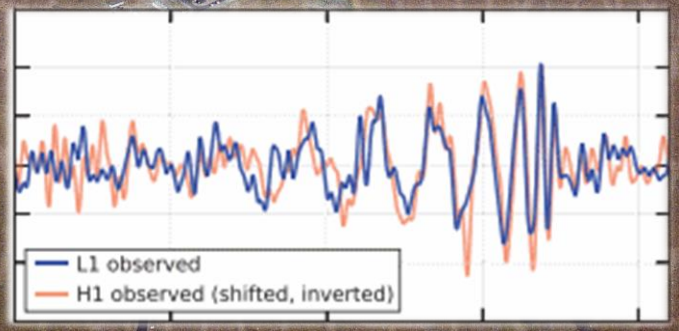
Heart of Darkness

:

Black Holes @ 100

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

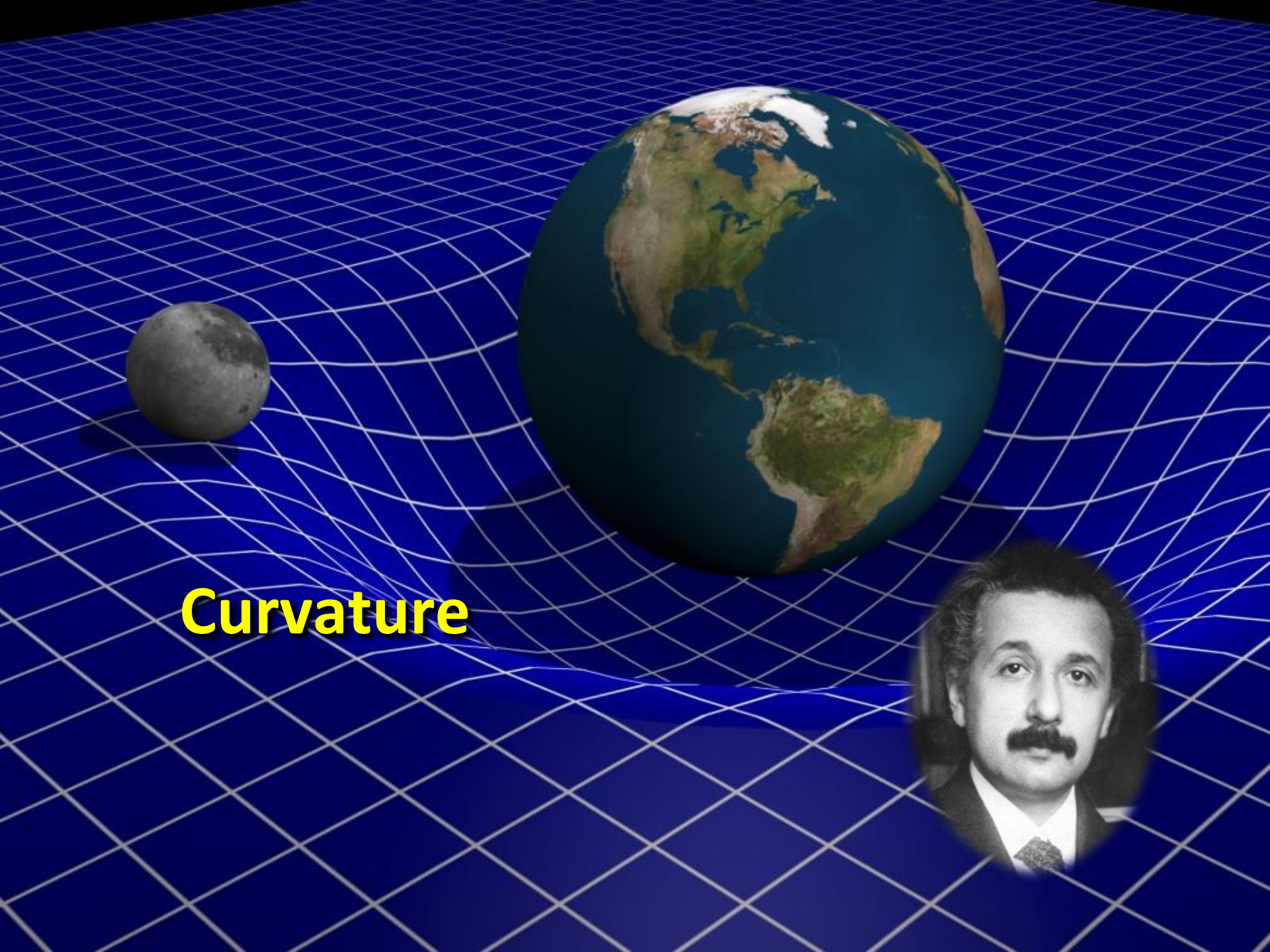


One cannot escape the feeling that these mathematical formulae have ... an intelligence of their own, that they are wiser than we are,

wiser even than their discoverers

Heinrich Hertz

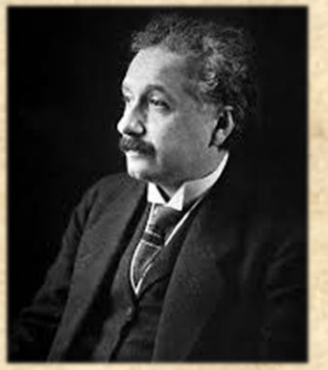
Force of gravity


Curvature

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:"

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

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

Something odd going on at $r = r_S \equiv \frac{2GM}{c^2}$

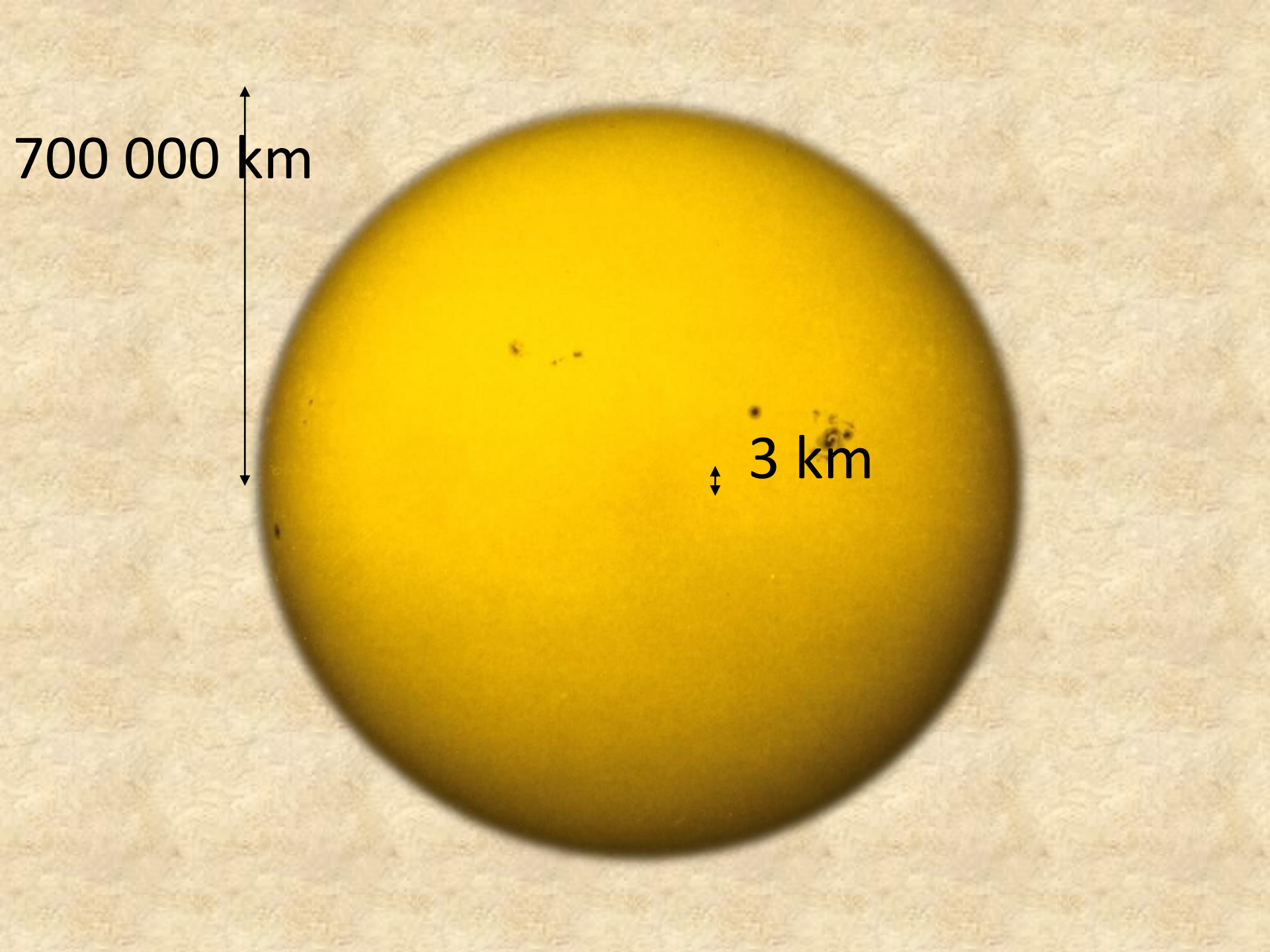
"Schwarzschild singularity"

(do not confuse with singularity at $r = 0$)

So?

For stellar-mass objects:

$$r_S = \frac{2GM}{c^2} \simeq 3\ km$$


700 000 km
3 km

That’s *way too small*!

Ignore it…

BUT...

Lemaître (1932-33)

$r = r_S$ is an apparent singularity, not real

much like the origin of polar coordinates

BUT...

Lemaître (1932-33)

$r = r_S$ is an apparent singularity, not real

much like the origin of polar coordinates

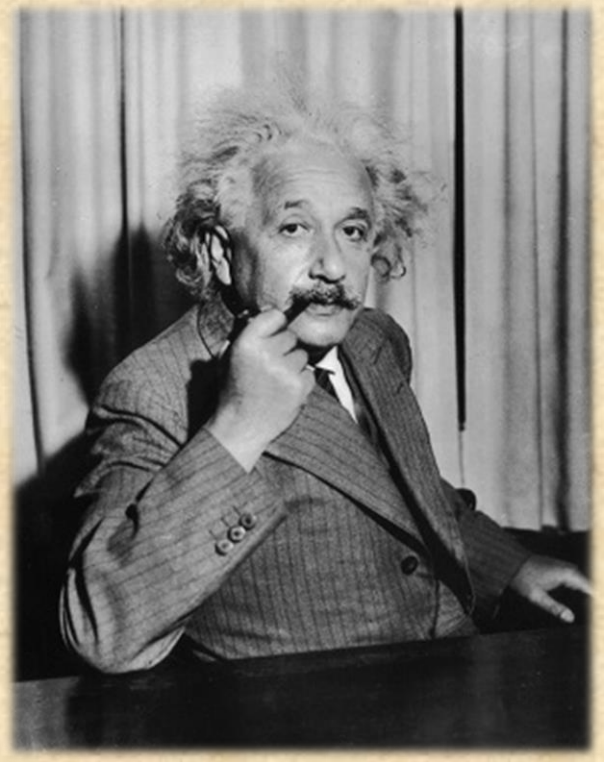
... published in a *Belgian journal*

So,

is this physical or not?

