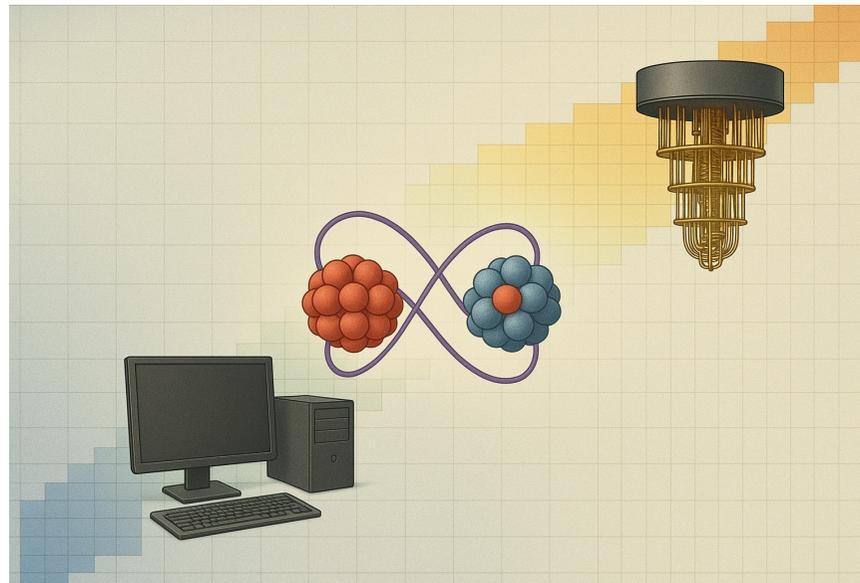


Quantum computing applied to nuclear and neutrino physics

Denis Lacroix



Many-body physics and QC - T. Ayril, 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 ?

Quantum technologies/devices

Simulating physics with computers-1982

Richard P. Feynman (Nobel Prize in Physics 1965)

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."



Quantum Theory



1927

Quantum Computer



1982

7 qubits
Los Alamos



2000

12 qubits
MIT



2006

128 qubits
DWave



2011

17 qubits
IBM



2015

50 qubits
IBM



2017

72 qubits
Google



2018

1152 qubits
DWave



2013

2048 qubits
DWave



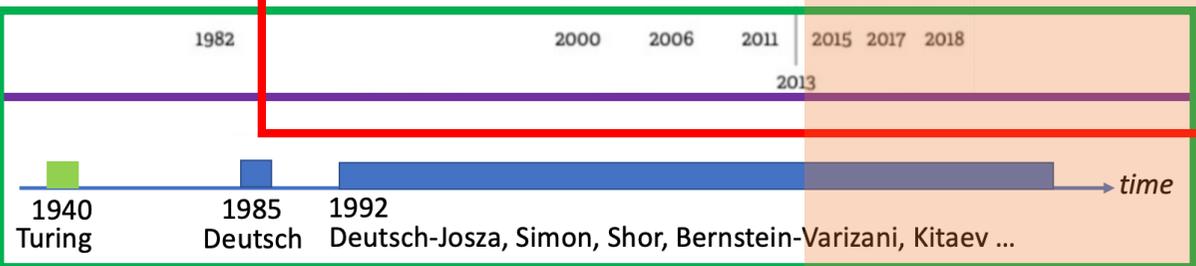
2013

128 qubits
Rigetti



2019

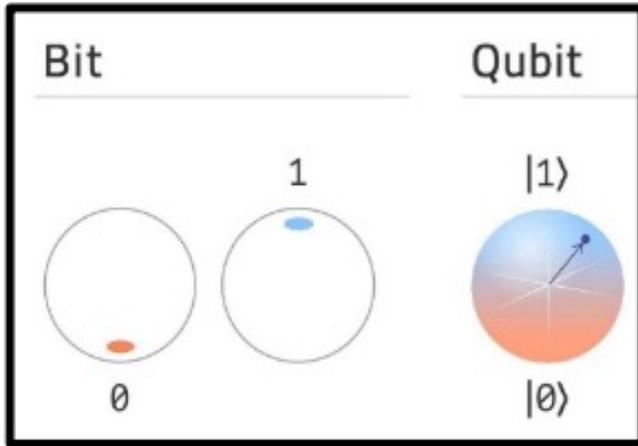
General Quantum mechanics



General Quantum algorithmic

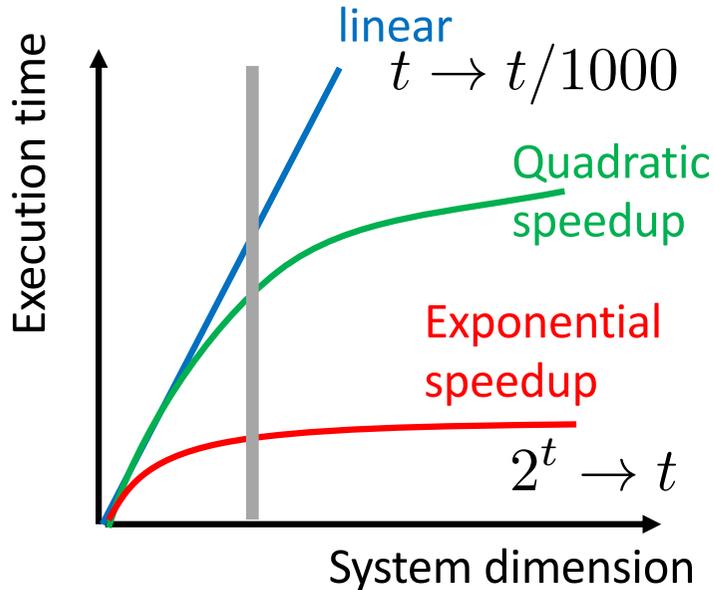
Quantum computing is democratizing

What are the promises of quantum computing?



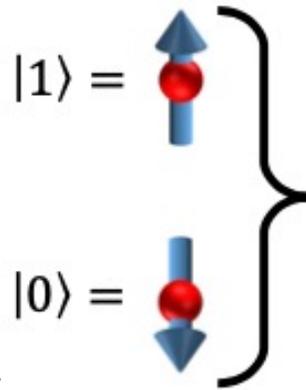
we are interested in accelerating to perform a calculation

Speedup can be:



A calculation that takes 1 year in a “linear” takes 24 seconds with exp. speedups!

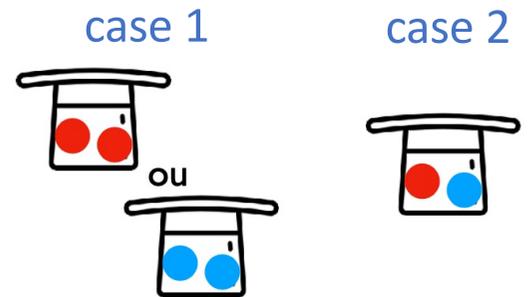
Quantum Algorithm advantage



A fundamental question is how much “computational time” it takes to solve a problem – this is linked to the complexity of the problem (Church-Turing thesis, Problem complexity classification, ...)

Quantum computers can lead to exponential speedup

The key is entanglement



How ?

