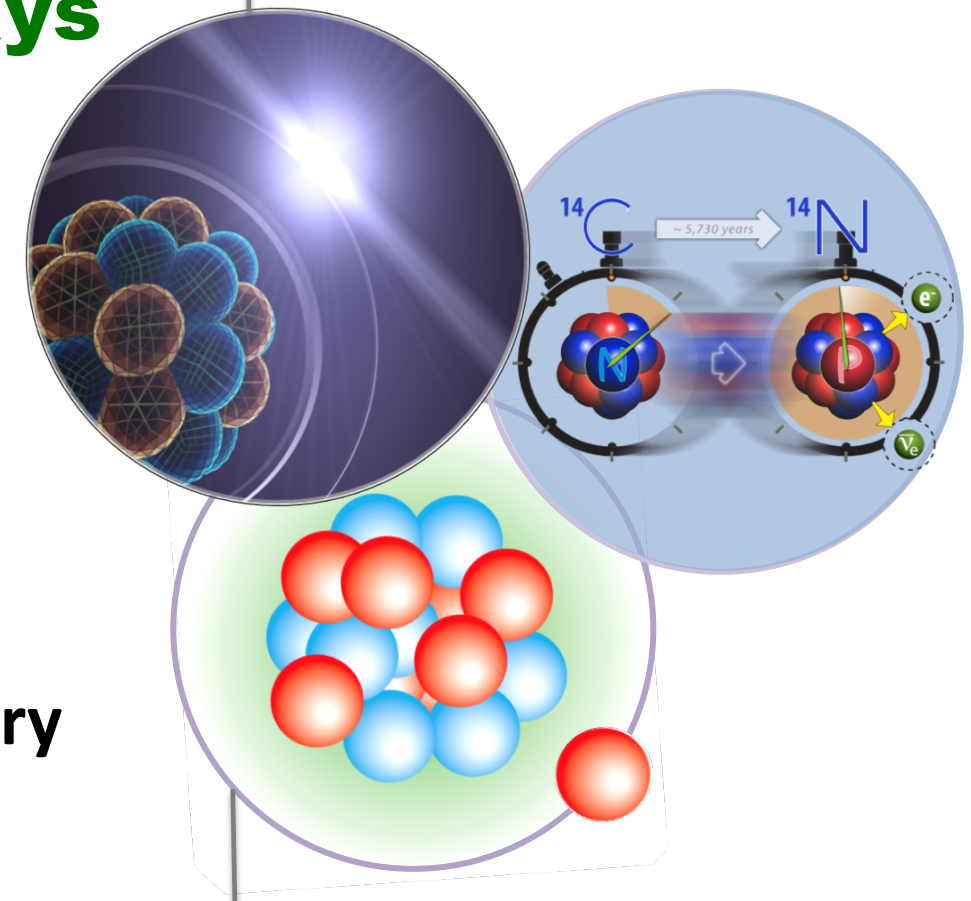
A (proposed) solution to the puzzle of quenched beta-decays

A quantum computation of an atomic nucleus



Gaute Hagen
Oak Ridge National Laboratory

TRIUMF Colloquium
Vancouver, March 1st, 2018

U.S. DEPARTMENT OF ENERGY

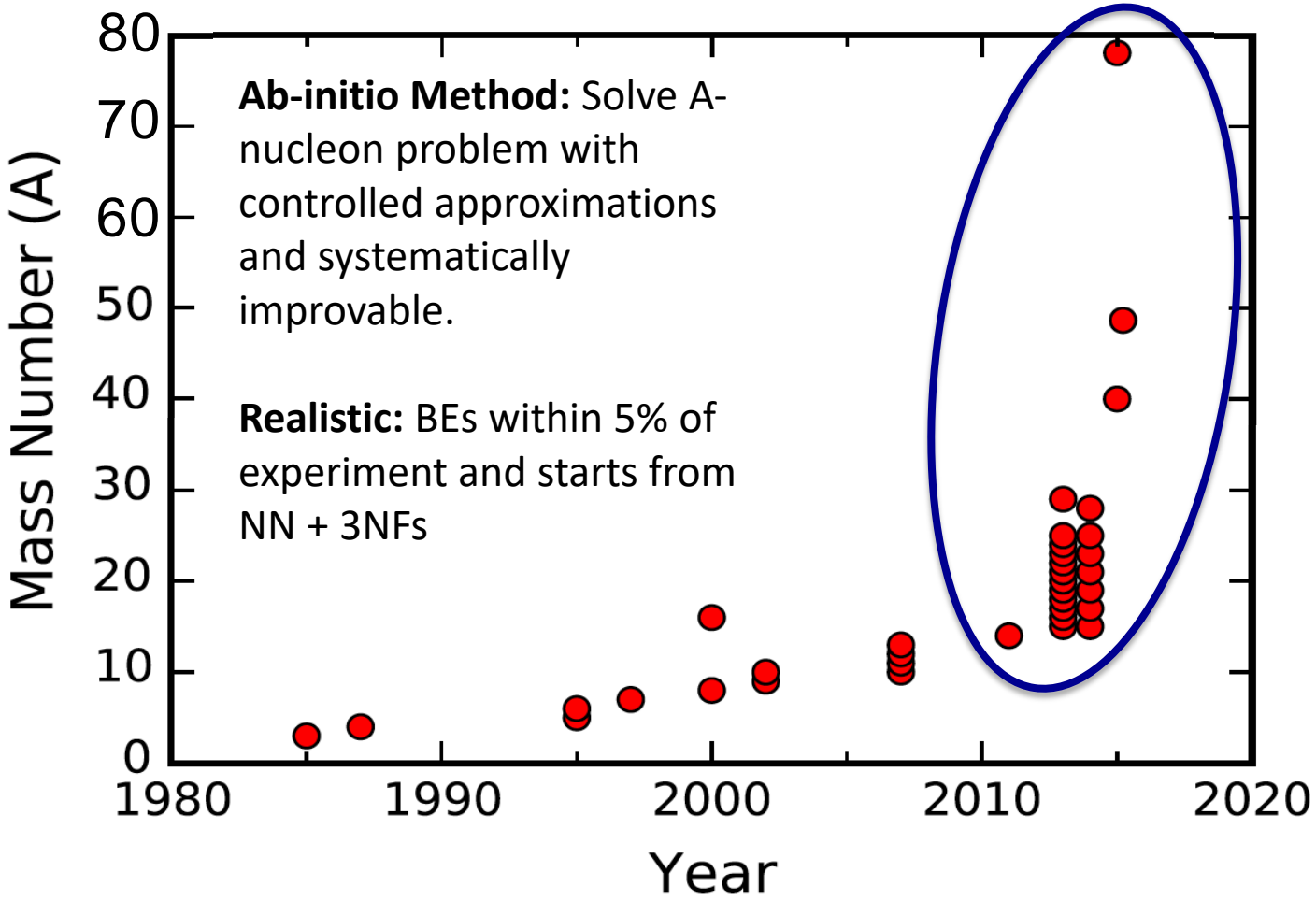
NUCLEI
Nuclear Computational Low-Energy Initiative

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

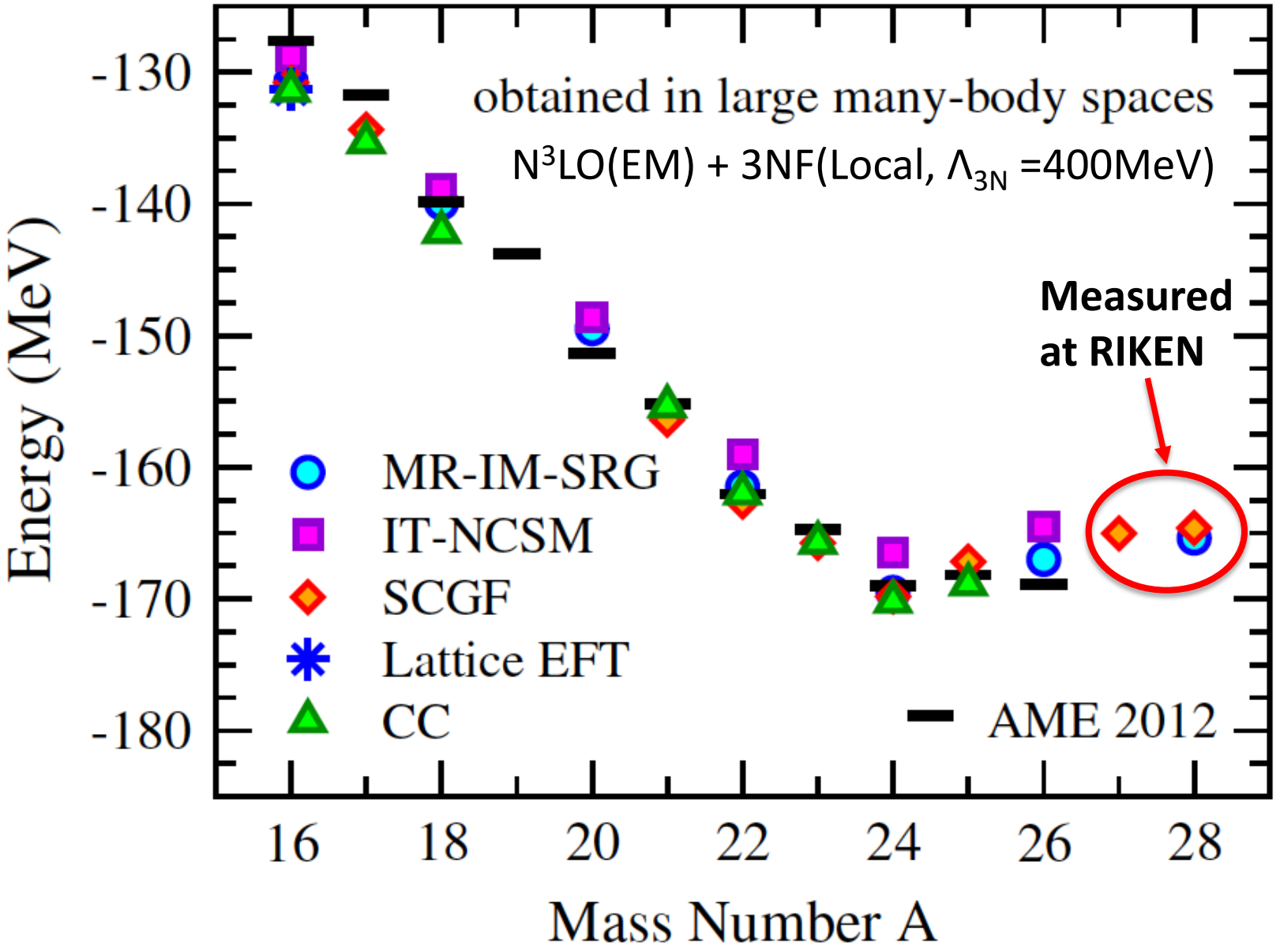
Trend in realistic ab-initio calculations

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 ($V_{low\text{-}k}$, Similarity Renormalization Group, …)



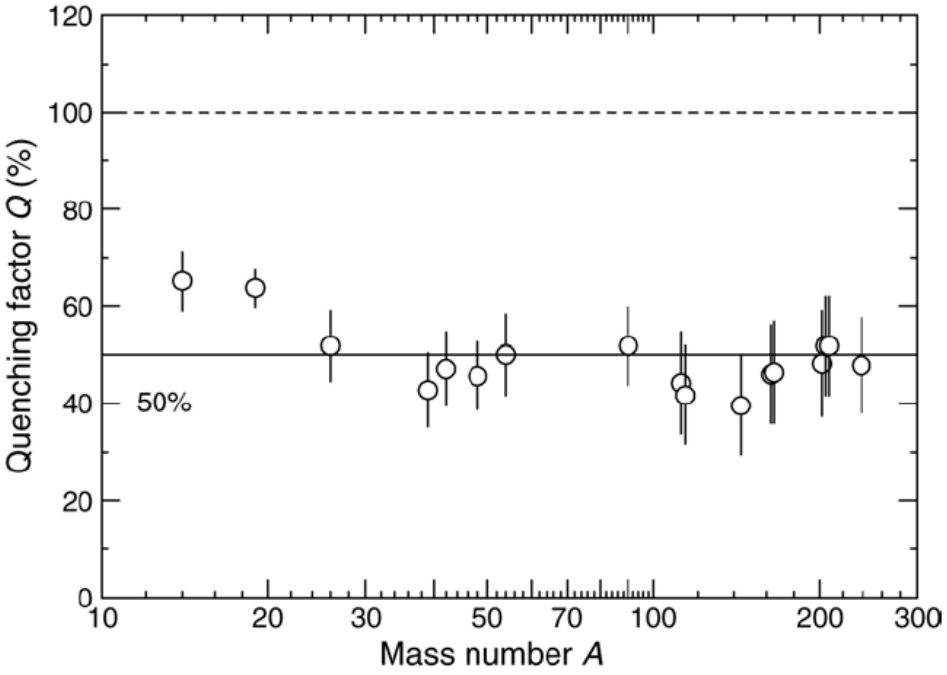
Oxgyen chain with interactions from chiral EFT



Hebeler, Holt, Menendez, Schwenk, Annu. Rev. Nucl. Part. Sci. 65, 457 (2015)

The puzzle of quenched of beta decays

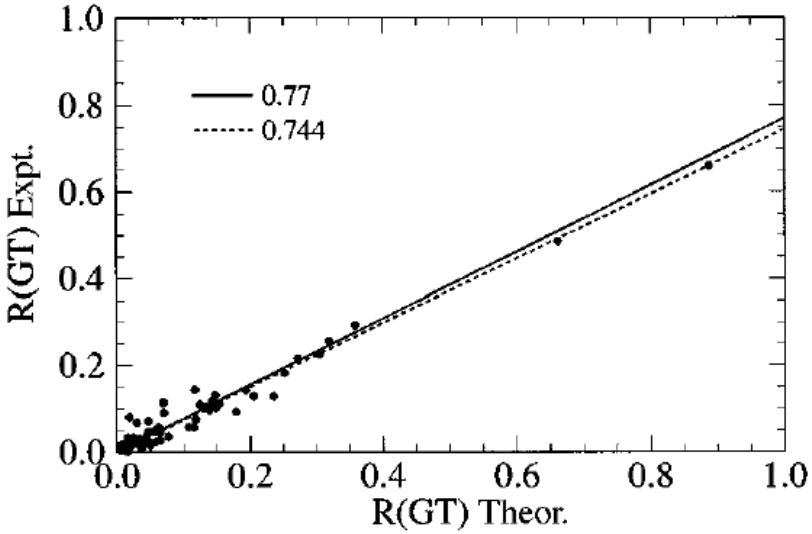
Long-standing problem: Experimental beta-decay strengths quenched compared to theoretical results.



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

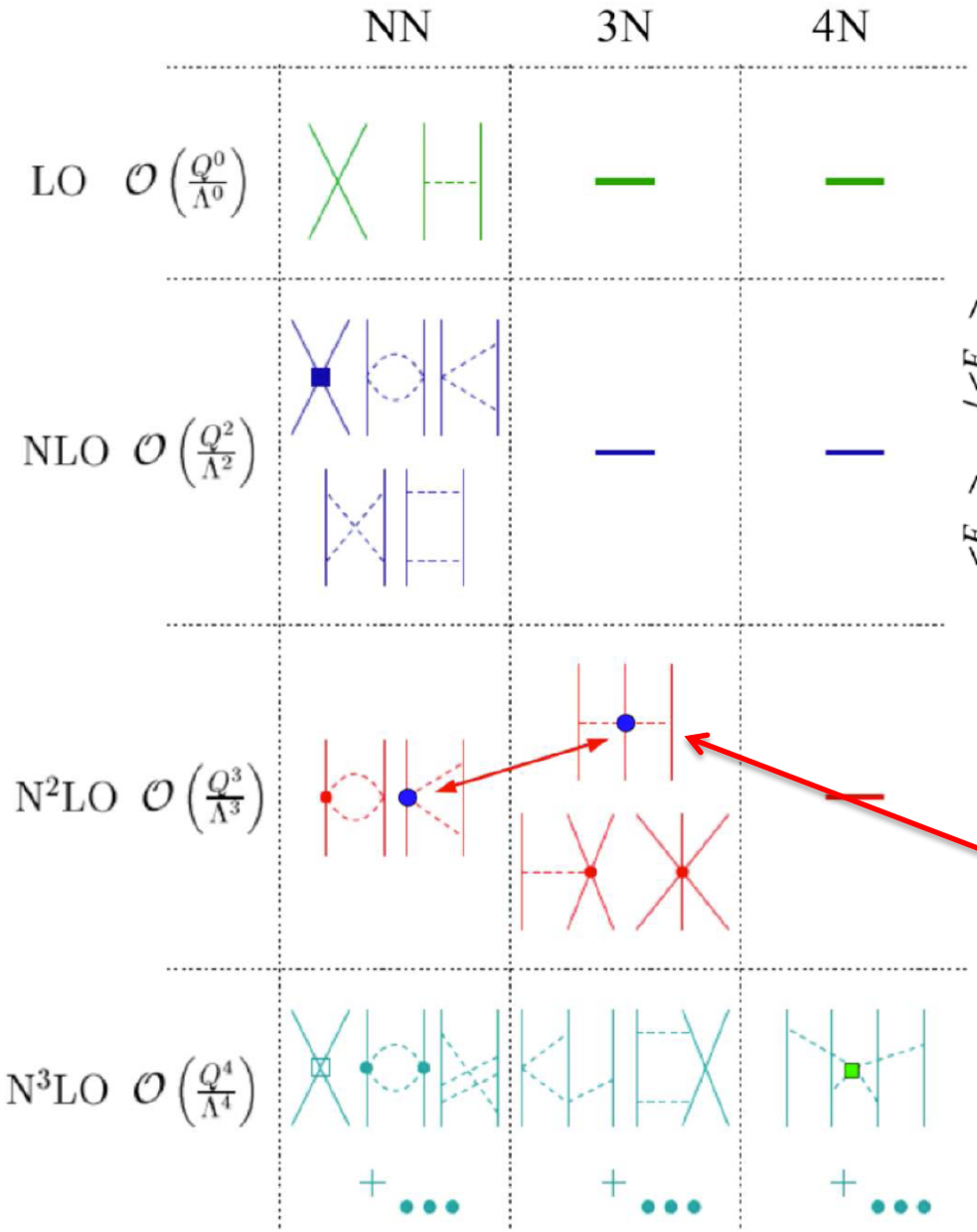
Quenching obtained from charge-exchange (*p,n*) experiments. (Gaarde 1983).

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

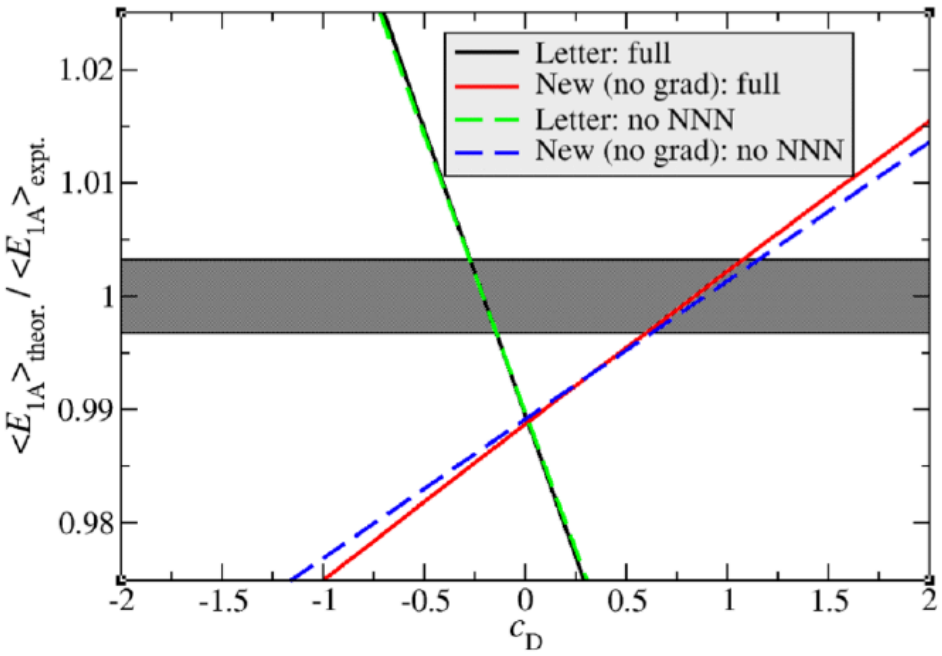


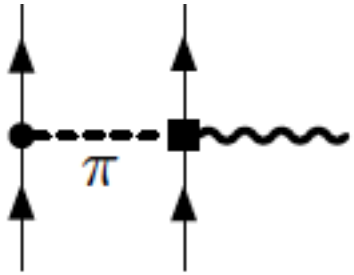
Nuclear forces from chiral effective field theory

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

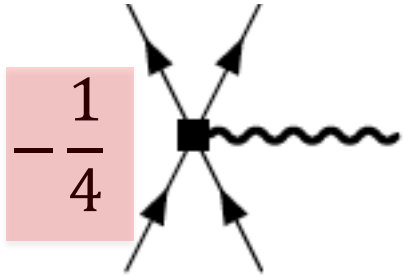


From Sofia Quaglioni and Kyle Wendt



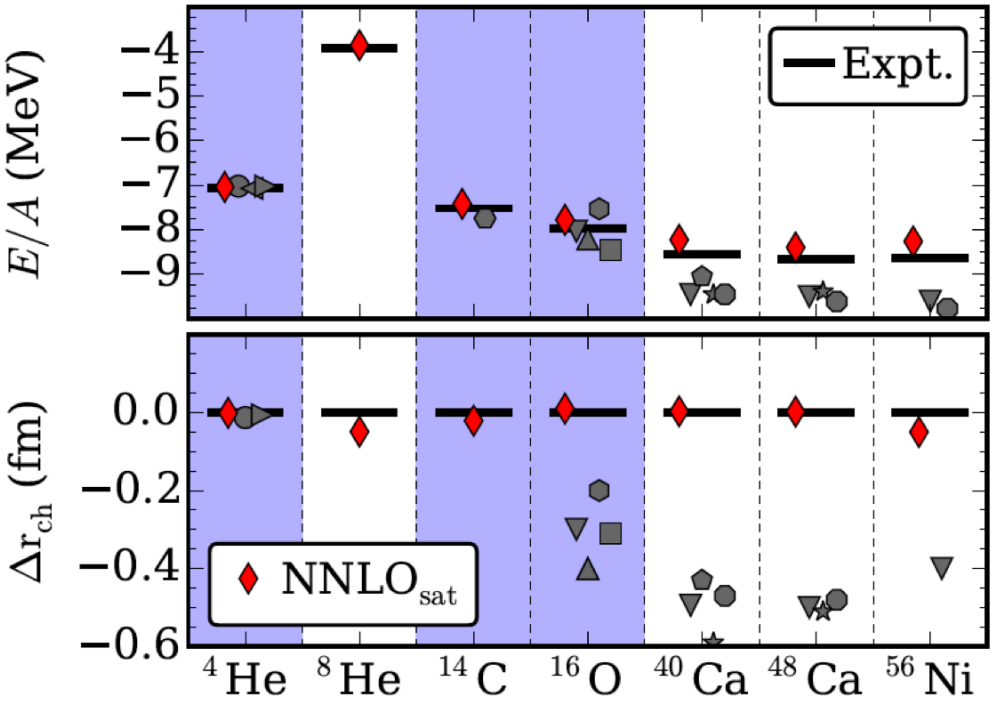


c_3, c_4



c_D

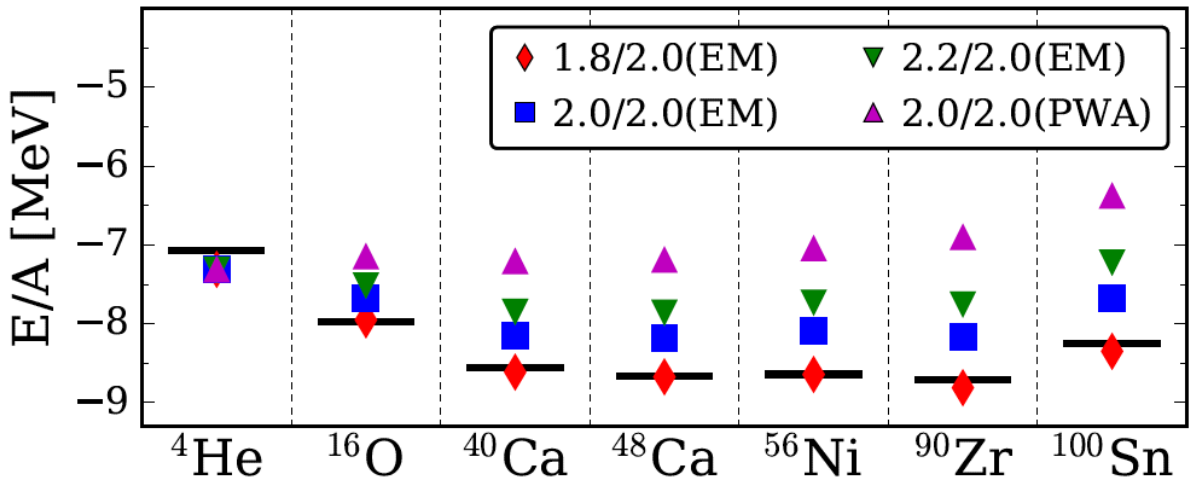
A family of interactions from chiral EFT



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).

