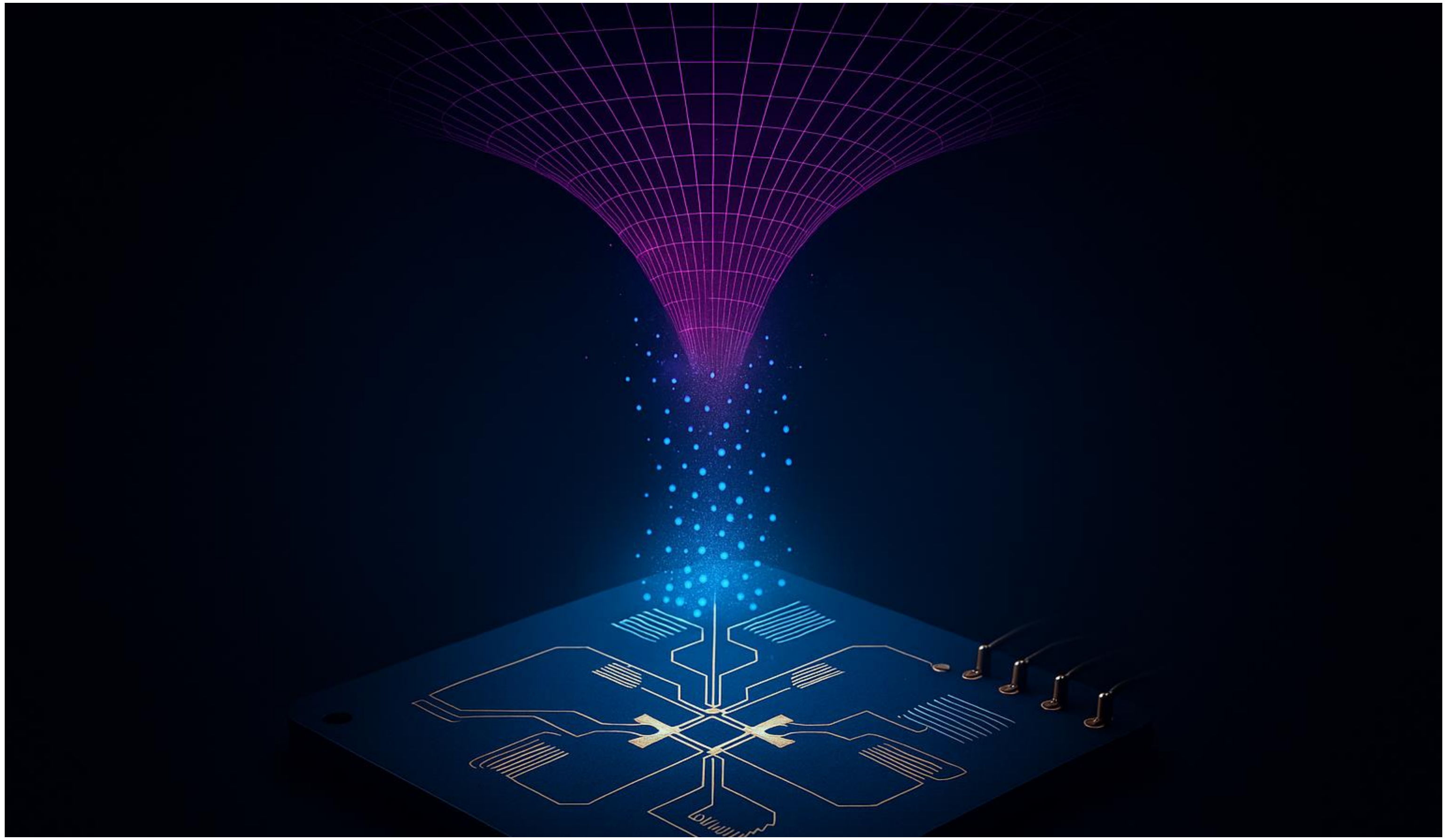
Quantum gravity in the lab?



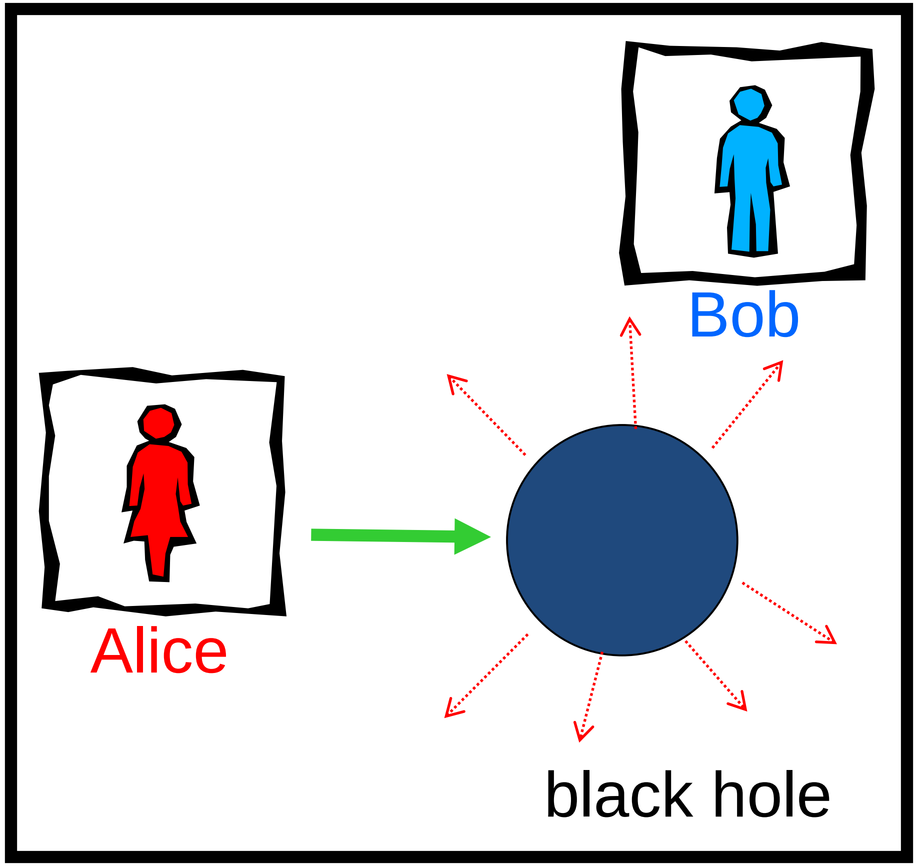
ChatGPT o3

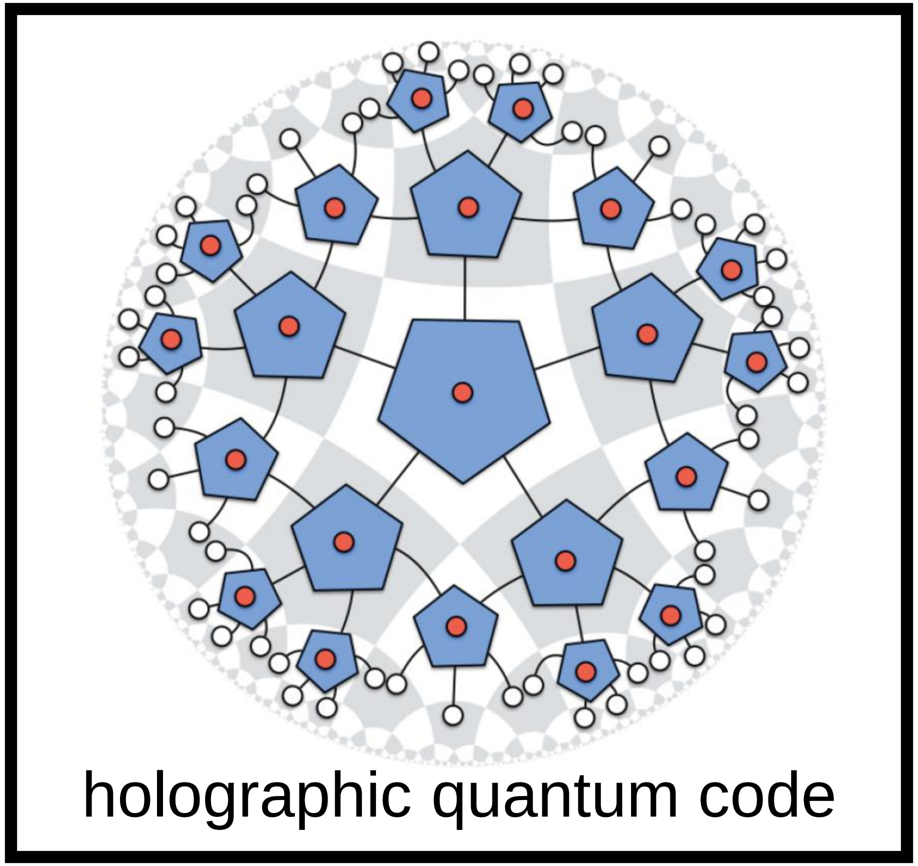
John Preskill
Caltech Physics Salon
19 July 2025

INSTITUTE FOR QUANTUM INFORMATION AND MATTER

@preskill

Quantum Information and Spacetime





INSTITUTE FOR QUANTUM INFORMATION AND MATTER

GORDON AND BETTY MOORE FOUNDATION

John Preskill, Caltech
Physics Salon, 27 May 2017

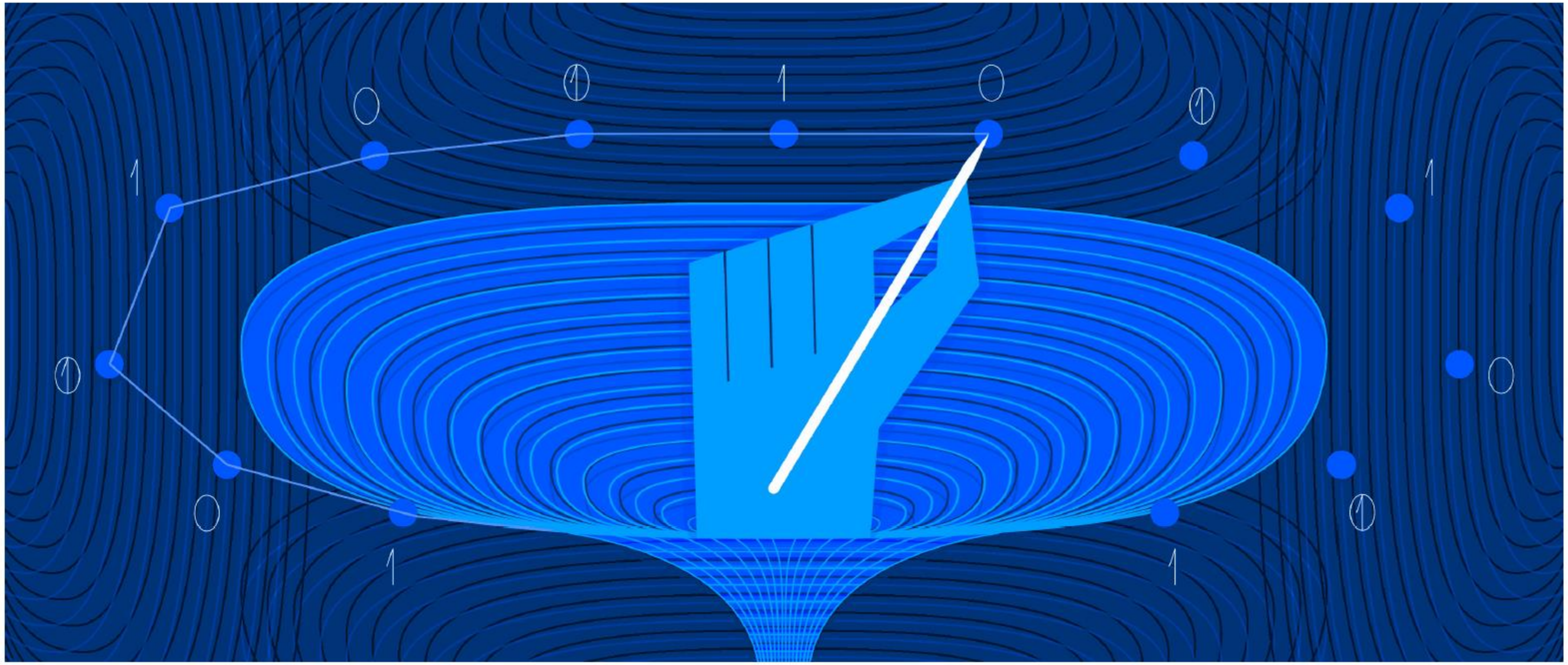
Quanta magazine

Spotting Quantum Black Holes in the Lab

By John Preskill

July 15, 2020

Can we test speculations about how quantum physics affects black holes and the Big Bang?



James O’Brien for Quanta Magazine

On June 6, 1925, a swollen-faced, stuffy-nosed Werner Heisenberg, then 23 years old and suffering from hay fever, left his home in central Germany for the fresh air of the North Sea island of Helgoland, hoping for relief. There, he had a breakthrough, becoming the first to articulate a mathematical framework of quantum mechanics and resolve the then-glaring contradictions of quantum theory.

