Neutrino Scattering with Quantum Computers

Alessandro Roggero

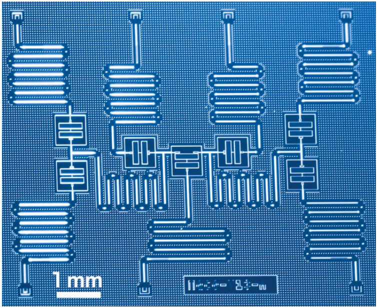


figure credit: IBM

Los Alamos NATIONAL LABORATORY EST. 1943

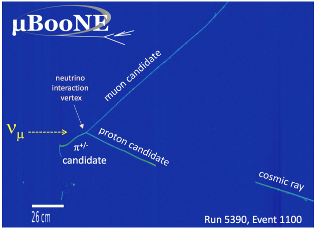
Fundamental Physics with EW Probes of Light Nuclei
12 July, 2018

NUCLEI Nuclear Computational Low-Energy Initiative

Outline

- Motivations
- Ab-initio response functions
    - the problem with integral transform methods
- Introduction to Quantum Computing
- Preparing the ground state on a Quantum Computer
- Nuclear cross-sections with Quantum Computers
- Exclusive processes
- Summary & Conclusions

Exclusive cross sections for neutrino oscillation experiments



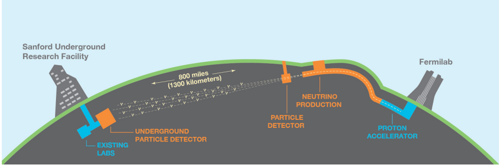
Goals for ν oscillation exp.

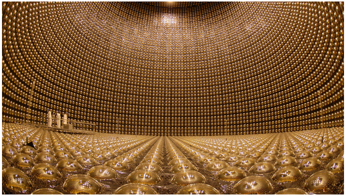
- neutrino masses
- accurate mixing angles
- CP violating phase

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

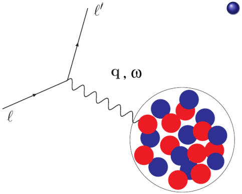
- need to use measured reaction products to constrain E_ν of the event

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





Inclusive cross section and the response function



- xsection completely determined by response function

$$R_O(\omega) = \sum_f \left| \langle f | \hat{O} | 0 \rangle \right|^2 \delta\left(\omega - E_f + E_0\right)$$

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

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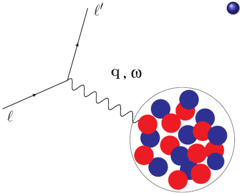

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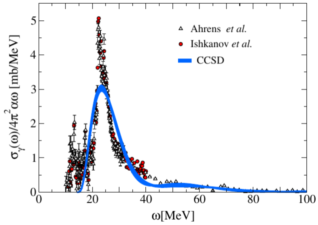
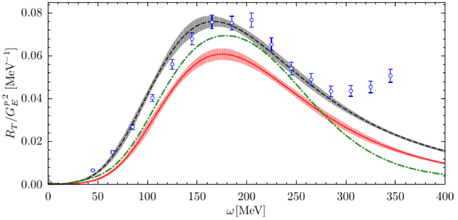
Extremely challenging classically for strongly correlated quantum systems

- dipole response of ^{16}O



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



Bacca et al. (2013) LIT+CC

Lovato et al. (2016) GFMC

Many body dynamics with Integral Transforms

$$R_O(\omega) = \sum_f \left| \langle f|\hat{O}|0\rangle \right|^2 \delta\left(\omega - E_f + E_0\right)$$

PROBLEM: need lots of detailed informations to compute this ab-initio

A possible way out: integral transform techniques

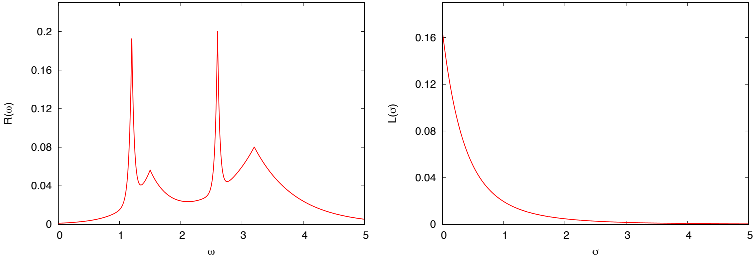
- integrated quantities are much easier to compute

$$T(\sigma) = \int d\omega K(\sigma,\omega) R_O(\omega) = \sum_f \left| \langle f|\hat{O}|0\rangle \right|^2 K\left(\sigma, E_f - E_0\right)$$
$$= \langle 0|\hat{O}^\dagger K\left(\sigma, \hat{H} - E_0\right)\hat{O}|0\rangle$$

