A Century of Black Holes

Enigmas, Insights, and Paradoxes

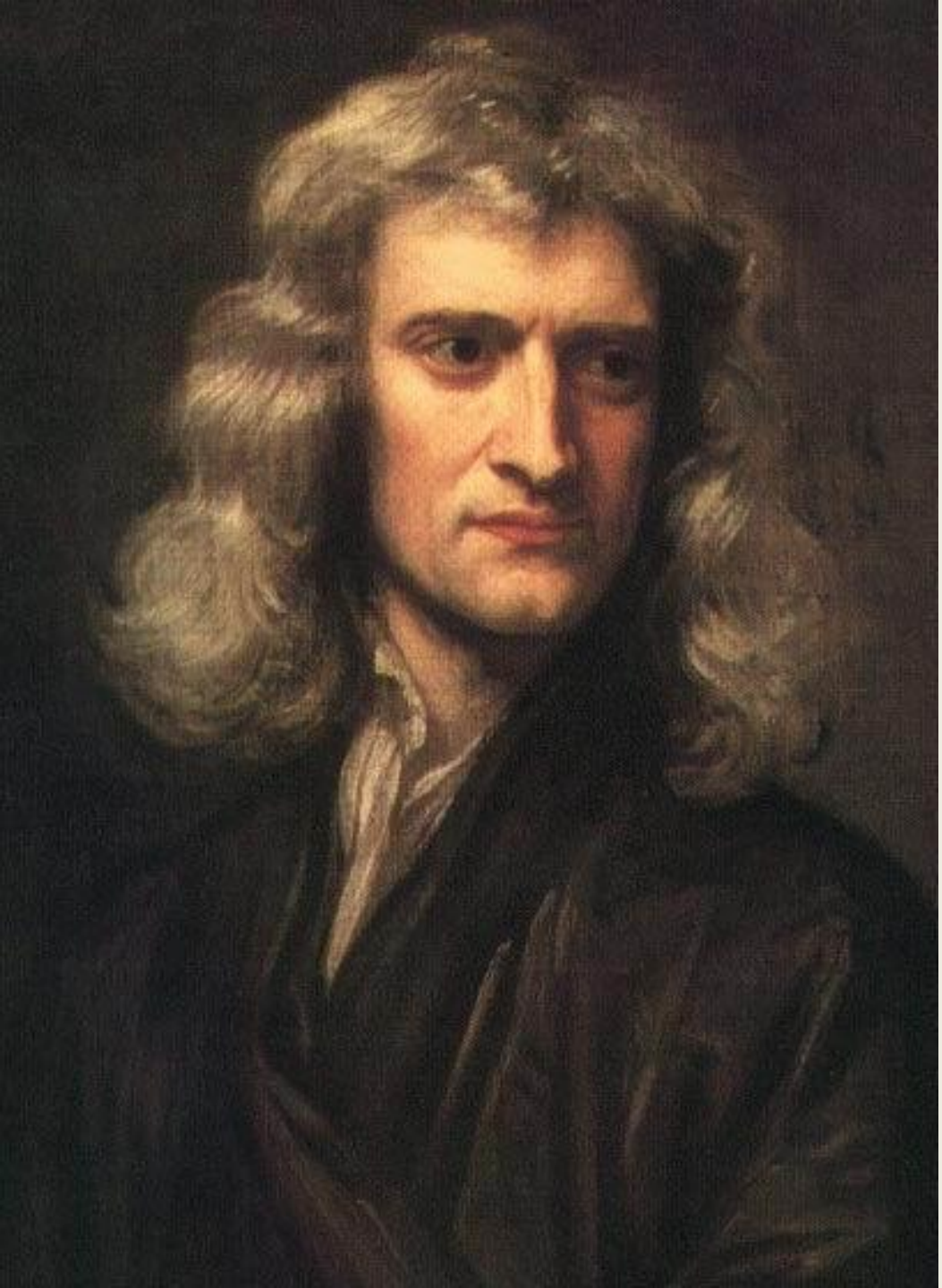
Ted Jacobson
University of Maryland & KITP

Einstein in the Bern patent office, 1905

"A practical profession is a salvation for a man of my type; an academic career compels a young man to scientific production, and only strong characters can resist the temptation of superficial analysis."

Theories of Relativity

- 1905: Special Relativity
  - simultaneity has no absolute meaning
  - speed of light same for all observers
  - $E = mc^2$
- 1915: General Relativity
  - gravity is the curvature of spacetime
  - bending of light rays
  - time runs slower lower down



Gravity

is a force of attraction between any two masses, proportional to each mass and inversely to the square of their separation.

With this Newton unified the fall of an apple, the ocean tides, and the orbits of the moon and the planets.

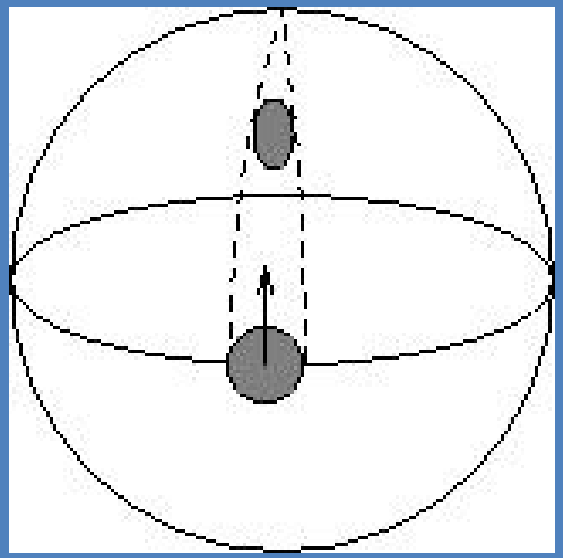
Isaac Newton, aged 46, 1689

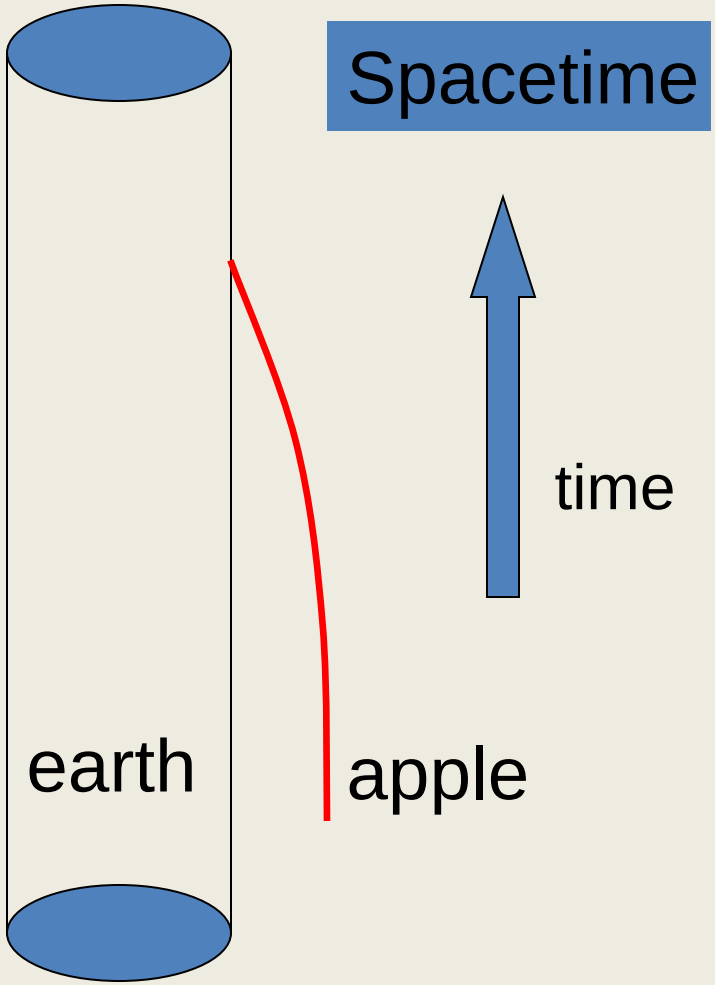
Albert Einstein, aged 33, 1912

Gravity is curvature of spacetime

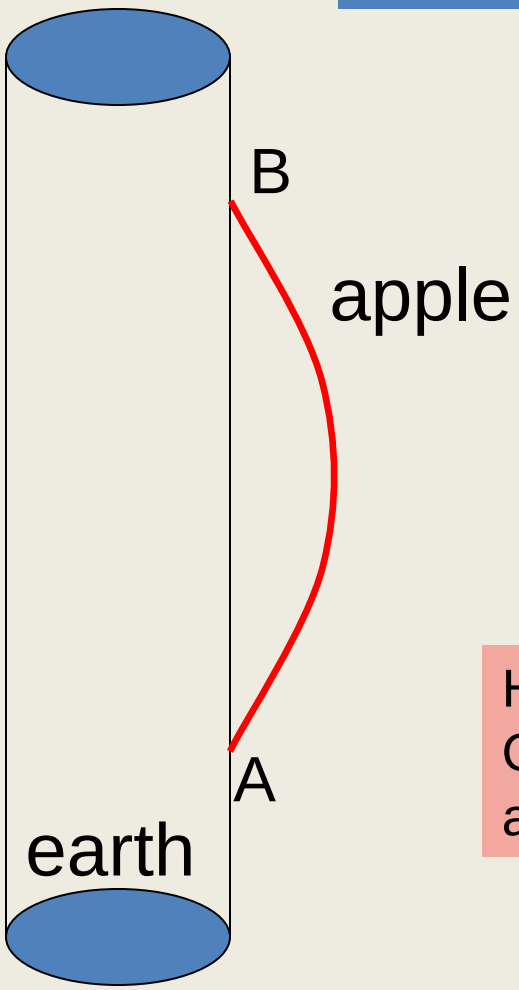
Spatial curvature analogy:

