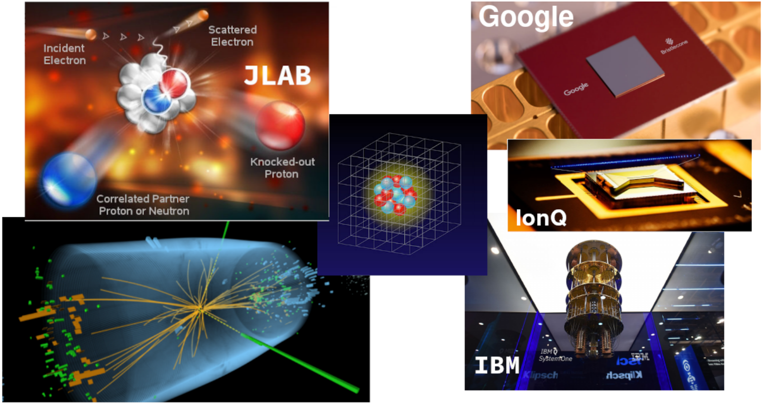
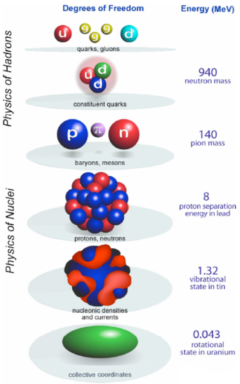
Nuclear dynamics on current generation quantum devices

Alessandro Roggero



ECT* - 4 November, 2020

The nuclear many-body problem



Bertsch, Dean, Nazarewicz (2007)

$$\mathcal{L}_{QCD} = \sum_f \overline{\Psi}_f \left(i\gamma^\mu D_\mu - m_f\right)\Psi_f - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

- in **principle** can derive everything from here

Effective theory for nuclear systems

$$H = \sum_i \frac{p_i^2}{2m} + \frac{1}{2}\sum_{i,j} V_{ij} + \frac{1}{6}\sum_{i,j,k} W_{ijk} + \cdots$$

- easier to deal with than the QCD lagrangian
- describes low energy physics correctly

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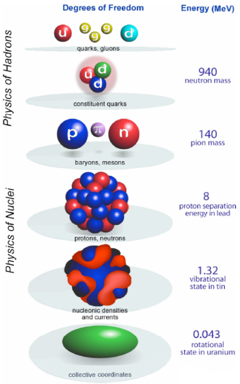

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- easier to deal with than the QCD lagrangian
- describes low energy physics correctly
- non-perturbative $\rightarrow$ still very challenging

Monte Carlo Calculations of the Ground State of Three- and Four-Body Nuclei

(Received July 2, 1962)

Kalos, Phys. Rev (1962)

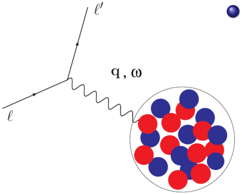
Structure of the Lightest Tin Isotopes

(Received 21 September 2017)

Morris et al, PRL (2018)

Inclusive cross section and the response function

see also talks by Alessandro & Krishnan



- cross section determined by the response function

$$R_O(\omega) = \sum_f \left| \langle f|\hat{O}|\Psi_0\rangle \right|^2 \delta\left(\omega - E_f + E_0\right)$$

  - excitation operator $\hat{O}$ specifies the vertex

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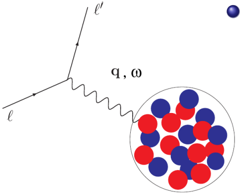

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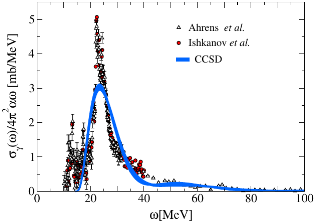
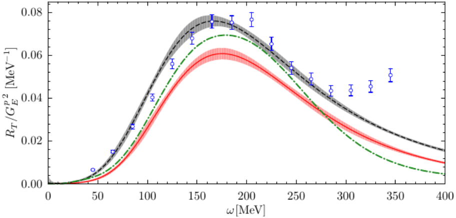
Extremely challenging classically for strongly correlated quantum systems

