The Road to Quantum Advantage

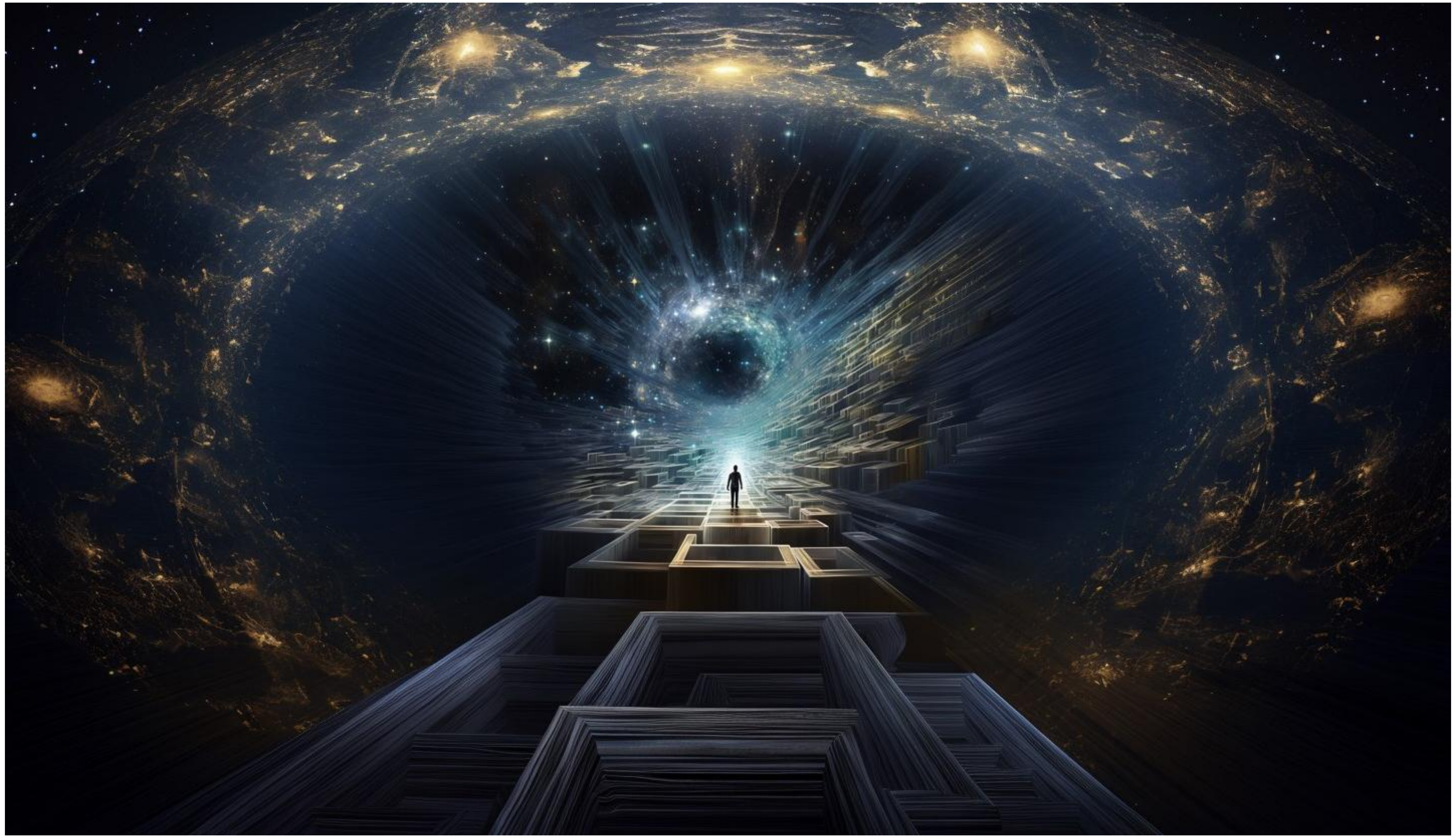
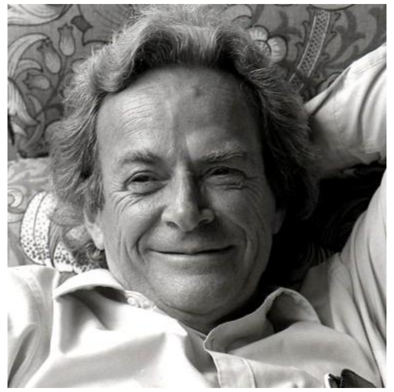


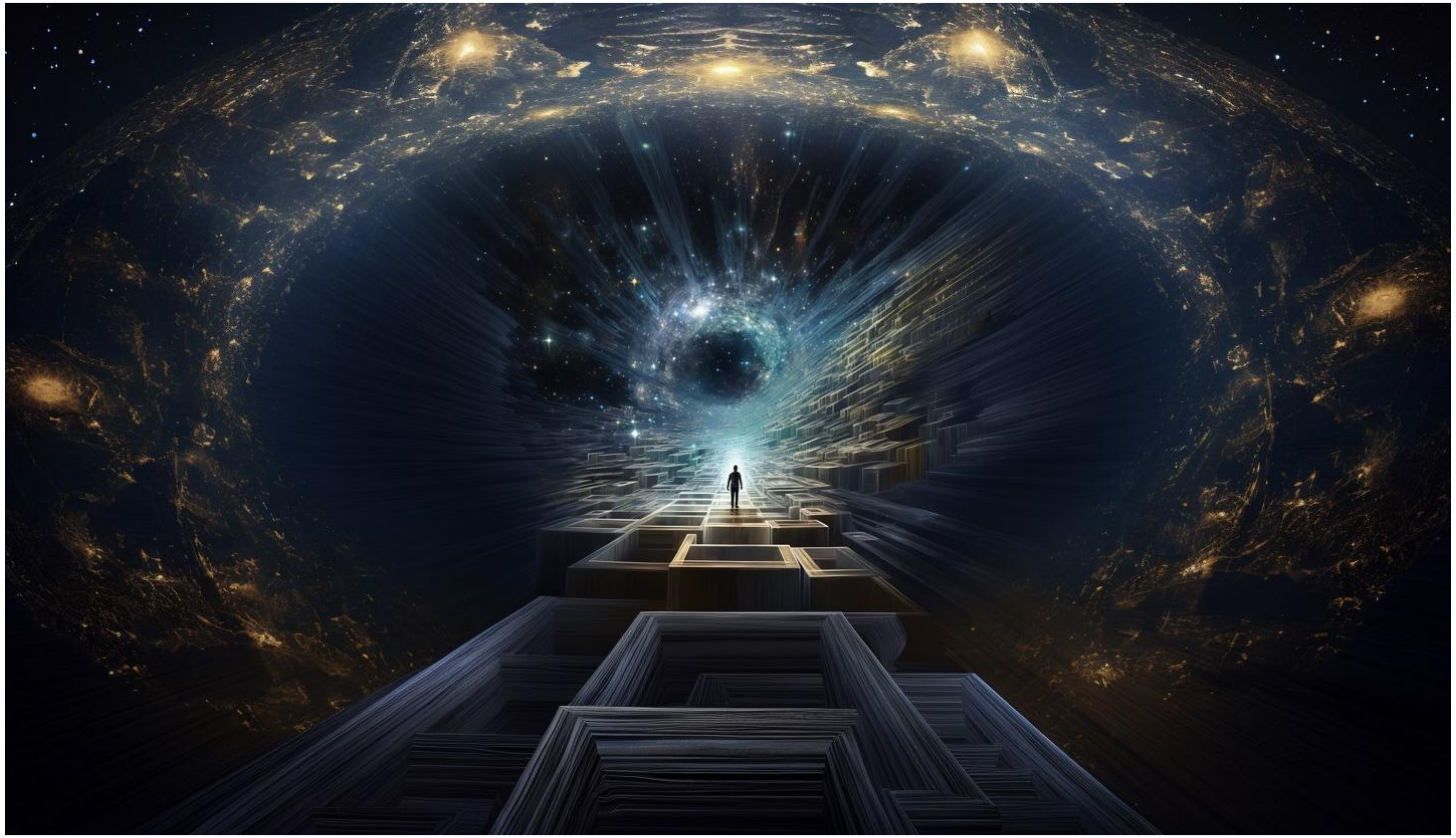
Image generated using Midjourney



INSTITUTE FOR QUANTUM INFORMATION AND MATTER

John Preskill
Kavli Symposium
APS Global Summit
19 March 2026

The Road to Quantum Advantage



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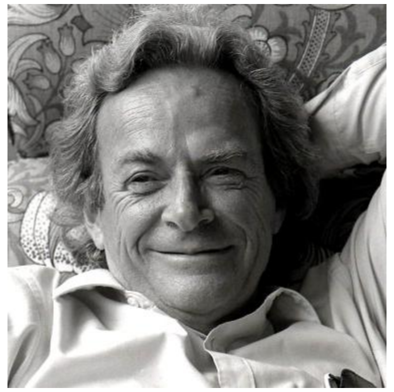


Note: Affiliation with Oratomic, Inc.

Oratomic

How Peter Shor Changed the World

1994: “These algorithms take a number of steps polynomial in the input size, for example, the number of digits of the integer to be factored.”

1995: “It is shown how to reduce the effects of decoherence for information stored in quantum memory, assuming that the decoherence process acts independently on each of the bits stored in memory.”

1996: “This paper shows both how to correct errors in encoded qubits using noisy gates and also how to compute on these encoded qubits without ever decoding the qubits.”