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

Ask the master



Einstein's *worst* blunder

He was blind to the *most striking* prediction of his theory:

Schwarzschild's solution describes a Black Hole

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

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On Continued Gravitational Contraction

J. R. Oppenheimer and H. Snyder
University of California, Berkeley, California

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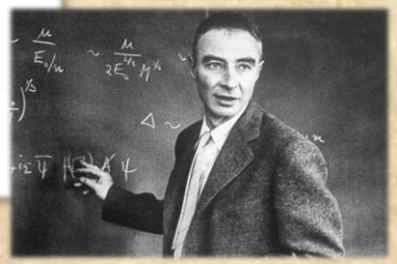

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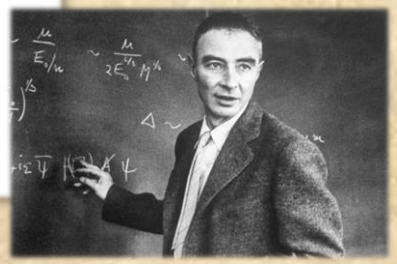

A star ***can*** collapse and shrink beyond $r = r_s = \frac{2GM}{c^2}$

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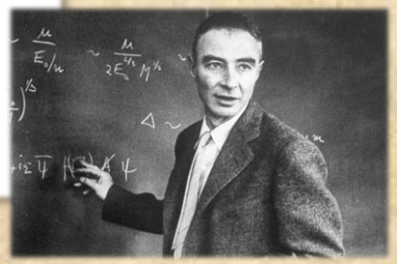


Einstein got it wrong

But he never knew about it

One cannot escape the feeling that these mathematical formulae have ... an intelligence of their own, that they are wiser than we are,

wiser even than their discoverers

Heinrich Hertz

Years later, at Princeton...

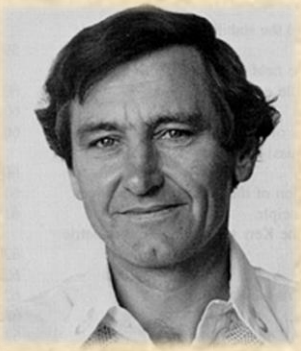
1950's-1960's

JA Wheeler

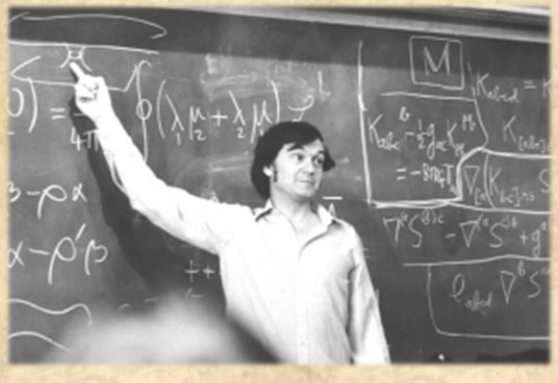
"Schwarzschild singularities" are physical, unavoidable consequences of General Relativity

D Finkelstein

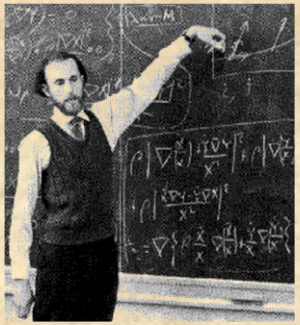
W Israel



R Kerr

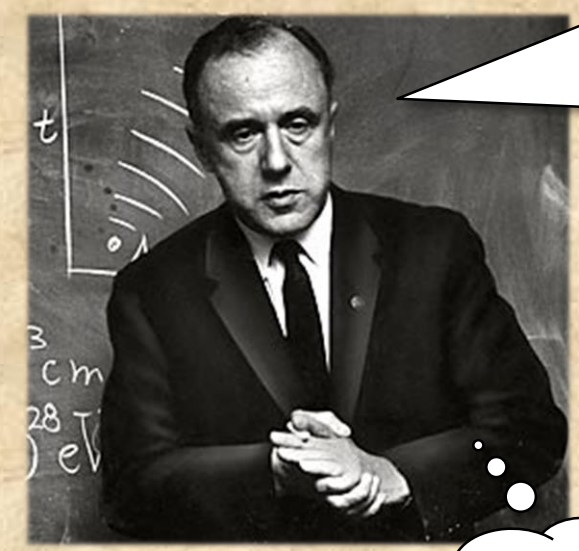


R Penrose



B Carter

JA Wheeler
1967



One can't keep calling it "gravitationally completely collapsed object"…

How about **BLACK HOLE**?

…yes!

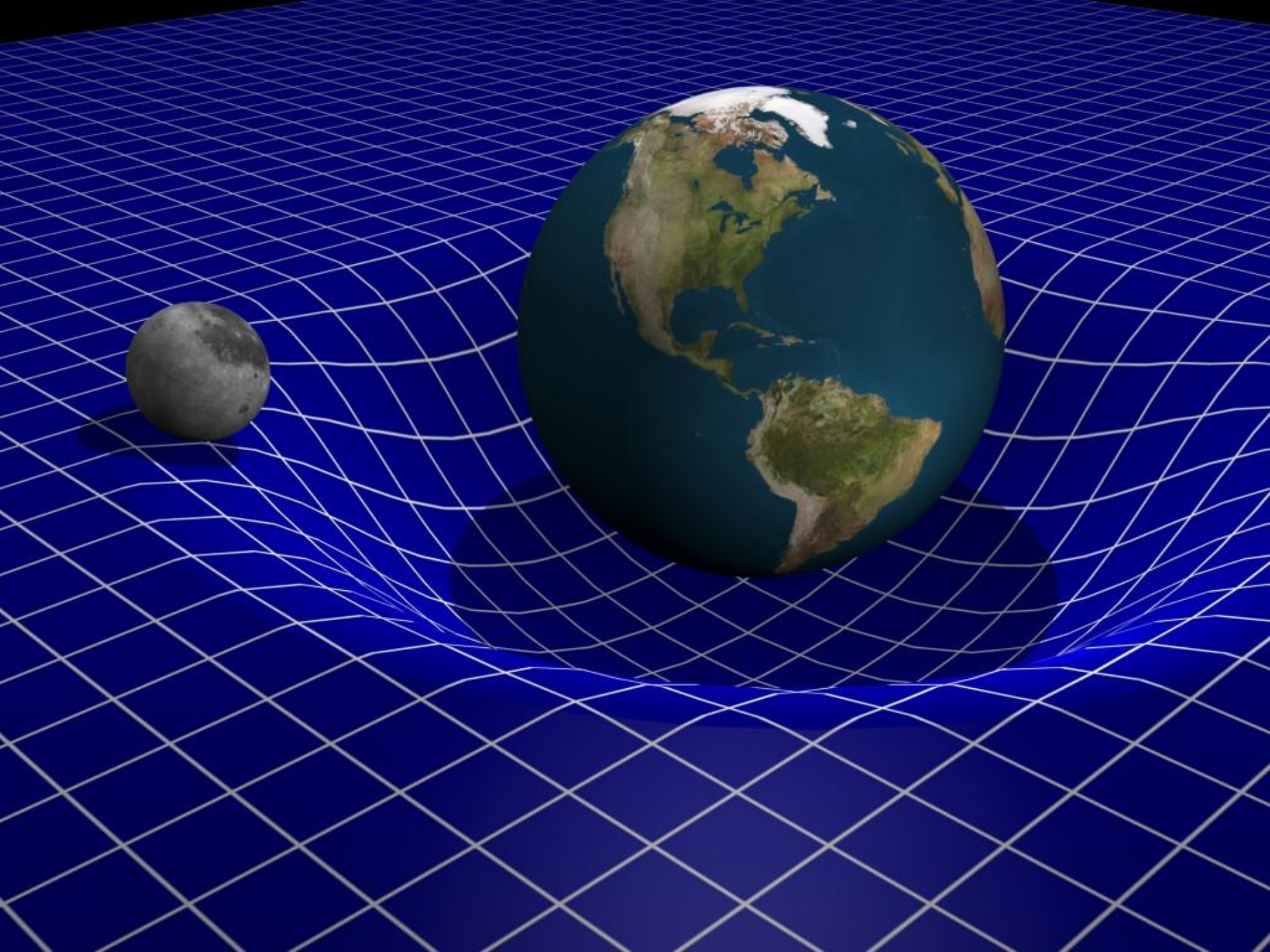
That's an obscene name!

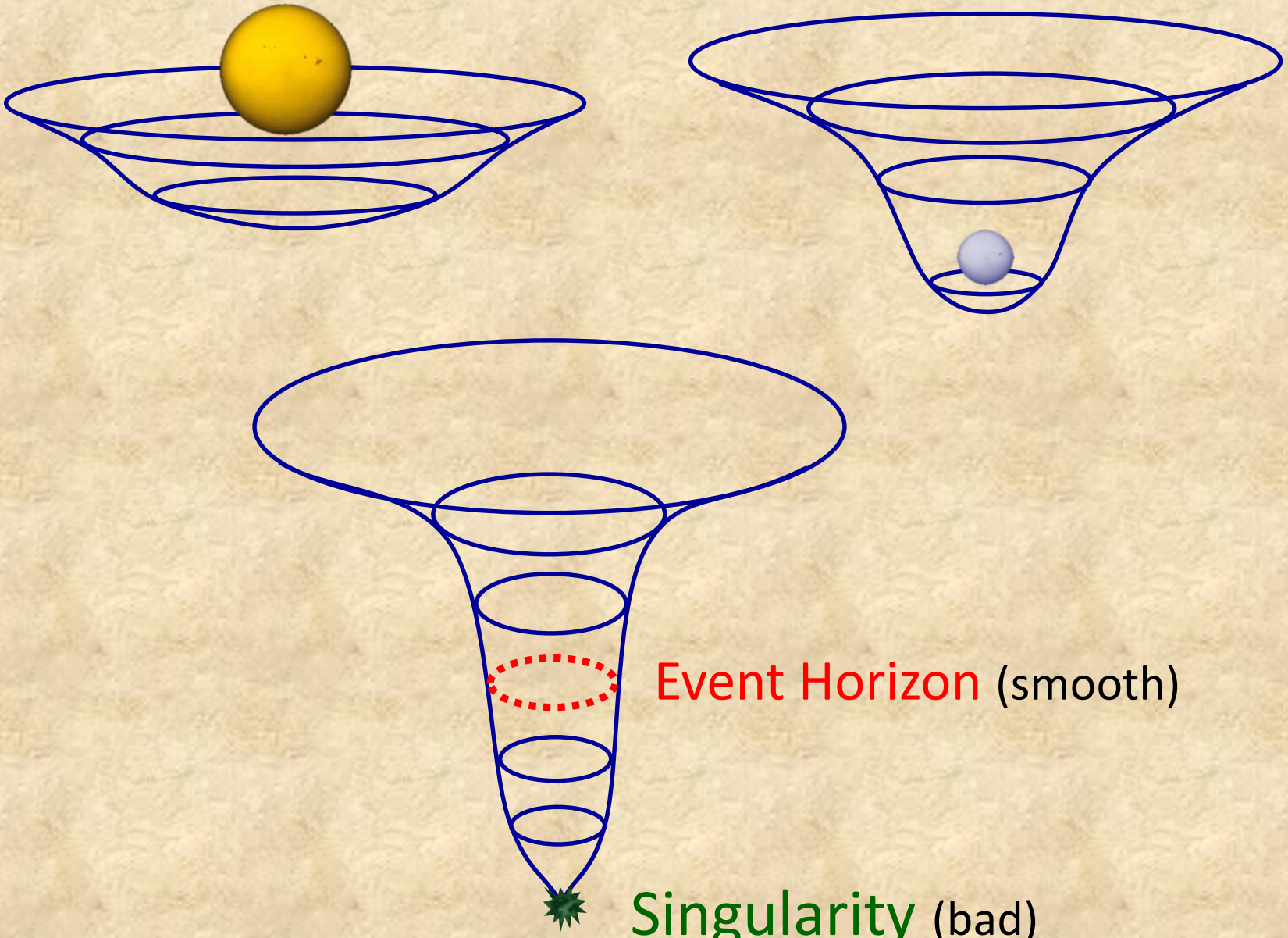
But…

What is a Black Hole?