- dipole response of ^{16}O



Bacca et al. PRL(2013) **LIT+CC**

- quasi-elastic EM response of ^{12}C



Lovato et al. PRL(2016) **GFMC**

Quantum Computing and Quantum Simulations

P.Benioff (1980)	quantum mechanical Hamiltonians can be used to represent universal computational devices
R.Feynman(1982)	we can use a controllable quantum system to simulate the behaviour of another quantum system

Quantum System we have control over

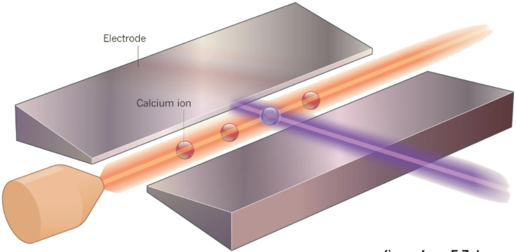
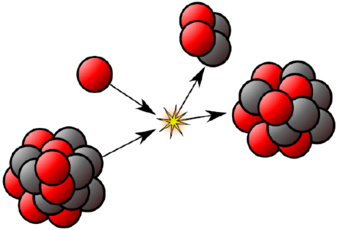
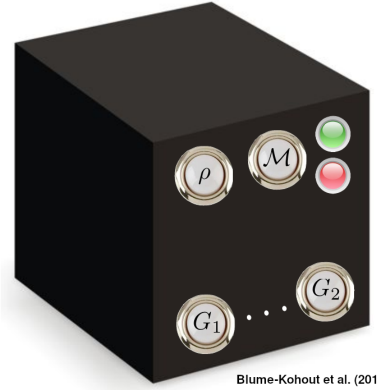


figure from E.Zohar

Quantum System we want to simulate



Black box model for a quantum computer

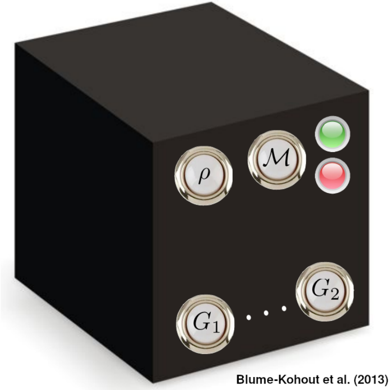


Blume-Kohout et al. (2013)

Box contains N qubits (2-level sys.) together with a set of buttons

- initial state preparation ρ
- projective measurement $\mathcal{M}$
- quantum operations G_k

Black box model for a quantum computer



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Solovay–Kitaev Theorem

We can build a **universal** black box with only a **finite number** of buttons

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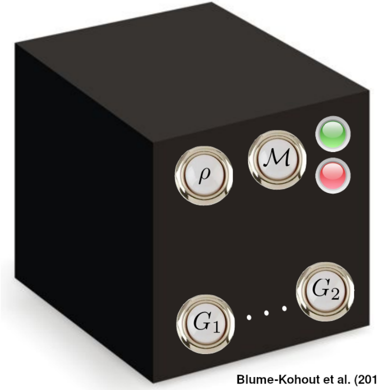

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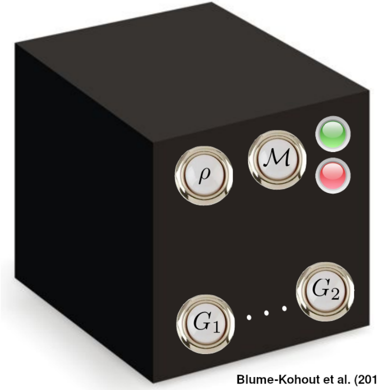

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$$|\Psi(0)\rangle \rightarrow |\Psi(t)\rangle = e^{-iHt}|\Psi(0)\rangle$$

