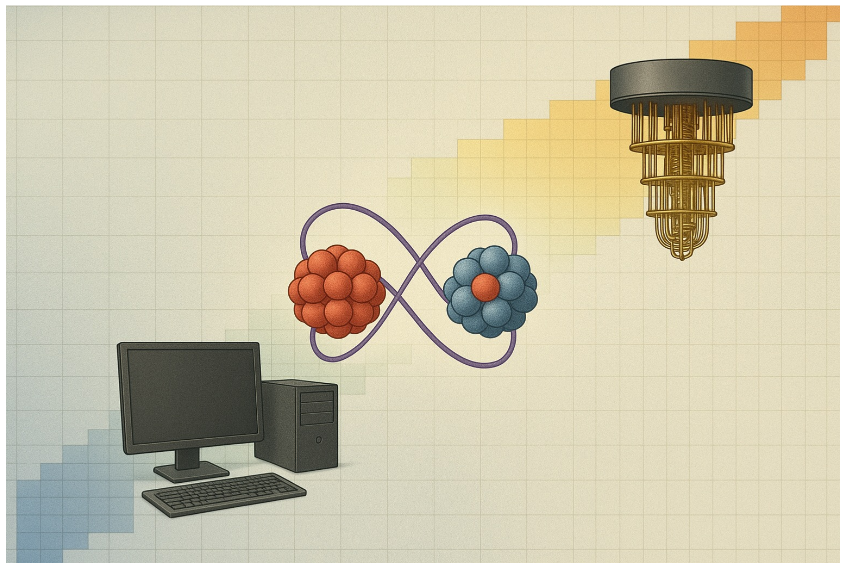
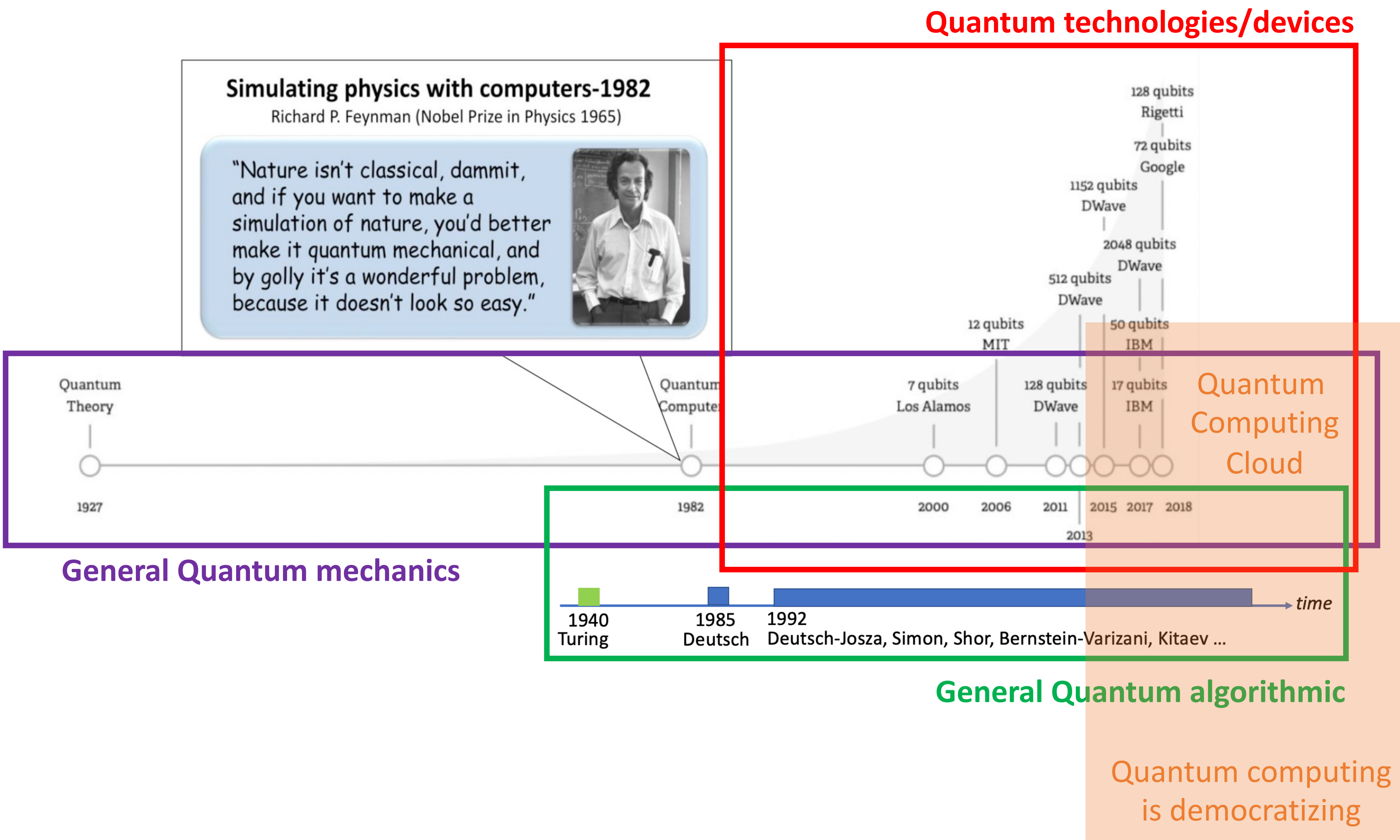
Progress in quantum computing for nuclear physics

Denis Lacroix



Many-body physics and QC - T. Ayral, P. Besserve, D. Lacroix, and E.A. Ruiz Guzman , Quantum computing with and for many-body physics, EPJA 59 (2023)
Symmetry and QC – D. Lacroix, A. Ruiz Guzman and P. Siwach, Symmetry breaking/symmetry preserving circuits and symmetry restoration on quantum computers, EPJA 59 (2023)
CERN Quantum Initiative – Di Meglio et al., Quantum Computing for High-Energy Physics: State of the Art and Challenges, PRX Quantum 5, 037001 (2024)

Why quantum computing is becoming mature now ?

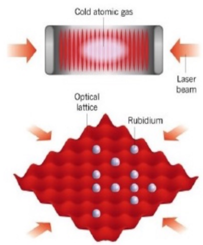


What means quantum devices today

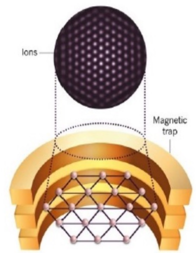
There are many types of quantum computers: ***analog versus digital quantum computers***

There are now many quantum objects one can manipulate

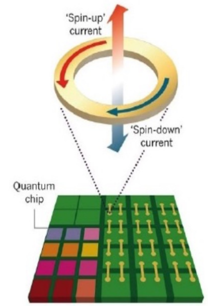
Cold atoms



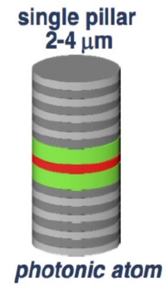
Trapped ions

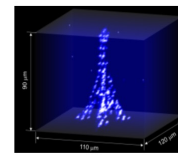


Superc. loops



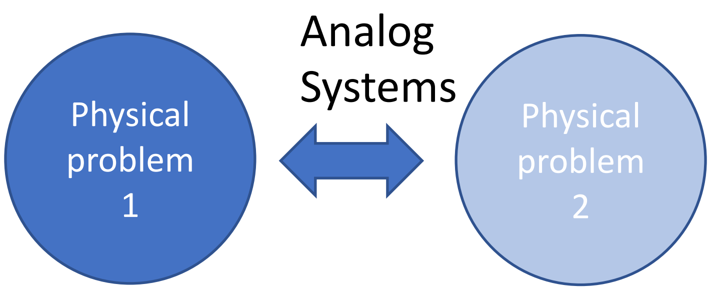
Polaritons





Atomes de Rydberg dans des pinces optiques

Analog quantum simulator

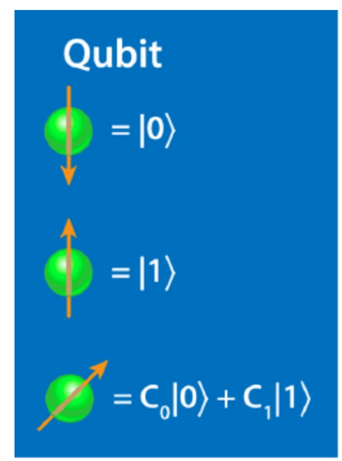


Complex problem that cannot or hardly be simulated on classical computers

Analog problem to 1 that could be tested in laboratory

➡ Non-universal

Digital quantum simulator



➡ Universal Quantum simulation

What means quantum devices today

There are many types of quantum computers: ***analog versus digital quantum computers***