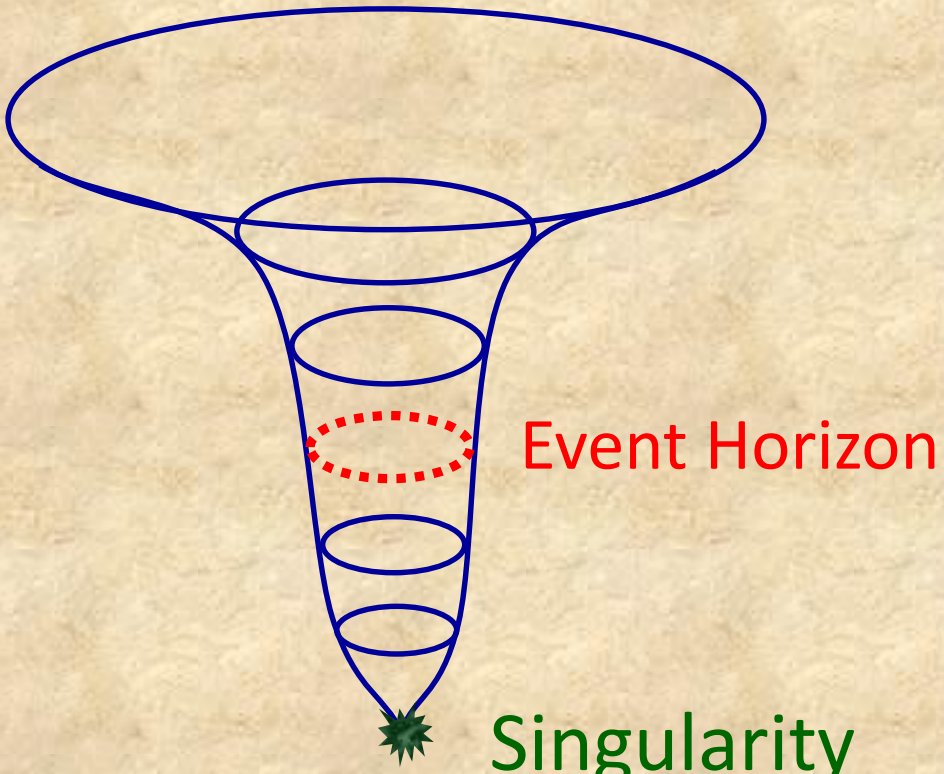
What is a Black Hole?

1. Rubber sheet version




Event Horizon (smooth)
Singularity (bad)

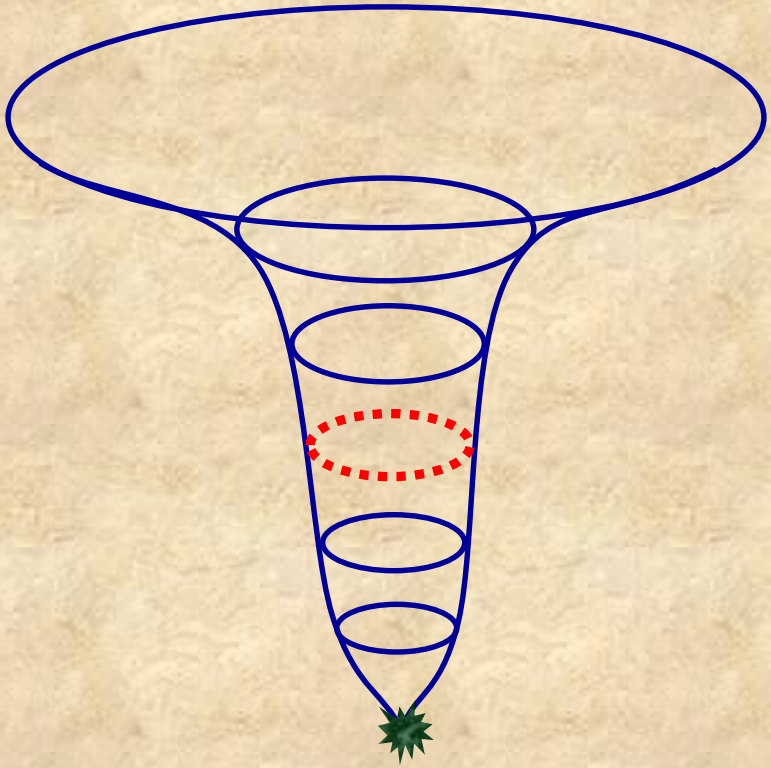
Light cannot escape the
event horizon



There is no matter:

it's been annihilated at the **singularity**

Only **curved spacetime** remains



What is a Black Hole?

2. Spacetime sink version

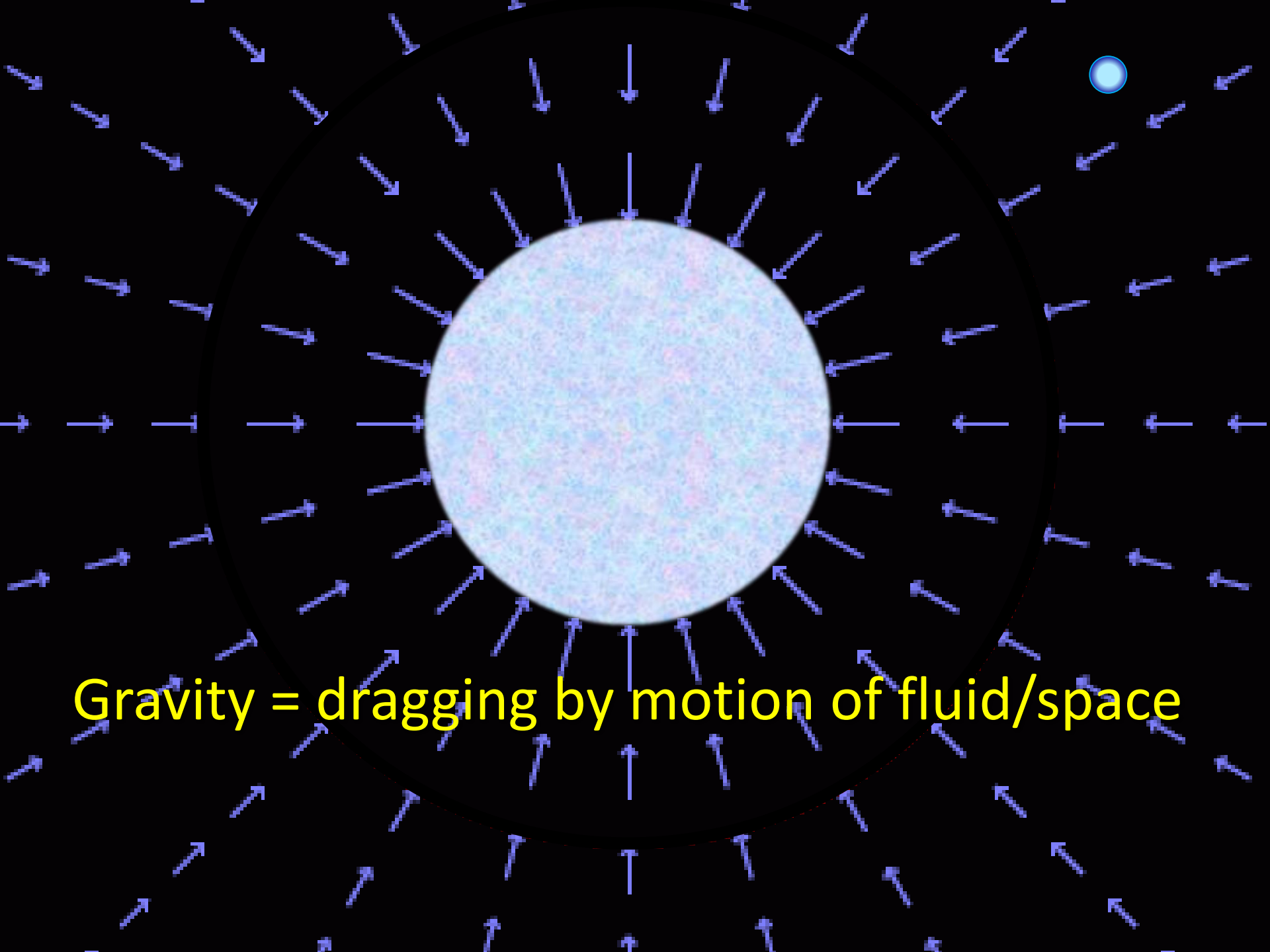
Gravity as spacetime **fluid** in motion

