Cien Años de Gravedad

.

One Hundred Years of Nigritude

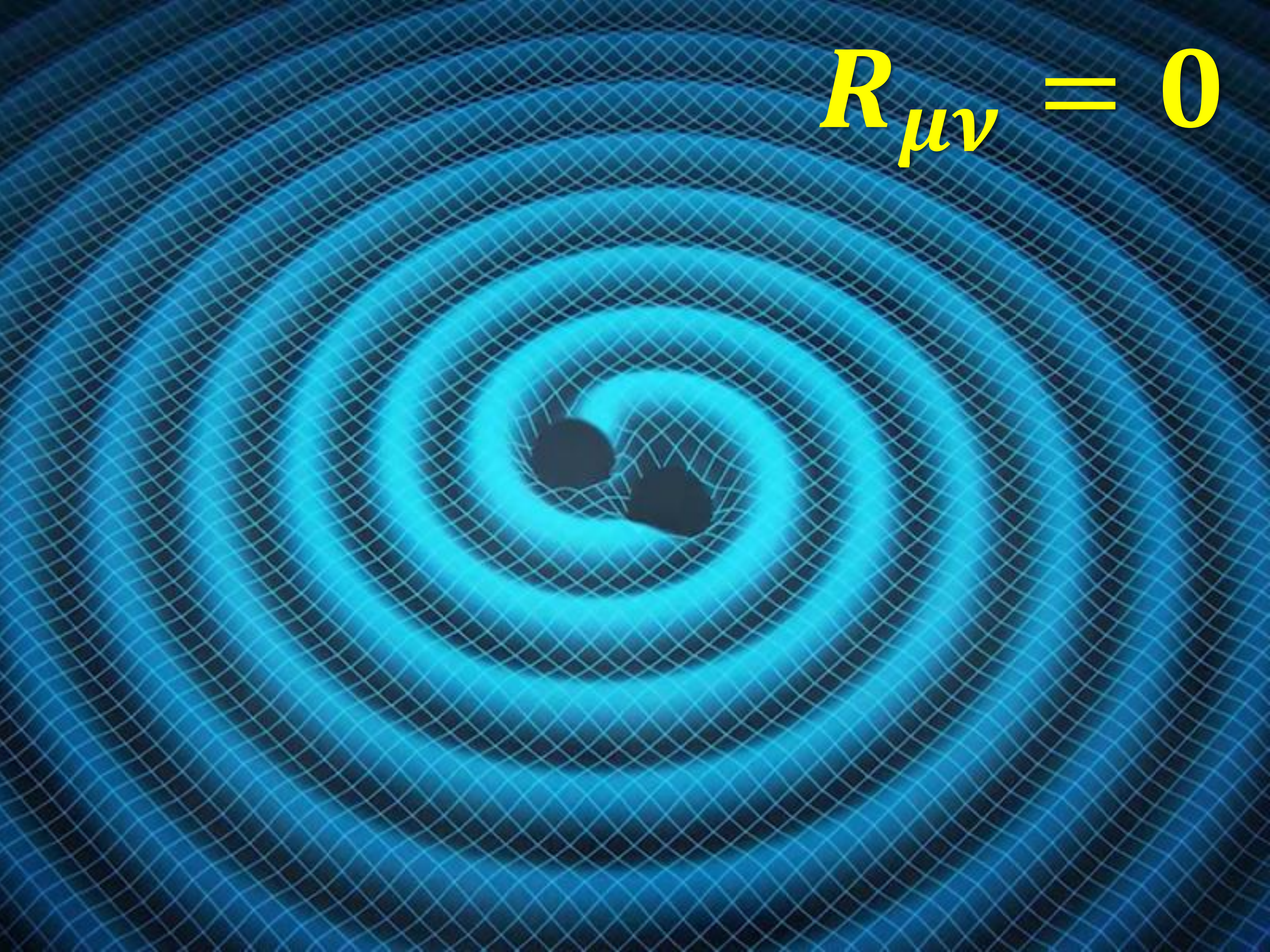
25 Nov 1915

$$\boldsymbol{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}}$$

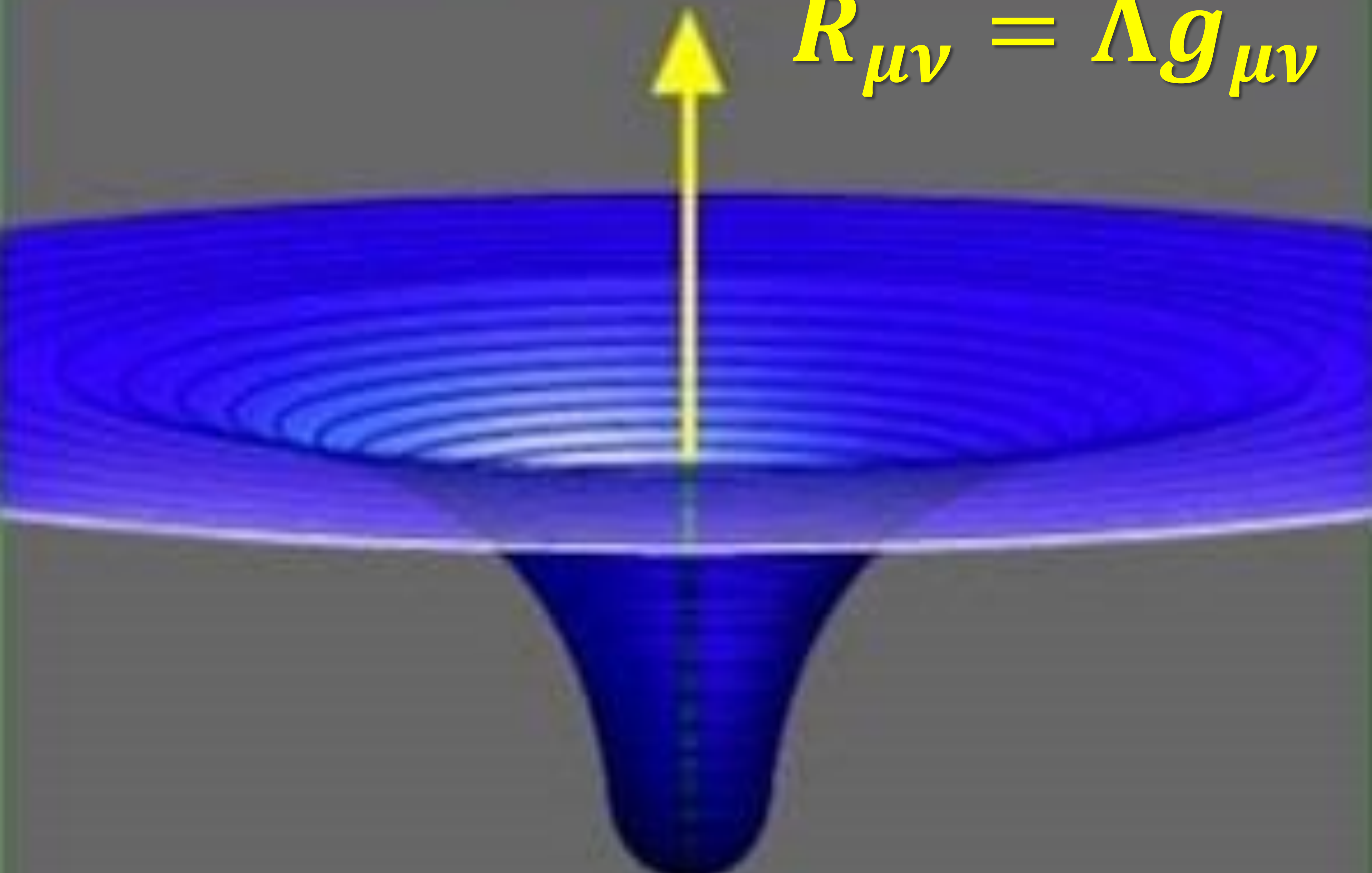
Die Feldgleichungen der Gravitation.

