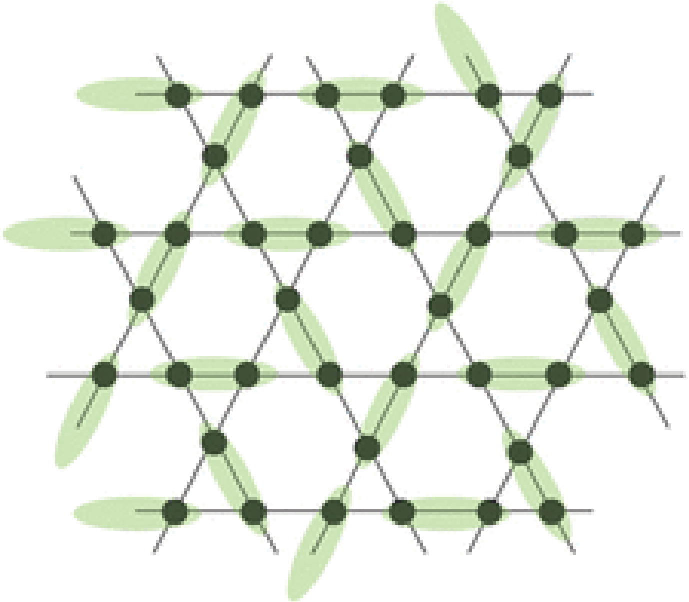
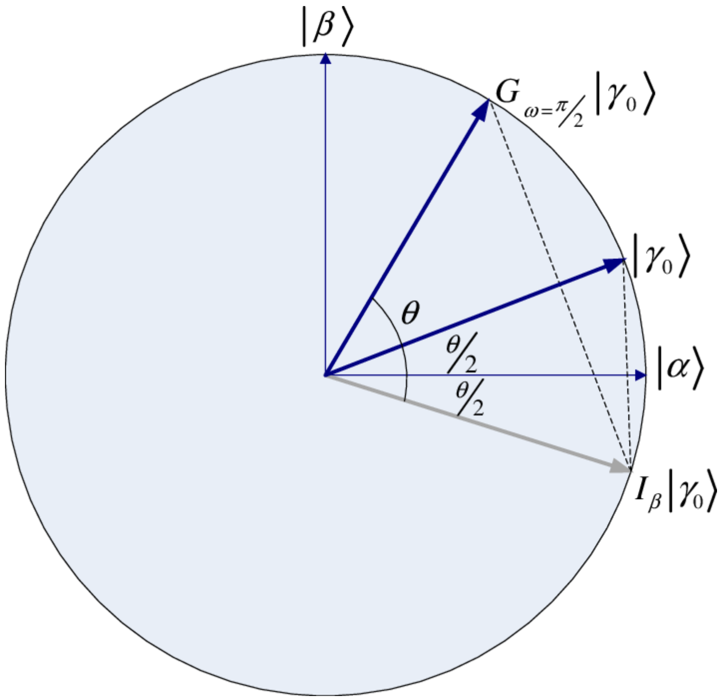
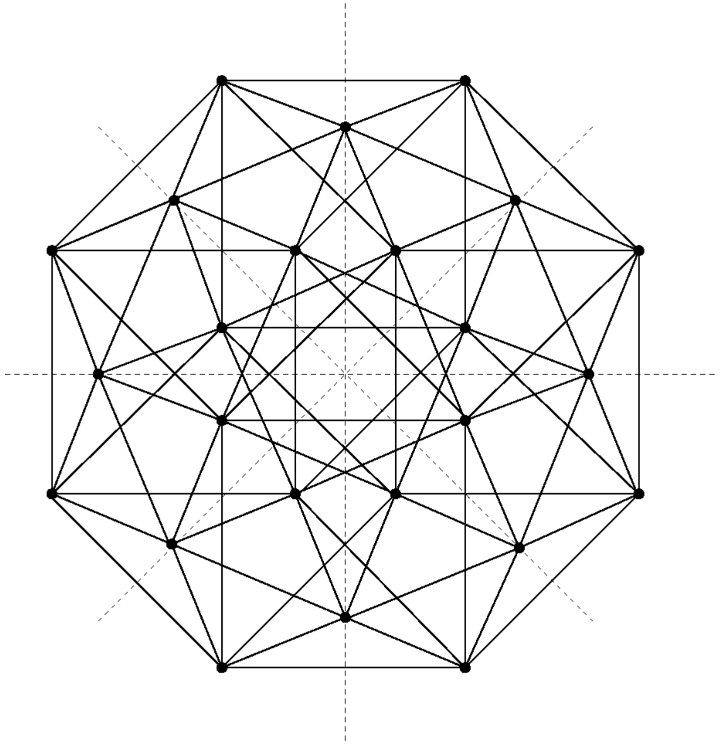
Quantum computers for particle physics simulations







Alessandro Mariani

3 November 2024

NewScientist

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Technology

Quantum computers teleport and store energy harvested from empty space

A quantum computing protocol makes it possible to extract energy from seemingly empty space, teleport it to a new location, then store it for later use

By Karmela Padavic-Callaghan

17 September 2024

Technology

Google launches $5m prize to find actual uses for quantum computers

Existing quantum computers can solve some problems faster than any ordinary computer, but none of those problems has any practical use. Google and XPRIZE hope to change that

By Alex Wilkins

4 March 2024

BRIGHTER SIDE OF NEWS

Scientists finally discover what's inside a black hole

Physicist Enrico Rinaldi used quantum computing and computer learning to describe what is believed to be the interior of a black hole.

JOSEPH SHAVIT Updated Oct 27, 2024 3:03 PM PDT

Quanta magazine

QUANTUM GRAVITY

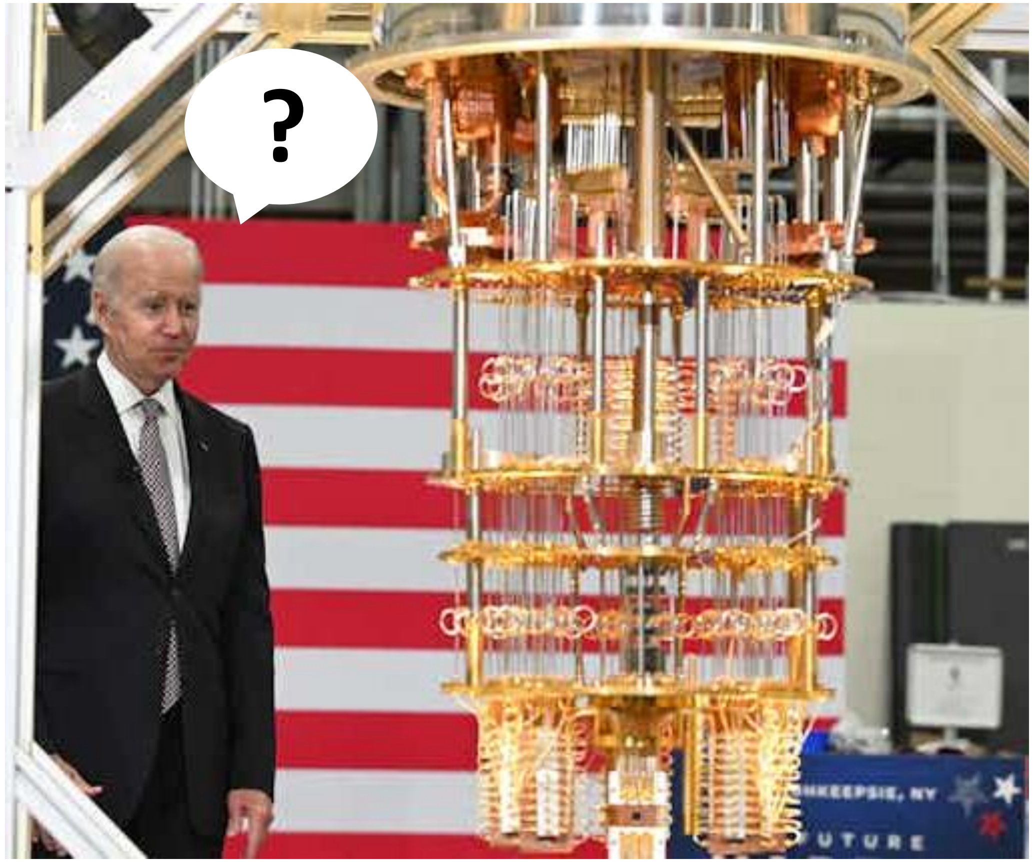
Physicists Create a Holographic Wormhole Using a Quantum Computer

