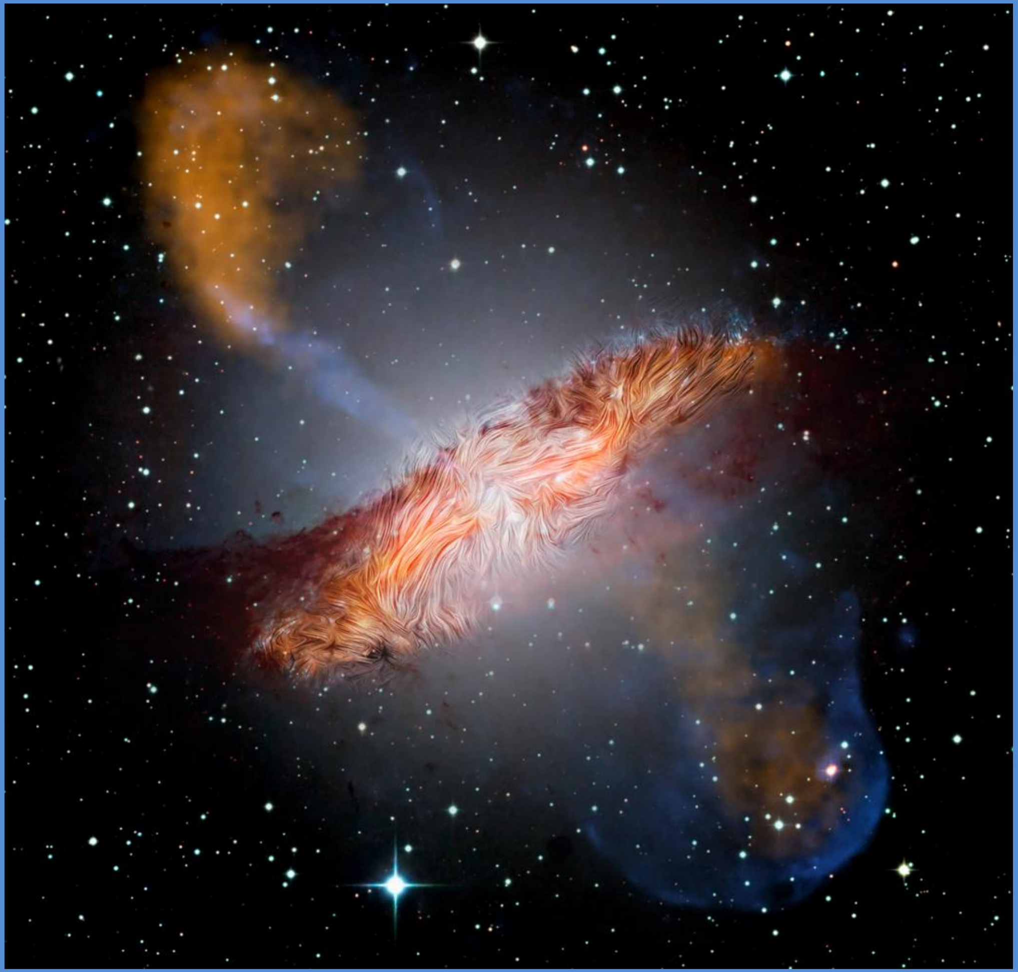
Black Holes:
Gateways to Understanding

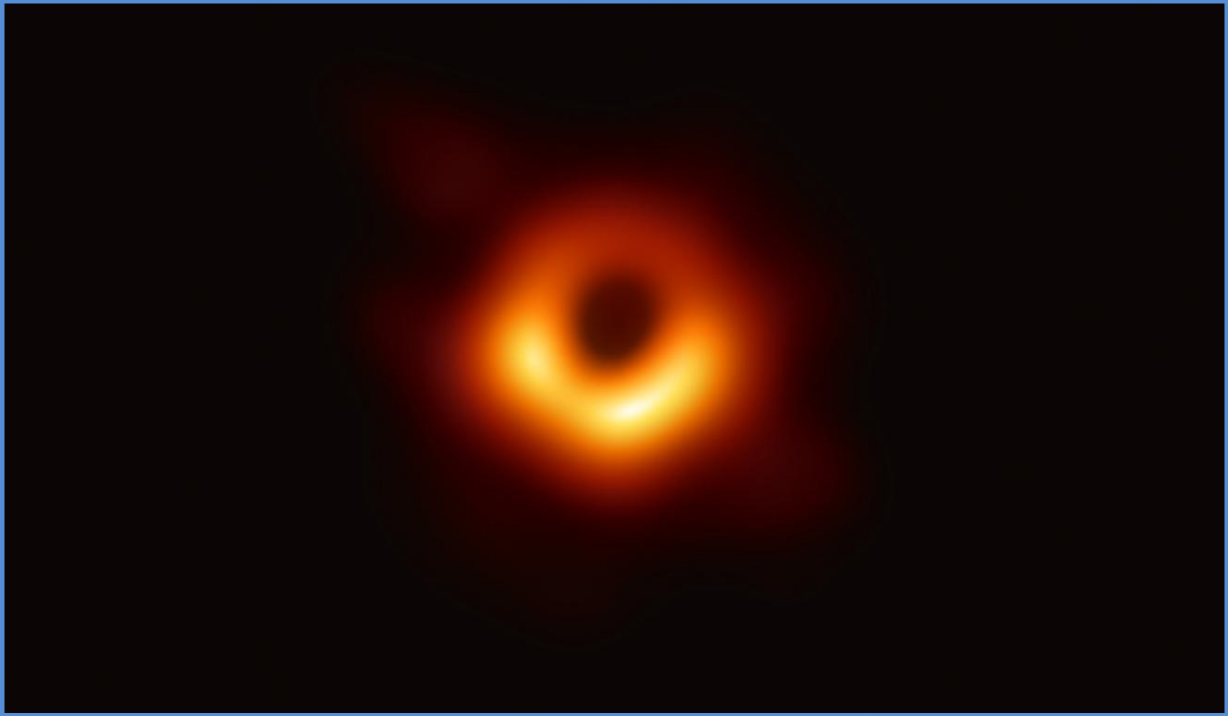


Bob Dorsett
May 2026

Centaurus A. image credits: NASA, ESO, ESA, Max Planck Institute

Introduction

Once dismissed as impossible, black holes now sit at the very center of scientific discovery. They are very strange and counter-intuitive objects in their own right, and they provide laboratories for further investigation into the fundamental laws of nature.



The supermassive black hole at the center of the galaxy M87, imaged by the Event Horizon Telescope.

Outline

- a brief history of black hole physics
- classical black holes
  - mass, charge, and spin
  - origins
  - black hole structure
  - journey into a black hole
- quantum mechanics and thermodynamics of black holes
  - Bekenstein entropy
  - Hawking radiation
- black holes and information
  - holography
  - the information paradox
- black holes in the laboratory

Some of the terms:

- **black hole** – a region of spacetime where gravity has overwhelmed all the other forces and nothing can escape from its boundary
- **event horizon** – the boundary separating a black hole from the outside universe, at which the escape velocity exceeds the speed of light
- **singularity** – a point in spacetime at which the known laws of physics are no longer capable of describing physical conditions
- **entanglement** – a correlation between two particles such that if you know the state of one particle you immediately know the state of the other, even if they are far apart
- **wormhole** – a physical tunnel that connects two points that are otherwise widely separated in normal spacetime
- **ER=EPR** – shorthand for the conjecture that (quantum) entanglement is the same as a (geometric) wormhole
- **holography** – the statement that a 3D region of spacetime can be fully described by information on its boundary
- **entropy** – the amount of information in a system that is inaccessible to an outside observer

Historical highlights, with some of the major players:

1783 John Michell postulates "stars" from which light cannot escape

1915 Albert Einstein publishes his theory of General Relativity

1915 Karl Schwarzschild publishes his solutions to GR Field Equations

mid-1900's

- Oppenheimer and Snyder predict stellar collapse black holes
- Roy Kerr models rotating black holes
- Reissner and Nordstrom model charged black holes

late 1900's

- John Wheeler's group in the U.S. and Yakov Zeldovich's group in USSR place black hole studies at the center of theoretical physics
- Hawking and Penrose prove the existence of black hole singularities
- Hawking and Bekenstein discover black hole thermodynamics and connection to quantum physics
- Susskind, t'Hooft, and Maldacena discover holography

2015 LIGO identifies gravitational waves from merging black holes

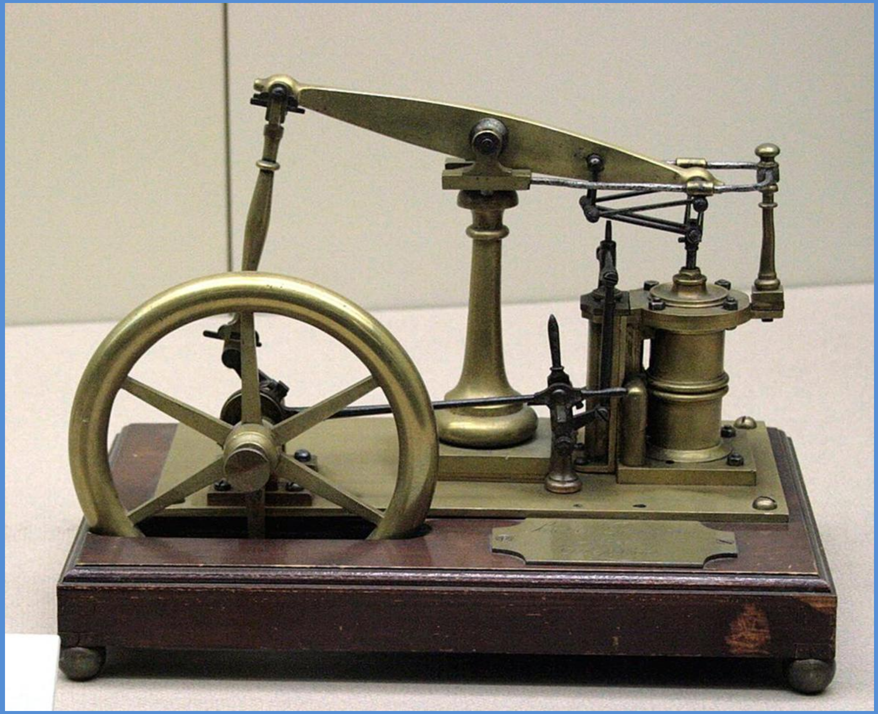
2019 EHT images the supermassive black hole in M87

2019 East Coast and West Coast teams solve (?) the information paradox

Now we travel beyond the classical GR description of black holes and encounter the remarkable new insights that guide research today. In the 1970's, Jacob Bekenstein and Stephen Hawking discovered that black holes aren't such secure prisons after all. Things escape. Their insights launched a revolution in our understanding of space and time. The following few slides provide essential background.