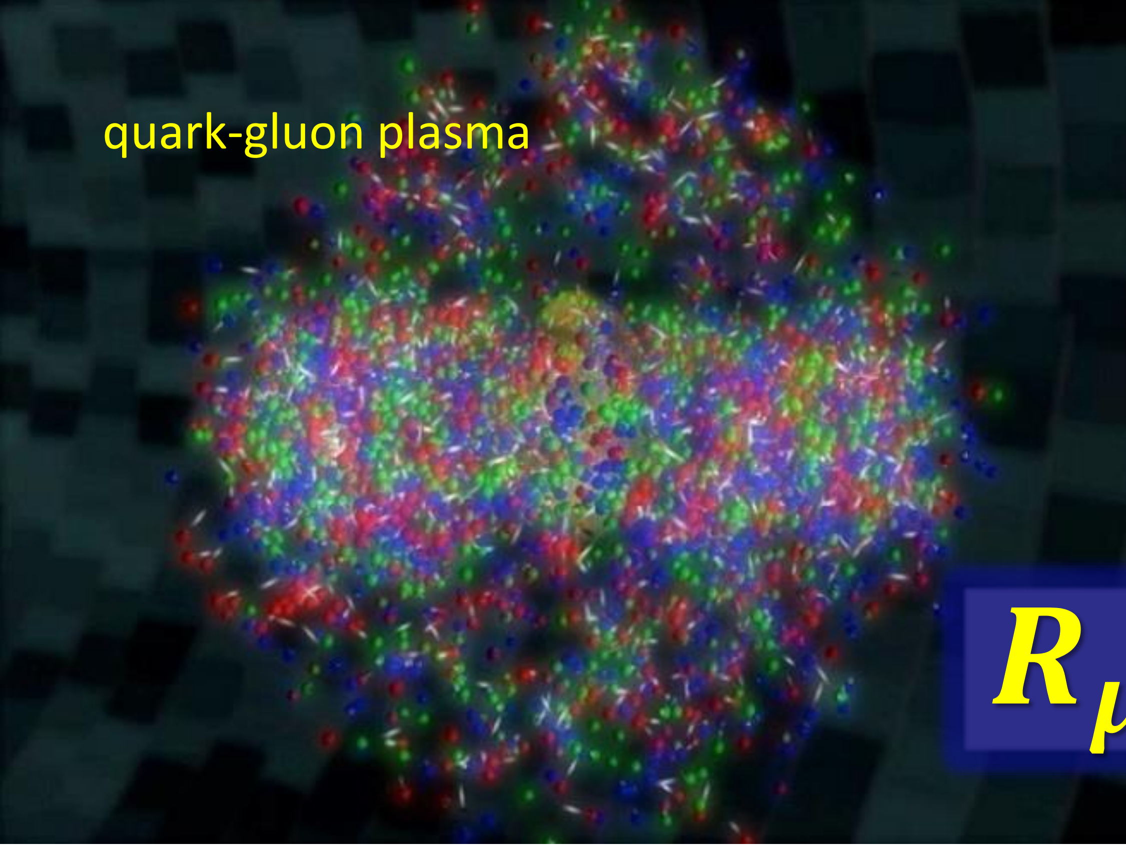
Von A. Einstein.

$$R_{im} = \sum_l \frac{\partial \Gamma^l_{im}}{\partial x_l} + \sum_{\rho l} \Gamma^\rho_{il} \Gamma^l_{m\rho} = -\varkappa \left(T_{im} - \frac{1}{2} g_{im} T \right)$$

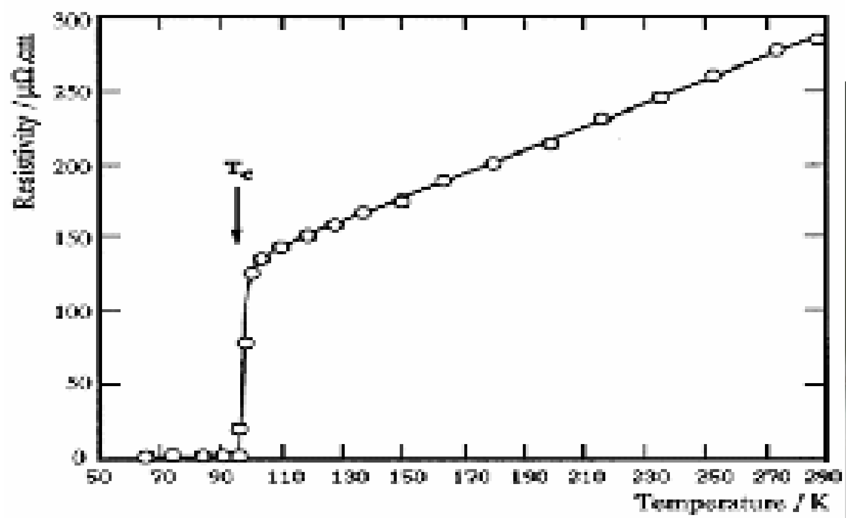

$R_{\mu\nu} = 0$

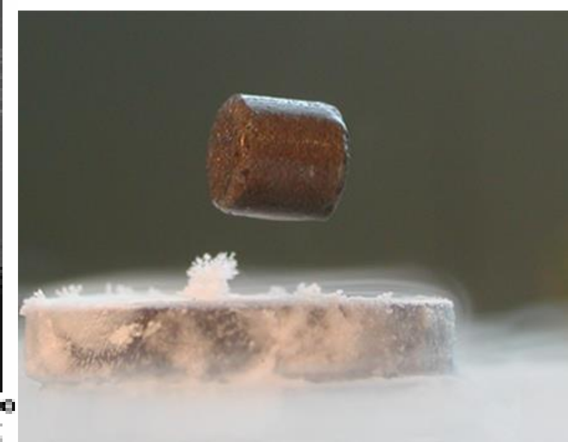
$$R_{\mu\nu} = \Lambda g_{\mu\nu}$$



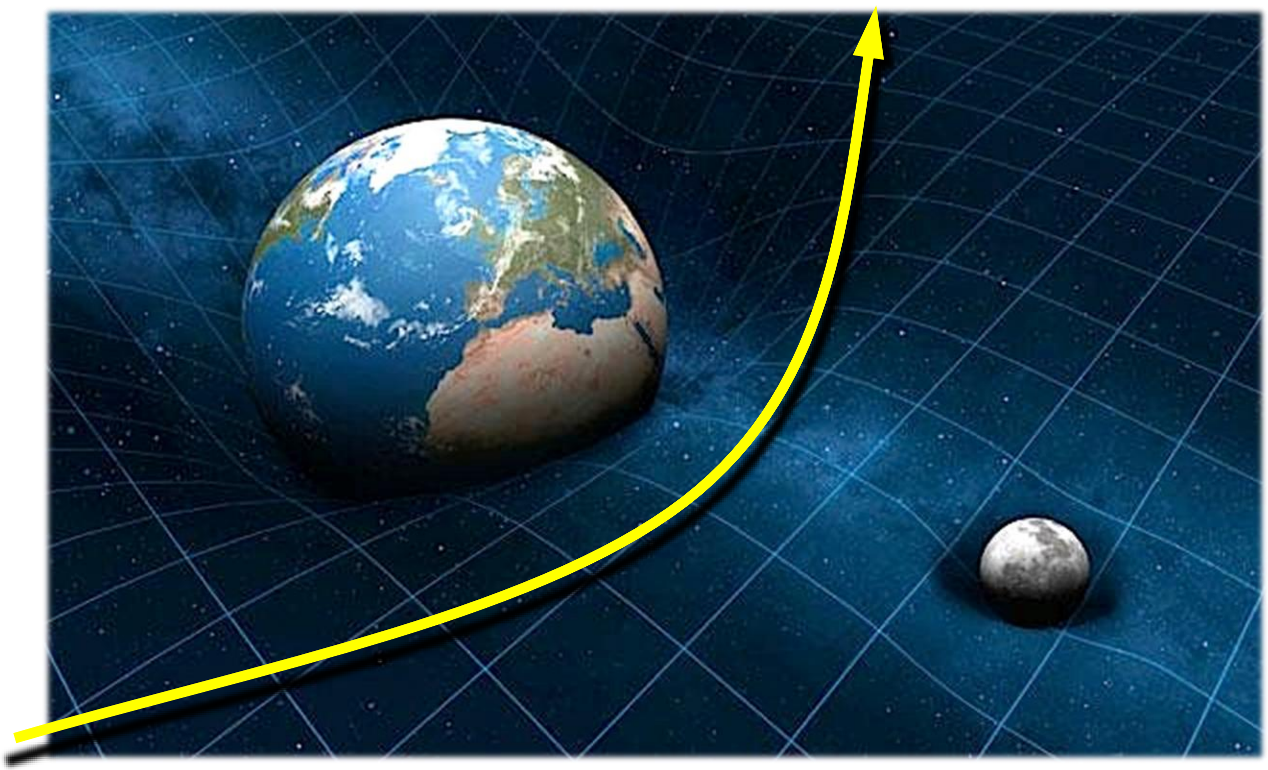


$$R_{\mu\nu} = -\Lambda g_{\mu\nu}$$





Gravity as curvature



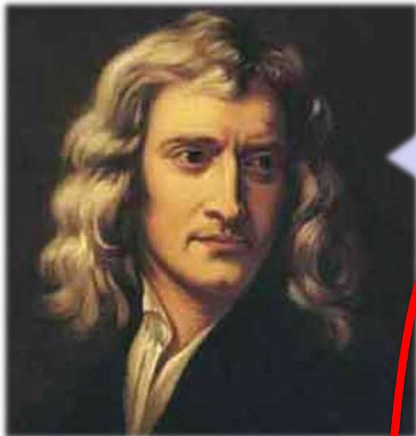
What's wrong with this picture?

