Towards electroweak reactions with quantum computers

Alessandro Roggero
with: R. Gupta & J. Carlson (LANL)
A. Li & G. Perdue (FNAL)

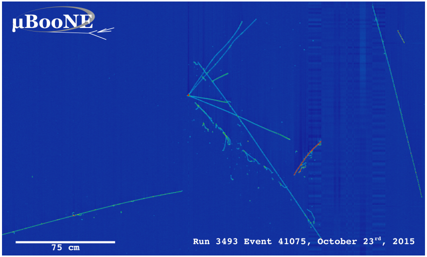
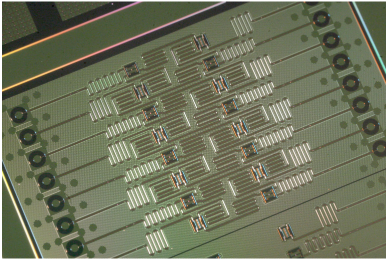


figure credit: μBooNE collab.



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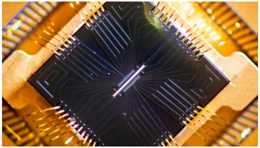
Santa Fe LQCD Meeting
Santa Fe – 30 August, 2019

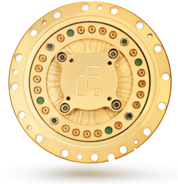
What is a Quantum computer?

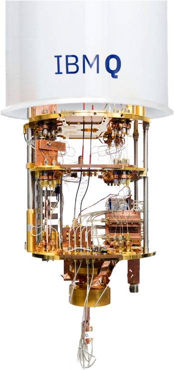
JQI@Univ. of MD



Google

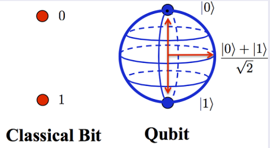
Righetti





- Microsoft?

Bits vs Qubits



- N bits: an integer number $< 2^N$
- N qubits: a vector $|\psi\rangle$ in 2^N-dim Hilbert-space

$\Longrightarrow$ exponentially more information available

Quantum Simulations with qubits

> *"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical."*
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> — R.Feynman (1982)

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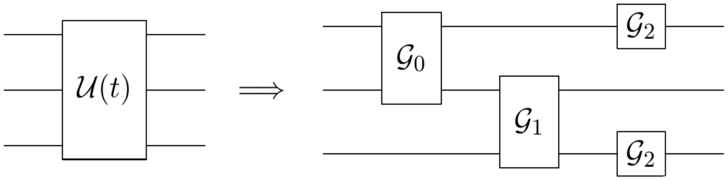
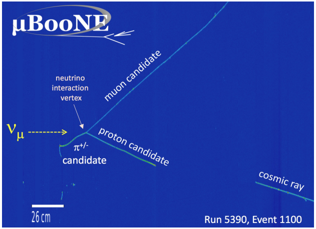
- choose a finite basis to discretize system $\longrightarrow dim(\mathcal{H}) = \Omega \propto e^A$
- physical states can be mapped in states of $\sim log_2(\Omega)$ qubits

$$|\Psi(t)\rangle = U(t)\,|\Psi(0)\rangle$$



Exclusive cross sections in neutrino oscillation experiments



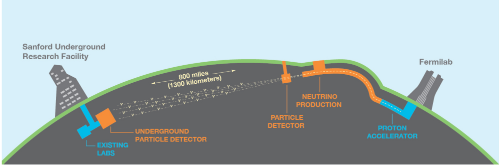
Goals for ν oscillation exp.

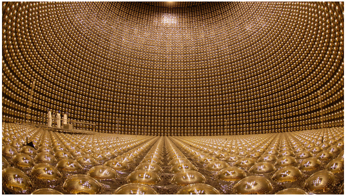
- neutrino masses
- accurate mixing angles
- CP violating phase

$$P(\nu_\alpha \to \nu_\alpha) = 1 - sin^2(2\theta) sin^2 \left(\frac{\Delta m^2 L}{4 E_\nu} \right)$$

- need to use measured reaction products to constrain E_ν of the event

DUNE, MiniBooNE, T2K, Minerνa, NOνA,. . .