Thermodynamics in brief:

- The First Law $dE = TdS$
- The Second Law $\frac{dS}{dt} \geq 0$
- Boltzmann Entropy $S = k_B \ln W$



Thermodynamics originated in the early days of the Industrial Revolution as scientists and engineers rushed to develop more efficient steam engines. Sadi Carnot, William Thomson (Lord Kelvin), James Joule, Rudolf Clausius, and other pioneers built 'effective theories' based on measurable, macroscopic physical properties like pressure, temperature, and volume.

image: model of James Watts' double action steam engine, Wikipedia

At the close of the 1800's Ludwig Boltzmann, James Clerk Maxwell, and Josiah Willard Gibbs found the underlying laws, the Statistical Mechanics, of molecular motion that explained the macroscopic observables. Pressure results from zillions of molecules pounding on the walls of their container. Temperature is the average kinetic energy of those molecules. Entropy counts how many different ways you can arrange a set of molecules and still get the same results when you measure temperature, pressure, volume, etc.

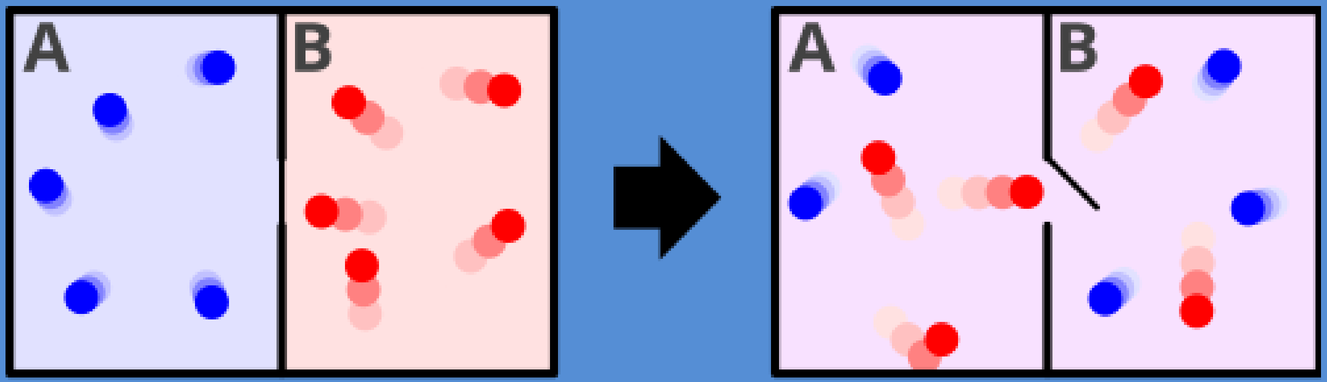


image: Wikipedia Statistical Mechanics

And then came Information Theory:

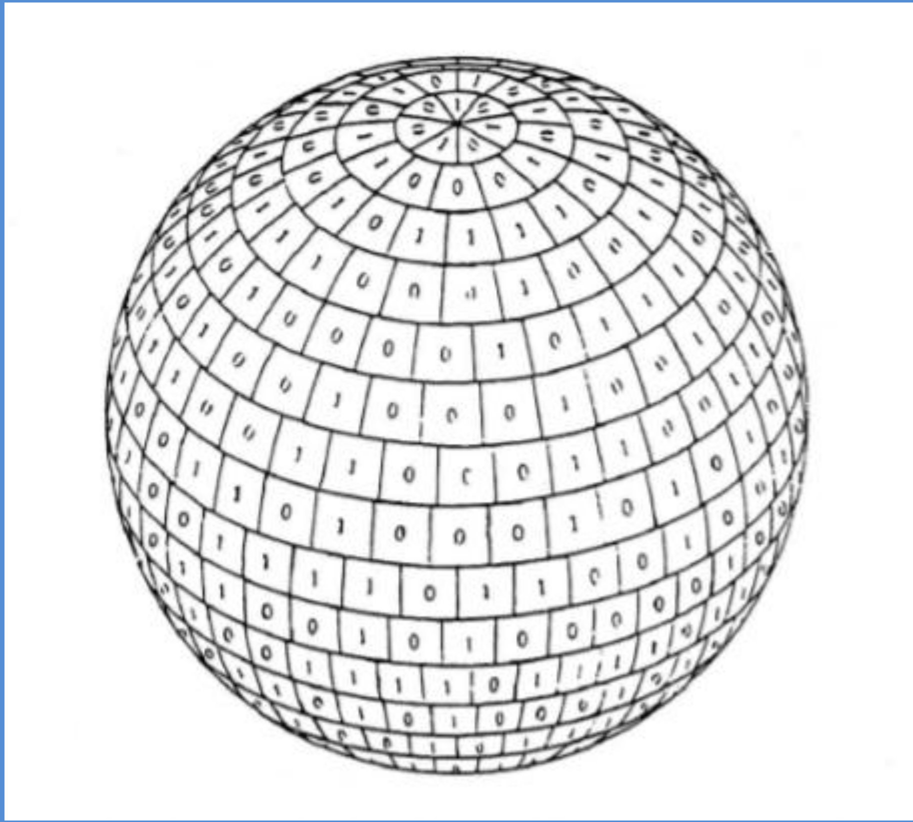
In the mid-1900’s John Von Neumann, Claude Shannon and others of the wizards at Bell Labs discovered that the laws governing communications channels looked a whole lot like the laws of thermodynamics. In fact, they are the same laws. While the steam engineers were trying to build more efficient steam engines, Bell Labs were trying to optimize communications systems. How much information can you transmit over a copper telephone wire compared to a radio transmitter? How much noise can you tolerate in a system and still get the message through? How can you correct any errors in the transmission?

image: ATT international switchboard 1943, Wikipedia

For our purposes what's important is Bell Labs' modern interpretation of entropy: **Entropy is the amount of information that is hidden in a system.** Before you start reading it, there's a lot of entropy in the book you just checked out from the library. And black holes have enormous entropy. We don't know what's inside.

Shannon Entropy $S = \sum p_i \, ln \, p_i$

image: John Wheeler, *Information, physics, quantum: the search for links*.



Entropy in the digital revolution:

Information theory in computer science puts a new perspective on entropy. All information can be expressed as strings of 1's and 0's. Suppose Bob wants to tell Charlie that his computer's IP address is $|0000000000000000\rangle$. That's a really low entropy state. Bob can describe the state in just a few words: "sixteen 0's."

The IP address $|0101010101010101\rangle$ is also relatively low entropy. Bob can tell Charlie "Repeat 01 eight times."

On the other hand, $|1101000101110110\rangle$ is a high entropy state. Bob has to read out the entire sequence to Charlie.

Tools in hand, we can build a new and improved black hole.

Black hole thermodynamics: Bekenstein and Hawking found that black holes behave like black-body thermal systems. They have a temperature, they radiate heat, and you can measure their entropy.

Bekenstein-Hawking entropy:

$$S = \frac{A}{4G}$$

and horizon area never decreases (verified by LIGO in 2025)

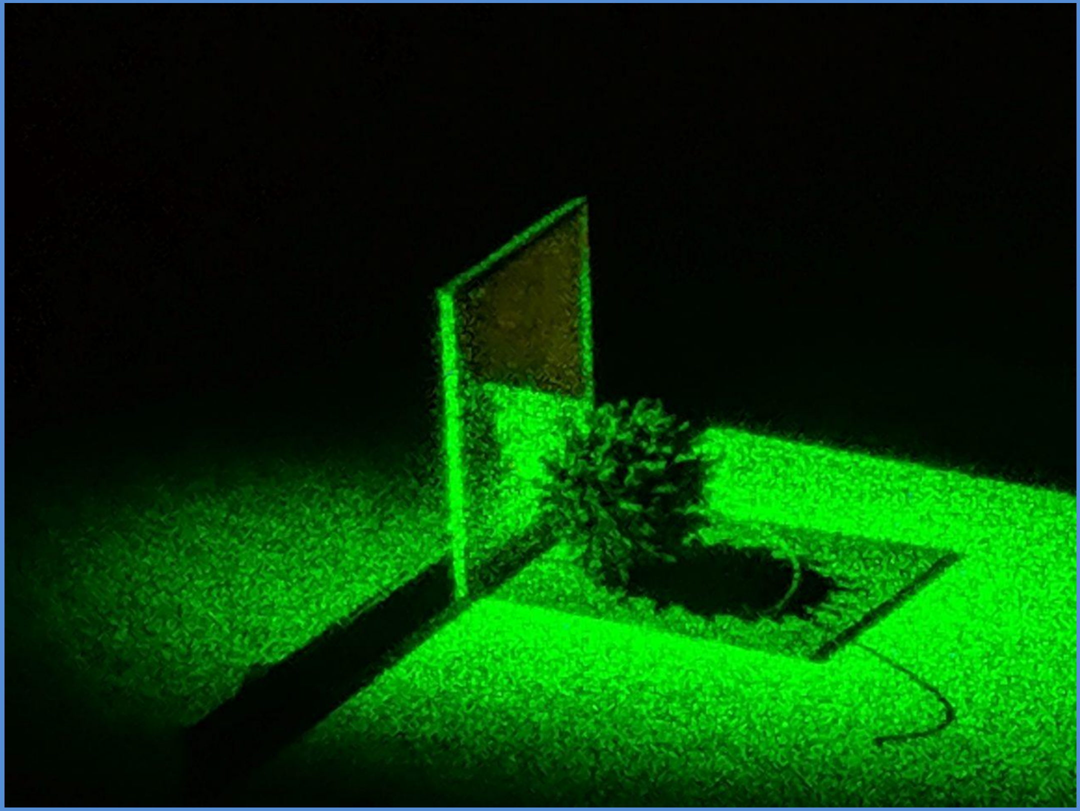
Hawking temperature:

$$T = \frac{\hbar c^3}{8\pi G k_B M}$$

Stephen Hawking, Cambridge
image: Wikipedia

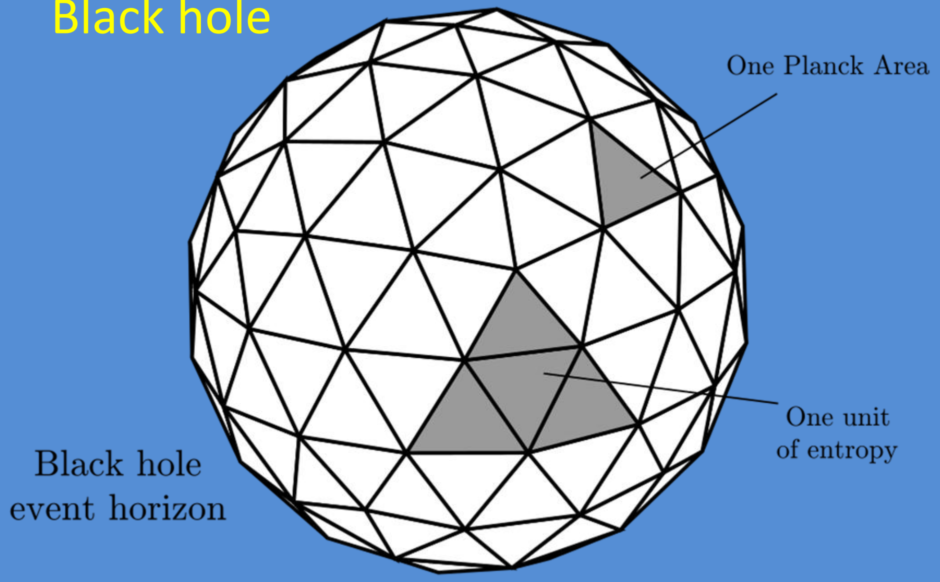
The entropy-area relation is surprising but not a problem. We know that 3-dimensional information can be recorded on a 2-D surface. Witness the laser hologram. And GR complementarity tells us that a stationary outside observer sees in-falling objects smeared over the event horizon of a black hole.

