Black Holes
and
the nature of space time

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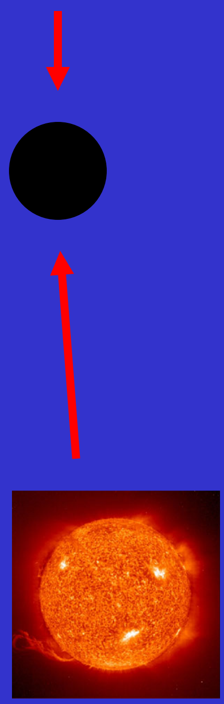
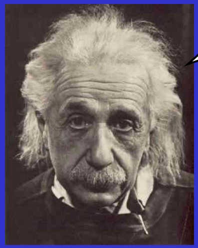
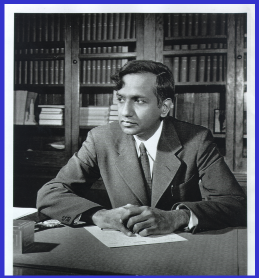
General relativity



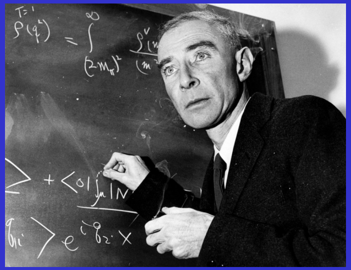


I do not think so…

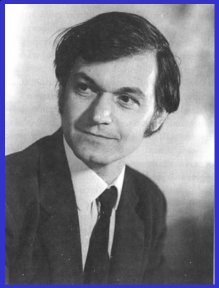
They are unavoidable



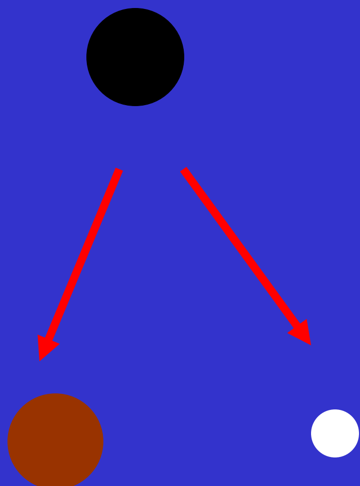
Chandrasekar



Oppenheimer, Snyder

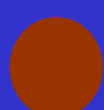


Penrose

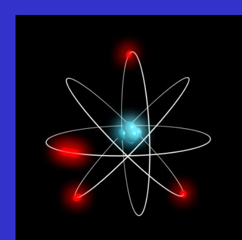


They are not black

They imply that quantum mechanics is incompatible with gravity

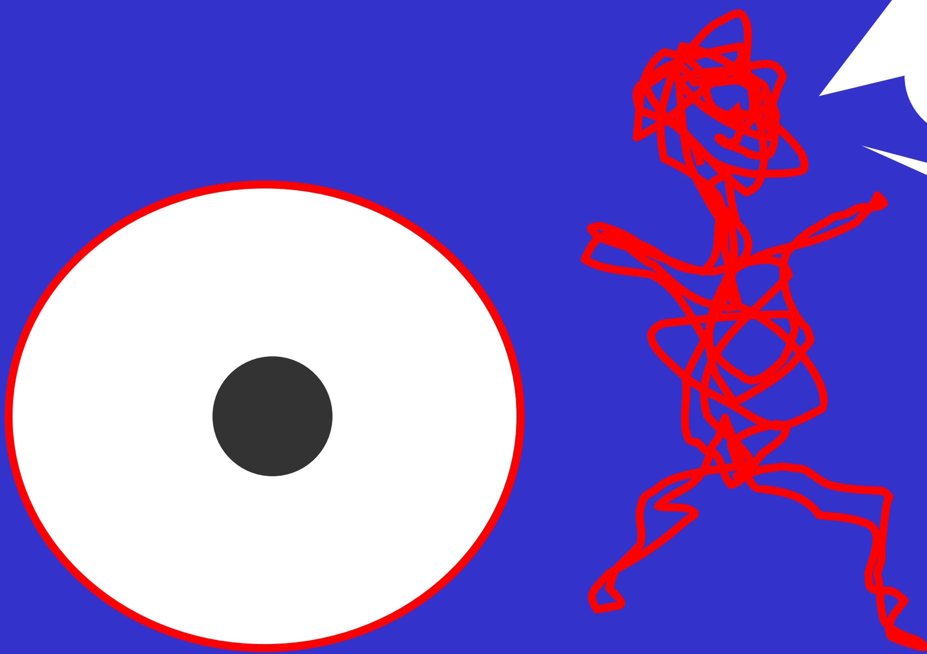


Incompatible ?



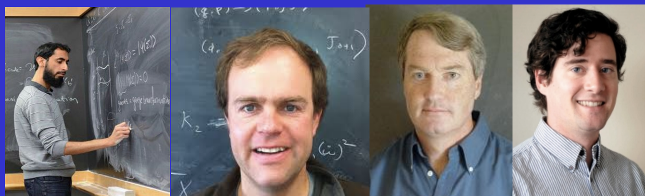
String theory

Black holes as seen from the outside are compatible with quantum mechanics



Relation between quantum mechanics and spacetime geometry

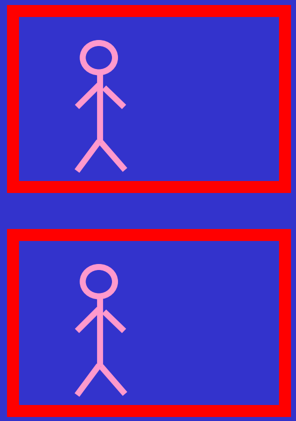
Still several puzzles with the interior



Principle of Relativity

Galileo

- An observer travelling with constant velocity observes the same laws of physics as one at rest



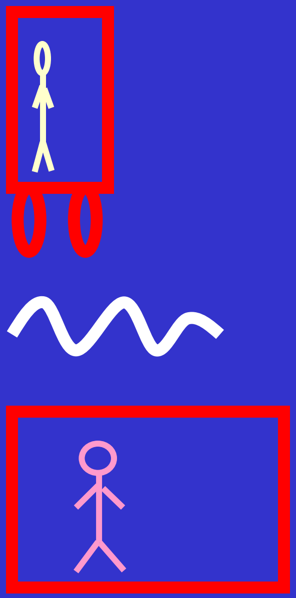
Special Relativity

Einstein

- Two observers travelling with constant velocity observe the same laws of physics
- There is a maximum velocity for signal propagation: The speed of light

Both measure the same speed of light

Time flows at different “speed” for each observer



The twin "paradox"

Felt some acceleration !

The twin "paradox"

Suppose that the rule is that when they meet again they would both die.
Who would you rather be ?

Constant velocity

Changing velocity

Even elementary particles prefer this → this is why they move in straight lines

Principle of maximal life (experienced time)

Lesson:

Space and time form a single entity: spacetime

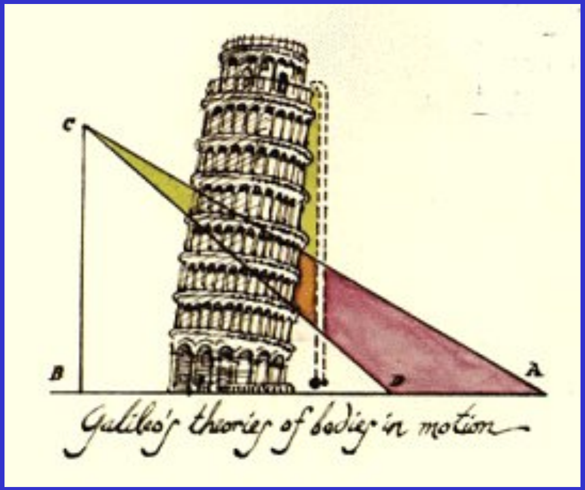
The time we measure depends on how we move.

Particles move in straight lines to maximize their lifetime.

Gravity

Aristotle: Heavier objects fall faster

Galileo: Everything falls in the same way (once we remove the air resistence)



Einstein’s happy thought:

When you fall freely gravity ``disappears’’

New physics law: ``Equivalence principle’’

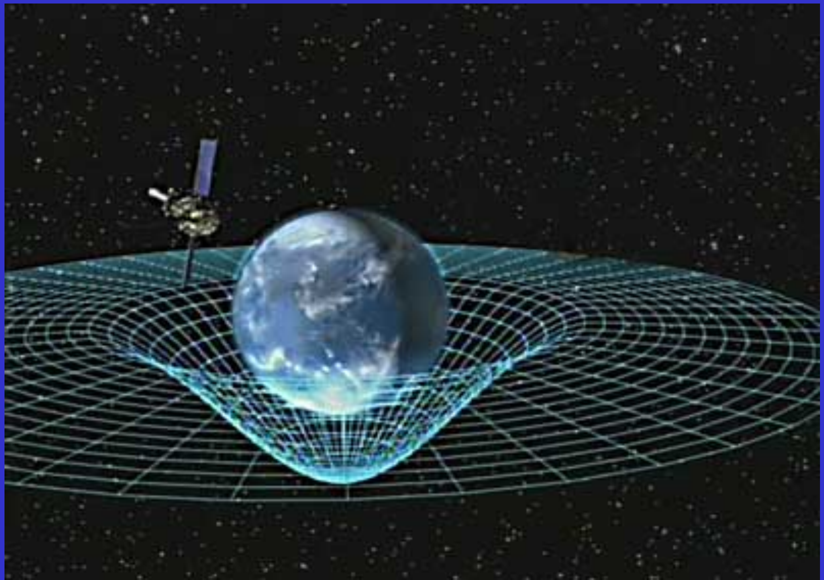
Going with the flow feels easier


Feels weightless

General Relativity

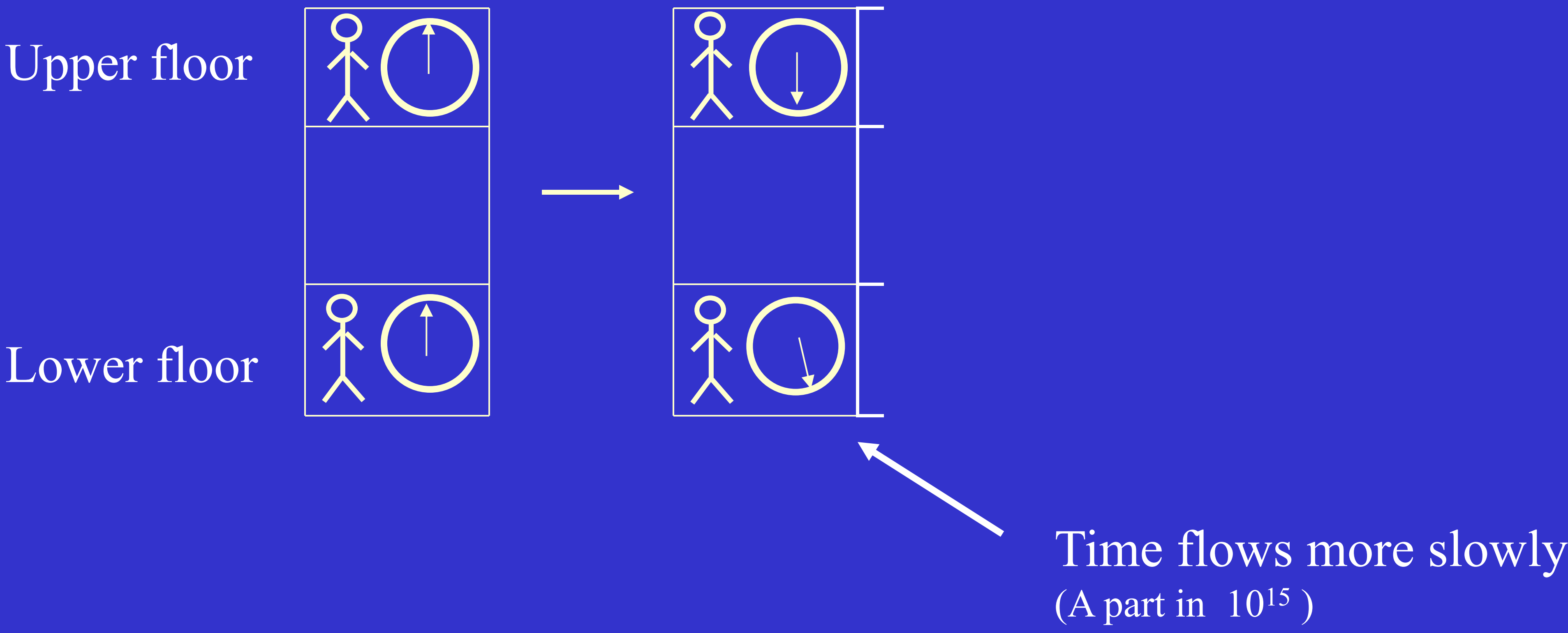
Einstein 1915

- ✓ Gravity is due to the geometry of space-time.
- ✓ A heavy object curves the space-time around it.
- ✓ A second particle follows the maximum lifetime trajectory in the space time.



Gravity changes the flow of time

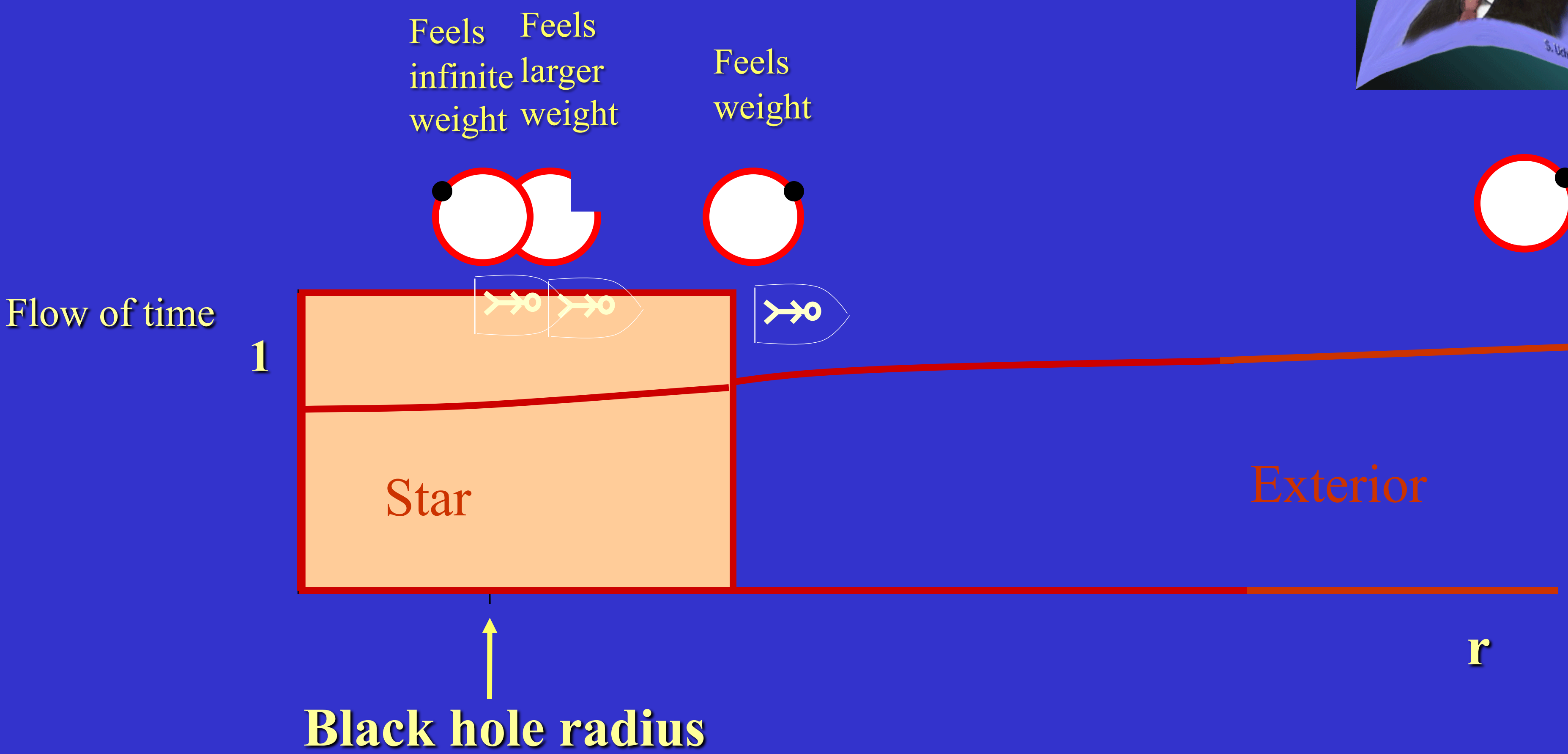
Time flows differently for two observers in a gravitational field.



Massive body

Karl Schwarzschild found the spacetime geometry outside a massive spherical body

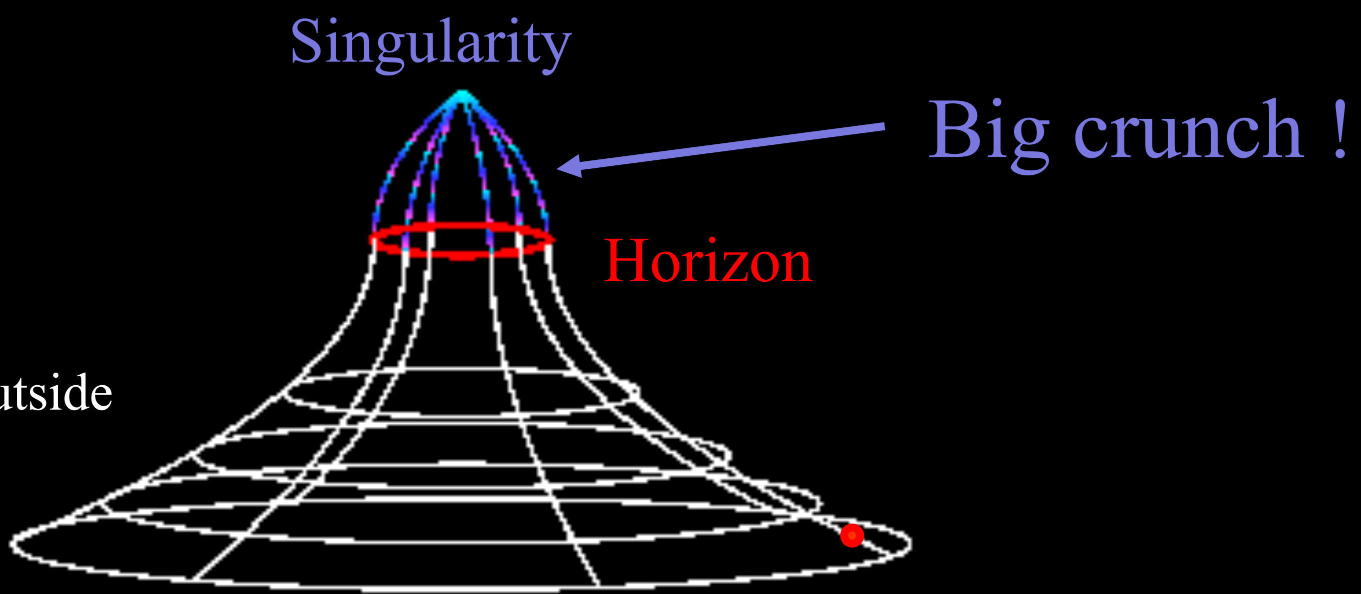
This geometry tells us how time flows.