Particles follow geodesics in a curved space:

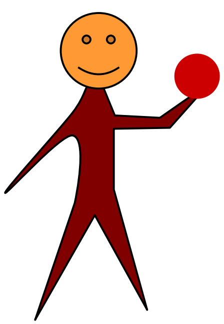
“most straight” (extremal) paths

On Earth, the curvature is small

On a weakly curved space, geodesics are very close to straight lines



Are you telling *me* that this trajectory is **almost straight** and **weakly curved ???**



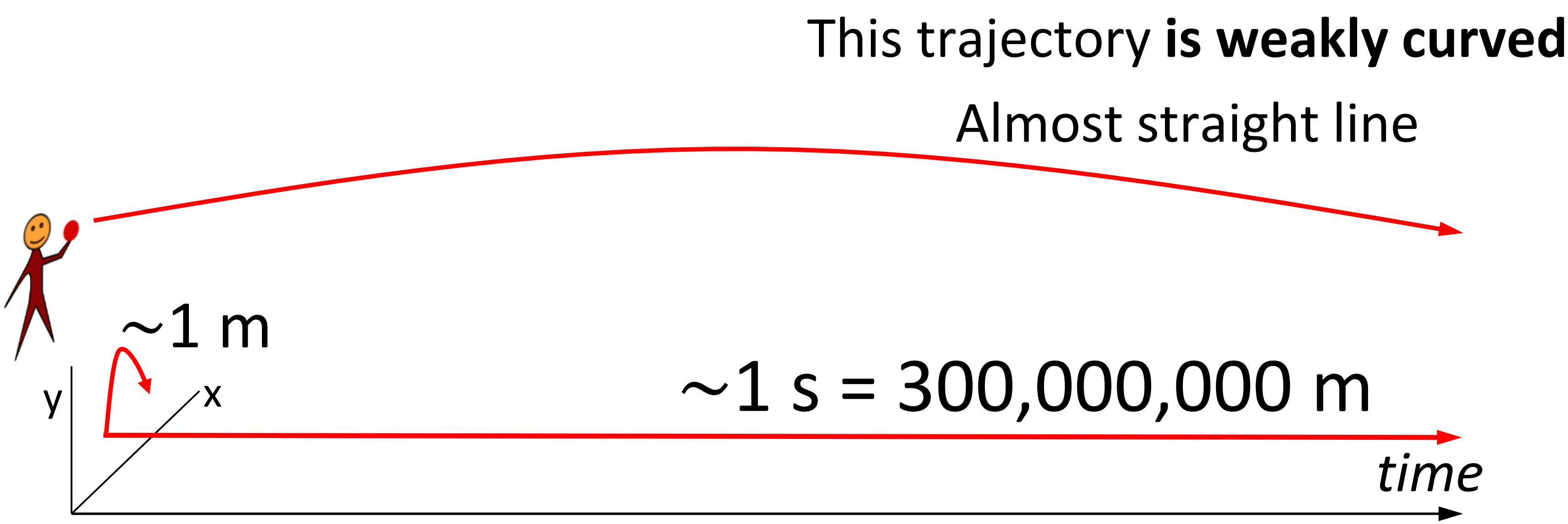
Massive particles follow trajectories in space *and time*

Since c = 300,000 km/s is large, they move **much more in time** than in space

1 s = 300,000,000 m

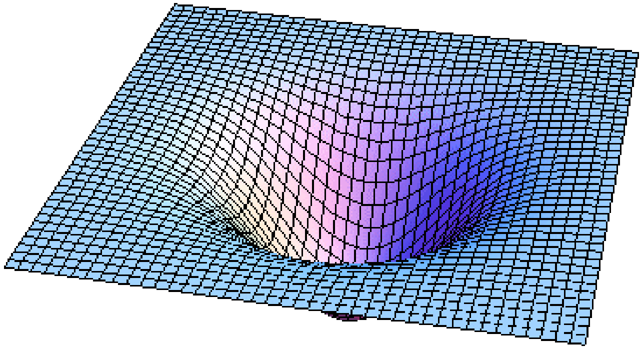
Massive particles follow trajectories in space *and time*

Since c = 300,000 km/s is large, they move **much more in time** than in space



Gravity as curvature

When we represent a gravitational field as

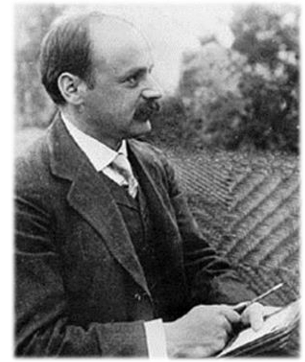


it is to be understood that there is also curvature in the *time* direction

K Schwarzschild to **A Einstein**

letter dated 22 December 1915

from the Russian war front



"I made at once by good luck a search for a full solution. A not too difficult calculation gave the following result:"

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

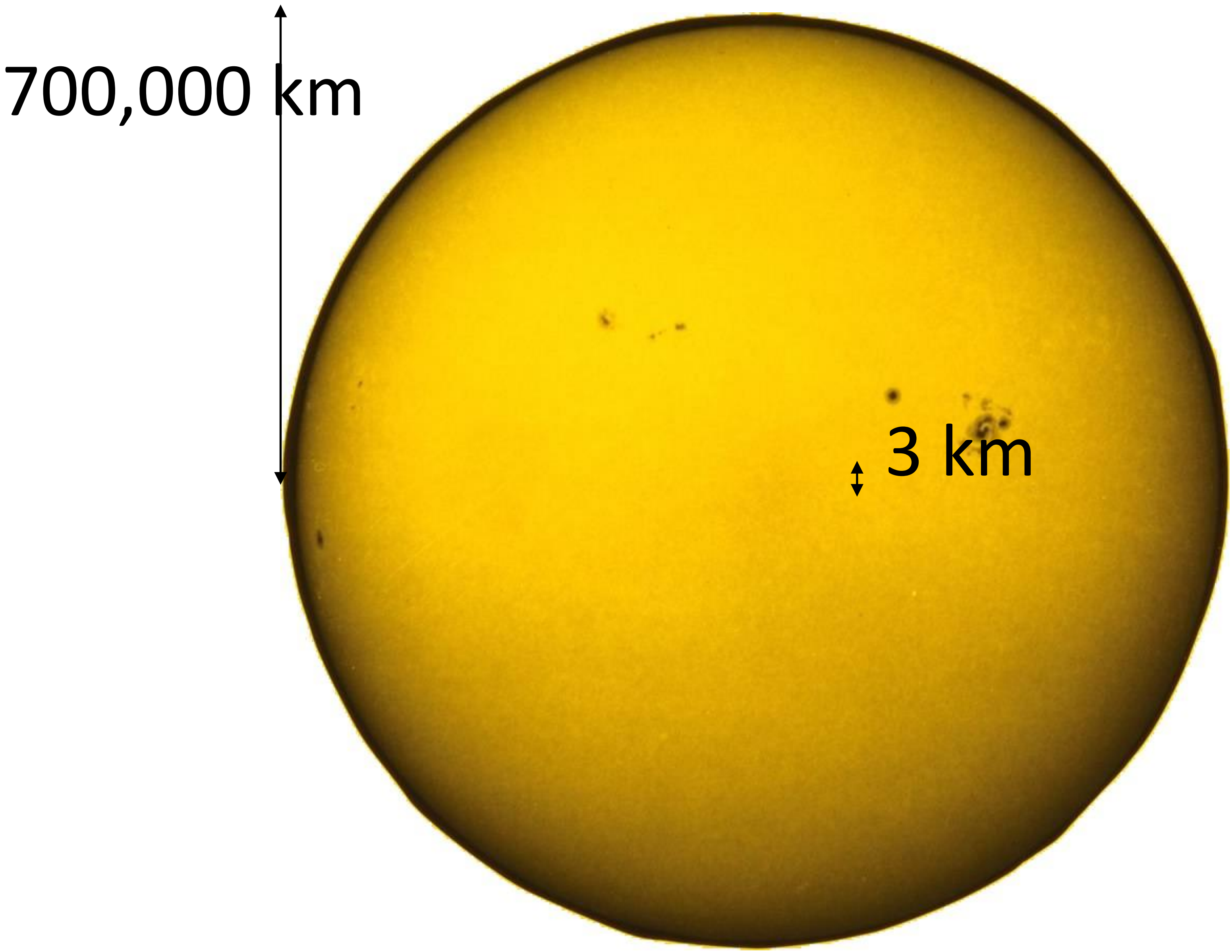
$$ds^2 = -\left(1 - \frac{2GM}{r}\right)dt^2 + \frac{dr^2}{1 - \frac{2GM}{r}} + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

Something odd going on at $r = r_S \equiv 2GM$

"Schwarzschild singularity"

So?

