



Quantum Simulation of Atomic Nuclei

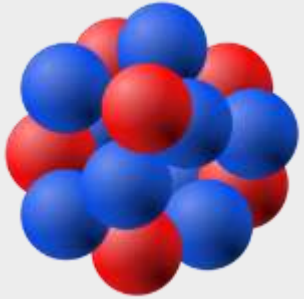
Paul Stevenson

University of Surrey

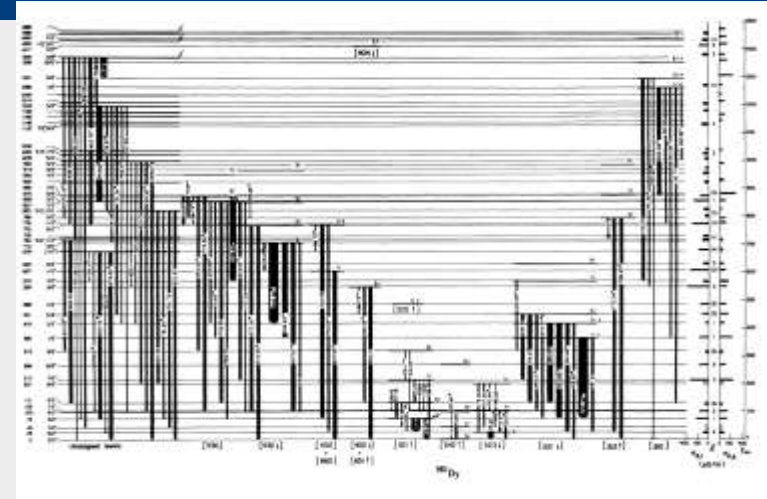
@ SparQ Access Showcase

Canterbury 2026

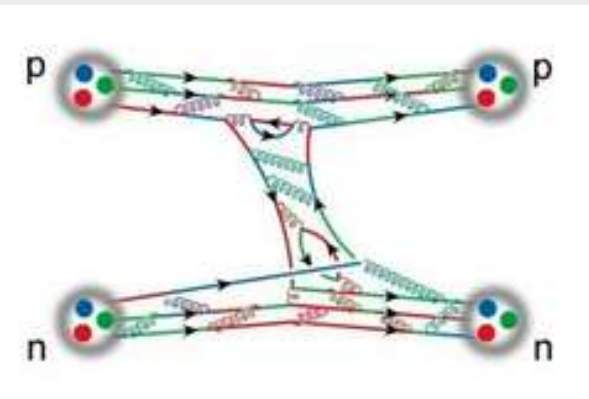
(Theoretical) Nuclear Physics



<- we want to take
a system of
protons & neutrons

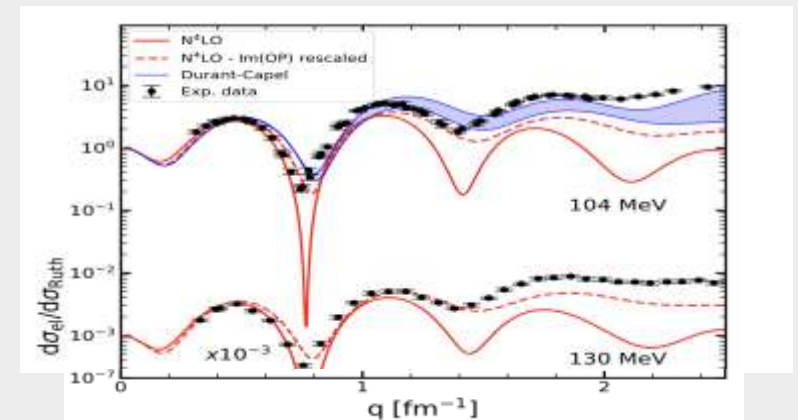


To understand the great complexity of
observed data in nuclear structure ...



<- and use
the forces
acting
between
them

... and
nuclear
reactions



Nuclear Structure: a microscopic view

A typical microscopic approach starts from the many-body Schrödinger equation:

$$\left(\sum_{ij} t_{ij} a_i^\dagger a_j + \frac{1}{2} \sum_{ijkl} V_{ijkl} a_i^\dagger a_j^\dagger a_l a_k \right) |\Psi\rangle + E |\Psi\rangle$$

One-body
interaction
(kinetic energy)

Two-body interaction
(nuclear potential)

