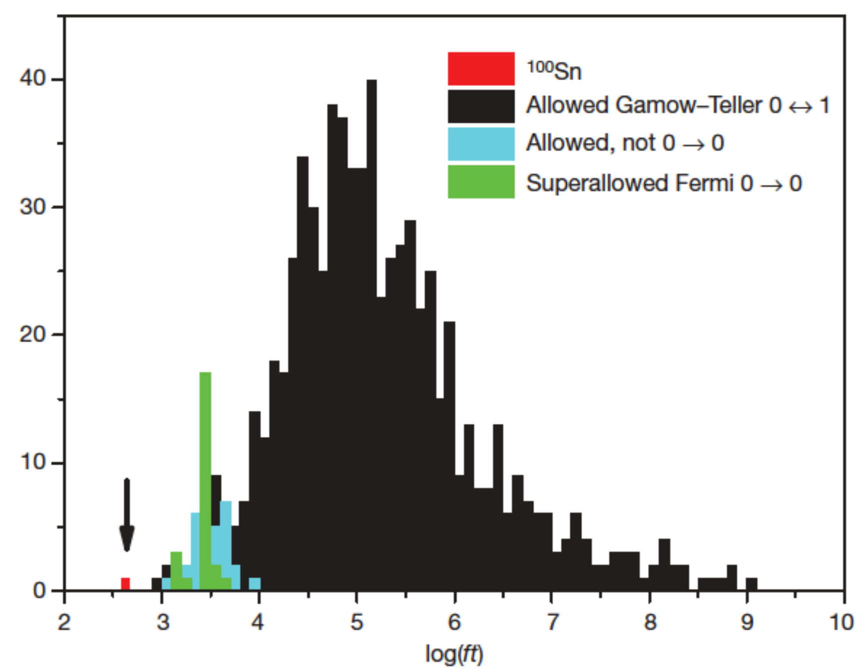


Gamow-Teller transition in ^{100}Sn

T. Morris *et al*, arXiv:1709.02786 (2017).

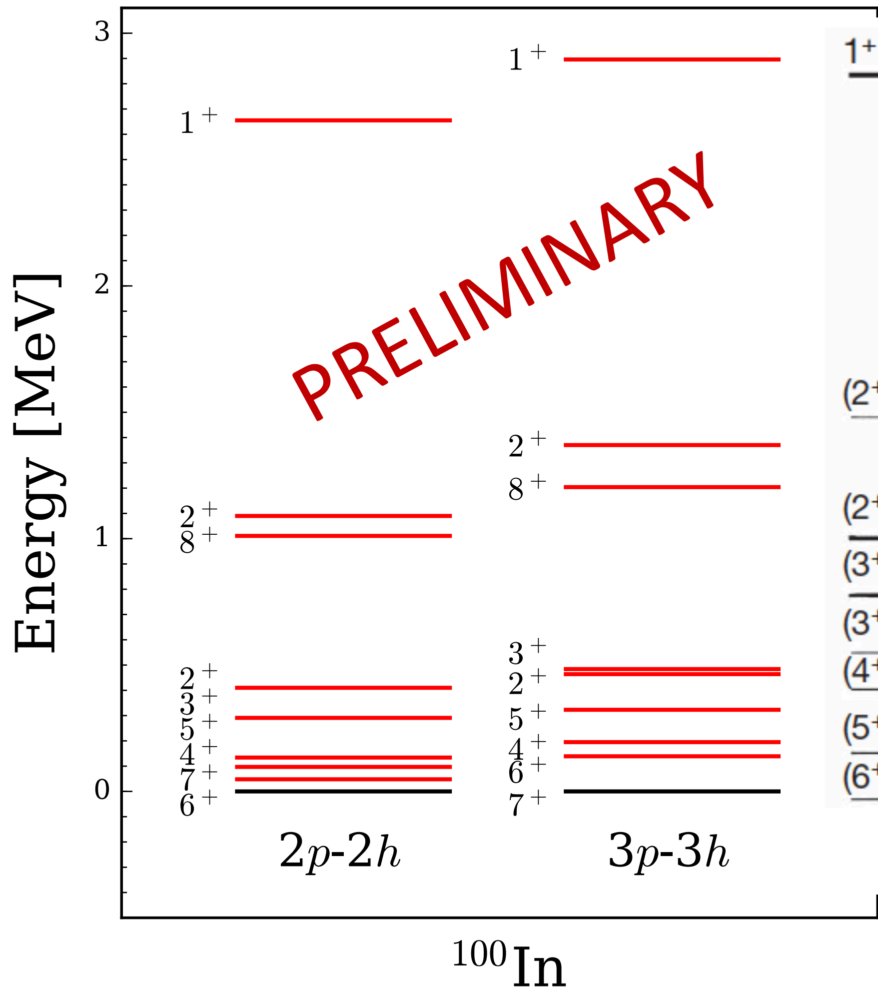


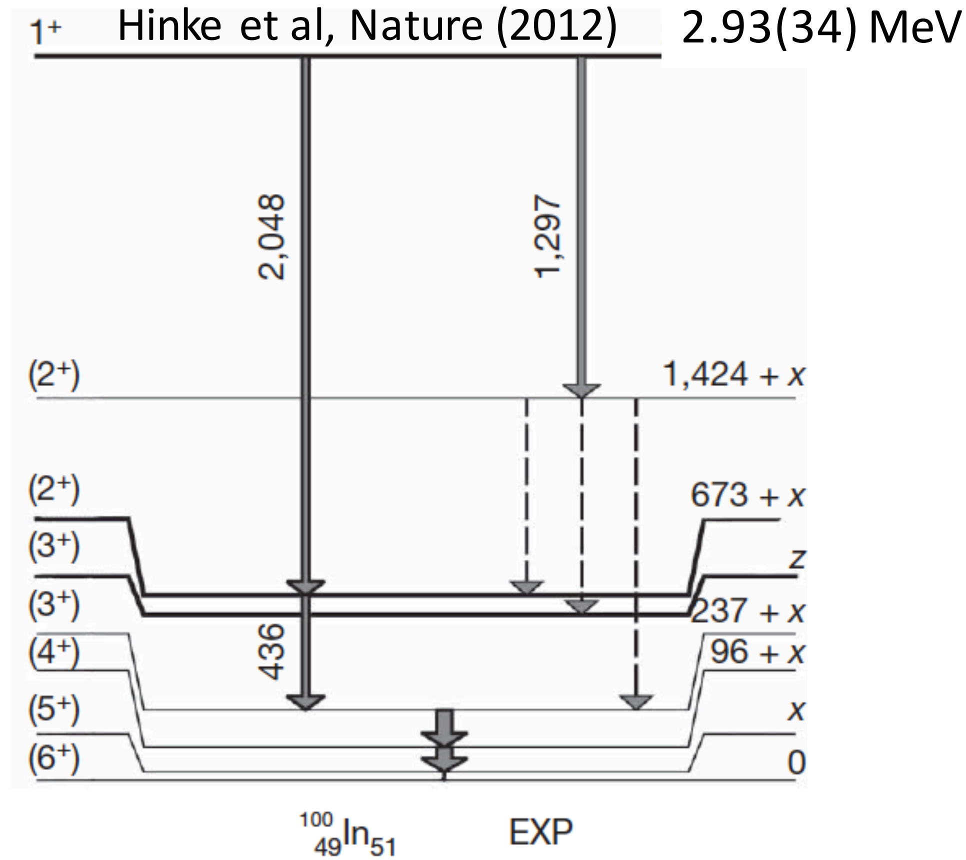
Hinke et al, Nature (2012)



- ^{100}Sn is doubly magic and in the closest proximity to the proton dripline
