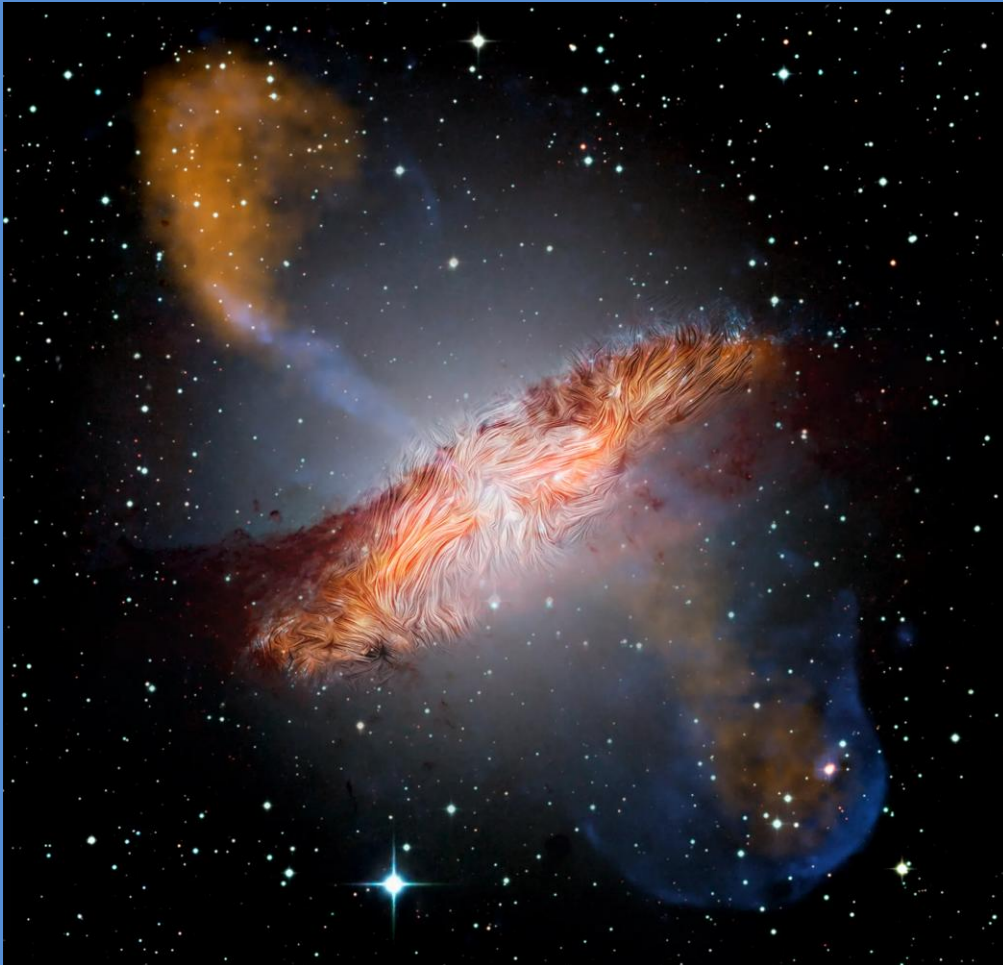


Black Holes: Gateways to Understanding



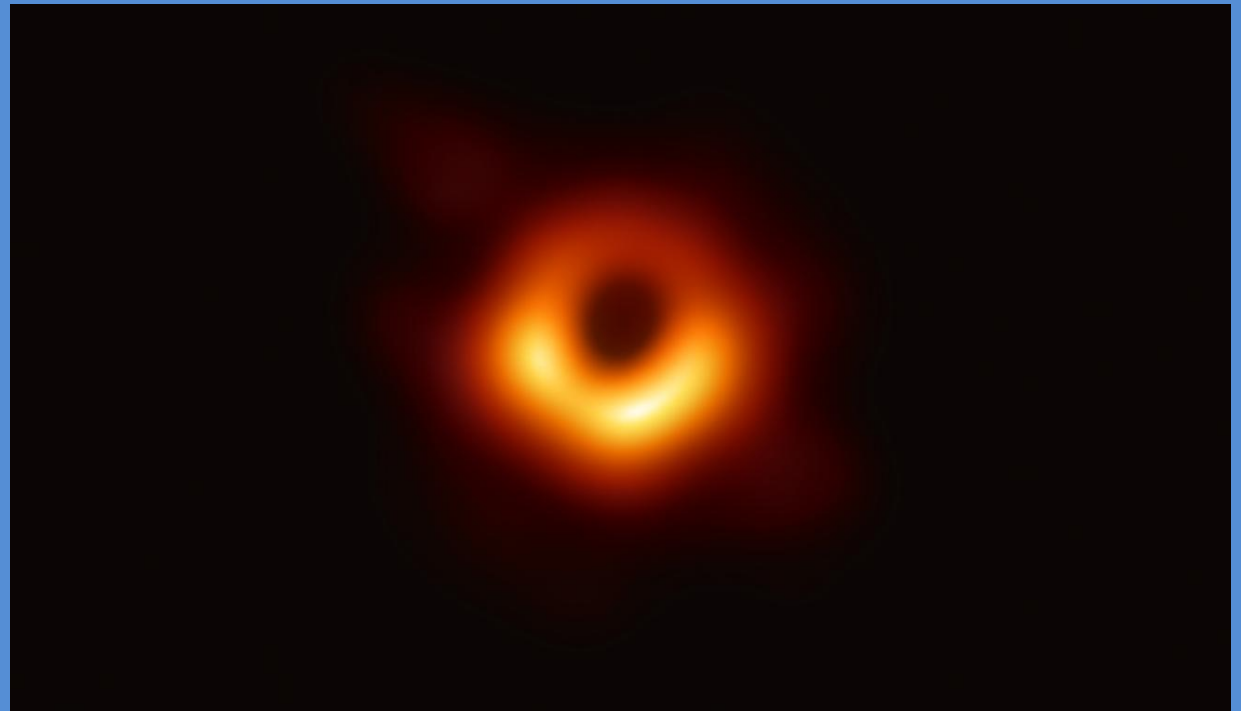
Bob Dorsett
April 2026

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

Classical black holes

Einstein's general theory of relativity (GR) predicts black holes, and observations so far confirm theoretical predictions of GR to high accuracy. GR black holes are characterized by just three parameters: mass, spin, and charge. If you know those three you can figure out everything else about the black hole. But GR can't be the whole story. It has become evident that black holes are quantum systems. They provide the best available laboratories to reconcile the two great realms of our understanding: general relativity and quantum mechanics. We will consider classical black holes first, then add the latest discoveries based on quantum theory.

The next few slides illustrate some essential ingredients of general relativity (GR) and different ways of thinking about the physical conditions implied by GR. All that we know with confidence comes from the mathematical equations, but the equations allow different ways of visualizing their predictions.

The Schwarzschild metric: the fundamental equation of black hole physics

$$ds^2 = -\left(1 - \frac{2GM}{r}\right) dt^2 + \frac{1}{\left(1 - \frac{2GM}{r}\right)} dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

Bad things happen when an object, at distance r , approaches the Schwarzschild radius $2GM$. There be dragons.

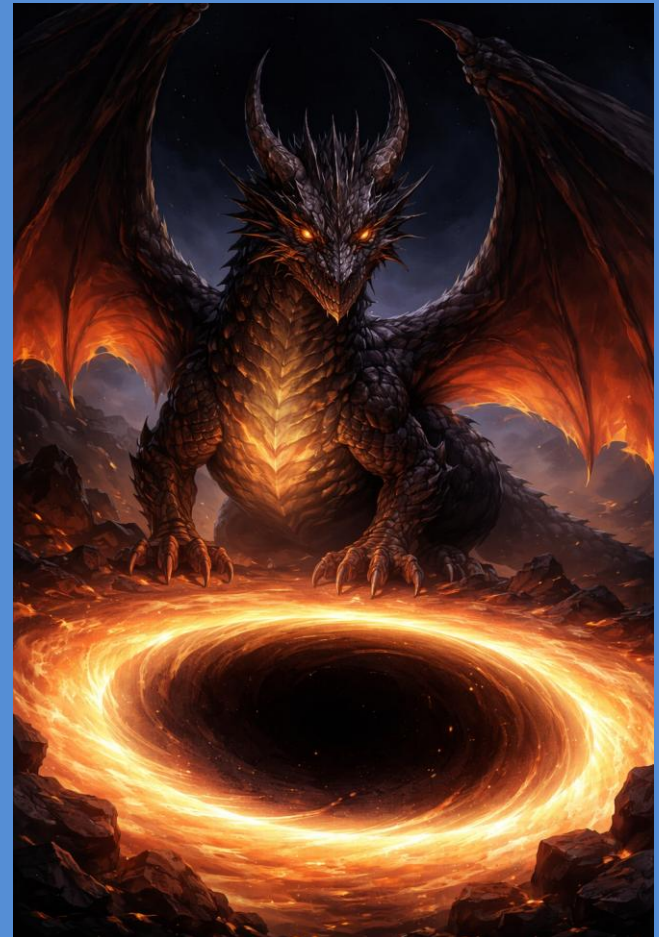


image credit: ChatGPT

GR spacetime: high energy density, e.g. mass, warps the metric (clocks and meter sticks) of spacetime.

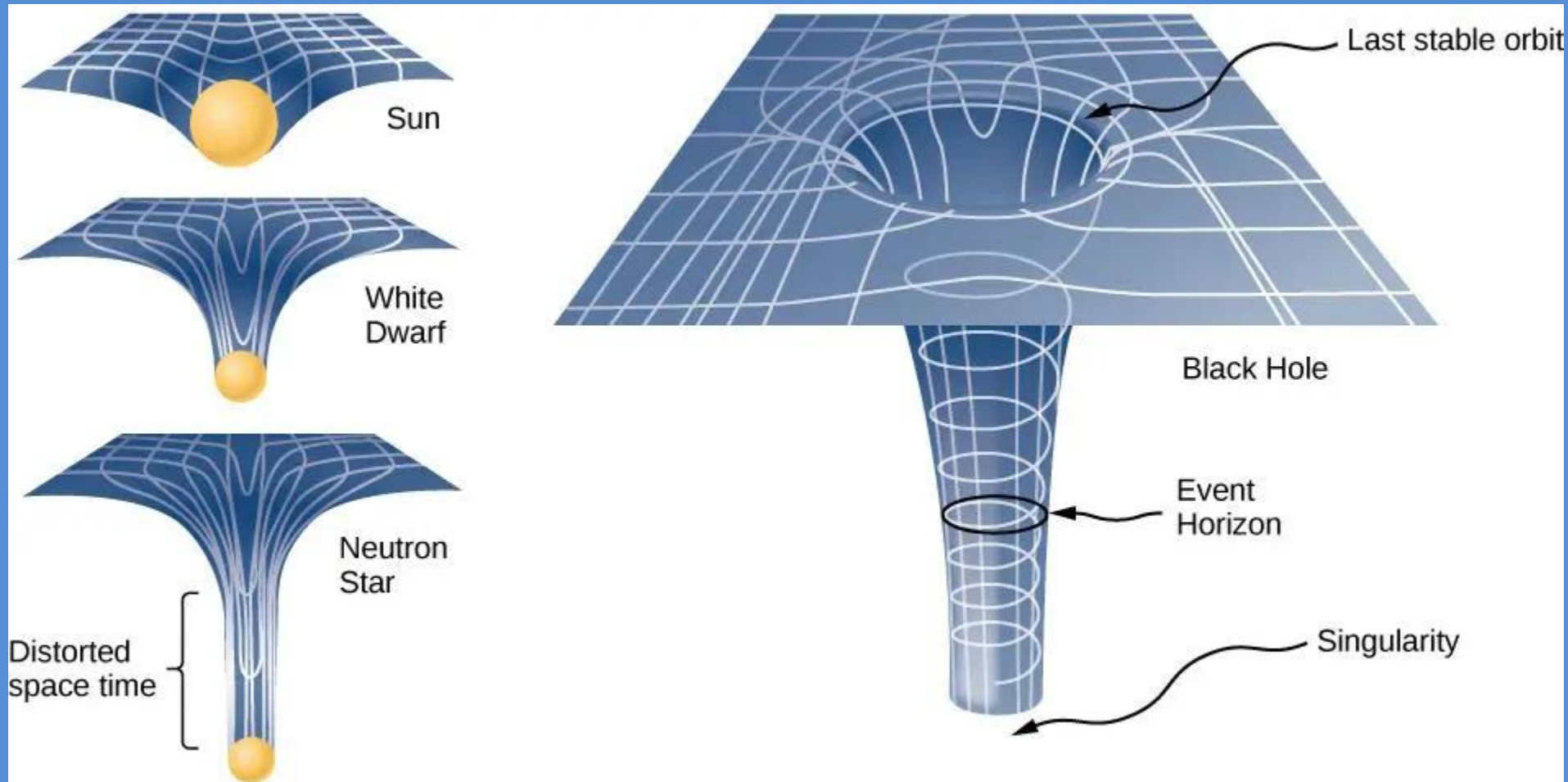


image: OpenStax University Physics

The metric near a Schwarzschild black hole

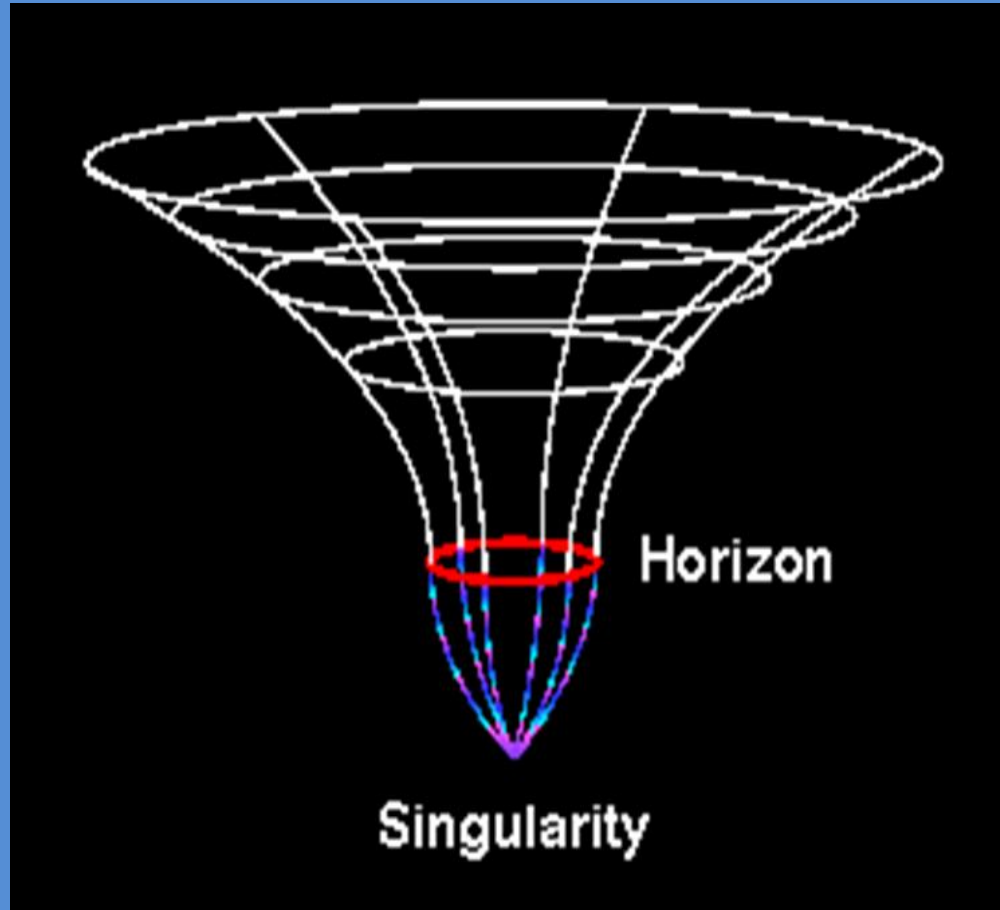
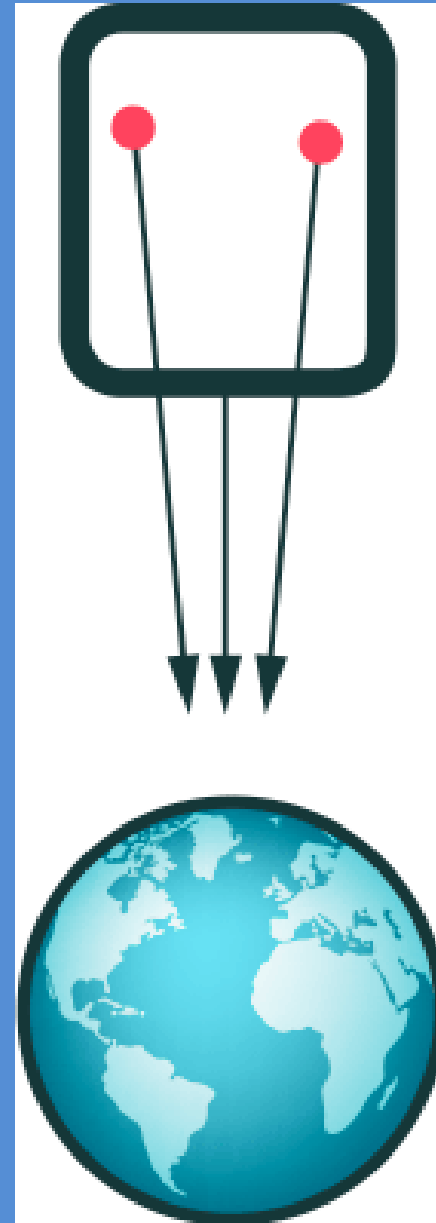


image: Andrew Hamilton, JILA

Tidal forces are the signature of the curved spacetime, i.e. gravity. Free-fall systems provide the laboratories with which to measure curvature.

