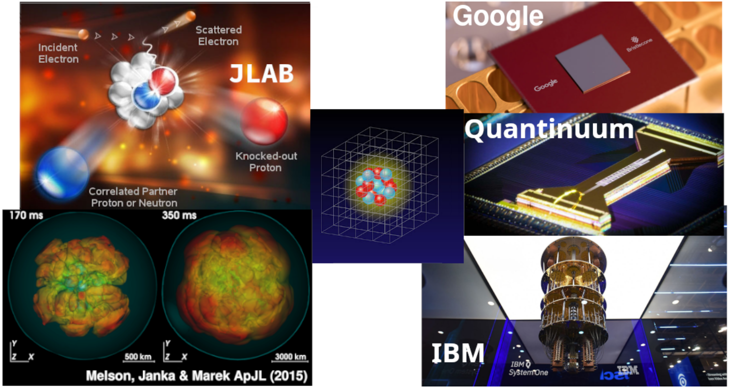
Nuclear dynamics on digital quantum computers

Alessandro Roggero



TIFPA INFN

QIS-HENP
– 17 June 2026 –

MOdeling Nuclear STructure and REactions

Quantum Computing in 2026: where are we?

Where we would like to be

Where we might be now

slide idea from A.Baldazzi's talk @ TIQIT'26

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The plan for the day

Important advances in recent years in both devices and algorithms are bringing us closer to do nuclear physics with quantum computers!

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Neutrino physics in explosive astrophysical environments

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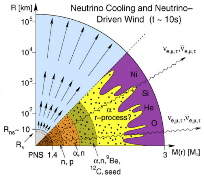

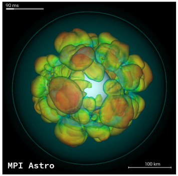

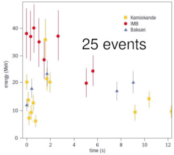

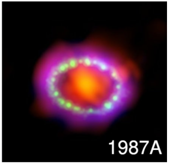

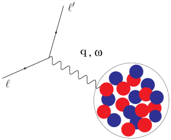

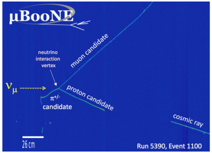

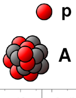

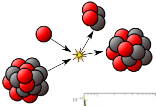

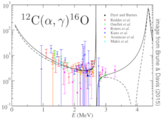

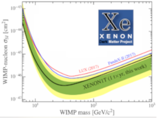

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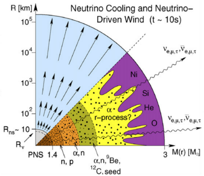

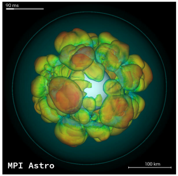

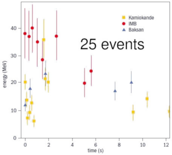

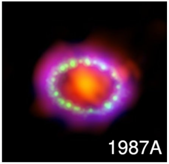

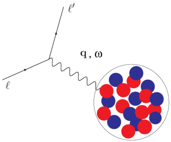

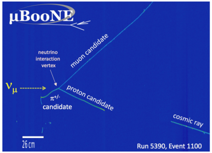

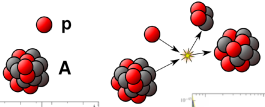

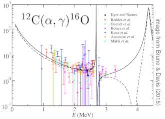

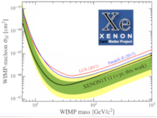

Two flavor neutrinos and the Heisenberg model

For neutrinos with only two flavors, we can use qubits to encode flavor as

$$|0\rangle = |\uparrow\rangle = |\nu_e\rangle \qquad |1\rangle = |\downarrow\rangle = |\nu_x\rangle$$

Vacuum oscillations drive rotations around the mass basis

$$H_{vac} = \sum_i \frac{\Delta m^2}{4E_i} \vec{B} \cdot \vec{\sigma}_i \qquad \vec{B} = (\sin(\theta_{mix}), 0, -\cos(\theta_{mix}))$$

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In CCSN or BNS merger we have incredibly large ν fluxes

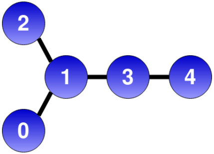
Forward scattering through neutral currents give $\nu\nu$ interaction

$$H_{int} = \frac{\sqrt{2} G_F \rho}{N} \sum_{i<j} J_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j \ ,$$

where ρ is the number density, N the number of neutrinos in the system and the coefficients J_{ij} encode the geometry.

