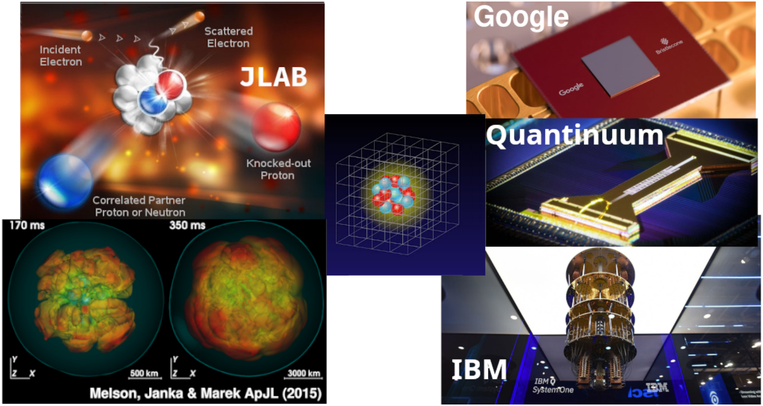
Quantum Computing for Nuclear Physics

Alessandro Roggero



INFN2024 - Trento

27 Feb, 2024

MOdeling Nuclear STructure and REactions

The need for ab-initio many-body dynamics in NP

- ν scattering for supernovae explosion and NS cooling
- capture reactions for crust heating and nucleosynthesis
- cross sections for dark-matter discovery and neutrino physics
- transport properties of neutron star matter for X-ray emission

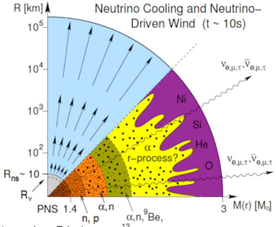
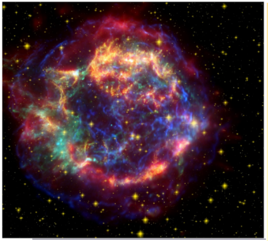


image from T.Janka



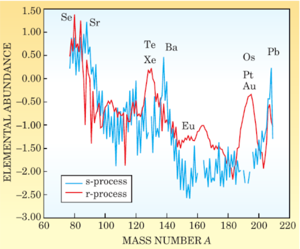
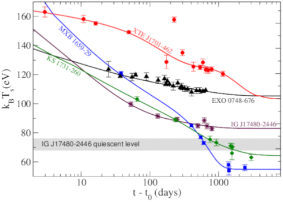


image from Cowan & Thielemann (2004)



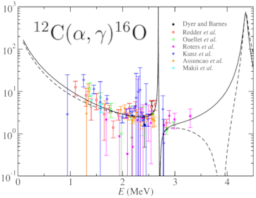
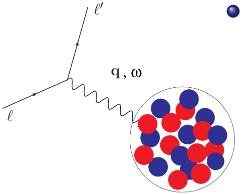


image from Brune & Davis (2015)

Inclusive cross section and the response function

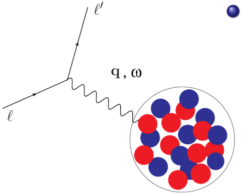


- cross section determined by the response function

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

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

Inclusive cross section and the response function



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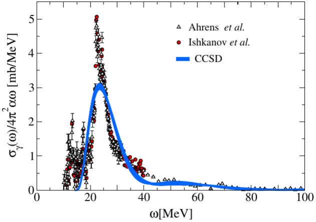
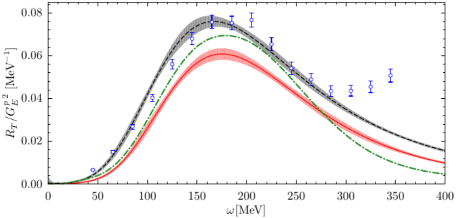
Extremely challenging classically for strongly correlated quantum systems

- dipole response of ^{16}O



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

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

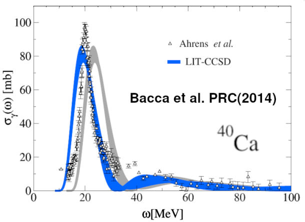


Lovato et al. PRL(2016) **GFMC**

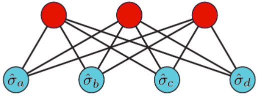
Prospects for classical simulations of nuclear dynamics