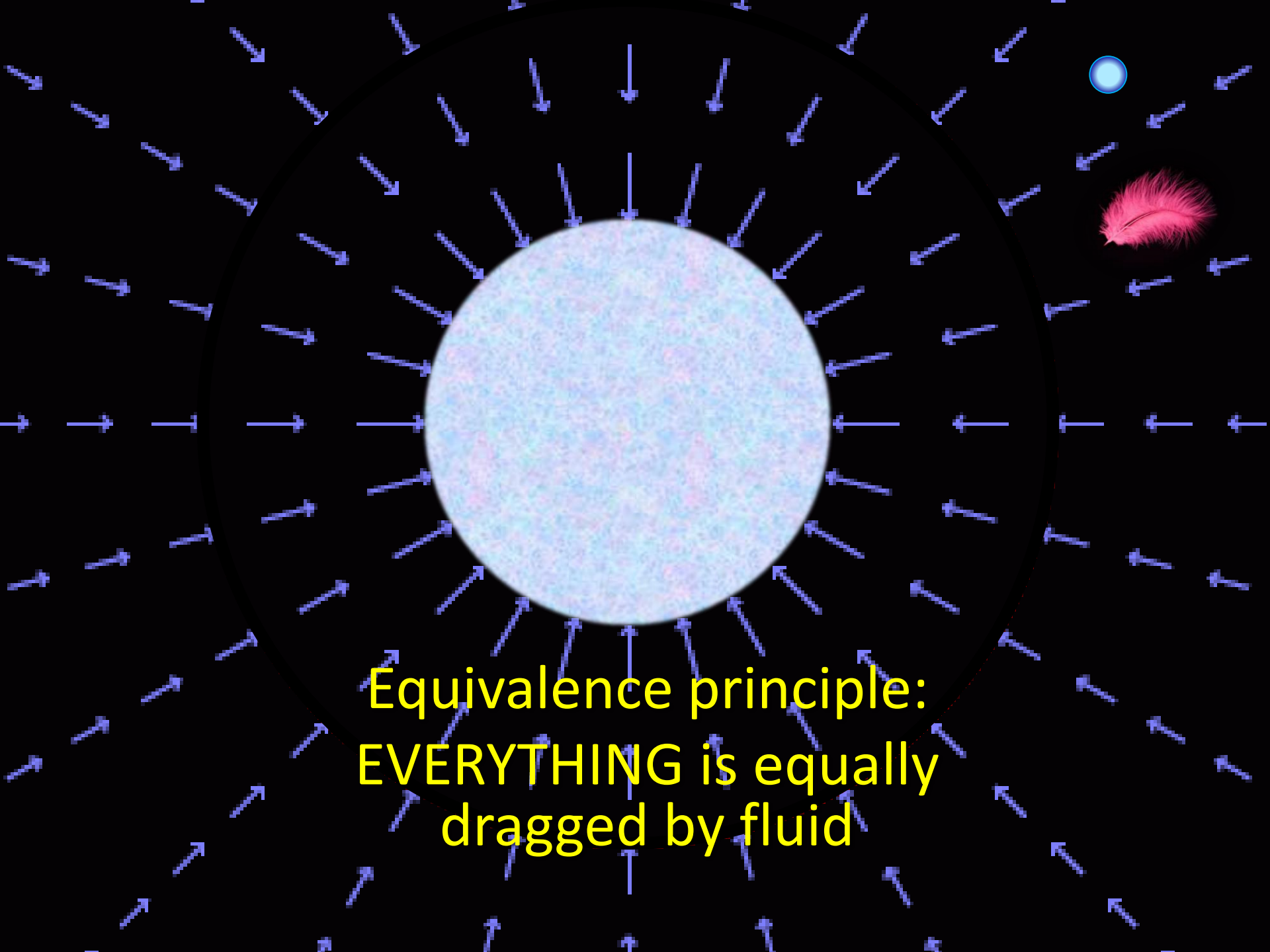
The river of life

Space moves like a fluid

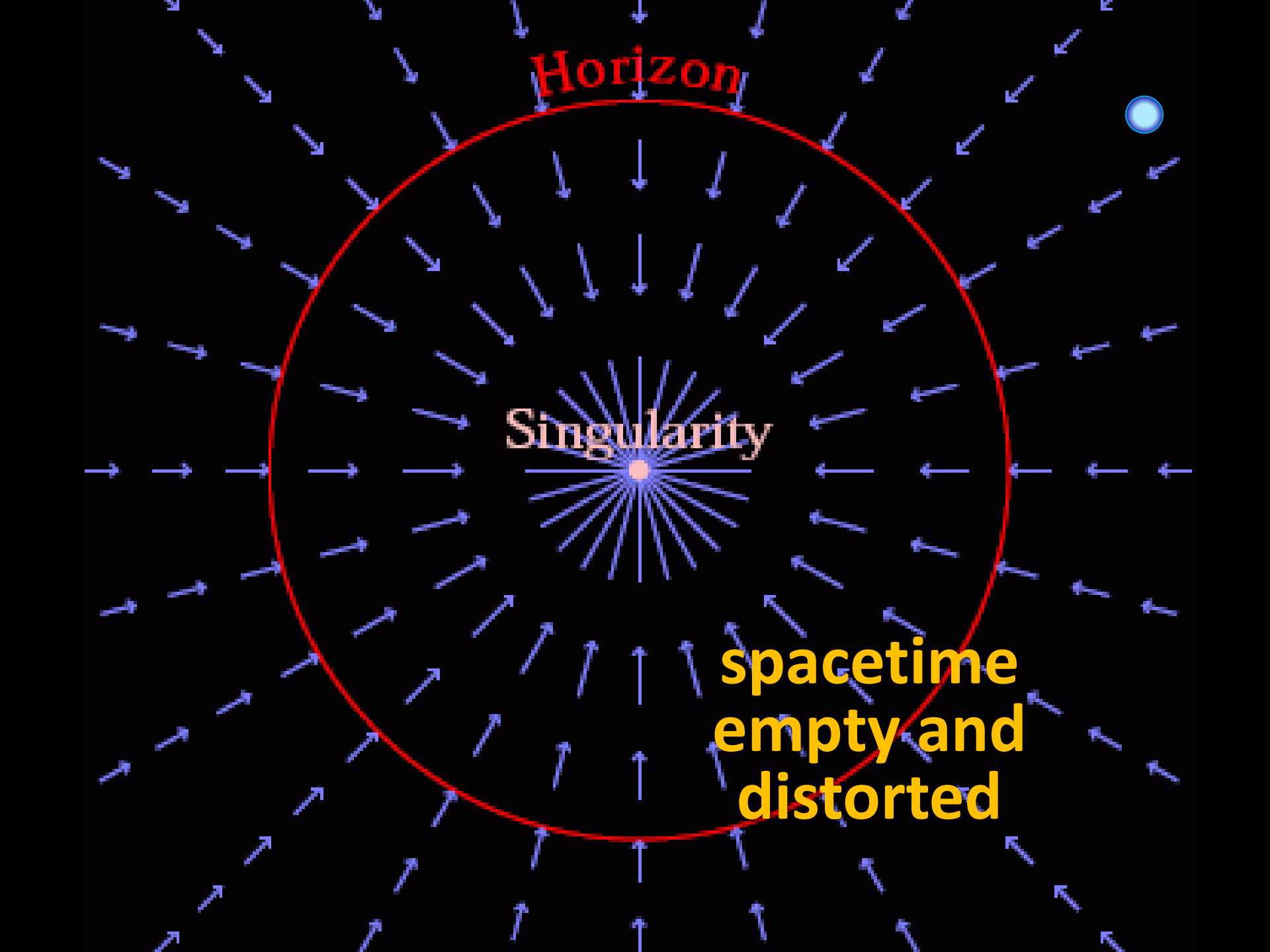
Points in the fluid move relative to each other

A freely falling (inertial) body moves along with the flow


Gravity = dragging by motion of fluid/space


Equivalence principle:
EVERYTHING is equally
dragged by fluid

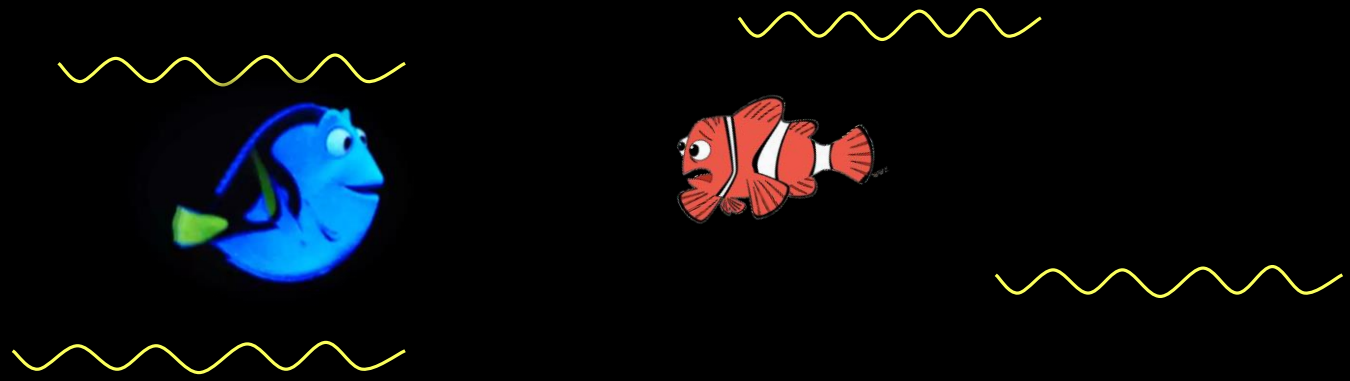

...what does remain?
The star collapses...


Horizon
Singularity
spacetime
empty and
distorted

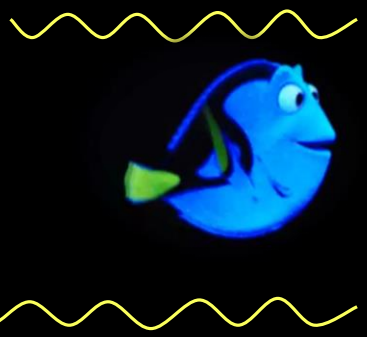
What is the horizon?

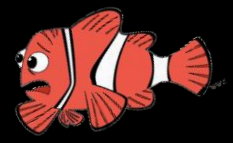
Why can nothing escape?