Imagine two objects on opposite sides of a box that is in free-fall toward earth. The objects approach each other over time. Objects separated radially would move farther apart.

image: Daniela Leitner and Markus Poessel, Einstein Online



Another way to think of conditions near black holes: waterfalls of (stretching) spacetime.

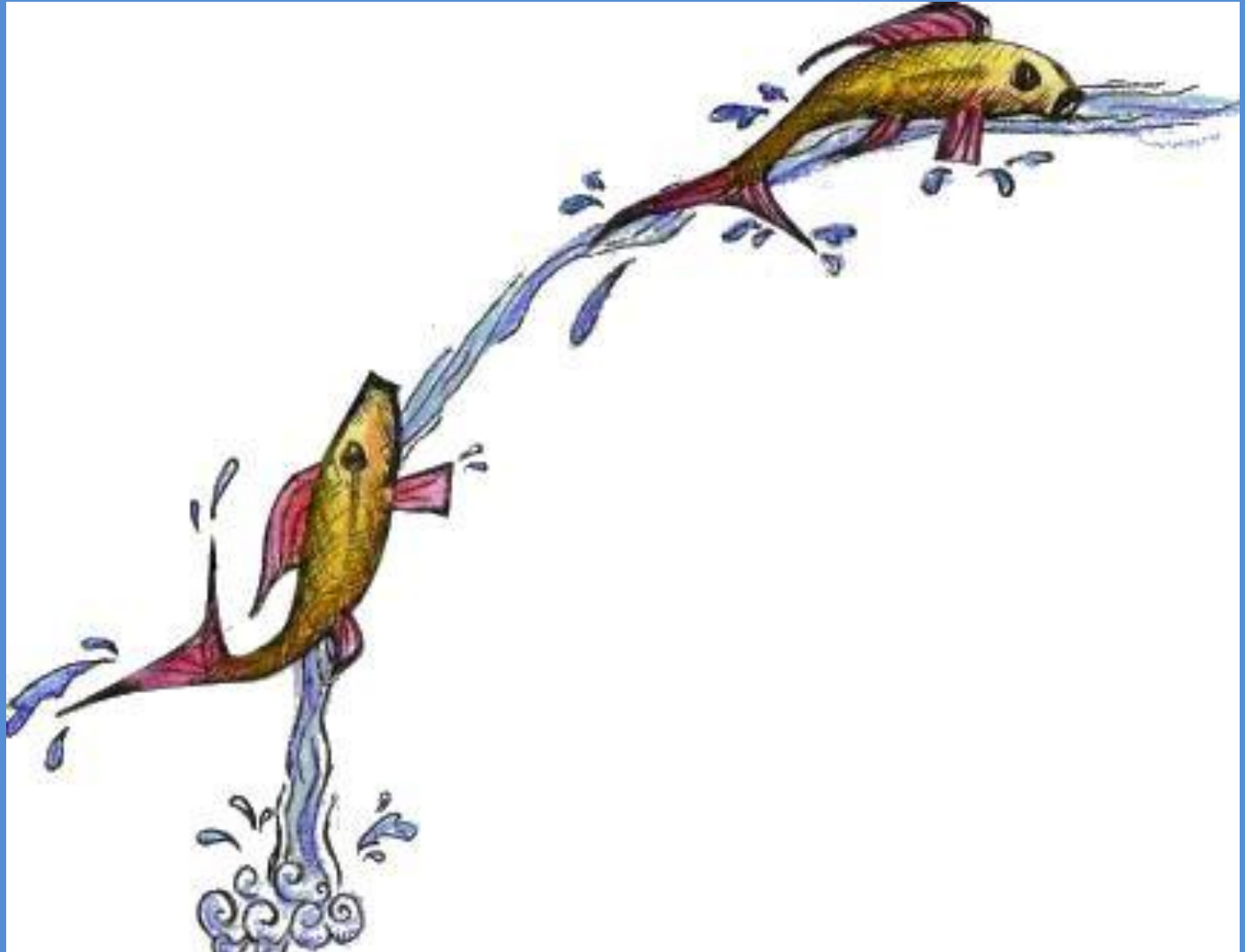


image: JILA, Wild Hamilton

The next few slides list the different kinds of black holes (discovered as of 2026) ranked in order of increasing mass.

Primordial black holes

- remnants of the big bang
- asteroid to stellar scale
- tentative evidence from micro-lensing

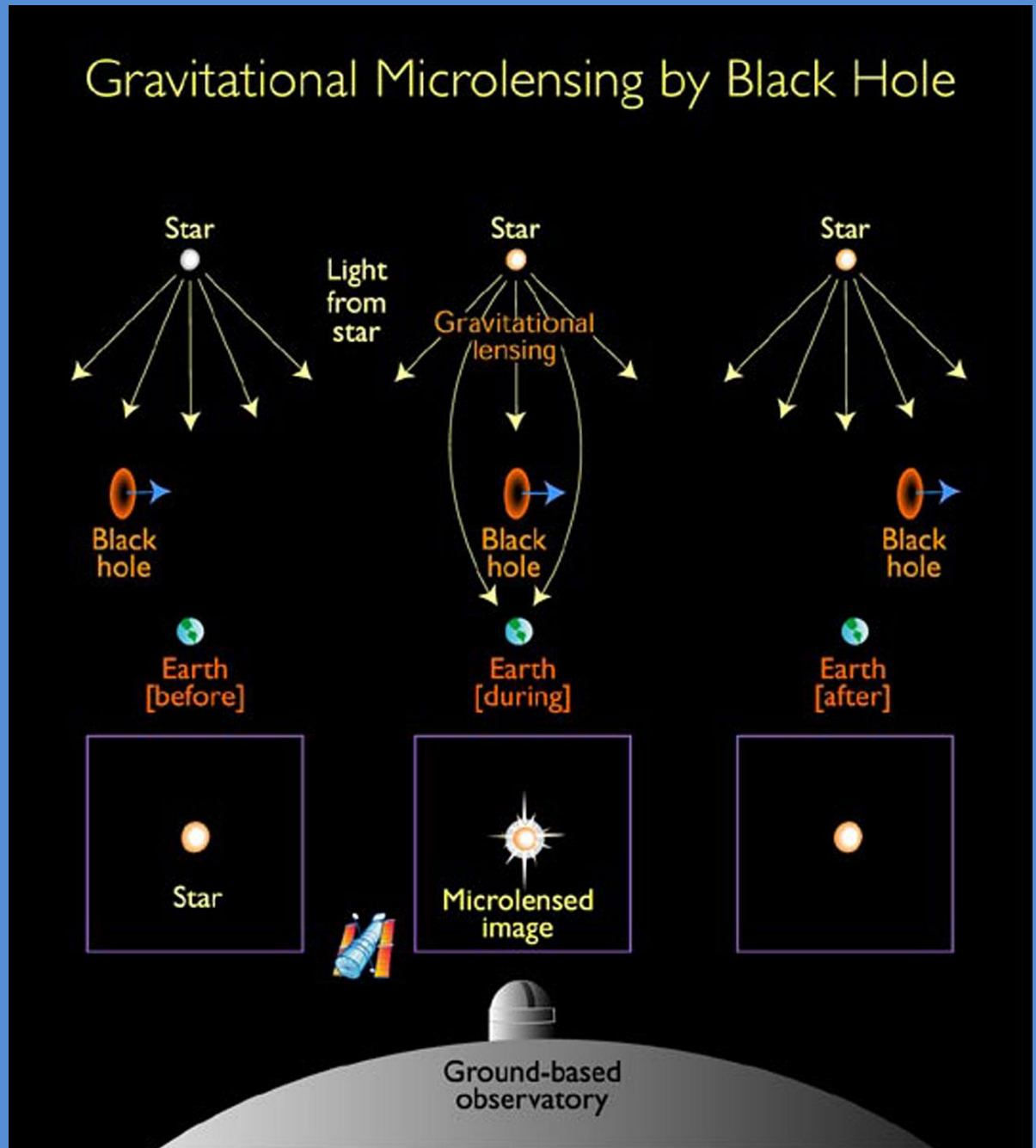


image: ESA / HUBBLE

Microlensing Black Hole

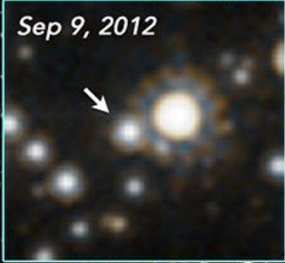
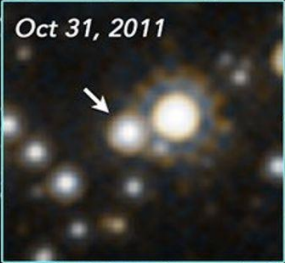
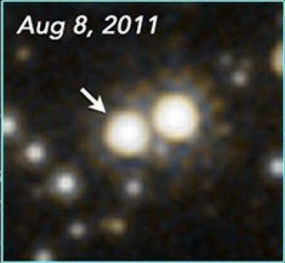


image: NASA/HST

Black hole remnants of stellar collapse

- mass range \sim tens of solar masses
- first type to be understood (Oppenheimer et al)

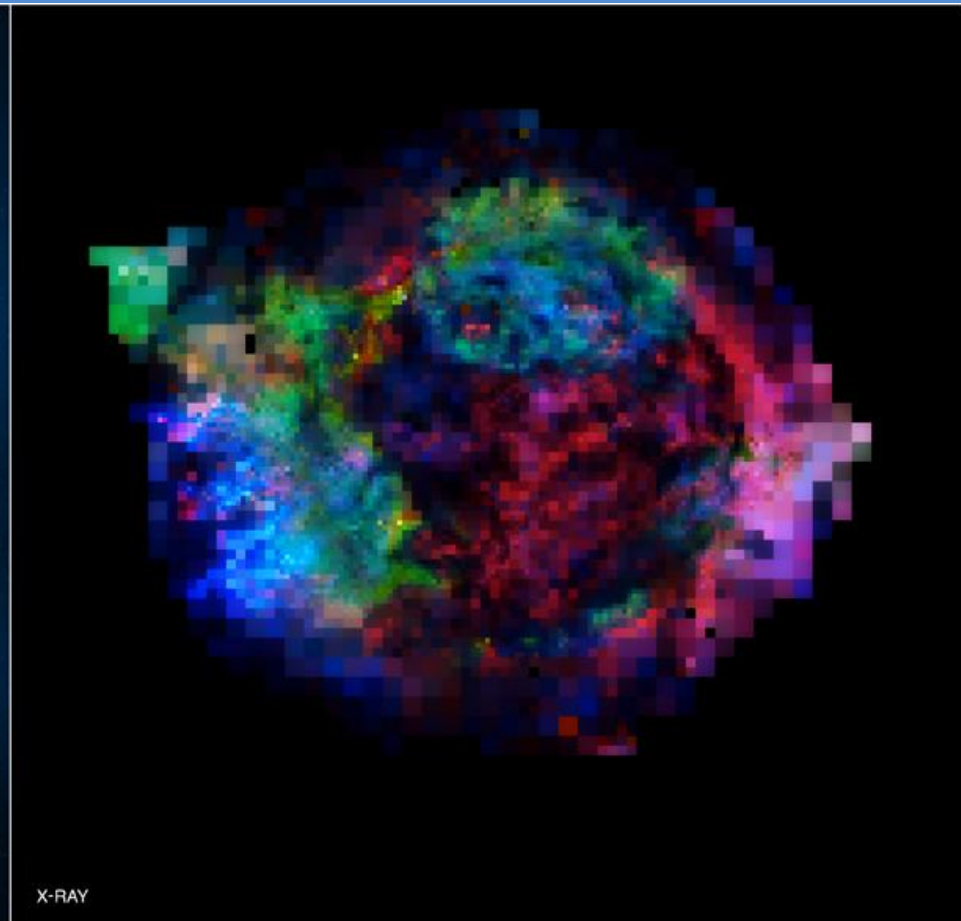
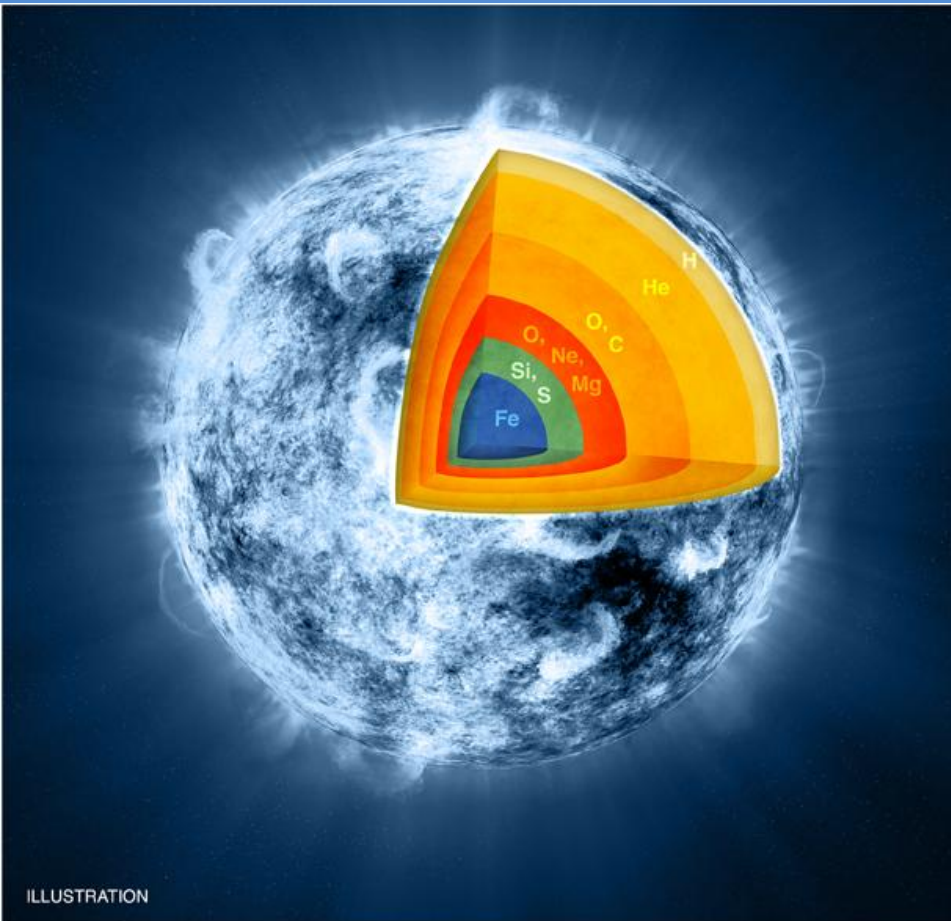
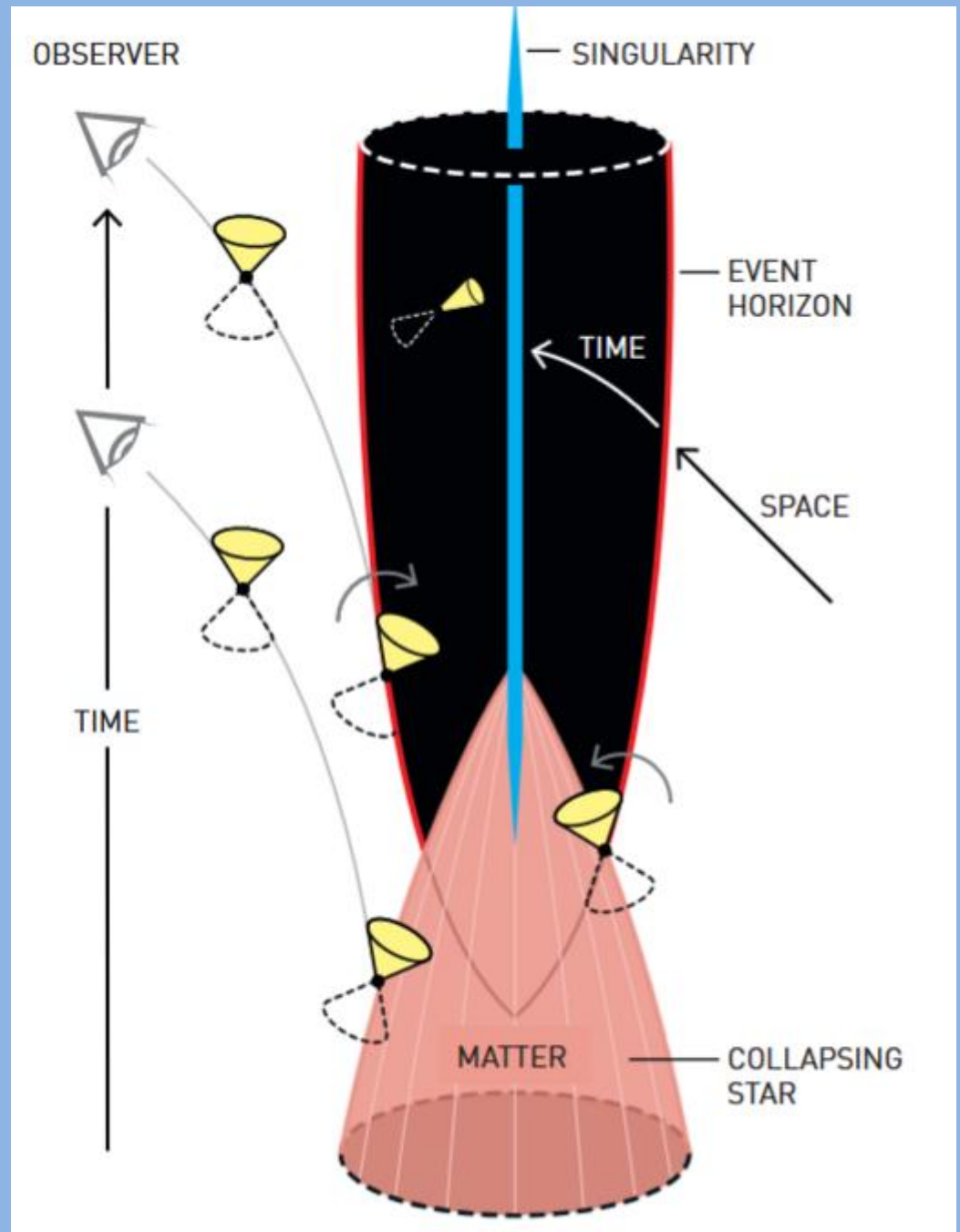