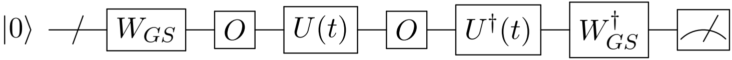


Quantum algorithms for the nuclear response

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

Blueprint of quantum algorithms

state preparation $\rightarrow$ unitary evolution $\rightarrow$ measurement



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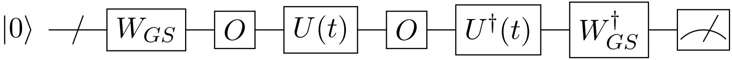

- strategy A [Ortiz, Somma et al (2001-2003)]
  - compute $C(t)$ on quantum computer for different times
  - perform Fourier transform classically
- strategy B [Roggero & Carlson (2018)]
  - sample directly final states from approximate response function

$$|\Phi_B\rangle = \sum_\omega \sqrt{R_\Delta(\omega)}\, |\omega\rangle \otimes |\Psi_\omega\rangle$$

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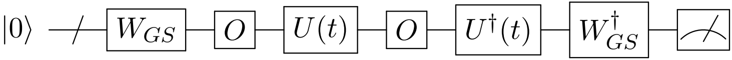

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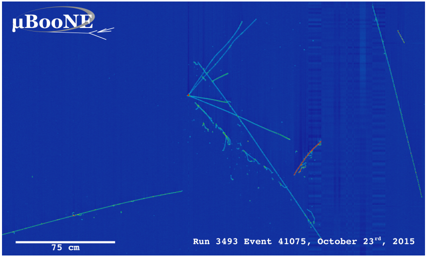
◦ both algorithms are $poly$ in A and target energy resolution !

Part I: baby steps on current machines



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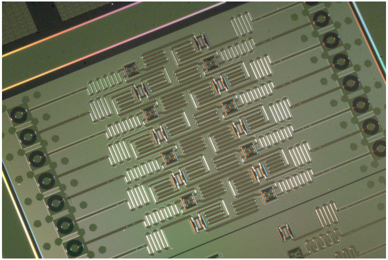

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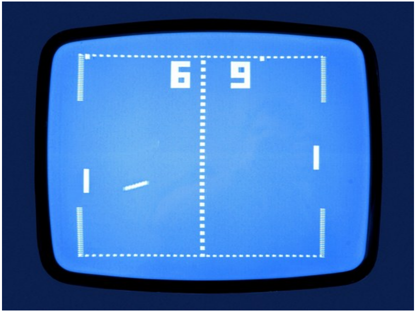

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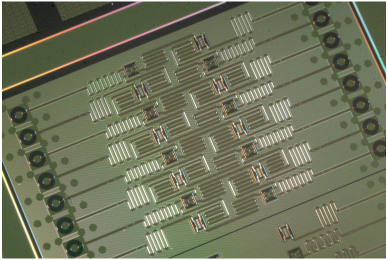

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A (very) simplified nuclear model

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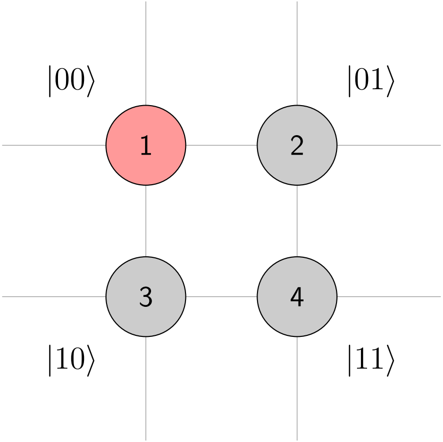

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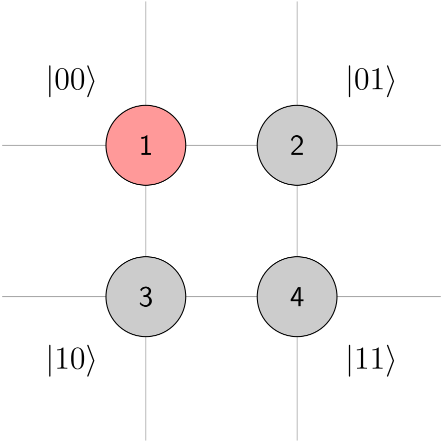

