The Universe Black Holes &Entanglement

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$$|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle$$

The Universe

https://scaleofuniverse.com

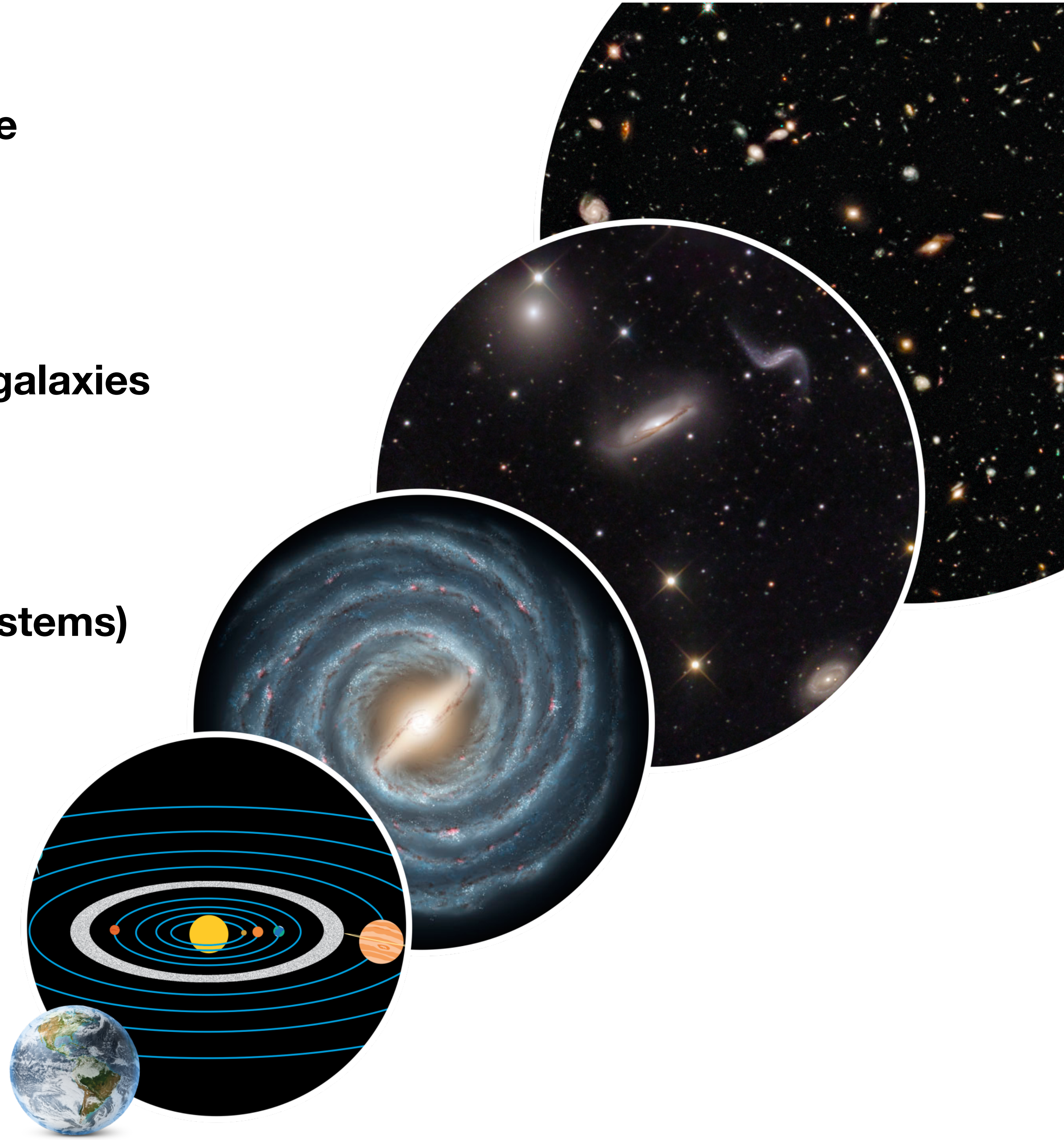
Large Structures of the Universe

Clusters (and superclusters) of galaxies

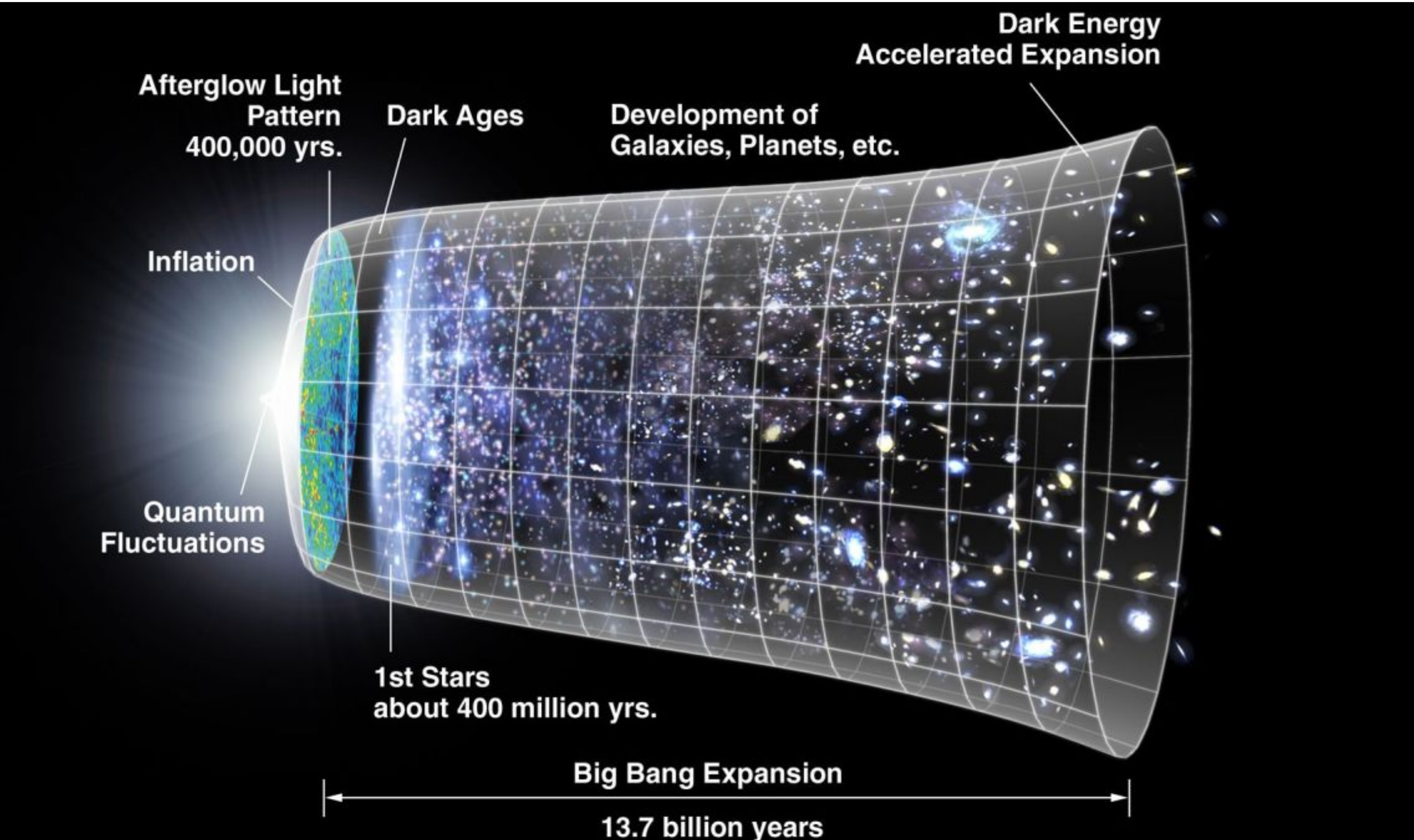
Galaxies (100 billions of solar systems)