Quantum simulation of collective neutrino oscillations

$$H = \sum_i \omega_i \vec{B} \cdot \vec{\sigma}_i + \frac{\mu}{2N} \sum_{i<j} J_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j$$



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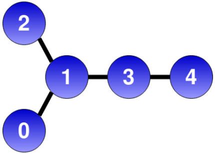

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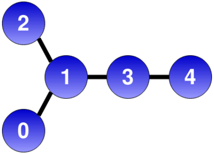

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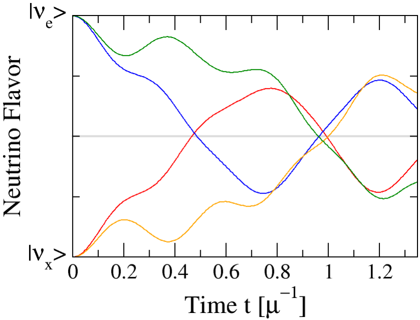

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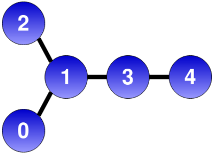

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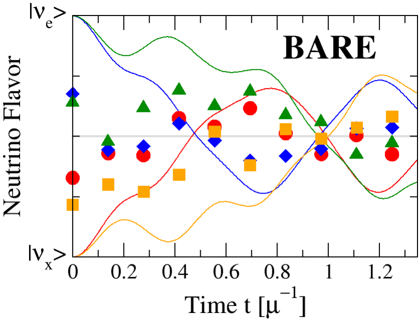

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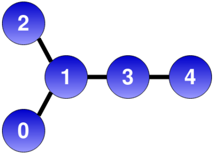

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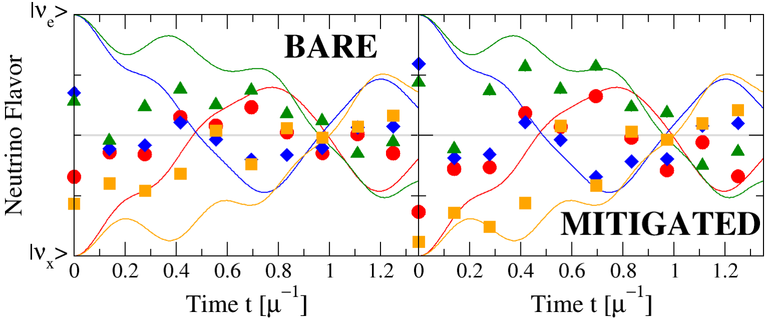
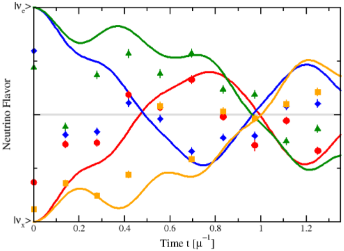


N=4 on IBM (2021)



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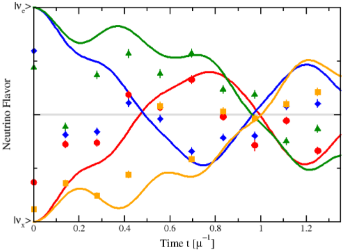

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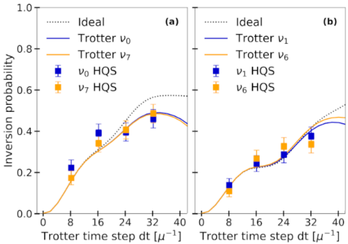

V.Amitrano et al. PRD(2023)

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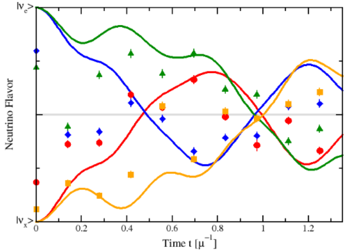