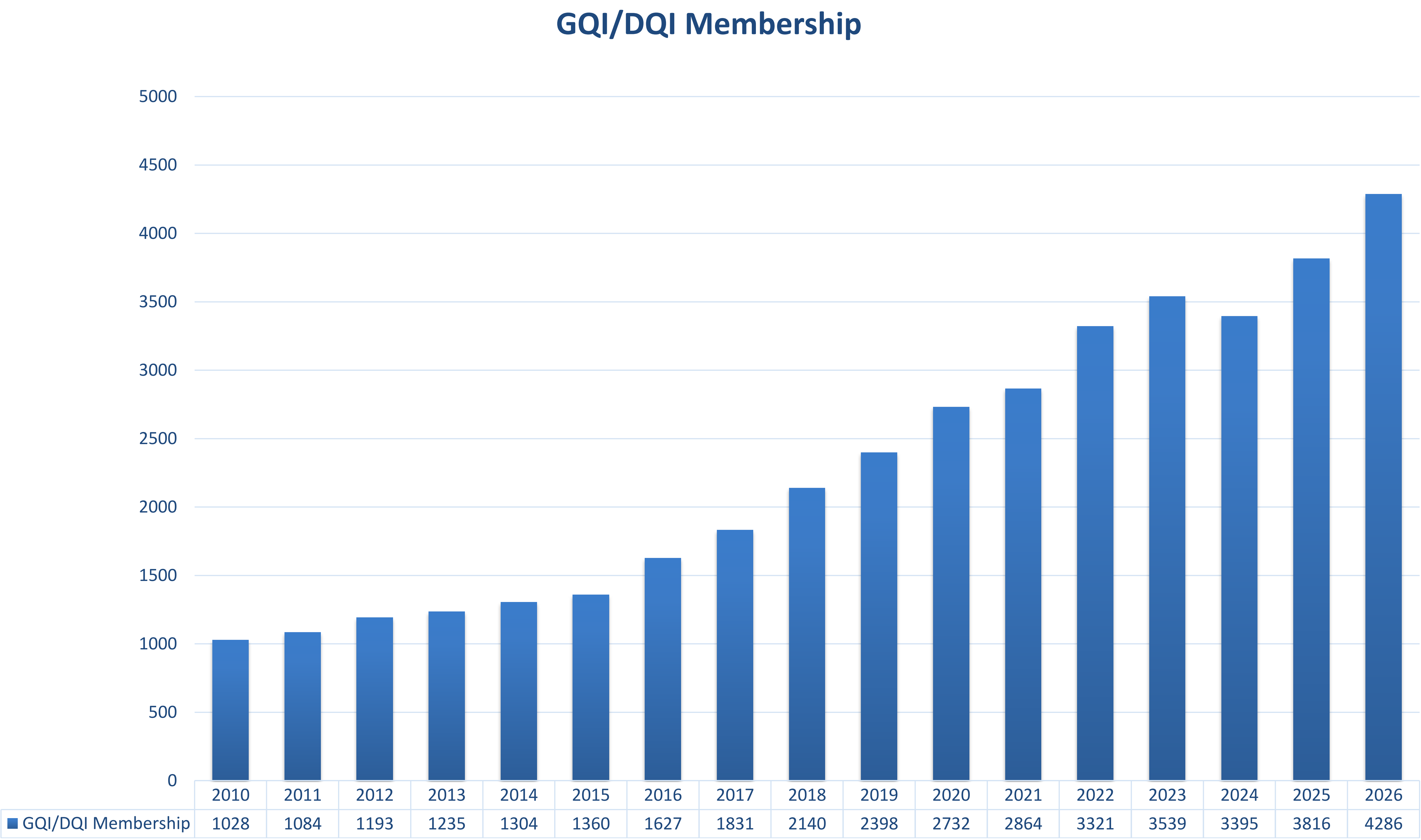
Things are changing

(1) *Quantum advantage emerges.*

(2) *Error correction gets real.*

(3) *Multiple billions invested.*

APS Division of Quantum Information

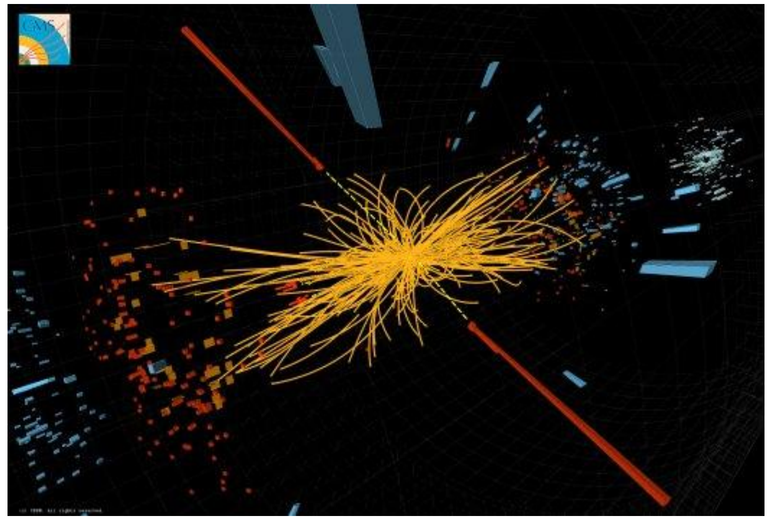


	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
■ GQI/DQI Membership	1028	1084	1193	1235	1304	1360	1627	1831	2140	2398	2732	2864	3321	3539	3395	3816	4286

Founded 2005. Now 8.4% of APS. Membership is 55% students.

Frontiers of Physics

short distance



Higgs boson

Neutrino masses

Supersymmetry

Quantum gravity

String theory

long distance

Large scale structure

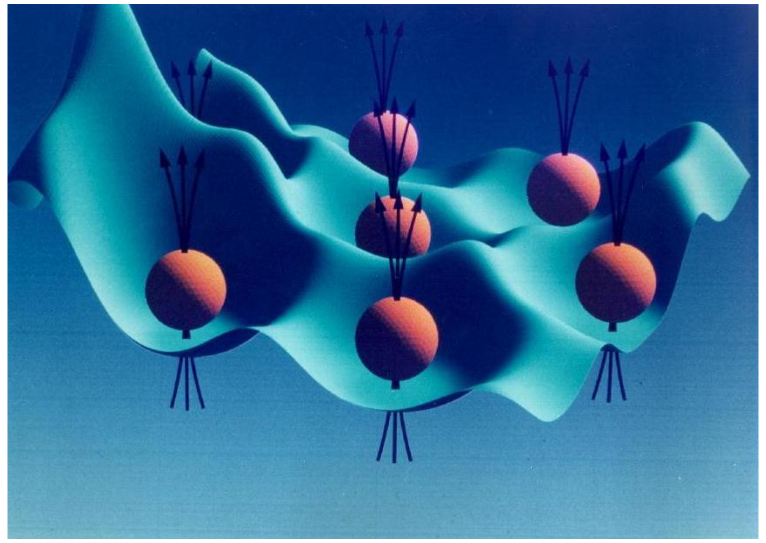
Cosmic microwave background

Dark matter

Dark energy

Gravitational waves

complexity



“More is different”

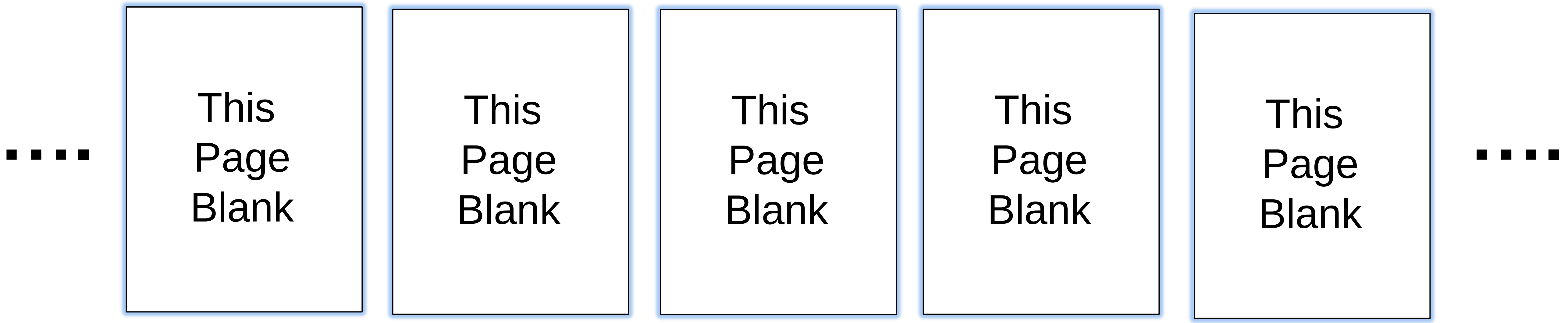
Many-body entanglement

Phases of quantum matter

Quantum computing

Quantum spacetime

Quantum entanglement



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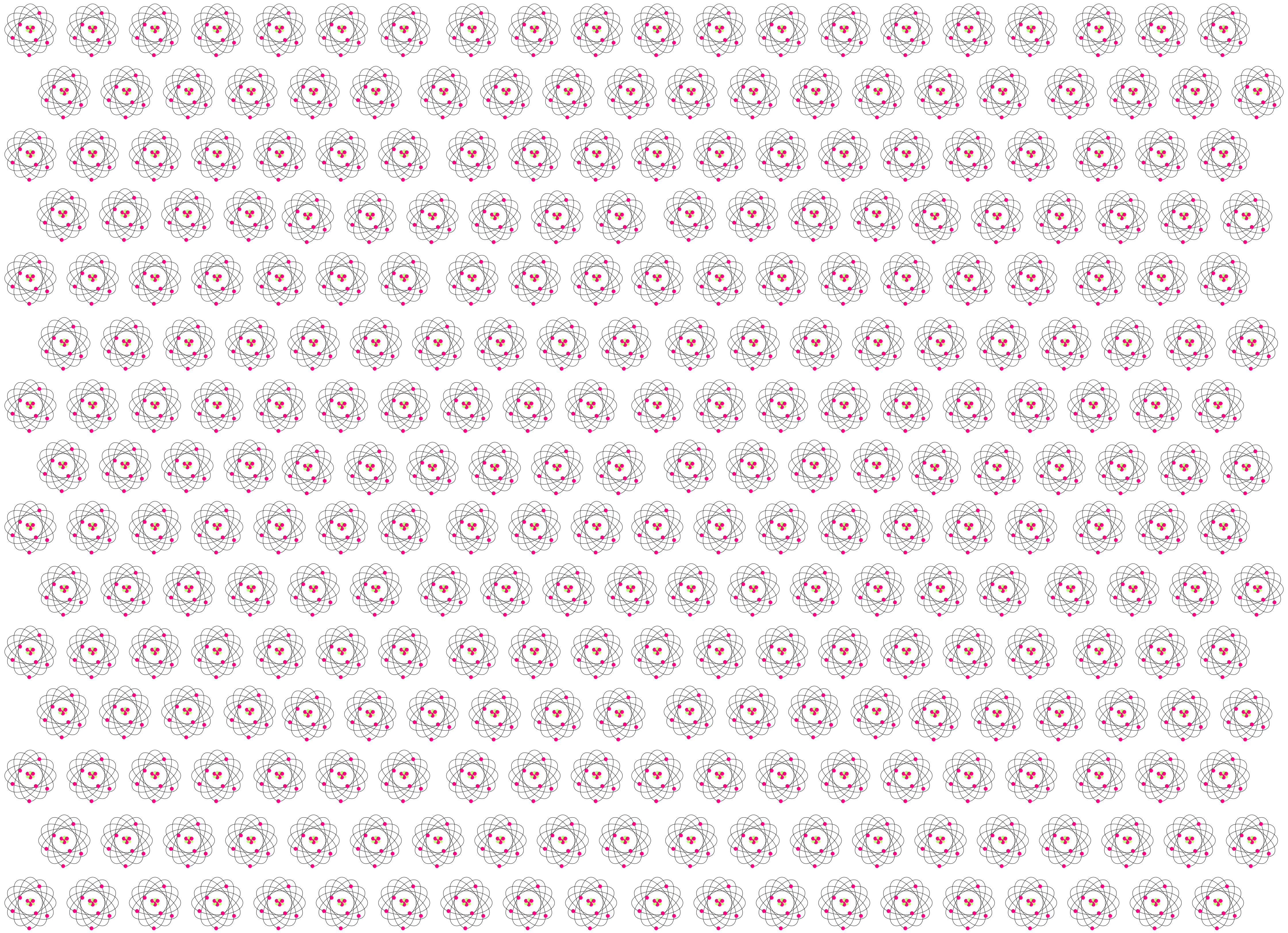
Nearly all the information in a typical entangled "quantum book" is encoded in the correlations among the "pages".