- $K(\sigma,\omega) = \omega^n \quad \Rightarrow \quad$ energy weighted sum-rules
- $K(\sigma,\omega) = e^{-\sigma\omega} \quad \Rightarrow \quad$ Laplace Transform (euclidean time/QMC)
- $K(\sigma,\omega;\Gamma) = \frac{\Gamma}{\Gamma^2 + (\sigma-\omega)^2} \quad \Rightarrow \quad$ Lorentz Integral Transform (NCSM,CC)

What is the issue: example with Laplace kernel

$$L(\sigma) = \int K(\sigma,\omega)R(\omega)d\omega = \int_0^\infty e^{-\sigma\omega}\, R(\omega)d\omega$$



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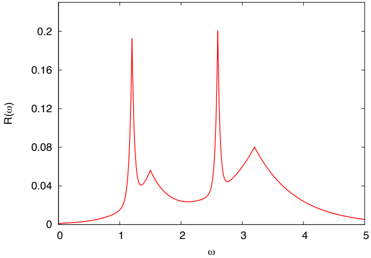

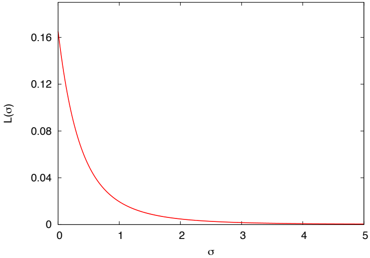

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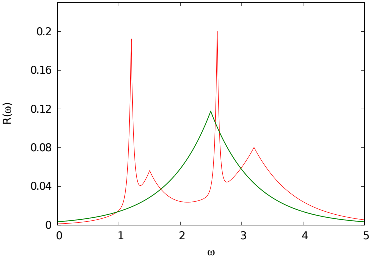

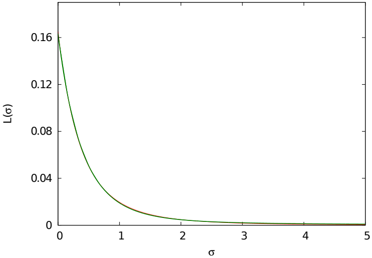

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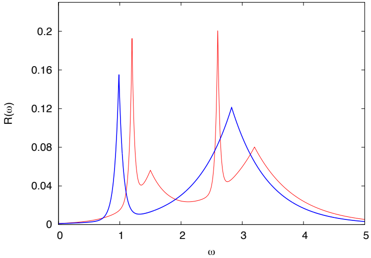

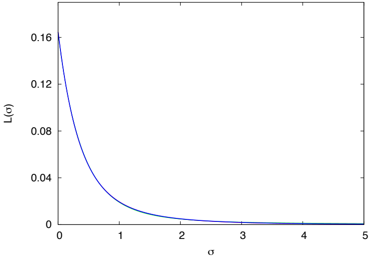

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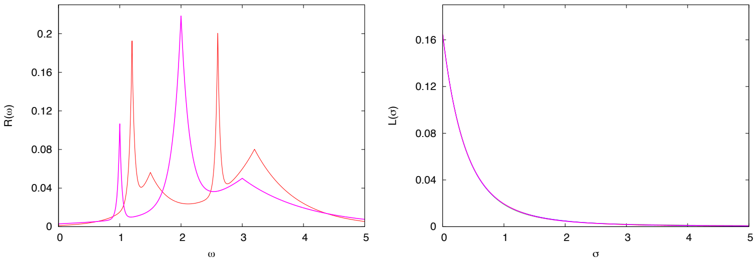

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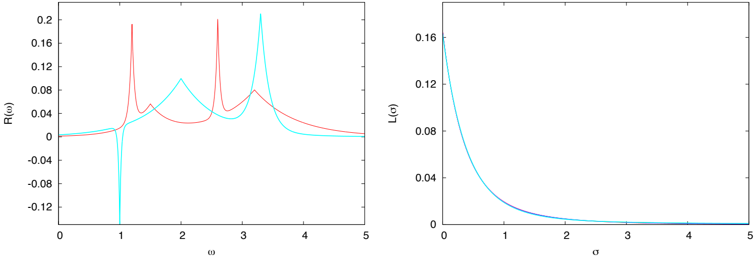

