The meaning of spacetime:

Black holes, wormholes and quantum entanglement.

Juan Maldacena

Carl P. Feinberg professor

Institute for Advanced Study

Strings 2023, public talk

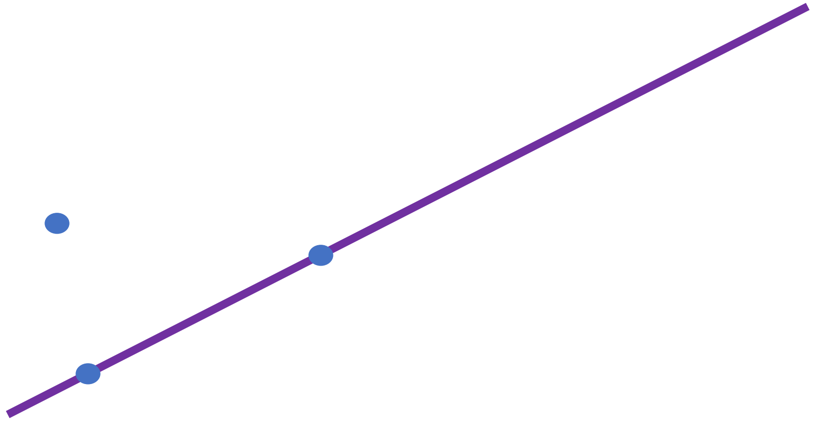
The book of nature is written in terms of mathematics and geometry…

Galileo

Let’s talk about geometry

Euclidean geometry

- Points
- Lines (straight)
- Circles, etc.



We use it to describe images…

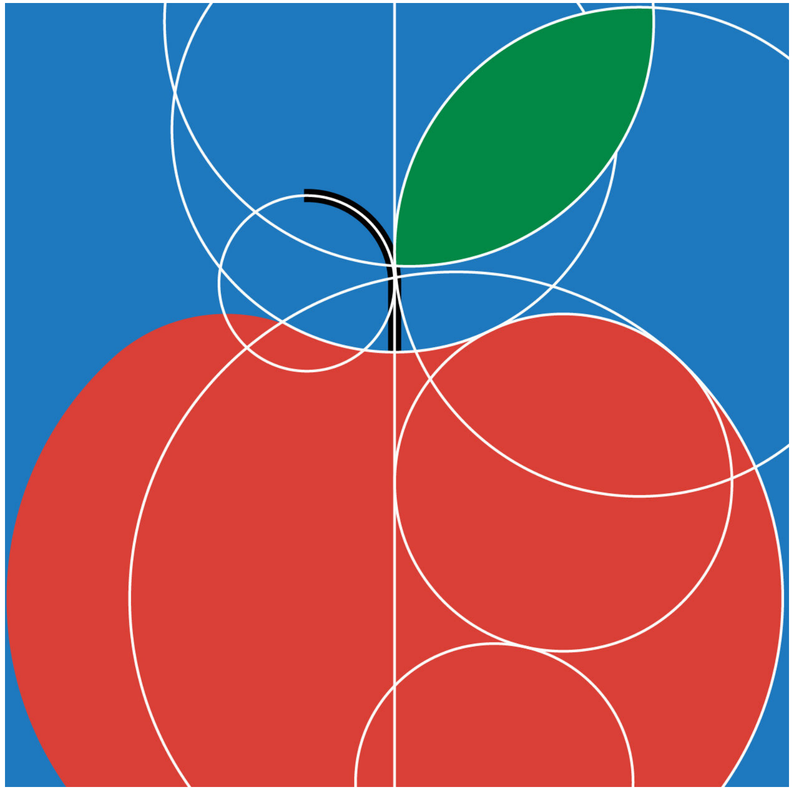
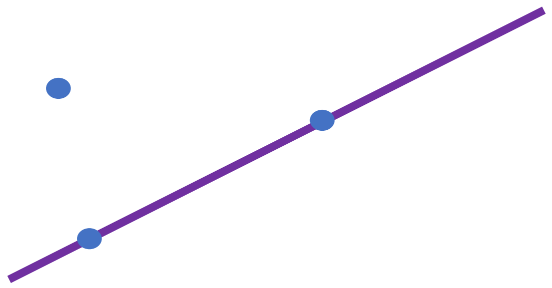


Image credit: Rocio Egio, nytimes.

Geometry arose from the technological necessities of the time: measuring fields, levying taxes, etc.

The greeks formalized and abstracted the rules for geometry.



Axioms:

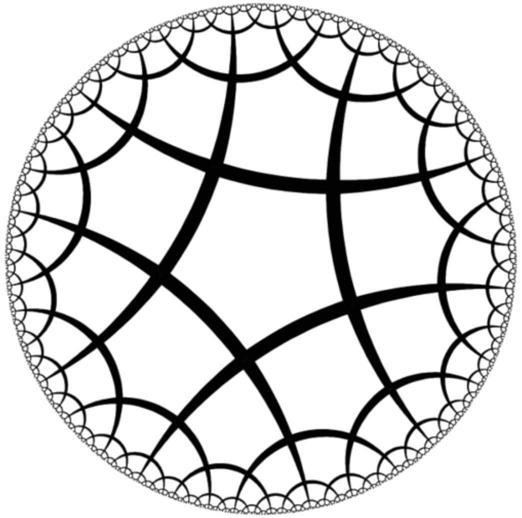
…

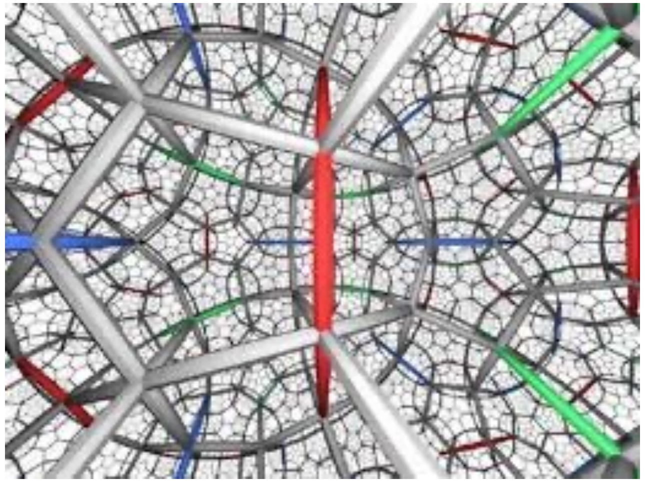
Given any two distinct points there is a unique line passing through them.

…

This process has continued to this day..

We can now imagine curved geometries, higher dimensional geometries, etc.





Geometry is a very basic notion

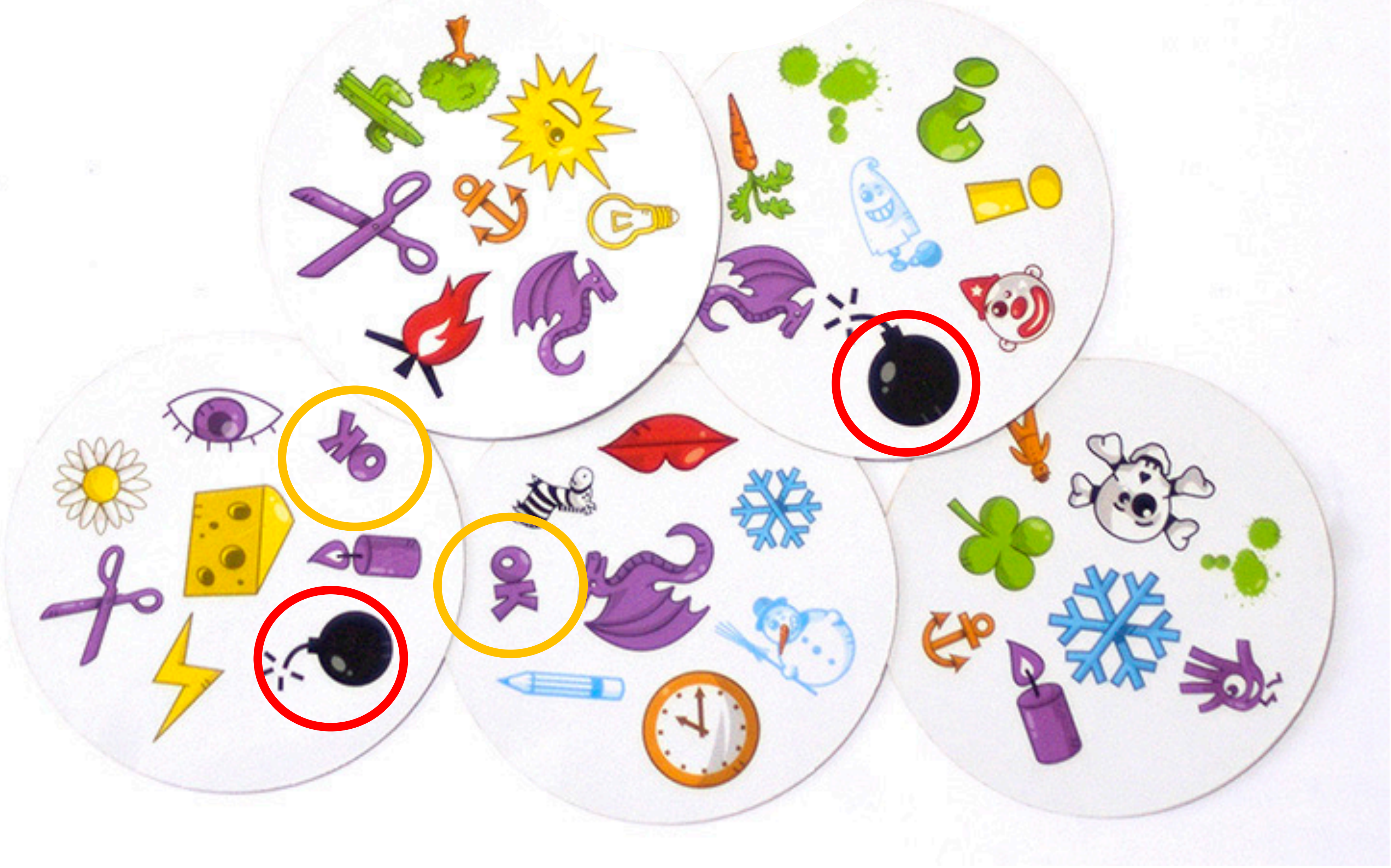
It is possible to find it unexpected places

Even in children’s games.

Geometry and “Spot it”

(I am not getting any add money!)

Given any two different cards, there is a unique image in common



Given any two different cards, there is a unique image in common

Geometry and "Spot it"

Given any two different <u>cards</u>,   there is a unique <u>image</u> in common
Given any two different <u>points</u>, there is a unique <u>line</u> in common

Each card is a ''Point"

Each image, is a "line''

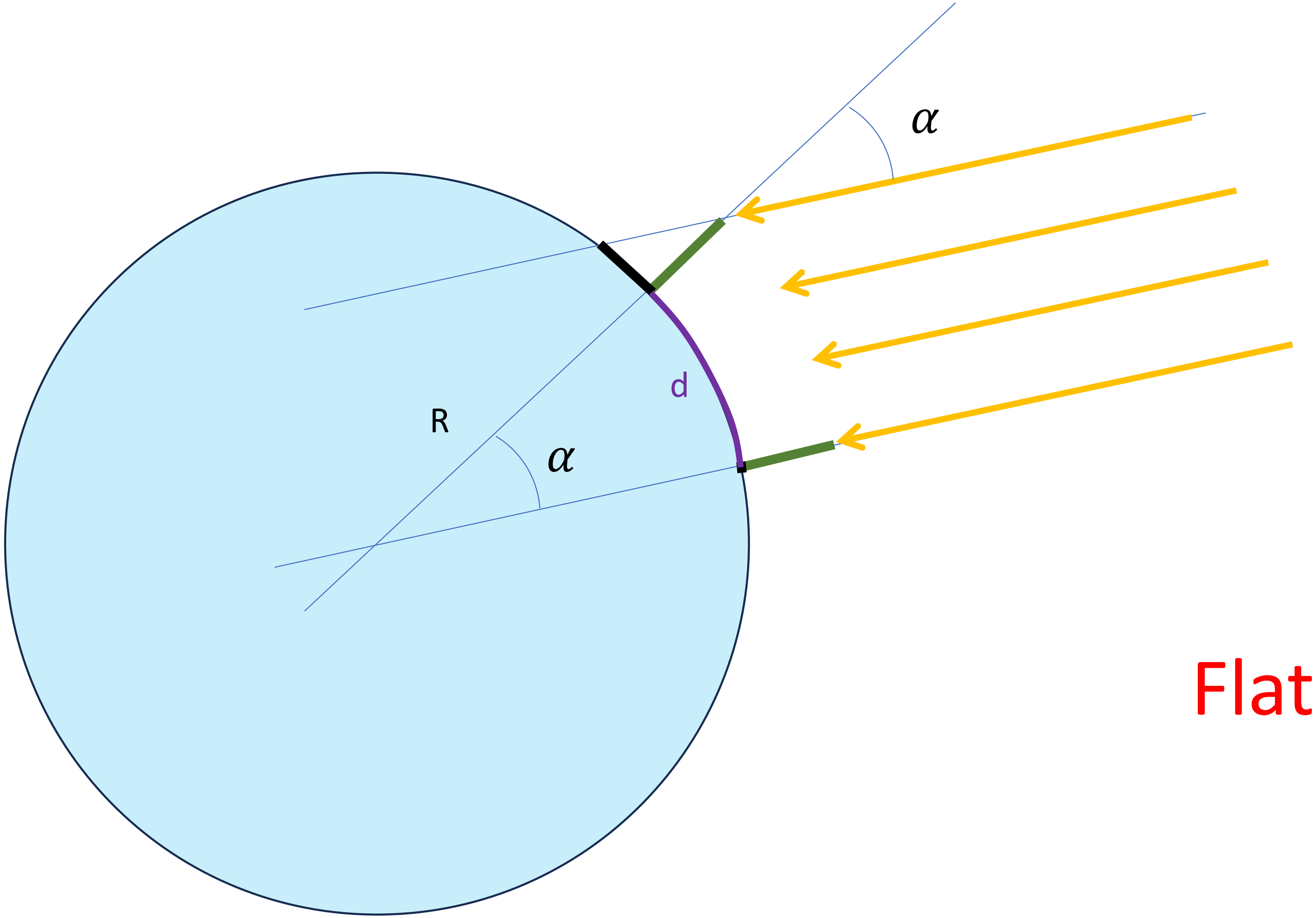
Finite geometry   17th , 18th centuries

There is a higher dimensional geometry behind language models such as Chat-GPT.