Initially parallel lines
don't stay parallel





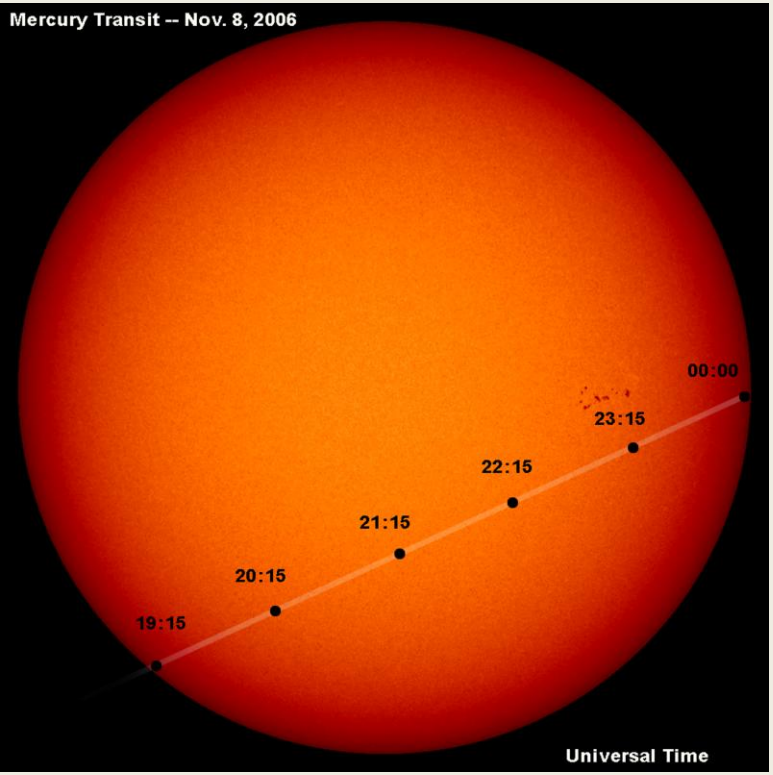
Time runs slower lower down!



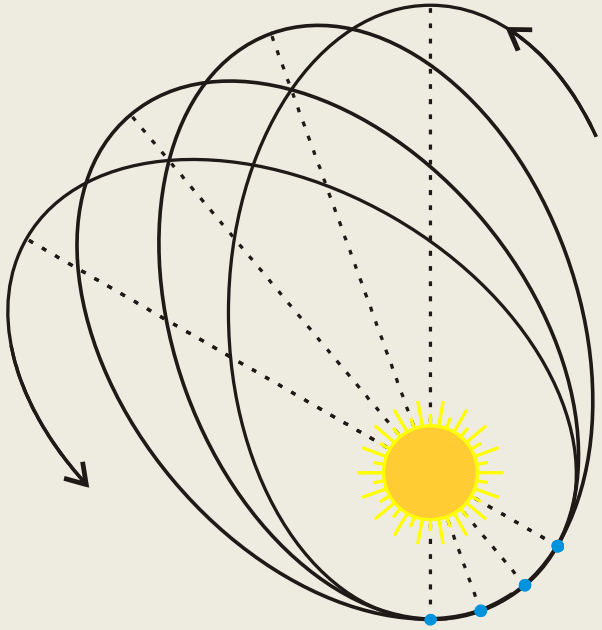
Apple free-fall
is the straightest path
in spacetime between A & B…
and the path of longest time.

How much slower?
One billionth of a second per year per foot at the earth's surface (g/c^2).

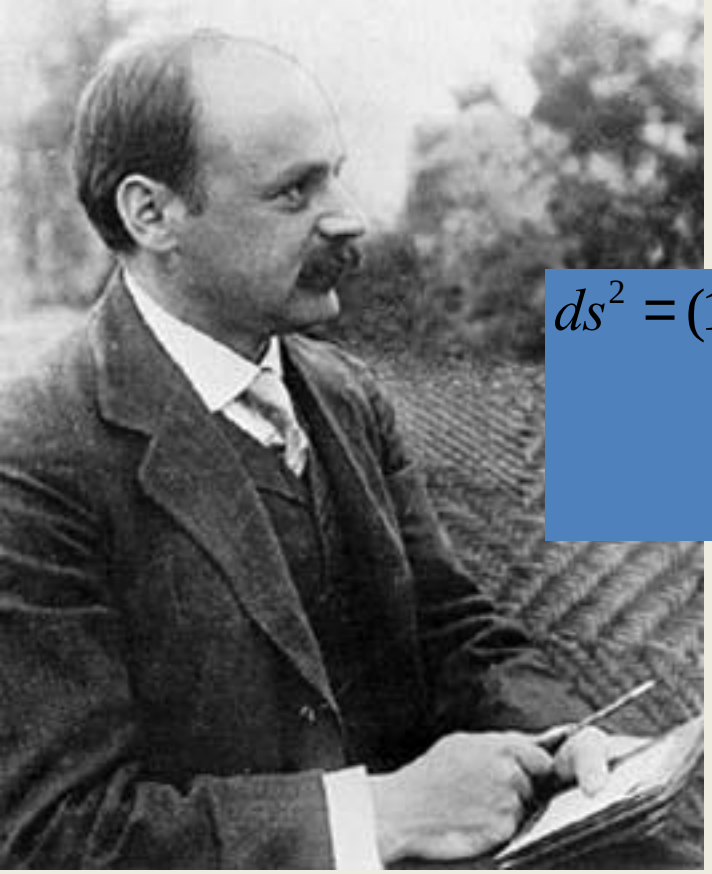
Spiral of Mercury's orbit: didn't fit Newton's theory, by 43"/century…



That's about 9 minutes advance time for the transit per century…



General relativity nailed it.



The Schwarzschild Singularity
(1916)

$$ds^2 = (1 - r_S/r)dt^2 - (1 - r_S/r)^{-1}dr^2 - r^2(d\theta^2 + \sin^2\theta\, d\phi^2)$$

$$r_S = 2GM/c^2 = 3\text{km} \quad \text{"Schwarzschild radius"}$$

Schwarzschild (1916): "in order that this discontinuity coincides with the origin" one should define the radial coordinate appropriately.

Droste (1916): "a moving particle can never pass that sphere because it would take an infinite amount of time"

The true, non-singular nature of the Schwarzschild "singularity" was not *widely* understood until 42 years later… but it was understood by one man perfectly well in 1932…

Georges Lemaitre

First person to understand the nature of the Schwarzschild singularity as an event horizon (1932).

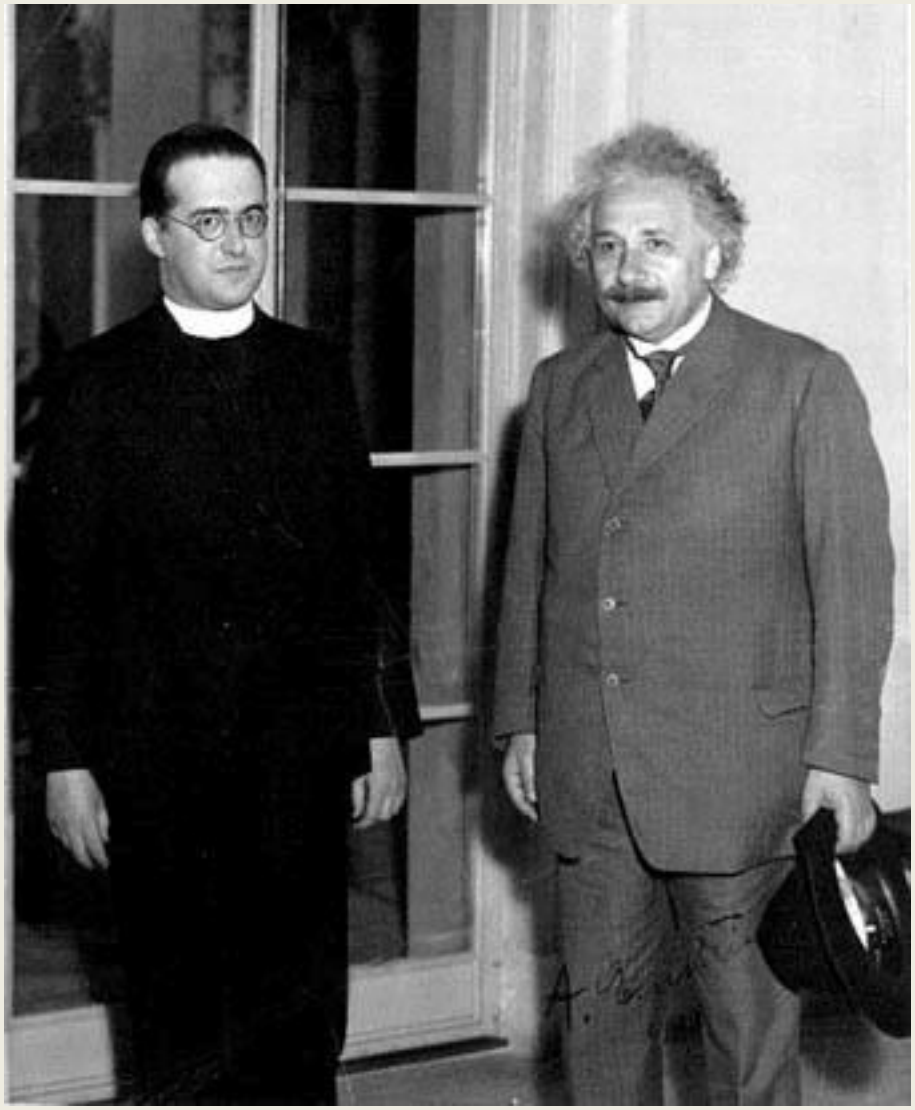
The singularity of the Schwarzschild field is thus of the same nature as the singularity, analogous to that which appears at the horizon of the centre in the original form of the de Sitter universe

Belgian mathematician and physicist, Catholic priest, President of Pontifical Academy of Sciences 1960-66

