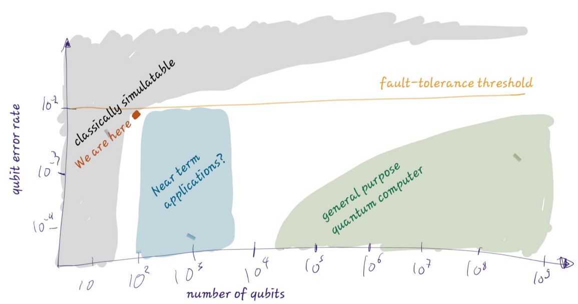
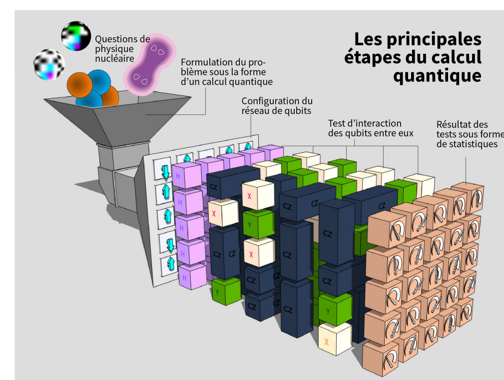
Quantum computing simulation of complex quantum systems

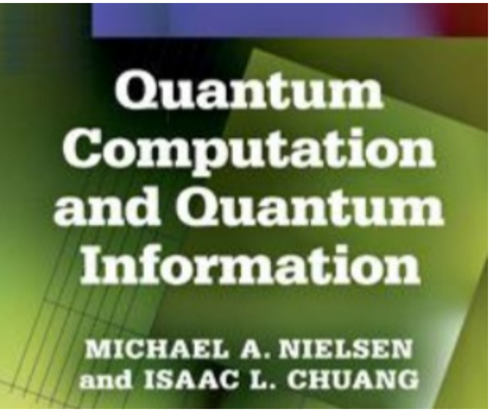
Denis Lacroix (IJCLab)

QC2I project

Discussion on
ongoing projects in complex
many-body systems

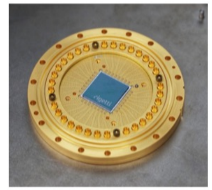


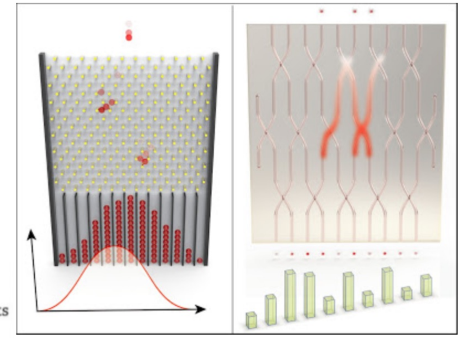


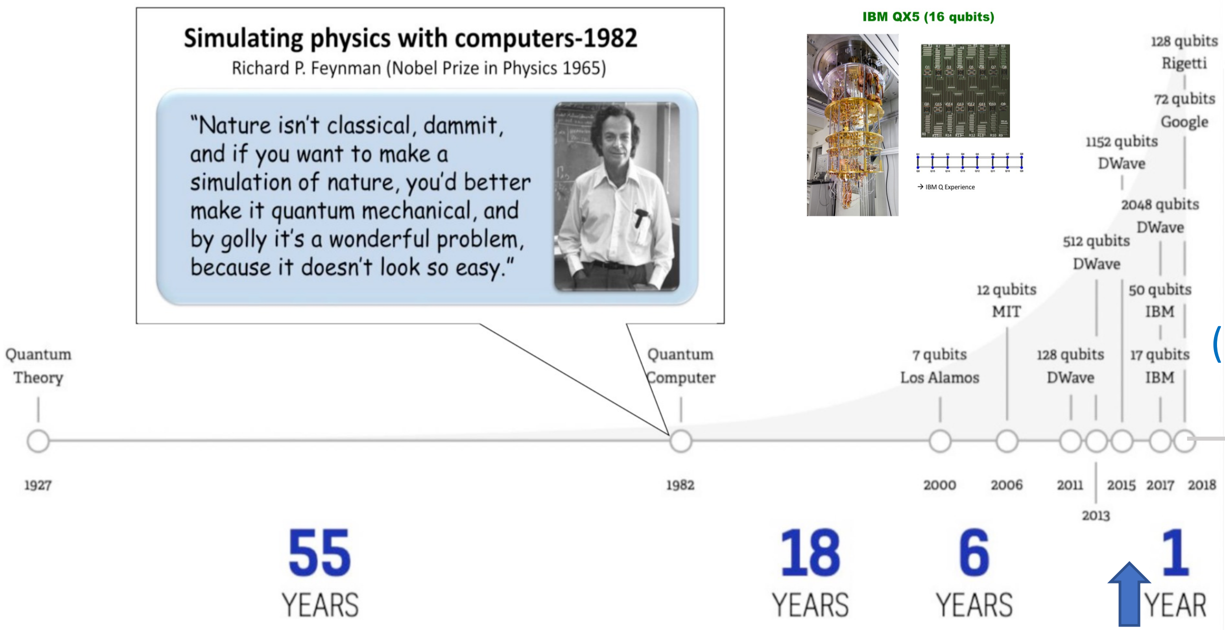


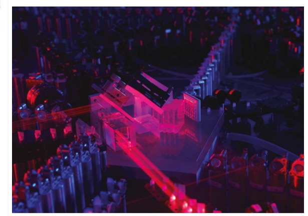
Quantum computational advantage using photons, Science 370 (2020)