Communication in water

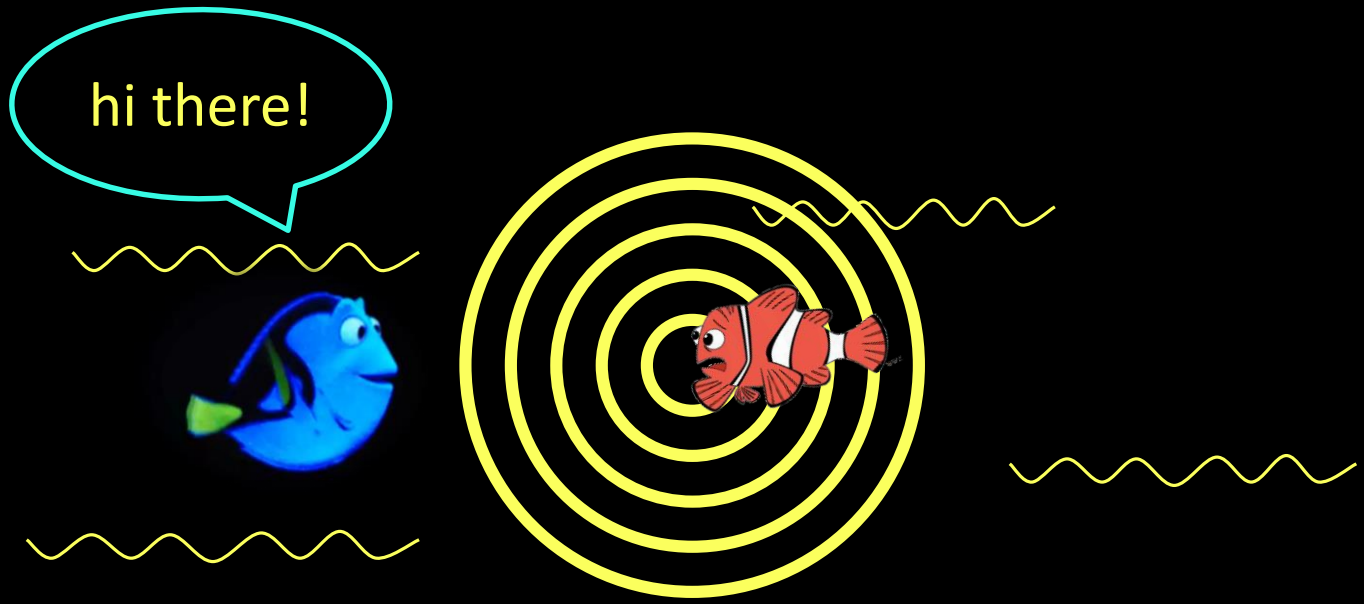


No signal can travel faster than the speed of sound



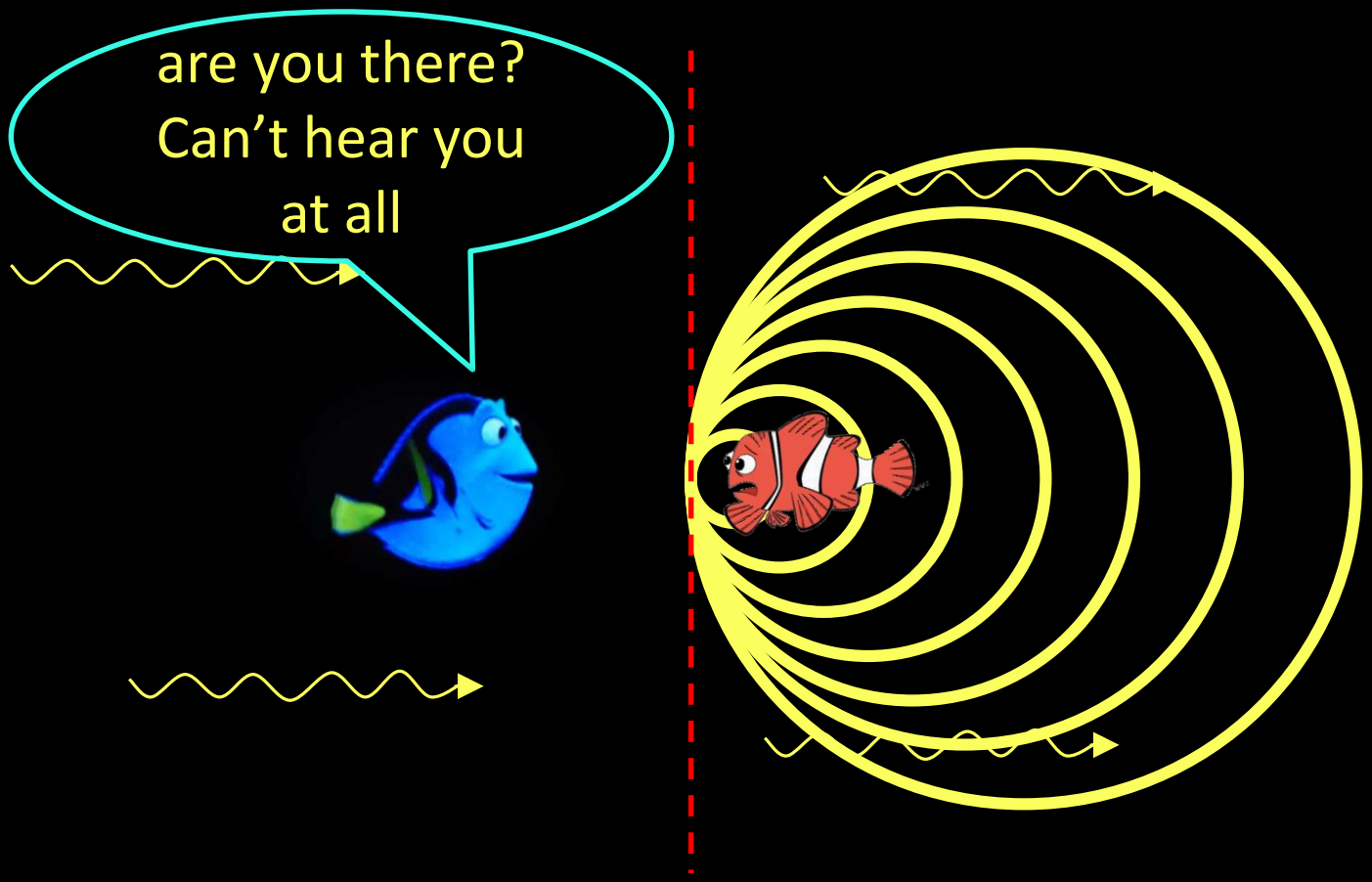


If the water does not move



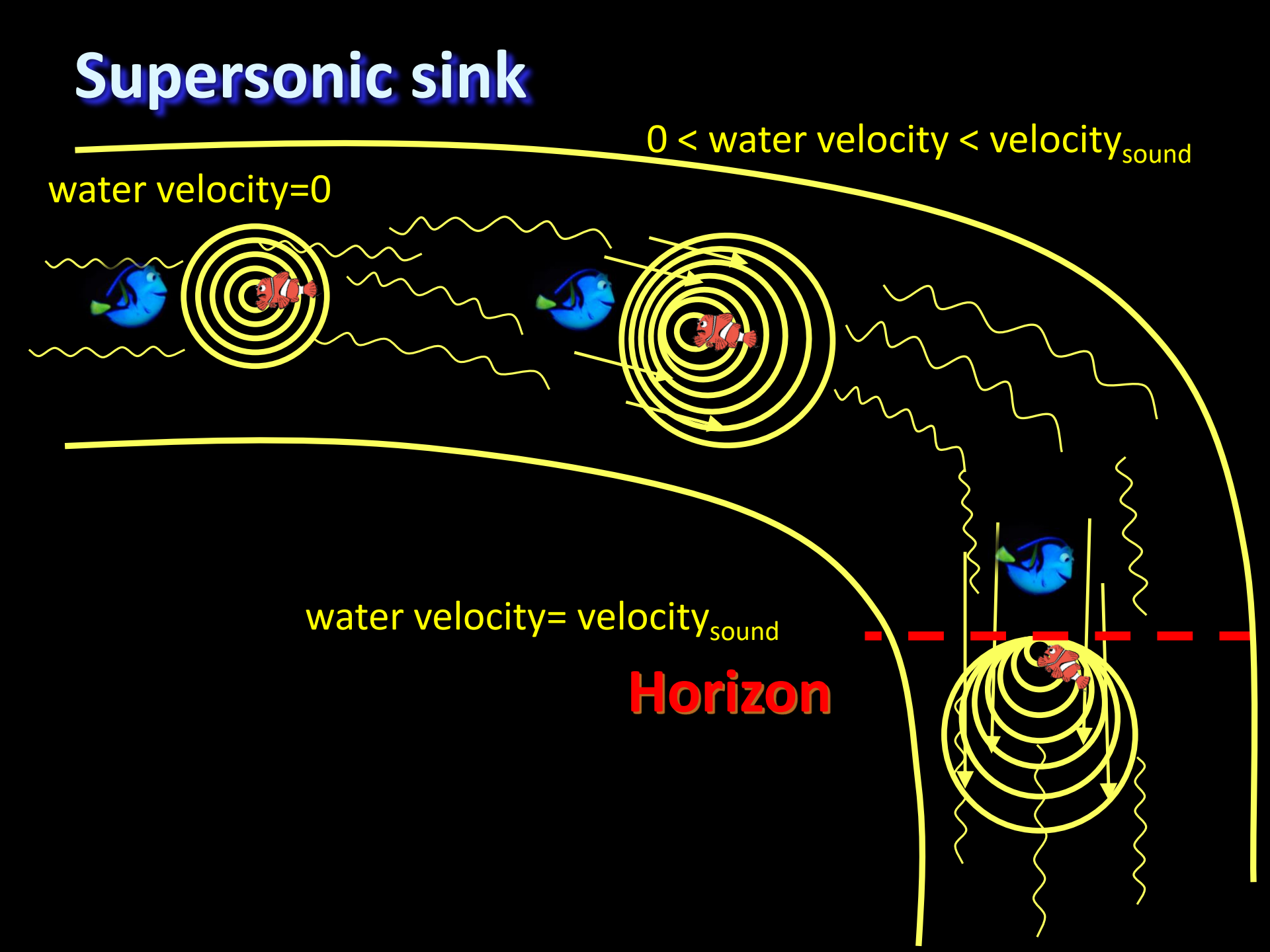
If water moves < velocity$_{sound}$

water moves = velocity$_{sound}$

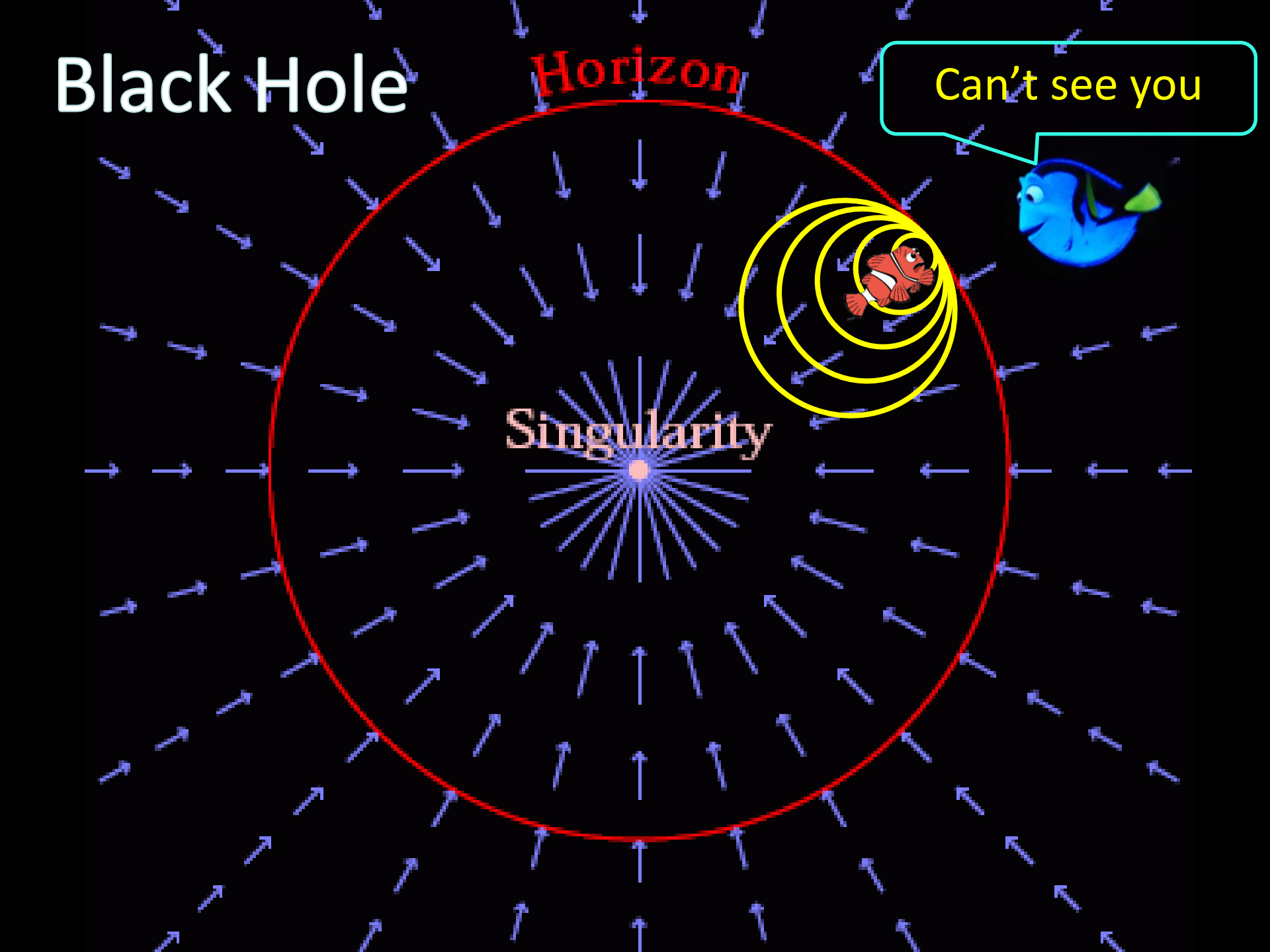


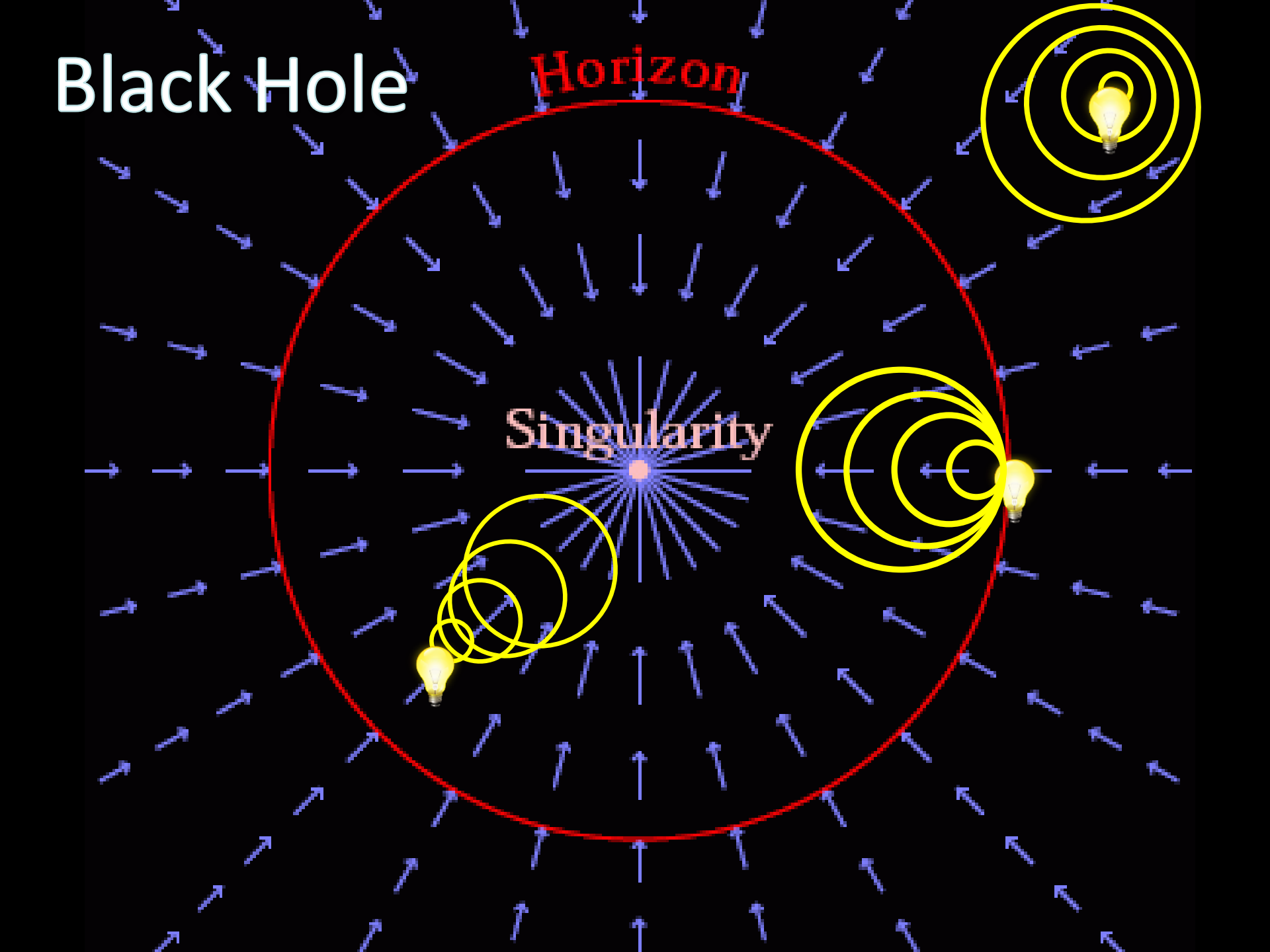
Sonic horizon

Supersonic sink

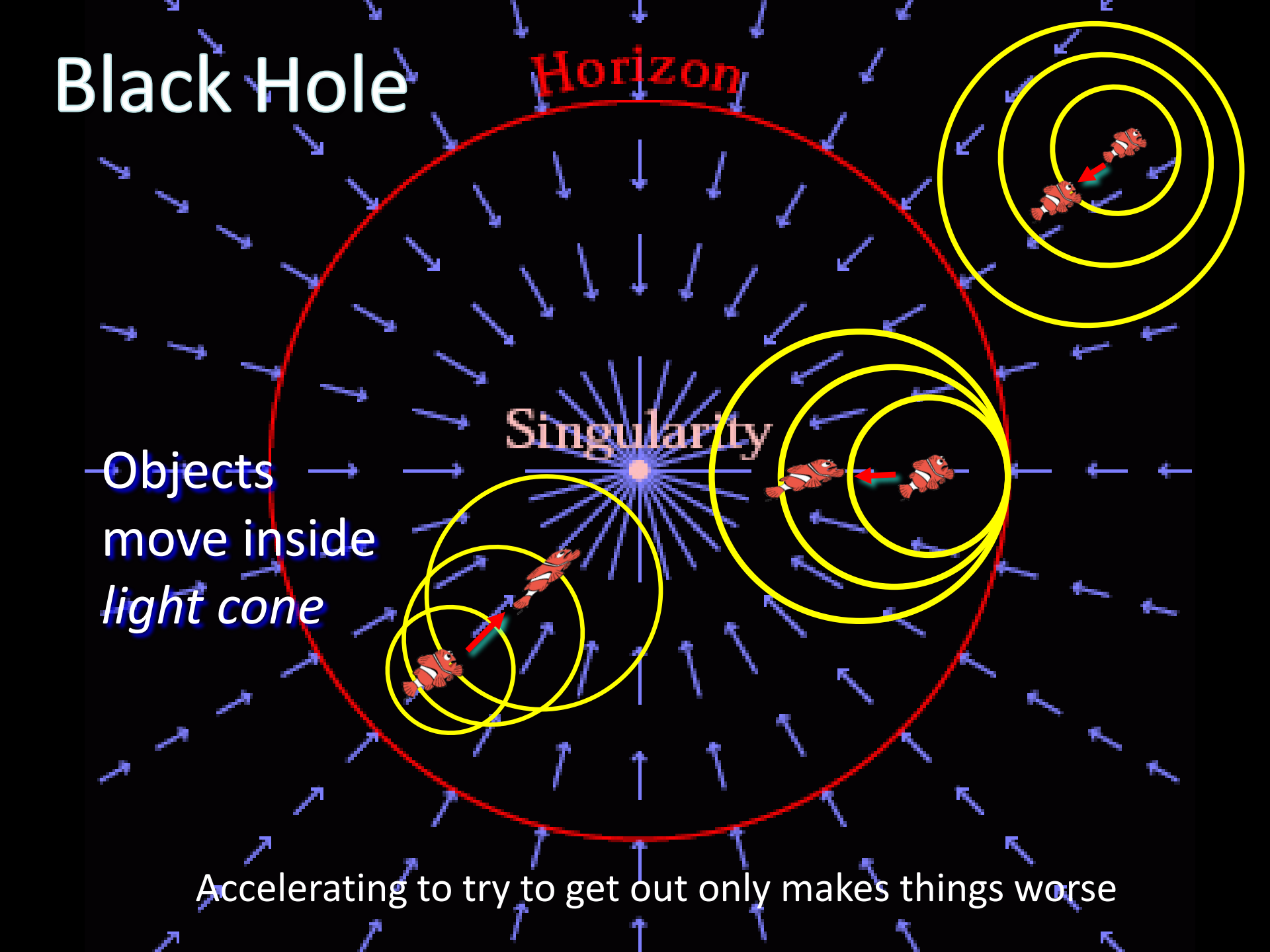


Black Hole