Quantum MC + Laplace/STA

- useful for quasi-elastic regime
- not yet accurate enough to go beyond $A = 12$ (sign-problem)



Machine Learning ideas could help



Coupled Cluster + Lorentz/Gauss

- useful for low energy regime
- accuracy limited by inversion

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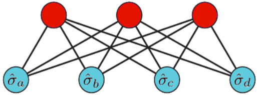

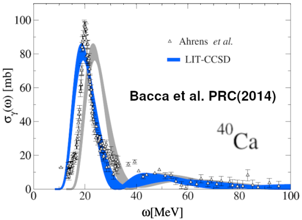

Coupled Cluster + Lorentz/Gauss

- useful for low energy regime
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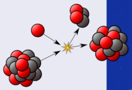
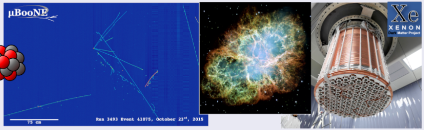
Some problems will still remain out of reach

- large open-shell nuclei
- exclusive cross-sections
- out of equilibrium





Quantum Computing and Quantum Simulations

R.Feynman(1982) we can use a controllable quantum system to simulate the behaviour of another quantum system

Quantum System we have control over

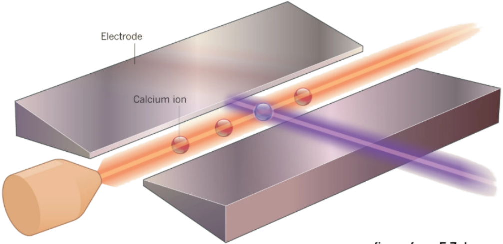


figure from E.Zohar

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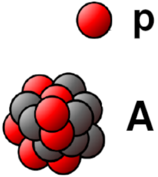

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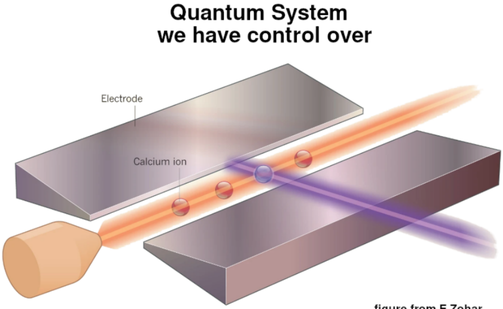

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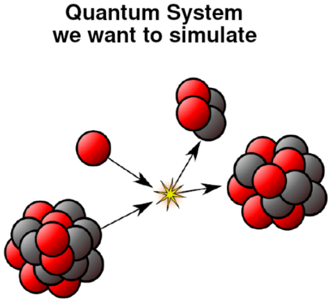

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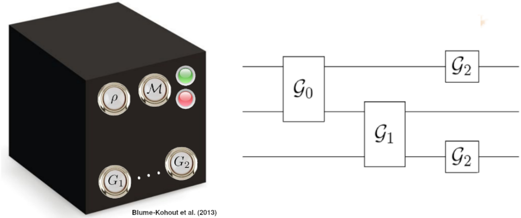

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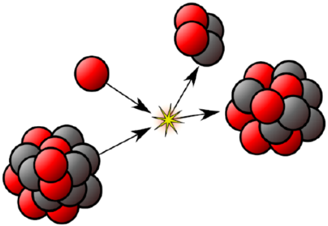
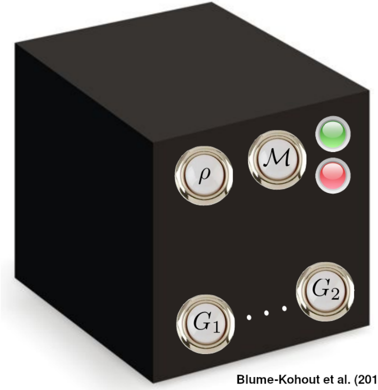