70

The unprecedented experiment explores the possibility that space-


Neural AI
Quantum
Processor
4K
Processore
Neural
Quantum 4K

Quantum computers



IBM **Quantum**

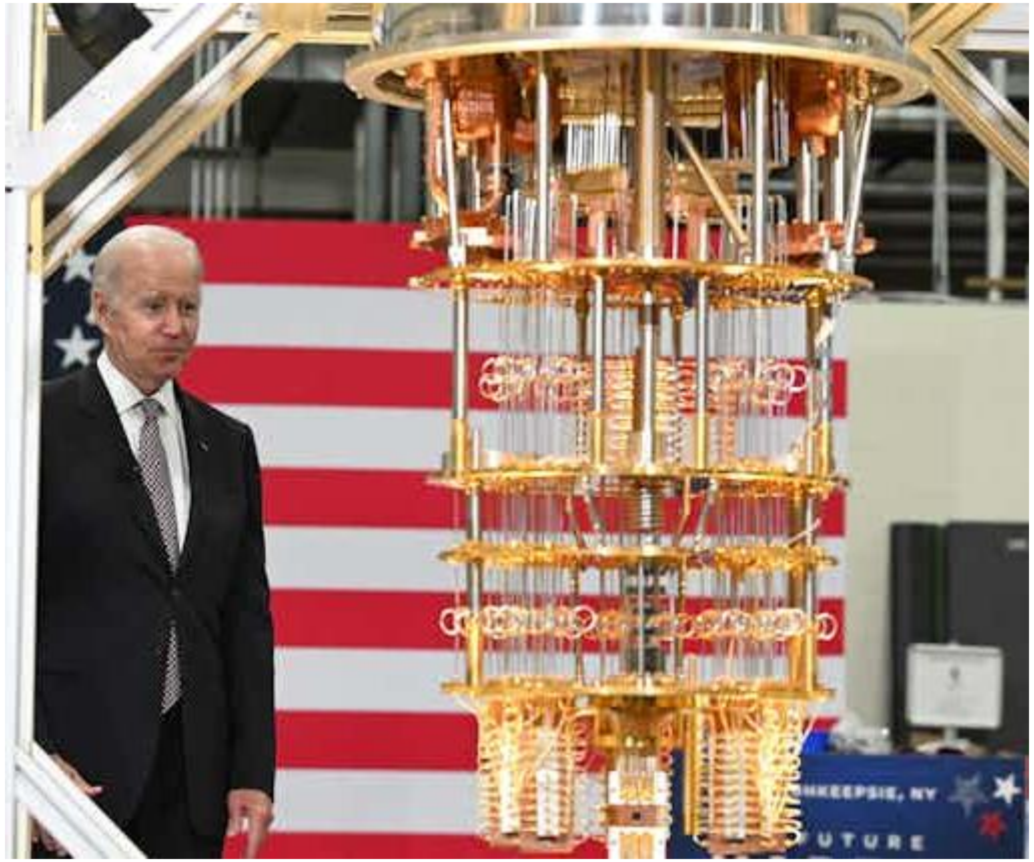
Quantum computer

=

system of highly controllable qubits

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Quantum computers



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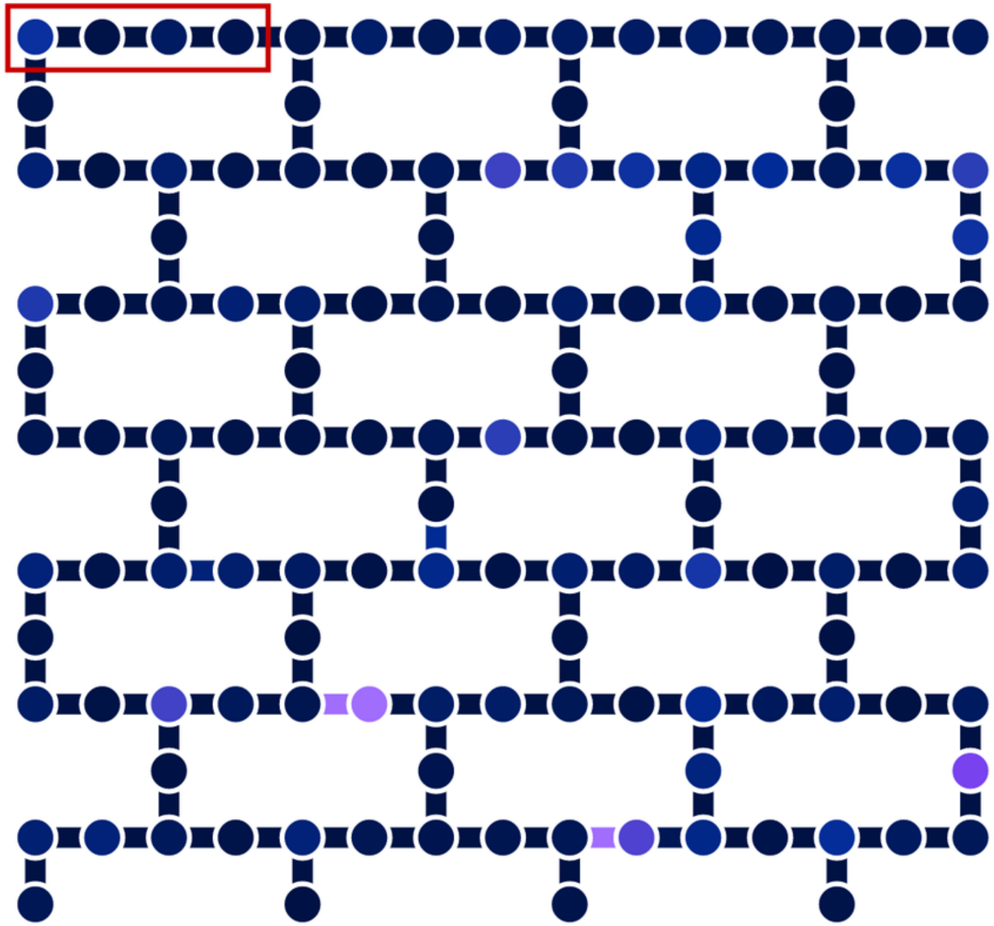
ibm_torino



Quantum computers

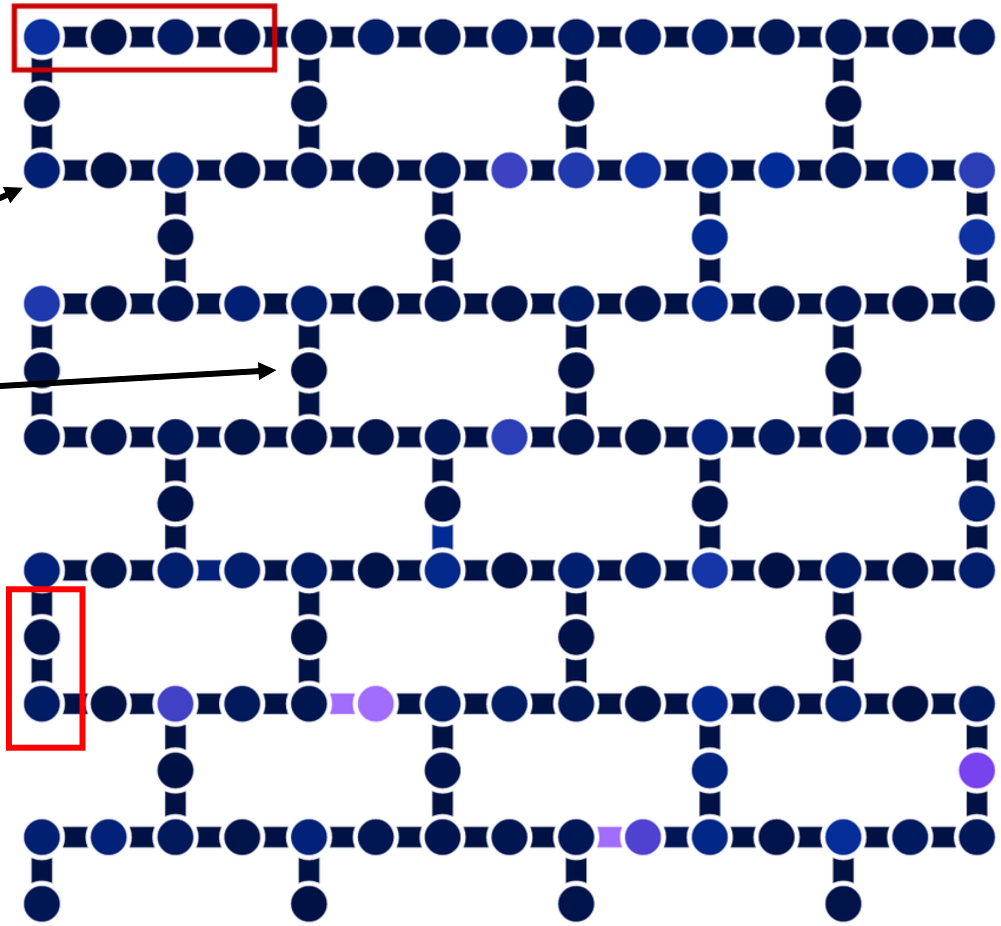
ibm_torino

133 qubits

Dots are qubits

Can apply unitary maps
to connected qubits

Color indicates quality



Applications of quantum computing

1) Integer factorization, i.e. $15 = 3 \cdot 5$
(Shor's algorithm)

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→ quantum chemistry, nuclear physics, particle physics, etc.