- ^{100}Sn is ideally suited for first principles approaches
- Largest known strength in allowed nuclear β-decay

^{100}In from charge exchange coupled-cluster equation-of-motion method



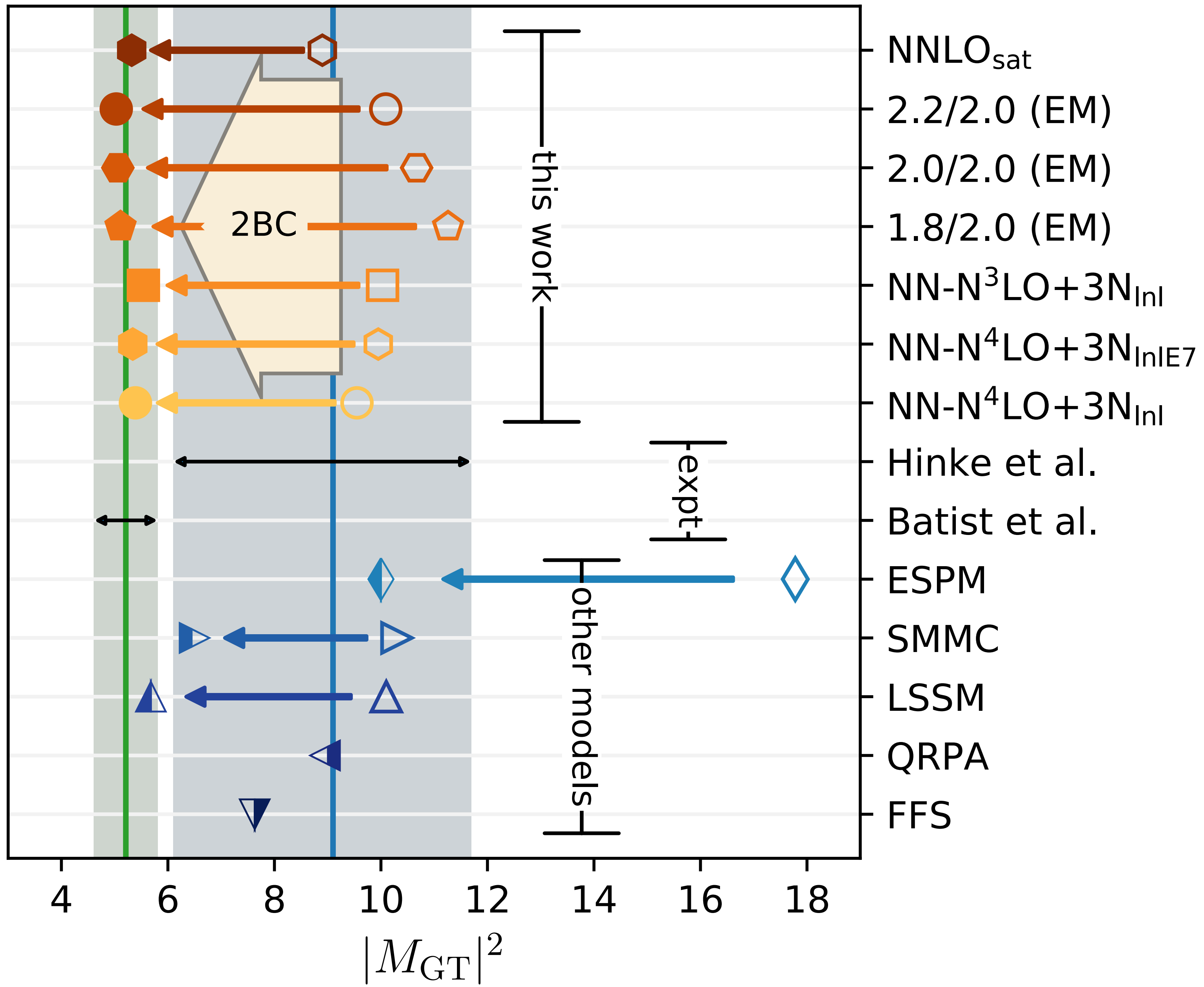


3p-3h charge-exchange EOM:

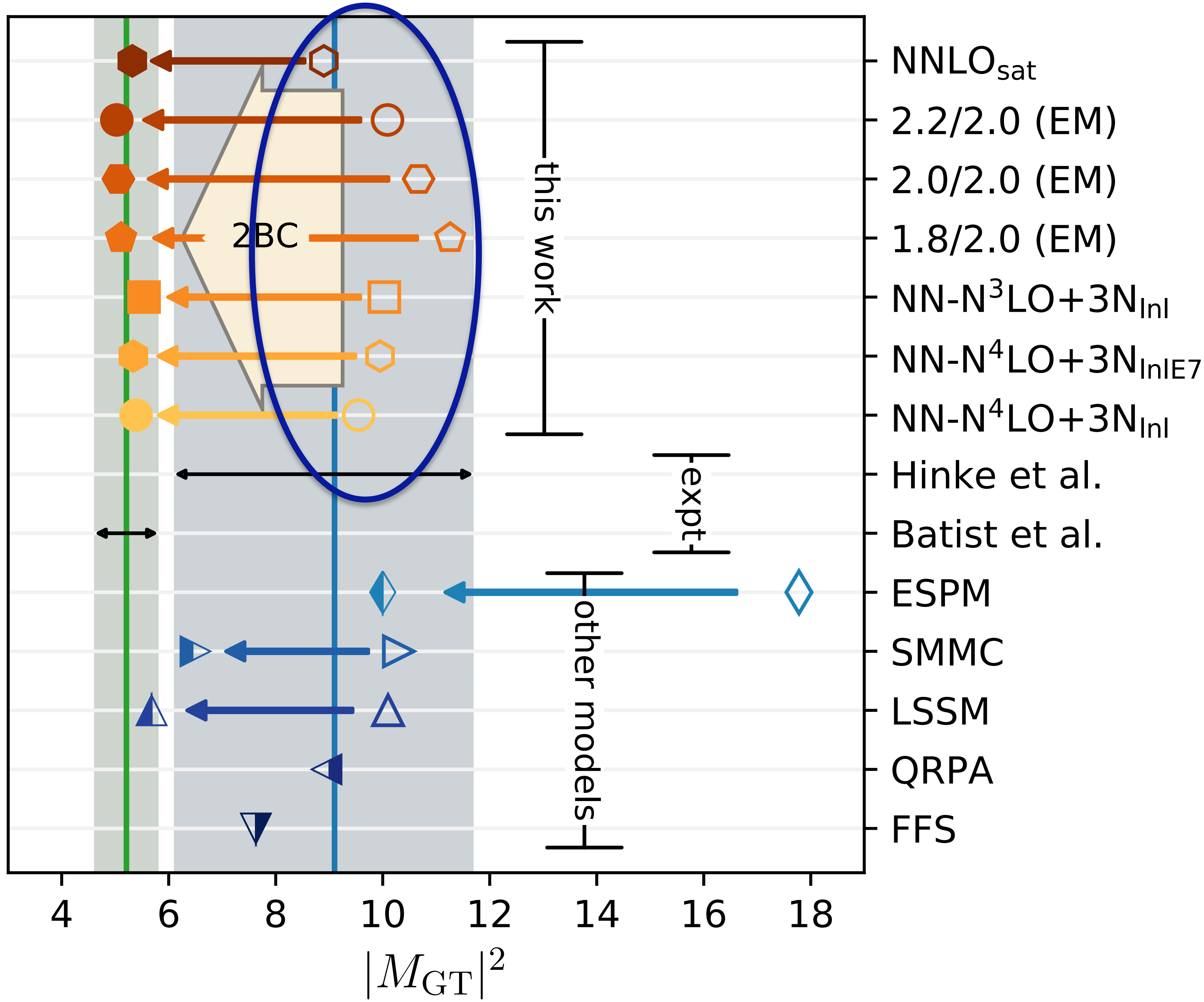
$$\overline{H}_N R_\mu |\Phi_0\rangle = E_\mu R_\mu |\Phi_0\rangle$$

- Reproduce known 1^+ state at 2.93(34) MeV
- Predict a 7^+ ground-state for ^{100}In
- Ground-state spin of ^{100}In can be measured by CRIS collab. at CERN