Solar systems

Planets



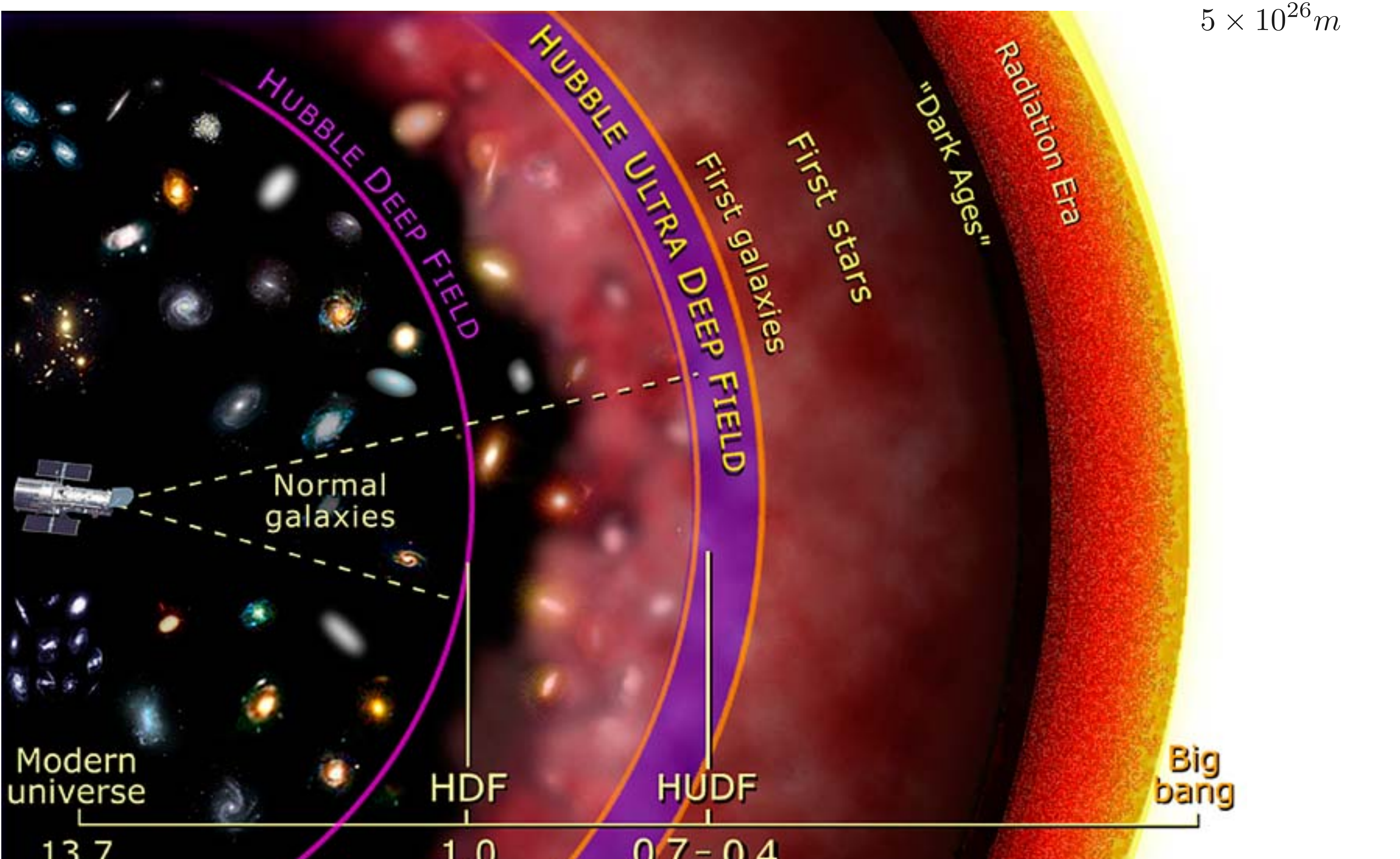
Expanding Universe



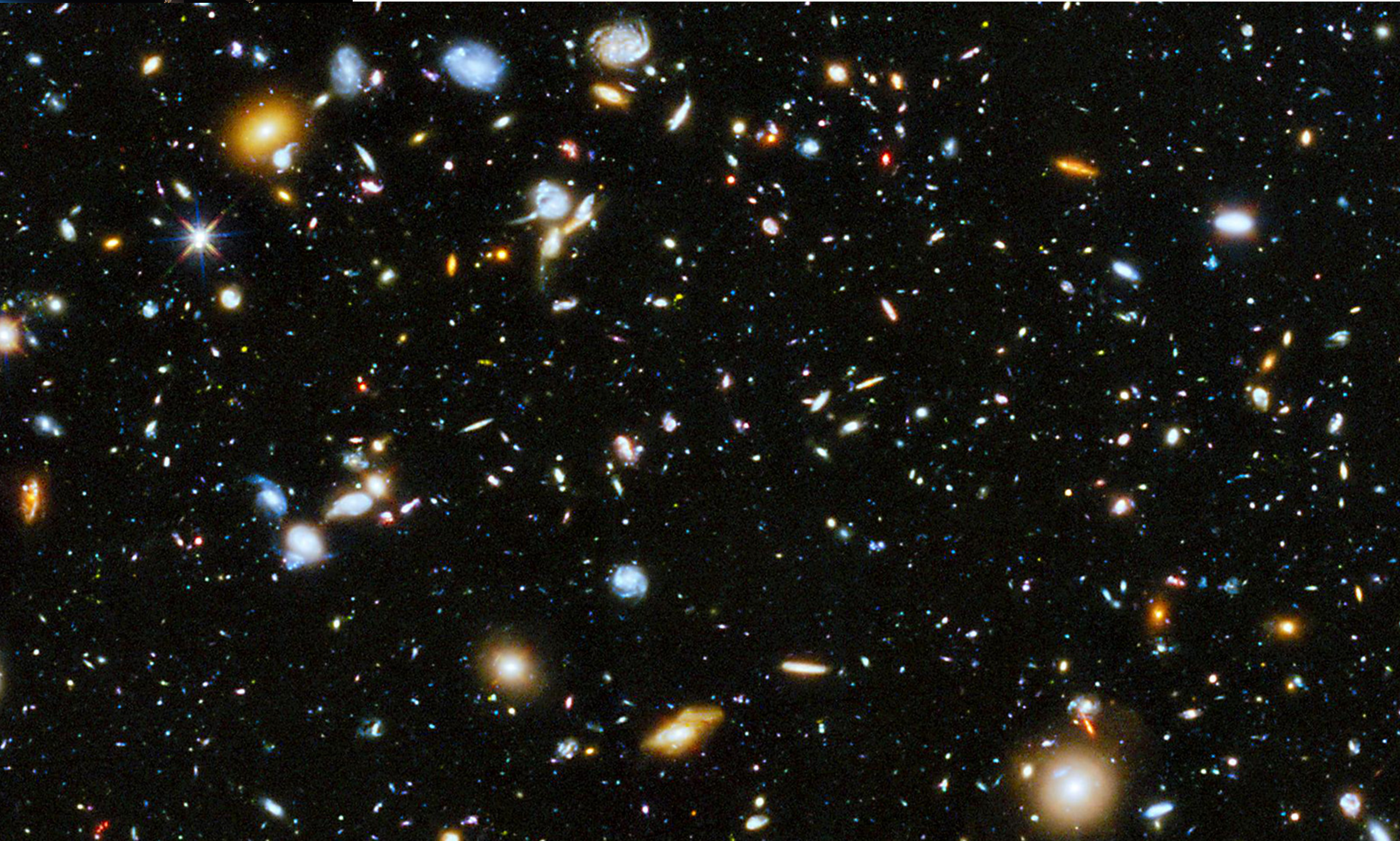
How far we can see

~13.2 billion years ago

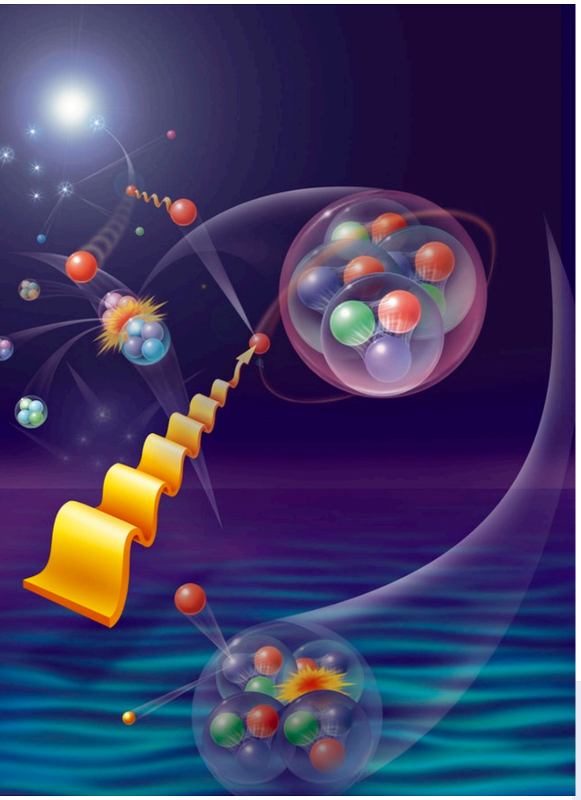
$5 \times 10^{26} m$



Hubble Ultra Deep Field



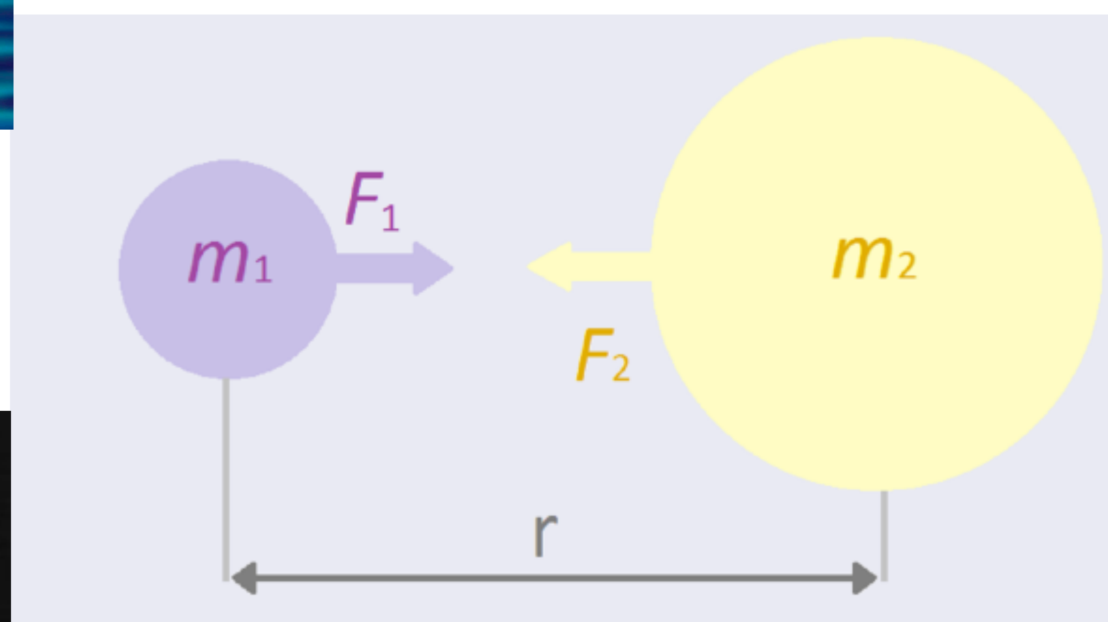
Scales in Physics



$\leq 10^{-5} m$

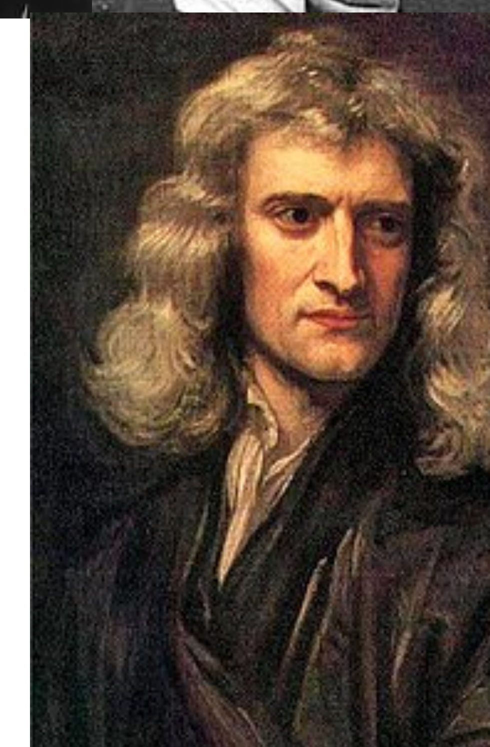
Quantum Mechanics

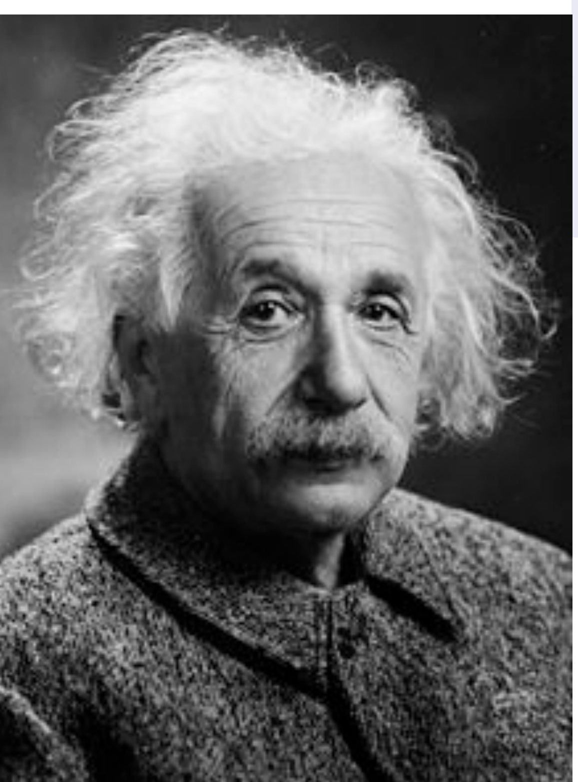
Quantum Field Theory



$10^{-5} - 10^{20} m$

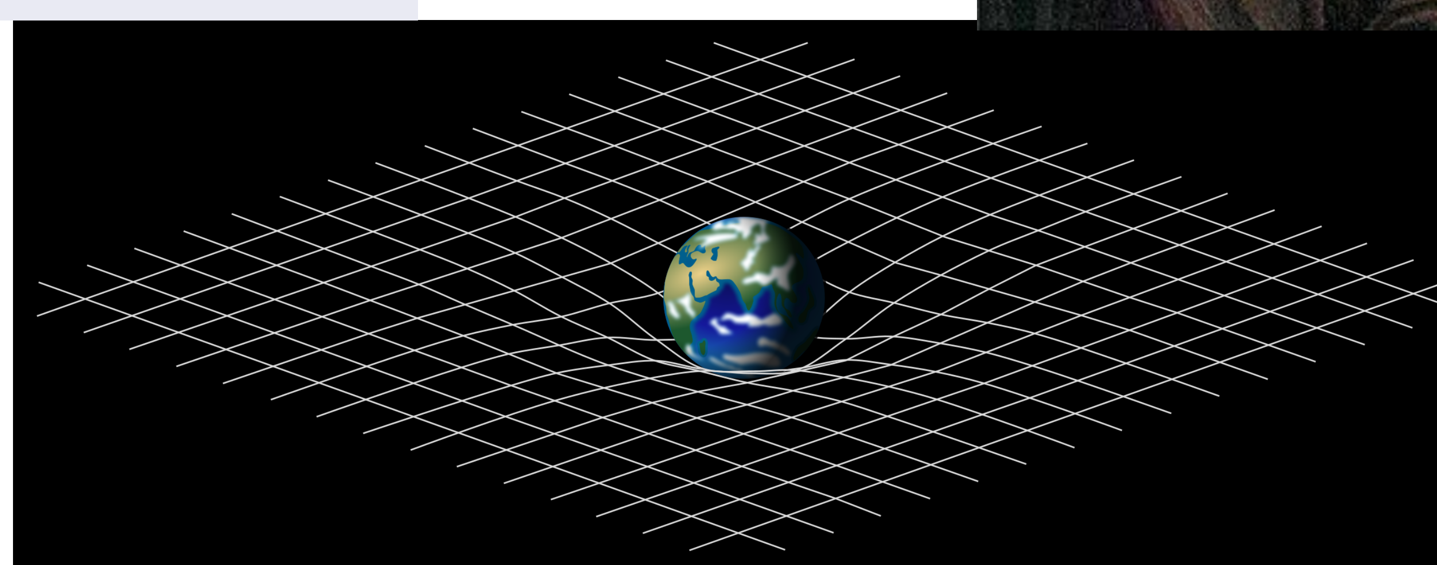
Newton theory





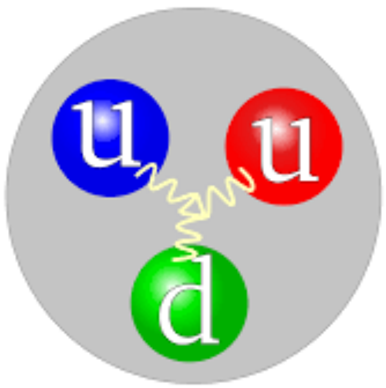
$\geq 10^{20} m$

General Relativity

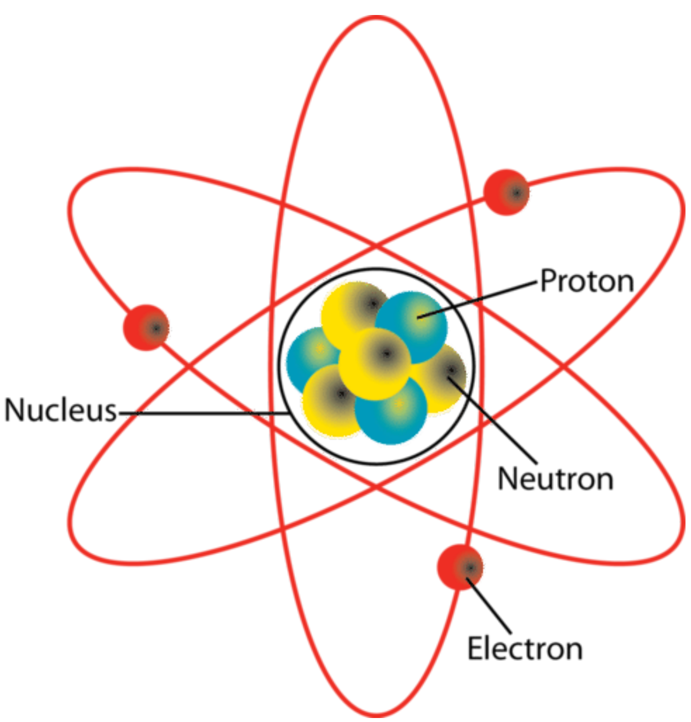


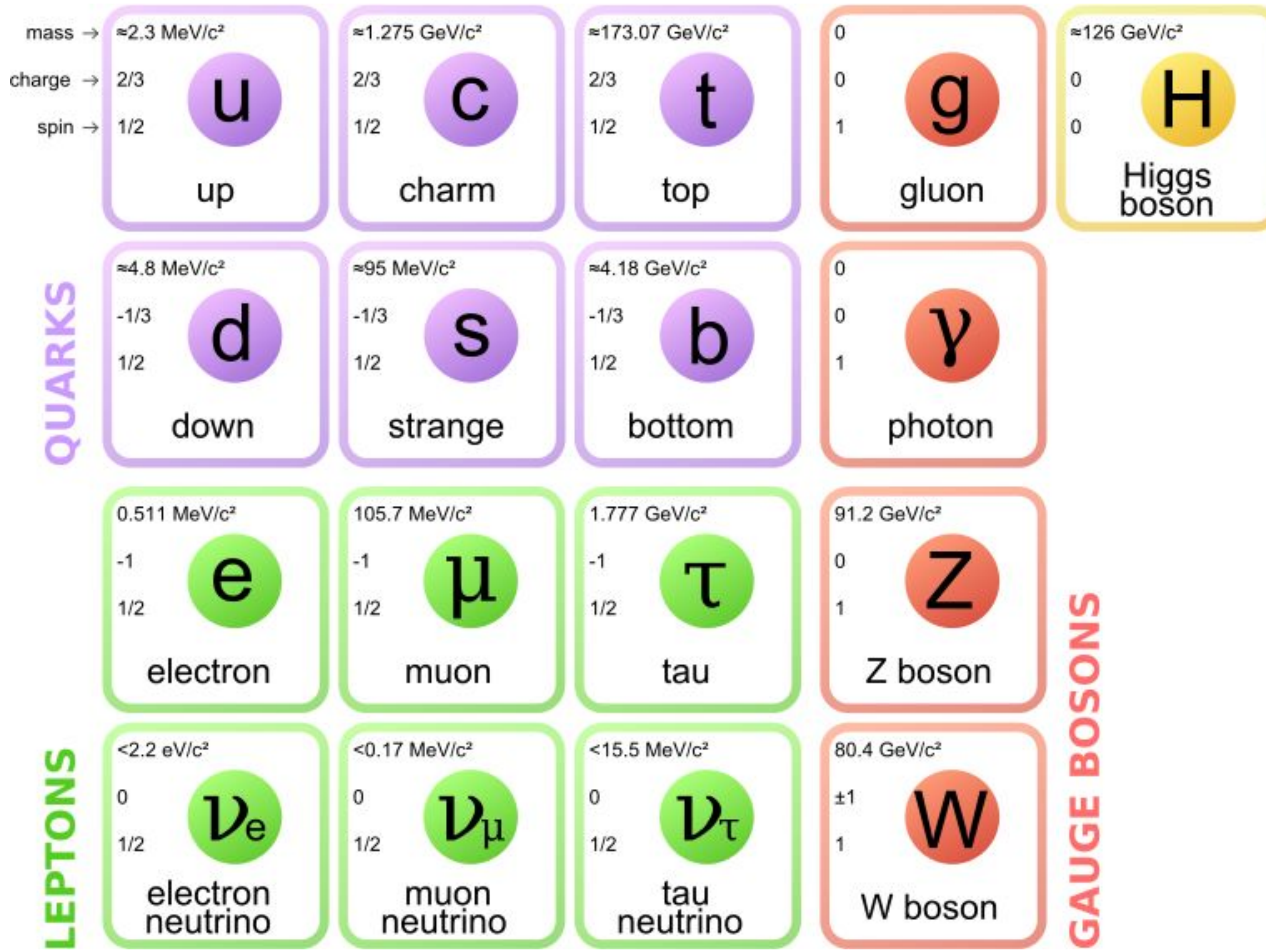
The Standard Model

proton



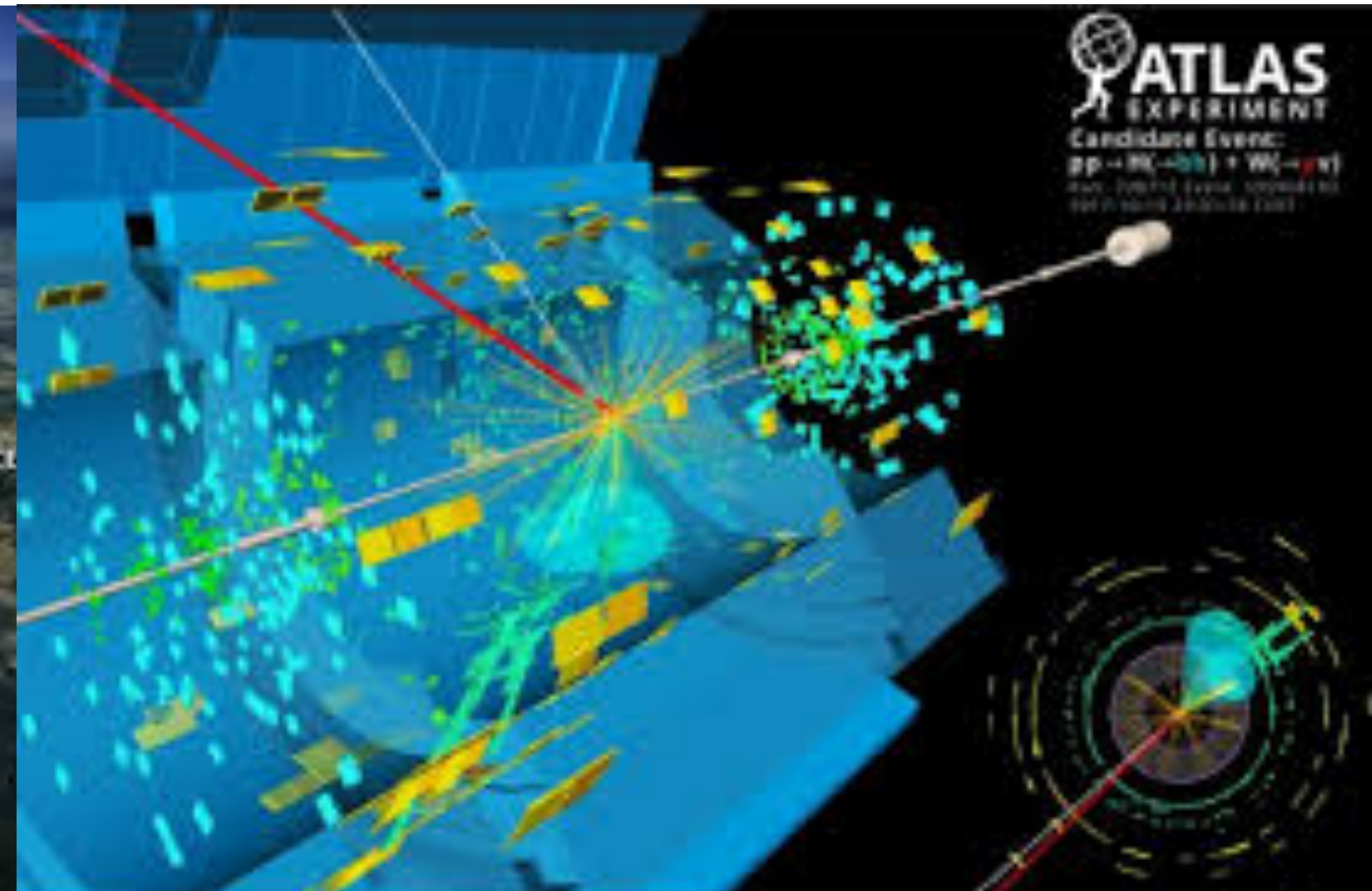
atom



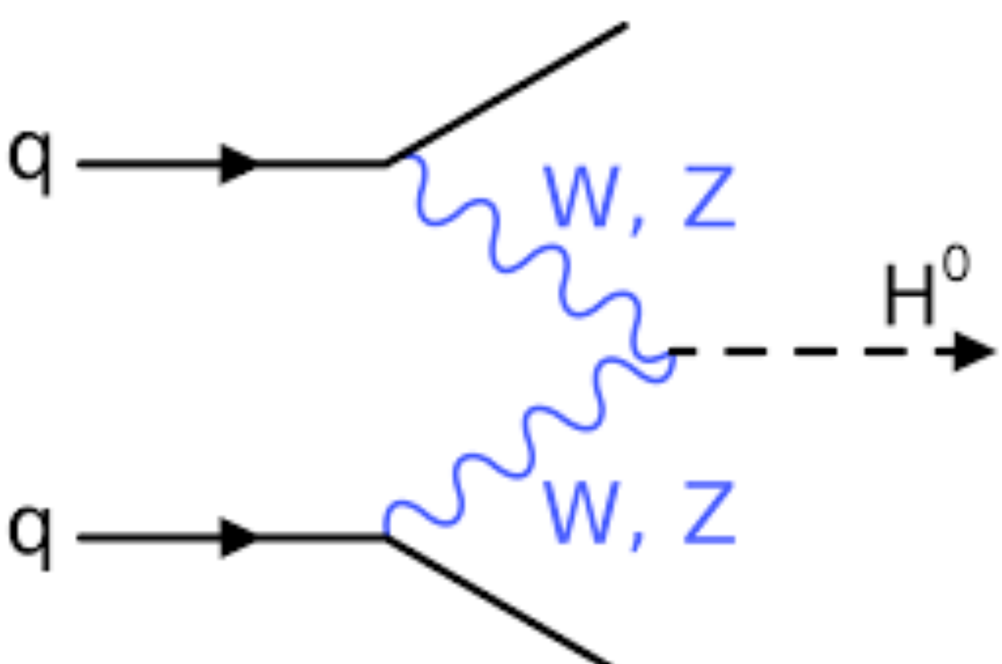


LHC

ATLAS
ALICE
CMS



ATLAS
EXPERIMENT
Candidate Event:

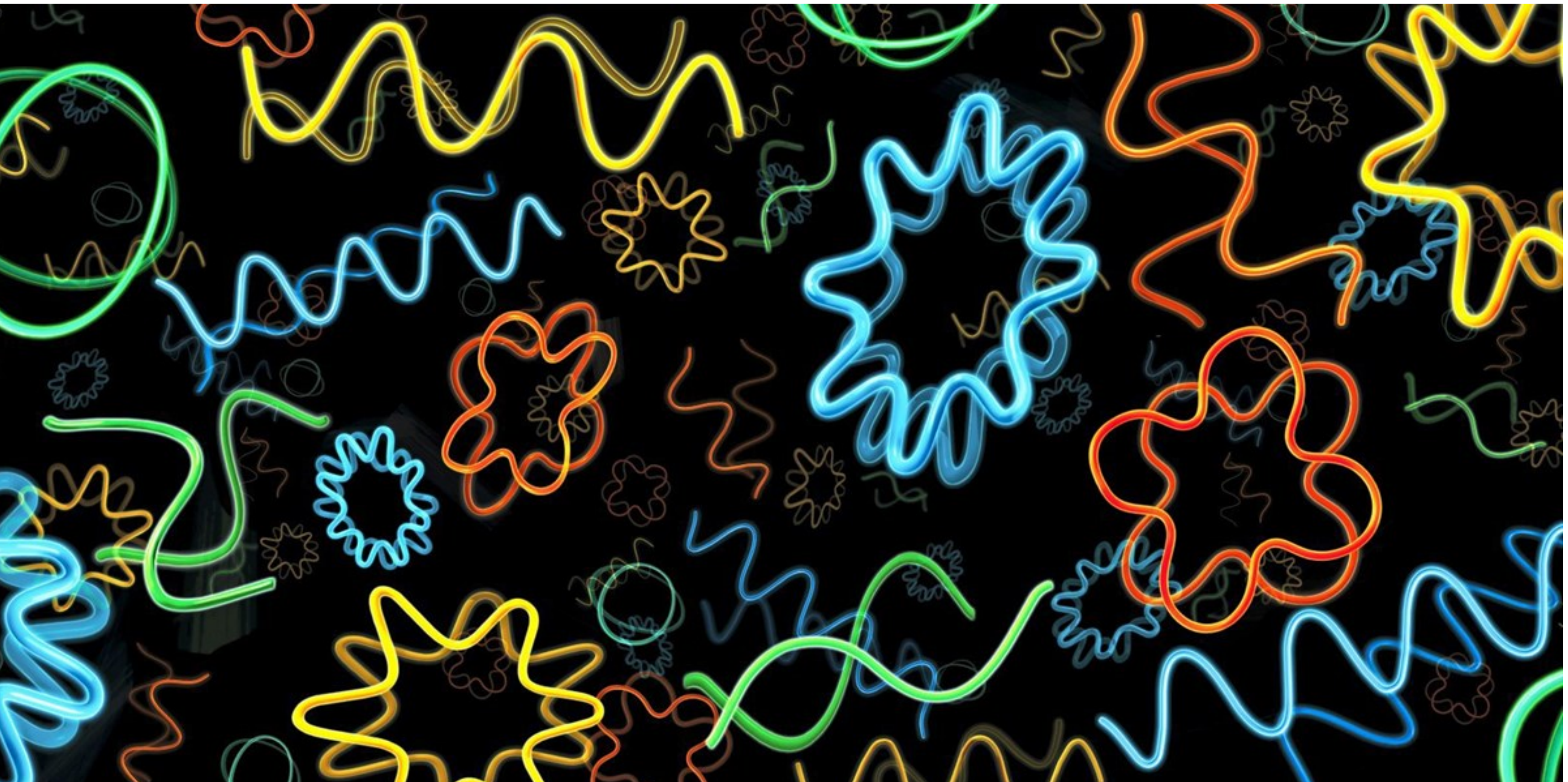


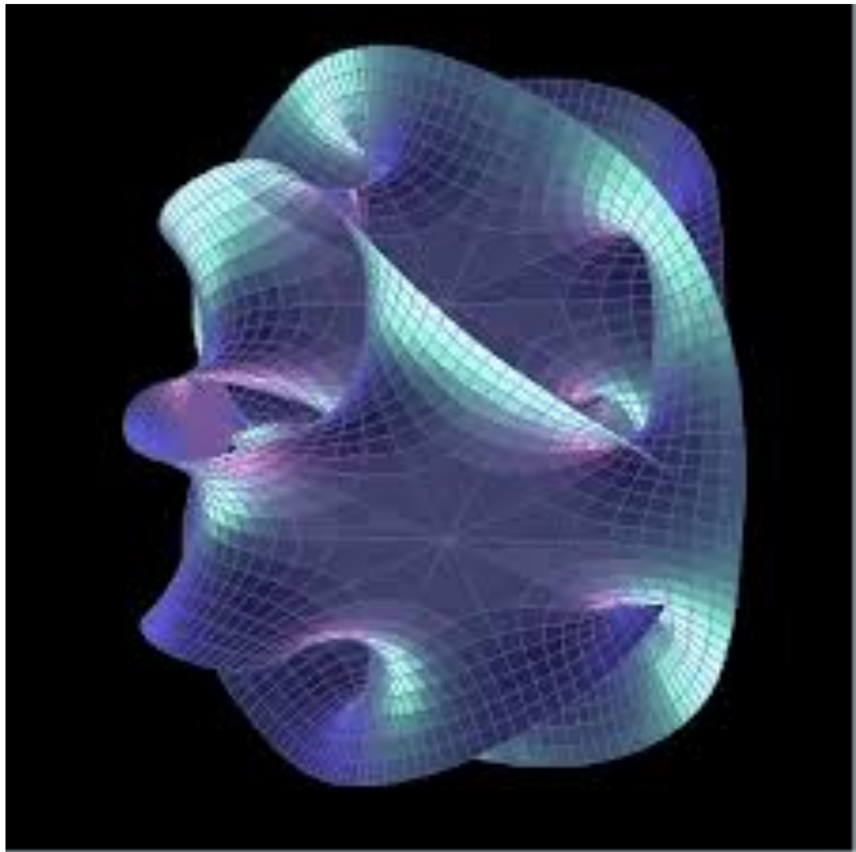
q
W, Z
H^0
W, Z
q

One of the fundamental problems of modern theoretical physics is to connect ***quantum mechanics*** with ***general relativity***

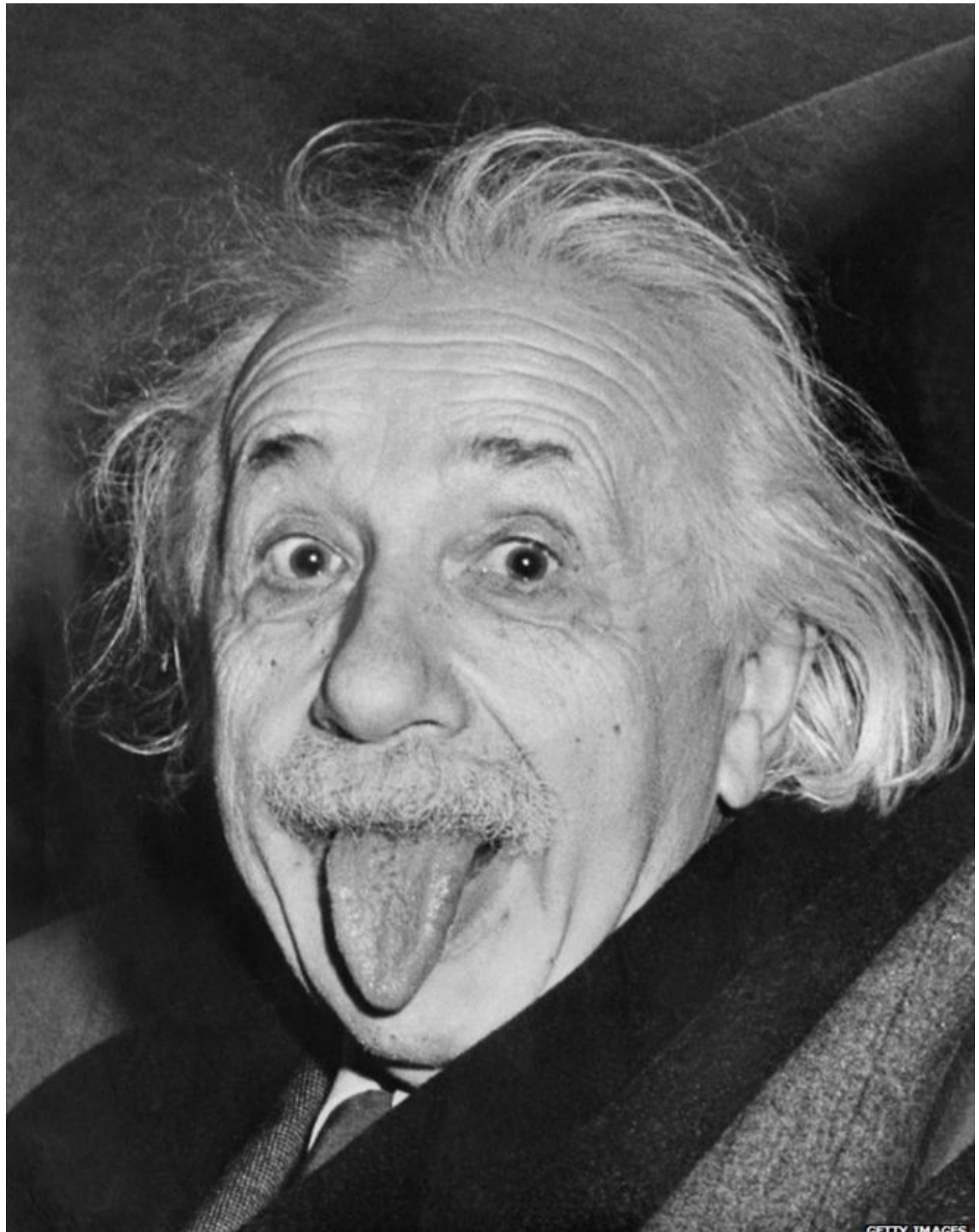
Best candidate — String Theory

Describes interaction of strings (1+1 dimensional objects) traveling inside 9+1 dimensional spacetime





General Relativity



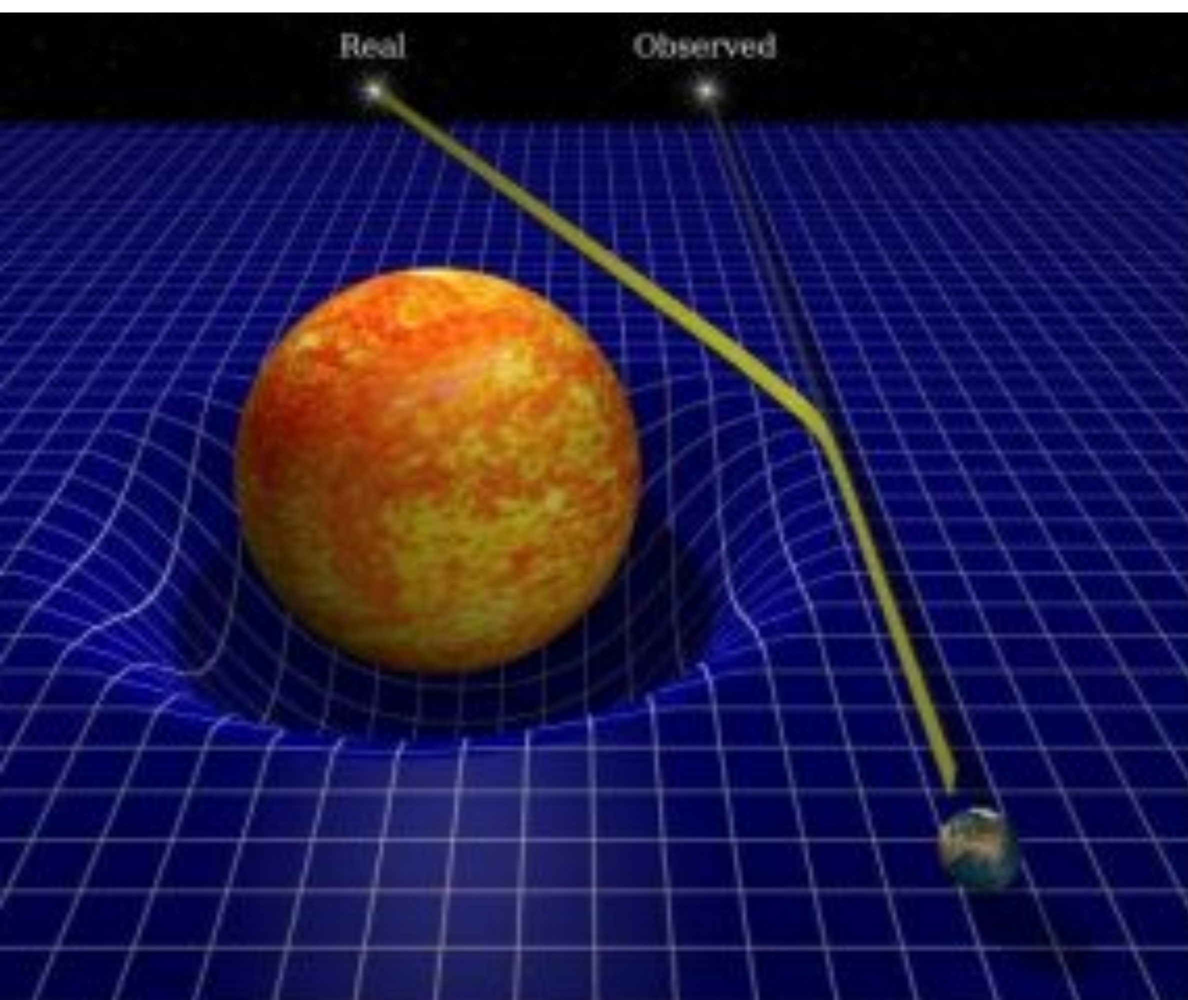
Einstein's Theory

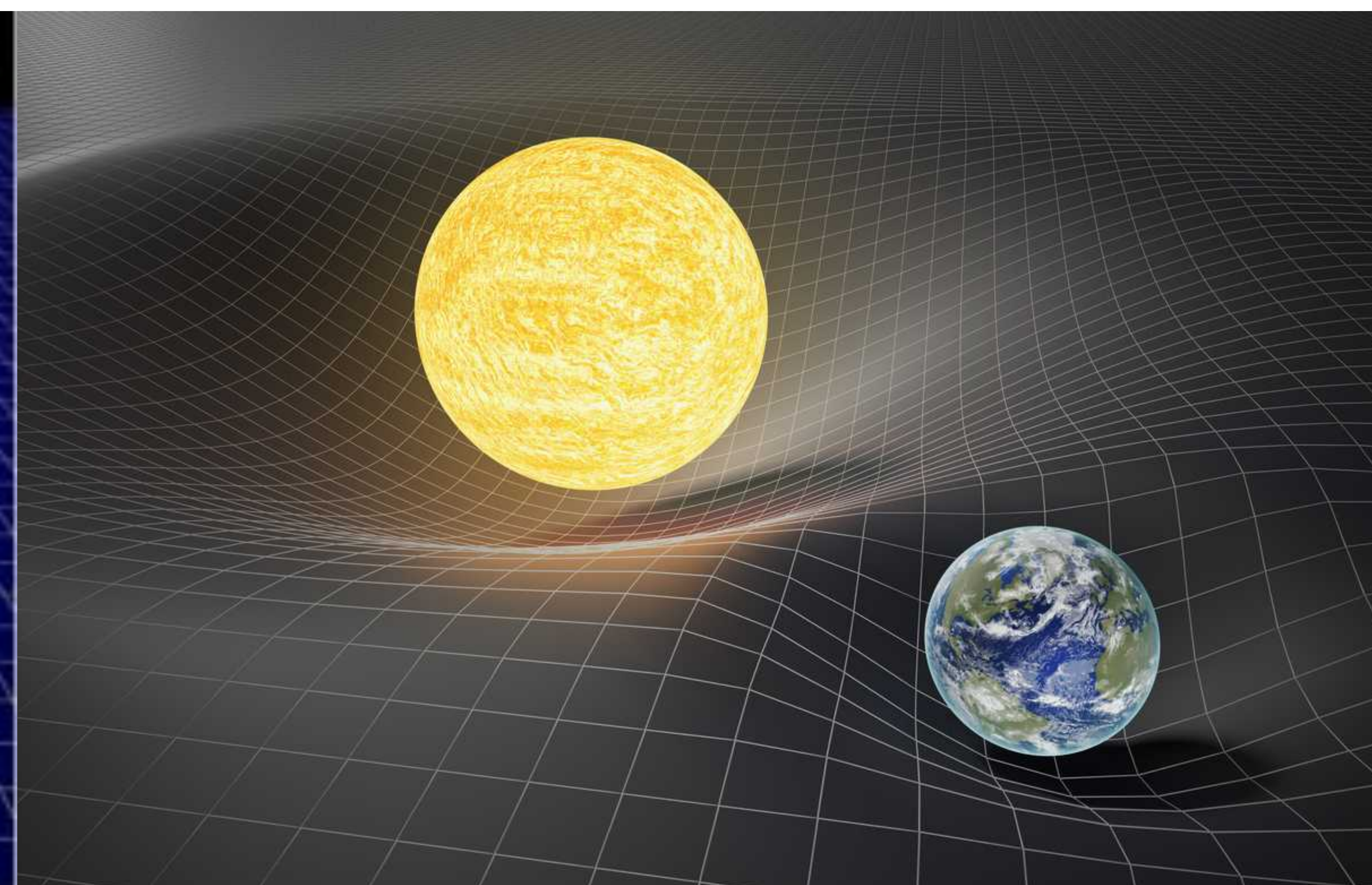
Mass creates **curvature** of space-time

$$G = T$$

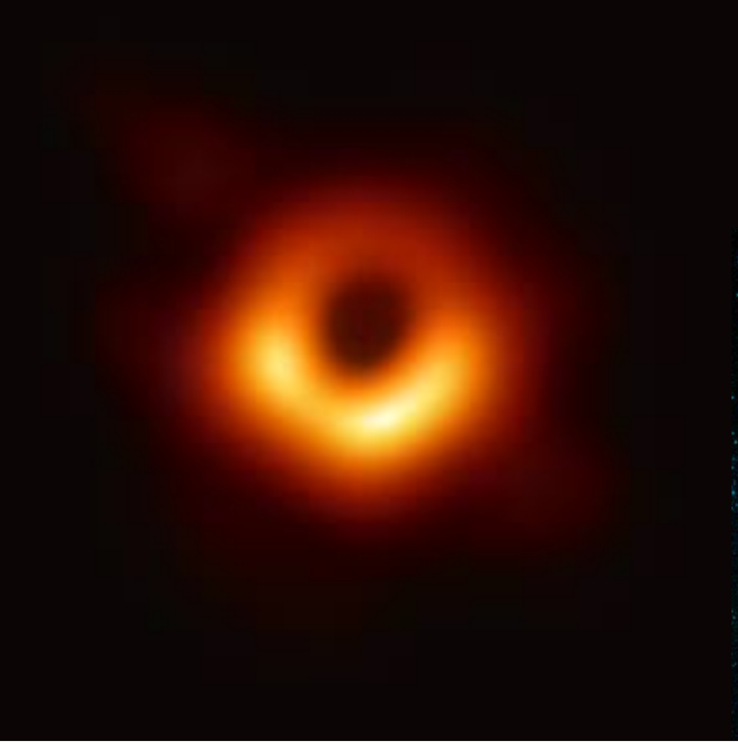
Geometry = Energy

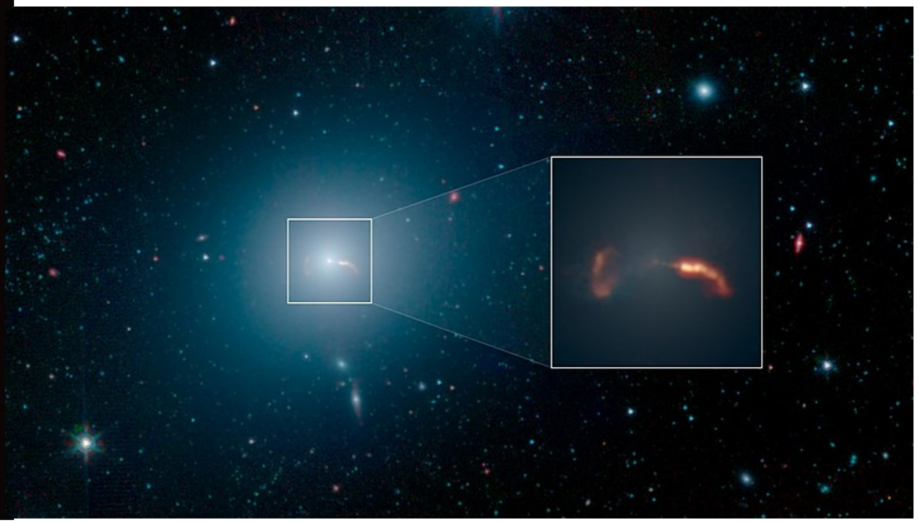
Light travels along the shortest pass
in the curved space