Words are represented as points in a higher dimensional space: 12,000 dimensions…

Geometry of the earth

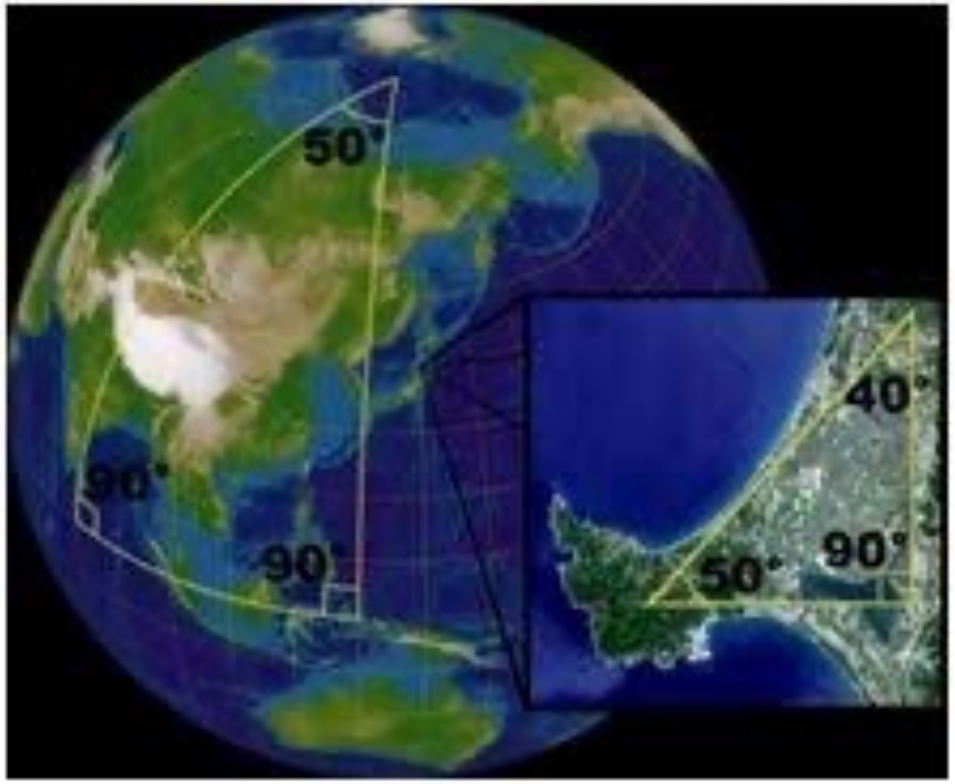
Eratosthenes



Flat → Sphere

Euclidean geometry is wrong for measuring fields…

But very good unless your ``field'' is very large.



First example of going between flat geometry to curved geometry

Euclidean geometry was still believed to be good for describing the three dimensional geometry of outer space.

Let’s go back to physics

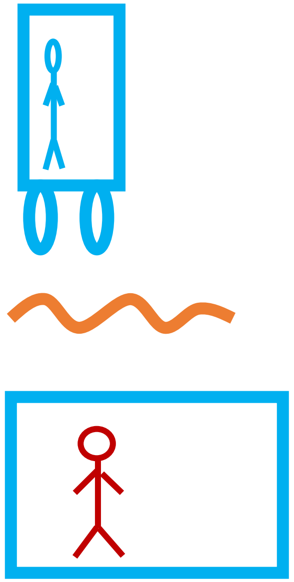
Let’s recall an important principle

Special Relativity

Einstein 1905

- Observers moving with constant relative velocity observe the same laws of physics.
- The speed of light is the maximal speed of propagations of signals. It is the same for both observers.

Special Relativity



→ Time flows differently for the two observers!

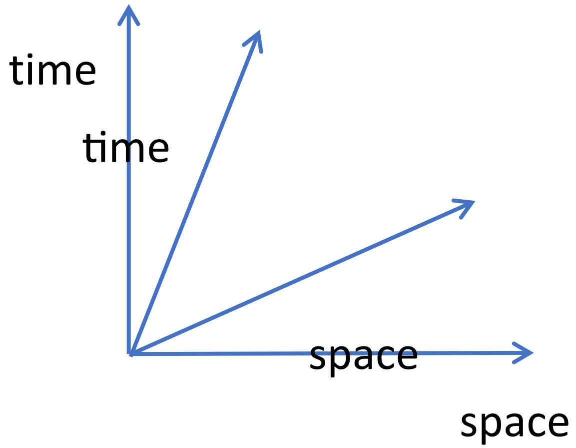
We can join space and time into a new kind of geometry = space-time

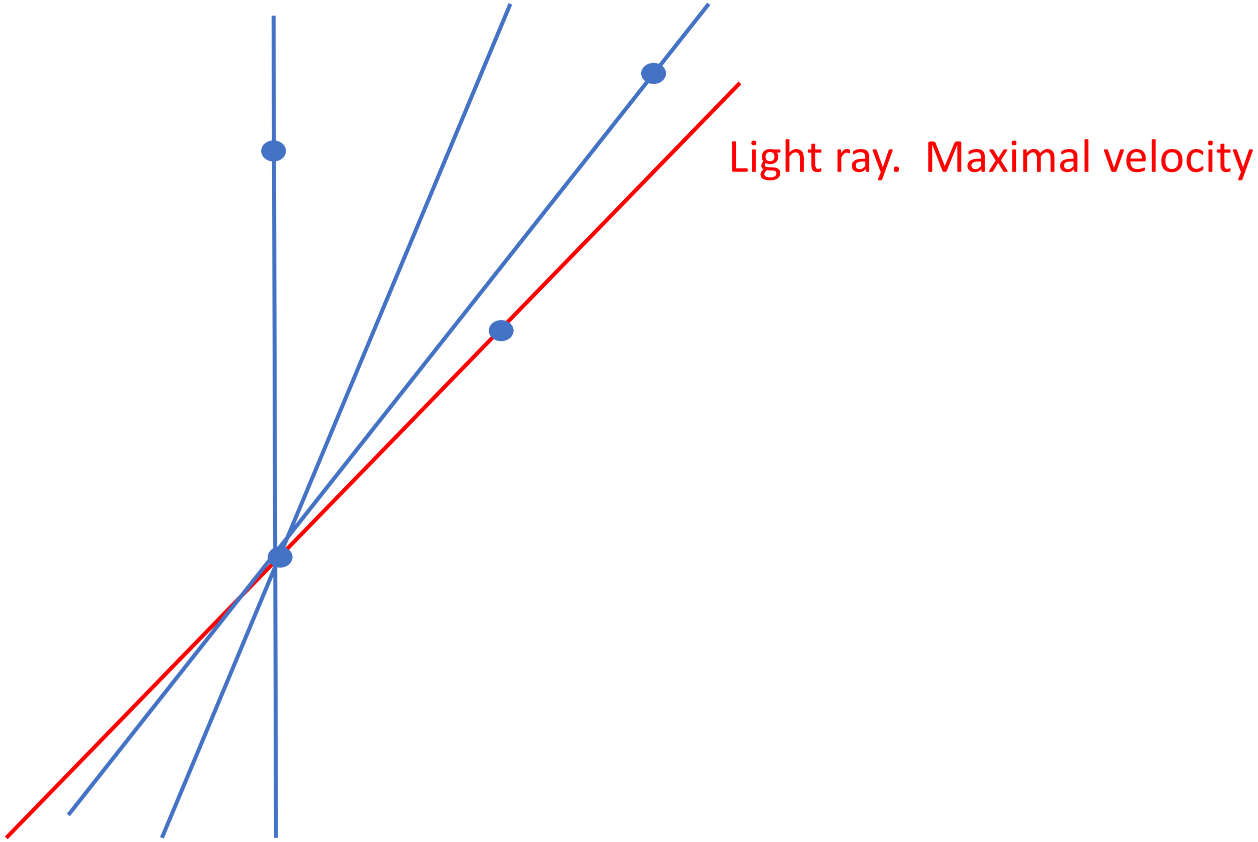
Lorentz,
Einstein
Minkowski

Points = Events (happen at some time at some place)

Lines = trajectories of particles

Straight lines = trajectories moving at constant velocity.





Conclusion:

Out of space and time we can make a geometry

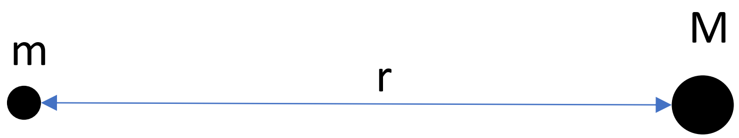
Now we will make a small (apparent) detour from geometry…

The force of gravity

Newtonian gravity

- $a_m = G_N \frac{M}{r^2},$

Newton constant, specifying the strength of the interaction



Features:

1) The acceleration on particle m is independent of its mass.

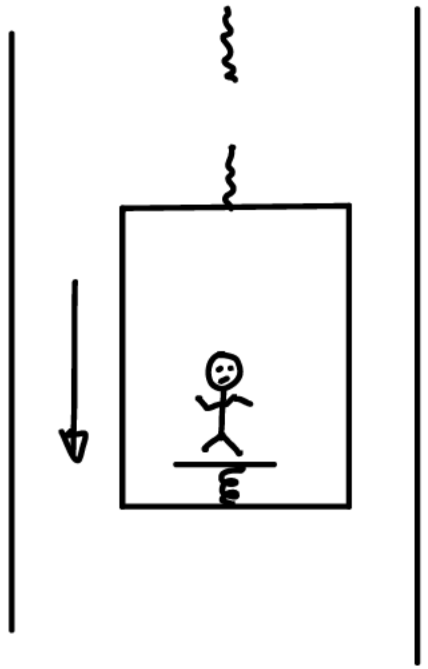
2) Instantaneous force. (☹ for relativity).

All objects fall in the same way in a gravitational field

Einstein’s happy thought:

If you fall freely in a gravitational field → your weight ``disappears’’, or the main effect of gravity disappears.

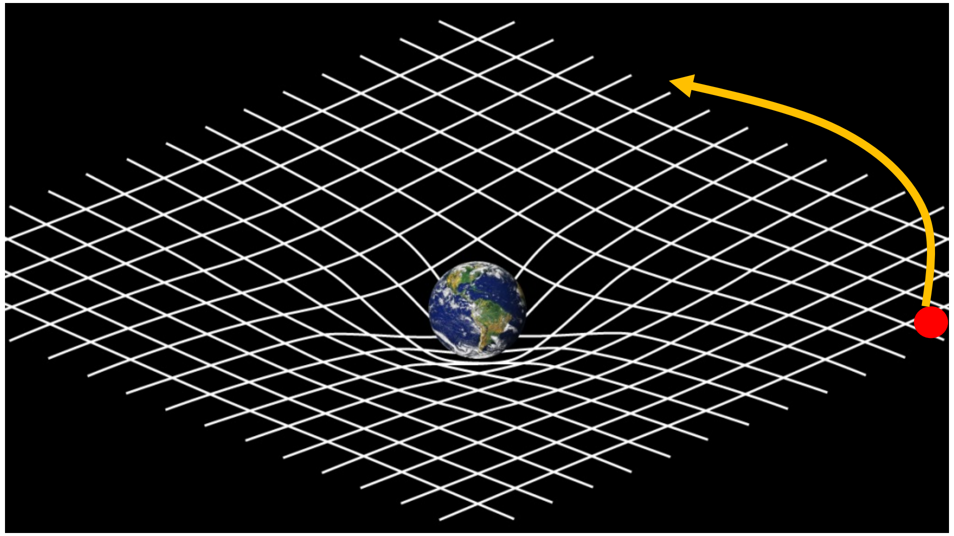
Falling elevator



General relativity

Einstein 1915

- It is Einstein's theory of gravity.
- The geometry of space-time is not flat, it is curved.
- A particle moves along this spacetime along the ``shortest trajectory''.
- Matter curves spacetime.



Einstein's equations:

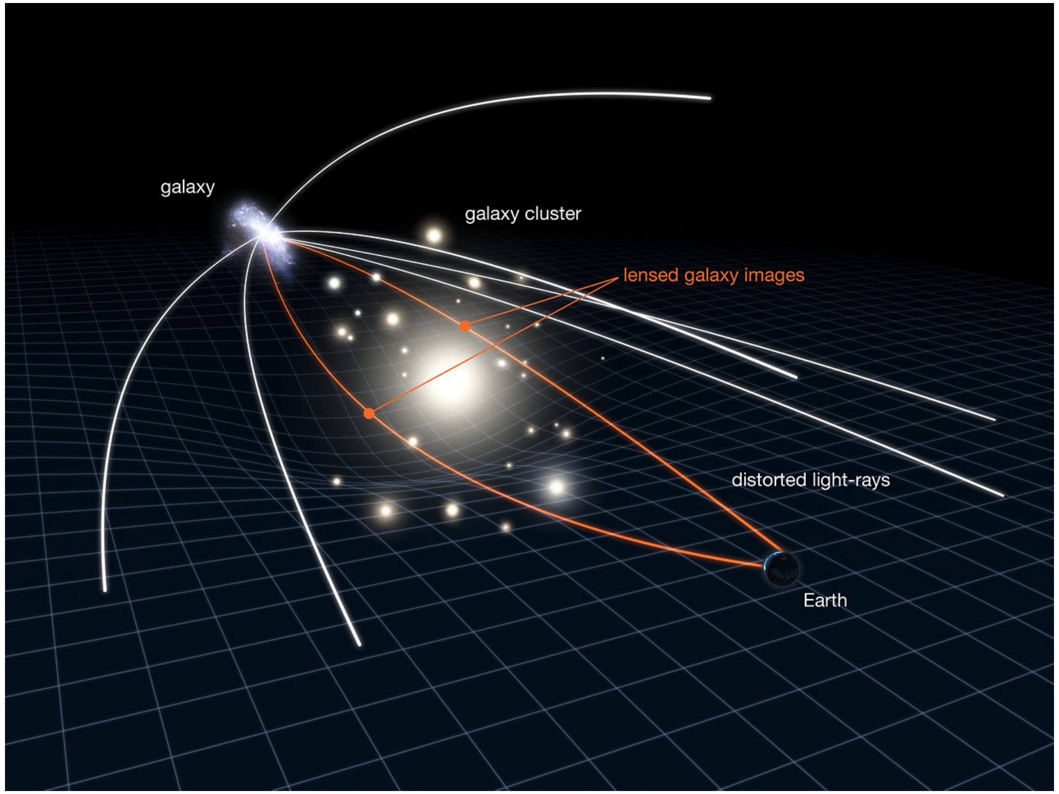
Curvature $= G_N$ (matter density)

Spacetime is a curved geometry

- Points = events
- ``straight lines” trajectories of observers falling freely.
- For everyday experience → pretty close to flat space.

Spacetime is a curved geometry

- Points = events
- ``straight lines” trajectories of observers falling freely.

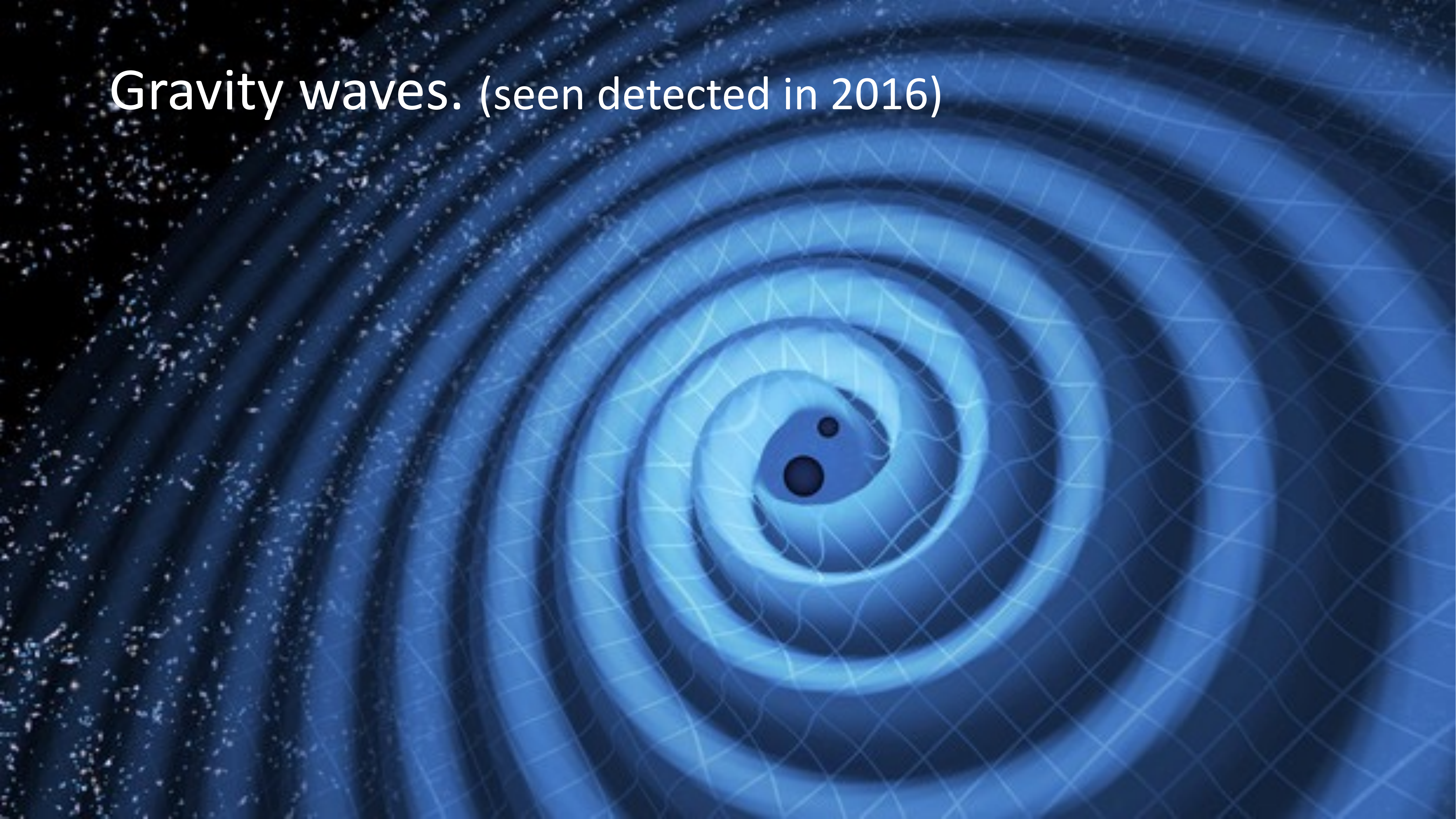


Spacetime is curved!