RIGETTI superconducting 19 Qubit

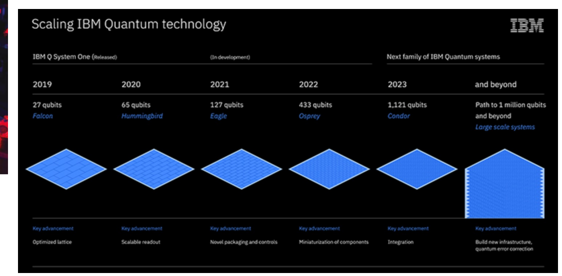


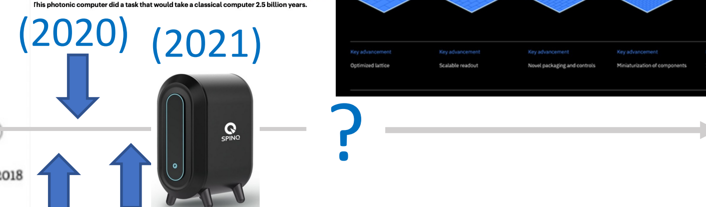




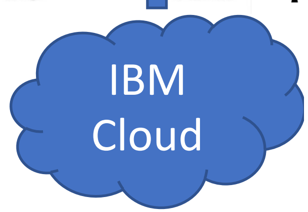


This photonic computer did a task that would take a classical computer 2.5 billion years.





IonQ Gemini desk computer



Quantum supremacy using a programmable superconducting processor

Nature | Vol 574 | 24 OCTOBER 2019 | 505

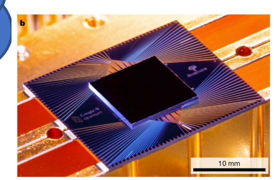
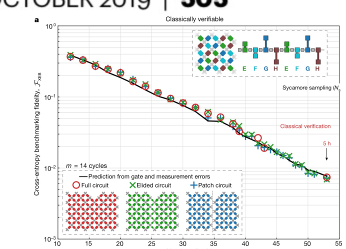
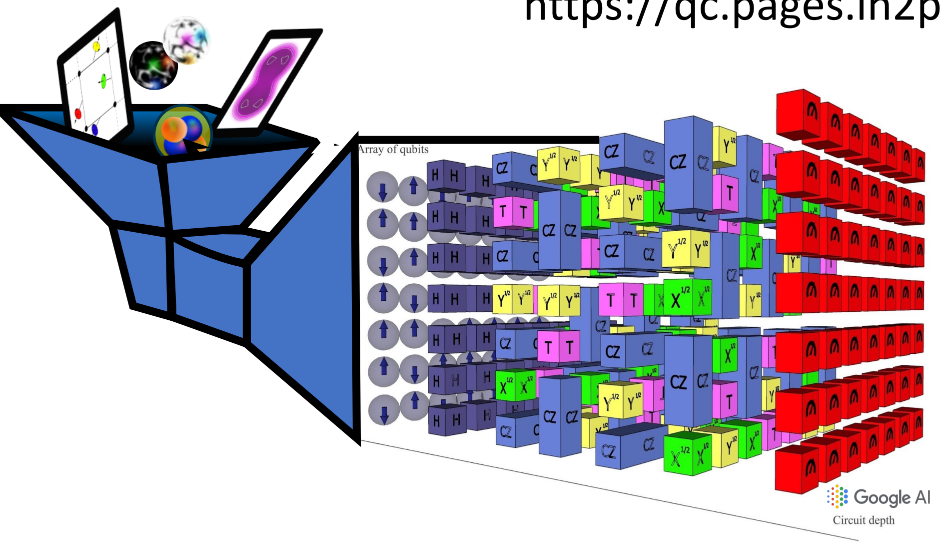
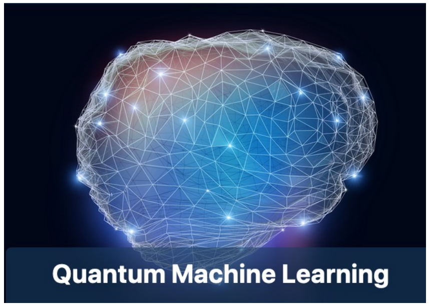


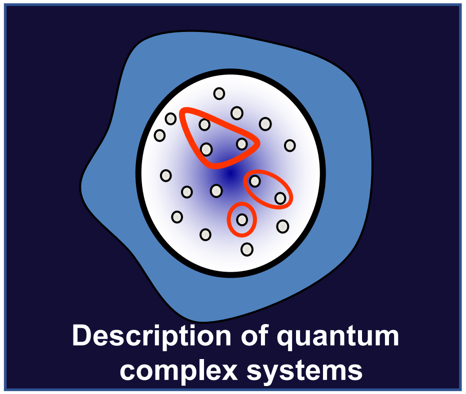
Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b,** Photograph of the Sycamore chip.