You can't access the information if you read the book one page at a time.



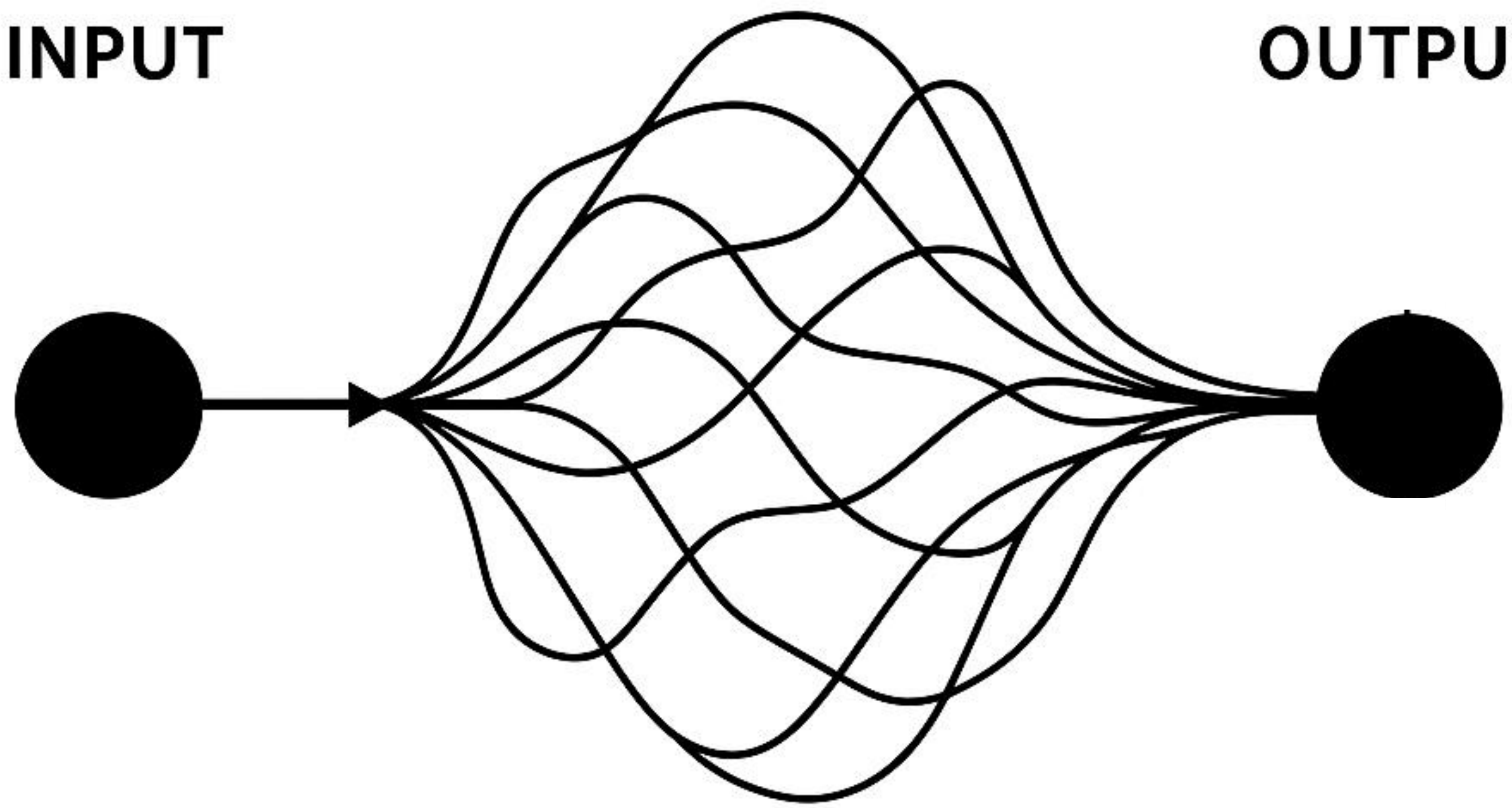
A complete description of a typical quantum state of just 300 qubits requires more bits than the number of atoms in the visible universe.

Why we think quantum computing is powerful

(1) Some computational problems are believed to be hard for conventional computers, yet are easy for quantum computers. Finding prime factors of large composite integers is a prominent example.

(2) We don’t know how to simulate a quantum computer efficiently using a conventional computer.

Quantum superposition and interference

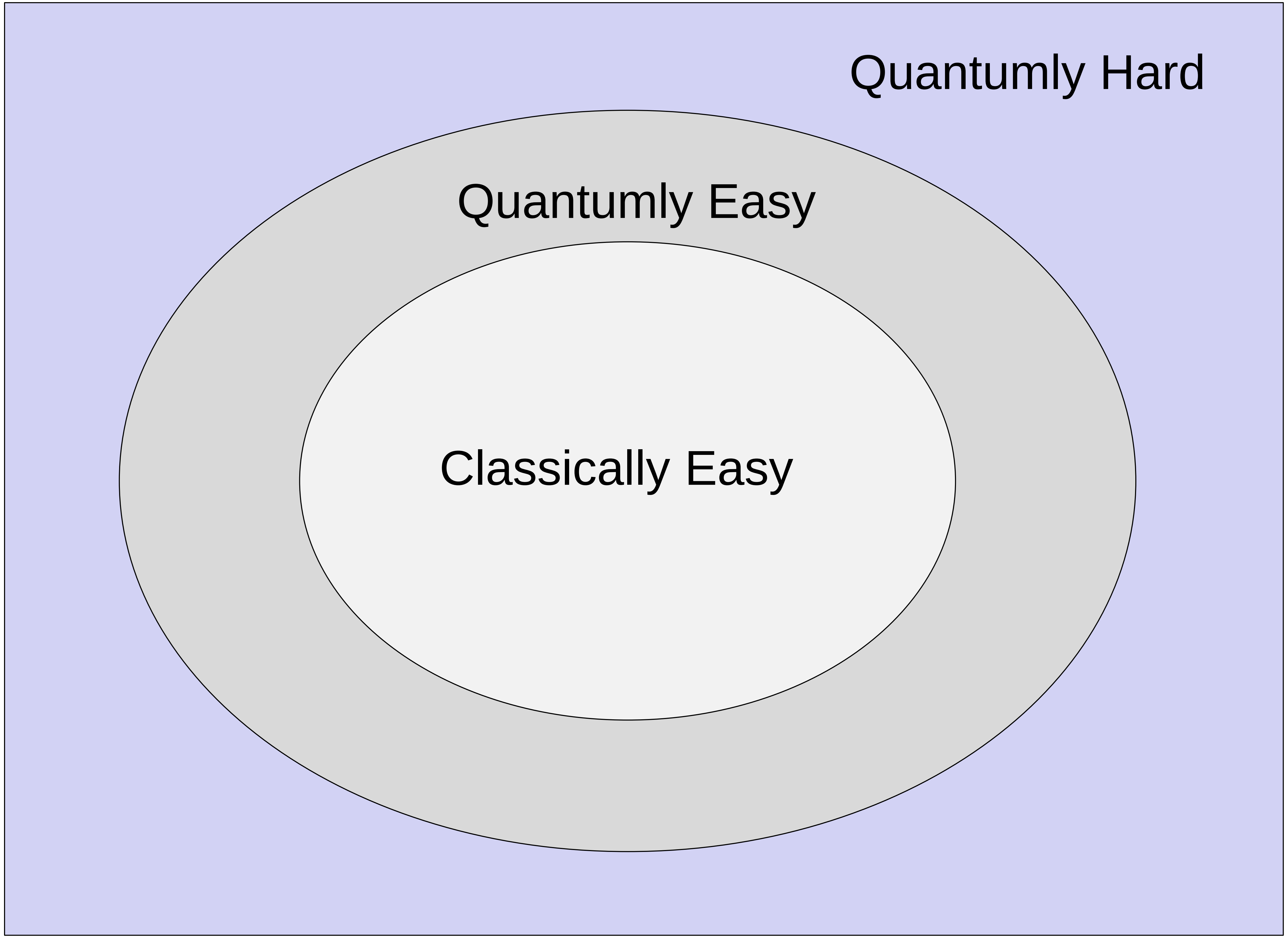


A quantum computation follows many different paths from input to output.

We want paths that end at the right answer to reinforce one another, and paths ending at the wrong answer to cancel out.

We know how to arrange this only for special problems with appropriate structure.