Light rays show us that spacetime geometry
is curved. As Eratosthenes did!.

One interesting prediction

Gravity waves. (seen detected in 2016)



Two very surprising predictions

- Black holes

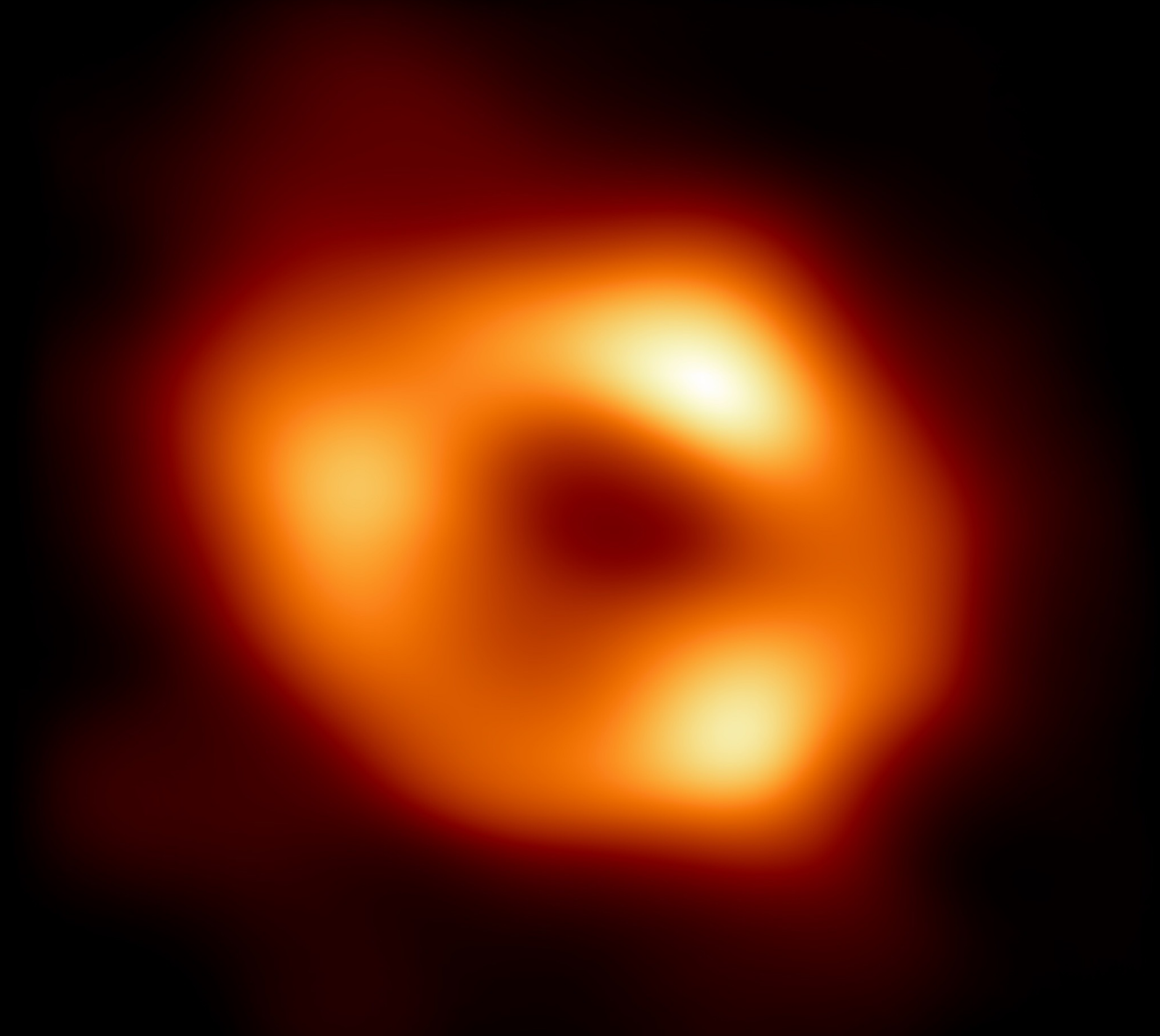
- Expansion of the universe

``Your math is great but your physics is dismal''

Einstein to Lemaitre

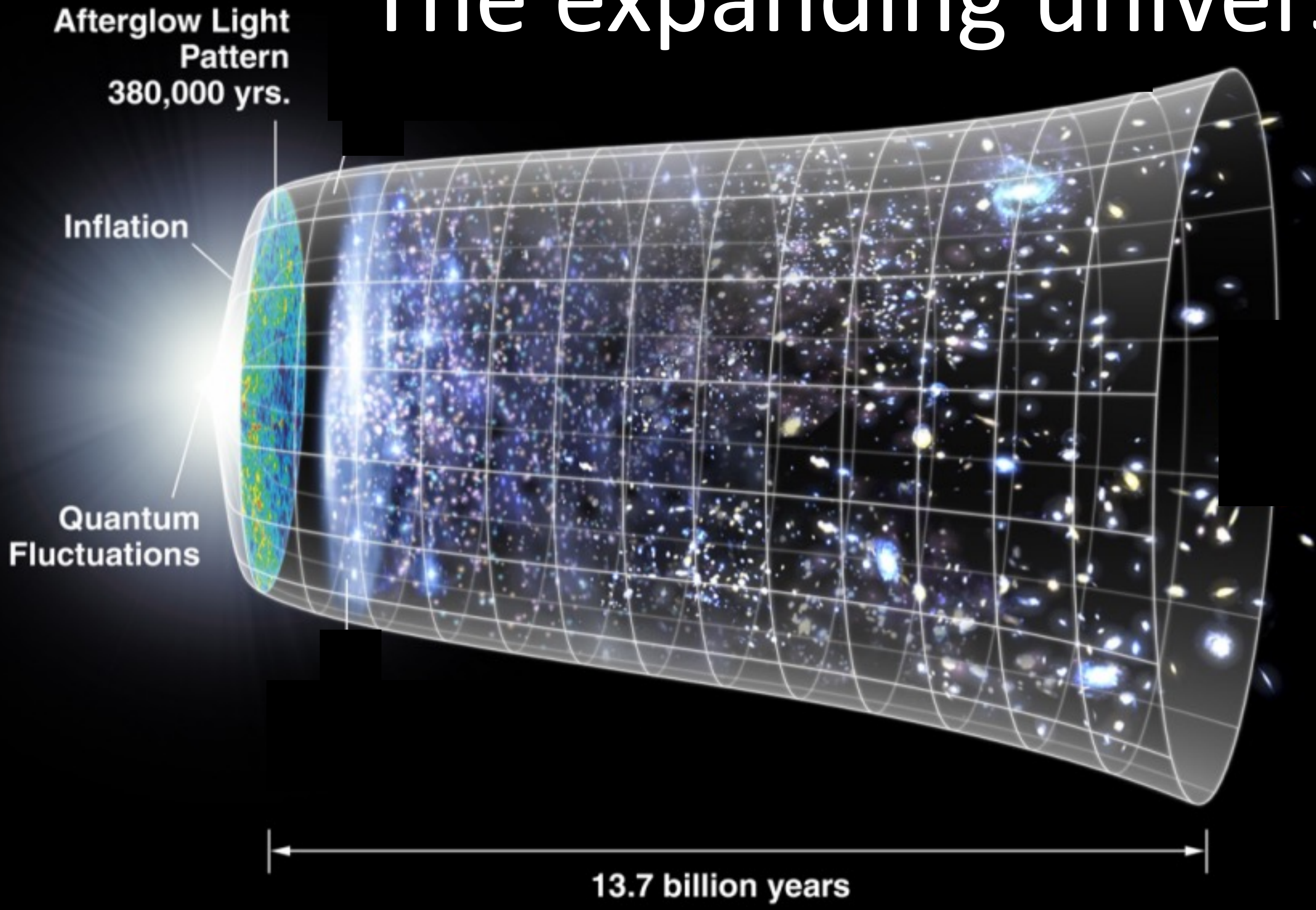
We now have great observational evidence for both!

Close up of the black hole at the center of the Milky way



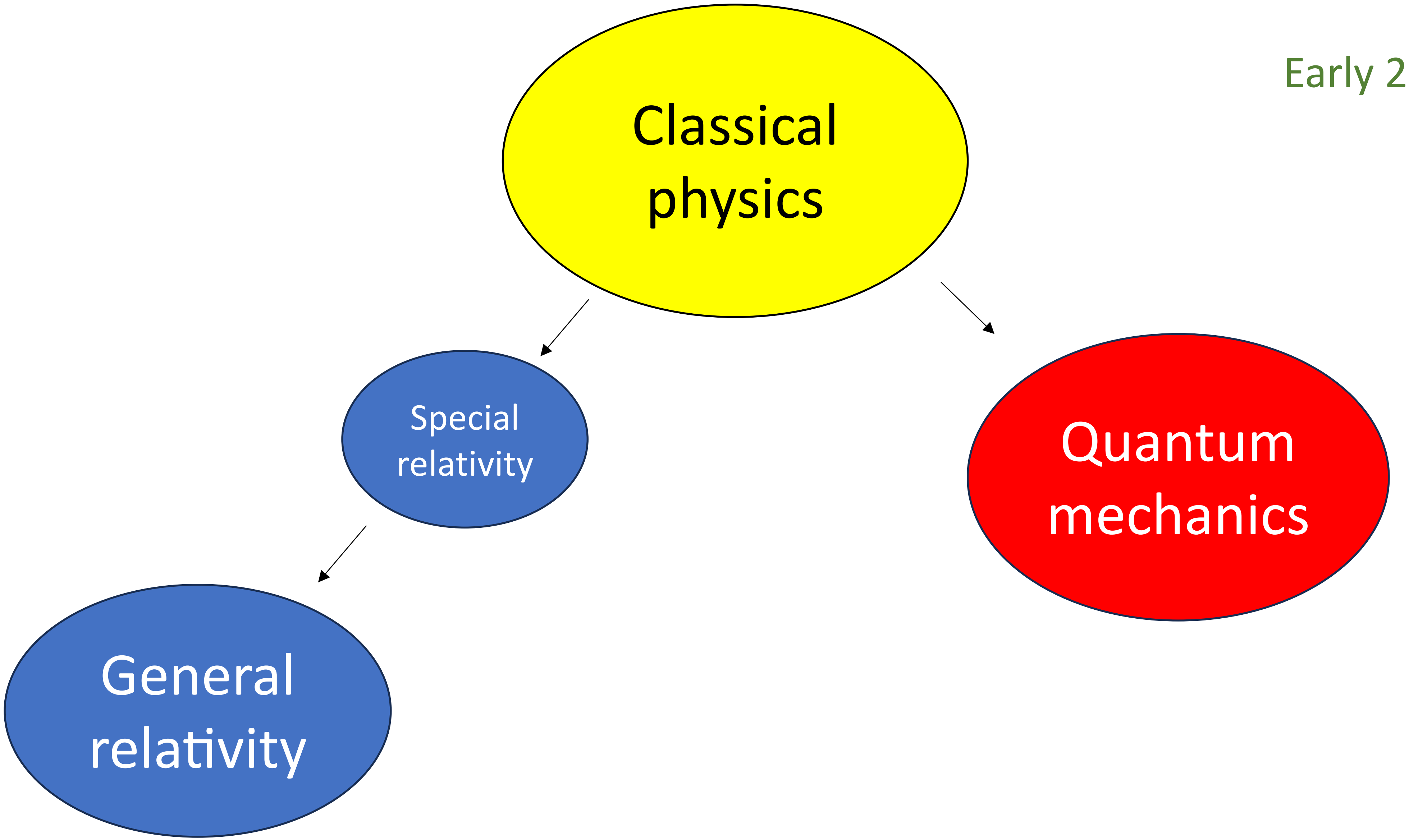
Picture taken by the Event Horizon Telescope, 2022

The expanding universe



We now will turn to a new topic

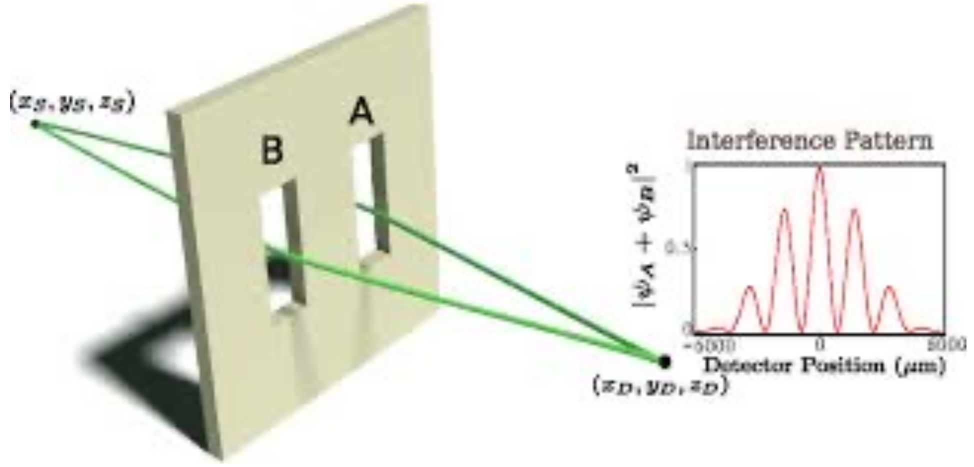
Early 20th century



Quantum mechanics

- Quantum mechanics is a new type of description of physical systems.
- It is intrinsically probabilistic.
- → Uncertainty principle: There are some things that you cannot know at the same time. (e.g. position and momentum of a particle)

Sum over paths:



Explains chemistry, atoms matter, etc.

It is weird explanation, where atoms are mostly empty space, …

It required some work to explain ``simple obvious things''…

The physical appearance of most substances are ``emergent properties''.