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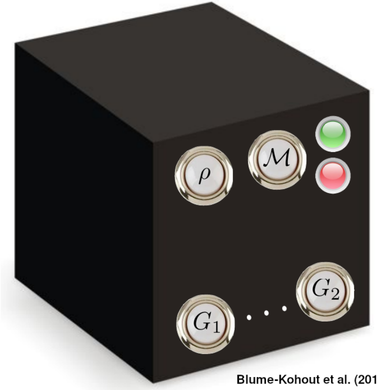

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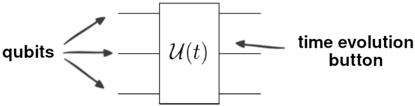

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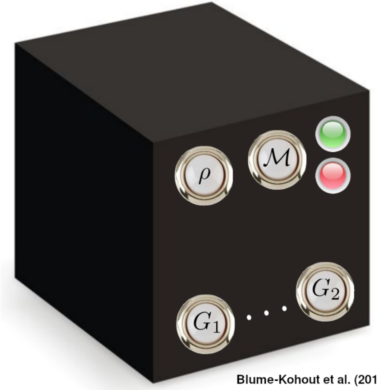

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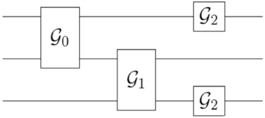
2. map physical states to bb states
3. push correct button sequence

$$|\Psi(0)\rangle \rightarrow |\Psi(t)\rangle = e^{-iHt}|\Psi(0)\rangle$$

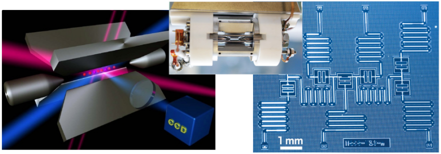


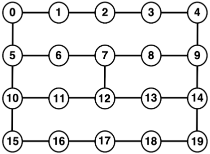
First programmable quantum devices are here

some figures from M.Savage

Real time dynamics on current generation devices

pictures from IQOQI & IBM





- First steps in HEP with 2-4 qubits

Martinez et al. Nature(2016)

Klco et al. PRA(2018), Klco et al. PRD(2020)

Quantum simulation of a "triton" model on 16 states (4 qubits)

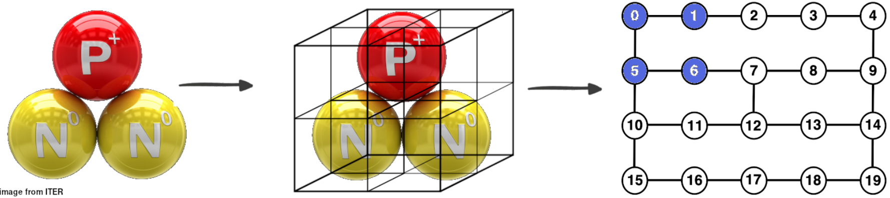
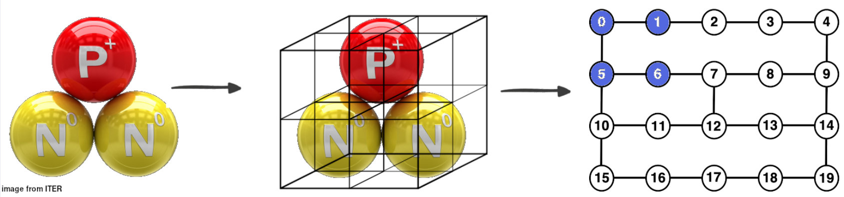


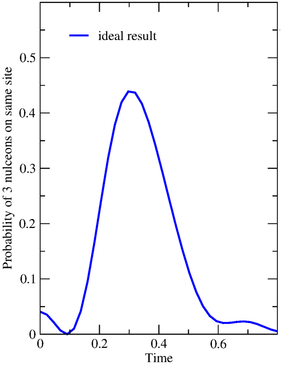
image from ITER

AR, Li, Carlson, Gupta, Perdue PRD(2020)

Real time dynamics on current generation devices II

AR, Li, Carlson, Gupta, Perdue PRD(2020)