image: Holocenter.org

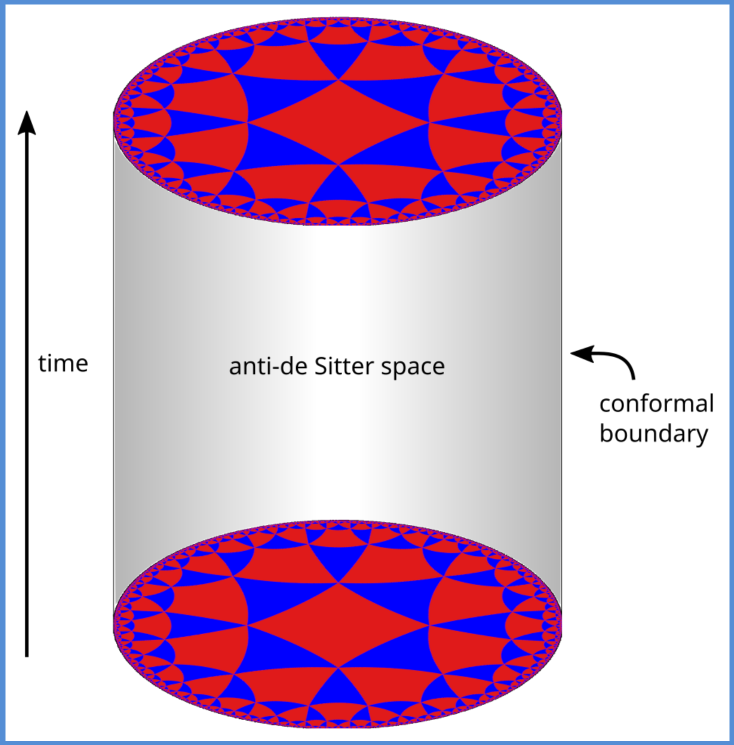


Further studies extend this Holographic Principle. Just as black hole horizons store information, the Principle implies that all the information in any closed region is encoded on its boundary.

Black hole



ADS/CFT Universe



images: Wikipedia

On the other hand, the Hawking temperature presents a BIG problem:

The known laws of physics are reversible. Information is strictly conserved. If a dictionary falls into a black hole, you should be able to ‘run the movie backward’ and recover all the information in the dictionary.

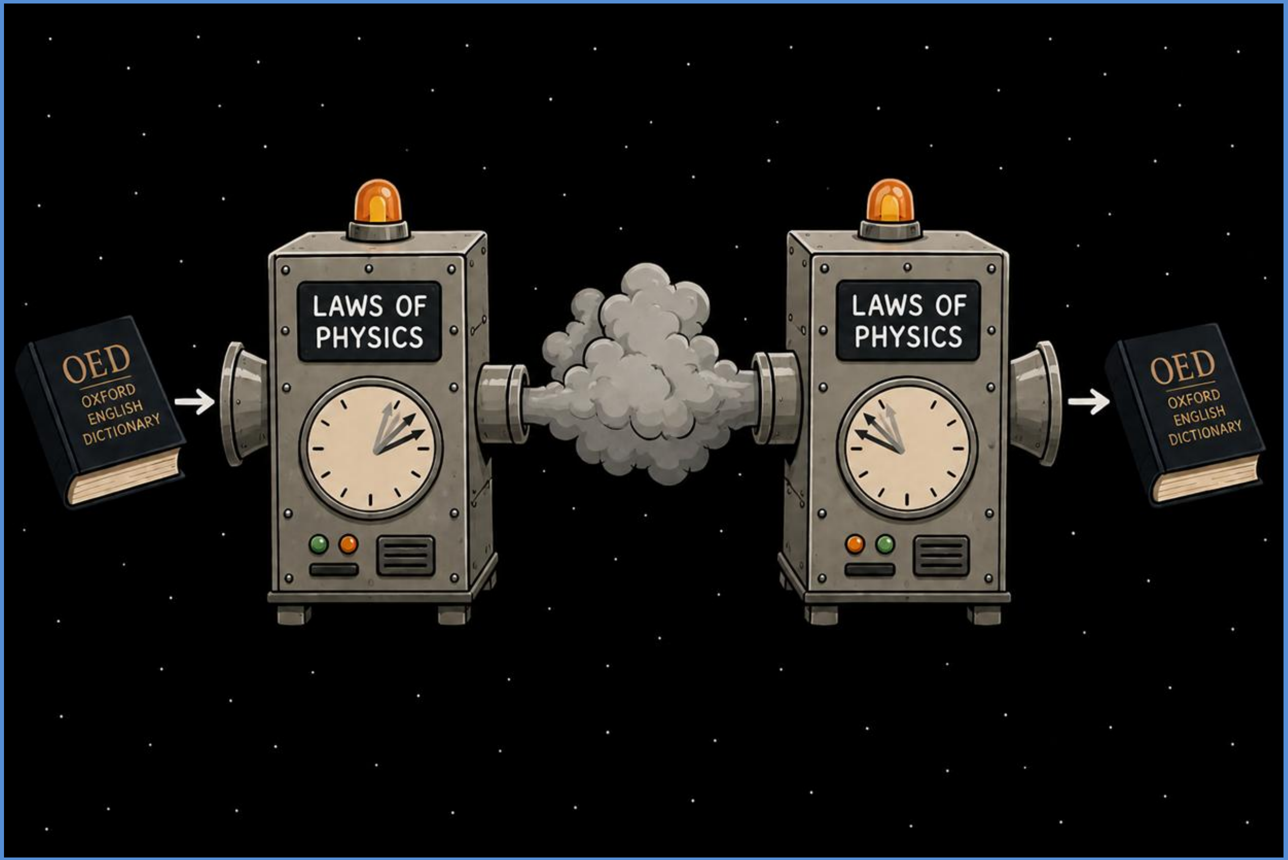


image: ChatGPT

The Hawking temperature equation tells us that a black hole evaporates over time. Clever devices should be able to collect that radiation and recover all the information that fell into the black hole. But the Hawking temperature is strictly thermal. You get the same spectrum of radiation from a dictionary as from an elephant that fell into the black hole. **This problem, the black hole information paradox, has driven much of theoretical research over the past fifty years.**

The black hole information paradox

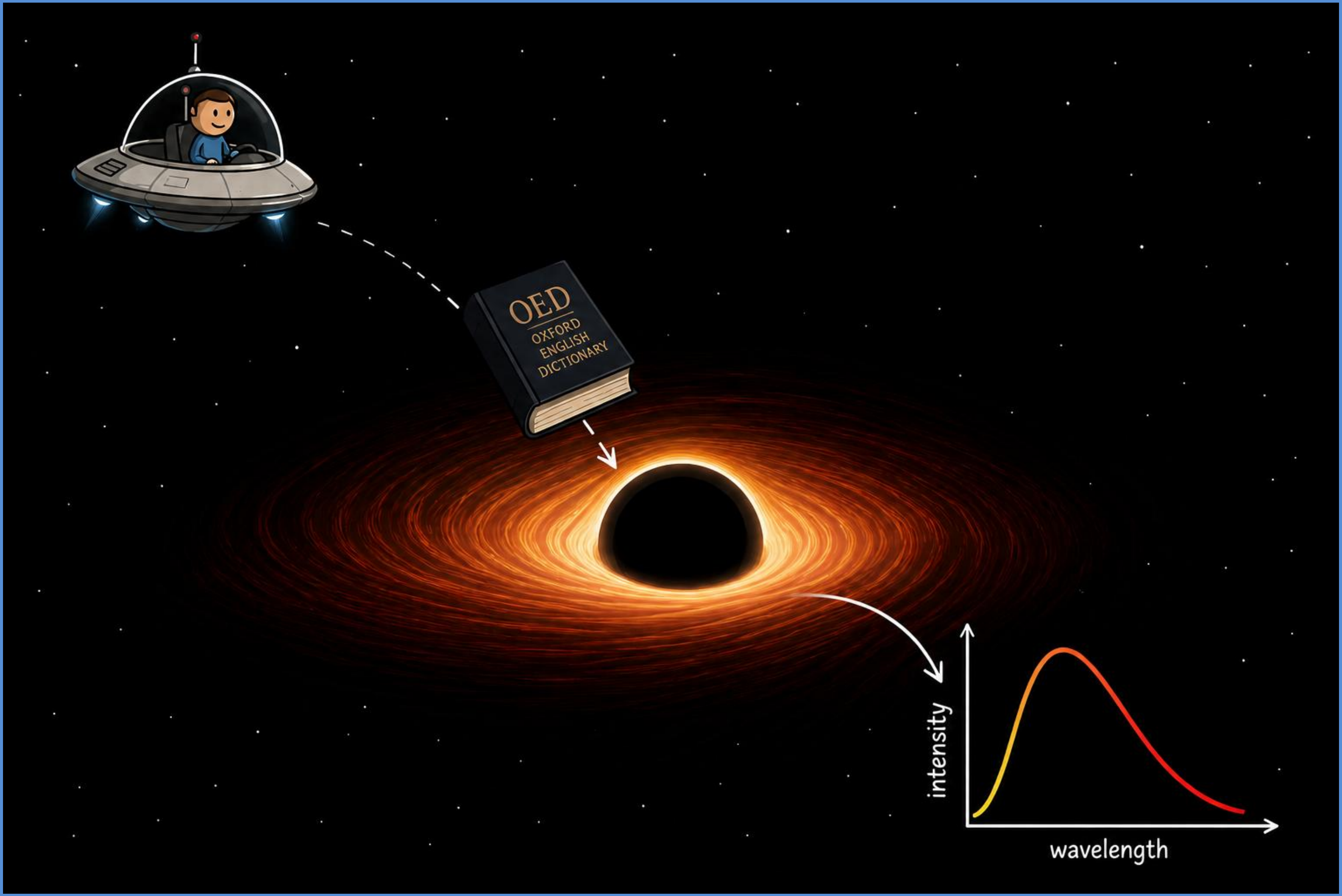


image: ChatGPT

Hawking radiation appears to violate the classical laws of physics, but we have these new information-theoretic tools. Here's The Plan to resolve the black hole information paradox and understand life, the universe, and everything:

Given:

- information = entropy
- area of the event horizon measures entropy
- information about all the stuff inside the black hole is recorded on the event horizon (holographic principle)
- as Hawking radiation evaporates a black hole, its horizon area decreases, and therefore its information content shrinks
- so Hawking radiation must carry information that was inside the black hole

The Plan:

- figure out the quantum physics of Hawking radiation and how it channels information from the horizon back out into the universe.

Black hole thermodynamics implies quantum mechanics:

Horizon area in the Bekenstein-Hawking entropy is measured in Planck units, and Planck's constant, the signature of quantum effects, also appears in the Hawking temperature. Understanding black holes, the extremes of spacetime curvature, requires understanding their quantum mechanics. GR meets QM.