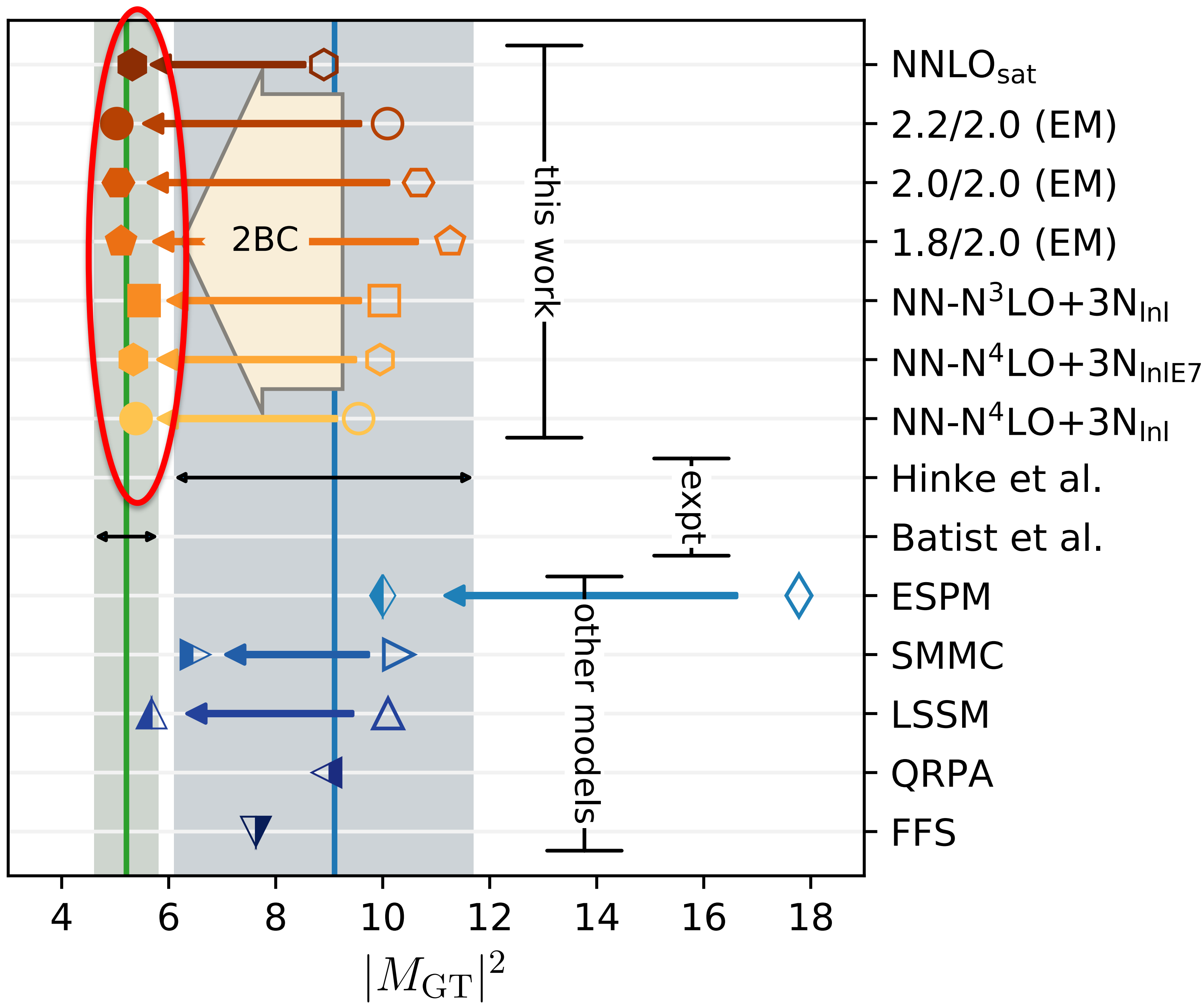
Super allowed Gamow-Teller decay of ^{100}Sn



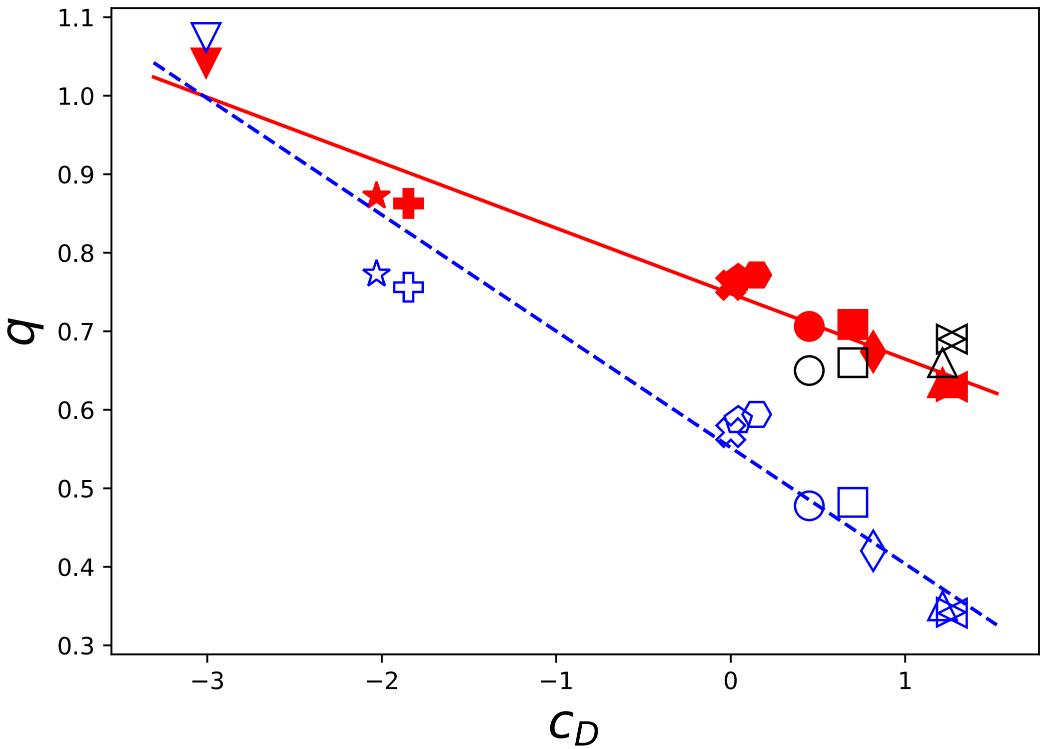
Super allowed Gamow-Teller decay of ^{100}Sn



Super allowed Gamow-Teller decay of ^{100}Sn



A simple interpretation of the quenching of beta decays



Contributions pion exchange to the 2BC gives roughly half of the necessary quenching

Contributions from the short range part accounts for the remainder.