Problems

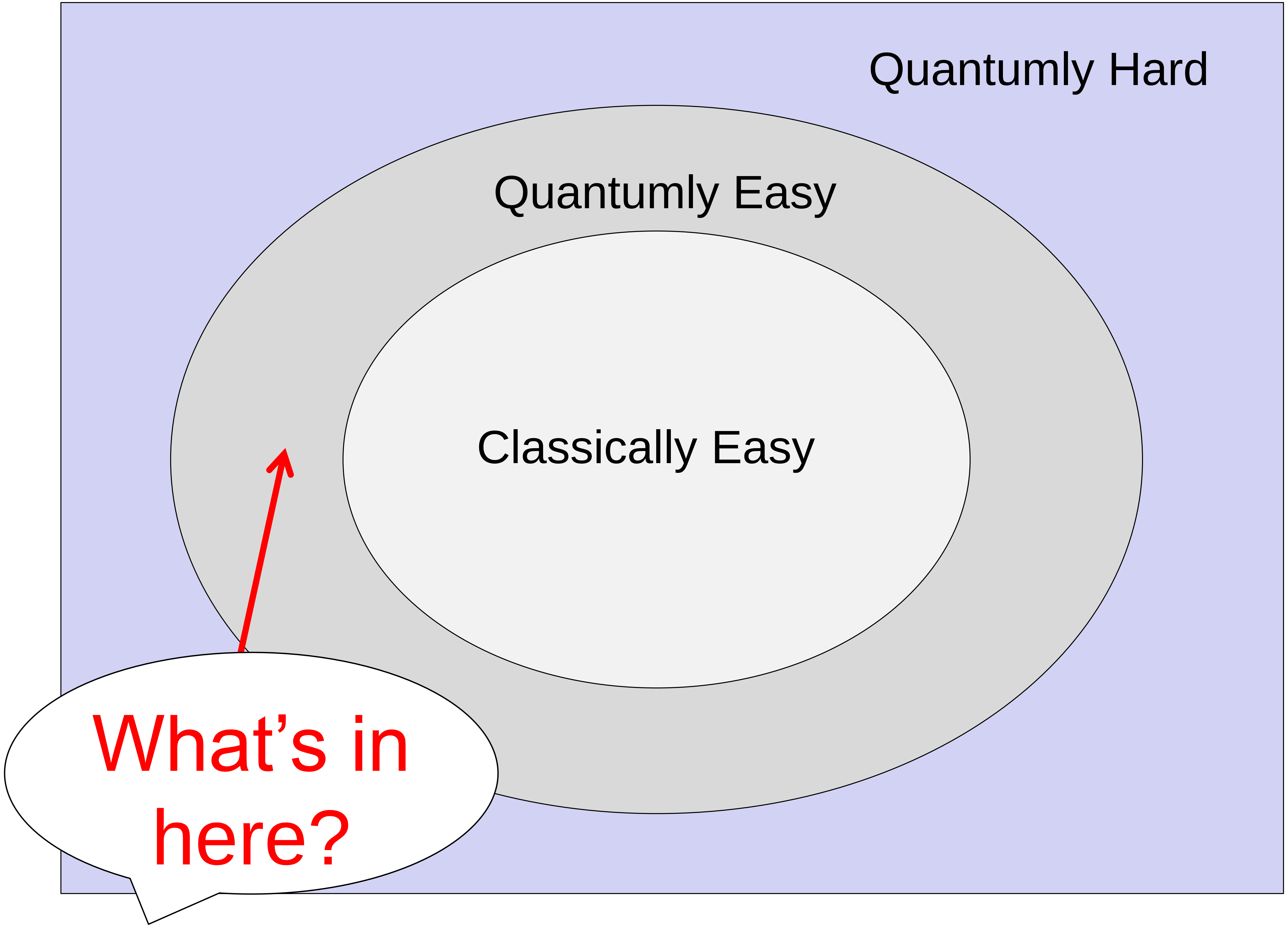


Quantumly Hard

Quantumly Easy

Classically Easy

Problems

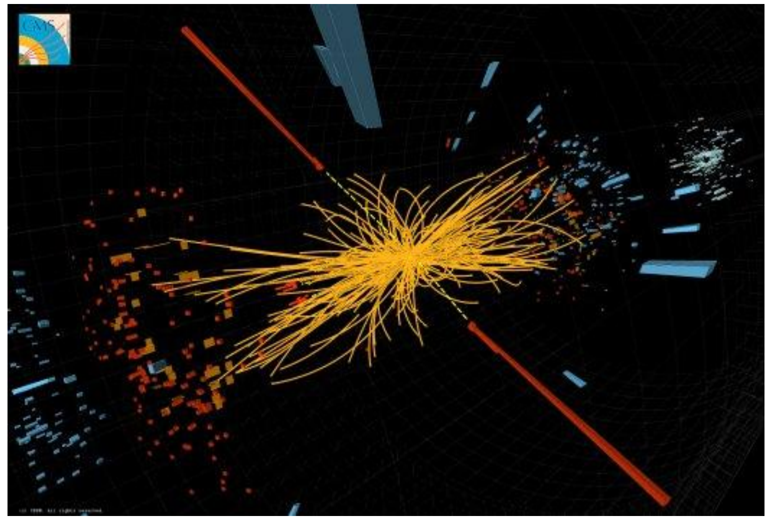


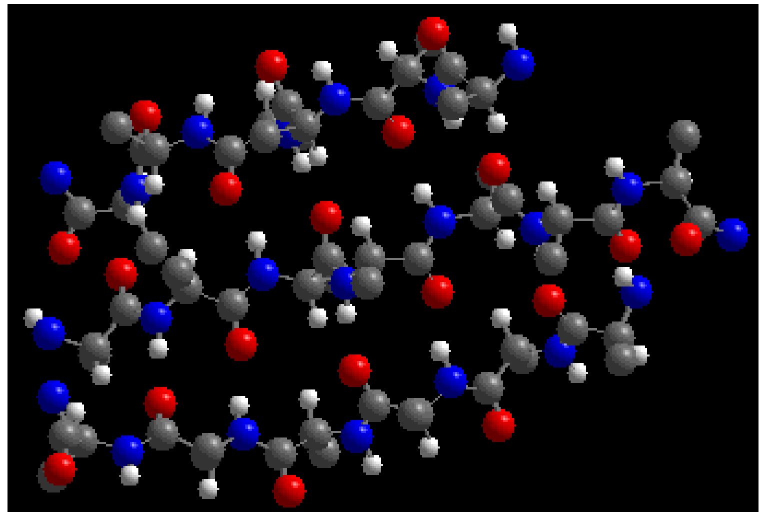
Quantumly Hard

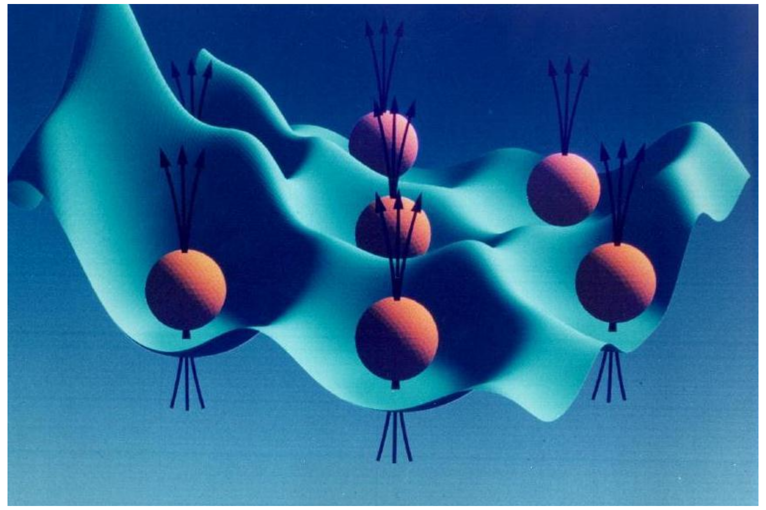
Quantumly Easy

Classically Easy

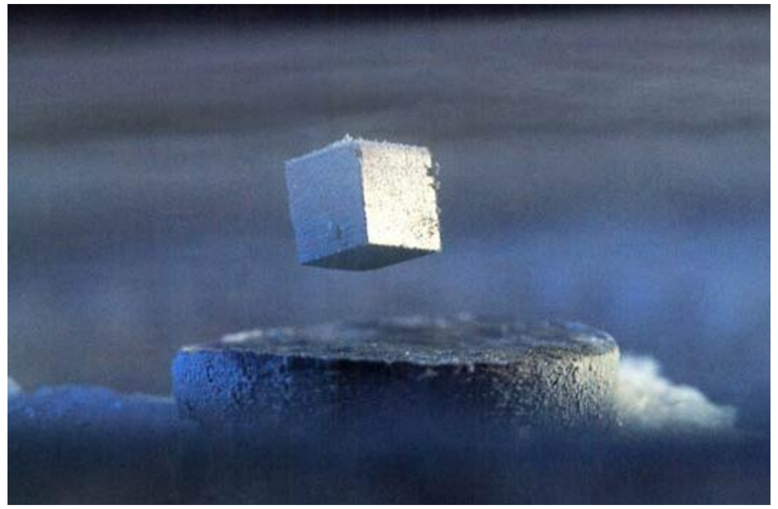
What's in here?

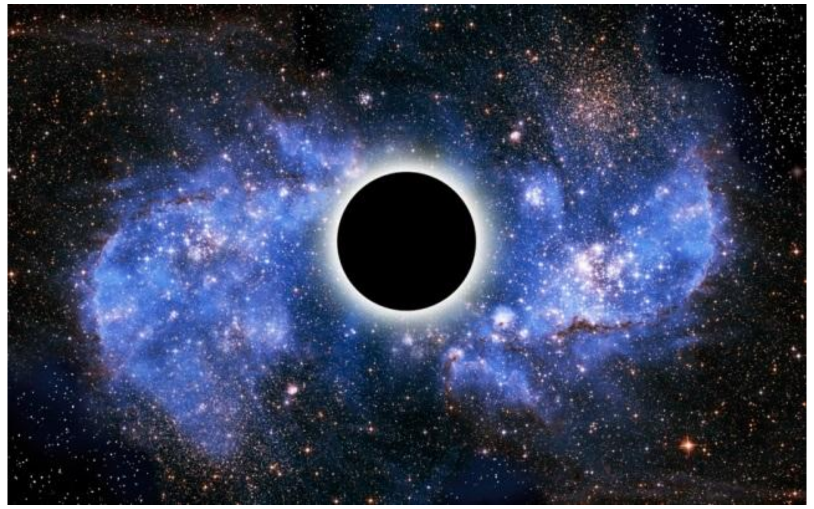

particle collision


molecular chemistry

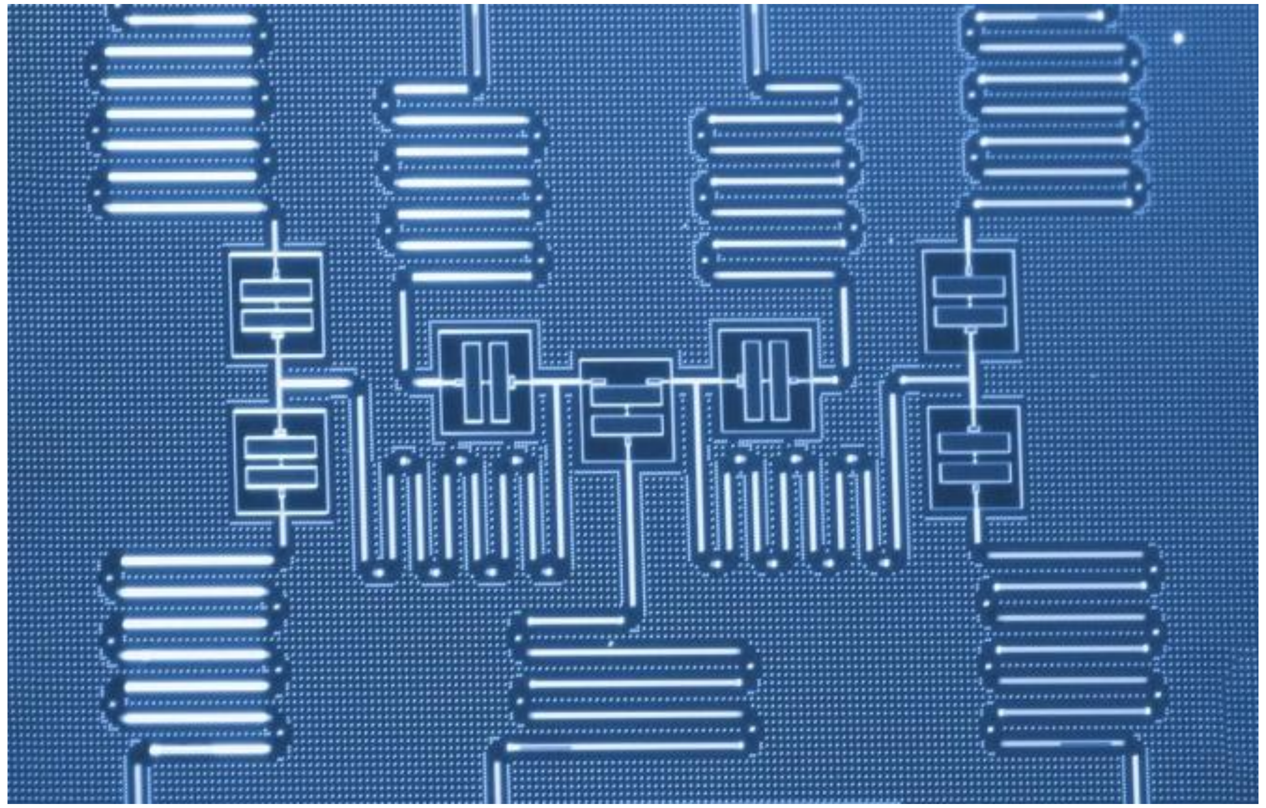

entangled electrons

(We think that) a quantum computer can simulate efficiently any physical process that occurs in Nature.