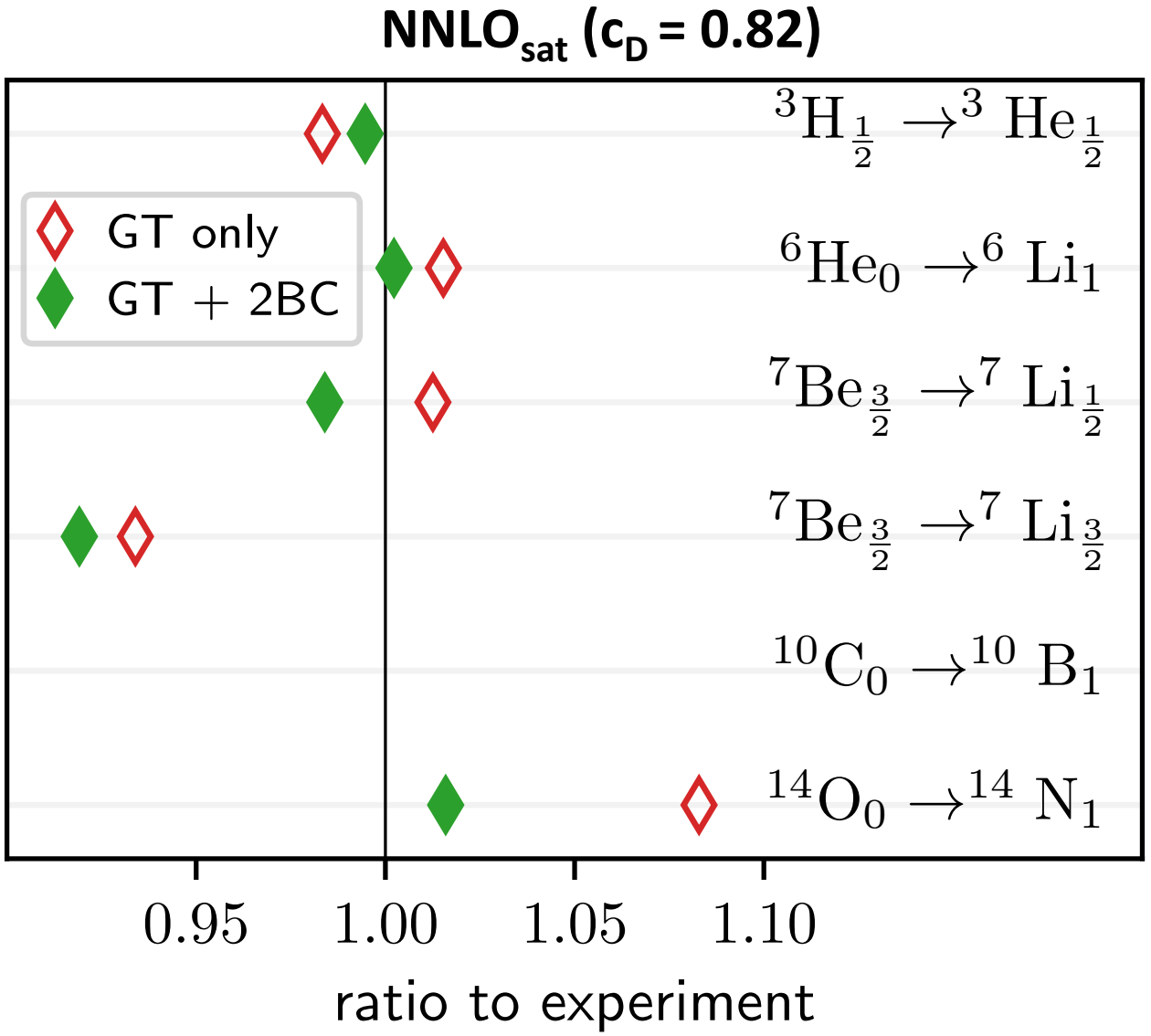


1.8/2.0(EM): Accurate BEs

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

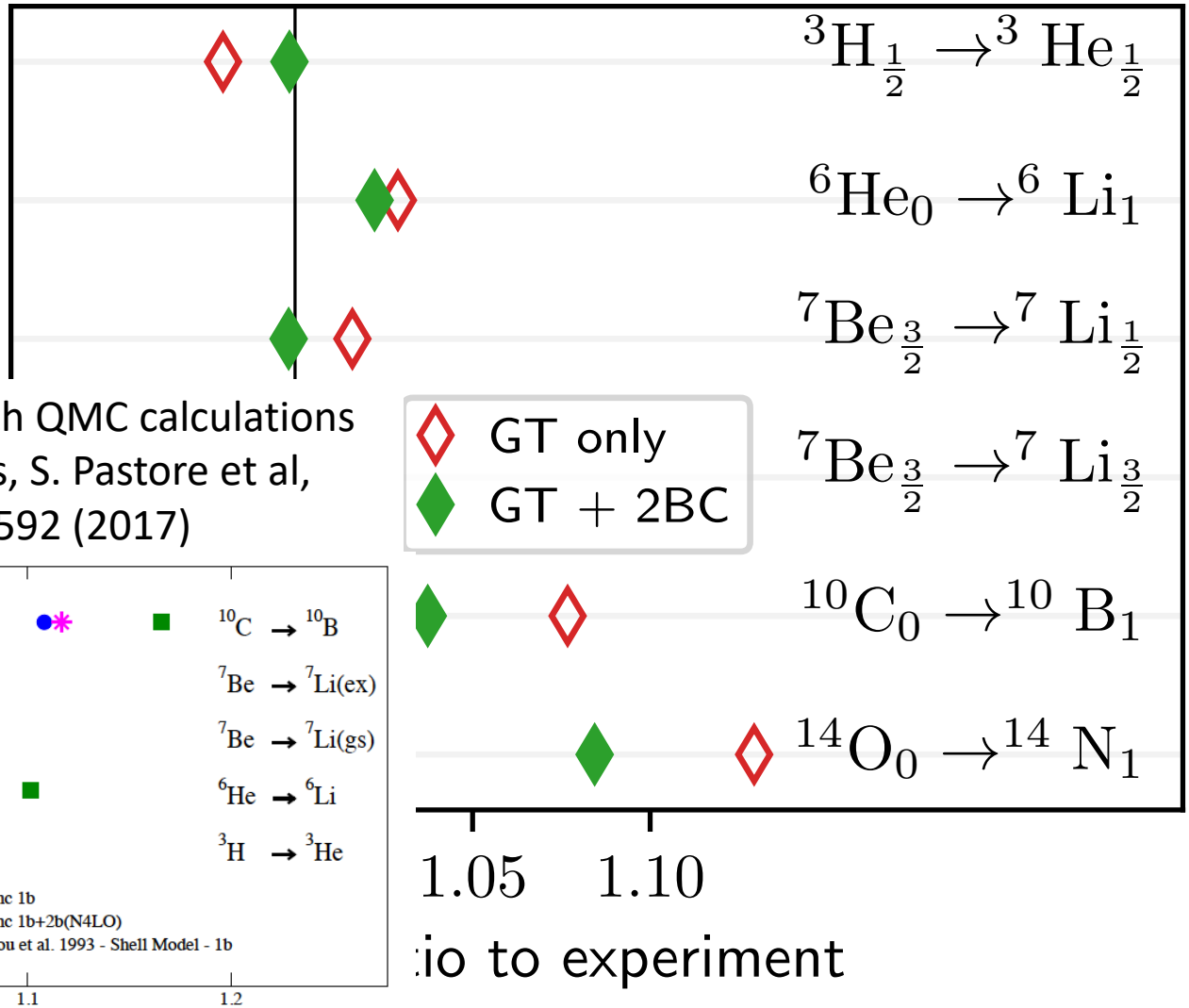
K. Hebeler *et al* PRC (2011).
T. Morris *et al*, arXiv:1709.02786 (2017).

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



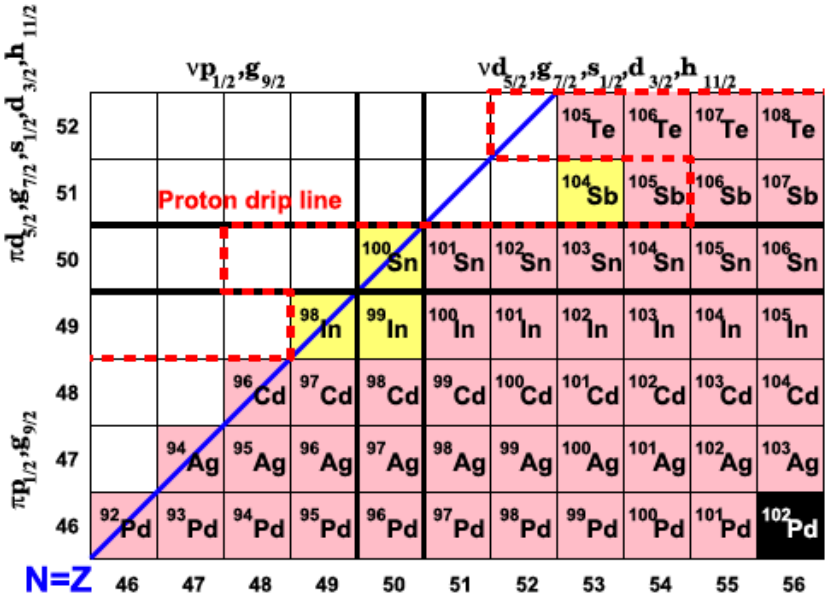
Theory to experiment ratios for beta decays in light nuclei from NCSM

N3LO(EM) + 3N$_{Inl}$ SRG-evolved to 2.0fm^{-1} (c_D = 0.7)



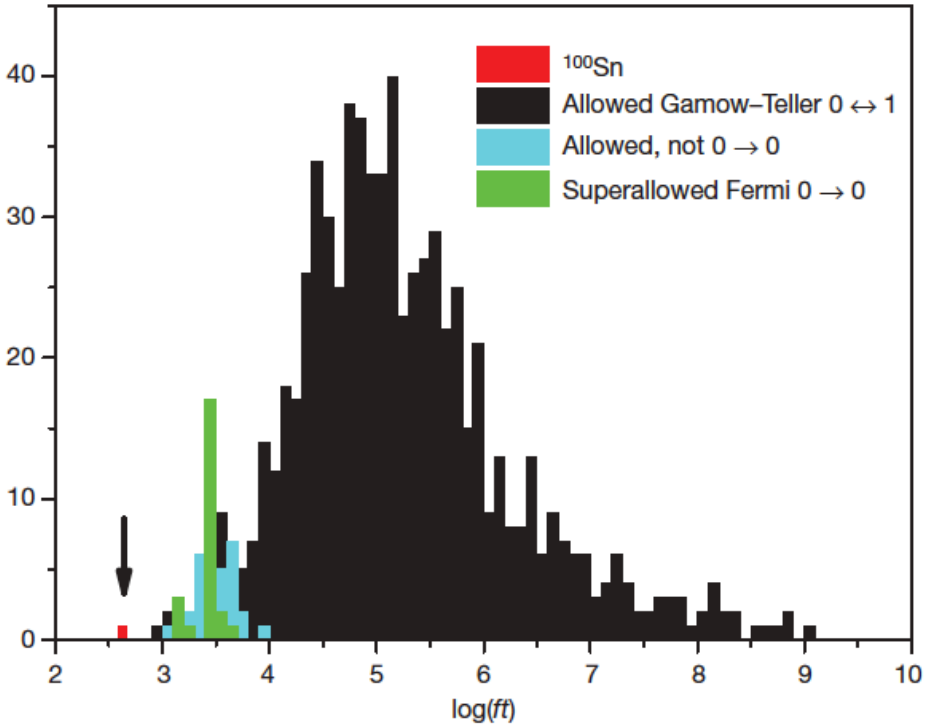
Consistent with QMC calculations of beta-decays, S. Pastore et al, arXiv:1709.03592 (2017)

Gamow-Teller transition in ^{100}Sn



- ^{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

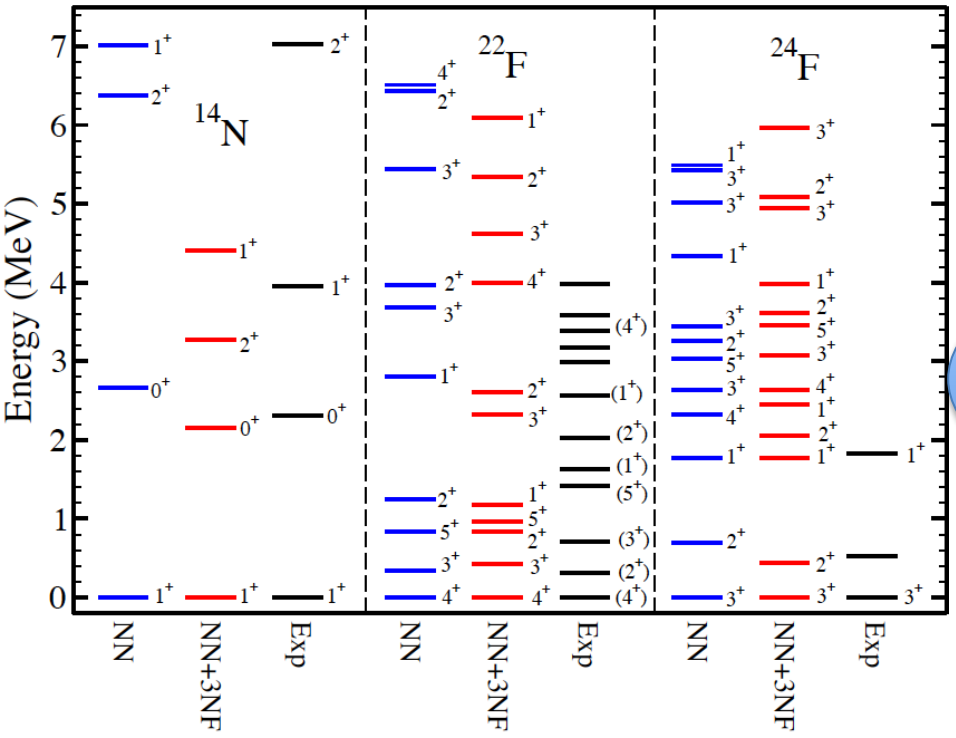
Hinke et al, Nature (2012)



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

- Bloch-Horrowitz is exact; iterative solution poss.

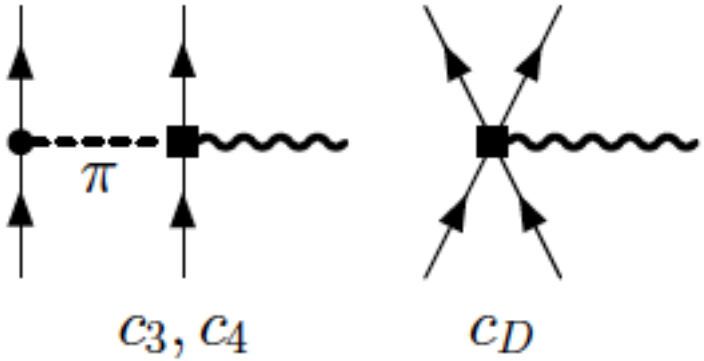
$$\overline{H}_{PP}R_P + \overline{H}_{PQ}(\omega - \overline{H}_{QQ})^{-1}\overline{H}_{QP}R_P = \omega R_P$$

- No large memory for mult R_3 lanczos vectors
- Can only solve for one state at a time
- Reduces matrix dimension from ~10^9 to ~10^6

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



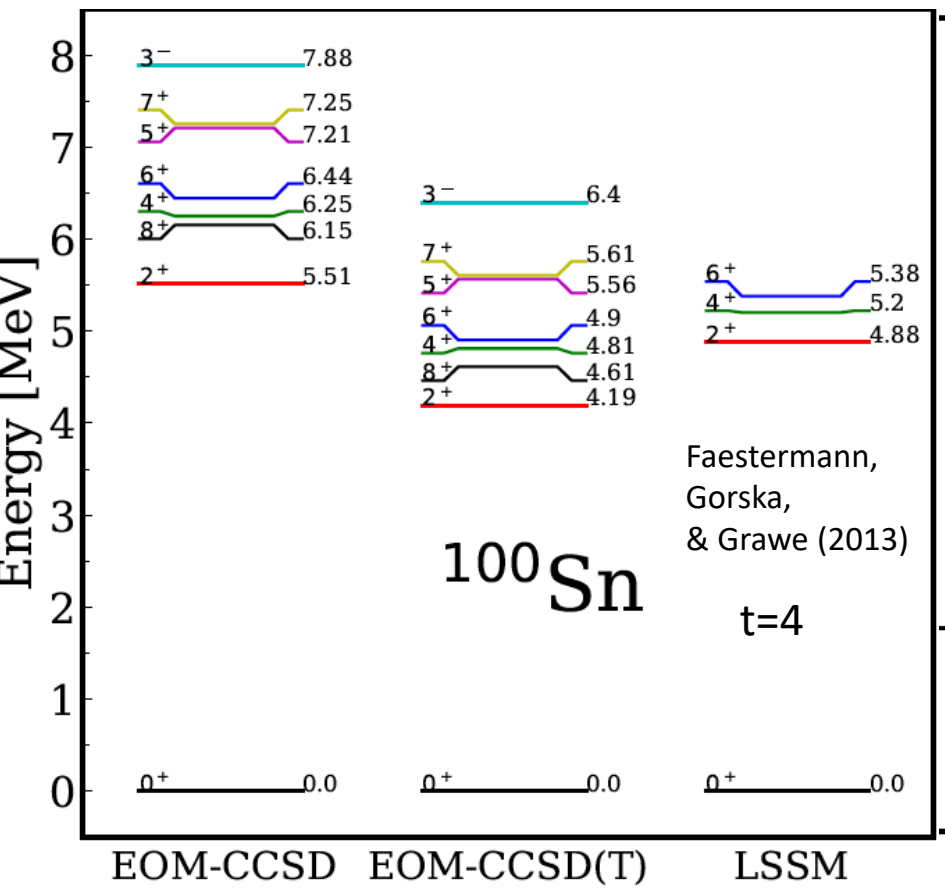
Normal ordered operator:

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

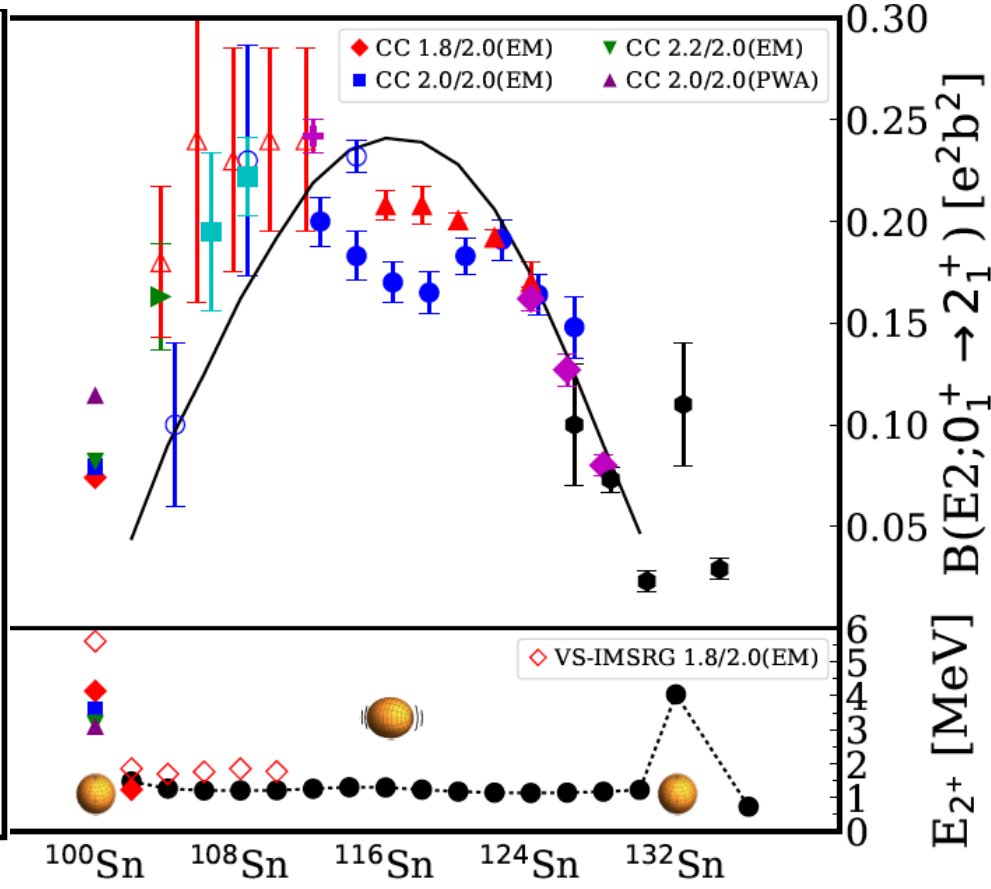
Benchmark between NCSM and CC for the large transition in ^{14}O using NNLO$_{\rm sat}$

Method	$\lvert M_{\rm GT}(\sigma\tau)\rvert$	$\lvert M_{\rm GT}\rvert$
EOM-CCSD	2.15	2.08
EOM-CCSDT-1	1.77	1.69
NCSM	1.80(3)	1.69(3)