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|\bullet\bullet\rangle + |\bullet\bullet\rangle)$$

A second important aspect: storing and manipulating data

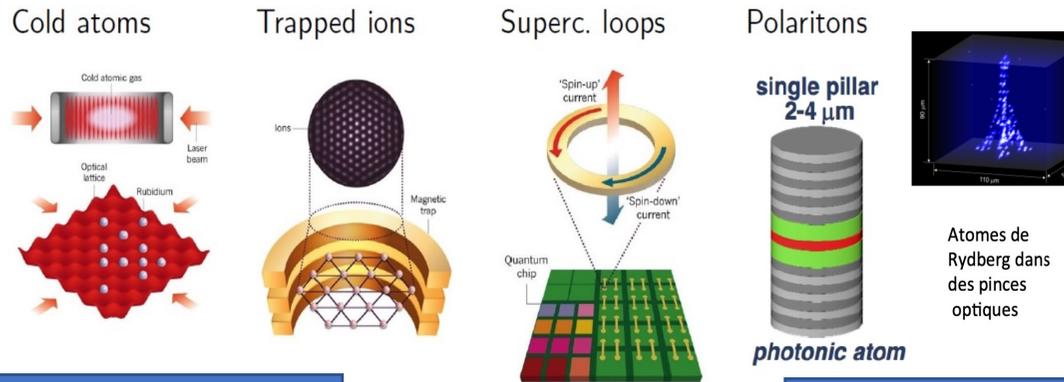
Matrix size scales as 2^n $n=100$ qubits \Rightarrow Size = 10^{30}



What means quantum devices today

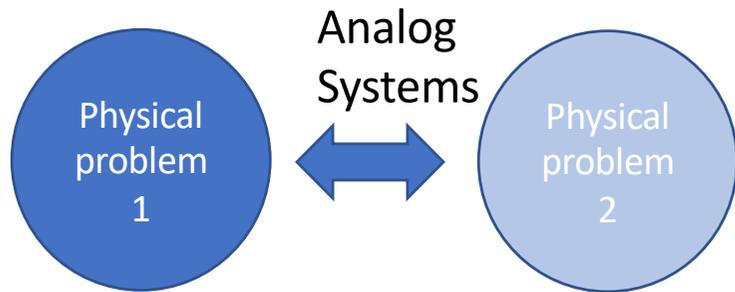
There are many types of quantum computers: ***analog versus digital quantum computers***

There are now many quantum objects one can manipulate



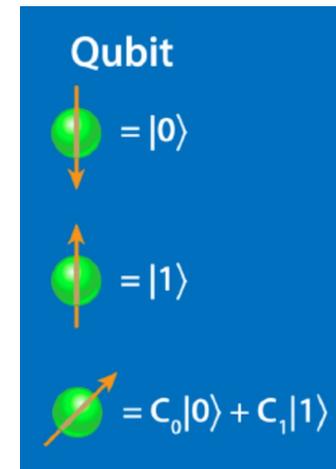
Analog quantum simulator

Digital 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

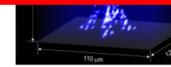
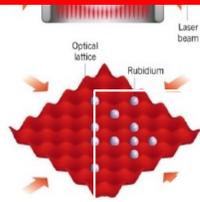
➔ Universal Quantum simulation



What means quantum devices today

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

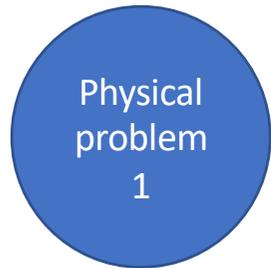
Quantum machines are often themselves many-body systems



Atomes de Rydberg dans des pinces optiques

Analog quantum simulation

Digital quantum simulator

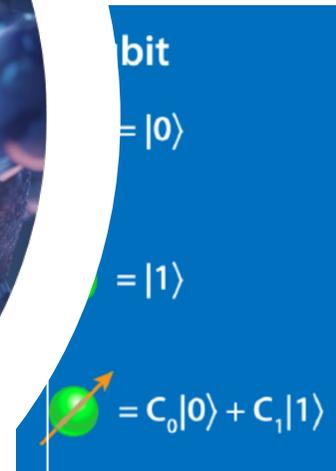
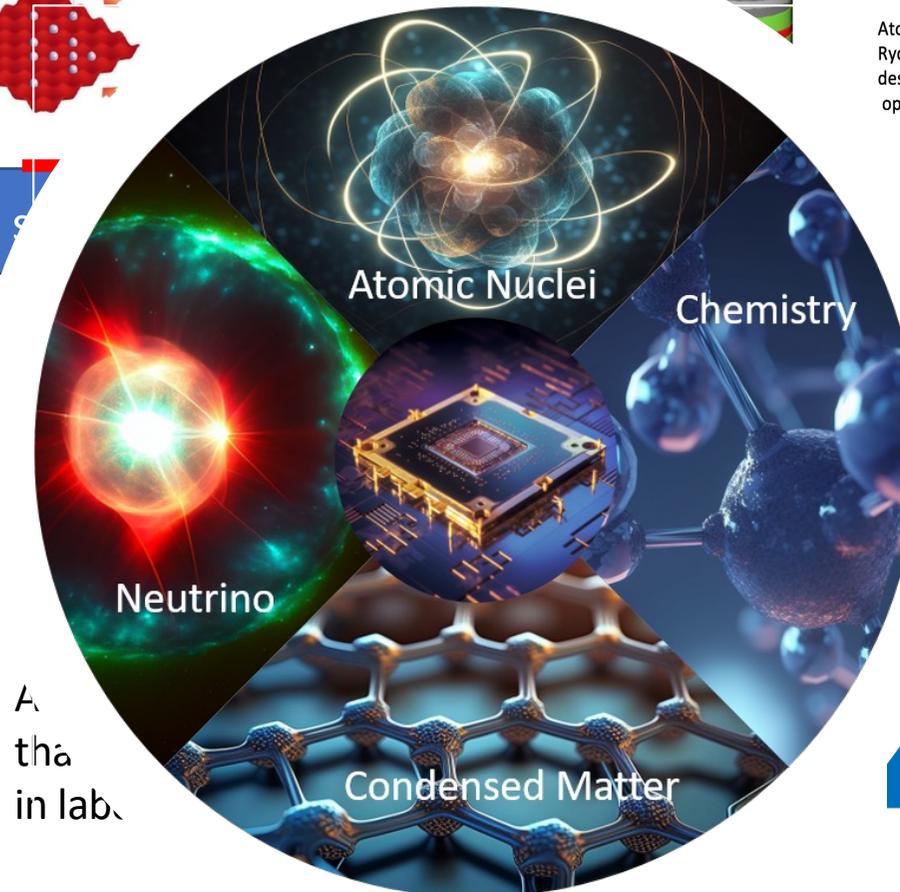


Analog System



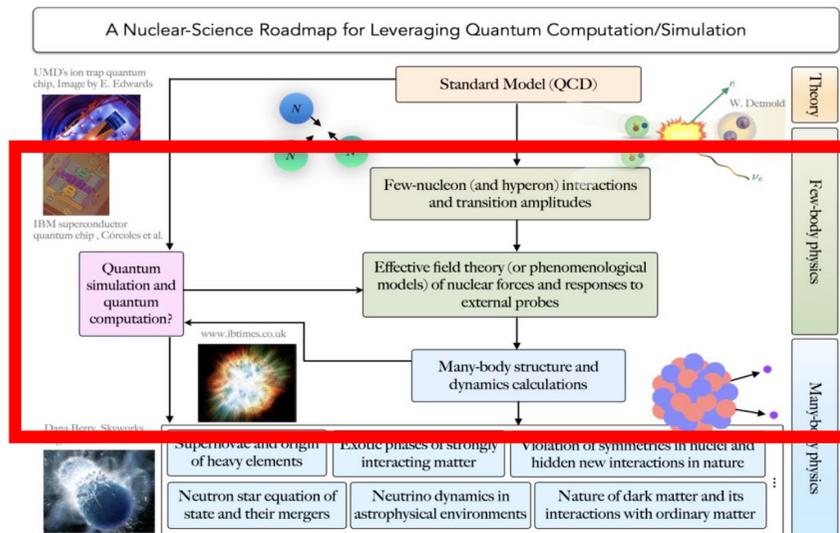
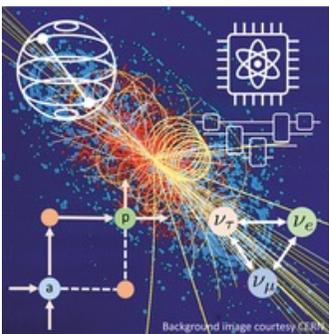
Complex problem that cannot or hardly be simulated on classical computers