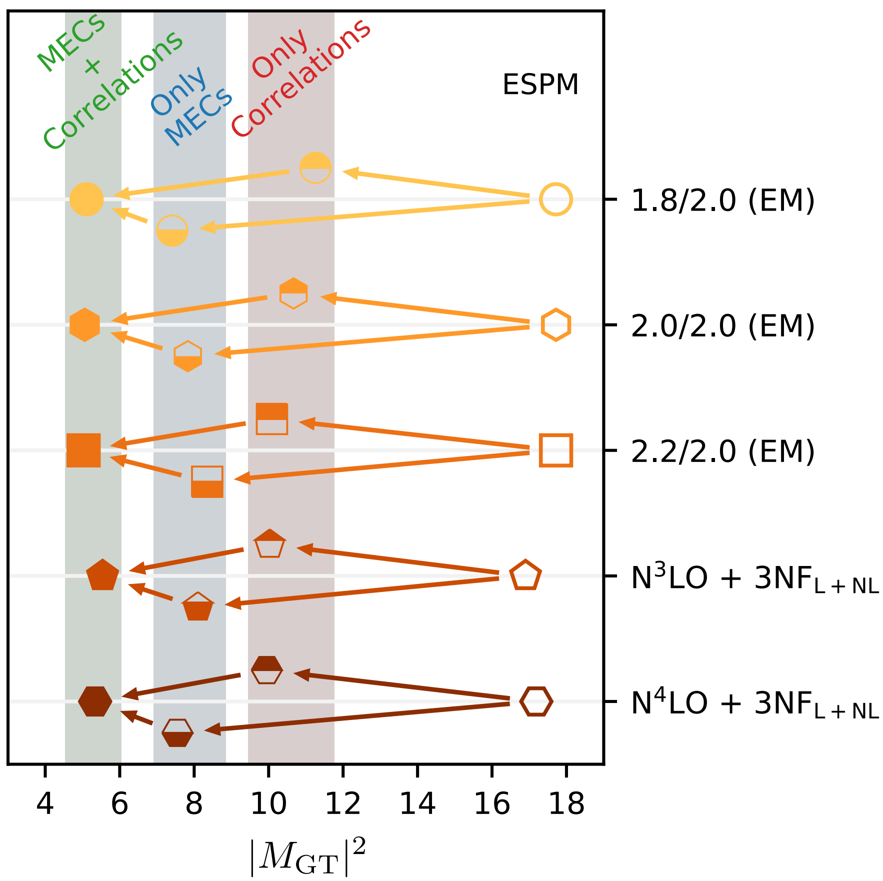
J. Menéndez, D. Gazit, A. Schwenk
PRL 107, 062501 (2011)

Interaction	c_D	$2c_4 - c_3$	Λ [GeV]	Ref.
NNLO$_{sat}$	0.817	11.46	0.7	[24]
NN-N^{4}LO +3N$_{lnl}$	0.45	13.88	0.7	[37]
NN-N^{4}LO +3N$_{lnlE7}$	0.45	13.88	0.7	
NN-N^{3}LO +3N$_{lnl}$	0.7	14.0	0.7	[25]
1.8/2.0 (EM)	1.264	14.0	0.7	[23]
2.0/2.0 (EM)	1.271	14.0	0.7	[23]
2.2/2.0 (EM)	1.214	14.0	0.7	[23]
2.0/2.0 (PWA)	−3.007	12.7	0.7	[23]
Pastore 500	−1.847	14.0	1.0	[26]
Pastore 600	−2.03	14.13	1.0	[26]
Ekström 450	0.0004	13.22	0.7	[50]
Ekström 500	0.0431	12.50	0.7	[50]
Ekström 550	0.1488	11.71	0.7	[50]

One-body normal ordering of 2BC in free Fermi gas

$$q \approx 1 - \frac{\rho \hbar^3 c^3}{F_\pi^2}\left(\frac{c_D}{g_A \Lambda} + \frac{I}{3}(2c_4 - c_3) + \frac{I}{6m}\right)$$

Role of 2BC and correlations



The role of correlations and 2BC for the family of EFT interactions employed in this work.

Depending on whether one goes along the upper or lower path the role of correlations versus the role of 2BC on the quenching is different. Of course, only the sum of the effects from correlations and 2BC are observable.

Interaction	$\lvert m_{GT}(\sigma\tau)\rvert^2$	$\lvert M_{GT}(\sigma\tau)\rvert^2$	$\lvert m_{GT}\rvert^2$	$\lvert M_{GT}\rvert^2$	q	q (ESPM)	ΔE [MeV]	BE/A [MeV]
NNLO$_{sat}$	17.7	8.9	10.3	5.3	0.77	0.76	7.4	not converged
NN-N^{4}LO+3N$_{lnl}$	17.2	9.6	8.7	5.4	0.75	0.71	6.3	8.1
NN-N^{4}LO+3N$_{lnlE7}$	17.2	10.0(6)	7.6	5.3(6)	0.73	0.66	3.6	8.9
NN-N^{3}LO+3N$_{lnl}$	16.9	10.0(6)	8.1	5.5(6)	0.74	0.69	6.1	7.6
1.8/2.0 (EM)	17.7	11.3(6)	7.4	5.1(6)	0.67	0.65	5.1	8.4
2.0/2.0 (EM)	17.7	10.7(6)	7.8	5.1(6)	0.69	0.66	6.0	7.7
2.2/2.0 (EM)	17.7	10.1(6)	8.4	5.0(6)	0.70	0.69	6.7	7.2
Batist *et al.* [6] Hinke *et al.* [5]				5.2 ± 0.6 $9.1^{+2.6}_{-3.0}$			5.11	8.25