Quantum machines are often themselves many-body systems

Experiment

Theory

Analog quantum s

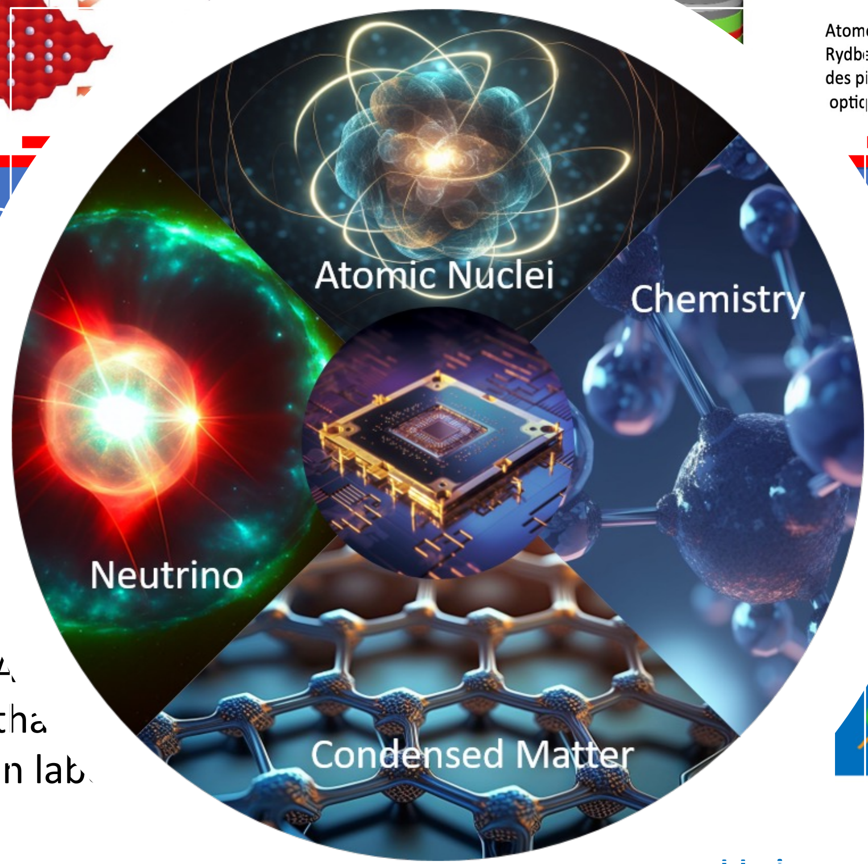
quantum simulator

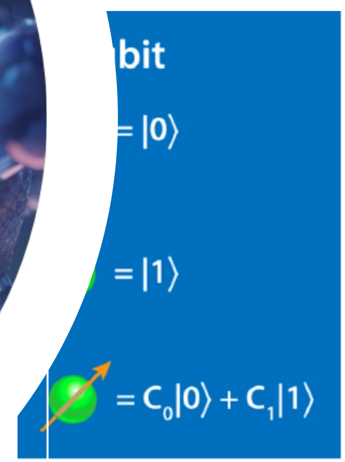
Physical problem 1

Analog System

Complex problem that cannot or hardly be simulated on classical computers

A
tha
in lab



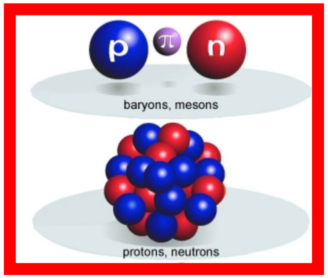


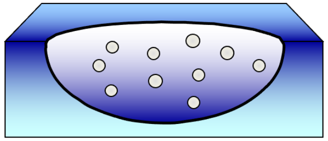
Non-universal

Universal Quantum simulation

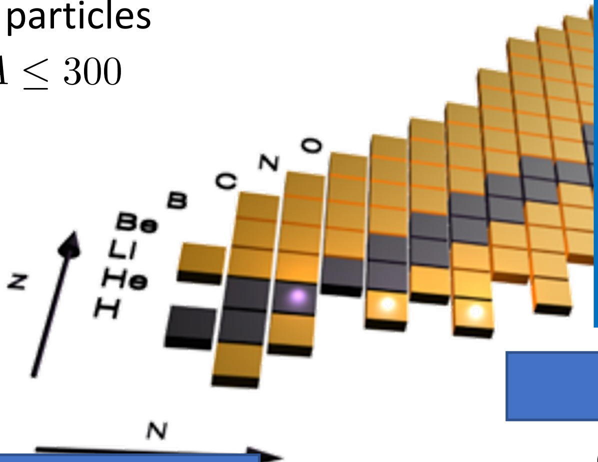
Quantum computing for the description of static and dynamical properties of atomic nuclei

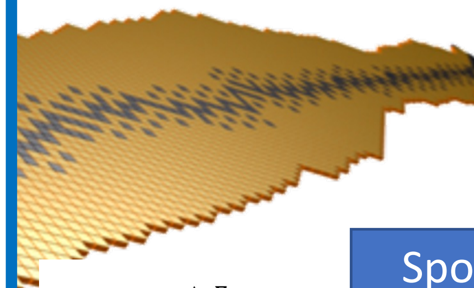
Problematic and challenges



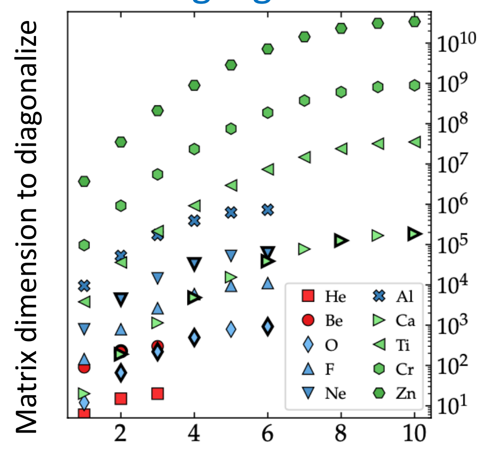


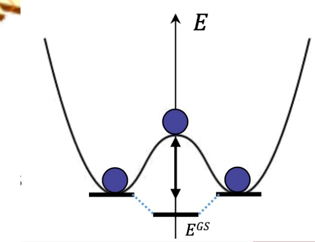
Nuclei are self-bound quantum mesoscopic systems
Nb of particles
$2 \leq A \leq 300$





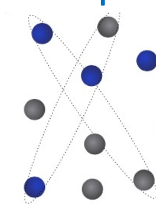
Finding eigenstates





Spontaneous Broken symmetries (SB)

Small superfluid

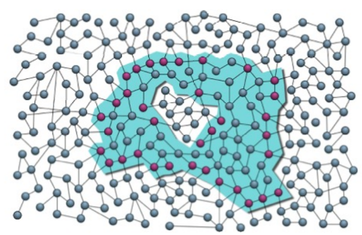


(particle number SB)

Symmetries /Entanglement

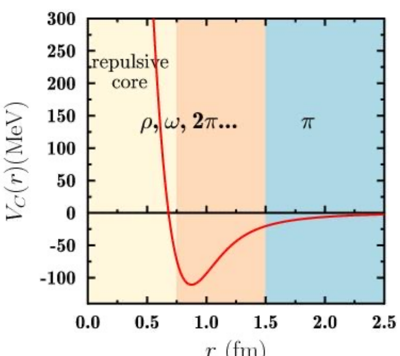
Global symmetries induce
All-to-all entanglement

$$S,\ T,\ J,\ \pi$$



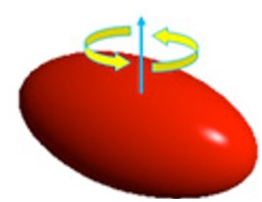
Nuclei are subject to entanglement volume law
(bad candidate for Tensor Network)

Interaction



The problem is highly non-perturbative

Deformation can happen

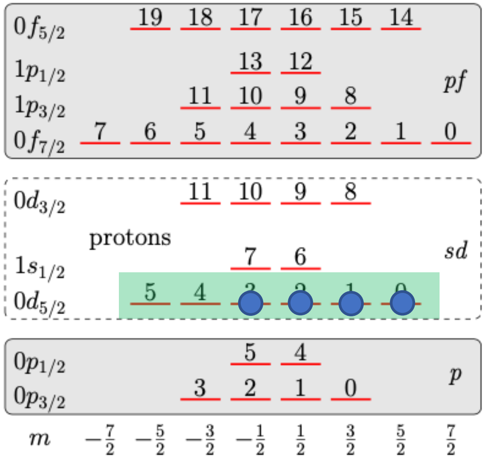


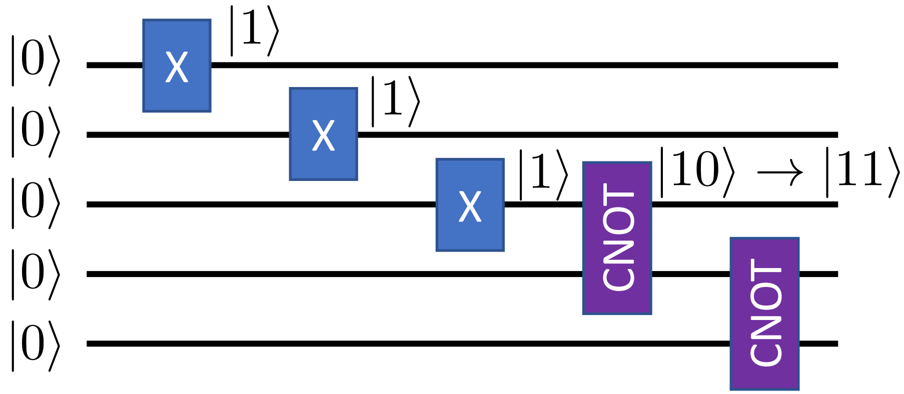
(rotational invariance SB)

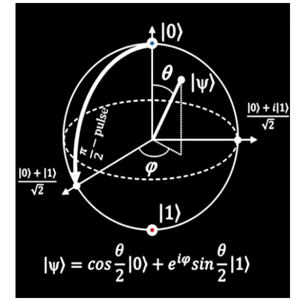
...

Encoding fermions on a quantum computer

For many-body problems

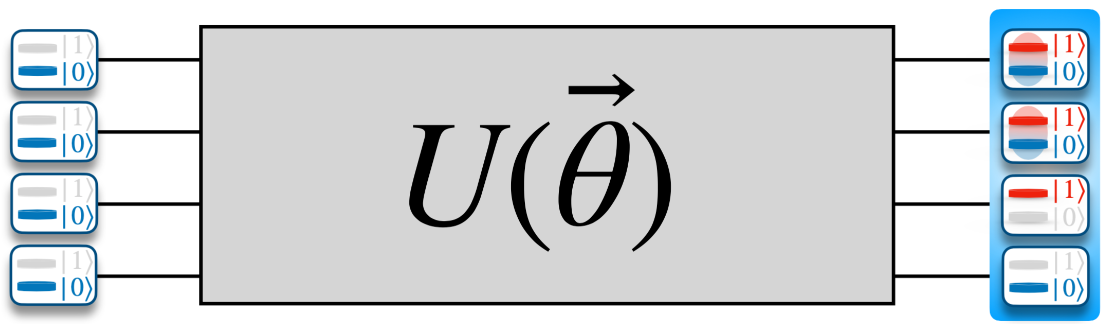






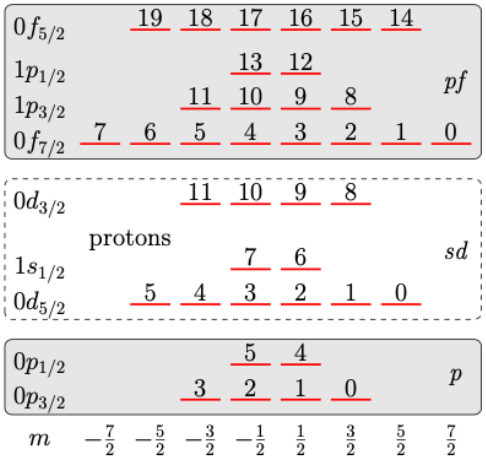
Today a number of teams
Have started to encode the nuclear shell model on quantum computers:

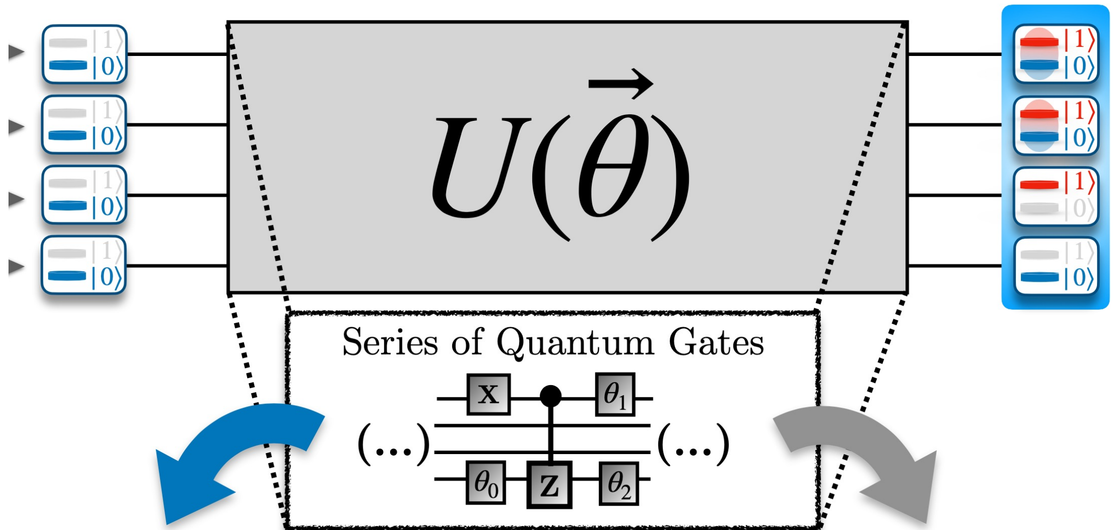
- Barcelona University
- Surrey University
- GANIL
- IJCLab
- Roorkee university
- …



Today’s and Tomorrow’s strategies

For quantum computing many-body problems





Near Term Era

Hardware limitations

Variational Quantum Eigensolver

Why?

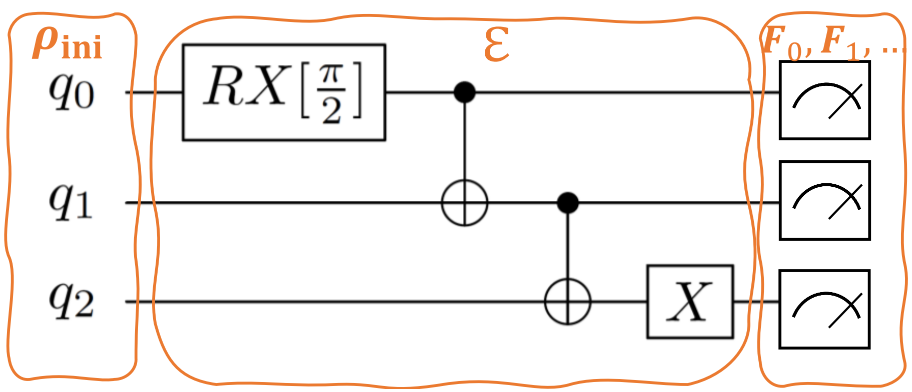
Fault Tolerant Era

No Hardware limitations

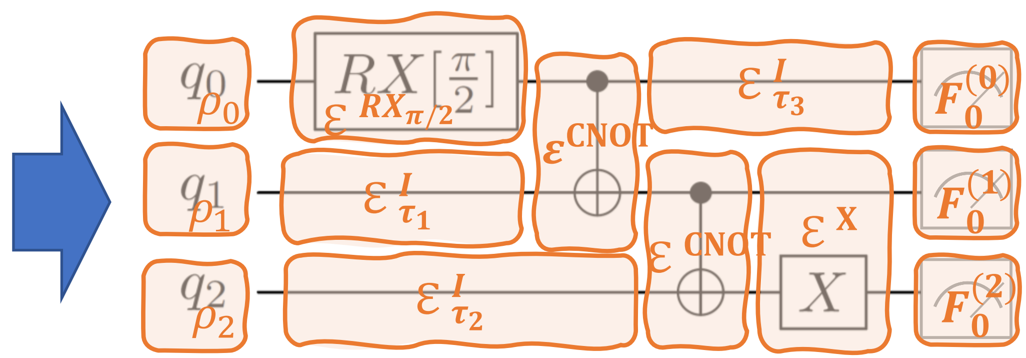
Quantum Phase Estimation

(credit: Y. Saad)

Ideal circuit



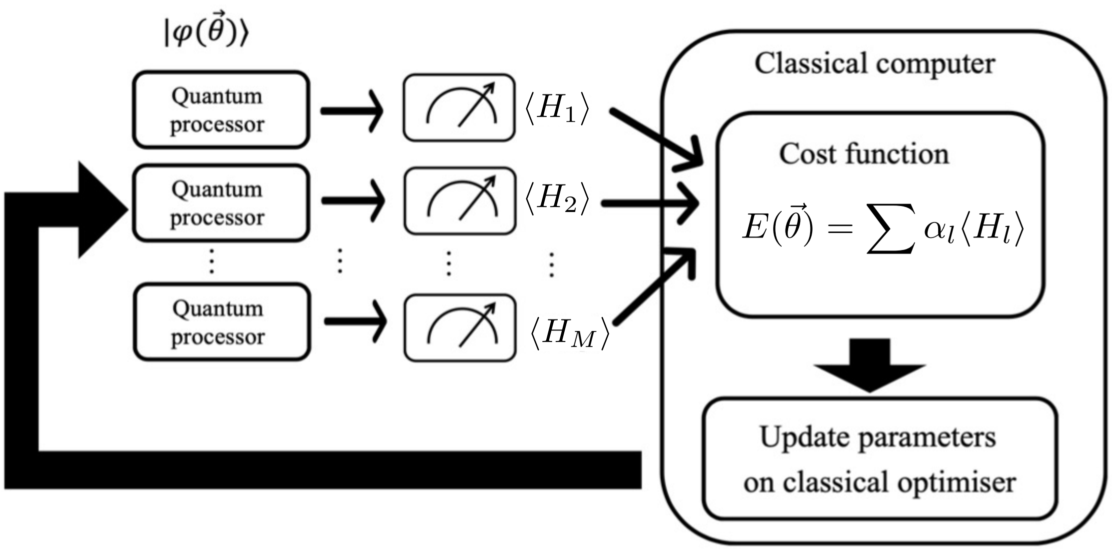
Reality circuit

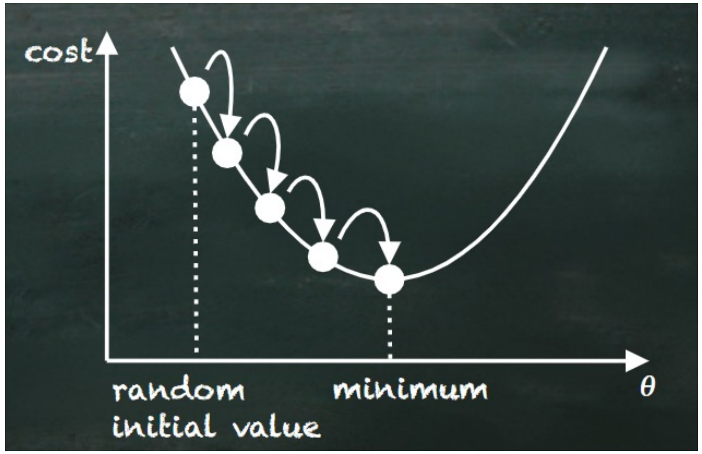


Ayral, Beserve, Lacroix, Ruiz Guzman, EPJA 2023

Main Idea of VQE

- Wave-functions can be better controlled by parametrizing them
- One can reduce the QC effort by computing expectation values of simpler operators $H = \sum \alpha_l H_l$
- The optimization task is left to a classical computer

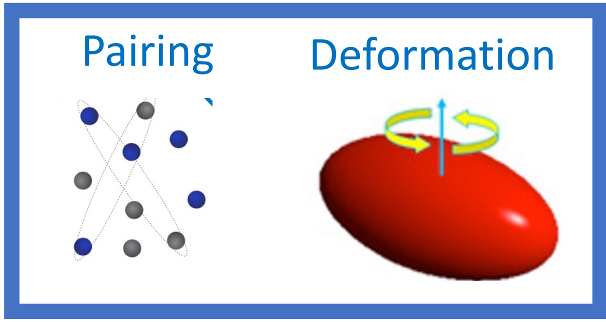




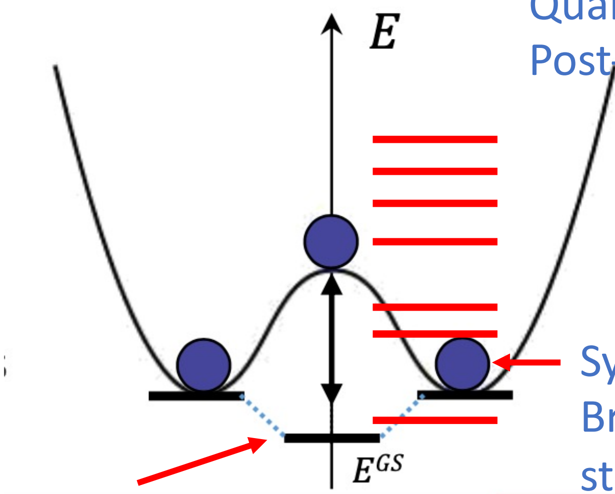
(Frank Zickert | Quantum Machine Learning)

Adapted from S. Endo et al, arxiv:2011.01382
(see also K. Bharti et al., Rev. Mod. Phys. 94, 015004 (2022).

Developing variational approaches based on symmetry-breaking (SB)/symmetry restoration (SR)



D. Lacroix, A. Ruiz Guzman and P. Siwach, Symmetry breaking/symmetry preserving circuits and symmetry restoration on quantum computers EPJA 59 (2023)



3 Further Quantum or hybrid Quantum-Classical Post-processing

1 Symmetry Breaking (SB) state

2 Symmetry Restored (SR) state (multi-reference)

Variational optimization

1 Preparation of SB states on QC

2 Symmetry restoration on QC

3 Post-processing for Improved ground state or excited States (QPE, Quantum Krylov, …)

Which symmetries ?