Black Holes





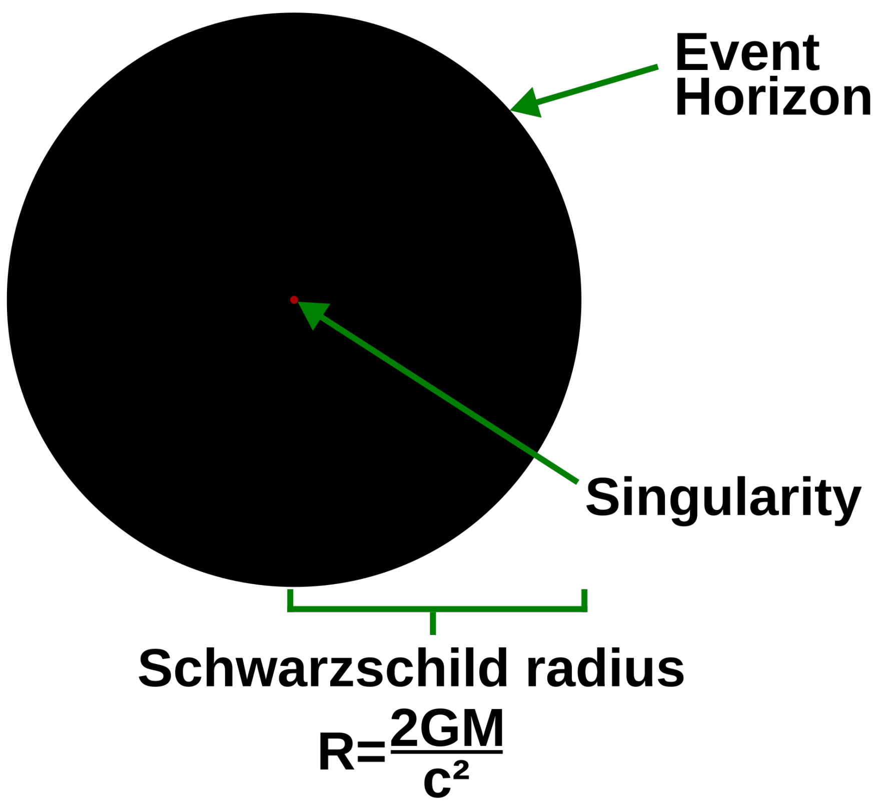
Too massive that even light cannot escape!

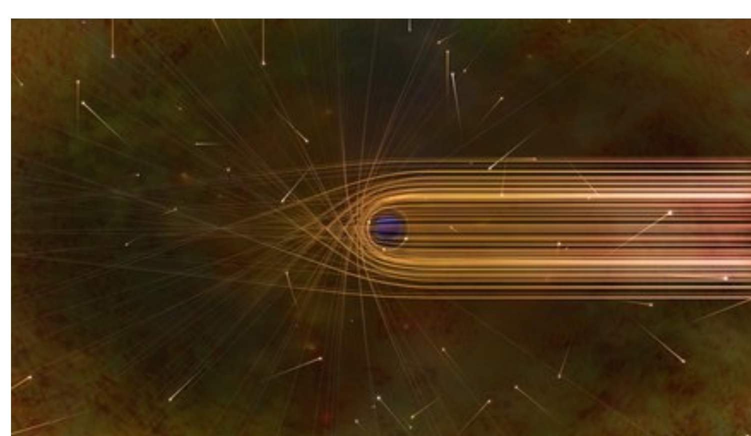
$$r_S = \frac{2G_{\rm N}M}{c^2} \simeq 3\,\frac{M}{M_{\rm Sun}}\,{\rm km}$$

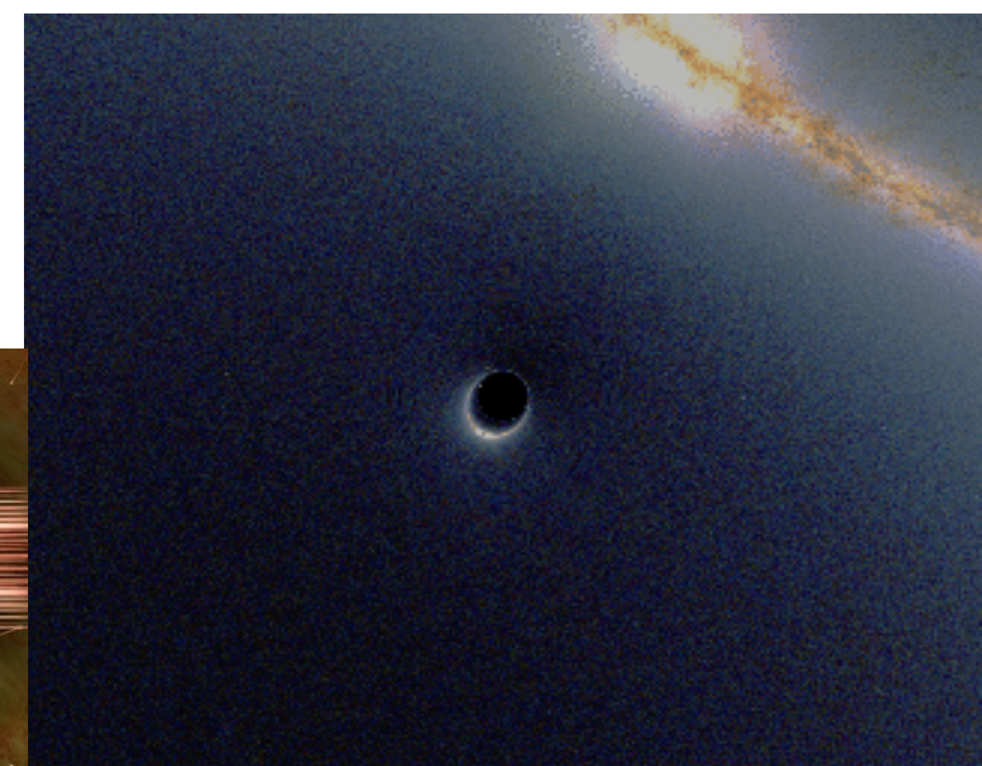
Time *s l o w s d o w n* as we approach a black hole

At the horizon it stops!

The horizon is the `zone of no return’

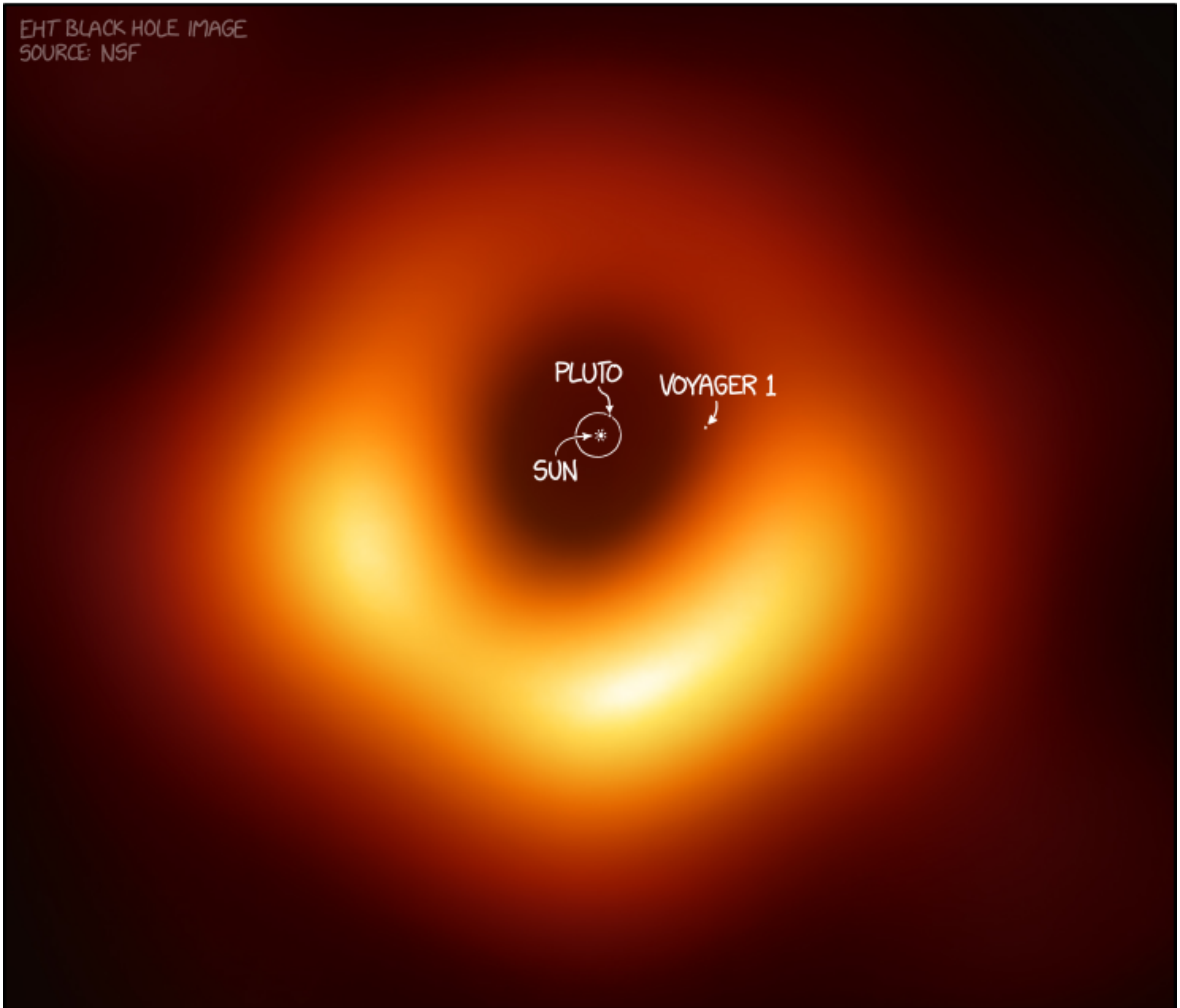




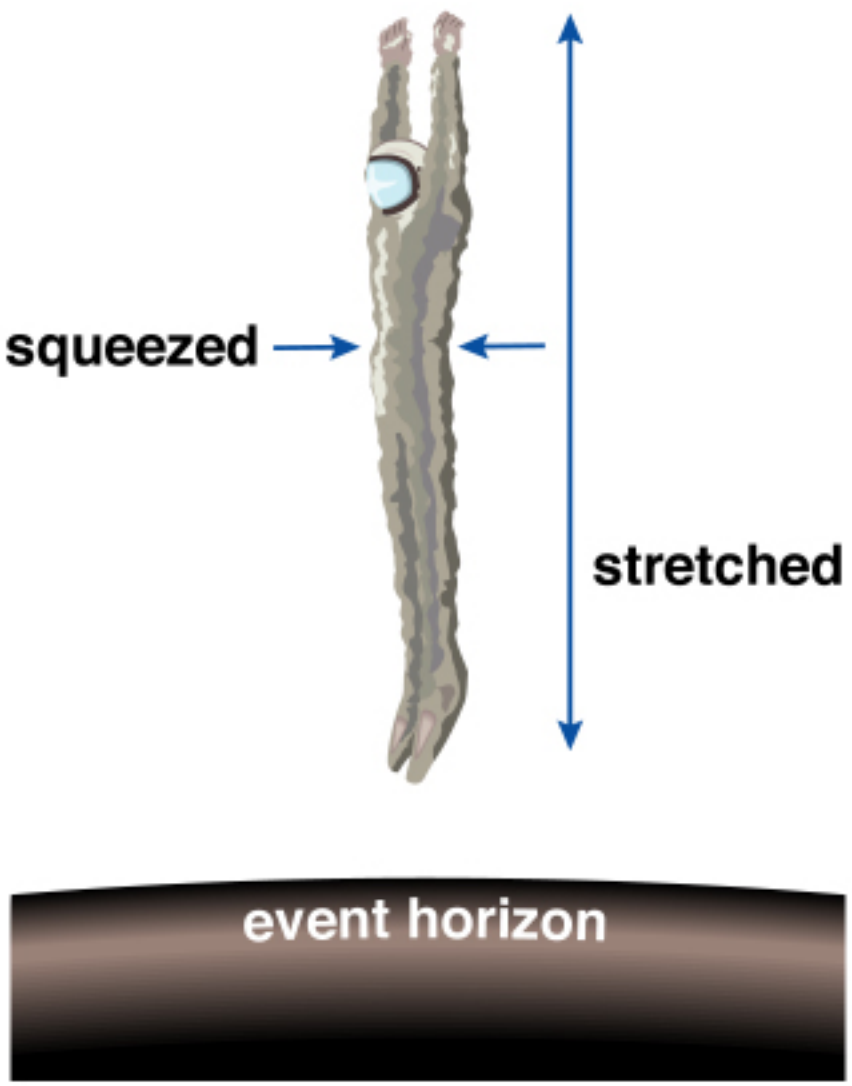


SIZE COMPARISON:

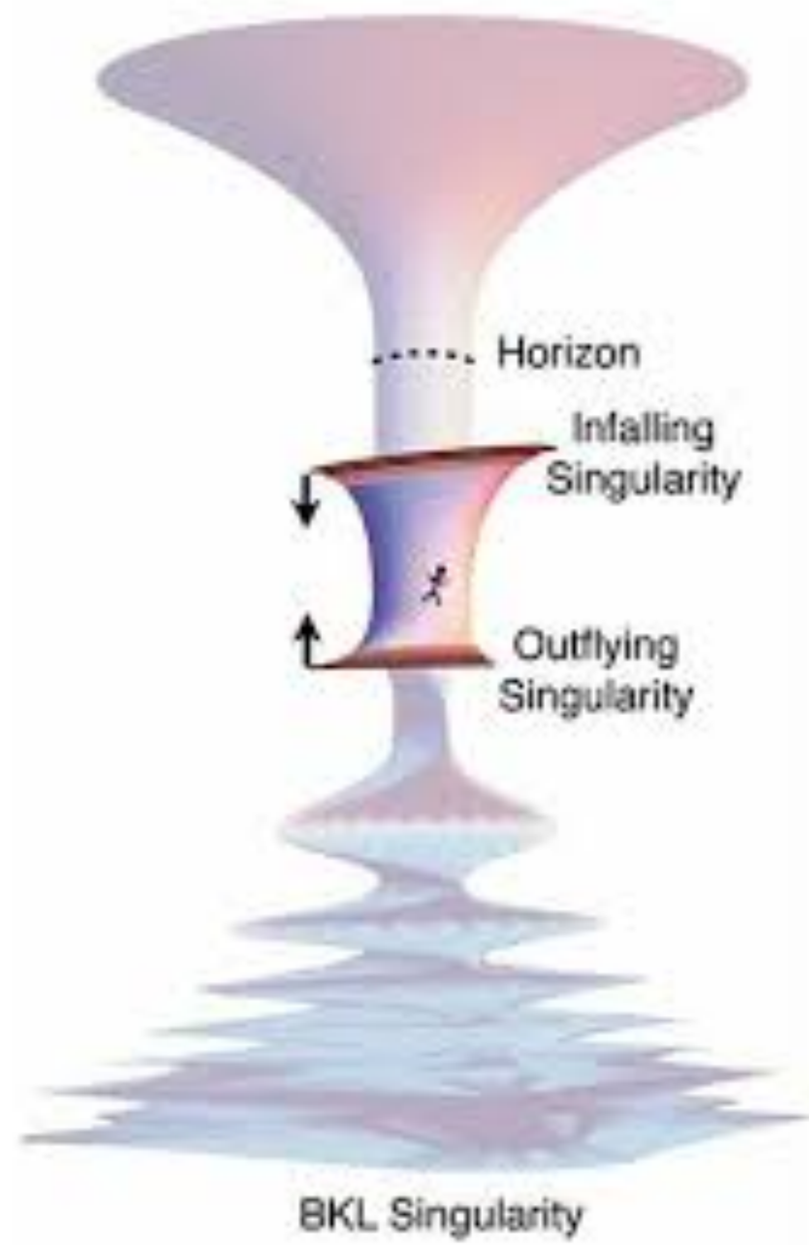
THE M87 BLACK HOLE
AND
OUR SOLAR SYSTEM



Falling into Black Hole



/esley

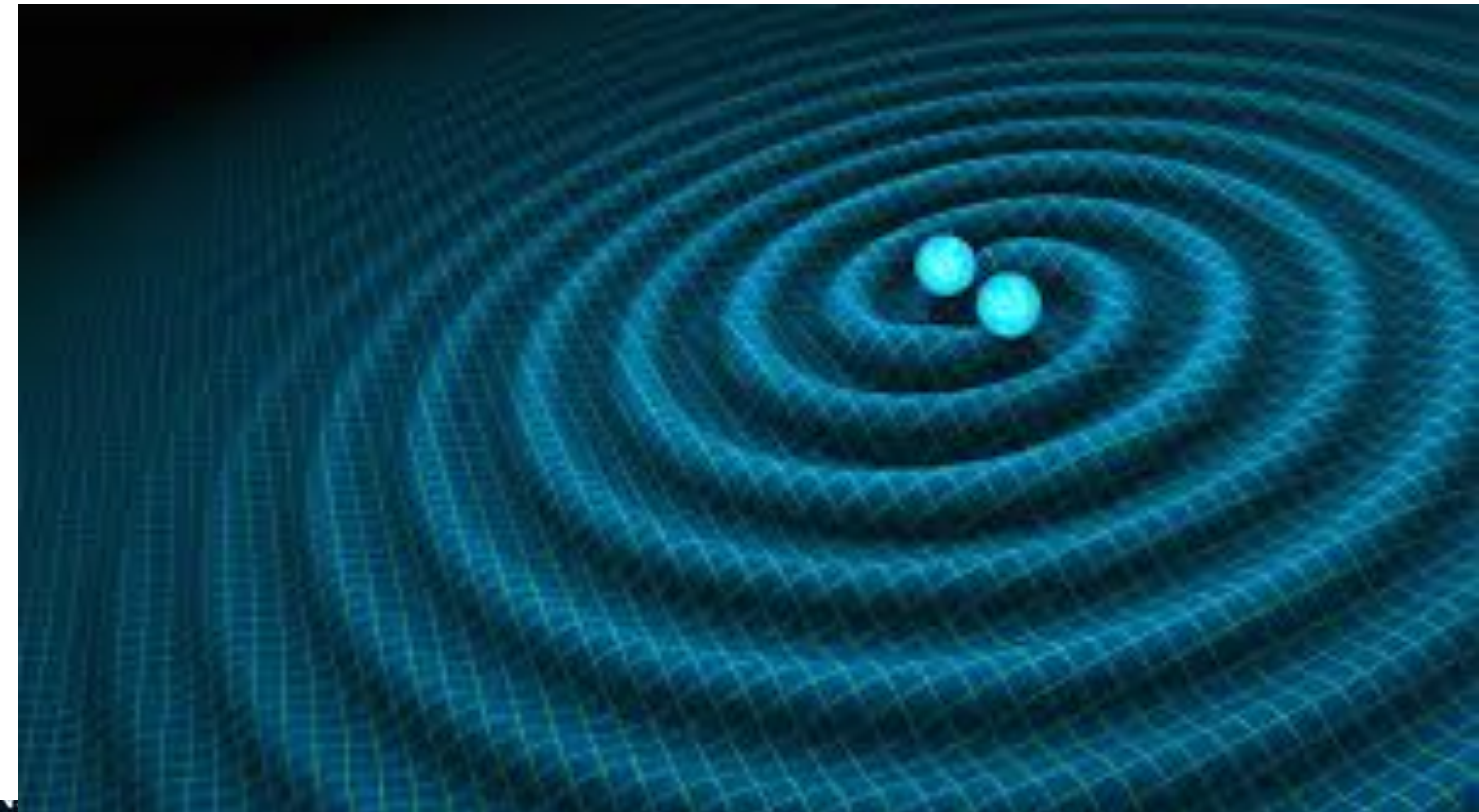


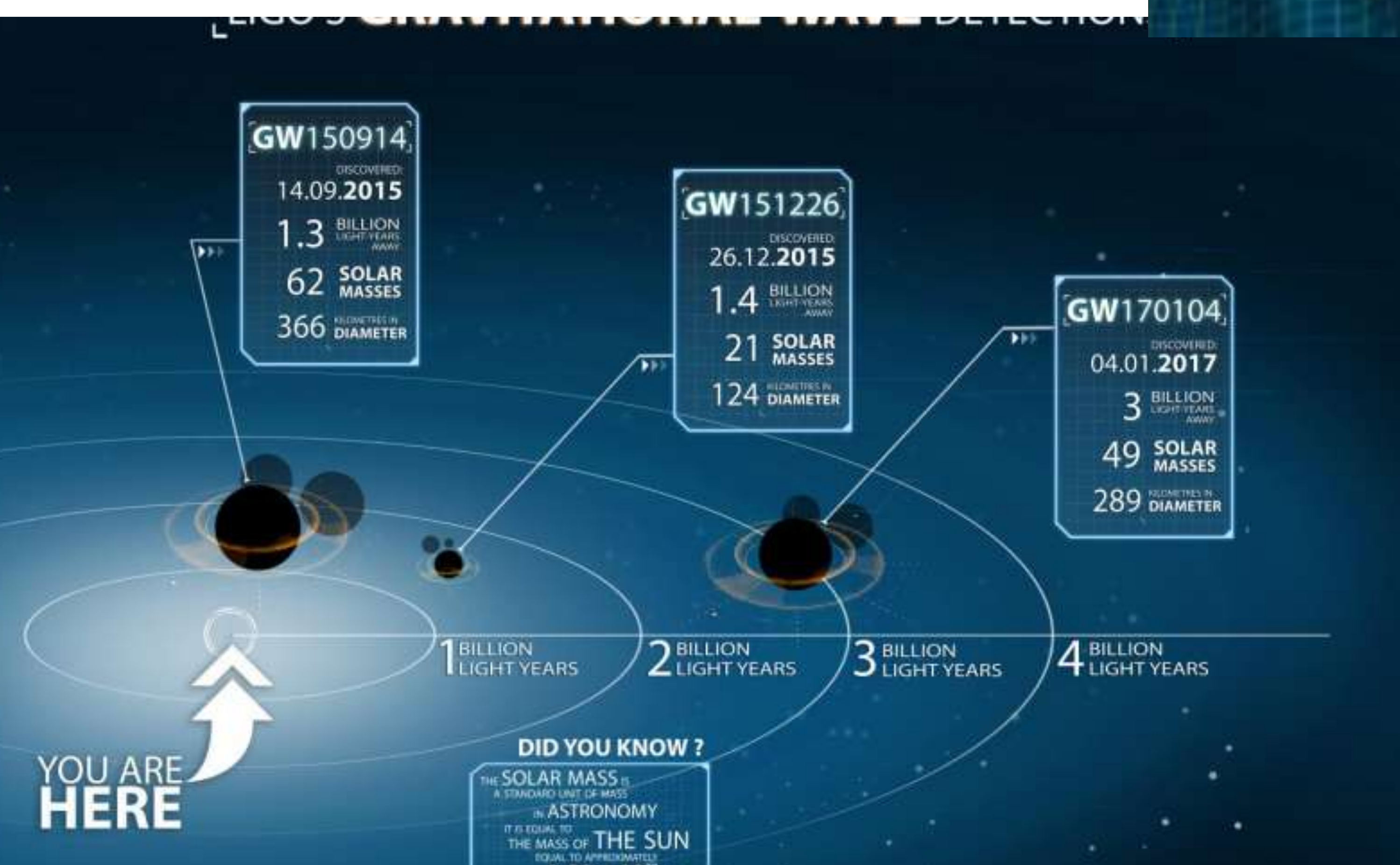
Gravitational Waves

Einstein equations

Geometry = Energy

$$G = T$$



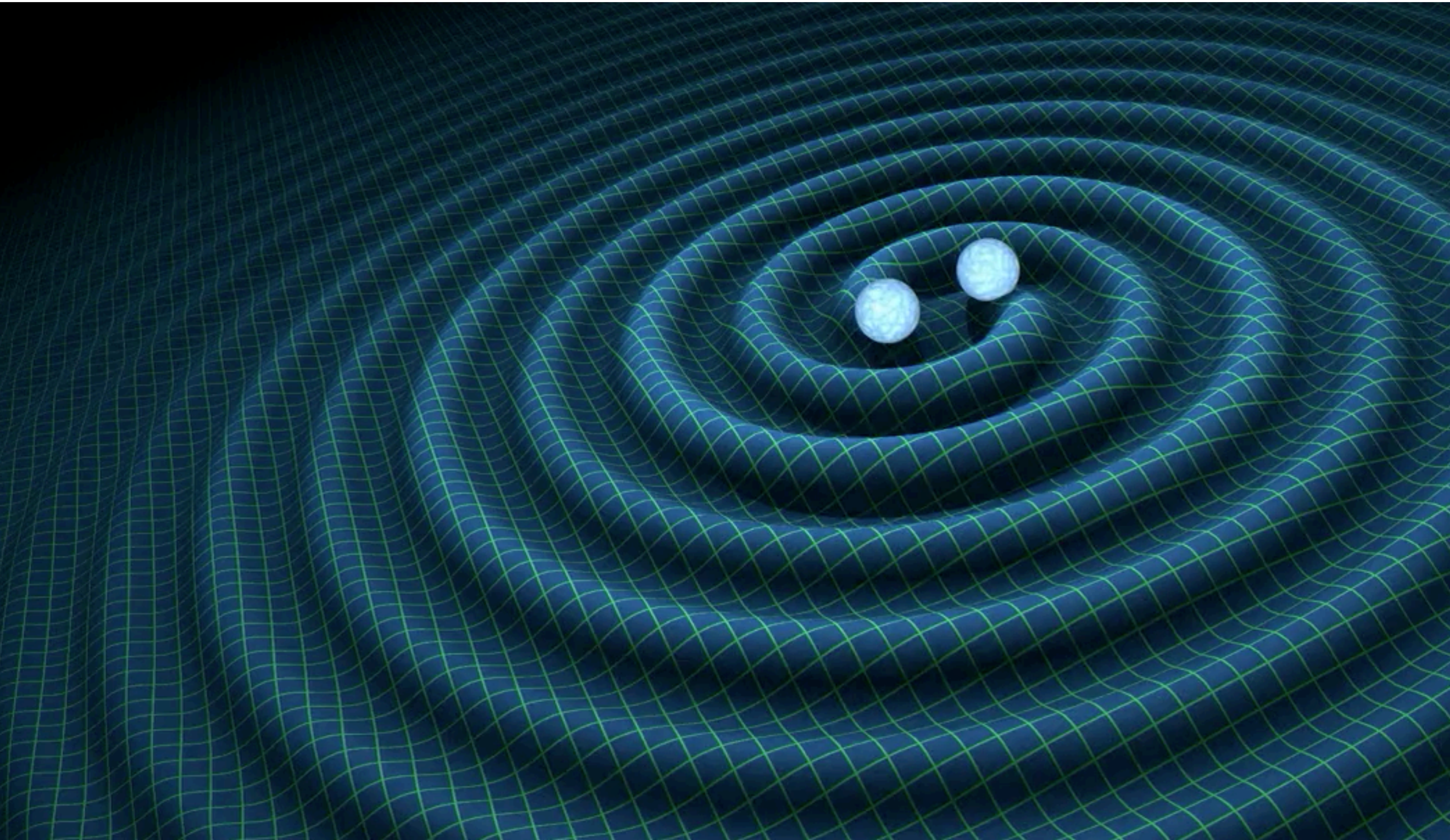


Fluctuations of the **fabric of space**

$$G = G + \delta G$$

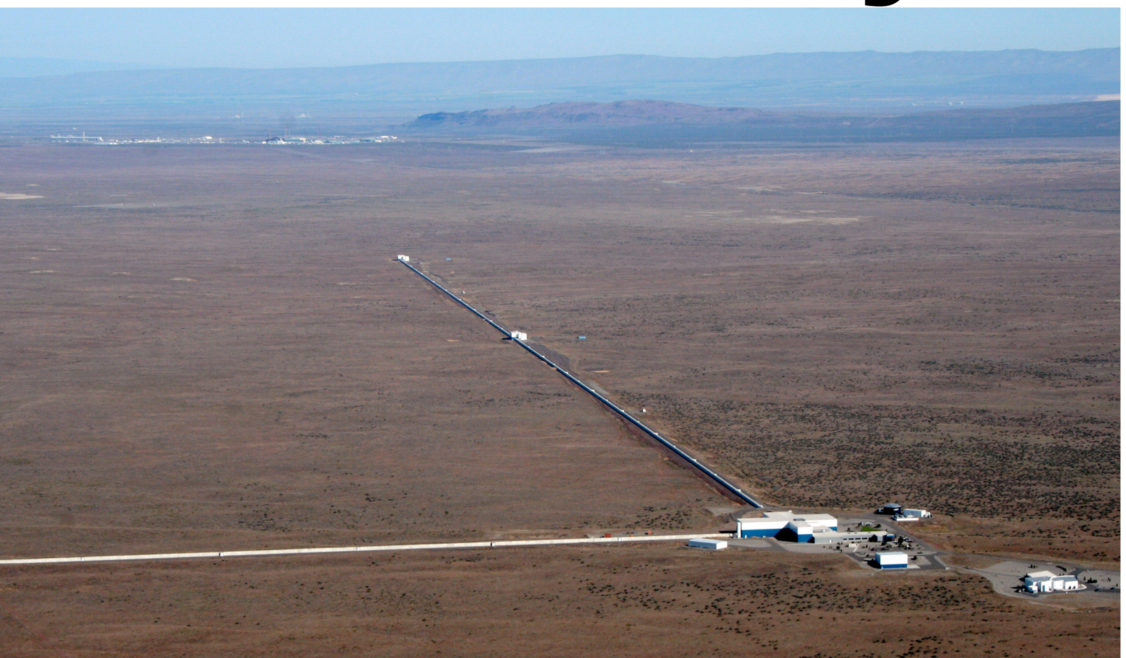
$$T = T + \delta T$$

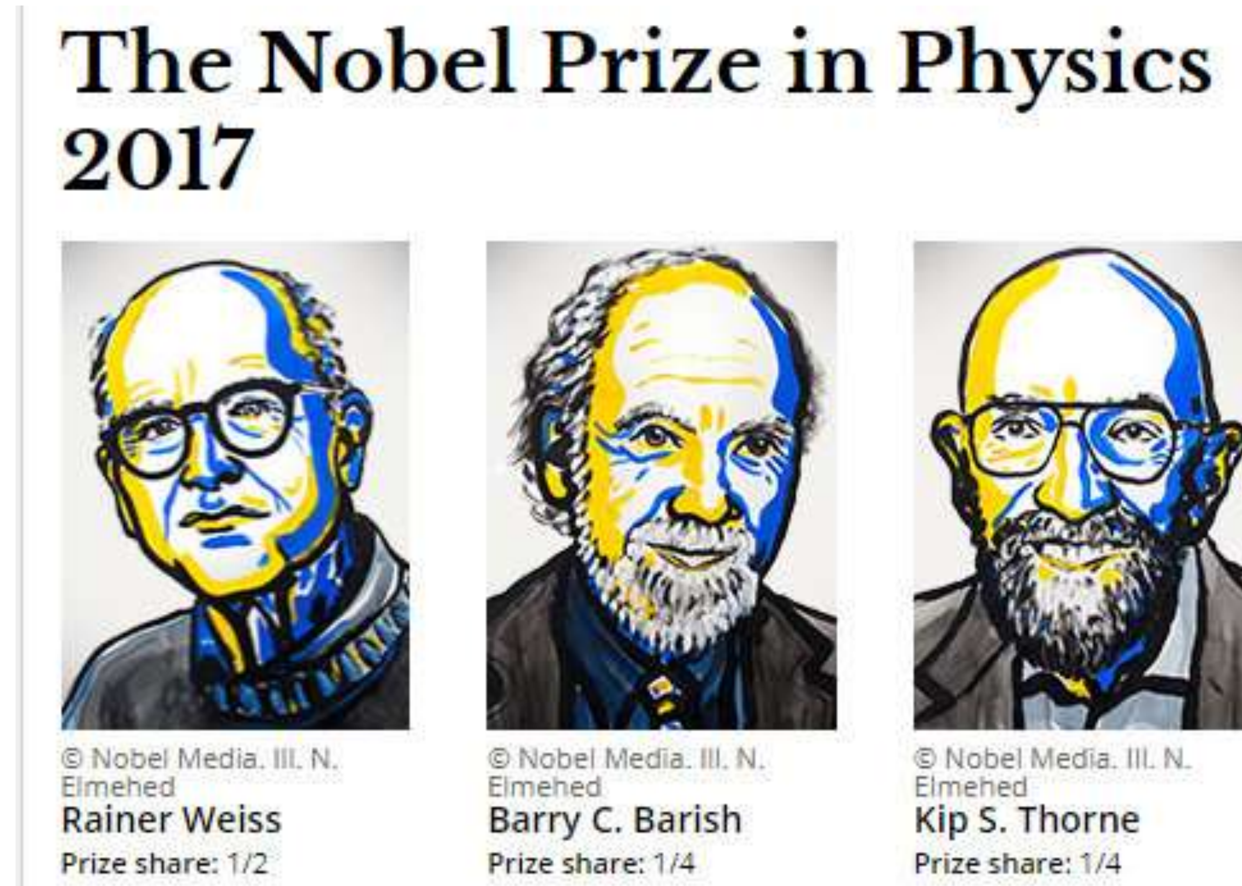
Waves from Binaries

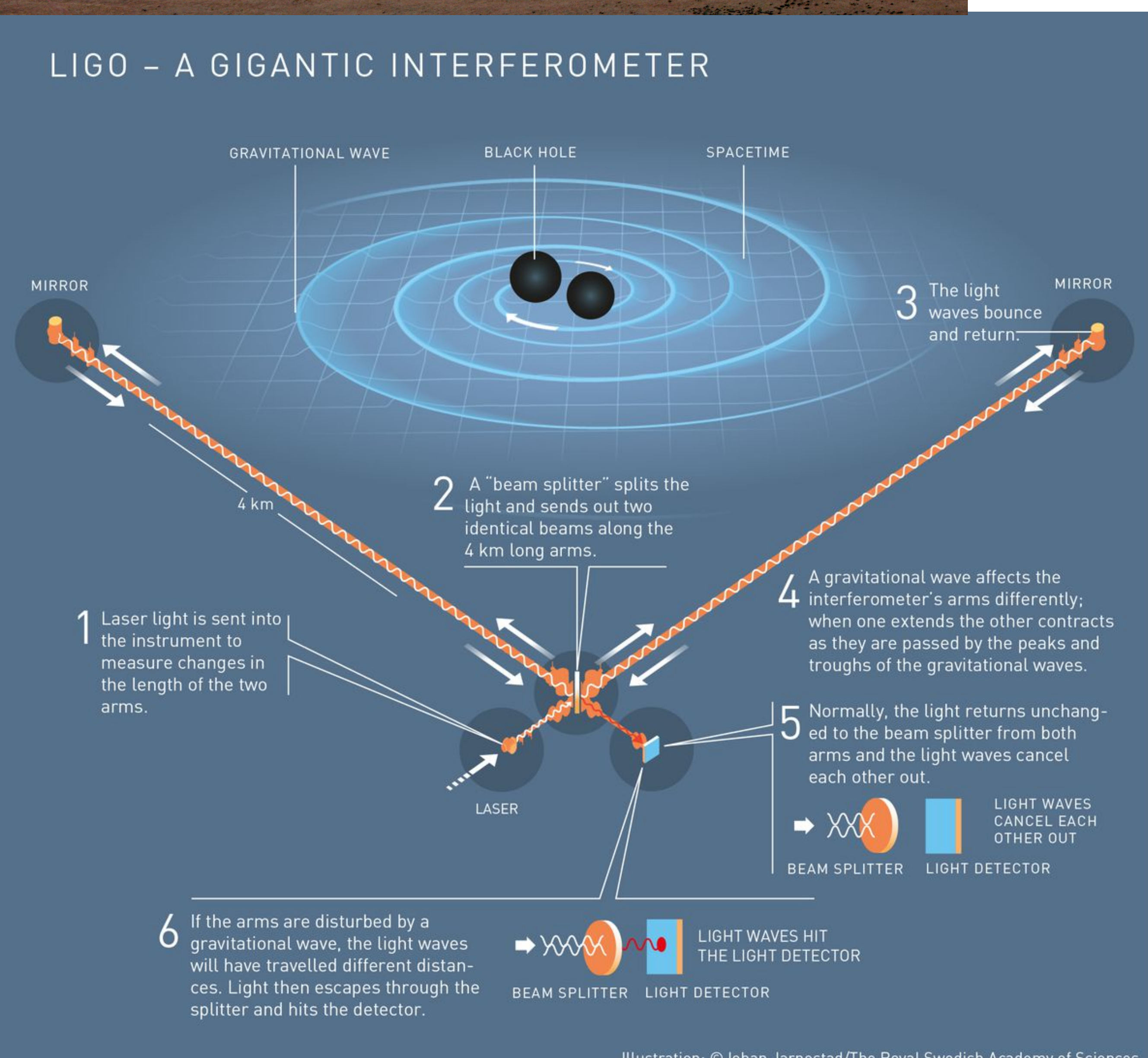


Gravity Wave

Gravity Wave Detectors



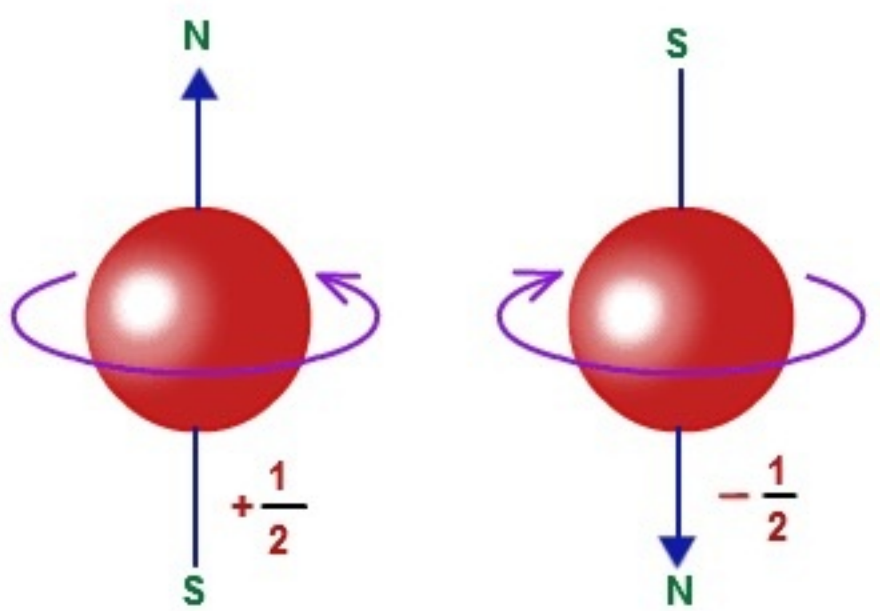




Quantum Mechanics
&
Entanglement

Spin

Electron can have spin up or down



$|\uparrow\rangle$ $|\downarrow\rangle$

According to quantum mechanics we can find an electron either with spin up or down with a probability

$$|\Psi\rangle = a|\uparrow\rangle + b|\downarrow\rangle$$

such that $a^2 + b^2 = 1$

Entanglement

Let us now take two electrons

All possible states

$|\uparrow\rangle|\uparrow\rangle \quad |\uparrow\rangle|\downarrow\rangle \quad |\downarrow\rangle|\uparrow\rangle \quad |\downarrow\rangle|\downarrow\rangle$