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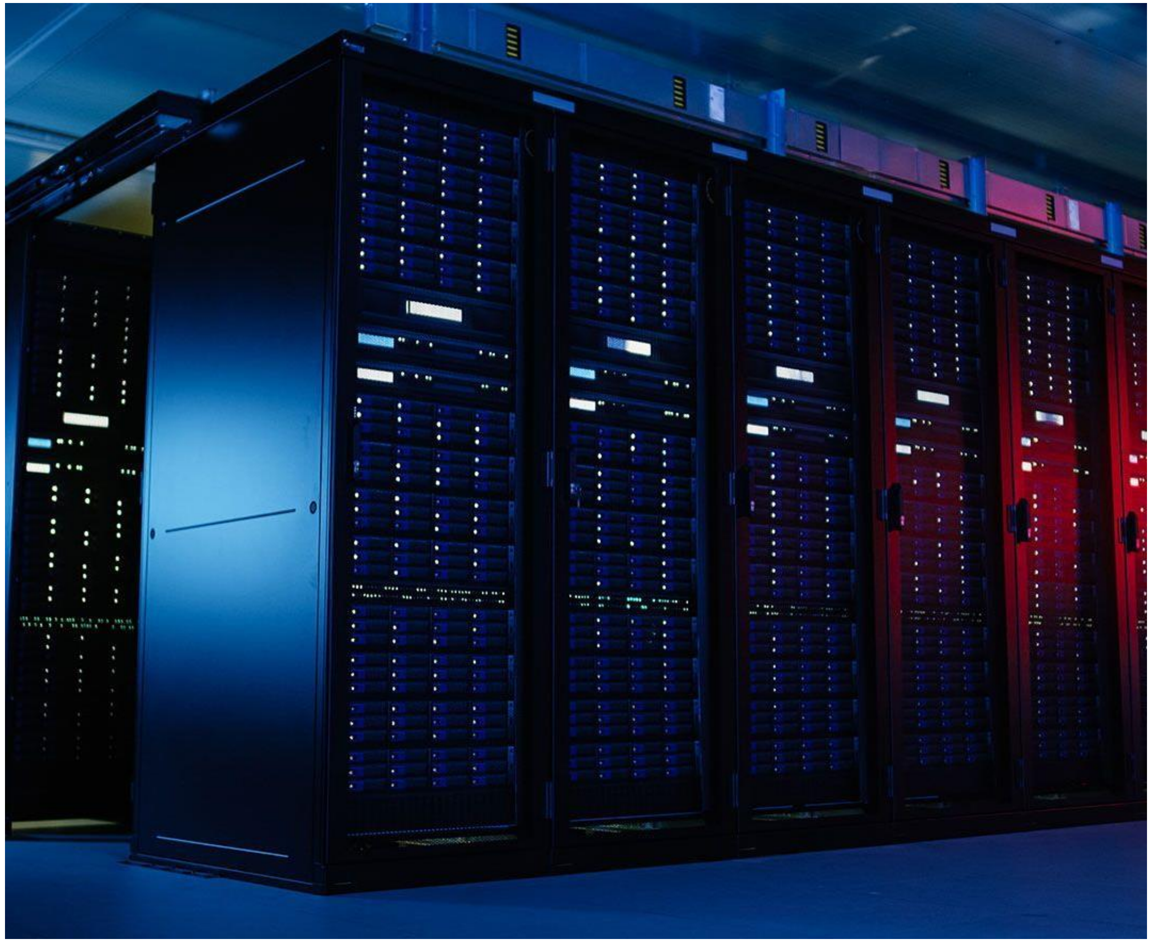
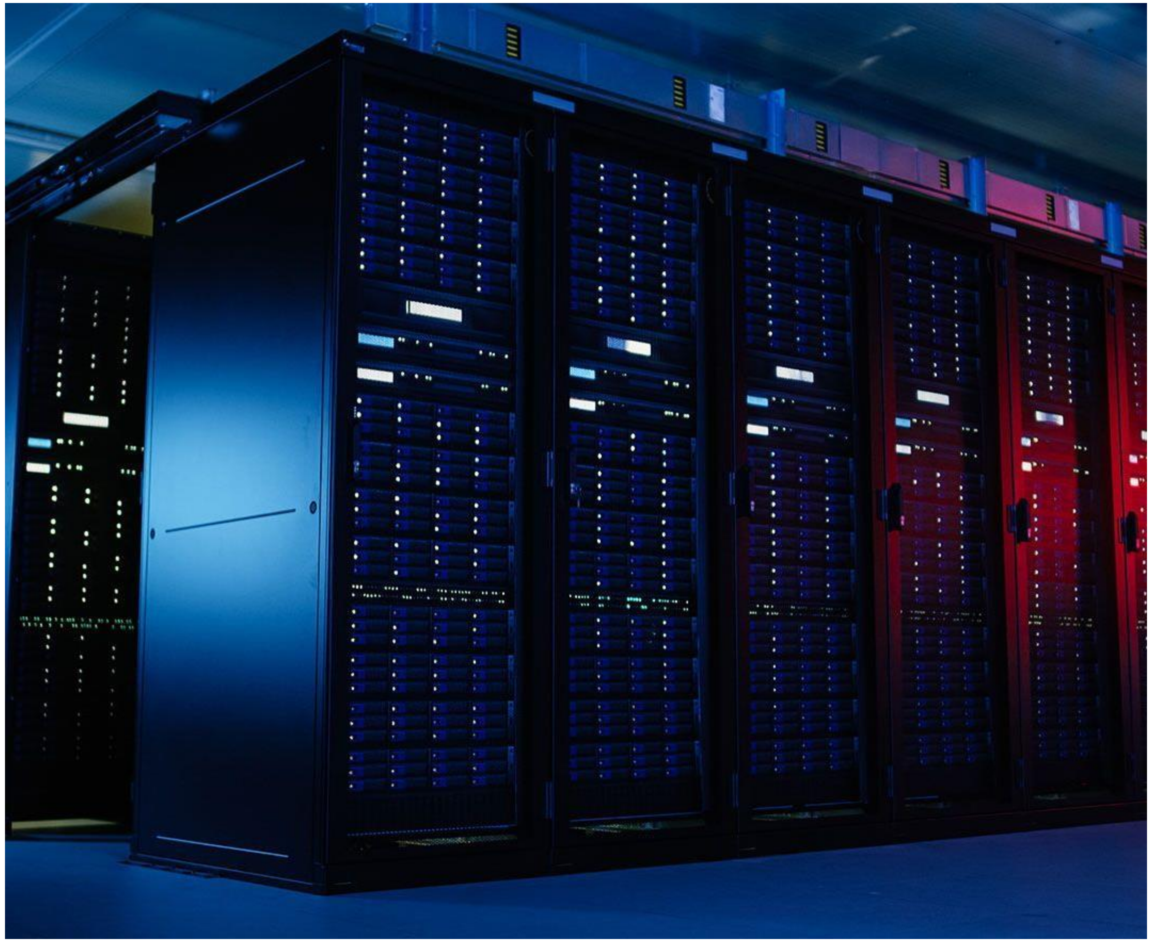
Classical computers for particle physics



Example: Lattice QCD $Z = \int DA\, e^{-S}$

Classical computers for particle physics



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Can do many things:
hadron spectrum,
equations of state,
muon $g - 2$, etc.