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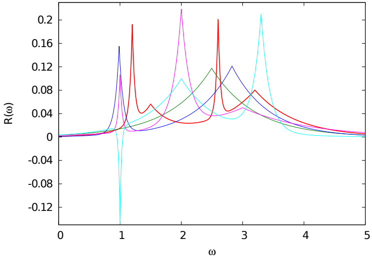

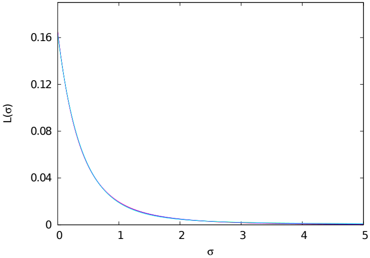

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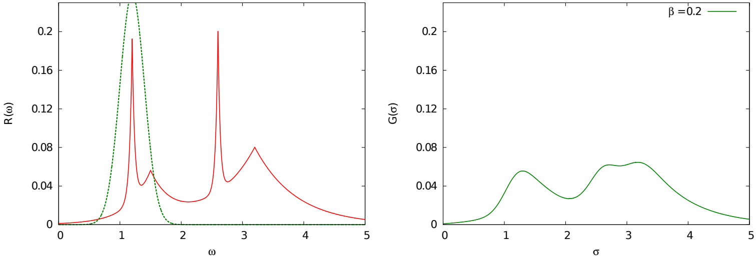
How can we solve the issue: example with Gaussian kernel

$$G(\sigma,\beta) = \int K(\sigma,\omega,\beta)R(\omega)d\omega = \int_0^\infty e^{-\frac{(\sigma-\omega)^2}{2\beta}}\,R(\omega)d\omega$$

- We have now one more parameter: β.



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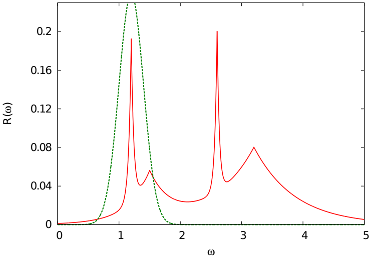

The transform $G(\sigma)$ is a smoothened version of the original signal!

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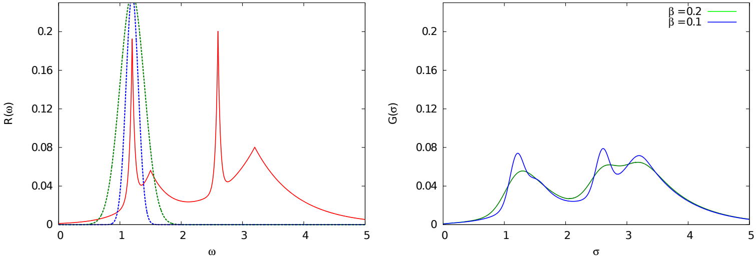

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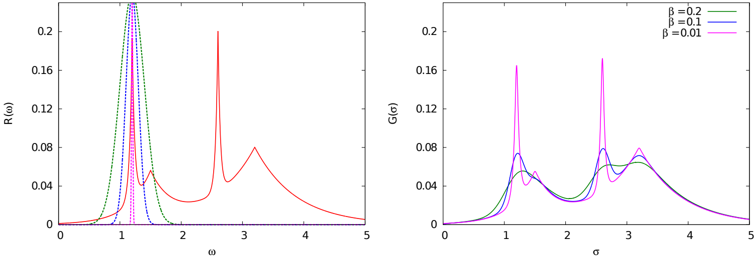

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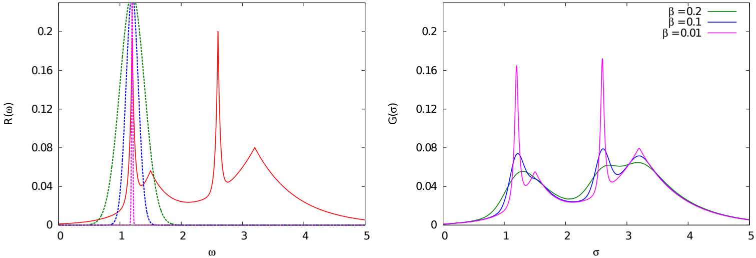

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PROBLEM: computational cost scales exponentially with $1/\beta$!!!