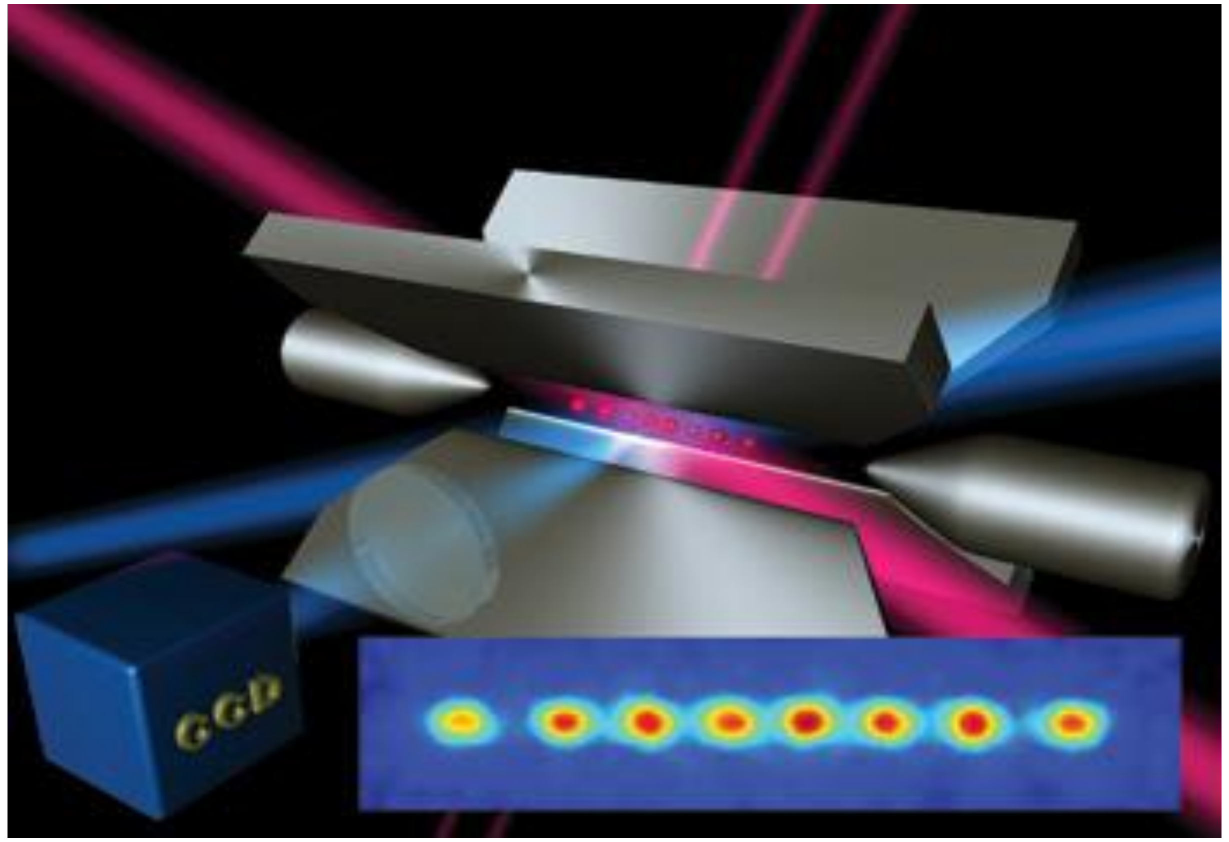

superconductor


black hole

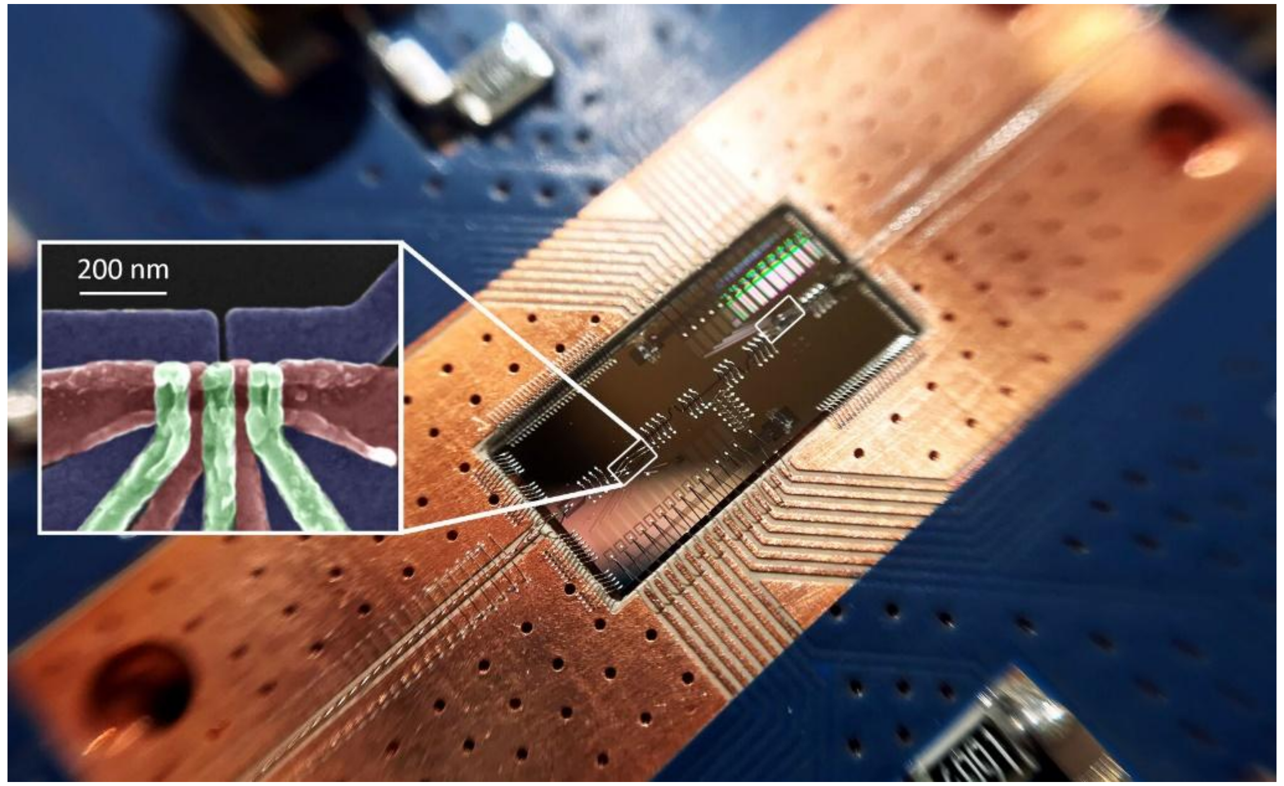

early universe



superconducting qubits



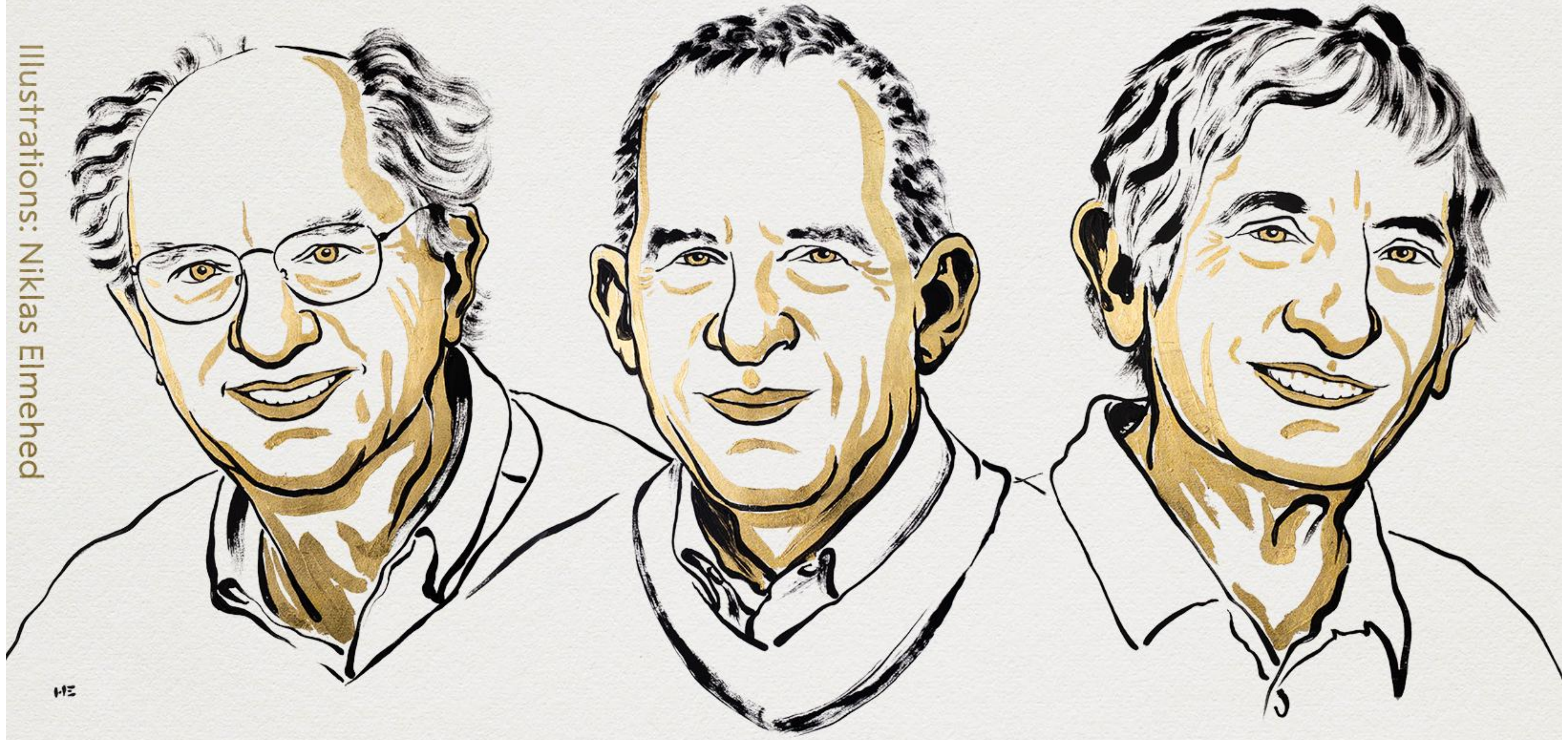
trapped atoms/ions



electron/nuclear spin qubits

photonics

THE NOBEL PRIZE
IN PHYSICS 2025



Illustrations: Niklas Elmehed

John Clarke — **Michel H. Devoret** — **John M. Martinis**

"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

THE ROYAL SWEDISH ACADEMY OF SCIENCES

Why quantum computing is hard

We want qubits to interact strongly with one another.