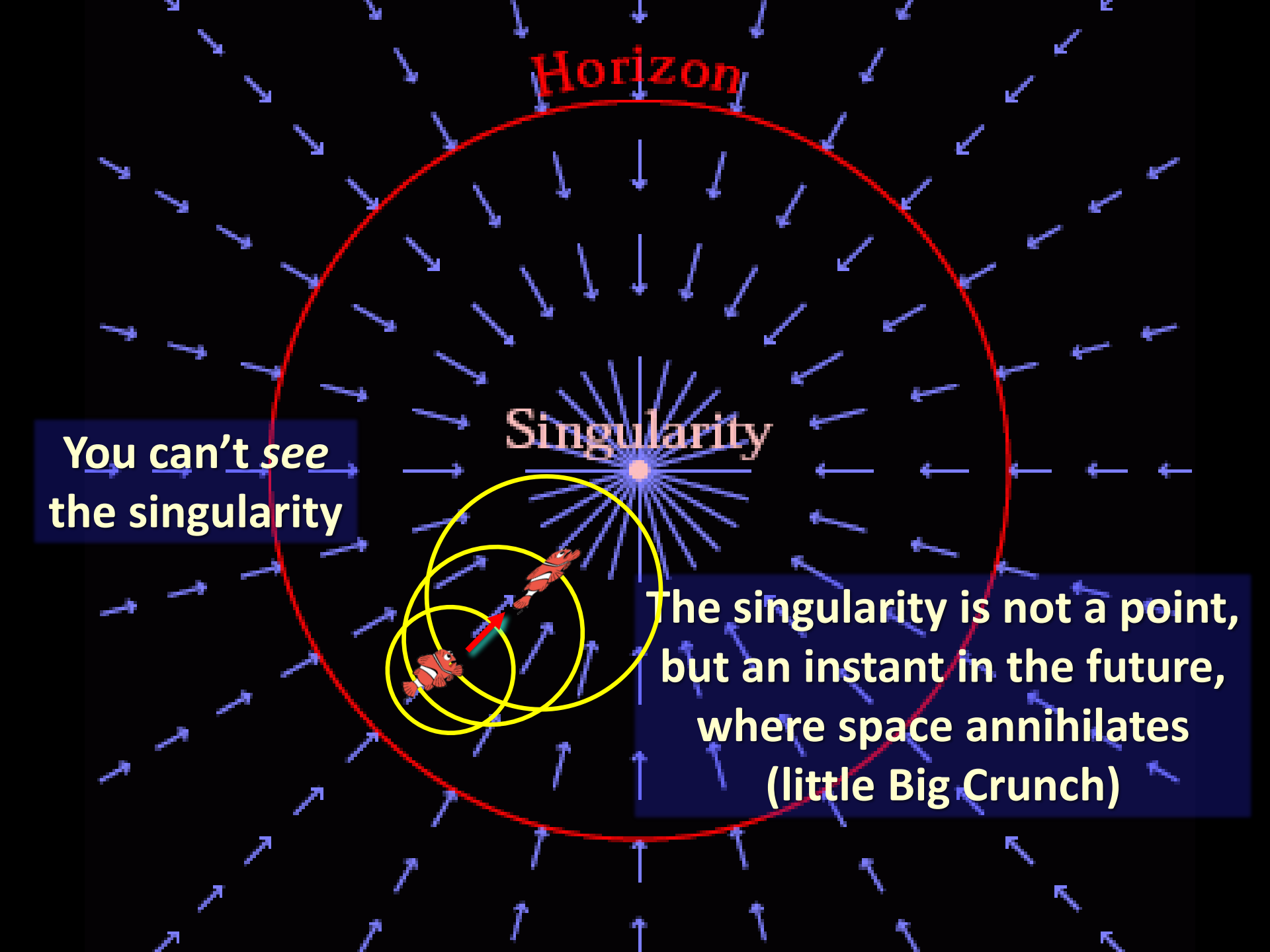

Black Hole
Horizon
Singularity

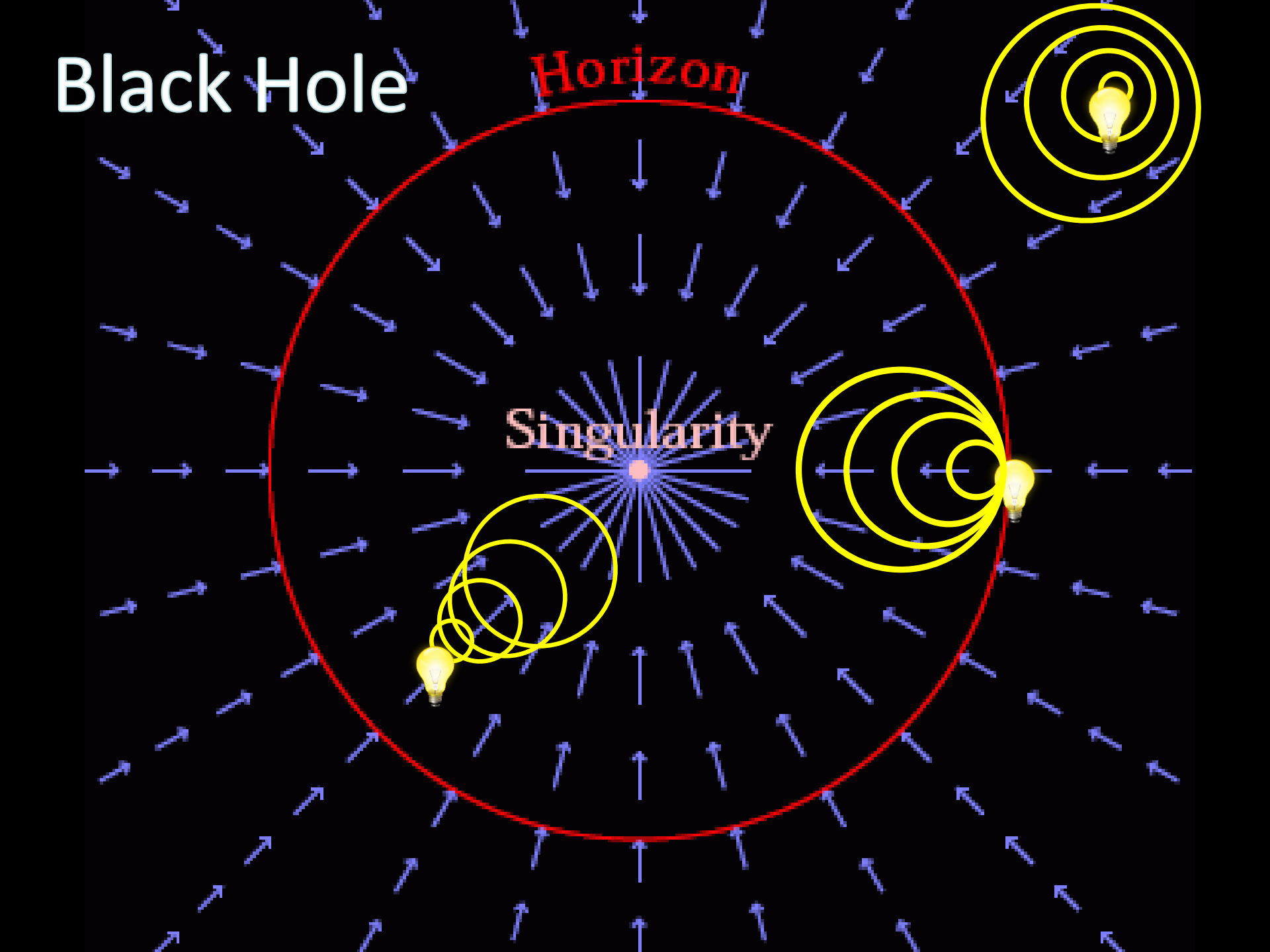
Black Hole



Objects move inside *light cone*

Accelerating to try to get out only makes things worse


Horizon
Singularity
You can't *see* the singularity
The singularity is not a point, but an instant in the future, where space annihilates (little Big Crunch)

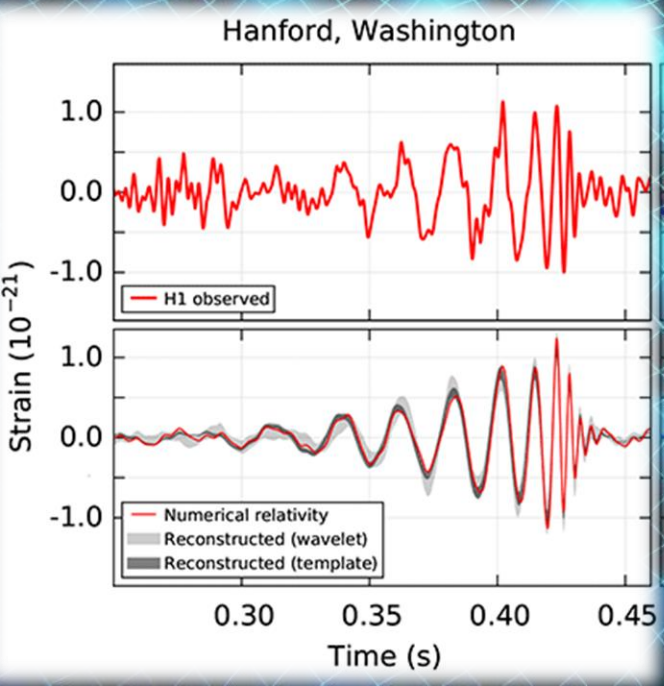

Black Hole
Horizon
Singularity

Do they exist?