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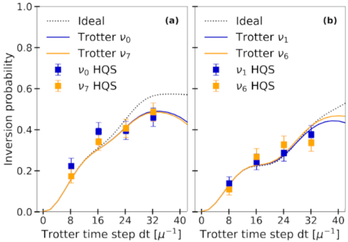

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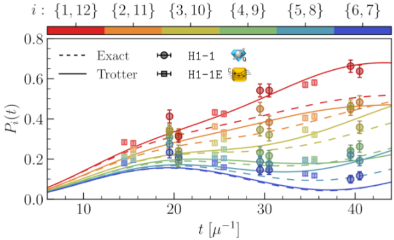

Illa & Savage PRL(2023)

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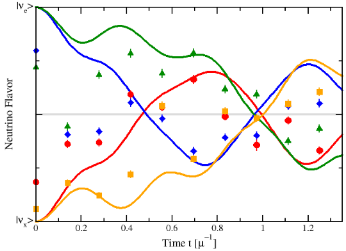

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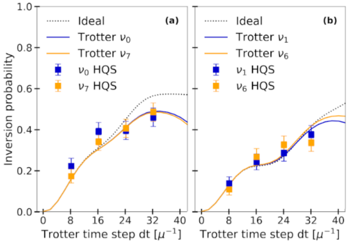

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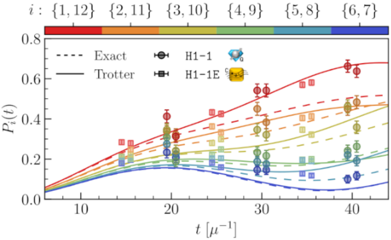

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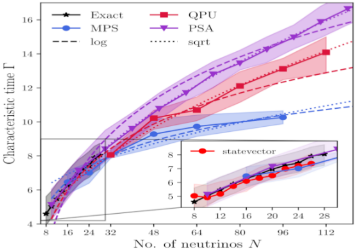
N=112 on IBM (2025)



O.Kiss et al. arXiv:2510.24841

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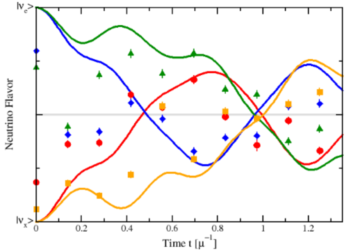

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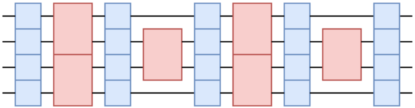
18 CNOT on **4** qubits



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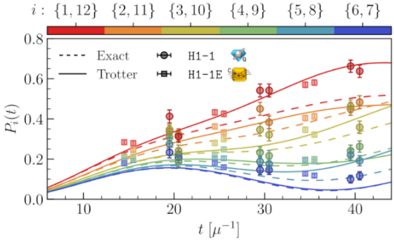

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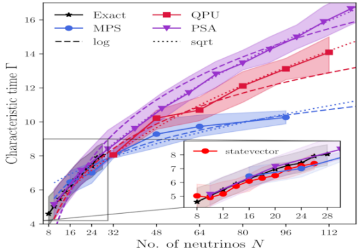

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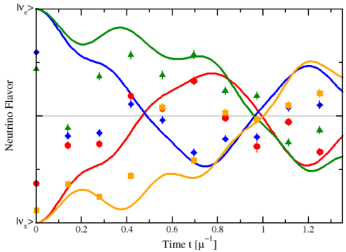

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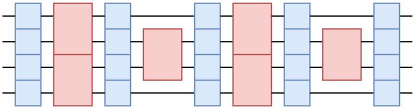
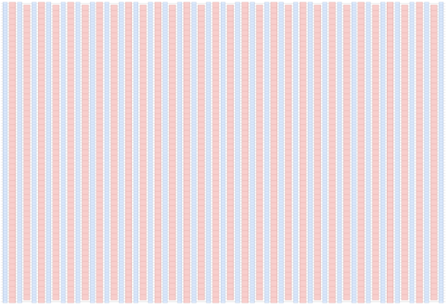


B.Hall et al. PRD(2021)