General state

$$|\Psi\rangle = c\,|\uparrow\rangle|\uparrow\rangle + d\,|\uparrow\rangle|\downarrow\rangle + e\,|\downarrow\rangle|\uparrow\rangle + f\,|\downarrow\rangle|\downarrow\rangle$$

Cannot be generally written as product

$$(a\,|\uparrow\rangle + b\,|\downarrow\rangle)(A\,|\uparrow\rangle + B\,|\downarrow\rangle)$$

If not then we say the spin 1 is **entangled** with spin 2

Examples

Not entangled

$$|\downarrow\rangle|\uparrow\rangle$$

$$|\uparrow\rangle|\uparrow\rangle + |\uparrow\rangle|\downarrow\rangle = |\uparrow\rangle(|\uparrow\rangle + |\downarrow\rangle)$$

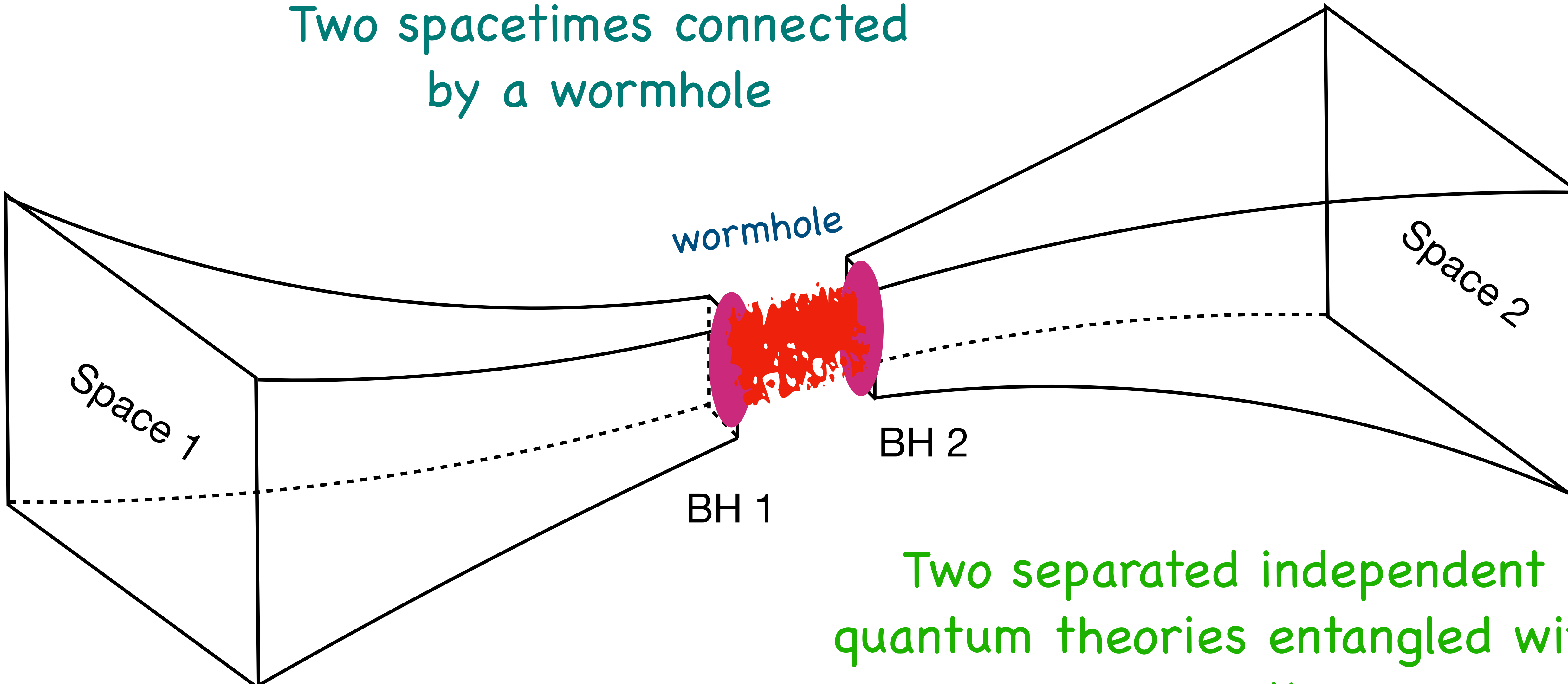
Entangled

$$|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle$$

$$|\uparrow\rangle|\uparrow\rangle + |\downarrow\rangle|\downarrow\rangle$$

Entanglement in Gravity

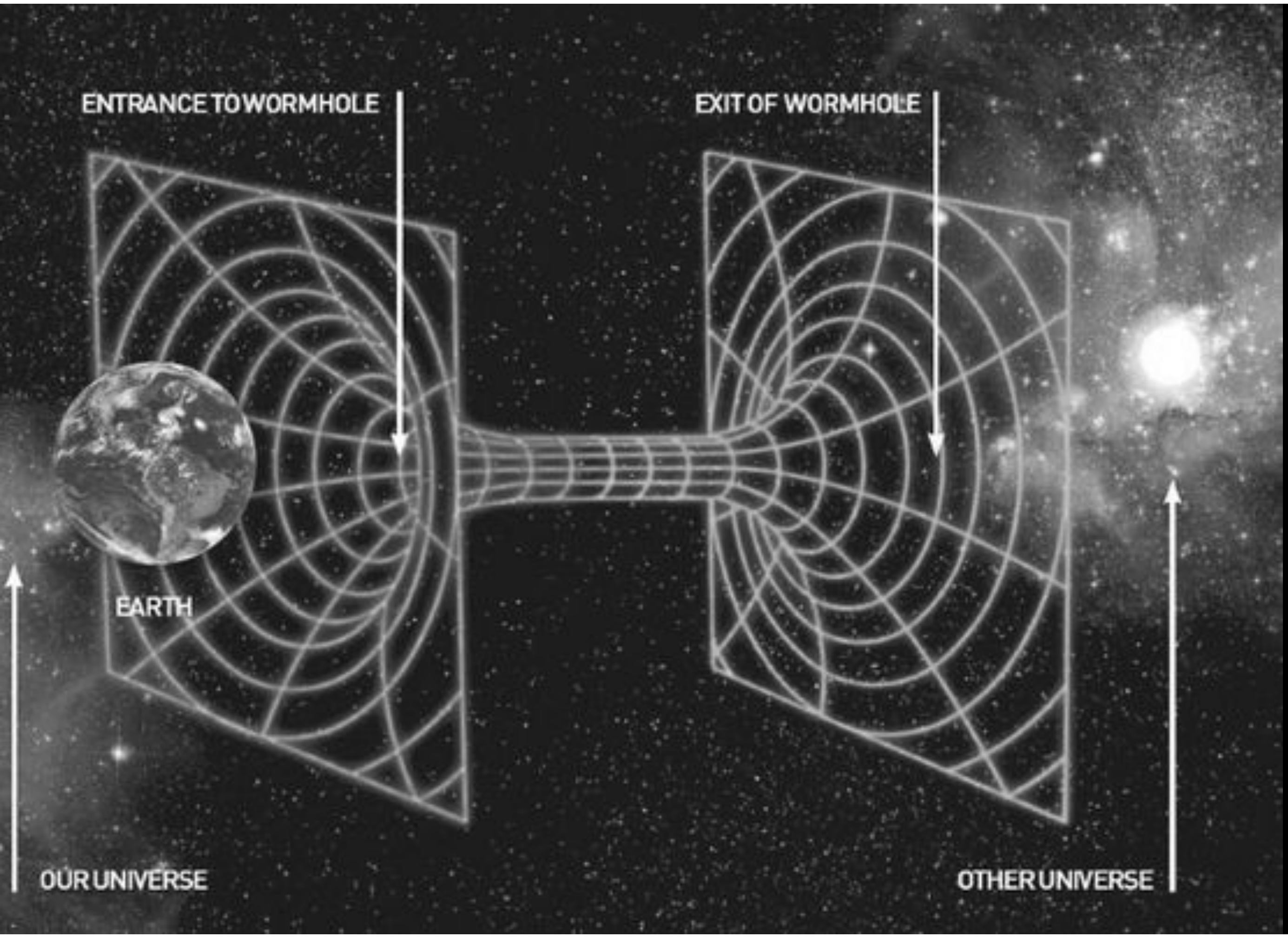
Two spacetimes connected by a wormhole

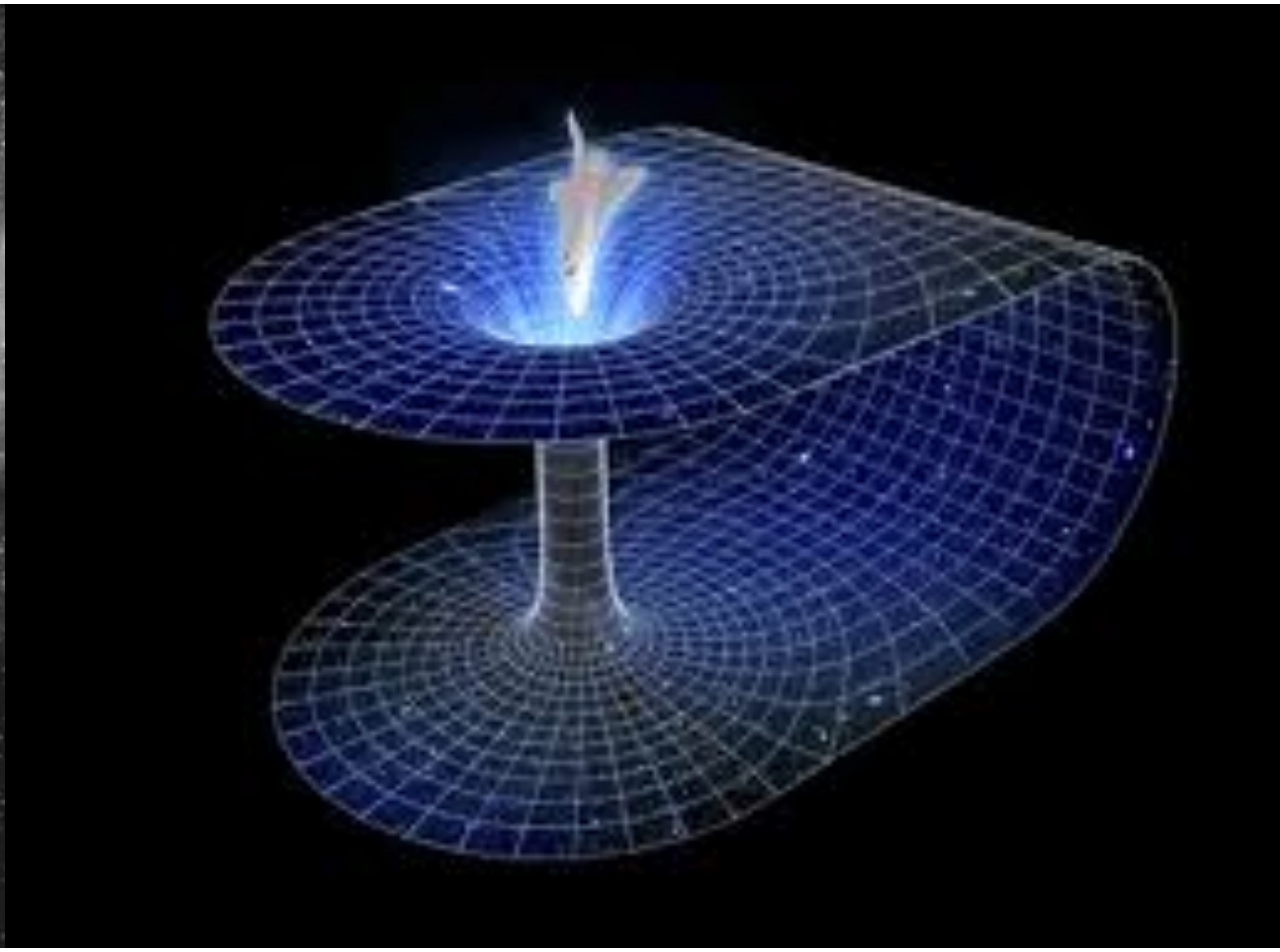


Two separated independent quantum theories entangled with one another

$$|\Psi\rangle = |0\rangle_1 |0\rangle_2 + c\, |\uparrow\rangle_1 |\uparrow\rangle_2 + d\, |\uparrow\rangle_1 |\downarrow\rangle_2 + \ldots$$

Wormholes

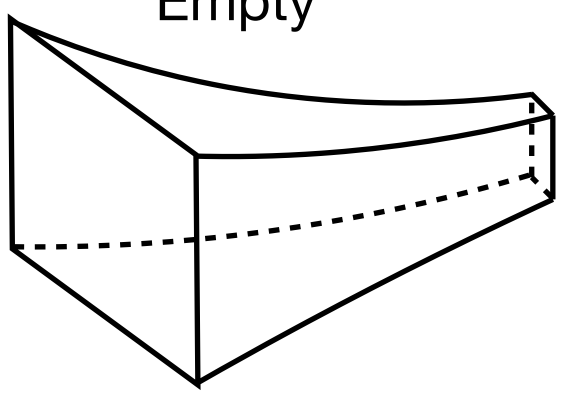

ENTRANCE TO WORMHOLE
EXIT OF WORMHOLE
EARTH
OUR UNIVERSE
OTHER UNIVERSE



Holographic Principle

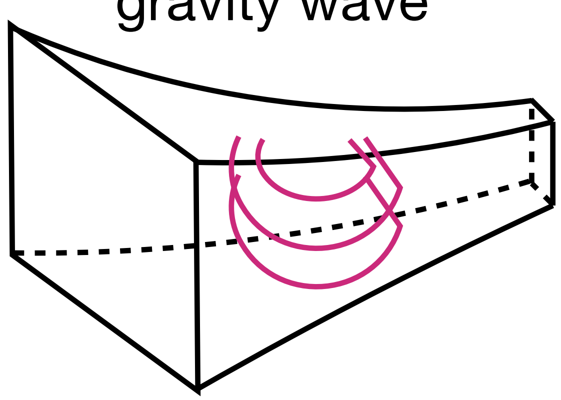
Spacetime | **States in quantum field theory**