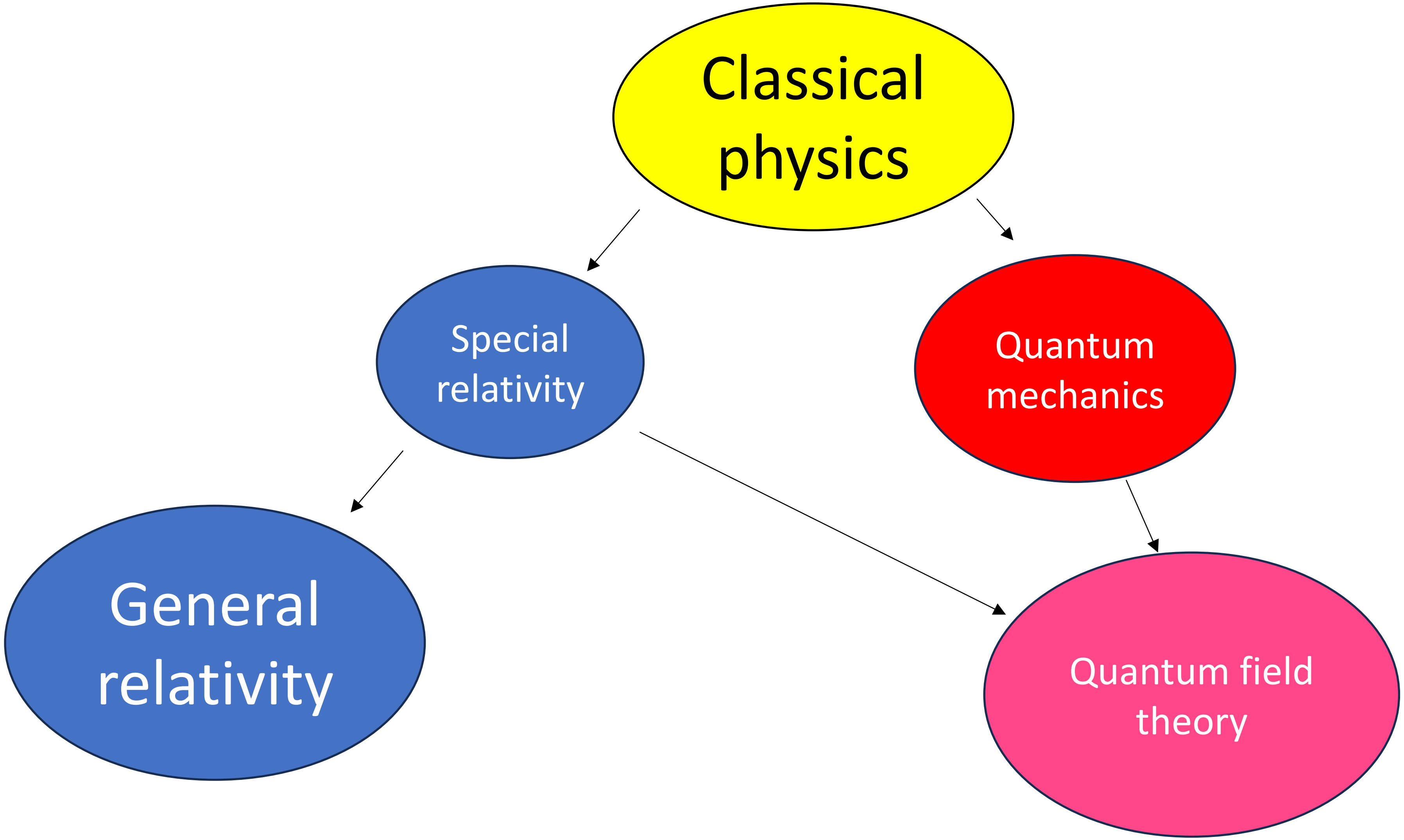
They arise from a large number of quantum particles and their interactions.

The mountain appears very solid. The water appears solid to the insect.

But in both cases they consist mostly of empty space.

A neutrino, or a dark matter particle, can go though the whole earth!

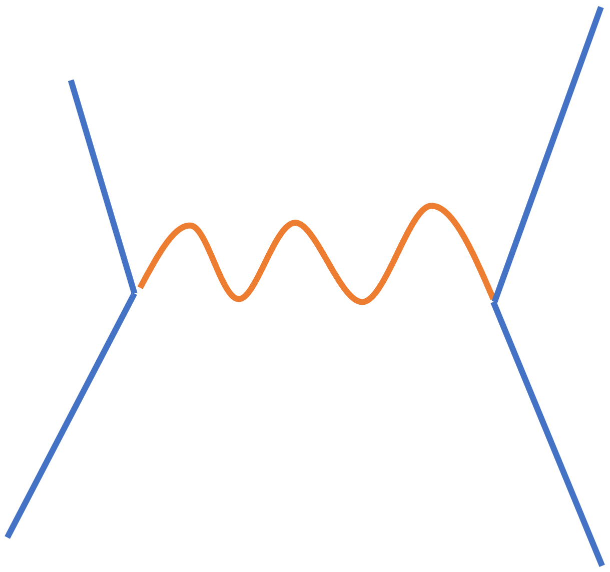
Yet another concept…


Classical physics
Special relativity
Quantum mechanics
General relativity
Quantum field theory

1930s – 1970s

Relativistic quantum mechanics

- Special relativity + quantum mechanics.
- Describes the interactions between elementary particles.
- Quantum of light → ``photon''



Classical geometry can be used
to describe picture

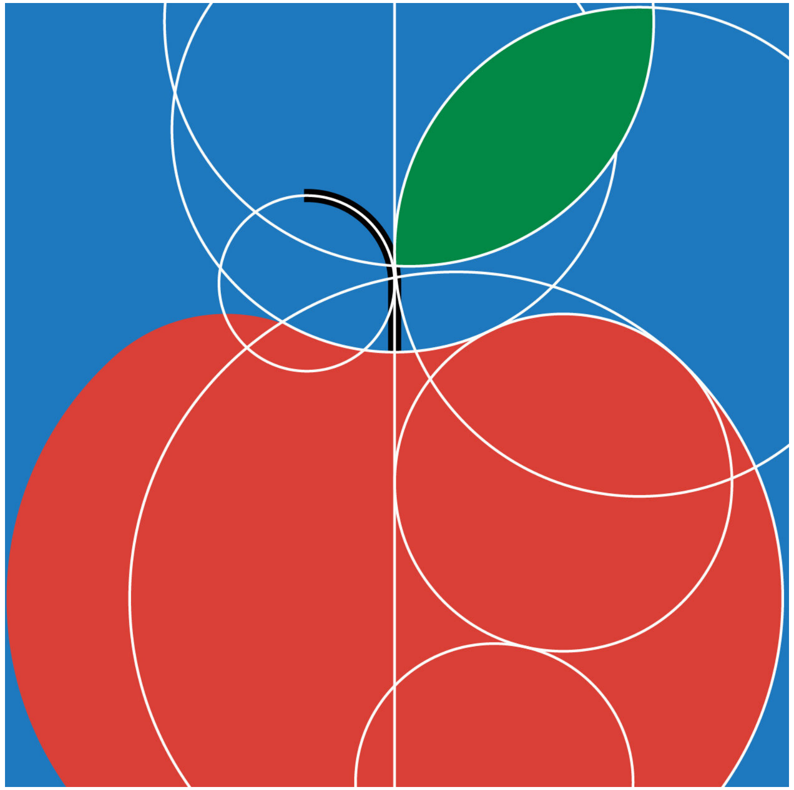
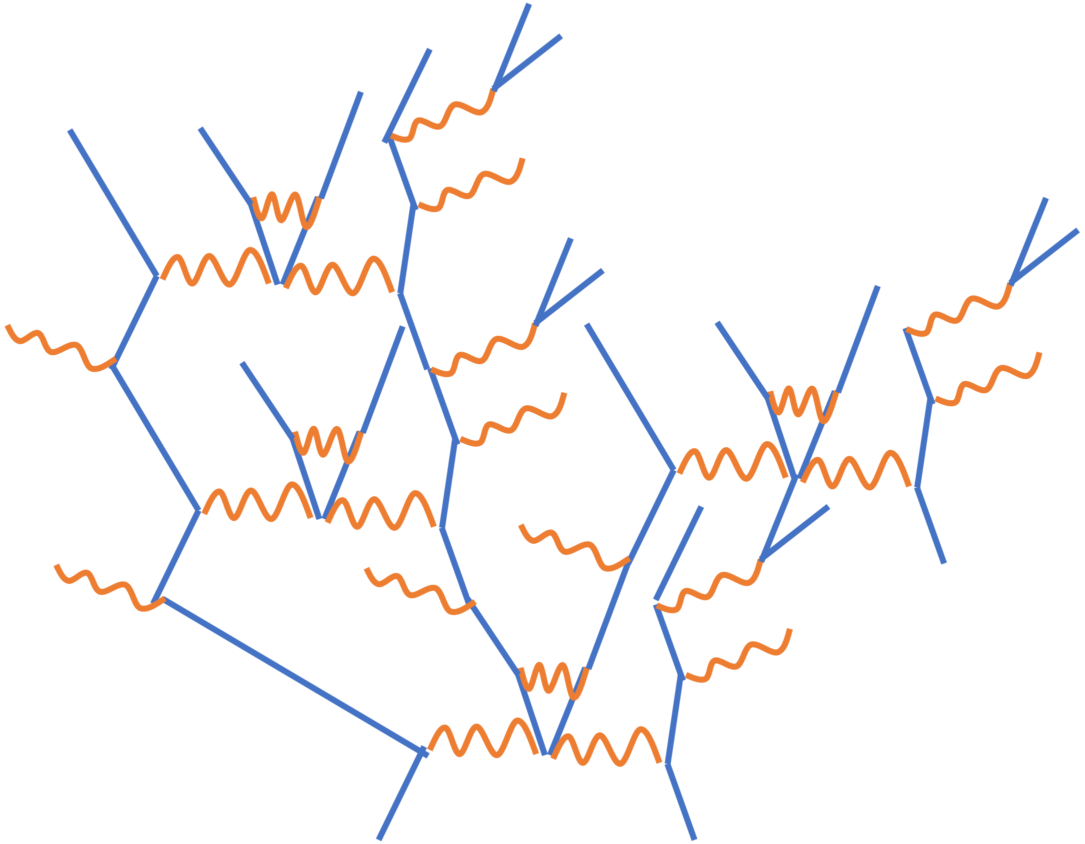


Image credit: Rocio Egio, nytimes.

We have similar lines in spacetime..



Classical geometry can be used
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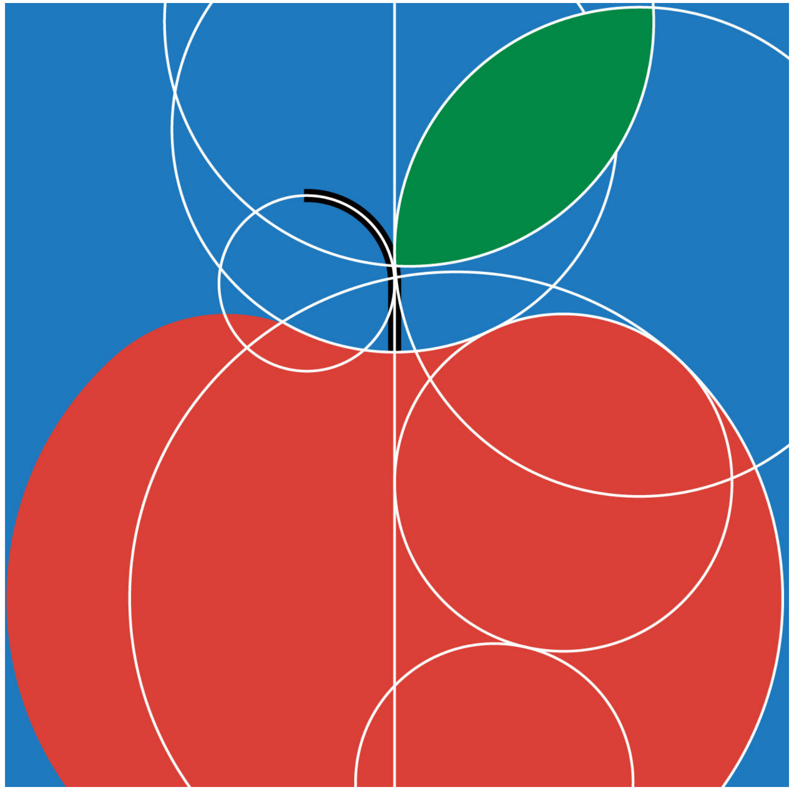
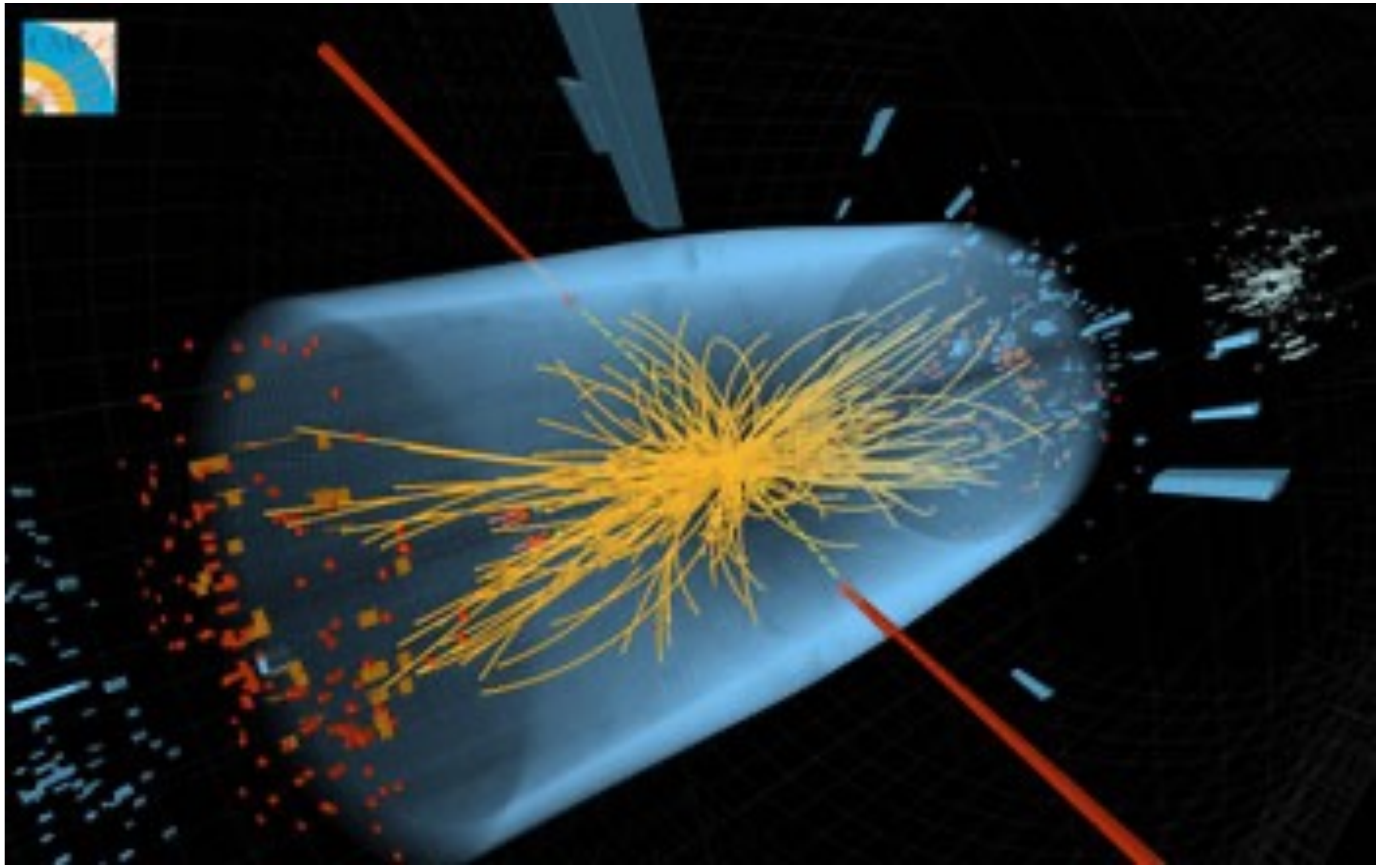


Image credit: Rocio Egio, nytimes.