➔ Non-universal



➔ Universal Quantum simulation

Target applications relevant for the IN2P3



Nuclear Physics

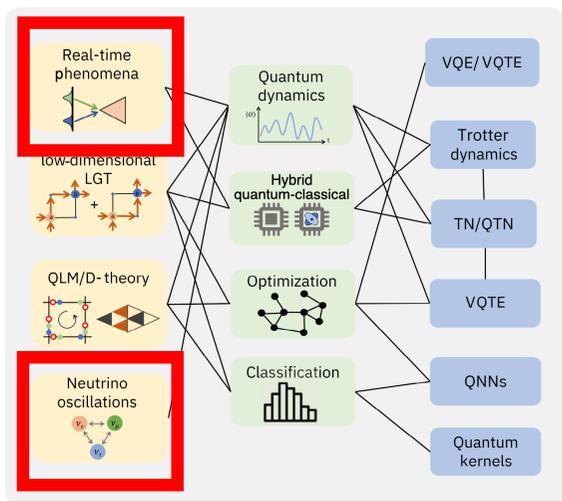
High energy physics

Quantum Information Science and Technology for Nuclear Physics
Beck et al, US Long Range Plane, [arXiv:2303.00113](https://arxiv.org/abs/2303.00113)

Physical phenomena description

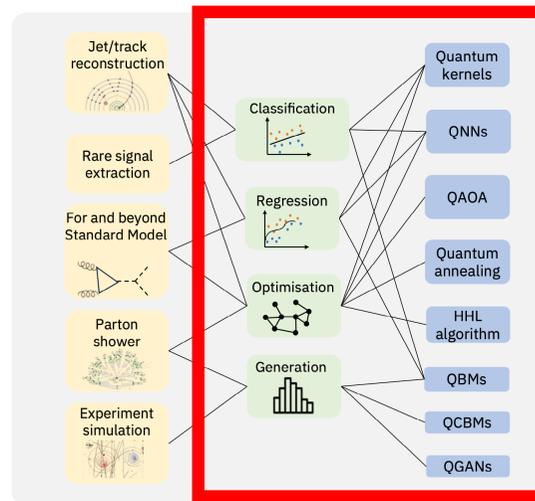
General Quantum Effects

Neutrino oscillations



Quantum Machine learning

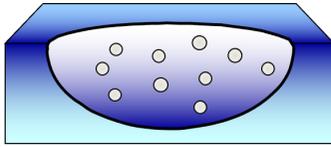
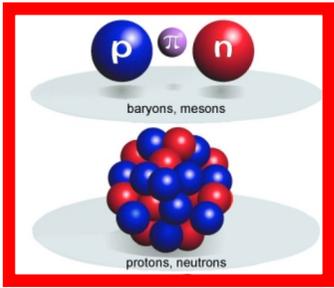
Quantum Machine Learning



Quantum computing for the description

of static and dynamical properties of atomic nuclei

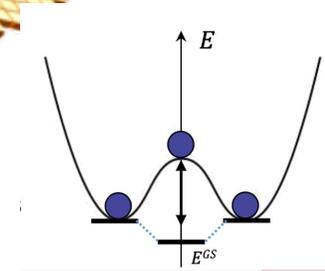
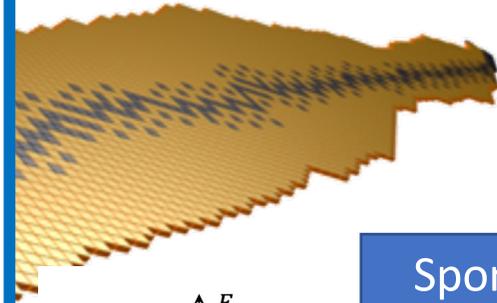
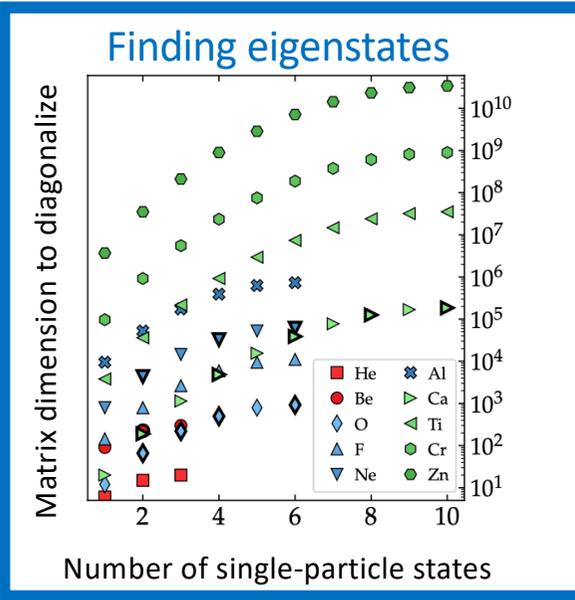
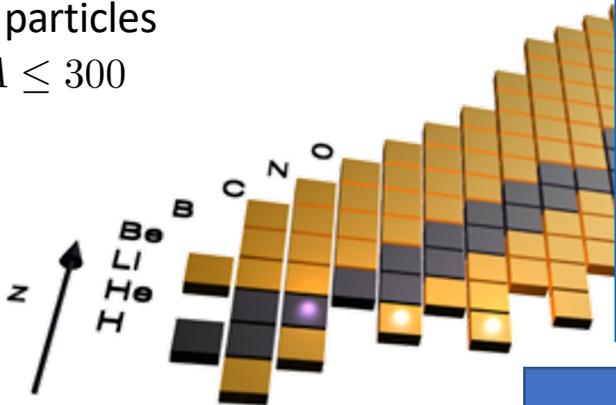
Problematic and challenges



Nuclei are self-bound quantum mesoscopic systems

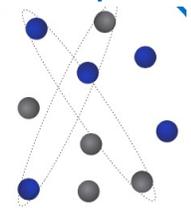
Nb of particles

$$2 \leq A \leq 300$$



Spontaneous Broken symmetries (SB)

Small superfluid

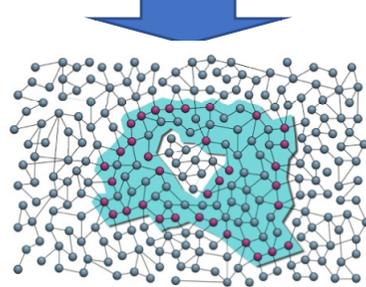


(particle number SB)

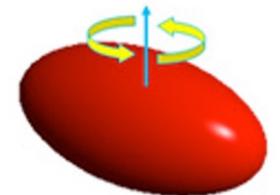
Symmetries / Entanglement

Global symmetries induce All-to-all entanglement

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

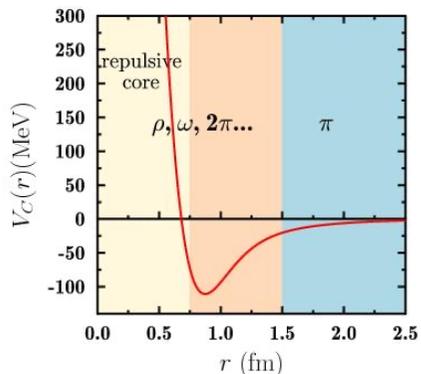


Deformation can happen



(rotational invariance SB)