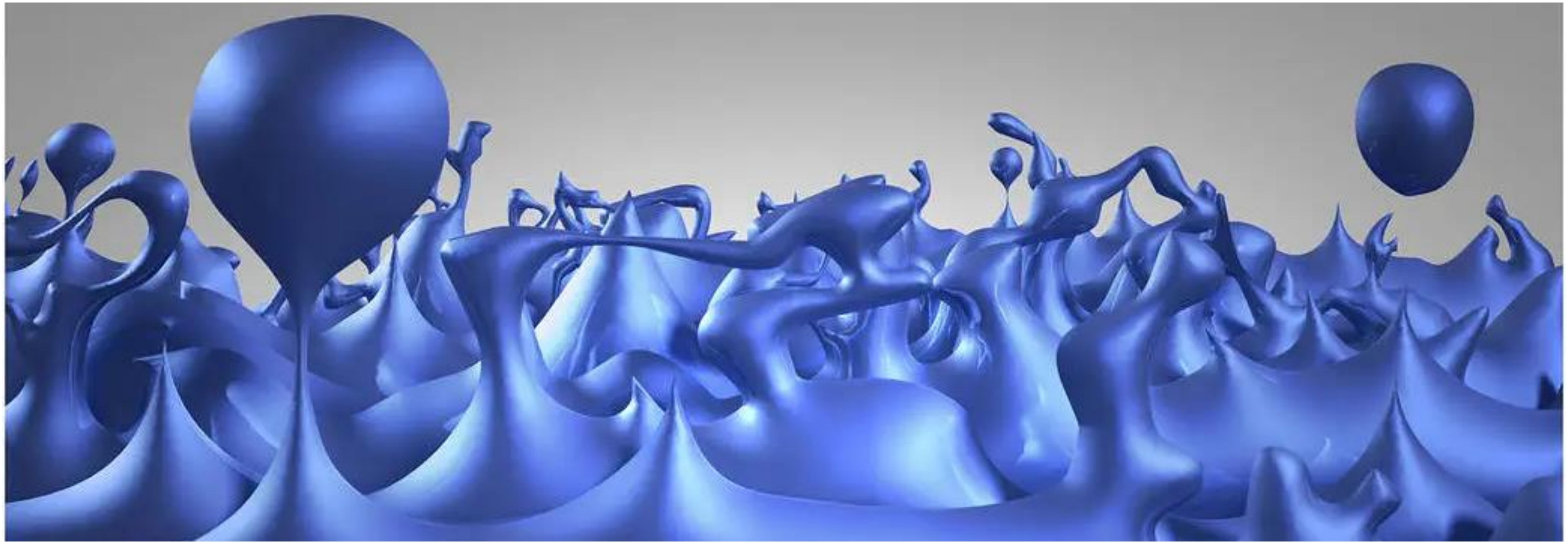
APS News, 1 July 2025

Heisenberg in the 1920s

Atoms, molecules, matter, elementary particles, quantum fields, ….

But … what about quantum gravity?

General relativity tells us spacetime is dynamical. What are its quantum properties?



NASA

Why quantum gravity?

Erect a complete theory of all fundamental interactions.

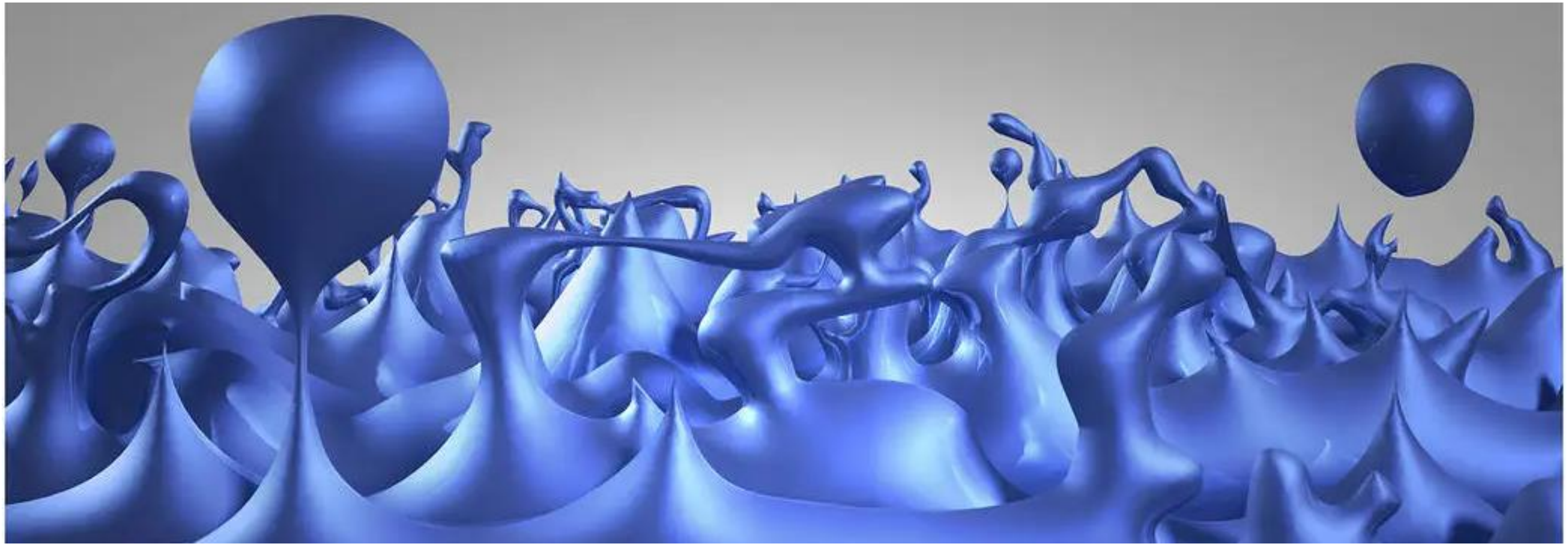
Resolve deep puzzles about quantum black holes.

Understand the early history of the universe.

Learn broader lessons applicable in other contexts.

Use gravitational intuition to understand complex emergent quantum phenomena.

It's fun.



NASA

Planck length $L_{Pl} = \sqrt{\frac{\hbar G}{c^3}} = 10^{-35}$ meters

Oy vey …

Quantum gravity is difficult!

Conceptual difficulties: defining observables in fluctuating spacetime.

Experiments provided essential guidance for building the standard model of particle physics, excluding gravity.

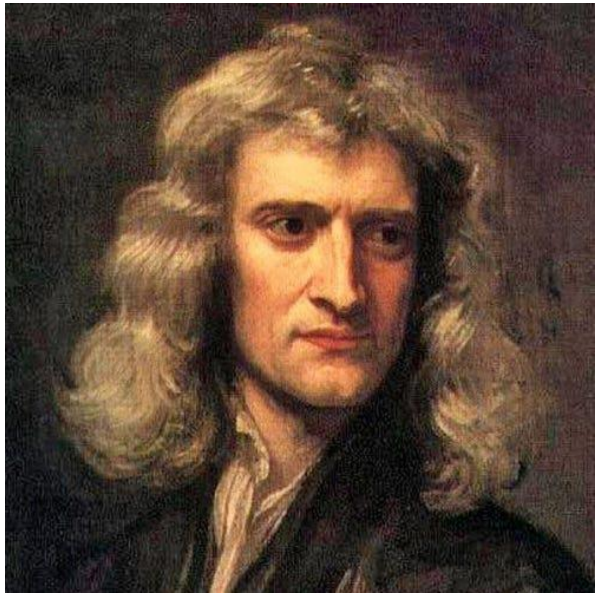
But it is hard to do experiments which explore quantum gravity.

We are trying simultaneously to determine both what the theory predicts and what the theory is.

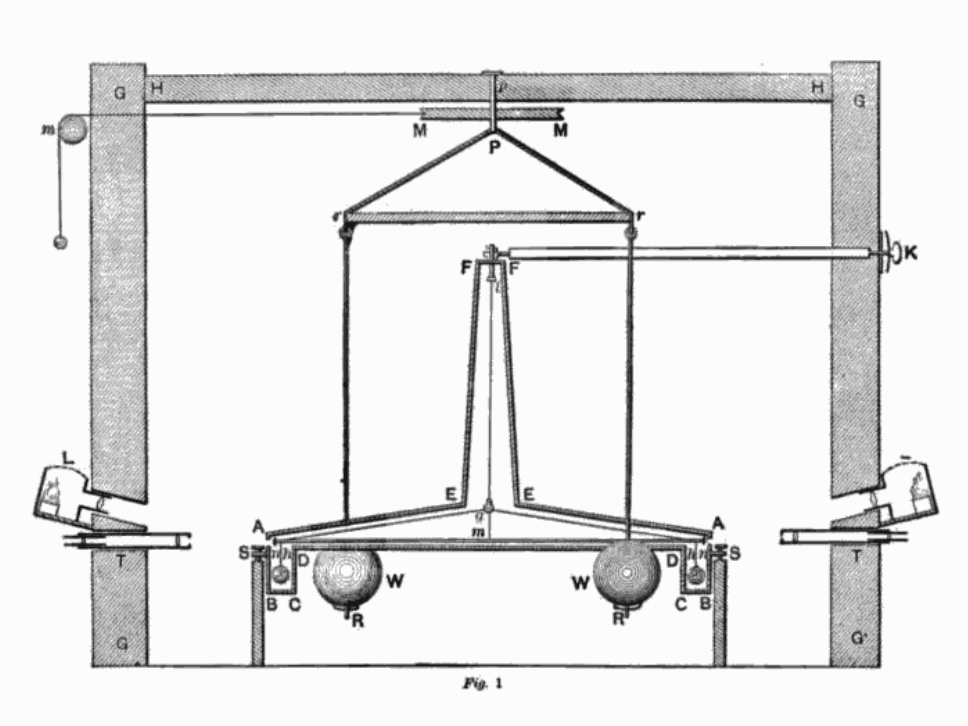
Are we smart enough to figure it out?

I don’t know … But why not?

Measuring Newton's constant



Isaac Newton



Henry Cavendish

227 years since Cavendish. Newton did not foresee the technology and ingenuity that would enable measurement of the gravitational constant G.

“The present generation of young physicists may envy those of us who had the excitement and delight of developing the standard model. This might be a mistake, just as it turned out that my generation would have been mistaken to envy the earlier heroes of quantum electrodynamics. Our newly minted experimentalists and theorists now have a chance to participate in making the next big step beyond the standard model. They may even be able to see their way clear to the very high energy scale where a final theory will be revealed.”

Half a century of the standard model, 2018

Matt Valentine

Steven Weinberg

Quantum Gravity

vs.

Quantum & Gravity

Quantum & gravity in the lab

Sub-millimeter gravitational redshift with ultra-precise clocks.

Quantum strategies for gravitational wave detection.

Gravitationally induced entanglement between test masses.

Dumb holes: Hawking radiation and supersonic flow.

Gravitationally driven intrinsic decoherence?

Detecting gravitons.

Black holes can illuminate cosmology

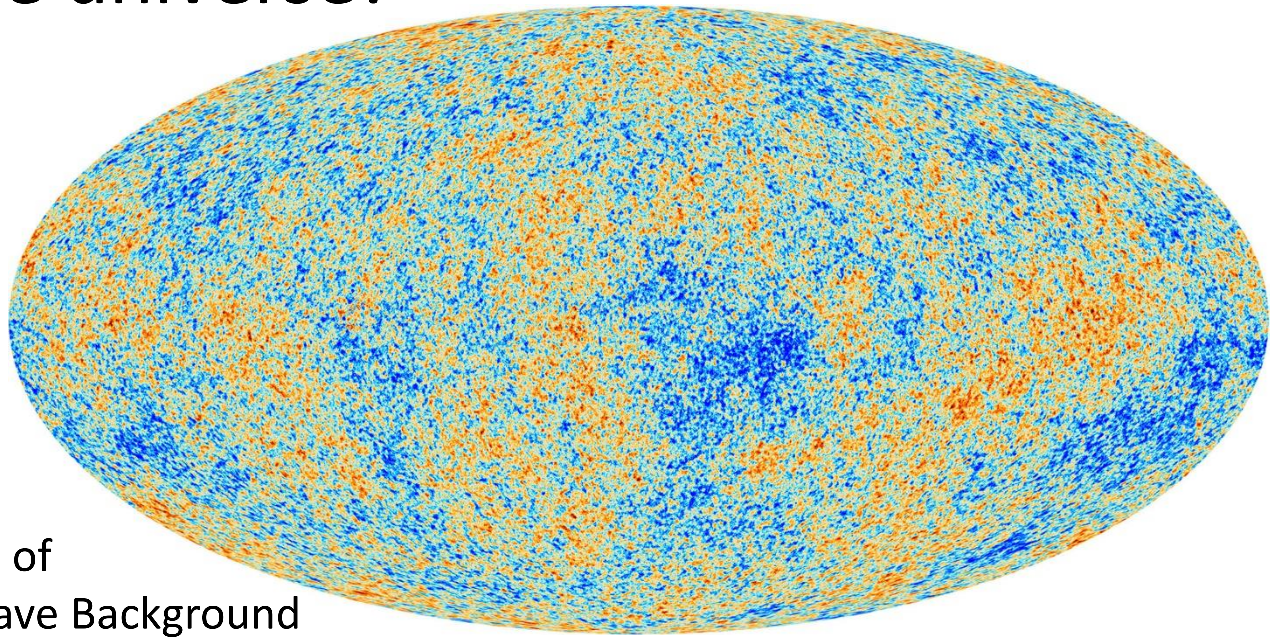
Hawking radiation from black holes

→ Quantum fluctuations during inflation in the early universe

→ Primordial density perturbations from quantum effects

→ The large-scale structure of the universe!