Black box model for a quantum computer



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

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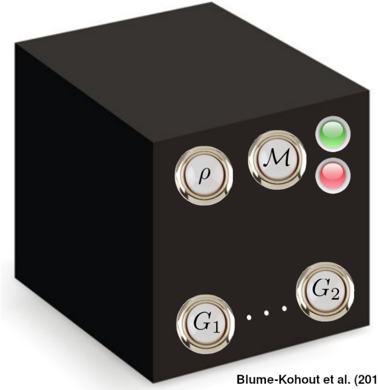

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We can build a **universal** black box with only a **finite number** of buttons

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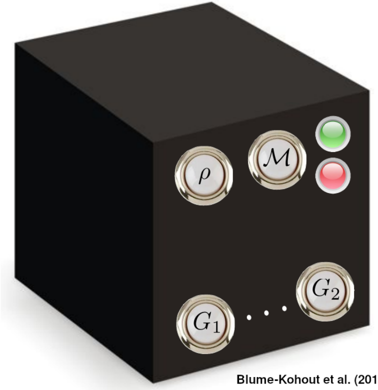

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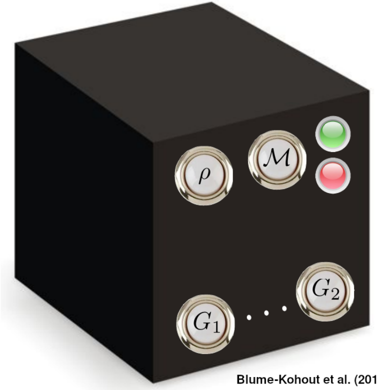

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$$|\Psi(0)\rangle \rightarrow |\Psi(t)\rangle = e^{-iHt}|\Psi(0)\rangle$$

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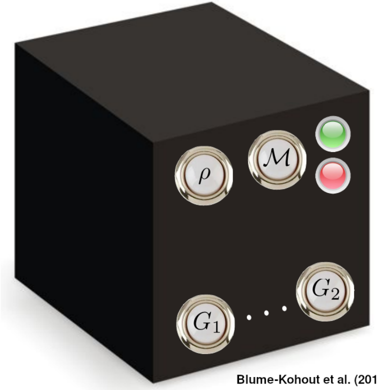

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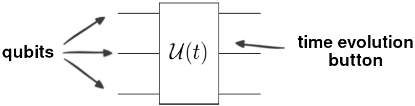

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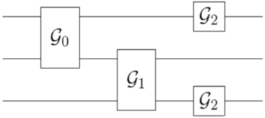
Lloyd (1996) We can simulate time evolution of **local** Hamiltonians

1. discretize the physical problem
2. map physical states to bb states
3. push correct button sequence

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

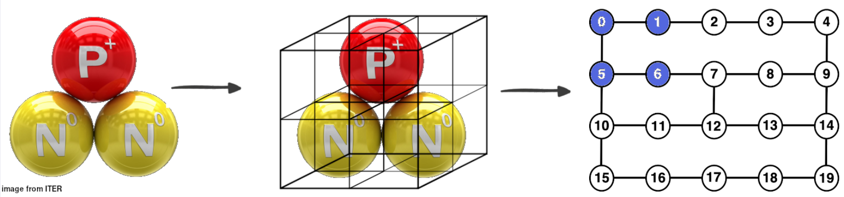


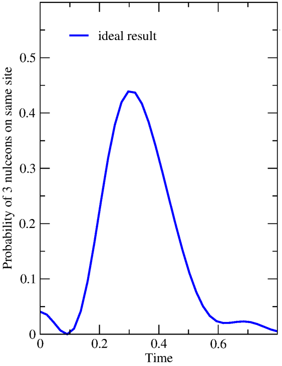
First programmable quantum devices are here