- for every nucleon map 4 states into 2 qubits $\Rightarrow$ 4 qubits total
- interaction Hamiltonian from pion-less EFT becomes

$$H = -t\sum_k X_k + U_1\sum_k Z_k + \sum_{i,j} U_{ij} Z_i Z_j + \sum_{i,j,k} V_{ijk} Z_i Z_j Z_k + \sum_{i,j,k,l} W_{ijkl} Z_i Z_j Z_k Z_l$$

Preparation of an approximate ground state

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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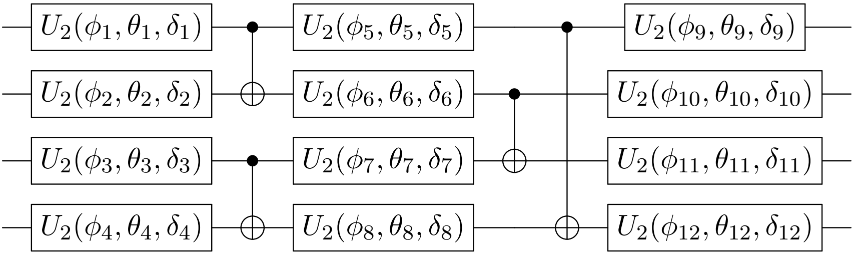

- up to 36 parameters $\longrightarrow$ could be reduced using symmetries

Preparation of an approximate ground state II

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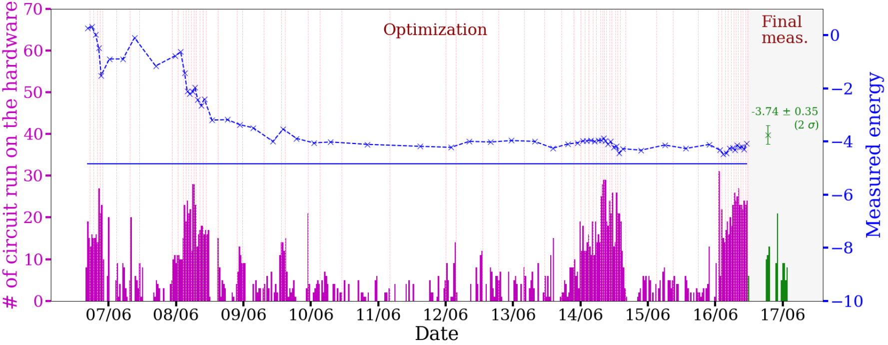

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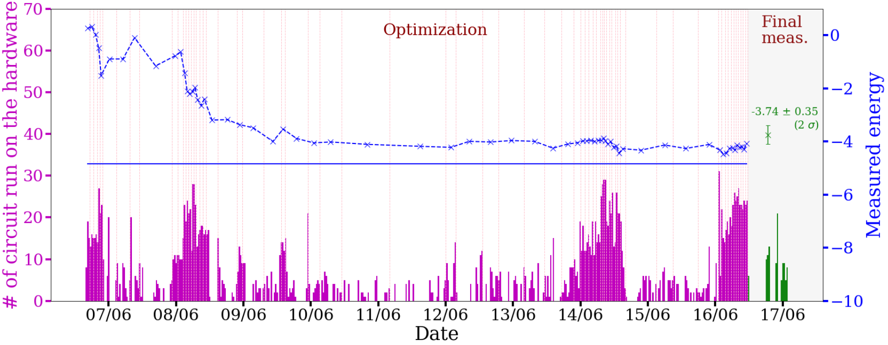
- first problem: latency $\longrightarrow$ more compact trial states, better optimizers