Many-Body	Quantum computing
Particle Number	Hamming weight
Parity	Odd/Even number of 1
Total Spin	Permutation Invariance

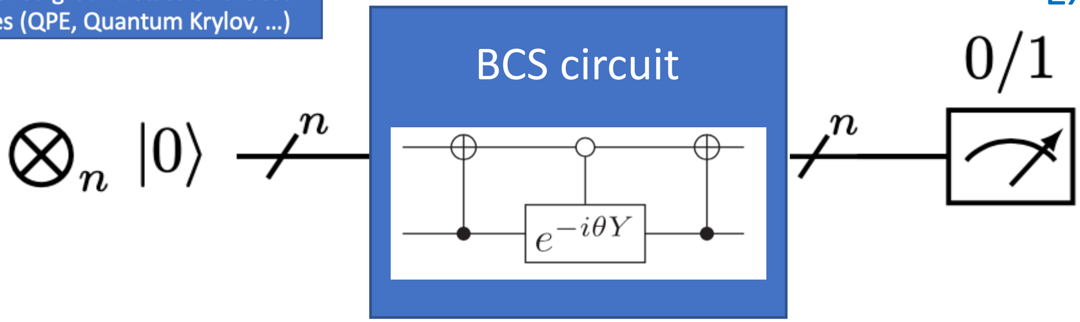
1. Preparation of SB states on QC
2. Symmetry restoration on QC
3. Post-processing for Improved ground state or excited States (QPE, Quantum Krylov, …)

Standard nuclear physics strategy based on symmetries

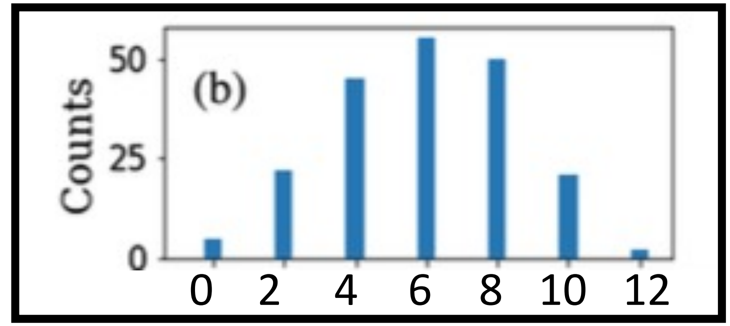
Where we are, where we go

1 Preparing symmetry-breaking state (BCS, …) ✓

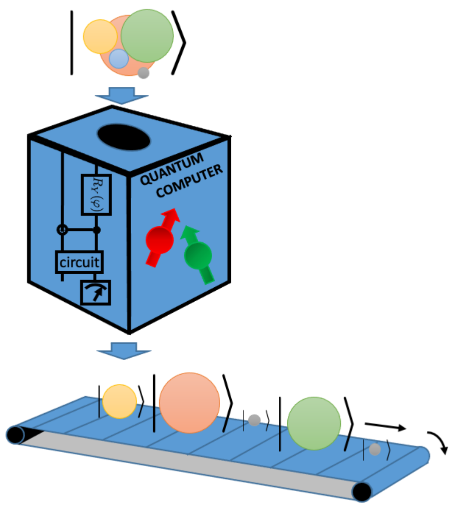
➡ Relatively easy, uses standard toolkit



Example of mixing for 12 qubits (with qiskit)



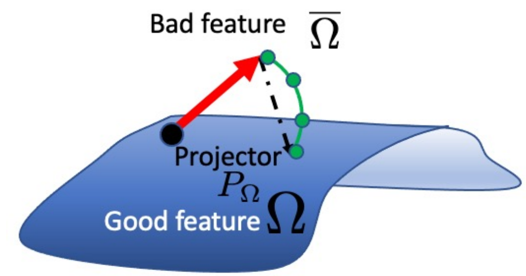
2 Restoring symmetries ✓



Various methods

-With phase-estimation

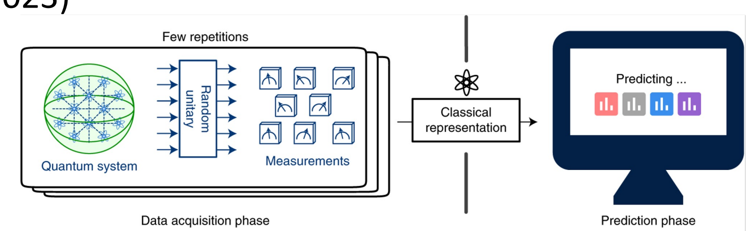
D. Lacroix, PRL 125, 230502 (2020).



-Using quantum Oracles

Ruiz Guzman, Lacroix, PRC 107 (2023)

-Using classical post-processing (shadows)



Ruiz Guzman, Lacroix, Eur. J. Phys. A 60 (2024)

Standard nuclear physics strategy based on symmetries

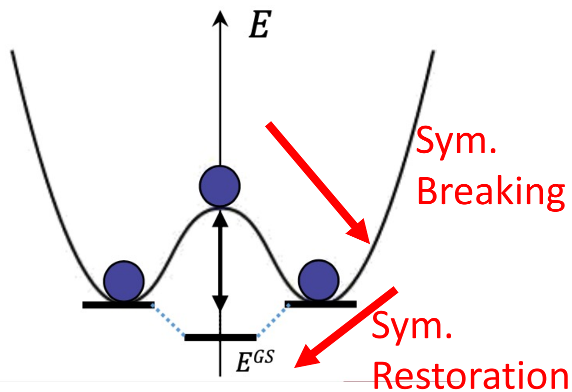
Where we are, where we go

1 Preparation of SB states on QC

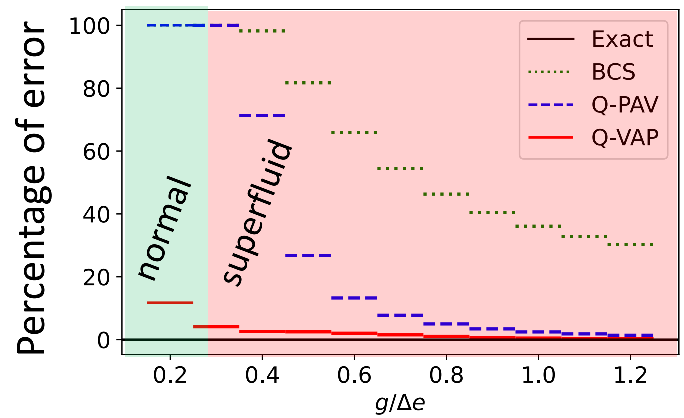
2 Symmetry restoration on QC

3 Post-processing for Improved ground state or excited States (QPE, Quantum Krylov, ...)

3 Using Symmetry-breaking / restoration



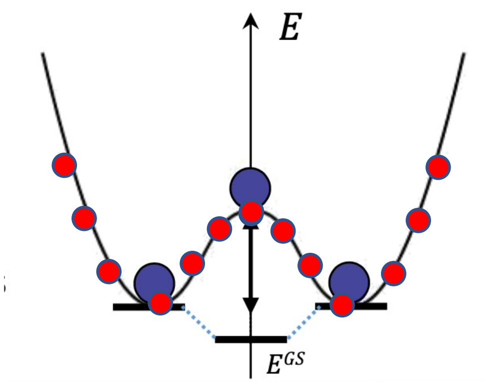
8 particles on 8 equidistant levels



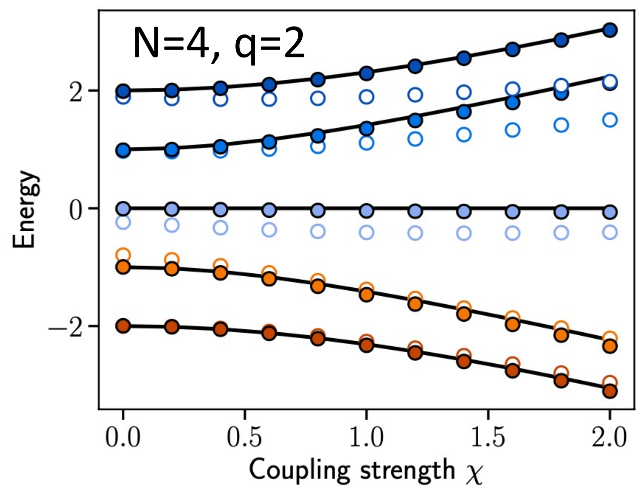
Quantum Generator Coordinate Method

$$|\Psi\rangle = \int_{\mathbf{q}} f(\mathbf{q})|\Phi(\mathbf{q})\rangle d\mathbf{q}$$

$$\int_{\mathbf{q}'} d\mathbf{q}' \left[\mathcal{H}(\mathbf{q},\mathbf{q}') - E\mathcal{N}(\mathbf{q},\mathbf{q}')\right] f(\mathbf{q}') = 0$$



Lipkin model

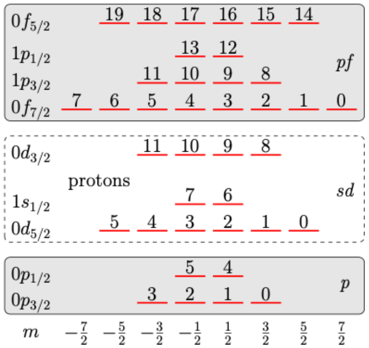


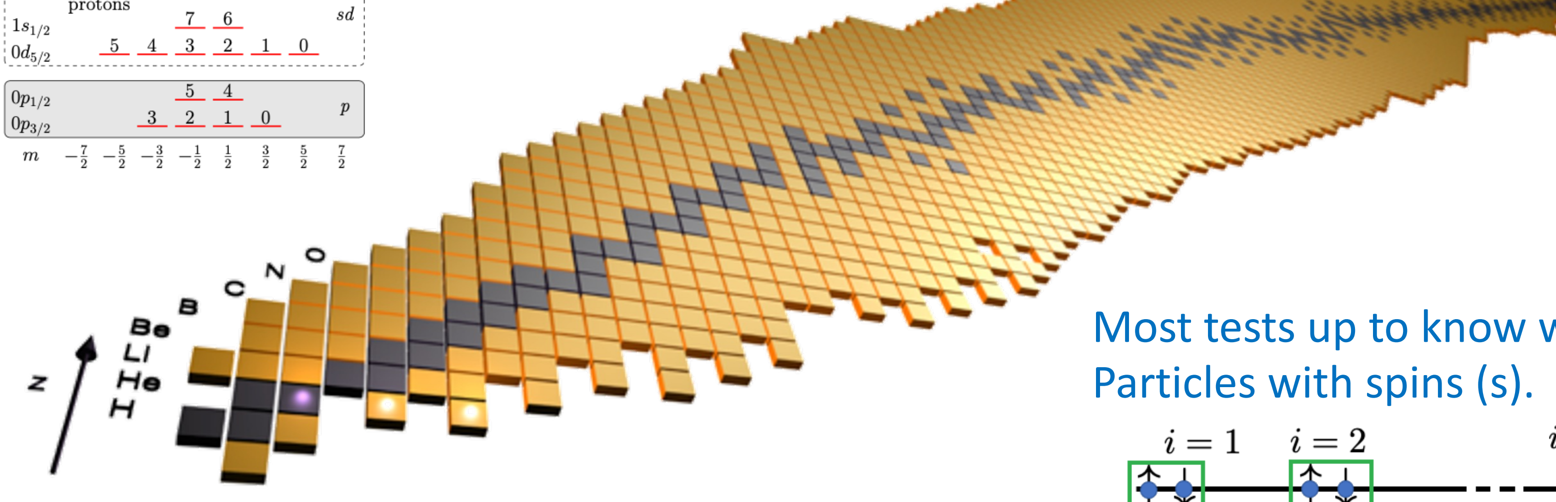
- Q-HFB
- Q-PAV
- Q-VAP
- Q-GCM

Beaujeault-Taudière, Lacroix, PRC 109 (2024)

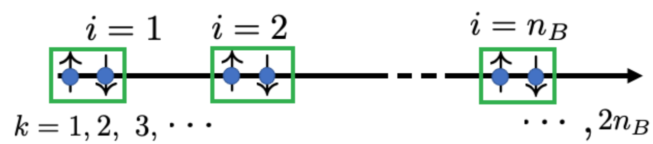
Getting closer to realistic problems

Is the breaking of symmetries always a good idea?