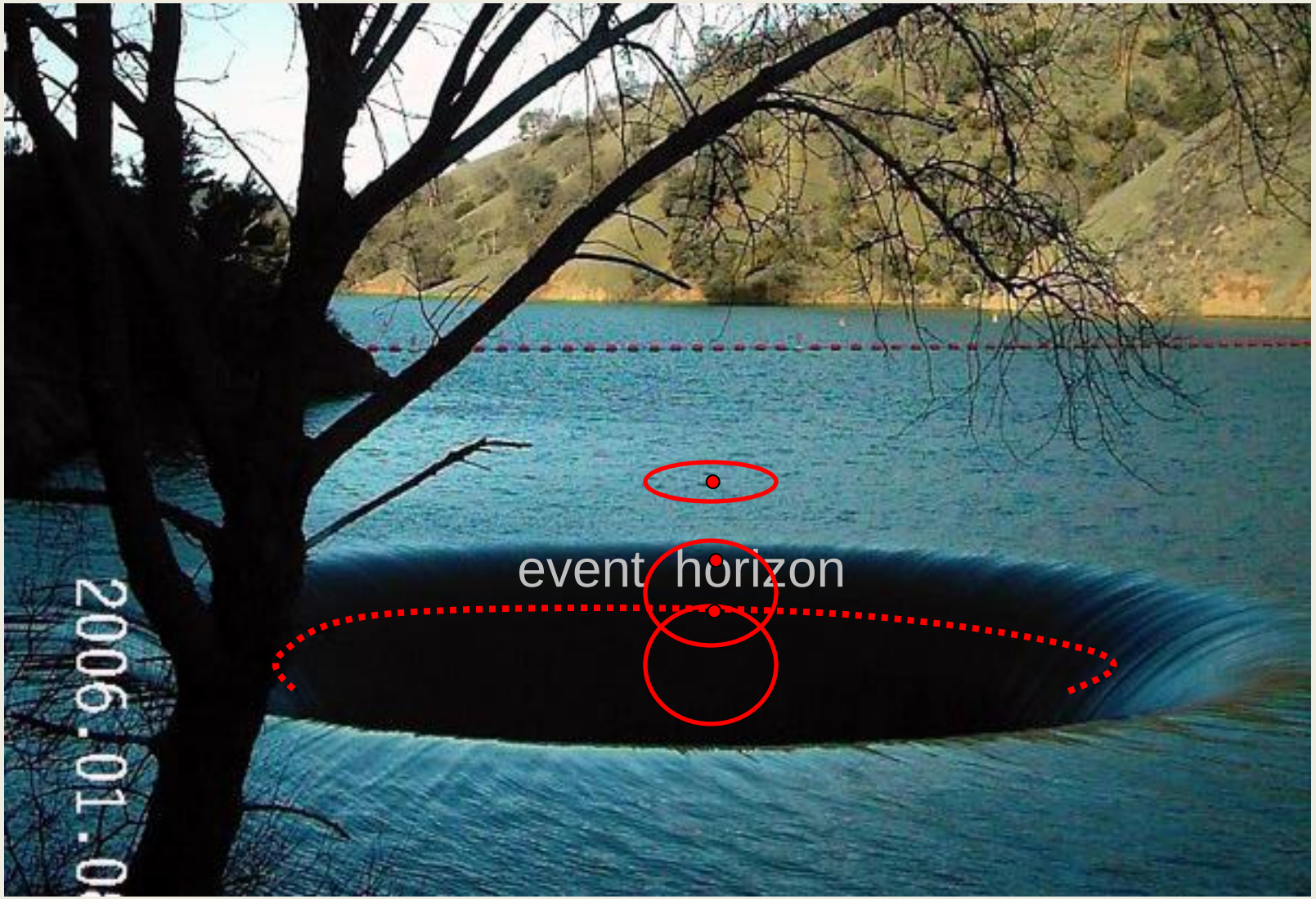
Educated at Cambridge and MIT

Pioneer of physical cosmology:

Expanding universe, cosmic fireball, origin of structure, beginning of time…



A black hole analogy



Einstein (1939) repeated his earlier, cosmological oversight, insisting on *stationary* matter configurations.

ANNALS OF MATHEMATICS
Vol. 40, No. 4, October, 1939

ON A STATIONARY SYSTEM WITH SPHERICAL SYMMETRY CONSISTING OF MANY GRAVITATING MASSES

BY ALBERT EINSTEIN

(Received May 10, 1939)

The essential result of this investigation is a clear understanding as to why the "Schwarzschild singularities" do not exist in physical reality. Although the theory given here treats only clusters whose particles move along circular paths it does not seem to be subject to reasonable doubt that more general cases will have analogous results. The "Schwarzschild singularity" does not appear for the reason that matter cannot be concentrated arbitrarily. And this is due to the fact that otherwise the constituting particles would reach the velocity of light.

Oppenheimer and Snyder (1939) analyzed *collapsing* matter and showed how an event horizon forms in a finite time.