Preparation of an approximate ground state III

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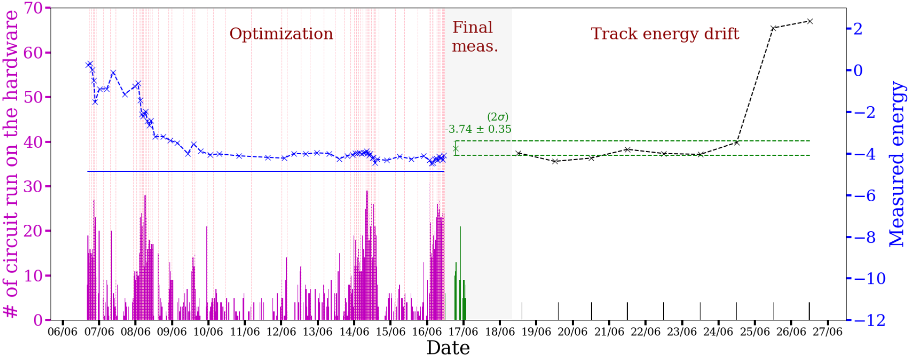
- second problem: persistence



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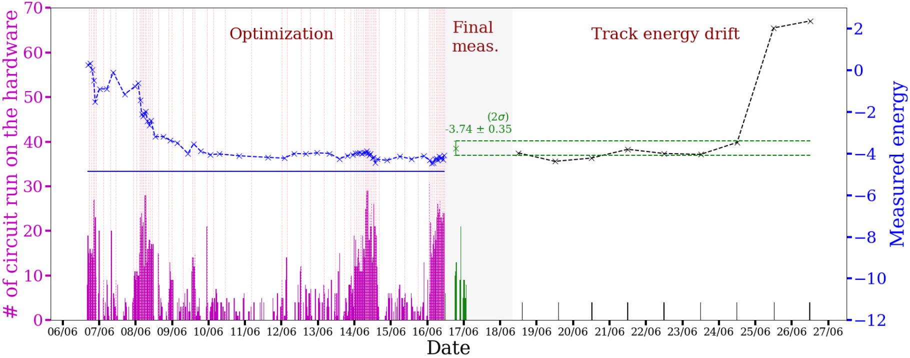
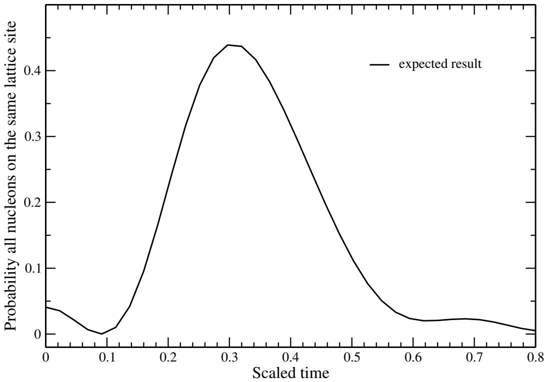
- second problem: persistence $\longrightarrow$ track changes and reoptimize



Preliminary results for real time dynamics

For now just $\langle\Psi|O(t)|\Psi\rangle \rightarrow$ move to 2pt functions in the future



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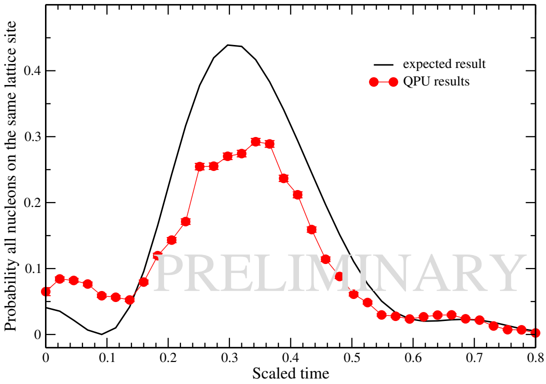

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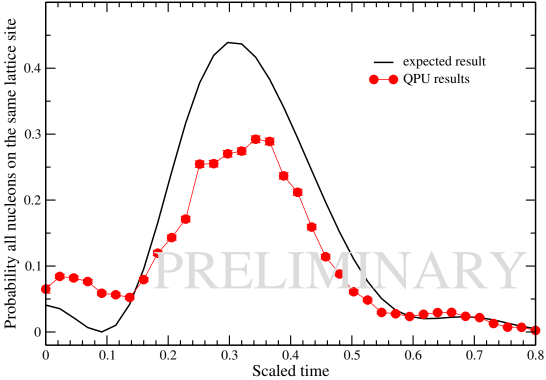