some figures from M.Savage

Real time dynamics on current generation devices

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





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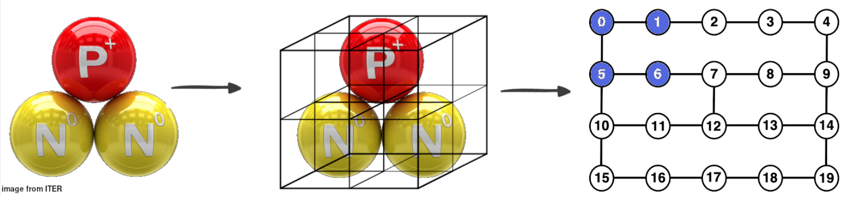
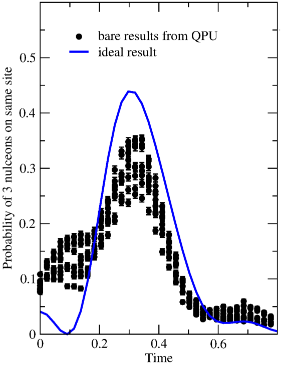
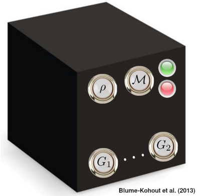




Error sources

- decoherence (environment)
- imperfect calibration



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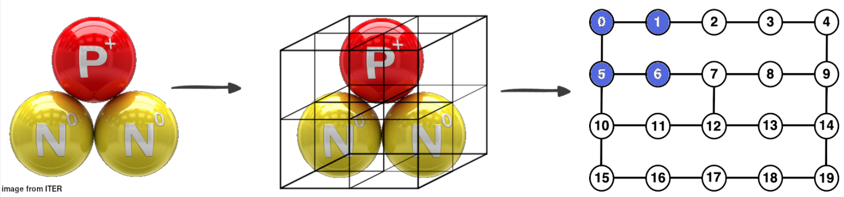
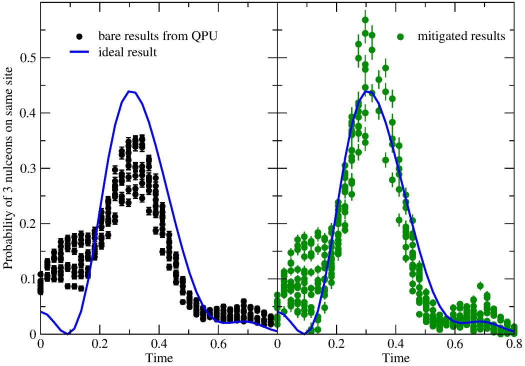
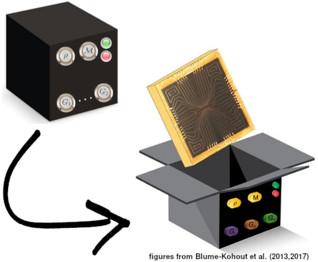


image from ITER



- Error mitigation is crucial


figures from Blume-Kohout et al. (2013,2017)

Fourier moments on (more) current generation devices

Both devices and error mitigation have come a long way in last few years

$$R(\omega) \approx \sum_k c_k(\omega) M(t_k) \quad \text{with} \quad M(t) = \langle \Psi_0 | O e^{-iHt} O | \Psi_0 \rangle$$

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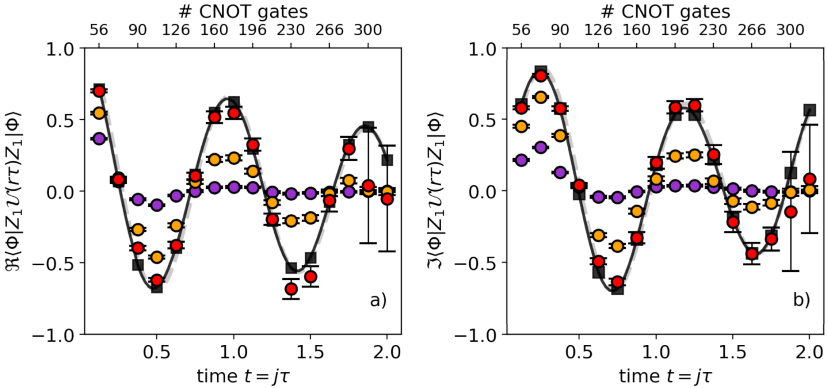
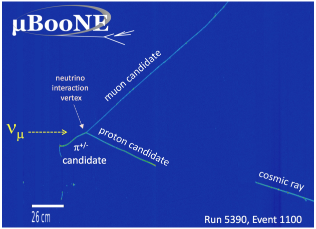