Structure of the ligthest tin isotopes

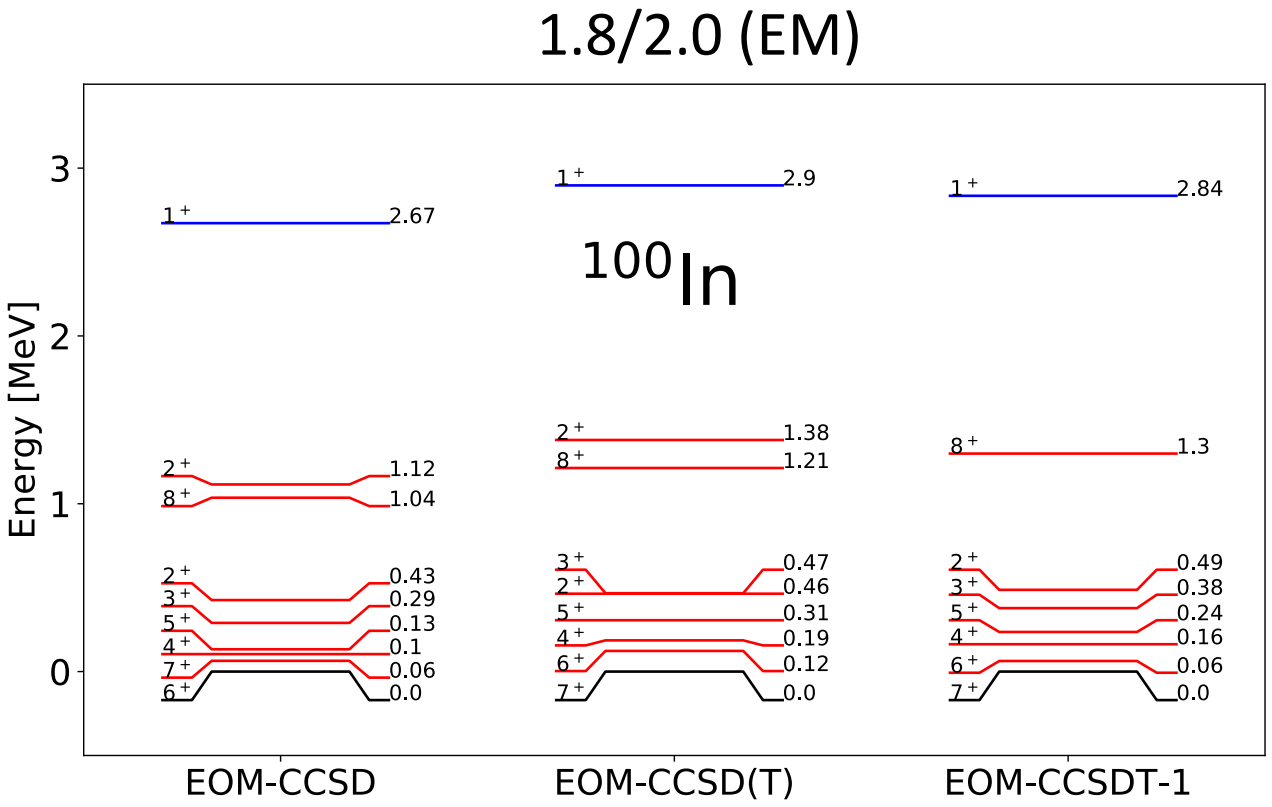


Faestermann, Gorska, & Grawe (2013)

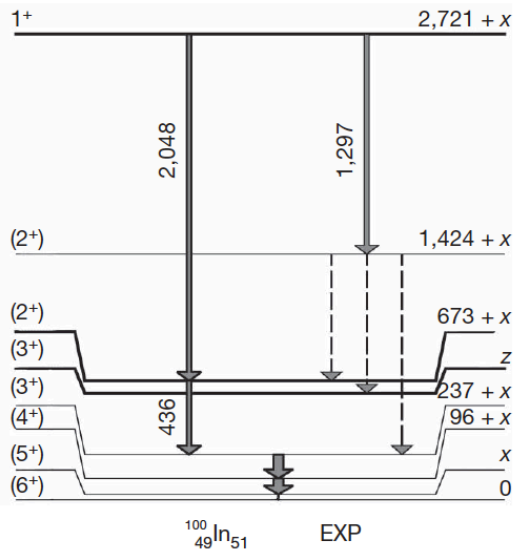


T. Morris *et al*, arXiv:1709.02786 (2017).

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



Hinke et al, Nature (2012)

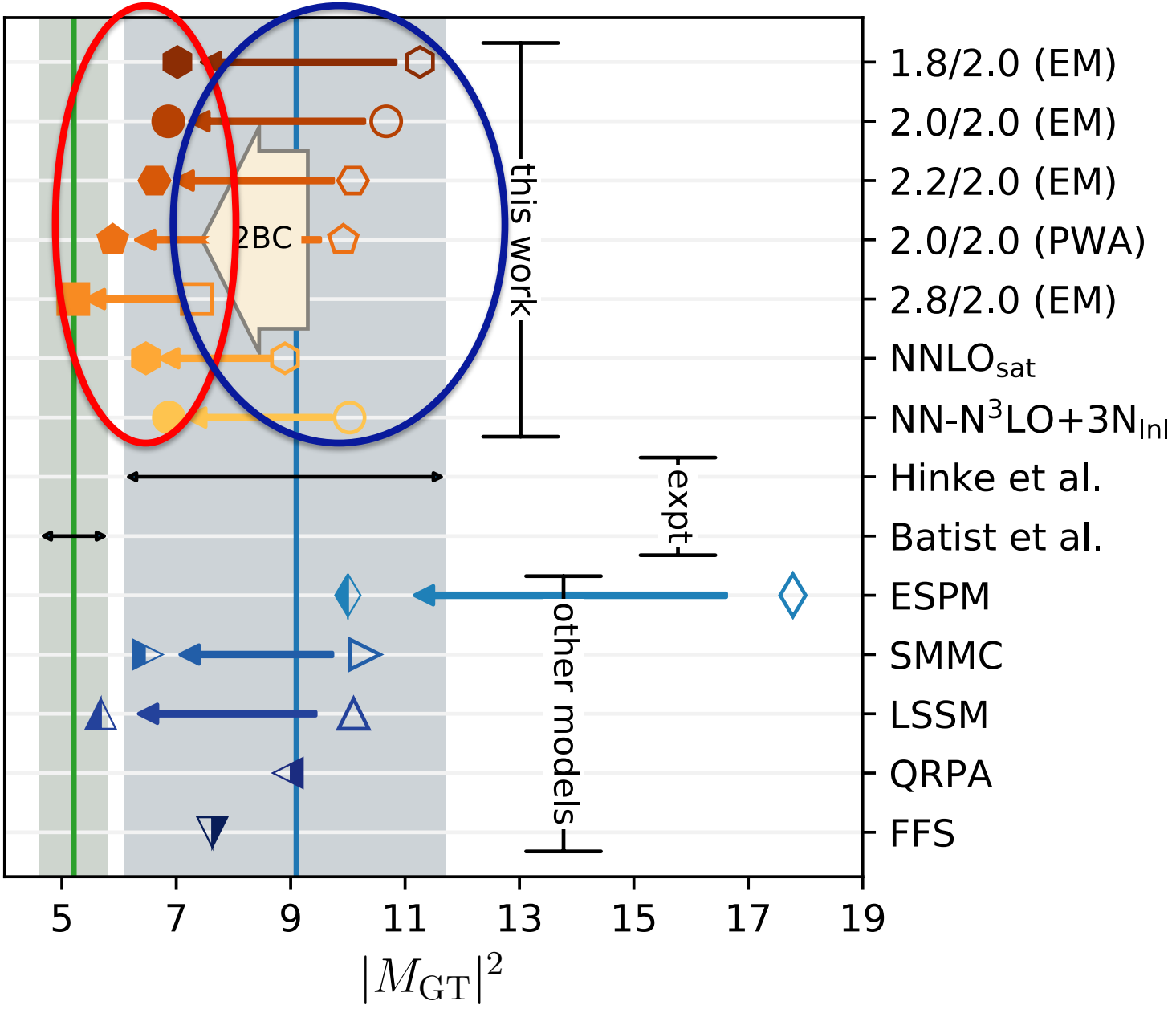


Charge-exchange EOM-CC with perturbative corrections accounting for excluded 3p3h states:

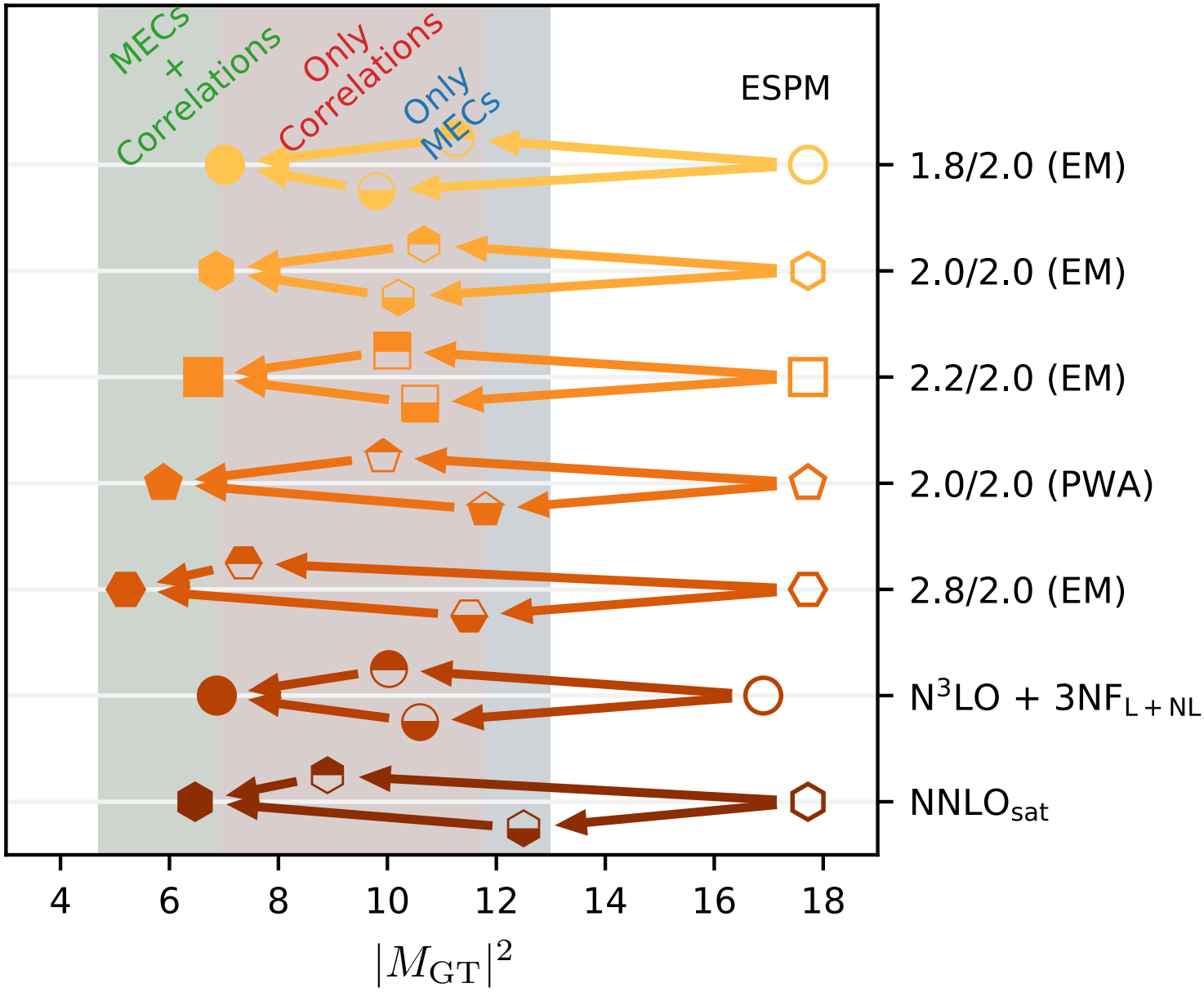
$$\overline{H}_N R_\mu |\Phi_0\rangle = E_\mu R_\mu |\Phi_0\rangle$$

$$\Delta\omega_\mu = \langle\Phi_0| L_\mu \overline{H}_{PQ'} (\omega_\mu - \overline{H}_{Q'Q'})^{-1} \overline{H}_{Q'P} R_\mu |\Phi_0\rangle$$

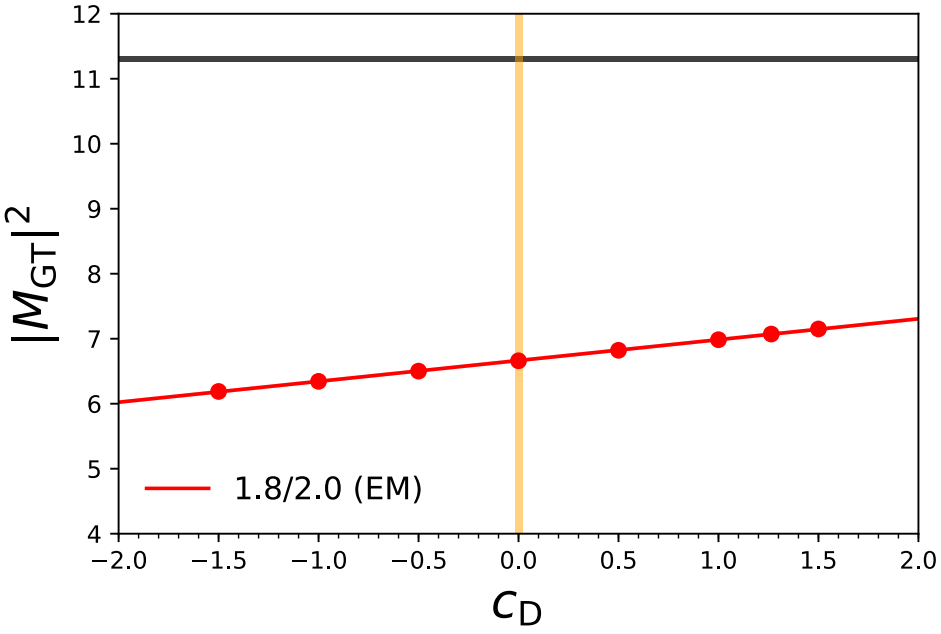
Super allowed Gamow-Teller decay of ^{100}Sn

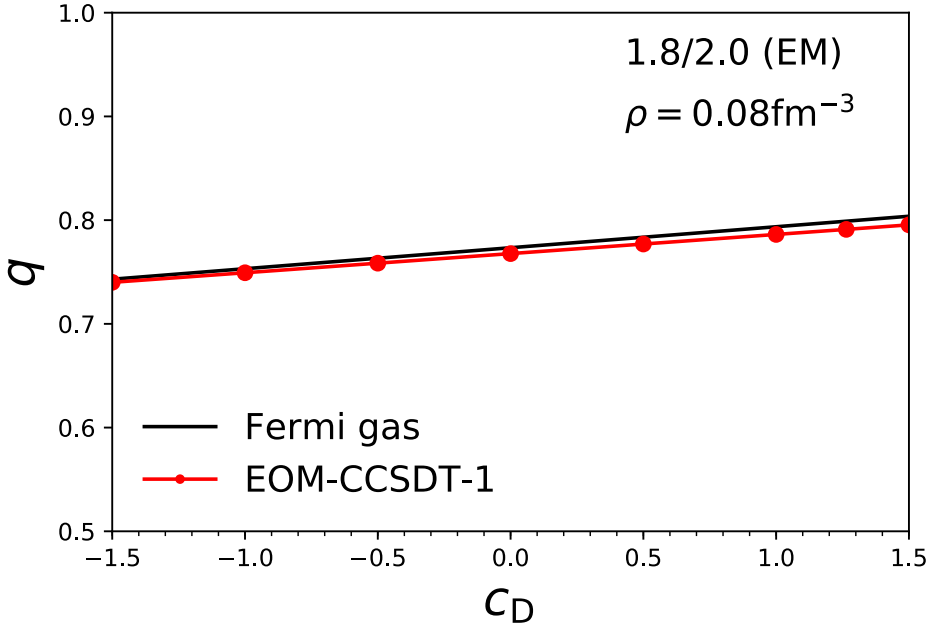


Role of 2BC and correlations in ^{100}Sn



The small role of short-ranged 2BC on GT decay



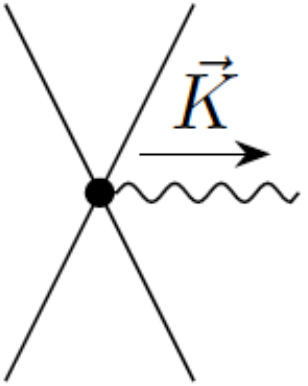


J. Menéndez, D. Gazit, A. Schwenk

PRL 107, 062501 (2011)

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

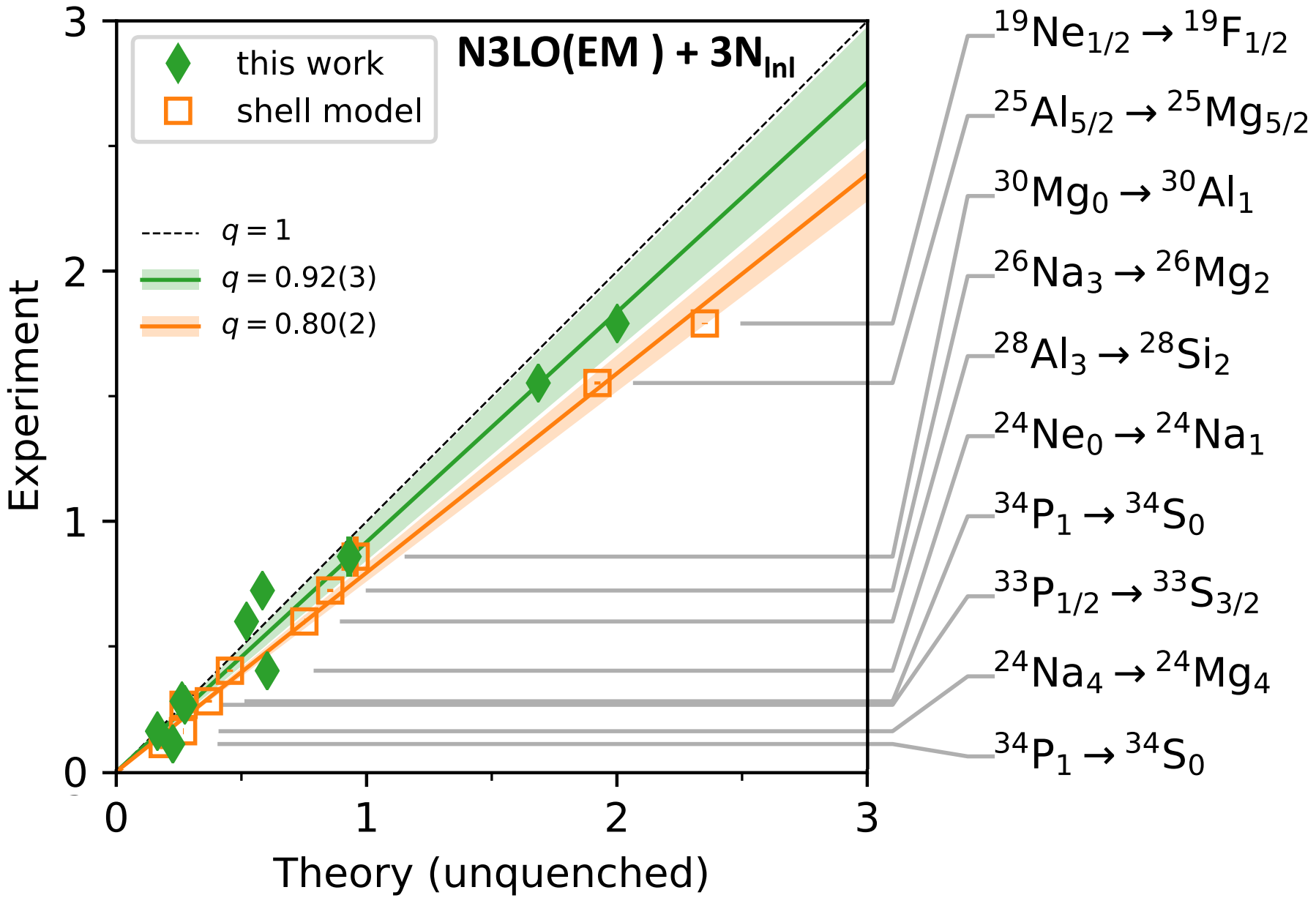
$$q \approx 1 - \frac{\rho\hbar^3 c^3}{F_\pi^2}\left(-\frac{c_D}{4g_A\Lambda} + \frac{I}{3}(2c_4 - c_3) + \frac{I}{6m}\right)$$



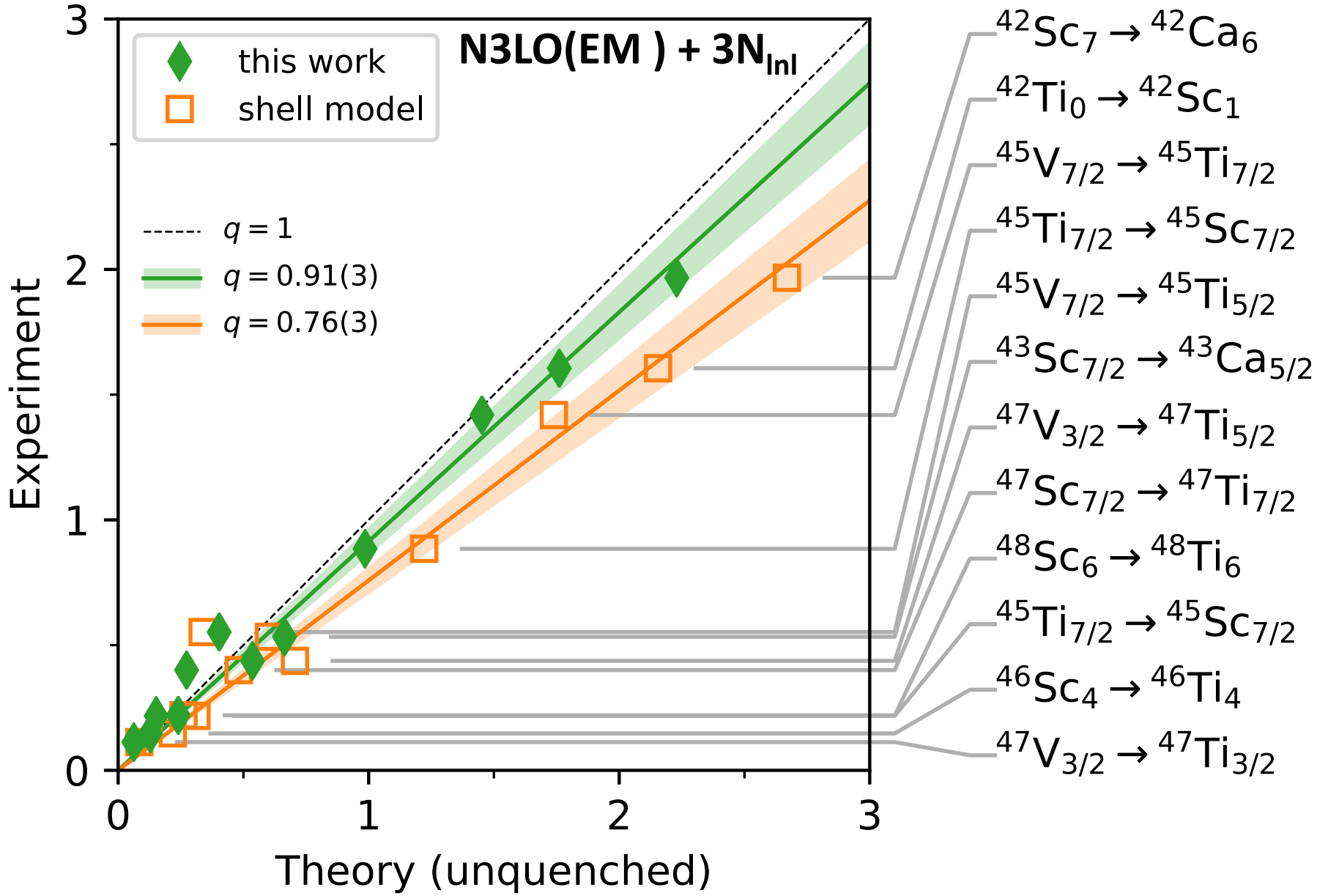
c_D

Short-ranged contact term of 2BC (heavy meson exchange)