Image: Chandra X-ray observatory

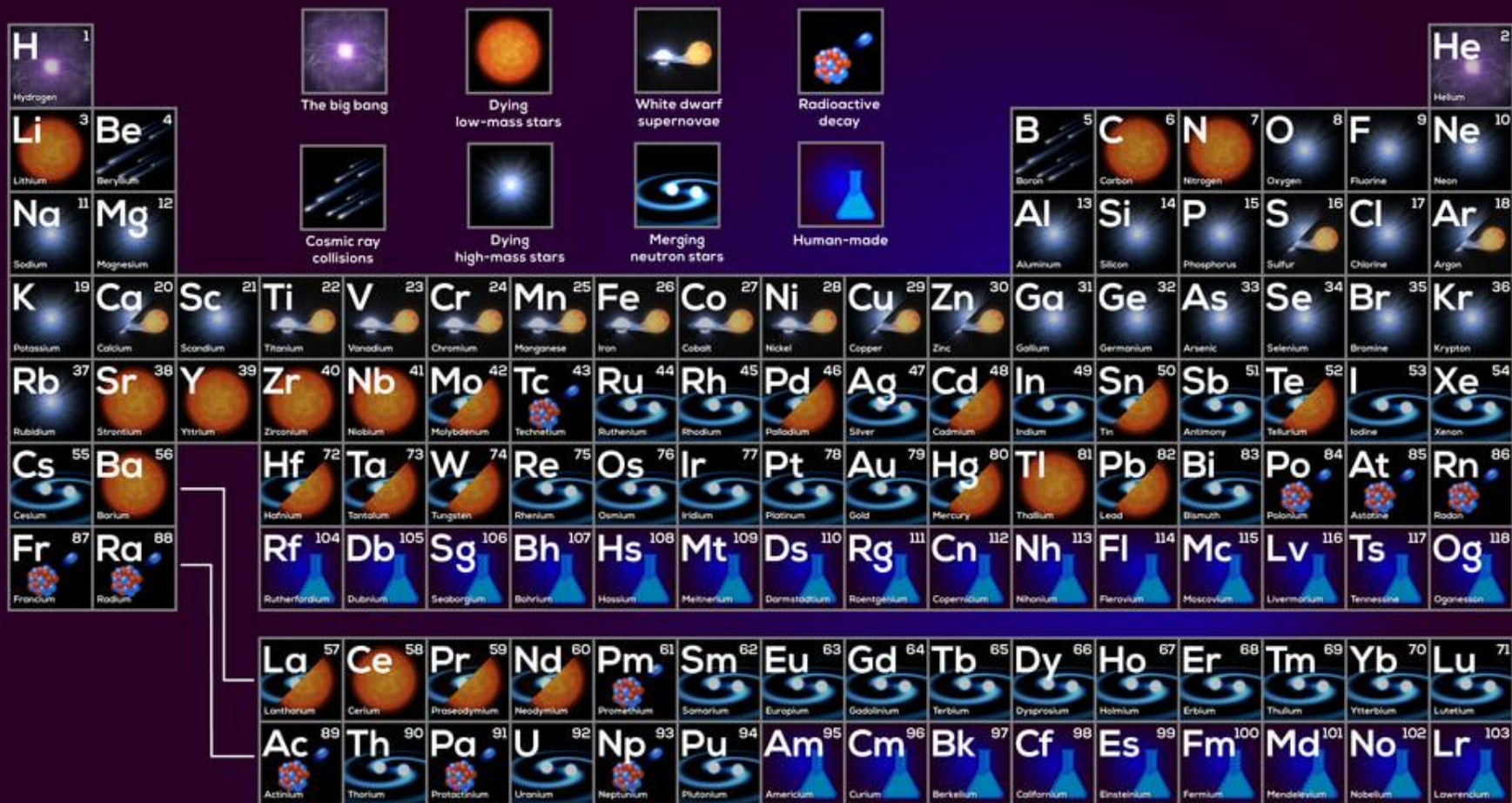
Origin of a Schwarzschild black hole from stellar collapse

Note the inevitability of being trapped behind the horizon if you're in the wrong spot. And note the sequence of events if you reverse time.

image: Johan Jarnestad, Royal Swedish Academy of Sciences



ORIGINS OF THE ELEMENTS



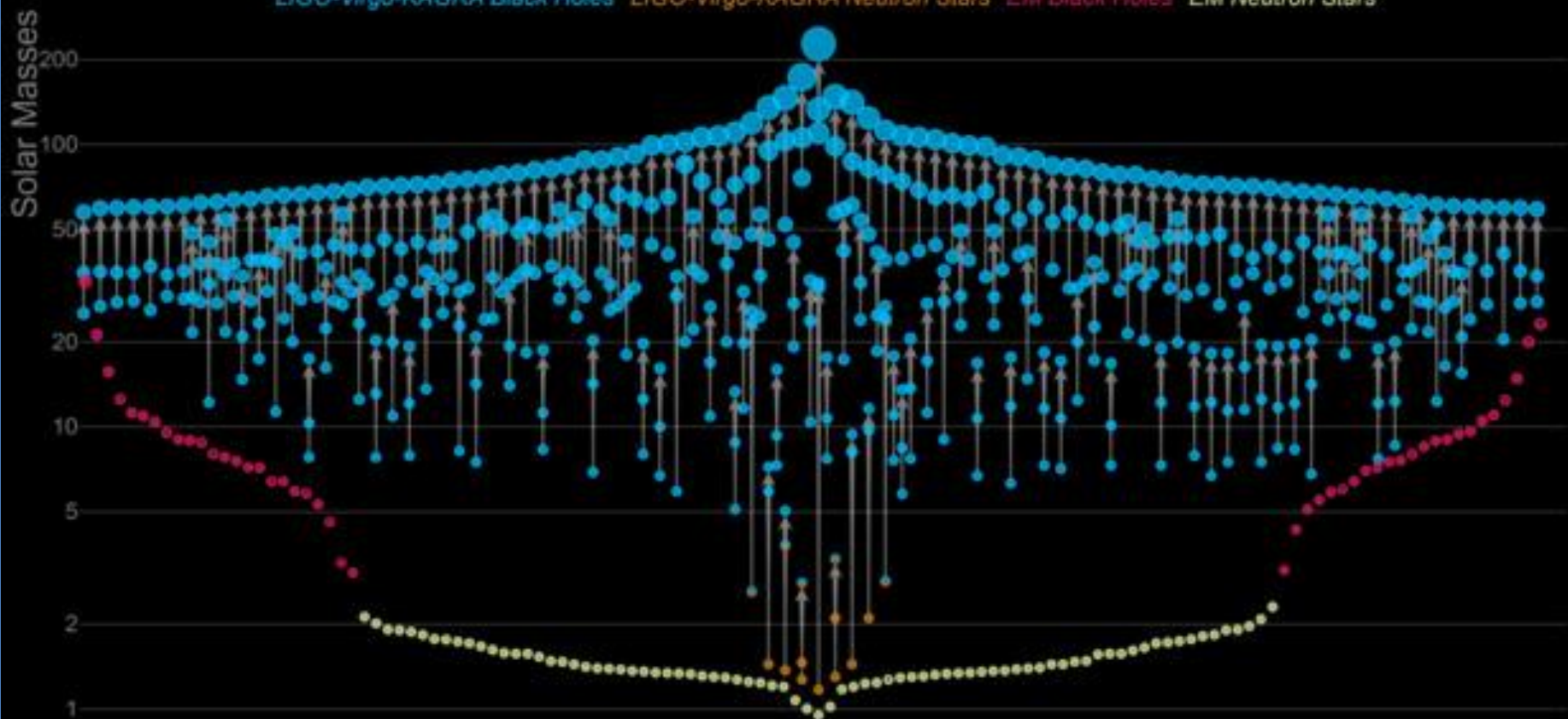
This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

Black holes grown by accretions and mergers

- mass range \sim hundreds to thousands of solar masses
- once formed, black holes swallow more material and may also merge with other black holes

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



Optical distortion of background star field by merging black holes

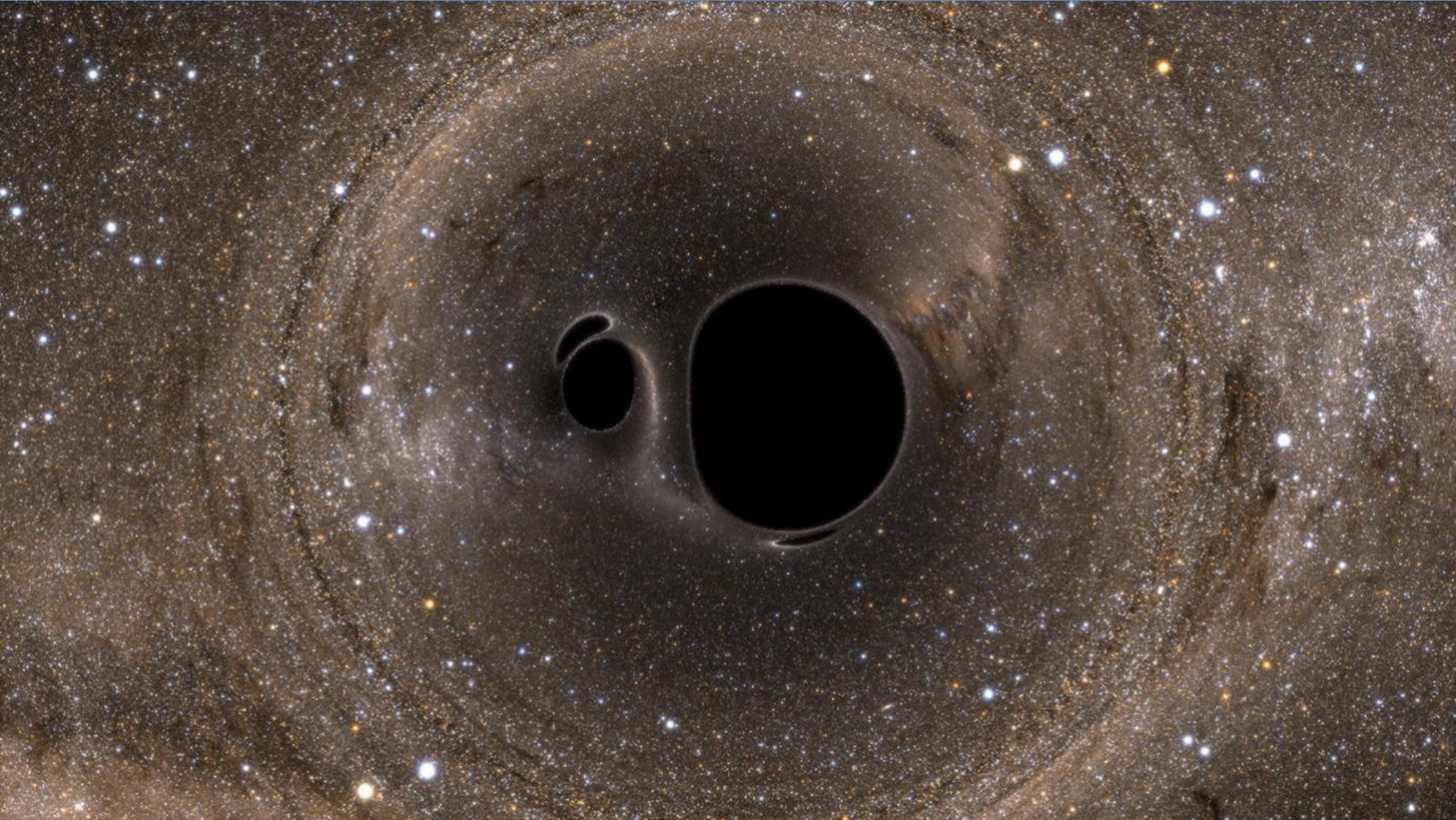


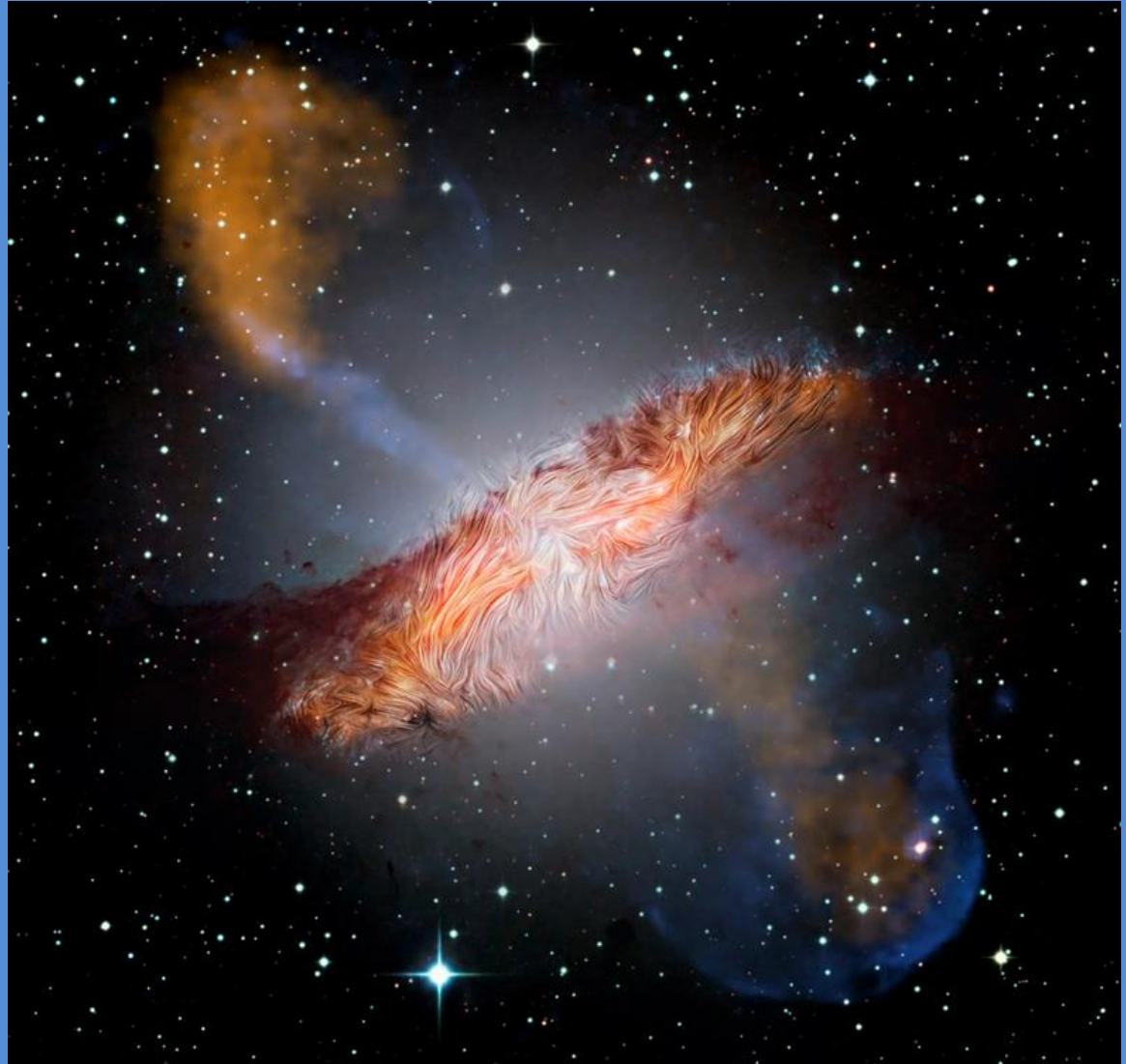
image: Simulating eXtreme Spacetimes Project

Supermassive black holes at the center of galaxies

- mass range $\sim 10^8$ to 10^{11} solar masses
- ? primordial super-giants, or rapid early accretion?