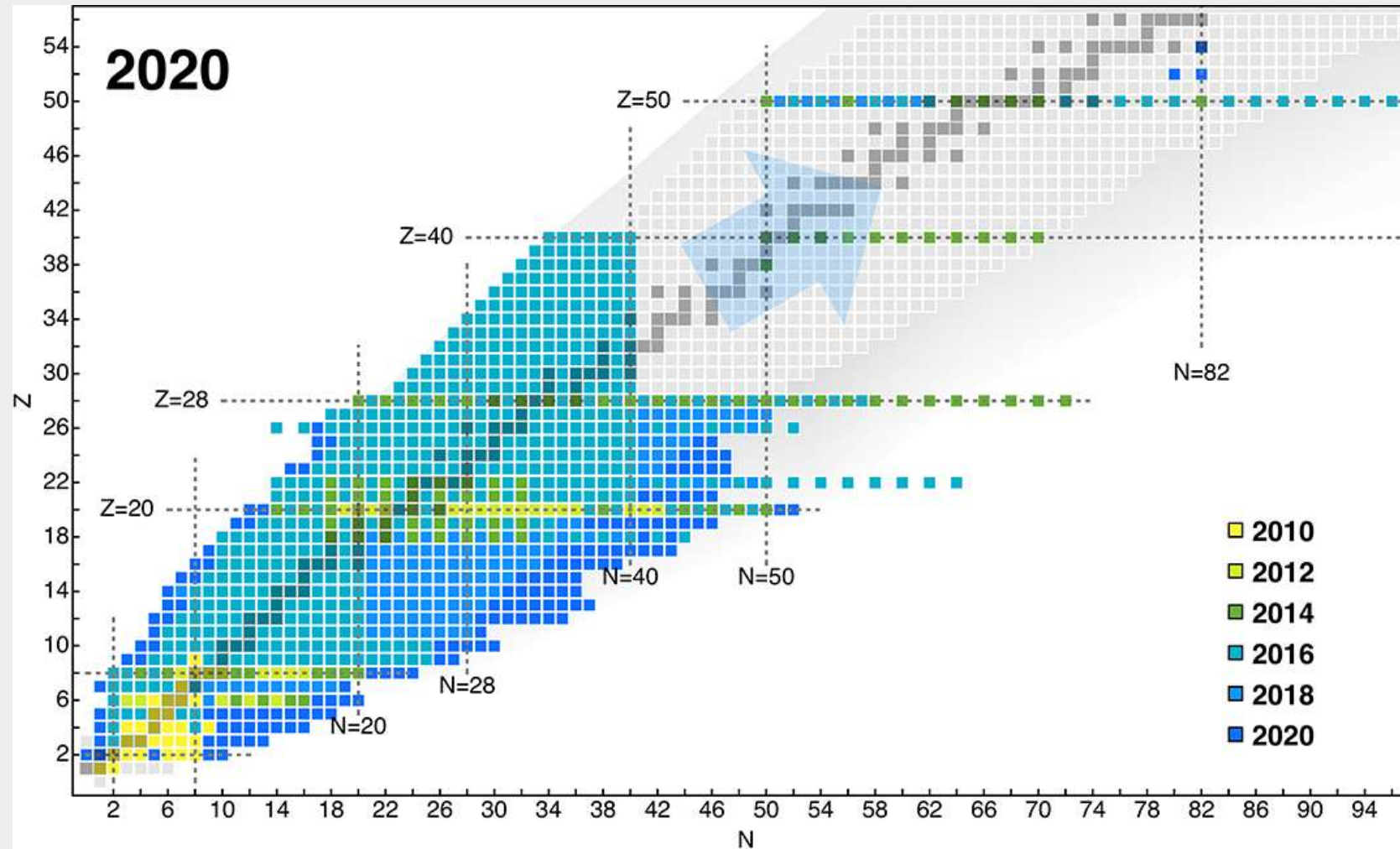
A very big matrix-eigenvalue problem

Difficulties in solving on classical computers:

- Complexity of problem / size of Hilbert space increases combinatorially with number of particles
- degree of entanglement of wave function makes various approximations slow to converge
- we don't know very well what the nuclear force looks like. Higher-body terms probably relevant (3-body, 4-body) ...

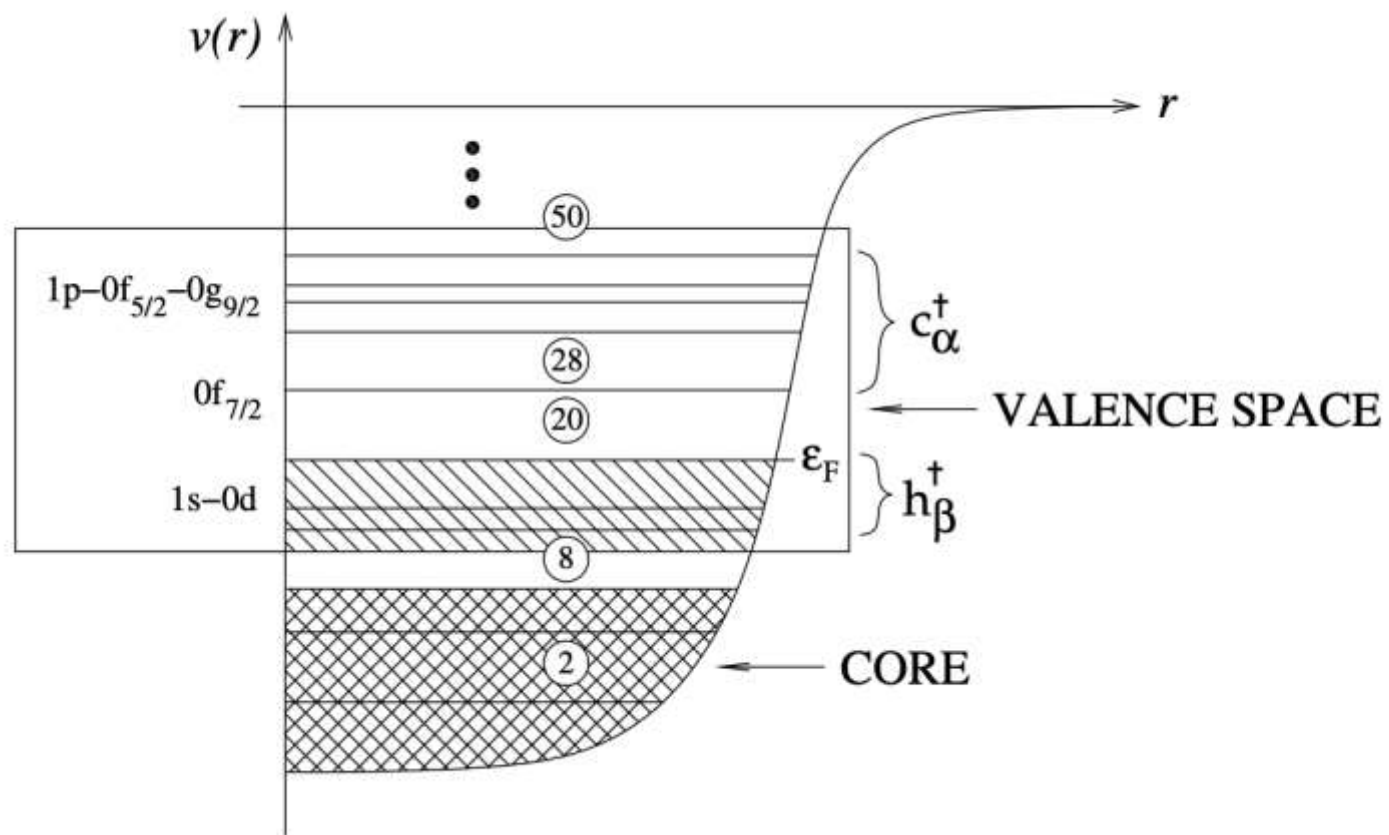
Quantum computing can help with the first two of these points, and could help a little with the third.