PROBLEM: large systematic errors from machine noise

for perturbative noise: $R(\epsilon) = R_0 + \epsilon R_1 + \epsilon^2 R_2 + \cdots$

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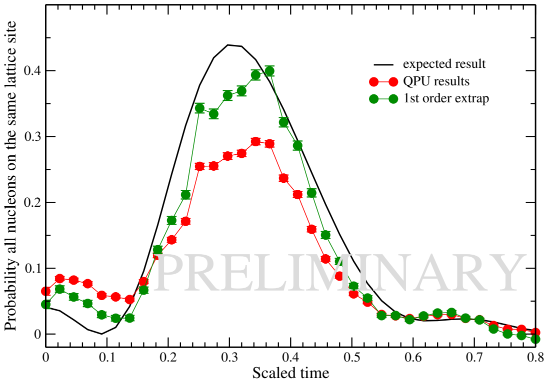

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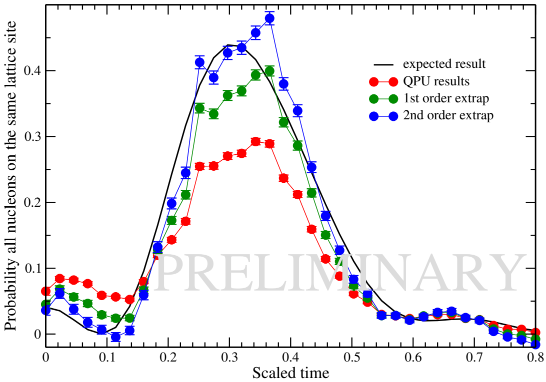

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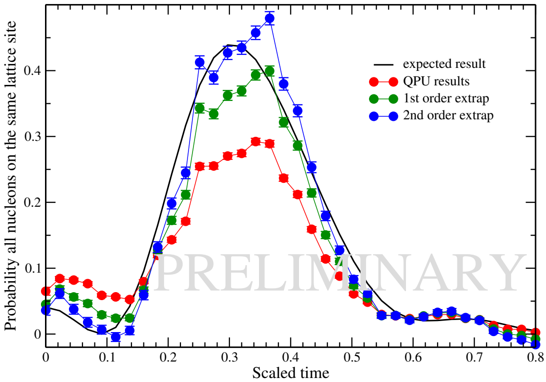

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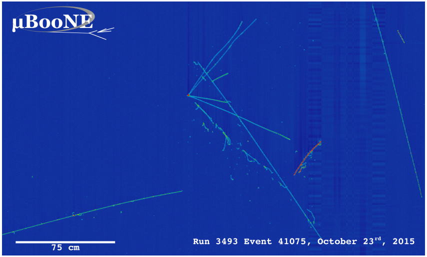
- currently we are working hard on different mitigation techniques

Part II: back to neutrino scattering off ^{40}Ar



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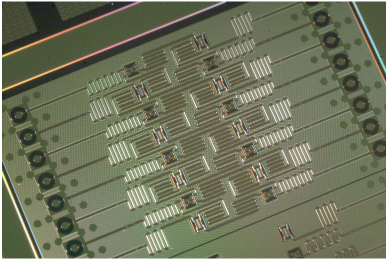

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Blueprint of quantum algorithms from beginning of talk

$$|0\rangle \; -/- \; \boxed{W_{GS}} - \boxed{O} - \boxed{U(t)} - \boxed{O} - \boxed{U^\dagger(t)} - \boxed{W^\dagger_{GS}} - \text{[measure]}$$

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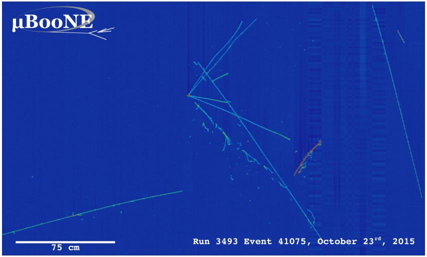

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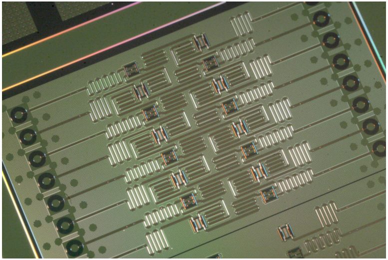