Neutrinoless ββ-decay of ^{48}Ca

$$|\langle {}^{48}\mathrm{Ti}|O|{}^{48}\mathrm{Ca}\rangle|^2 = \langle {}^{48}\mathrm{Ti}|O|{}^{48}\mathrm{Ca}\rangle\langle {}^{48}\mathrm{Ca}|O^\dagger|{}^{48}\mathrm{Ti}\rangle$$

Closure approximation with Gamow-Teller, Fermi and Tensor contributions:

$$M_{GT}^{0\nu} + \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu} + M_T^{0\nu}$$

The ground-state of ^{48}Ca is computed in the CCSD approximation:

$$\overline{H}_N|\Phi_0\rangle = E_0|\Phi_0\rangle,\;\; \overline{H}_N = e^{-T}H_N e^{T},\;\; T = T_1 + T_2$$

The CC energy functional is expressed in term of left/right ground-states

$$\langle\Phi_0|(1+\Lambda)\overline{H}_N|\Phi_0\rangle = E_0,\;\; \langle\Phi_0|(1+\Lambda)|\Phi_0\rangle = 1.$$

$$\Lambda = \sum_{ia}\lambda_a^i a_a a_i^\dagger + \frac{1}{2}\sum_{ijab}\lambda_{ab}^{ij} a_b a_a a_i^\dagger a_j^\dagger$$

Neutrinoless ββ-decay of ^{48}Ca

^{48}Ti is computed using a double charge exchange equation of motion method with 2p2h and 3p3h excitations

$$\overline{H}_N R_\mu |\Phi_0\rangle = E_\mu R_\mu |\Phi_0\rangle$$

$$\langle\Phi_0| L_\mu \overline{H}_N = \langle\Phi_0| L_\mu E_\mu$$

$$R_\mu = \frac{1}{4}\sum_{ijab} r_{ij}^{ab} p_a^\dagger p_b^\dagger n_i n_j + \frac{1}{36}\sum_{ijkabc} r_{ijk}^{abc} p_a^\dagger p_b^\dagger N_c^\dagger N_k n_i n_j$$

$$L_\mu = \frac{1}{4}\sum_{ijab} l_{ab}^{ij} p_b p_a n_i^\dagger n_j^\dagger + \frac{1}{36}\sum_{ijkabc} l_{abc}^{ijj} p_a p_b N_c N_k^\dagger n_i^\dagger n_j^\dagger$$

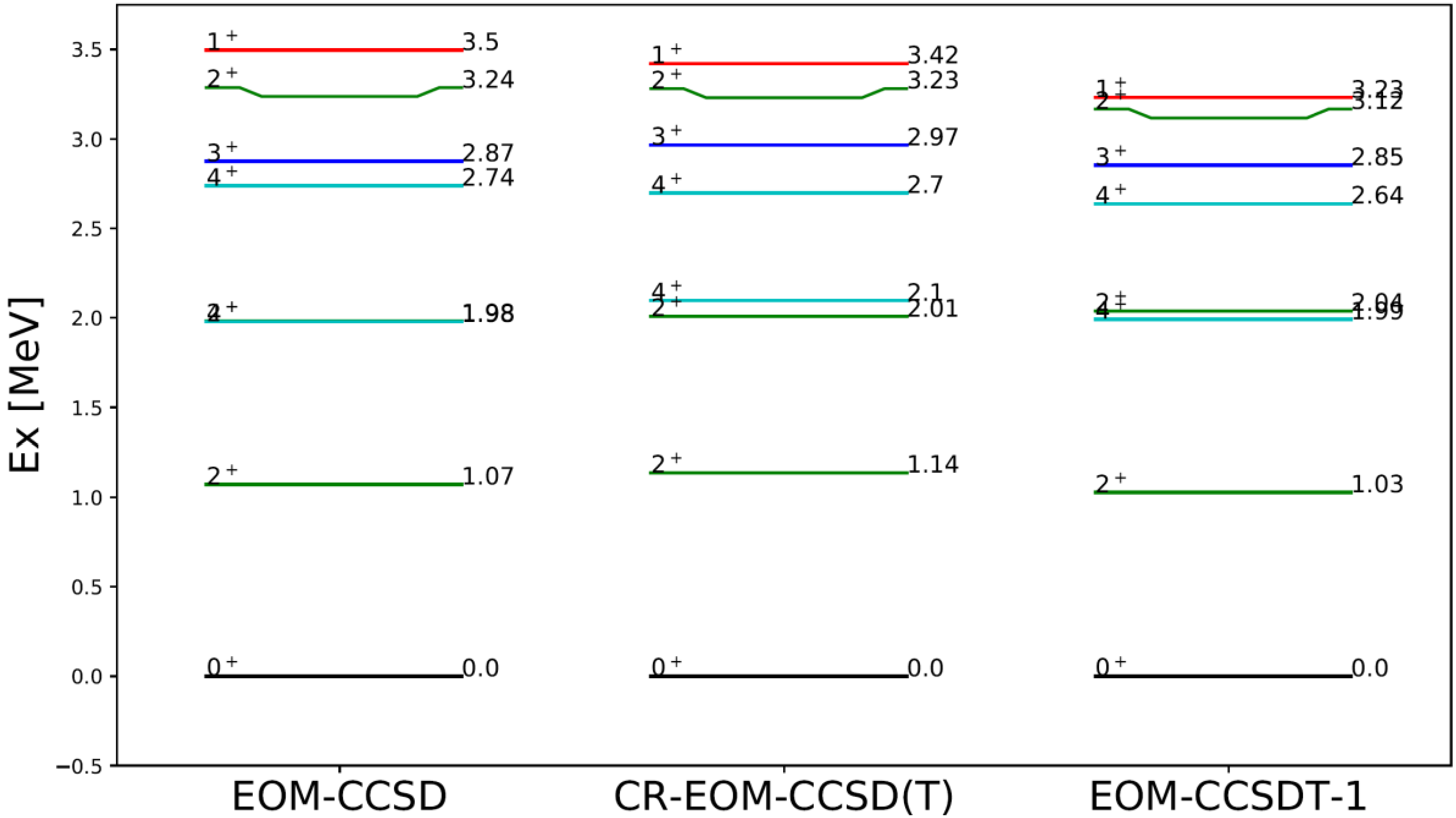
The Nuclear matrix element for 0νββ in ^{48}Ca is given by:

$$|\langle {}^{48}\mathrm{Ti}|O|{}^{48}\mathrm{Ca}\rangle|^2 = \langle {}^{48}\mathrm{Ti}|O|{}^{48}\mathrm{Ca}\rangle\langle {}^{48}\mathrm{Ca}|O^\dagger|{}^{48}\mathrm{Ti}\rangle$$

$$= \langle\Phi_0|L_0\overline{O}_N|\Phi_0\rangle\langle\Phi_0|(1+\Lambda)\overline{O^\dagger}_N R_0|\Phi_0\rangle$$

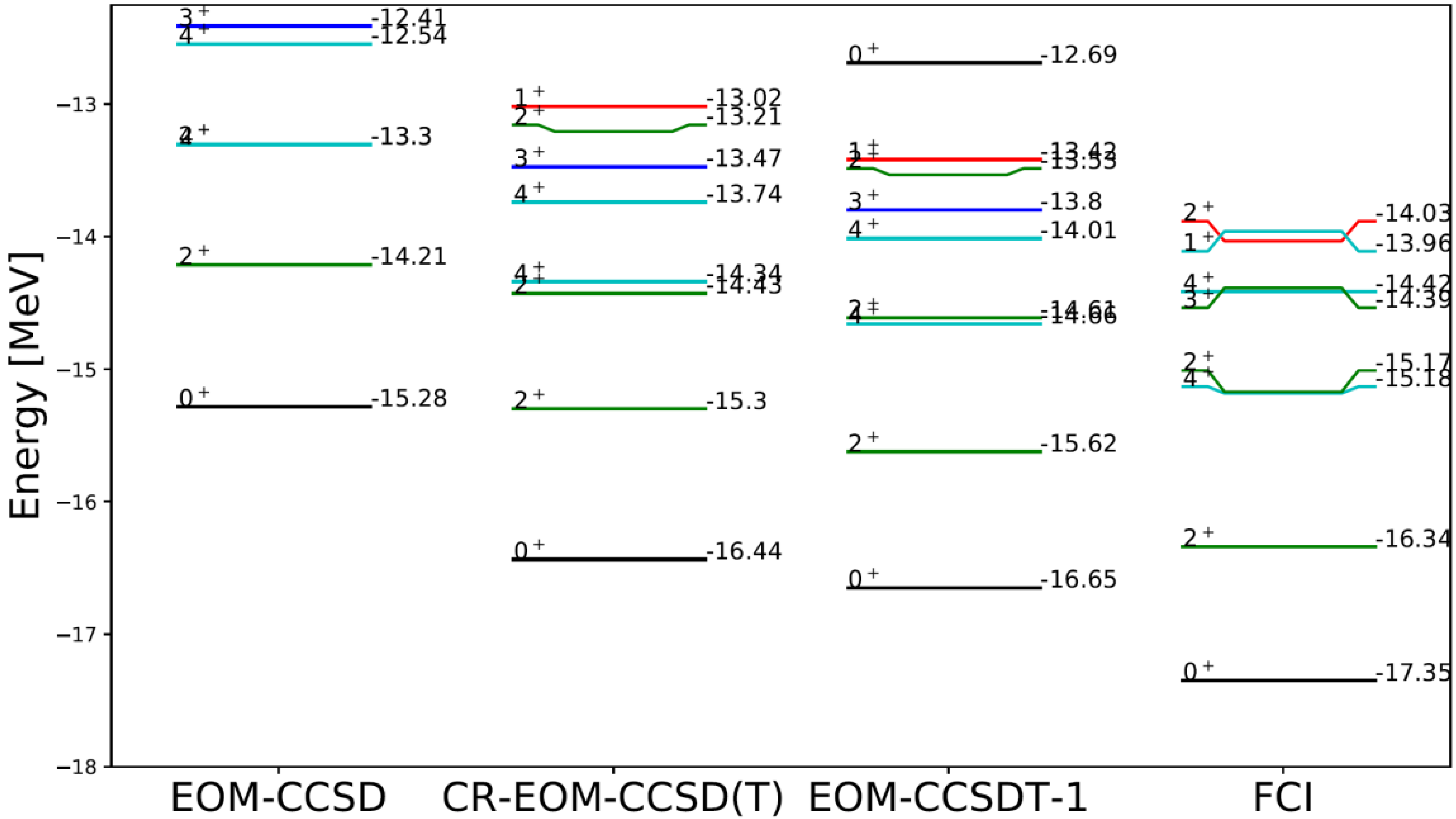
^{48}Ti from CR-EOM-CCSD(T)

$$R_\nu = \frac{1}{4}\sum r_{ij}^{ab}\, p_a^\dagger p_b^\dagger n_j n_i \qquad + \frac{1}{3!^2}\sum r_{ijk}^{abc}\, p_a^\dagger p_b^\dagger N_c^\dagger N_k n_j n_i$$