We don’t want qubits to interact with the environment.

Except when we control or measure them.

Quantum Computer

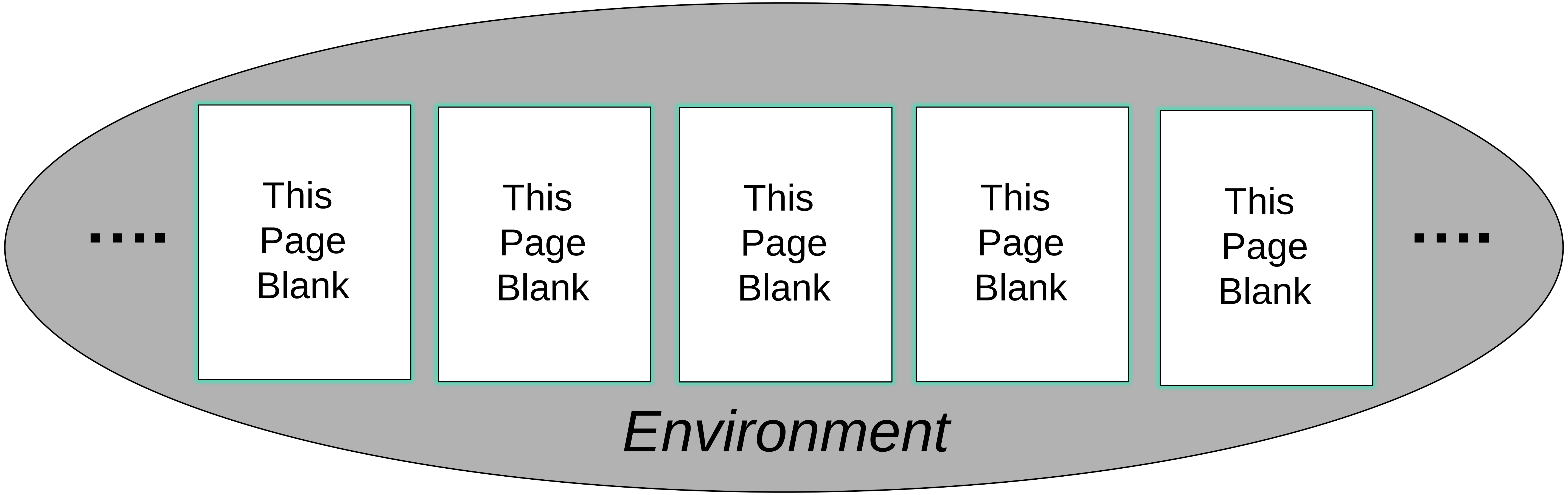
Decoherence

Environment

ERROR!

To resist decoherence, we must prevent the environment from “learning” about the state of the quantum computer during the computation.

Quantum error correction



The protected "logical" quantum information is encoded in a highly entangled state of many physical qubits.

The environment can't access this information if it interacts locally with the protected system.

From NISQ to FASQ

What we have now:

-- *Noisy Intermediate-Scale Quantum (NISQ) machines*.

-- Capable of performing thousands of two-qubit operations.

-- Becoming useful for scientific exploration.

-- Limited commercial value.

What we want to have:

-- *Fault-Tolerant Application-Scale Quantum (FASQ) machines*.

-- Capable of performing billions or trillions of two-qubit operations.

-- Opening a wide variety of scientific and commercial applications.

-- Need to improve error rates by many orders of magnitude!

-- Quantum error correction is essential for crossing from NISQ to FASQ.

Some Recent Highlights

Applications:

Simulations of quantum dynamics

Hardware:

Advancement of superconducting and atomic processors

Error correction:

Advantages from long-range connectivity

Quantum machines for science

Quantinuum Helios: 98 qubits, 2Q gate F=.9992 (MS, all pairs)

IBM Heron: 156 qubits, 2Q gate F=.9988 (median CNOT)

Google Willow: 105 qubits, 2Q gate F=.9988 (mean CZ)

Harvard/QuEra/MIT: 448 qubits, 2Q gate F=.9954 (CZ, low depth)

More than 5K 2Q gates for correlated dynamics, mitigated.

Higher fidelity and nonlocal connectivity vs. more shots.

Correlated fermions in 2D (digital)

Phasecraft / Google Willow (superconducting): Fermi-Hubbard dynamics on 6 x 6 lattice, 2 qubits per site, compare with free fermions for mitigation. 72 qubits, 4372 2Q gates.

Quantinuum Helios (ions): Fermi-Hubbard pairing correlations on 6 x 6 lattice + 18 ancillas, local fermion encoding. 90 qubits, 3439 2Q gates.

Harvard (neutral atoms): Non-abelian spin liquid and Fermi-Hubbard quench dynamics. 72-qubit honeycomb + 32 ancillas, 104 qubits, low depth circuits.

Analog simulations (neutral fermionic atoms in optical lattices): Thousands of lattice sites, but digital provides more flexible initial states, output observables and tunable Hamiltonians.

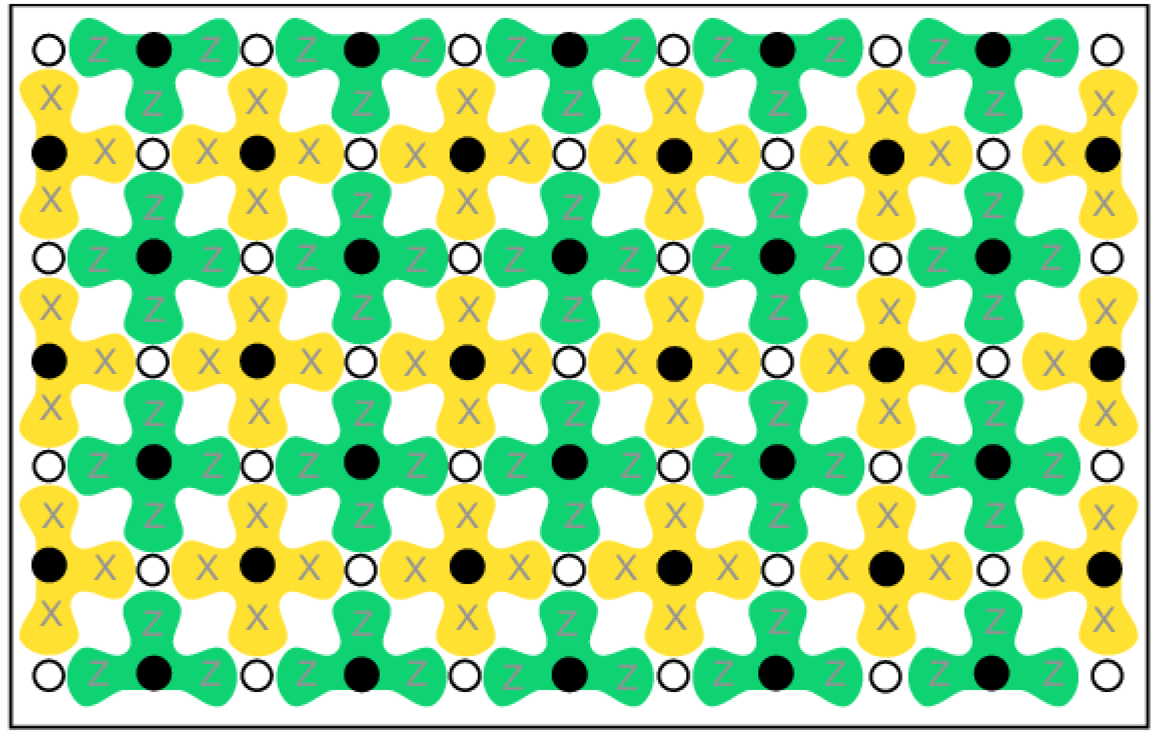
Overhead cost of fault tolerance

$$P_{\text{logical}} \approx C\left(P_{\text{physical}} / P_{\text{threshold}}\right)^{(d+1)/2}$$

$$d = \sqrt{n}, \quad C \approx 0.1, \quad P_{\text{threshold}} \approx .01$$

surface code

Suppose $P_{\text{physical}} = .001, P_{\text{logical}} = 10^{-11}$
$\Rightarrow d = 19, n = 361$ physical qubits per logical qubit, plus a comparable number of ancilla qubits for syndrome measurement. (Improves to $d = 9$ for $P_{\text{physical}} = 10^{-4}$.)



white = data
black = check

Quantum error correction below the surface-code threshold

[*Google Quantum AI 2024*]

105-qubit superconducting Willow processor. Improved transmon lifetime, measurement error, leakage correction.

Millions of rounds of surface-code error syndrome measurement, each lasting ~1 microsecond (600 nanosecond measurement time).

Logical error rate for quantum memory improves by $\Lambda \approx 2$ when code distance increases by 2 (from 3 to 5 to 7).

Looking ahead: Better Λ, larger codes, high-fidelity logical two-qubit gates.

Quantum low-density parity-check codes

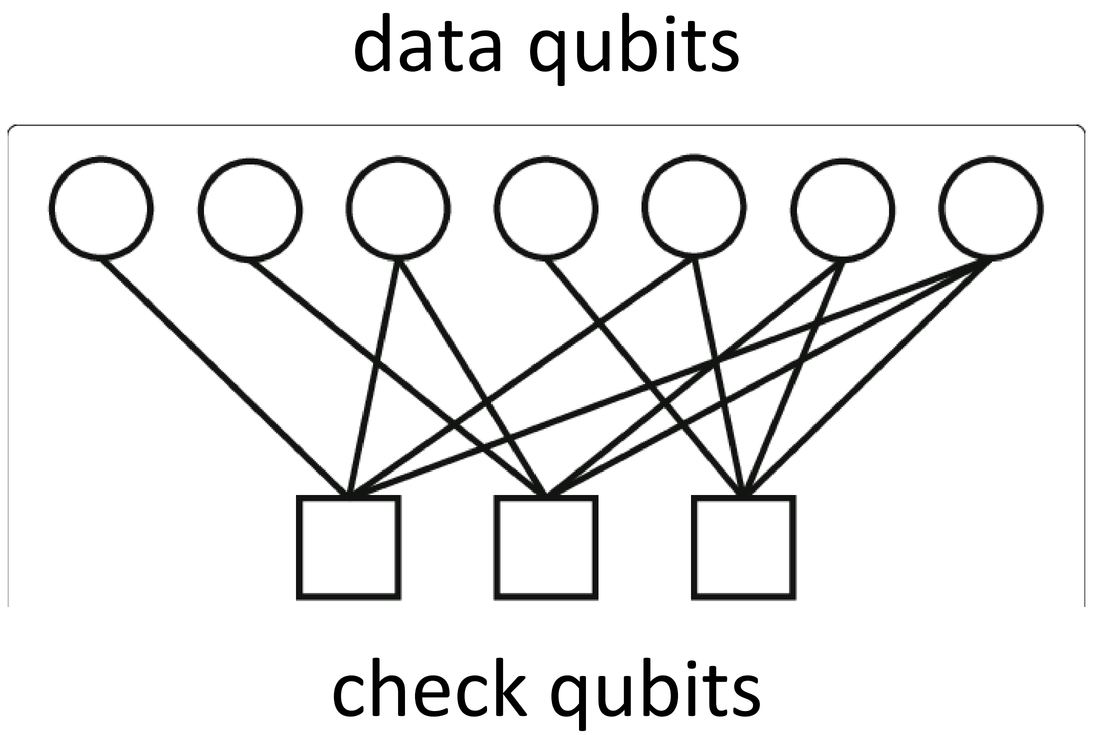
The *n* physical qubits obey *n*-*k* constraints ("checks"), leaving *k* "logical" qubits.