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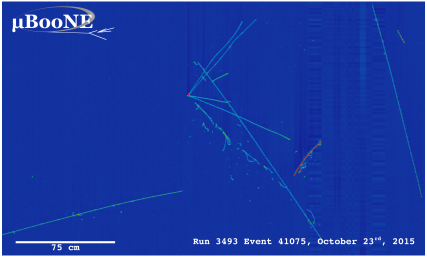

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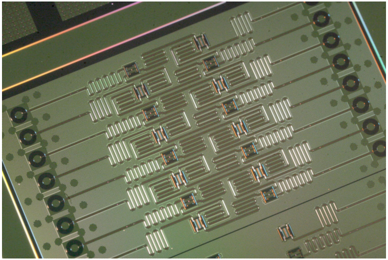

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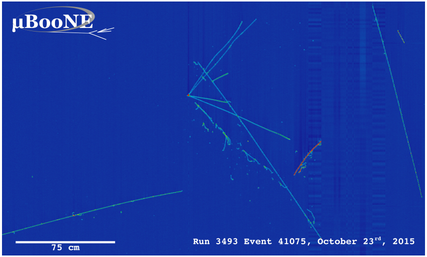

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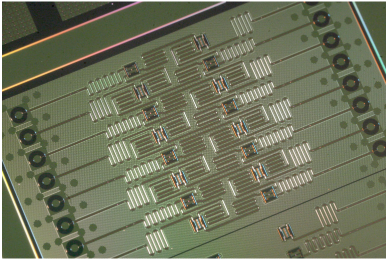

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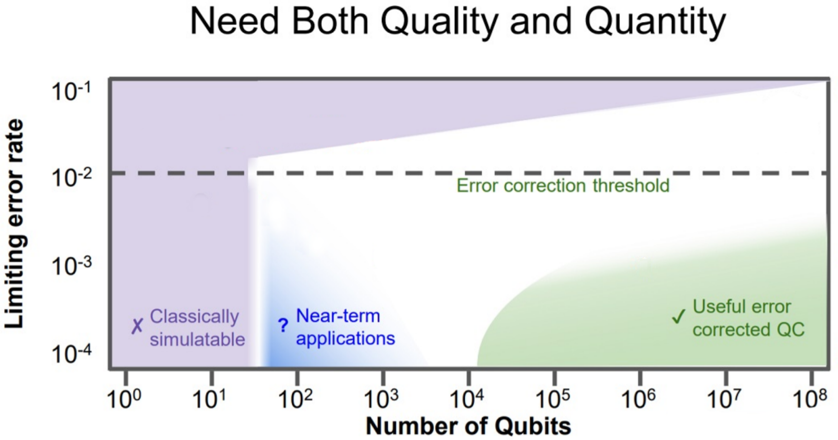
- need to repeat for many values of momentum transfer $O \equiv O(q)$

Where are we right now?

figure adapted from Google AI



- inverse error rate gives the total coherence time τ_{coh}

Threshold Theorem(s) Ben-Or, Aharonov, Kitaev, Knill, Gottesman,...

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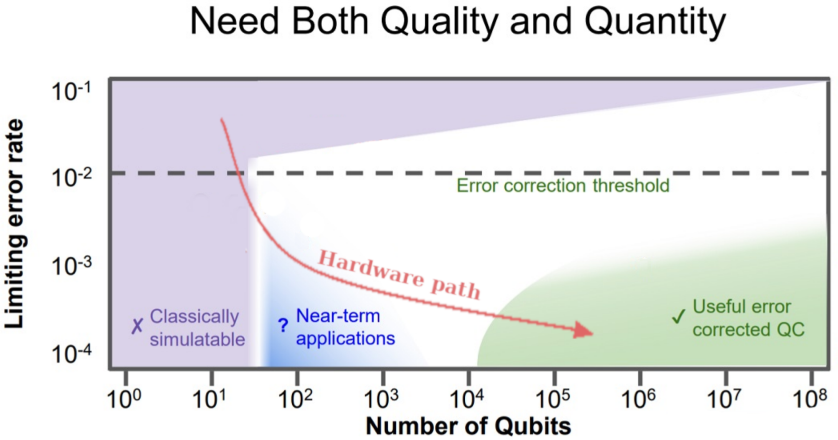