For a star: $r_S \simeq 3\ km$


700,000 km
3 km

That's *way too small*!

Ignore it…

BUT...

Eddington (1924)

found new coordinates that are

not singular at $r = r_S$

(he did not mention this)

Lemaitre (1932-33)

$r = r_S$ just a coordinate singularity

So,

is this physical or not?

Can gravitational collapse shrink a star beyond the "Schwarzschild singularity"?

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY.

Friday, 1935 January 11.

The President then closed the discussion on Nova Herculis, and asked Dr. Chandrasekhar to give an account of his recent investigation of Stellar Configurations.

If the star's mass is greater than $\mathfrak{M}$ the star cannot have a degenerate core, but if the star's mass is less then $\mathfrak{M}$ it will tend, at the end of its life history, towards a completely collapsed state.

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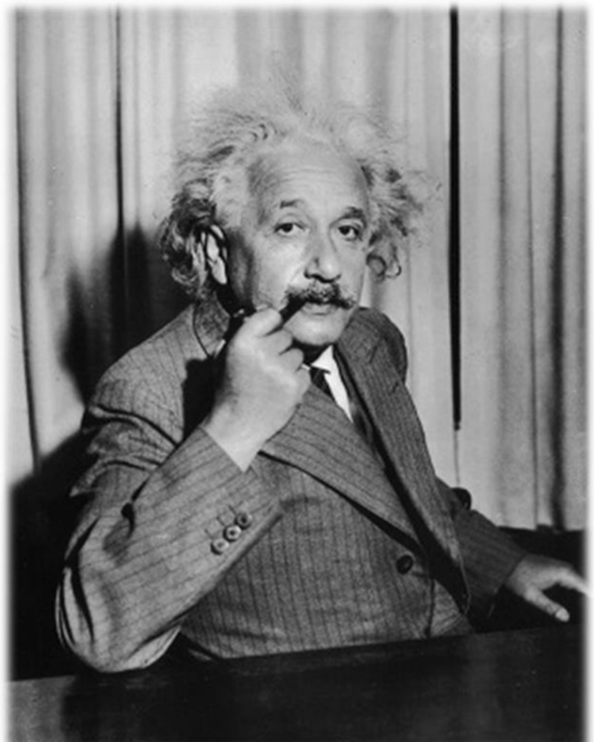
Sir Arthur Eddington.

The star has to go on radiating and radiating and contracting and contracting until, I suppose, it gets down to a few km. radius, when gravity becomes strong enough to hold in the radiation, and the star can at last find peace.

I felt driven to the conclusion that this was almost a *reductio ad absurdum* of the relativistic degeneracy formula. Various accidents may intervene to save the star, but I want more protection than that. I think there should be a law of Nature to prevent a star from behaving in this absurd way!

Ask the master



Einstein's *worst* blunder

He failed to recognize a *most striking* prediction of his theory:

Schwarzschild's solution describes a Black Hole

He even wrote a regrettable, confused paper **denying** the possibility

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.

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

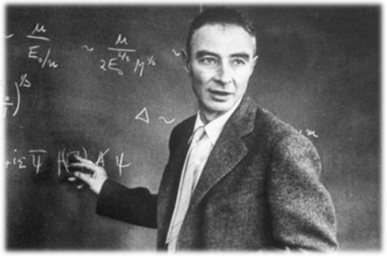
BY ALBERT EINSTEIN

(Received May 10, 1939)

On Continued Gravitational Contraction

J. R. OPPENHEIMER AND H. SNYDER
University of California, Berkeley, California

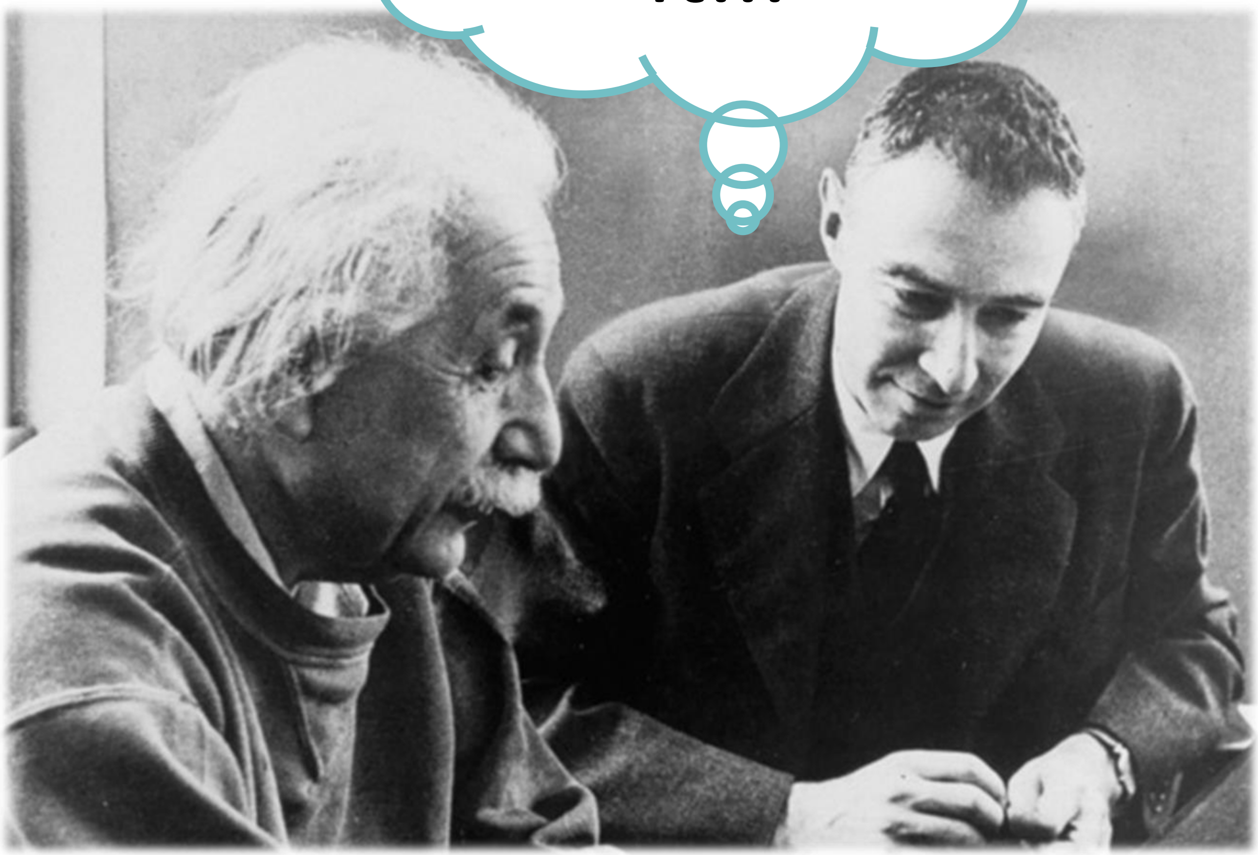
(Received July 10, 1939)



But Einstein never knew about his blunder

Years later,
at IAS...

Let’s not talk about it...