Centaurus A,
image built from
multi-wavelength
stacking to show
magnetic
polarization and
jets

credits: NASA, ESO,
ESA, Max Planck
Institute



Sgr A*, at
the center
of the
Milky Way

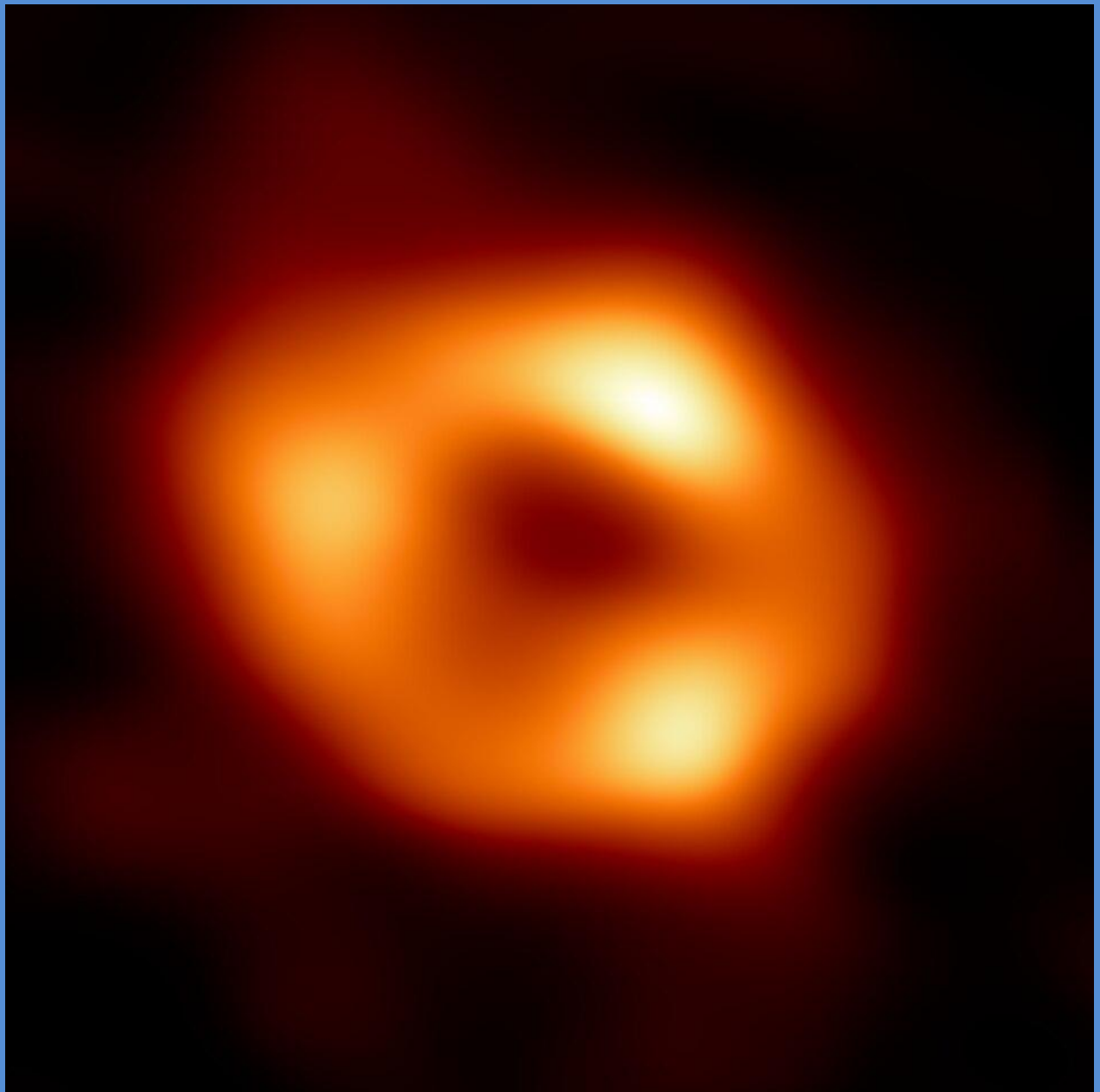
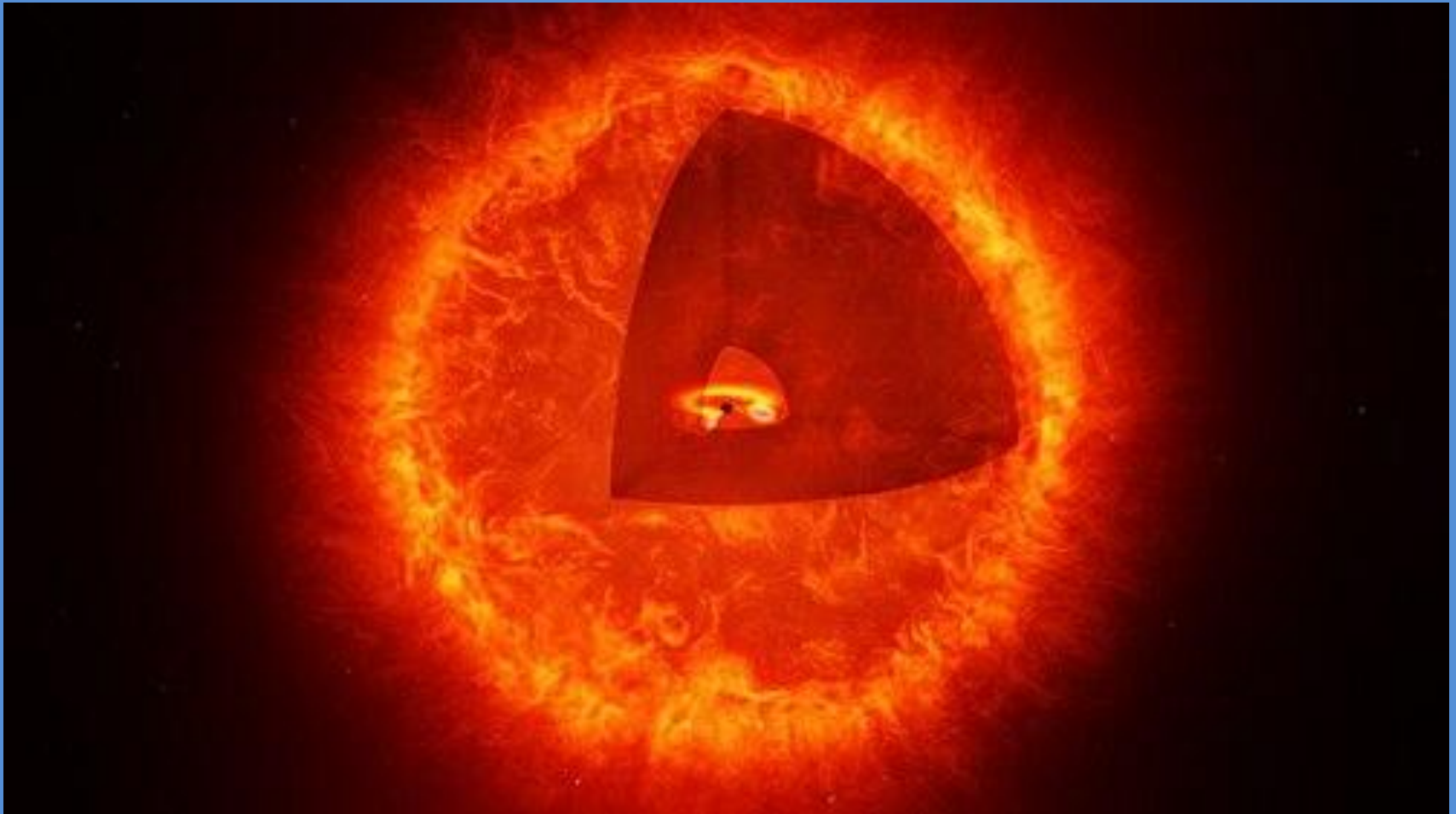


image: Event Horizon Telescope

New in the catalog: supermassive black hole stars

JWST has discovered “little red dots,” a new class of objects in the very early universe. Preliminary spectra show they are supermassive black holes in cocoons of gravitationally heated gas.



Simulations

binary black hole merger

<https://www.ligo.caltech.edu/video/ligo20160211v3>

stars orbiting Sgr A*, ESO 20-year time lapse

Google search “SC23: A journey to the center of the Milky Way”

<https://www.youtube.com/watch?v=m6wnz00XtDM&t=263s>

NASA Goddard black hole visualizations

<https://science.nasa.gov/universe/black-holes/supermassive-black-holes/new-nasa-black-hole-visualization-takes-viewers-beyond-the-brink/>

Black hole structure

<https://science.nasa.gov/universe/black-holes/anatomy/>

The next slides illustrate the structures of the different types of black holes and their immediate environment. Schwarzschild black holes are the simplest and best understood. Kerr black holes are by far the most common.

The black hole environment



Artist's Concept

image (illustration): NASA, Ralf Crawford

see <https://science.nasa.gov/universe/black-holes/anatomy/>

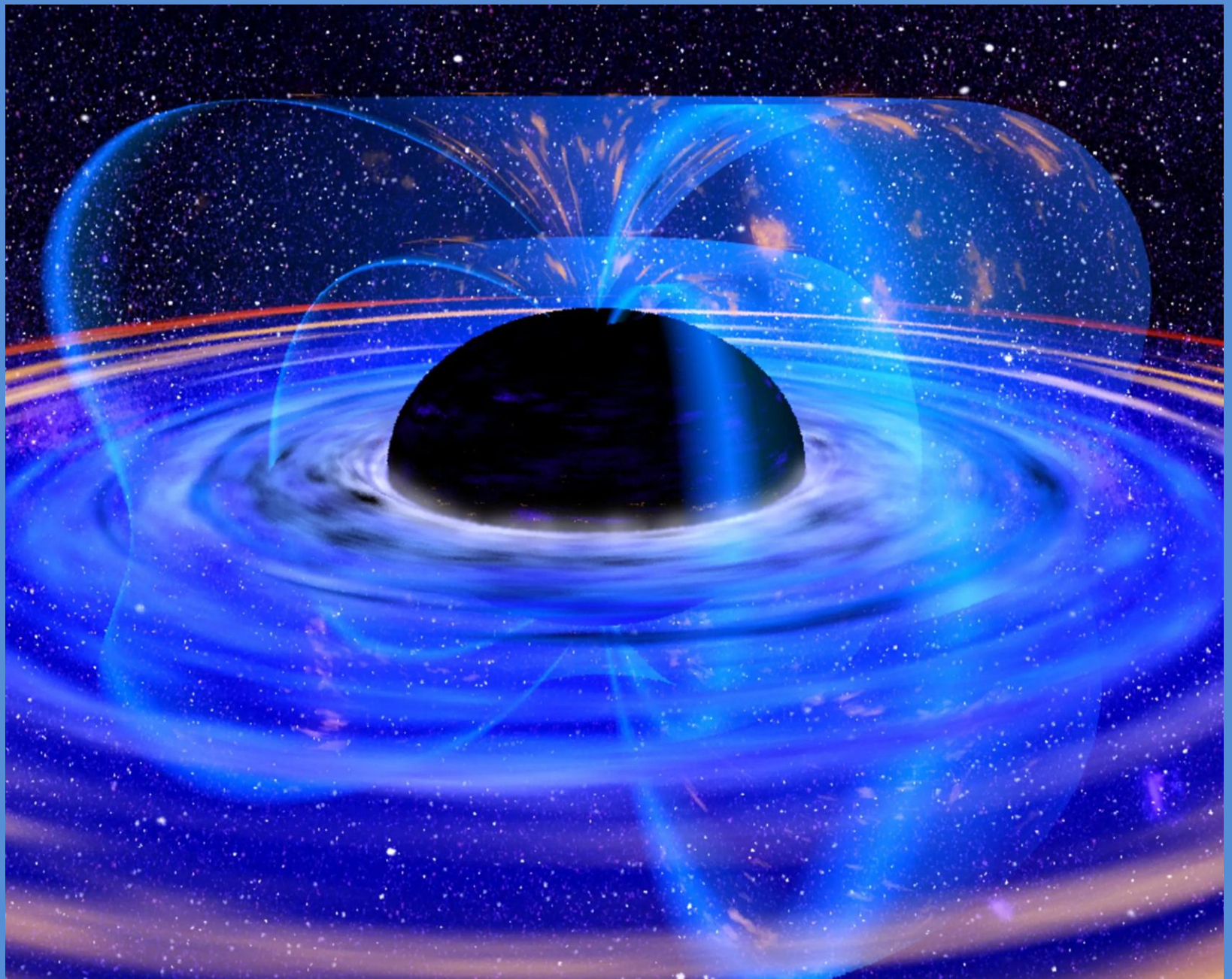


image: NASA/Dana Berry, Skyworks Digital Inc.