→ (Maybe) gravitational waves from inflation



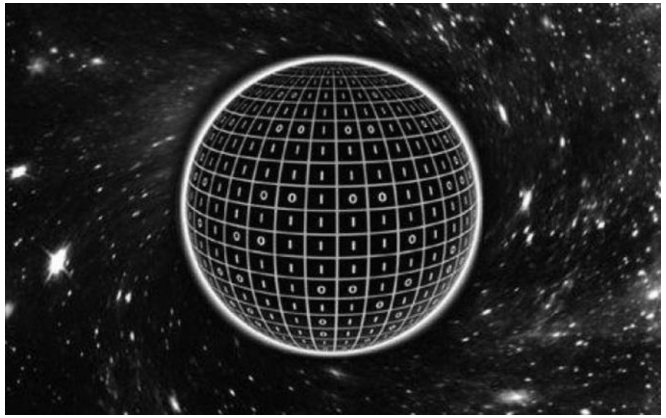
ESA Planck map of
Cosmic Microwave Background

Black hole entropy

Quantum entanglement →Hawking radiation from black holes

→ Black hole entropy → a huge number of microstates.

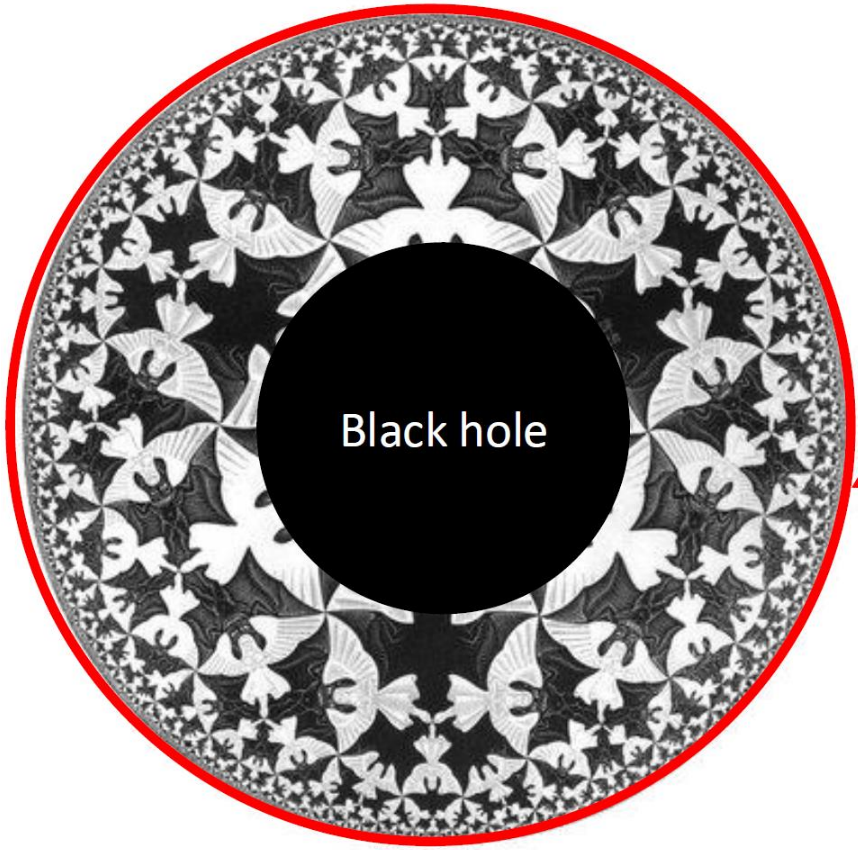
$$\frac{S}{k_B} = \frac{c^3}{4G_N\hbar} Area = \frac{Area}{4L_P^2}$$



One equation that encompasses: information (S), special relativity (c), quantum mechanics ($\hbar$), gravity (G), geometry ($Area$).

In a few special cases (unfortunately not yet including the real world), we have understood what these microstates are.

Holographic correspondence



Two equivalent descriptions:

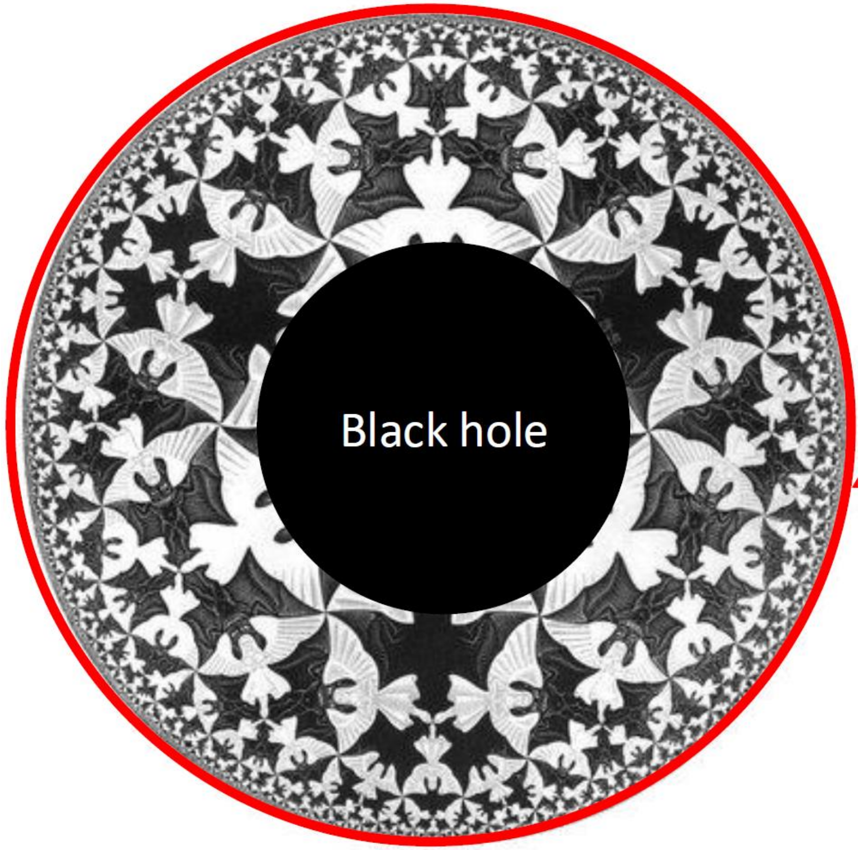
In the bulk: A black hole in anti-de Sitter spacetime.

On the boundary: a thermal fluid in a conformal quantum field theory (without gravity).

Black hole entropy = entropy of this fluid.

Not our universe: Negative dark energy. Different particle content and forces. Different symmetries. Different spacetime dimension.

Holographic quantum states of matter



Special quantum systems with *N* degrees of freedom, which are described by Einstein's gravitational equations when *N* is very large.

In principle, we can simulate this system in the laboratory using a quantum computer, and study its properties.

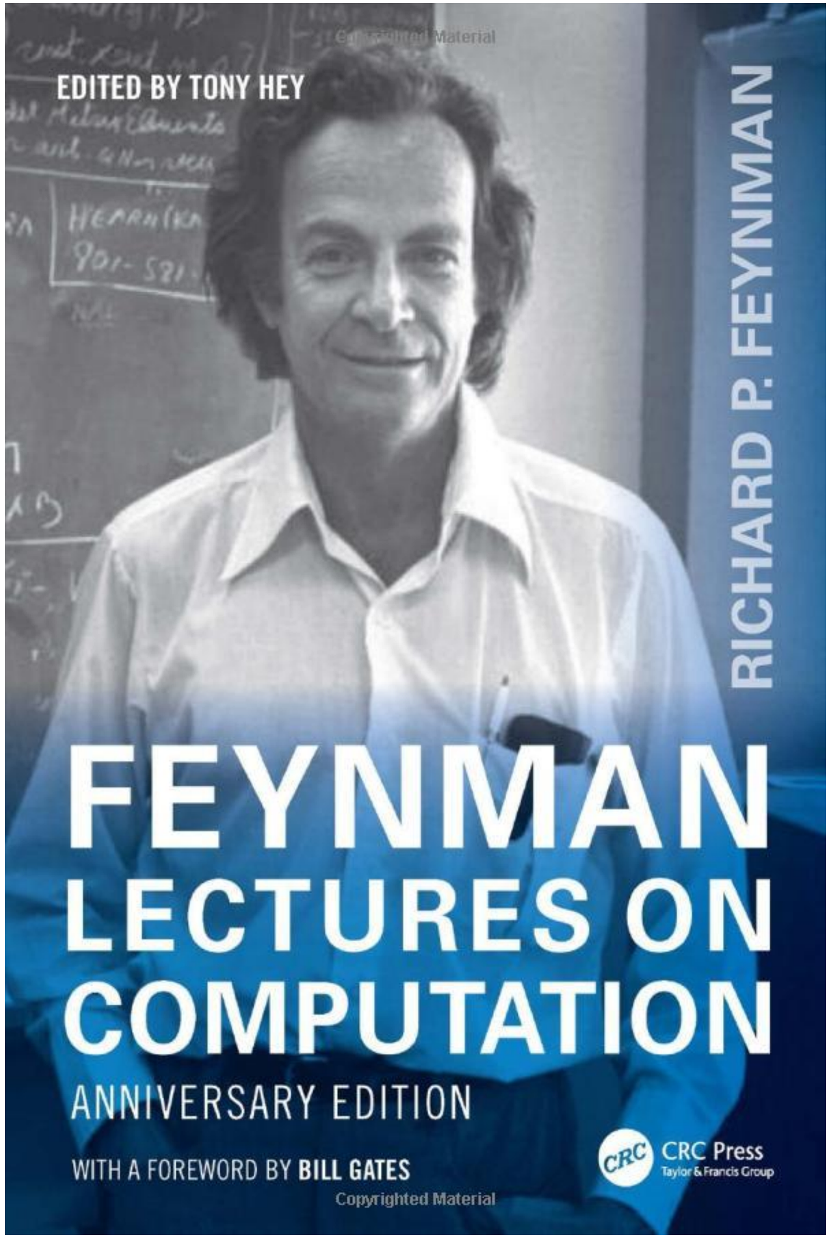
We cannot create such states today, but as quantum technology advances it will eventually become possible.

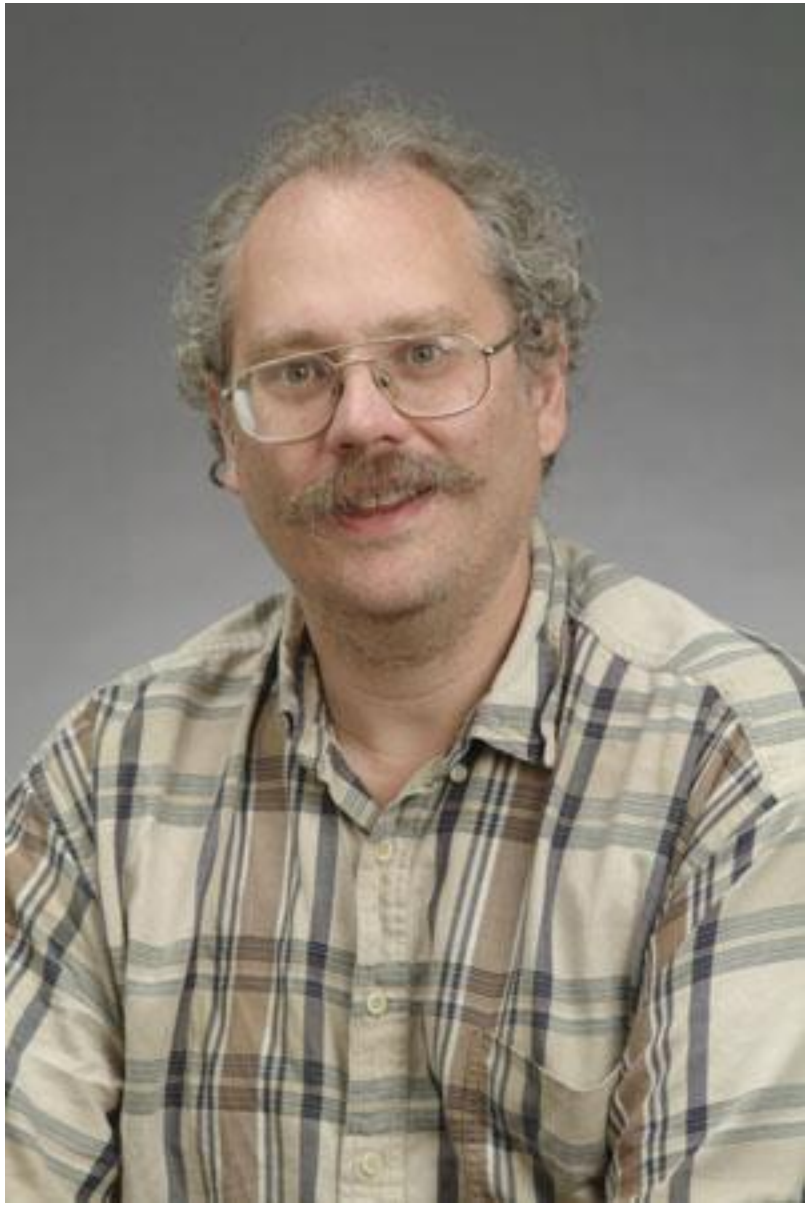
The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble.