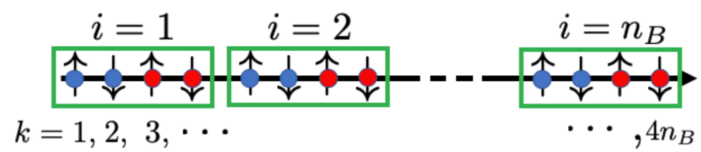




Most tests up to know were made on Particles with spins (s).



But nuclei have both spin (s) and isospin (t) (neutron/proton)



This increases the number of qubits

$$S_z,\ S^2,\ \pi$$

This increases the number of symmetries that could be broken

$$S_z,\ S^2,\ T_z,\ T^2,\ \pi$$

Symmetry-breaking states become extremely hard to control
Symmetry restoration becomes very demanding

J. Zhang, PhD thesis Paris-Saclay Univ. (2025).

Going beyond traditional nuclear physics methods: Use of adaptative methods

Iterative construction of the ansatz

Grimsley, et al, Nat. Commun. 10 (2019)

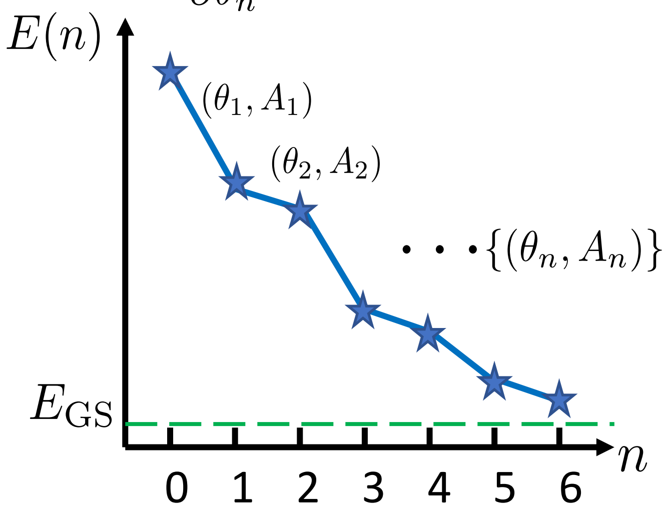
- Start from a state $|\Psi_0\rangle = |n=0\rangle$
- Built iteratively the ansatz such as:

$$|n\rangle = e^{i\theta_n A_n}|n-1\rangle = \prod_{k=1}^{n} e^{i\theta_k A_k}|0\rangle$$

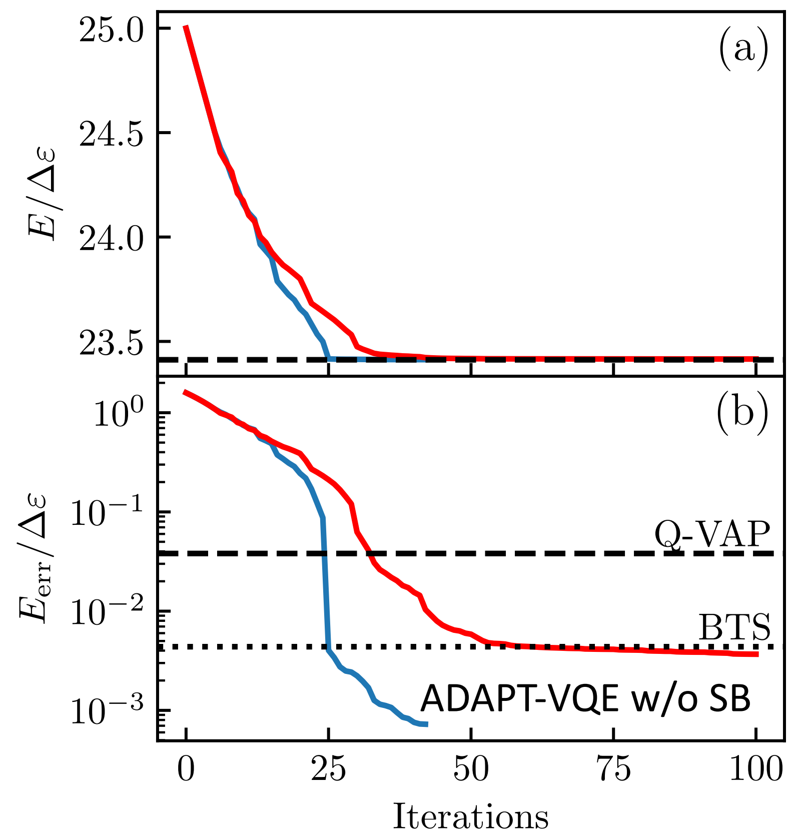
$$A_n \in \{O_1, \cdots, O_\Omega\}$$

Such that

$$\frac{\partial E(n)}{\partial \theta_n} = i\langle n|\,[H, A_n]\,|n\rangle \quad \text{is maximum}$$

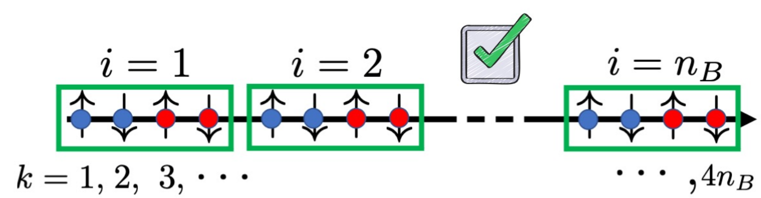


ADAPT-VQE applied to the Superfluid problems: only spins



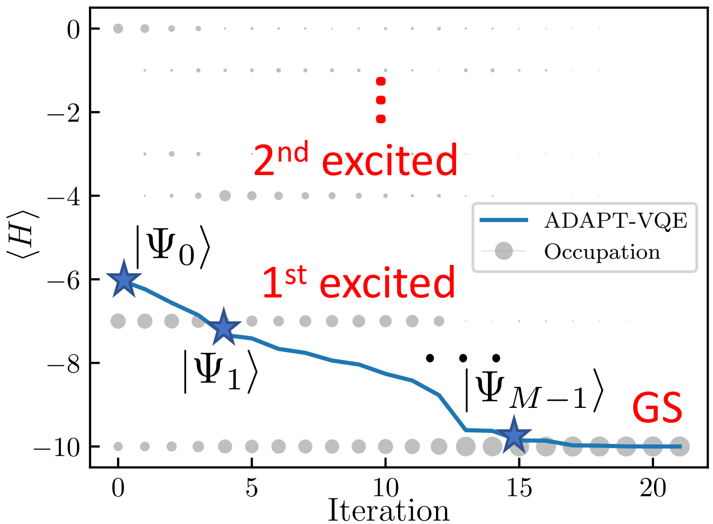
J. Zhang, D. Lacroix, and Y. Beaujeault-Taudière, PRC (2025)

Extension to spin and isospin



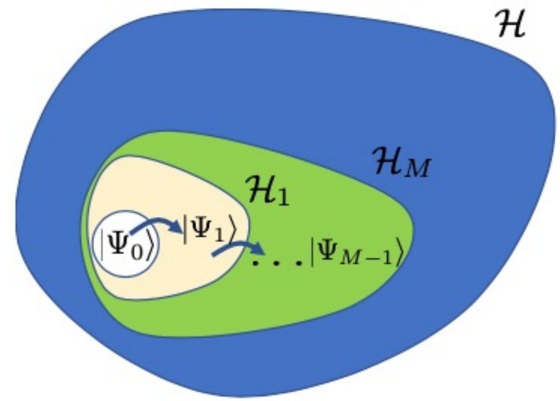
From ground state only to excited states

The states generated during the convergence contain information on excited states



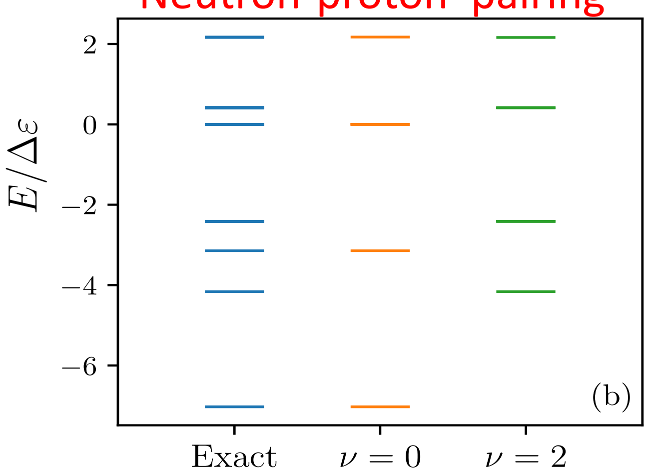
J. Zhang, D. Lacroix, Phys. Lett. B (2025)

We used these states in a Quantum Subspace Diagonalization method (QSD)