Schwarzschild's discovery: simplest of the black holes

Embedding diagram (left) and cross section of a Schwarzschild black hole

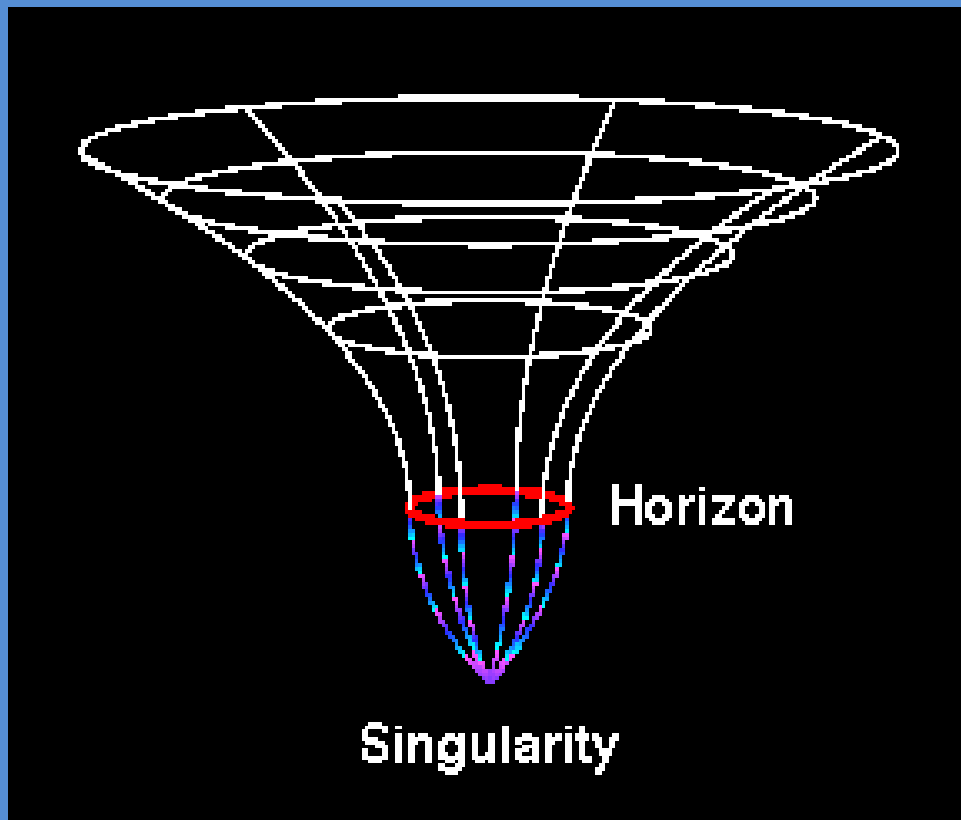


image: Andrew Hamilton, JILA

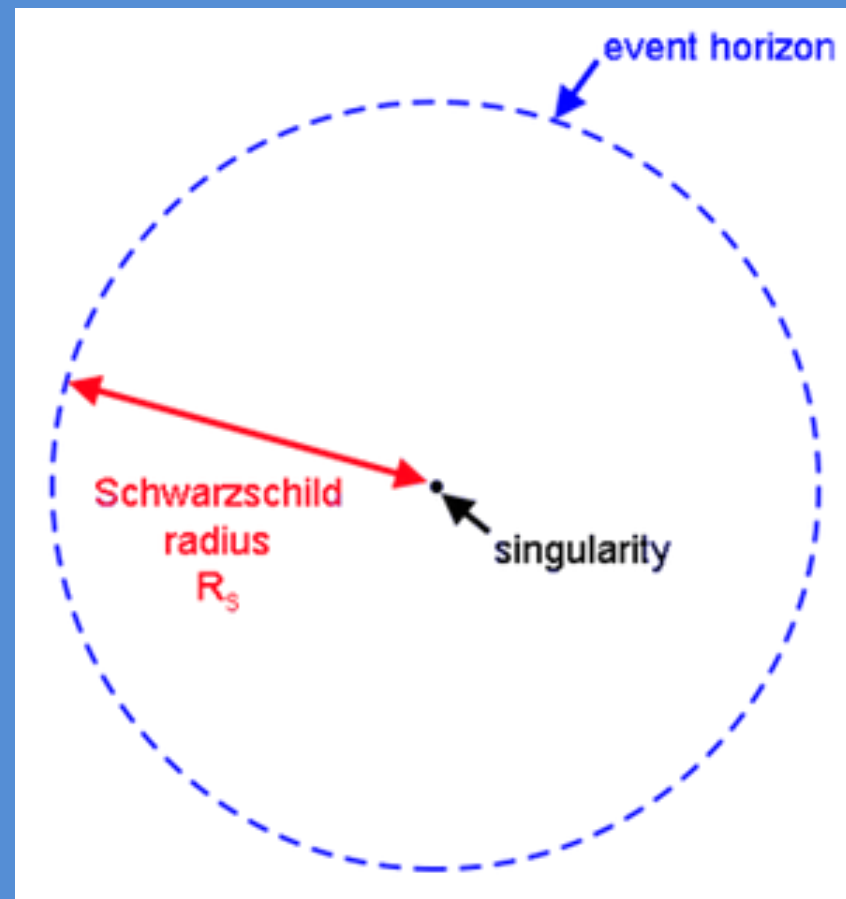


image: NASA, Imagine the Universe

Trajectories of light waves near a Schwarzschild black hole

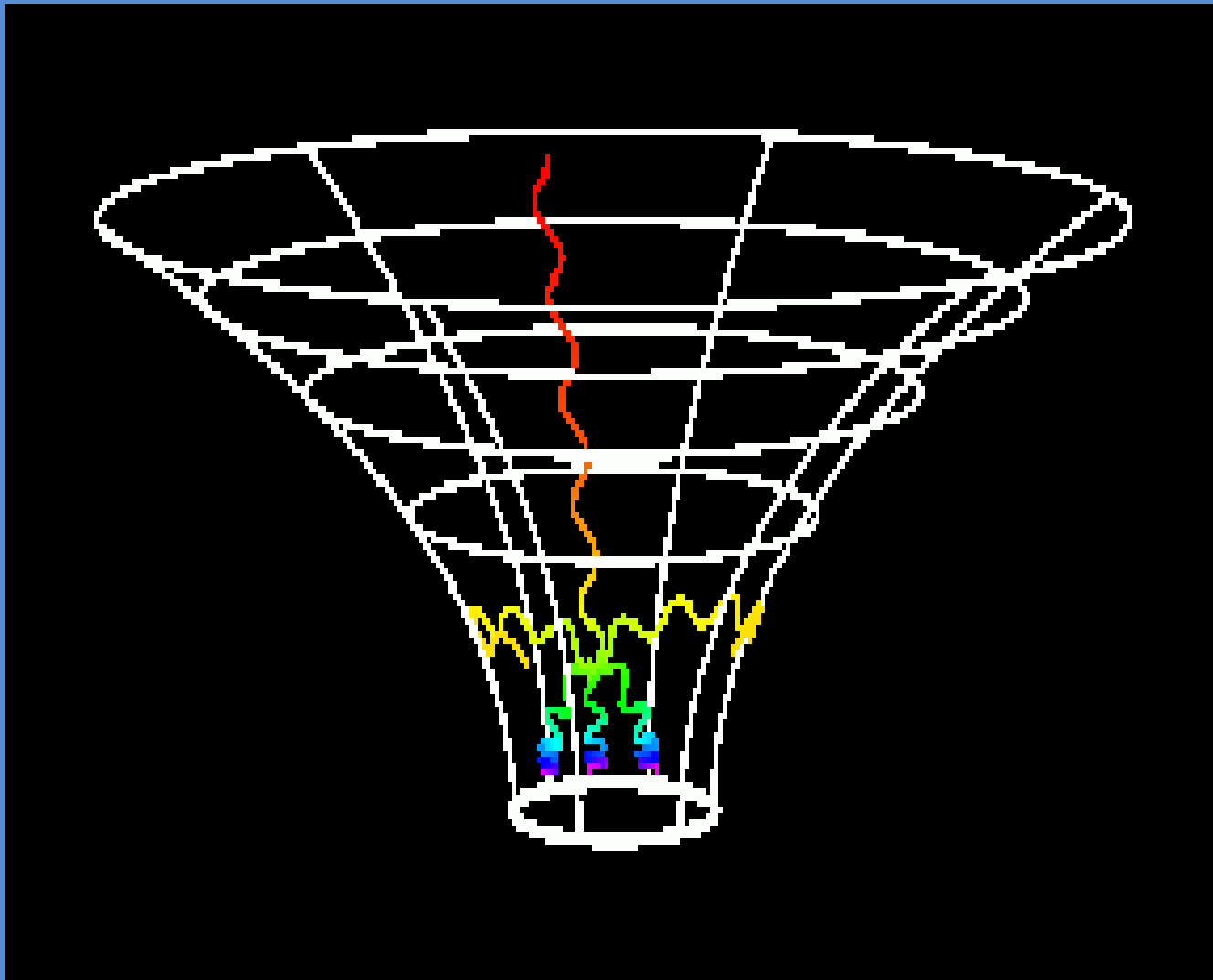


image: Andrew Hamilton, JILA

Penrose diagram of a black hole: how physicists think about their spacetime structure

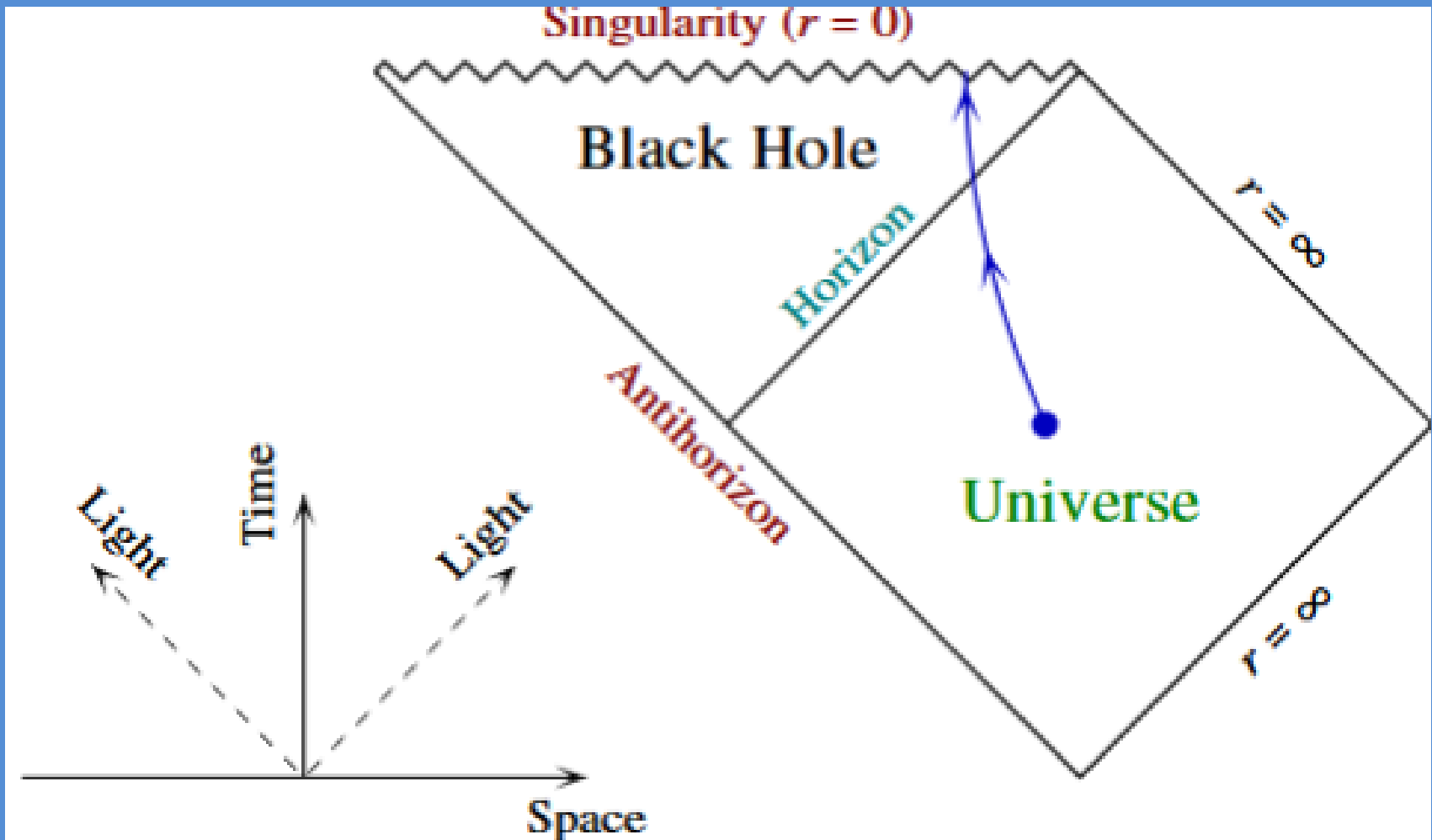


image: Andrew Hamilton, JILA

Structure of a Kerr (rotating) black hole

Everything in the universe spins, and black holes spin rapidly

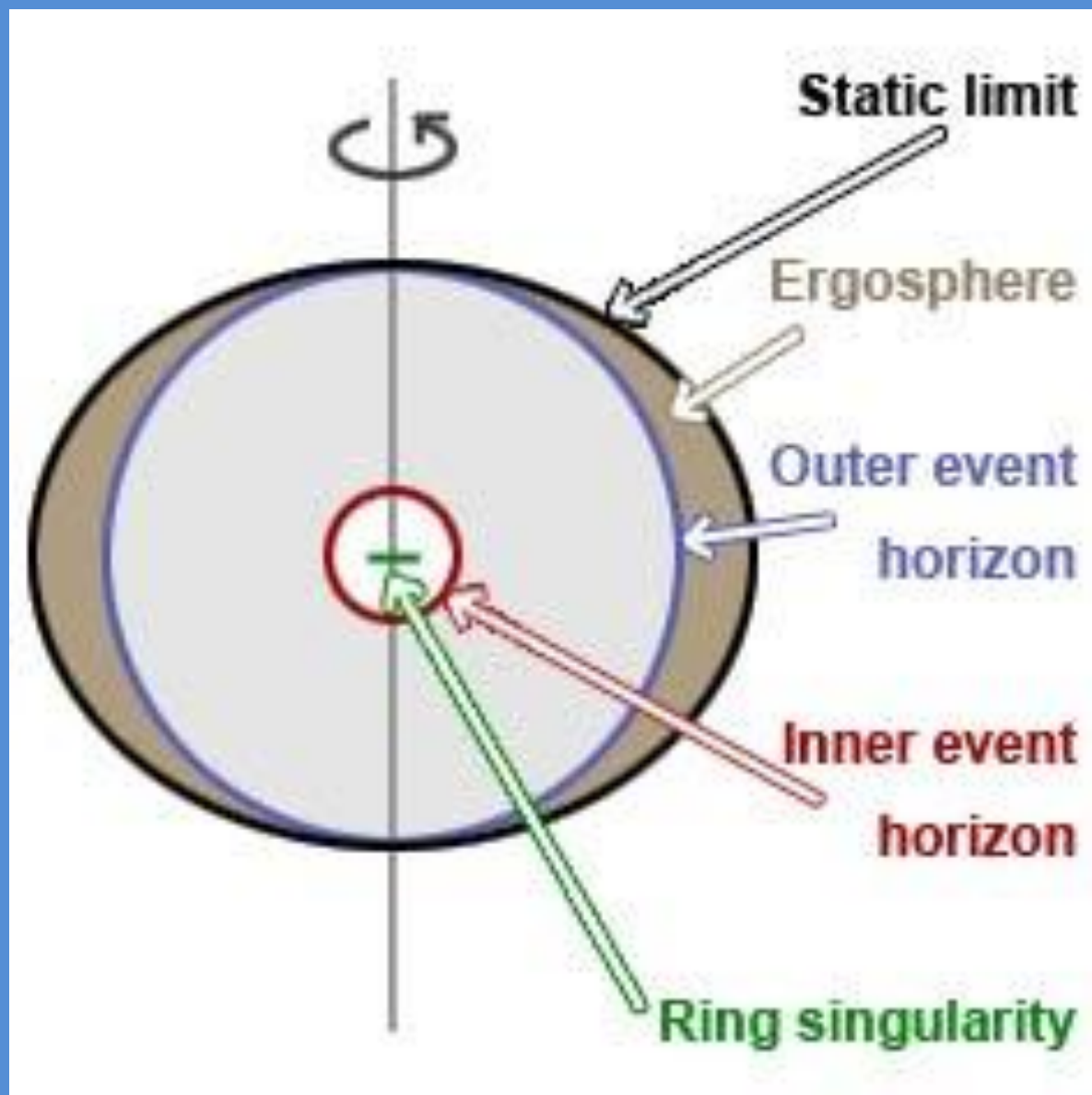


image: STScI

Kerr black holes drag spacetime as they spin. Schwarzschild black hole, left, vs. Kerr black hole on the right.

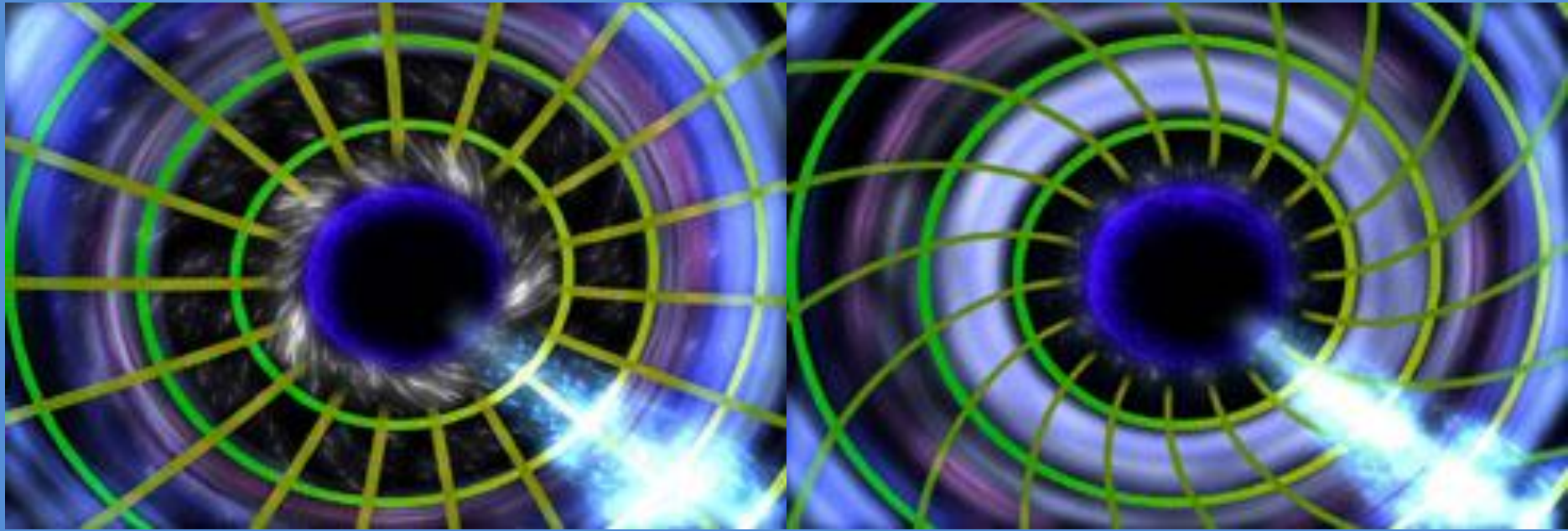


Image Credit: NASA/Honeywell Max-Q Digital Group/Dana Berry

The next few slides describe what different classical observers see when they study black holes, according to general relativity. A free-fall observer sees completely different physics than does an observer at stationary radius above the event horizon. The difference results because the stationary observer must continually accelerate away from the black hole to keep from falling in.

Black hole complementarity: according to general relativity, a free-fall observer, Alice, sees interesting optics as she crosses the event horizon but otherwise experiences the same physical conditions as she would in any other free-fall reference frame. She can't tell she's crossed the horizon – until tidal forces become extreme near the singularity. A stationary observer hovering above the black hole, however, sees Alice approach the horizon but never cross it. Her descent slows down. Her image is red-shifted further and further into the infrared until she is no longer visible.

What Bob sees as Alice falls toward the horizon.



Alice is getting redshifted and slowing down!



ALICE'S CLOCK RUNS NORMALLY



ALICE'S CLOCK RUNS VERY SLOWLY



As Alice approaches the black hole, Bob sees her image increasingly red-shifted and her clock runs slower and slower. According to Bob, Alice never crosses the horizon.