Additional challanges: the nuclear many-body problem

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

- much easier to deal with than not the QCD lagragian
- being non-perturbative it is still extremely challenging
  - nuclear states live in huge Hilbert spaces: $dim\left(\mathcal{H}\right) > 4^A$

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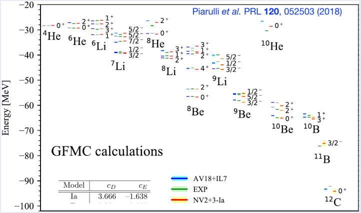
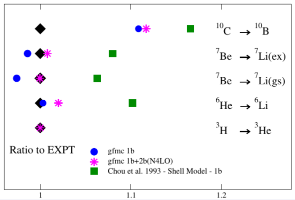
Great success for light systems with regular (super) computers

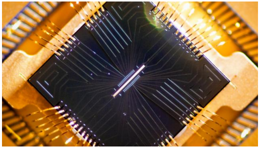




Pastore, Baroni et al. (2018)

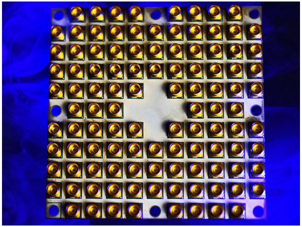
What is a Quantum computer?

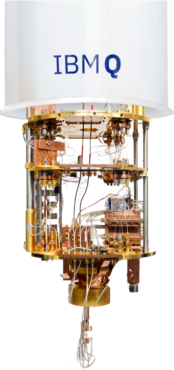
JQI@Univ. of MD



Google

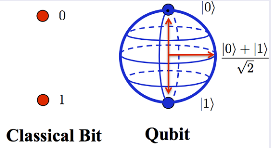
Intel





- Microsoft?

Bits vs Qubits



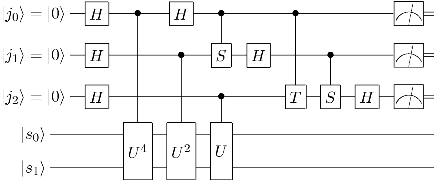
- N bits: an integer number $\leq 2^N$
- N qubits: a vector $|\psi\rangle$ in 2^N-dim Hilbert-space

$\Longrightarrow$ exponentially more information available

What can they do?

Stages of quantum computations

- prepare the initial state
- perform unitary operations
- measure the final state



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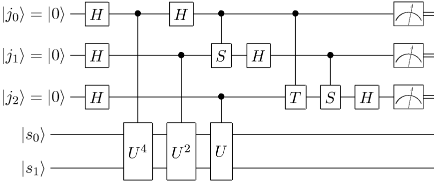

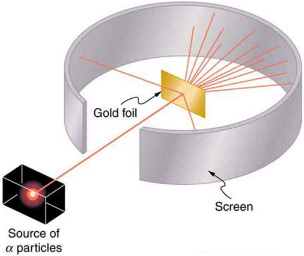

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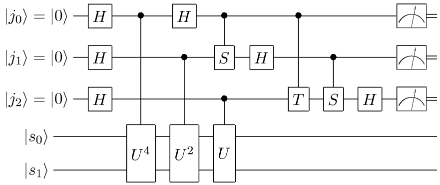

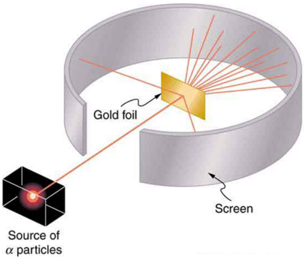

Sleator & Weinfurter, Barenco et al., Lloyd (1995)

Can access ALL unitary matrices via a small set of universal gates

- integer factorization — Schor (1994)
- database search — Grover (1996)
- Hamiltonian simulation — Lloyd (1996)
- linear equations — Harrow et al. (2009)
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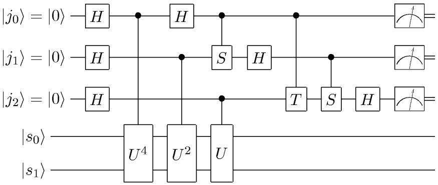

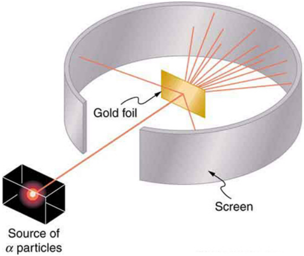

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Preparing low-energy states on quantum computers

Quantum Adiabatic Algorithm

Farhi et al. (2000,2001), McClean et al. (2016)

$$H(\lambda) = (1-\lambda)H_A + \lambda H_B$$

PROBLEM:

- number of steps scales with gap Δ: $N_s = \frac{\lambda}{\delta\lambda} \approx \Delta^{-2}$
- gap could scale exponentially with system size

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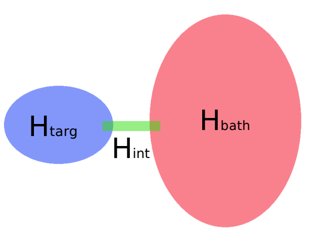
Spectral Combing Algorithm