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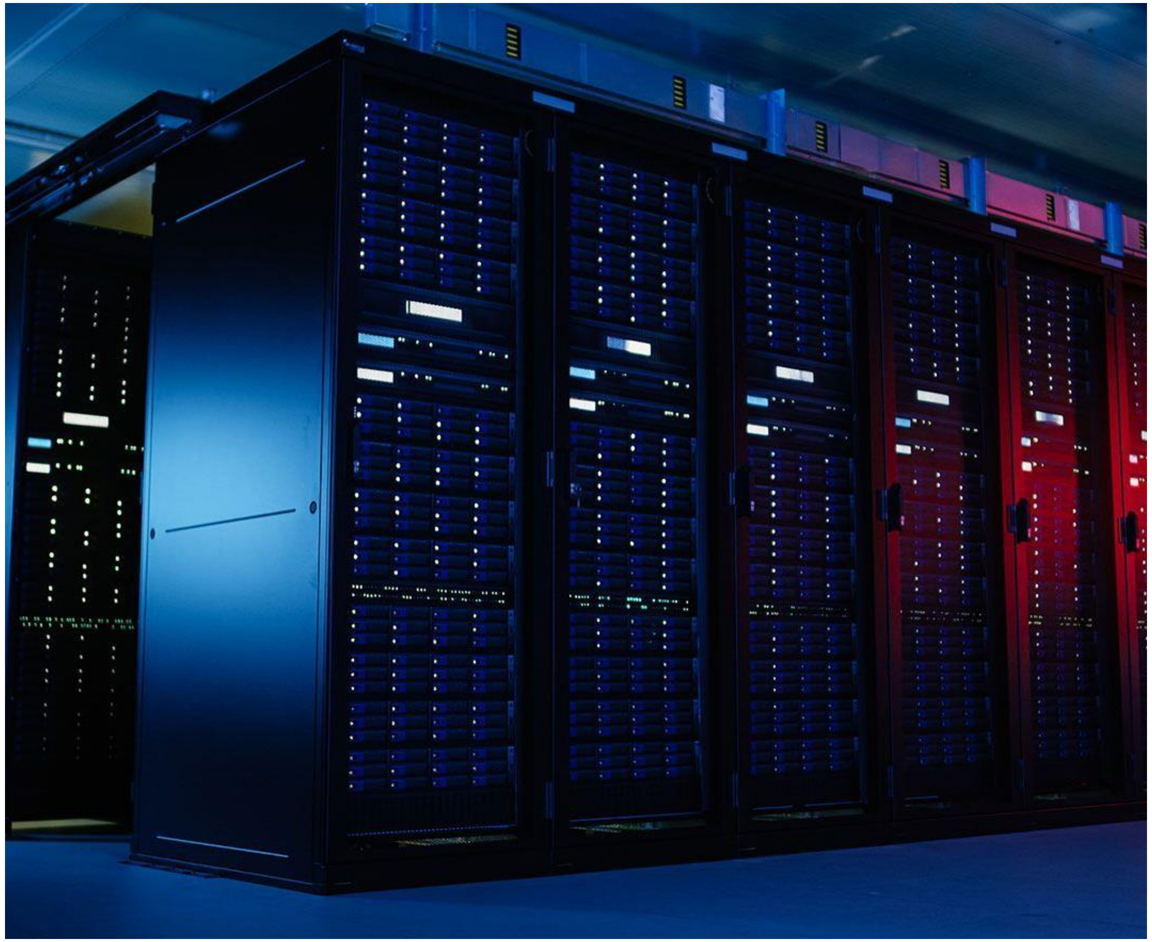

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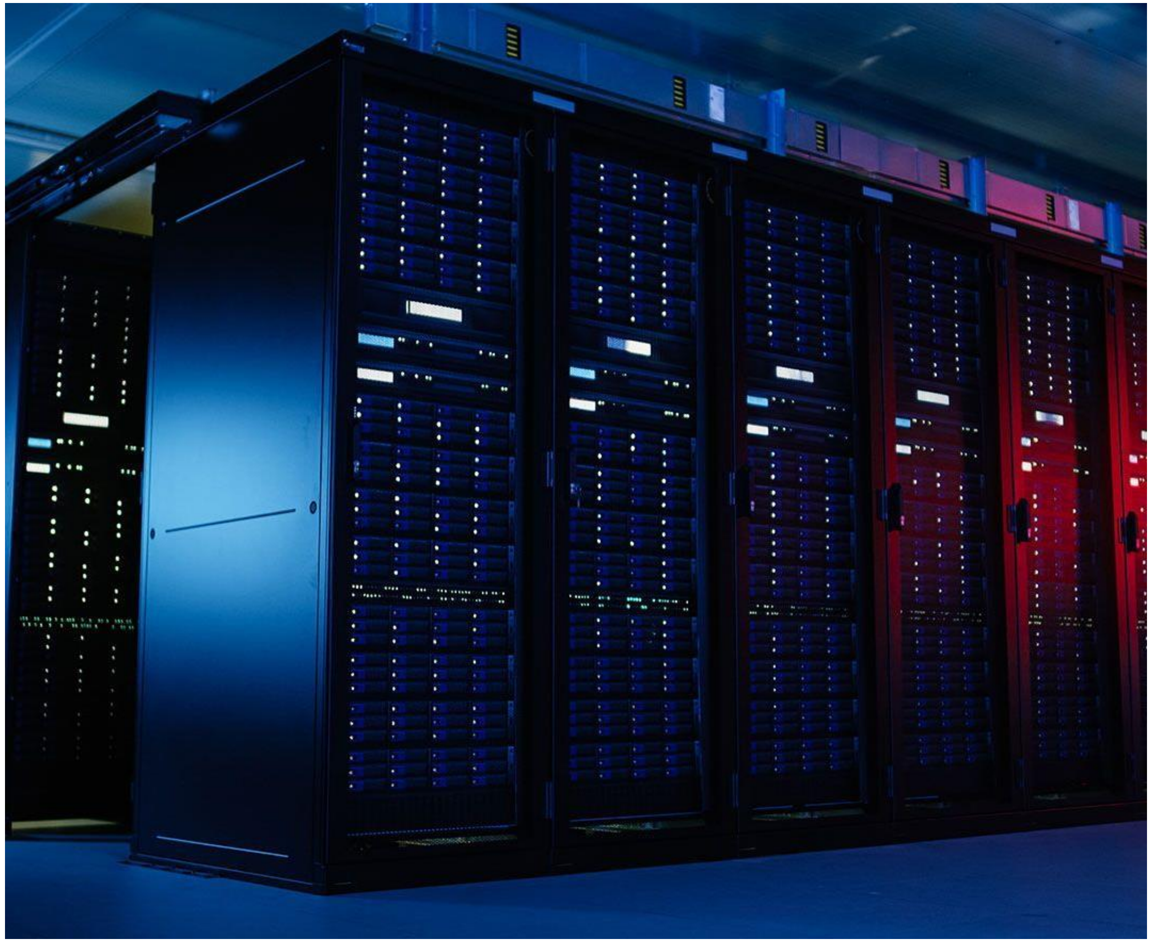