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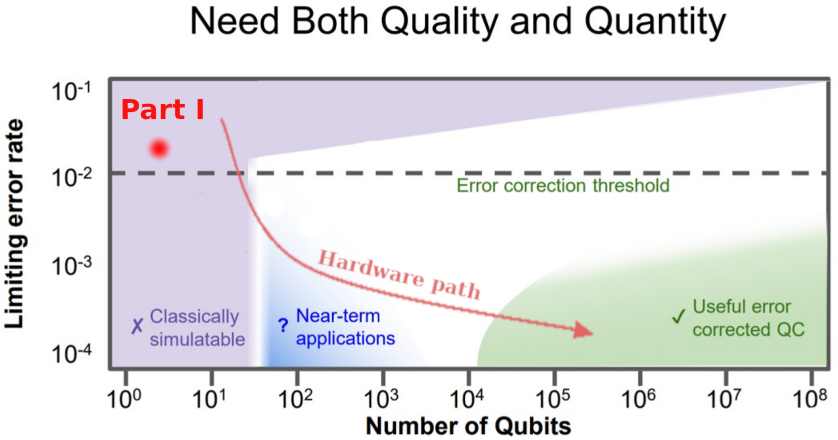

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How practical is all this? Can we do it in time for DUNE?

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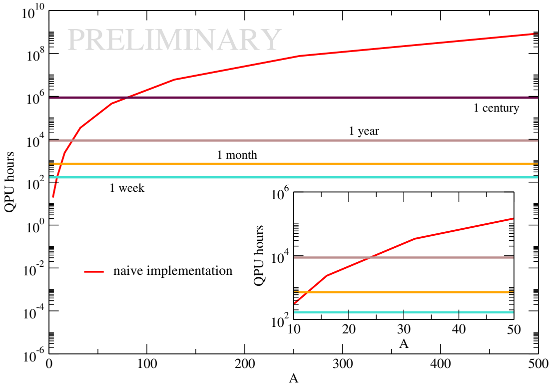

How practical is all this? Can we do it in time for DUNE?

- pionless EFT on a 10^3 lattice of size 20 fm [$a = 2.0$ fm]
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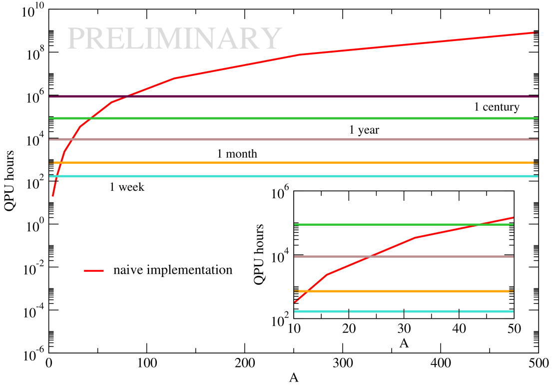

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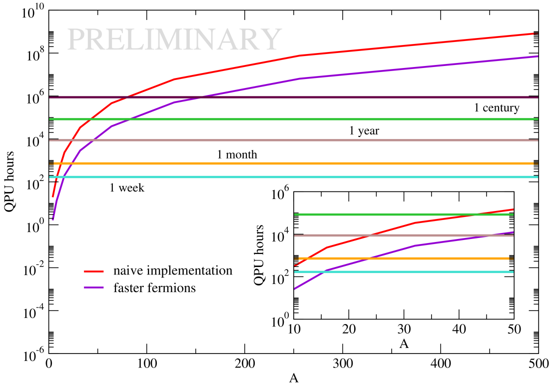

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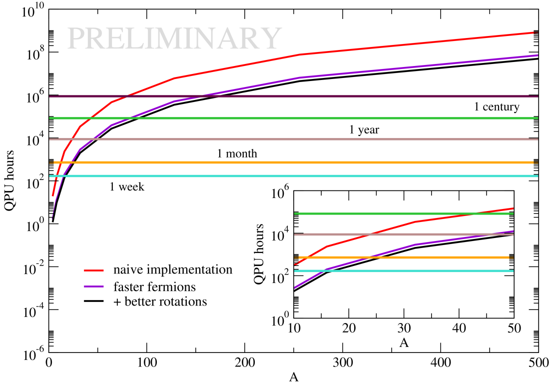