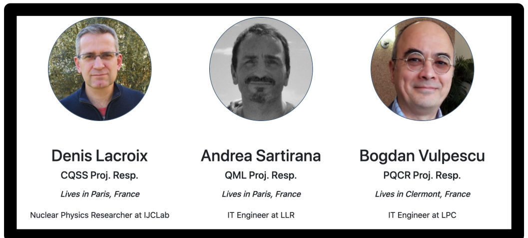


https://qc.pages.in2p3.fr/web/

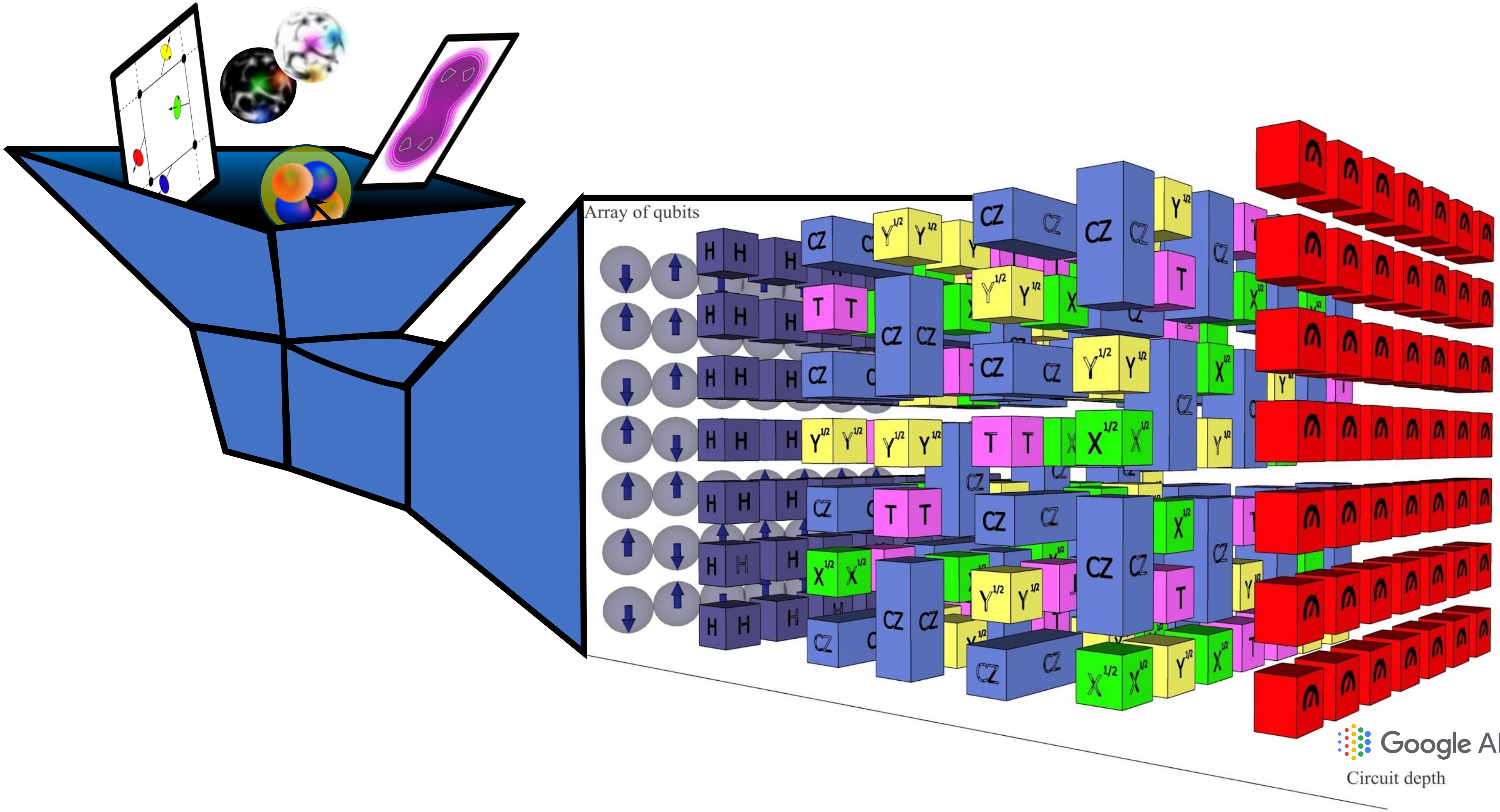




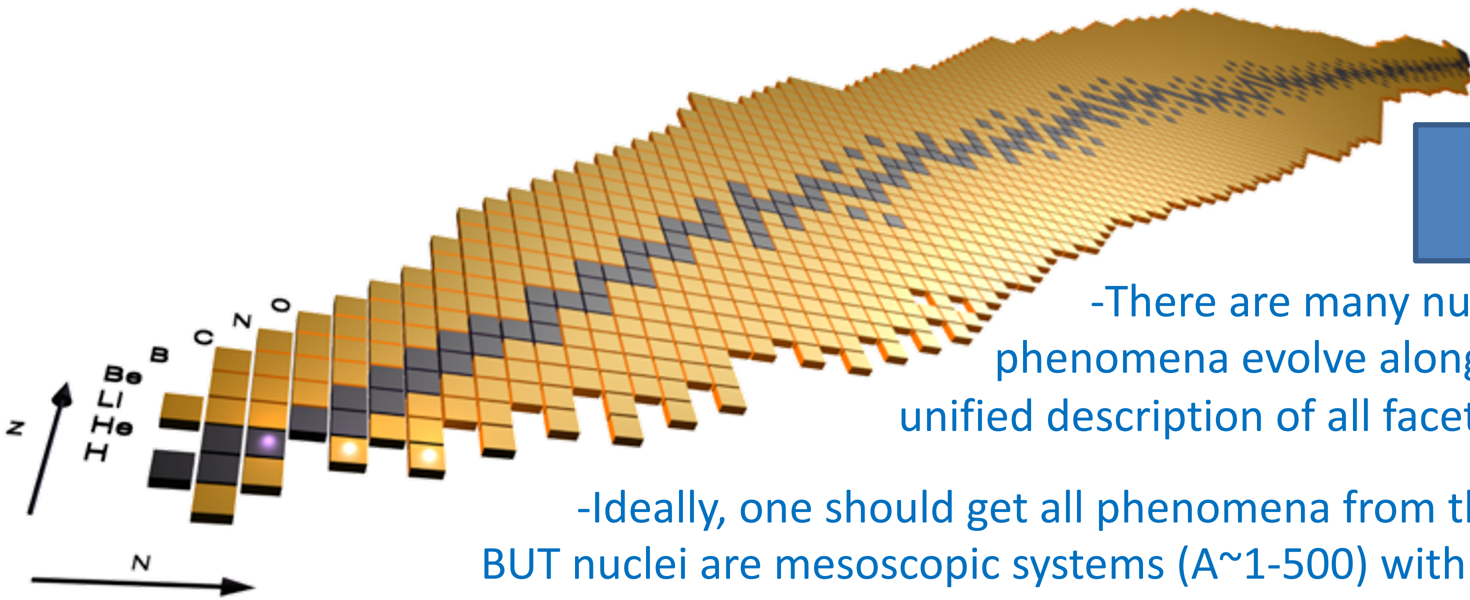




Ongoing projects that are starting now



Why quantum computing can help to describe nuclear physics ?

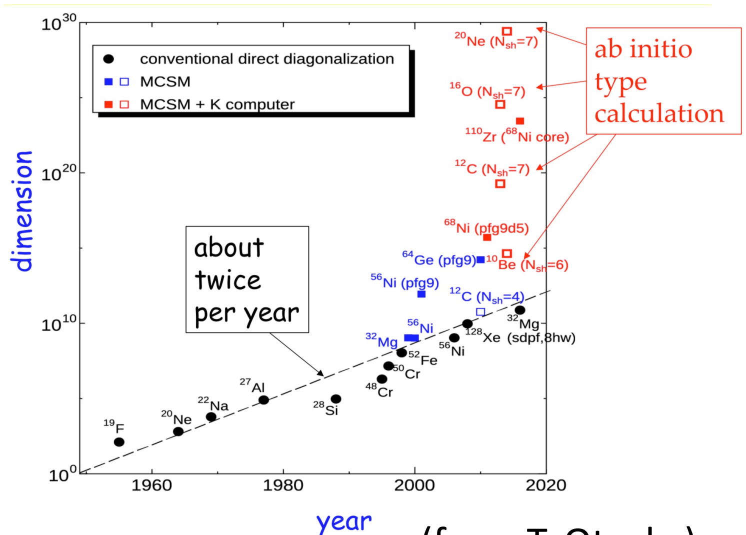


Some evident sources of complexity in nuclei

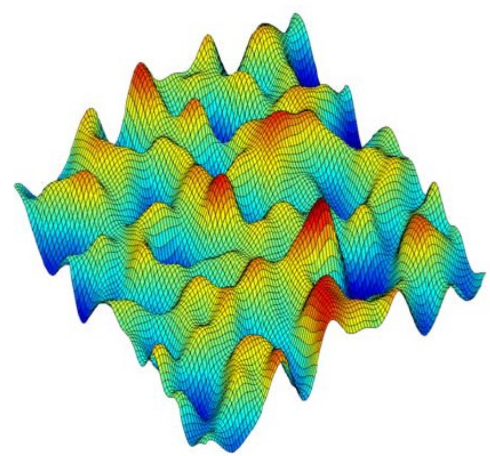
-There are many nuclei (>3000). Nuclear phenomena evolve along the nuclear chart. A unified description of all facets would be desirable.

-Ideally, one should get all phenomena from the bare interaction
BUT nuclei are mesoscopic systems (A~1-500) with bad numerical scaling.

-Each nucleus is a complex problem per se.



(from T. Otsuka)

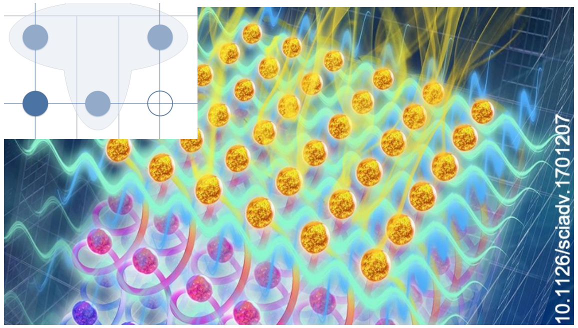


(Energy landscape of a molecule)

This motivates the search of disruptive techniques (high risk/high potential benefits)