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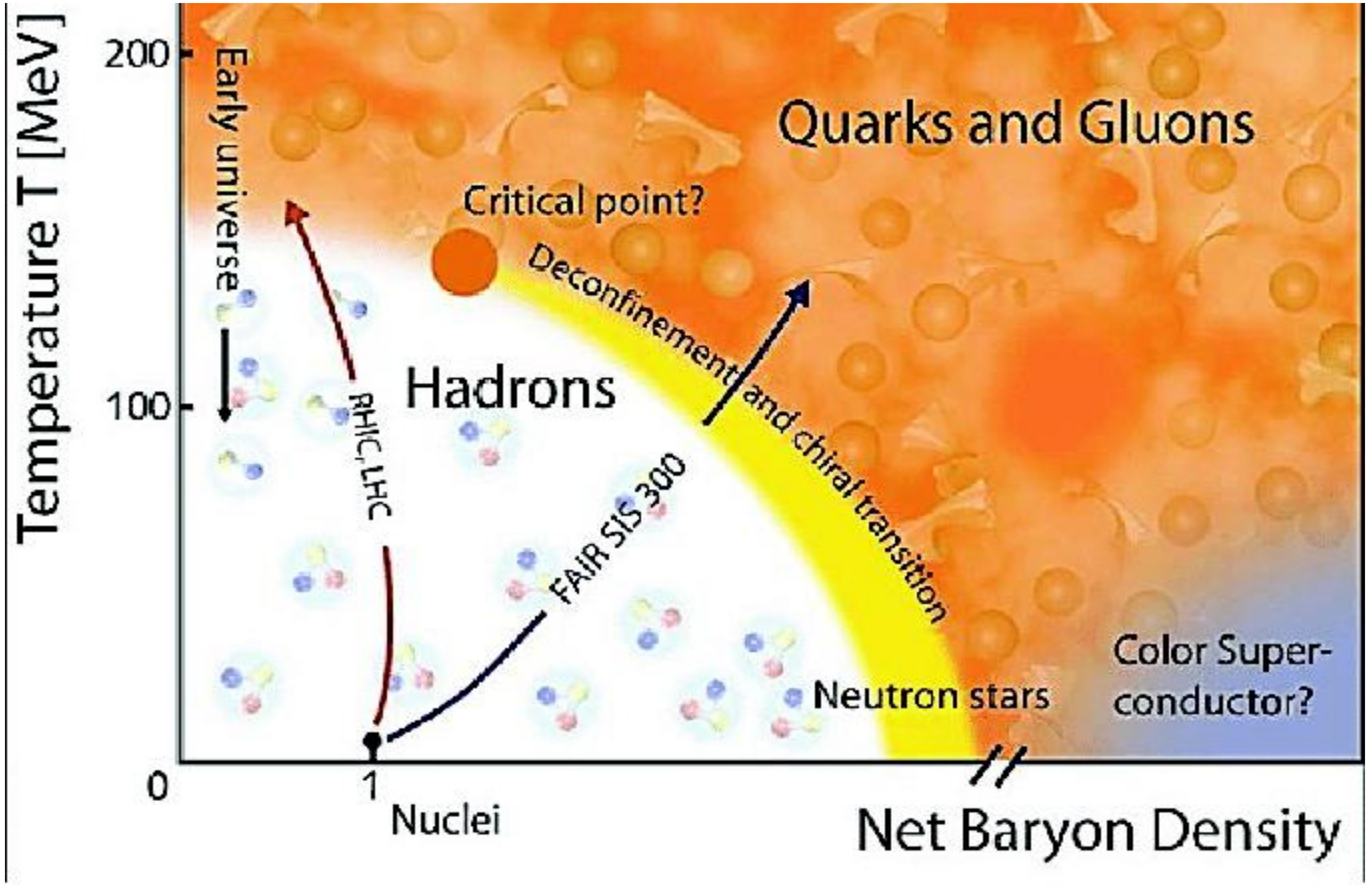
Finite density

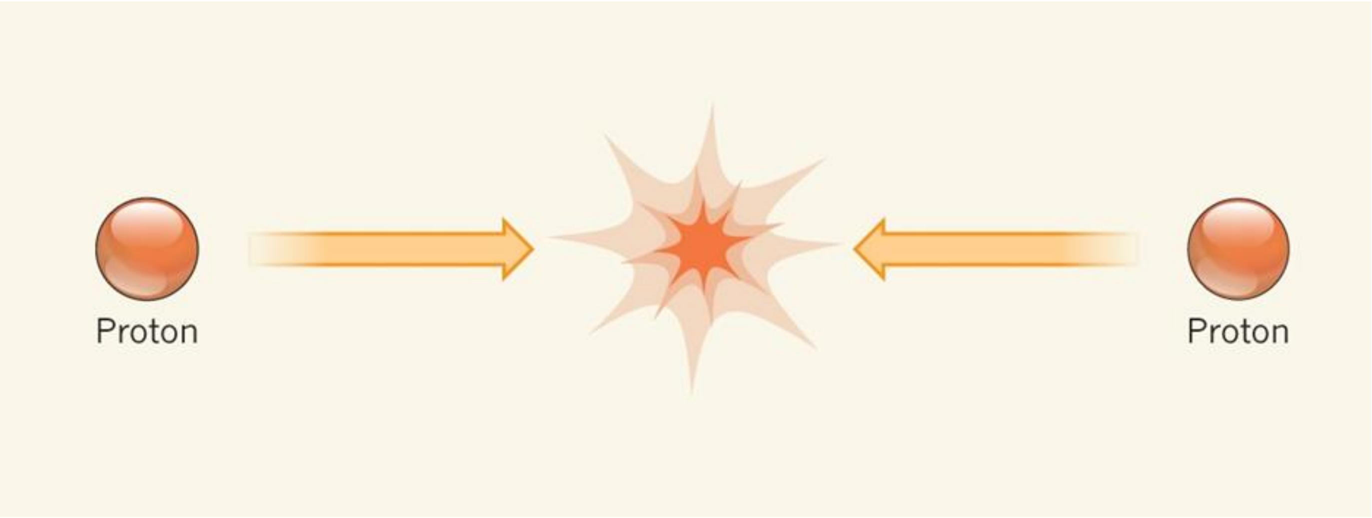


$$Z = \int DA\, e^{-S}$$

Currently can't do non-zero density

Sign problem: the action S is complex-valued.

Real time dynamics



Prepare proton state
$|\psi\rangle$

Time-evolve:
$e^{-iH_{QCD}t}|\psi\rangle$

Measure various properties

Why not classical?

Classical representation for N qubits requires 2^N complex numbers. → Unfeasible for large N

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Bosonic QFTs have infinite-dimensional Hilbert space → Need a method to truncate Hilbert space (lots of literature)

Naïve estimate for QCD (my own):
$N \approx 50 \cdot 10^6$

General structure of quantum computation

Prepare initial state $|\psi_0\rangle$

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↓

Perform arbitrary unitary operations

$U|\psi_0\rangle$

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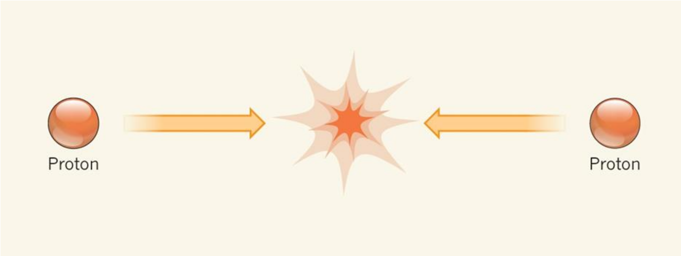

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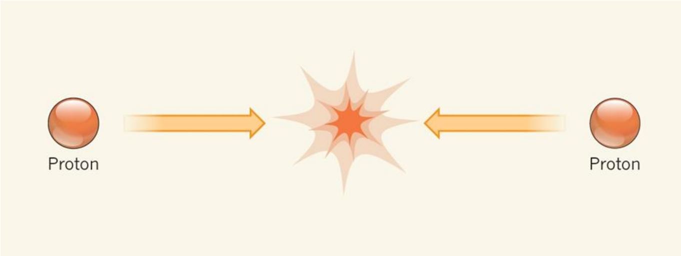

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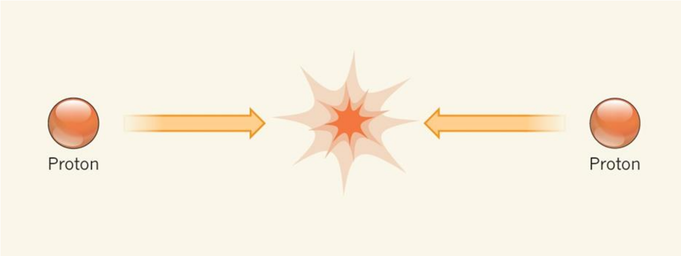