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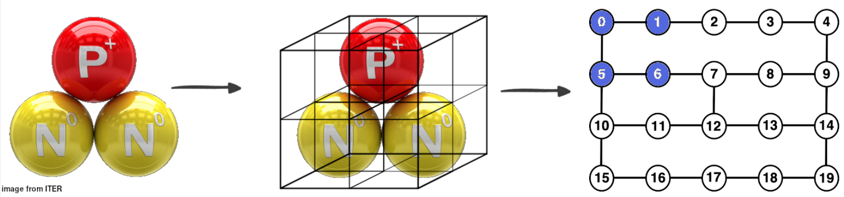

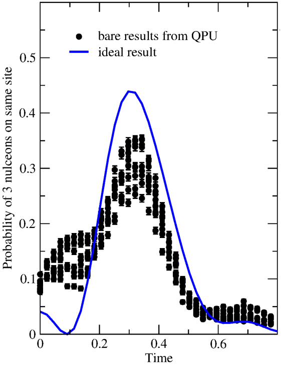

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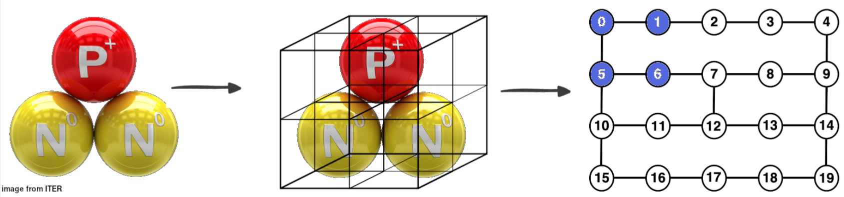
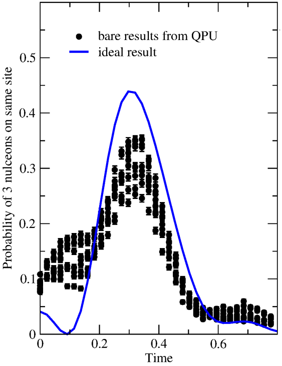
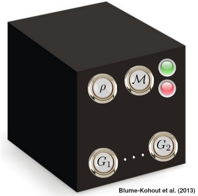




Error sources

- decoherence (environment)
- imperfect calibration



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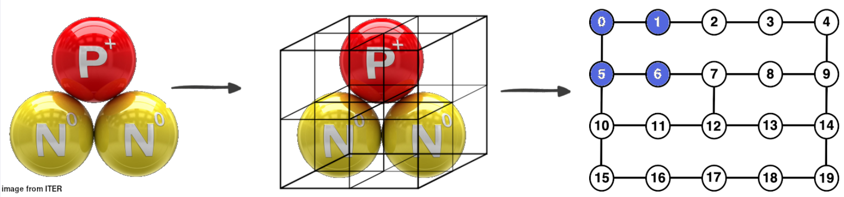
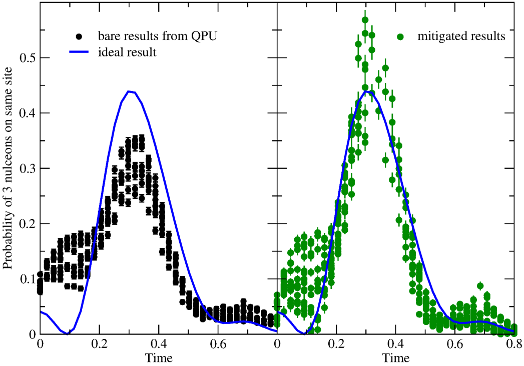
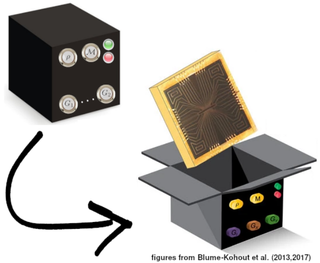




- Error mitigation is crucial



Error mitigation with zero-noise extrapolation

Li & Benjamin PRX(2017), Temme, Bravy, Gambetta PRL(2017), Endo,Benjamin,Li PRX(2018)