Few initiated applications in the world related to the infinities

Lattice gauge theories



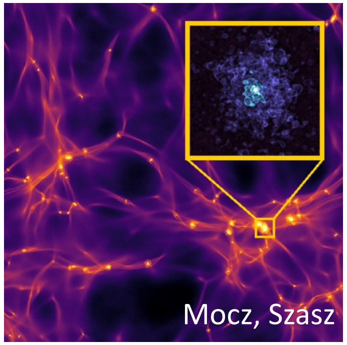
Zohar, Klco, Savage, …

N-body problem

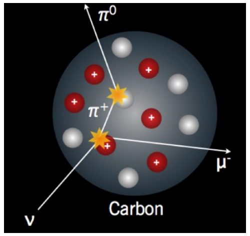
N-body nuclear systems

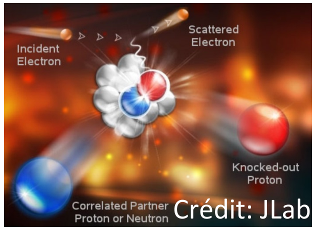
Dumitrescu, Hagen, Carlson, Papenbrock…

Dark matter

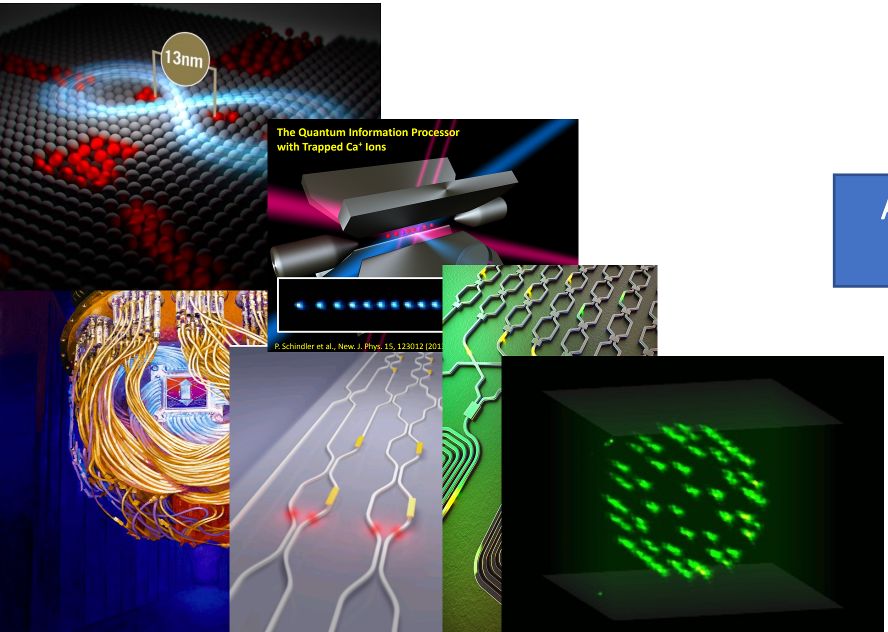


Dynamics: e, ν scattering

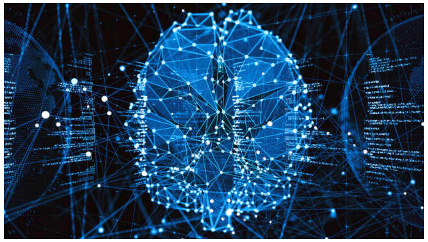




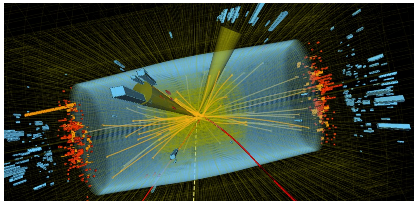
Roggero, Carlson, …



Applications to data mining (event classification)



CMS-detector (with LLR)