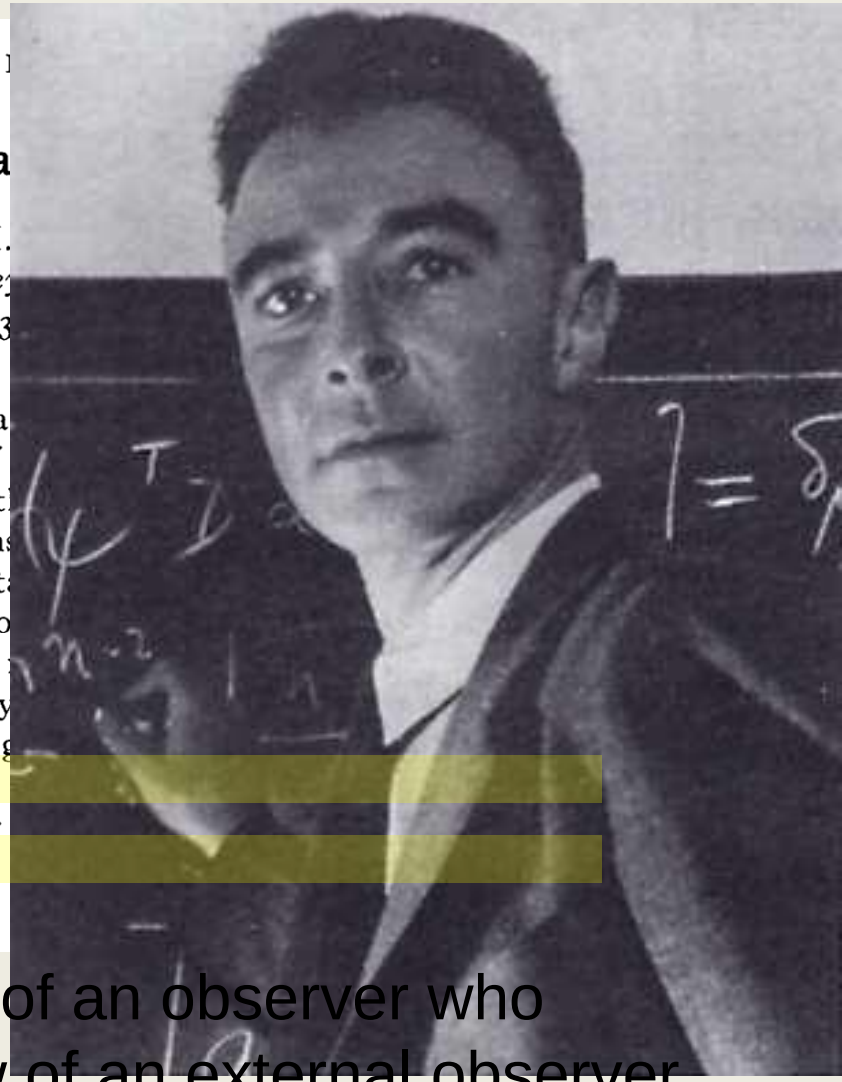
SEPTEMBER 1, 1939 PHYSICAL REVI

On Continued Gravitationa

J. R. OPPENHEIMER AND H.
University of California, Berkele

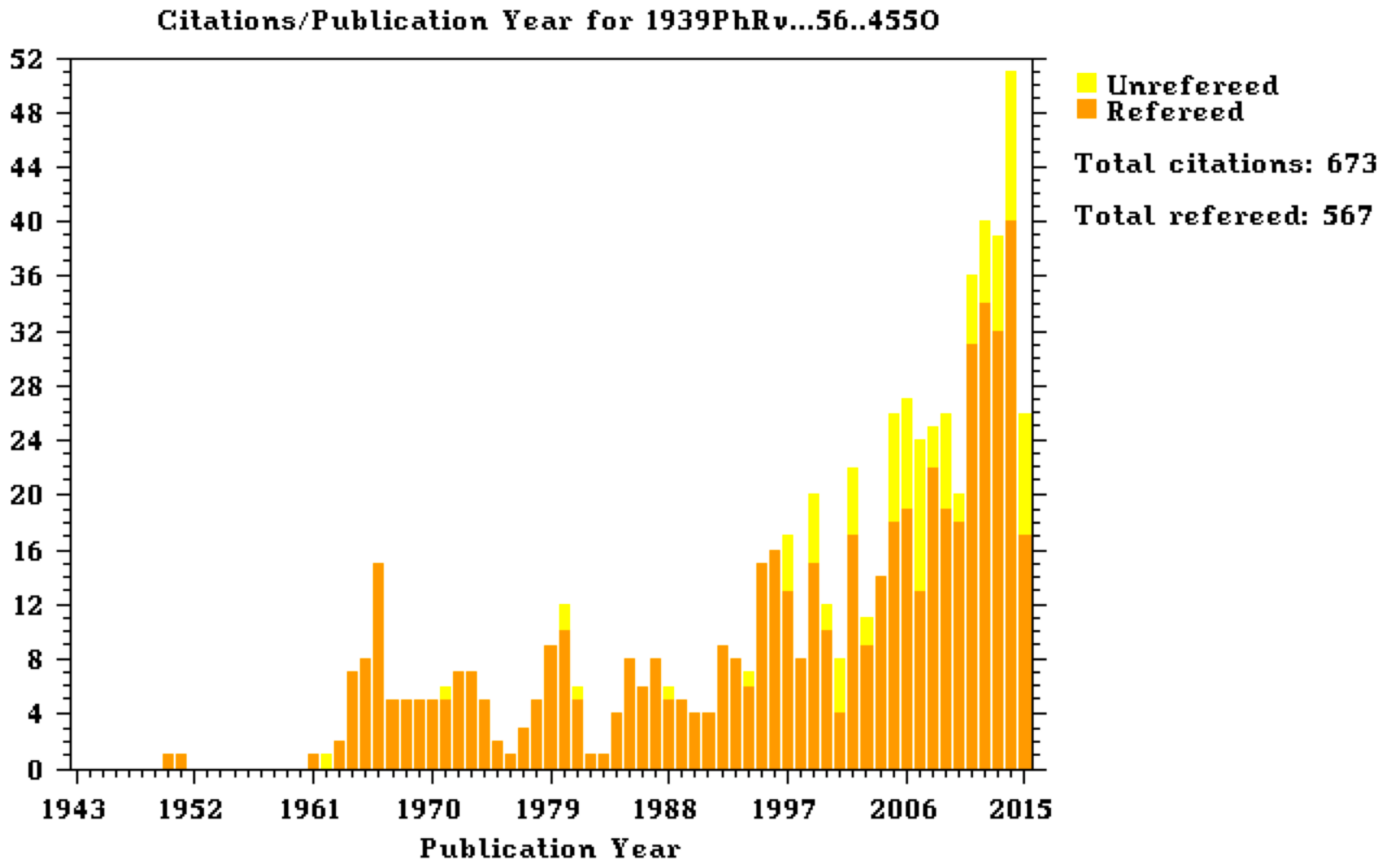
(Received July 10, 193

When all thermonuclear sources of energy are exha
collapse. Unless fission due to rotation, the radiation of
radiation, reduce the star's mass to the order of that of t
indefinitely. In the present paper we study the solutions
which describe this process. In I, general and qualit
behavior of the metrical tensor as the contraction pro
proaches asymptotically its gravitational radius; light
gressively reddened, and can escape over a progressively
analytic solution of the field equations confirming these
case that the pressure within the star can be neglected.
server comoving with the stellar matter is finite, and for
masses, of the order of a day; an external observer sees
its gravitational radius.



First paper to discuss the viewpoint of an observer who falls in, and contrasted with the view of an external observer.

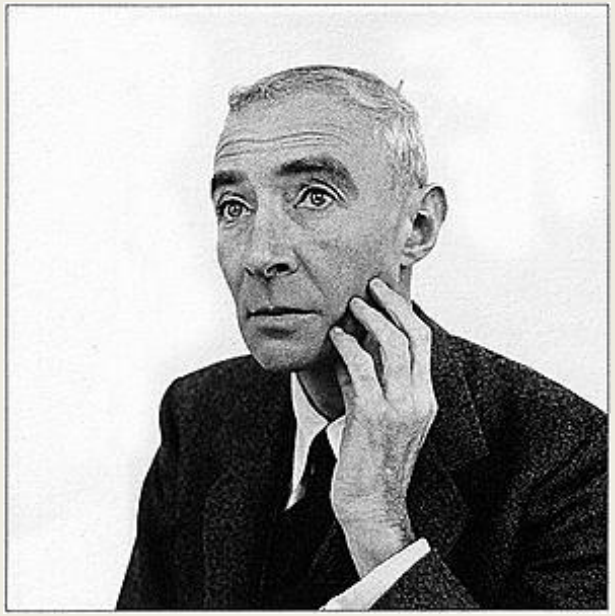
The Citation database in the ADS is **NOT** complete. Please keep this in mind when using the ADS Citation lists.



Twenty years later, it still wasn’t accepted.

Oppenheimer, at 1958 Solvay Congress:

“Would not the simplest assumption about the fate of a star more than the critical mass be this, that it undergoes continued gravitational contraction and cuts itself off from the rest of the universe?”



Oppenheimer,1958
(by Richard Avedon)

J.A. Wheeler said that the collapse theory “does not give an acceptable answer” to the fate of matter in such a star.

It was difficult to conceive of collapse to nothing but empty curved space, and the disappearance of matter into the unknown …

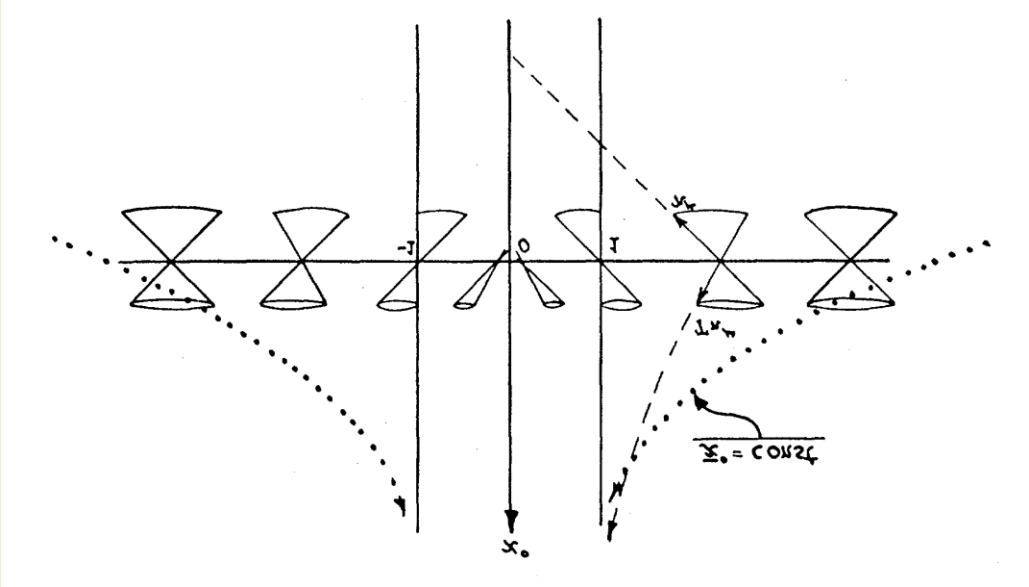
Also, missing was a *picture* that could unify the outside and inside views…

PHYSICAL REVIEW VOLUME 110, NUMBER 4 MAY 15, 1958

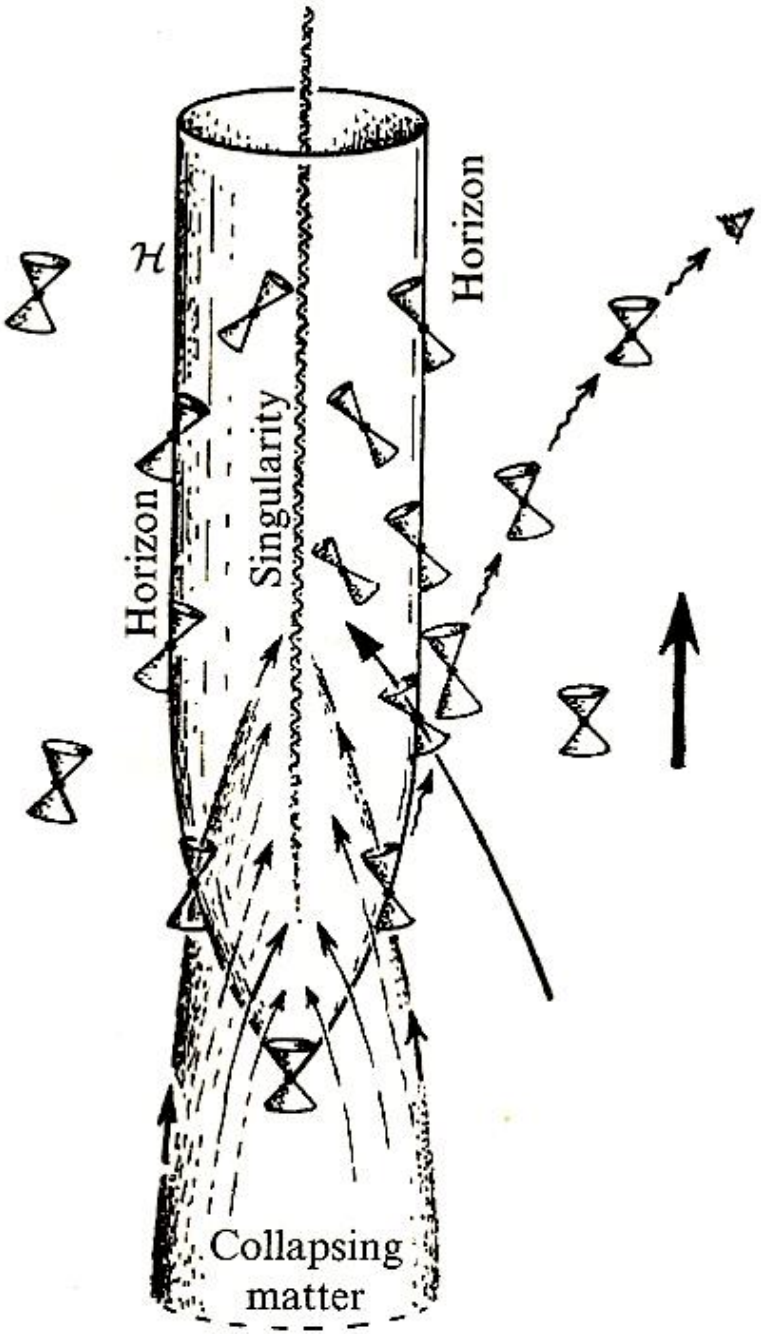
Past-Future Asymmetry of the Gravitational Field of a Point Particle

DAVID FINKELSTEIN
Stevens Institute of Technology, Hoboken, New Jersey, and New York University, New York, New York
(Received January 9, 1958)

The analytic extension of the Schwarzschild exterior solution is given in a closed form valid throughout empty space-time and possessing no irregularities except that at the origin. The gravitational field of a spherical point particle is then seen not to be invariant under time reversal for any admissible choice of time coordinate. The Schwarzschild surface $r=2m$ is not a singularity but acts as a perfect unidirectional membrane: causal influences can cross it but only in one direction. The apparent violation of the principle of sufficient reason seems similar to that which is associated with instabilities in other nonlinear phenomena.