4995 CNOT on **112** qubits



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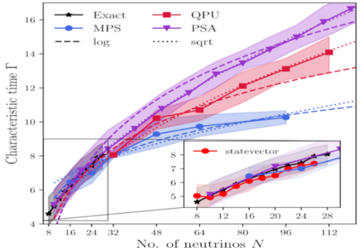

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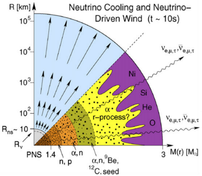

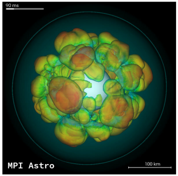

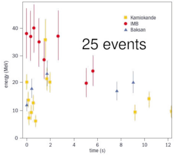

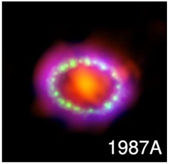

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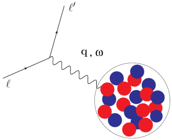
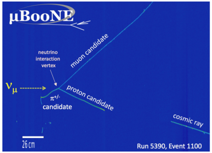
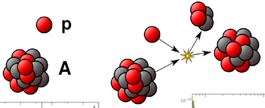
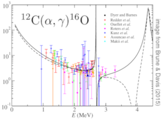
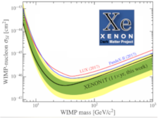




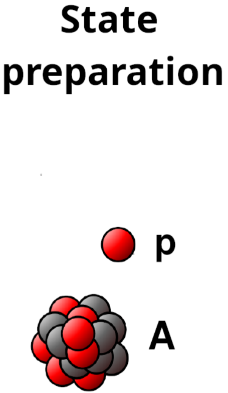






Steps in a quantum simulation

The quantum simulation of a nuclear reaction requires three main steps



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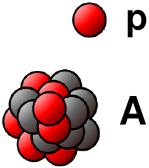
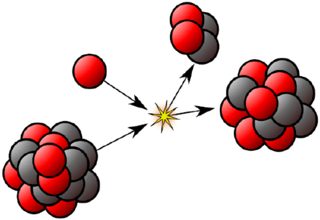
Time evolution





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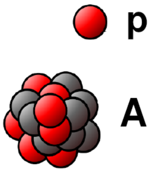
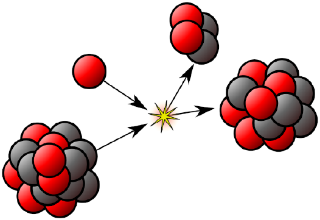
State preparation | **Time evolution** | **Measurement**





Time evolution is the better characterized for fault tolerence so far

Progress on time evolution for NP

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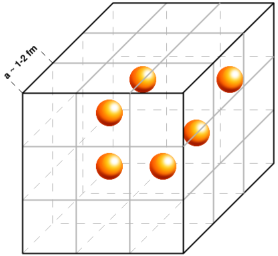

Minimal setup

- 10^3 lattice with spacing $a \approx 1 - 2fm$
- 4 spin-isospin states for each particle

  $\longrightarrow$ we need at least 4000 orbitals
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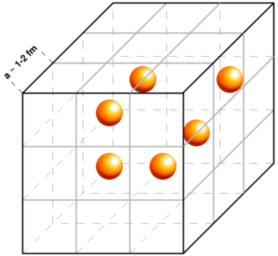

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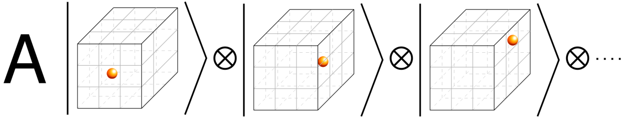
- $10^{11} - 10^{12}$ operations and ≈ 4000 qubits [Roggero et al. PRD (2020)]
- $10^9 - 10^{11}$ operations and ≈ 6000 qubits [J.Watson et al. arXiv:2312.05344]

Progress on time evolution for NP II

For nuclear reactions we want large volumes V with few particles N inside
$\rightarrow$ IDEA: why not use first quantization instead?