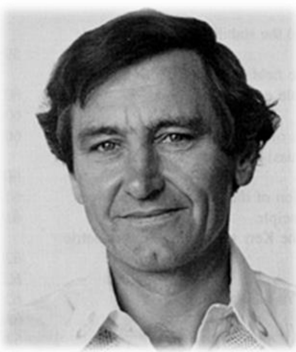
1950's-1960's

JA Wheeler

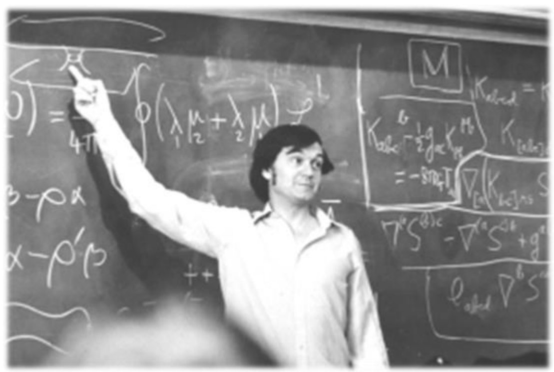
"Schwarzschild singularities"
are physical,
unavoidable consequences
of General Relativity

D Finkelstein

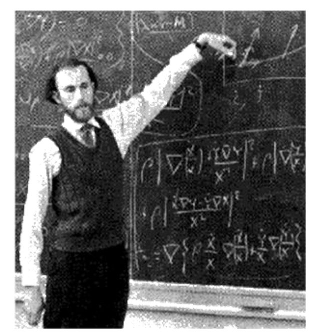
W Israel



R Kerr



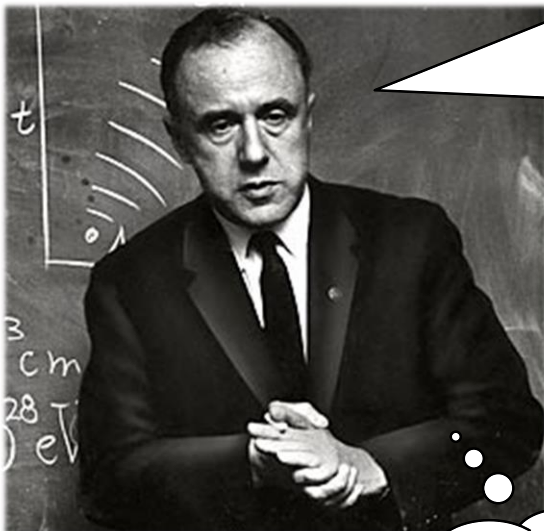
R Penrose



B Carter

Since the baby has survived childbirth
let’s give him a proper name...

JA Wheeler 1967



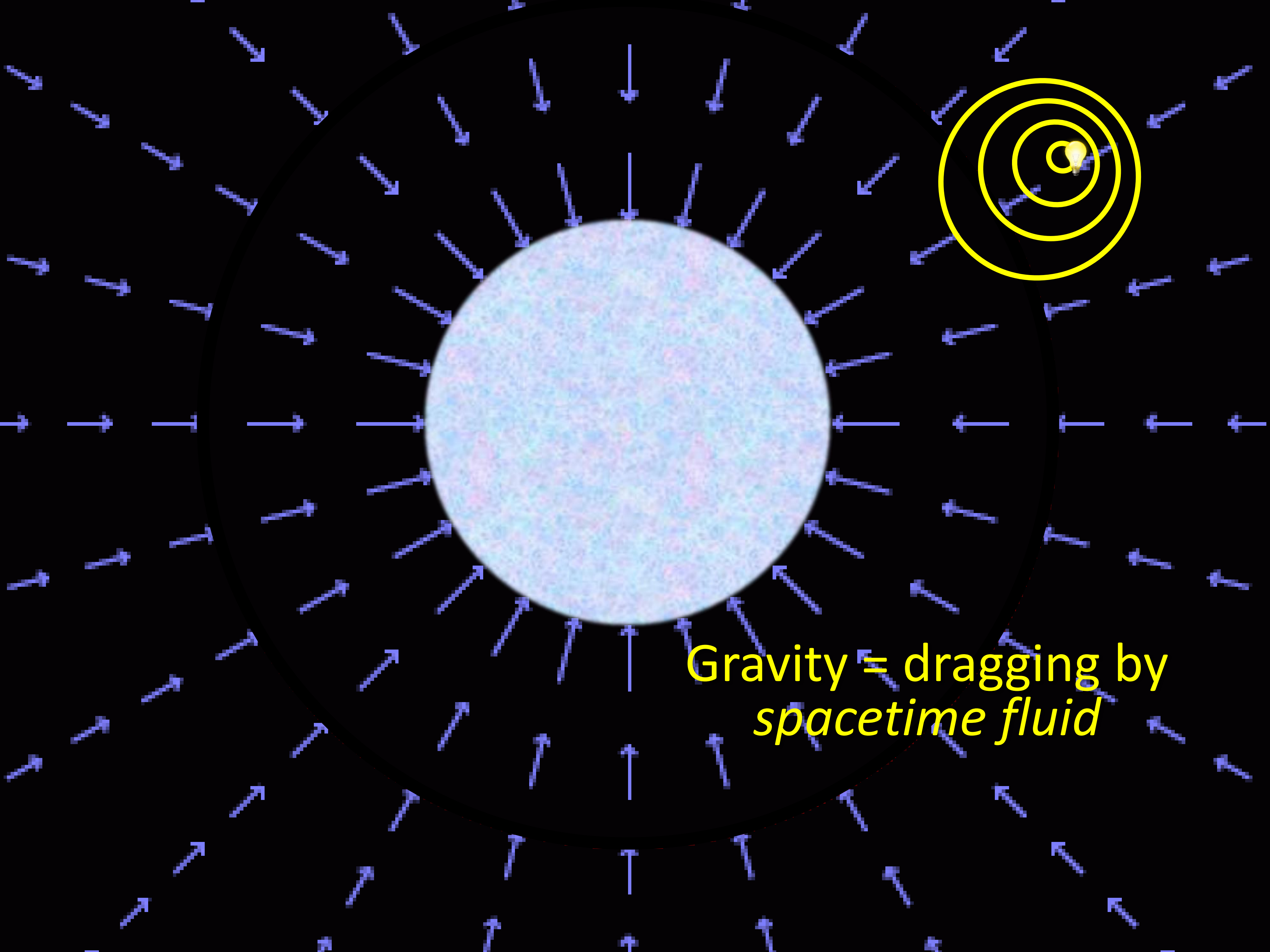
One can’t keep calling it “gravitationally completely collapsed object”…

How about **BLACK HOLE**?

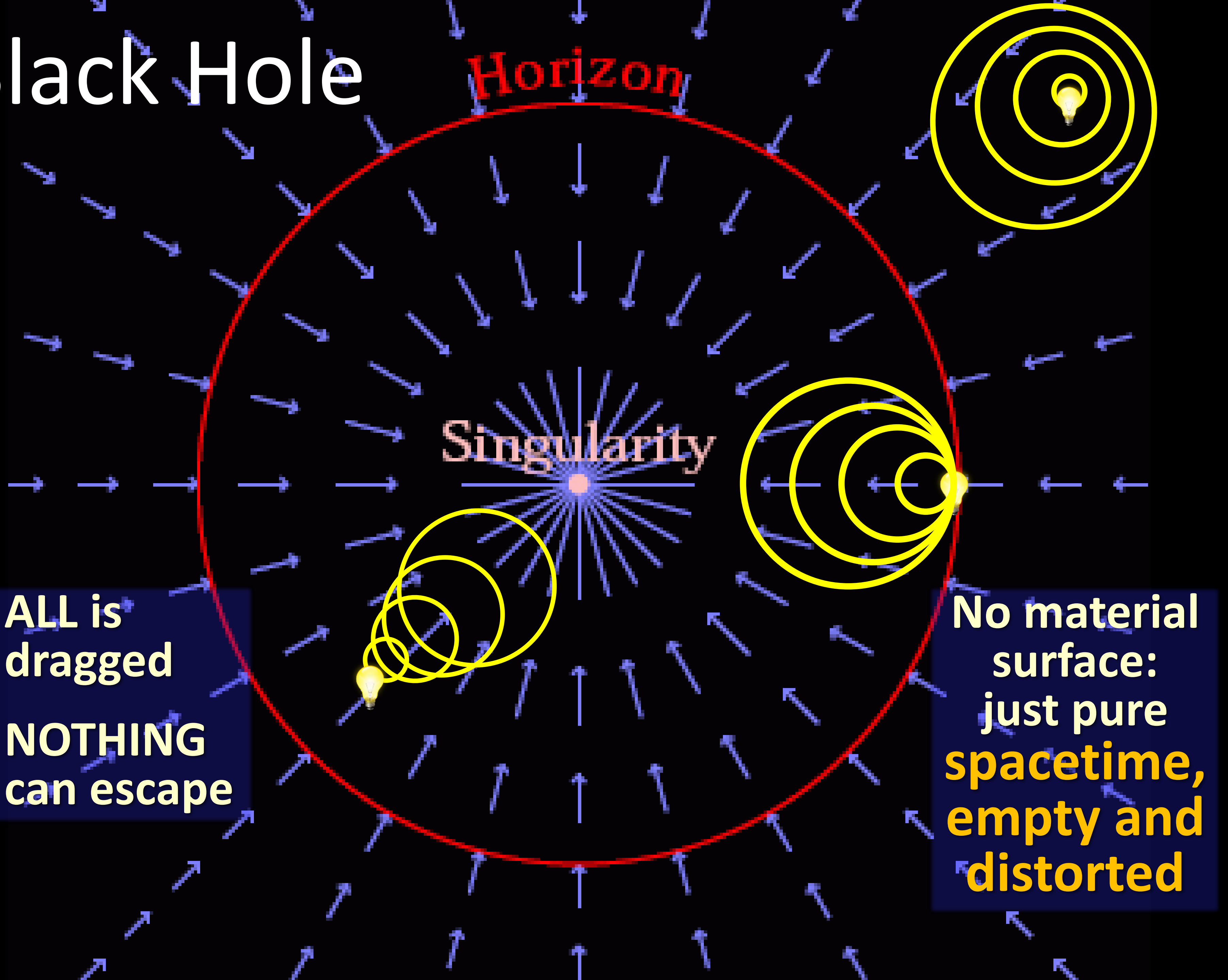
…yes!