The role of 2BC in the sd-shell



The role of 2BC in the pf-shell



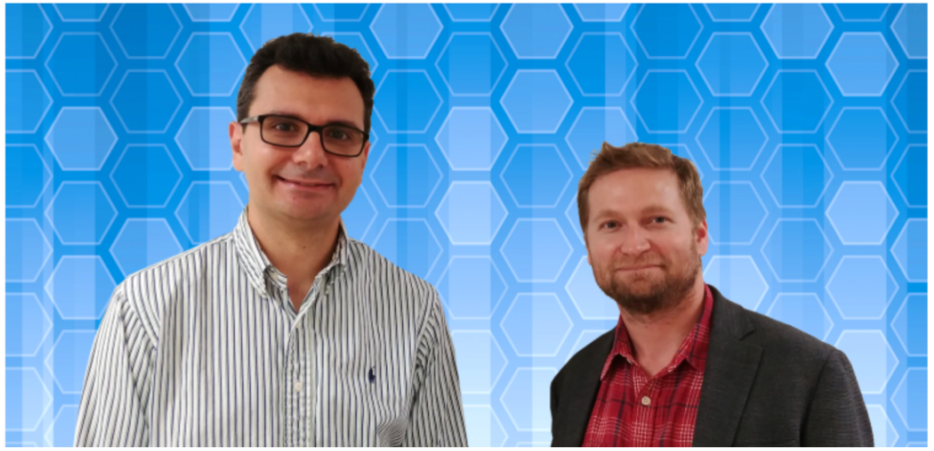
Nuclear Physics & Quantum Computing Collaboration at ORNL

Cloud quantum computing of an atomic nucleus
Dumitrescu, McCaskey, Hagen, Jansen, Morris, TP, Pooser, Dean, Lougovski, arXiv:1801.03897]

Two ORNL-led research teams receive $10.5 million to advance quantum computing for scientific applications (ORNL news, October 2017)

Eugene Dumitrescu

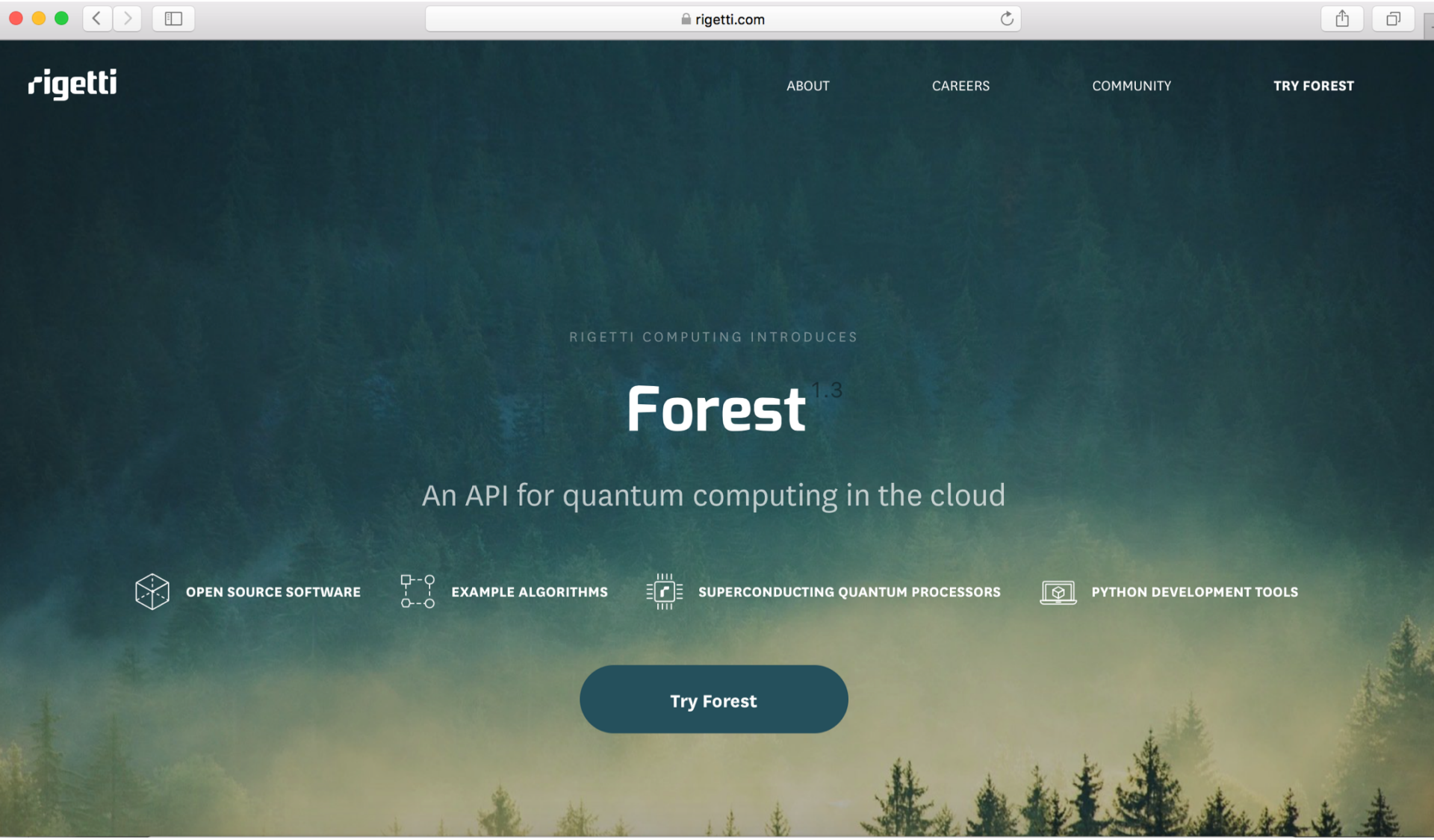
Alex McCaskey



Pavel Lougovski

Raphael Pooser

Cloud access to quantum computers/simulators



Quantum computing

There is a lot of excitement in this field due to substantial progress

1. Quantum processing units now have ten(s) of qubits
2. Businesses are driving this: Google, IBM, Microsoft, Rigetti, D-Wave, …
3. Software is publicly available (PyQuil, XACC, OpenQASM, OpenFermion)
4. First real-world problems solved on 2 to 6 qubits [O'Malley et al. Phys. Rev. X 6, 031007 (2016); Kalandar et al., Nature 549, 242(246 (2017)]

The scientific works were collaborations between theorists and hardware specialists (owners/operators of quantum chips)

Now: Cloud access possible; no insider knowledge required!
[Dumitrescu, McCaskey, Hagen, Jansen, Morris, Papenbrock, Pooser, Dean, Lougovski, arXiv:1801.03897]

Quantum computing – who's doing it?

Company	Type	Technology	Now	Next Goal
Intel	Gate	Superconducting	49	TBD
Google	Gate	Superconducting	22	49
IBM	Gate	Superconducting	50	TBD
Rigetti	Gate	Superconducting	19	TBD
USTC (China)	Gate	Superconducting	10	20
IonQ	Gate	Ion Trap	7	20-50
Silicon Quantum Computing Pty	Gate	Spin	N/A	10
Univ. of Wisconsin	Gate	Neutral Atoms	49	TBD
Harvard/MIT	Quantum Simulator	Rydberg Atoms	51	TBD
Univ. of Maryland / NIST	Quantum Simulator	Ion Trap	53	TBD
D-Wave	Annealing	Superconducting	2048	5000
iARPA QEO Research Program	Annealing	Superconducting	N/A	100
NTT/Univ. of Tokyo/Japan NII	Qtm Neural Network	Photonic	2048	100,000

Many more are building a quantum chip.

Source: QuantumComputingReport.com

Quantum computation of H_2 molecule

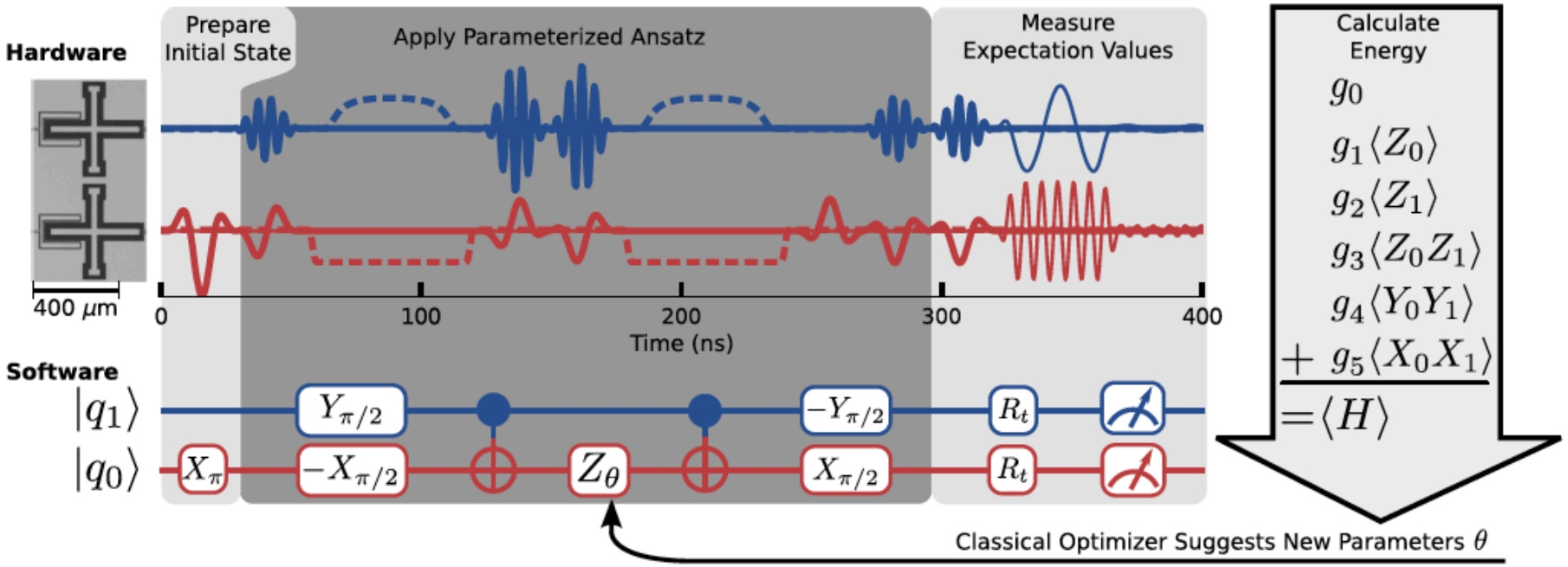
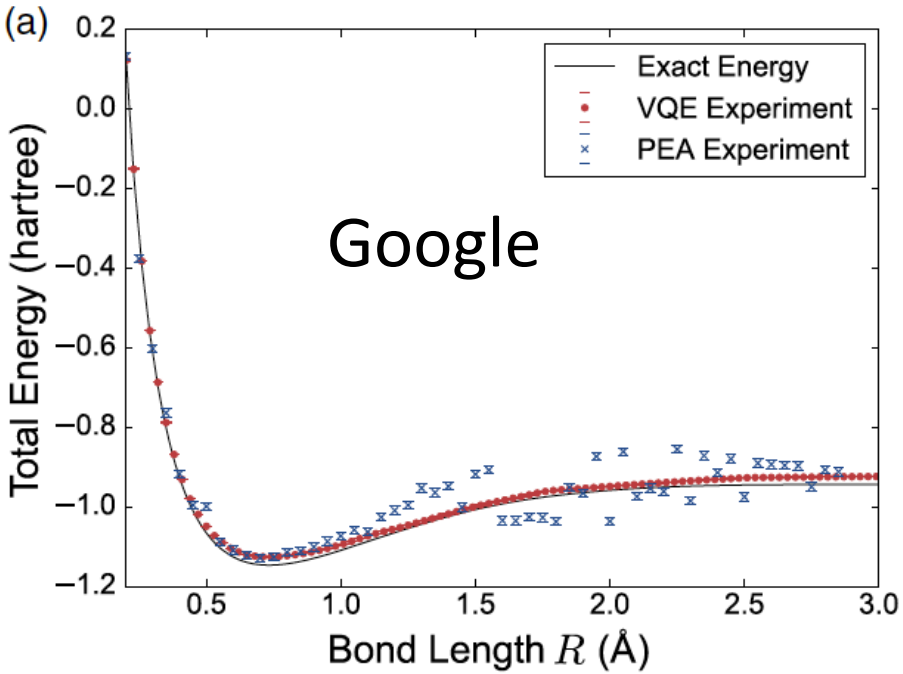


FIG. 1. Hardware and software schematic of the variational quantum eigensolver. (Hardware) micrograph shows two Xmon transmon qubits and microwave pulse sequences to perform single-qubit rotations (thick lines), dc pulses for two-qubit entangling gates (dashed lines), and microwave spectroscopy tones for qubit measurements (thin lines). (Software) quantum circuit diagram shows preparation of the Hartree-Fock state, followed by application of the unitary coupled cluster ansatz in Eq. (3) and efficient partial tomography (R_t) to measure the expectation values in Eq. (1). Finally, the total energy is computed according to Eq. (4) and provided to a classical optimizer which suggests new parameters.

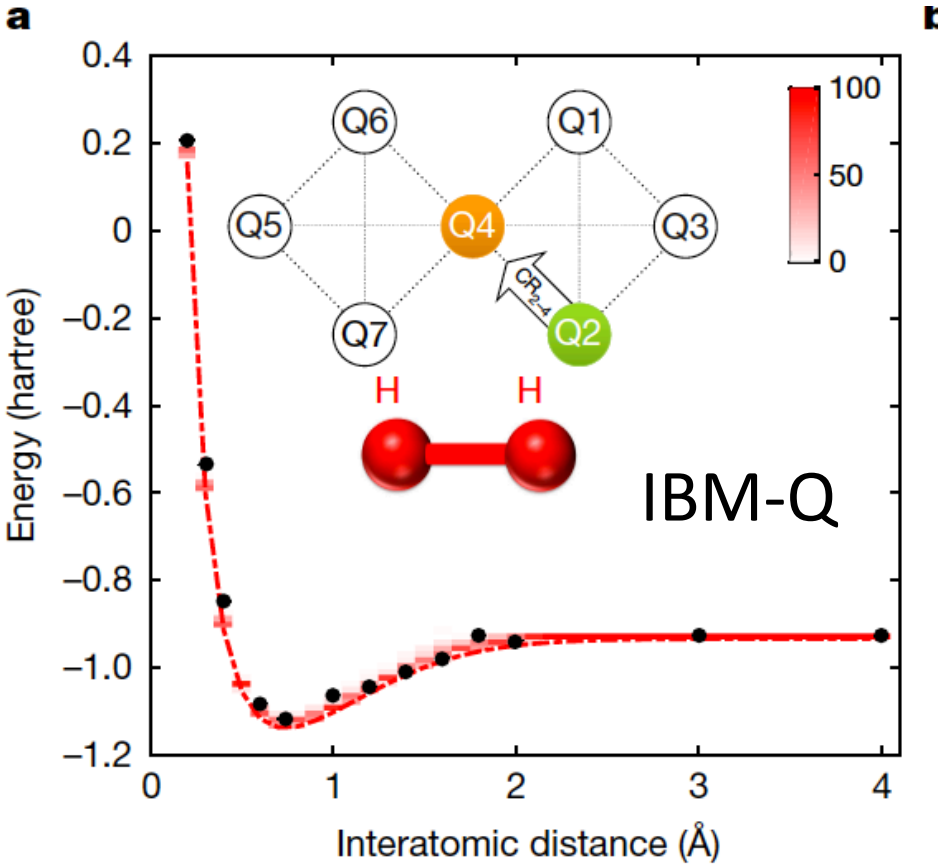
$$H = g_0\mathbb{1} + g_1Z_0 + g_2Z_1 + g_3Z_0Z_1 + g_4Y_0Y_1 + g_5X_0X_1$$

Quantum computation of H_2 molecule

O'Malley et al. Phys. Rev. X 6, 031007 (2016)

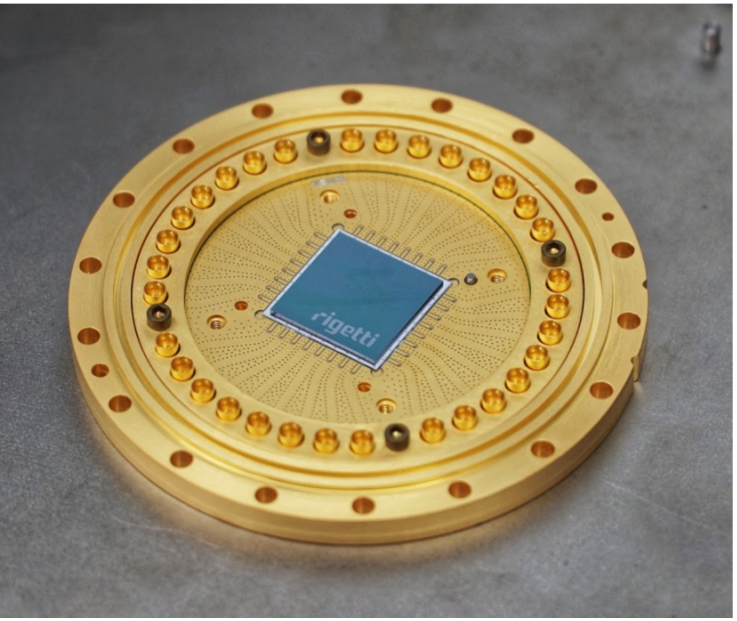


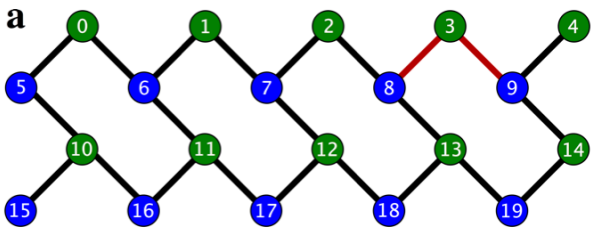
Kalandar et al., Nature 549, 242-246 (2017)

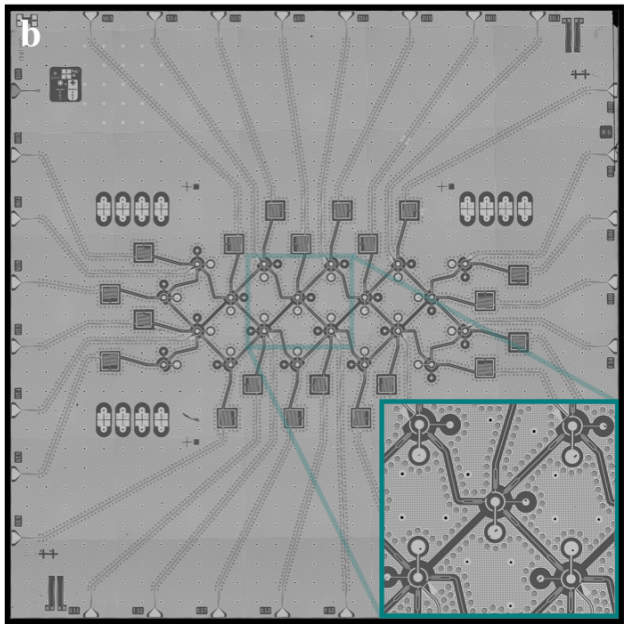


Rigetti 19Q

Superconducting qubits



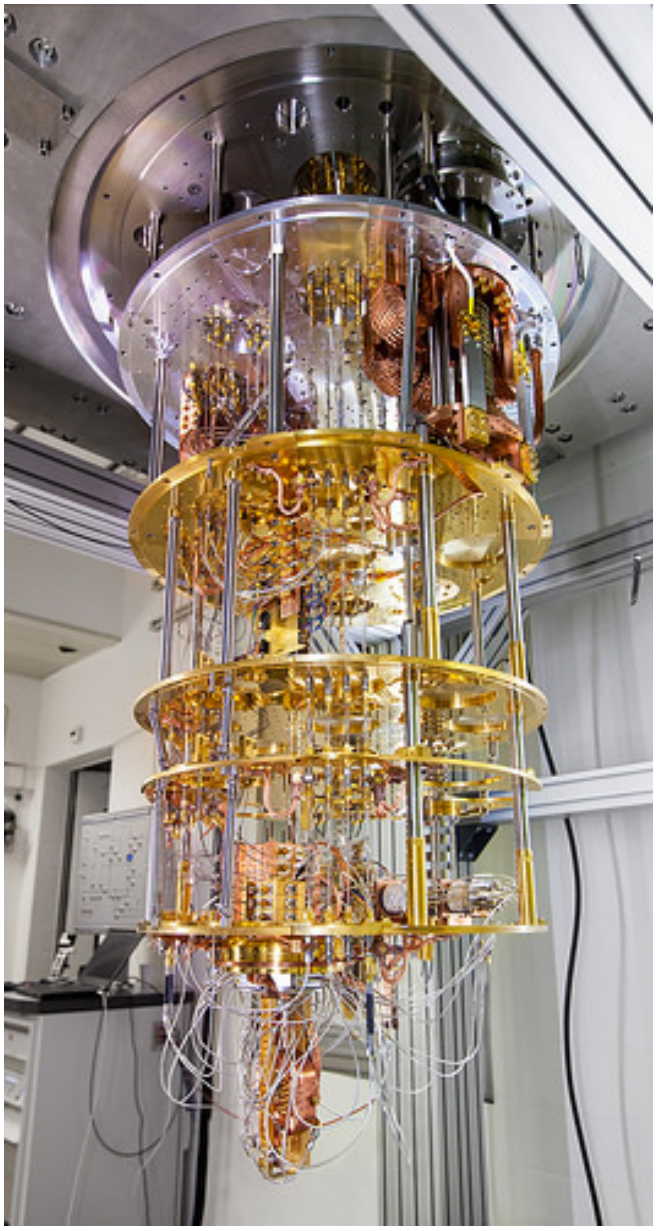


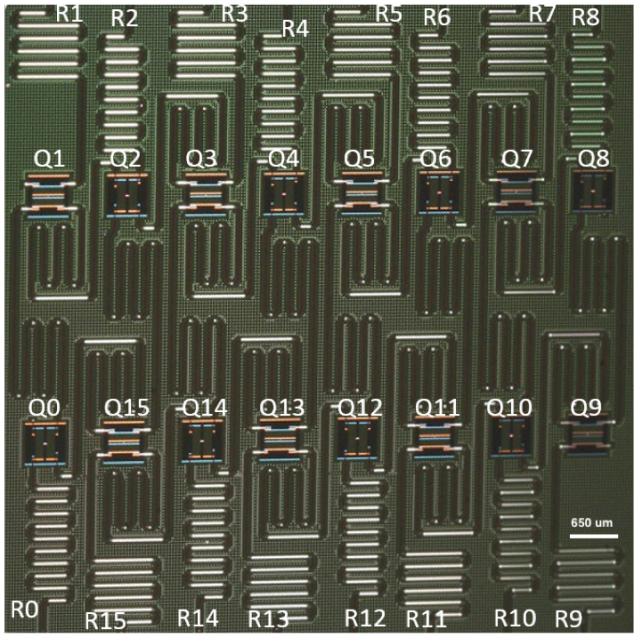


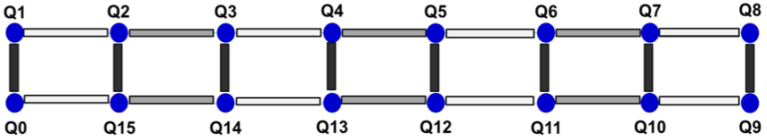
Connectivity of Rigetti 19Q.
a, *Chip schematic showing tunable transmons (green circles) capacitively coupled to fixed-frequency transmons (blue circles).*
b, *Optical chip image. Note that some couplers have been dropped to produce a lattice with three-fold, rather than four-fold connectivity.*