Kiss, Grossi, **AR** arXiv:2401.13048 (2024)

Exclusive cross sections in neutrino oscillation experiments



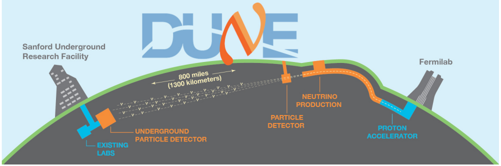
Goals for ν oscillation exp.

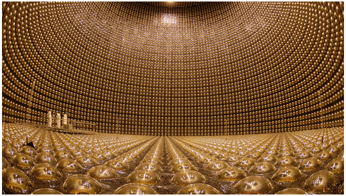
- neutrino masses
- accurate mixing angles
- CP violating phase

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

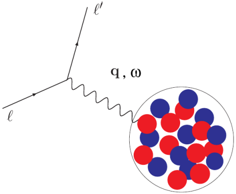
- need to use measured reaction products to constrain E_ν of the event

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





Towards exclusive scattering using quantum computing



- response $R(\omega) \Leftrightarrow$ probability for events at fixed ω
- exclusive x-sec $\rightarrow$ events with specific final states

IDEA: prepare the following state on QC

$$|\Phi\rangle = \sum_\omega \sqrt{R(\omega)}\,|\omega\rangle \otimes |\psi_\omega\rangle$$

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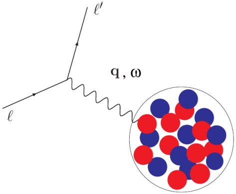

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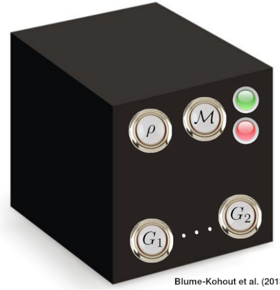
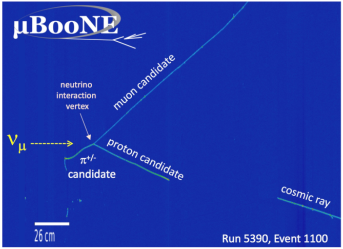
- measurement of first register returns ω with probability $R(\omega)$!
- after measurement, the second register contains final states at ω!



Blume-Kohout et al. (2013)



AR & Carlson PRC(2019)

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 $\approx 10^6 - 10^8$ times

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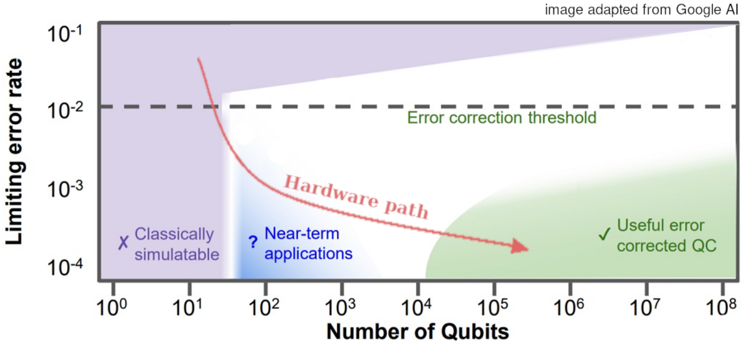

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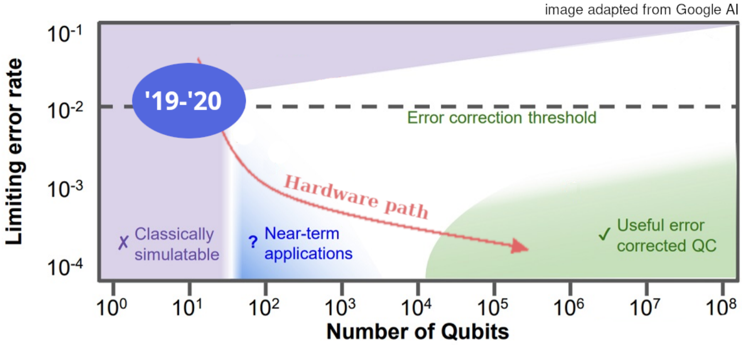