Nuclear structure landscape

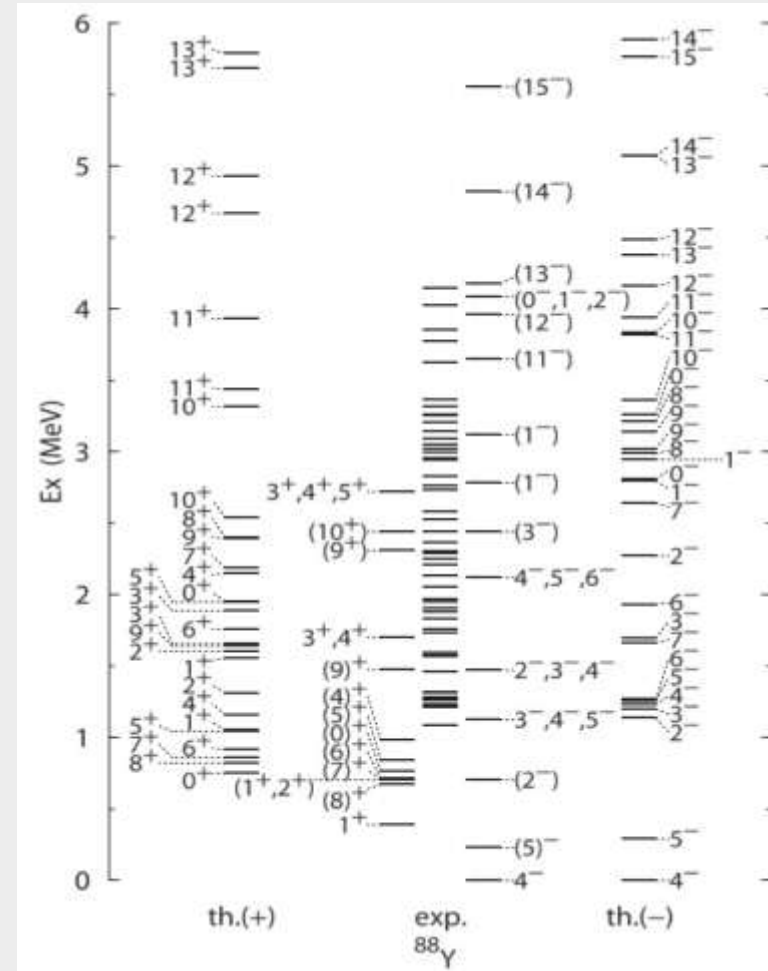


Hergert, “A Guided Tour of ab initio Nuclear Many-Body Theory”, Front. Phys. 8, 00379 (2020)

Shell model

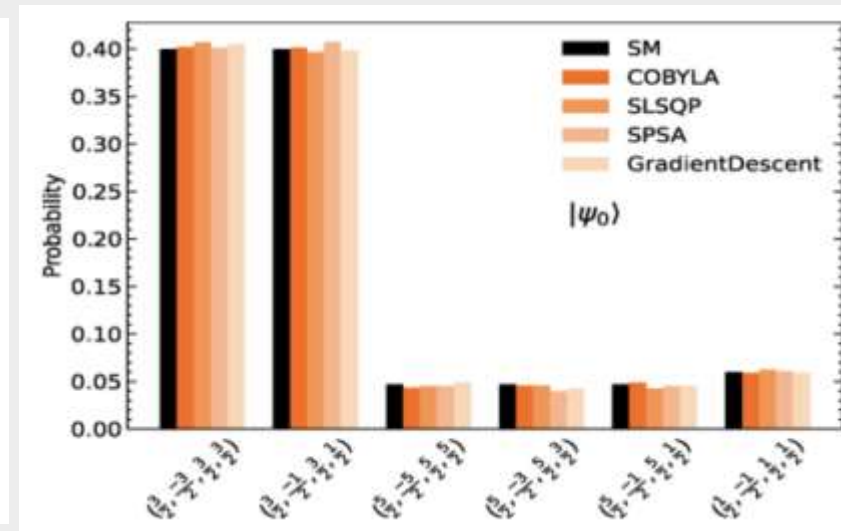
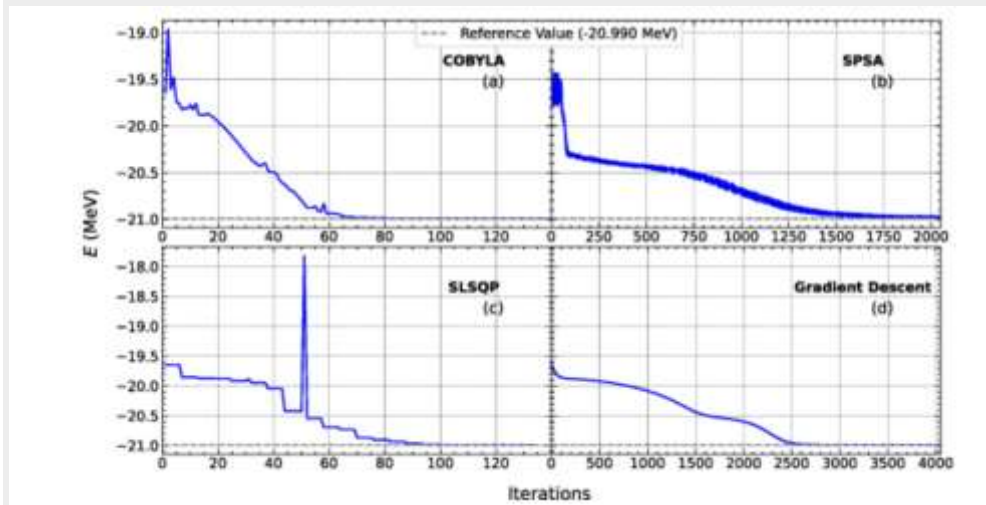


Suhonon, *From Nucleons to Nucleus*, Springer Verlag



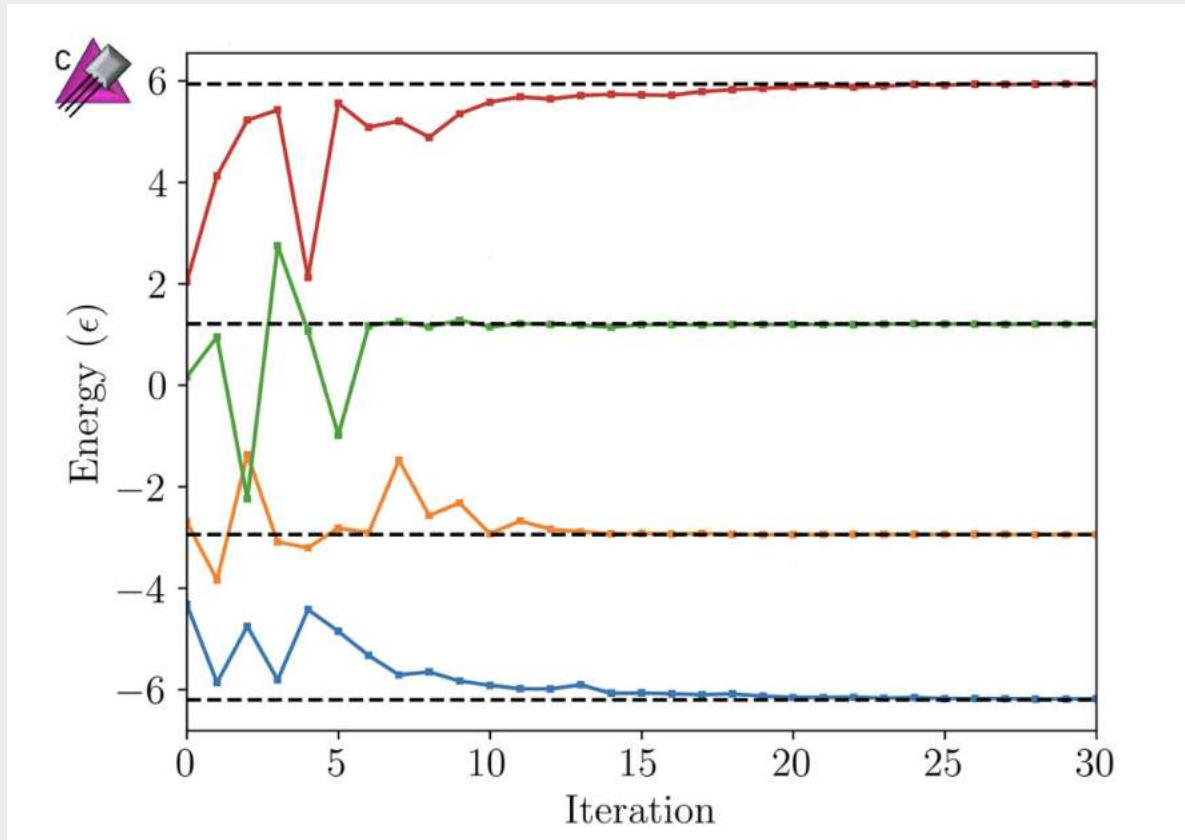
Honma et al PRC80, 064323 (2009)