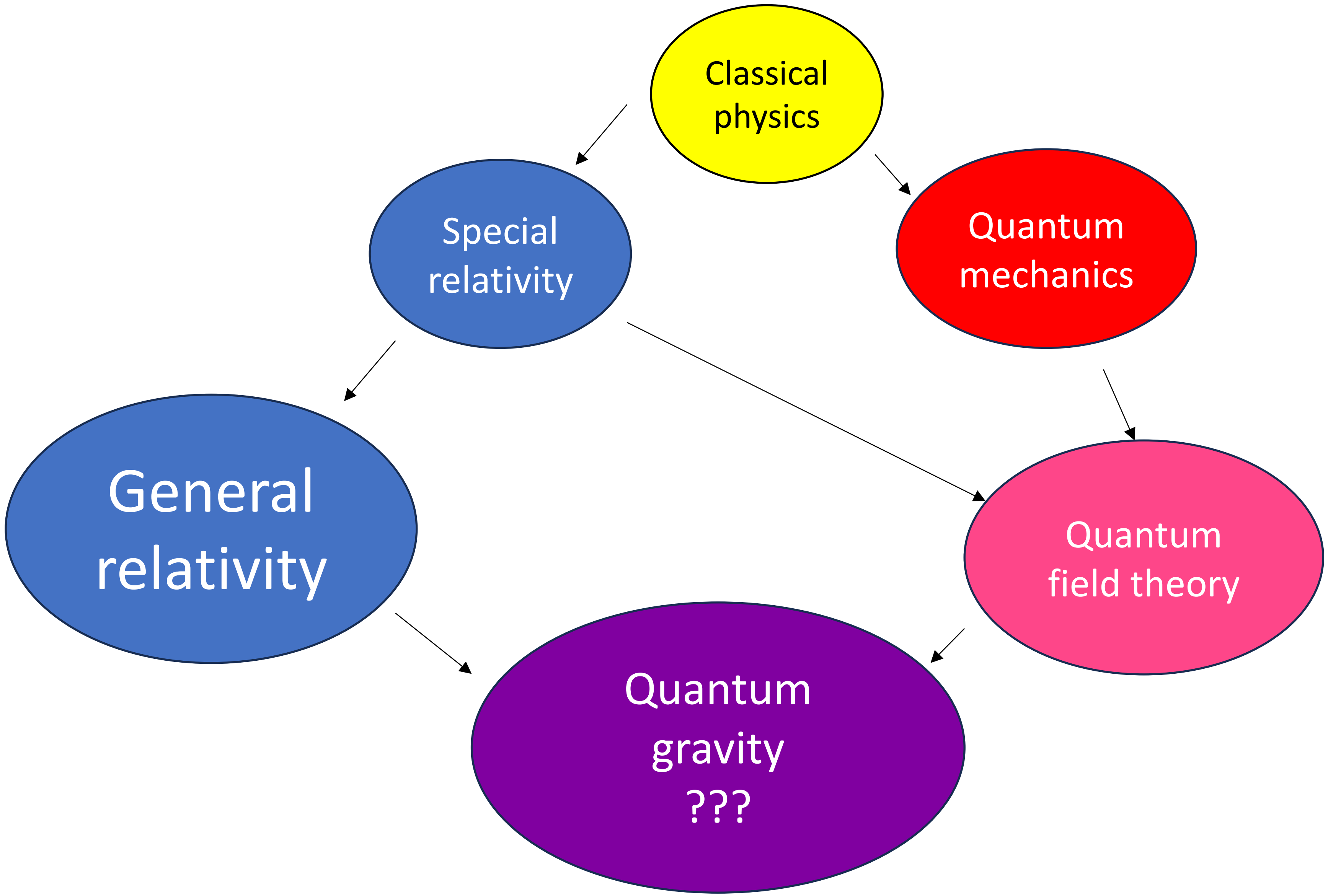
… describing particle collisions



In this way we can describe all of the matter we see.

An important question

Can we include gravity ?



Two approaches

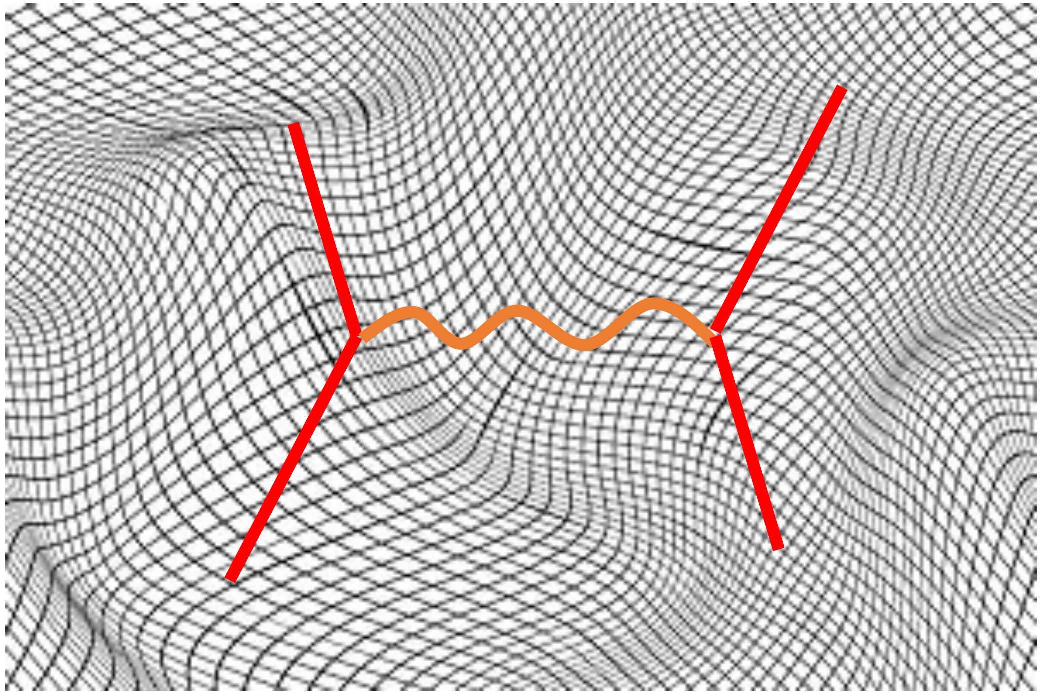
Two approaches

Approximate approach: Similar to quantum field theory.

An precise approach: Full theory of quantum gravity

The approximate approach

Add the ``graviton''



When the radius of curvature of the universe is much larger than the Planck distance.

Planck distance = combination of G_N, $\hbar, c$ = 10^{-35} meters = very, very tiny.

= Basic length scale is quantum general relativity

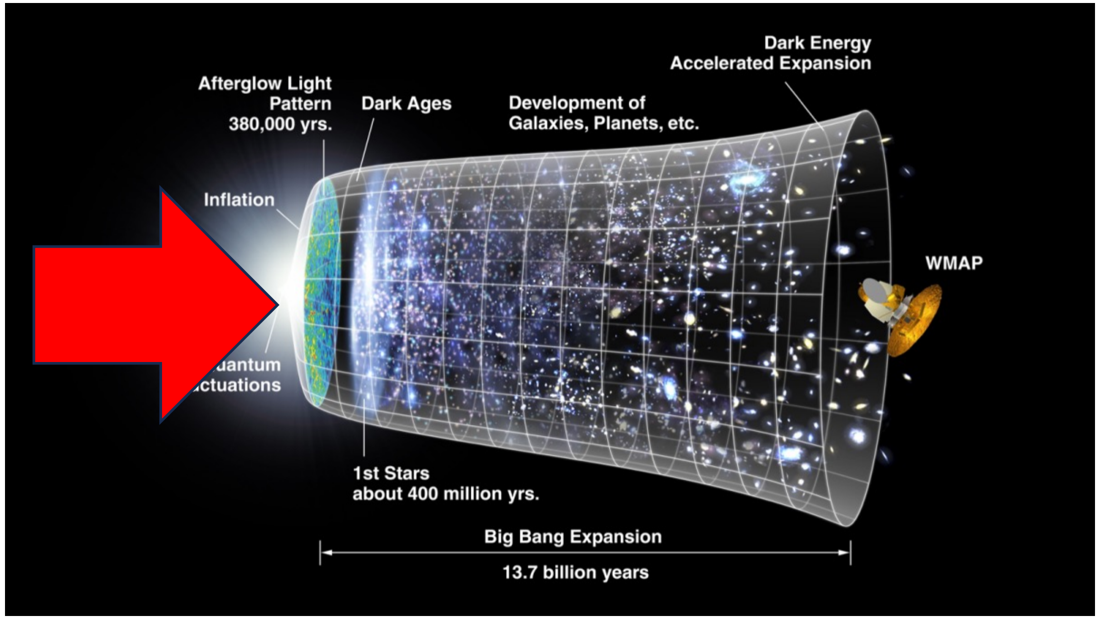
Smallest size we can explore today 10^{-18} m .

This approximation is enough for all circumstances of daily life, and in almost all places in our universe.

Complete failure of the approximate approach

Singularity at the beginning of the big bang

Singularity in the interior of black holes



For that we need a full theory of quantum gravity, the full theory.

We will come back to the full theory later.

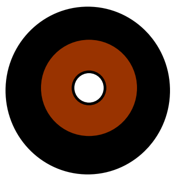
Important success of the approximate approach

It leads to a <u>big</u> surprise for black holes

White Black Holes!

The laws of quantum mechanics imply that black holes emit thermal radiation. Hawking 1974

The temperature increases as the size decreases



Temperatures for black holes of various masses:

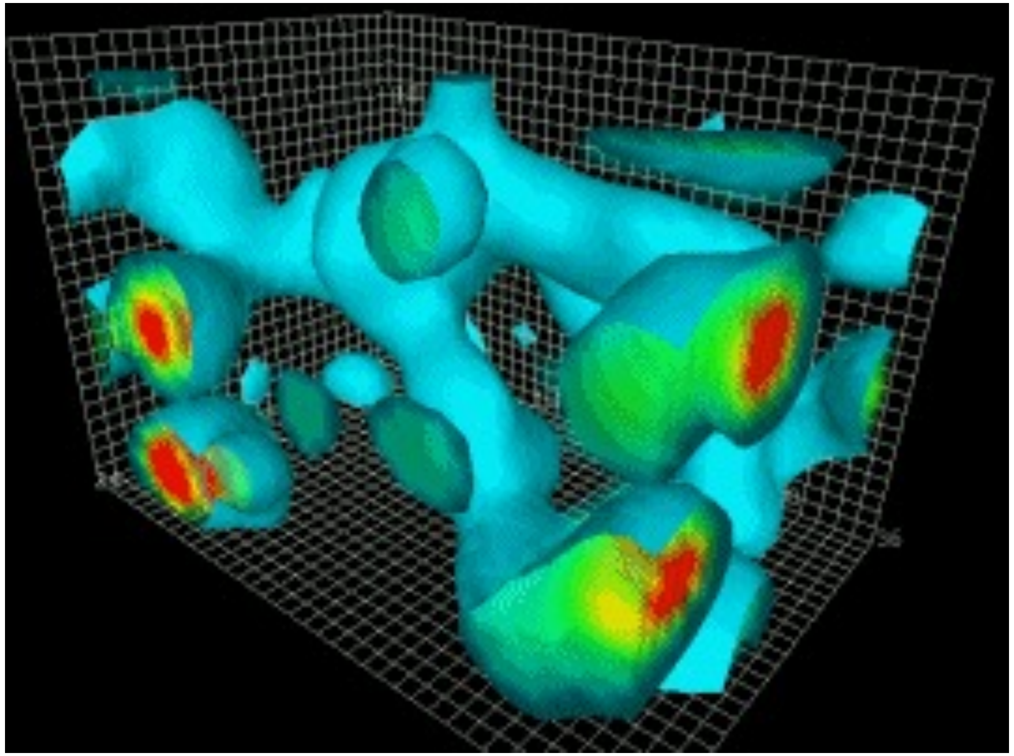
$T_{M=sun}$ = 0.000003 °K (This temperature is too small for astrophysical black holes)

$T_{M=continent}$ = 7000 °K (white light) has the size of a bacterium

Why ?

The quantum vacuum is complicated

A small region of the vacuum is very random and fluctuating

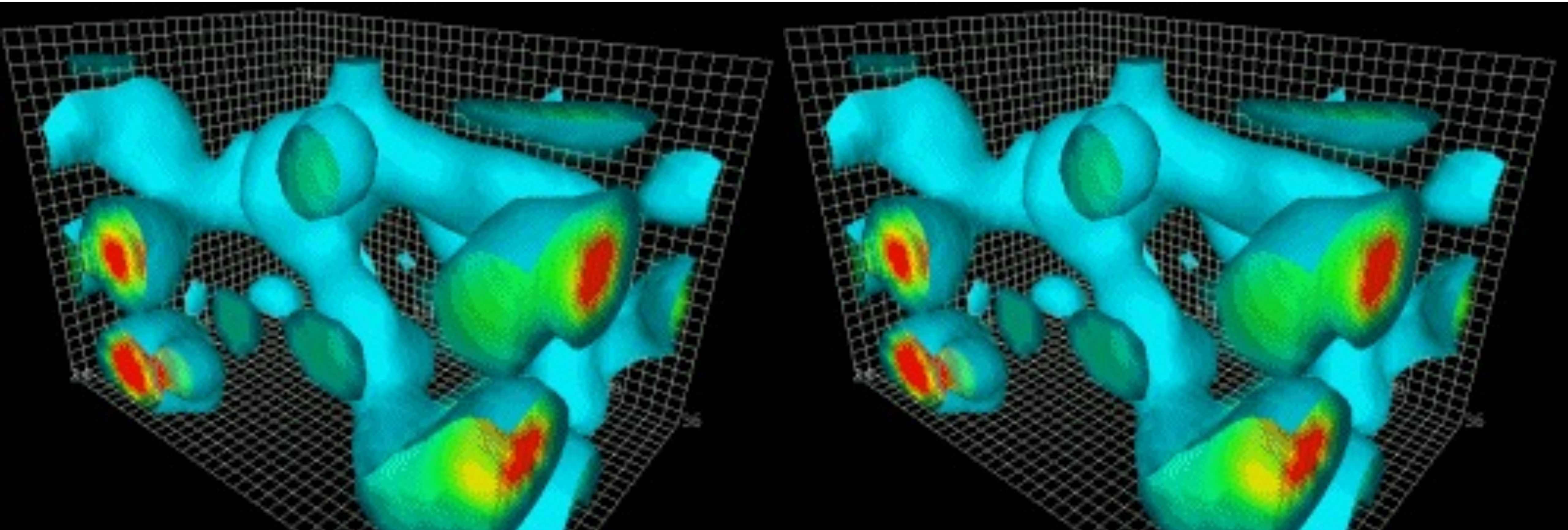


Lattice QCD visualizations from the University of Adelaide

The whole vacuum is simpler

The whole vacuum is simpler

All these local fluctuations are correlated (entangled) in a harmonious way that produces a precise, predictable, state.



Let’s describe an analogy

Let’s say somebody tells you a portion of a sentence.

Mary stepped out of her…

What does this sentence mean?

We know it involves Mary, but we do not know the full meaning.

It could end in many different ways

But if somebody told you the full sentence:

Mary stepped out of her comfort zone by explaining quantum physics to a group of investors.

Then you get a well formed sentence.