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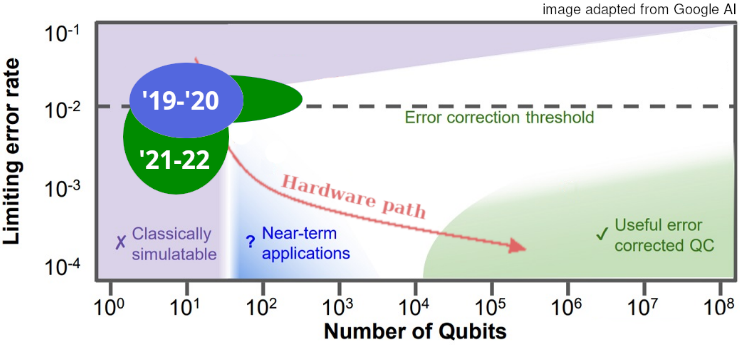

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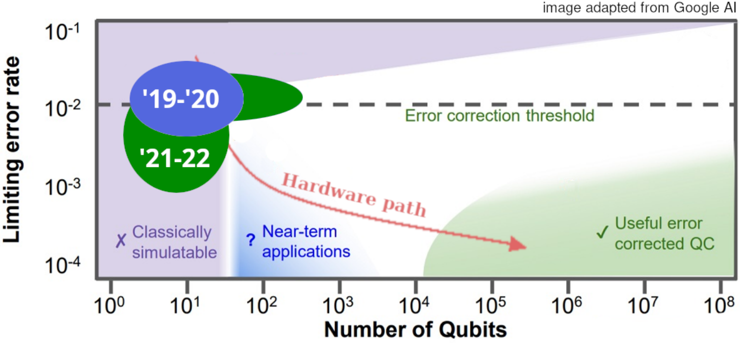
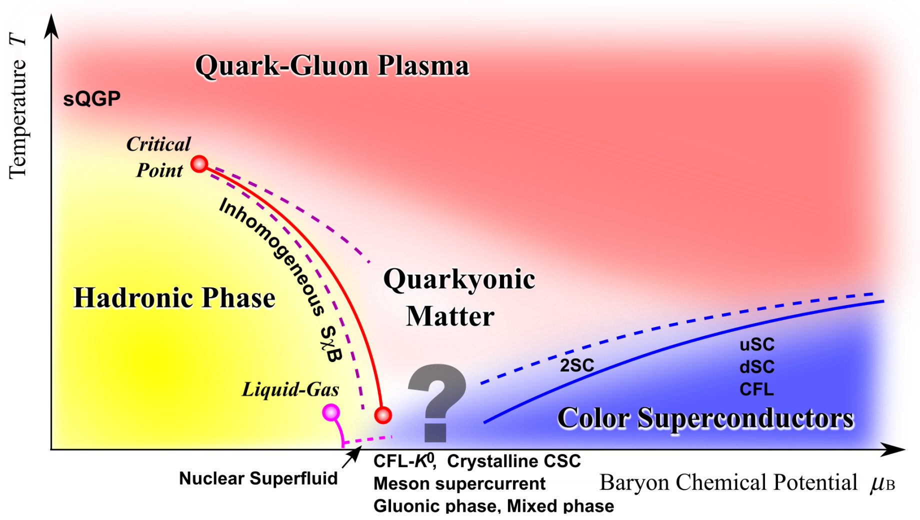


- Still possible to optimize further (other encodings need ≈ 500 qubits)
- Insights for classical methods could come before we have a large QC!