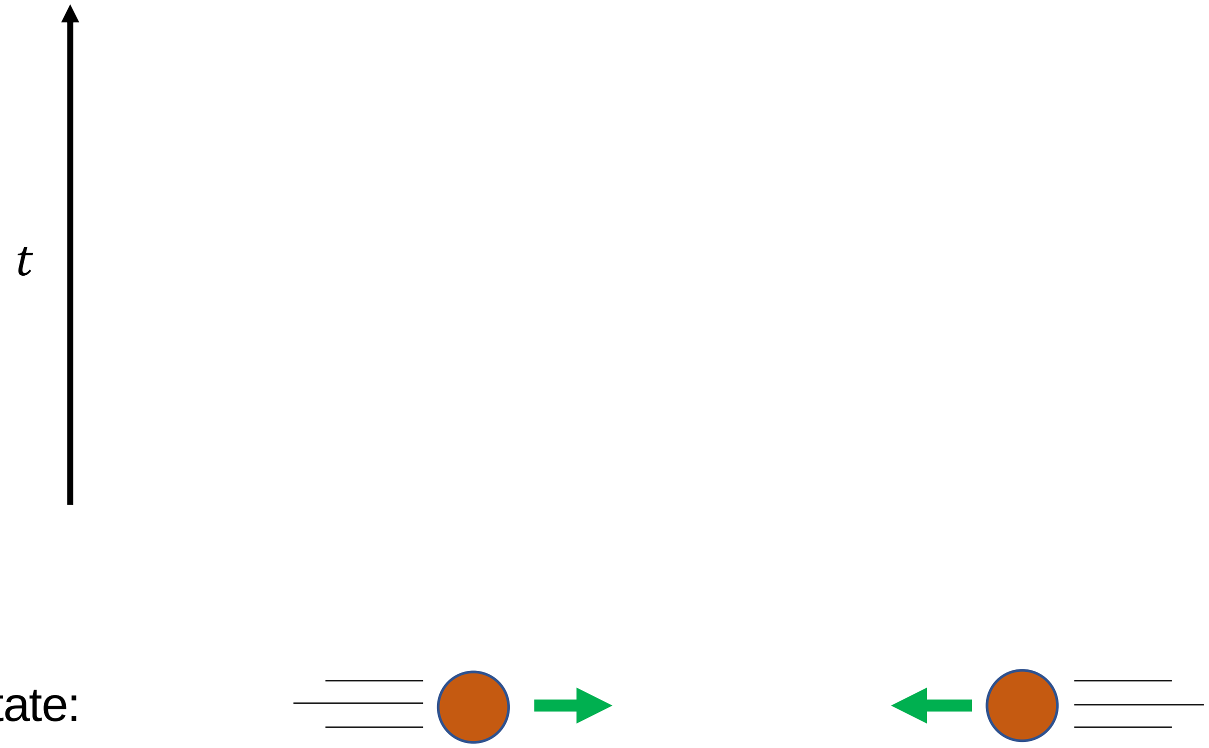
$$e^{-iH_{QCD}t}$$

Measure relevant observables

Toy model: 1+1 dimensional Abelian gauge theory

From Papaefstathiou et al (2024)

Final state:



Initial state:

Simulation of particle collision using a **classical heuristic** (tensor network)

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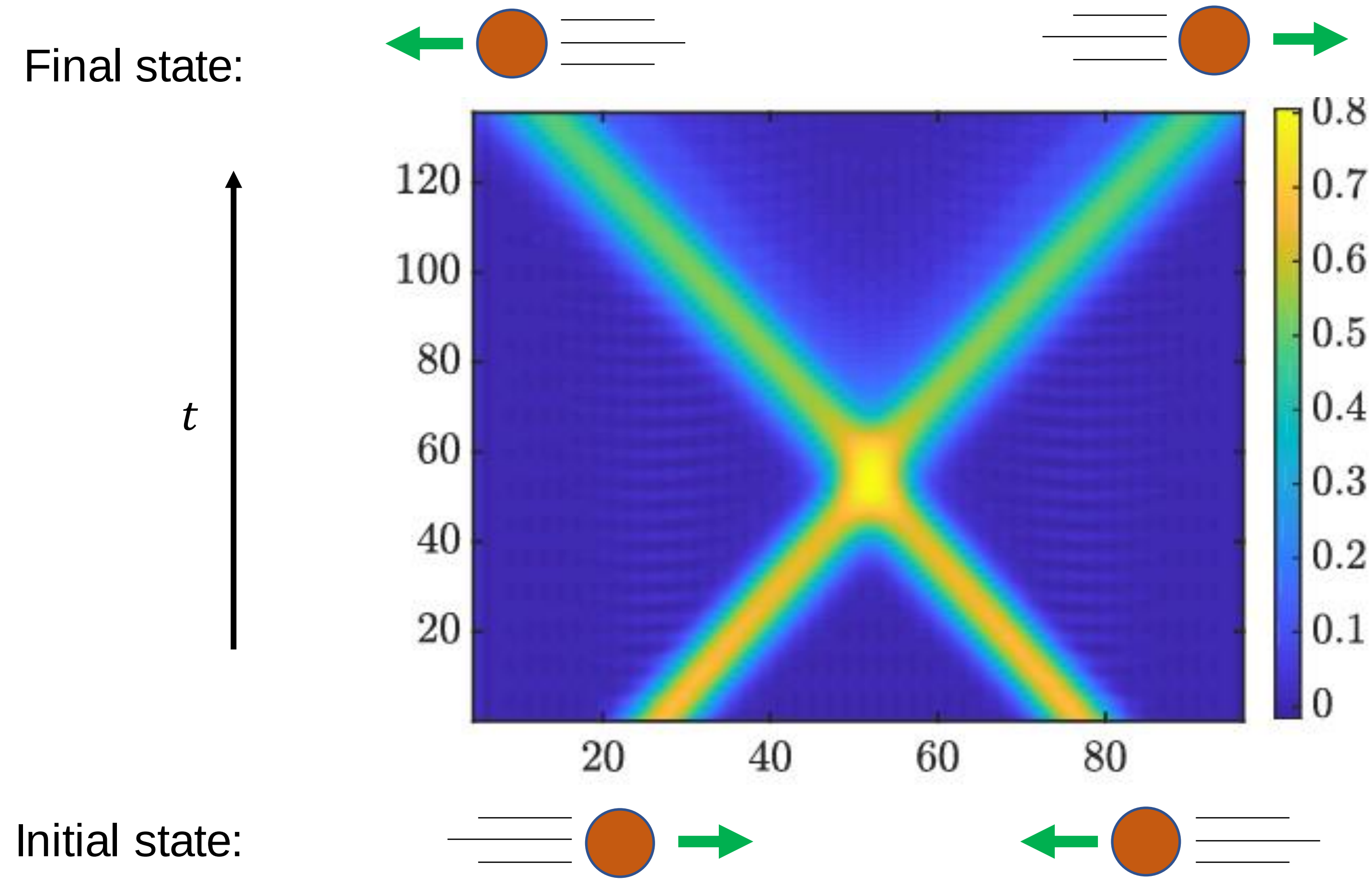

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Elastic collision

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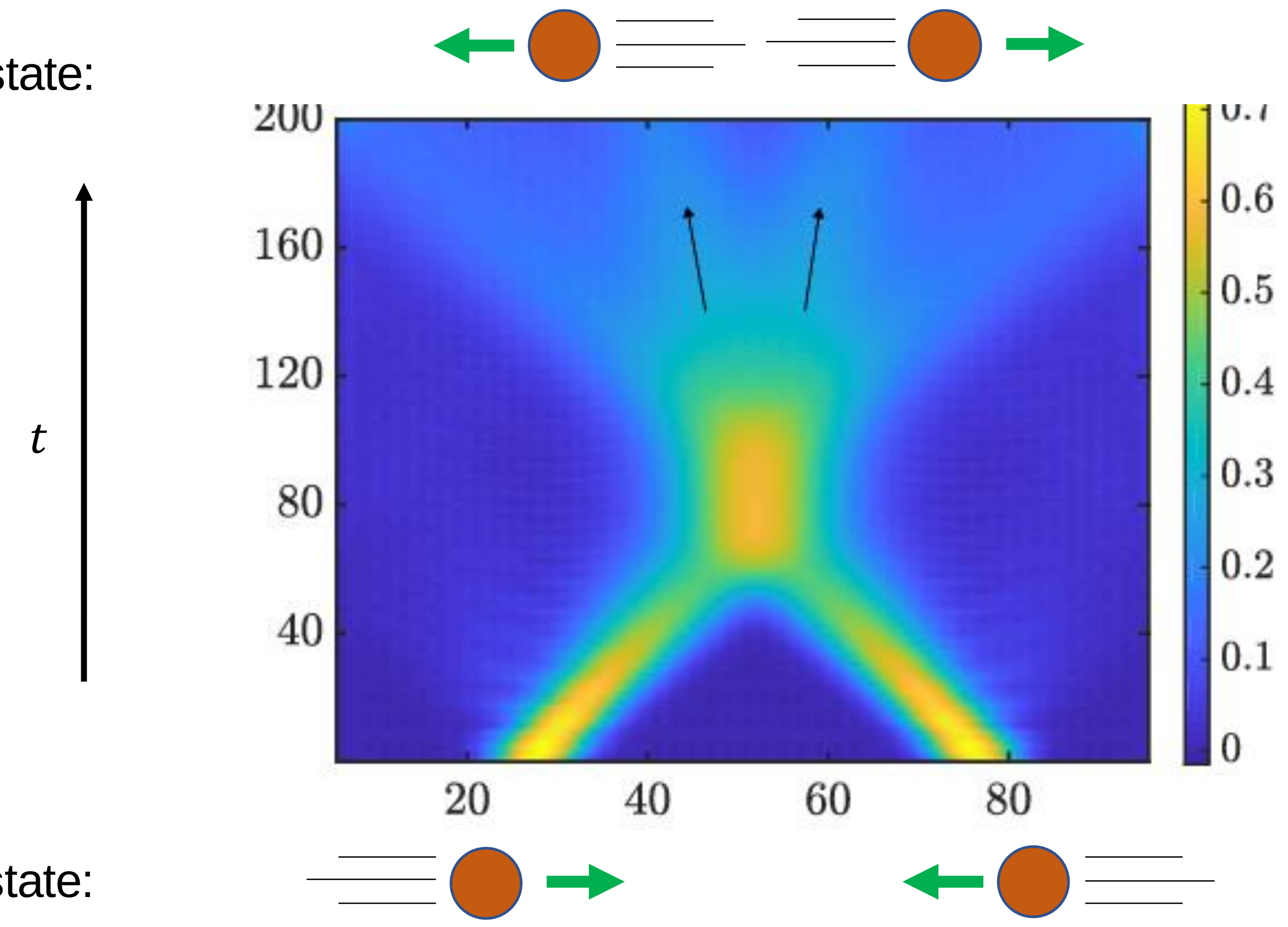