Yes!
GW150914

Direct evidence

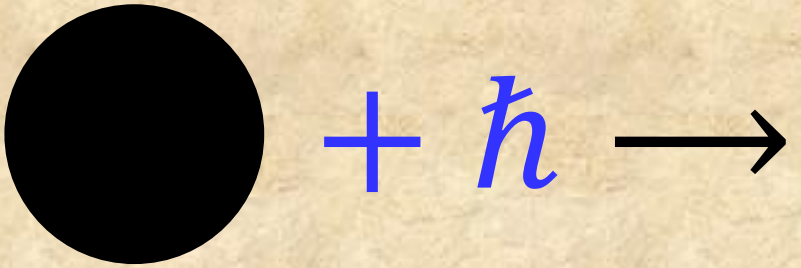
GW150914

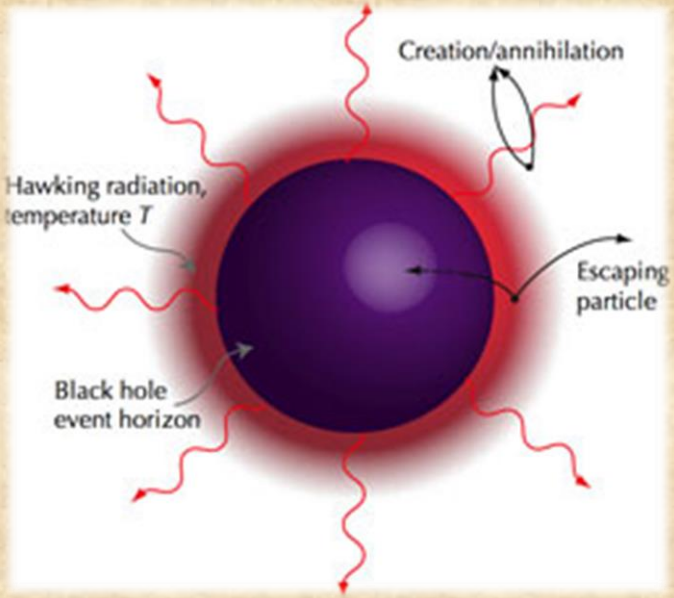


Observed

Theory

Enter Quantum Mechanics




Creation/annihilation
Hawking radiation,
temperature T
Escaping
particle
Black hole
event horizon

1974

Black Hole Information Paradox

A problem of

fundamental irreversibility

Is information lost forever inside a black hole?

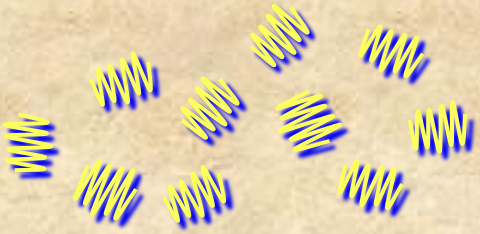
Have I lost forever all the info in my tablet?

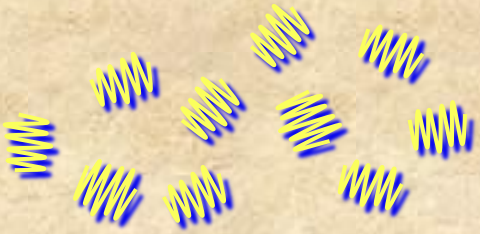
A similar problem?

Have I lost forever all the info in my tablet?

Have I lost forever all the info in my tablet?

NO!

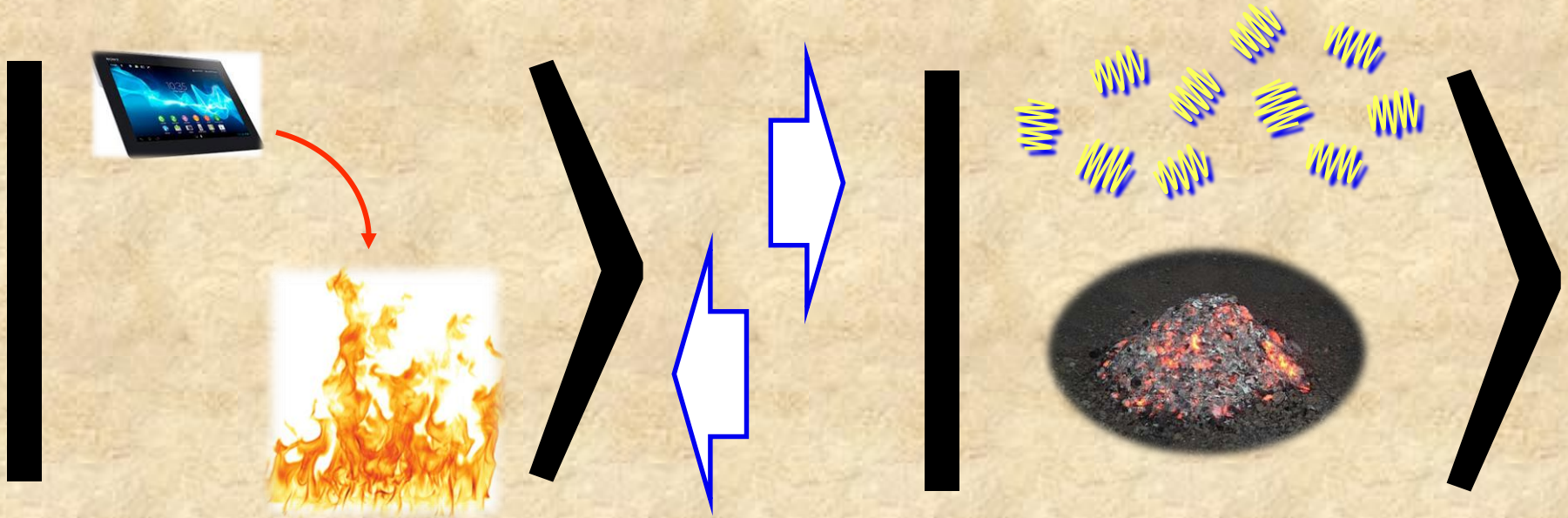




You *only* need to gather *all* the ashes and radiation and process them through a quantum supercomputer*