Paul A. M. Dirac, Quantum Mechanics of Many-Electron Systems, Proceedings of the Royal Society, 1929

"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."

Richard Feynman
Simulating Physics with Computers
May 1981





Peter Shor

(1994)

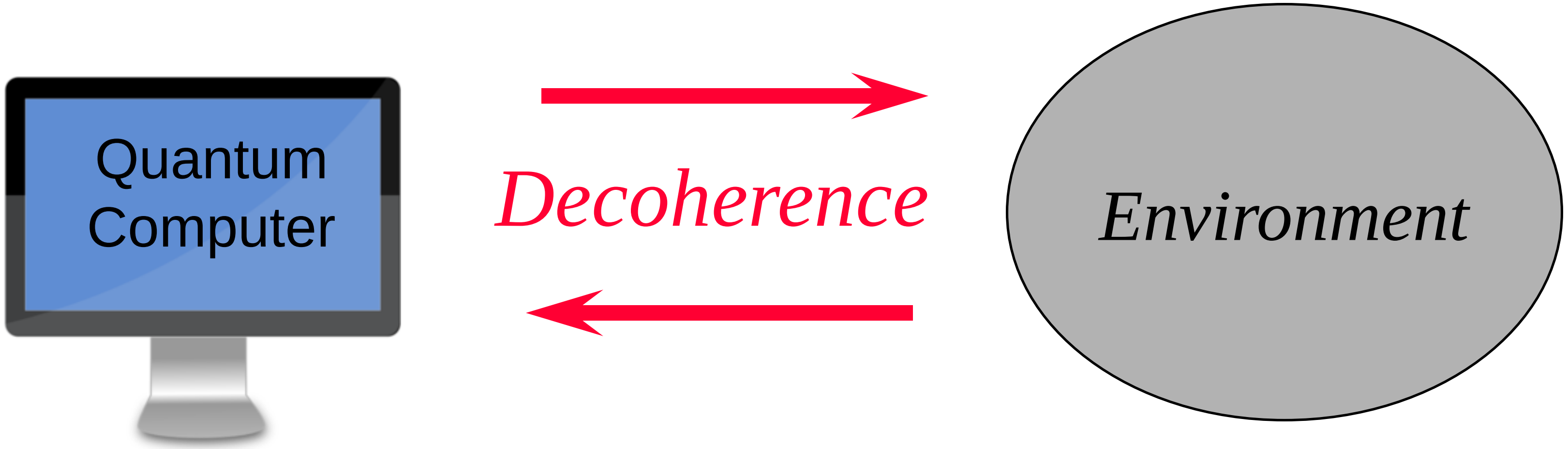
"These algorithms take a number of steps polynomial in the input size, for example, the number of digits of the integer to be factored."

Why quantum computing is hard

We want qubits to interact strongly with one another.

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

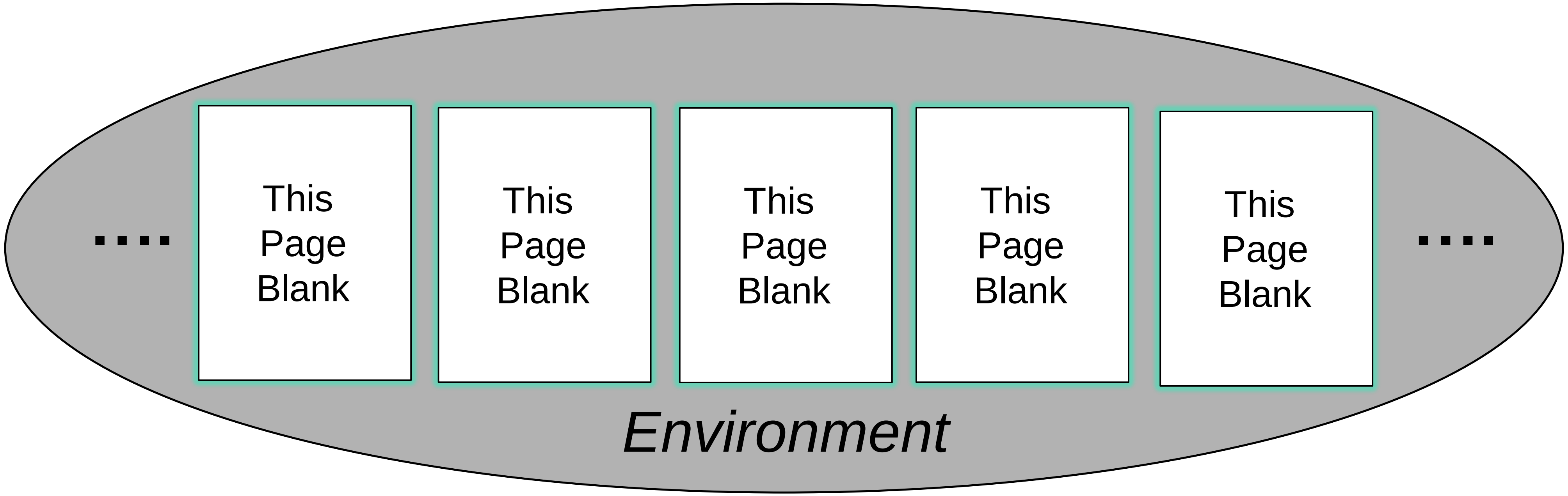
Except when we control or measure them.



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.

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?

Applications

Quantumly easy.

Classically hard.

Useful.

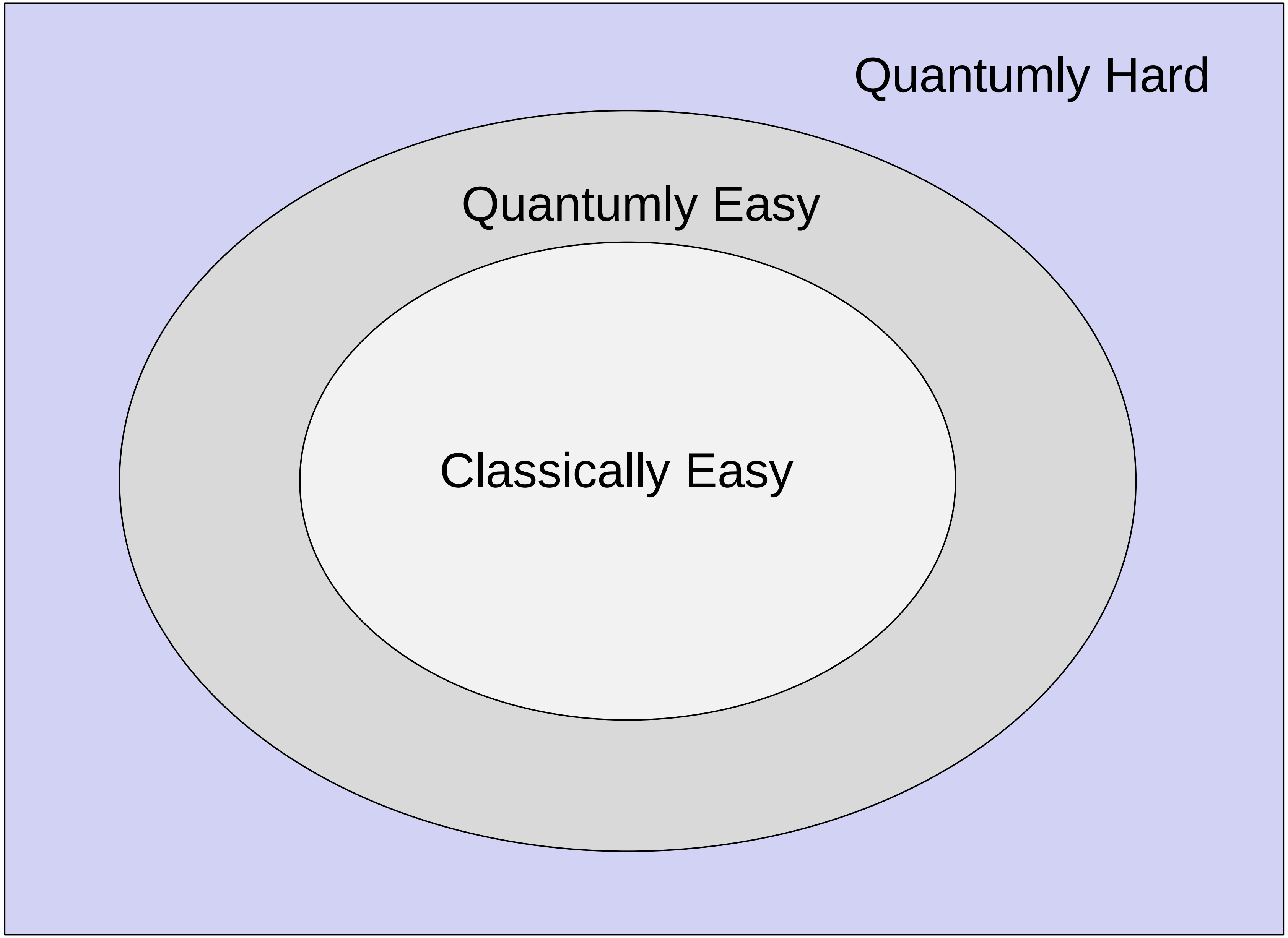
Scaling

Devices.

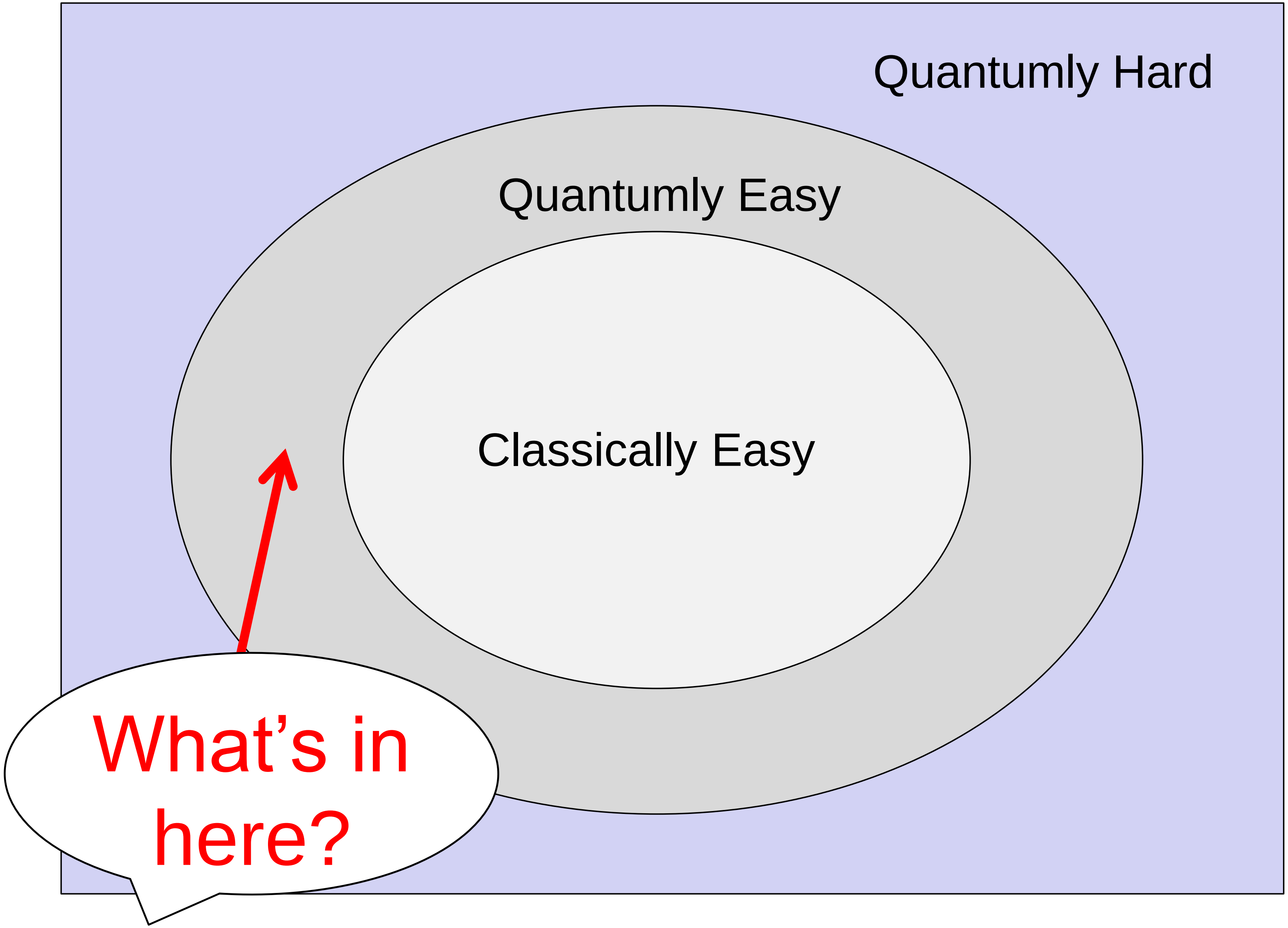
Error correction.