Otterbach et al, arXiv:1712.05771

IBM QX5 (16 qubits)







→ IBM Q Experience

Qubit fidelities

	1-Qubit Gate Fidelity			2-Qubit Gate Fidelity			Read Out Fidelity		
Computer	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
IBM QX2	99.71%	99.88%	99.79%	94.22%	97.12%	95.33%	92.20%	98.20%	96.24%
IBM QX4	99.83%	99.96%	99.88%	95.11%	98.39%	97.11%	94.80%	97.10%	95.60%
IBM QX5	99.59%	99.87%	99.77%	91.98%	97.29%	95.70%	88.53%	96.66%	93.32%
IBM QS1_1	96.93%	99.92%	99.48%	82.28%	98.87%	95.68%	69.05%	93.55%	83.95%
Rigetti 19Q	94.96%	99.42%	98.63%	79.00%	93.60%	87.50%	84.00%	97.00%	93.30%

Sources: QuantumComputingReport.com; Rigetti.com

Mitigating exisiting constraints

1. Gate errors, decoherence → low-depth circuit
2. Limited connectivity of qubits → tailored, simple Hamiltonian
3. Cloud access → only expectation values on QPU
4. Limited fidelity → noise correction

Game plan

1. Hamiltonian from pionless EFT at leading order; fit to deuteron binding energy; constructed in harmonic-oscillator basis of ${}^3S_1$ partial wave [à la Binder et al. (2016); **Aaina Bansal et al. (2017)**]; cutoff at about 150 MeV.

$$H_N = \sum_{n,n'=0}^{N-1} \langle n'|(T+V)|n\rangle a^\dagger_{n'} a_n \qquad \langle n'|V|n\rangle = V_0 \delta^0_n \delta^{n'}_n$$

$$V_0 = -5.68658111 \text{ MeV}$$

2. Map single-particle states $|n\rangle$ onto qubits using $|0\rangle = |\uparrow\rangle$ and $|1\rangle = |\downarrow\rangle$. This is an analog of the Jordan-Wigner transform.

$$a^\dagger_p \leftrightarrow \sigma^{(p)}_- \equiv \frac{1}{2}\left(X_p - iY_p\right) \qquad a_p \leftrightarrow \sigma^{(p)}_+ \equiv \frac{1}{2}\left(X_p + iY_p\right)$$

3. Solve H_1, H_2 (and H_3) and extrapolate to infinite space using harmonic oscillator variant of Lüscher's formula [More, Furnstahl, TP (2013)]

$$E_N = -\frac{\hbar^2 k^2}{2m}\left(1 - 2\frac{\gamma^2}{k}e^{-2kL} - 4\frac{\gamma^4 L}{k}e^{-4kL}\right) + \frac{\hbar^2 k\gamma^2}{m}\left(1 - \frac{\gamma^2}{k} - \frac{\gamma^4}{4k^2} + 2w_2 k\gamma^4\right)e^{-4kL}$$

Variational wave function

Wave functions on two qubits

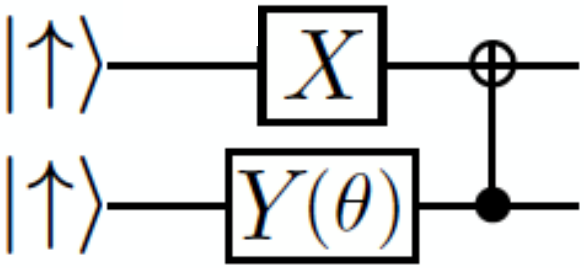
$U(\theta)|\downarrow\uparrow\rangle$ $\qquad U(\theta) \equiv e^{\theta\left(a_0^\dagger a_1 - a_1^\dagger a_0\right)} = e^{i\frac{\theta}{2}(X_0 Y_1 - X_1 Y_0)}$

Wave functions on three qubits

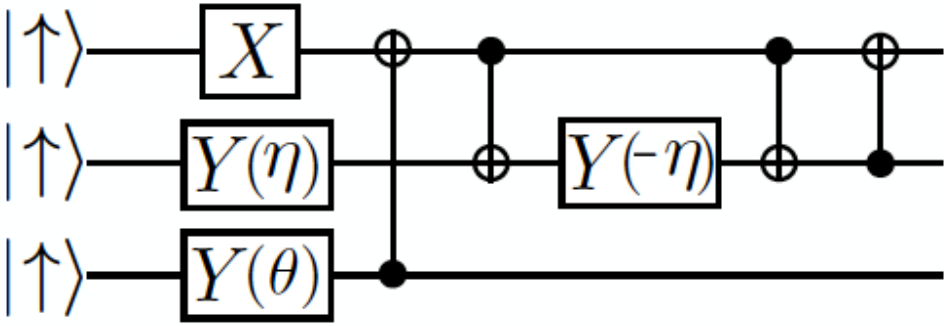
$U(\eta,\theta)|\downarrow\uparrow\uparrow\rangle$ $\qquad U(\eta,\theta) \equiv e^{\eta\left(a_0^\dagger a_1 - a_1^\dagger a_0\right)+\theta\left(a_0^\dagger a_2 - a_2^\dagger a_0\right)}$

Minimize number of two-qubit CNOT operations to mitigate low two-qubit fidelities (construct a “low-depth circuit”)

$U(\theta)$

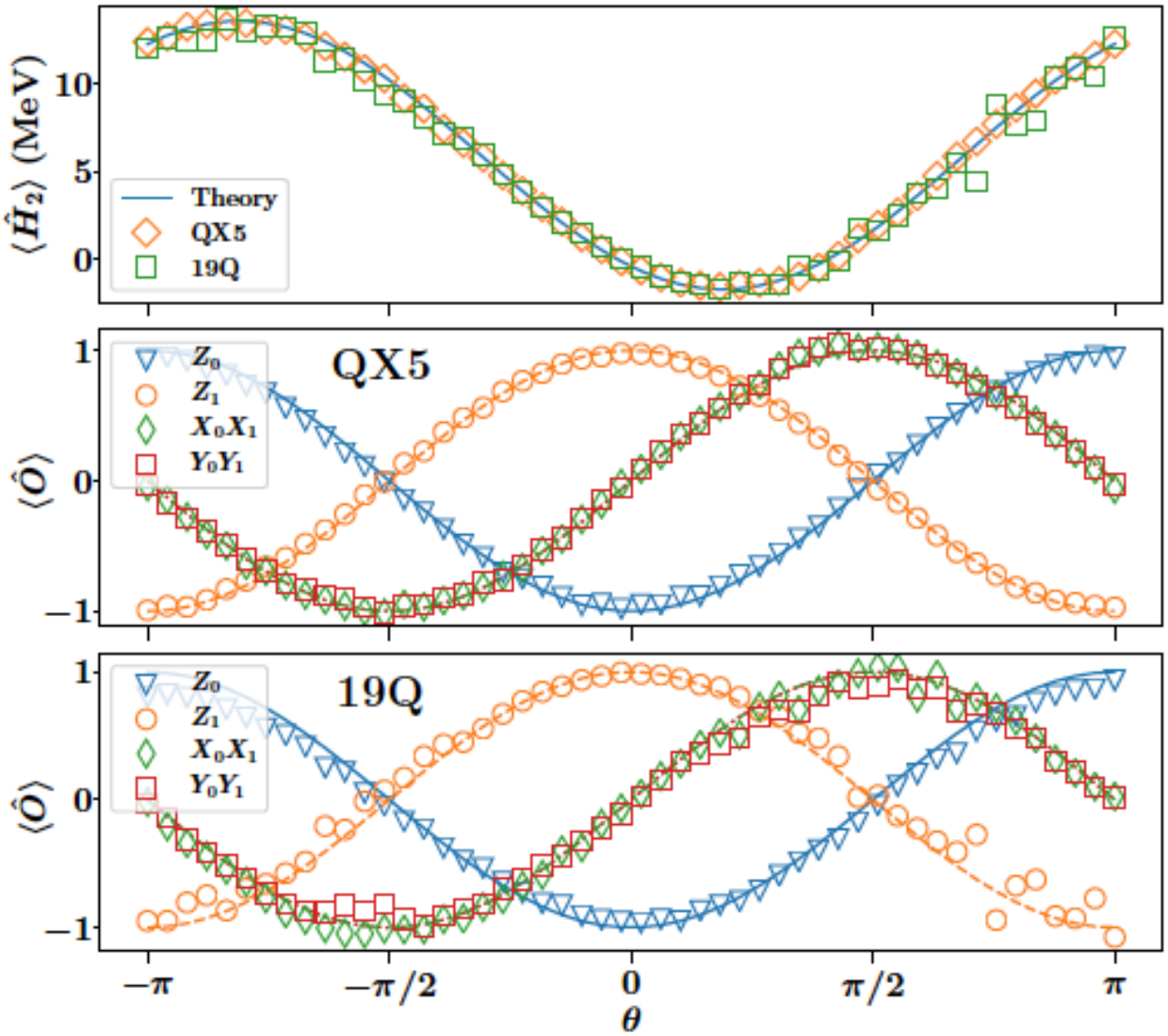


$U(\eta,\theta)$



Hamiltonian on two qubits

$$H_2 = 5.906709I + 0.218291Z_0 - 6.125Z_1 - 2.143304\,(X_0X_1 + Y_0Y_1)$$



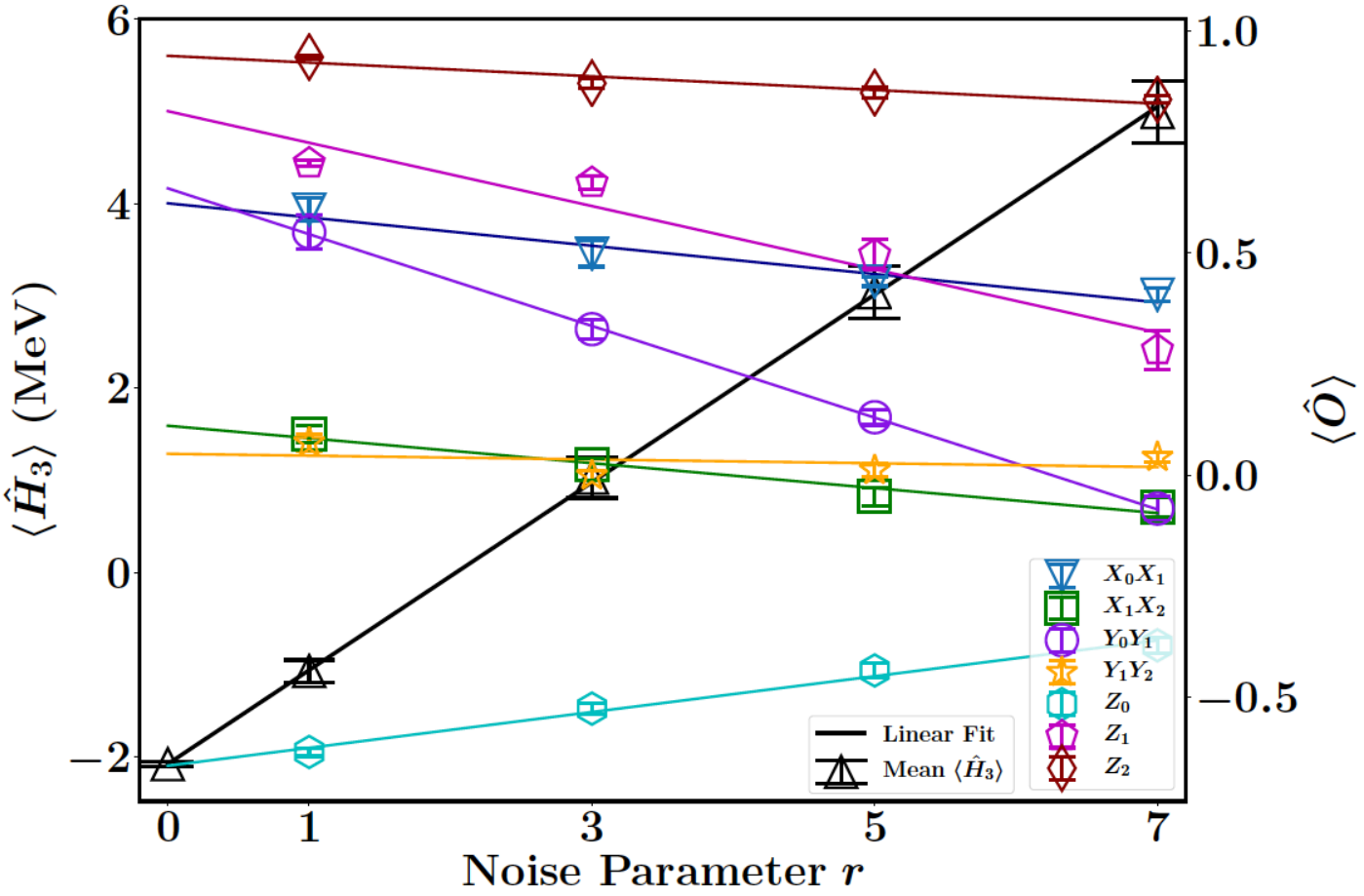
Quantum-classical hybrid algorithm VQE [Peruzzo et al. 2014; McClean et al 2016]:

Expectation values on QPU. Minimization on CPU.

To manage noise we performed 8,192 (10,000) measurements on QX5 (19Q)

Three qubits

$$H_3 = H_2 + 9.625(I - Z_2) - 3.913119\,(X_1X_2 + Y_1Y_2)$$



Three qubits have more noise. Insert pairs of CNOT (unity operators) to extrapolate to *r*=0. [See, e.g., Ying Li & S. C. Benjamin 2017]

Final results

Deuteron ground-state energies from a quantum computer compared to the exact result, E_∞=-2.22 MeV.

E from exact diagonalization				
N	E_N	$\mathcal{O}(e^{-2kL})$	$\mathcal{O}(kLe^{-4kL})$	$\mathcal{O}(e^{-4kL})$
2	-1.749	-2.39	-2.19	
3	-2.046	-2.33	-2.20	-2.21
E from quantum computing				
N	E_N	$\mathcal{O}(e^{-2kL})$	$\mathcal{O}(kLe^{-4kL})$	$\mathcal{O}(e^{-4kL})$
2	$-1.74(3)$	$-2.38(4)$	$-2.18(3)$	
3	$-2.08(3)$	$-2.35(2)$	$-2.21(3)$	$-2.28(3)$

$$E_N = -\frac{\hbar^2 k^2}{2m}\left(1 - 2\frac{\gamma^2}{k}e^{-2kL} - 4\frac{\gamma^4 L}{k}e^{-4kL}\right) + \frac{\hbar^2 k\gamma^2}{m}\left(1 - \frac{\gamma^2}{k} - \frac{\gamma^4}{4k^2} + 2w_2 k\gamma^4\right)e^{-4kL}$$

[Dumitrescu, McCaskey, Hagen, Jansen, Morris, TP, Pooser, Dean, Lougovski, arXiv:1801.03897]

MIT Technology Review

The Best of the Physics arXiv (week ending January 20, 2018

This week's most thought-provoking papers from the Physics arXiv.

by Emerging Technology from the arXiv January 20, 2018

A roundup of the most interesting papers from the arXiv:

Cloud Quantum Computing of an Atomic Nucleus

Black Holes as Brains: Neural Networks with Area Law Entropy

The Dynamical Structure of Political Corruption Networks

Measuring the Complexity of Consciousness

Scale-Free Networks are Rare

IOP Physics World - the member magazine of the Institute of Physics

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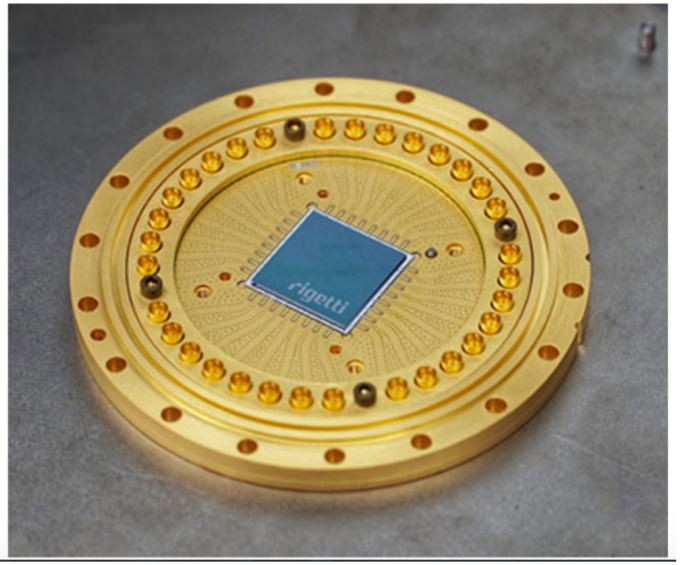
- 2018
  - February 2018
  - January 2018
- 2017
- 2016
- 2015
- 2014
- 2013
- 2012
- 2011
- 2010
- 2009
- 2008
- 2007
- 2006
- 2005
- 2004
- 2003
- 2002
- 2001

Cloud quantum computing calculates nuclear binding energy

Jan 29, 2018



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Home » Physics » Quantum Physics » February 2, 2018

Cloud based quantum computing used to calculate nuclear binding energy

February 2, 2018 by Bob Yirka, Phys.org report

Summary

- Forces and 2BCs from chiral EFT explain (to large extent) the quenching of GT strength in atomic nuclei
- Make predictions for the super allowed GT transition in ^{100}Sn
- First step towards scalable nuclear structure calculations on a quantum processors accessed via the cloud
- Cloud quantum computation of atomic nuclei now possible

Collaborators

@ ORNL / UTK: D. J. Dean, G. R. Jansen, **E. Dumitrescu**, P. Lougovski, A. J. McCaskey, **T. Morris**, T. Papenbrock, R. C. Pooser