That’s an obscene name!

Space and time
flow


Gravity = dragging by
spacetime fluid

Black Hole

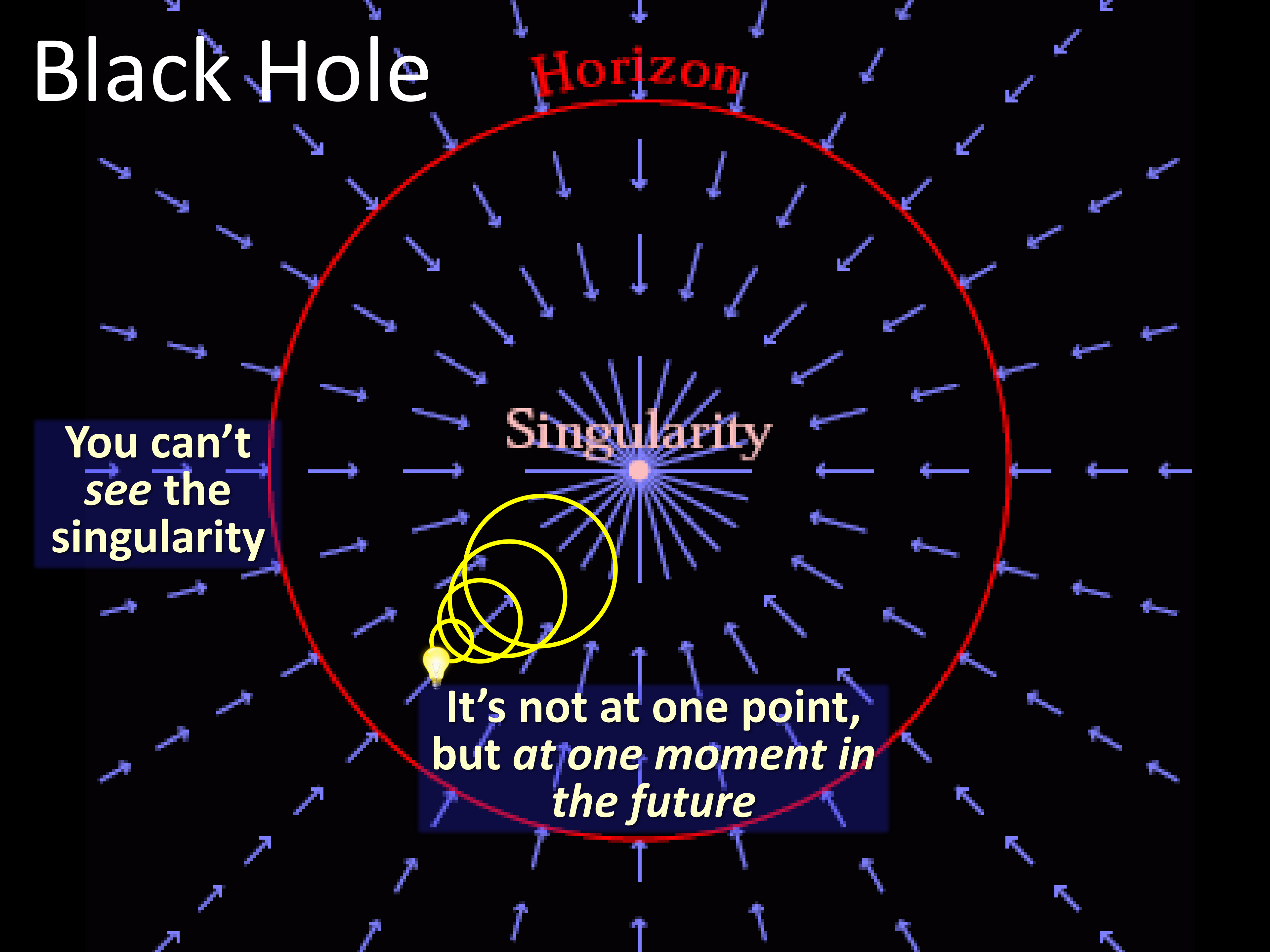


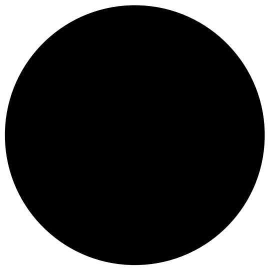
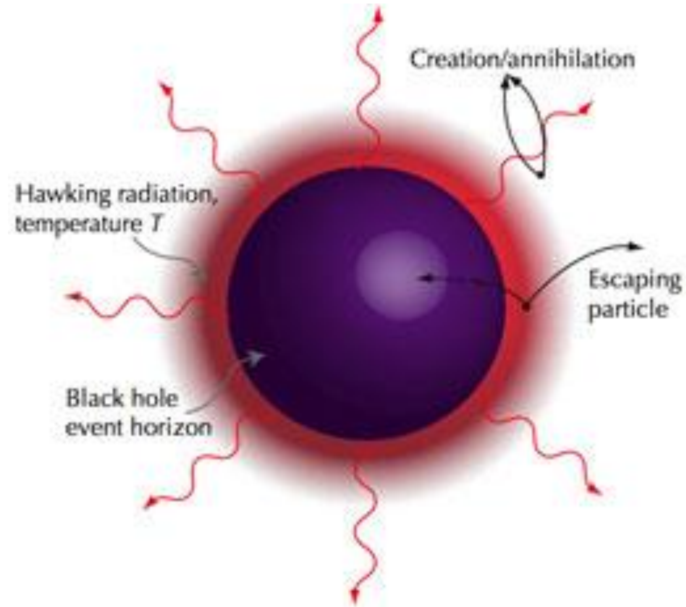
ALL is dragged

NOTHING can escape

No material surface: just pure spacetime, empty and distorted

Black Hole

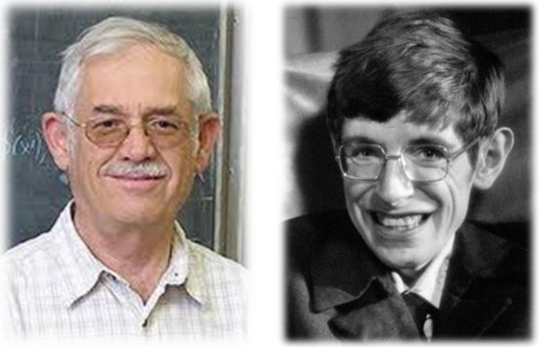

Horizon
Singularity
You can't *see* the singularity
It's not at one point, but *at one moment in the future*

 $+ \hbar \longrightarrow$ 

1974

First equation of Quantum Gravity

$$S_{BH} = \frac{Area}{4G\hbar}$$



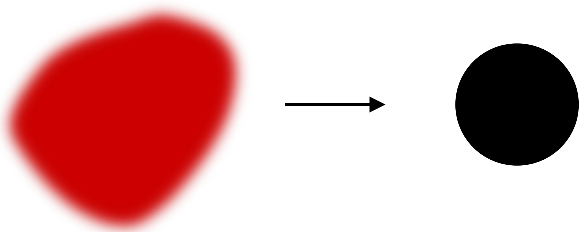
Bekenstein – **H**awking

Black Hole
Information Problem

Hawking 1976

A problem of *fundamental irreversibility*

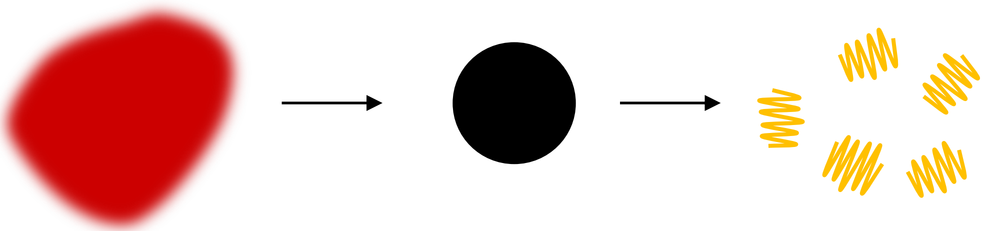
Black holes have no hair



Where does the information about the initial state go?