Klco, Kaplan, Roggero (2017)

IDEA: couple target to bath



- bath prepared in a cold state
- unitary evolution could entangle the 2 systems such that entropy has maximum at $|GS\rangle_{\text{targ}}$

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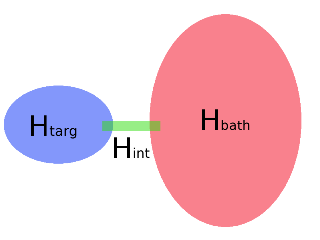

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PROBLEM

needs huge density of states - $N_{bath} \gg N_{targ}$

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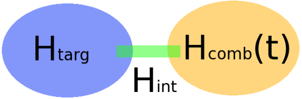
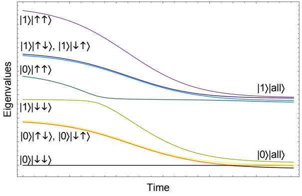
BETTER IDEA: couple to a small system with time-dependent spectrum

- comb energies decreasing with t
- energy transferred to the *comb* through avoided level crossings





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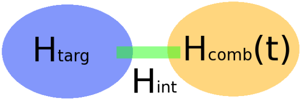

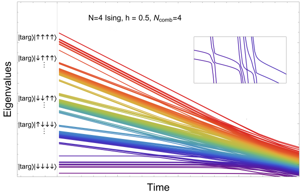

Energy spectra with Quantum Phase Estimation

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

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

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- 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 $P(\lambda_n) \approx |c_n|^2$

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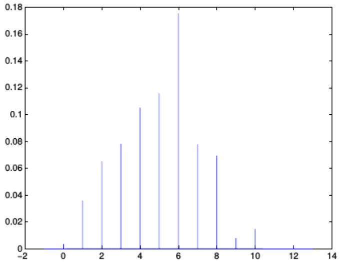
Ovrum&Hjorth-Jensen (2007)



Energy spectra with Quantum Phase Estimation

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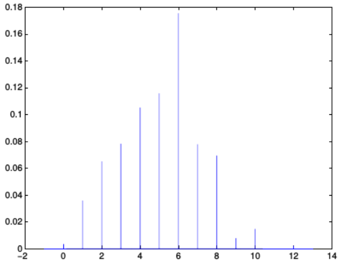

BONUS: final state after measurement is $|\psi_{fin}\rangle \approx \sum_k \delta(\lambda_k - \lambda_n) c_k|\xi_k\rangle$

Response functions as a probability distribution

$$R_O(\omega) = \sum_f \left| \langle f | \hat{O} | 0 \rangle \right|^2 \delta\left(\omega - E_f + E_0\right)$$

- positive definite quantity with finite integral $\int_{-\infty}^{\infty} R_O(\omega) < \infty$
- properly normalized version $\overline{R_O}(\omega)$ defines a probability density

$\rightarrow$ scattering events with energy transfer ω happen with probability $\overline{R_O}(\omega)$

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Strategy on a Quantum Computer (Roggero & Carlson (2018))

- generate final states $|f\rangle$ with energy transfer ω distributed as

$$P(\omega) \propto \sum_f \left|\langle f|\hat{O}|0\rangle\right|^2 \delta_\Delta\left(\omega - E_f + E_0\right)$$

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- finite width Δ can be made exponentially small with modest resources
- direct access to final states with given $\omega \rightarrow$ exclusive information

Response functions on a Quantum Computer

Additional ingredient:

- quantum circuit that prepares $|E\rangle = \hat{O}(q)|0\rangle$ (Roggero & Carlson (2018))

By performing quantum phase estimation with W ancilla qubits we will measure frequency ν with probability:

$$P(\nu) = \sum_f |\langle f|E\rangle|^2 \delta_W(\nu - E_f + E_0)$$

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- need only $W \sim \log_2(1/\Delta\omega)$ ancillae
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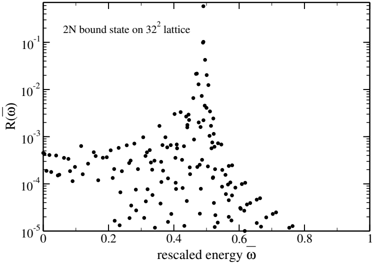

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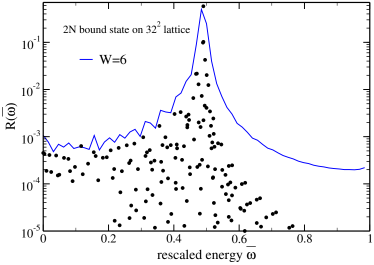