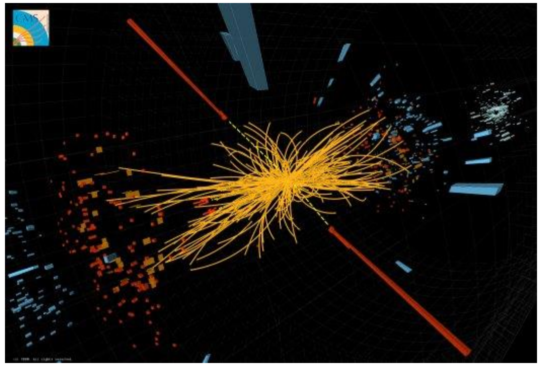
Systems engineering.

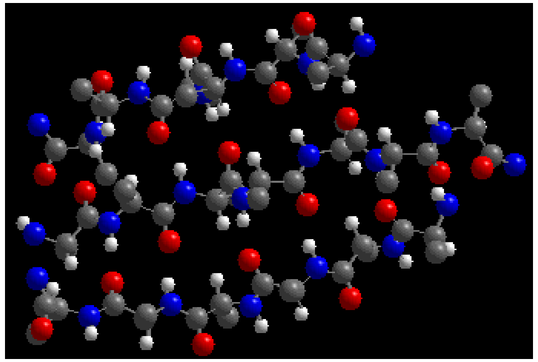
Problems

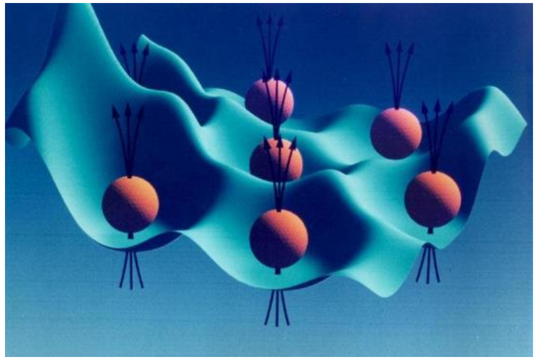


Problems

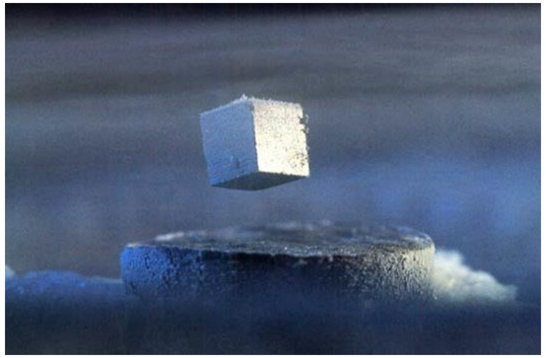

Quantumly Hard
Quantumly Easy
Classically Easy
What's in here?

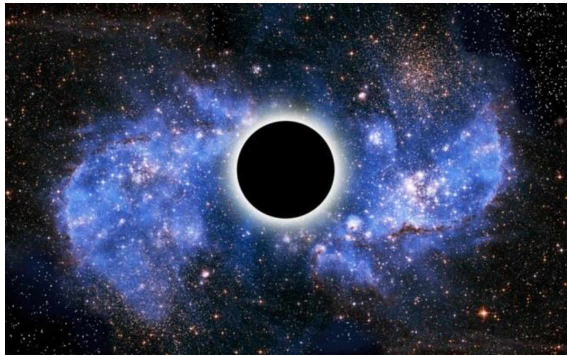

particle collision


molecular chemistry

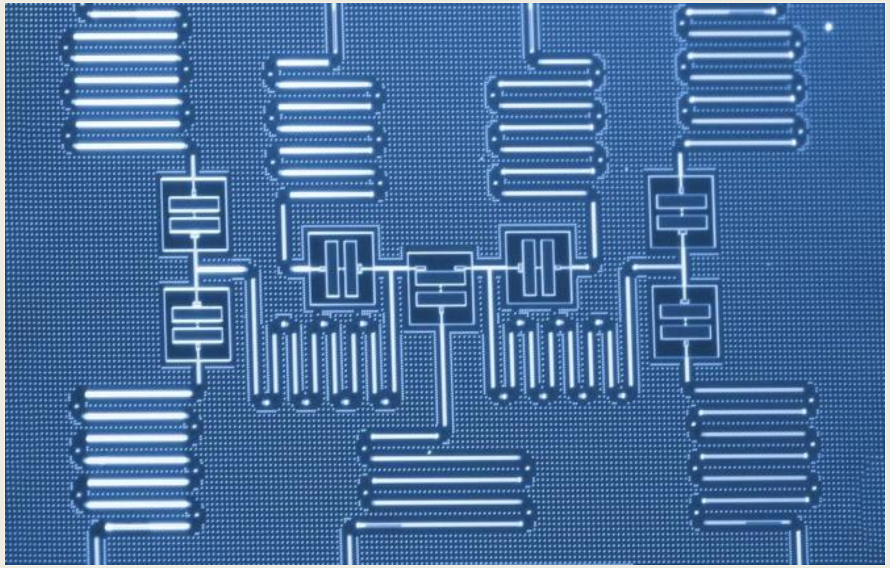

entangled electrons

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

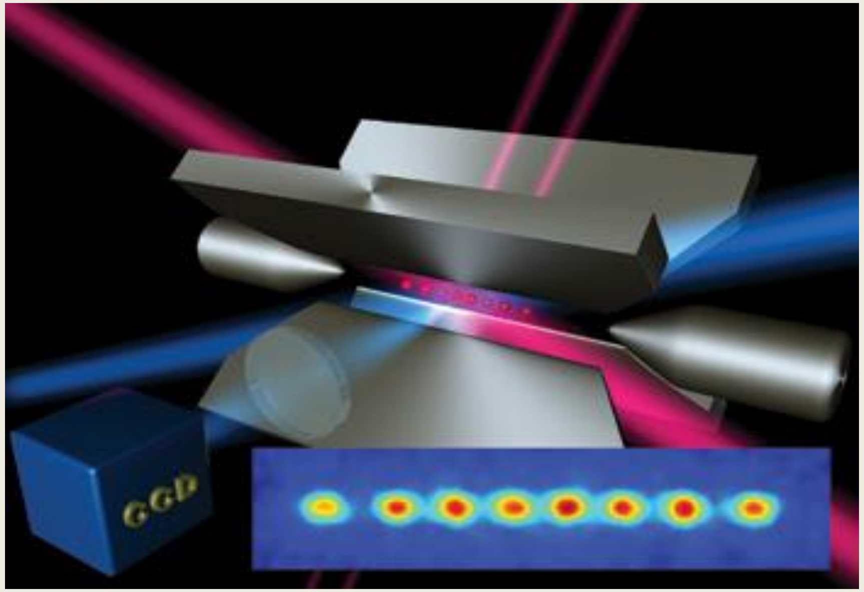

superconductor


black hole

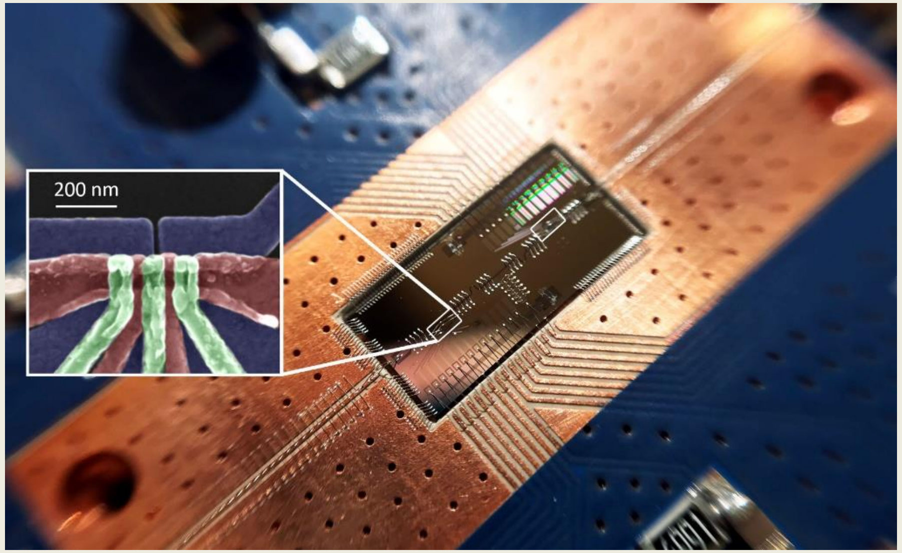

early universe



superconducting qubits



trapped atoms/ions



silicon spin qubits

photonics

Superconducting Circuits

~ 100 qubits in a two-dimensional array with nearest-neighbor coupling.

Transmons: artificial atoms, carefully fabricated and frequently calibrated.

Microwave resonator for readout, microwave pulses for single-qubit gates.

Two-qubit gates via tunable frequency, tunable couplers, or cross-resonance drive (tens of nanoseconds).

Scaling: modular devices, microwave control lines, materials, fabrication, alternative qubit designs.

Neutral Atoms

100s to 1000s of atoms in optical tweezer arrays. Highly excited Rydberg states for entangling operations.

Atoms are movable, hence no geometrical constraints.

Global control, move to processing zones for local gates.

Atomic movement and readout are relatively slow.

Continuous loading of fresh atoms under development.

Noisy Intermediate Scale Quantum (NISQ) Era

What we have now.

NISQ is valuable for scientific exploration. But there is no proposed application of NISQ computing with *commercial* value for which quantum advantage has been demonstrated *when compared to the best classical hardware running the best algorithms for solving the same problems*.

What we can reasonably foresee.

Nor are there persuasive theoretical arguments indicating that commercially viable applications will be found that do *not* use quantum error-correcting codes and fault-tolerant quantum computing.

Fault-tolerant Application Scale Quantum (FASQ) Era

What we want to have.

-- Quantum computers running a wide variety of useful computations.

-- Machines that can execute of order 10^{12} quantum operations ("teraquop machines").

-- This requires improving quantum gate error rates by about 9 orders of magnitude beyond the current state of the art.

-- Quantum error correction and will be essential for crossing the chasm from NISQ to FASQ. We may need devices with millions of physical qubits.

When will we have it?

No one knows. It might take decades.

Quantum computing for chemistry and materials

Dirac (1929): "… equations much too complicated to be soluble."

Yet, heuristic classical algorithms are often very successful, and these methods are continually improving.

Quantum computing targets the relatively small "strongly correlated" corner of chemistry and materials science, where such methods falter.

How useful are quantum computers in physically relevant situations that are beyond the reach of classical methods?

Artificial intelligence may drive future progress in (strongly correlated) chemistry and materials science. Eventually, quantum computers can accelerate progress by providing abundant training data.

arXiv:2502.17368

Beyond NISQ: The Megaquop Machine

JOHN PRESKILL, Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, United States

1M quantum ops or more: Requires QEC, and allows tasks beyond classical, NISQ, or analog quantum.

Do science for now.
Economic impact will inevitably follow.

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?

Theorem [Huang 2025, Classical hardness of predicting quantum advantage]

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.

Richard Feynman: “You can simulate this with a quantum system, with quantum computer elements. It’s not a Turing machine, but a machine of a different kind.”

Kip Thorne: “By squeezing the vacuum, one can reduce the shot noise at the price of increasing the radiation-pressure noise.”

Jeff Kimble: “Individual photons circulating in a high-finesse resonator can interact strongly via their mutual coupling to a single intracavity atom.”

Alexei Kitaev: “Such computation is fault-tolerant by its physical nature.”

Institute for Quantum Information

IQI

2000-2013 NSF

Theory:
Physics + Computer Science

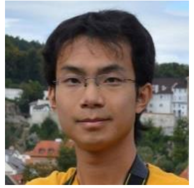
IQIM

INSTITUTE FOR QUANTUM INFORMATION AND MATTER

2011- NSF

Theory + Experiment:
Physics, Computer Science, Applied Physics, Electrical Engineering, Materials Science, Chemistry

Recent Theory Postdocs → Faculty



Charles Cao
(2023) → Virginia Tech

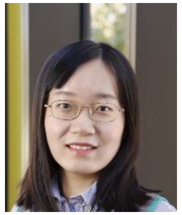
Matthias Caro
(2023) → U. Warwick

Ulysse Chabaud
(2023) → ENS, Paris

Arpit Dua
(2023) → Virginia Tech

Tuvia Gefen
(2023) → Hebrew U.

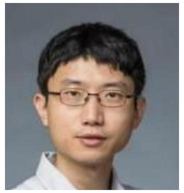
Alexander Jahn
(2023) → Free U. Berlin



Sisi Zhou
(2023) → Perimeter

Andreas Elben
(2024) → PSI, ETH

Iliya Esin
(2024) → Bar-Ilan U.