Maybe it’s still inside the BH...

What about this?



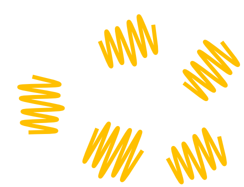
Thermal radiation

Quantum evolution is reversible

Pure state ⇄ Pure state

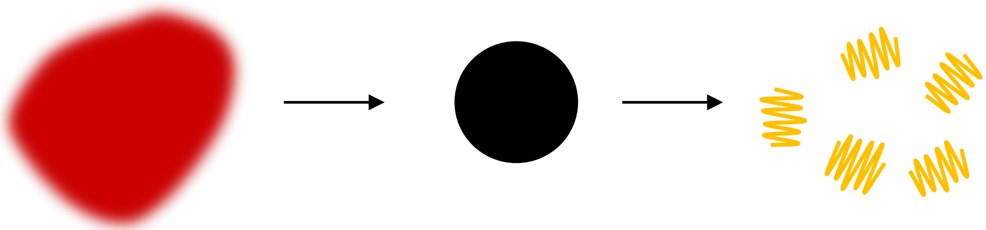
$\Big|$  $\Big\rangle$

$$\underset{U^{-1} = U^{\dagger}}{\overset{U}{\rightleftarrows}}$$

$\Big|$  $\Big\rangle$

Non-Unitary Quantum evolution?

Pure state → Mixed state ?



no hair → no info in radiation

Possibility A

Information is **fundamentally lost**

Yes, Non-unitary evolution in Quantum Gravity

Most of Quantum Field Theory, incl. perturbative Quantum Gravity, remains as usual

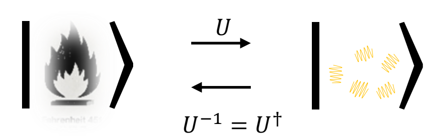
In the presence of bhs, *small subtle* violations of unitarity

We just have to live with this

Possibility B

Information is **not lost**

Quantum mechanics is extremely difficult to modify in a consistent manner

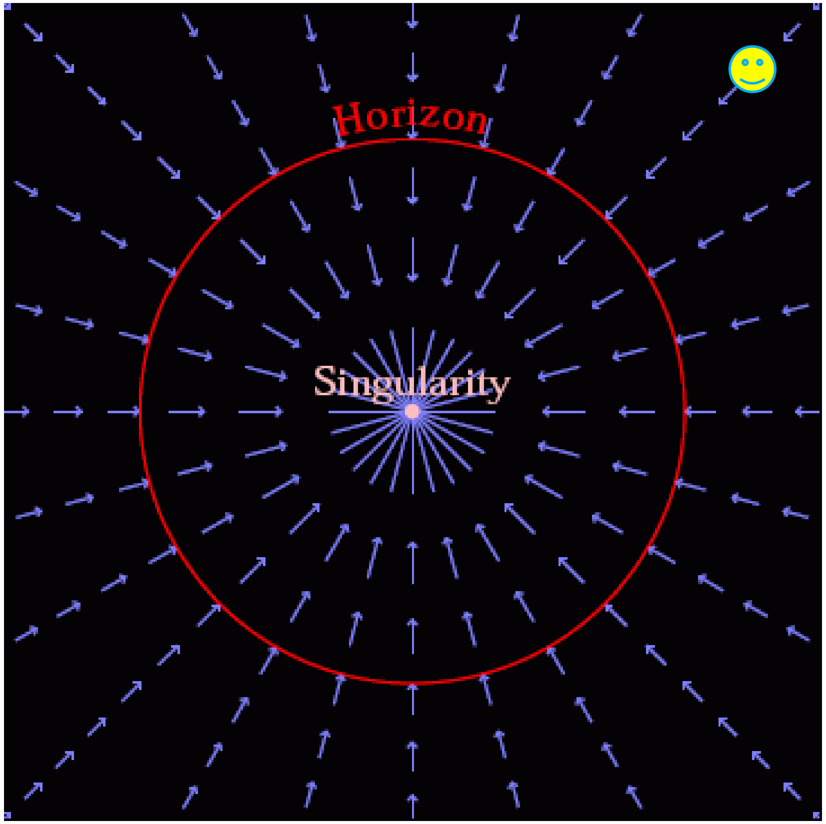
Info must be retrievable outside bh and after evaporation, much like 

But how? Info that has fallen inside the bh can't be cloned outside

Firewall argument – simplified version

Almheiri+Marolf+Polchinski+Sully

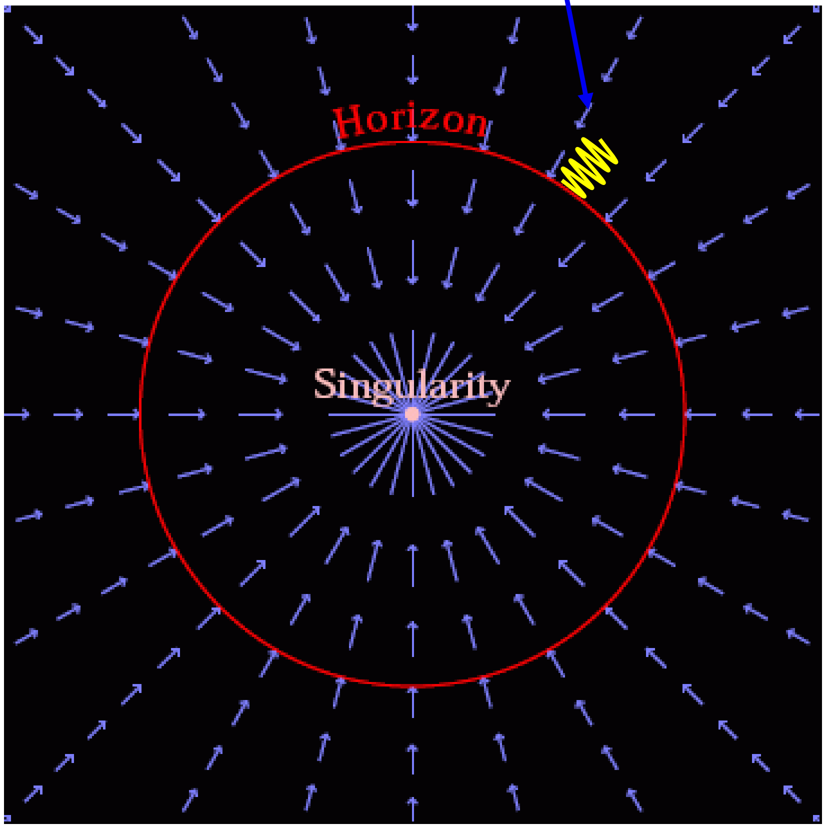
1. An observer in free-fall would not feel anything special when crossing the horizon



Firewall argument – simplified version

2. **If the information** about what formed the black hole **is not lost** in the interior, then it must somehow be outside the horizon
3. Storing information requires energy
4. Hence information gravitates and tends to fall into the black hole
5. To keep it outside requires applying a huge force
6. Huge force is like a 'firewall' outside the horizon
7. An observer in free fall would not perceive the horizon as a smooth place
8. **GR breaks down at places of very low curvature**