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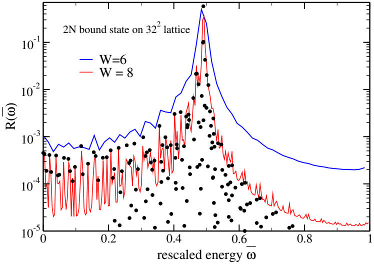

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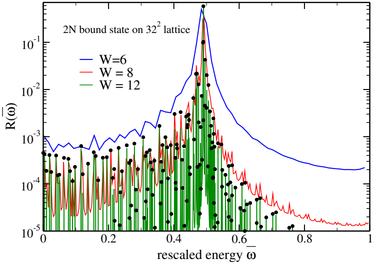

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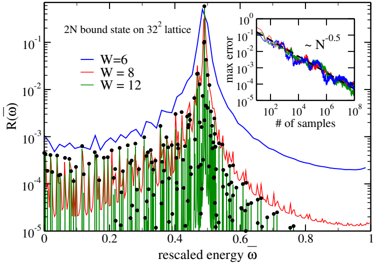

We need around $\sim 10^4$ samples to get within 1% error

Final state properties from a Quantum Computer

- after measuring energy ν with QPE, state-register is left in

$$|out\rangle_\nu \sim \sum_f \langle f|\hat{O}(q)|0\rangle|f\rangle \quad \text{with } E_f - E_0 = \nu \pm \Delta\omega$$

- we can then measure eg. 1- and 2-particle momentum distributions

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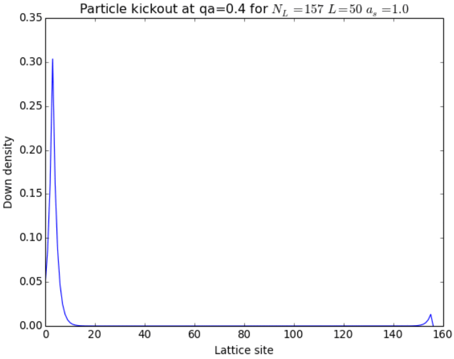

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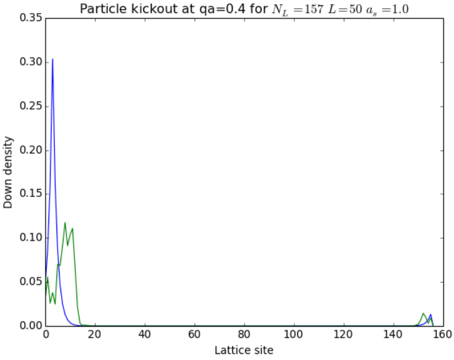

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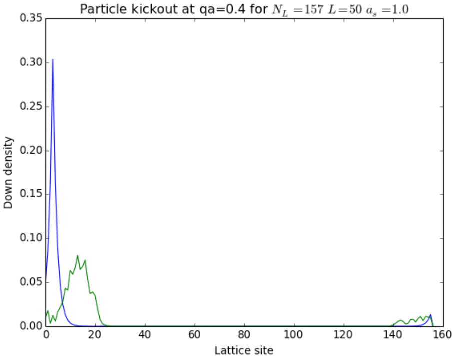

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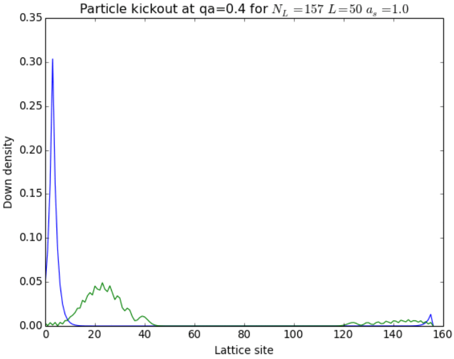

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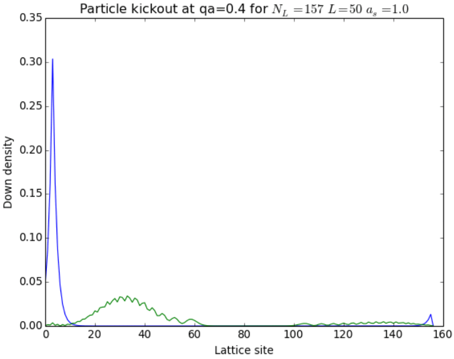

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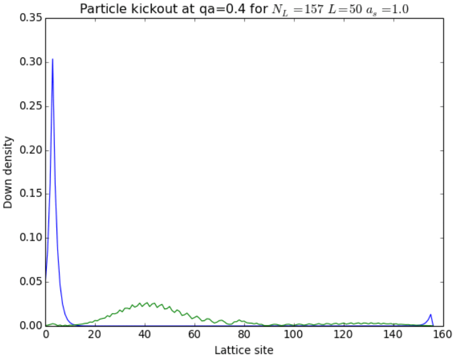

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How practical is all this?