e.g. “standard” orbital $\rightarrow$ qubit JW mapping, Bhoy & Stevenson, New J. Phys. 26, 075001 (2025)

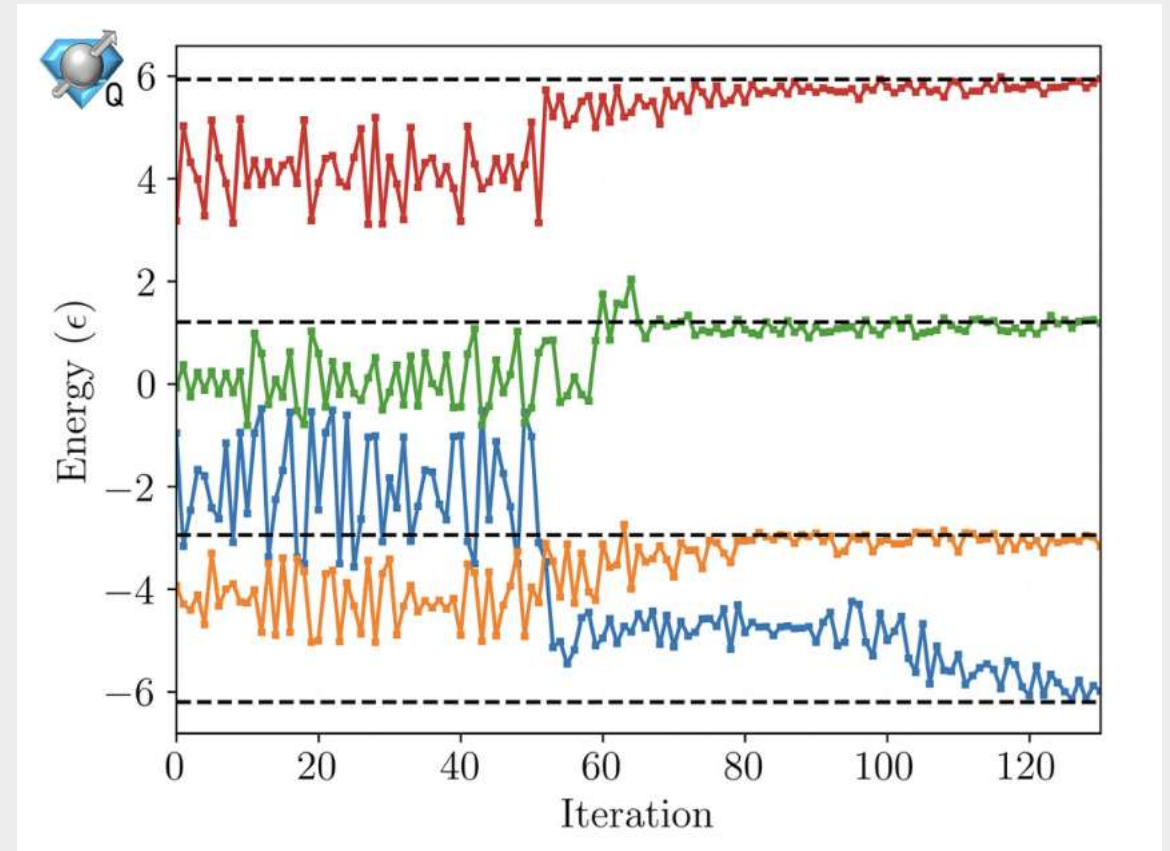


Excited States – Variance Minimisation

Hobday et al., Phys. Rev. C 111, 064321 (2025)