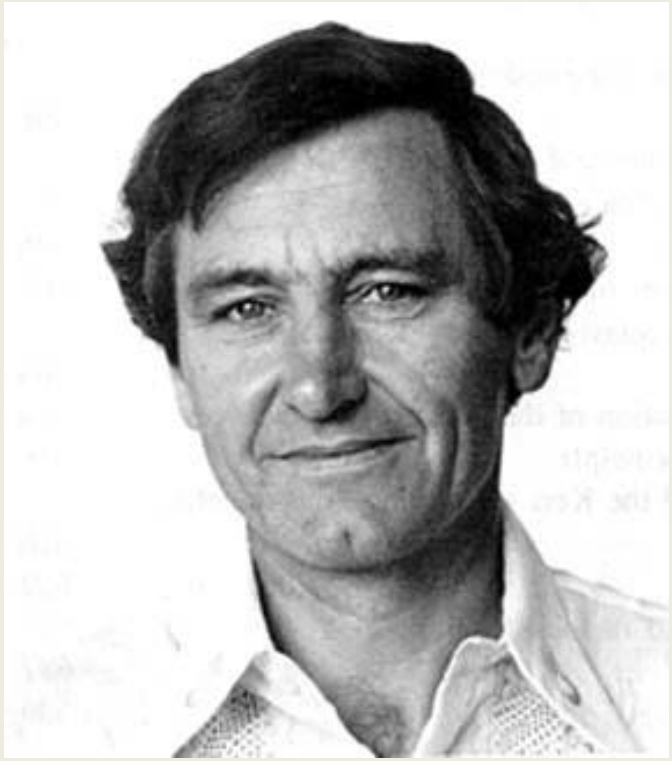


The combined outside-inside view visualized…



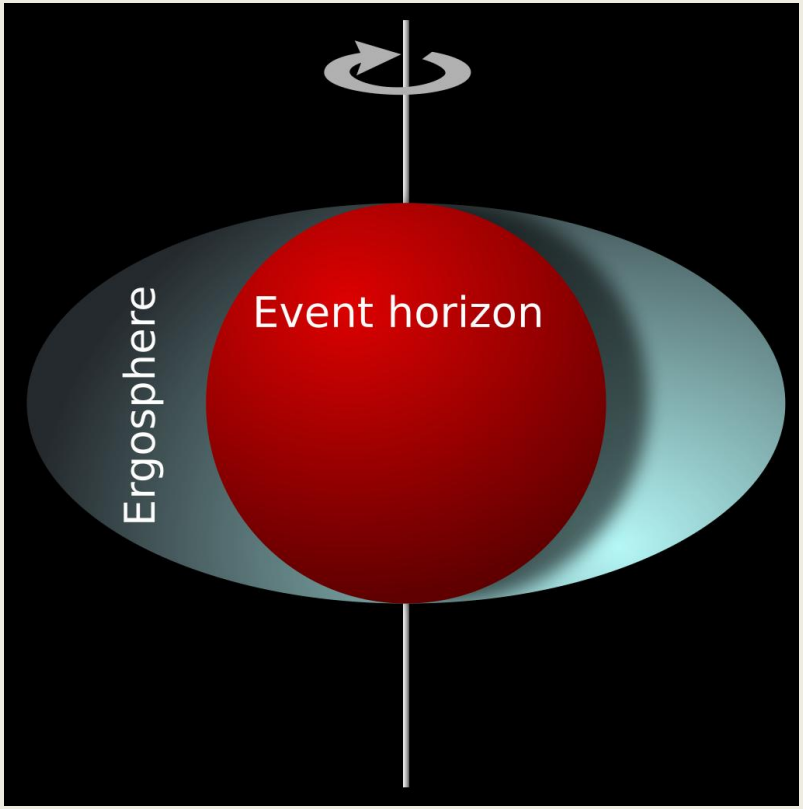
The light cones tip over
and close off communication
with the outside…

Picture by Roger Penrose
The Road to Reality (Knopf, 2005)

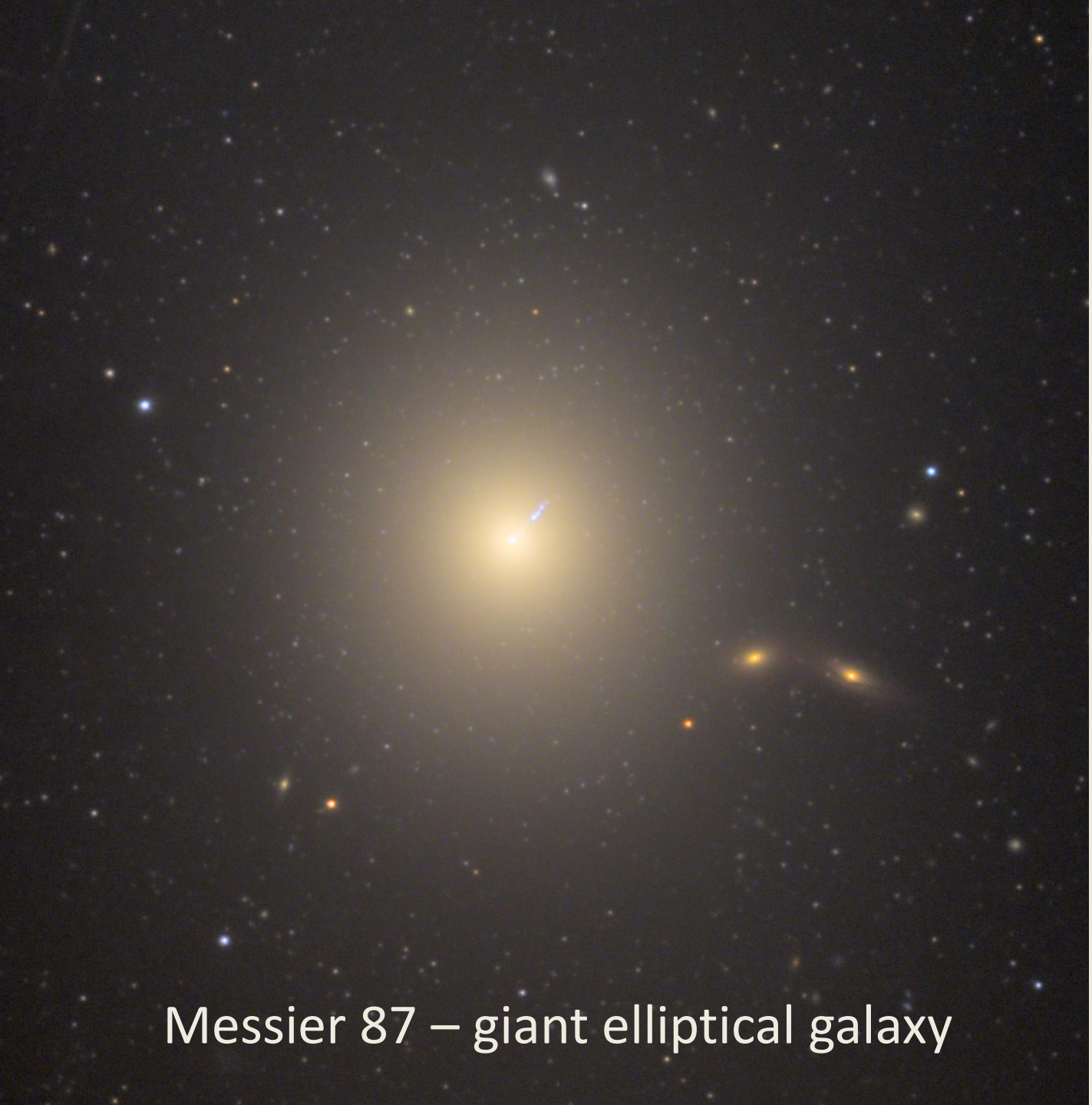


Roy Kerr in 1975

In 1963, Kerr found the exact, spinning black hole solution to Einstein's equation.



This revealed that the rotational energy of a black hole could be tapped!