The QCD phase diagram

figure from Fukushima & Hatsuda (2011)



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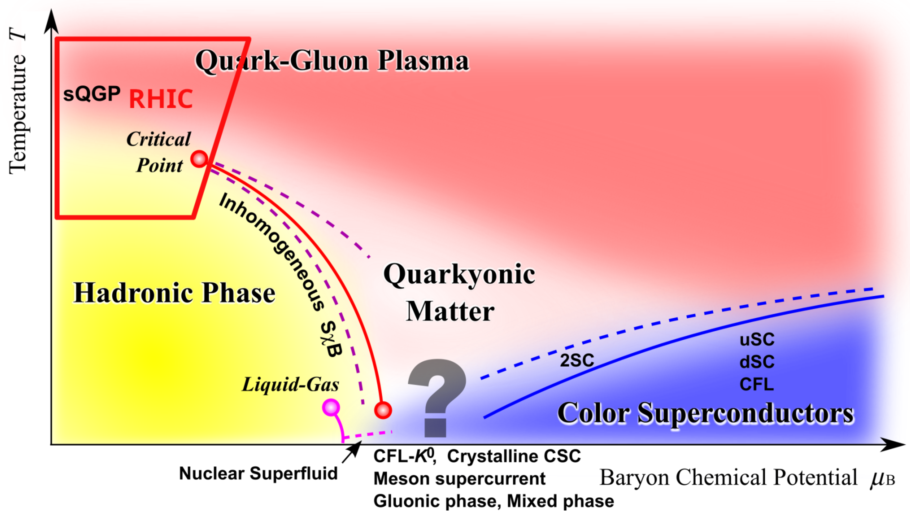

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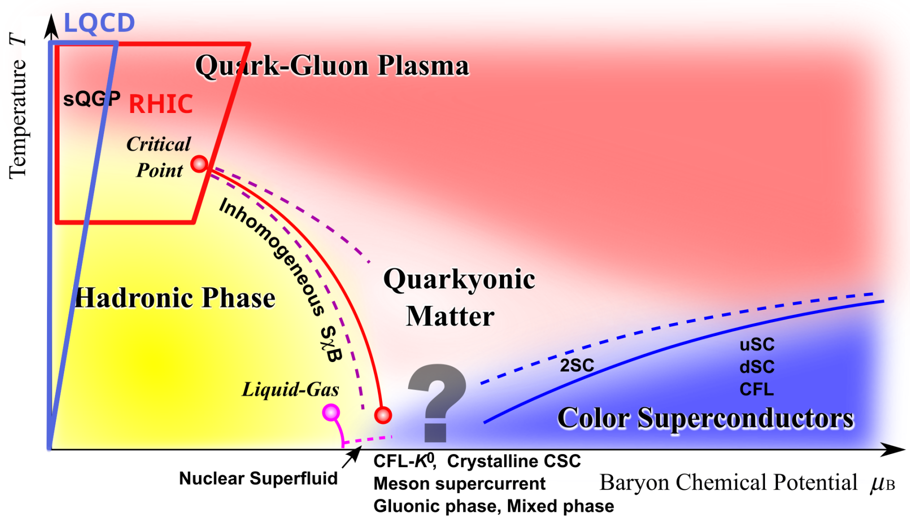

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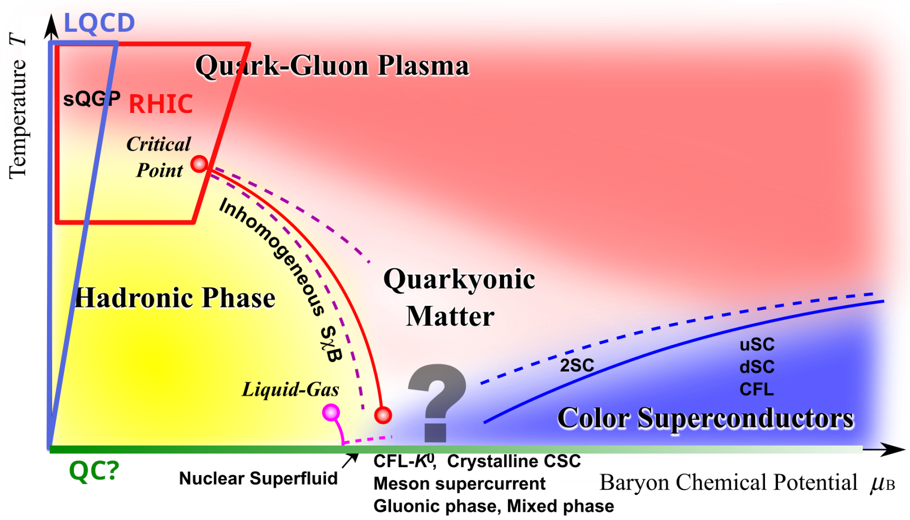
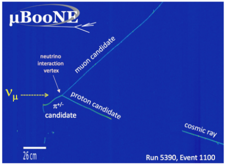