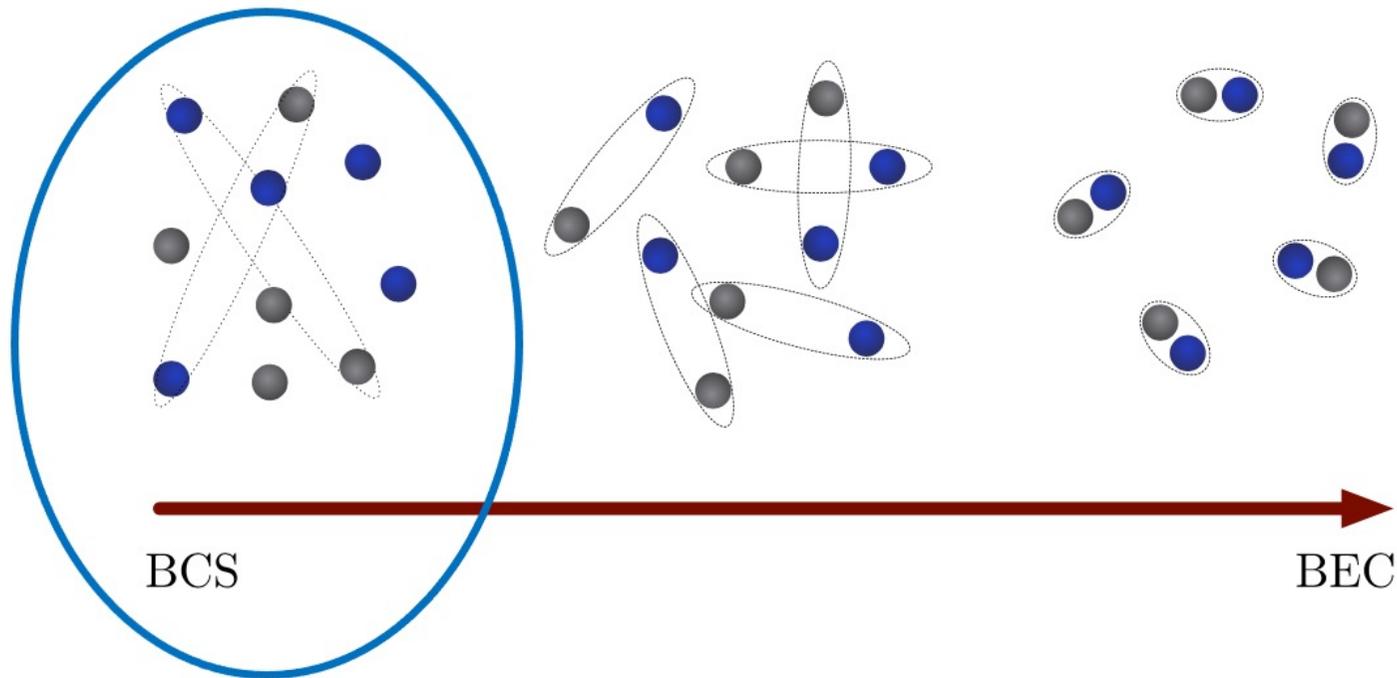
Interaction



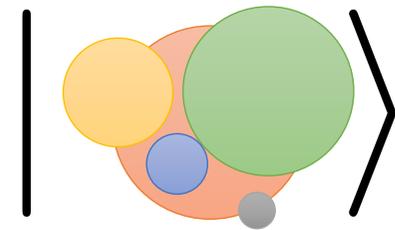
The problem is highly non-perturbative

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

Illustration with small superconductors



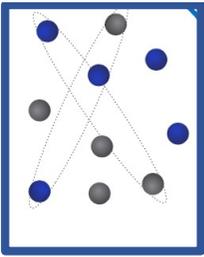
This problem is an archetype of spontaneous symmetry breaking. An “easy” way to describe it is to break the particle number symmetry, i.e. consider a wave function that mixes different particle numbers



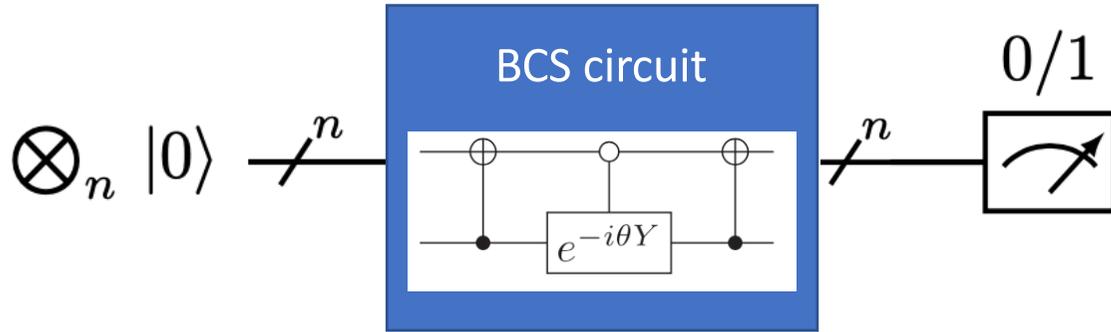
But ultimately number of Particle should be restored !

Quantum computing for atomic nuclei

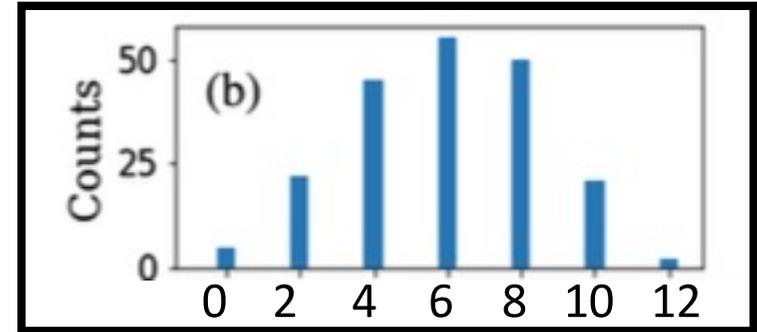
Illustration for small superfluids



Superfluidity can be described by breaking particle number



Example of mixing for 12 qubits (with qiskit)



Projection on particle number

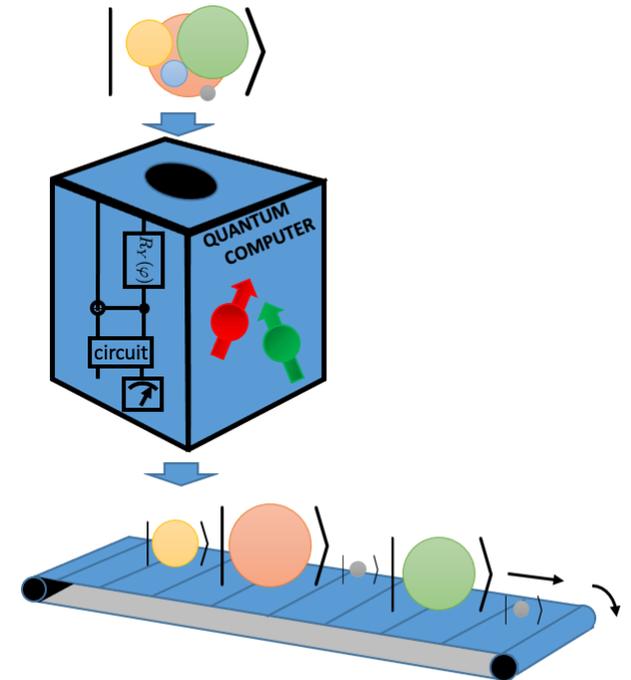
$$|\Psi\rangle = \sum_N c_N |N\rangle \rightarrow |N\rangle$$

For 2 qubits

$$|\Psi\rangle = \alpha |00\rangle + \beta |01\rangle + \gamma |10\rangle + \delta |11\rangle$$

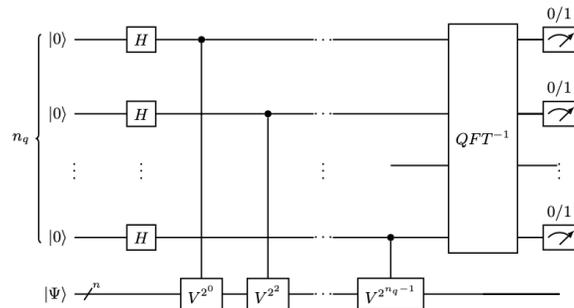
$|N=0\rangle$
 $\propto |N=1\rangle$
 $|N=2\rangle$

➔ A possible way to perform the projection is to use The Quantum-Phase-Estimation method with N itself