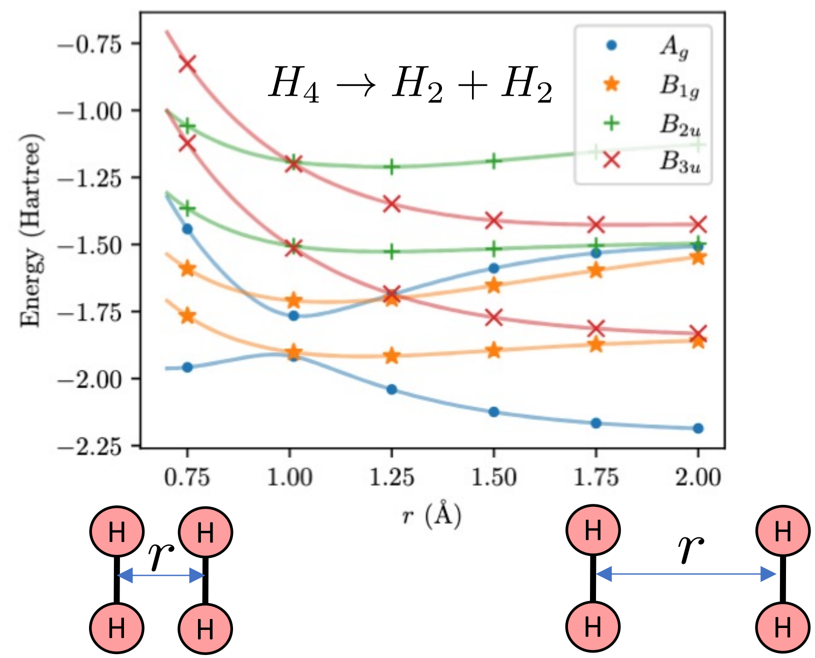


Applications

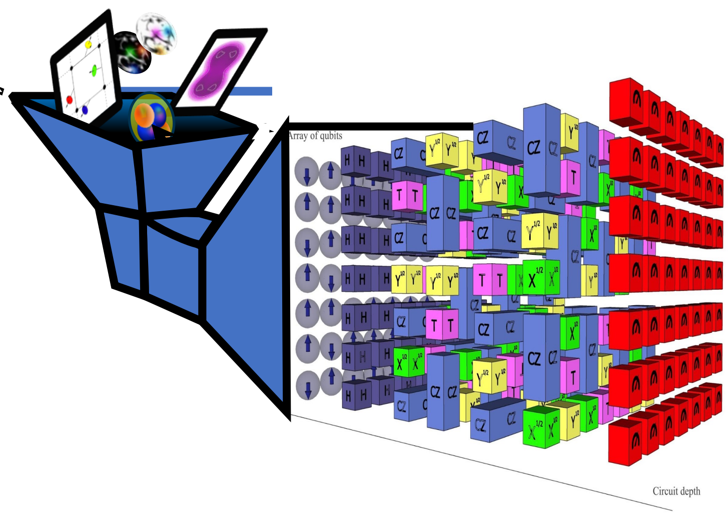
Neutron-proton pairing



molecule dissociation

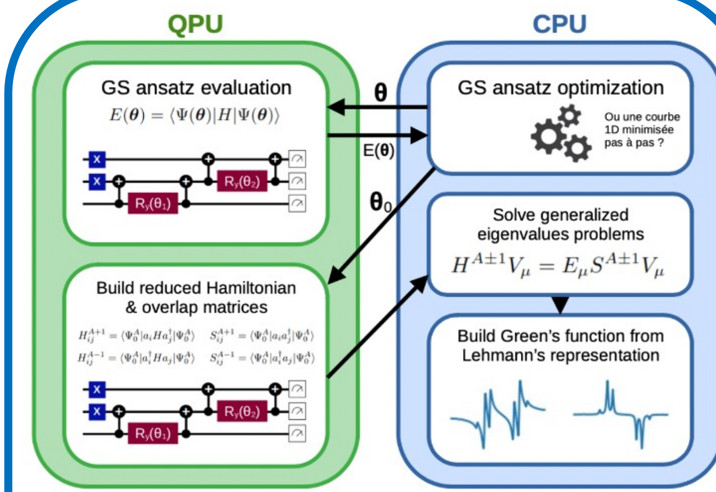


Intermediate summary



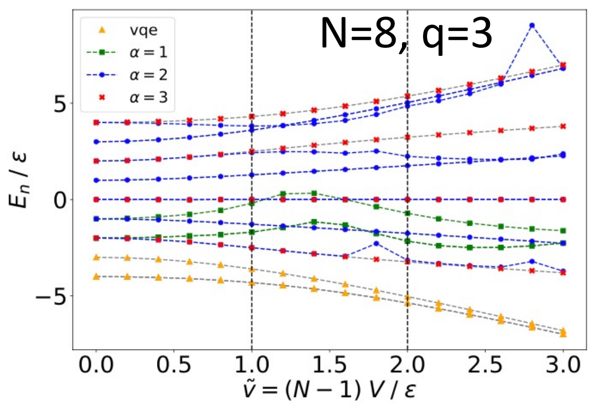
We have progressing on nuclear physics problems (Full CI, Q-HFB, Q-VAP, Q-GCM, Q-EOM, Green's func…)

Green's function



Aychet-Claisse, et al, arxiv:209.022272

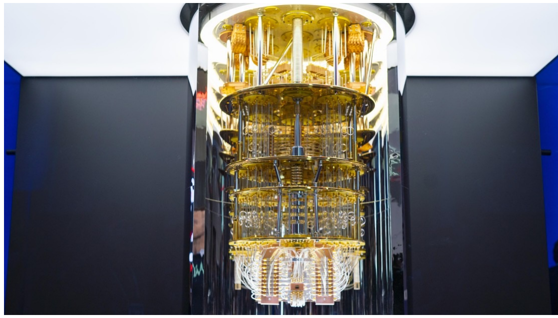
Quantum Eq. of Motion



Hlatshwayo et al, PRC 106 (2022), & PRC 109 (2024)

These works remains rather "academic"

What about real quantum experimental Devices ? Access, types of machines

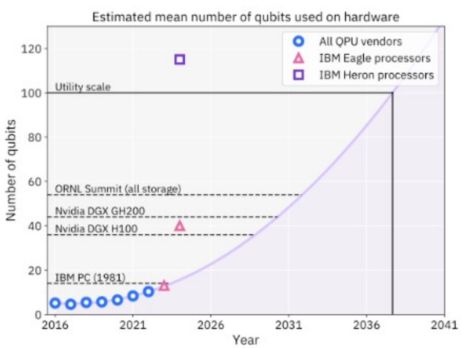


A word on accessing quantum computers today

Today the simplest way to perform "digital" quantum simulation
Is through the IBM quantum cloud

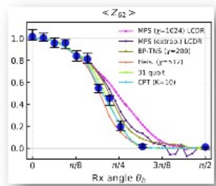
The era of quantum utility (c. 2022)

Quantum simulation beyond classical brute-force.



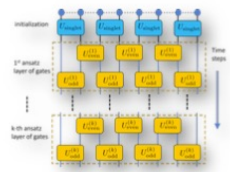
Evidence for the utility of quantum computing before fault tolerance [Nature, 618, 500 (2023)]

127 qubits / 2880 CX gates



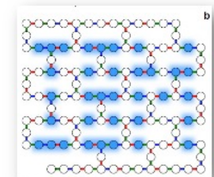
Simulating large-size quantum spin chains on cloud-based superconducting quantum computers [arXiv:2207.09994]

102 qubits / 3186 CX gates



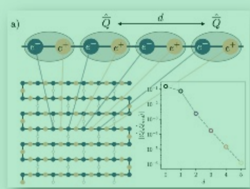
Uncovering local integrability in quantum many-body dynamics [arXiv:2307.07552]

124 qubits / 2641 CX gates



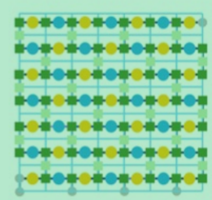
Quantum simulations of hadron dynamics in the Schwinger model using 112 qubits [arXiv:2401.08044]

112 qubits / 13858 CX gates



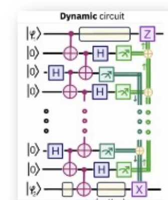
Quantum Simulation of SU(3) Lattice Yang Mills Theory at Leading Order in Large N [arXiv:2402.10265]

127 qubits / 113 CX layers



Efficient long-range entanglement using dynamic circuits [arXiv:2308.13065]

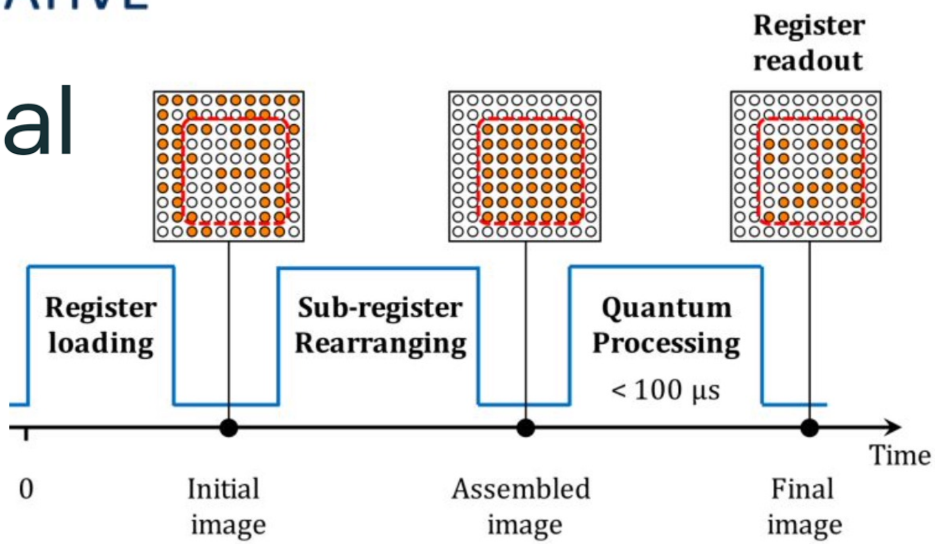
101 qubits / 504 gates + meas.