If we have only a portion of a sentence → we lack some information.

We can quantify the information we lack by listing the various ways to complete it. Ignorance quantified by the entropy = idea in information theory.

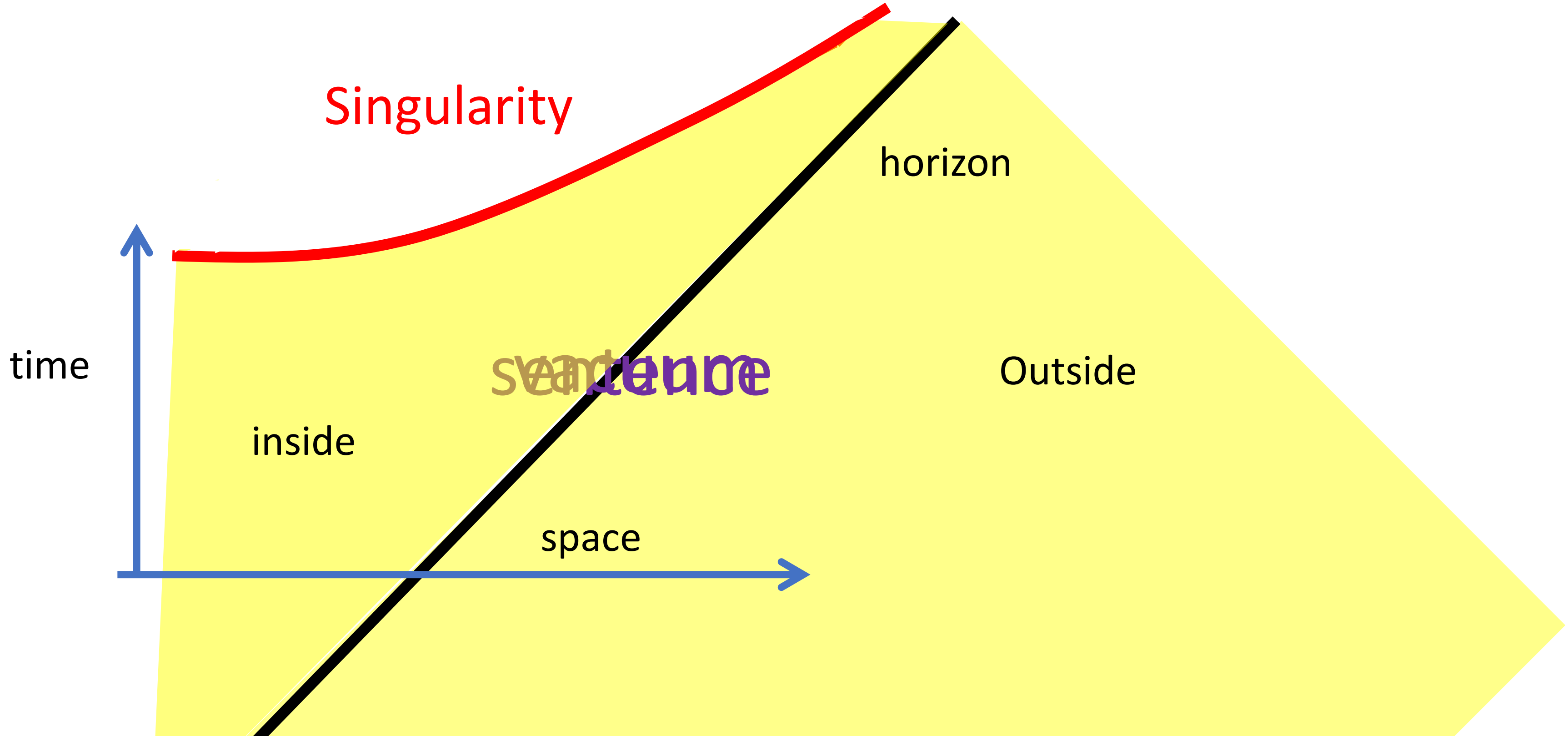
Shanon

The full vacuum is like a well formed sentence.

Return to black holes

When we have a black hole, the spacetime geometry has a so called ``horizon''.

According to classical general relativity we cannot get any signal from the portion of the spacetime that is behind the horizon.



This leads to some randomness = Temperature.

→ entropy = disorder.

For a black hole, we can calculate the entropy (or amount of disorder) using the laws of thermodynamics.

Bekenstein, Hawking, 1970s

Entropy = disorder = $\frac{Area}{l_p^2} = \frac{Area}{(10^{-35} m)^2}$

2nd Law of thermodynamics = area always increases

Black holes emit radiation → lose mass → "evaporate"

- Irrelevant for astrophysical black hole.

Black holes emit radiation → lose mass → "evaporate"

For a black hole of a 1 Kg, $E = mc^2$ → like a 20 Megaton nuclear bomb.

Fortunately there are no such black holes around

We described some results for black holes from the approximate method.

There are some questions we cannot answer using the approximate method:

What precisely comes out of a black hole?

How do we recover the information of the matter than formed the black hole?

Is black hole formation and evaporation consistent with quantum mechanics?

→ We need the full theory.

We have a theory under construction.
``String Theory''

We are now having the annual international conference here at the Perimeter Institute

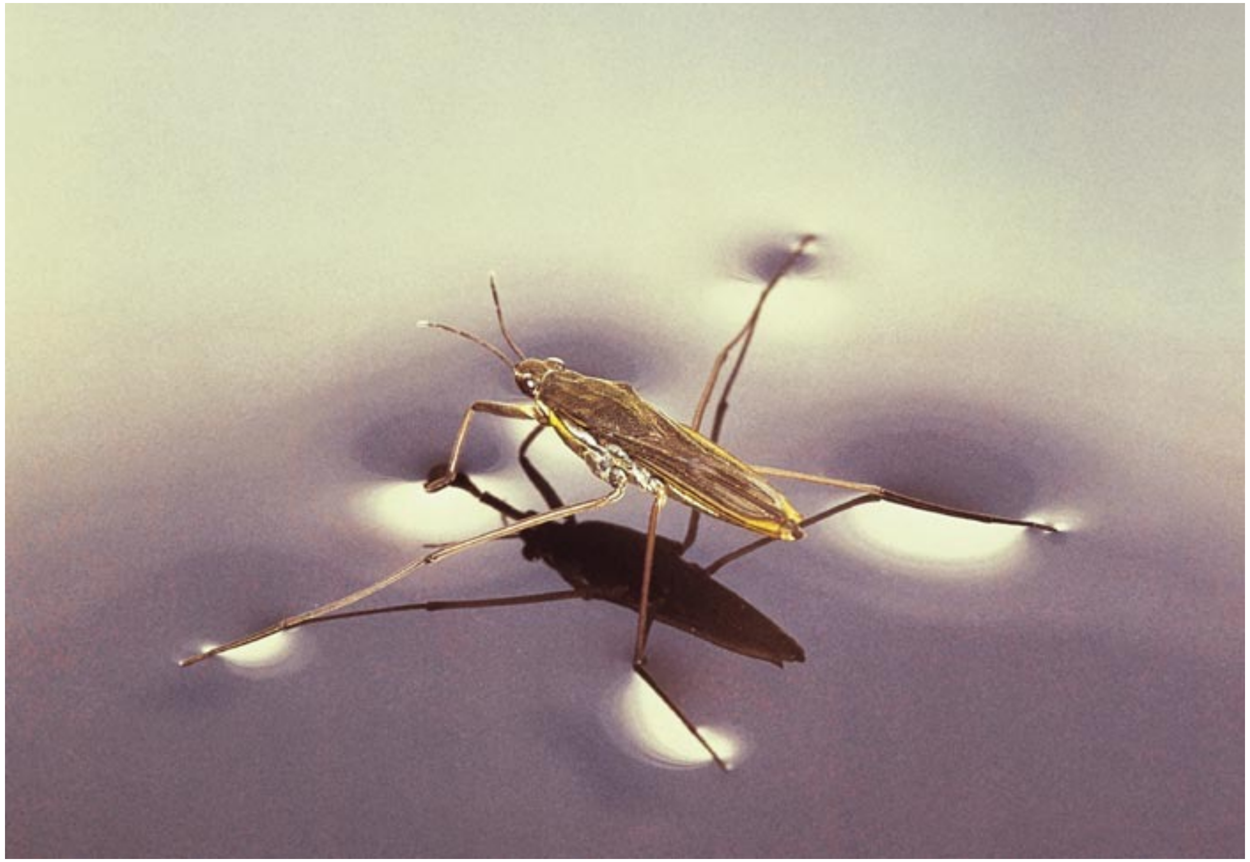
It is a theory under construction


Without mathematics

We are learning interesting things about the quantum aspects of black holes.

We will focus on just one aspect of the theory

The idea of spacetime as an emergent concept



Water is to atoms as spacetime is to ???

… Spacetime atoms ?

Similar, but the elementary ``atoms'' or ``qubits'' are far away!

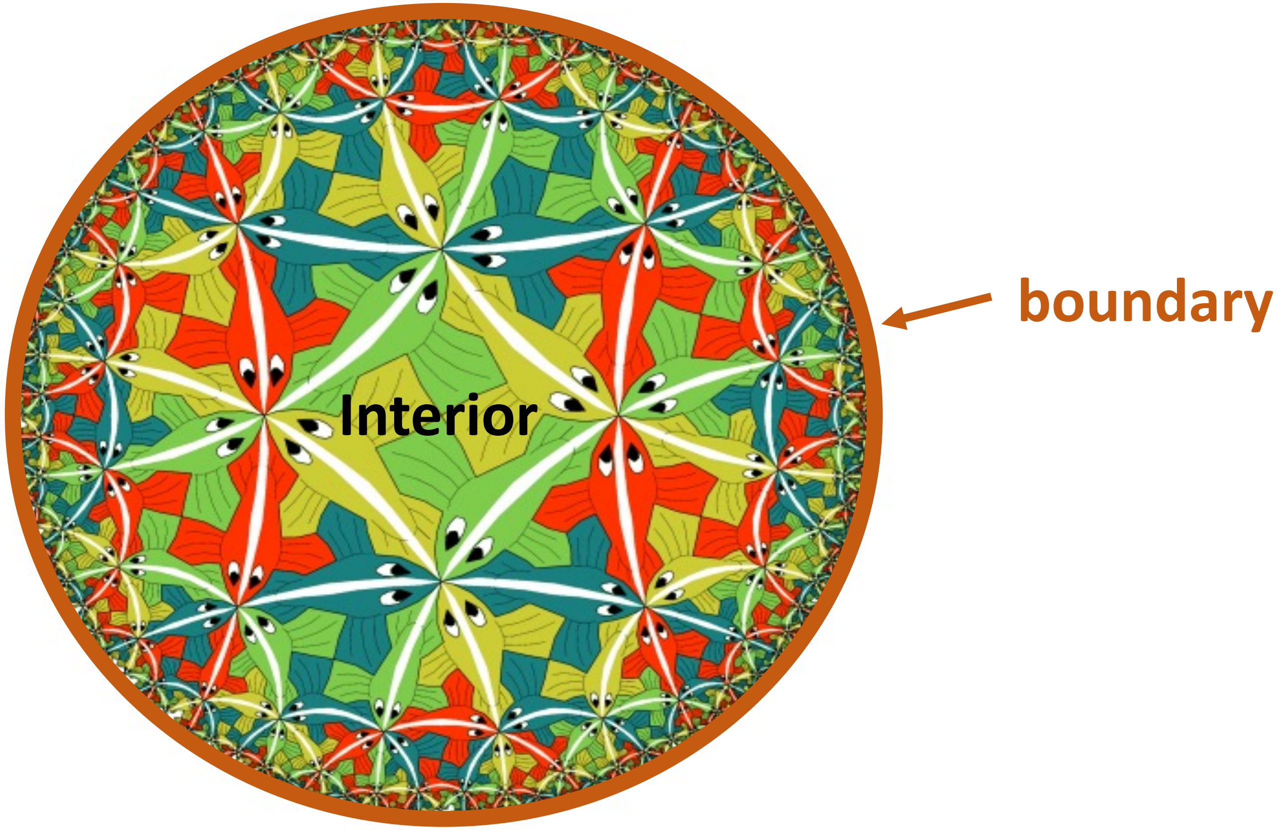
Holography

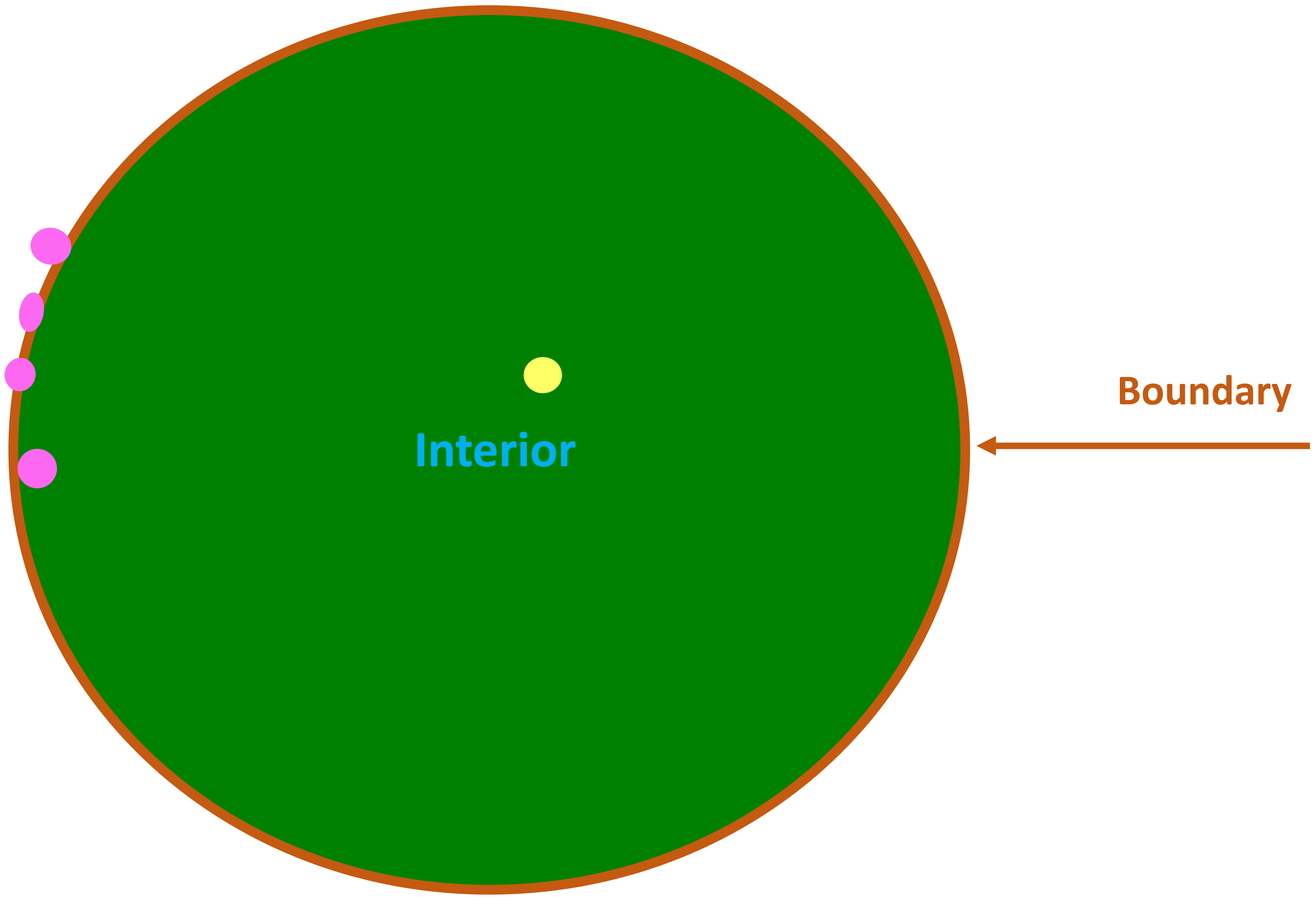
We can describe the physics of gravitational spacetimes in terms of particles (or qubits) living at its boundary.