They are not falling freely!

What if they fell freely ?

The geometry continues behind the horizon



We would not feel anything special when we cross the horizon

But we cannot avoid crashing into the singularity = end of time

Singularity is in the future. Interior is not “inside” but “into the future”. It is a crushing future, but it is hidden from the outside.

Space-time as a river

Unruh

The fish can swim with maximum velocity c. If they go into the region where the river flows at a speed greater than c, they fall into the waterfall.

They do not feel anything special when they cross the region where the speed of the river is equal to c.

Some lessons

1) Once you cross the horizon, you cannot get out!

2) A star can collapse into a black hole.

3) There are objects in the sky that seem to be black holes.

Real black holes

1) Produced by the collapse of massive stars

(size ~ 10-200 km)

2) Black holes at the center of galaxies

(size ~ size of the solar system)

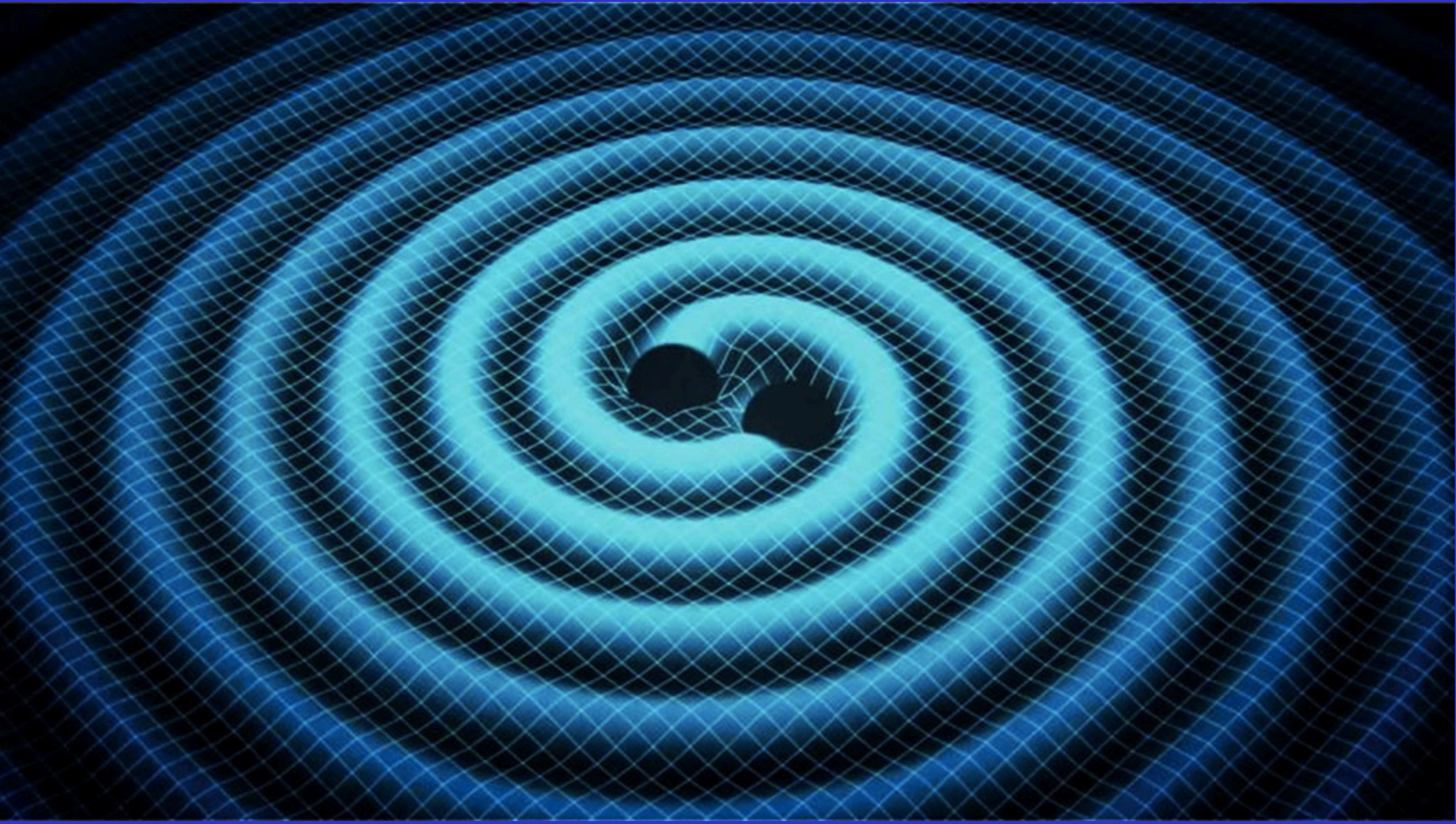
How do we see them?

- Matter falls in, heats up and emits light or other radiation.

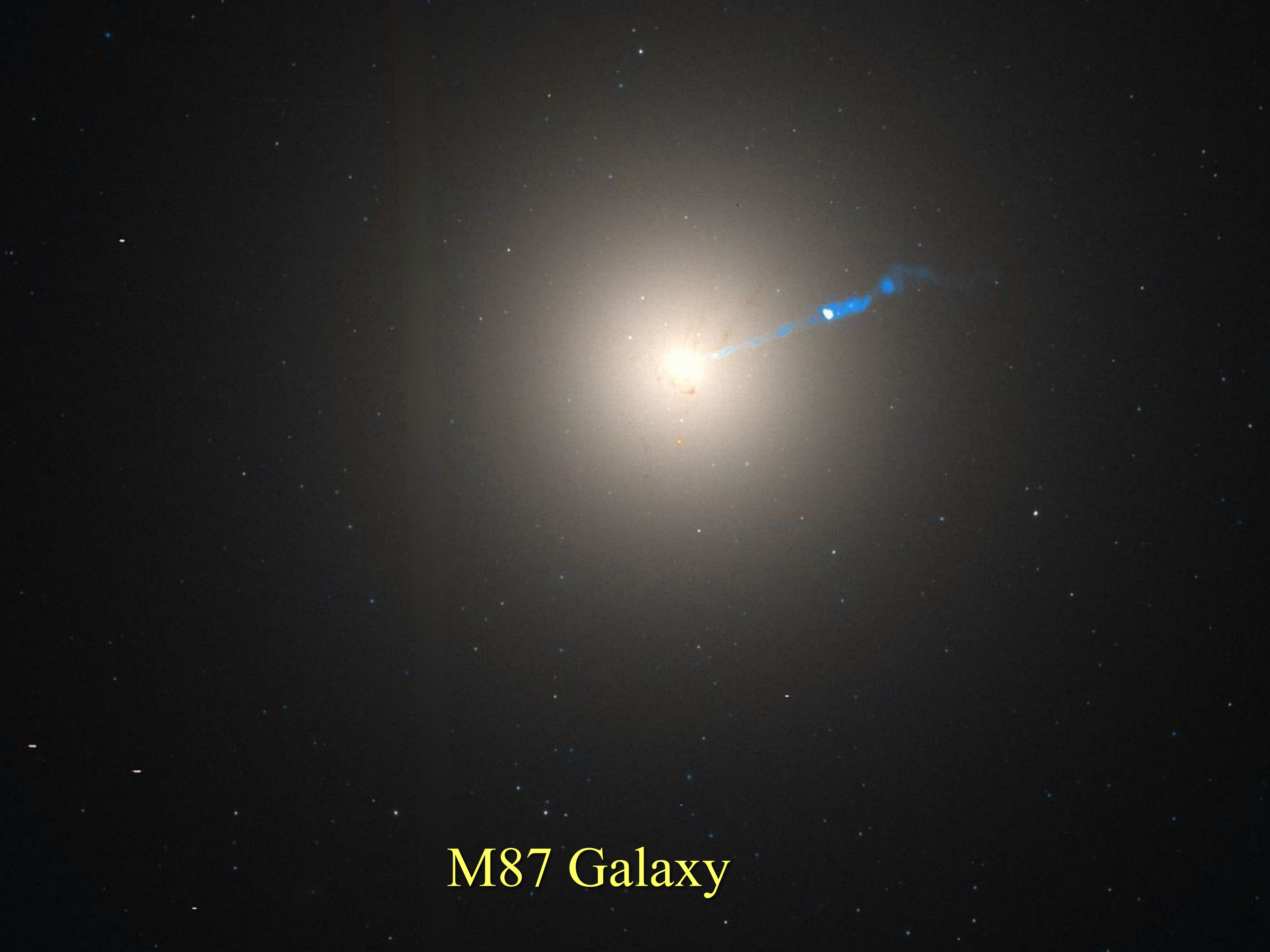
- See the gravity waves produced when two black holes collide.

Black hole collisions produce gravity waves

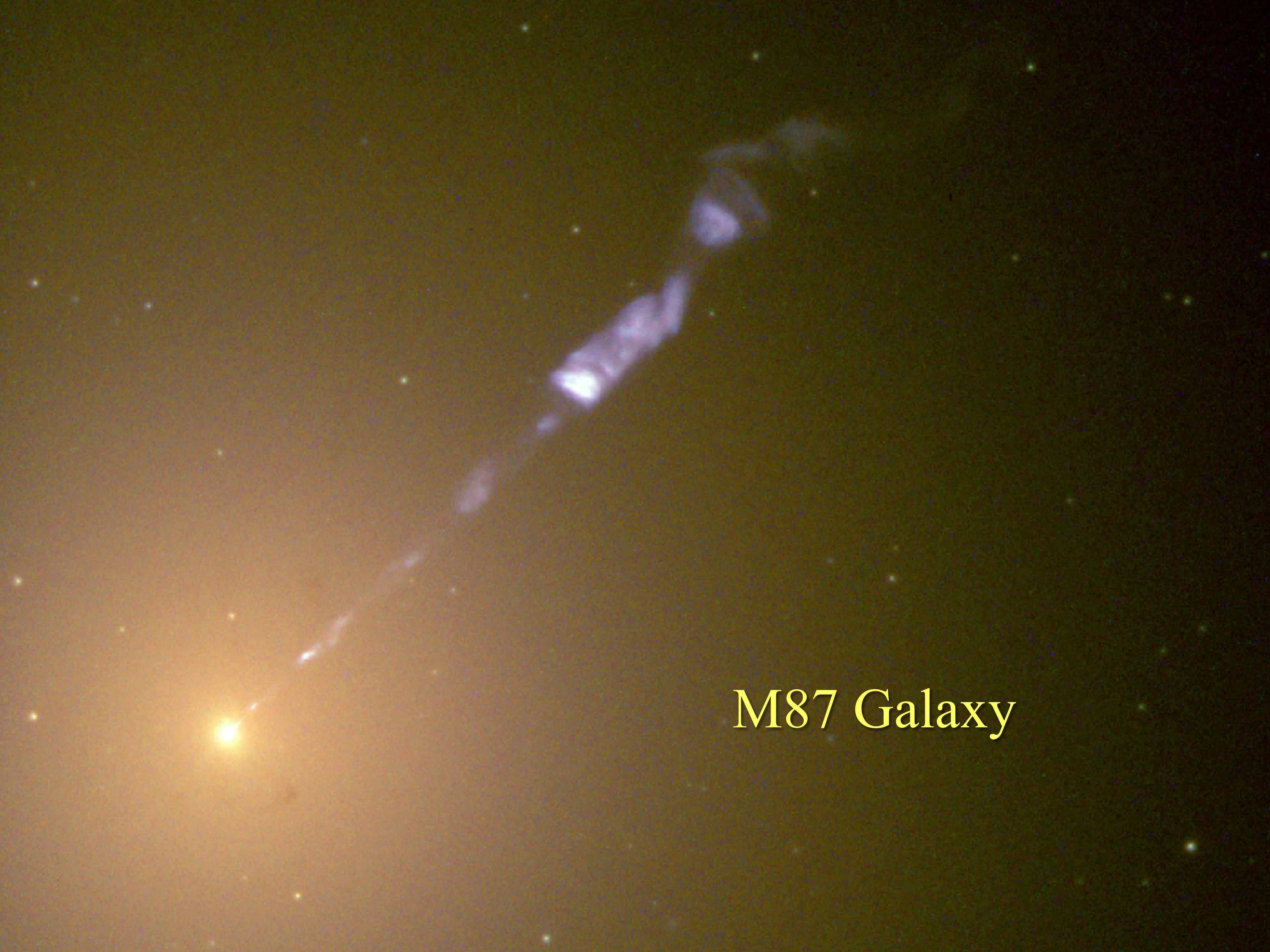
LIGO/VIRGO since 2016



Black holes at the centers of galaxies



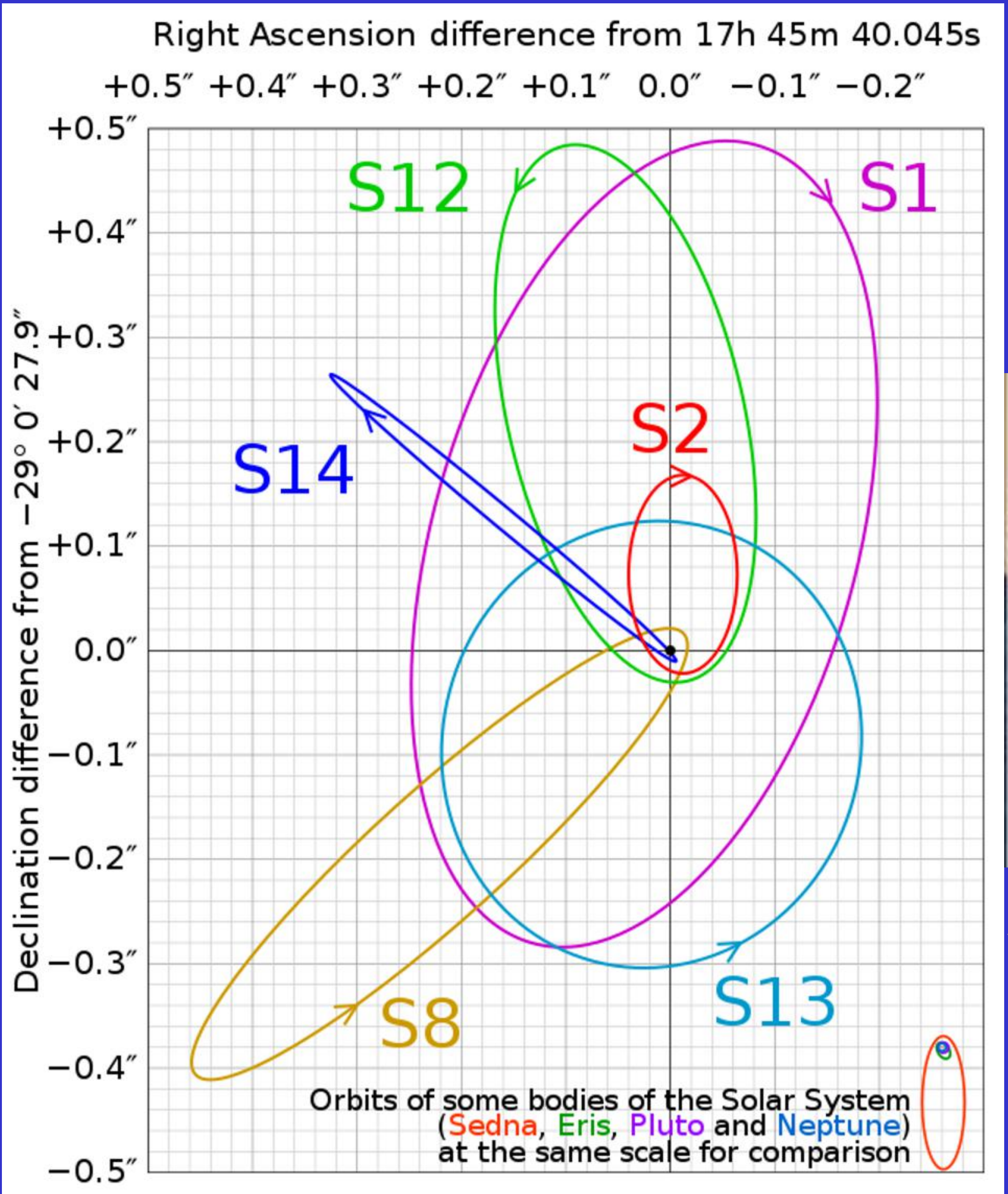
M87 Galaxy


M87 Galaxy

M87 center , from the Event Horizon Telescope

Many galaxies similar to ours have these black holes at the center.

The black hole at the center of our galaxy



Andrea Ghez, Reinhard Genzel

We are in a golden era for black hole observations!

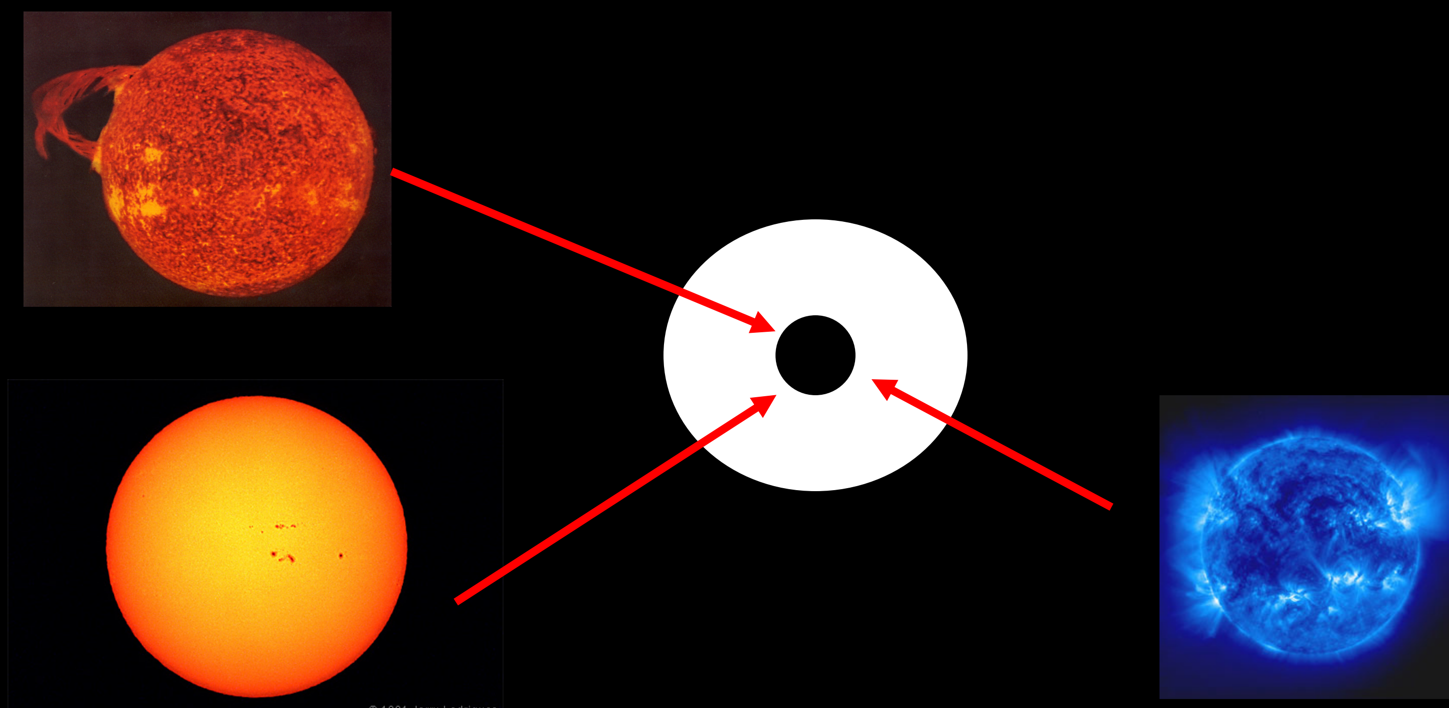
However, this talk will be about some theoretical aspects of black holes.