Zero noise extrapolation

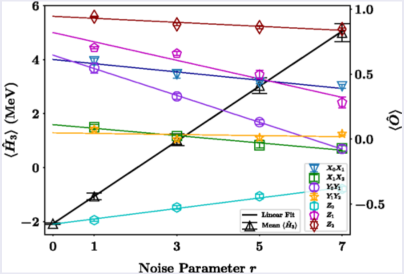
For small enough noise we can write

$$M(\epsilon) = M_0 + \epsilon M_1 + \frac{\epsilon^2}{2} M_2 + \dots$$

Using two points $\epsilon_2 = \eta\epsilon_1$ we have

$$M_0 \approx M(\epsilon_1) - \frac{M(\epsilon_1) - M(\epsilon_2)}{\eta - 1}$$

picture from Dumitrescu et al. PRL(2018)



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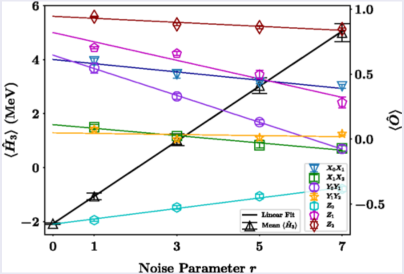

For moderate ϵ other parametrizations (like exp) might be more useful

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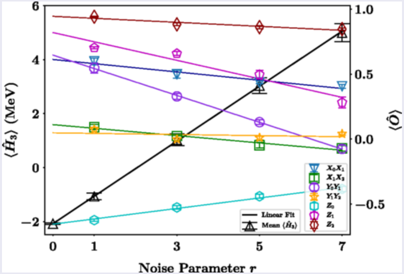

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Questions

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Real time dynamics on current generation devices III

- First steps toward nuclear response: real-time correlators

$$R(\omega) = \int dte^{i\omega t}C(t) \quad \text{with} \quad C(t) = \langle\Psi_0|O(t)O(0)|\Psi_0\rangle$$

- Can be done "easily" using one additional qubit (Somma et al. (2001))

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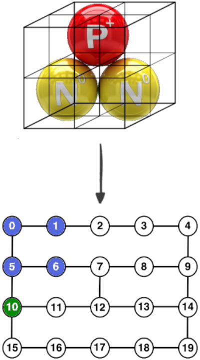
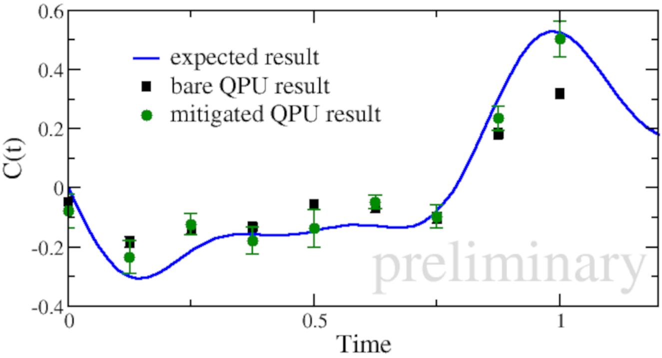




AR, Baroni, Li, Carlson, Gupta, Perdue (in prep.)

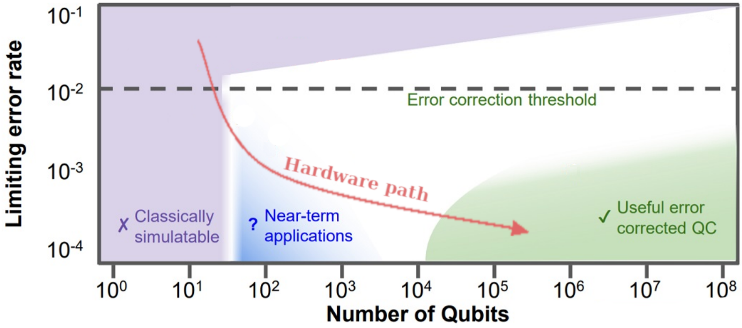
Prospects of impact of QC on Nuclear Physics

AR, Li, Carlson, Gupta, Perdue PRD(2020)