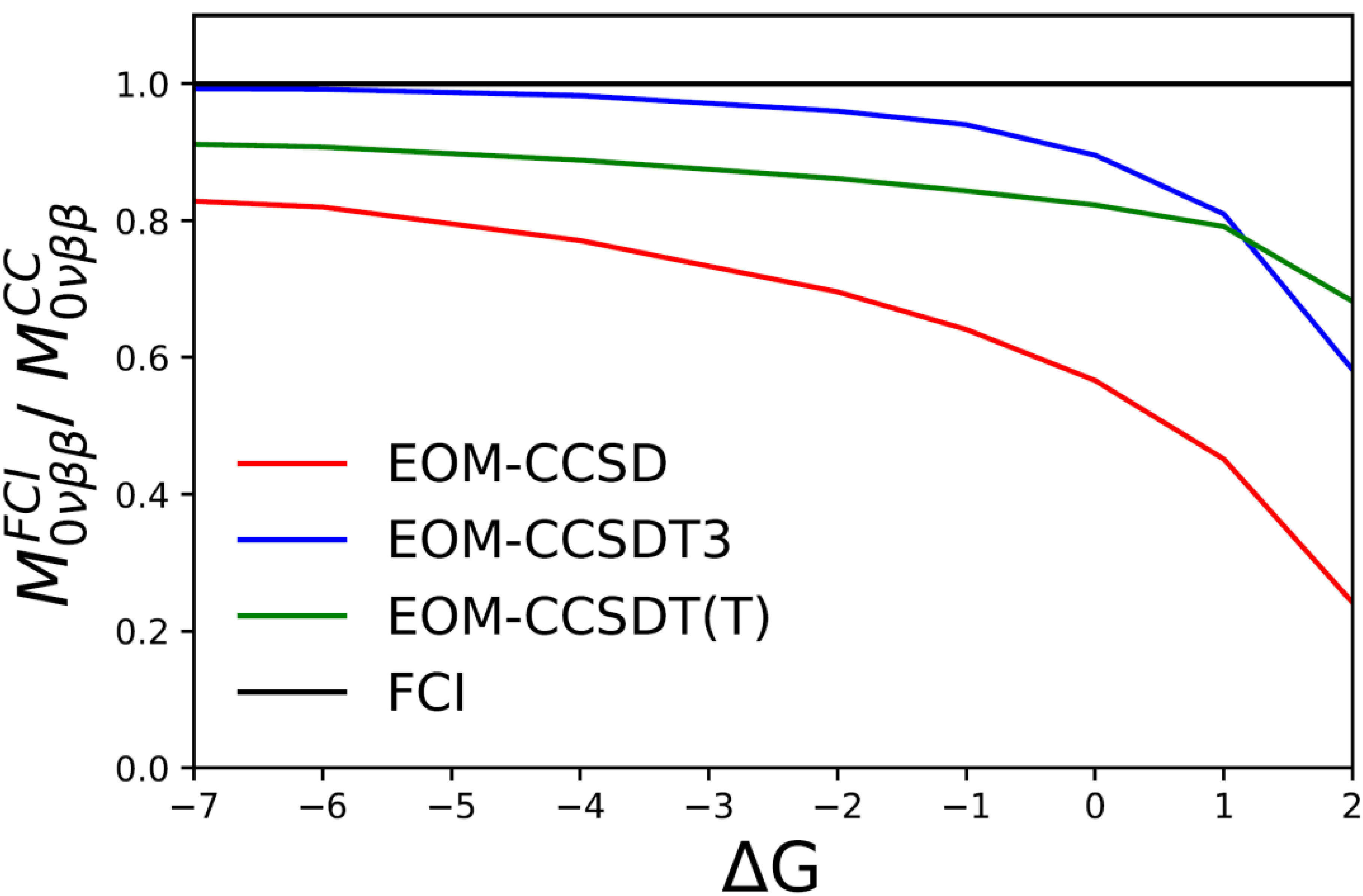


^{48}Ti from CR-EOM-CCSD(T)

$$R_\nu = \frac{1}{4}\sum r_{ij}^{ab}\, p_a^\dagger p_b^\dagger n_j n_i \qquad + \frac{1}{3!^2}\sum r_{ijk}^{abc}\, p_a^\dagger p_b^\dagger N_c^\dagger N_k n_j n_i$$



EOM-CR-CCSD(T)



1.0
0.8
0.6
0.4
0.2
0.0
−7
−6
−5
−4
−3
−2
−1
0
1
2
ΔG
$M^{FCI}_{0\nu\beta\beta} / M^{CC}_{0\nu\beta\beta}$
EOM-CCSD
EOM-CCSDT3
EOM-CCSDT(T)
FCI

Neutrinoless ββ-decay of ^{48}Ca

NME for $0\nu\beta\beta$			
Method	GT	Fermi	Tensor
CCSD	0.97	0.31	-0.12
CCSDT-1(10)	0.44	0.09	-0.11
CCSDT-1(12)	0.50	0.11	-0.11
CCSDT-1(14)	0.45	0.10	-0.11

PRELIMINARY

- NME computed with the chiral NN + 3N interaction 1.8/2.0 (EM) [K. Hebeler *et al* PRC (2011)]
- Model-space N_{max} =10, hw = 22MeV.
- Not fully converged
- Consistent with IM-SRG results (See Jason Holt's talk)

Summary

- Forces and 2BCs from chiral EFT explain the quenching of GT strength in atomic nuclei (Also see talk by Jason Holt).

- Make predictions for the super allowed GT transition in ^{100}Sn

- The NME for $0\nu\beta\beta$ in ^{48}Ca from coupled-cluster calcualtions consistent with IM-SRG results and smaller than expected

Collaborators

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