First we will mention interesting theoretical aspects of black holes

Interesting properties

Universality:

The final shape of the black hole is independent on how it formed. It is only characterized by its mass, its angular rotation velocity and its charge.



The ancients thought that heavenly bodies were perfect spheres.

We know that planets and stars are not perfect spheres.

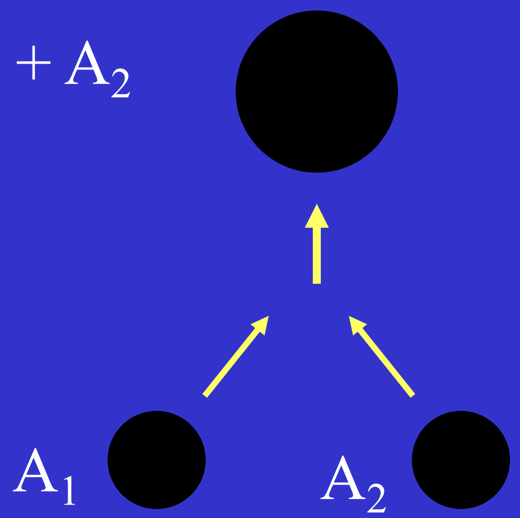
But a non-rotating black hole is supposed to be a perfect sphere!

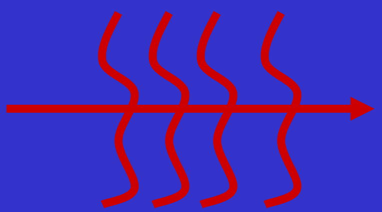
Area law

The area of the horizon always increases.

Hawking

$A > A_1 + A_2$





Gravitational waves

The total mass of the black holes decreases, $M < M_1 + M_2$.

We have discussed black holes according to Einstein's theory of general relativity, which is a clasical theory.

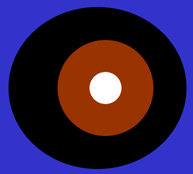
When we include quantum mechanics we find a new surprise:

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:

$T_{sun} = 0.000003\ ^\circ\ K$ (This temperature is too small for astrophysical black holes)

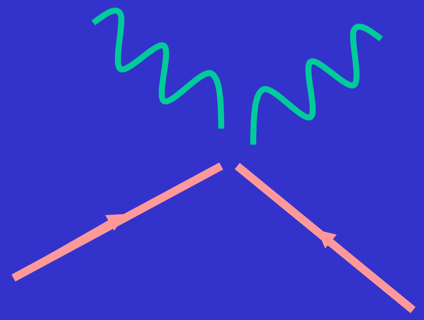
$T_{M=continent} = 7000\ ^\circ\ K$ (white light) has the size of a bacterium

Experimental evidence

- None for the case of black holes.
- But there is a similar effect in cosmology. When we have a fast expanding universe there is a temperature.
- This is our current best explanation, via inflation, for the origin of the primordial fluctuations (which are observed the CMB).

Why?
Relativistic quantum mechanics

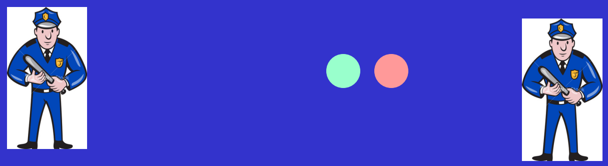
- Particles can be created and destroyed.



The vacuum

→ Energies should be positive.

Negative energy **Positive energy**



$\Delta E \Delta t \leq \hbar$

You can have negative energy for a short enough time.

But the particles should annihilate again soon otherwise they will be in trouble!

In flat space: there is no net particle creation.

The vacuum

In the presence of a horizon

Net particle creation.

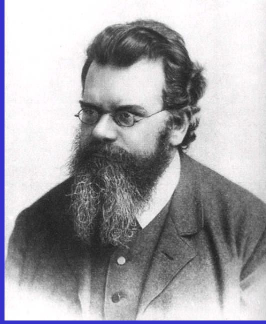
The life of a black hole

- ✓ As it emits radiation it loses mass. It has a finite lifetime

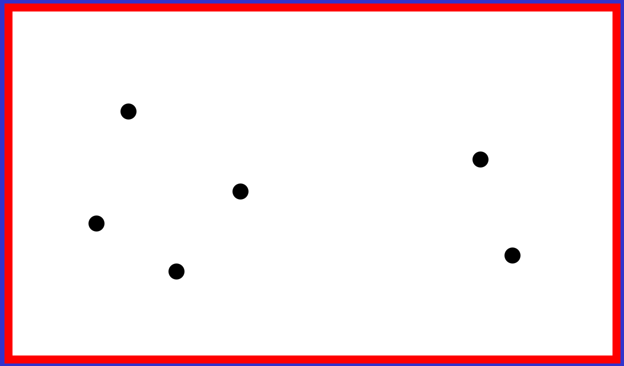
Lifetimes of various black holes:

- ✓ A black hole of the mass of the sun or the earth would live much longer than the age of the universe
- ✓ A black hole with an ordinary mass (say 100 Kg) would evaporate in a very tiny fraction of a second. Worse than a nuclear bomb!
- ✓ A black hole of a mass of 10^{12} Kg produced at the begining of the Big Bang would be evaporating now.
- ✓ There could be very small black holes produced in particle accelerators → would decay very quickly

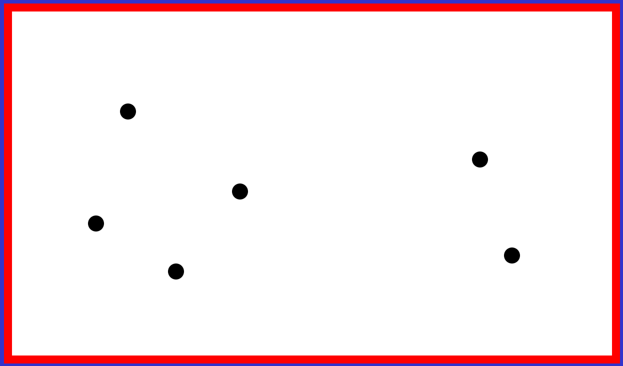
Temperature



Boltzman
1866



Cold



Hot

Heat is due to the microscopic motion of the constituents of matter

Heat and entropy (disorder)

Entropy → number of configurations of the constituents

First law of thermodynamics: Gives us the entropy if we know the energy and the temperature

Bekenstein, Hawking

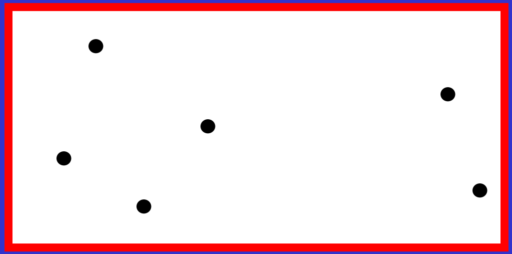
$$S = \frac{Area}{4G_N\hbar}$$

$$S = \frac{Area}{(10^{-33}\,cm)^2}$$

Area law → second law of thermodynamics (entropy increases)

What are the constituents of a black hole?

- Microscopic constituents of spacetime
- Structure and nature of spacetime



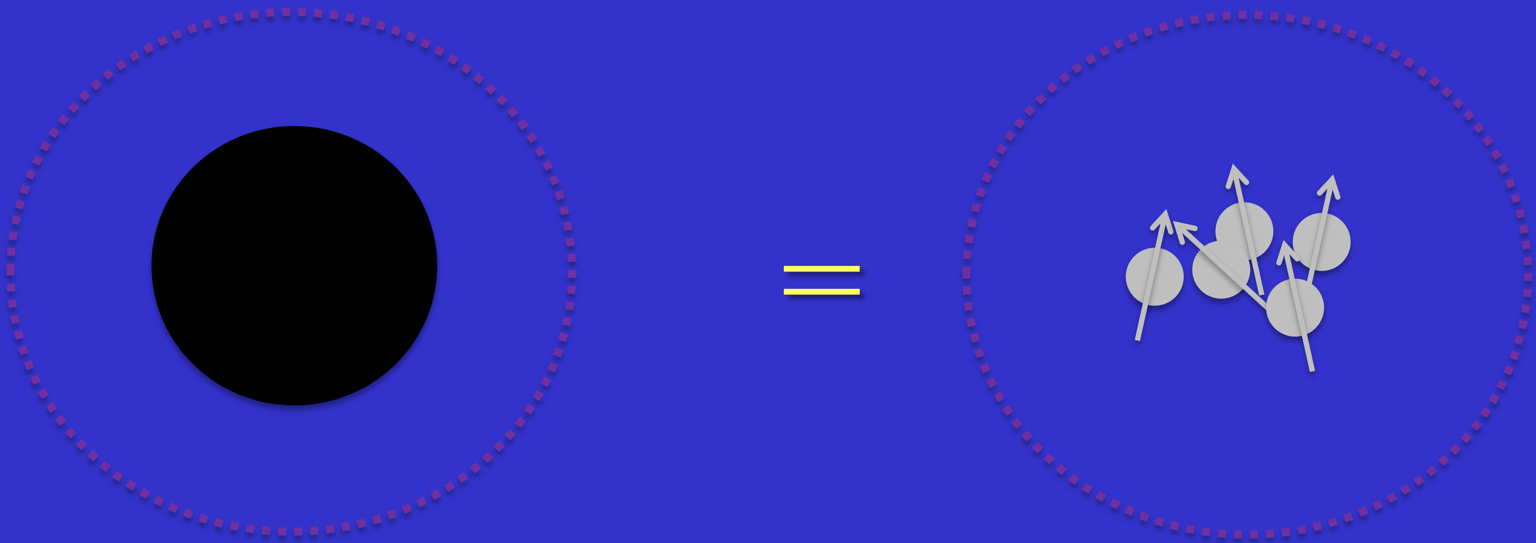
For the air: the air appears to be uniform, but at the molecular scales it is not uniform, it consists of random moving molecules.

For black holes: they were classically perfect ``spheres”, but quantum mechanically we conclude they should not be totally uniform… What are the ``atoms of spacetime”?

These results have inspired a certain hypothesis

Black holes as quantum systems

- A black hole seen from the outside can be described as a quantum system with S degrees of freedom (qubits). $S = \text{Area}/4$ $(l_p = 1)$
- It evolves according to unitary evolution, seen from outside.



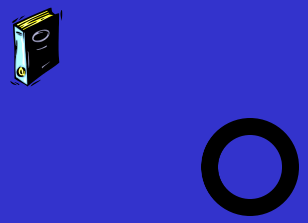
Not everyone agreed with this.

Can’t be true!

Hawking '70

Information loss

We can form a black hole in many different ways but it always evaporates in the same way



Quantum mechanics → Thermal aspects arise due to an approximation. There must be subtle differences in the outgoing radiation which carry the information of how the black hole was made.

Who is right?

We need a theory that puts together quantum mechanics and gravity

<u>String theory</u>

Veneziano

String theory

(1968 – 1986 – 90’s -)

Schwartz

Green

Is a theory under construction

Is a theory of quantum gravity= quantum mechanics of spacetime.

It reduces to Einstein’s theory under ordinary circumstances
(low energies or long distances).

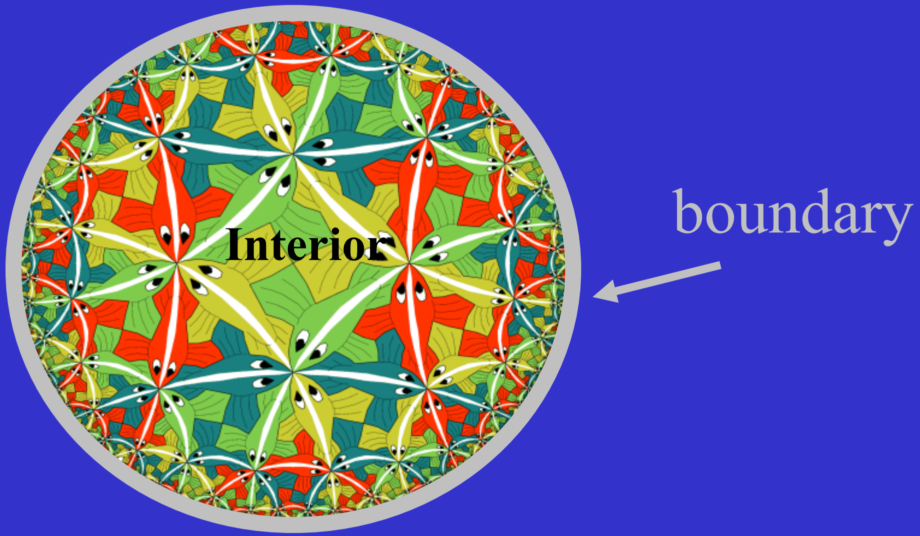
It can describe in a complete way certain simple universes
with negative curvature.

Holography

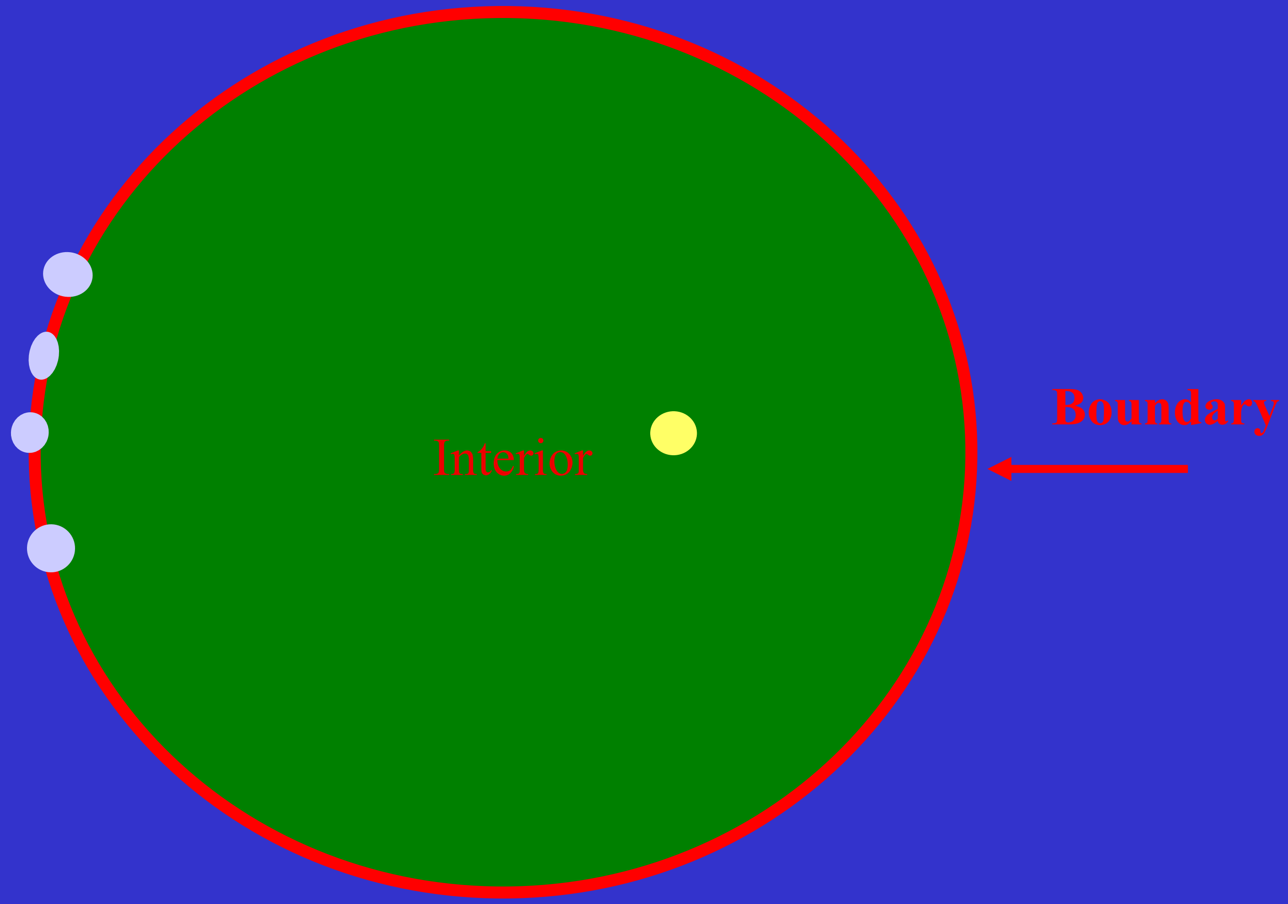
Conjecture!
(with evidence)

We can describe the interior of certain spacetimes in terms of a theory on their boundary.

The boundary theory is a theory of strongly interacting particles, without gravity.



JM
Gubser, Klebanov, Polyakov, Witten



Gravity in the interior → Described by interacting particles on the boundary.