The boundary theory is strongly interacting, but with no gravity.

Conjecture!
(with evidence)

JM 1997
Gubser, Klebanov, Polyakov, Witten





Gravity in the interior → Described by interacting qubits on the boundary

A black hole?

- The theory on the boundary obeys the rules of quantum mechanics
- So does the black hole in the interior
- Black holes are consistent with quantum mechanics.*

* If you accept the holographic conjeture

Emergent geometry

Qubits live here

Emergent geometry

An analogy

If a man does not keep pace with his companions, perhaps it is because he hears a different drummer

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State of the quantum system

Extra long distance correlations → particles

study various aspects of wormholes that are made traversable by an interaction beween the two asymptotic boundaries. We concentrate on the case of nearly-AdS2 gravity and discuss a very simple mechanical picture for the gravitational dynamics. We derive a formula for the two sided correlators that includes the effect of gravitational backreaction, which limits the amount of information we can send through the wormhole. We emphasize that the process can be view

grees of freedom.

A bulk observer is like a character in a novel whose text is written at the boundary

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egrees of freedom.

A slightly more accurate way to describe this is as follows.

The boundary is a superposition of many possible sentences.

The bulk spacetime represents statistical correlations present in those possible sentences.

What is a black hole in the spacetime?

Back to the sentence

If a man does not keep pace with his companions, perhaps it is because he hears a different drummer

Back to the sentence

If a man does not keep pace with its companions, perhaps it is because she hears a different lecturer

We lost longer distance correlations.

Change some words

If a man does not keep pace with its companions, perhaps it is because she hears a different lecturer

Horizon of meaning

Make more changes

If a man does not shine pace with its companions, perhaps its all because she hears a different lecturer

Horizon of meaning

Make more changes

If a man does not shine pace with its companions, perhaps its all because she hears a different lecturer

Horizon grows. Area grows.

Random letters

Salkf ie fslkent eosi egmwl jwie fla eighalie fal eial dlfie nalt naeing ;laehwuenfa bgagrgna;o gye a ;d dleibdo dovie dk

Black hole grows.

Area = ignorance.
Area growth → Random changes will mess up a sentence.

If the changes came from a reversible process
For example, an encryption algorithm

Salkf ie fslkent eosi egmwl jwie fla eighalie fal eial dlfie nalt naeing ;laehwuenfa bgagrgna;o gye a ;d dleibdo dovie dk

Then we can reverse the process and recover the original sentence.

Laws of physics on the boundary → change the state of the boundary.

Analogous to an encryption process → it is reversible

We can undo the formation of the black hole and recover the original information.

Let’s discuss again portions of a sentence

Mary little lamb

You are missing part of the meaning

State of the quantum system

Missing part

study various aspects of wormholes that are made traversable by an interaction beween the two asymptotic boundaries. We concentrate on the case of nearly-AdS2 gravity and disc of gravitational backreaction, which limits the amount of information we can send through the wormhole. We emphasize that the process can be view

egrees of freedom.

Interesting formula for characterizing the ``ignorance'' or entropy

Ryu, Takayanagi, 2006
Hubeny, Rangamani, Faulkner, Lewkowycz, JM, Dong,
Engelhardt, Wall 2014

Quantum information = Entropy = $\frac{Minimal\ Area}{l_p^2}$

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Relates geometry (area) and quantum information

What can be recover from the bulk if we miss a portion of the boundary?

We miss only a portion of the bulk

study various aspects of wormholes that are made traversable by an interaction beween the two asymptotic boundaries. We concentrate on the case of nearly-AdS2 gravity and disc … of gravitational backreaction, which limits the amount of information we can send through the wormhole. We emphasize that the process can be view

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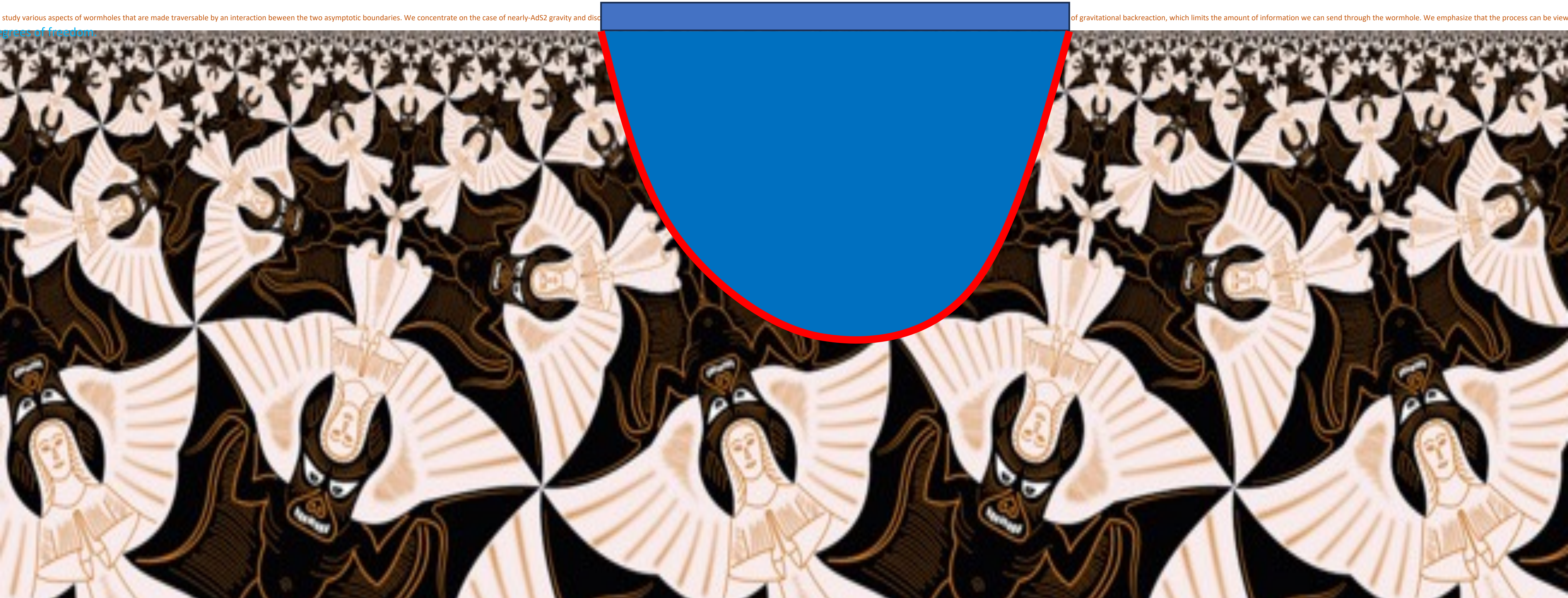

In the analogy:

we miss only a part of the meaning of the sentence

study various aspects of wormholes that are made traversable by an interaction beween the two asymptotic boundaries. We concentrate on the case of nearly-AdS2 gravity and disc of gravitational backreaction, which limits the amount of information we can send through the wormhole. We emphasize that the process can be view

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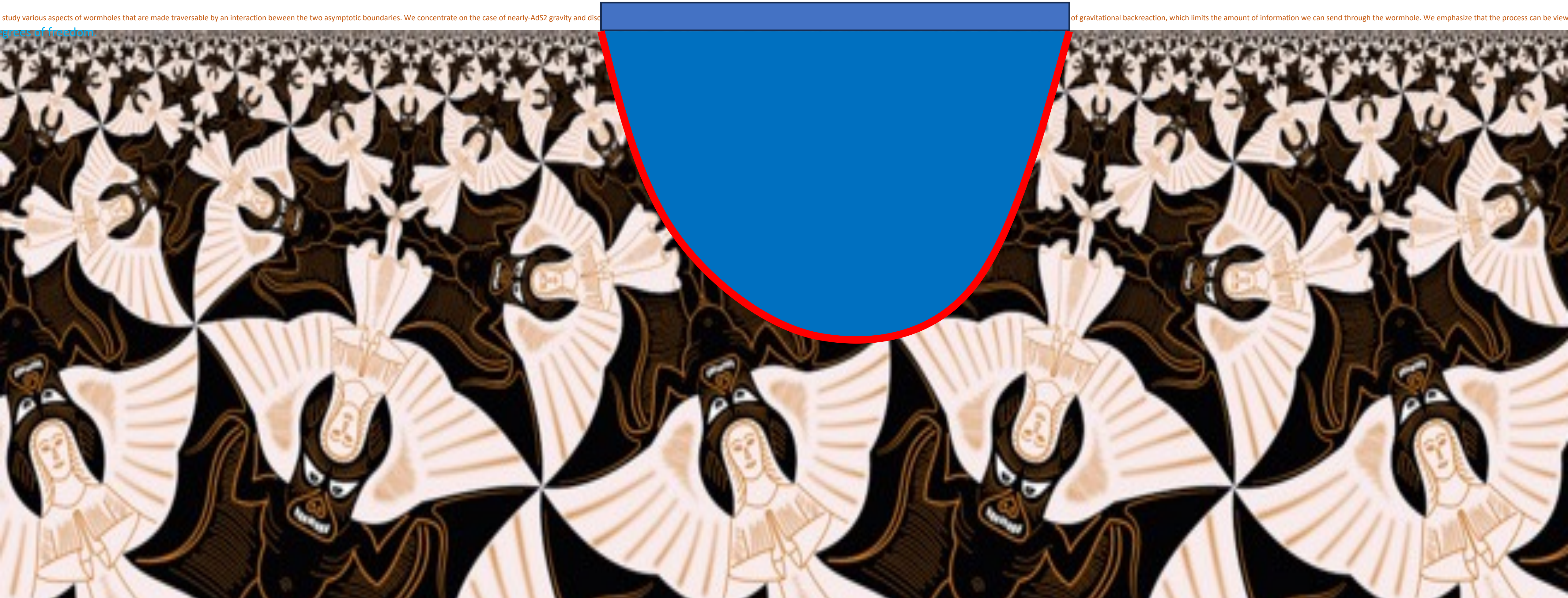


→ The bulk is encoded in the boundary in a way similar to how quantum information can be stored in quantum computer.

Via a quantum error correcting code

Shor 1995

Almheiri, Dong, Harlow 2014

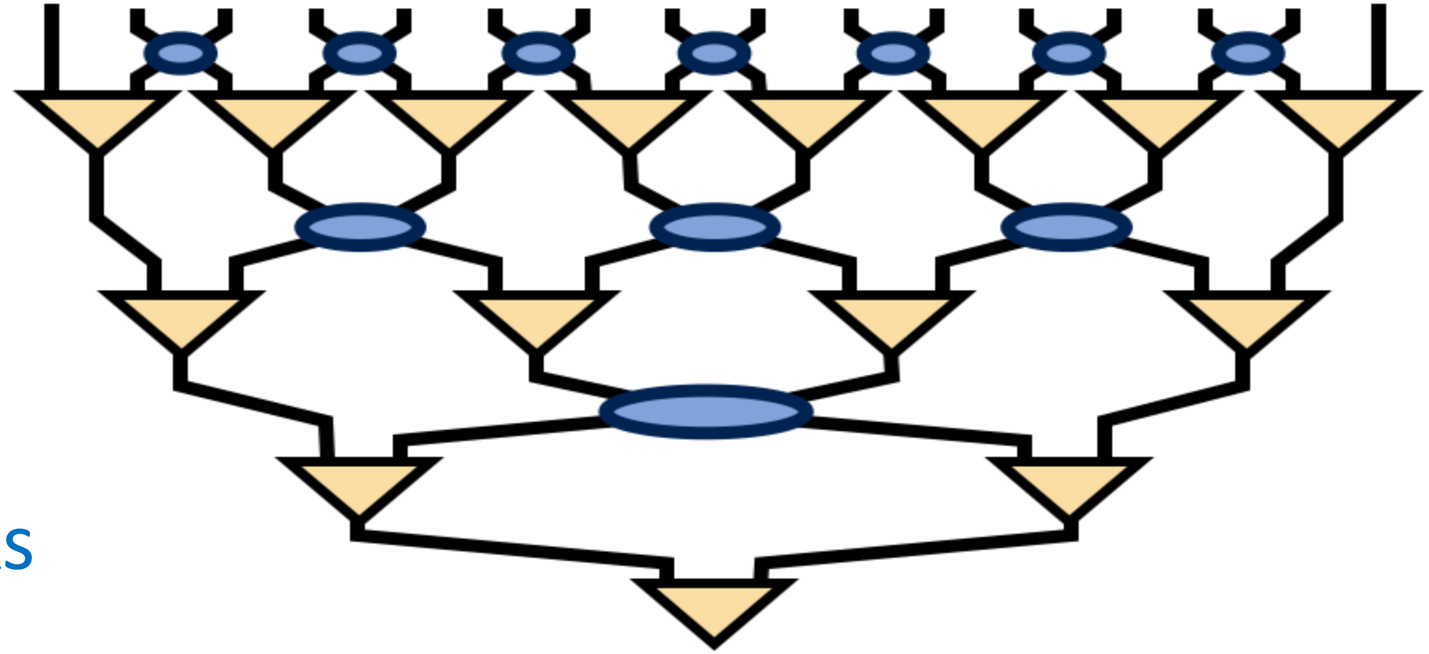
Spacetime emerges from quantum entanglement = correlations of the boundary quantum system.

Geometry = patterns of entanglement = patterns of correlations.

Like meaning emerges from the correlations between the words.

Patterns of entanglement

If a man does not keep pace with his companions, perhaps it is because he hears a different drummer



Vidal
Swingle

Tensor networks

A comment

In principle we could make these quantum systems in the laboratory and build a ``small universe'' = emergent geometry governed by Einstein equations .

It would need to have about 10,000 qubits.

(In contrast, our big universe needs about 10^{120} qubits**)

Now we will discuss an interesting case of the relation between entanglement and geometry.