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Simulation of particle collision using a **classical heuristic** (tensor network)

Inelastic collision

Toy model: harmonic oscillator

Example on IonQ quantum device. Plot $\langle x \rangle$ density:

From Burdine et al (2024)

$$H = \frac{1}{2}p^2 + \frac{1}{2}x^2$$

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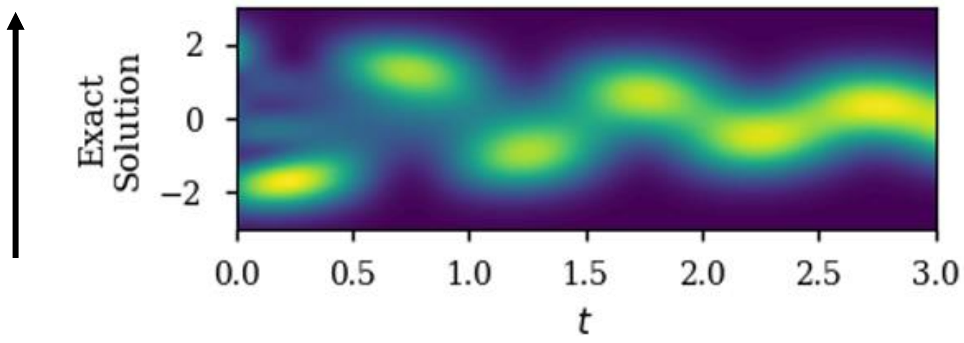

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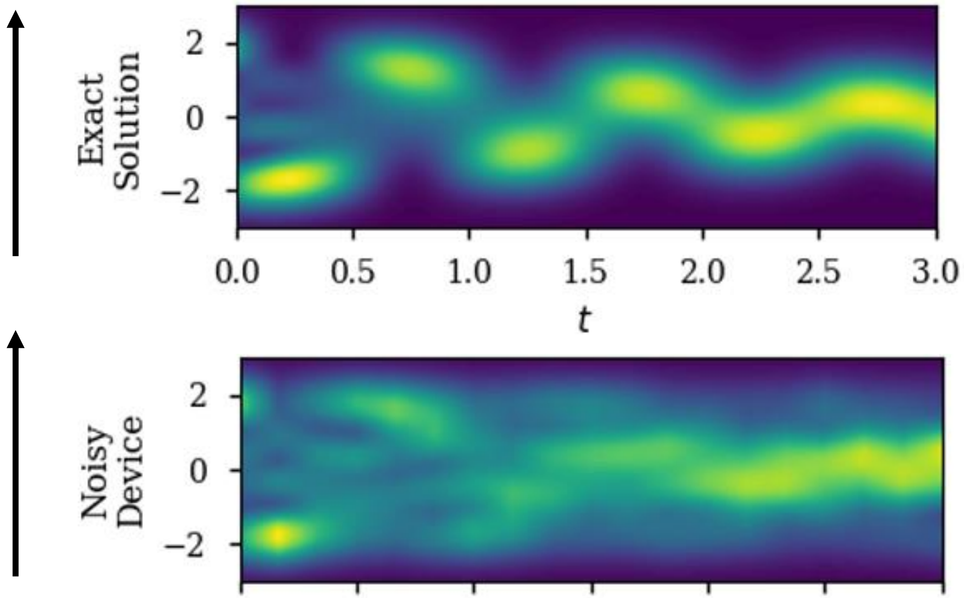

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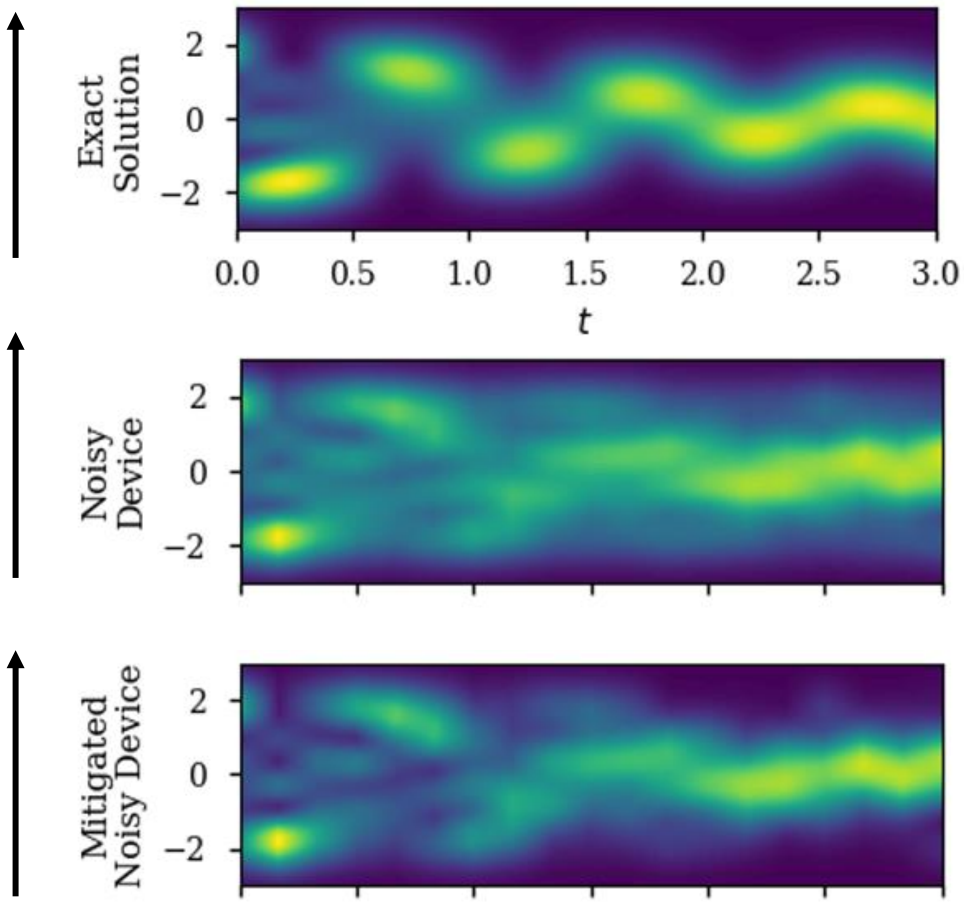