@ TU Darmstadt: **C. Stumpf**, R. Roth, A. Schwenk, **J. Simonis**

@ TRIUMF: **P. Gysbers**, J. Holt, P. Navratil

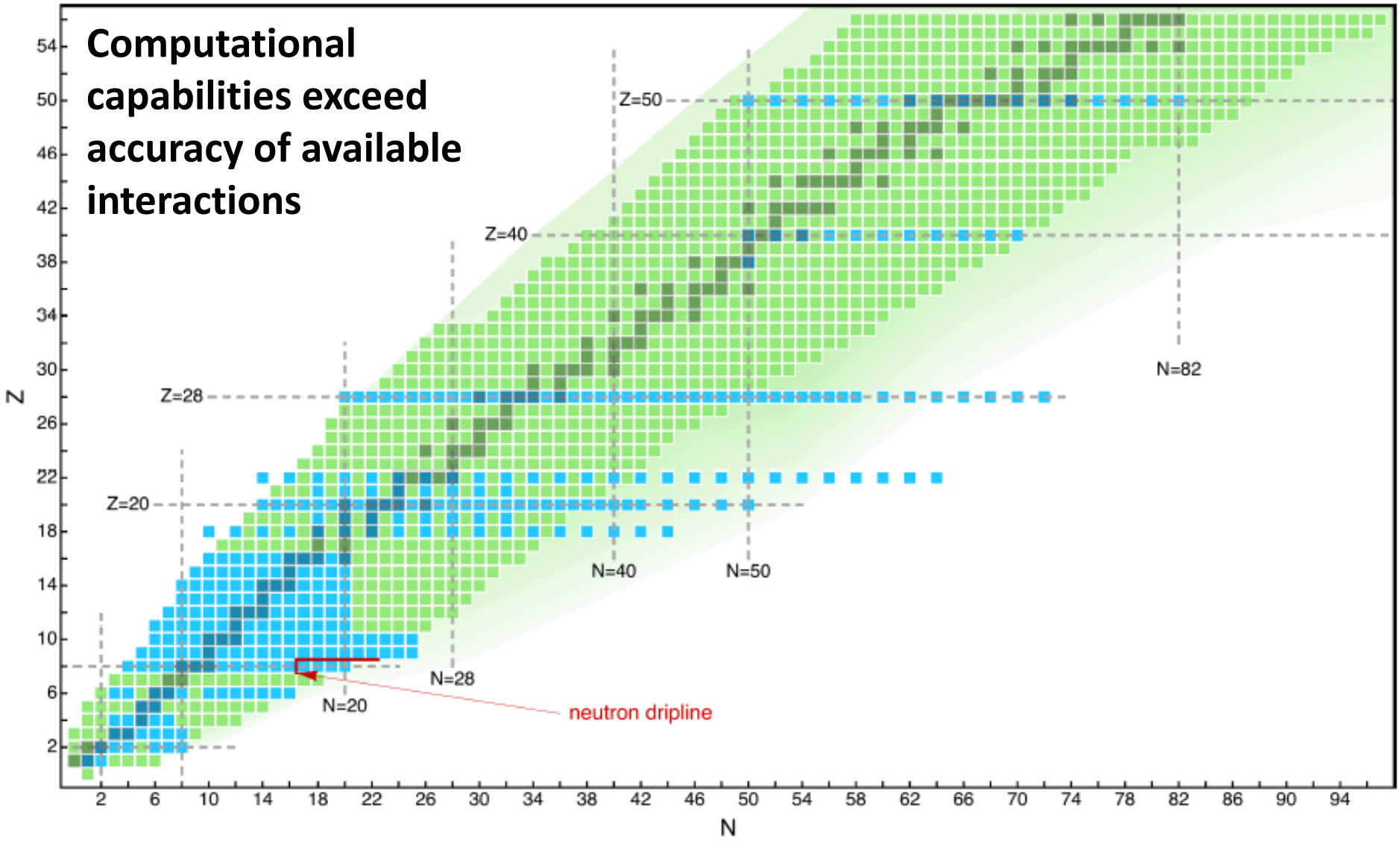
@ Reed College: **S. R. Stroberg**

@ LLNL: K. Wendt, Sofia Quaglioni

Quantum computing

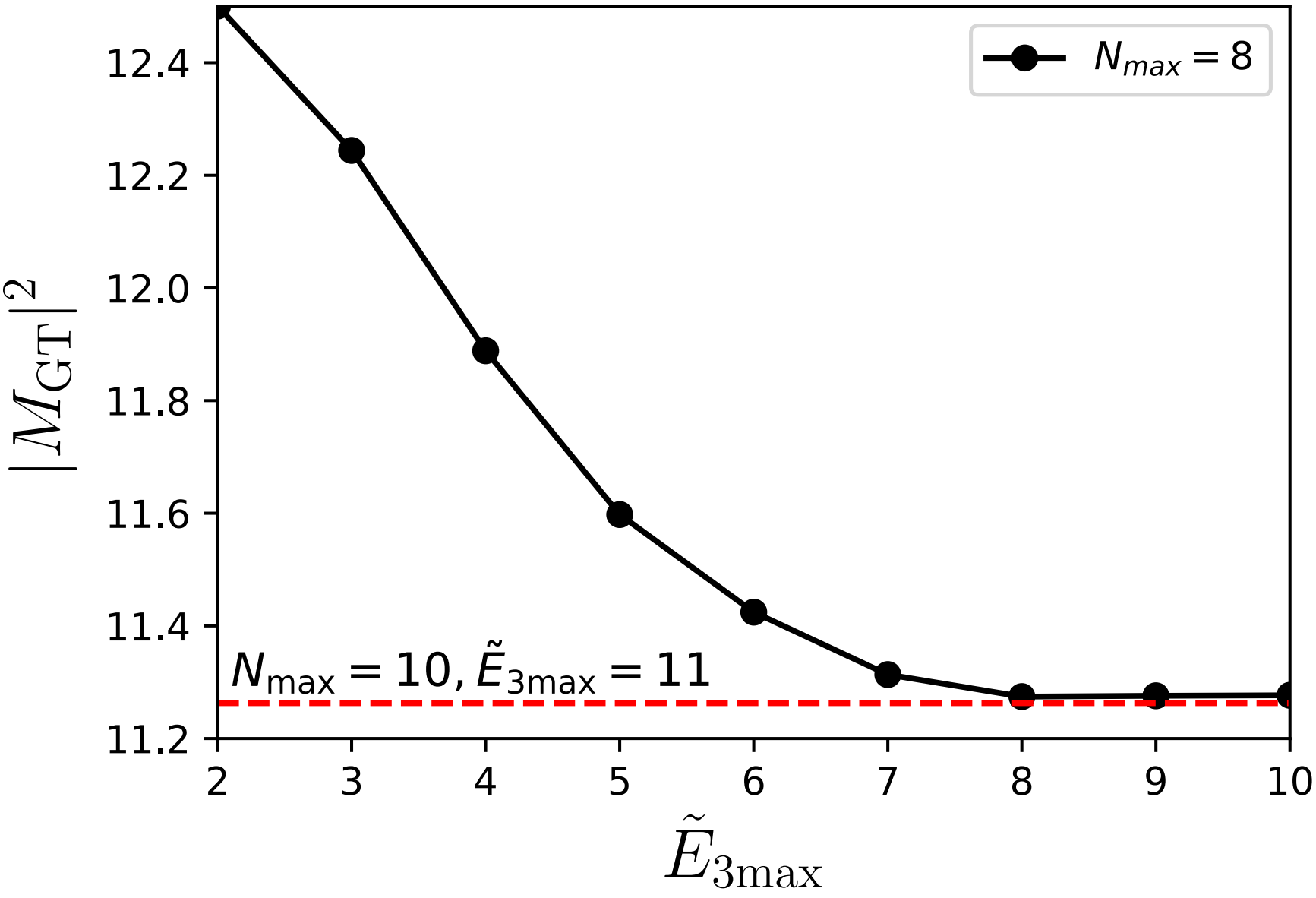
1. The quantum many-body problem is one the key challenges in physics
2. Exponential growth of Hilbert space in wave function based methods and sign problem in Monte-Carlo methods.
3. Quantum computers promise to reduce computational complexity from exponential to polynomial cost
4. A quantum computer with about 100 error corrected qubits could potentially revolutionize nuclear shell-model calculations

Reach of ab-initio computations of nuclei

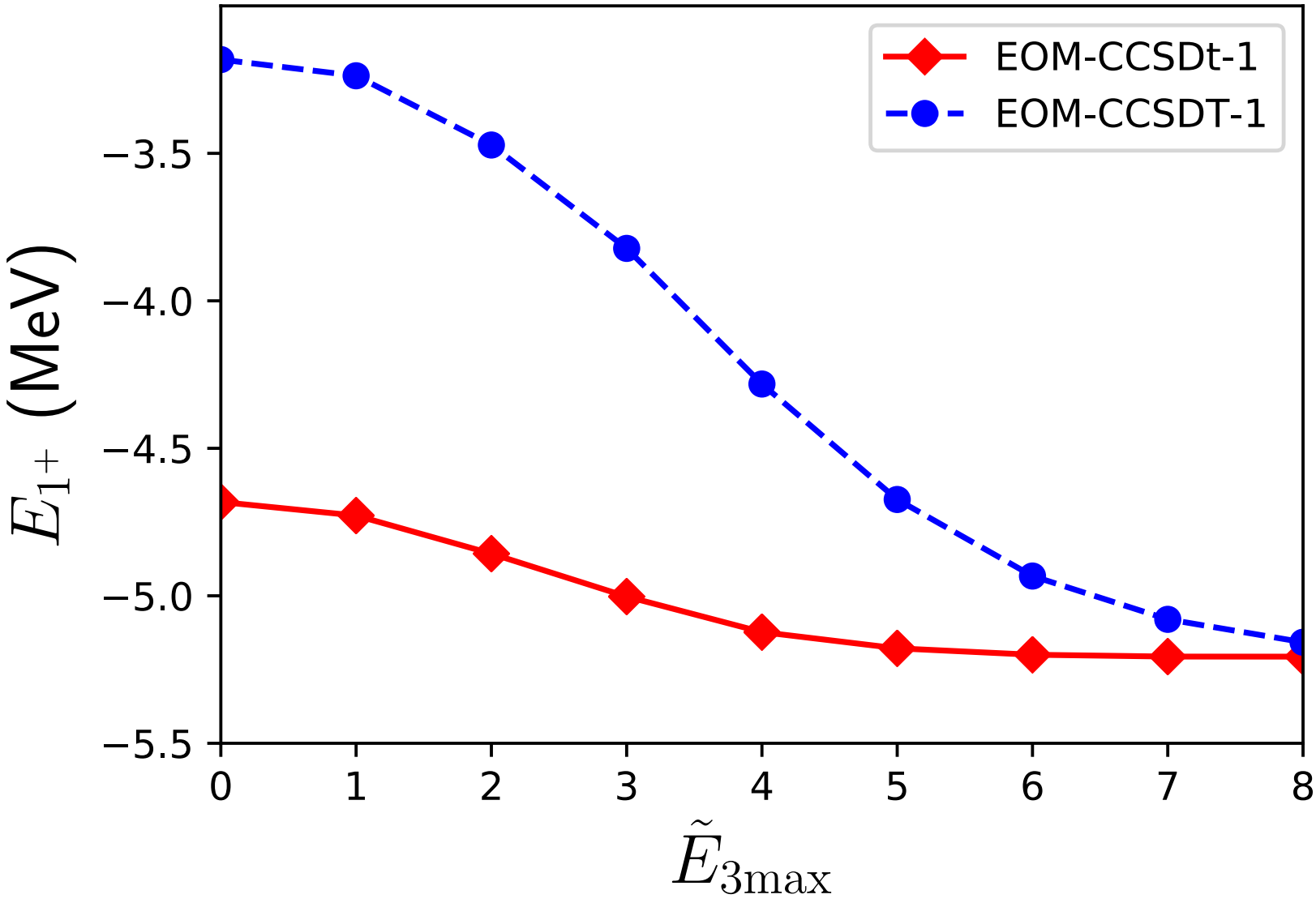


H. Hergert *et al*, Physics Reports 621, 165-222 (2016)

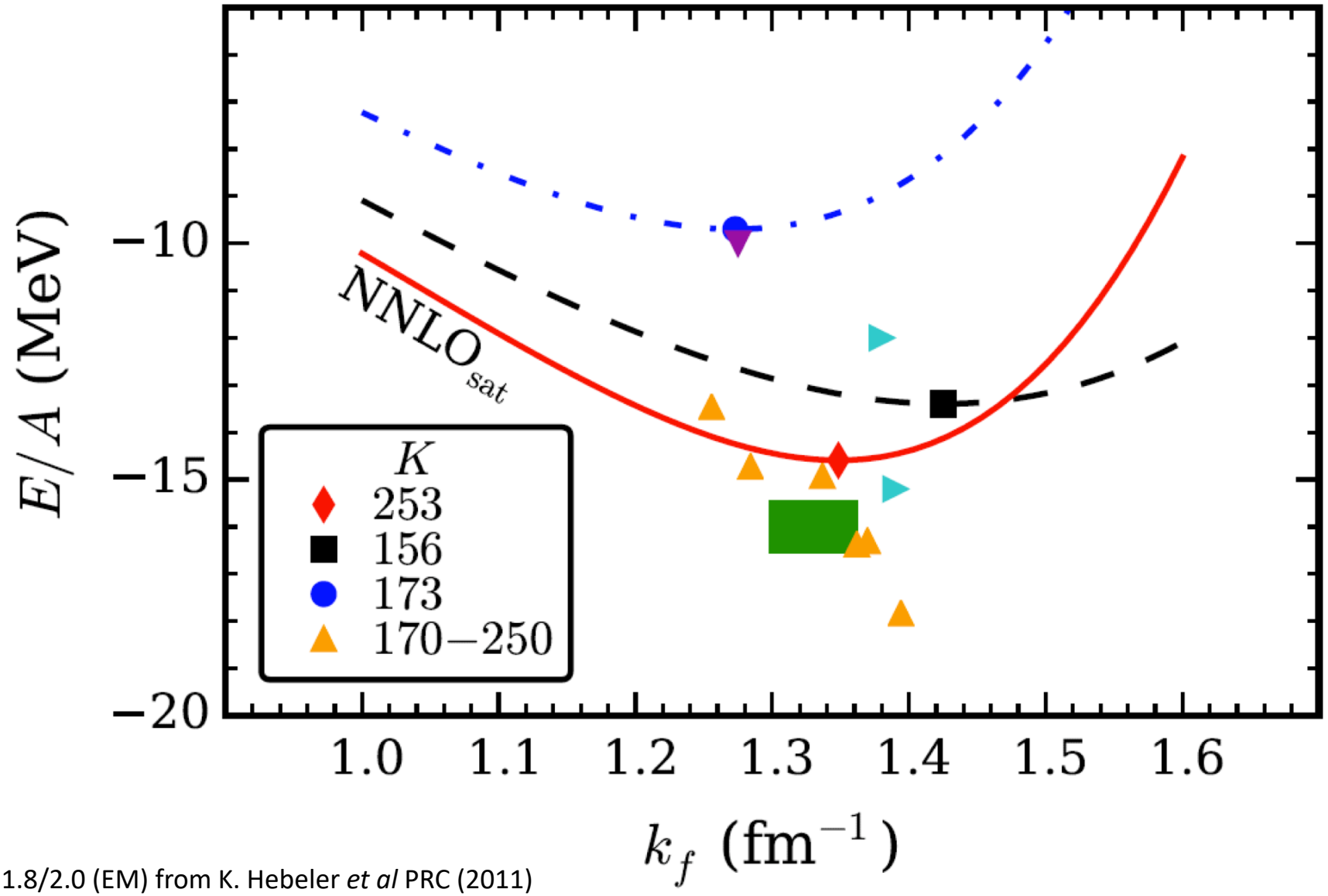
Convergence of GT transition in ^{100}Sn



Convergence of excited states in ^{100}In



Saturation in nuclear matter from chiral interactions



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

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

Classical computing logical gates

Information is physical (Landauer).

Classical computing uses irreversible gates

0 = False
1 = True

INPUT		OUTPUT
A	B	A OR B
0	0	0
0	1	1
1	0	1
1	1	1

Classical gates implement logical operations (AND, OR, etc), and any function can be build from NOR gates alone.

Classical computer: classical gates operate on bits (0, 1).

Current limitations/challenges

- Faced with limited connectivity between qubits on a quantum chip
- Limited to low depth (the number of sequential gates) of quantum circuits due to decoherence
- Limited number of measurements via the cloud
- Intermittent cloud access in a scheduled environment must be taken into account

What is quantum computing

Quantum computing uses qubits, i.e. two-level quantum systems

Examples:

- spin up / spin down
- two polarization states of a photon
- ion in a trap on two levels

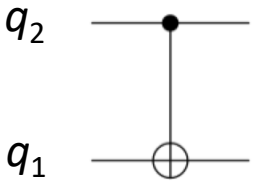
A qubit can be in a superposition of $|0\rangle$ and $|1\rangle$.

Quantum logical gates

Quantum computing is based on reversible processes (quantum gates perform unitary operations).

Single qubit unitary

Two qubit unitary



$$\text{CNOT} = \begin{array}{c} \begin{matrix} |00\rangle & |10\rangle & |01\rangle & |11\rangle \end{matrix} \\ \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \end{array}$$

A set of universal of quantum logical gates can implement any unitary operator.

Quantum circuits

Quantum circuits consist of quantum gate operations on qubits (reversible), followed by measurements / projections (irreversible).

Measurements are irreversible and connect qubits to classical bits

A measurement is irreversible (collapse of the wave function; decoherence due to interaction with a macroscopic environment).

How are QPUs realized?

- Transmon qubits (two-level system of Josephson junctions coupling an island with 0 or 1 Cooper pairs to a superconducting reservoir) → quantum chips we used for this paper
- Nitrogen vacancy in diamond (“NV diamond”)
- Ion traps
- Photonics
-
-
-

What can quantum computers possibly do well?

Some quantum algorithms outperform their classical counter parts:

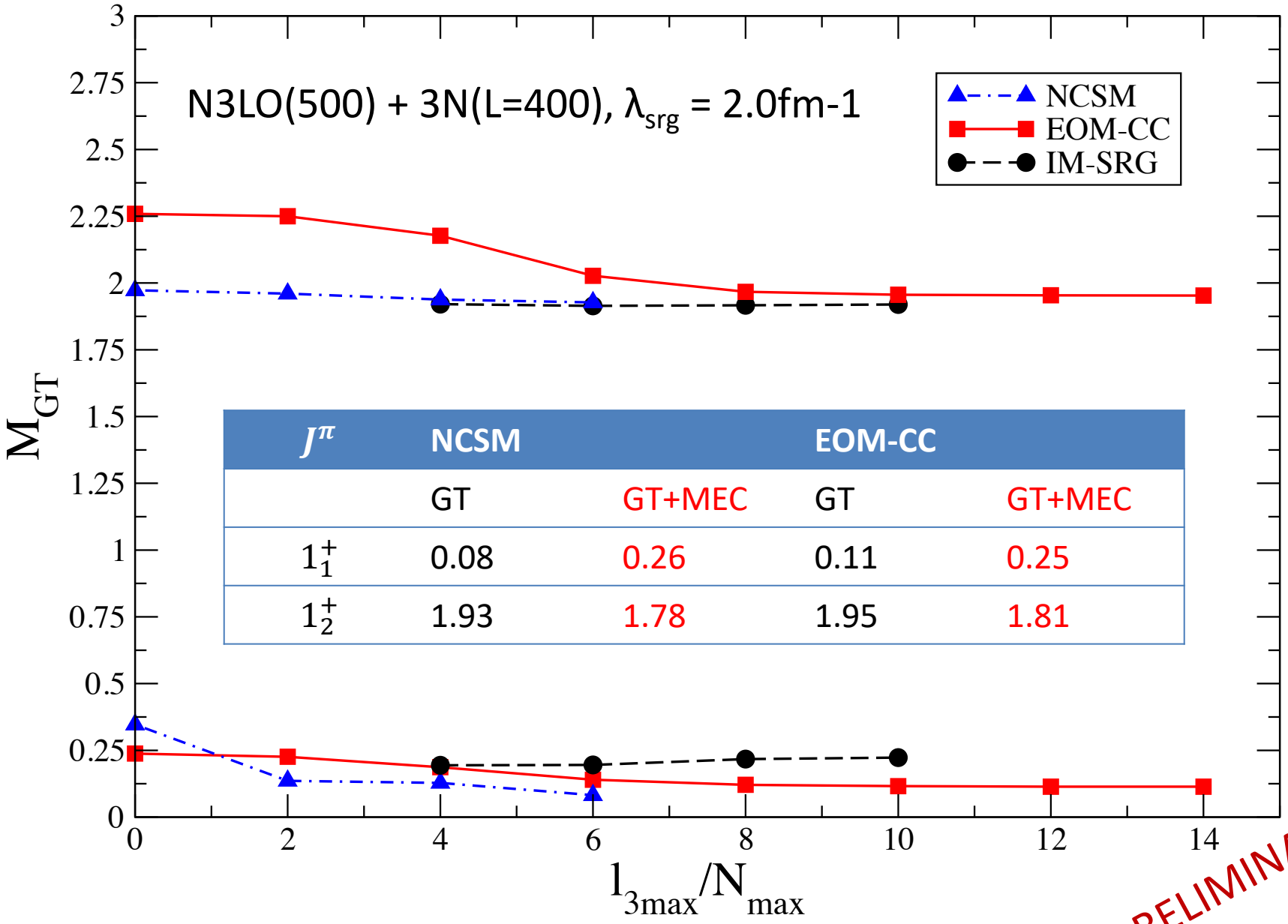
- Shor's algorithm: factoring of integers
- Grover's algorithm: inverting a function / searching an unordered list
- Quantum Fourier transform
- Quantum mechanics simulation: N qubits vs. 2^N complex numbers

Hope/expectation: quantum computing could solve problems with polynomial effort that are exponentially hard for classical computers.

Contrasting views:

1. We already have classical algorithms that yield approximate ground states for certain Hamiltonians/systems in polynomial time (e.g. DFT, coupled cluster method, IMSRG, Monte Carlo methods, …).
2. See Gil Kalai, arXiv:1605.00992 for a pessimistic view.

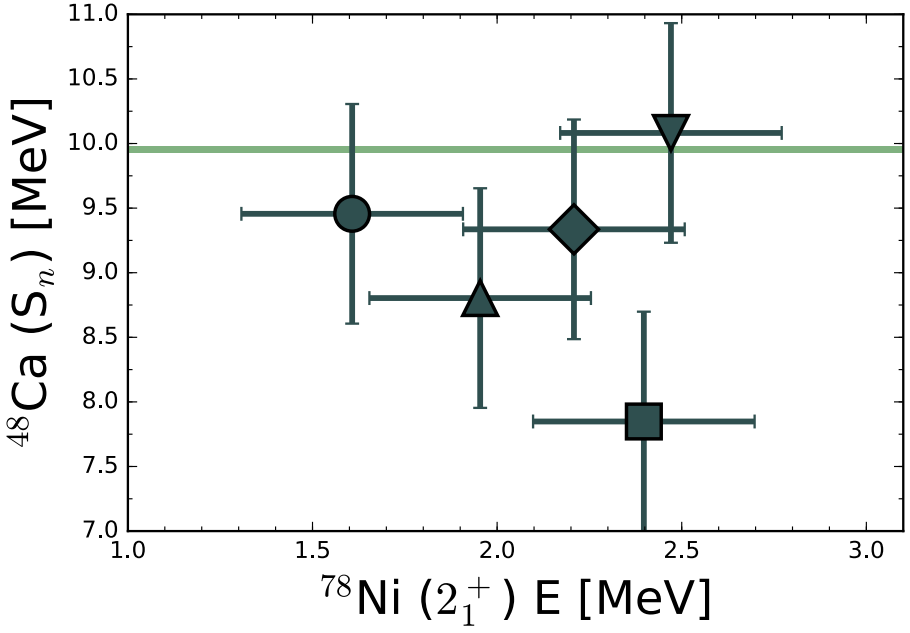
Benchmarks for Gamow-Teller transitions in ^{14}C



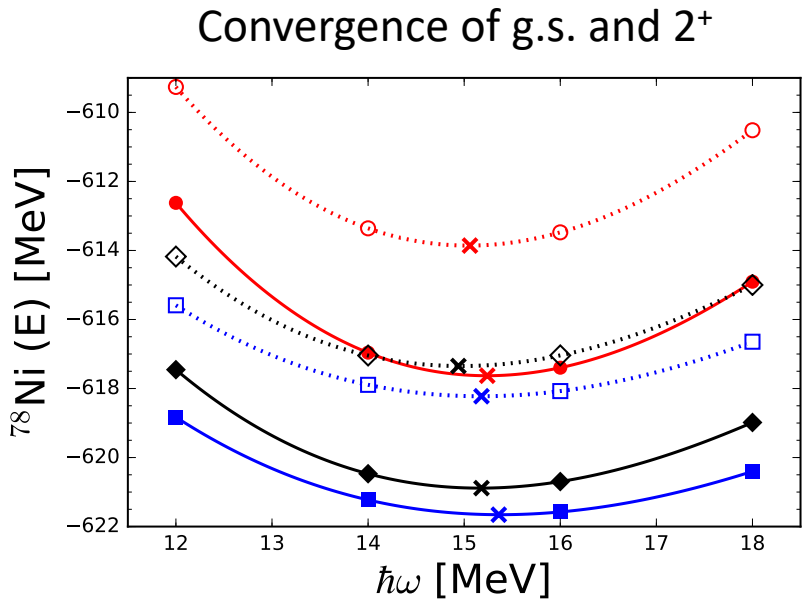
J^π	NCSM		EOM-CC	
	GT	GT+MEC	GT	GT+MEC
1_1^+	0.08	0.26	0.11	0.25
1_2^+	1.93	1.78	1.95	1.81