Simulated

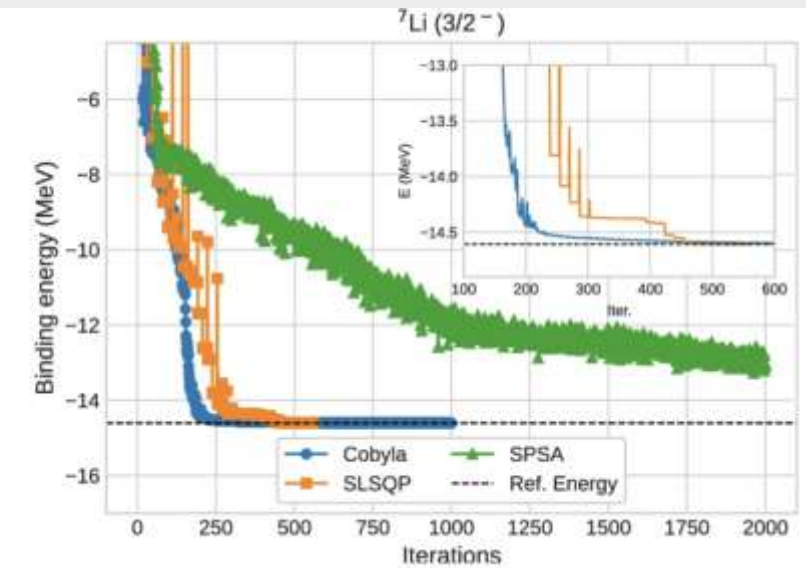
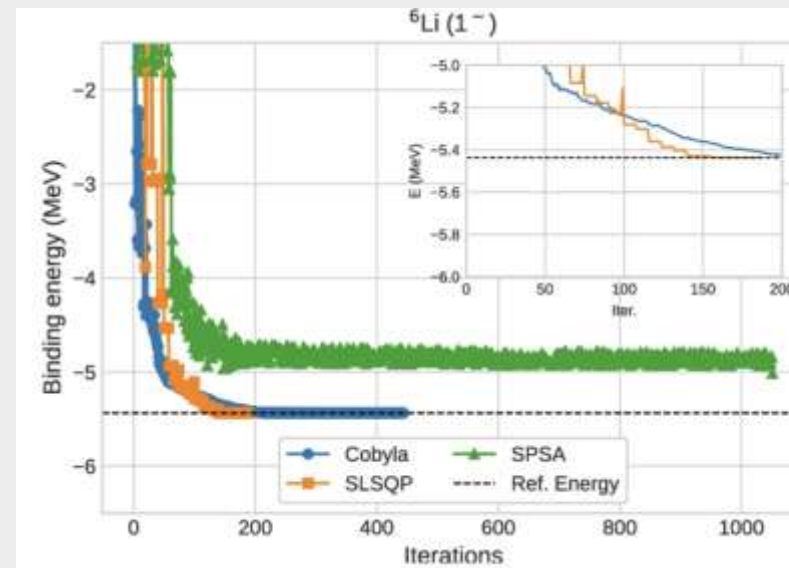
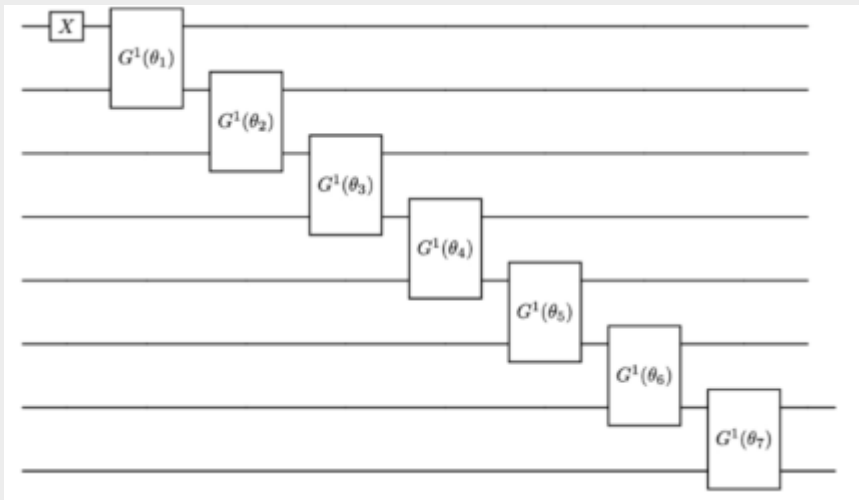


IBM quantum hardware
(IBM_Nairobi, Pre-NQCC days)

Slater-Determinant to qubit mapping

Instead of mapping a single particle state to a qubit, we map a configuration

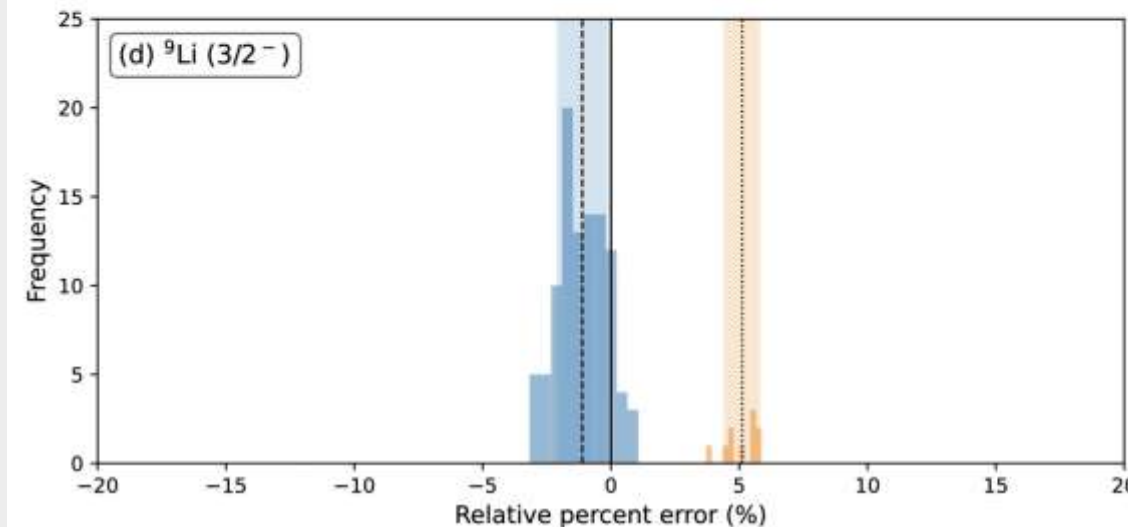
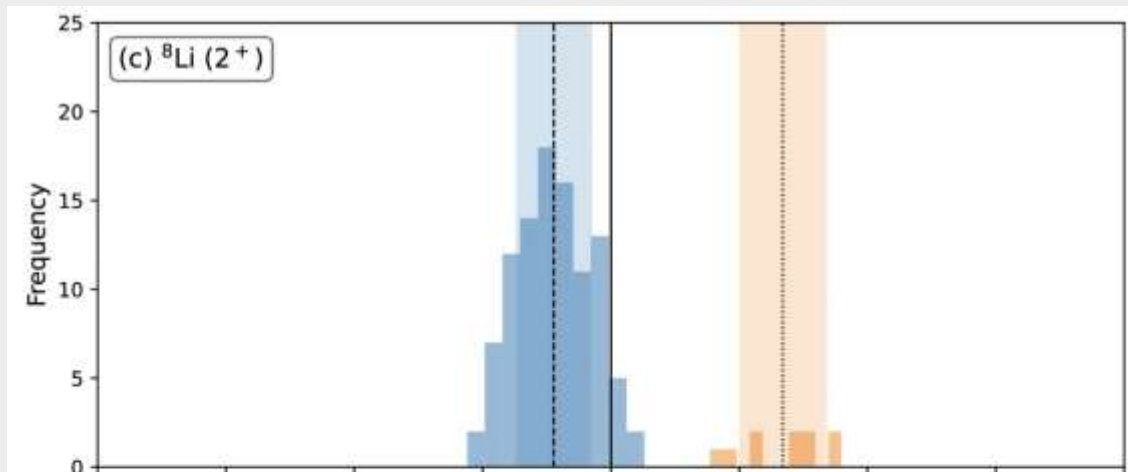
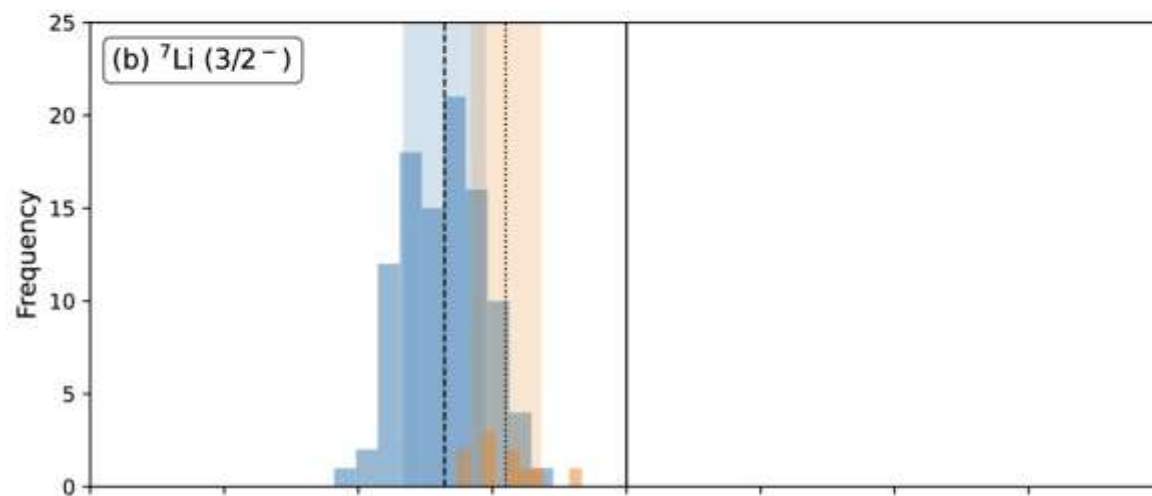
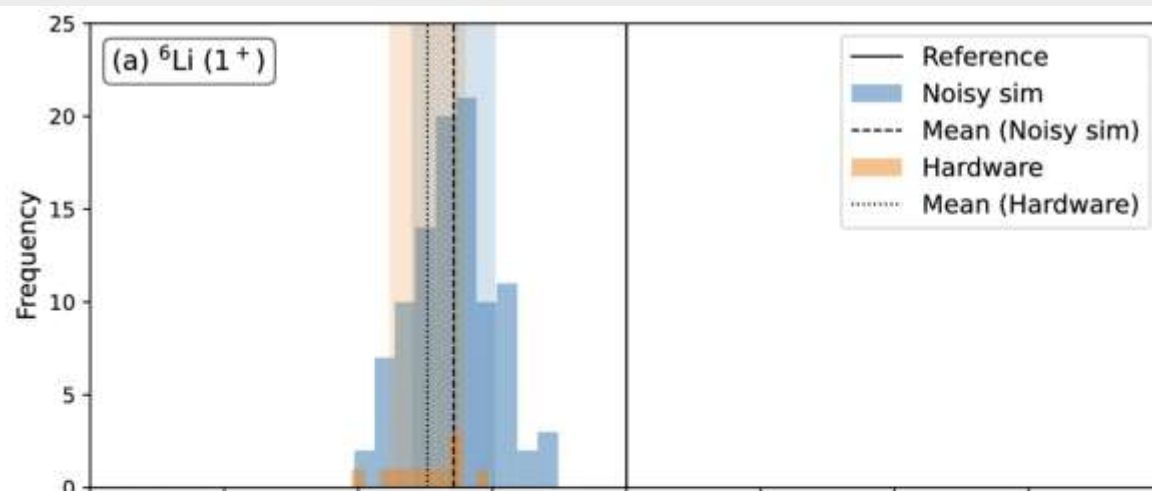
- Lowers circuit complexity, but increases # of qubits
- Need no more than single Givens' rotations