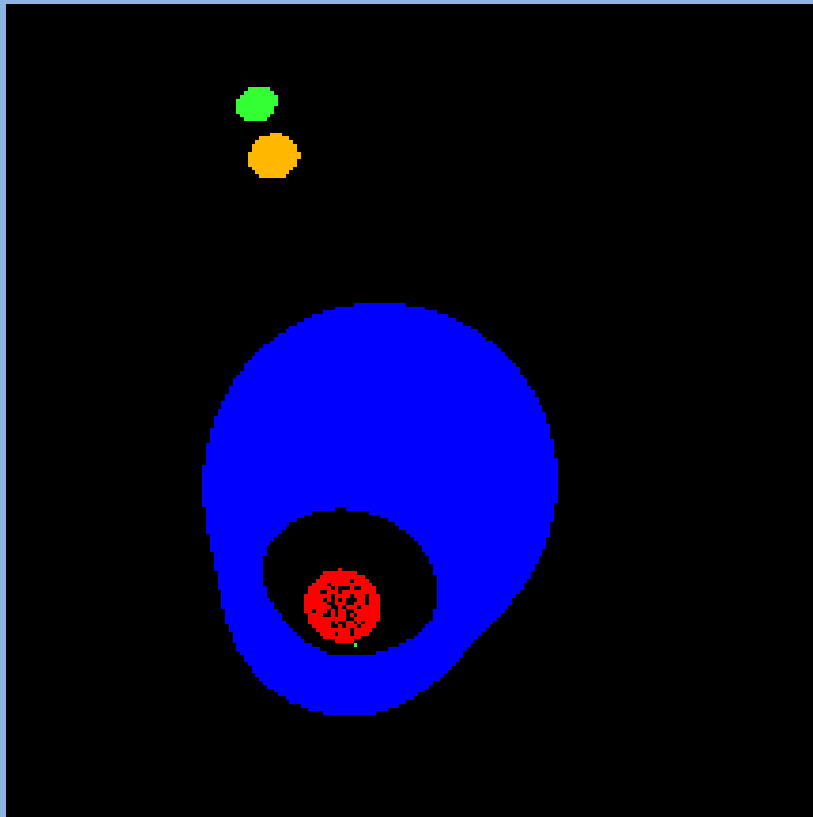
Journey into a black hole

Falling into a black hole

<https://jila.colorado.edu/~ajsh/bh/schw.html>

Black hole flight simulator

<https://jila.colorado.edu/~ajsh/insidebh/schw.html>



Now we leave the purely classical realm 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.

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

Bekenstein-Hawking entropy:

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

Hawking temperature:

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

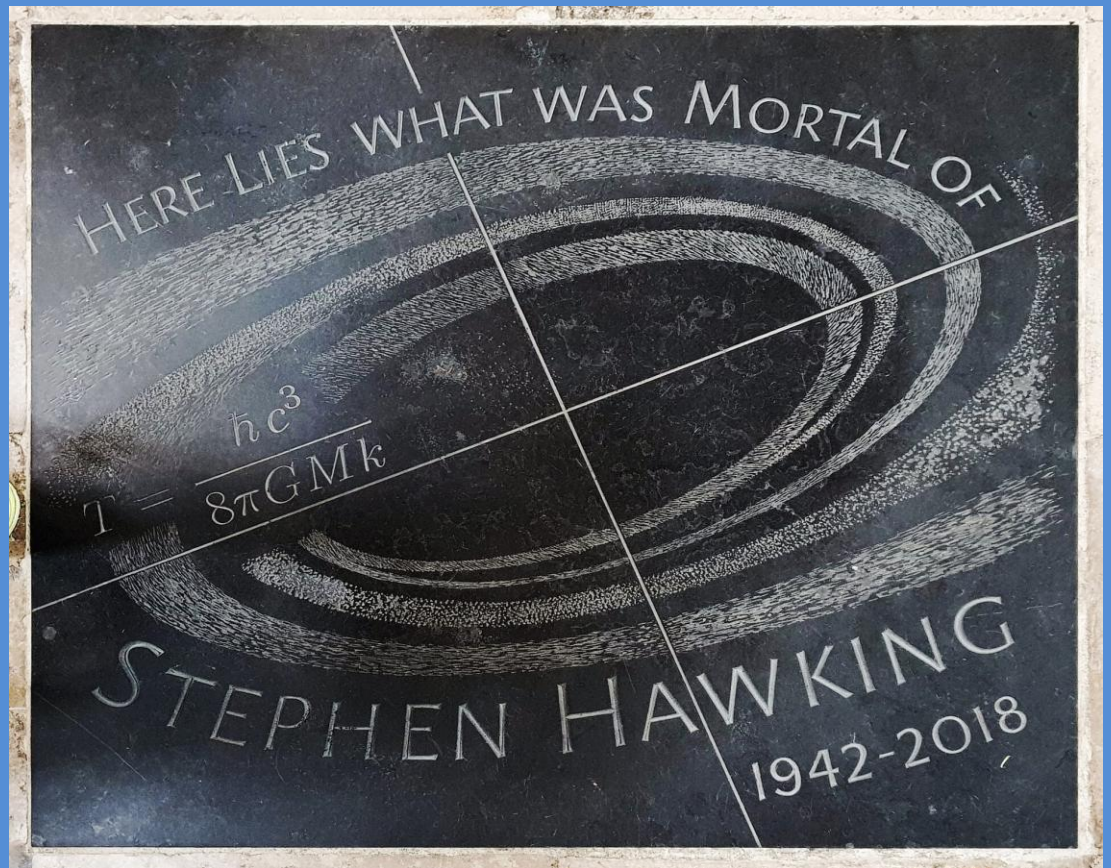
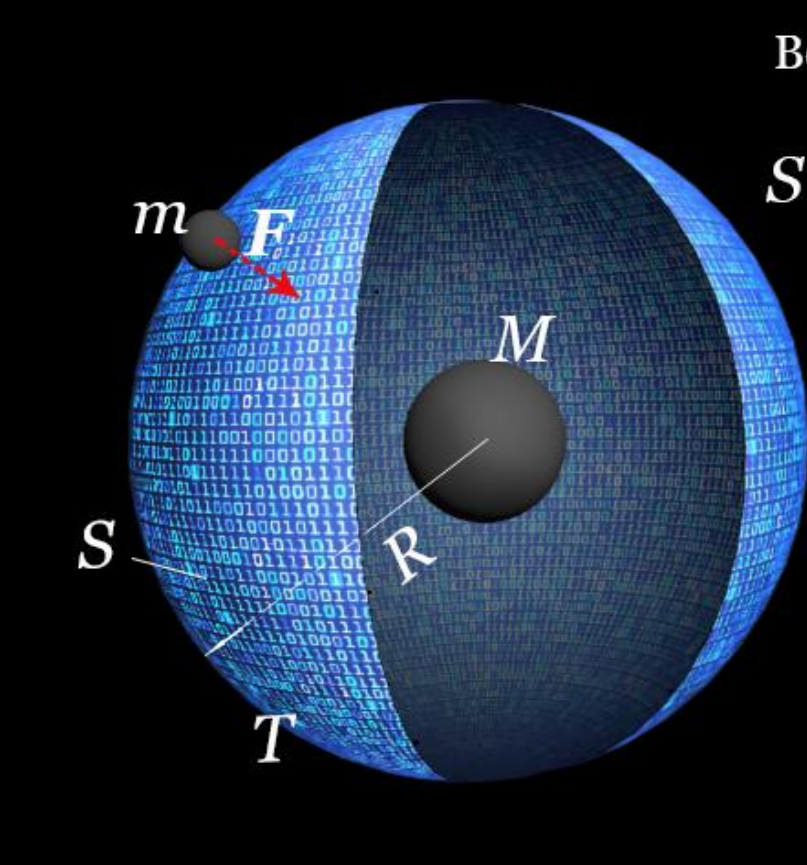


image: Westminster Abbey

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.



Bekenstein, Hawking equations

$$S = k_B \frac{Ac}{4\pi G\hbar} \quad T = \frac{\hbar g}{2\pi c}$$

$dE = TdS$
The first law of TD

$$dM = \frac{g}{2\pi} \frac{dA}{4G}$$

Einstein equation

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!

Hawking radiation by particle pair creation: quantum fluctuations in the spacetime vacuum.

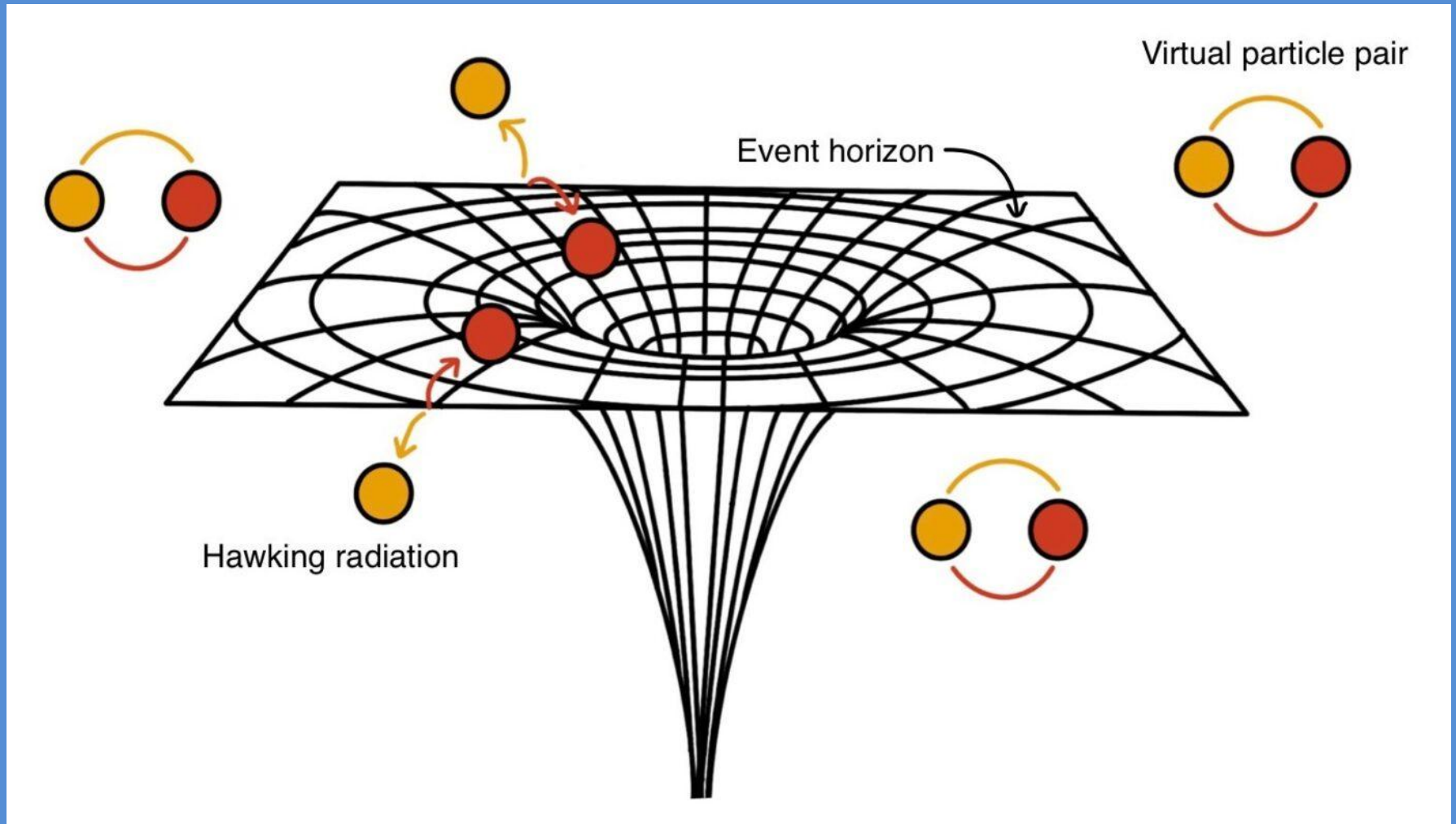


image: Amelie Orban, Quantum Universe. Also see <https://jila.colorado.edu/~ajsh/bh/hawk.html>

Practical considerations: you have to wait a while for a black hole to evaporate . . .

PRIMORDIAL BLACK HOLE LIFETIMES

- ☄ Black hole mass
- 📏 Event horizon diameter
- 🕒 Black hole lifetime

GREAT PYRAMID

☄ 5 billion kilograms



- 📏 1% width of a proton
- 🕒 381,000 years

MOUNT EVEREST

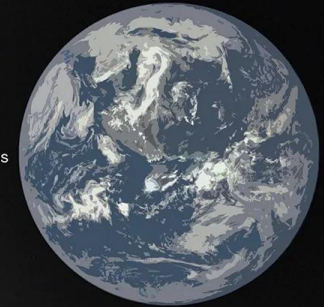
☄ 175 trillion kilograms



- 📏 33 times width of uranium nucleus
- 🕒 1 billion times present age of universe

EARTH

☄ 6 septillion kilograms



- 📏 Width of U.S. dime
- 🕒 40 trillion octillion times present age of universe

📏 2,000 times smaller than current measurement limit

🕒 0.41 seconds



BLUE WHALE

☄ 170,000 kilograms

HUMAN

☄ 70 kilograms



📏 5 million times smaller than current measurement limit

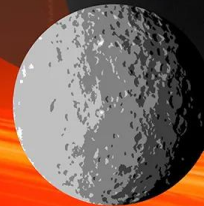
🕒 29 picoseconds

📏 Size of E. coli bacterium

🕒 160 octillion times present age of universe

DWARF PLANET CERES

☄ 940 billion billion kilograms



Black holes slowly shrink as they lose tiny amounts of energy via a process called Hawking radiation. The lifetime estimates listed here assume the black holes are warmer than their surroundings and not actively pulling in additional material or rotating.

Curiouser and curiouser: Not only do we need a quantum theory of gravity, but the best approach to that theory requires tools from computer information science. It seems all threads in the physics of spacetime are anchored in black holes!

The Holographic Principle: all the information that falls into a black hole – stellar matter, refrigerators, encyclopedias, Alice, toothpicks, everything – gets distributed onto the horizon. Everything in the interior is recorded on the horizon.

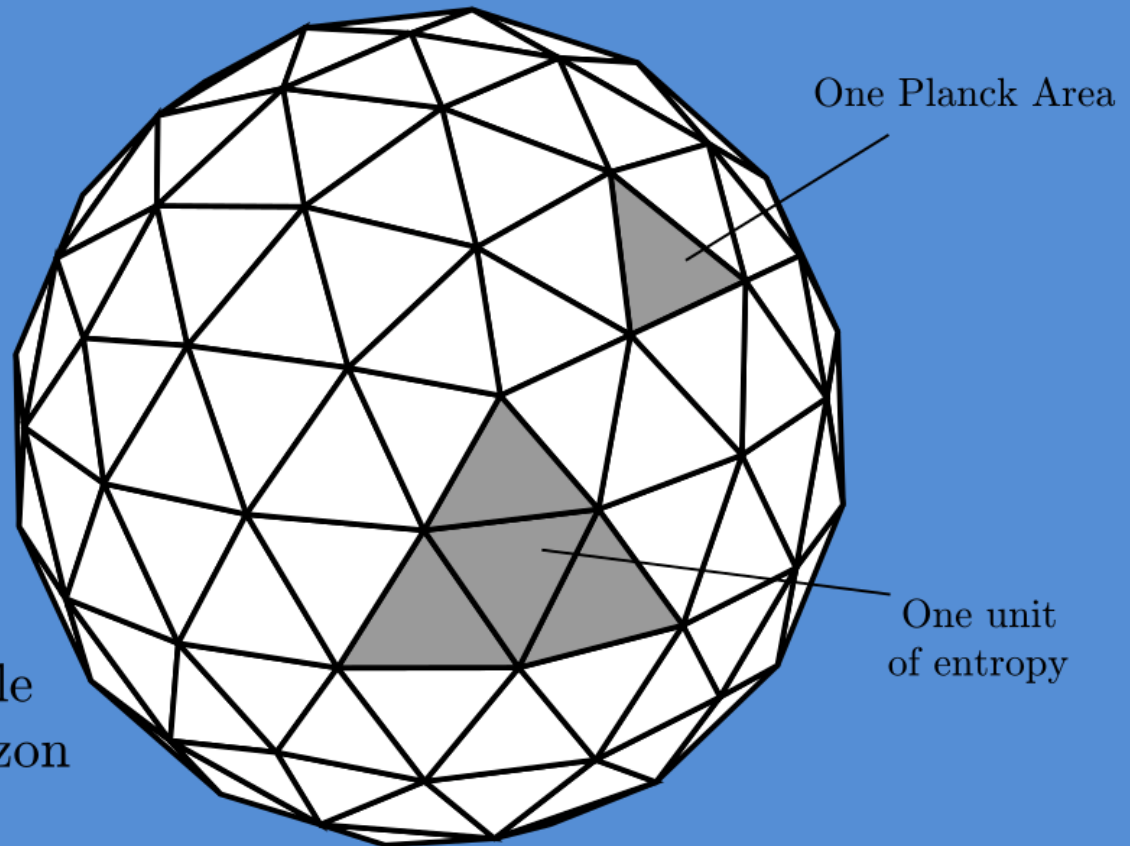


image: Wikipedia

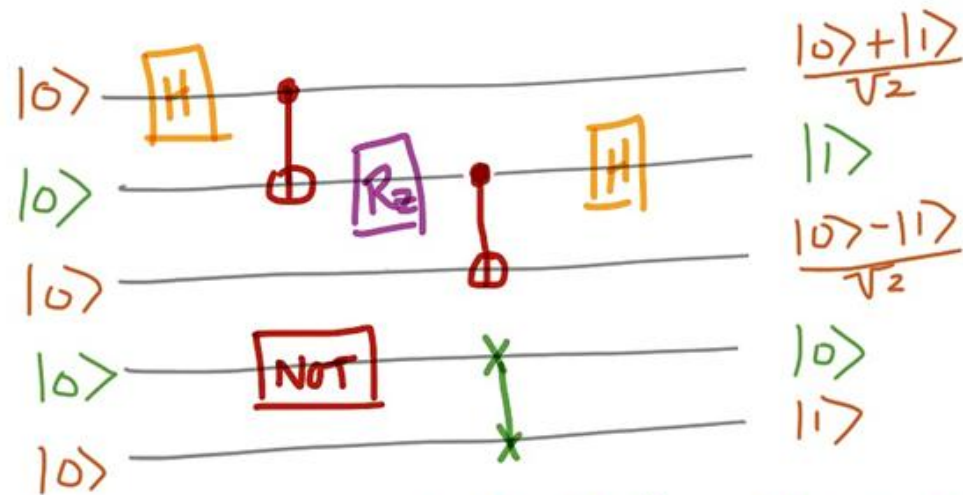
Black hole
event horizon

And black holes process that information. They behave like quantum computers. Here is a very brief, and still tentative, overview. The following slides will illustrate these ideas:

1. information (a copy of Wikipedia, 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
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

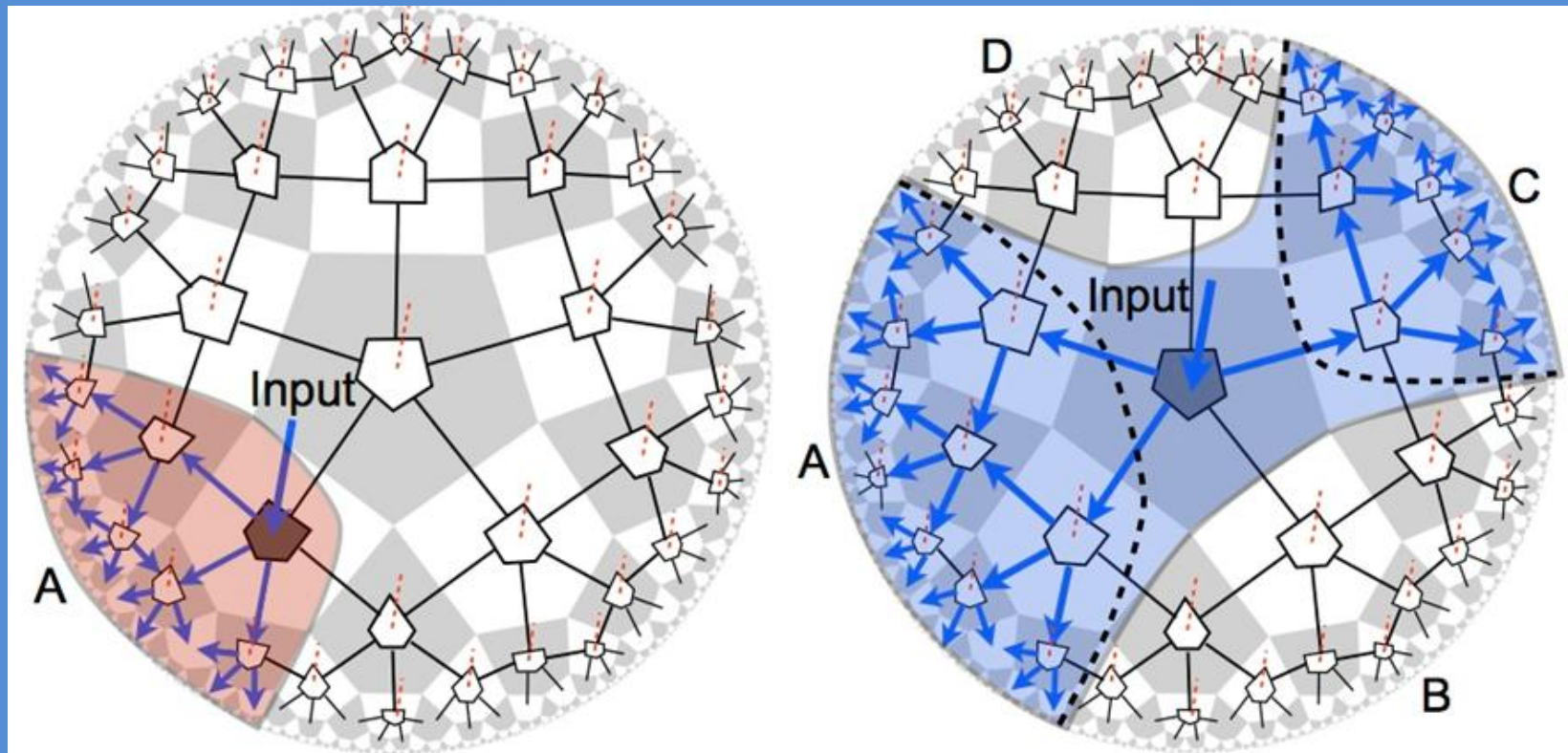
In one of the most stunning discoveries of this century, Michael Nielsen (2006) proved that minimizing the complexity of a quantum logic circuit is equivalent to finding the geodesic through that circuit. Quantum circuits have a geometry, and that geometry matches the geometry of general relativity!

Circuit complexity and geometry



One gate set - but is it the minimum set?

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.



Black holes as tensor networks: Information in the ‘bulk,’ inside the black hole, is accessible through the connectivity within the quantum circuit on the horizon.

image: Beni Yoshida

ER = EPR, how information escapes a black hole: Hawking radiation is entangled with the partner pairs in 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.

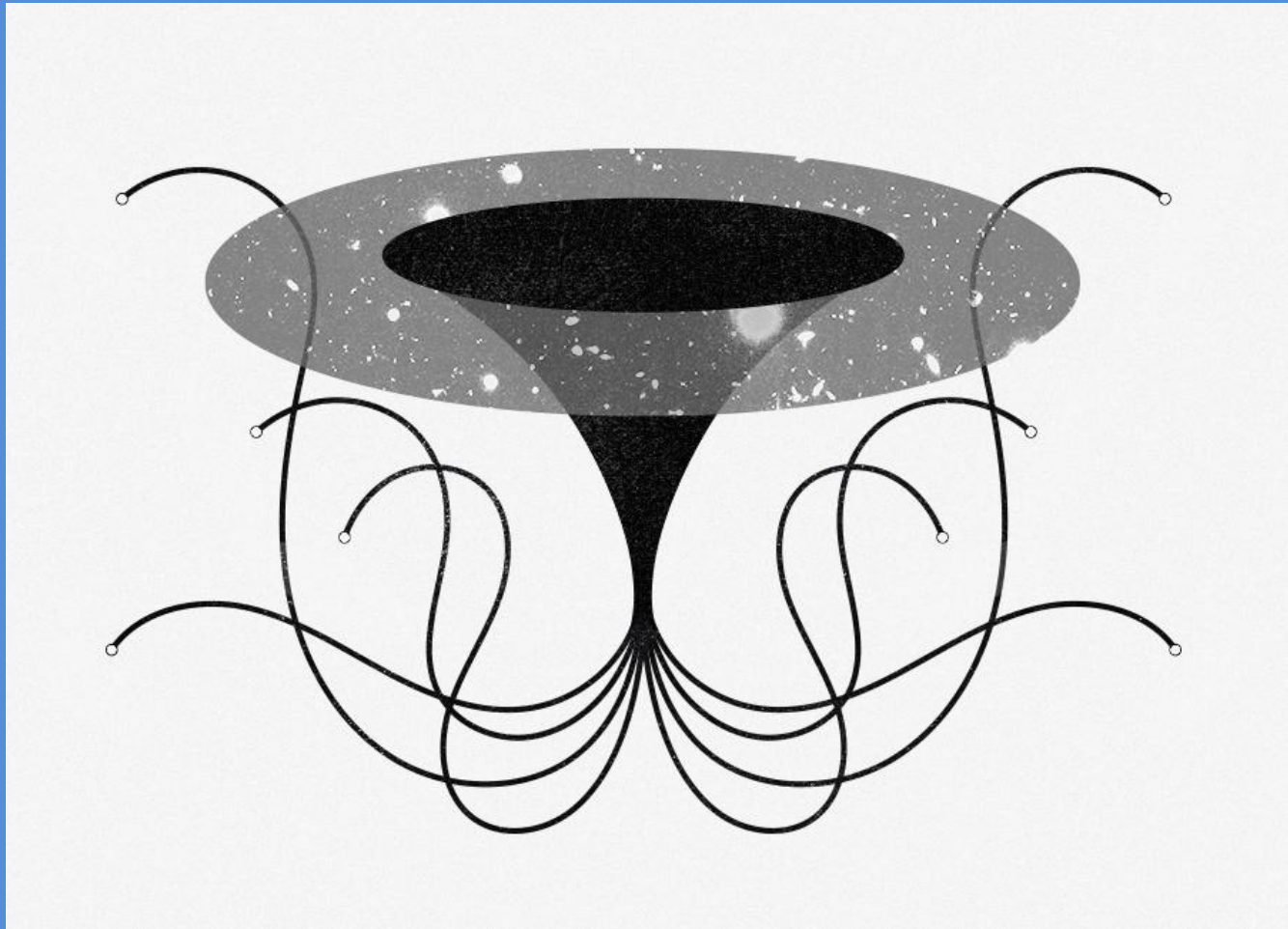


image: Olena Shmahalo, Quanta Magazine

ER = EPR: Quantum entanglement is equivalent to wormholes in spacetime. Entanglement records information. Wormholes chip through the prison walls and allow that information to escape.

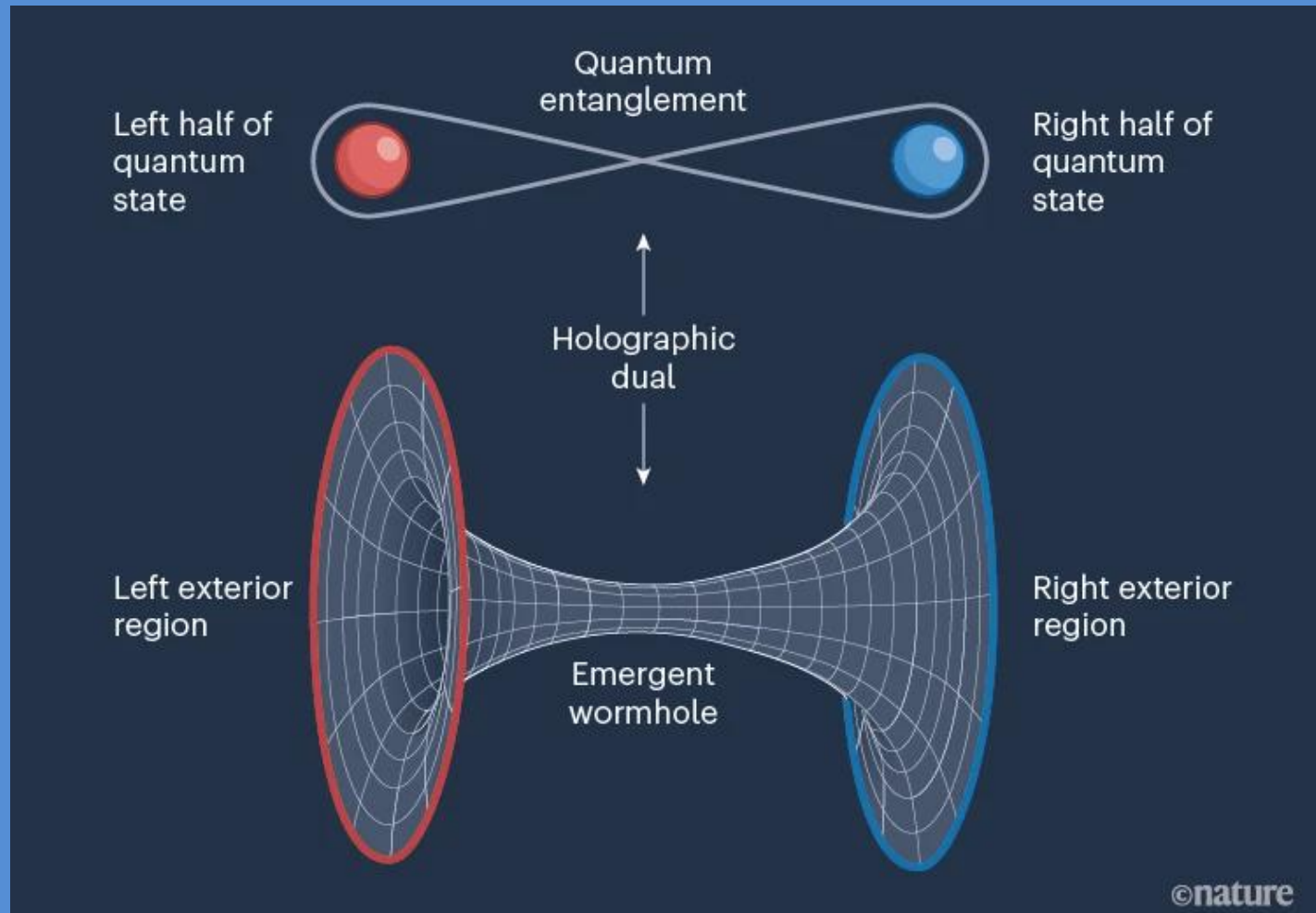


image: Susskind and Wall. 2022.

Finally, let's take a look at black holes in the lab. New experiments are testing these crazy 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.