Black holes correspond to a
large nu
on the b

Temp
boundary

- 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

Quantum system lives at the boundary

Emergent geometry

A verbal analogy

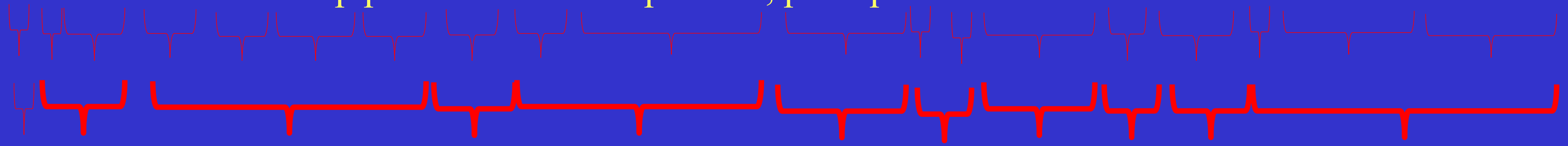
If a man does not keep pace with his companions,

perhaps it is because he hears a different drummer

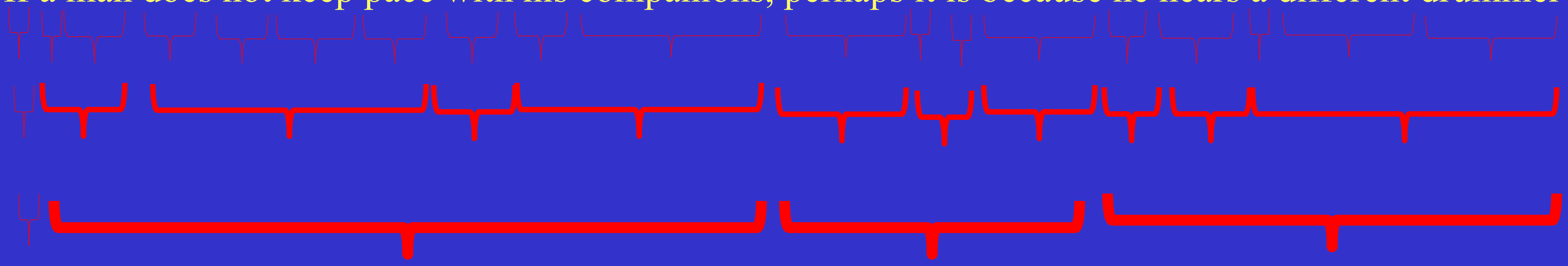
If a man does not keep pace with his companions, perhaps it is because he hears a different drummer

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

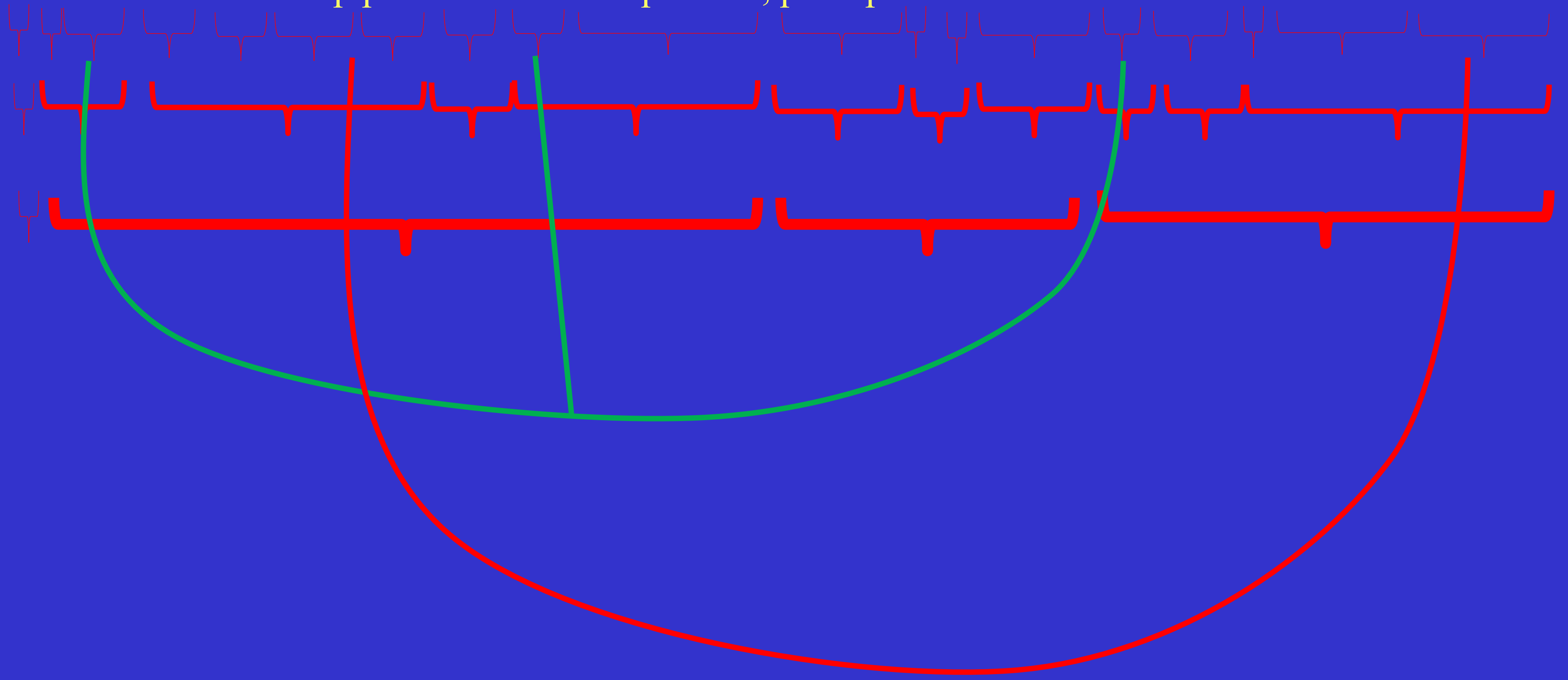
If a man does not keep pace with his companions, perhaps it is because he hears a different drummer

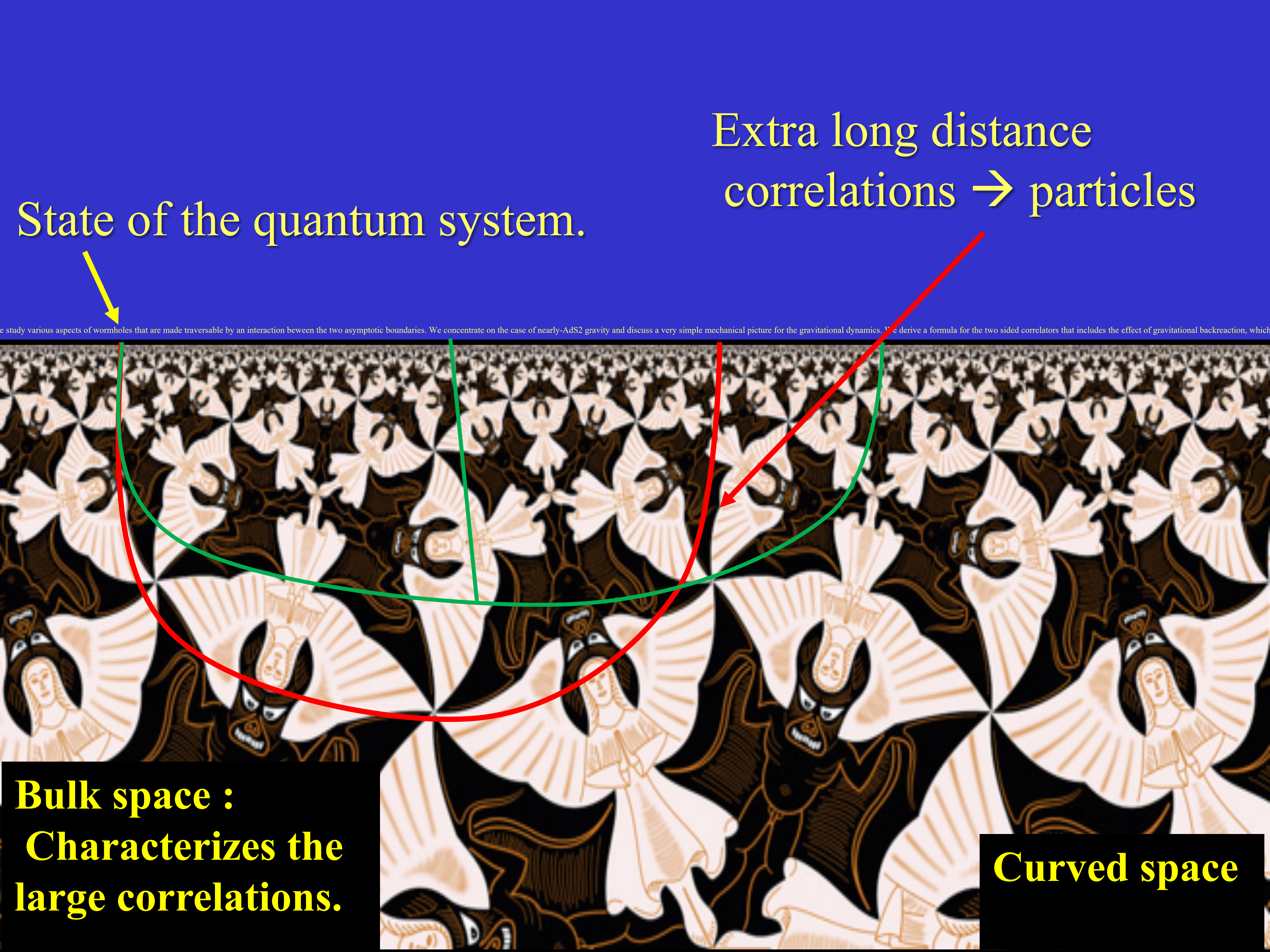


If a man does not keep pace with his companions, perhaps it is because he hears a different drummer



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

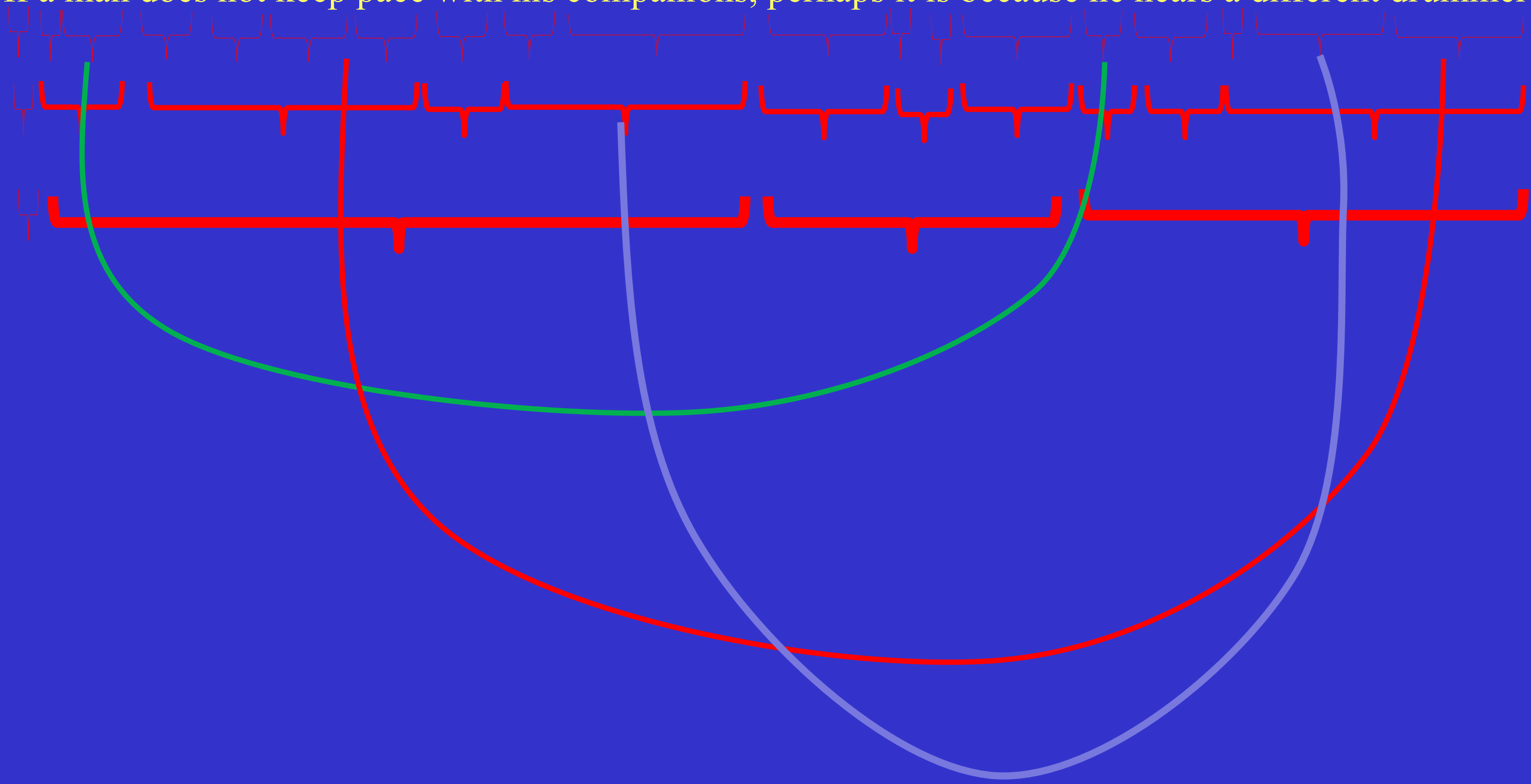



Extra long distance correlations → particles
State of the quantum system.
e study various aspects of wormholes that are made traversable by an interaction beween the two asymptotic boundaries. We concentrate on the case of nearly-AdS2 gravity and discuss a very simple mechanical picture for the gravitational dynamics. We derive a formula for the two sided correlators that includes the effect of gravitational backreaction, which
Bulk space :
Characterizes the large correlations.
Curved space

What is a black hole in the spacetime ?

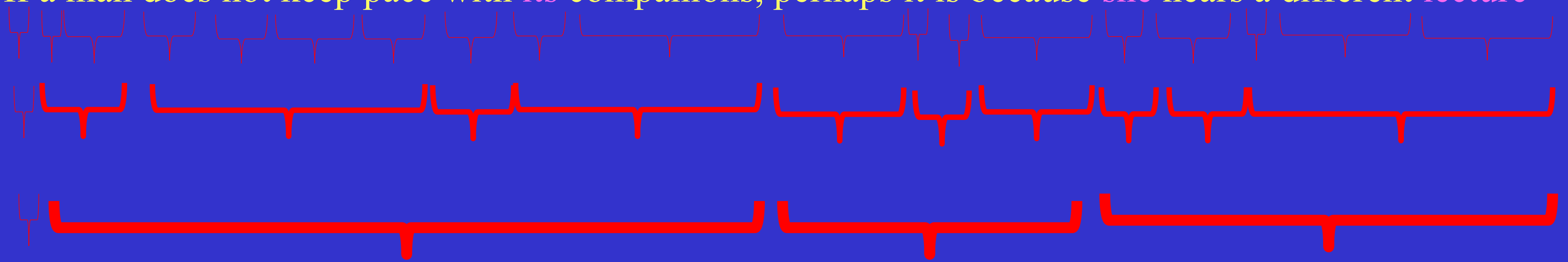
Back to the sentence

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



Make a couple of changes

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



We lost longer distance correlations.

More changes…

If a man my nice mother pace with its companions the moon tells me she writes a different lecture

Black hole grows

No words…

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

Black hole grows.

Area = ignorance.

Area growth → Changes are more likely to mess up a sentence if we edit it randomly.

If the changes were produced by a reversible process, e.g. an encryption algorithm.

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

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

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

Analogous to an encryption process, it is reversible

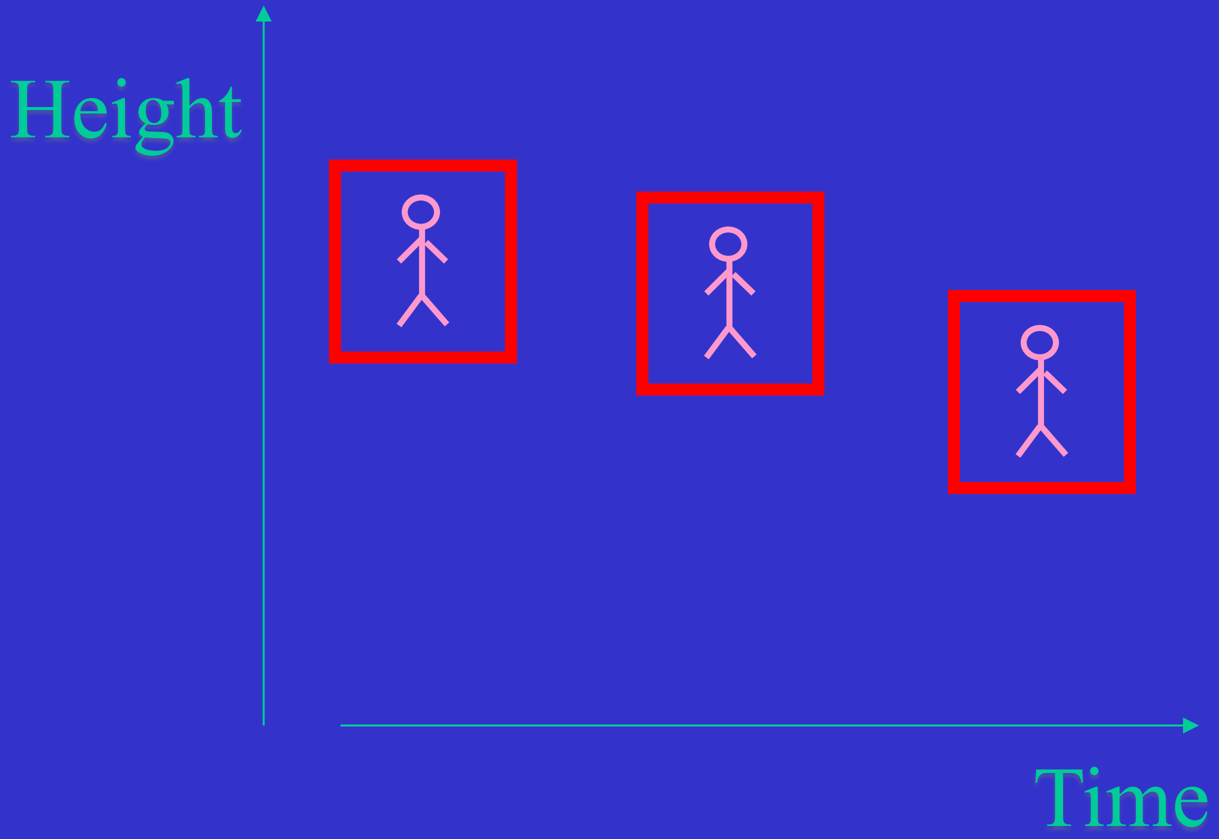
We can undo the formation of the black hole (in principle) and recover the original information.

I will like to end with a somewhat philosophical comment about our methodology

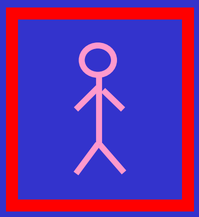
The role of thought experiments

- Thought experiments were important in developing general relativity.
- We will discuss one example.