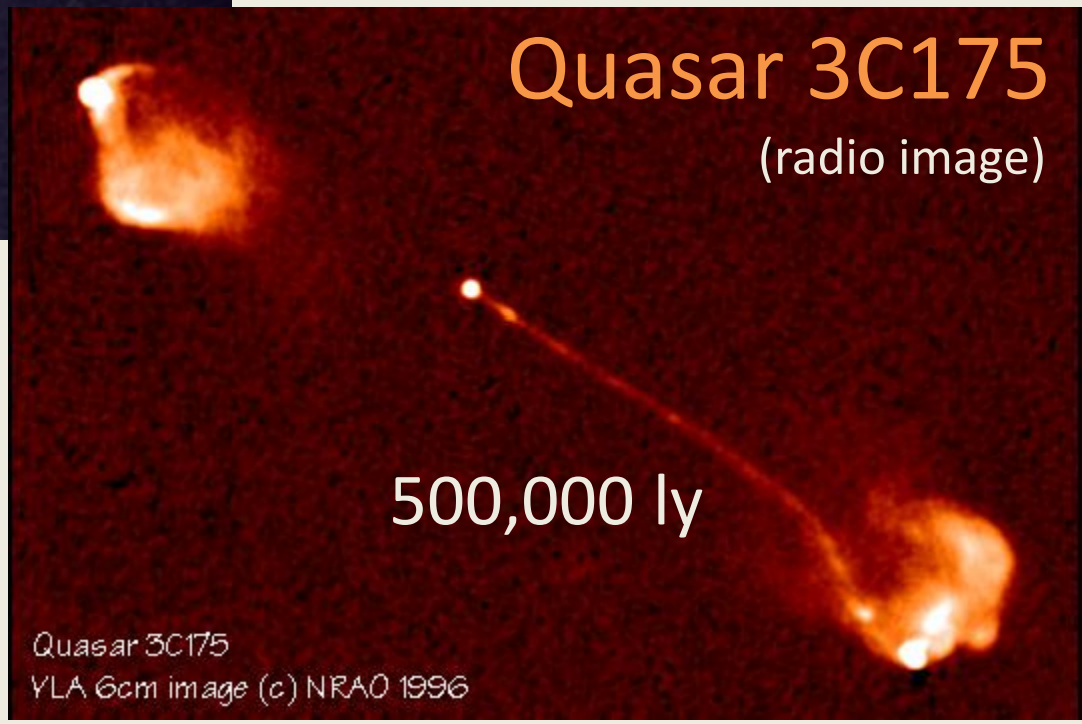
Messier 87 – giant elliptical galaxy

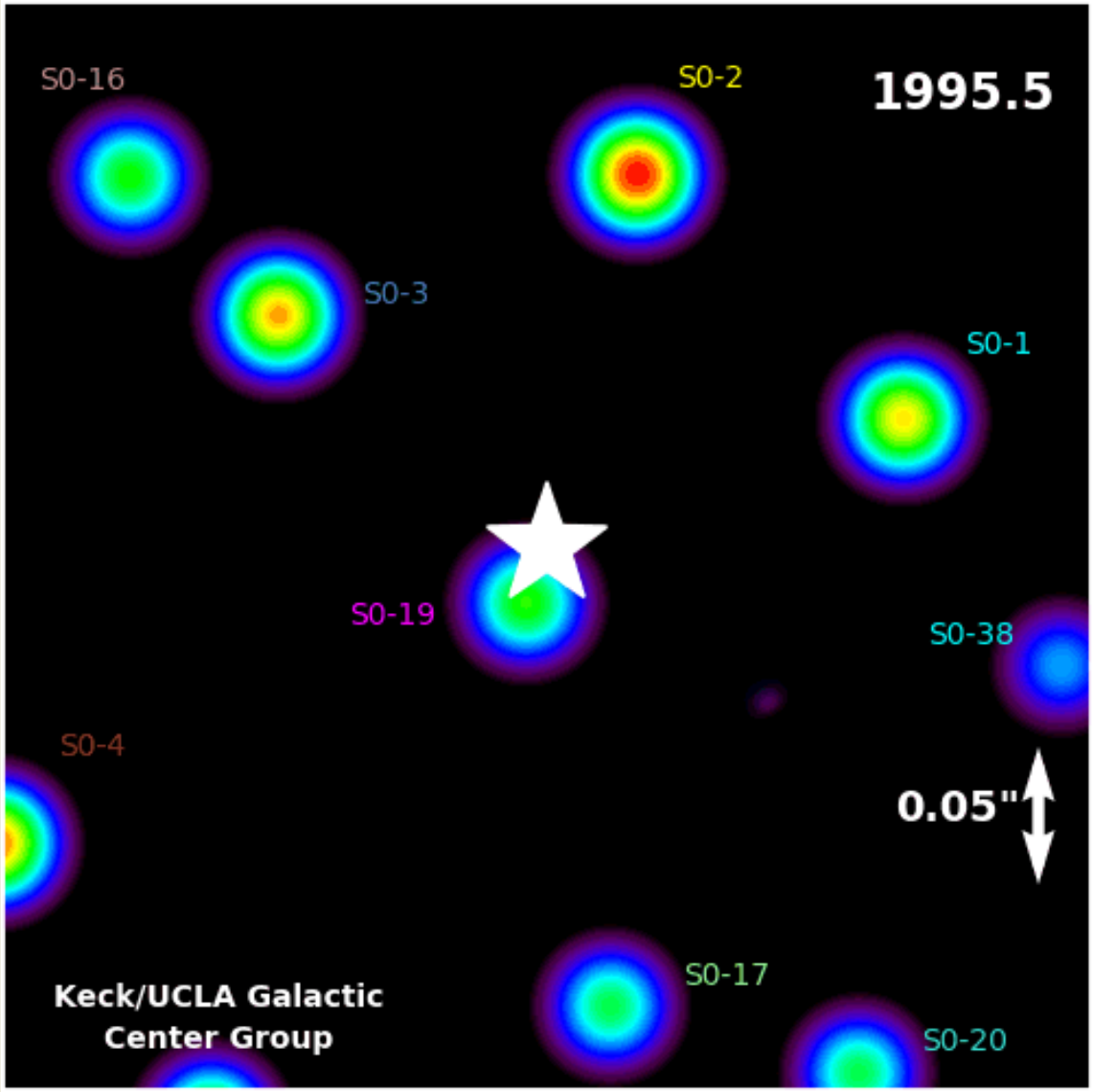
In 1918, Heber Curtis of Lick Observatory noticed a "*curious straight ray ... apparently connected with the nucleus by a thin line of matter*."

Powered by a spinning black hole, 3.5 billion M_{sun}, 10 billion km radius.

M87 jet (Hubble, optical image)