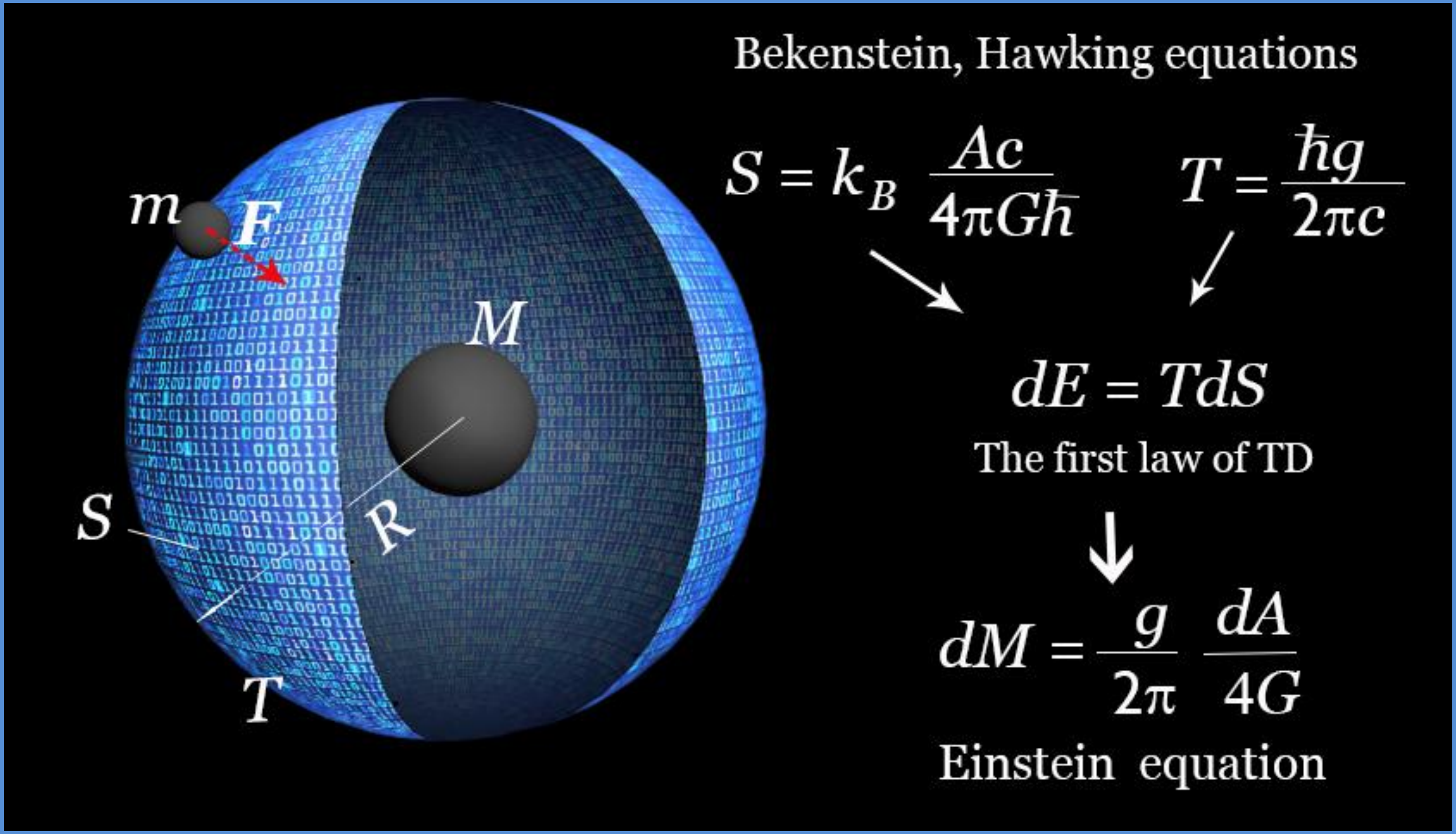


image: Yormahmad Kholov, Wikipedia

We need quantum mechanics, the physics of the very smallest components of our universe, in order to understand black holes, the extremes of spacetime at the very largest scales!

QM tells us that Hawking radiation originates in particle pair creation: information leaks out via quantum fluctuations in spacetime

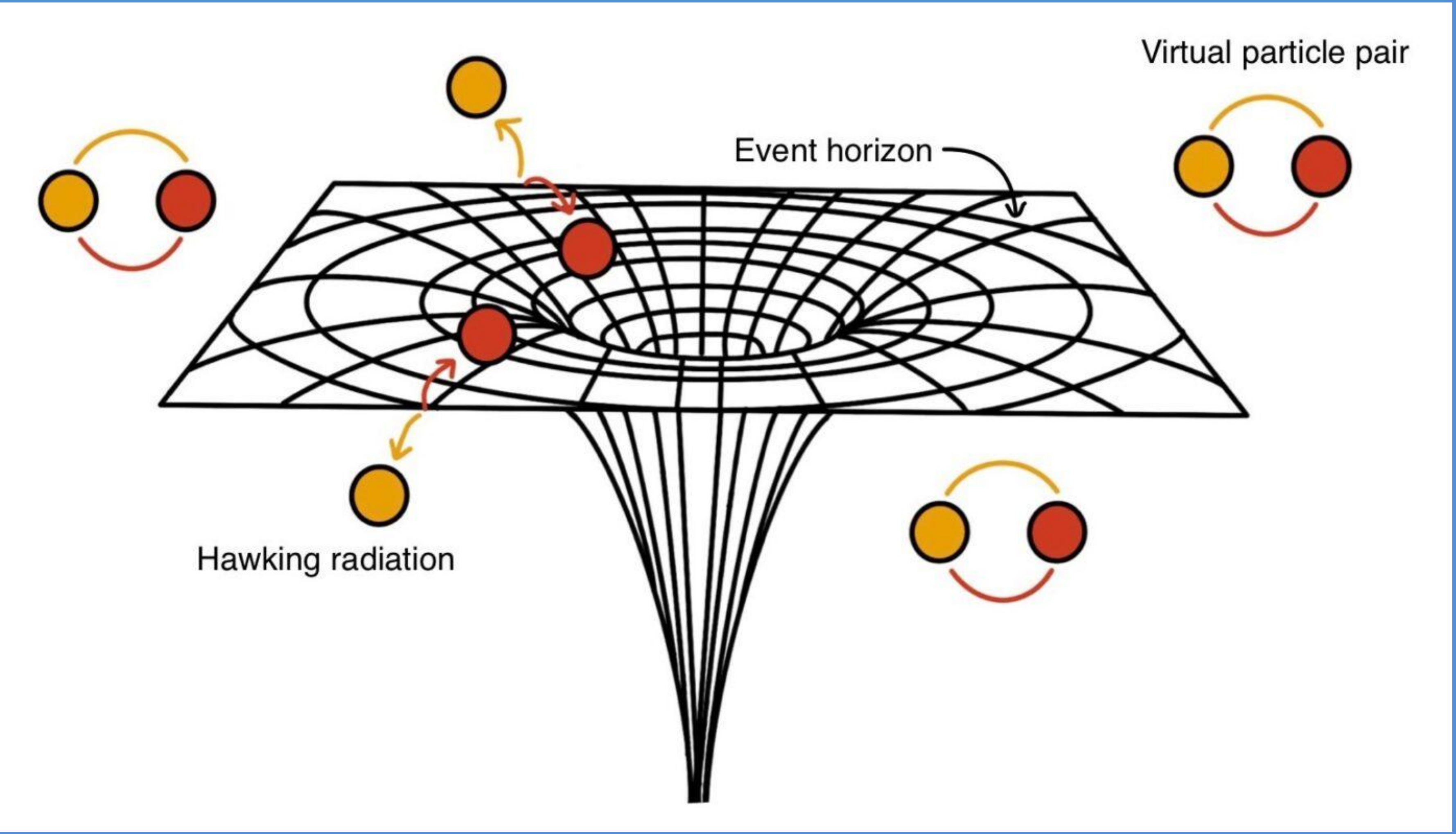


image: Amelie Orban, Quantum Universe. Also see
https://jila.colorado.edu/~ajsh/bh/hawk.html

But you have to wait a long, long time for a black hole to evaporate . . .

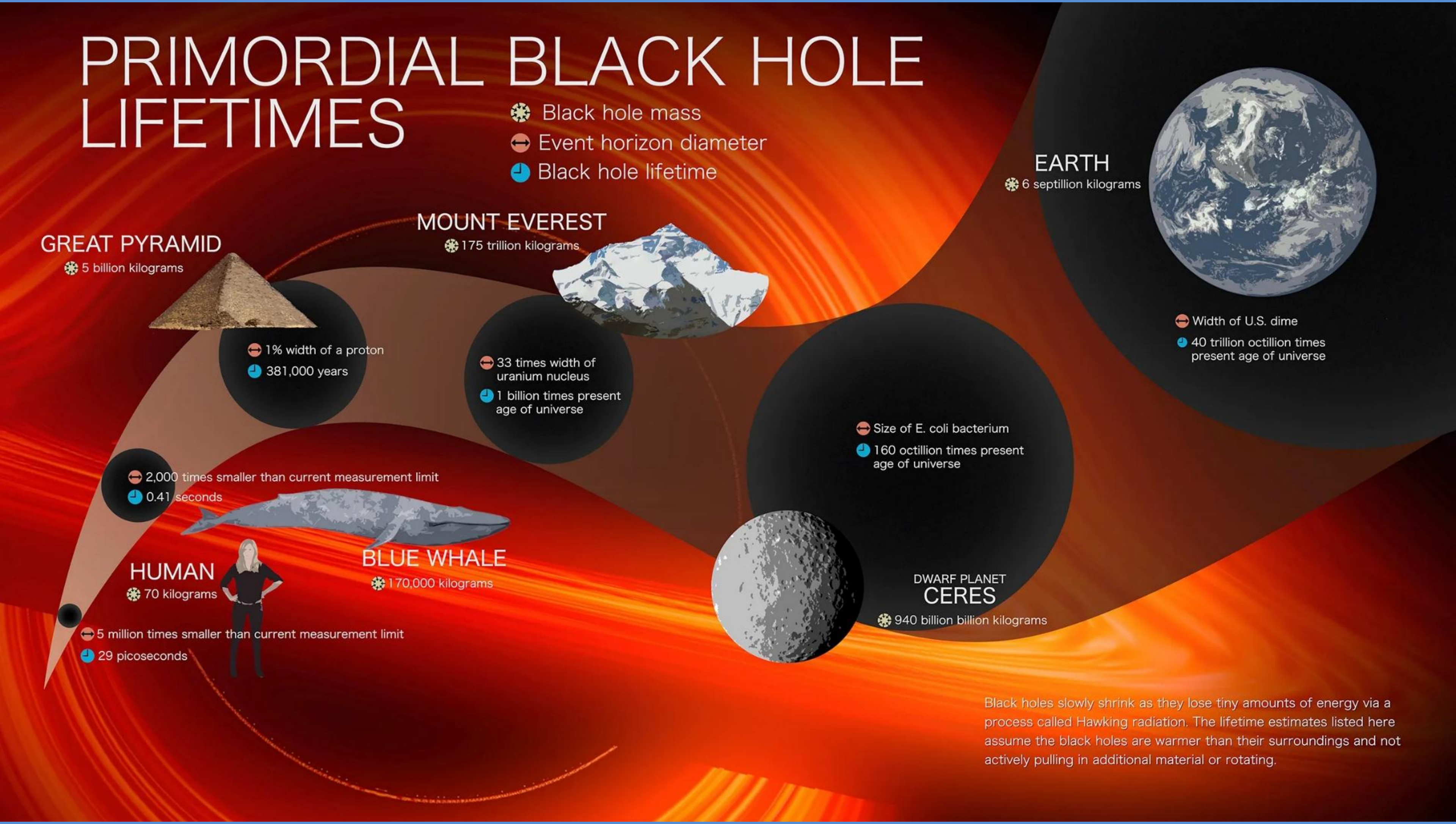
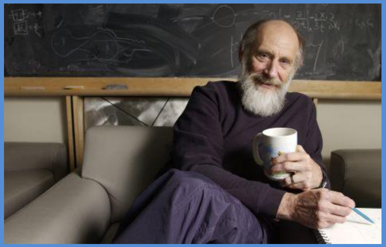


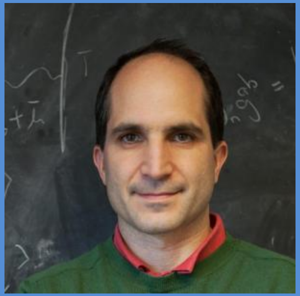
image: NASA Goddard Space Flight Center

Can we find a better way to extract information from a black hole? Do we really have to wait that long?