Empty

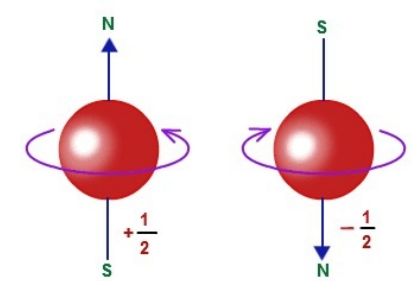


vacuum $|0\rangle$

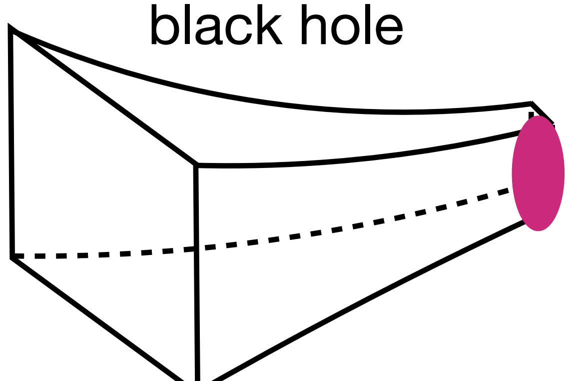
gravity wave



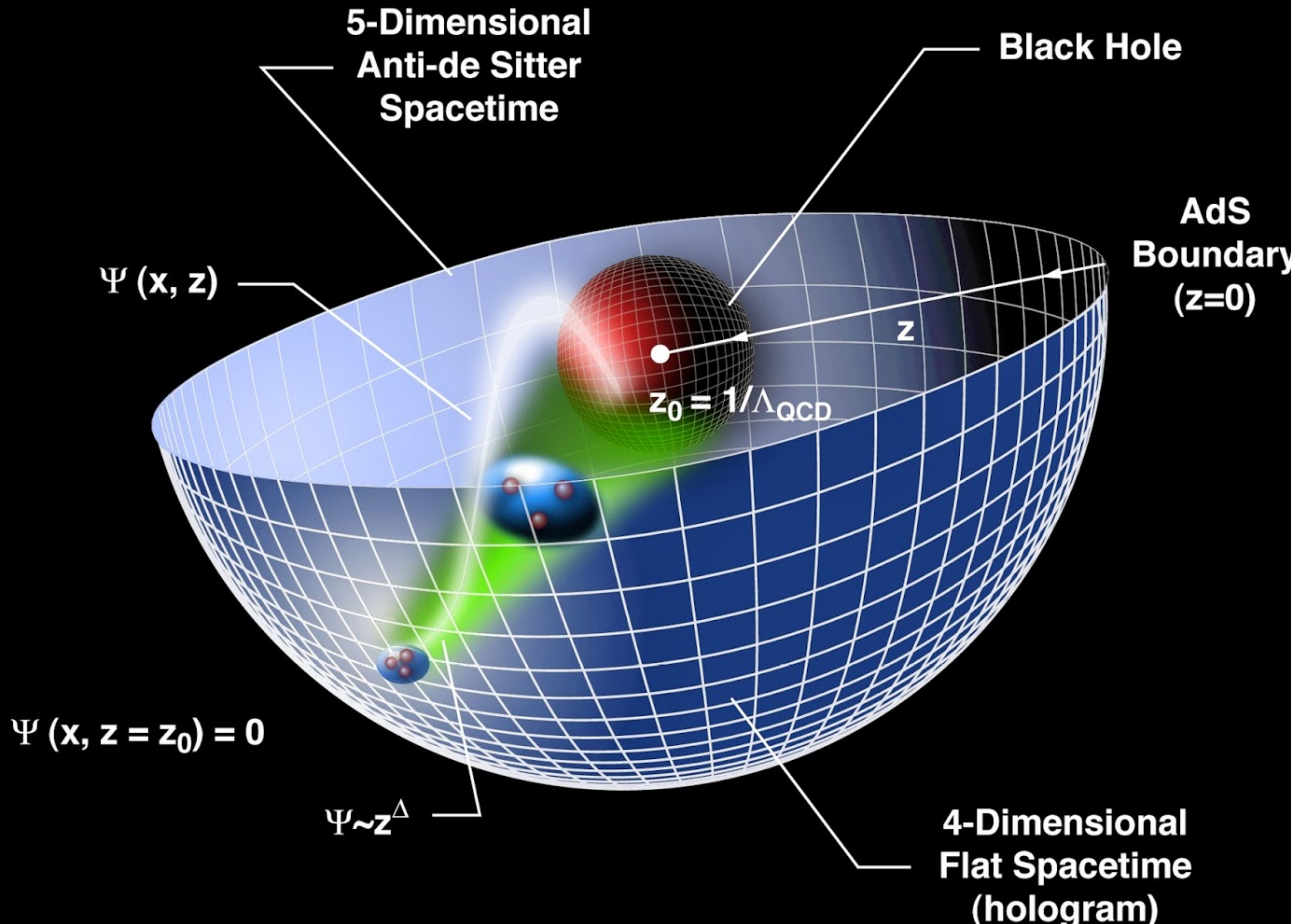
particles



black hole



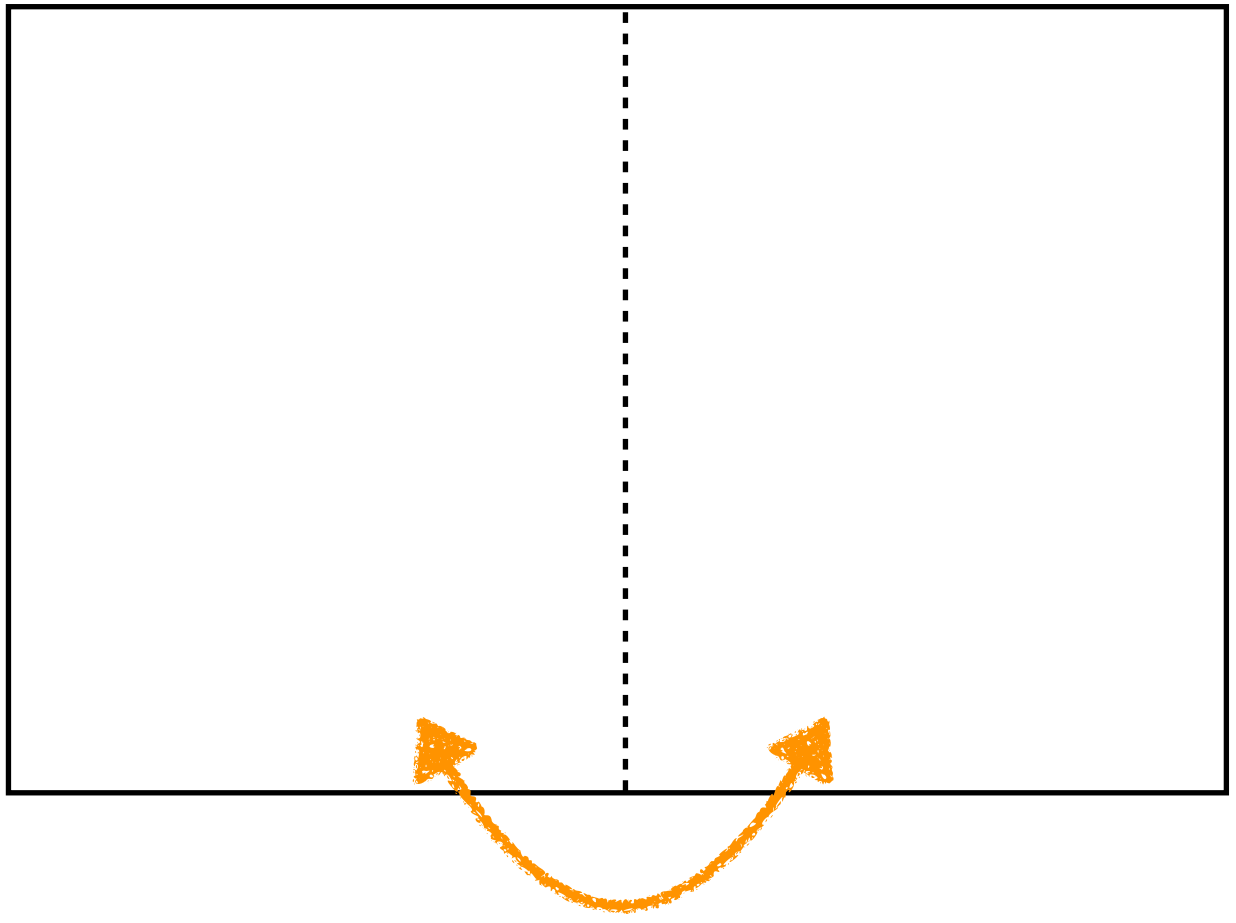
higher excitations



5-Dimensional
Anti-de Sitter
Spacetime
Black Hole
AdS
Boundary
(z=0)
Ψ (x, z)
z
$z_0 = 1/\Lambda_{QCD}$
Ψ (x, z = z_0) = 0
$\Psi \sim z^{\Delta}$
4-Dimensional
Flat Spacetime
(hologram)

Entanglement in QFT

Vacuum state has a lot of entanglement already

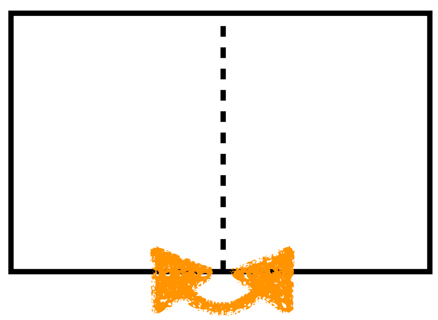


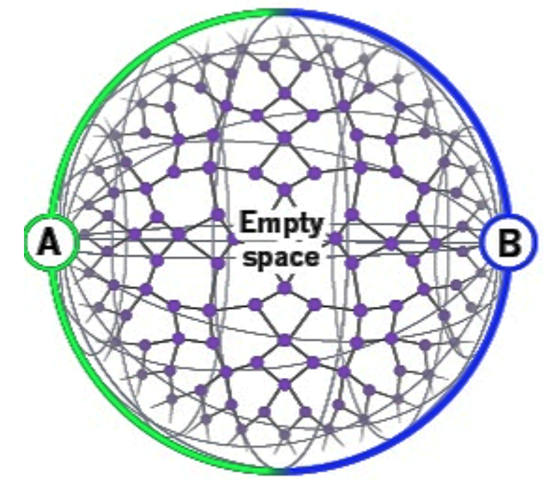
In this room electromagnetic field on one side is entangled with that on another side

Pulling space apart

Highly entangled

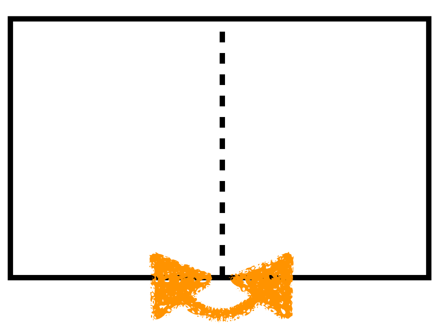
$|0\rangle$

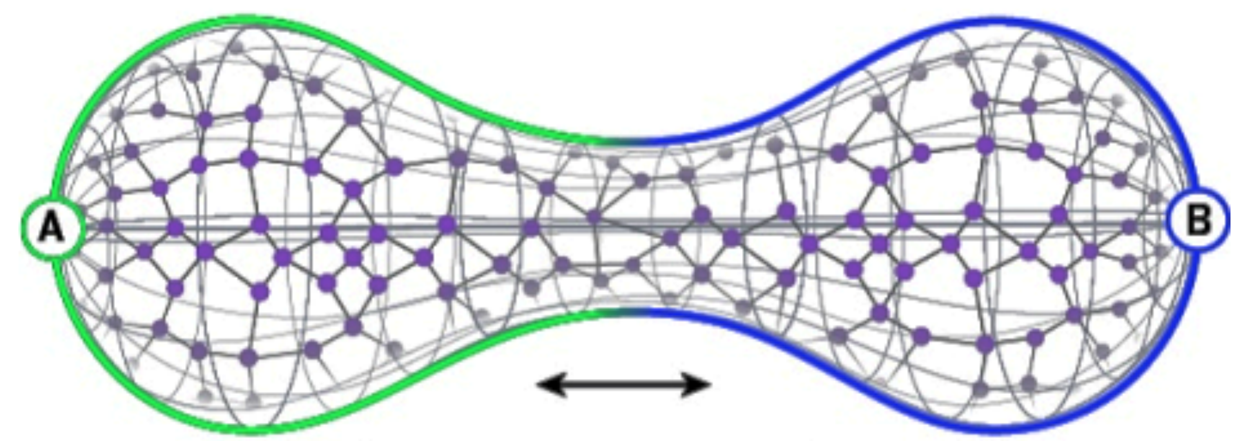




Less entangled

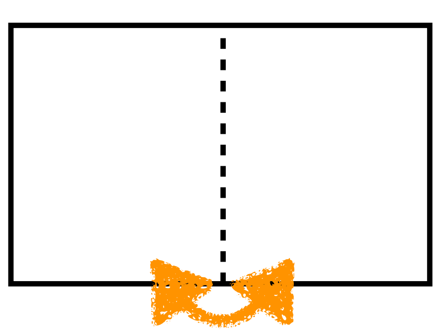
$|\Psi_1\rangle$

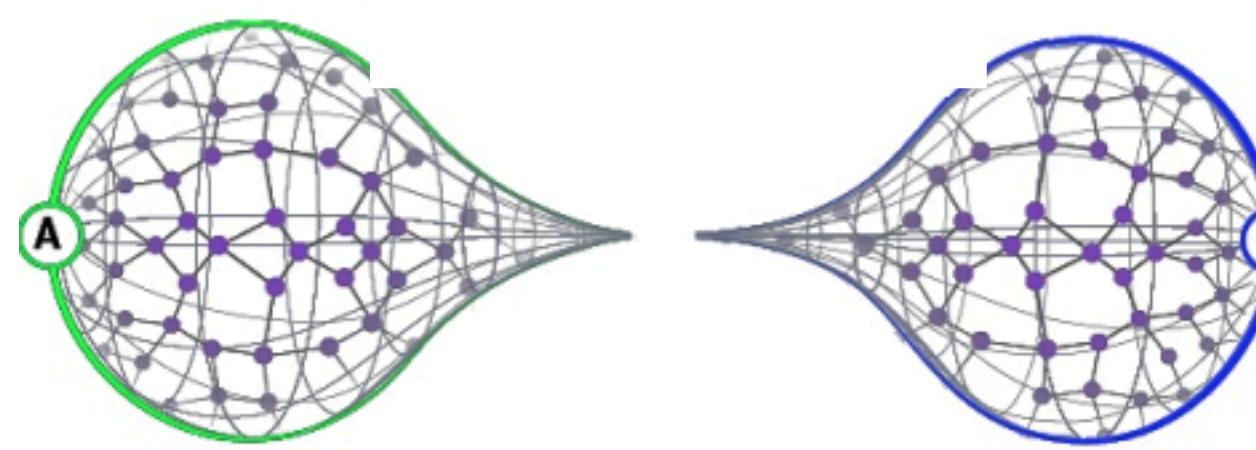




Even less entangled

$|\Psi_2\rangle$





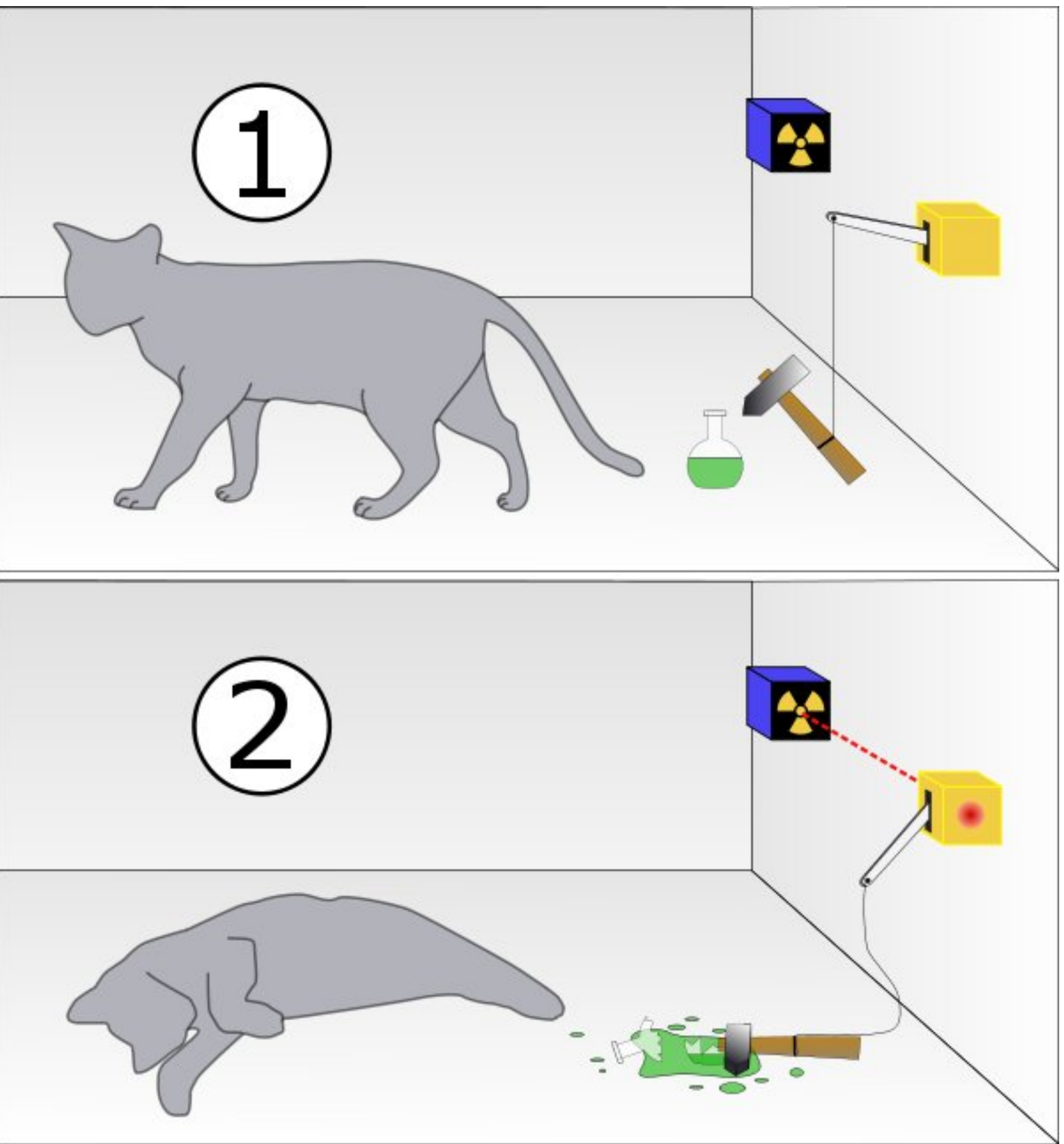
Space via Entanglement

This suggests that **spacetime geometry** emerges via **entanglement** of degrees of freedom of the dual field theory!