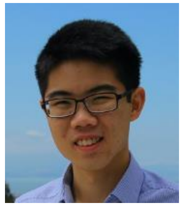
Yu Tong
(2024) → Duke U.

Leo Zhou
(2024) → UCLA

Alex Milekhin
(2025) → U. Kentucky

Sara Murciano
(2025) → CNRS Saclay

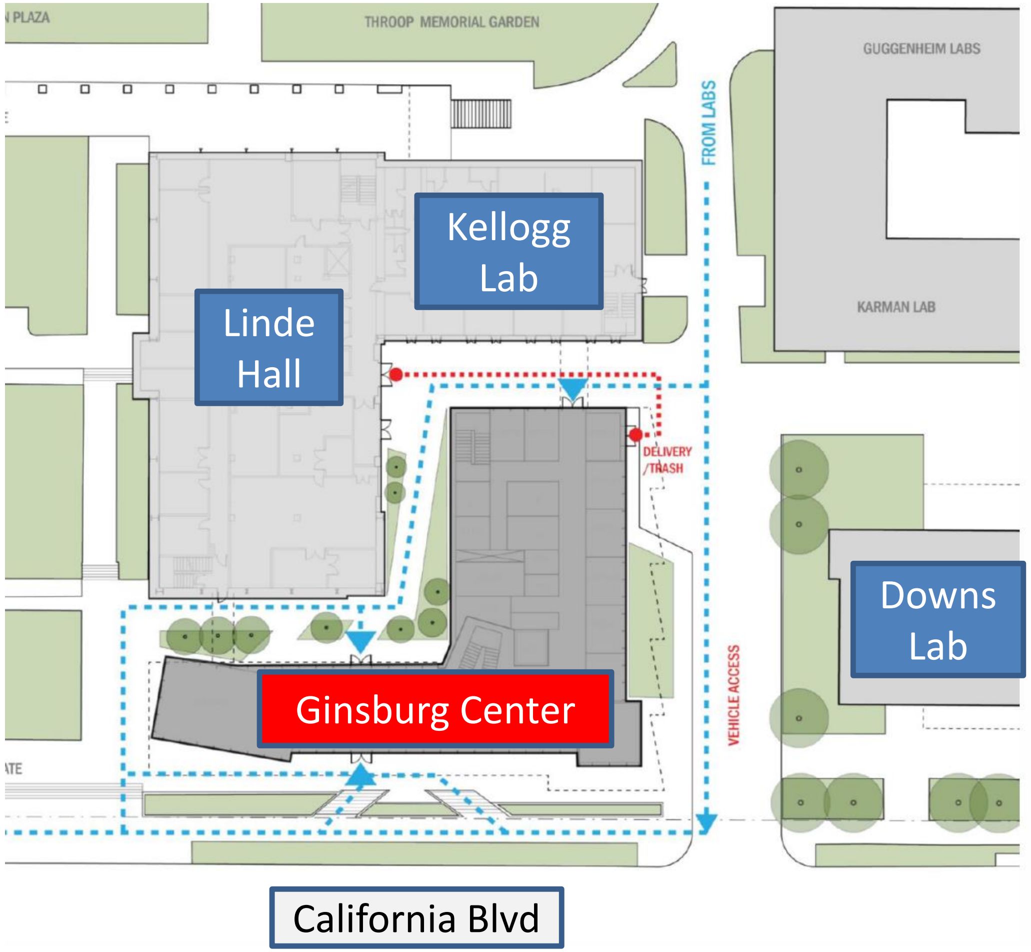
Federica Surace
(2025) → Trinity College Dublin



Nat Tantivasadakarn
(2025) → Stony Brook U.

Ginsburg Center for Quantum Precision Measurement

Opens 2026. Architectural firm: HOK



Adjacent to Linde, Kellogg, Downs. Seamless cutting-edge laboratory space conducive to intellectual interaction and collaboration, and high-quality contiguous office space for theorists and experimentalists, establishing a vibrant hub for quantum research on campus.

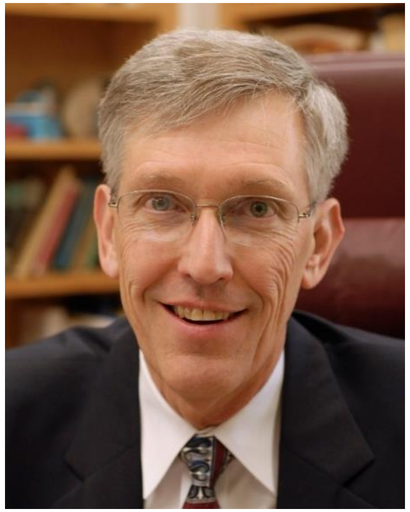
Ginsburg Center for Quantum Precision Measurement

18 July 2025

Surpassing the "standard" quantum limit on measurement precision

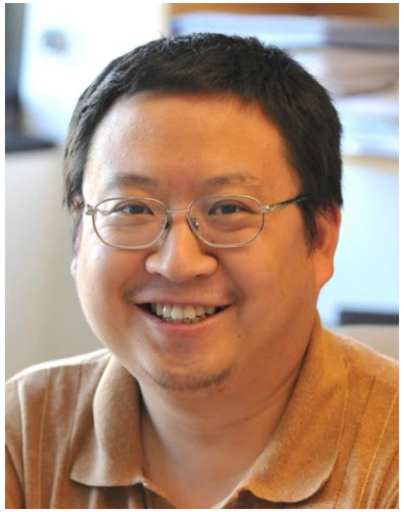
LIGO

Kip Thorne



Jeff Kimble

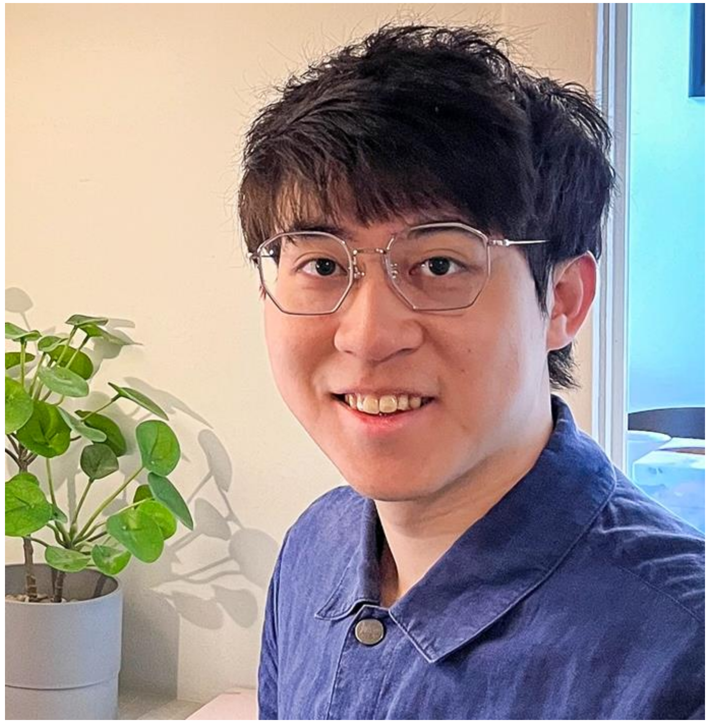
Rana Adhikari



Yanbei Chen

Lee McCuller

New Physics Faculty!



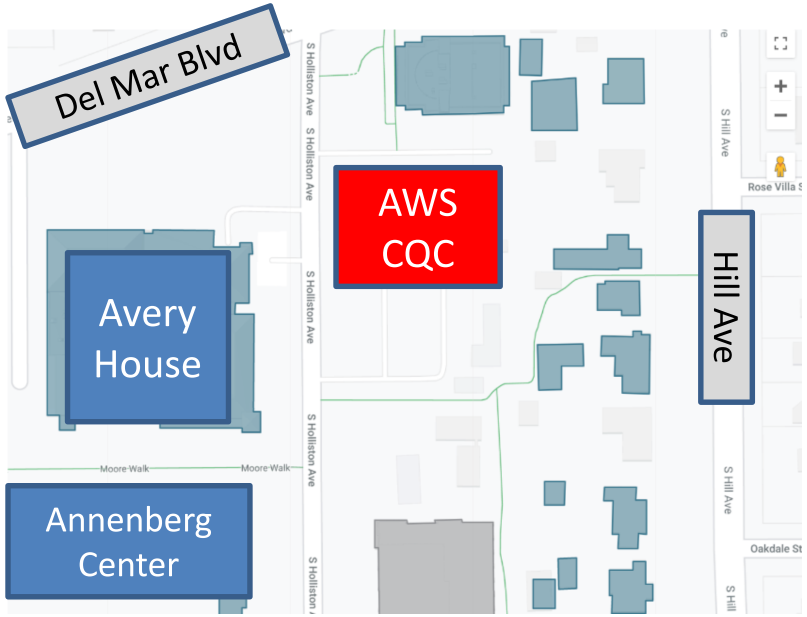
Hsin-Yuan (Robert) Huang
Theoretical Physics

Nelson Darkwah Oppong
Experimental Physics

Dolev Bluvstein
Experimental Physics

Caltech continues to search actively for quantum science faculty across multiple departments.

AWS Center for Quantum Computing at Caltech



Opened
2021

Oskar Painter

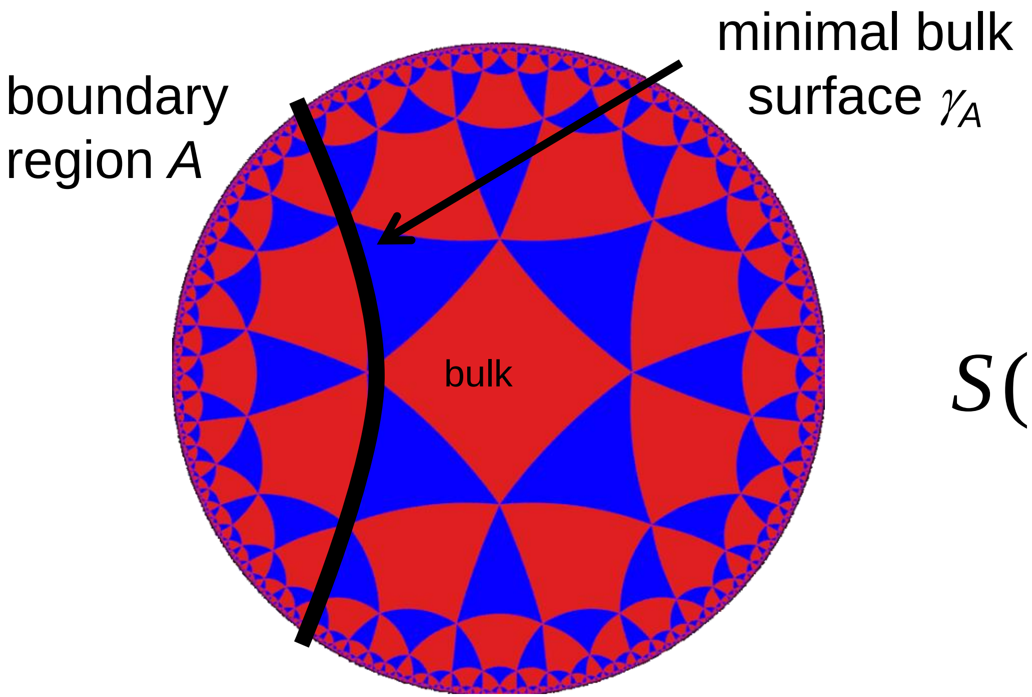
Fernando Brandão

Led by IQIM faculty (Painter and Brandão)