QM entanglement and ER = EPR. Particles become entangled. If you know the state of one, you immediately know the state of the other. Entanglement carries information. Furthermore, quantum entanglement is equivalent to wormholes in spacetime.



Leonard Susskind, SITP



Juan Maldacena, IAS

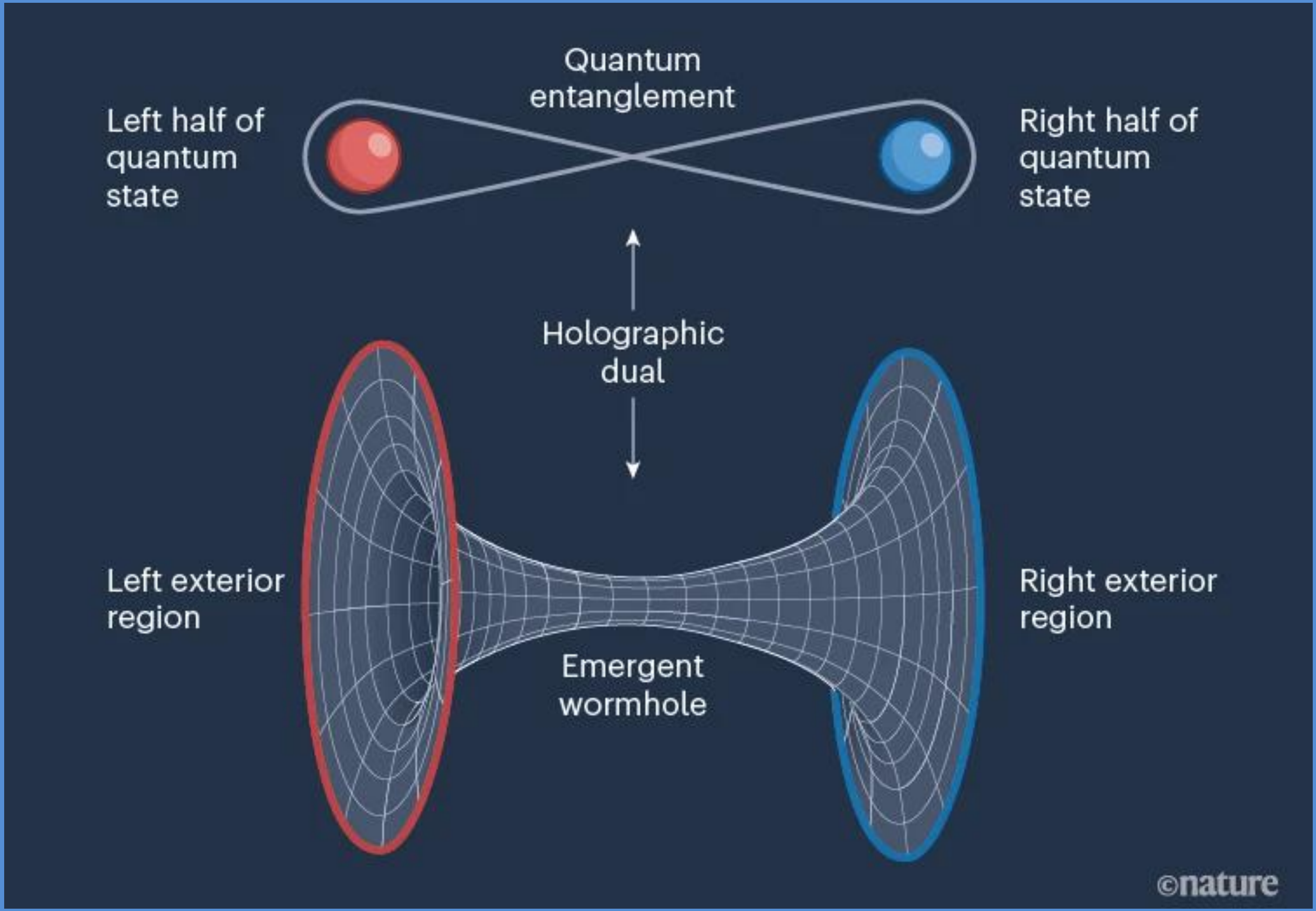


image: Susskind and Wall. 2022.

How to probe a black hole: Hawking radiation is entangled with the partner pairs in the black hole interior (the ‘bulk’), and those partners are entangled with all the information in the bulk. Collect the Hawking radiation and you can read what’s inside the black hole.

Eva Silverstein, Stanford
image: American Academy of Arts and Sciences

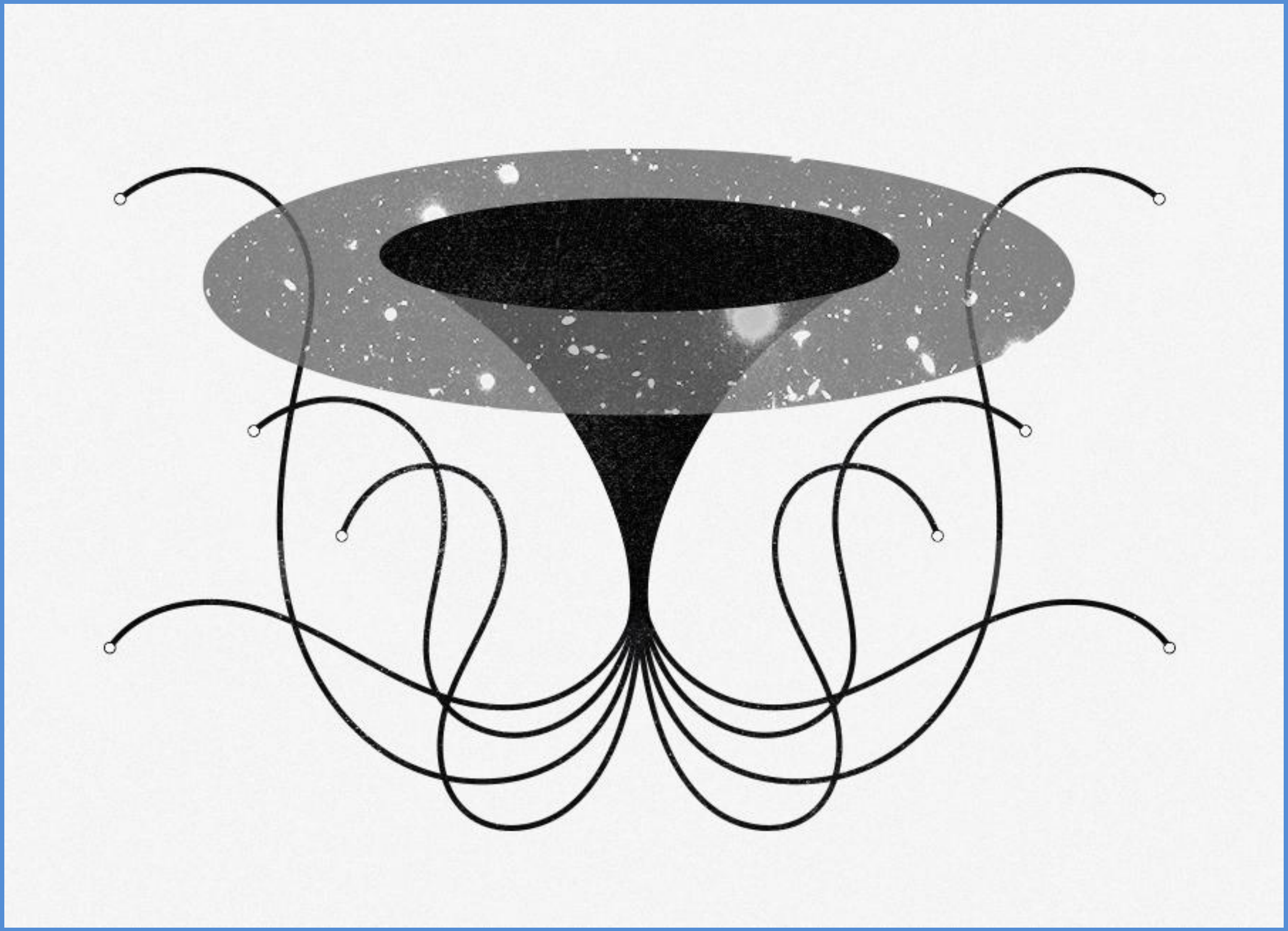


image: Olena Shmahalo, Quanta Magazine

Quantum information theory, latest kid on the block, provides further insights how black holes process information. It might be possible to read out entire volumes of information, not just one letter (or qubit) at a time.

Black holes process the information inside. They behave like quantum computers. The following slides illustrate these ideas:

1. information (a copy of the OED, say) falls into the black hole
2. that information immediately becomes entangled with all the other qubits on the horizon
3. logical ‘operators’ (physical laws) process the information, just as logic gates process quantum computer circuits
4. conditions in the ‘bulk’ (interior) of the black hole can be accessed by applying quantum error correction algorithms on the horizon
5. complexity in the bulk, i.e. the web of quantum circuits, increases exponentially faster than the entropy, but
6. information can be recovered (eventually) in the Hawking radiation

In one of the most stunning discoveries of this century, Michael Nielsen (2006) proved that minimizing the complexity of a quantum logic circuit is equivalent to finding the geodesic path through that circuit. Quantum circuits have a geometry, and that geometry matches the geometry of general relativity!