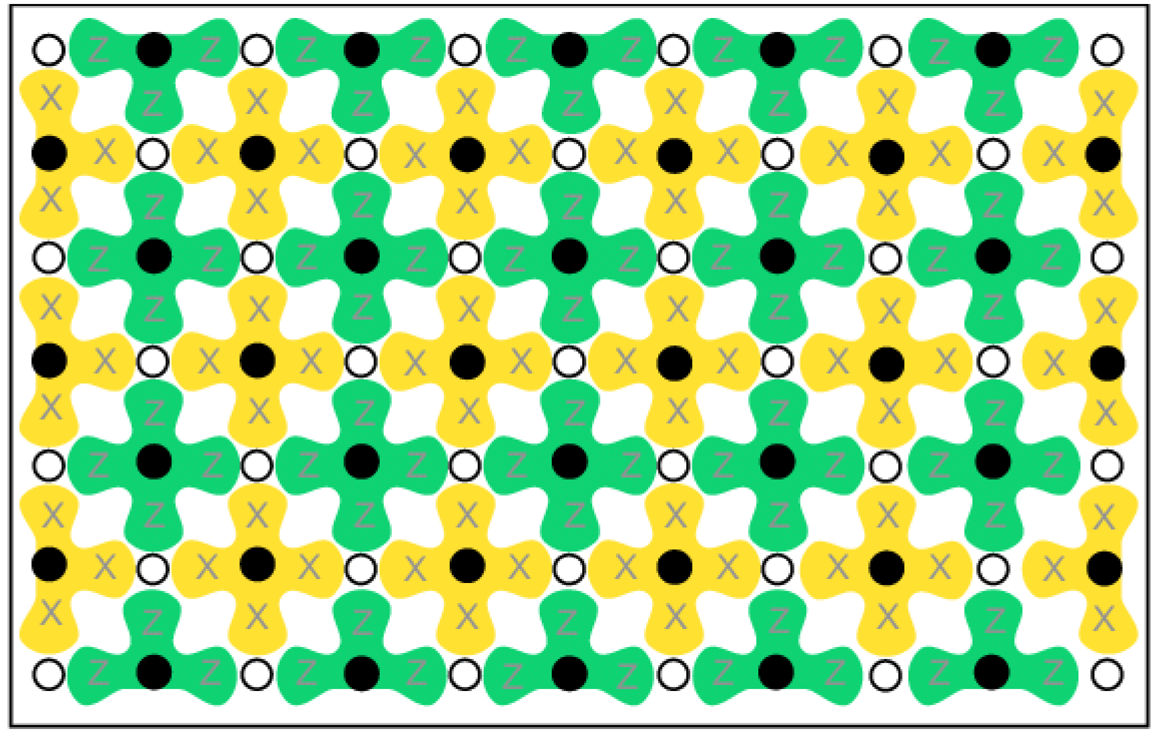
Each logical operator acts on at least *d* physical qubits ("distance" *d*).

Each constraint acts on few physical qubits, and each physical qubit is involved in few constraints.

Surface code: checks are geometrically local in 2 dimensions. *k*=1 logical qubits per block.

High-rate codes: large *k* and *d* via nonlocal connectivity.





surface code

The joy of nonlocal connectivity

Long-range connections might require complex fabrication in solid state devices.

More natural for movable qubits in ion traps and neutral atom arrays.

Higher encoding rates with quantum low-density parity-check (qLDPC) codes. Reduced number of physical qubits, high threshold, feasible decoders.

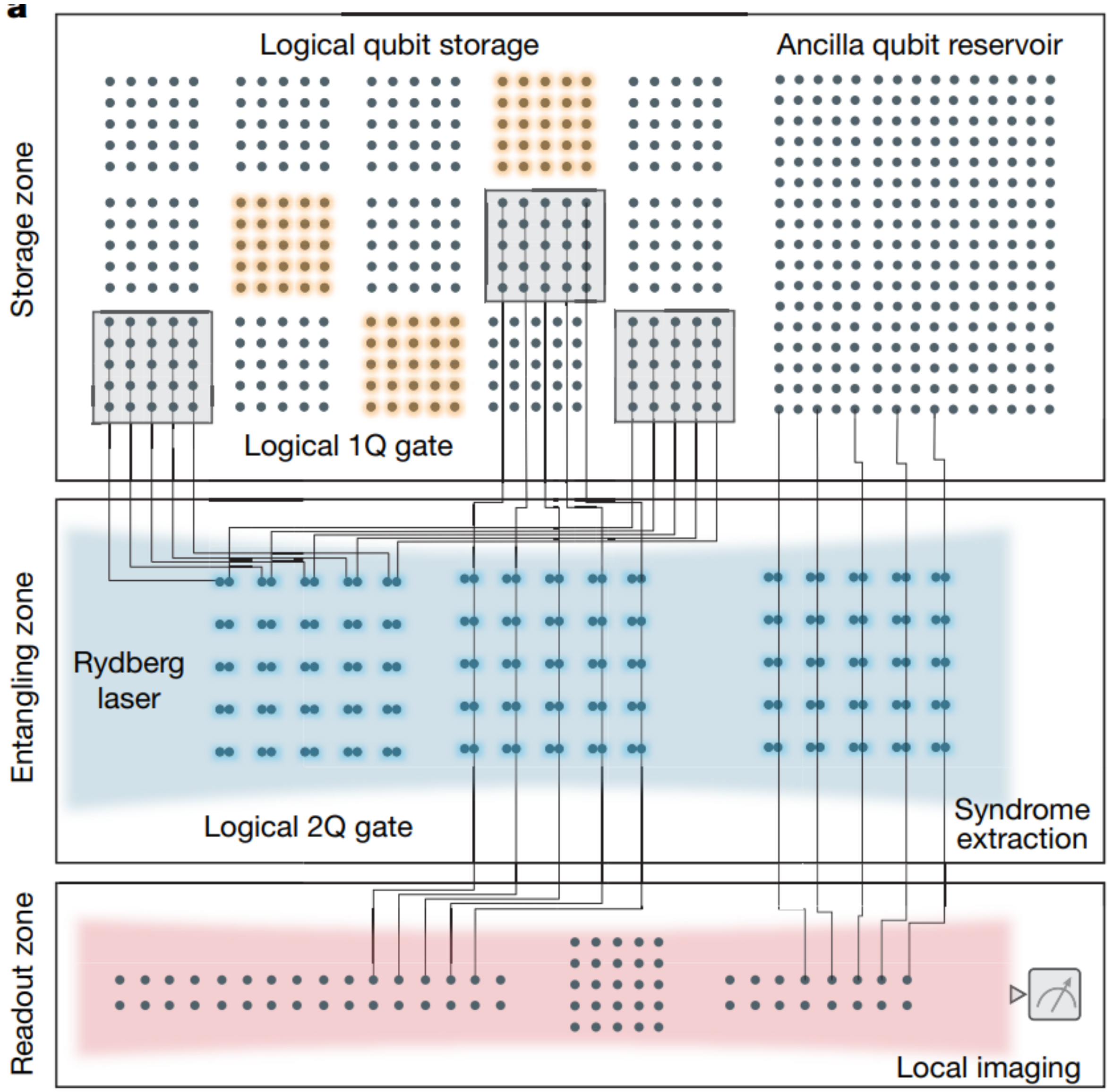
Universal gate gadgets for qLDPC codes with reduced spacetime cost.

These advantages partially compensate for the slow clock speed.