Cost estimates for realistic response in medium mass nuclei

We need ≈ 4000 qubits and push the gate buttons $\approx 10^8$ times

image adapted from Google AI



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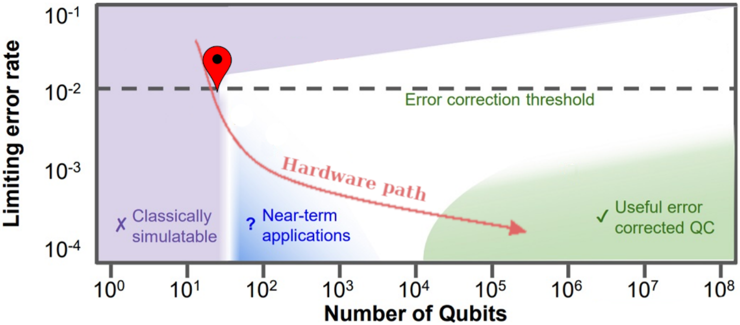

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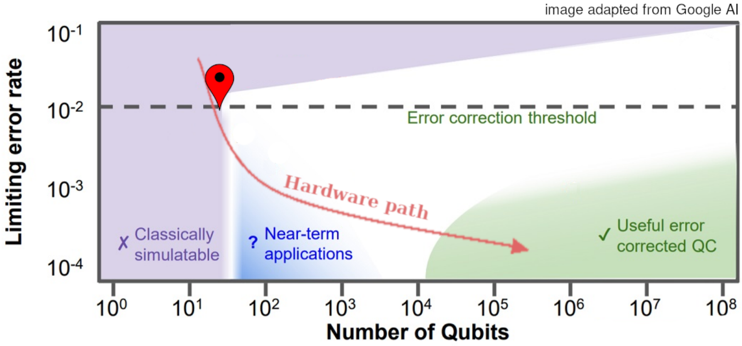

- what ~~can we~~ should we do with ≈ 200 qubits and $\approx 2k$ gates?
- are our original problems still difficult when we introduce noise?

A side note on variational algorithms

Variational Quantum Eigensolver Perruzzo(2014), McClean(2015), ...

Use Rayleigh-Ritz variational principle to find the lowest energy state

$$\min \ \langle\phi(\vec{p})|H|\phi(\vec{p})\rangle \quad \text{with} \quad |\phi(\vec{p})\rangle = U(\vec{p})\,|0\rangle$$

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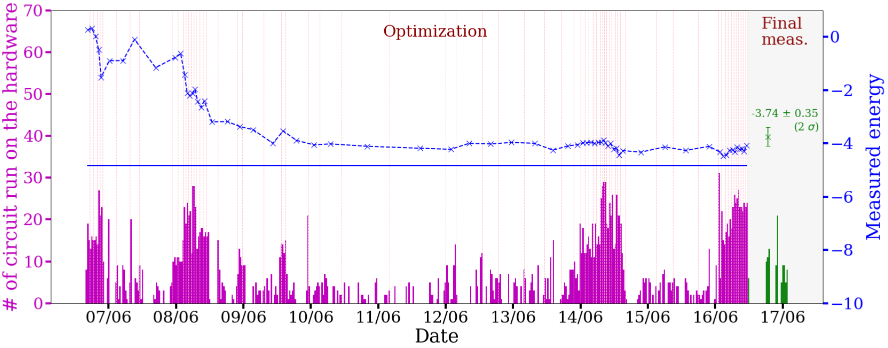

figure thanks to Andy Li

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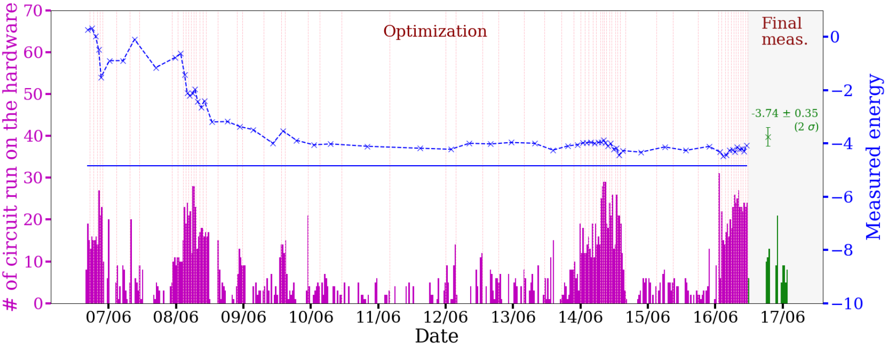
- first problem: latency $\longrightarrow$ more compact trial states, better optimizers