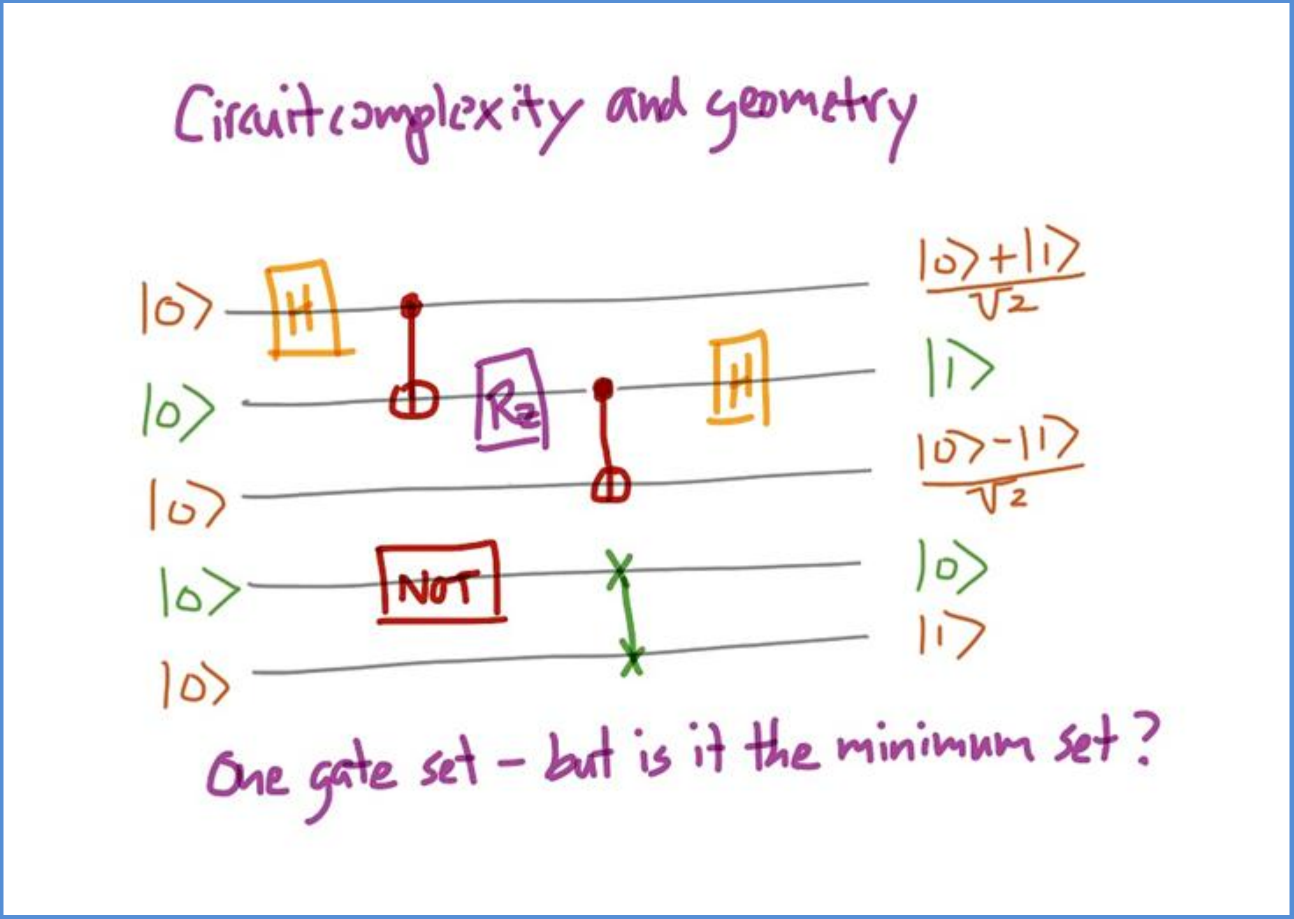
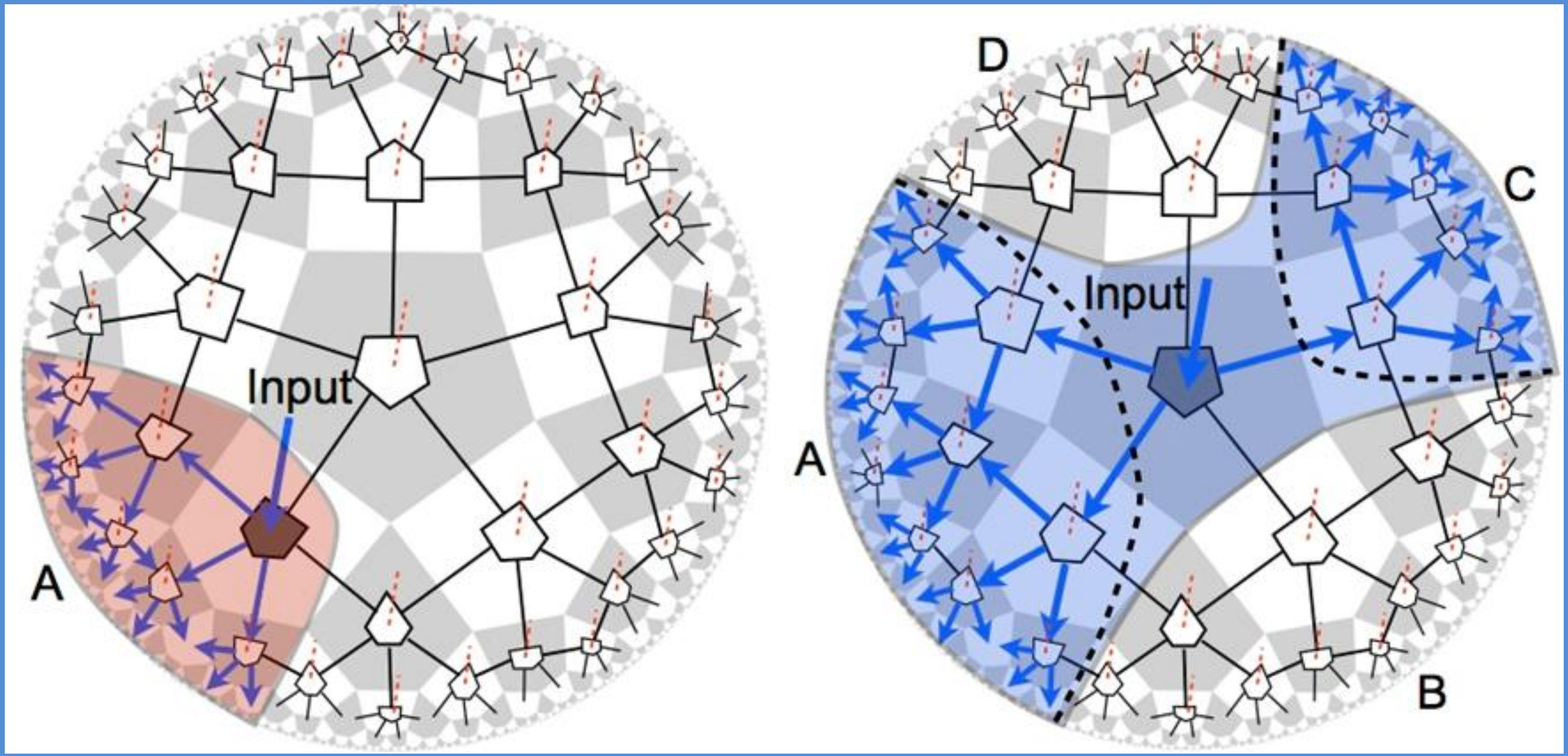


image: Bob Dorsett

Given that black holes are pure spacetime geometry and quantum complexity mirrors that geometry, then we should be able to model black holes as quantum circuits.



<u>Black holes as tensor networks:</u> Information in the 'bulk,' inside the black hole, is accessible through the connectivity within the quantum circuit on the horizon.

image: Beni Yoshida

Sounds crazy! How do we know any of this may be true? Well, for one thing, LIGO confirms that black holes are fast scramblers.

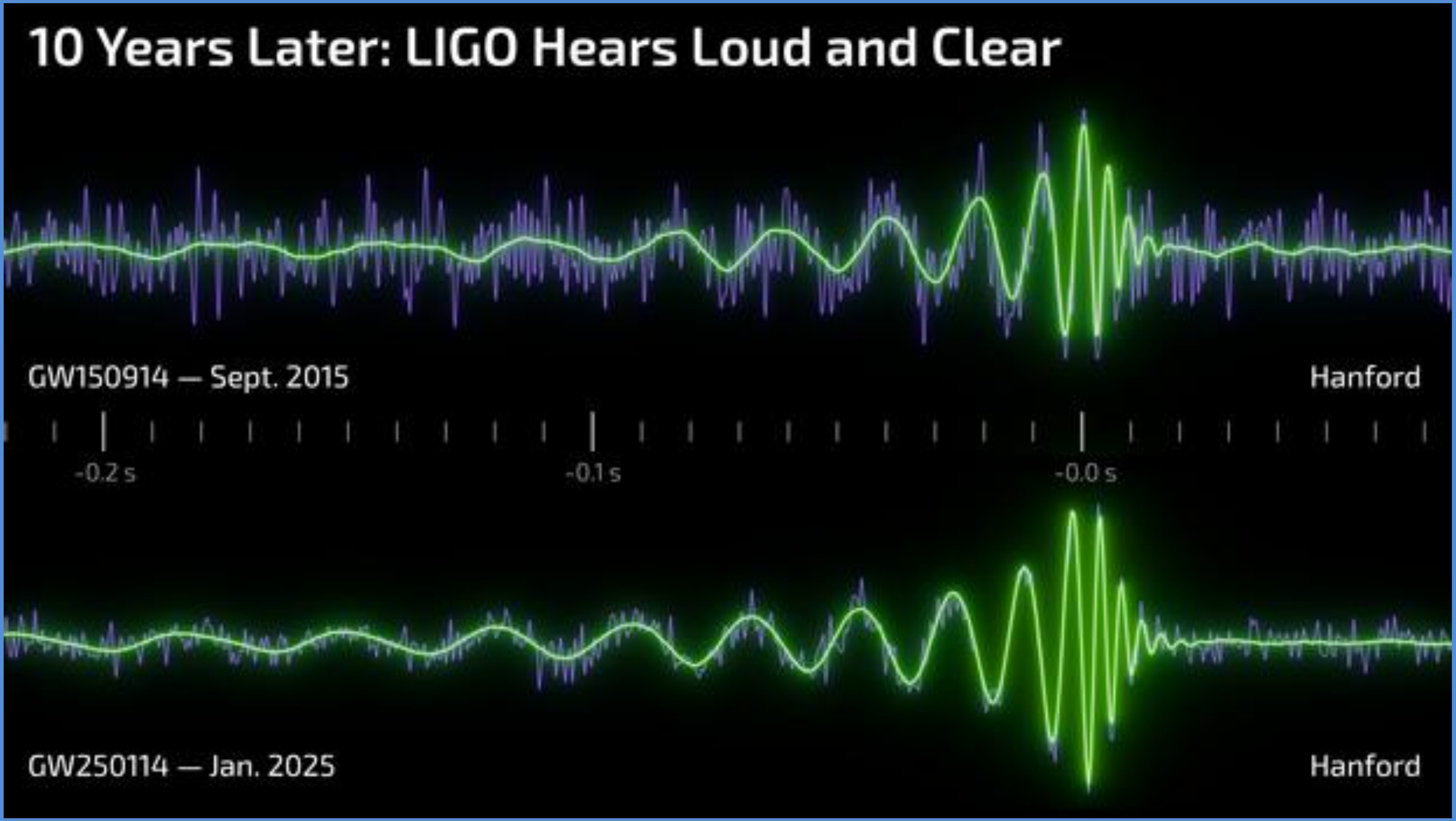


image: LIGO

And the quantum computer wizards are studying black holes in the lab. New experiments are testing these outlandish ideas. As quantum computers improve, we may be able to see black hole phenomena directly.