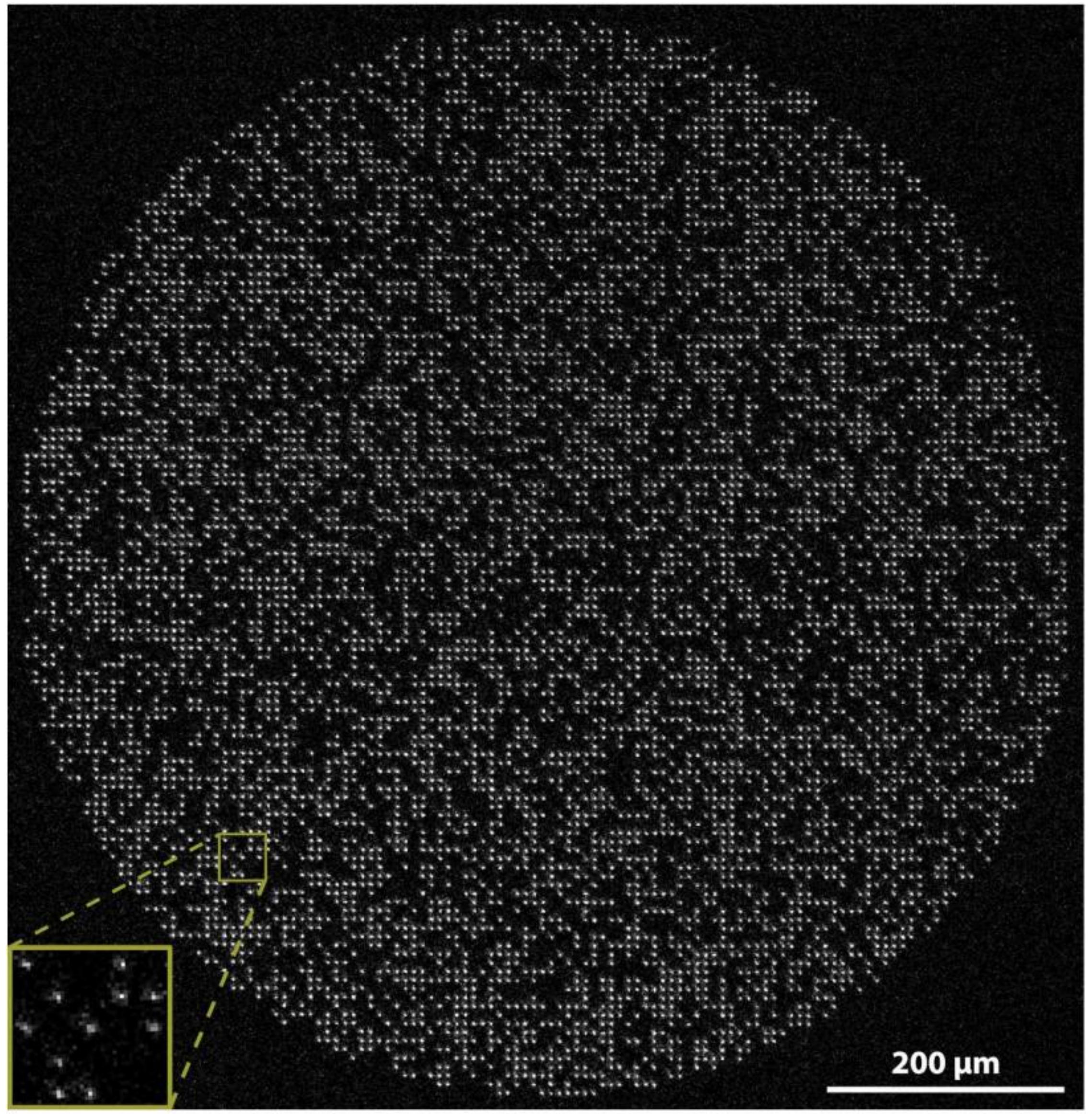
Reconfigurable arrays of neutral atoms

Traveling qubits for measuring nonlocal check operators.

Efficient logical operations on high-rate code blocks.



Logical processor based on reconfigurable atom arrays
Bluvstein et al. Nature 2024



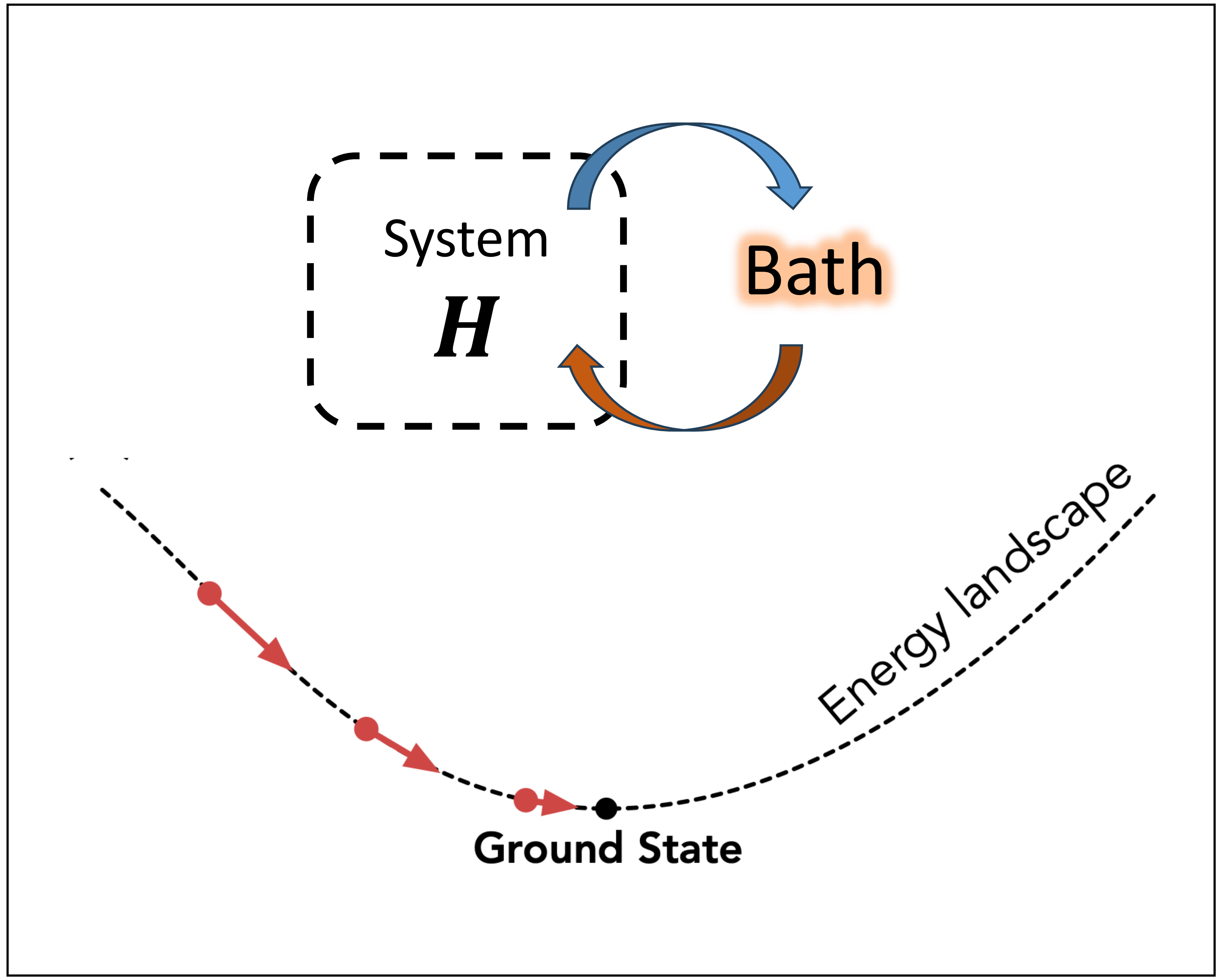
Tweezer array with 6100 highly coherent atomic qubits
Manetsch et al. Nature 2025

Quantum advantage in cooling to local minima

For a 2D quantum system, finding a local minimum under thermal perturbations is (worst-case) classically hard and quantumly easy!

For typical physical systems, classical algorithms are nonetheless used routinely (e.g. DFT, DMRG, tensor networks, etc.), often with great success.

How to identify physically relevant systems where *quantum beats classical*?



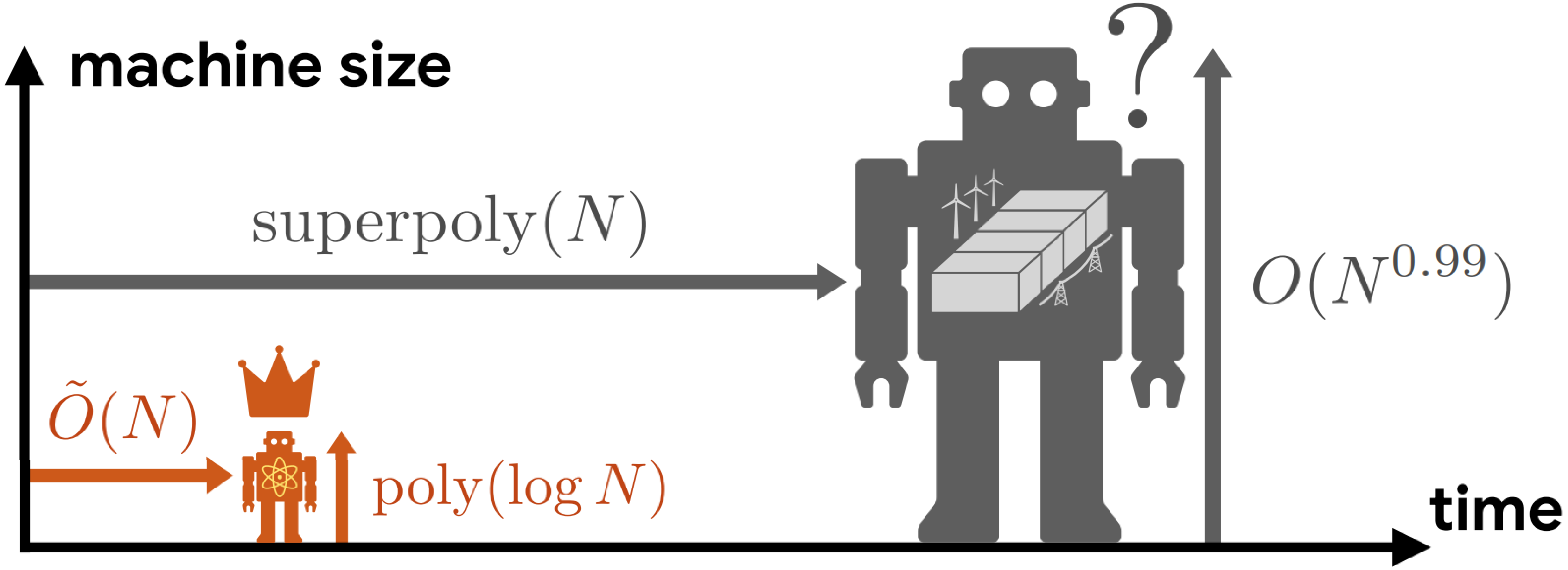
Chen, Kastoryano, Brandão, Gilyén 2025
Chen, Huang, Preskill, Zhou 2025
Ding, Zhan, Preskill, Lin 2025

Will AI eat quantum's lunch?

We'll need training data from quantum computers, simulators, experiments.

Huang, Boughton, Cotler, et al. 2022
Lewis, Huang, Tran, et al. 2024

Processing massive classical data on small quantum computers



Exponential memory advantage for e.g. classification, dimension reduction.

Quantum memory size poly(log *N*) suffices for dimension-*N* task.

Classical machine with size sublinear in *N* requires superpoly(*N*) time.

Exponentially compact classical models possible only with quantum technology.

Zhao, Zlokapa, Neven, Babbush, Preskill, McClean, Huang 2026

Open Questions

How will we scale up to quantum computing systems that can solve hard problems?

What are the important applications for science and for industry?

Prospects for the next 5 years

Encouraging progress toward scalable fault-tolerant quantum computing.

Scientific insights enabled by programmable quantum simulators and circuit-based quantum computers.

Imagining the future

In 1945, John von Neumann wrote to Lewis Strauss about the potential uses of fast electronic computers:

"... Uses which are not, or not easily, predictable now, are likely to be the most important ones. Indeed they are by definition those which we do not recognize at present because they are farthest removed from what is now feasible, and they will therefore constitute the most surprising and farthest-going extension of our present sphere of action in mathematics and in applied mathematics."

The world of quantum advantage extends far beyond what we can rigorously establish.

Reasonable … but to what extent can this be formalized as a meta-theorem?

Huang, Choi, McClean, Preskill 2025

Theorem:
Predicting quantum advantage is classically hard

Decision problem: Does executing a given quantum computation achieve advantage over a classical heuristic for the same computation?

A quantum computer can solve this efficiently; a classical computer cannot.

Huang, Choi, McClean, Preskill 2025

Prospects for the next 100 years

Past 100 years:
The relatively simple quantum behavior of weakly correlated particles like electrons, photons, etc.

Next 100 years:
The extraordinarily complex quantum behavior of many profoundly entangled particles.