*thought experiment
work in progress

$$U = e^{-iHt}$$

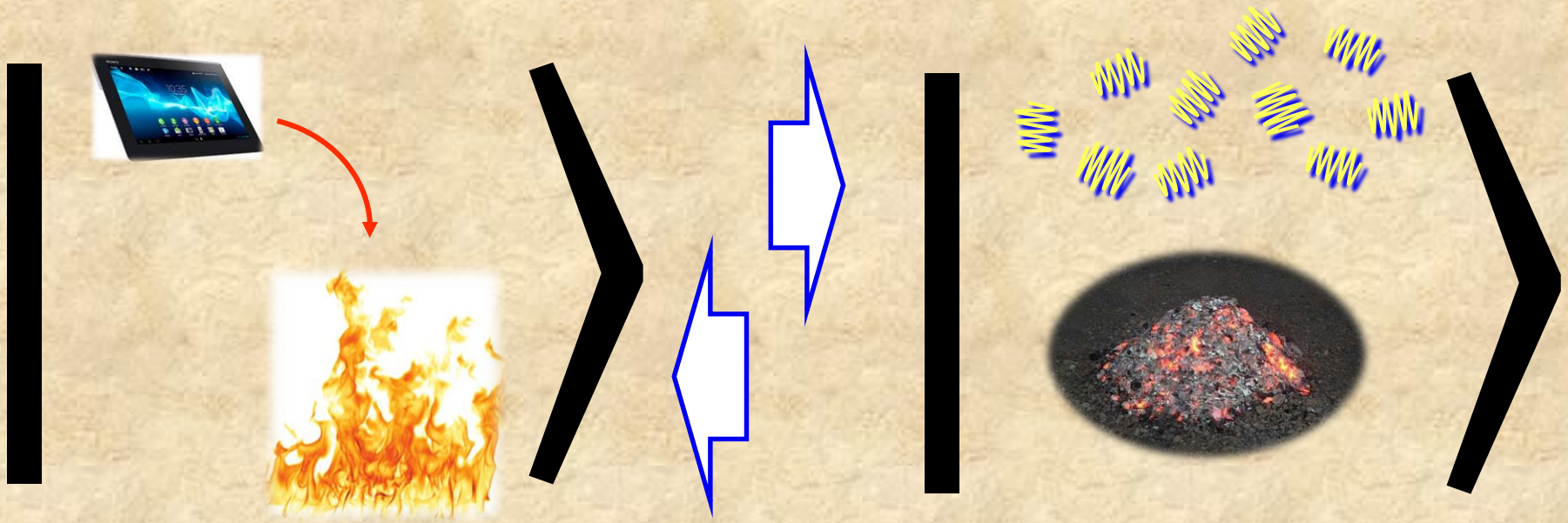


$$U^{\dagger} = U^{-1}$$

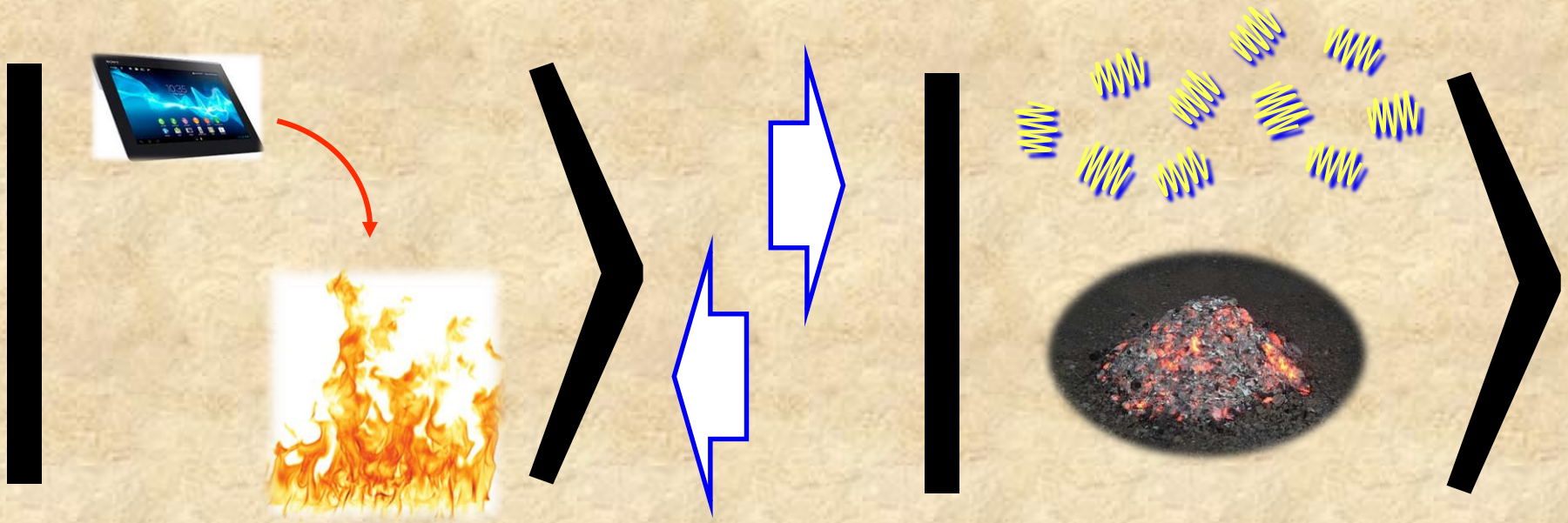
$$= e^{-iH(-t)}$$

Quantum evolution is **unitary**

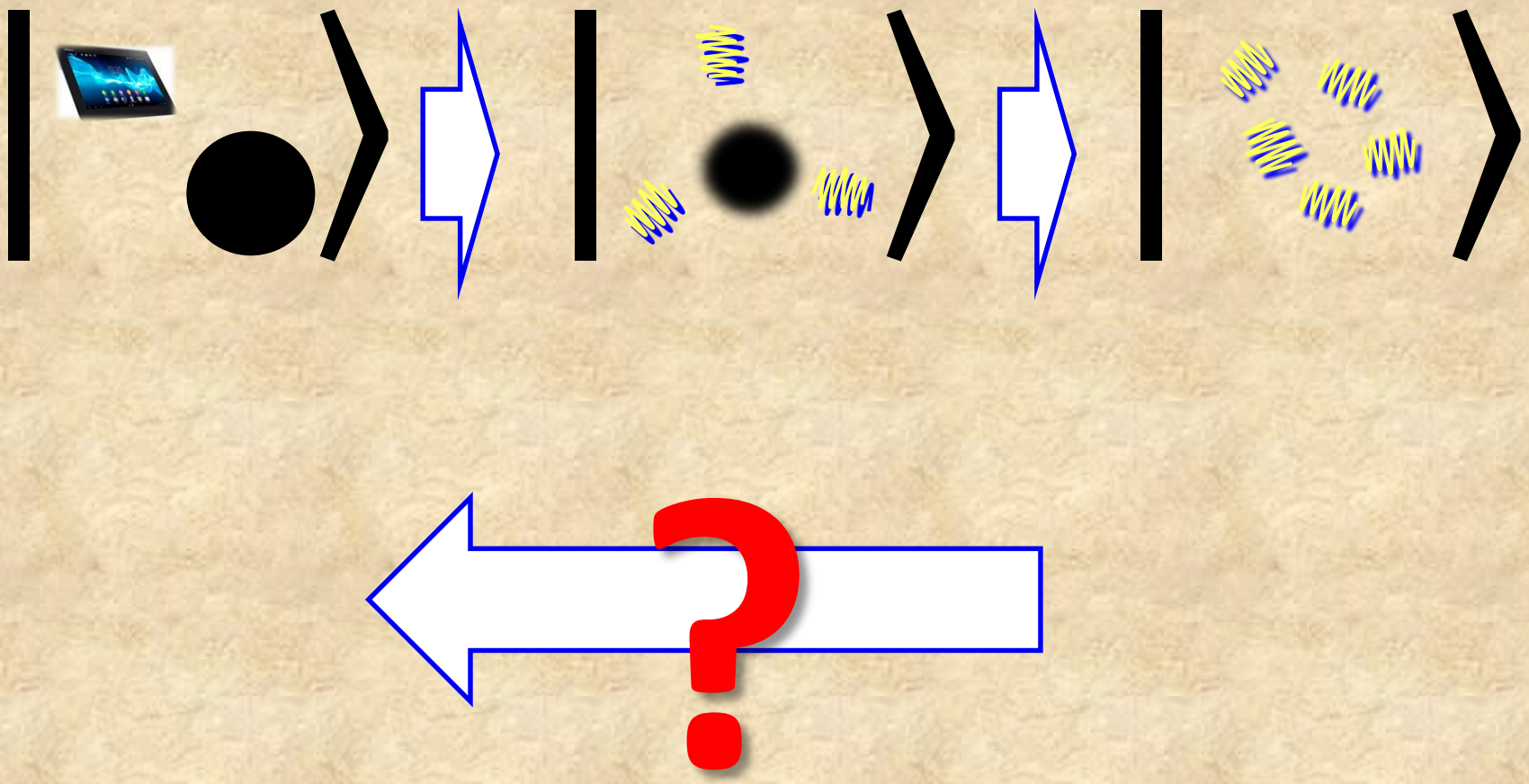
= **reversible** at fundamental level



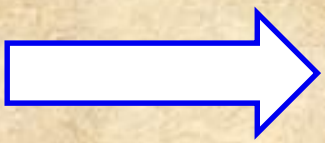
Initial information is
always present,
only terribly scrambled



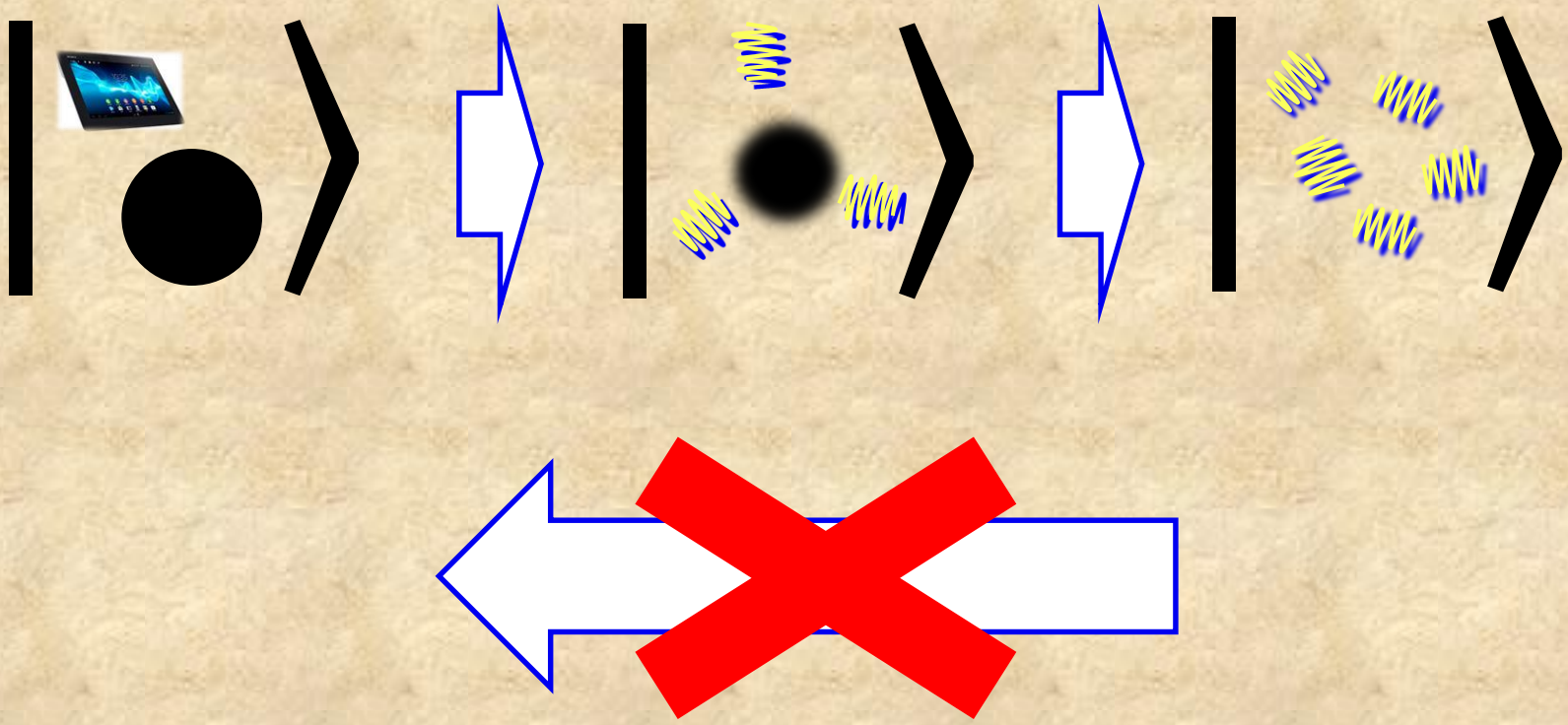
All parts of the system can exchange information with each other



Once inside the black hole, nothing can be communicated to exterior



⇒ radiation cannot communicate information about what fell in the black hole



Option A

Information ***is lost***, even at a fundamental level

Black holes win

Quantum mechanics must change

Option B

Information ***is not lost***

Quantum mechanics does not change

Somehow information must remain outside the black hole

Have I lost **forever** all the information?

YES!!

1976-2004

Have I lost **forever** all the information?

NO!!

2004-...


cc
creative
confusion

Contradictions between well-established theories

⇓

Conceptual revolutions in Physics

This debate has sparked work on the role of

quantum entanglement

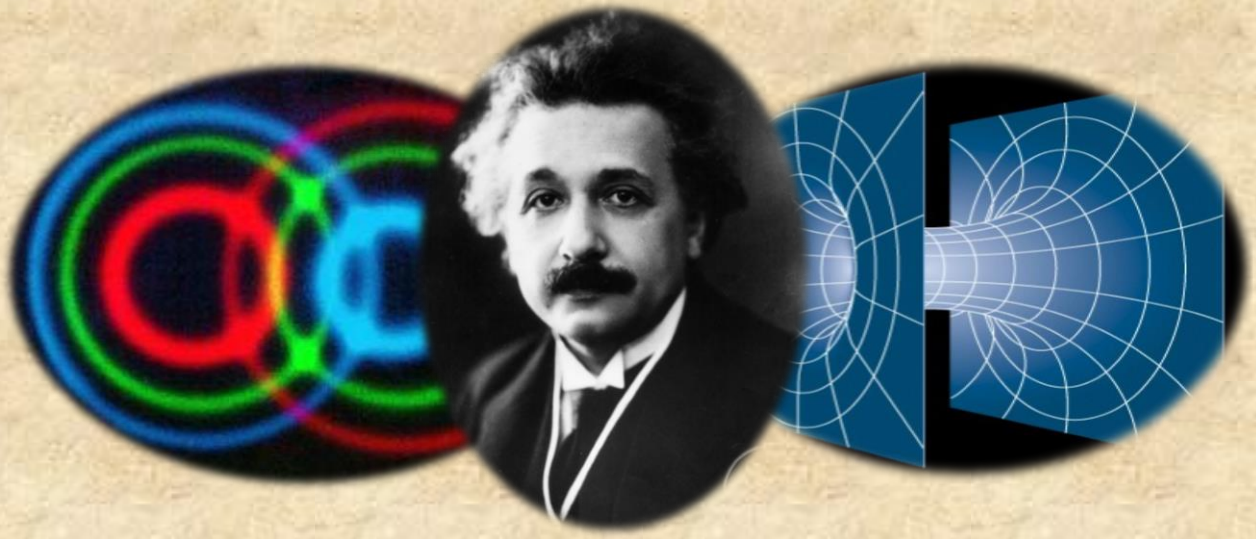
in the

emergence of spacetime

Einstein understood the fundamental importance of both:

spacetime geometry (1915)

quantum entanglement (1935)



Time to merge them?

Slogan for the next 100 years?

“Spacetime is a geometric way of encoding quantum correlations”

Homework assignment:
Precisely what does this mean?

Questions?