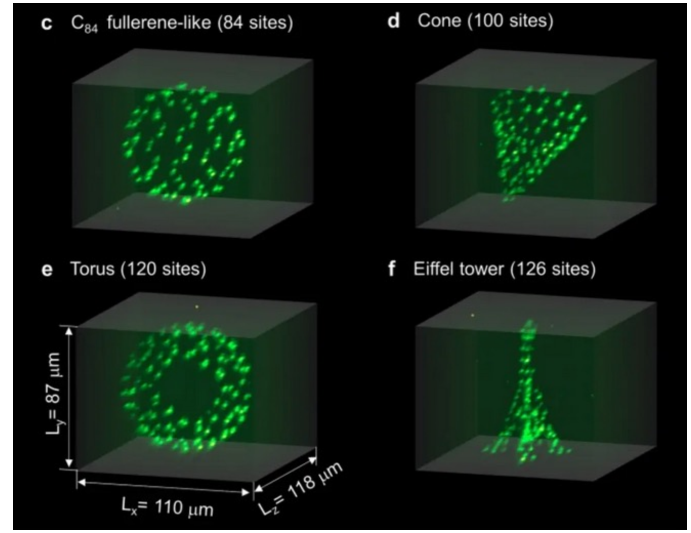


The quantum “French initiative”

FRANCE HYBRID HPCQUANTUM INITIATIVE

Pasqal

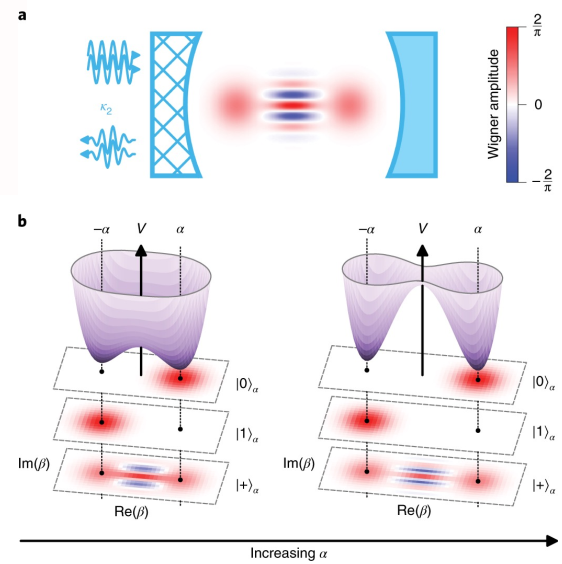




QUANDELA

Photonic machine

ALICE & BOB



By-products of quantum computing
I – Focusing on entanglement

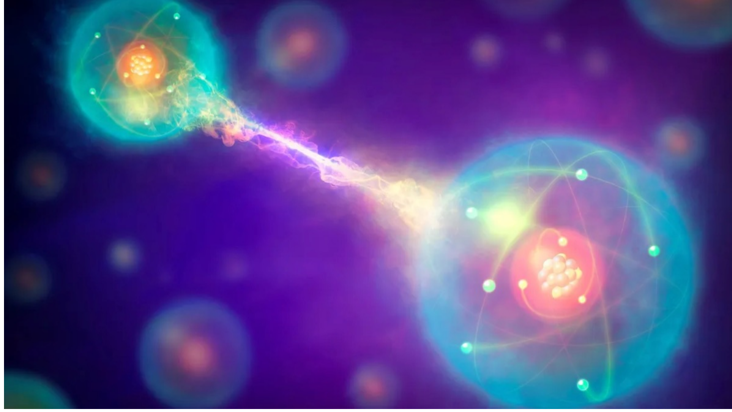
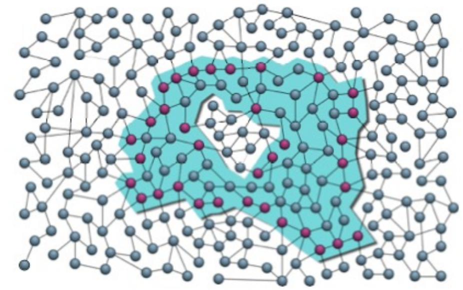


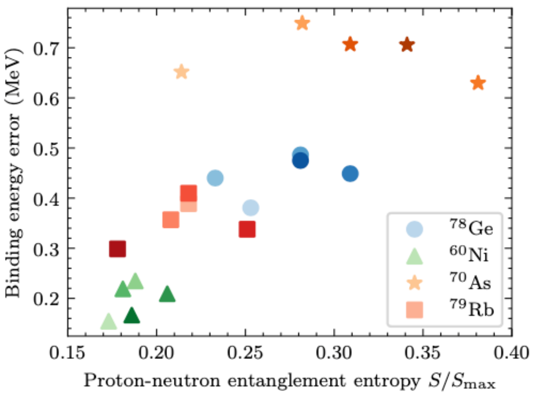
Image credit: MARK GARLICK/SCIENCE PHOTO LIBRARY via Getty Images

Nature of the entanglement in nuclei



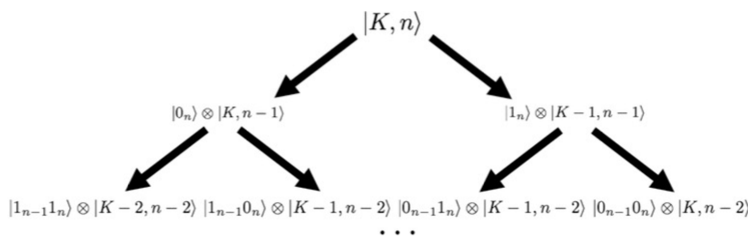
Gu et al, PRC108 (2023)

Weakness of neutron-proton ent.



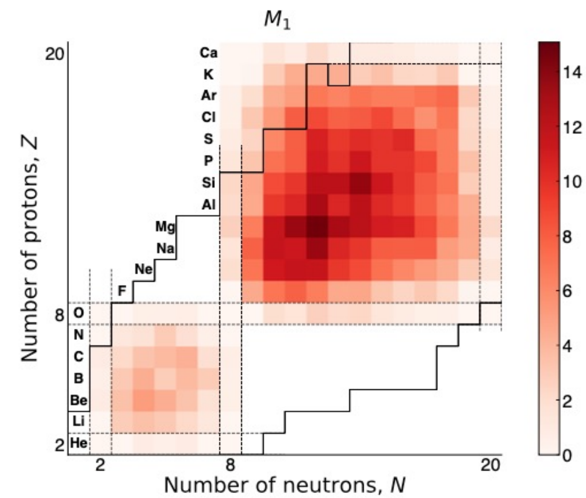
Gorton, Johnson, PRC 110 (2024)

Role of symmetries On entanglement



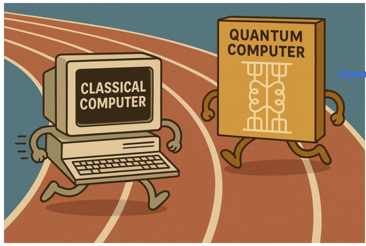
Lacroix, PRC 110 (2024)

Quantum Magic in nuclei



Brökemeier et al, PRC 111 (2025)

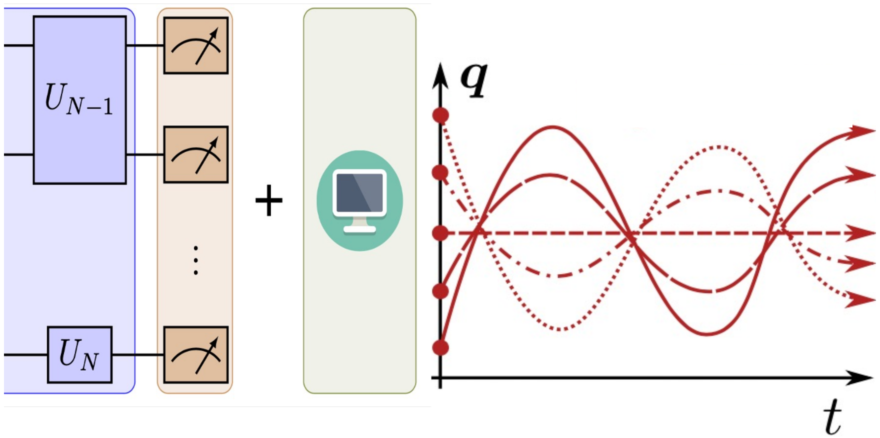
. . .



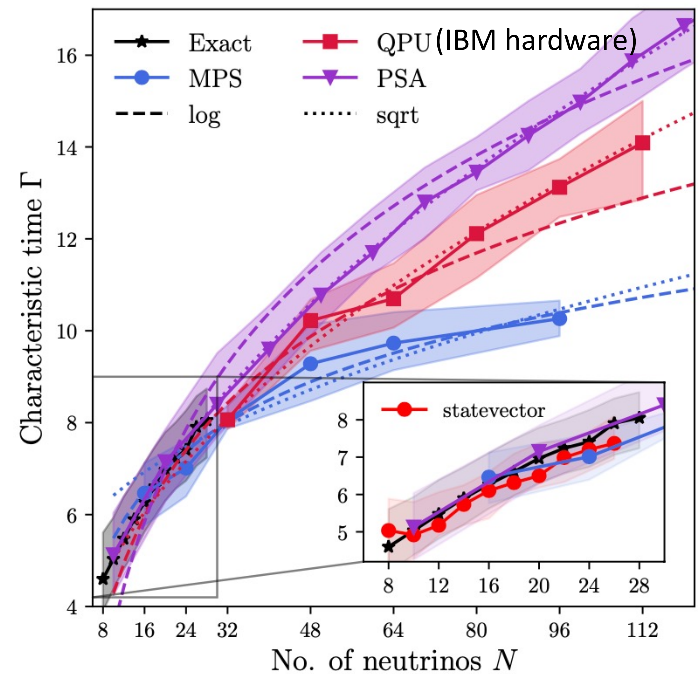
By-products of quantum computing
I – Challenging classical computers