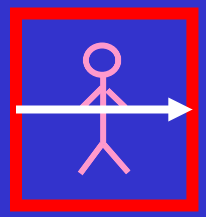
The falling elevator



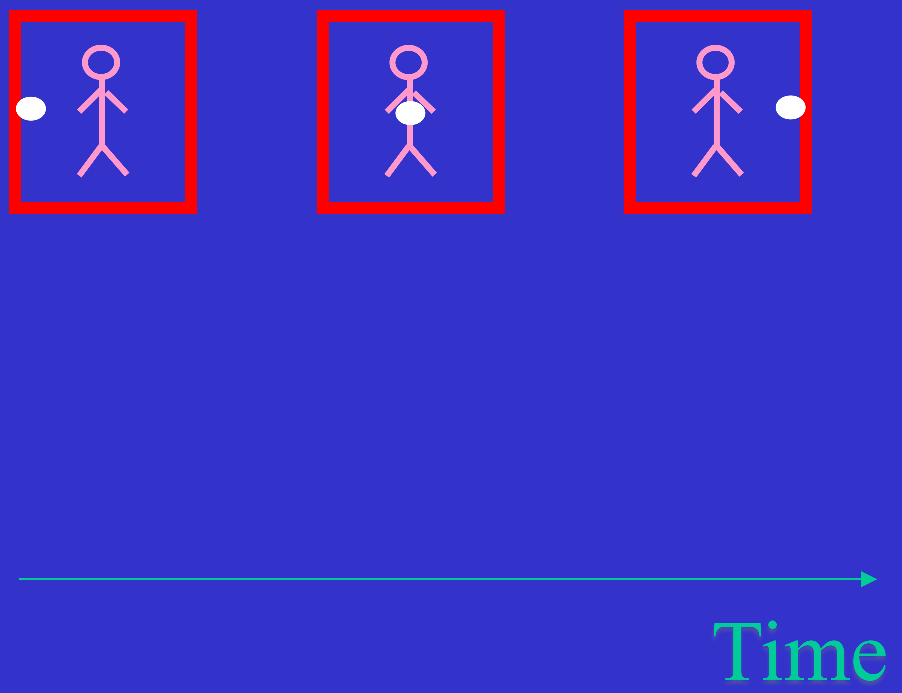
Inside perspective: No gravity



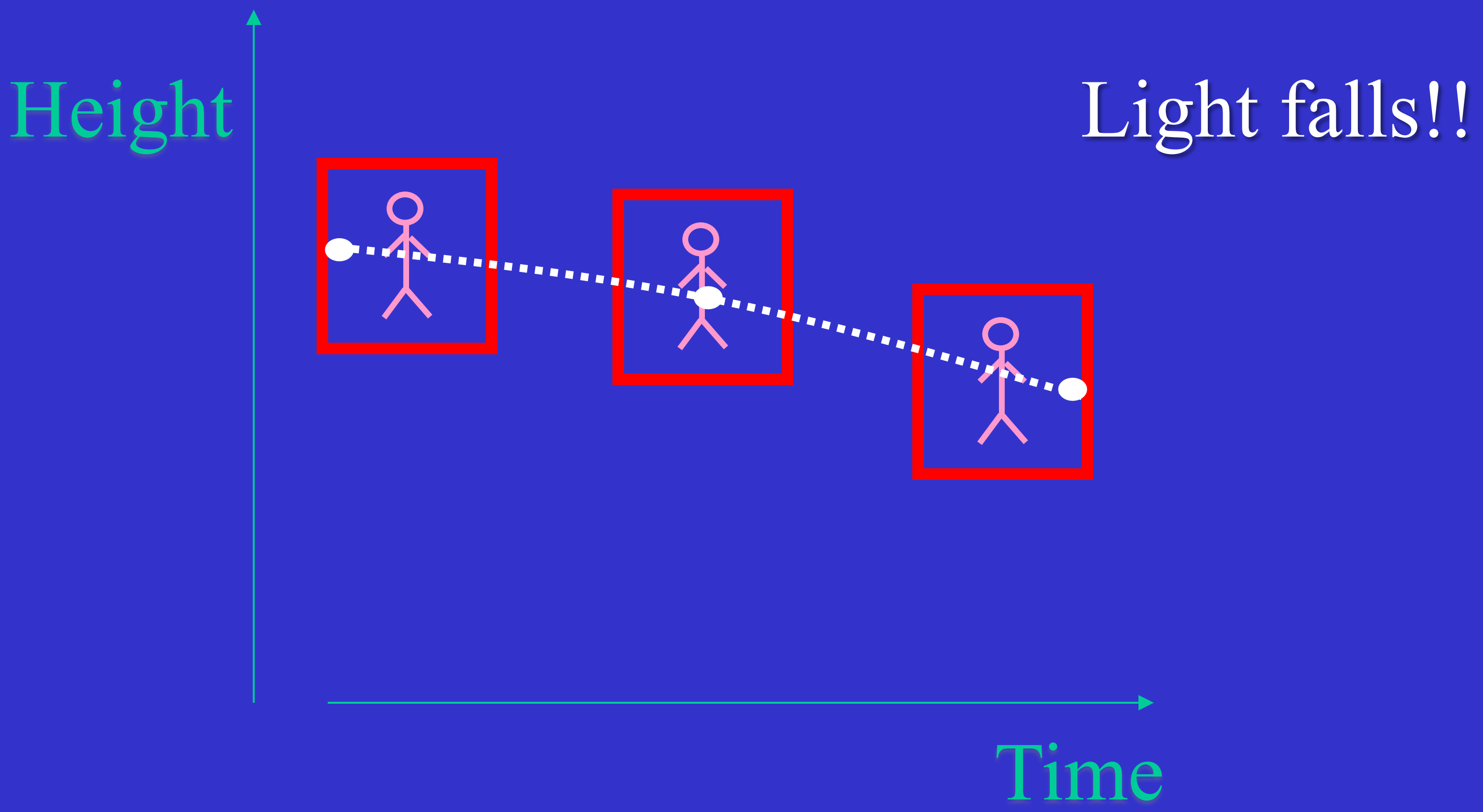
Inside perspective: Send a pulse of light



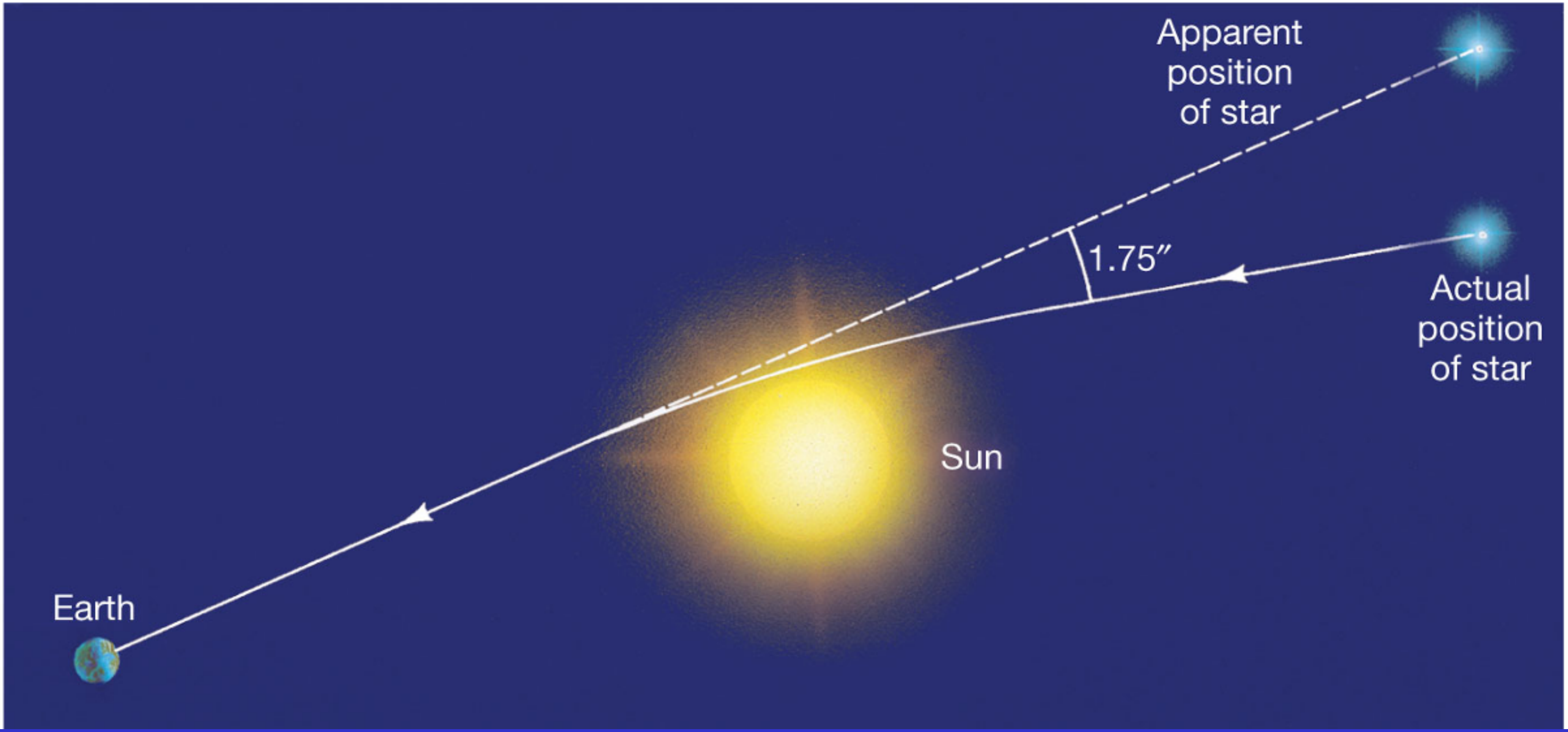
Inside perspective:



Outside perspective



Deflection of light by the sun

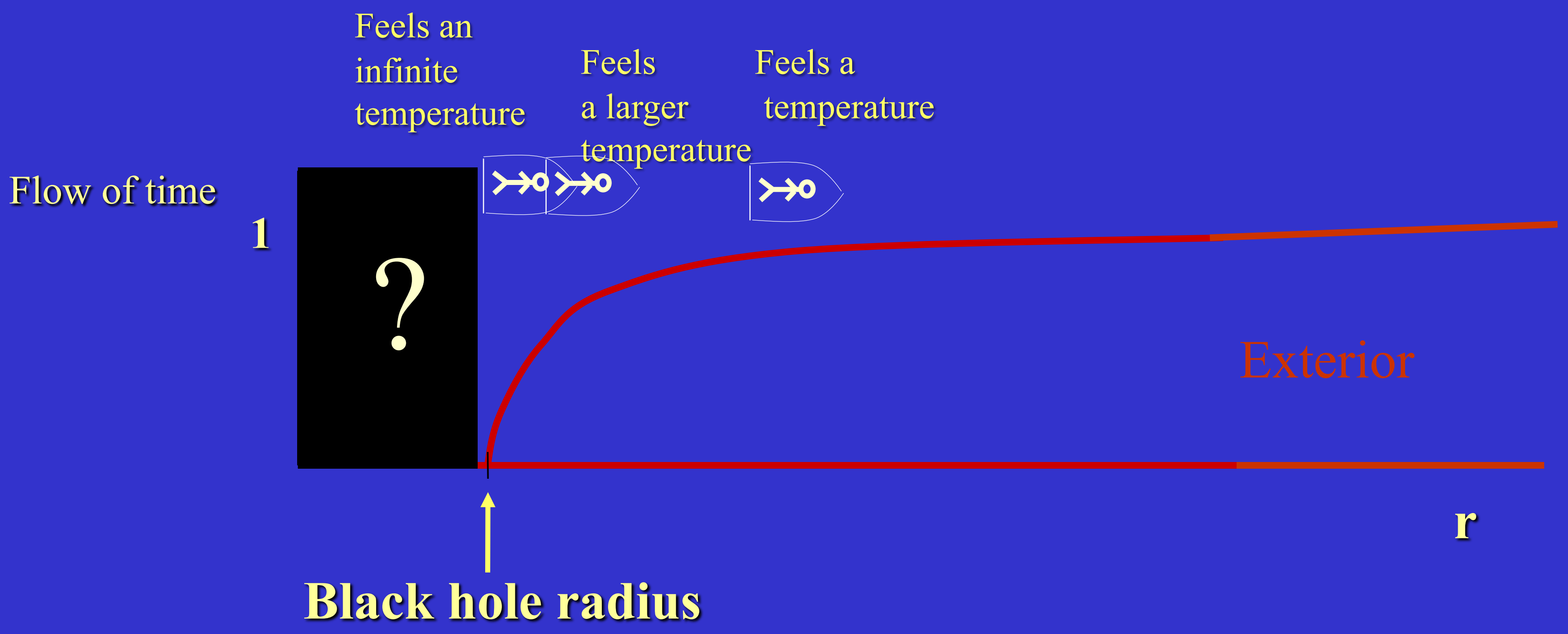


Our thought experiment

Two perspectives for an observer falling into a black hole

- Freely falling → nothing happens
- Outside perspective ?

Static observer, including Hawking radiation.



- For the outside observer, somebody who falls in gets burnt by Hawking radiation at the horizon.

- We again have two different perspectives.
- Reconciling them has lead to some of the ideas that I mentioned before, such as holography.
- Ideas of quantum entanglement play an important role.

For falling light

- Einstein did not get the right value for the deflection angle from his initial thought experiment alone.
- The right value came from the complete theory of general relativity.

For quantum gravity

- We do not have a full theory of quantum gravity, valid for any process.
- But we think that the lessons we are learning are useful steps for developing this theory. And there are deep connections between different areas of physics.
- We hope that once we find the right theory there will be predictions that can be more easily checked, than the black hole ones we discussed.

Conclusions

- ✓ Black holes are fascinating objects where the geometry of spacetime is deformed in a dramatic way

- ✓ Black holes and quantum mechanics give rise to interesting theoretical challenges

- ✓ String theory can describe black holes in a consistent way (from the outside).

- ✓ Spacetime is an effective (approximate) concept which arises from more elementary particles living on the boundary of spacetime.

- ✓ Entanglement plays a crucial role in determining the structure of spacetime.

The end

Thank you !

Extra slides

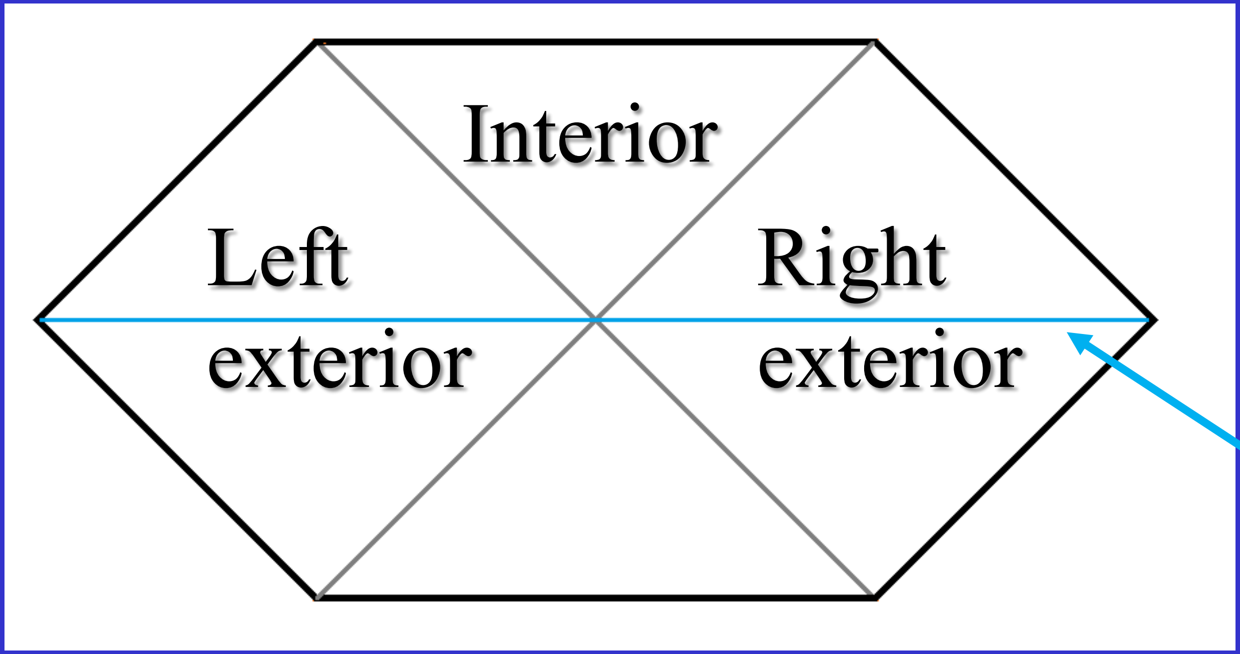
Entanglement and geometry

Entanglement and geometry

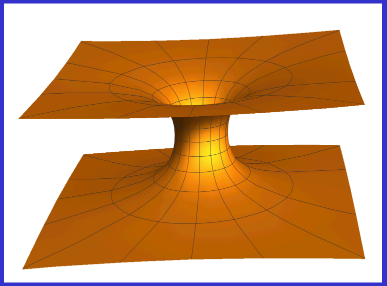
- The quantum mechanical property of entanglement plays an important role in constructing the spacetime geometry.

- We will discuss just one example.

Two sided Schwarzschild solution

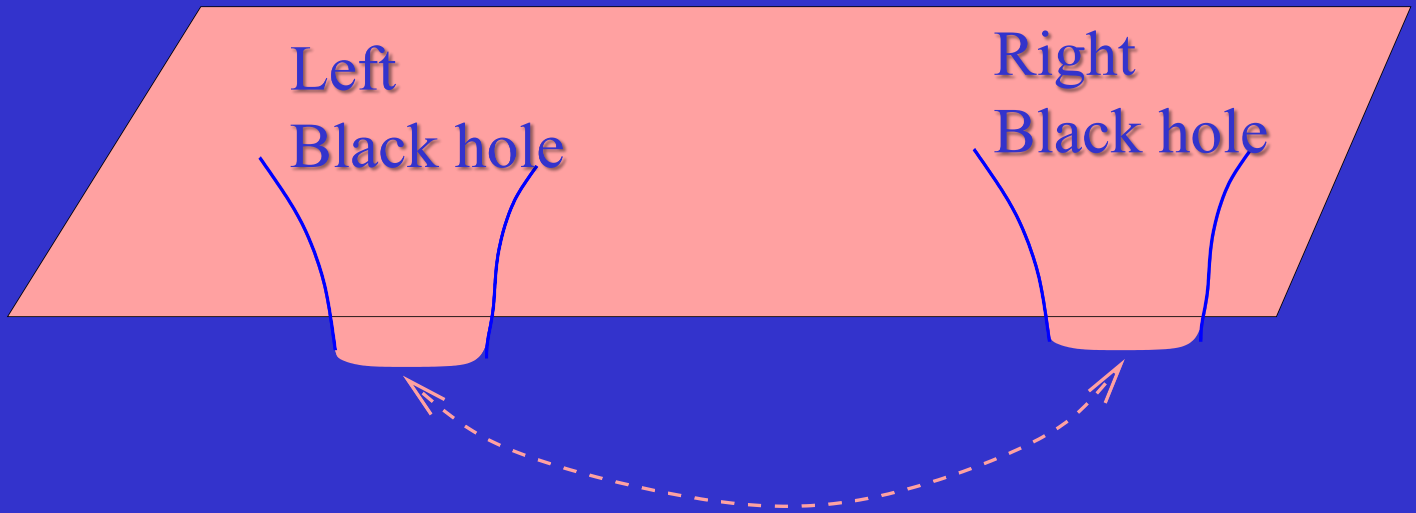


Eddington, Lemaitre, Einstein, Rosen, Finkelstein Kruskal



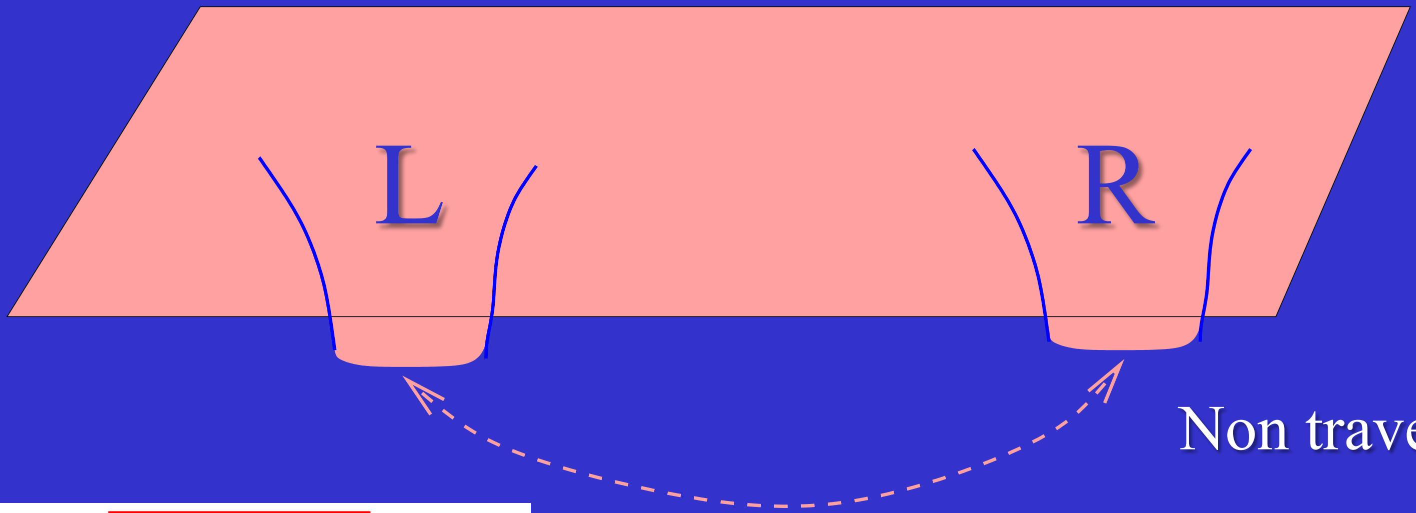
Simplest spherically symmetric solution of pure Einstein gravity (with no matter)

Wormhole interpretation.