M87 jet
(Hubble, optical image)
5000 ly


Quasar 3C175
(radio image)
500,000 ly
Quasar 3C175
VLA 6cm image (c) NRAO 1996

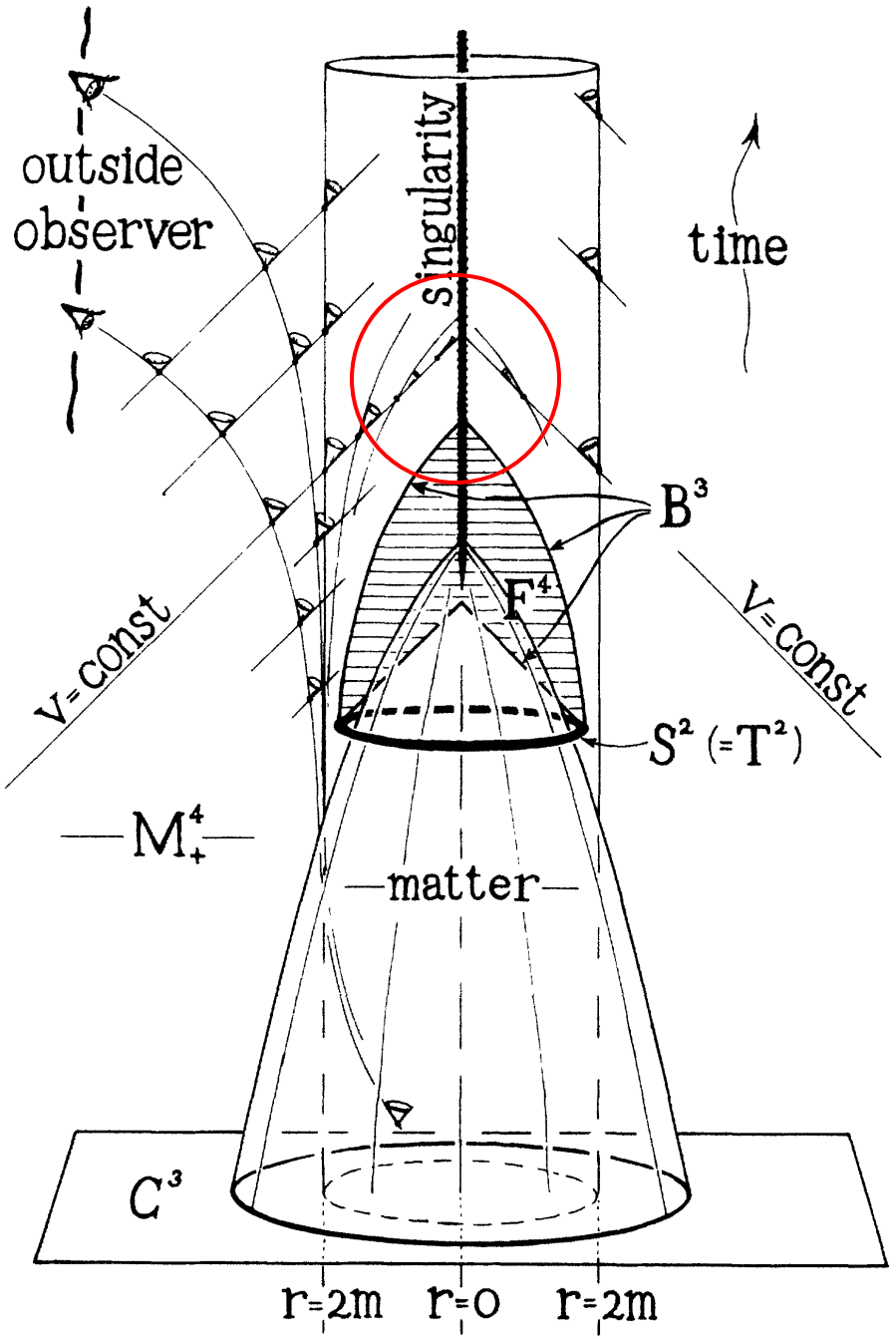


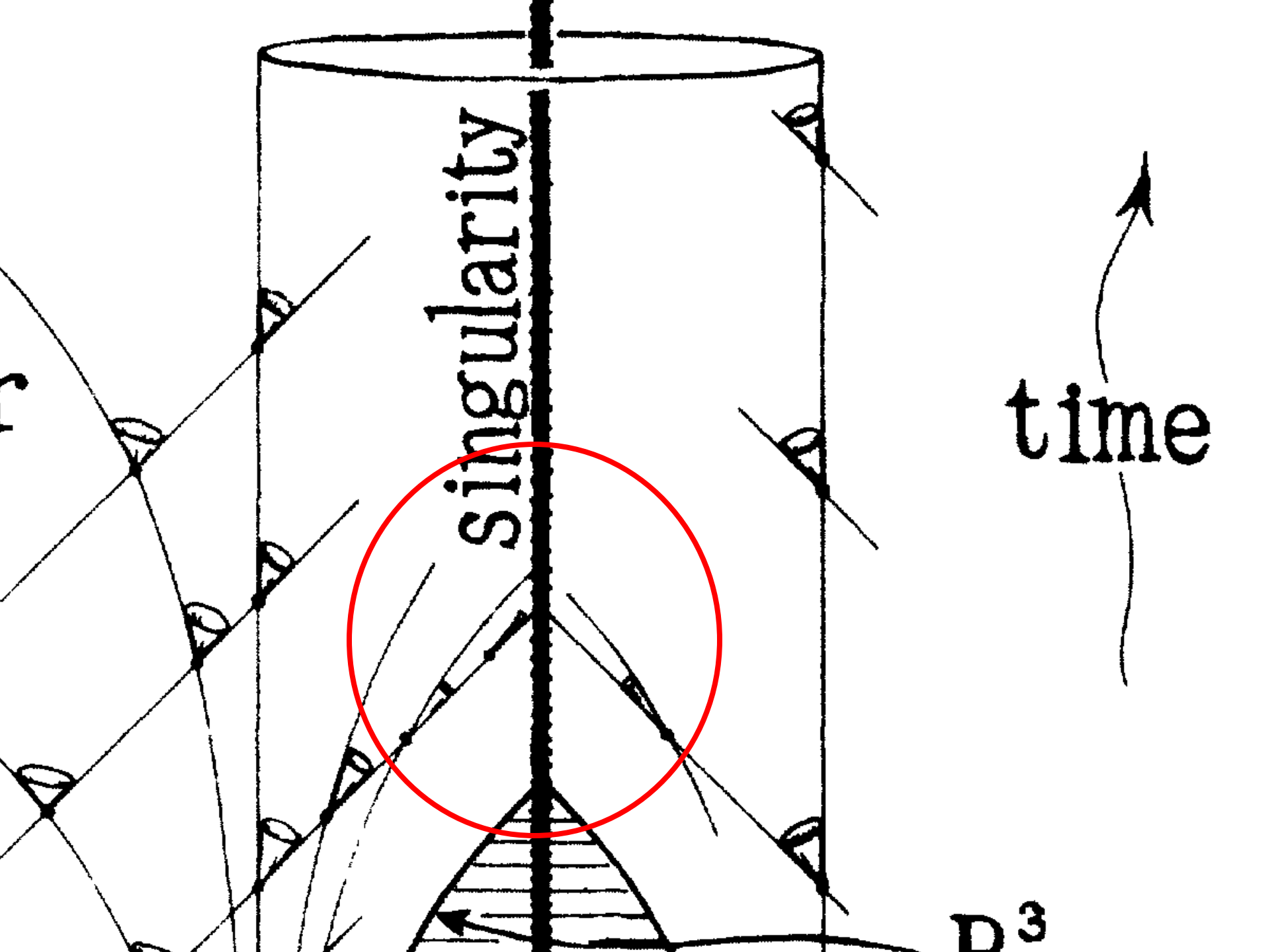
Stars orbiting the 4 million solar mass black hole at the center of the Milky Way galaxy.

Penrose singularity theorem (1964)

Once a trapped surface forms, a singularity is inevitable.

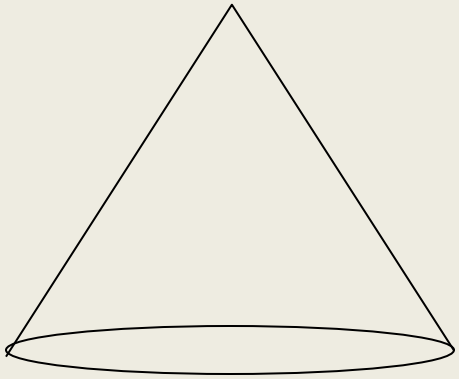
"When eventually we have a better theory of nature, then perhaps we can try our hands again, at understanding the extraordinary physics which must take place at a space-time singularity."
(Penrose, 1969)



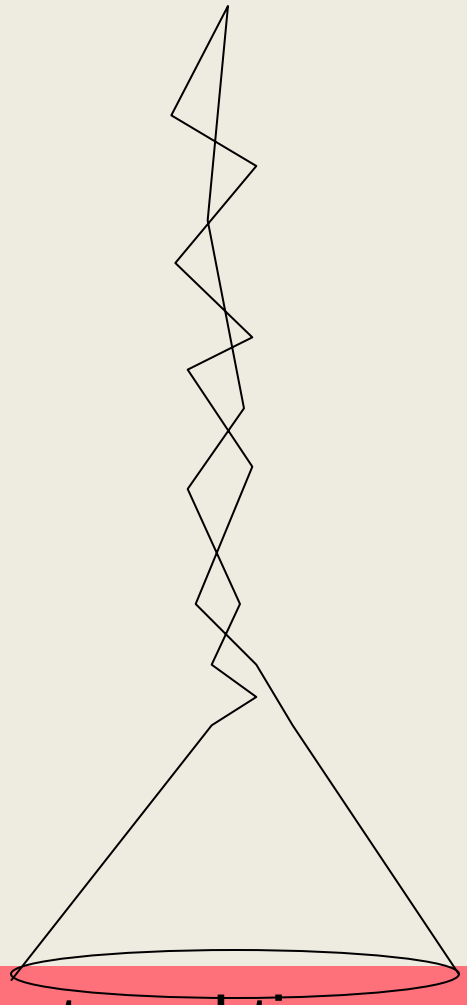

singularity
time
R^3

Fate of a black hole singularity?