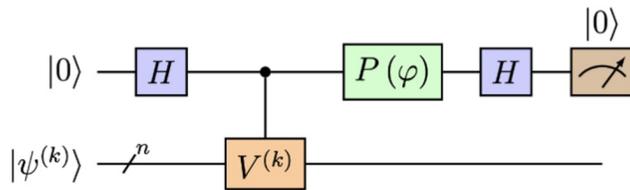


Systematic of Symmetry filtering methods

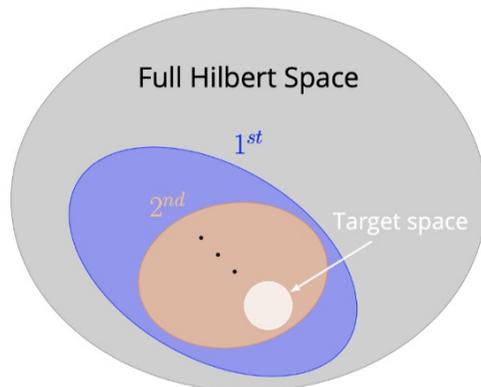
Standard Quantum Phase estimation



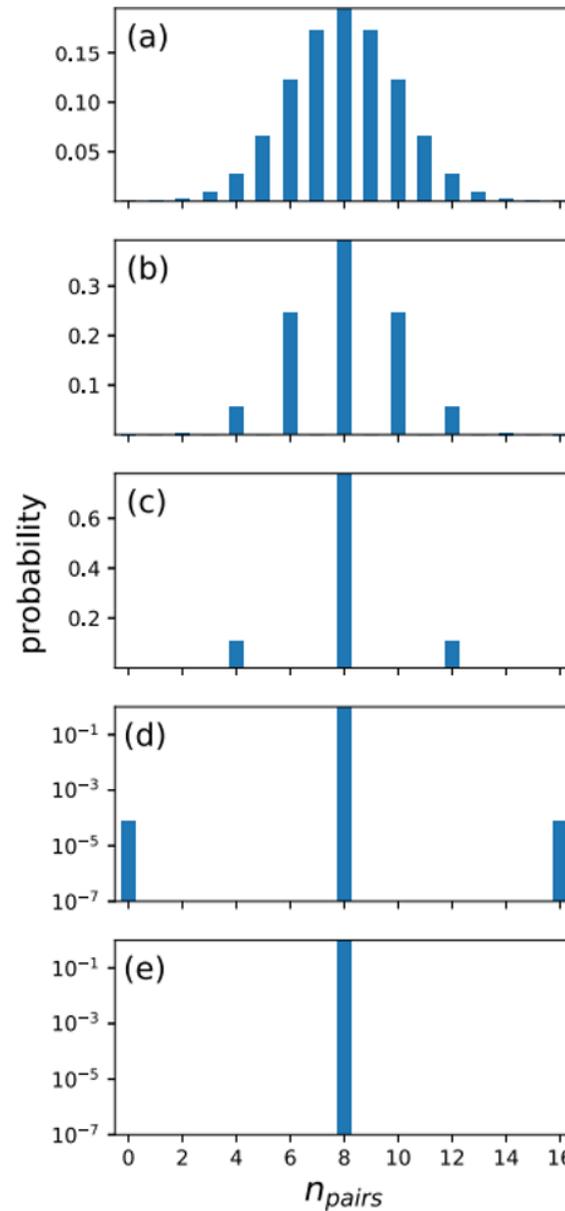
Iterative Quantum Phase estimation



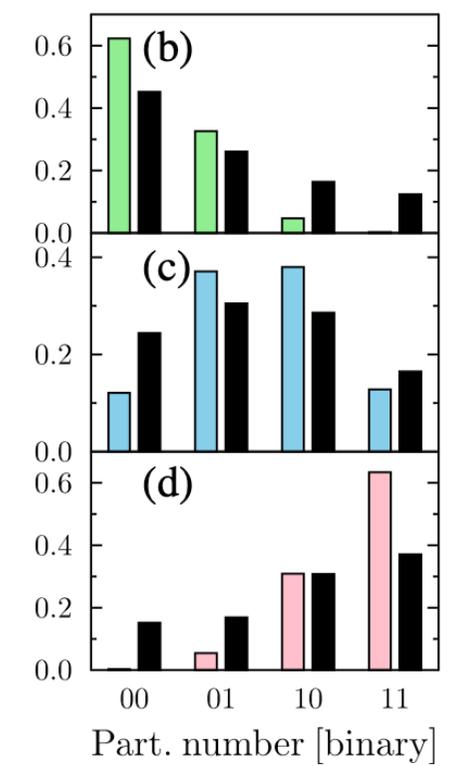
$$\hat{V}(k) = e^{i\phi_k \hat{N}} \quad ; \quad \phi_k = \frac{\pi}{2^k}$$



16 qubits, N = 8

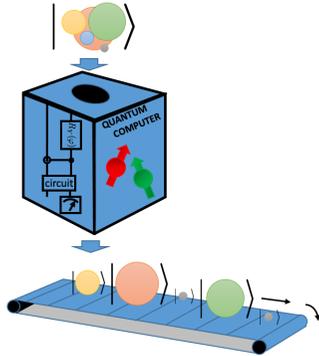


Test on real devices



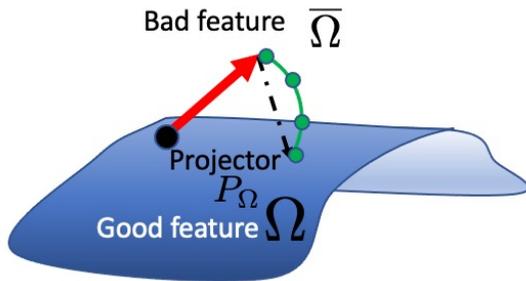
Ongoing developments in nuclear physics

Symmetry problems

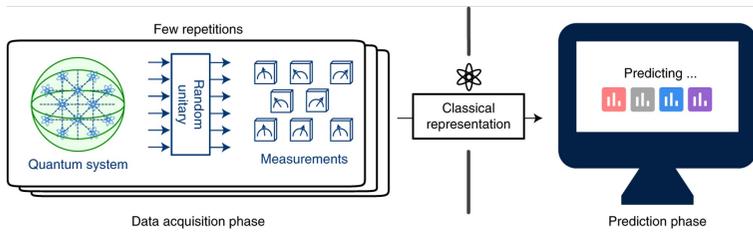


- Using quantum Oracles

Ruiz Guzman, Lacroix, PRC 107 (2023)



- Using classical post-processing (shadows)

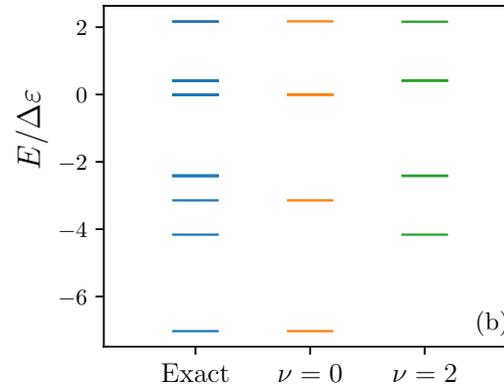


Ruiz Guzman, Lacroix, Eur. J. Phys. A 60 (2024)

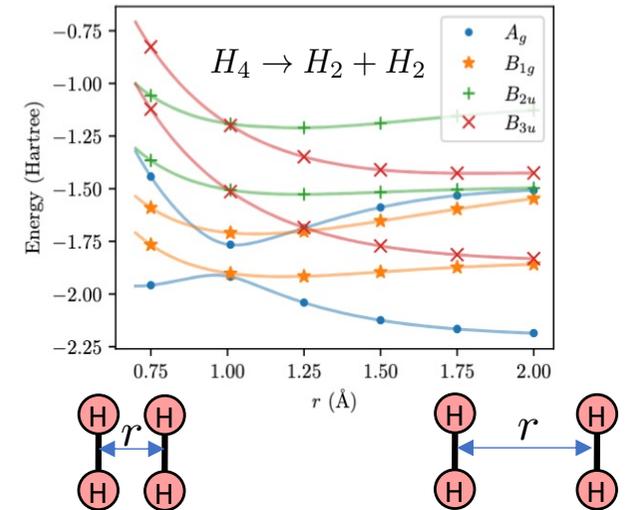
Spectroscopy (static properties)

Zhang, Lacroix, Phys. Lett. B869 (2025)