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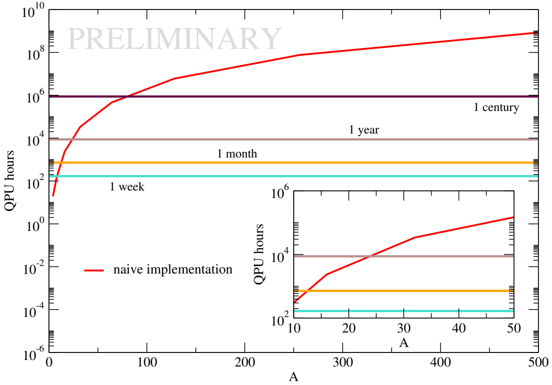

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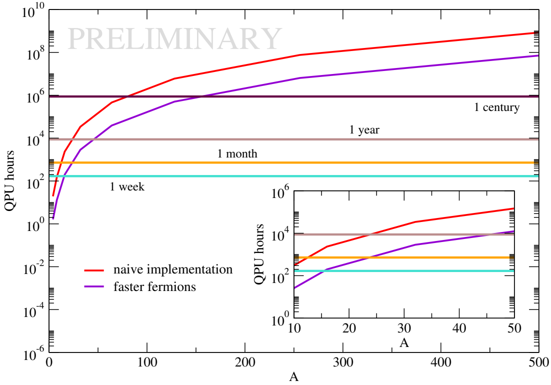

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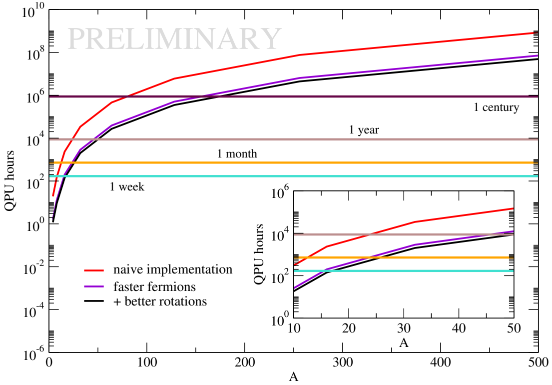

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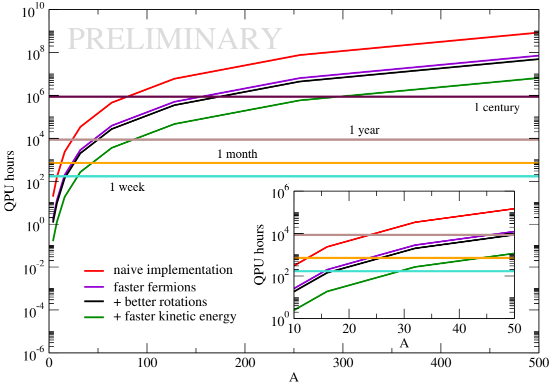

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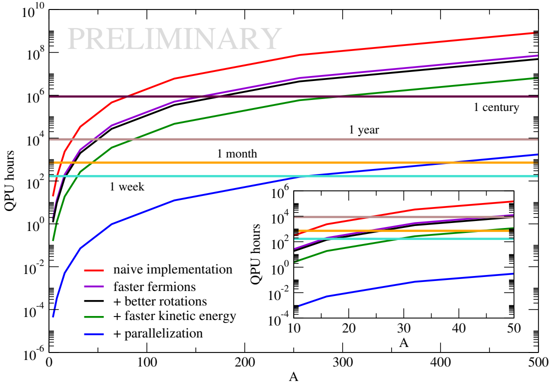

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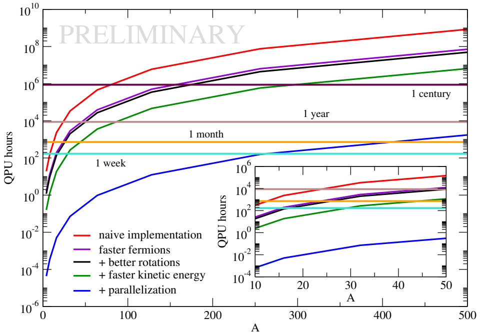

cost for ^{40}Ar at $\approx 1\%$ accuracy

naive $\approx 10^5$ years per q

optimized ≈ 3 weeks per q

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

Summary

- accurate input from nuclear physics is critical to extract reliable informations from current and planned neutrino experiments
- current ab-initio techniques are getting better especially for ground state properties and inclusive scattering cross sections
  - still not enough, need new ideas: quantum computing?