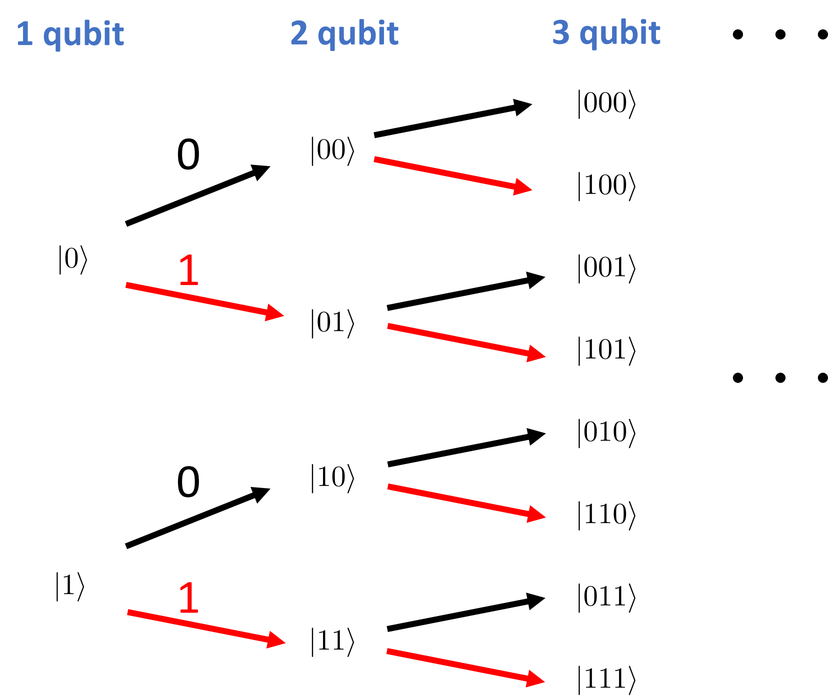


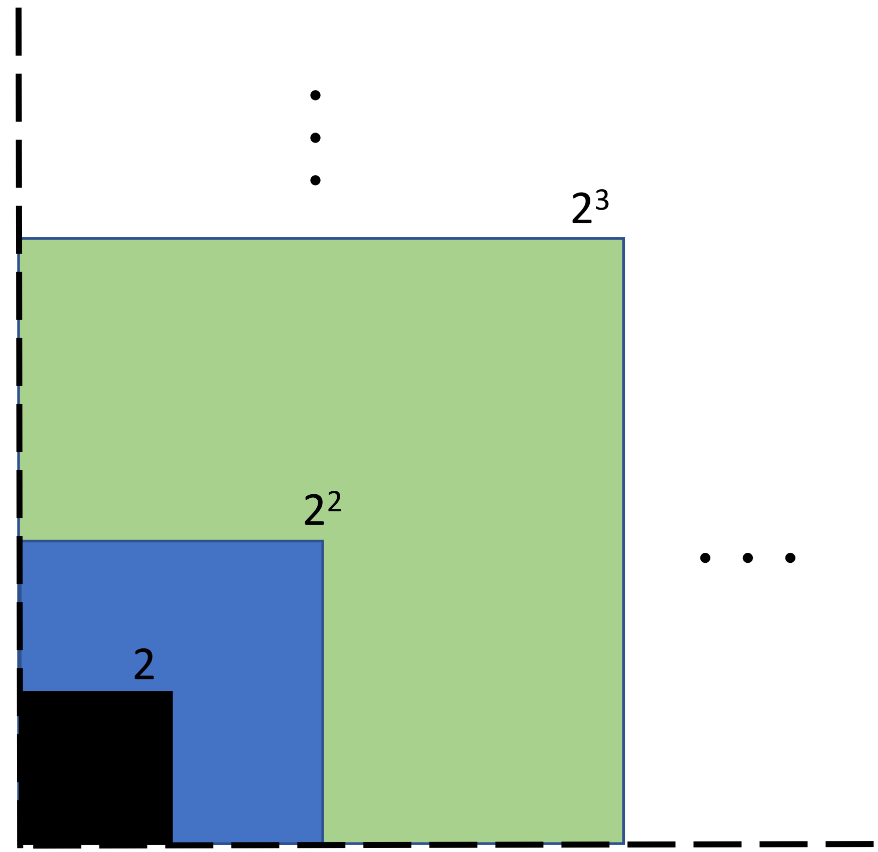
Hilbert Space dimention with qubits

Illustration of quantum advantages

Systems described on qubits

$$|\Psi\rangle = \sum_{s_i=0,1} \Psi_{s_1,\cdots,s_N} |s_1,\cdots,s_n\rangle$$

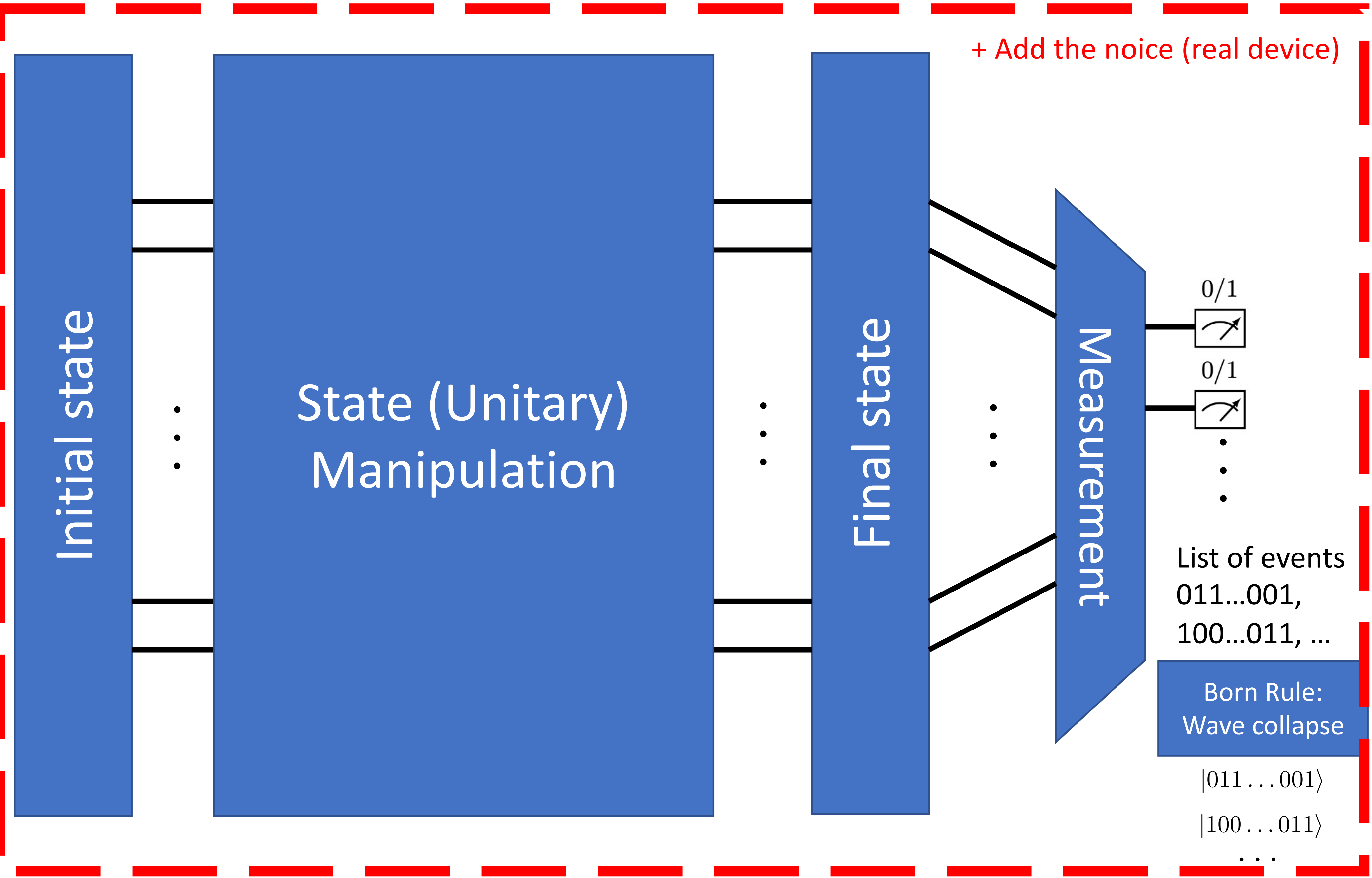




Quantum supremacy $\sim 2^{50}$

With 2^{300} (i.e. 300 qubits) the size is more than the number of particles In the universe. J. Preskill

« Roadmap » for quantum simulations of complex quantum systems



« Roadmap » for quantum simulations of complex quantum systems

Some pre-requist

NB: there are two way of simulating (analogue or digital)- for the moment I only explored digital encoding

➡ Learn quantum programming (qubit manipulation, circuits, …)
(greatly simplified by existing package)

➡ Learn how to encode a problem (quantum or not) into a quantum register