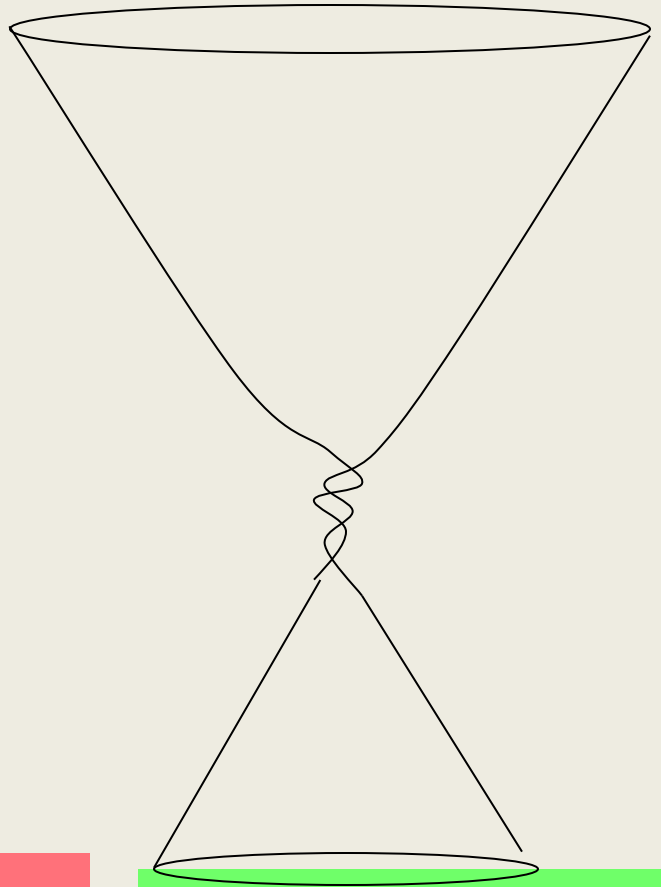
The End



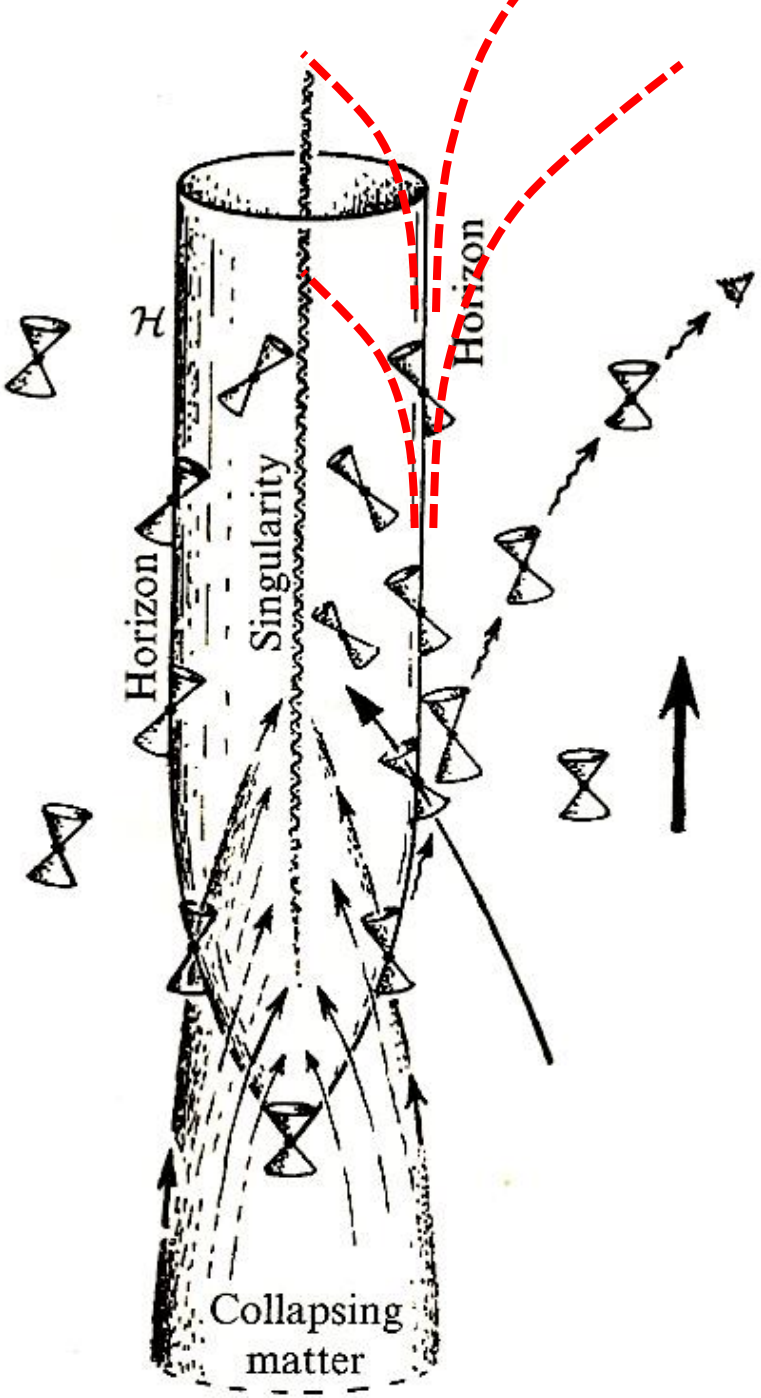
time ends



fractured time continues



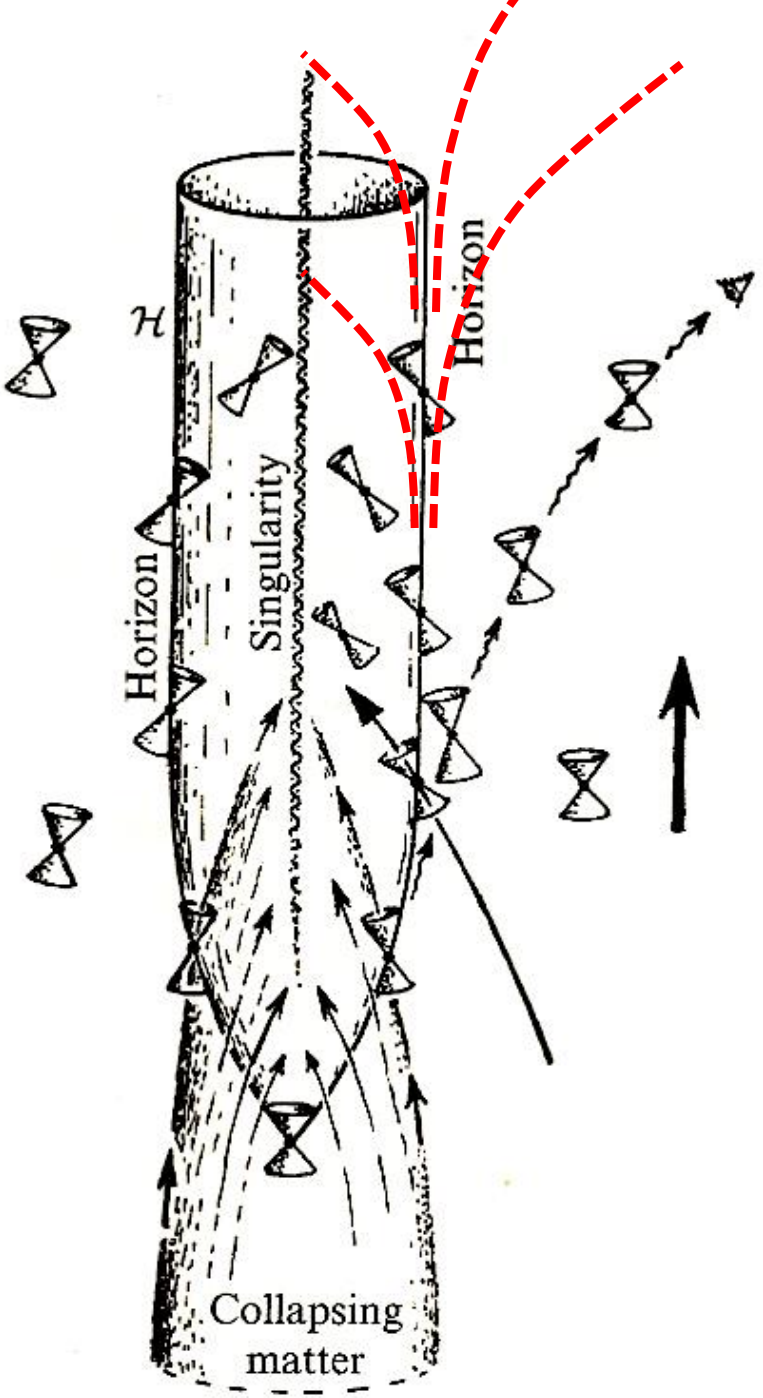
plump baby Universe born



Hawking radiation:

(1974)

Quantum physics implies black holes have a temperature --- and they "evaporate by radiation"



Black holes also have *ENTROPY*

which saves the Second Law of Thermodynamics…

but poses a new puzzle,

"the information paradox"

We have reason to believe that NO information can be lost forever inside a black hole … but loss seems inevitable.

Black Holes: Complementarity or Firewalls?

Ahmed Almheiri, Donald Marolf, Joseph Polchinski, James Sully

(Submitted on 13 Jul 2012 (v1), last revised 13 Apr 2013 (this version, v4))

We argue that the following three statements cannot all be true: (i) Hawking radiation is in a pure state, (ii) the information carried by the radiation is emitted from the region near the horizon, with low energy effective field theory valid beyond some microscopic distance from the horizon, and (iii) the infalling observer encounters nothing unusual at the horizon. Perhaps the most conservative resolution is that the infalling observer burns up at the horizon. Alternatives would seem to require novel dynamics that nevertheless cause notable violations of semiclassical physics at macroscopic distances from the horizon.

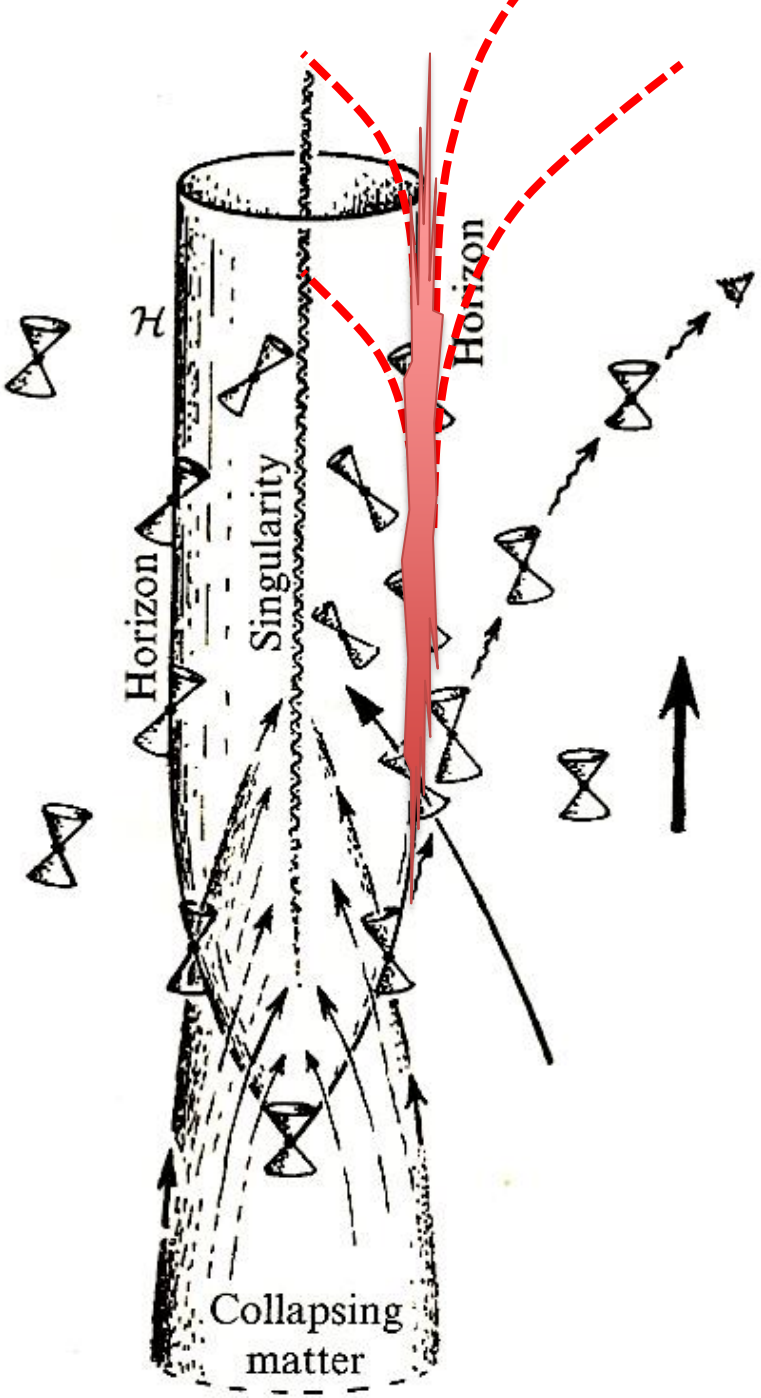
Comments: 22 pages, 1 figure. v2: We have not changed our minds. Various arguments are expanded and sharpened. v3: Relation to previous work clarified. v4: Additional reference to earlier work

Subjects: **High Energy Physics - Theory (hep-th)**; General Relativity and Quantum Cosmology (gr-qc)

Cite as: **arXiv:1207.3123 [hep-th]**

(or **arXiv:1207.3123v4 [hep-th]** for this version)

Has over 300 citations as of May 2015



We have reason to believe that NO information can be lost forever inside a black hole … but loss seems inevitable because the pairs have *joint information* --- called quantum entanglement.

Possible Resolutions:

1. There is a "firewall" at the horizon, i.e. a fissure in the vacuum.

2. Something else…but WHAT??

This is a huge puzzle, controversy, source of debate and discussion… there was a related KITP program in 2012 which produced the firewall paper, a dedicated workshop for 3 weeks in 2013, and it's a major theme in the current program on quantum gravity.

My take: The joint information is also available in another, form, far from the black hole, communicated by the quantum gravitational interaction which ties everything together. (http://arxiv.org/abs/1212.6944)