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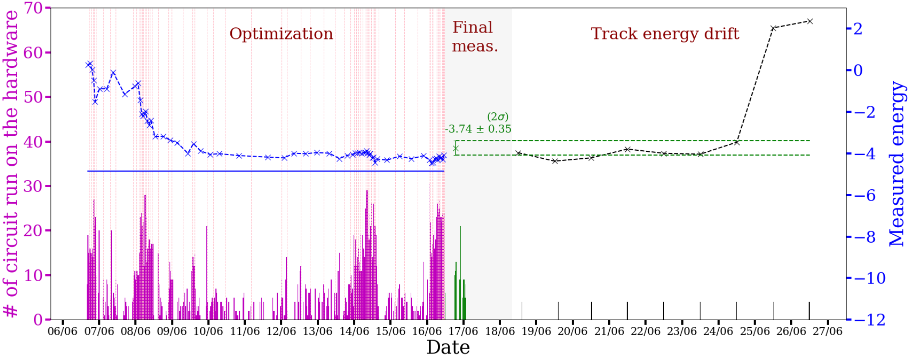
- second problem: persistence



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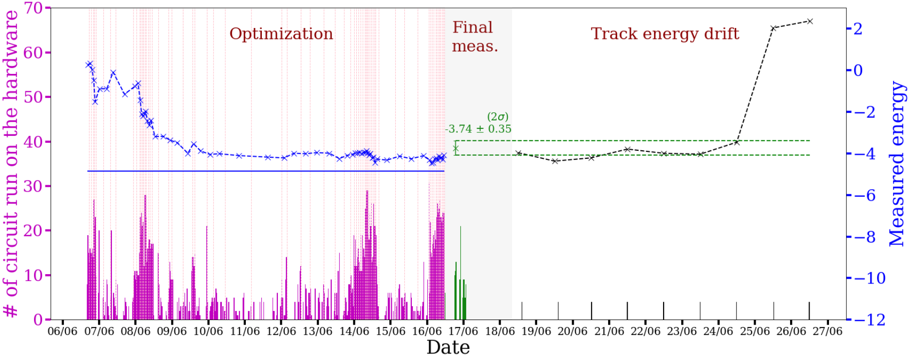
- second problem: persistence $\longrightarrow$ track changes and reoptimize



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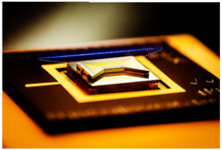
Summary & Conclusions

- Advances in theory and computing are opening the way to ab-initio calculation of equilibrium properties in the medium-mass region
- New ideas are needed to study nuclear dynamics in large open-shell nuclei, exclusive scattering or out-of-equilibrium scenarios
- Quantum Computing has the potential to bridge this gap and increasingly better experimental test-beds are being built
- Noise is here to stay. Error mitigation techniques will be critical to make the best use of near-term quantum devices
- Early impact of QC on nuclear physics might come as insights into classical many-body methods and the role of entanglement


Thanks to my collaborators

- Joe Carlson (LANL)
- Alessandro Baroni (LANL)
- Rajan Gupta (LANL)
- Andy Li (FNAL)
- Gabriel Perdue (FNAL)

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- can we learn something about the noise process by doing this?
  - can we use the trained models to detect hardware faults?
- what ~~can we~~ should we do with ≈ 200 qubits and $\approx 2k$ gates?
- are our original problems still difficult when we introduce noise?
  - can we use classically efficient states (MPS, ANN) to get dynamics?
- how do we build realistic noise simulators to benchmark new algorithms?

Simulations with noise models