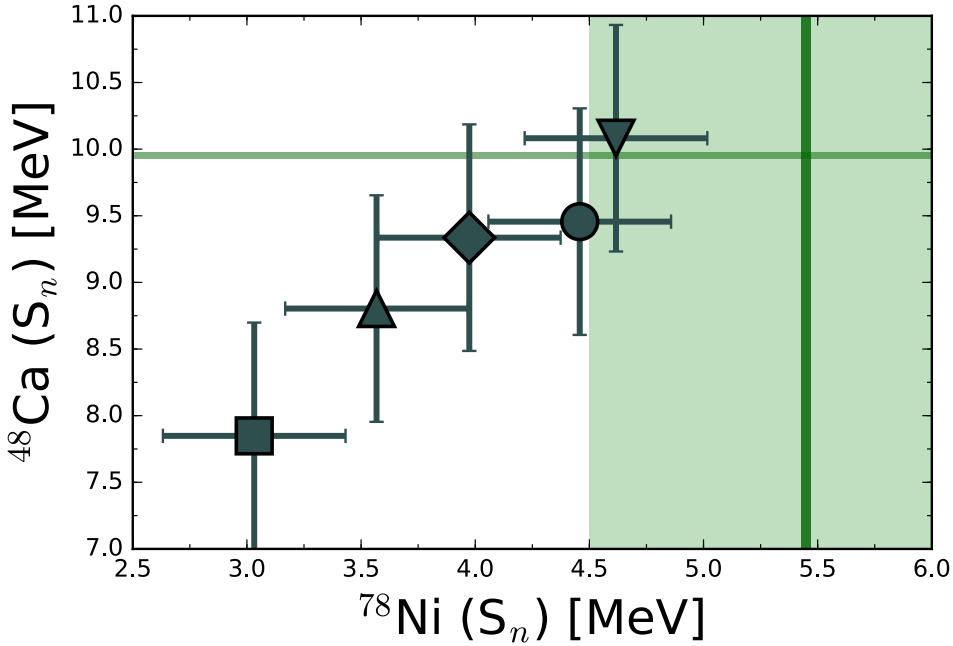
PRELIMINARY

Other correlations in ^{48}Ca and ^{78}Ni

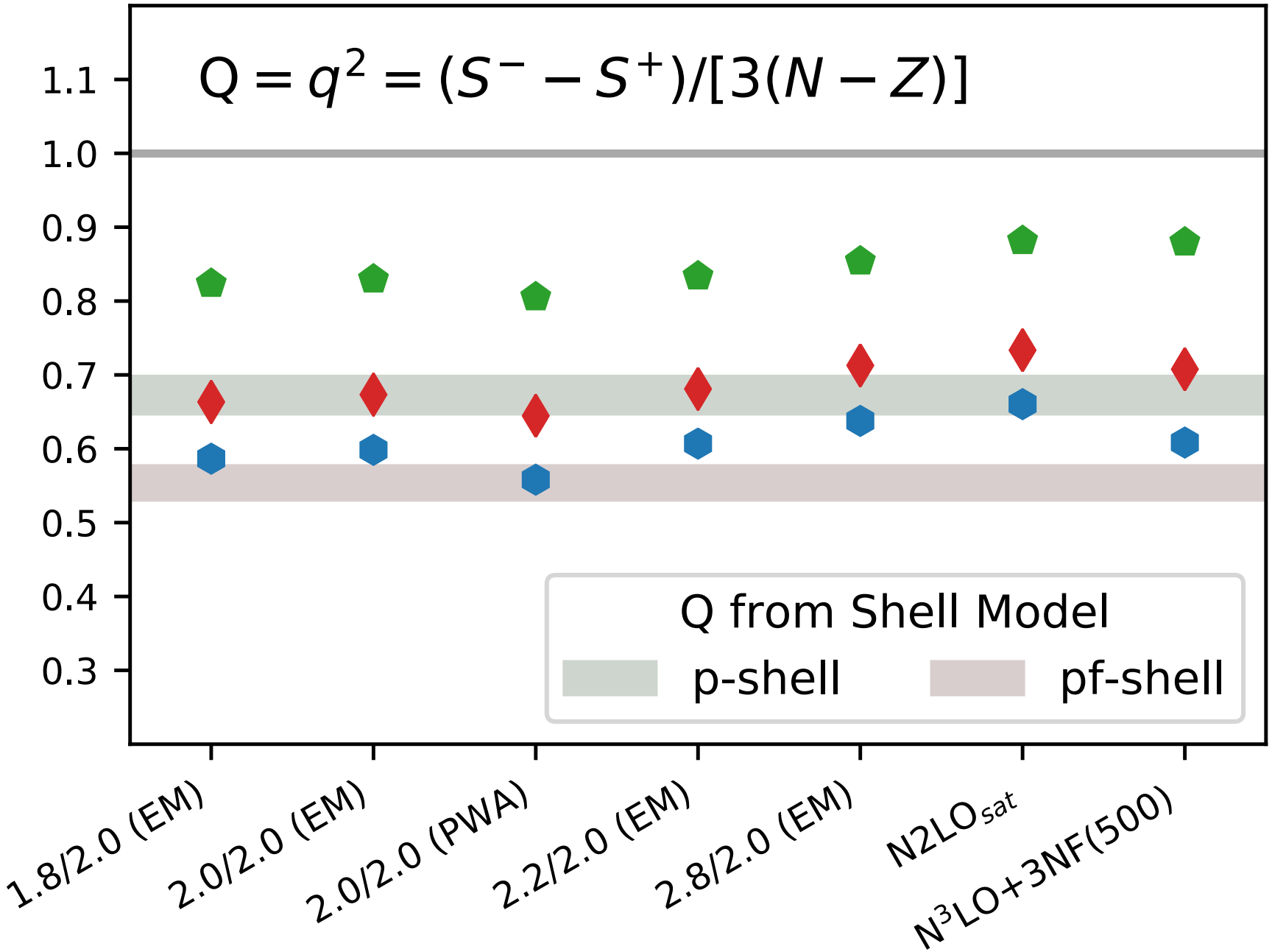


- Separation energy of ^{48}Ca and 2^+ energy of ^{78}Ni does not correlate
- Separation energies of ^{48}Ca and ^{78}Ni do correlate
- Non-trivial correlation between the 2^+ energy of ^{78}Ni and ^{48}Ca

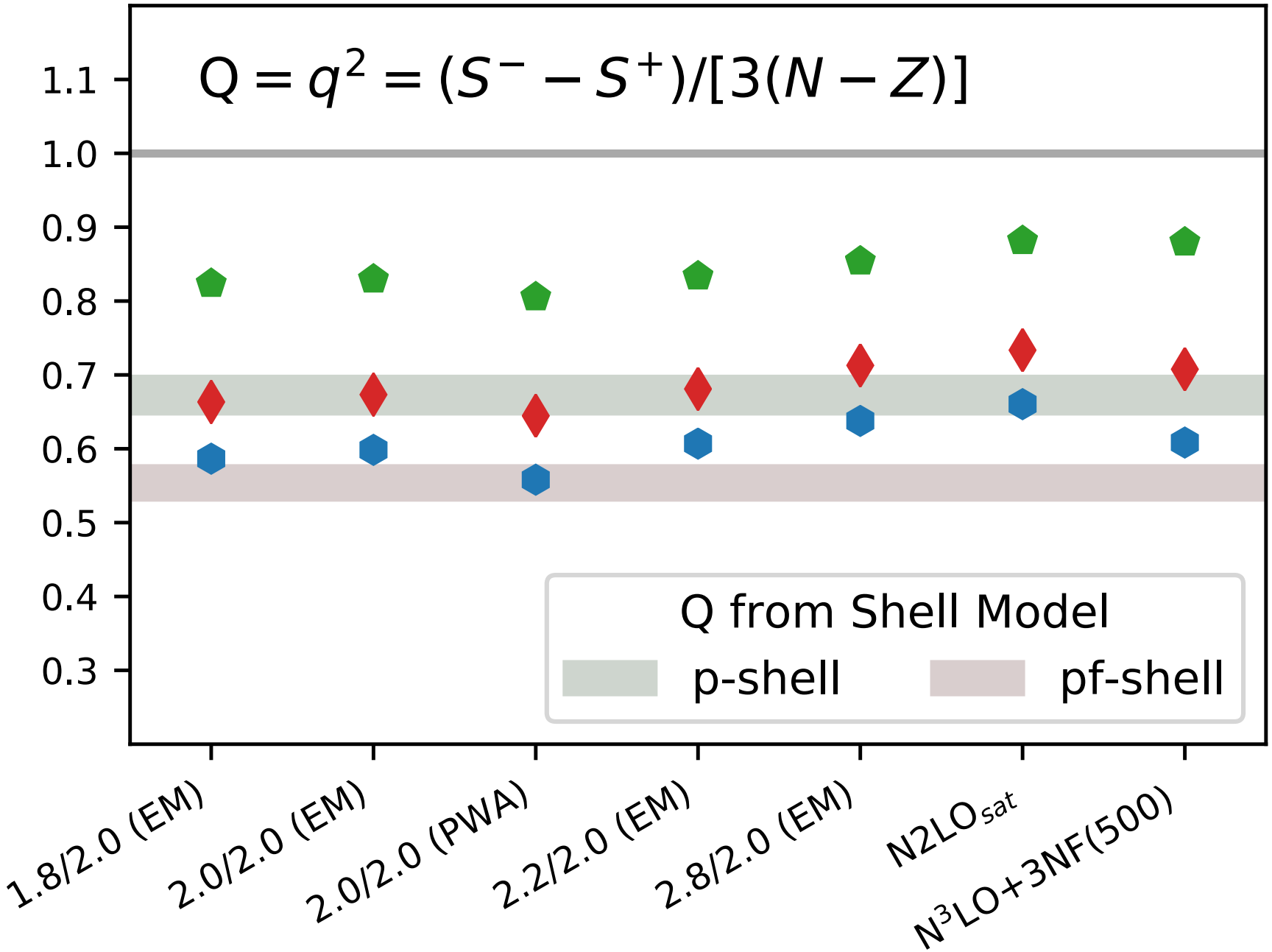




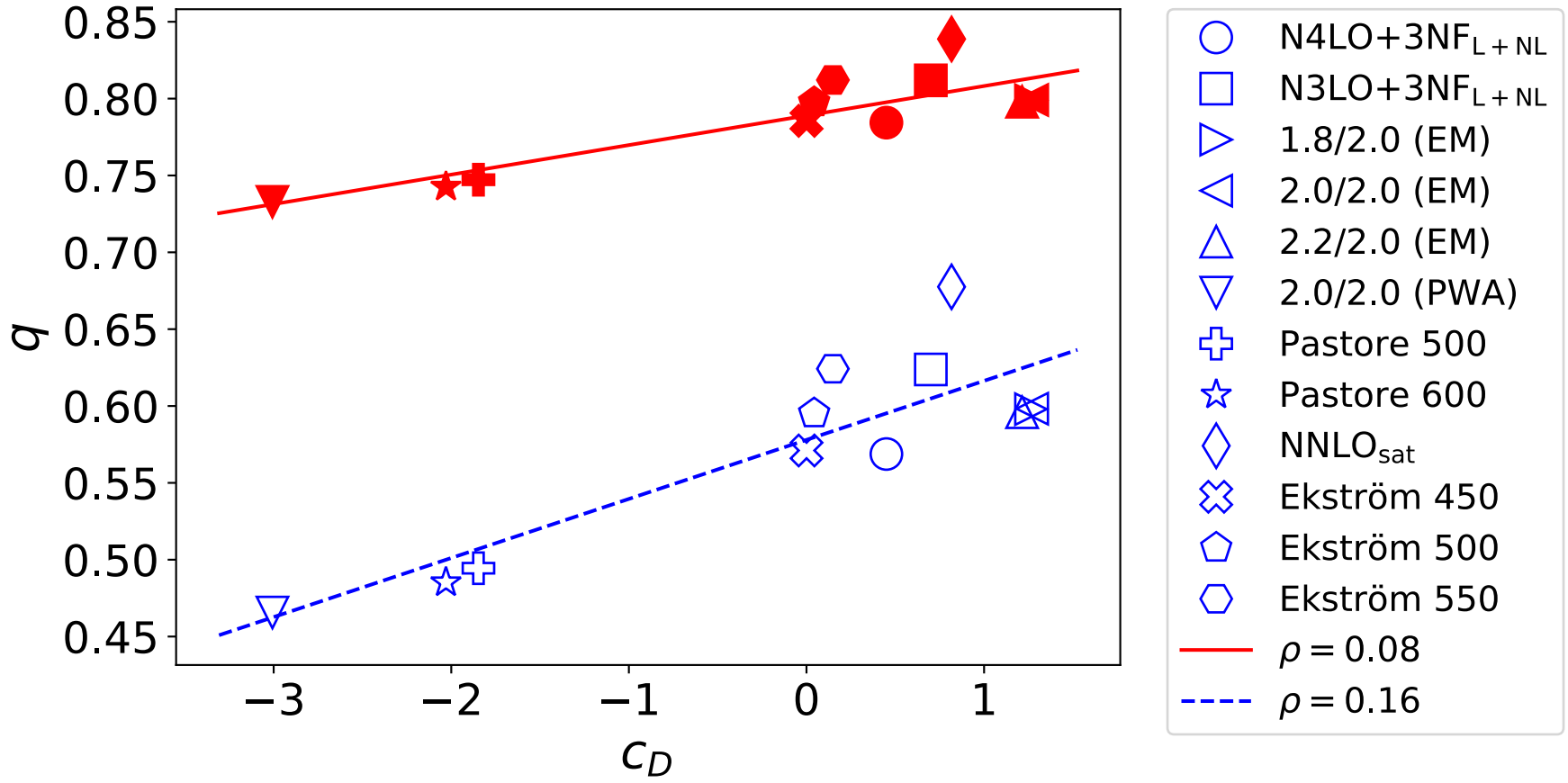
Ikeda sum-rule



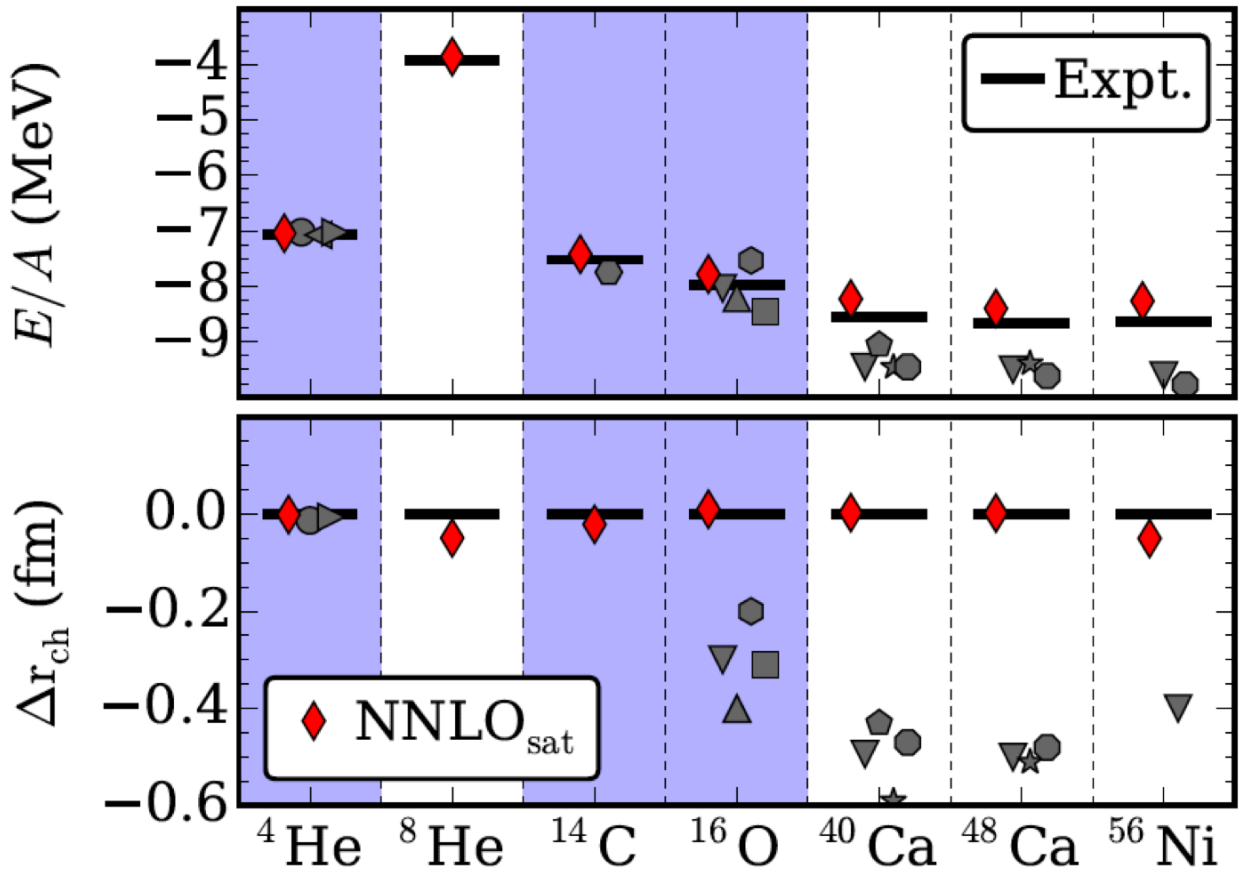
Ikeda sum-rule



The small role of short-ranged 2BC on GT decay



Accurate nuclear binding energies and radii from a chiral interaction



Navratil et al (2007); Jurgenson et al (2011)

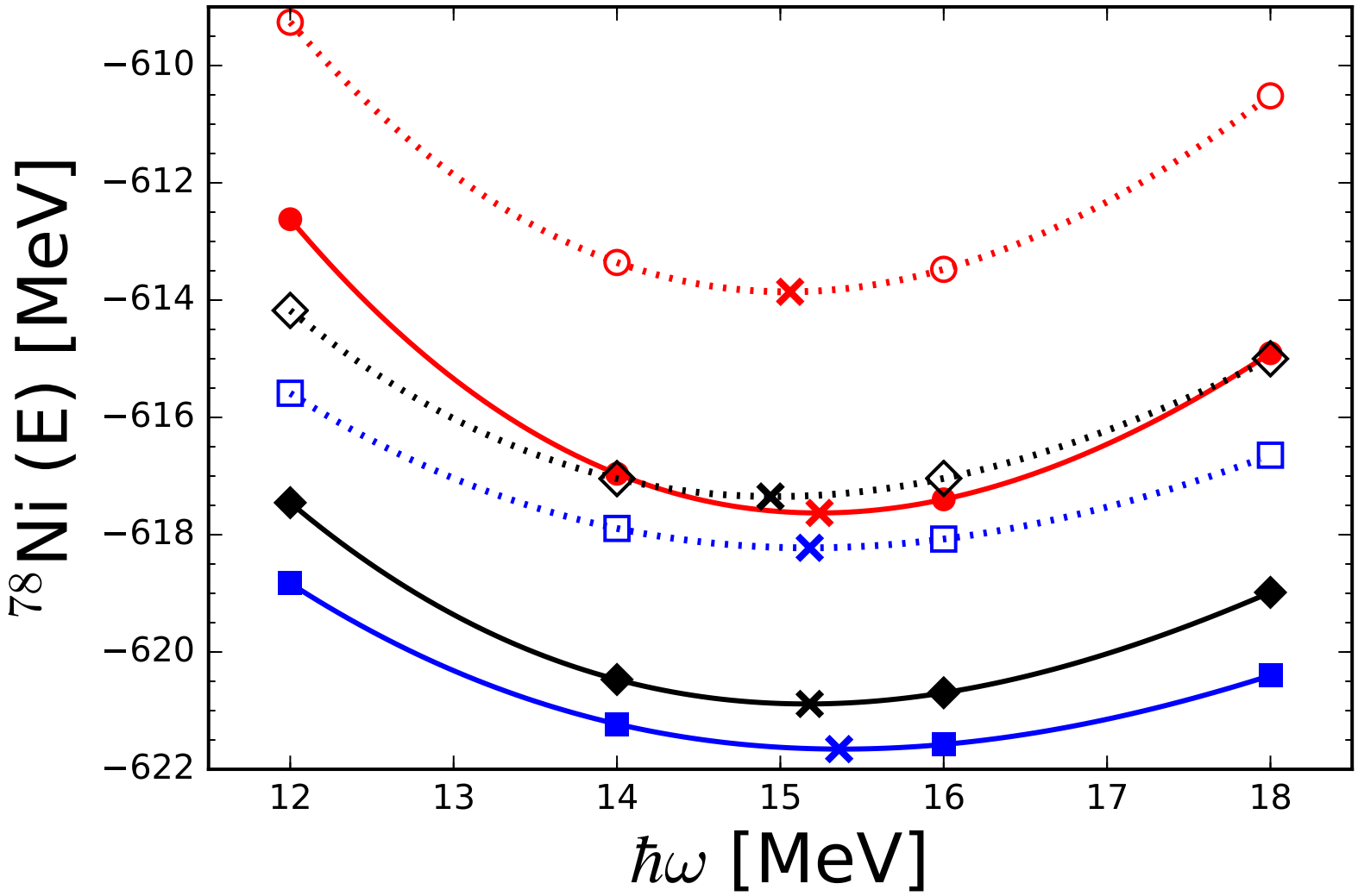
- a
- b Binder et al (2014)
- c Epelbaum et al (2014)
- d Epelbaum et al (2012)
- e Maris et al (2014)
- f Wloch et al (2005)
- g Hagen et al (2014)
- h Bacca et al (2014)
- i Maris et al (2011)
- j Hergert et al (2014)
- k Soma et al (2014)

Solution: 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 (NNLO$_{sat}$)

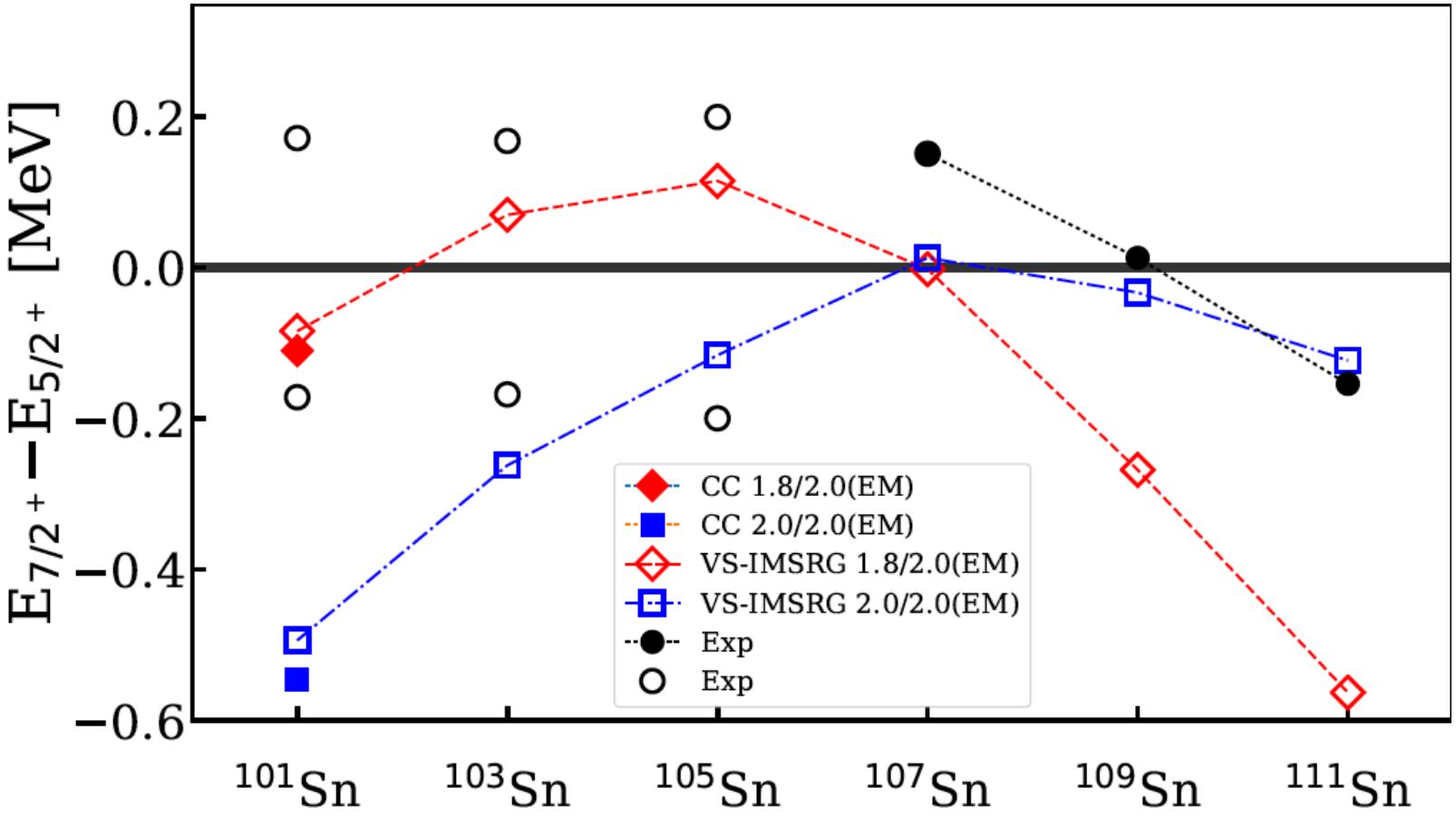
A. Ekström *et al*, Phys. Rev. C **91**, 051301(R) (2015).
G. Hagen et al, Phys. Scr. **91**, 063006 (2016).