Leveraging technology and ideas developed in IQIM

Sponsored research and extensive collaboration

Geometry from entanglement



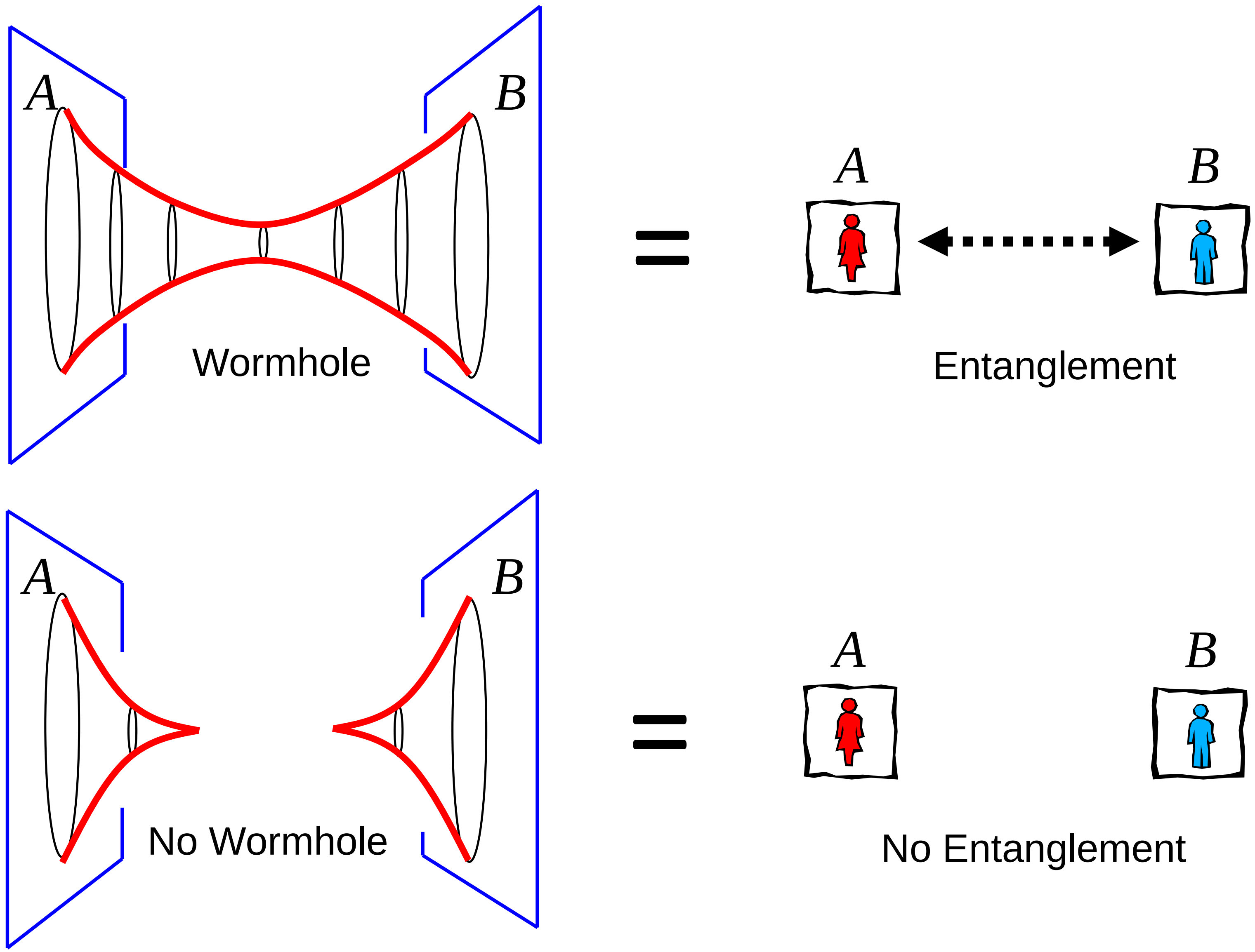
$$S(A) = \frac{1}{4G_N}\,\mathrm{Area}(\gamma_A) + \cdots$$

To compute entanglement entropy of region *A* in the boundary field theory, find minimal area of the bulk surface γ_A with the same boundary.

(Ryu,Takayanagi 2006. Hubeny, Rangamani, Takayanagi 2007.)

Entanglement on the boundary determines geometry in the bulk.

Building spacetime from quantum entanglement



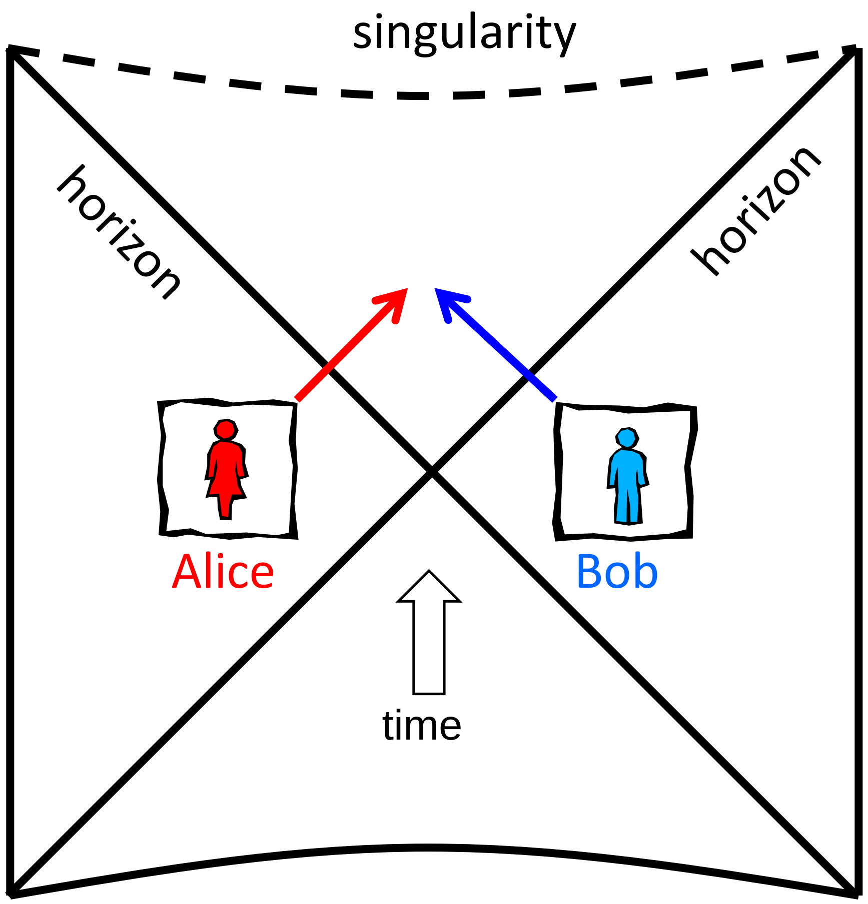
(Maldacena 2003, Van Raamsdonk 2010, Maldacena-Susskind 2013)

Entanglement is the “glue” that holds space together.

If, with your quantum computer, you transformed the highly entangled vacuum state to a product state, then space would fall apart into tiny pieces.

This would require an enormous amount of energy.

Love in a wormhole throat

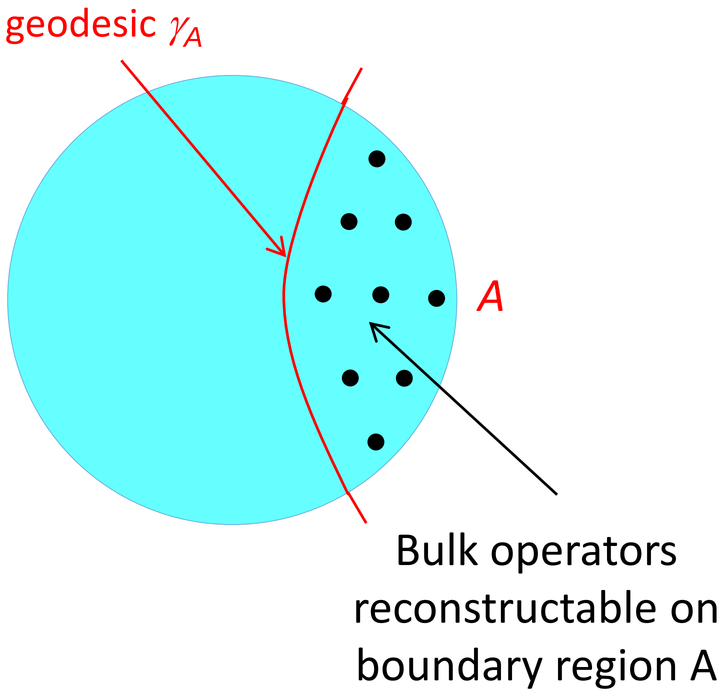


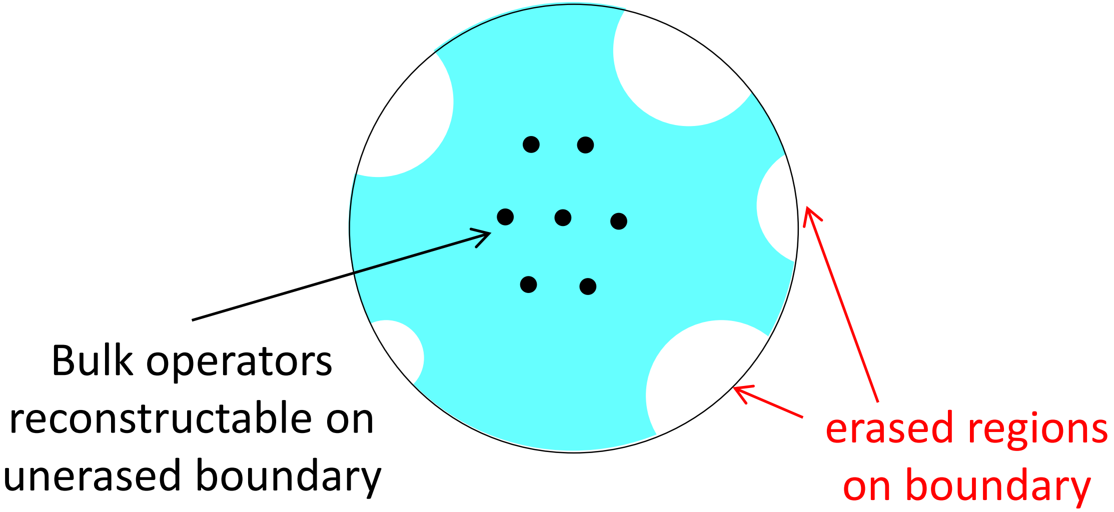
Alice and Bob are in different galaxies, but each lives near a black hole, and their black holes are connected by a wormhole. If both jump into their black holes, they can enjoy each other's company for a while before meeting a tragic end.

Spacetime as an error-correcting code

For a connected region A on the boundary there is a corresponding *geodesic* γ_A . Bulk operators in the wedge between A and γ_A can be reconstructed on the boundary in region A.

Operators deeper in the bulk have better protection against erasure on the boundary.





Bulk operators at the center of the bulk are robust against erasure of up to half of the boundary qubits.

Almheiri, Dong, Harlow (2015). Pastawski, Yoshida, Harlow, Preskill (2015).

Quantum gravity: how experiments might help

Probe bulk geometry by measuring *boundary entanglement* structure.

Probe *bulk locality*, e.g. by studying boundary linear response.

Probe *fast scrambling*, Lyapunov spectrum.

Measure higher-order *quantum gravity corrections*.

Simulate very-high-energy bulk scattering.

Holographic dictionaries *beyond anti-de Sitter*.

Use gravitational intuition to understand emergent phenomena.

Sachdev-Ye-Kitaev (SYK)Model

Alexei Kitaev

The simplest holographic correspondence.

Many fermions with all-to-all coupling at low temperature.

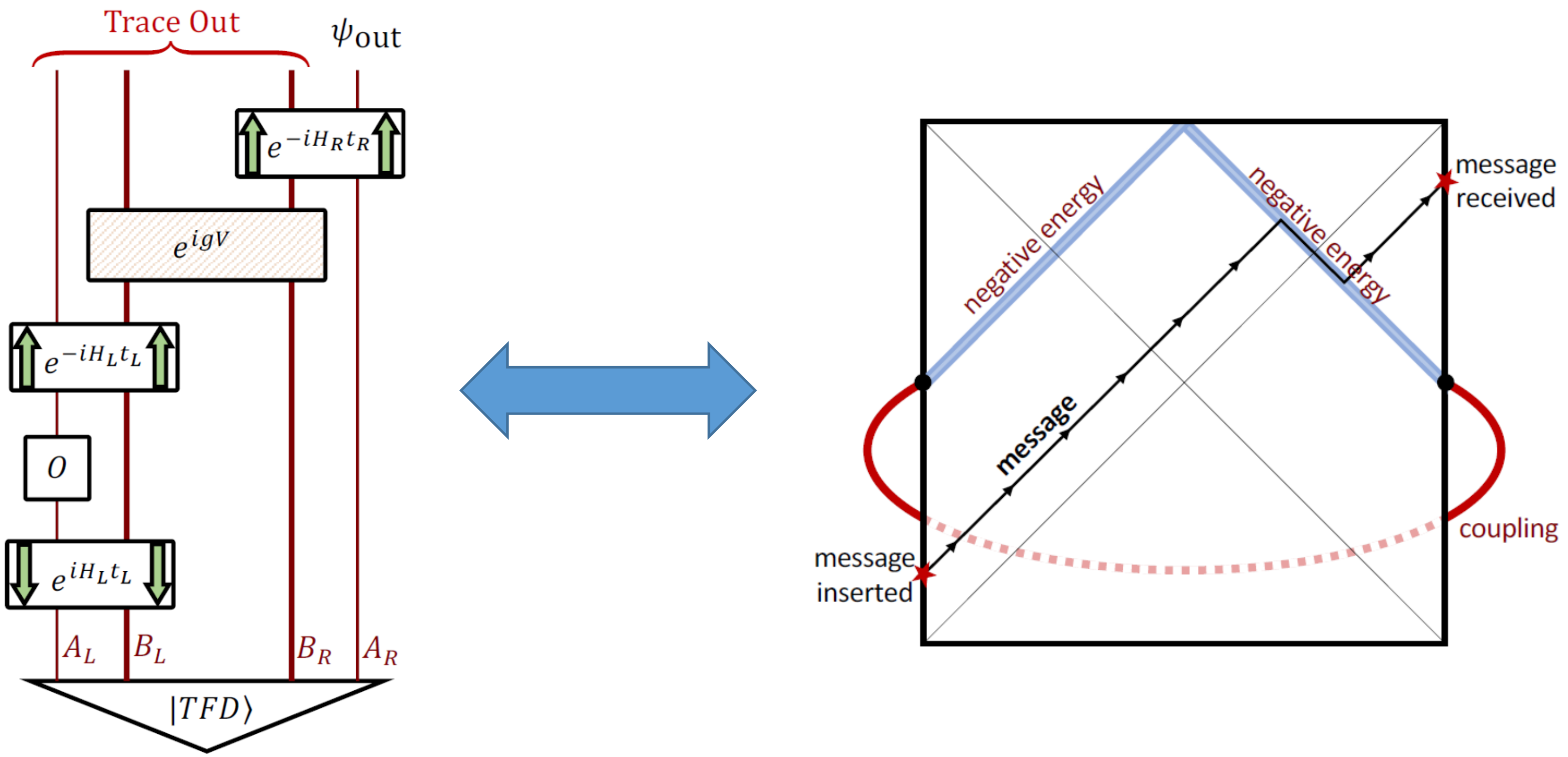
=

A black hole in one spatial dimension.