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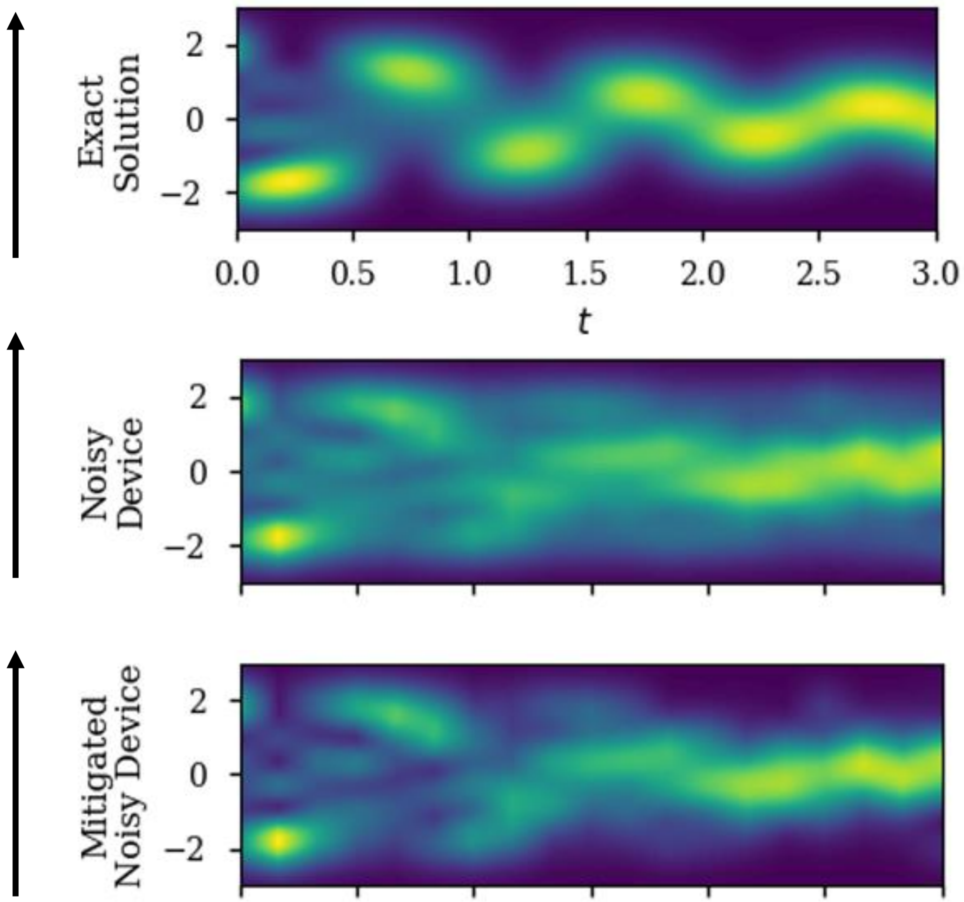

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Quantum computers are very noisy!

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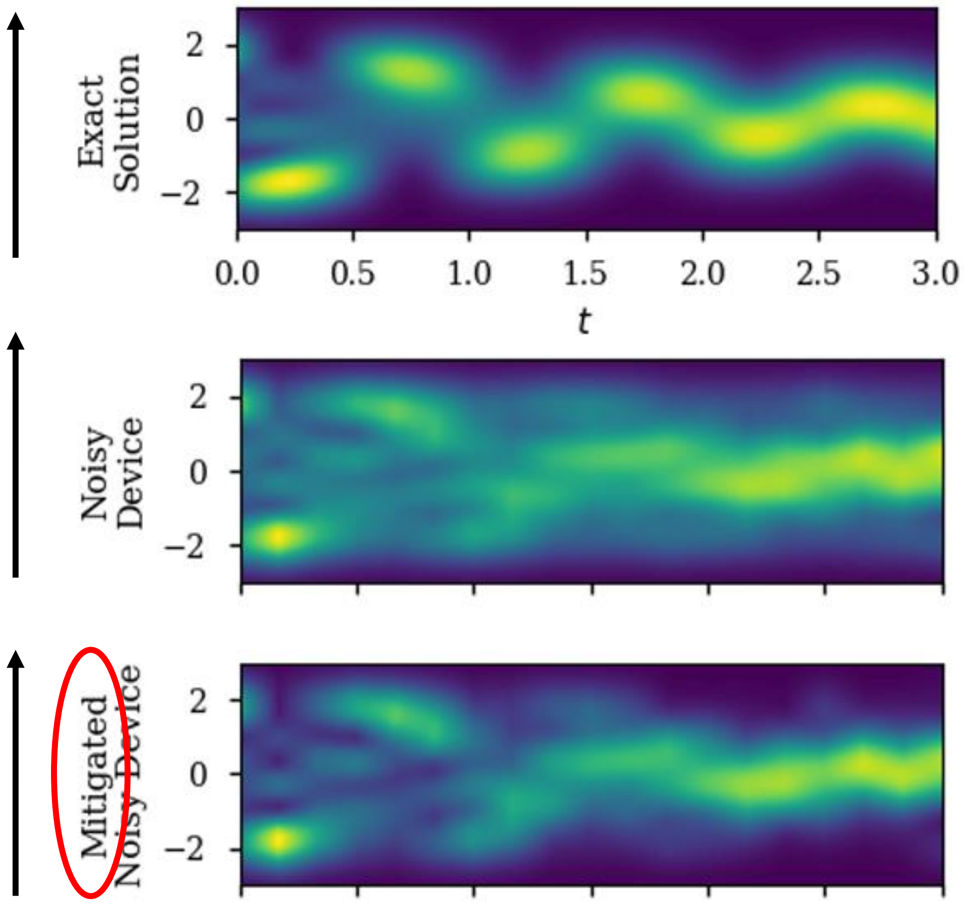

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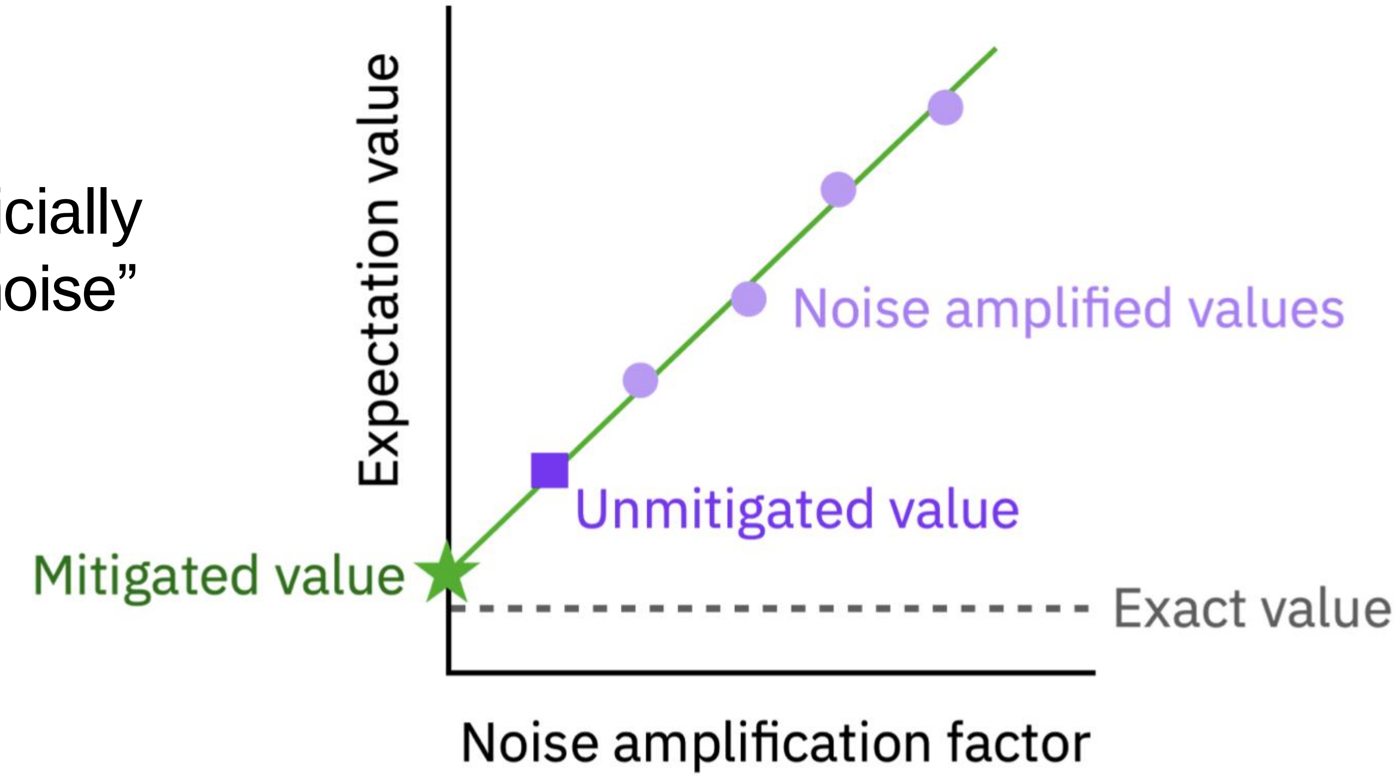
Quantum computers are very noisy!

Error mitigation example: zero noise extrapolation

Idea:
1) increase noise artificially
2) extrapolate to “no noise”
(not necessarily linear)



From Qiskit Github

Conclusions

In the long term, quantum computers will be useful for particle physics calculations

Currently, they are limited by **noise** and **memory**

Many practical and theoretical challenges on the way