Note: If you find two black holes in nature, produced by gravitational collapse, they will <u>not</u> be described by this geometry

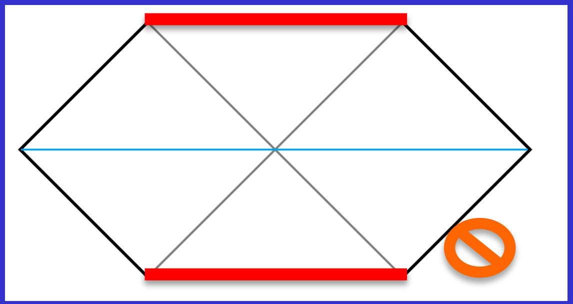
Not the typical science fiction wormhole



Non travesable

No signals

No causality violation



Fuller, Wheeler, Friedman, Schleich, Witt, Galloway, Wooglar

These are consistent with the laws of physics, as we know them !

In the exact theory,
each black hole is described by a set of microstates from the outside

Wormhole is an entangled state.
Entanglement is a form of correlation in quantum mechanics.

Geometric connection
from entanglement.

Israel
JM

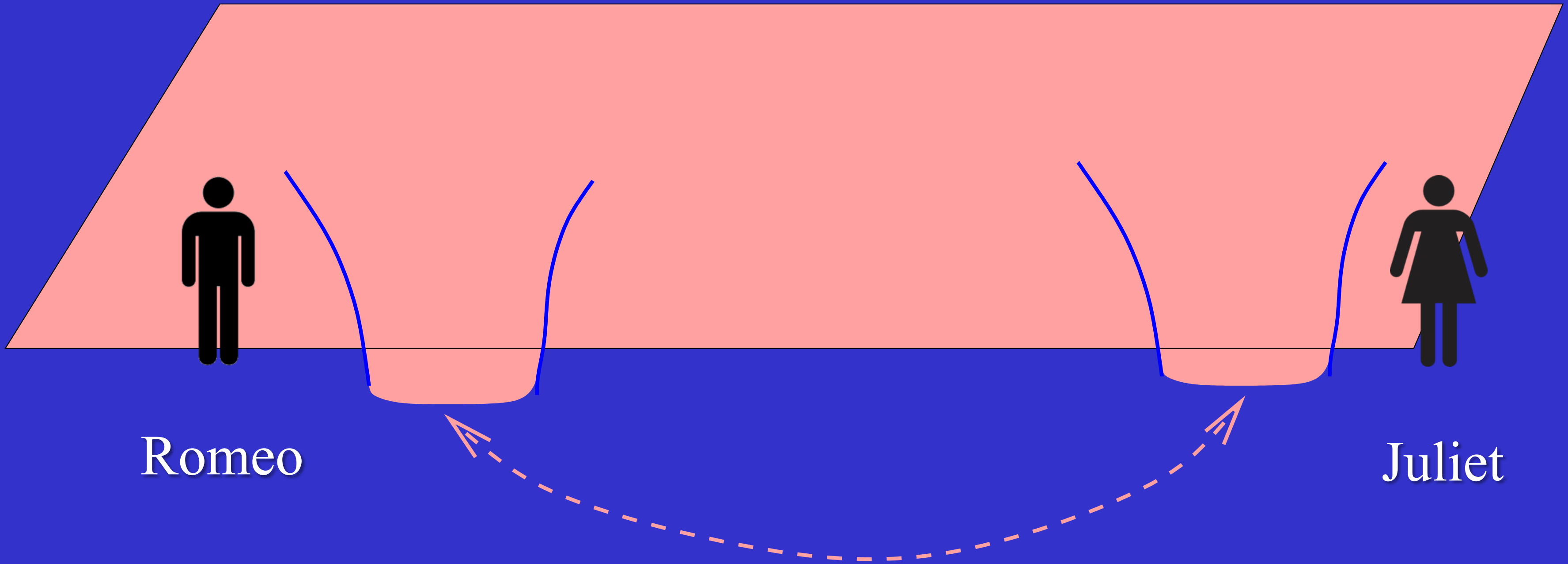
Susskind JM

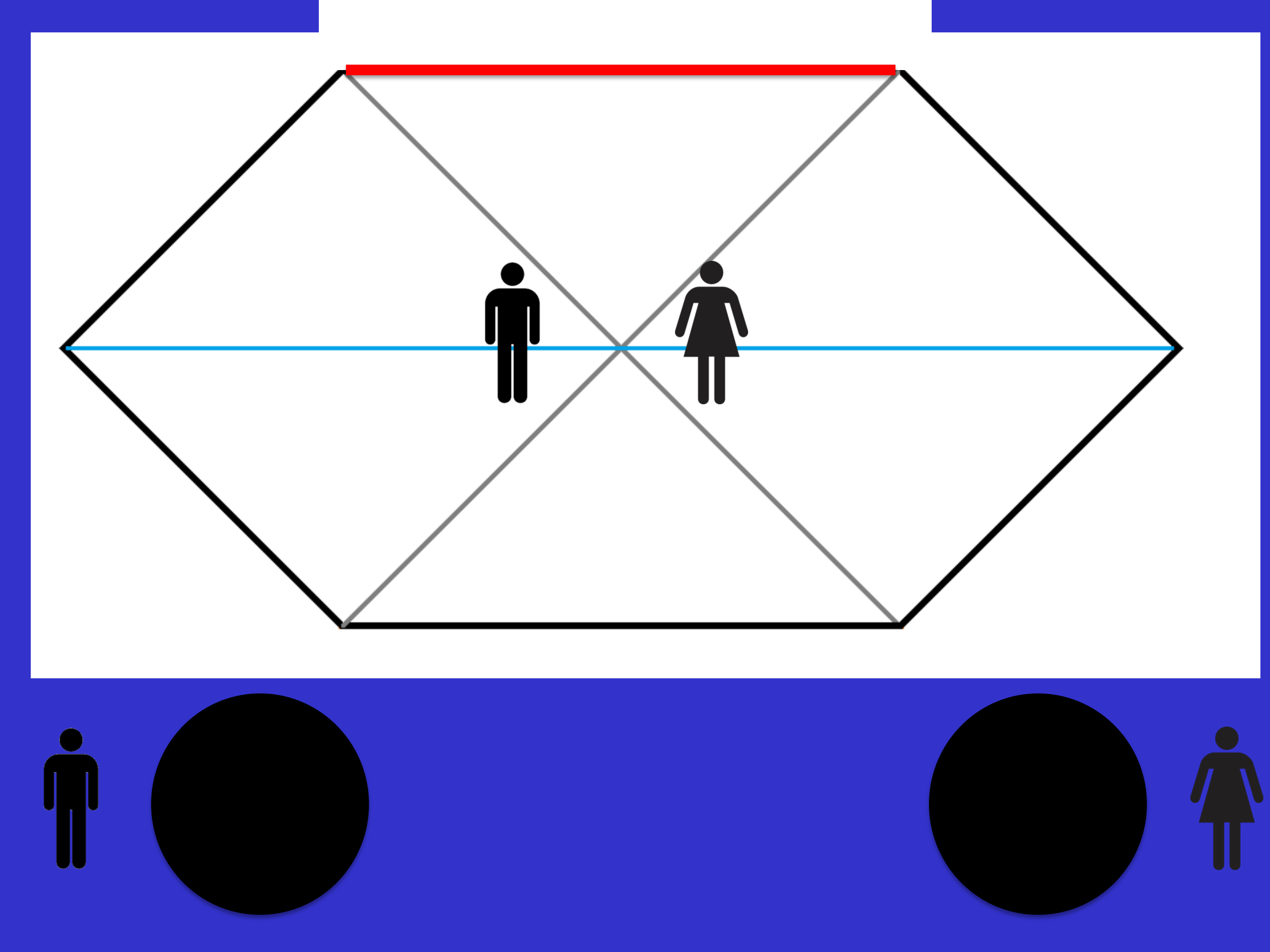
Analogy

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

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

A forbidden meeting

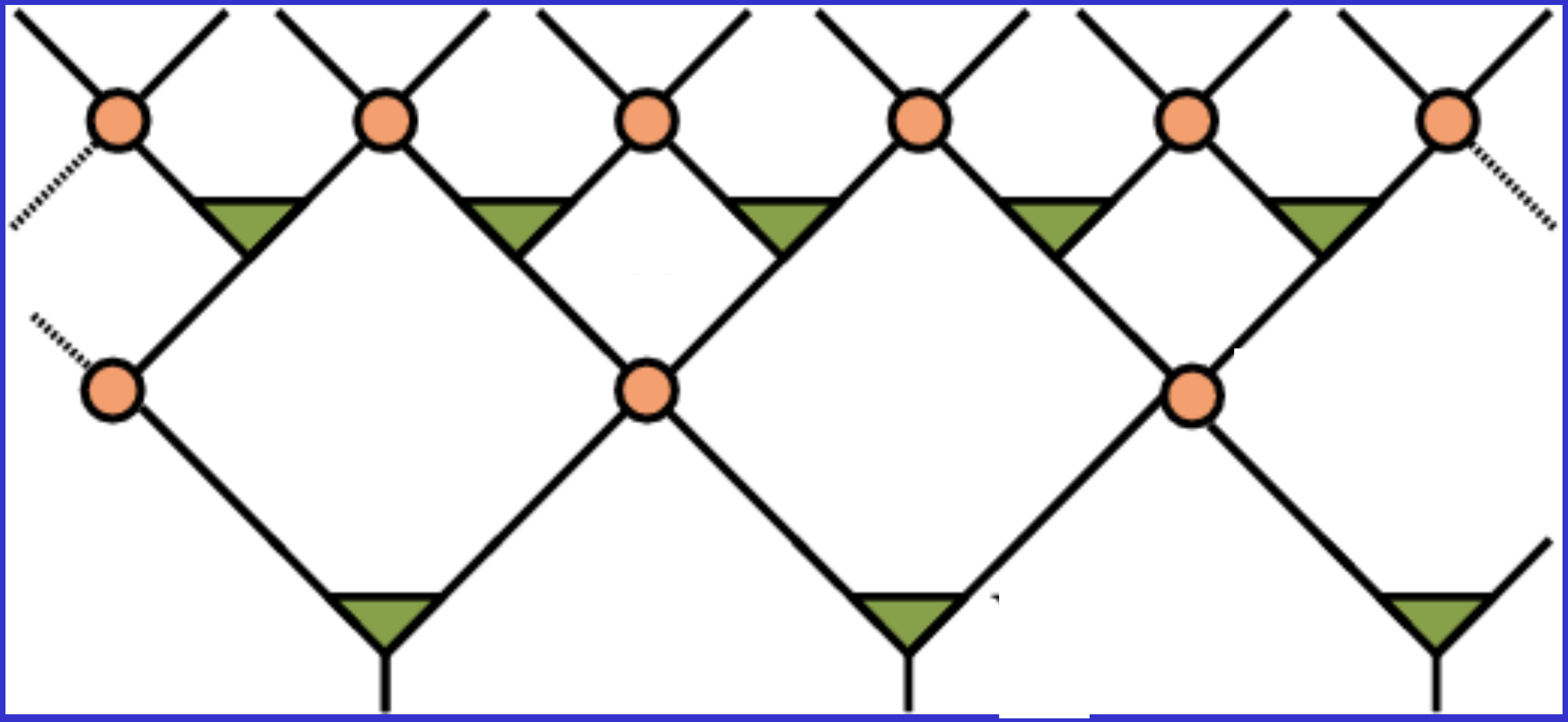




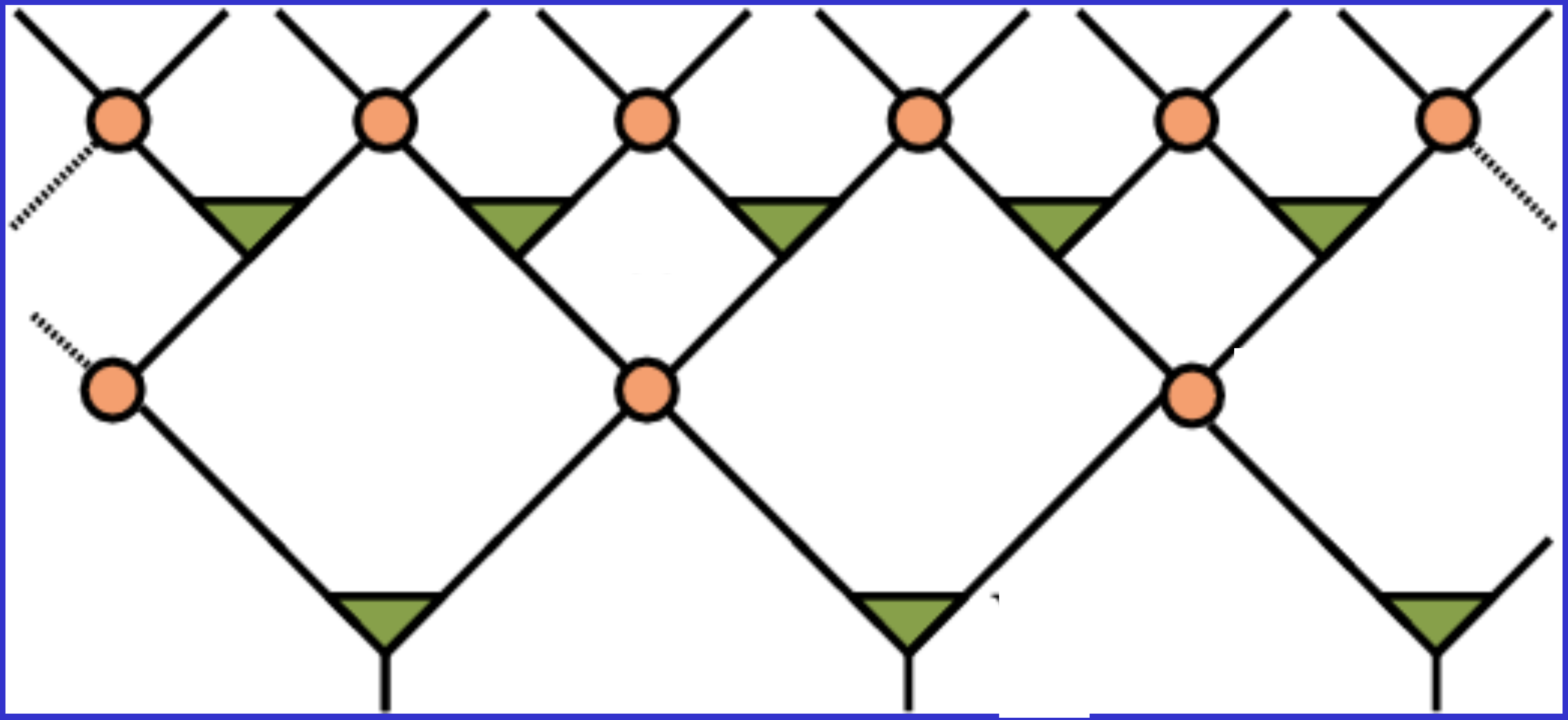
Future

- ✓ Many remaining mysteries, including the meaning of the singularity…
- ✓ Lessons for cosmology?

Tensor networks



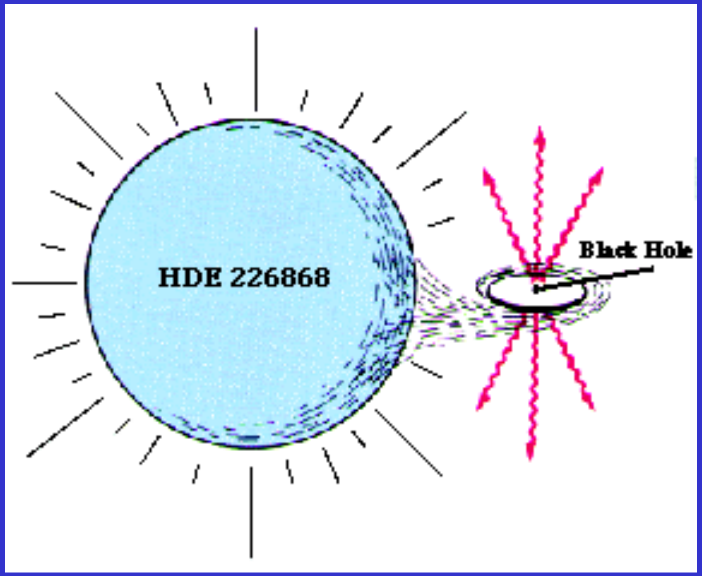
Artificial neural networks → deep learning