Not new: GFMC with AV18 and Illinois-7 are fit to 23 levels in nuclei with A <10

Convergence of ^{78}Ni g.s. energy and 2^+ excited state energy



Structure of the ligthest tin isotopes



- Splitting between $7/2^+$ and $5/2^+$ reproduced
- Ground-state spins of $^{101\text{-}121}$Sn will be measured at CERN (CRIS collaboration)

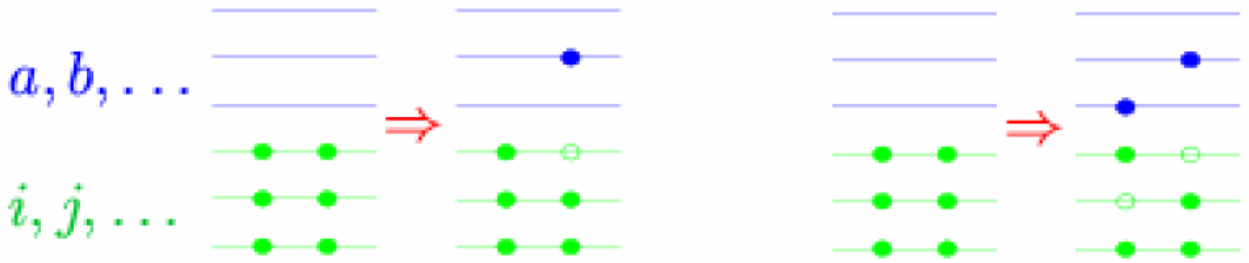
Coupled-cluster method (CCSD approximation)

Ansatz:

$$
\begin{aligned}
|\Psi\rangle &= e^{T}|\Phi\rangle \\
T &= T_1 + T_2 + \dots \\
T_1 &= \sum_{ia} t_i^a a_a^\dagger a_i \\
T_2 &= \sum_{ijab} t_{ij}^{ab} a_a^\dagger a_b^\dagger a_j a_i
\end{aligned}
$$

- ☺ Scales gently (polynomial) with increasing problem size o^2u^4 .
- ☺ Truncation is the only approximation.
- ☺ Size extensive (error scales with A)
- ☹ Most efficient for closed (sub-)shell nuclei

Correlations are *exponentiated* 1p-1h and 2p-2h excitations. Part of np-nh excitations included!



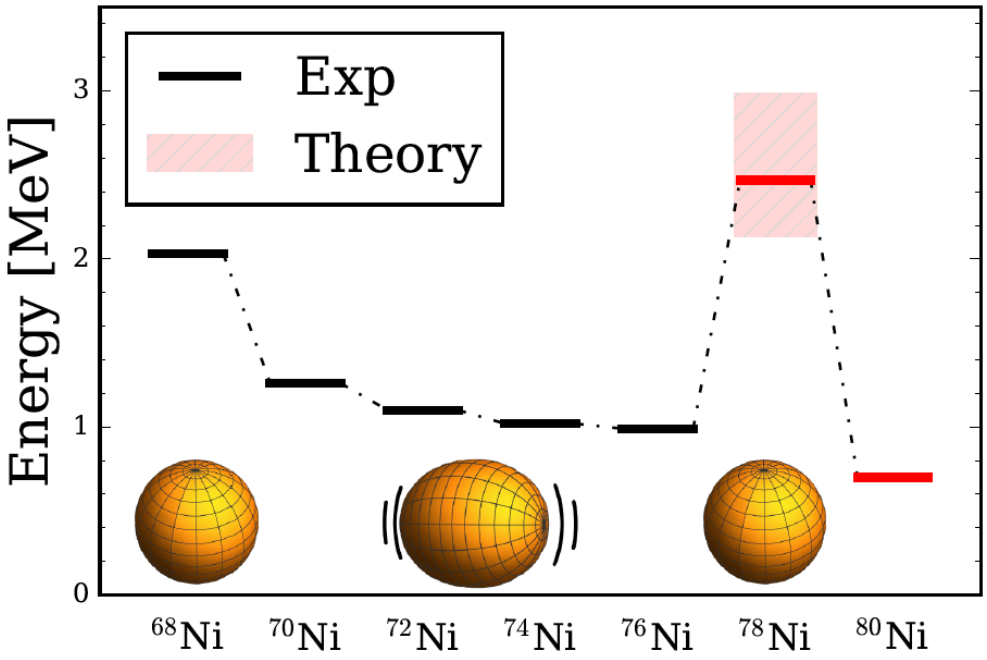
Coupled cluster equations

$$
\begin{aligned}
E &= \langle\Phi|\overline{H}|\Phi\rangle \\
0 &= \langle\Phi_i^a|\overline{H}|\Phi\rangle \\
0 &= \langle\Phi_{ij}^{ab}|\overline{H}|\Phi\rangle
\end{aligned}
$$

Alternative view: CCSD generates similarity transformed Hamiltonian with no 1p-1h and no 2p-2h excitations.

$$
\overline{H} \equiv e^{-T} H e^{T} = \left(He^{T}\right)_c = \left(H + HT_1 + HT_2 + \frac{1}{2}HT_1^2 + \dots\right)_c
$$

Structure of ^{78}Ni from first principles

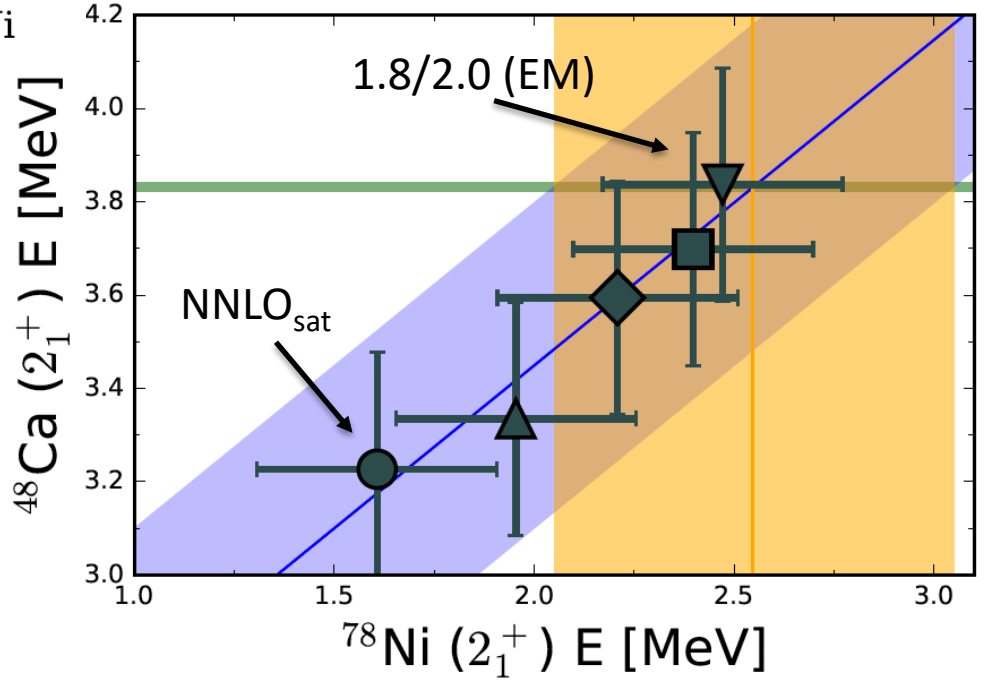


A high 2^+ energy in ^{78}Ni indicates that this nucleus is doubly magic

Consistent with recent shell-model studies
F. Nowacki *et al.,* PRL 117, 272501 (2016)

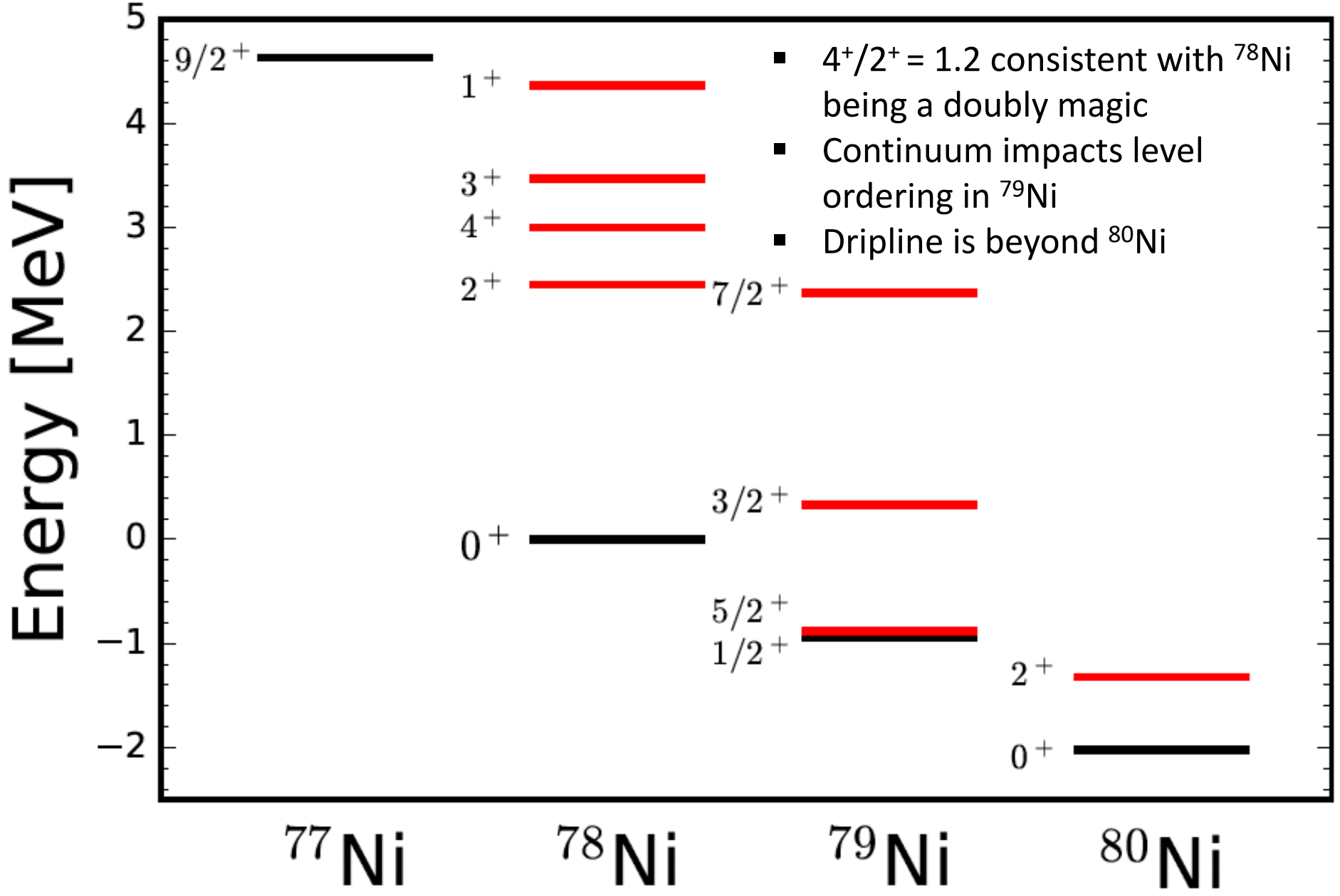
A measurement of this state has been made at RIBF, R. Taniuchi *et al.*, in preparation

- From an observed correlation we predict the 2^+ excited state in ^{78}Ni using the experimental data for the 2^+ state in ^{48}Ca
- Similar correlations have been observed in other nuclei, e.g. Tjon line in light nuclei



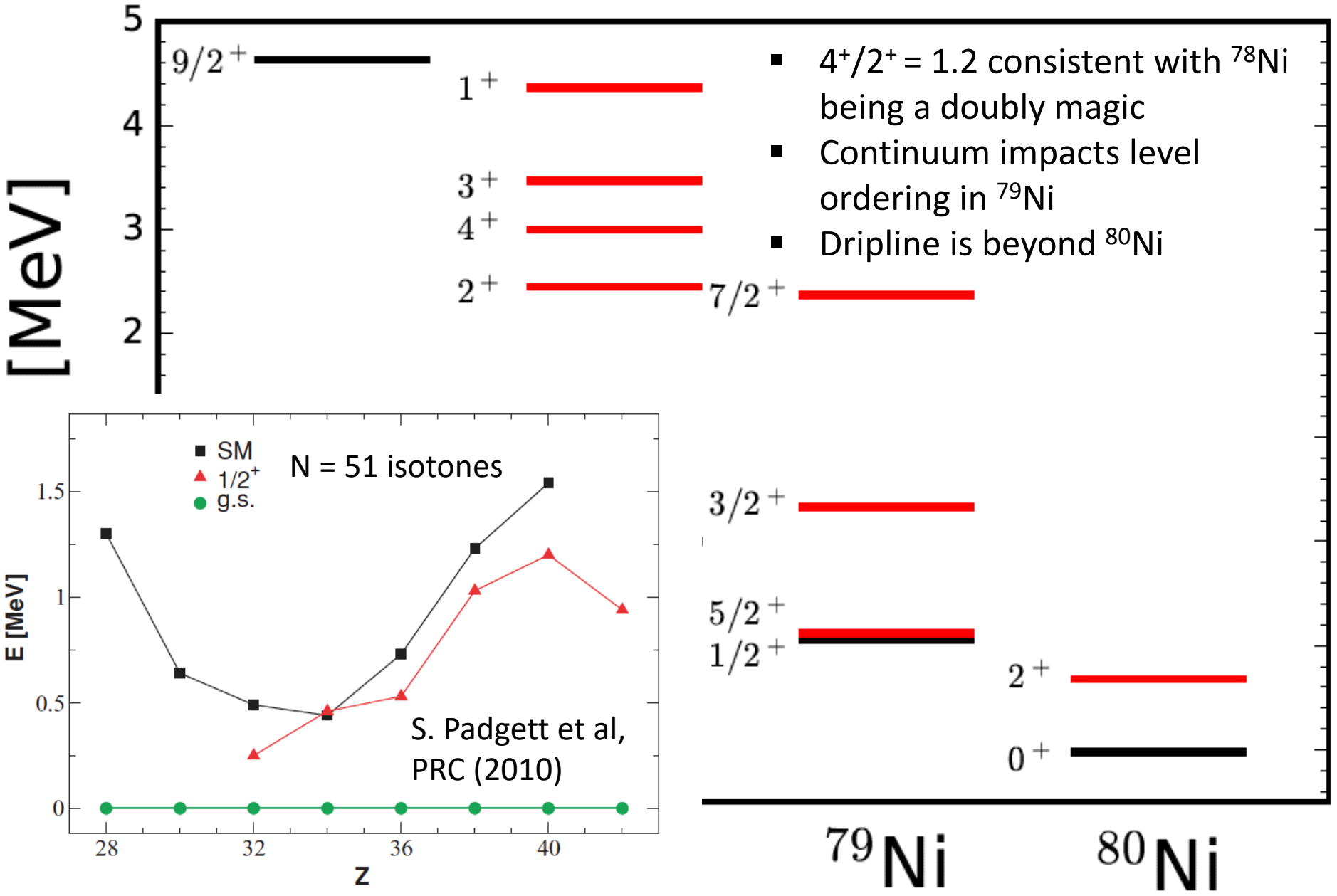
G. Hagen, G. R. Jansen, and T. Papenbrock
Phys. Rev. Lett. **117**, 172501 (2016)

Excited states in ^{78}Ni and its neighbors



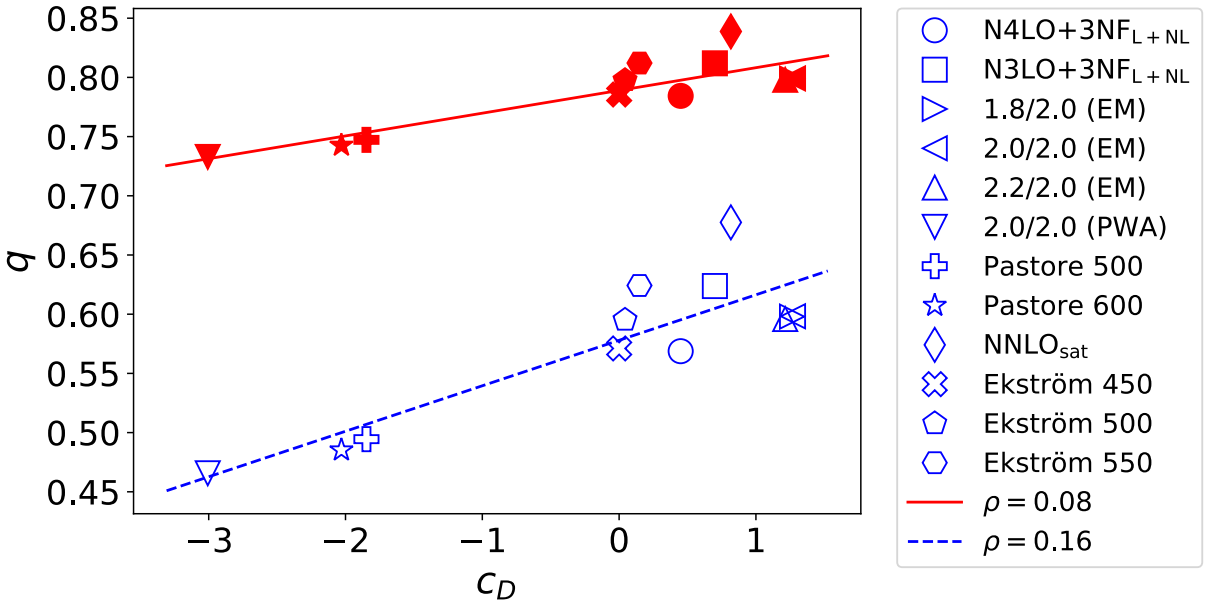
- $4^+/2^+ = 1.2$ consistent with ^{78}Ni being a doubly magic
- Continuum impacts level ordering in ^{79}Ni
- Dripline is beyond ^{80}Ni

Excited states in ^{78}Ni and its neighbors



- $4^+/2^+ = 1.2$ consistent with ^{78}Ni being a doubly magic
- Continuum impacts level ordering in ^{79}Ni
- Dripline is beyond ^{80}Ni

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 a smaller part.

J. Menéndez, D. Gazit, A. Schwenk

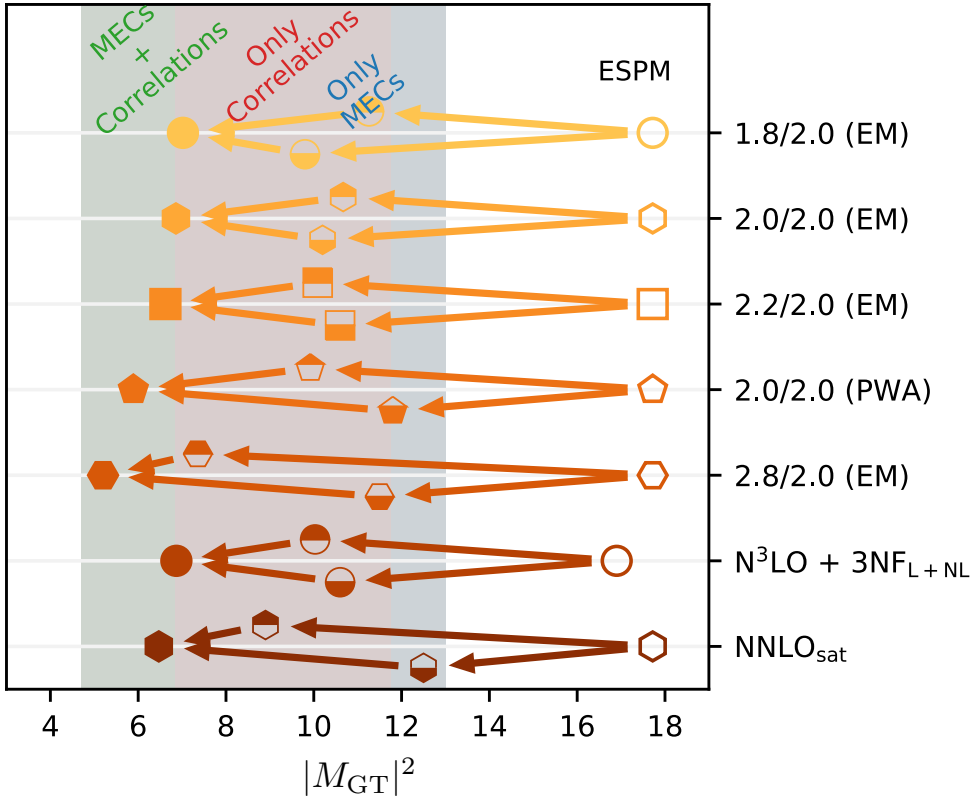
PRL 107, 062501 (2011)

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

$$q \approx 1 - \frac{\rho\hbar^3 c^3}{F_\pi^2}\left(-\frac{c_D}{4g_A\Lambda} + \frac{I}{3}(2c_4 - c_3) + \frac{I}{6m}\right)$$

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]

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	12.5	6.5	0.85	0.84	7.4	not converged
NN-N^3LO+$3N_{lnl}$	16.9	10.0(6)	10.6	6.9(6)	0.83	0.79	6.1	7.6
1.8/2.0 (EM)	17.7	11.3(6)	9.8	7.0(6)	0.79	0.74	5.1	8.4
2.0/2.0 (EM)	17.7	10.7(6)	10.2	6.9(6)	0.80	0.76	6.0	7.7
2.0/2.0 (PWA)	17.7	9.9(6)	11.5	5.9(6)	0.77	0.81	6.8	6.4
2.2/2.0 (EM)	17.7	10.1(6)	10.6	6.6(6)	0.81	0.77	6.7	7.2
2.8/2.0 (EM)	17.7	7.4(6)	11.8	5.2(6)	0.84	0.82	8.3	not converged
Batist *et al.* [6]				5.2 ± 0.6			5.11	8.25
Hinke *et al.* [5]				$9.1^{+2.6}_{-3.0}$				

Excited states in ^{78}Ni and its neighbors

- $4^+/2^+$ = 1.2 consistent with ^{78}Ni being a doubly magic
- Continuum impacts level ordering in ^{79}Ni
- Dripline is beyond ^{80}Ni

Energy [MeV]

5
4
3
2

$9/2^+$
1^+
3^+
4^+
2^+
$7/2^+$
$3/2^+$
$5/2^+$
$1/2^+$
2^+
0^+

^{79}Ni ^{80}Ni

F. Nowacki *et al.,* PRL 117, 272501 (2016)