- QC is an emerging technology with the potential of revolutionarize the way theory calculations are done
- we already know how to simulate (more or less) efficiently the time-evolution of non relativistic systems
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Collaborators:

- N.Klco, D.Kaplan (INT)
- J.Carlson (LANL)

Los Alamos NATIONAL LABORATORY EST.1943

Interactions among nucleons derived in EFT

Weinberg,van Kolck,Ordonez,Kaplan,Savage,Weise,Kaiser,Entem,Machleidt,Epelbaum,Meißner,. . .

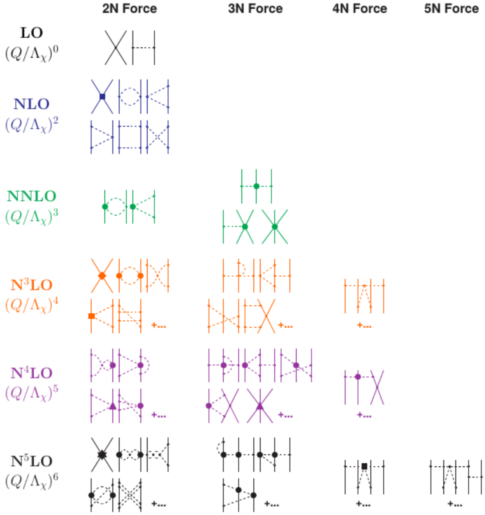


Fig: Machleidt (2016)

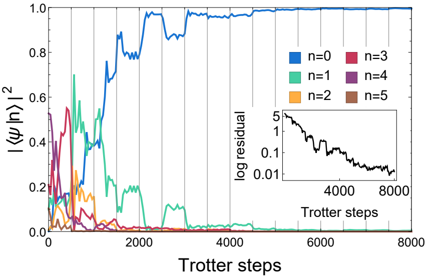
- systematic expansion that allows (in principle) full control on the errors
- in practice renormalization issues spoils this (in part)*
- can be used to derive consistently nuclear currents needed for reactions
- naturally predicts presence of intrinsically many-body interactions

[*] see talks of ECT* Workshop, New Ideas in Constraining Nuclear Forces (2018)

Application to the 1D Ising model in a transverse field

The Spectral Combing algorithm

- initialize system in $|\psi\rangle \otimes |\downarrow\downarrow \cdots\rangle$
  1. propagate state from $t = 0$ to $t = t_f$ using full Hamiltonian $H = H_{\text{targ}} + H_{\text{comb}} + H_{\text{int}}$
  2. if more iteration needed perform a measurement of z-projection of spins in the comb otherwise exit
  3. return spins in the comb to their ground-state and repeat



Kaplan,Klco,Roggero (2017)

$$H_{\text{targ}} = -h \sum_i^{N_{\text{targ}}} \sigma_i^x - \sum_i^{N_{\text{targ}}} \sigma_i^z \sigma_{i+1}^z$$

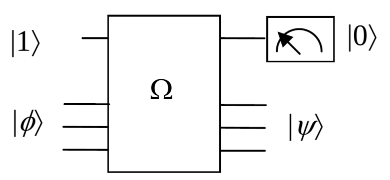
- $N_{\text{targ}} = 3,\ N_{\text{comb}} = 3$ and $h = 2.0$

$N_{\text{comb}} = 3$ sufficient for $N_{\text{targ}} = 3, 4, 5$ and variety of h across phase transition

Non-unitary operators on a quantum computer

Measurement based non-unitary gates with ancilla

Gingrich & Williams (2004), Terashima & Ueda (2005)



- entangle system with ancilla
- measure ancilla
- if ancilla is $|0\rangle$ system left in

$$|\psi\rangle \propto \hat{N}|\phi\rangle$$

- probability of success $P(|0\rangle) \leq 1$

For our purpose we can very easily prepare in this way the wanted state

$$|\Phi_O\rangle \propto \hat{O}|\psi_0\rangle + O(\delta)$$

paying the price that $P(|0\rangle) = O(\delta)$.

One can raise $P(|0\rangle) \approx 1$ deterministically! Roggero & Carlson (2018)