Approximate Phase-space methods

Lacroix et al, Phys Rev. D106 (2022), Phys Rev D110 (2024), arxiv:2507.18482

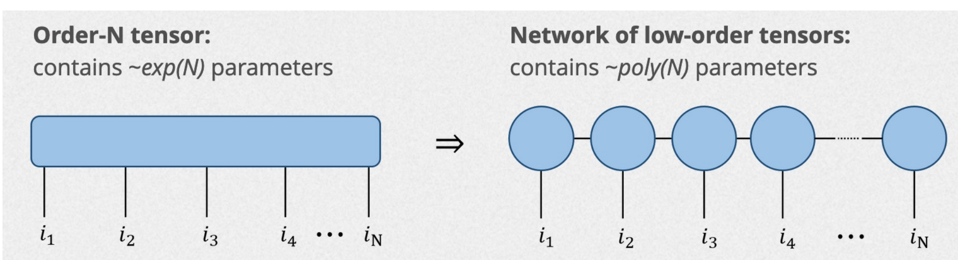


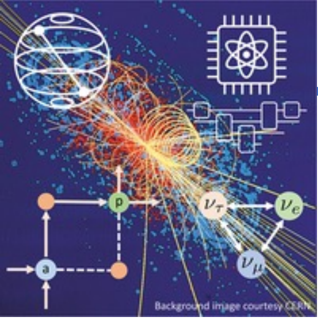
Neutrino thermalization time



Kiss, Tavernelli, Tacchino, Lacroix, Roggero
arxiv:2510.24841

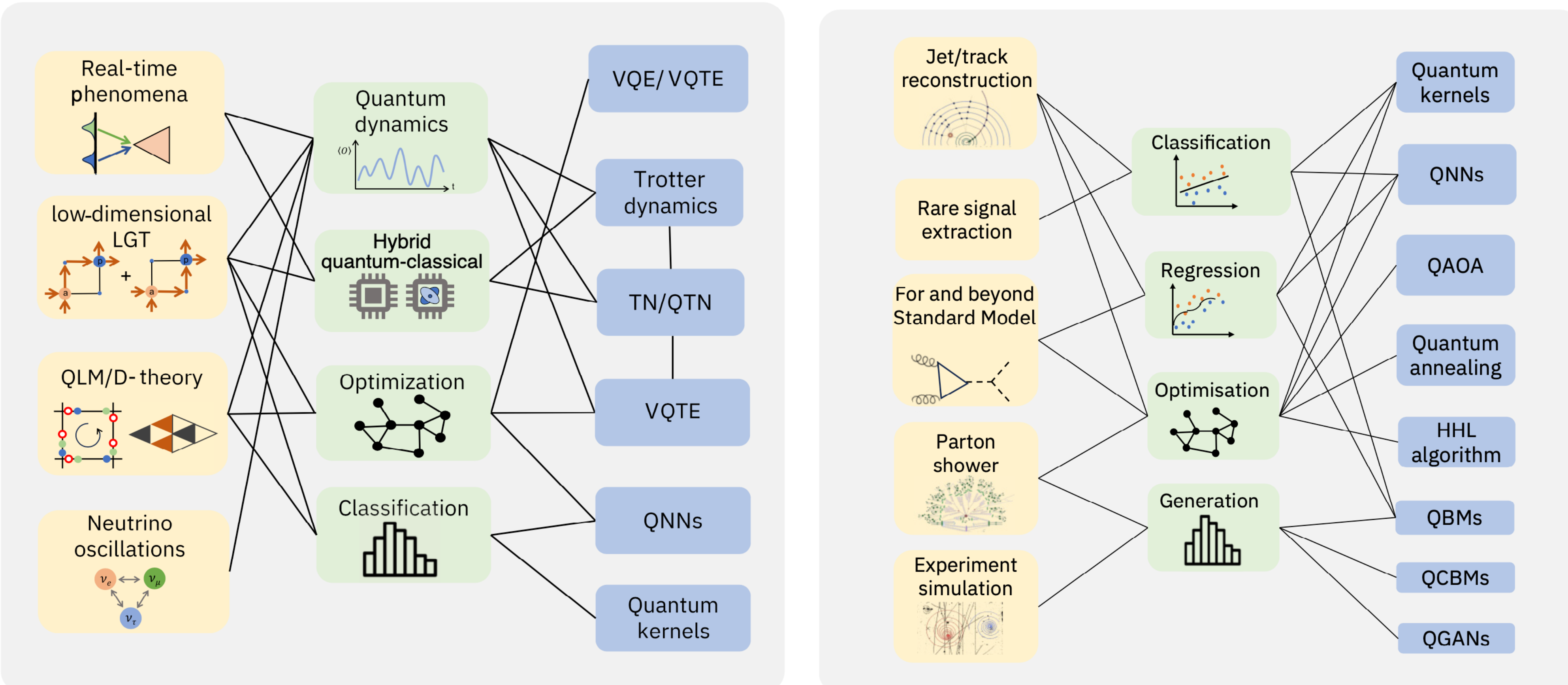
Tensor network (MPS) Matrix Product State





Some other applications

Illustration in High energy physics



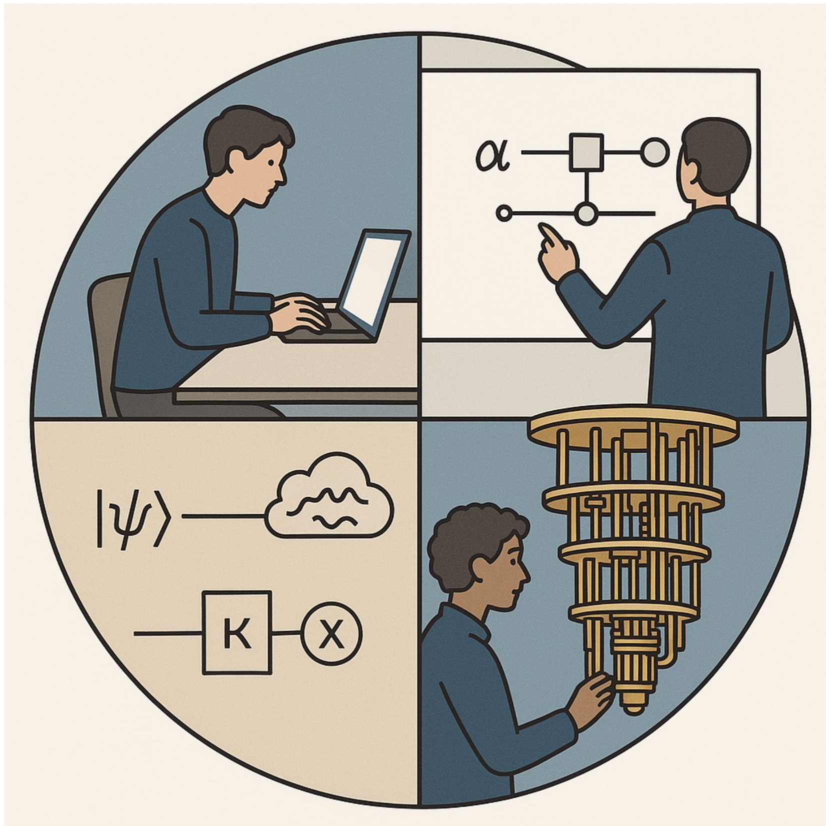
CERN Quantum Initiative – Di Meglio et al., Quantum Computing for High-Energy Physics: State of the Art and Challenges, PRX Quantum 5, 037001 (2024)

High-level summary

The domain is at the Crossroad between physics, math, informatics

...

and experimental aspects
(signal processing, error corrections, real-time data analysis, crosstalk ...)



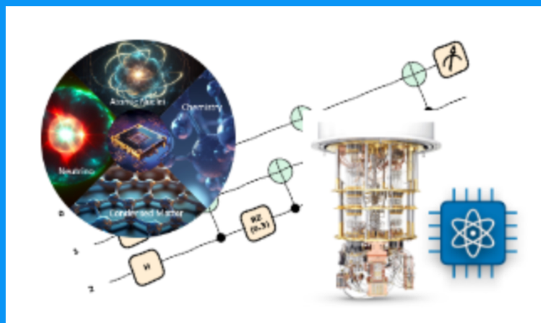
We are gaining expertise in quantum algorithms.

Applications are mainly on pilot applications

We now explore (ab-initio) non-equilibrium phenomena, entanglement properties, ...

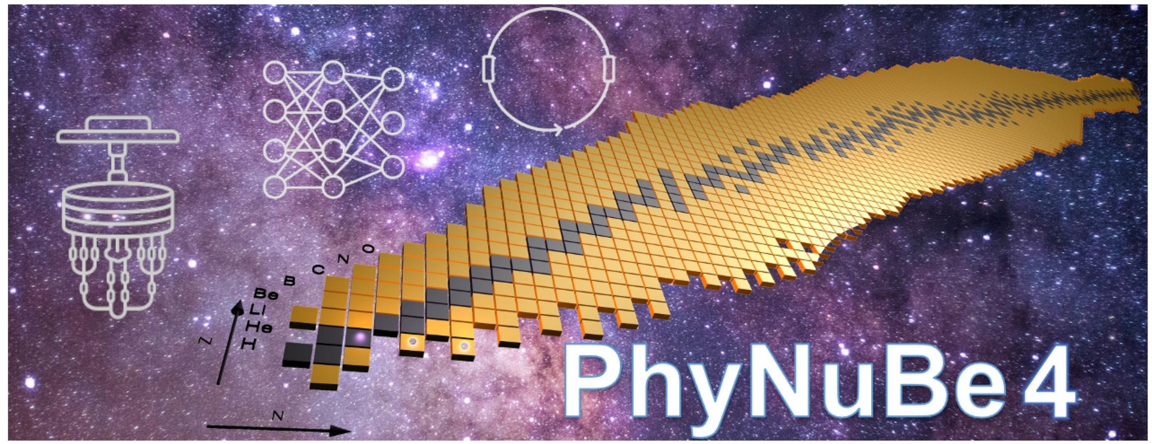
Experimental platforms are improving fast worldwide. Access to them might rapidly be an issue

Easy things have been done, the domain is becoming highly competitive ...



Advanced Quantum Algorithms for Many-body systems (AQAM-2025)

Nov 18 – 21, 2025
Montpellier
Europe/Paris timezone



4th PhyNuBe school : Innovative Technologies, Theories, and Methodologies in Nuclear Physics

17–22 May 2026
Europe/Paris timezone

Enter your search term

- Machine learning and artificial intelligence in experiment and theory
- Bayesian methods to predict physics phenomena from observations and theories
- Quantum computing
- Quantum sensors
- Storage rings for spectroscopy and reactions
- Study of open nuclear quantum systems and synergy with other quantum objects

Thanks to my Collaborators

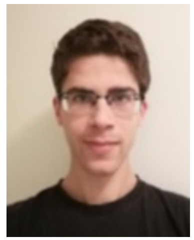
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis — université PARIS-SACLAY — cnrs

E. A. Ruiz Guzman

Now at

IBM Quantum

J. Zhang



S. Aychet Claisse

Y. Beaujeault-Taudiere

WESTERN MICHIGAN UNIVERSITY

M. O. Hlatshwayo

Now at

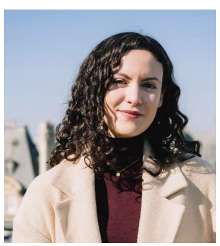
UKRI National Quantum Computing Centre

A | Physics

P. Siwach

EVIDEN an atos business

T. Ayral



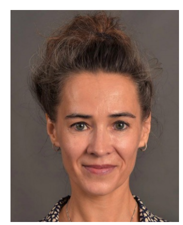
P. Besserve

Now at Edimbourg

LPSC Grenoble Laboratoire de Physique Subatomique et de Cosmologie

M. Mangin Brinet

WESTERN MICHIGAN UNIVERSITY



E. Litivinova

UNIVERSITÀ DI TRENTO

A. Roggero

cea

Vittorio Somà

Thank you!