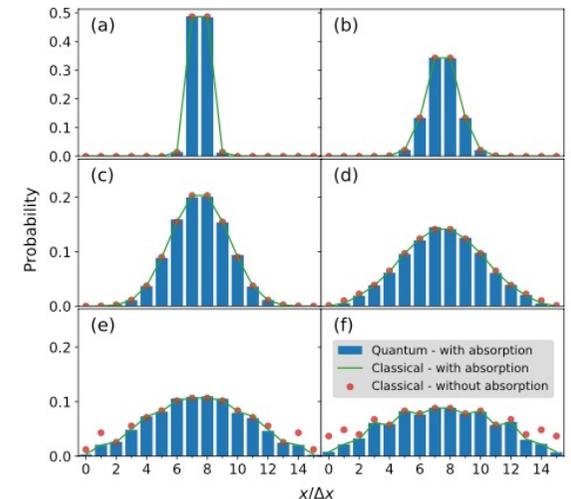
Neutron-proton pairing



molecule dissociation



1D free wave-evolution

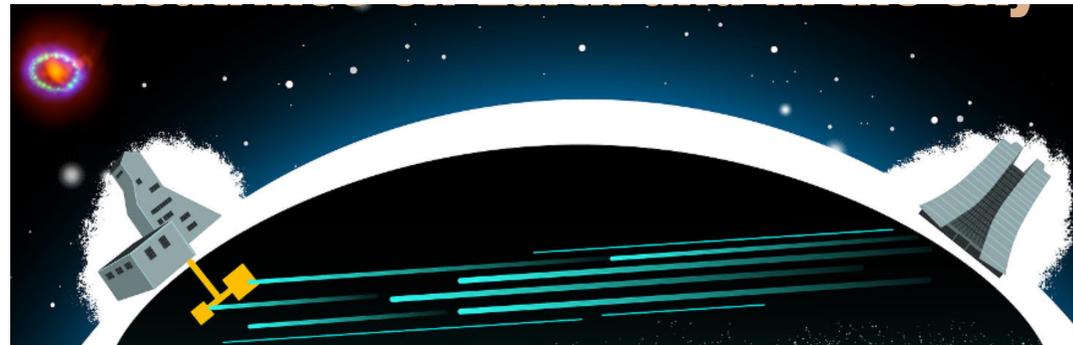
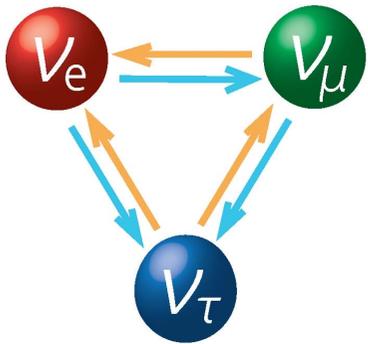


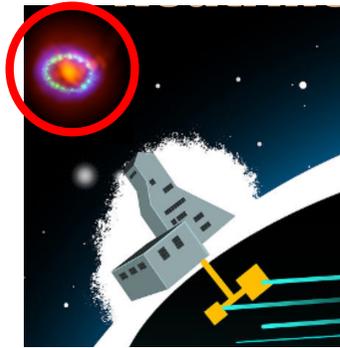
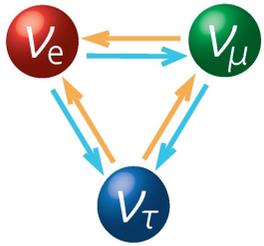
Non-equilibrium

Mangin Brinet et al, Quantum (2024)