The Steinhauer Lab at the Technion University found a phonon analog of Hawking radiation in the Bose-Einstein condensate of accelerating Rubidium atoms.

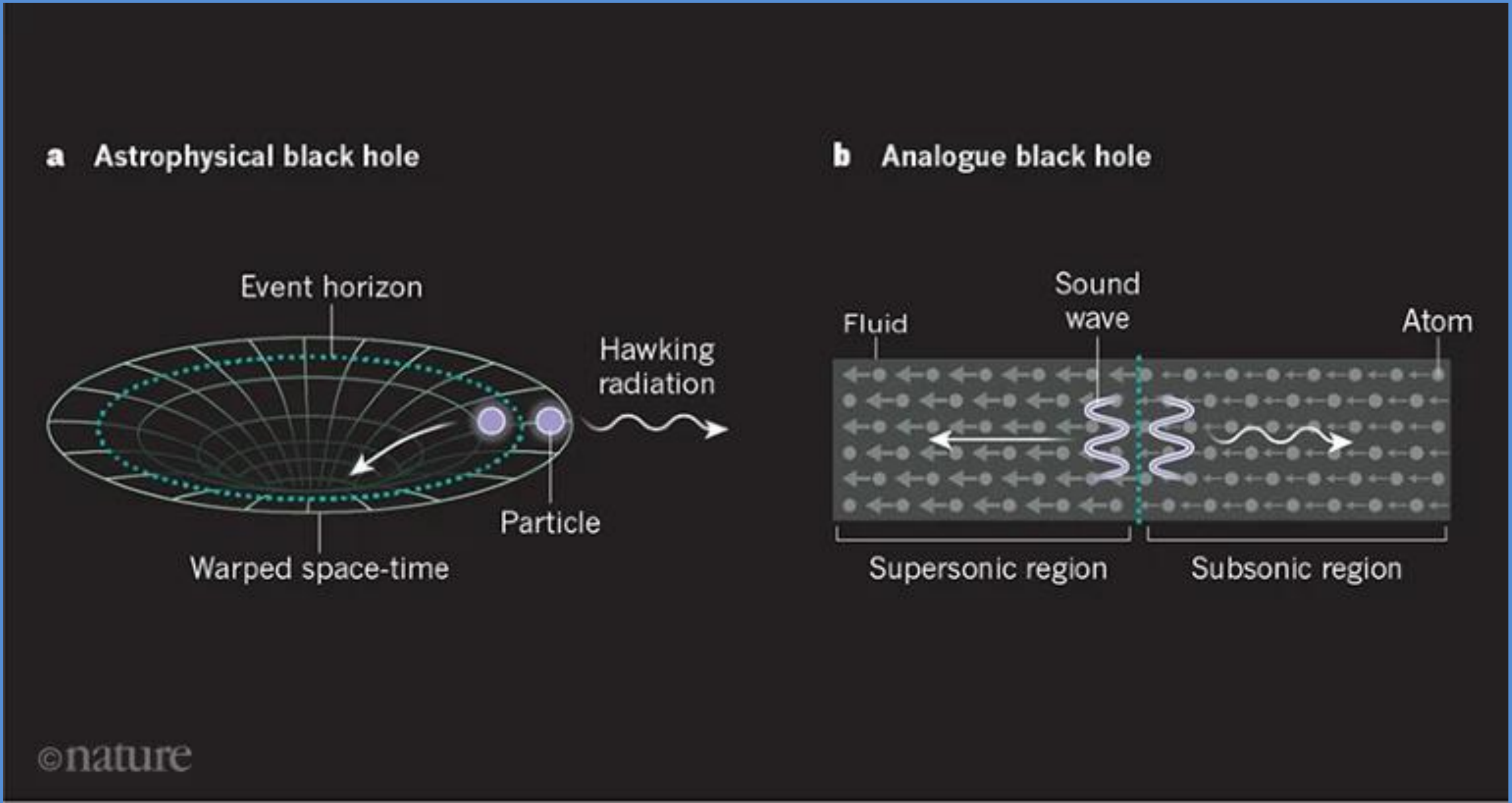
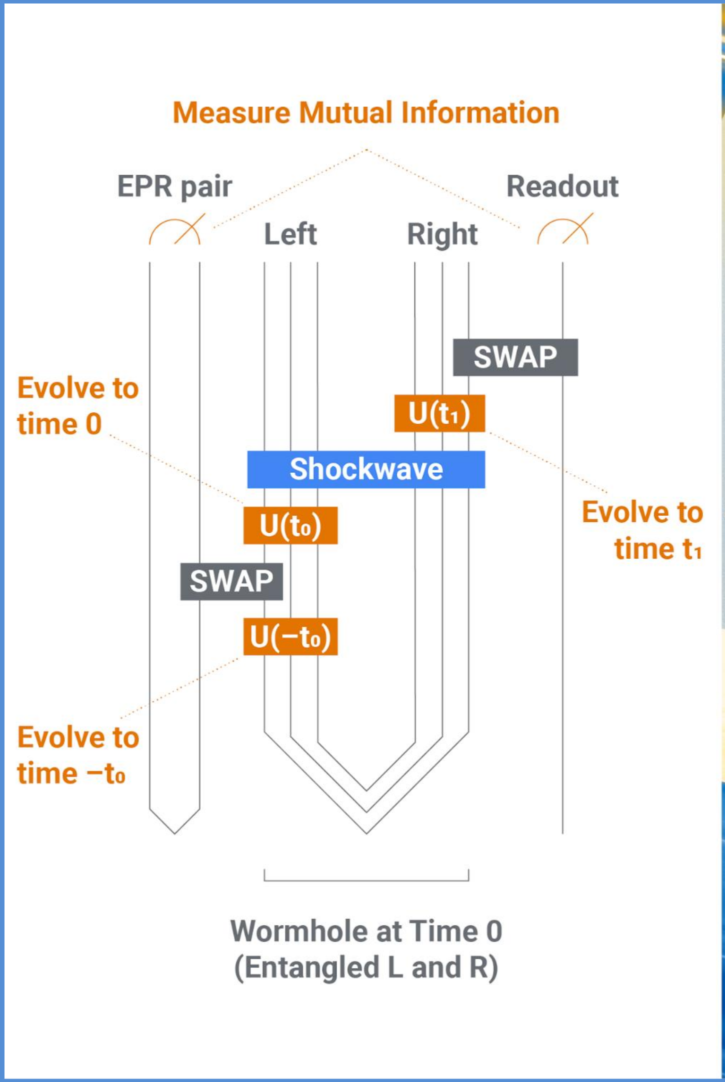


image: Weinfurtner, 2019

<u>Traversable wormhole on a chip</u>: Jafferis et al, 2022, transported a quantum state through a simulated wormhole in the Google Sycamore QC, providing experimental evidence for ER = EPR.



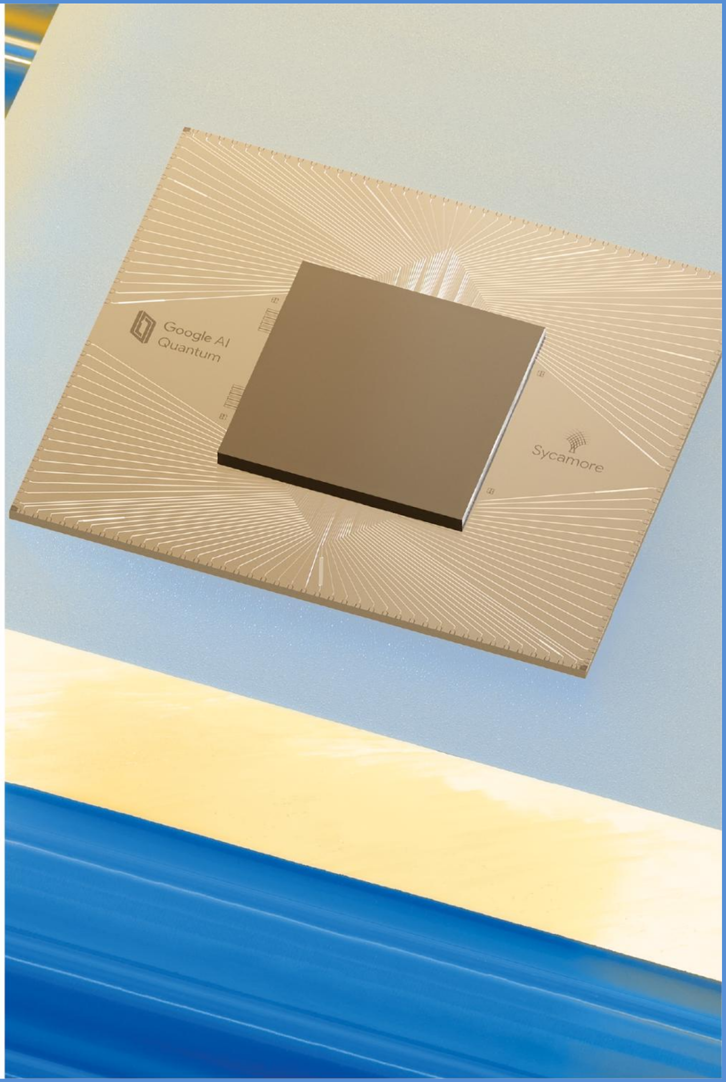


image: Google Quantum AI

Chris Monroe's lab, 2019, created quantum circuit fast scramblers analogous to black holes.