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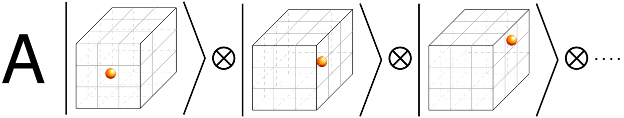

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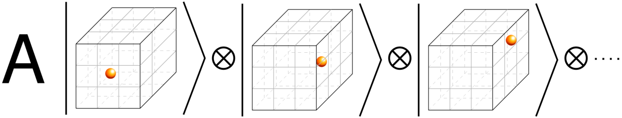

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Turns out 1st quant. can beat 2nd quant. in both memory and gates

$$C^T_{2nd} = \mathcal{O}\left(\frac{t^{3/2}}{\sqrt{\epsilon}}\sqrt{N}V\right) \qquad C^T_{1st} = \mathcal{O}\left(\frac{t^{3/2}}{\sqrt{\epsilon}}N^{7/2}\log(V)\right)$$

Spagnoli, Lissoni, Roggero arXiv:2507.22814

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$$C^{QSP}_{1st} = \mathcal{O}\left(N\log(V)\left(Nt + \log\left(\frac{1}{\epsilon}\right)\right)\right)$$

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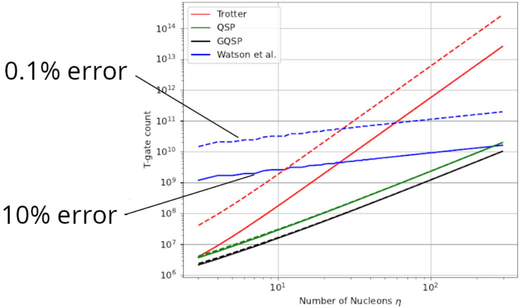

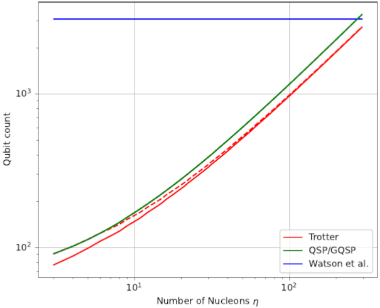

- $10^7 - 10^9$ operations and $\approx 70 - 500$ qubits [Spagnoli, Lissoni, Roggero (2025)]

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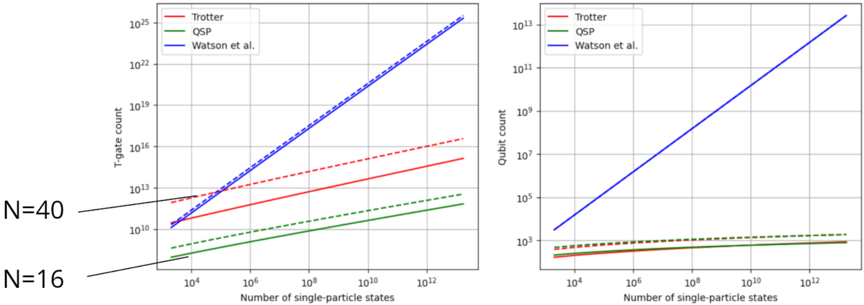

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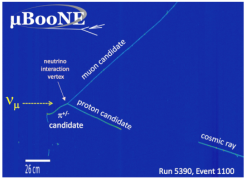
Summary and perspective

- Quantum computing is a strong candidate to considerably improve our simulations of nuclear physics, especially dynamical properties
- Digital quantum devices are constantly getting better at a very fast pace and early fault tolerance might be in sight
- Substantial advances in the last years in the implementation of time evolution for simple nuclear Hamiltonians. Recent results seem to suggest that a **first-quantization** formulation could be advantageous
- More work needed in state preparation and in measurement protocols: what should we measure for **semi-exclusive** scattering processes?
- Classical simulation methods continue to improve also thanks to work on quantum algorithms. Quantum advantage constantly rising bar



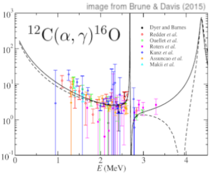
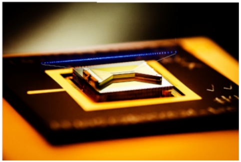


image from Chandra collab.



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Thank you for your attention!