Photon carrying 1 bit

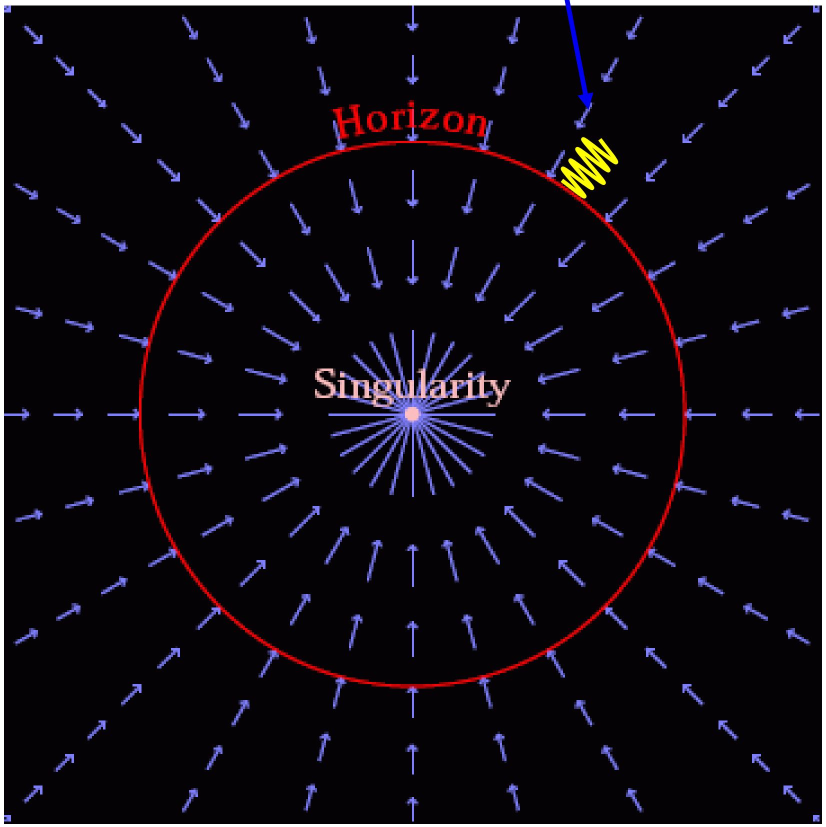


Firewall argument – simplified version

2. **If the information**

   is not lost

Photon carrying 1 bit



8. **GR breaks down at places of very low curvature**

So, black holes
don’t exist, after all?

A possible way out

Papadodimas+Raju

Operators describing the interior of the black hole are a highly-scrambled combination of operators that describe the exterior

The interior of the bh does not exist at a fundamental level, but it can be an extremely good effective description for certain macroscopic observers

It’s quintessentially a theorist’s conundrum

Even if LHC had been churning out
10^7 bhs/year, extremely hard to decide the
problem experimentally

But it remains as a problem of principle
and a very confusing one

Is it leading anywhere, or just a waste of time?

This problem is an old chestnut.

Proposed in 1976, largely ignored in the 1980's.

Brought to fore in the early 1990's

Led to intense activity to understand bhs in string theory

Problem was not solved, but had fruitful spinoffs:

- BH entropy from microscopic stat-mech
- AdS/CFT and holography

2012-2015: disagreement among parties remains significant

But once again, the debate has sparked fruitful progress in other directions

This time by emphasizing the role of concepts from quantum information

Quantum Entanglement

and

Spacetime Geometry

One can convincingly argue that the existence of black holes with thermodynamic properties leads to Holography

Physics at the highest energy densities is dominated by black holes,

with a degeneracy of states $\propto$ Area (***not*** $\propto$ Vol)

Quantum Gravity described by fundamental degrees of freedom on the boundary of spacetime

This insight is not dependent on String Theory

Lower-dimensional quantum field theory $\Rightarrow$ higher-dimensional theory of quantum gravity

QFT at boundary$_D$ $\rightarrow$ QG in bulk$_{D+1}$

Extra dimension is emergent: not directly visible in field theory

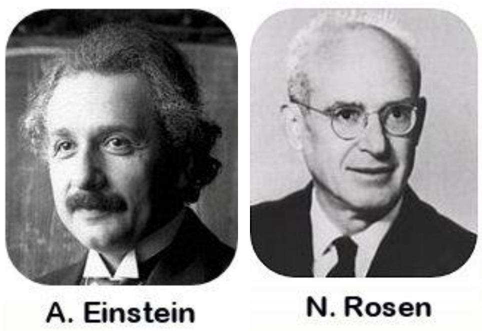
Qualitatively, it corresponds to the energy scale of field theory

QFT magnitudes must have a gravitational counterpart

– in some cases in terms of classical geometry (not necessarily simple)

Quantum entanglement seems to admit simple geometric counterparts

ER = EPR



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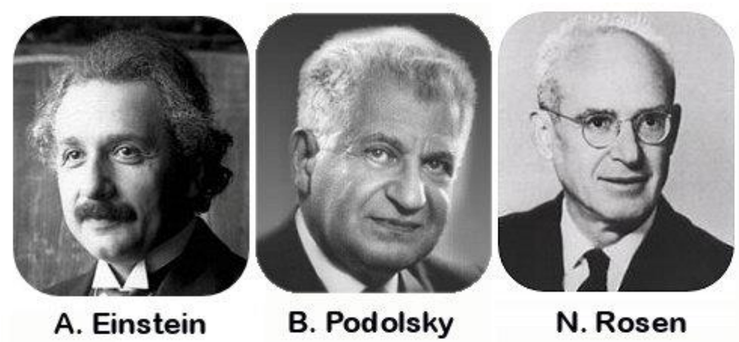
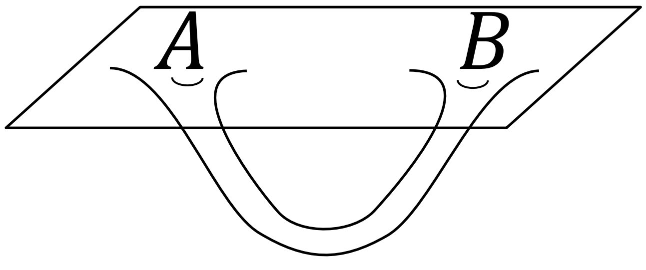


Maldacena+Susskind 2013

A **non-traversable** (ER) **wormhole** is a geometric encoding of EPR-type quantum correlations

EPR-type quantum correlations are quantum-gravity wormholes

$$\frac{1}{\sqrt{2}}(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B) \Leftrightarrow$$



Bell pair

Wormhole

EPR pairs (Bell states)

describe spatially-separated entangled states

cannot be used to send superluminal information

can be formed by pair-creation (Schwinger)

ER wormholes

describe spatially-separated regions

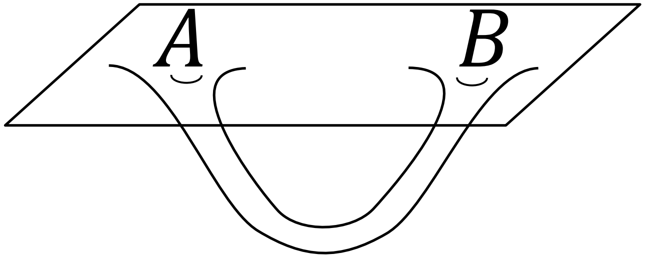
cannot be crossed by timelike trajectories

can be formed through pair-creation (eg of black holes)

Few Bell pairs = highly quantum wormhole

Many Bell pairs = (semi)classical wormhole

$$\frac{1}{\sqrt{2}}(|0\rangle_A|0\rangle_B + |1\rangle_A|1\rangle_B) \Leftrightarrow$$



Bell pair

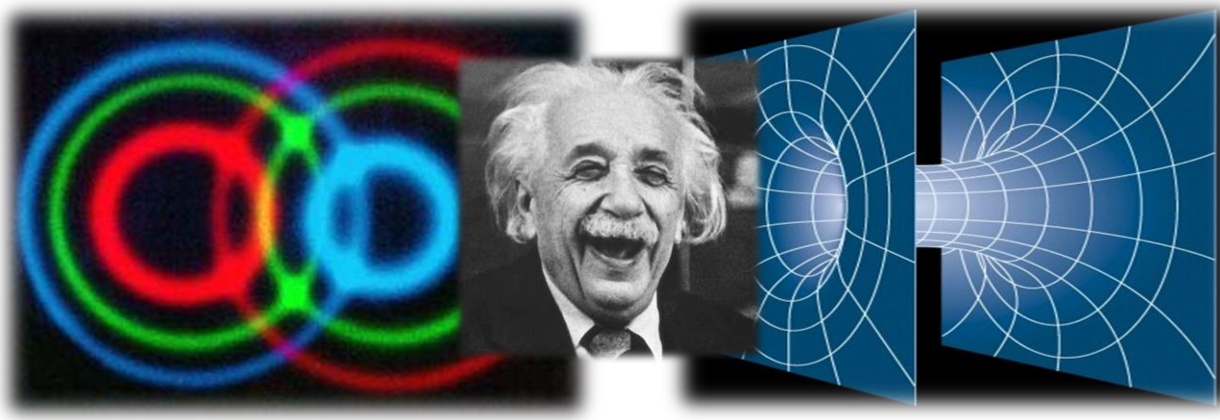
Wormhole

A spacetime is a geometric way of encoding quantum correlations organized by scale

Einstein understood the fundamental importance of both:

spacetime geometry (1915)

quantum entanglement (1935)



Time to merge them?

Questions?