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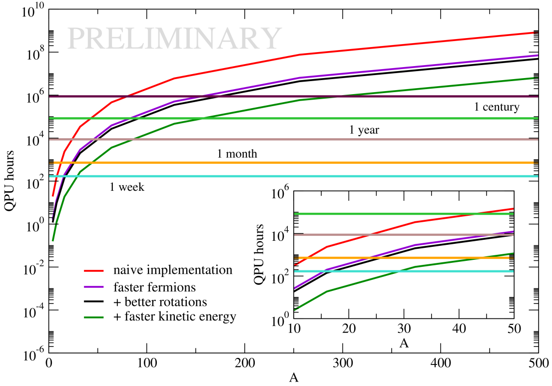

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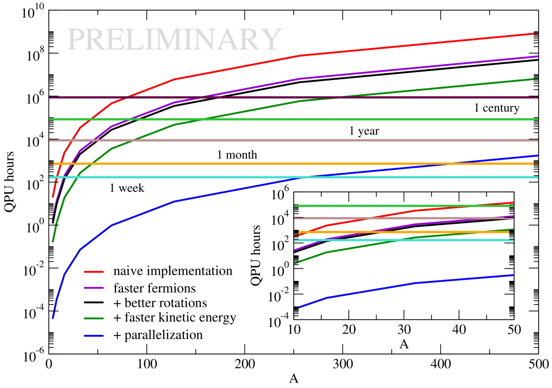

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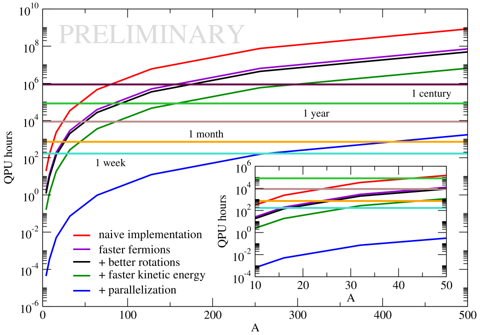

coherence time for ^{40}Ar	
naive	≈ 9 years
optimized	≈ 3 minutes

- algorithm efficiency is critical
- there is still a long way to go
- find new algorithms and/or approximations for near term

Summary

- understanding low-energy dynamics of nuclear many-body systems is important for current and planned neutrino oscillation experiments

- QC is an emerging technology with the potential of revolutionarize the way theory calculations are done
- we already know how to simulate efficiently the time-evolution of non relativistic systems and how to study exclusive scattering
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- J. Carlson & R. Gupta (LANL)
- Andy Li & G. Perdue (FNAL)

◦ QPU access thanks to ORNL

Quantum Phase Estimation

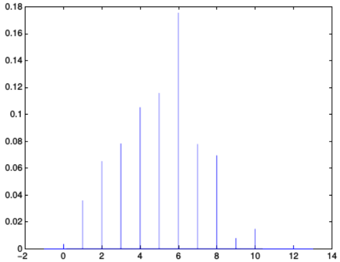
Kitaev (1996), Brassard et al. (2002), Svore et. al (2013), Weibe & Granade (2016),...

QPE is a general algorithm to estimate eigenvalues of a unitary operator

$$U|\xi_k\rangle = \lambda_k|\xi_k\rangle \,, \lambda_k = e^{2\pi i\phi_k} \quad \Leftarrow \quad U = e^{-itH}$$

- starting vector $|\psi\rangle = \sum_k c_k|\xi_k\rangle$
- store time evolution $|\psi(t)\rangle$ in auxiliary register of M qubits
- perform (Quantum) Fourier transform on the auxiliary register
- measures will return λ_n with probability $P(\lambda_n) \approx |c_n|^2$

Ovrum&Hjorth-Jensen (2007)



BONUS: final state after measurement is $|\psi_{fin}\rangle \approx \sum_k \delta(\lambda_k - \lambda_n)c_k|\xi_k\rangle$