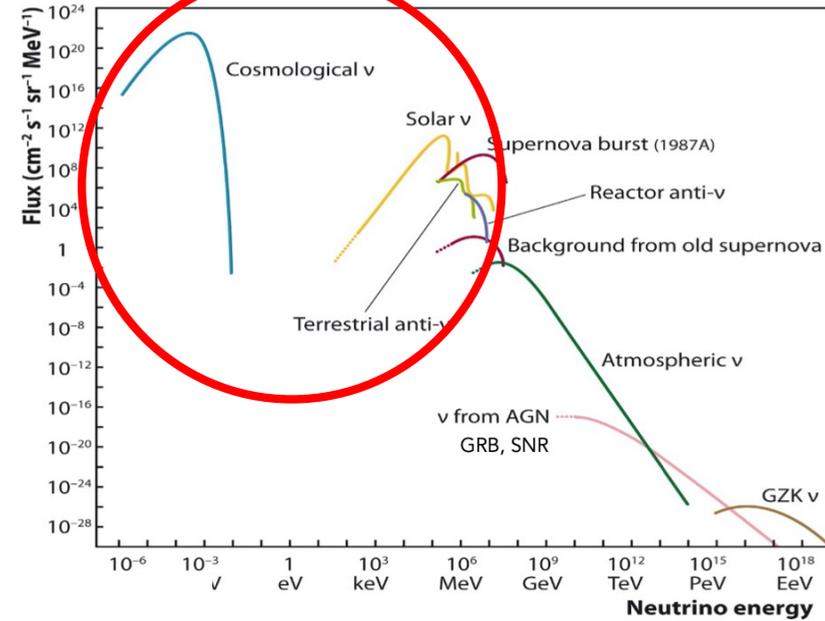
Other today's applications

Oscillations of neutrinos emitted
from Stellar objects

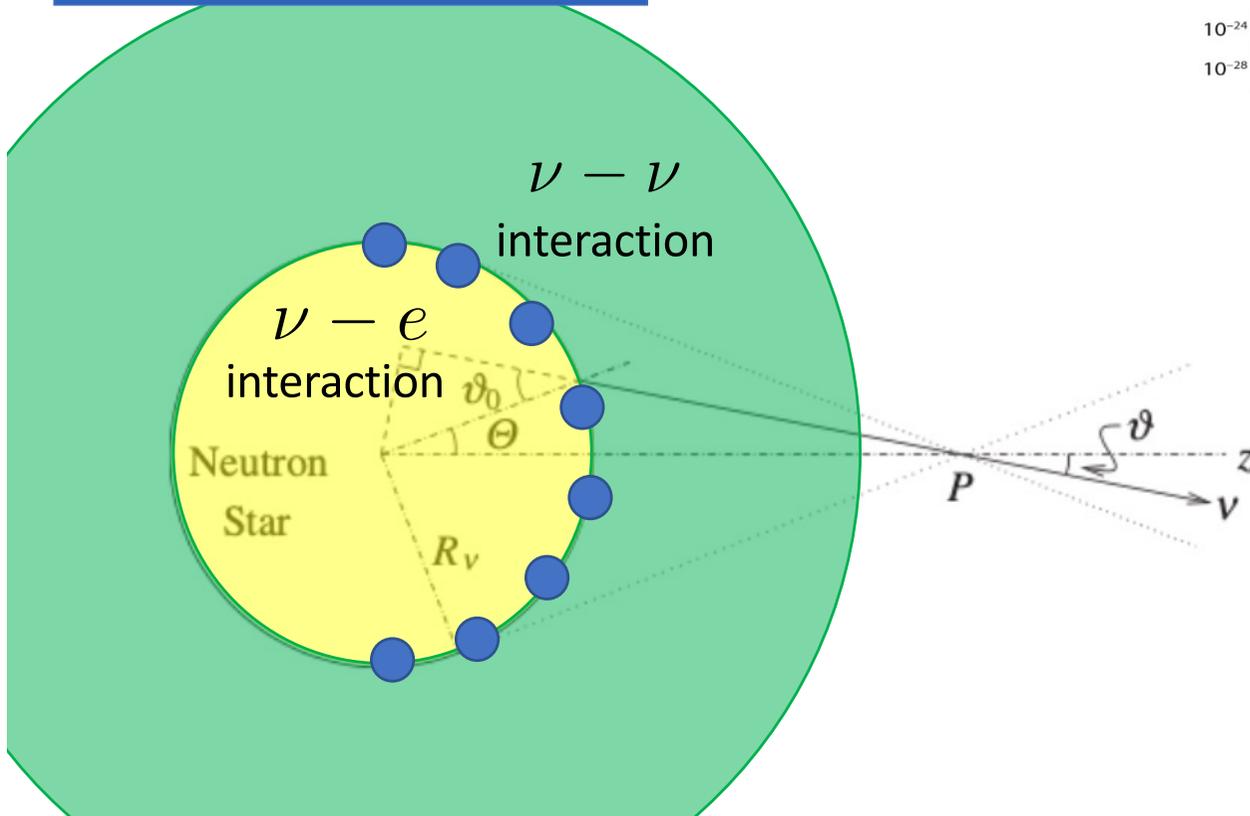




Neutrino fluxes at Earth



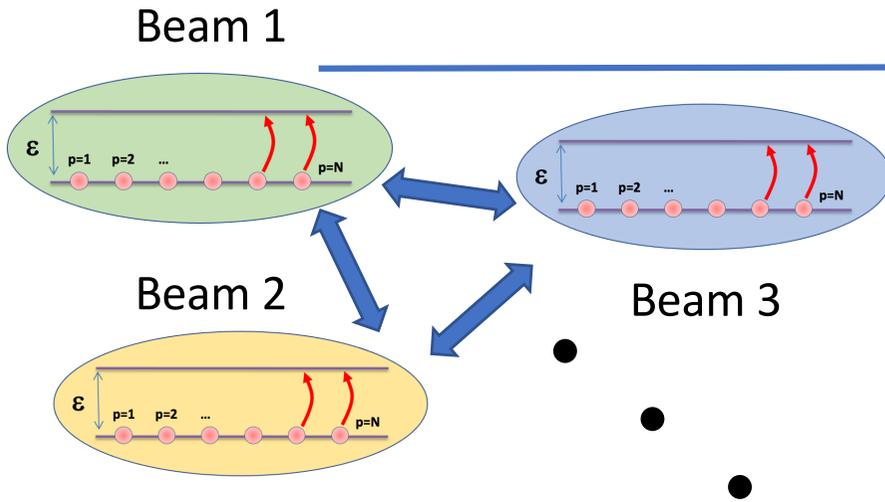
Where is the complexity?



The problem is mapped to a many-body open quantum system problem equivalent to interacting qubits or qutrits.

A focus on neutrino oscillation physics simulated on quantum computers

Illustration of the Hamiltonian (2 flavor approx)



Oscillation $H_\nu = \frac{1}{N} \sum_{i=0}^{N-1} \sin(2\theta_\nu) X_i - \cos(2\theta_\nu) Z_i$

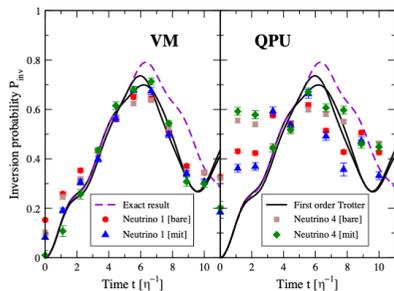
Coupling $H_{\nu\nu} = \sum_{i<j}^{N-1} G_{i,j} [X_i X_j + Y_i Y_j + Z_i Z_j]$

4 neutrinos
IBM-Vigo QPU

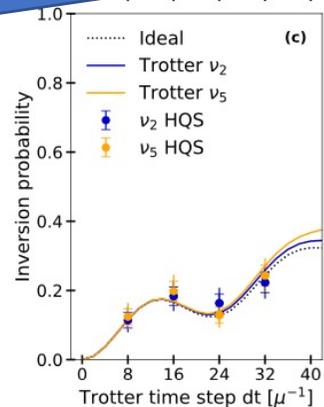
4 & 8 neutrinos
HQP-H1
Trapped Ion device

12 neutrinos
Quantinuum's H1-1
20 qubit trapped-ion

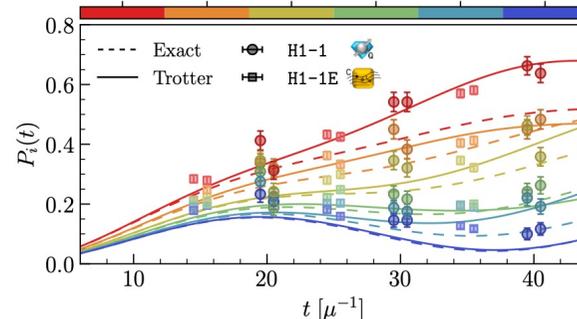
12 neutrinos / qutrits
H1-1 & ibm_torino



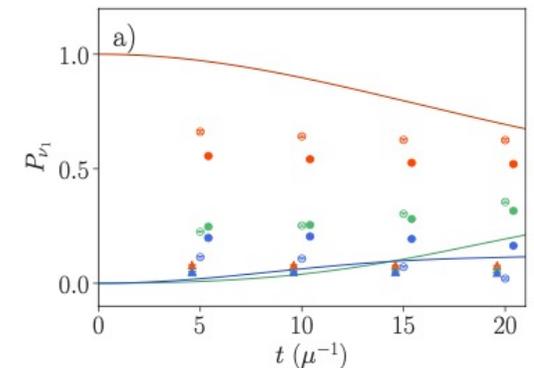
Hall et al, PRD 104 (2021)



Amitrano, et al, PRD 107, (2023)



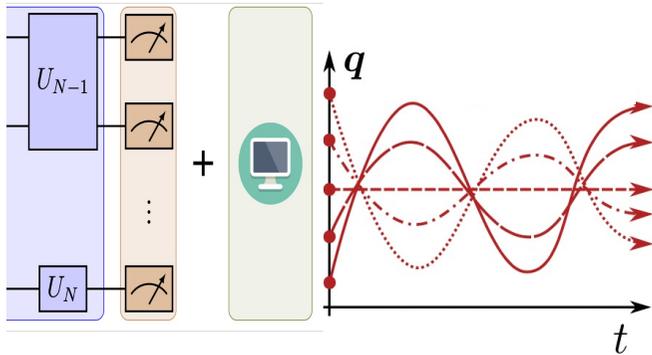
Illa et al, PRL 130 (2023)



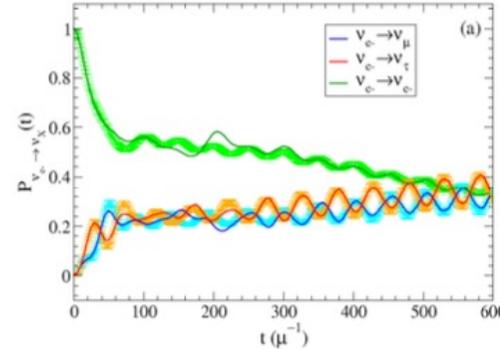
Turro et al, PRD D 111 (2025)

Example 2: Neutrino oscillation physics

Two directions: - Simulation of neutrinos on qubits and qutrits
 - Classical simulation on large qubits sets



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



Mangin Brinet, Lacroix, PRD 13 (2026)

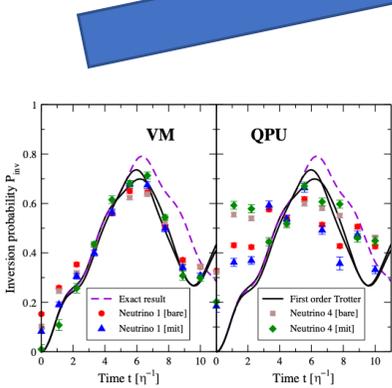
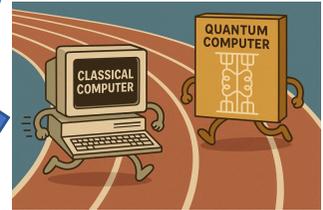
4 neutrinos
IBM-Vigo QPU
4 qubits

4 & 8 neutrinos
HQP-H1
Trapped Ion device
4 & 8 qubits

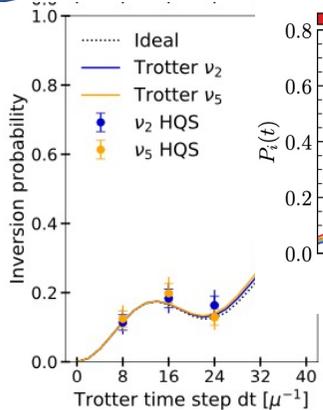
12 neutrinos
Quantinuum's H1-1
20 qubit trapped-ion

12 neutrinos / qutrits
H1-1 & ibm_torino

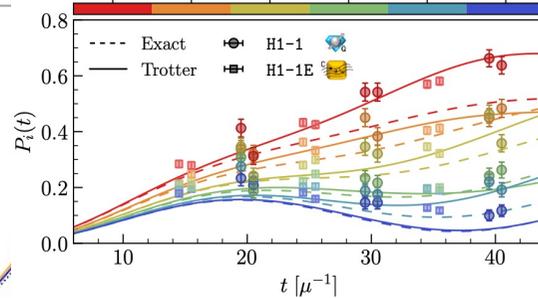
>100 neutrinos
IBM machines



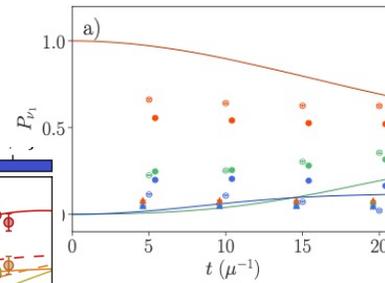
Hall, PRD 104 (2021)