Summary & Conclusions

- 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, out-of-equilibrium processes and QCD at finite μ
- Quantum Computing has the potential to bridge this gap and increasingly better experimental test-beds are being built
- Error mitigation techniques will be critical to make the best use of these noisy near-term devices
- Early impact of QC on nuclear physics might come as insights into classical many-body methods and the role of entanglement



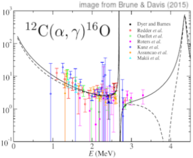
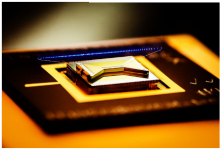
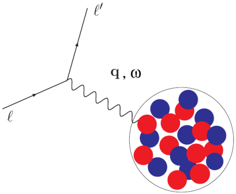



image from Chandra collab.



Towards exclusive scattering using quantum computing



- response $R(\omega) \Leftrightarrow$ probability for events at fixed ω
- exclusive x-sec $\rightarrow$ events with specific final states

IDEA: prepare the following state on QC

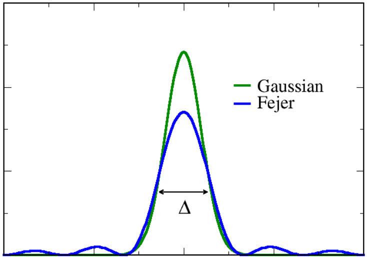
$$|\Phi\rangle = \sum_\omega \sqrt{R(\omega)}\,|\omega\rangle \otimes |\psi_\omega\rangle$$

- measurement of first register returns ω with probability $R(\omega)$!
- after measurement, the second register contains final states at ω!

Difficult to prepare $|\Phi\rangle$ but we can prepare instead the following state

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

with R_Δ is an integral transform of the response with energy resolution Δ



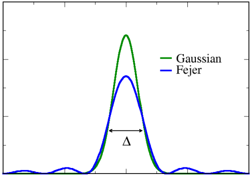
AR & Carlson PRC(2019), **AR** PRA(2020)

Nuclear dynamics with quantum (inspired) computing?

We can prepare the following state

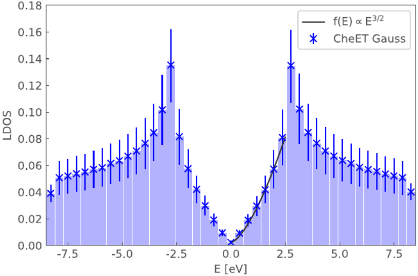
$$|\Phi_\Delta\rangle = \sum_\omega \sqrt{R_\Delta(\omega)}\,|\omega\rangle \otimes |\psi_\omega\rangle$$

with R_Δ is an integral transform of the response with energy resolution Δ

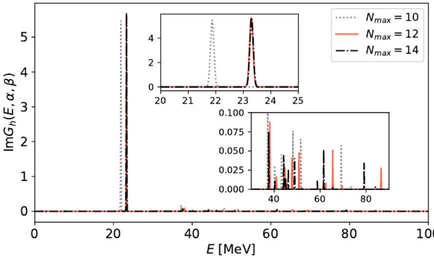


AR & Carlson PRC(2019), **AR** PRA(2020)

- Gaussian approach uses the fact that Chebyshev polynomials can be evaluated efficiently on quantum computers (Berry, Childs, Low, Chuang, ...)



Sobczyk, **AR** PRE(2022)



Sobczyk, Bacca, Hagen, Papenbrock PRC(2022)