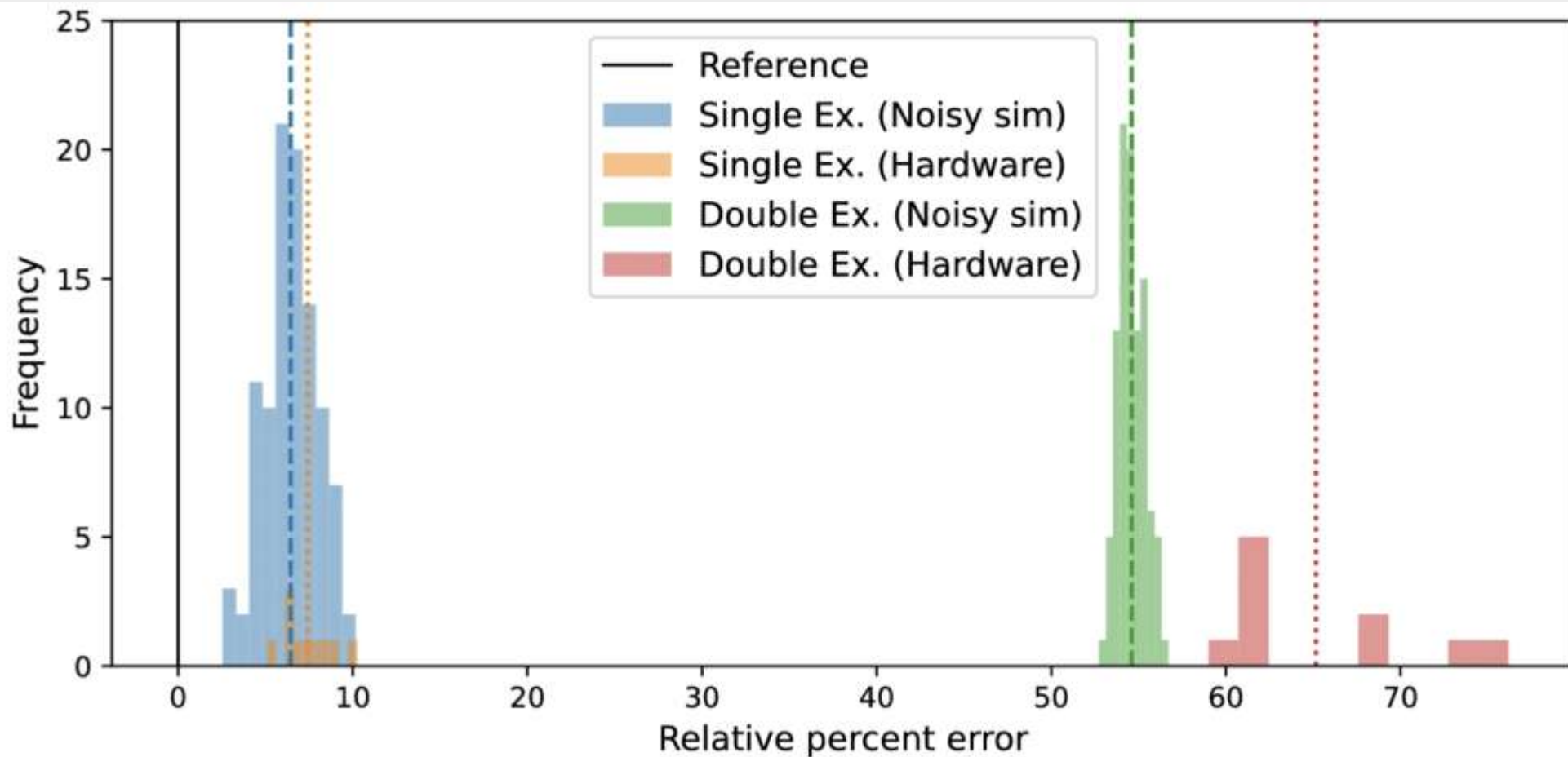
VQE process in simulation: Evaluation of resulting wave function on real hardware on next slide