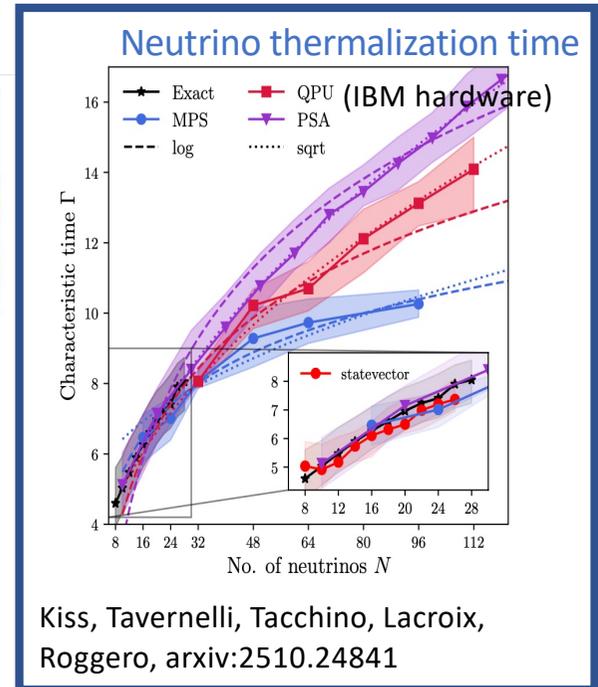
Amitrano, PRD 107 (2023)



Illa, PRL 130 (2023)

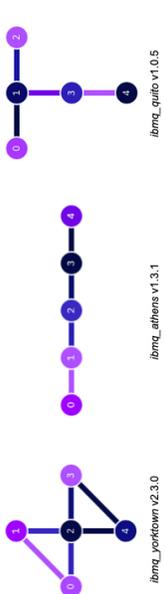
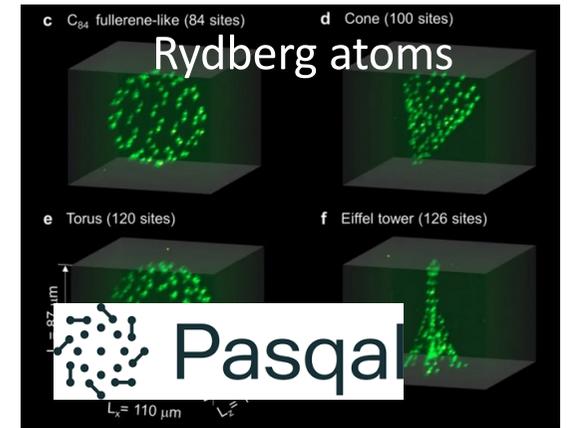
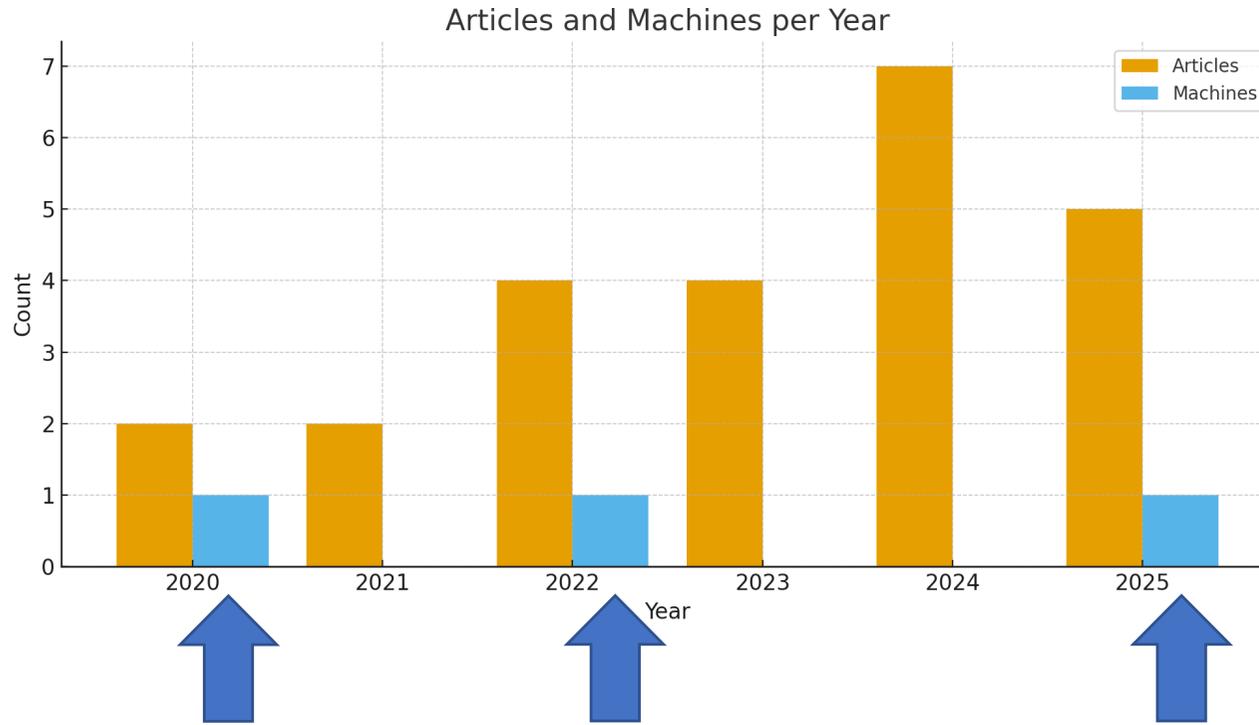


Turro, PRD 111 (2025)



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

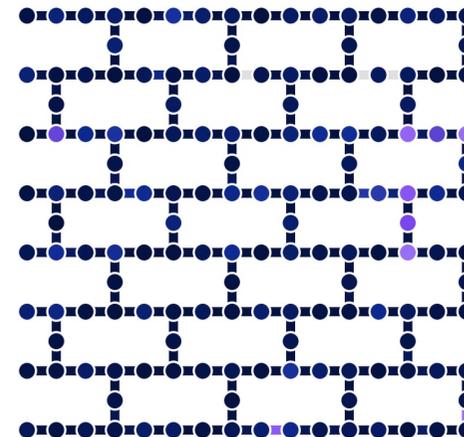
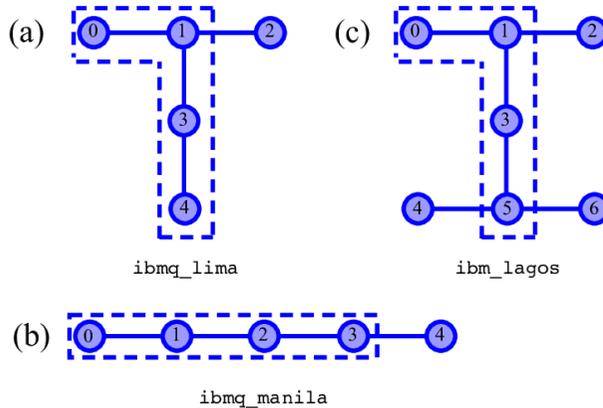
Real Quantum Machine access



IBM Q5
(5 qubits)

IBM santiago,
manila, and bogota

ibmq fez,
ibmq aachen
(156 qubits)



Thank you !

Thanks to my Collaborators

Nuclear Physics



M. O. Hlatshwayo



E. Litivnova



Vittorio Somà



P. Siwach

Neutrinos Physics



M. Mangin Brinet



B. Balantekin



A. Roggero



O. Kiss

IBM Quantum



F. Tavernelli



F. Tacchino

General Quantum computing/many-body/Quantum Machine Learning



T. Ayrat



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