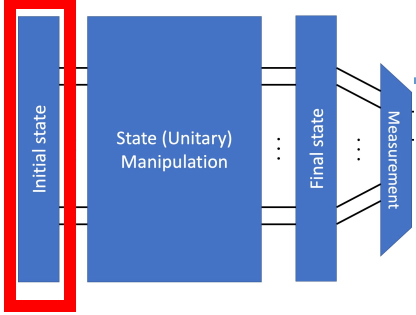
Ex : Fermions to qubits (Jordan-Wigner, Gray, Bravyi–Kitaev, …).

➡ Reach a sufficient expertise to bring something to this field (i.e. know all Existing techniques with pro and con)

Work on real devices

➡ Add the noise component with its machinery/zoology of noise corrections

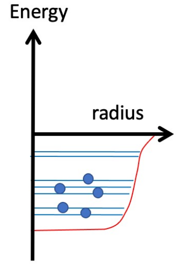
➡ Have access to good machines

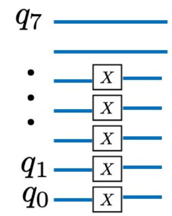


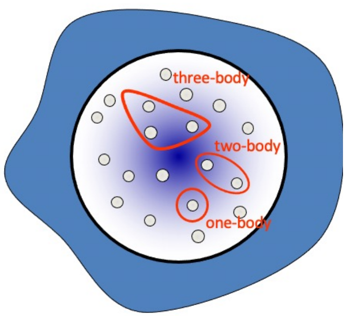
Some flash of what is happening now: many-body systems

The many ways to prepare a system

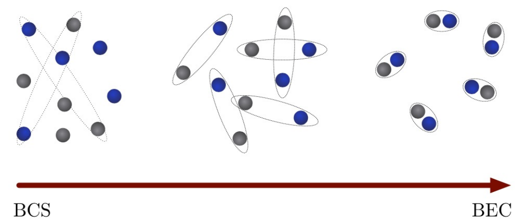
Independent particles

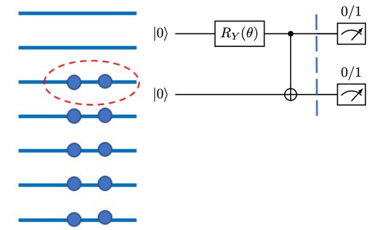




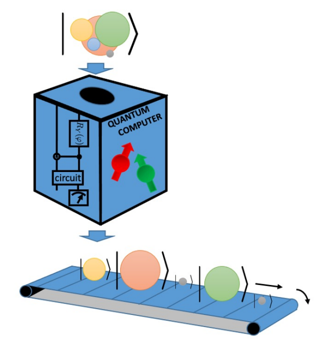


Superfluid systems





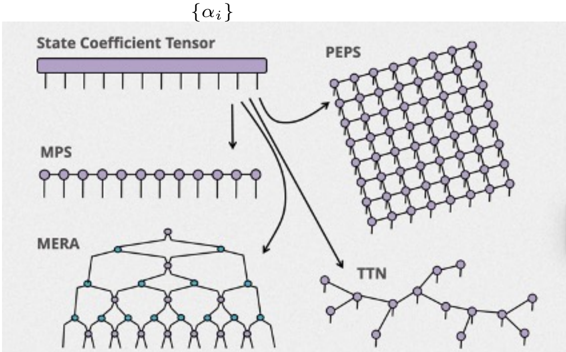
Requires symmetry breaking and restauration tools



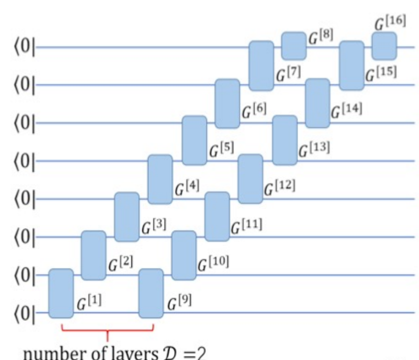
D. Lacroix, PRL 125, 230502 (2020).