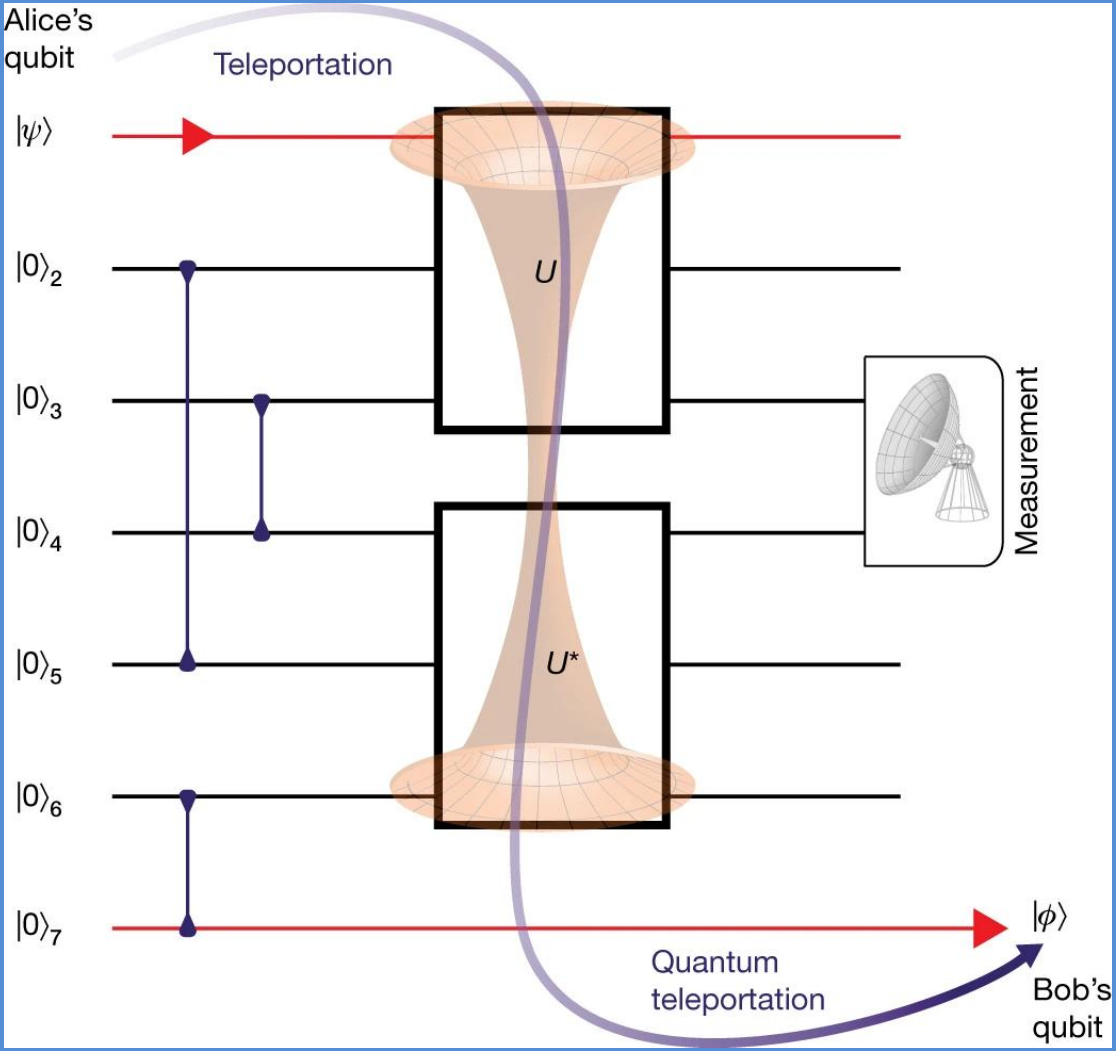
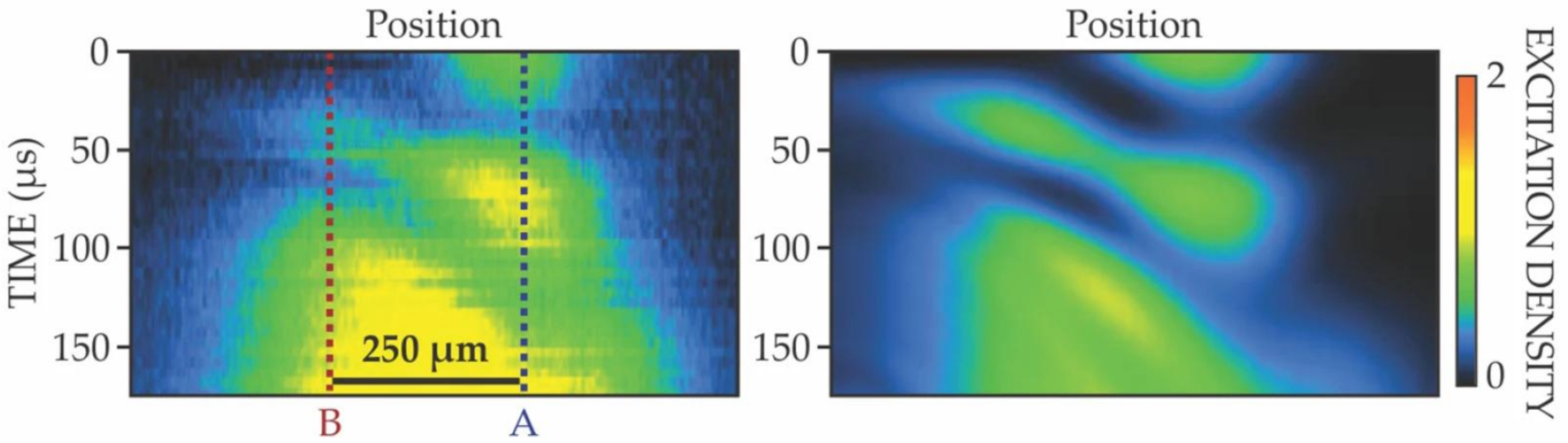


image: Landsman et al. 2019.

Beyond the phenomena, a complete black hole (simulation) in the lab? The Schleier-Smith lab at Stanford is constructing a cold-atom tensor network that behaves like a black hole.

image: Monika Schleier-Smith, Stanford



Entangled clouds of Rubidium atoms scramble information. Information from laser pulse at A is quickly entangled with B, then oscillates back and forth. image: Schleier-Smith lab, 2019.

We don't yet understand the quantum mechanics of black holes. Speculation is rife. "Firewall" calculations postulate extreme quantum energy fluctuations at the horizon. "Fuzzball" posits a black hole of strings, like a chaotic ball of yarn. Or maybe spacetime itself undergoes a phase transition at the horizon, unraveling hidden dimensions.

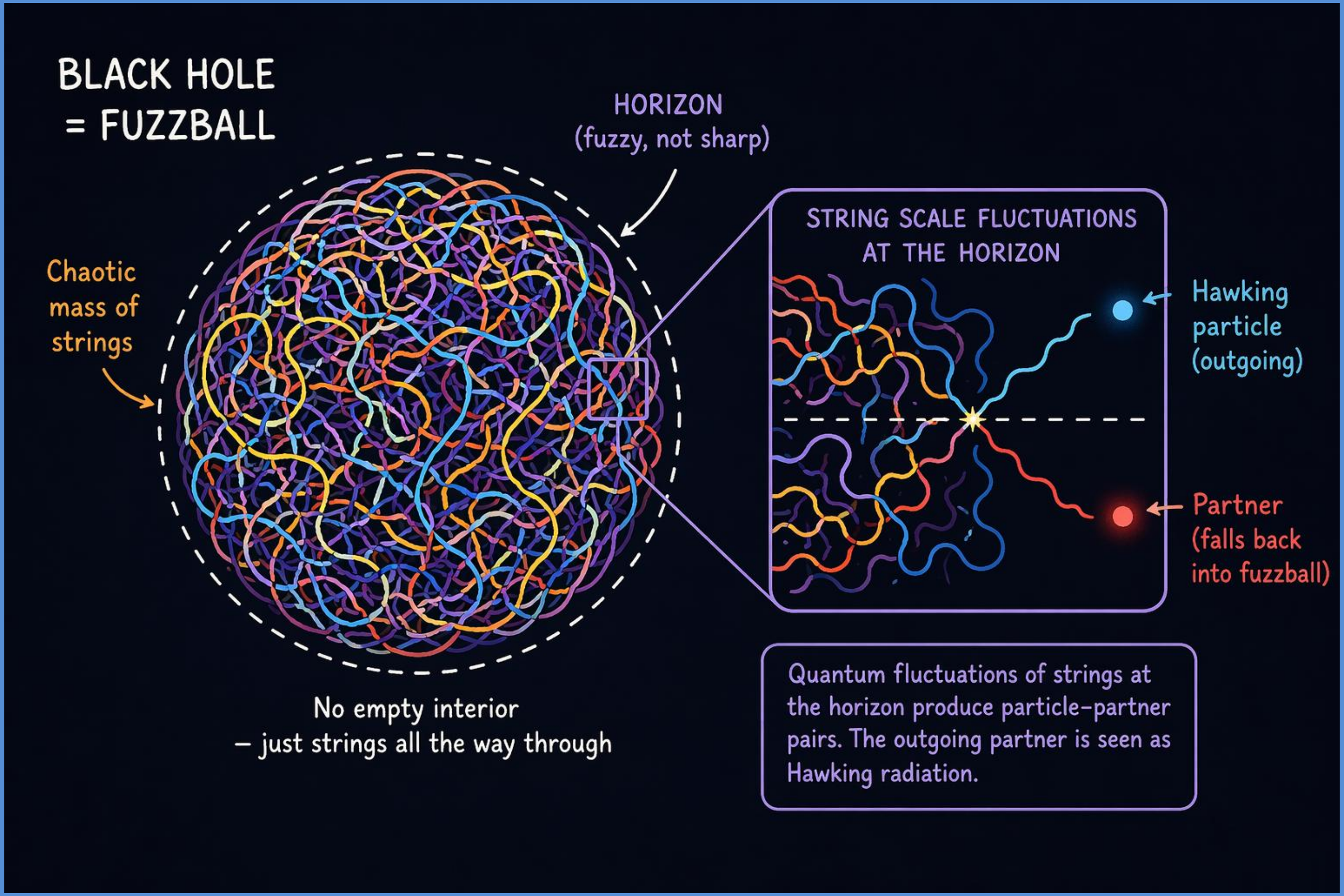


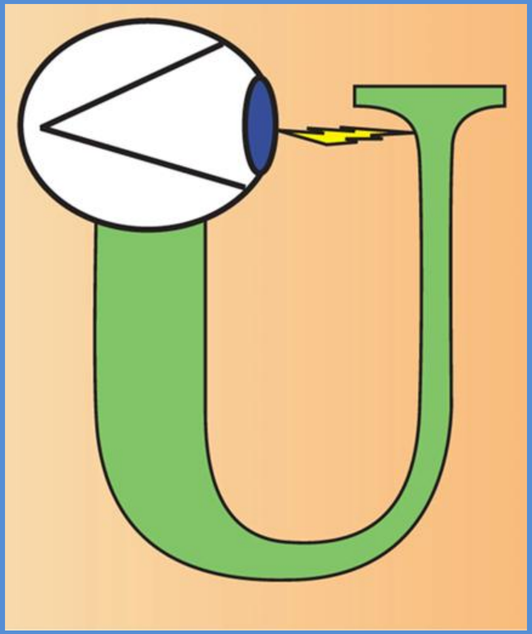
image: ChatGPT

General relativity, thermodynamics, quantum mechanics, and information theory have guided us well. Their predictions have survived observational tests even in the extremes of the black hole environment. New observatories are measuring those extremes to great precision. But we know GR can’t be the complete story. The equations break down near a singularity. And singularities are kind of important. They represent the end of spacetime in black holes and the beginning of spacetime in the Big Bang. We need a new mathematics, a quantum theory of gravity. That’s the Holy Grail of modern theoretical physics.

"What is it that breathes fire into the equations and makes a universe for them to describe?"

Stephen Hawking

Misner, Thorne, Zurek. 2006. *Wheeler's Participatory Universe.* Physics Today.



References:

Brown, Adam and Leonard Susskind. 2022. A holographic wormhole traversed in a quantum computer. *Nature*: 569, News and Views.

de Nova et al. 2019. Observation of thermal Hawking radiation and its temperature in an analog black hole. *Nature*: 569, 688-691

Dorsett, Robert. 2021. Quantum information and quantum gravity. https://dorsett-edu.net/Articles/Quantum_Information_&_Quantum_Gravity_PDF.pdf

Jafferis, Daniel et al. 2022. Traversable wormhole dynamics on a quantum processor. *Nature*: 612, 51-55

K.A. Landsman et al. 2019. Verified quantum information scrambling. Nature: 567, 61-65

Weinfurtner, Silke. 2019. Quantum simulation of black hole radiation. *Nature*: 569, 634-635

Thank you!