Classically hard, quantumly easy.

Quantum gravity in the lab

Nezami, Lin, Brown, Gharibyan, Leichenauer, Salton, Susskind, Swingle, Walter 1911.06314, 2102.010064
Schuster, Kobrin, Gao, Cong, Khabiboulline, Linke, Lukin, Monroe, Yoshida, Yao 2102.00010



Using gravitational intuition to understand complex emergent quantum phenomena.

What quantum systems have useful gravitational duals?

Measuring higher-order gravitational corrections?

How noise tolerant?

Simulating quantum field theory on a quantum computer

50 years since Ken Wilson proposed lattice gauge theory!

Real-time evolution (collider physics), nonzero chemical potential (early universe, neutron stars), …

What's classically hard? Processes that produce highly entangled states, e.g., multiparticle production, quench, …

Laying the foundations for more revealing future work.

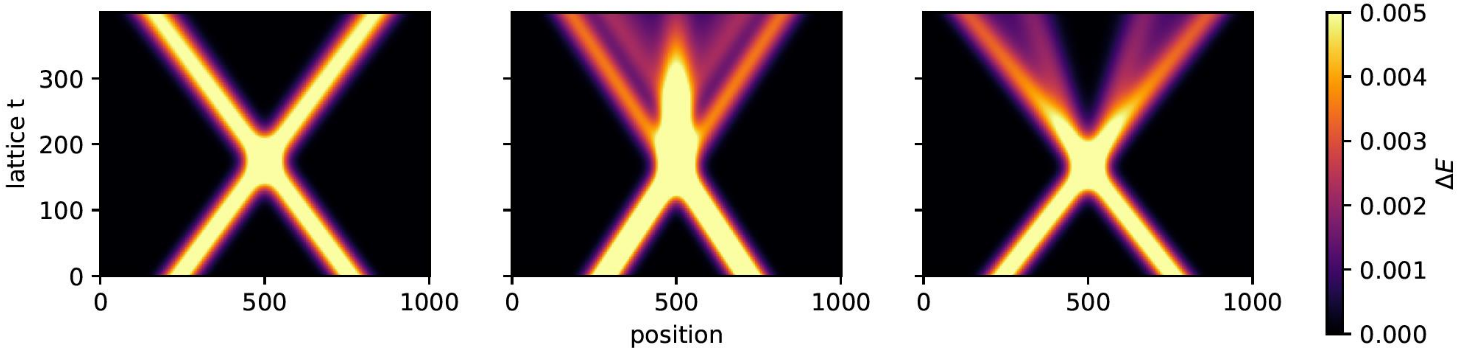
Stepping stone to quantum gravity.

New concepts and insights?

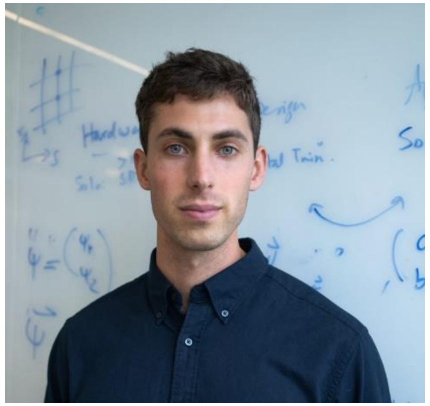
Toward simulation of quantum field theory on a quantum computer

Ash Milsted (AWS)

Real-time scattering in Ising field theory using matrix product states, arXiv:2411.13645.



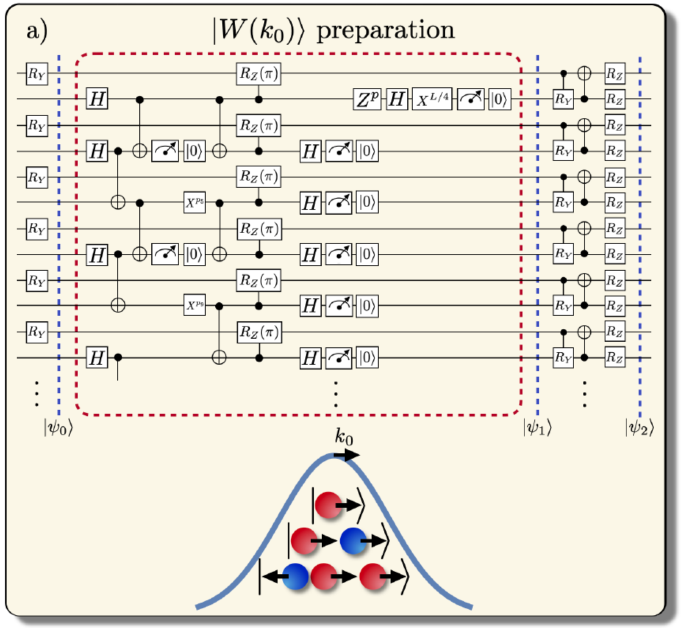
elastic resonance inelastic



Roland Farrell

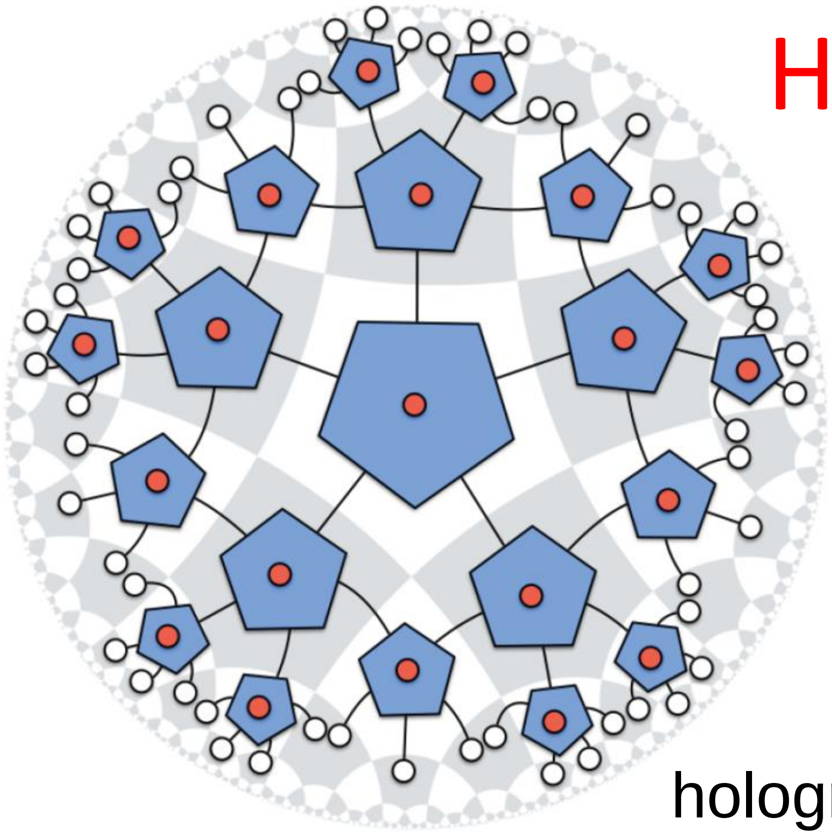
Quantum simulations of scattering in quantum field theories, arXiv:2505.03111

Currently running on IBM quantum hardware!



Quantum circuit for wavepacket preparation

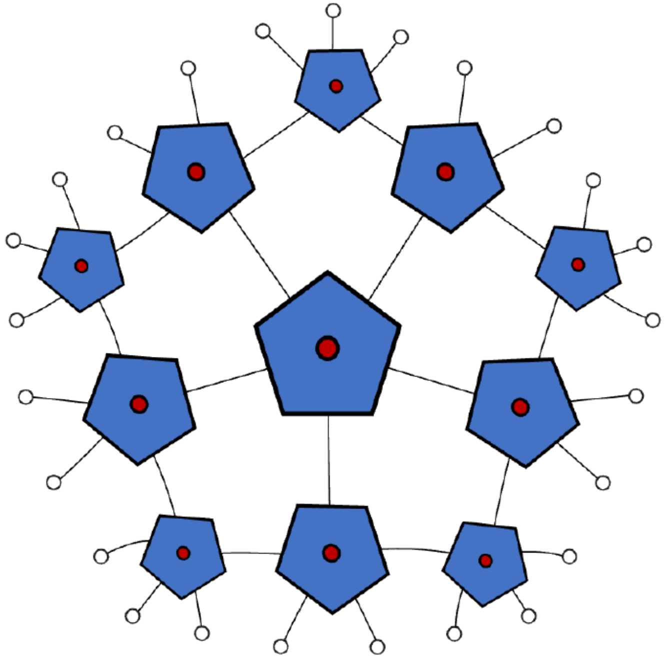
HaPPY Code in the lab

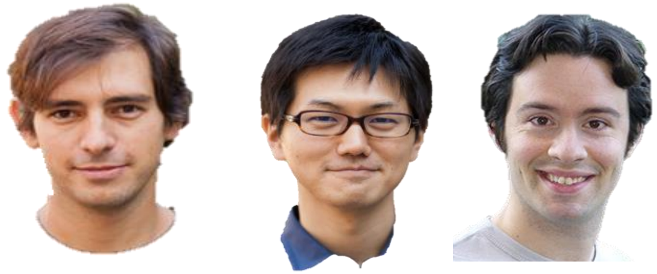


25 boundary qubits and 11 bulk qubits
in an ion trap quantum processor.

Imperfections are a blessing, not a curse.
Add “magic” and gravitational back reaction.

holographic
quantum code





Pastawski, Yoshida, Harlow, Preskill = HaPPY

Matrix quantum mechanics

Harmonic oscillators and fermions with specified quartic and cubic interactions.

Dual to a black hole in 10-dimensional spacetime. Black hole entropy scales like the number of qubits.

Study how the emergent spacetime is encoded, and the formation and evaporation of black holes.

About 10,000 (logical) qubits and a few billion quantum gates.

Comparable to resources for breaking encryption [Maldacena 2023].

The most important ideas in physics in the past 40 years?

1. The holographic principle (1994)
2. Topological quantum order (1989)
3. Quantum error correction (1995)

All three ideas are closely related!

The common thread: many-particle quantum entanglement.

Quantum error correction

We can protect quantum information from local noise by encoding it in a highly entangled state that hides the information from local probes.

We can control the behavior of large-scale quantum systems, including powerful quantum computers.

Topological Quantum Order

Quantum phases of matter that look identical when observed locally can be distinguished by their global properties.

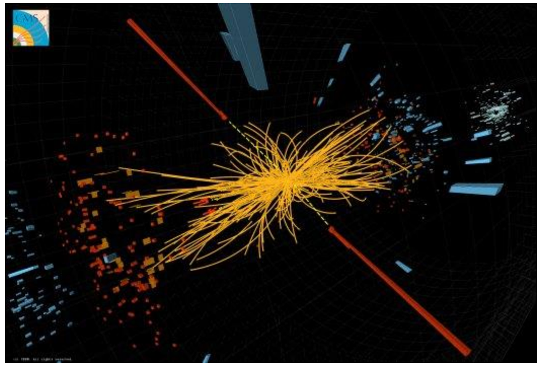
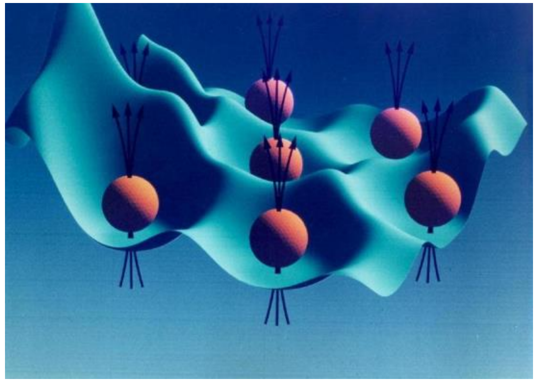
An electron in a topological phase can split into pieces, each carrying a fraction of the electron's charge.

The Holographic Principle

All the information contained in a three-dimensional region of space is encoded on the two-dimensional boundary of the region.

Our most important clue about how to reconcile quantum mechanics with gravitational physics.

Frontiers of Physics

short distance	long distance	complexity
		
Higgs boson	Large scale structure	“More is different”
Neutrino masses	Cosmic microwave background	Many-body entanglement
Supersymmetry	Dark matter	Phases of quantum matter
Quantum gravity	Dark energy	Quantum computing
String theory	Gravitational waves	Quantum spacetime

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.

Advances in quantum metrology from improved control of quantum many-body systems.

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.