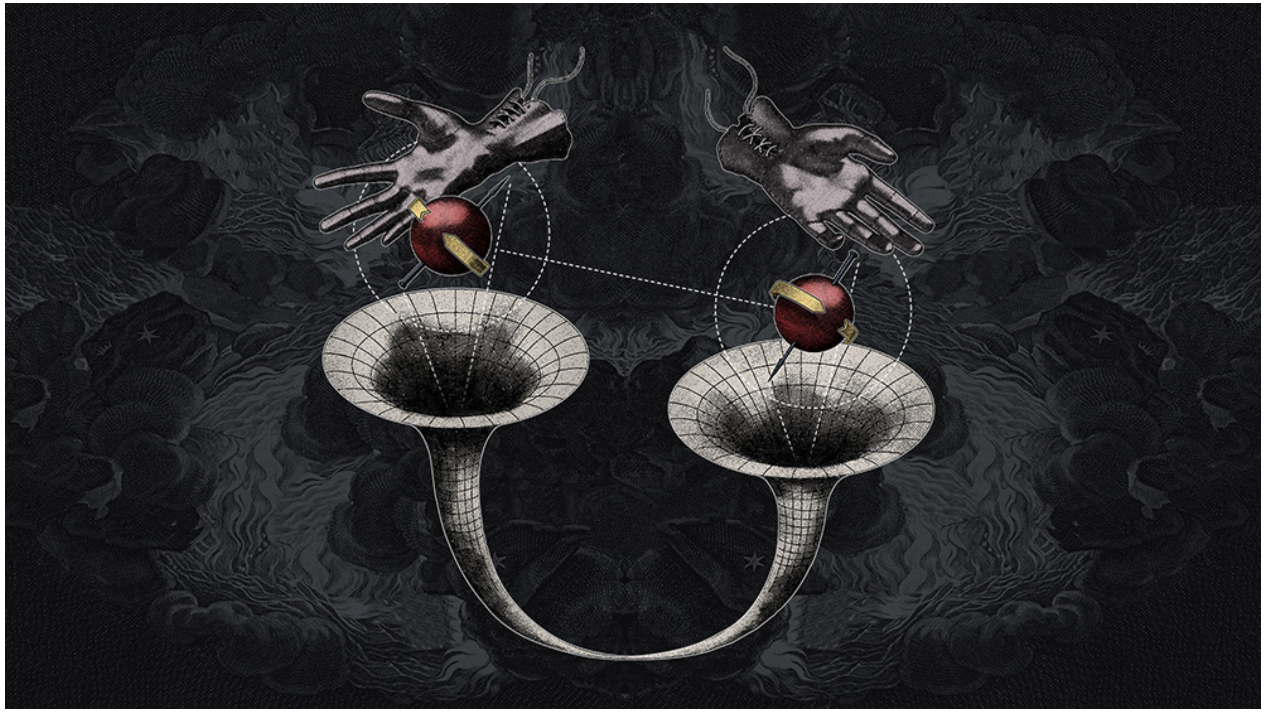
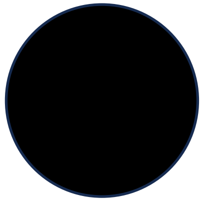


Image credit: quanta magazine

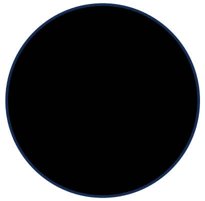
There is a funny feature of the simplest black hole solution.

It describes two black holes!

Einstein and Rosen, 1935

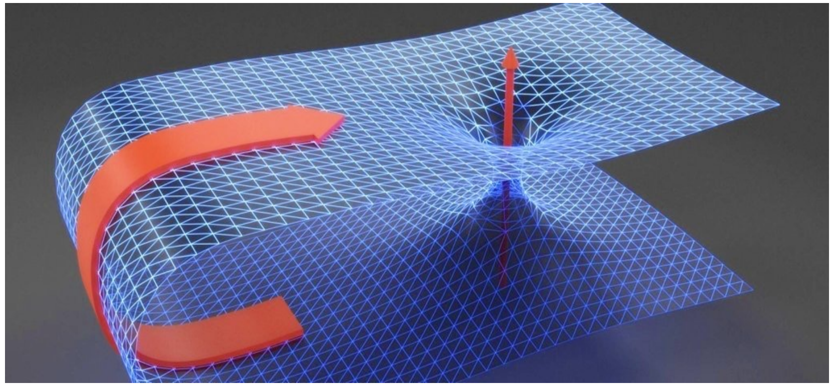


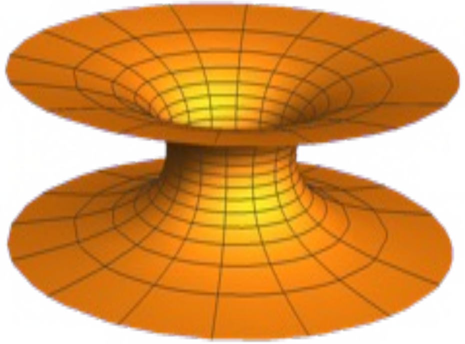
Two black holes far, far away.

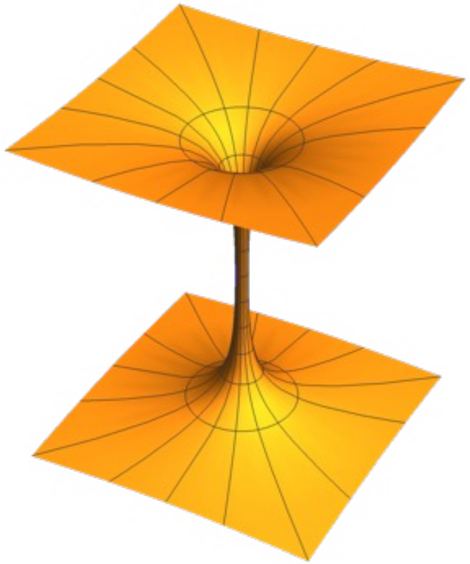


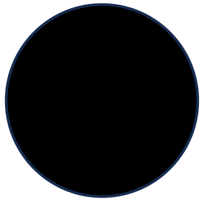
But sharing a single interior!.

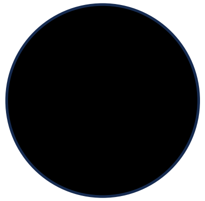
The interior is time dependent: It stretches and collapses:
a traveler cannot go from one to the other



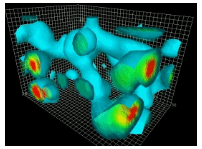




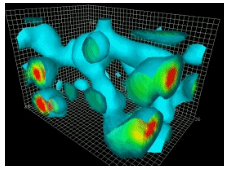




Interpretation



It corresponds to two entangled black holes



If a man does not keep pace with his companions, perhaps it is because he hears a different drummer

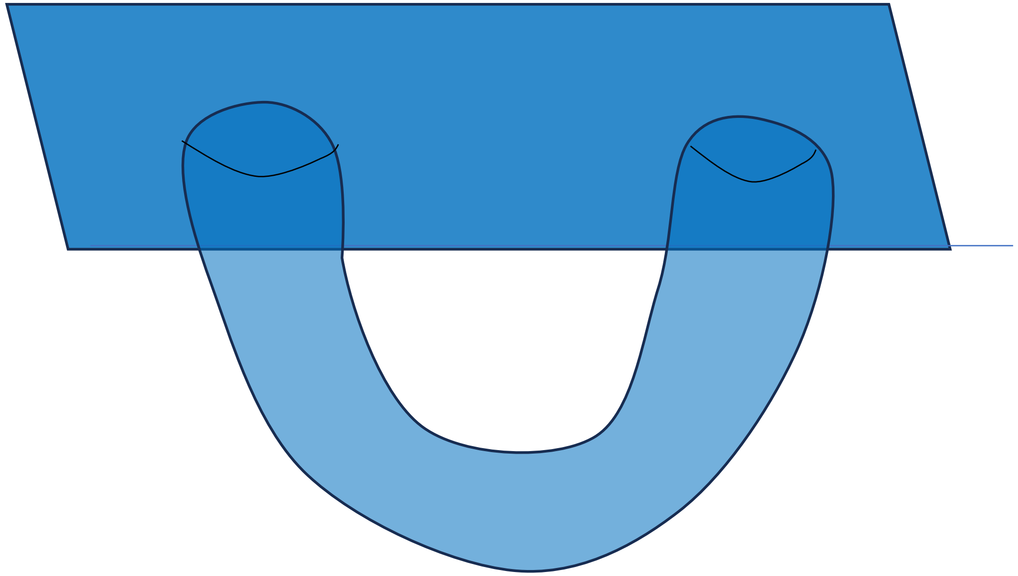
Si un hombre no lleva el paso de sus compañeros, quizas sea porque está escuchando a otro tamborista

If a man does not keep pace with his companions, perhaps it is because he hears a different drummer

Si un hombre no lleva el paso de sus compañeros, quizas sea porque está escuchando a otro tamborista

Bring them closer and allow some simple form of interaction
Then the wormhole can become traversable
(but not a shortcut)

Gao, Jafferis, Wall, 2016



In quantum mechanics, this is called quantum teleportation.

When spacetime is emergent, this teleportation can happen through a wormhole.

Analogy for quantum teleportation through a wormhole

Three elements

1) Entanglement.

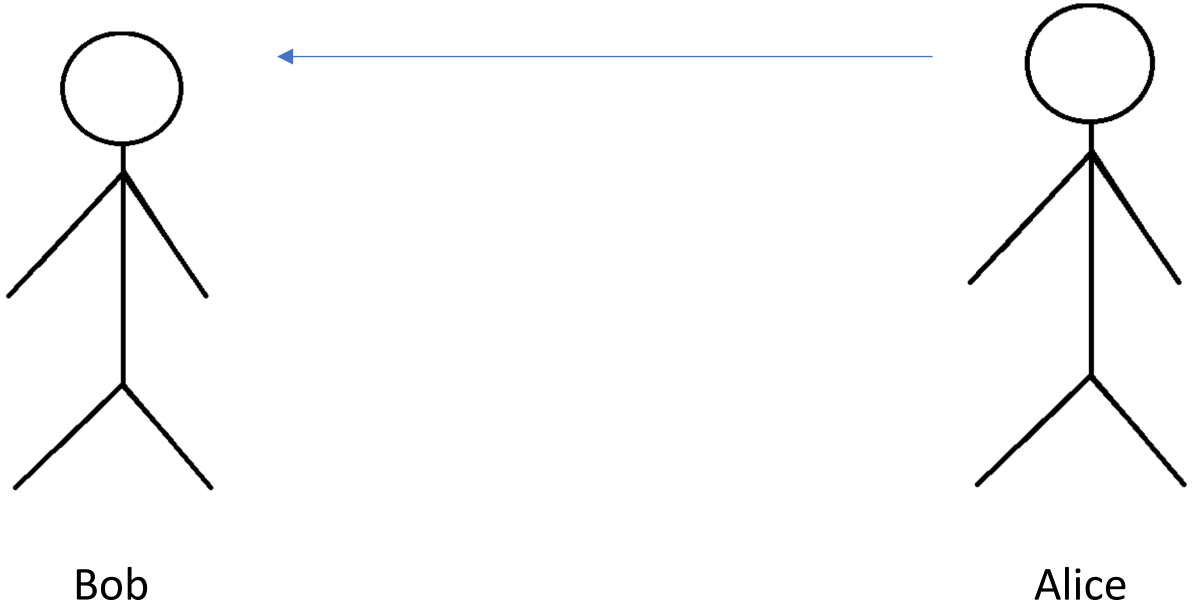
2) Communication

3) ``wormhole’’

Entanglement → shared experiences

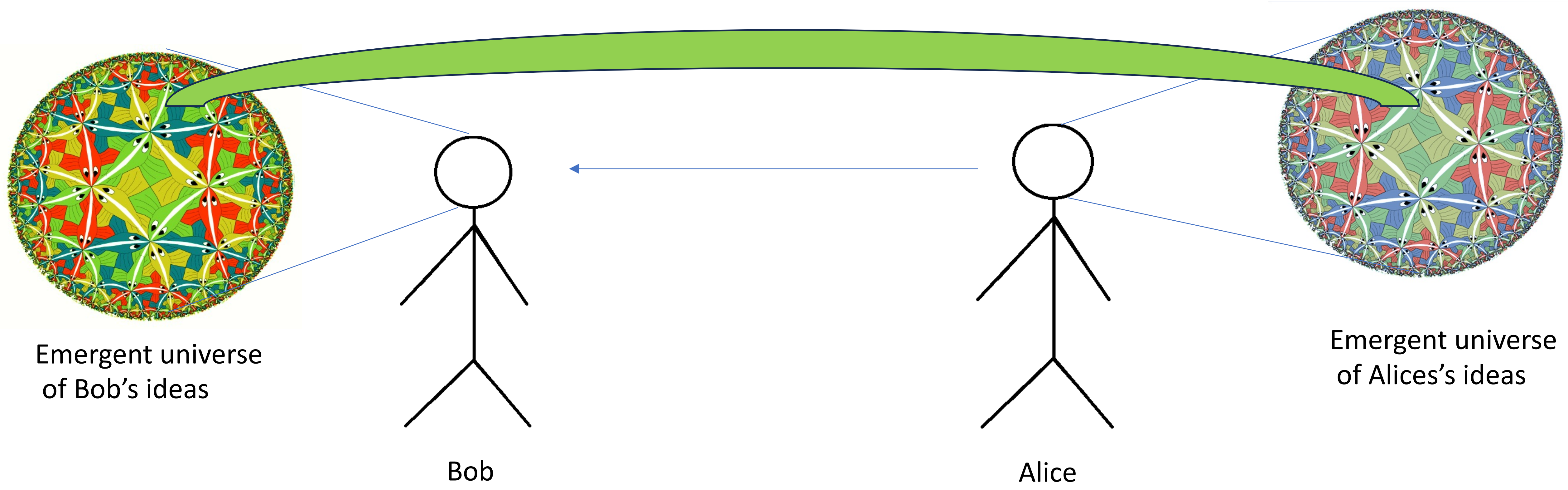
Bob and Alice have been married for many years.
They share many common memories.

Communication = a look



Transfer of ideas

An idea gets transferred from Alice's mind to Bob's mind



People who just saw the look could not guess what the idea was, because they do not know their common experiences

Similar wormholes are important for understanding how information is encoded in Hawking radiation and the black hole interior.

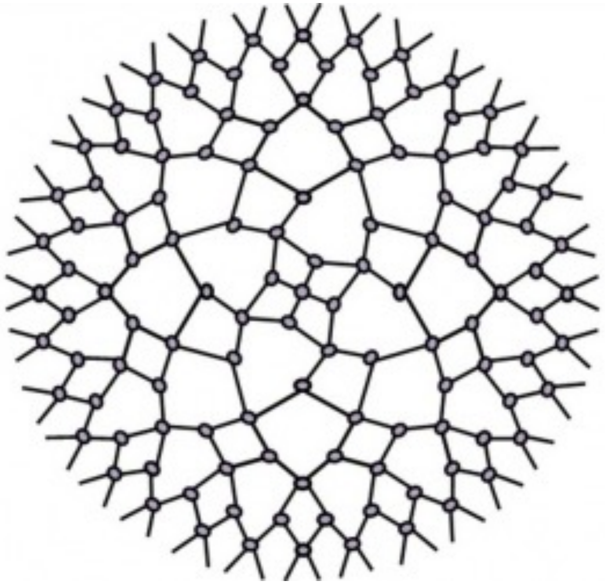
Penington; Almheiri, Engelhardt, Marolf, Maxfield 2019

Saad, Shenker Stanford 2018

+ …

Conclusions

- Quantum systems → geometry.
- Our spacetime geometry could be emergent.



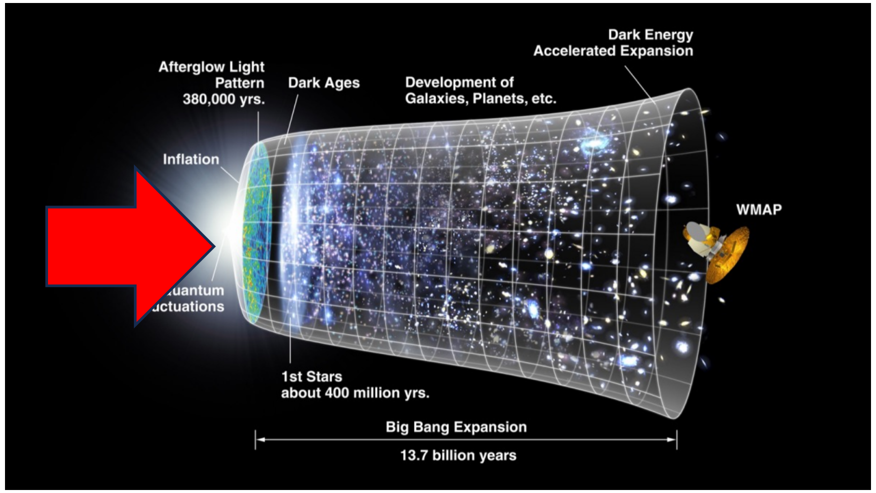
An interesting consequence

- We could make tiny ``universes’’ in the laboratory.

Future

- Probably, this will lead to understanding of the singularity inside black holes.

- Hopefully, we will then understand the beginning of the universe!



Thank you