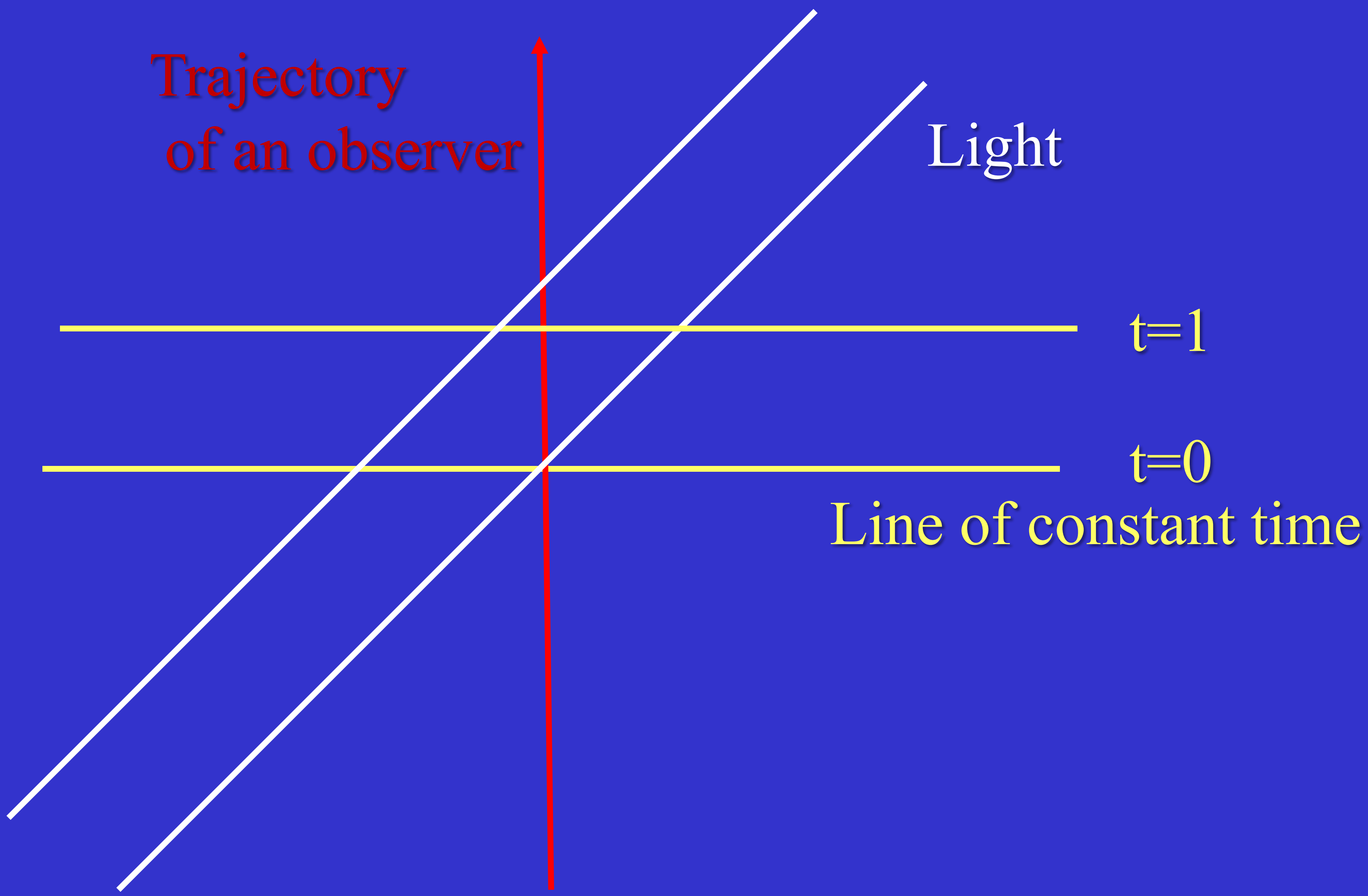


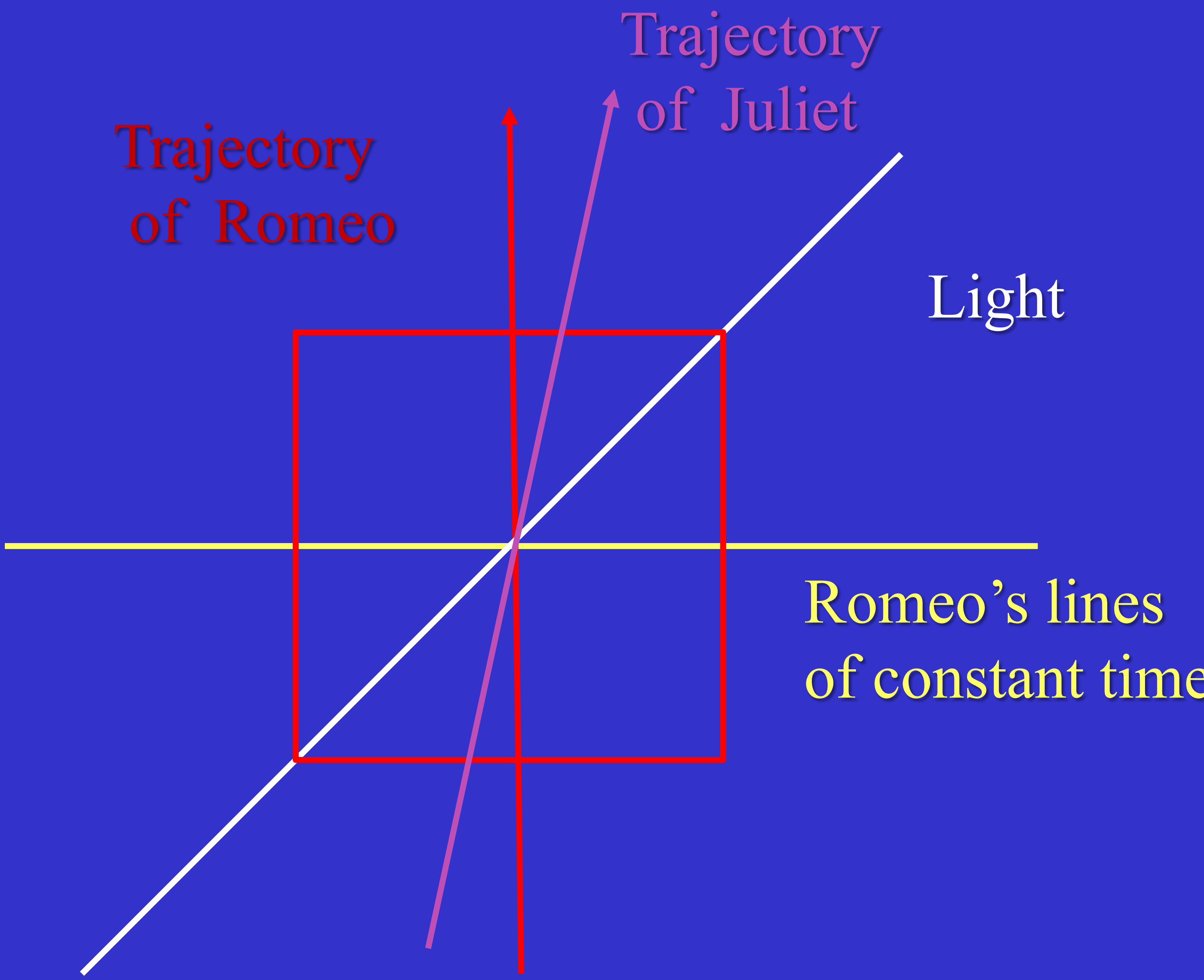
How do we see them?

- Watching matter fall in and heating up.

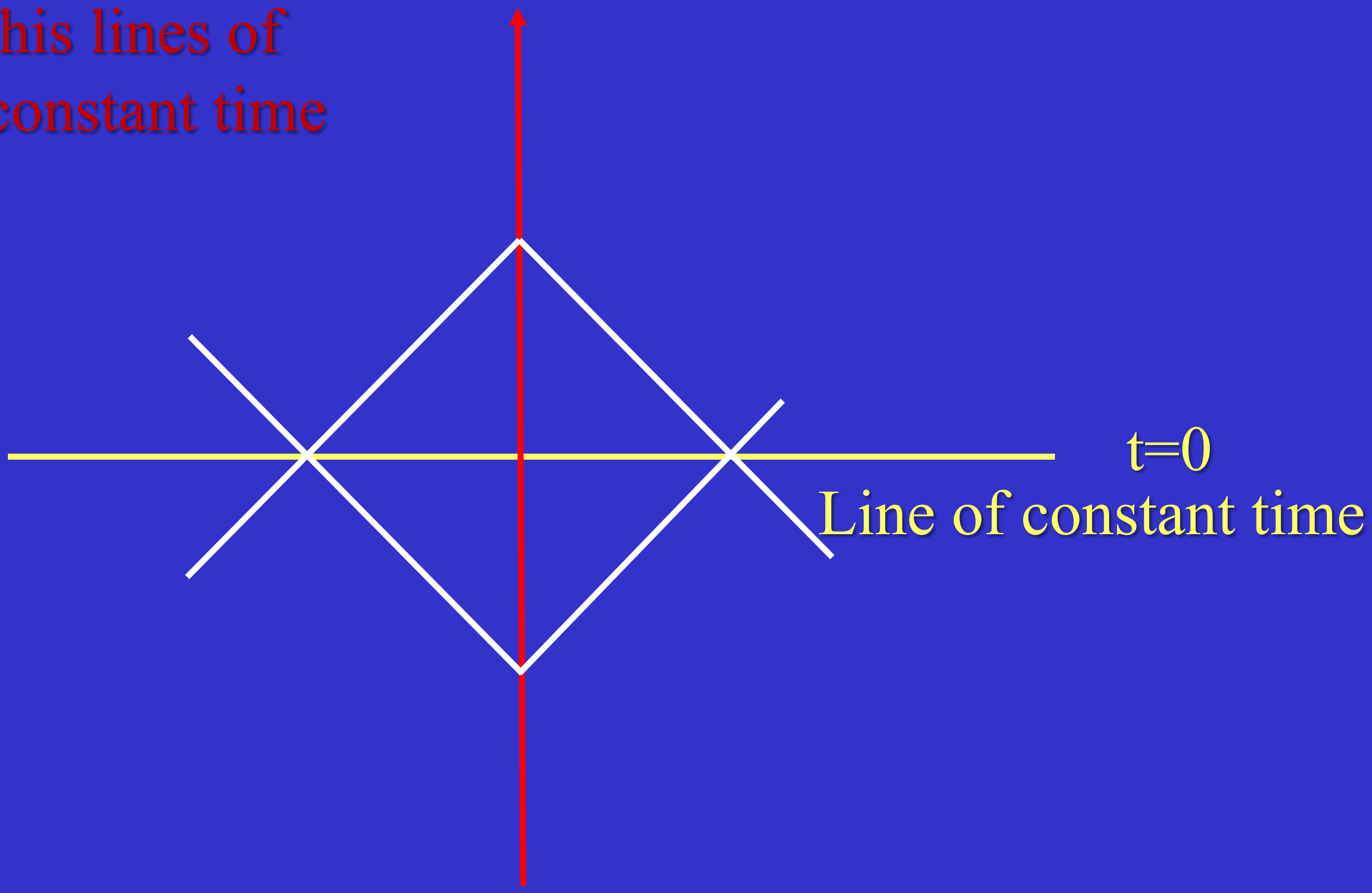
- Seeing the gravity waves produced by their collisions.



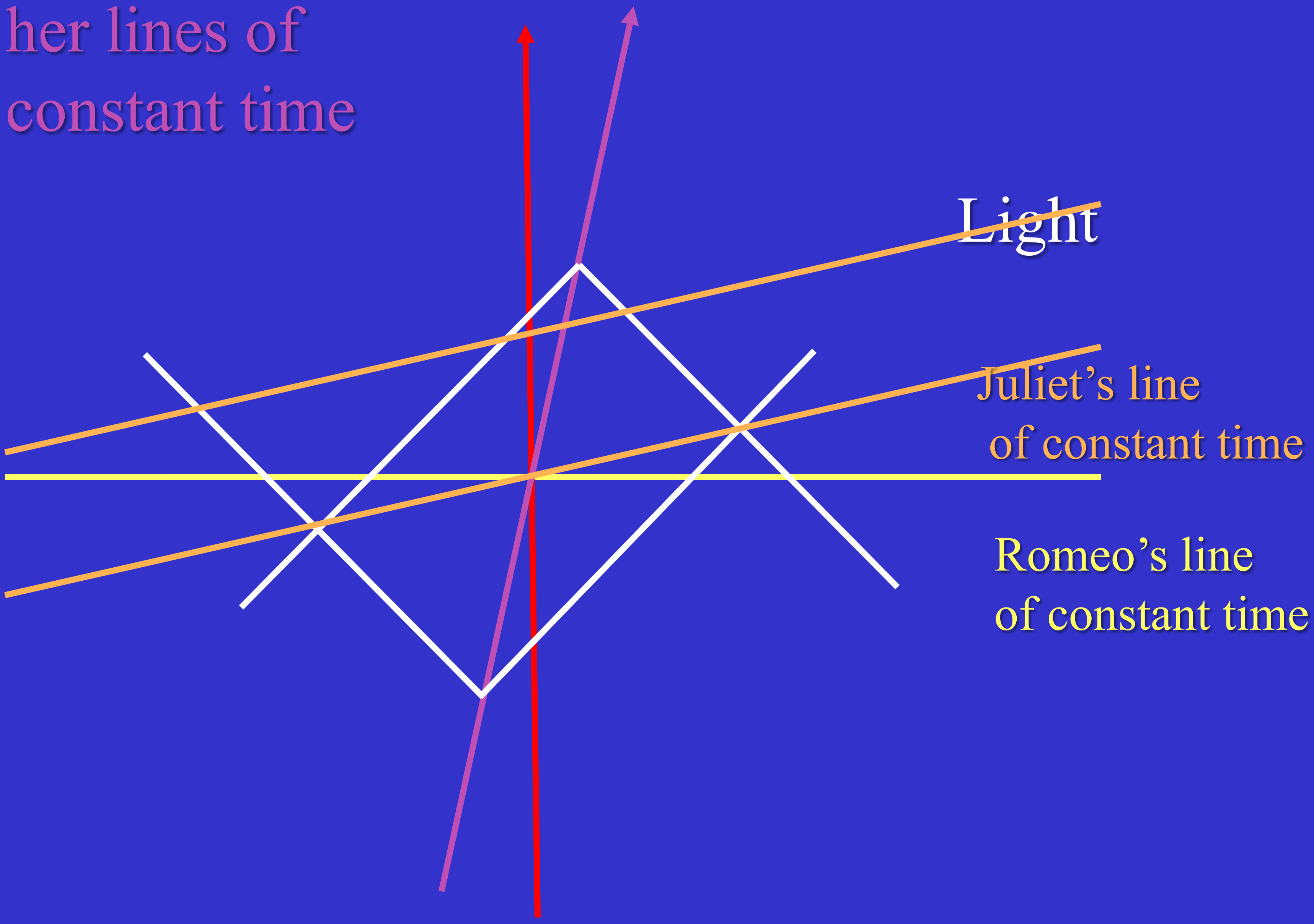

Trajectory
of an observer
Light
t=1
t=0
Line of constant time


Trajectory
of Juliet
Trajectory
of Romeo
Light
Romeo's lines
of constant time

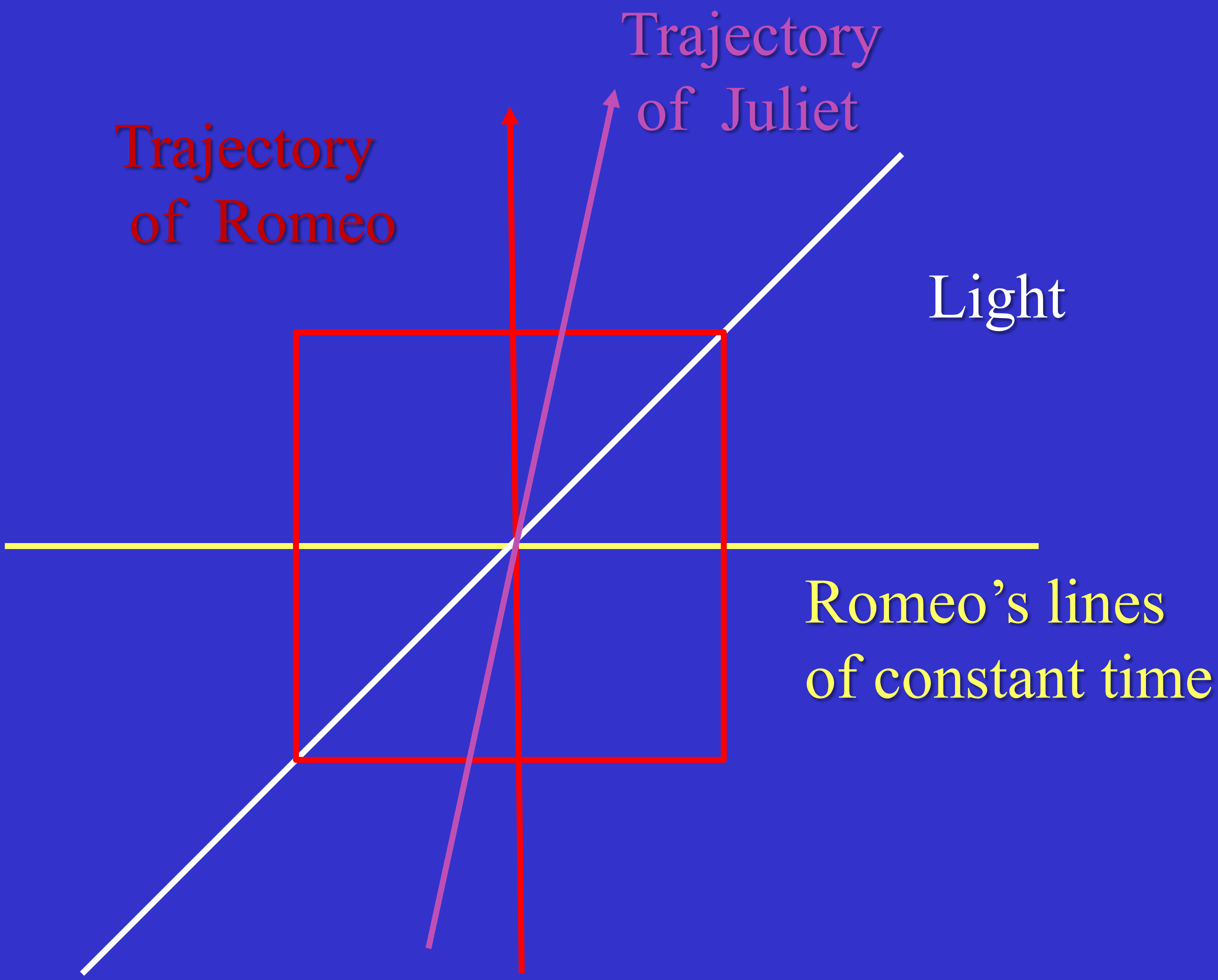
Romeo's determines
his lines of
constant time