Parametrizing general states:
Tensor network

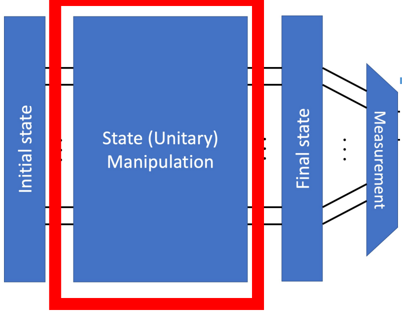
$$\Psi^{s_1,s_2,\cdots s_{n-1},s_n} = \sum_{\{\alpha_i\}} G^{s_1}_{\alpha_1} G^{s_2}_{\alpha_1\alpha_2}\cdots G^{s_{n-1}}_{\alpha_{n-2}\alpha_{n-1}} G^{s_n}_{\alpha_{n-1}}$$



Examples:



(now tested with A. Ruiz Guzman [PhD])



Some flash of what is happening now: many-body systems

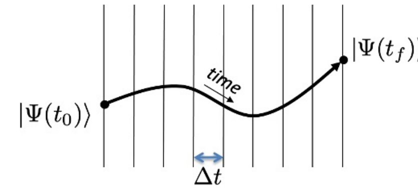
State manipulation/evolution

Exact evolution

$$= e^{\frac{1}{i\hbar}(t-t_0)H}|\Psi(t_0)\rangle$$

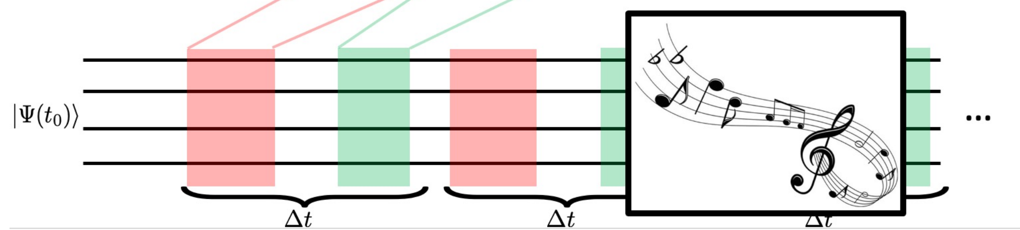
H is usually a big matrix

Example Trotter-Suzuki



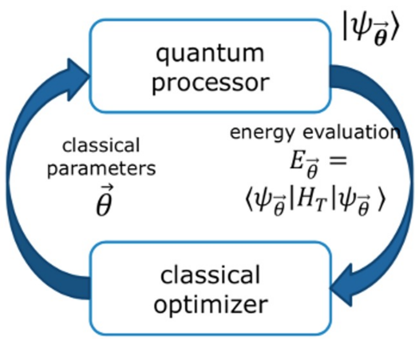
$$e^{-ix(A+B)} = \left(e^{-iAx/N}e^{-iBx/N}\right)^N + \mathcal{O}(t^2/N)$$

Example : $e^{i\Delta t H_1/\hbar} = e^{-i\Delta t H_1/\hbar}e^{-i\Delta t H_2/\hbar}$

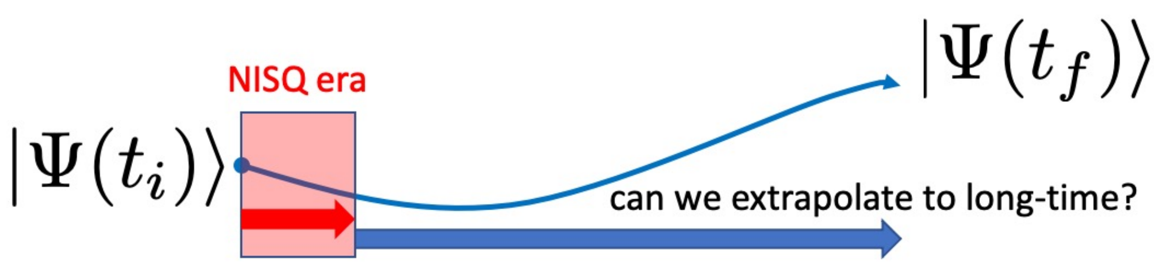


Approximate evolutions

Variational methods



Long time evolution from short time simulation



A. ruiz-Guzman and DL, arXiv:2104.08181

- Projects are at their early stage and are quite generic (state preparation/evolution)

- Developments in one field can be used in other fields (of physics, of QML, …)

- Enormous potential but many aspects not yet considered
  -ex: digital versus analogue

- *Quantum programming is "easy" but working really with quantum computers is difficult*

  -adapt to the technology.
  -search of efficient algorithms on this technology.
  -try to correct for nasty noise as much as possible.

  This looks mor like an experimental program than informatic or quantum theory.