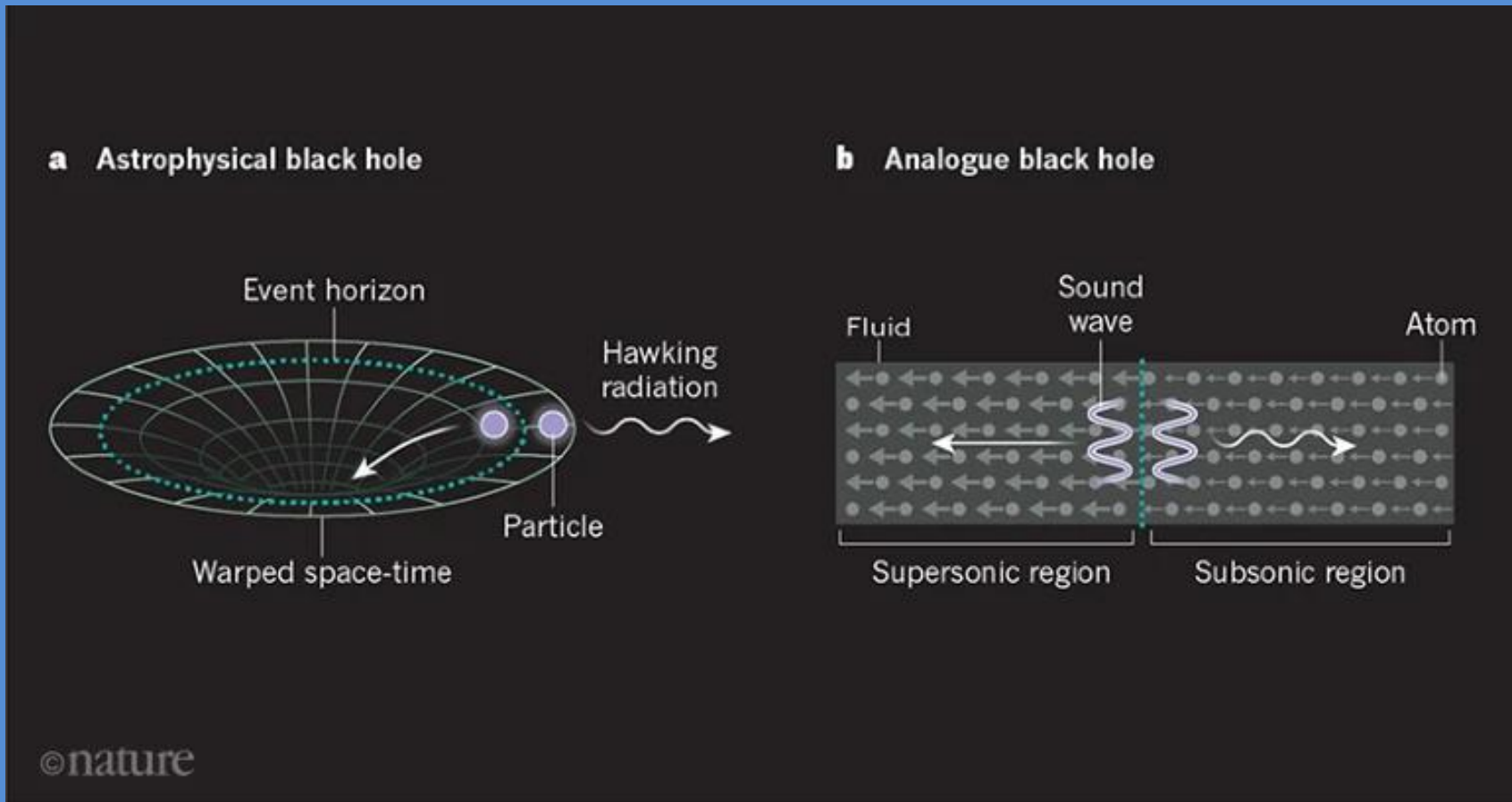


image: Weinfurtner, 2019

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

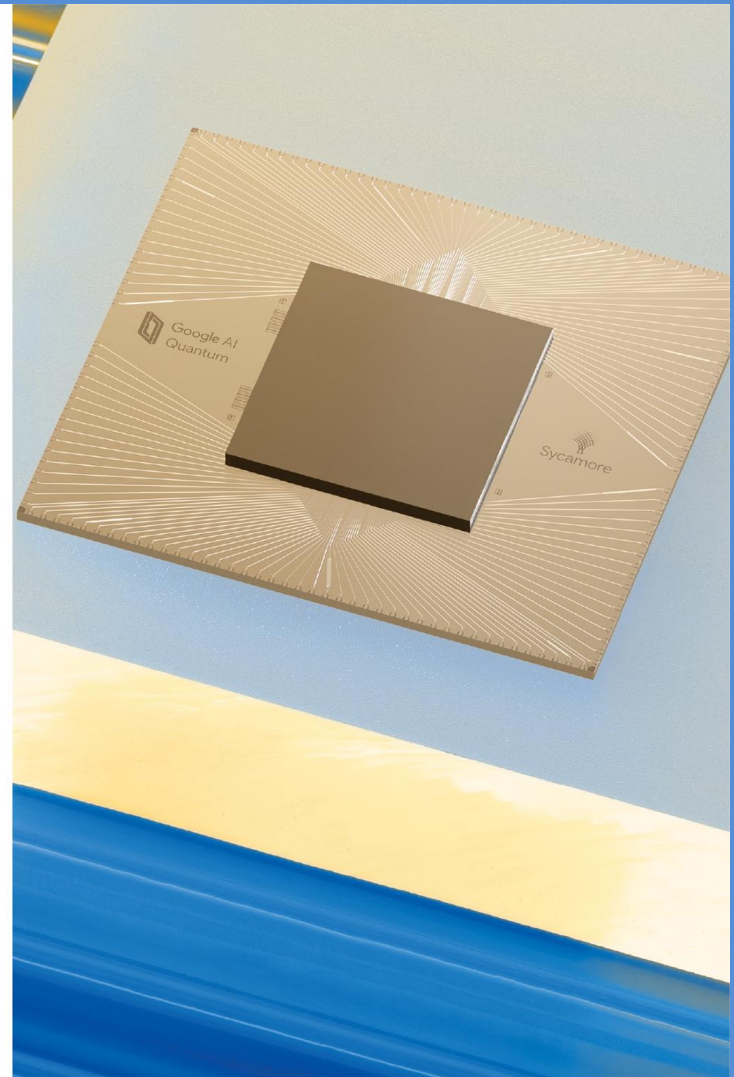
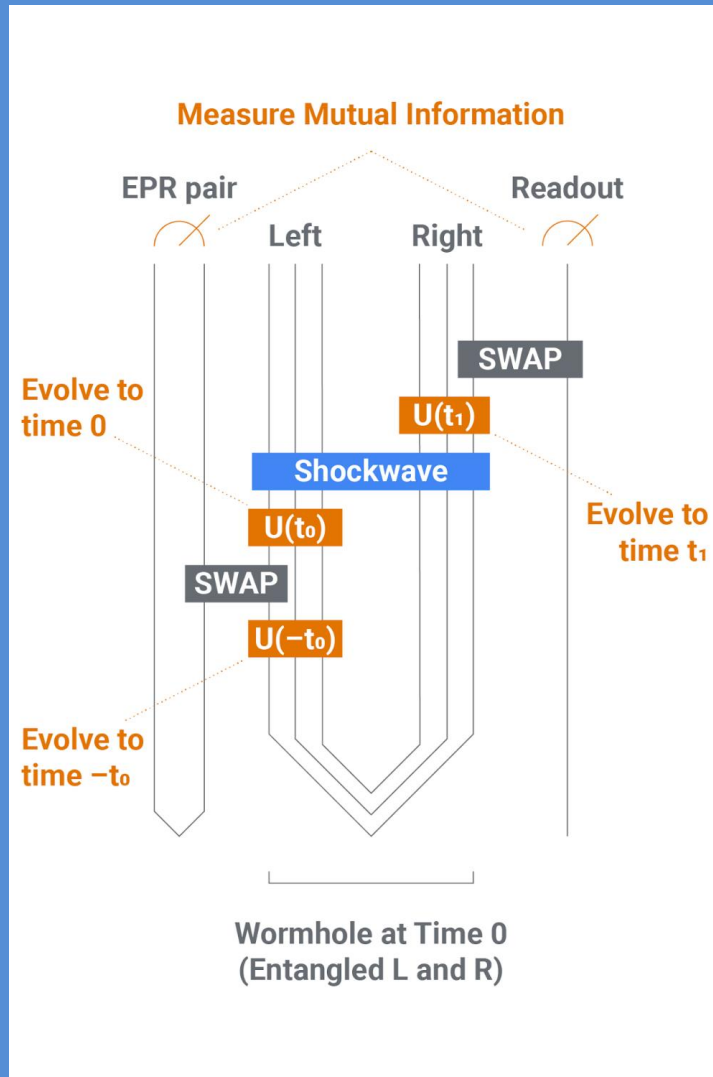


image: Google Quantum AI

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

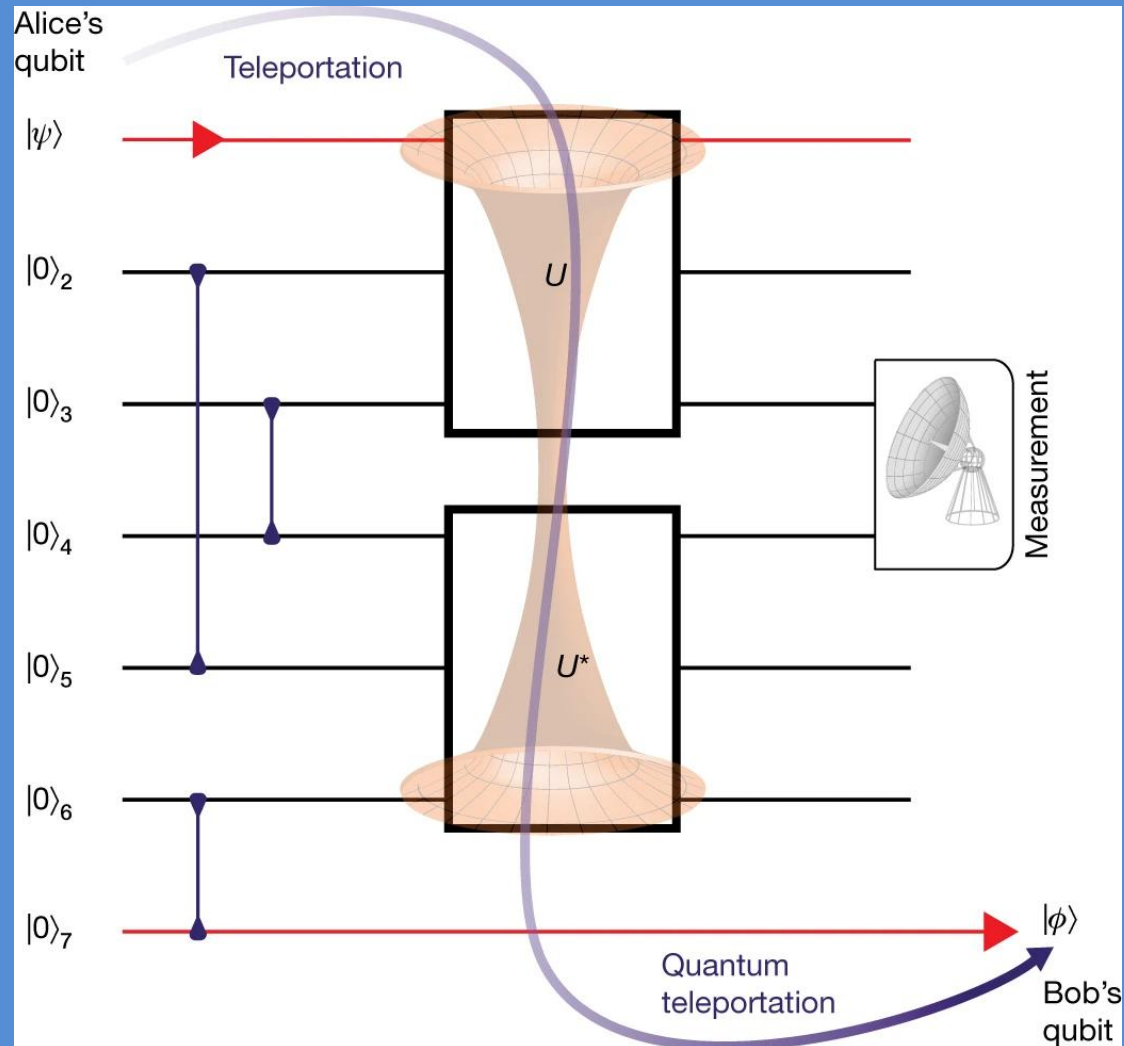
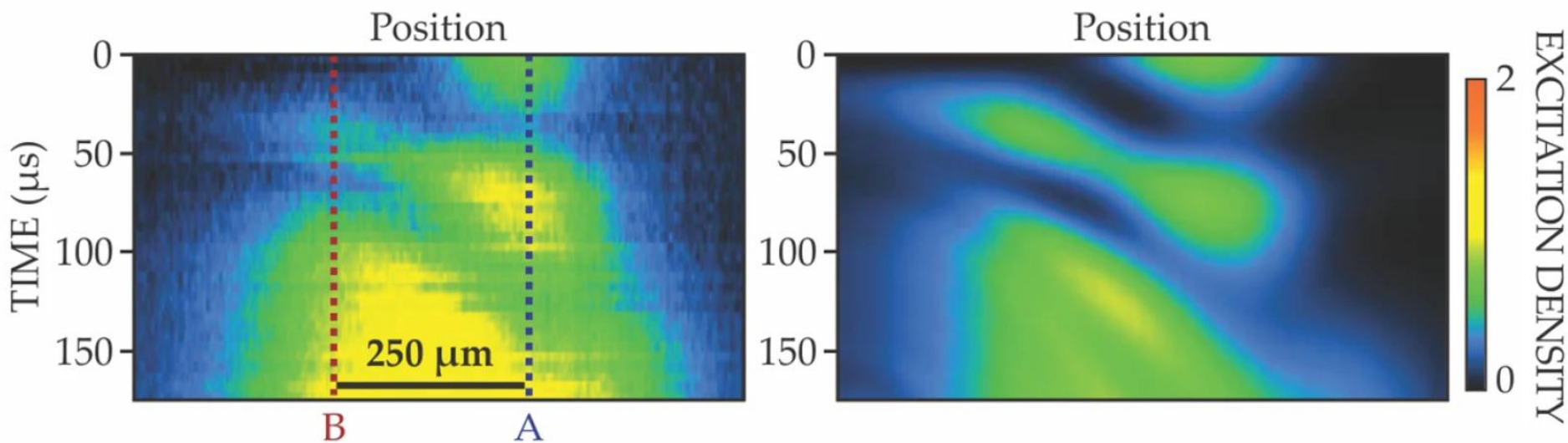


image: Landsman et al. 2019.

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 is beginning to look like and quack like a black hole.



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.

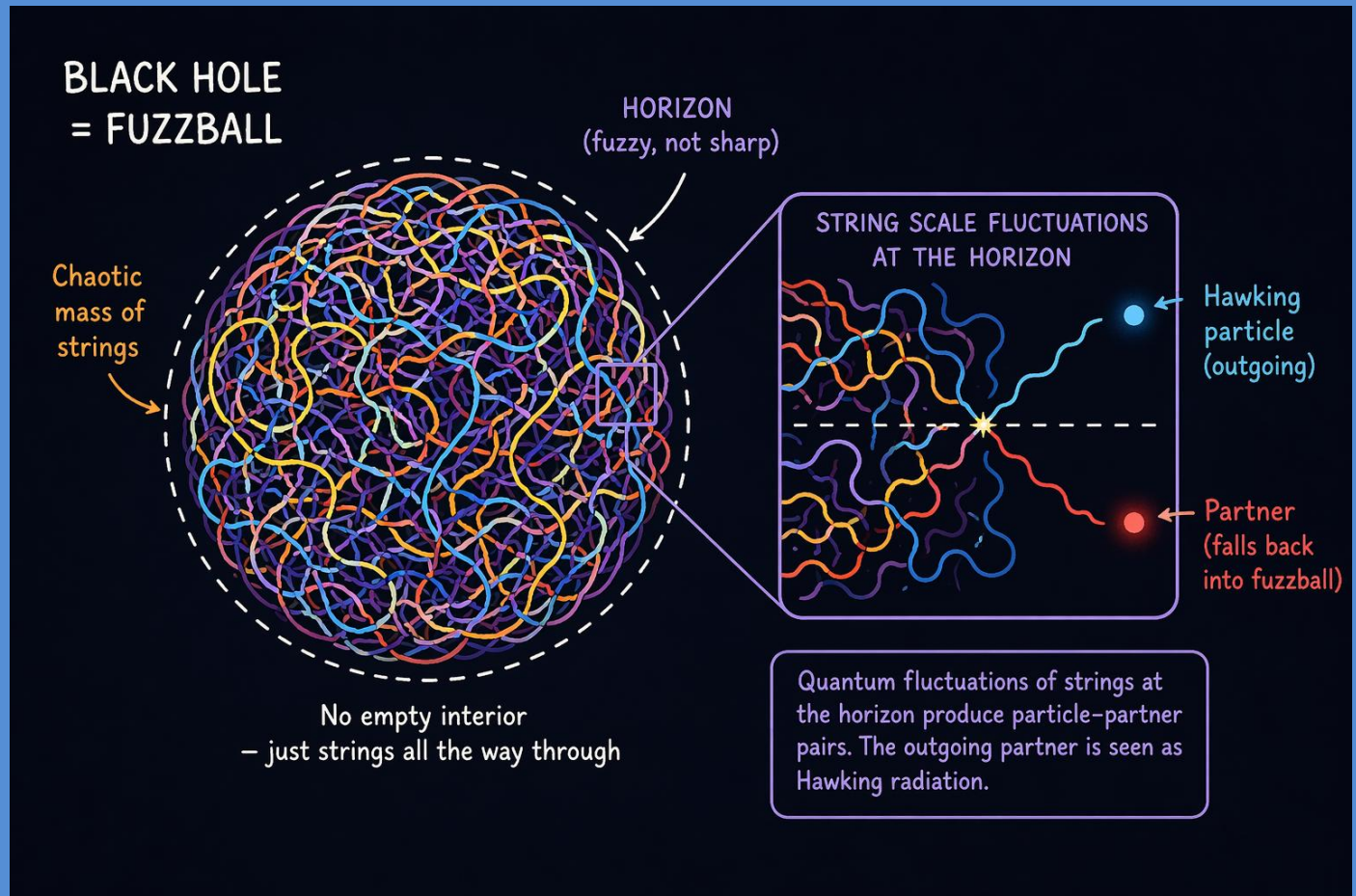


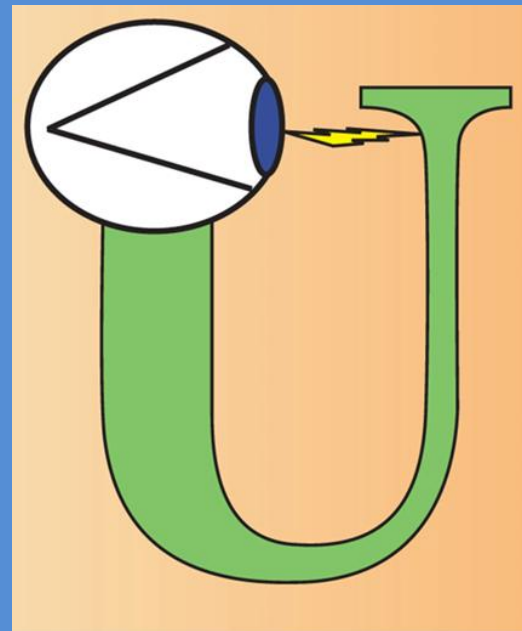
image: ChatGPT

General relativity has guided us well. Its 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*.



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Thank you!