Sarma & Stevenson, *Discov. Quantum Sci.* 2, 6 (2026)

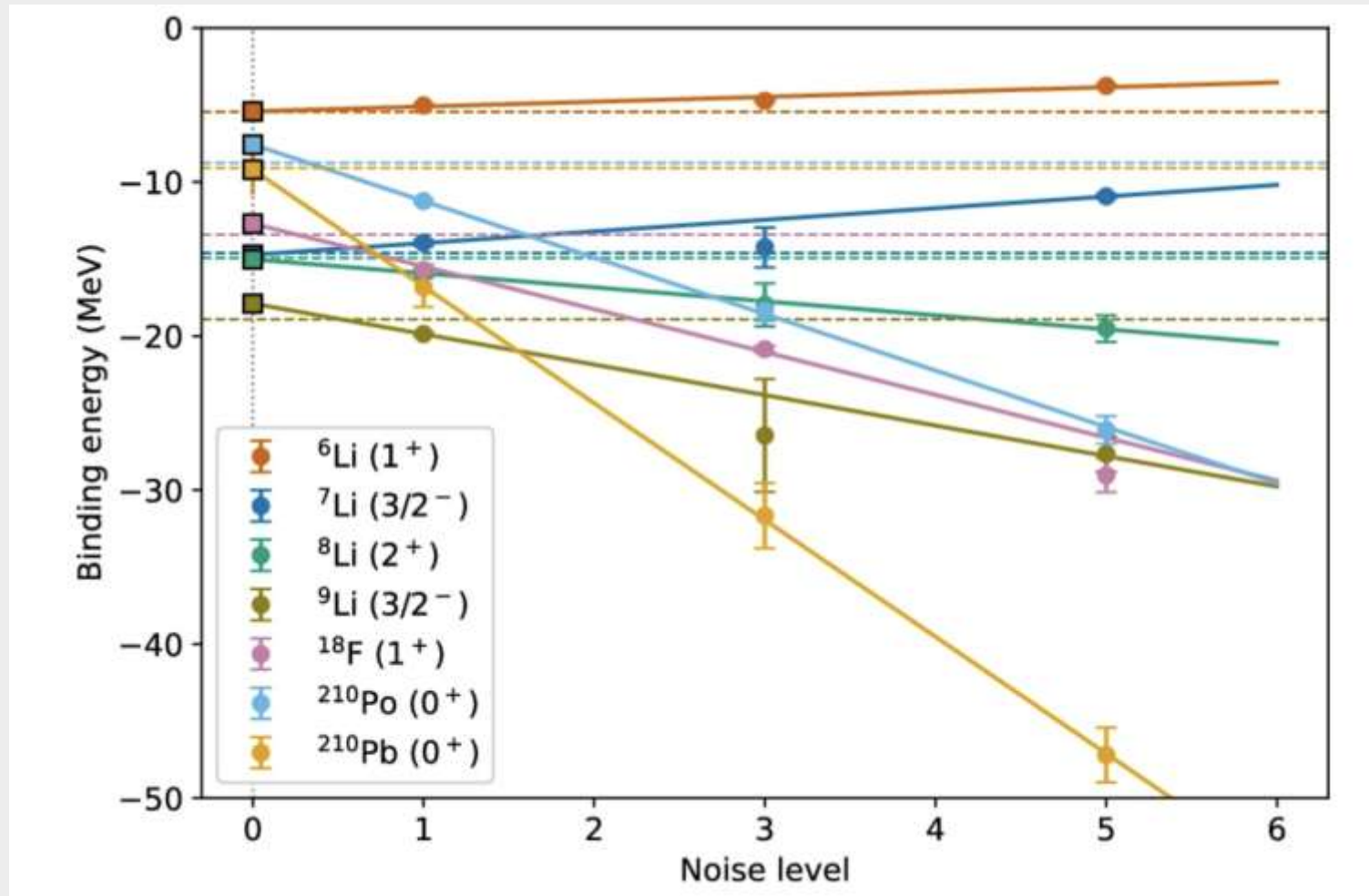
Evaluation on hardware (IBM Pittsburgh)