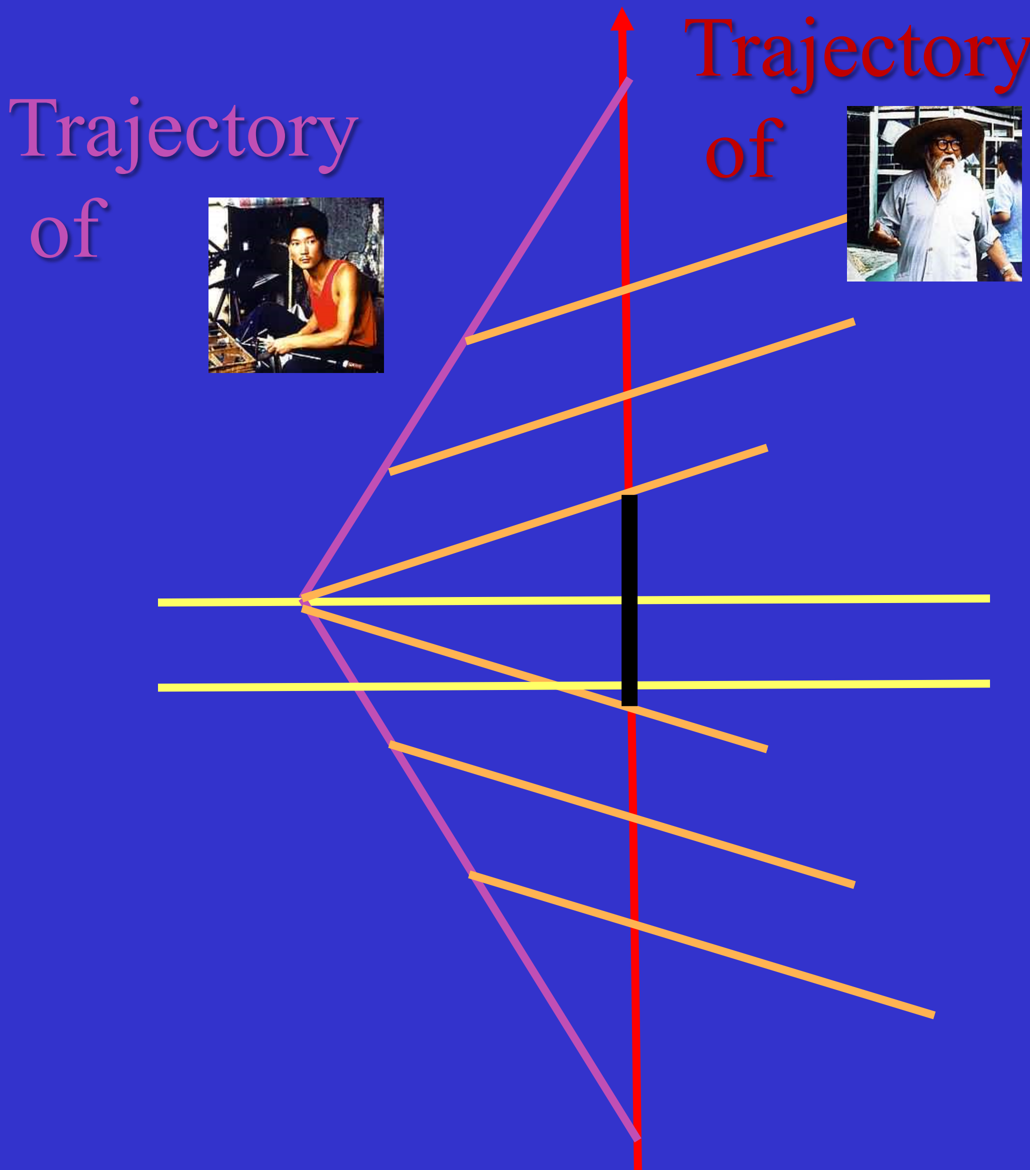


Juliet determines her lines of constant time

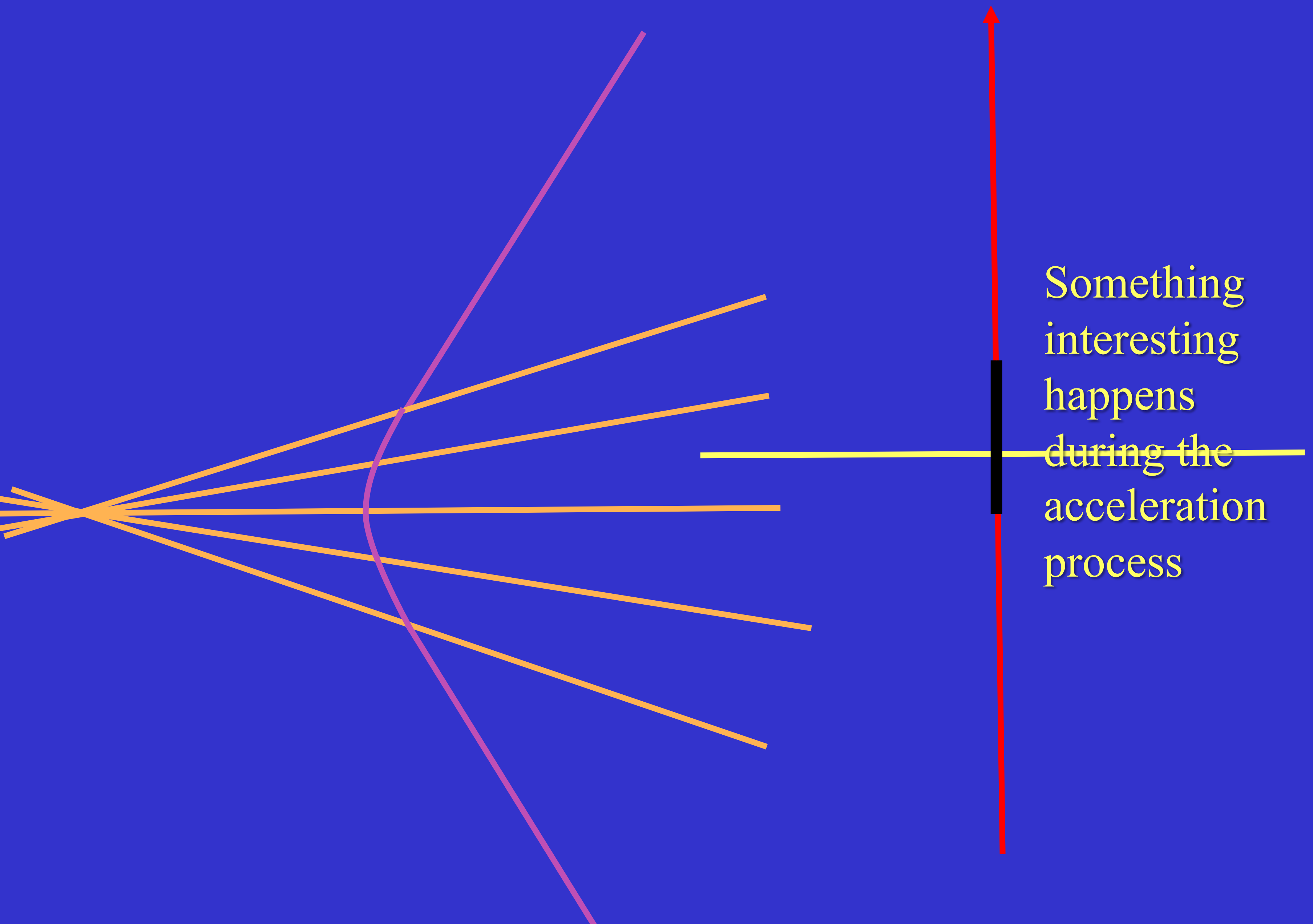


The twin “paradox”


Trajectory
of Juliet
Trajectory
of Romeo
Light
Romeo's lines
of constant time

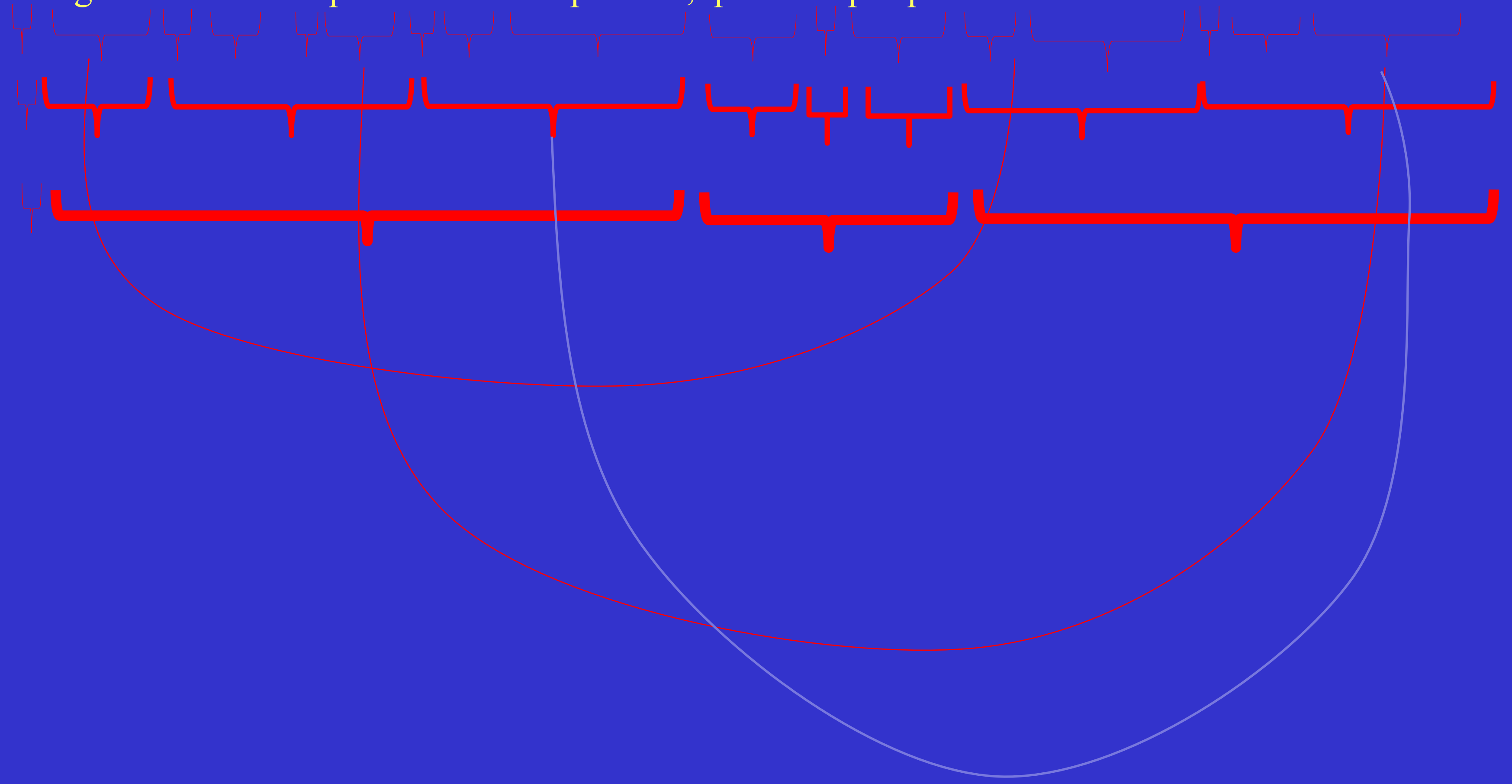


Something interesting happens during the acceleration process


Something
interesting
happens
during the
acceleration
process

This sentence has a different short distance structure but similar long range structure

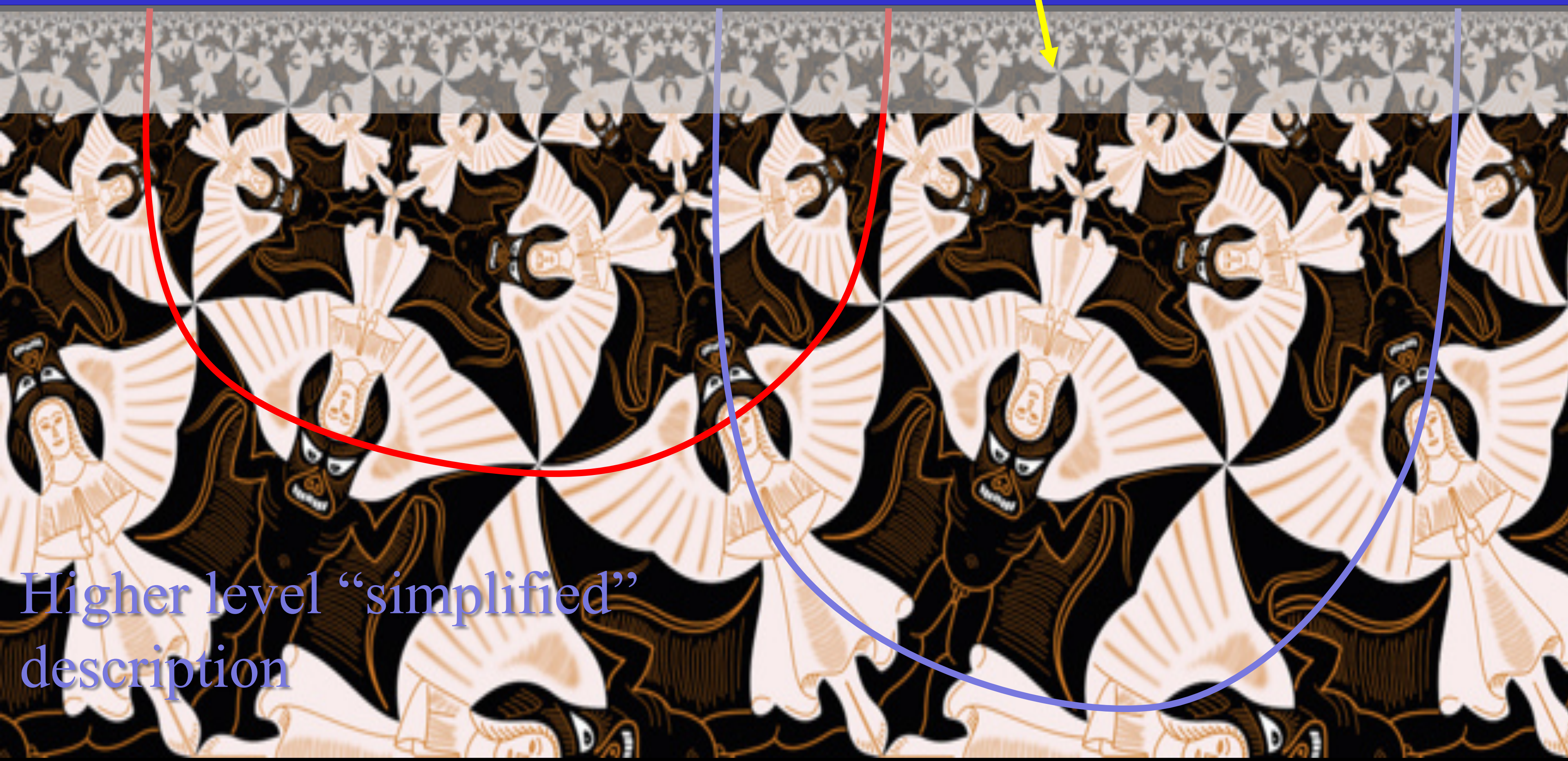
Si alguien no lleva el paso de sus compañeros, quizas es porque está escuchando a otro tamborista

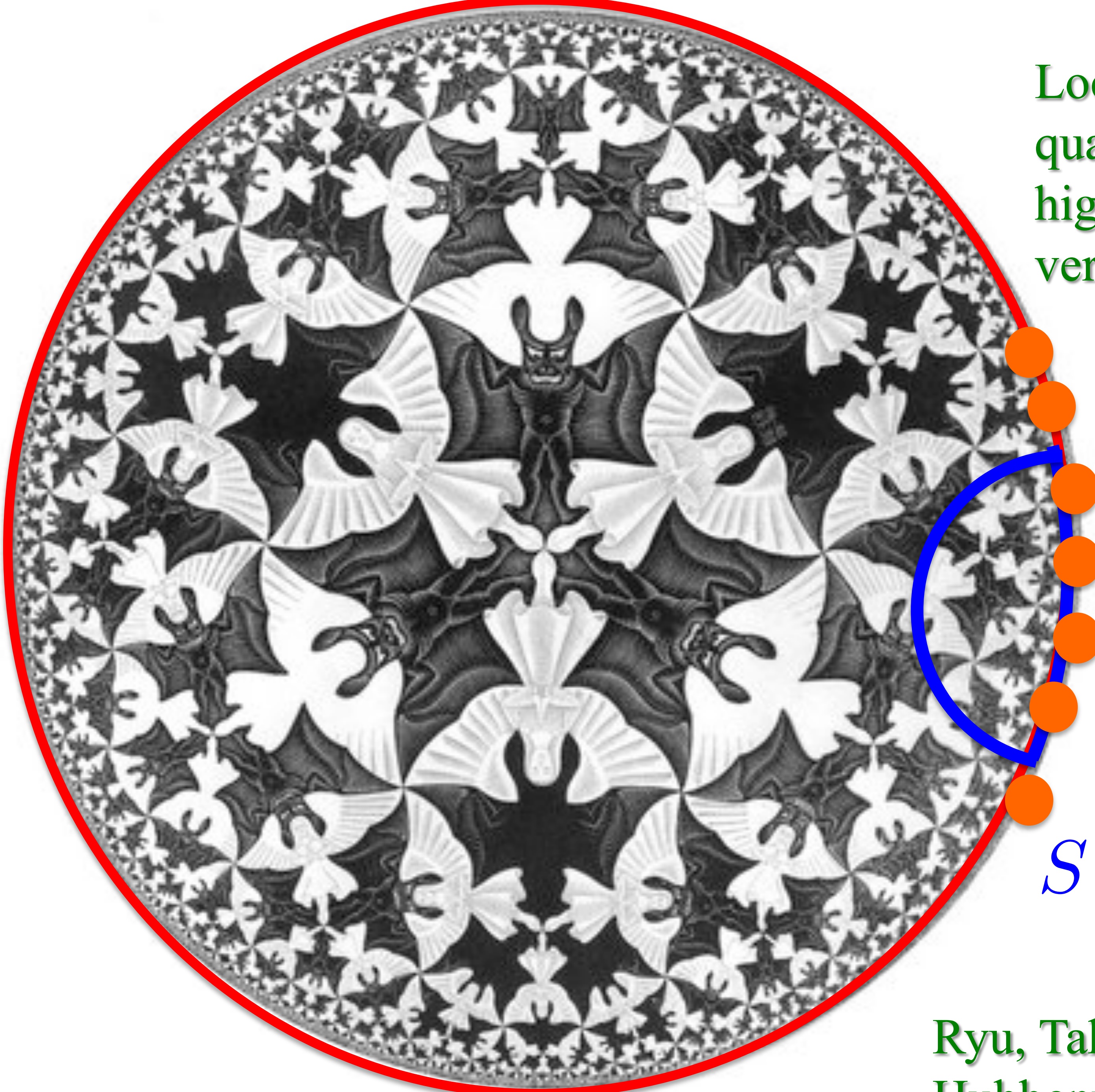


Different quantum systems in detail, that give the same long long distance structure

Spacetime different near the boundary

e 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 gravitation dynamics. We derive a formula for the two sided correlators that includes the effect of gravitational backreaction, which





Local boundary quantum bits are highly interacting and very entangled

$$S(R) = \frac{A_{\min}}{4G_N}$$

Ryu, Takayanagi, Hubbeny, Rangamani

Entanglement and geometry

- The entanglement pattern present in the state of the boundary theory can translate into geometrical features of the interior.

Van Raamsdonk, Swingle

- Spacetime is closely connected to the entanglement properties of the fundamental degrees of freedom.

- Slogan: Entanglement are the threads the weave the spacetime fabric…

- Spacetime is the hydrodynamics of entanglement.

Emergent geometry

- View the boundary theory as the ultimate description.
- Then the bulk emerges in some approximation.
- Quantum mechanical entanglement plays an important role.

MAY 15, 1935 PHYSICAL REVIEW

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

EPR

JULY 1, 1935 PHYSICAL REVIEW

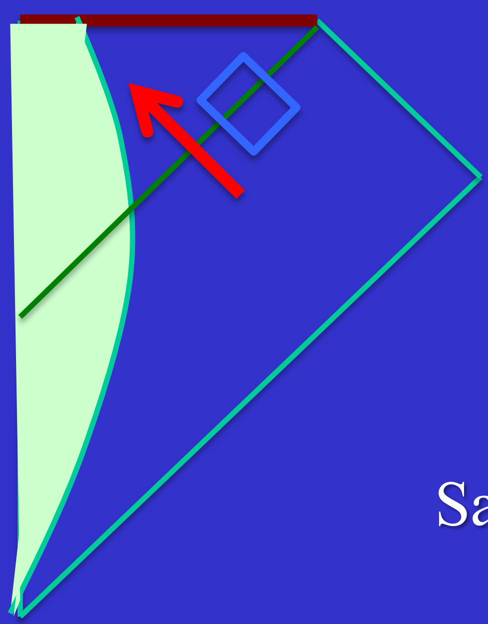
The Particle Problem in the General Theory of Relativity

A. EINSTEIN AND N. ROSEN, *Institute for Advanced Study, Princeton*

ER

Black hole interior ?

Equivalence principle



From outside: in-falling observer never crosses the horizon. It just gets hidden by the Hawking radiation.

Inside: No problem when crossing the horizon.

Same thought experiment that Einstein did !

Mystery: How do we describe it using the same variables that make unitarity manifest for the outside observer ?

The next two lectures

- Wormholes and entanglement.
  - The problem with science fiction wormholes.
  - Traversable wormholes that could exist.
  - Their connection with entanglement.

- The entropy of Hawking radiation.
  - Hawking found that the entropy of Hawking radiation is larger that that of the matter that made the black hole.
  - We will compute it using a recently developed gravitational entropy formula and find a different answer which is consistent with quantum mechanics