In other words, there is no classical spacetime without entanglement

Measurement in Quantum Mechanics

Schrodinger's cat



We cannot find out till we open the box whether:

$|\uparrow\rangle$ Cat is alive

$|\downarrow\rangle$ Cat is dead

Measuring Probabilities

Not entangled

$|\downarrow\rangle|\uparrow\rangle \longrightarrow |\downarrow\rangle$ p = 1

$|\uparrow\rangle|\uparrow\rangle + |\uparrow\rangle|\downarrow\rangle = |\uparrow\rangle(|\uparrow\rangle + |\downarrow\rangle) \longrightarrow |\uparrow\rangle$ p = 1

Entangled

$$\frac{1}{\sqrt{2}}|\uparrow\rangle|\downarrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle|\uparrow\rangle$$

$$\frac{1}{\sqrt{2}}|\uparrow\rangle|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle|\downarrow\rangle$$

$\longrightarrow$

$|\downarrow\rangle$ p = 1/2

$|\uparrow\rangle$ p = 1/2

Less entangled

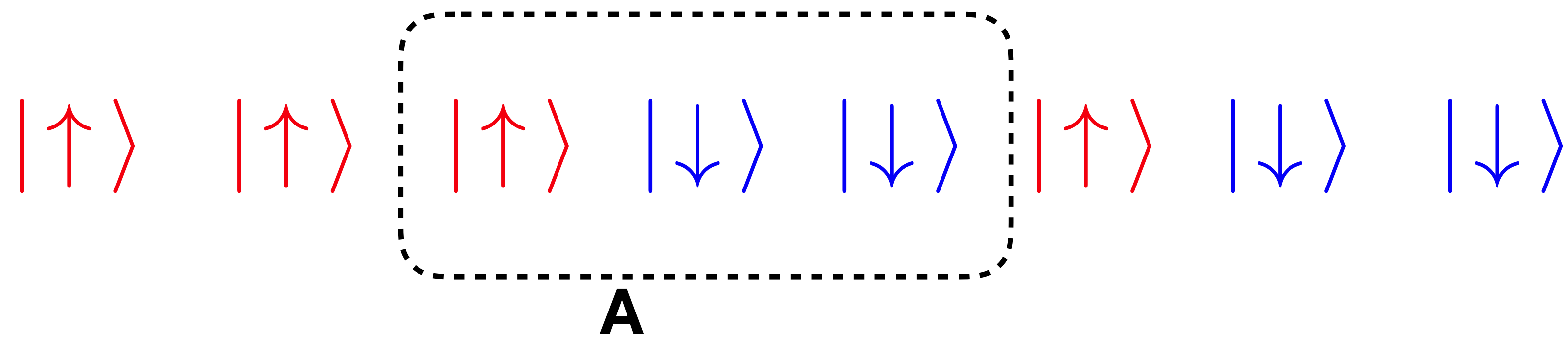
$$\sqrt{\frac{9}{10}}|\uparrow\rangle|\downarrow\rangle + \sqrt{\frac{1}{10}}|\downarrow\rangle|\uparrow\rangle \longrightarrow$$

$|\downarrow\rangle$ p = 1/10

$|\uparrow\rangle$ p = 9/10

Entanglement Entropy

Entropy of the subsystem A counts the total number of states



$|\Psi_i\rangle$ has probability p_i

Entanglement of the subsystem A with the rest of the system can be quantified by the entropy of the ensemble when we count only states of the subsystem

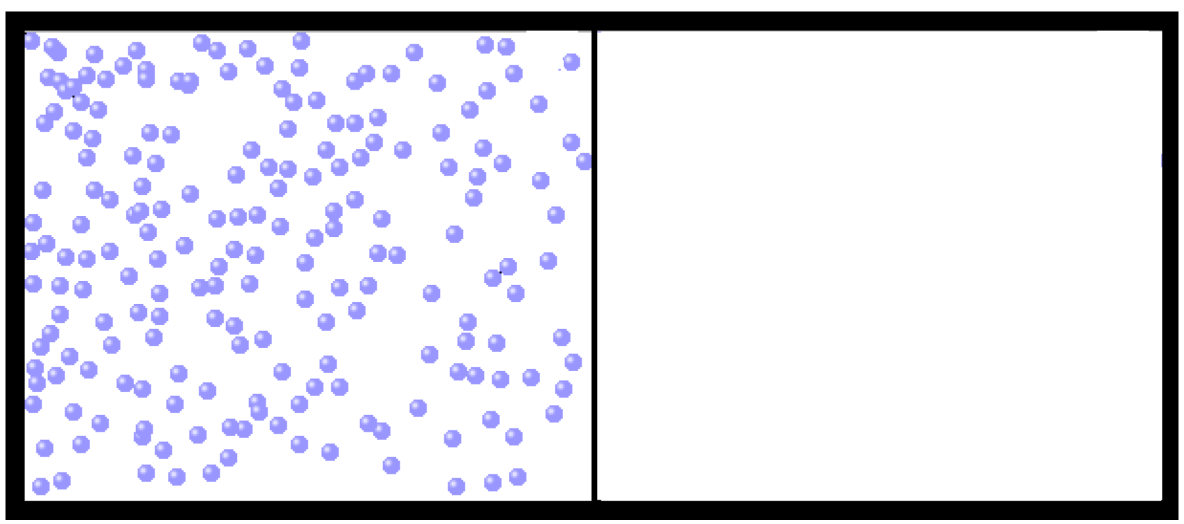
Entropy and Temperature

Entropy counts the (logarithm of) the number of states a system can have

$$S = k \log \Omega$$

Discrete in quantum statistics, continuous in classical

The second law states that entropy never decreases in a thermodynamical system



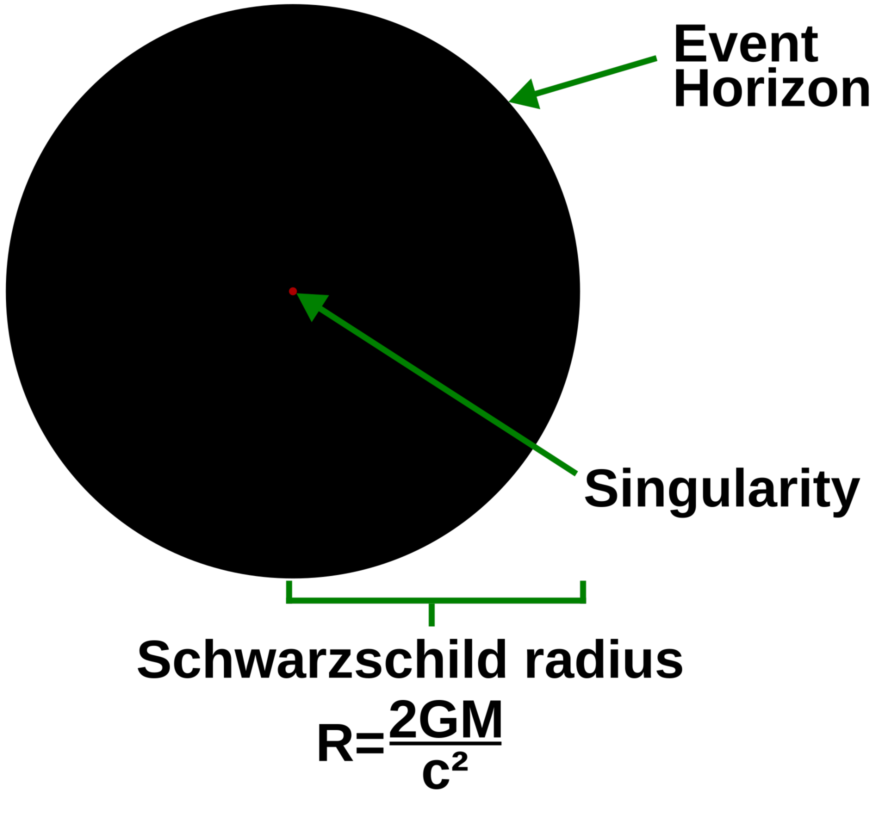
Temperature $$\frac{1}{T} = \frac{\Delta S}{\Delta E}$$

The Second Law of Thermodynamics, Stated as the Law of Entropy

The total entropy (or microscopic disorganization) of all the participants in any physical process cannot decrease during that process, but it can increase.

Black Hole Entropy

Entropy $S = \frac{\text{Area of the BH horizon}}{4}$

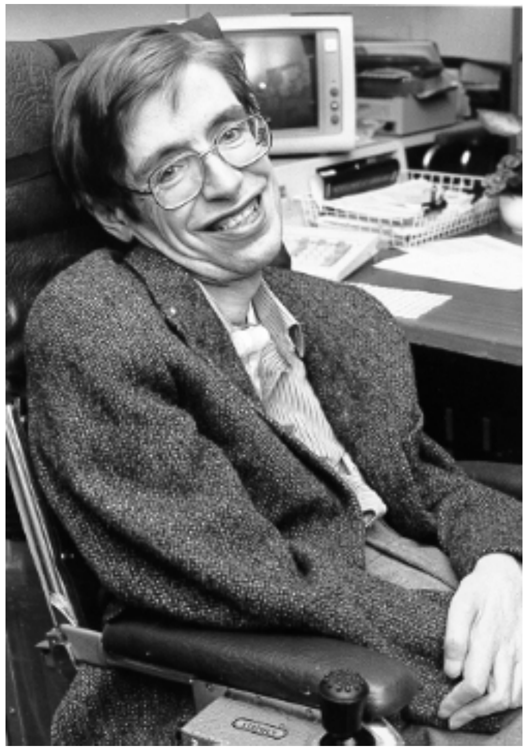


BH formula provides the (entanglement) entropy for a holographically dual theory at Hawking temperature

$$Energy = \frac{Entropy}{Temperature}$$

$$E = mc^2$$

Black Hole Radiation



Stephen Hawking realized that black holes should be considered as thermodynamical objects so they should have temperature

Entropy $$S = \frac{\text{Area of the BH horizon}}{4}$$

When an object falls into the BH it causes the horizon to expand slightly, which causes the changes in the entropy and hence defines the temperature

$$T_{\mathrm{H}} = \frac{1}{8\pi M}$$

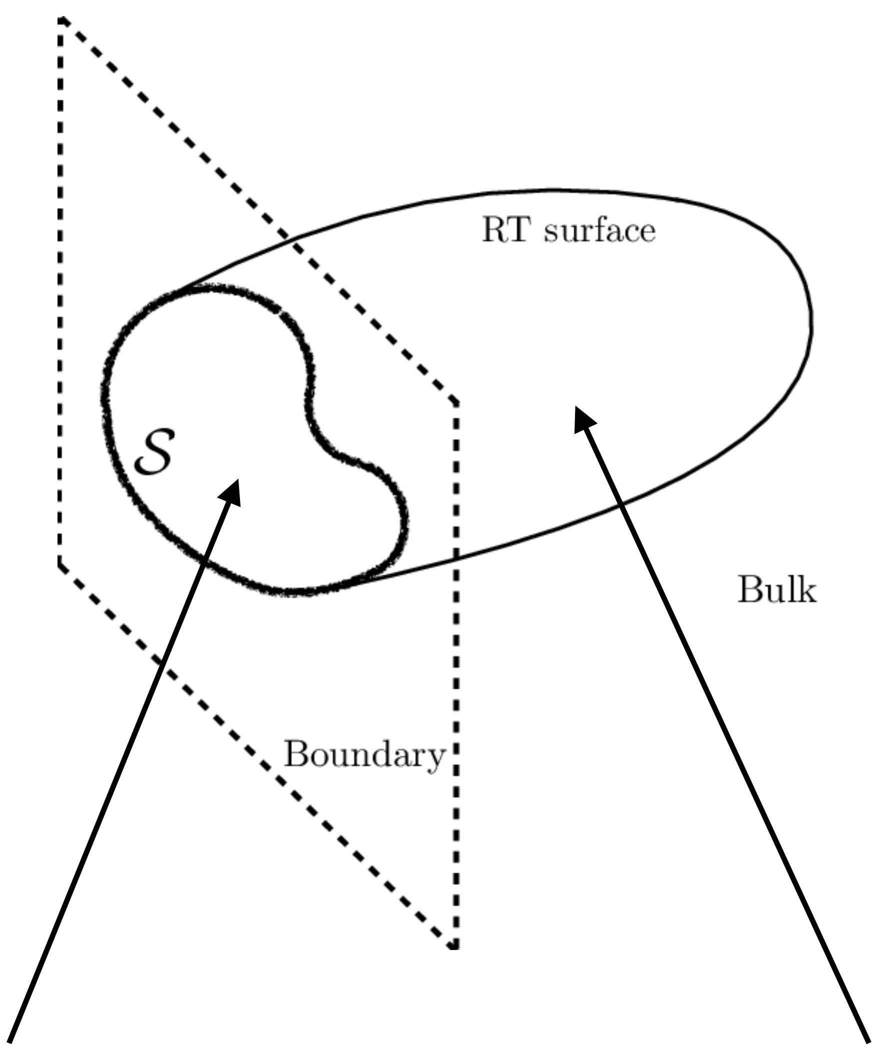
A body with nonzero temperature radiates (photons) so it looses energy into the outer space

One can estimate how quickly a BH will have evaporated completely. Those times are gigantic: a solar mass black hole will take about 10^{64} years

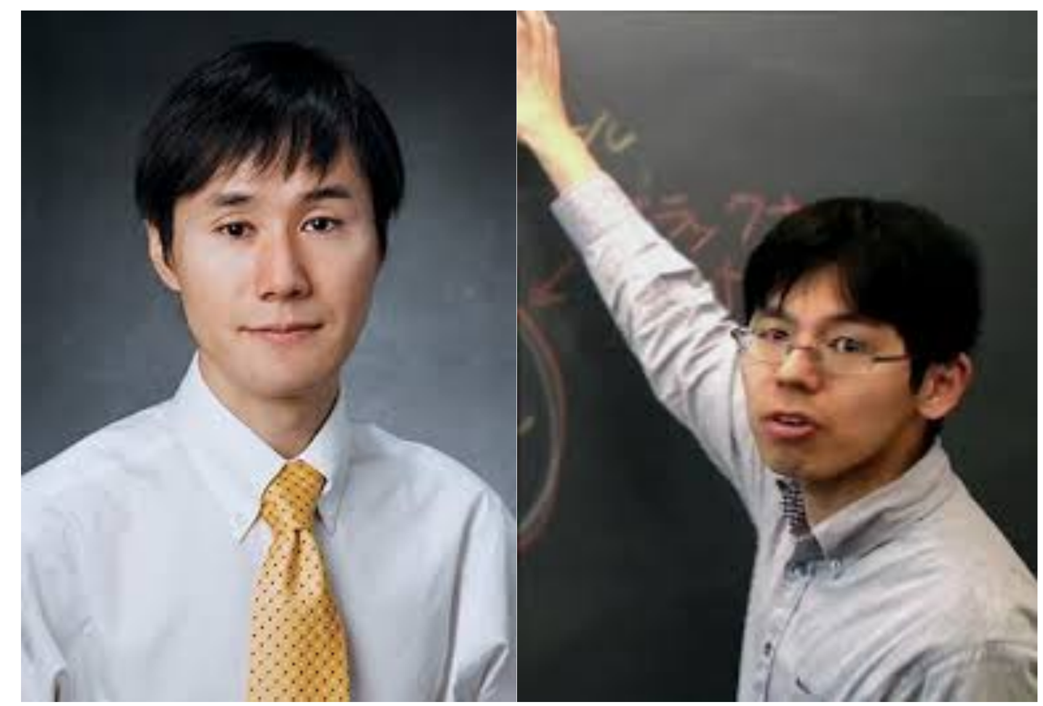
However, tiny BHs which could exist in principle may be evaporating in the Universe right now as we speak !

Entanglement in Holography

Entropy of any QFT subsystem (i.e. entanglement entropy)
has a geometric interpretation in the dual gravity theory

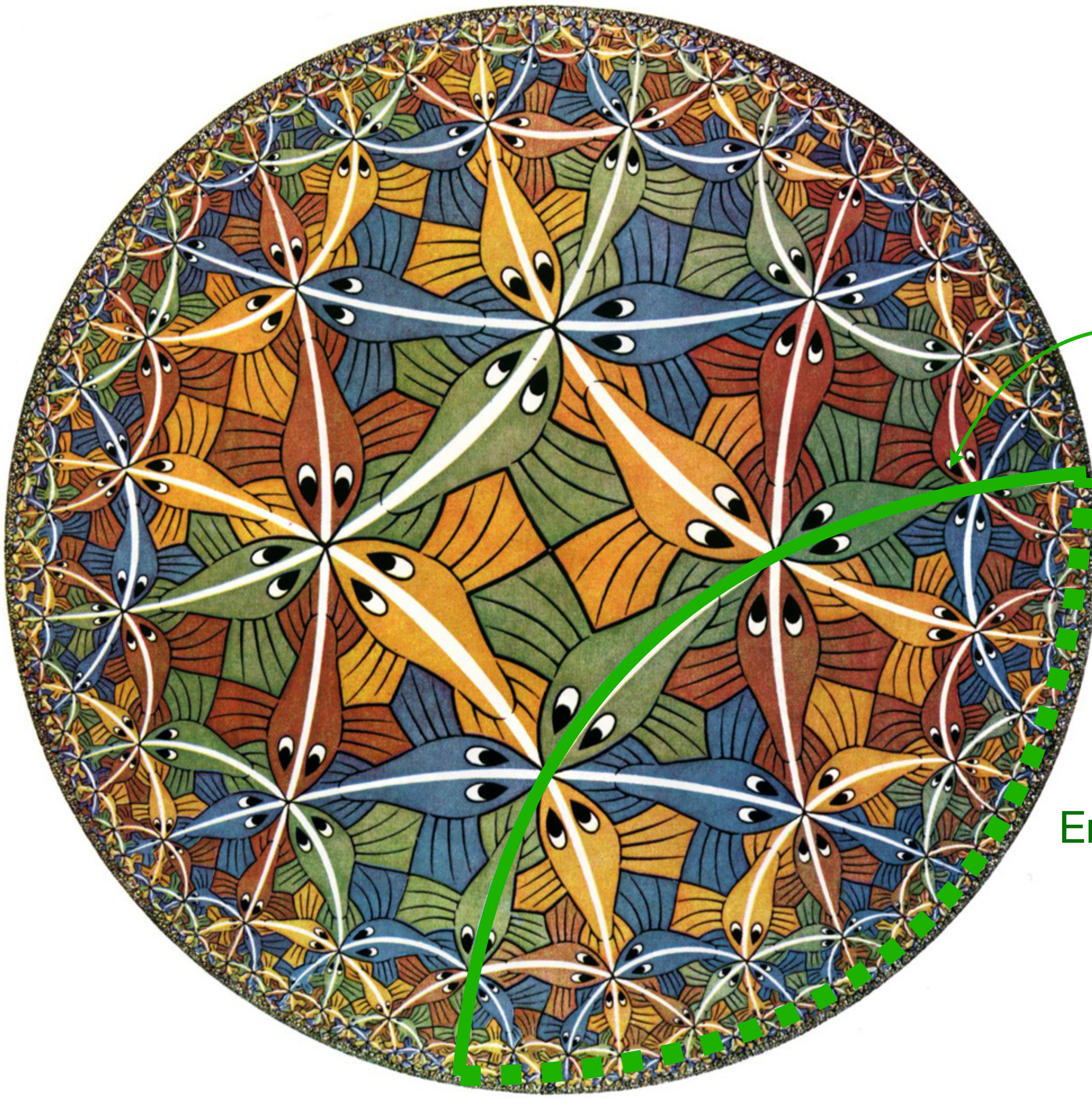


Entropy of this region = Area of the minimal surface



Ryu **Takayanagi**

Entropy vs Area



Anti-deSitter space

Shortest path through the bulk which has the same length as the boundary

Entanglement entropy of the boundary

From Entanglement to Geometry

One can now calculate entanglement entropy for any region of the boundary theory. We then *declare* that this **entropy** should be equal to the **area** of some region in the bulk of the dual spacetime. Thus by studying **entanglement** we can try to deduce geometry.

$|\Psi\rangle$ ⟶ Calculate S(A) for many A ⟶ Find dual geometry to $|\Psi\rangle$ so that S(A)= Area

$S(A) + S(B) \geq S(AB)$ ⟶ These geometries should satisfy Einstein equations

$$\Delta S(A) = \frac{\Delta \langle E \rangle}{T}$$

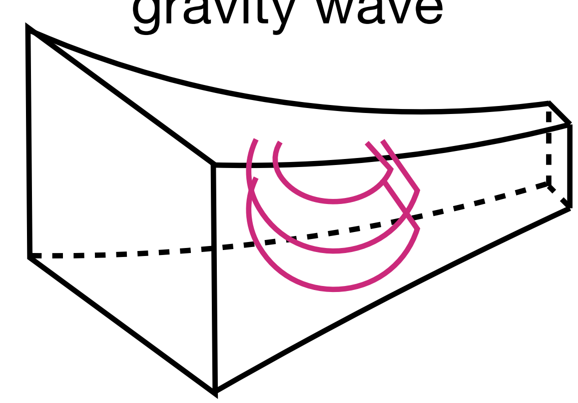
Perturbing States

Set of entropy constraints for all regions A on the boundary

↓ Some math …

Geometry must satisfy linearized Einstein equations!
(gravitational waves!)

gravity wave



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