Domain ansatz = improvement on hardware

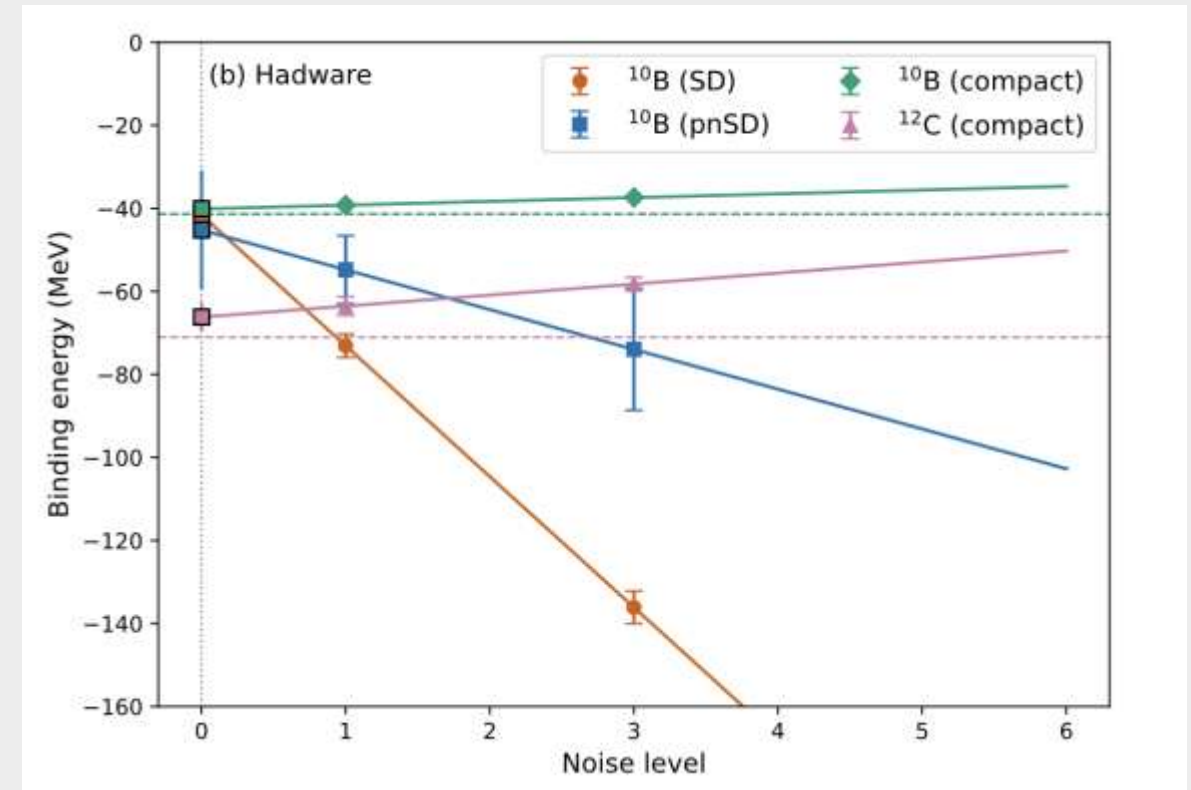
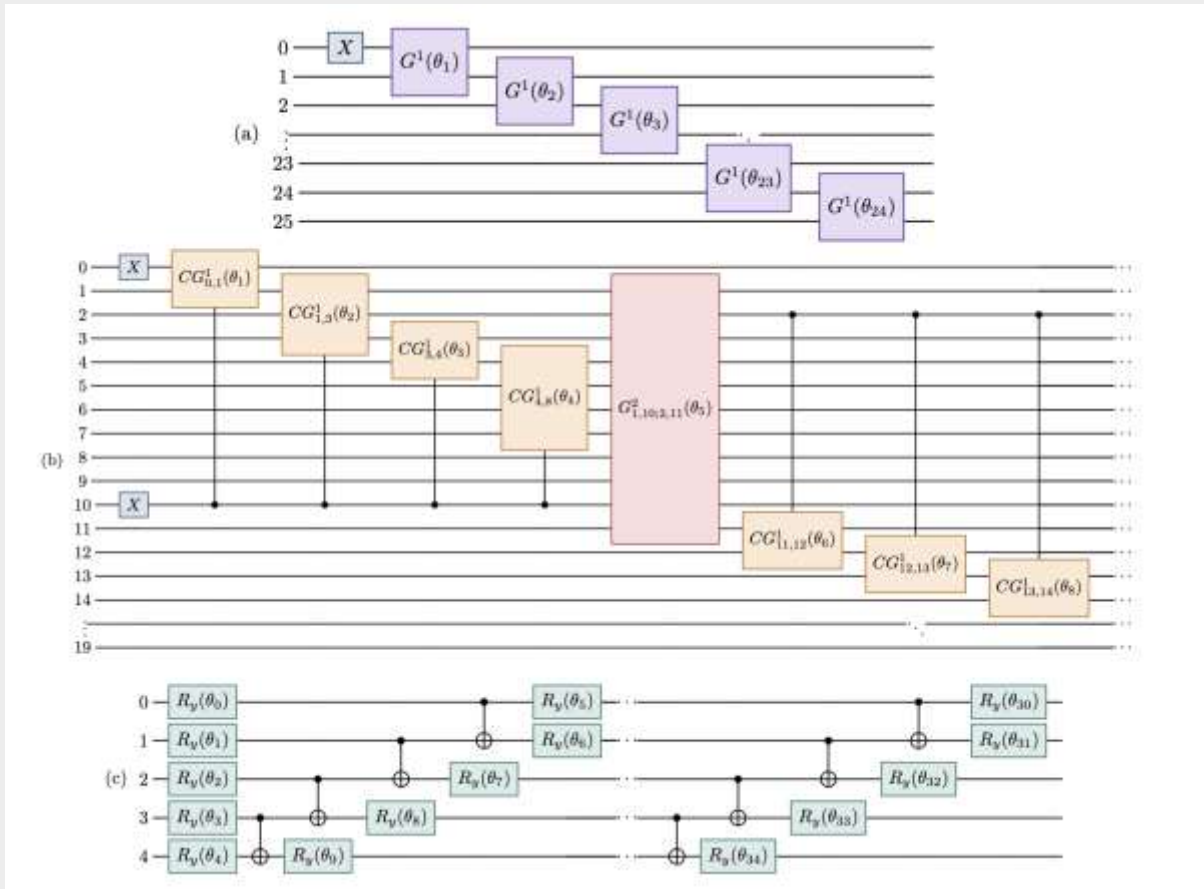


Noise Mitigation (IBM Pittsburgh)



Hybrid mapping

Exploring different mappings using domain knowledge: First quantization / p-n separated



Sarma and Stevenson, arXiv: 2605.30261

Resource estimation

Table 2: The ground state spins and parities of ^{10}B and ^{12}C , and their ground state reference (“Ref.”) energies (in MeV) from shell model calculations are shown along with the required resource counts to simulate ^{10}B ground state using three different mappings. In addition, resource counts for ^{12}C ground state are also shown following qubit-efficient cSD mapping.

Nucleus (J^π)	Mapping	Qubits	Params	Pauli	Comm. Pauli	1Q	2Q	Depth	Ref. Energy
^{10}B (3^+)	SD (Noiseless sim.)	26	25	451	4	101	50	102	-41.504
	SD (Noisy sim.)	26	25	451	4	391	50	229	
	SD (Hardware)	26	25	451	4	364	50	211	
	pnSD (Noiseless sim.)	20	25	1271	530	122	166	258	
	pnSD (Noisy sim.)	20	25	1271	530	1071	305	746	
	pnSD (Hardware)	20	25	1271	530	1143	314	762	
	cSD (Noiseless sim.)	5	35	528	122	35	24	21	
	cSD (Noisy sim.)	5	35	528	122	169	24	61	
	cSD (Hardware)	5	35	528	122	169	24	61	
^{12}C (0^+)	cSD (Noiseless sim.)	6	66	2072	365	66	50	34	-71.045
	cSD (Noisy sim.)	6	66	2072	365	336	50	97	
	cSD (Hardware)	6	66	2072	365	336	50	97	

Summary

- Nuclear Structure is a many-body quantum problem well suited to quantum simulation
- 2 kinds of interacting fermion (protons and neutrons)
- force more complicated than Coulomb, but short range
- Ansatzes using domain knowledge allow exploration on current hardware

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