

**Black Holes
and
the structure of space time**

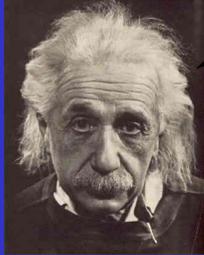
Juan Martín Maldacena

Institute for Advanced Study

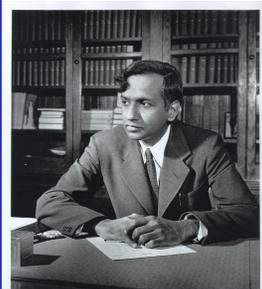
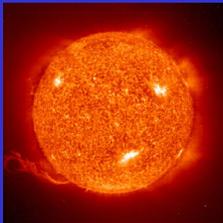
General
relativity

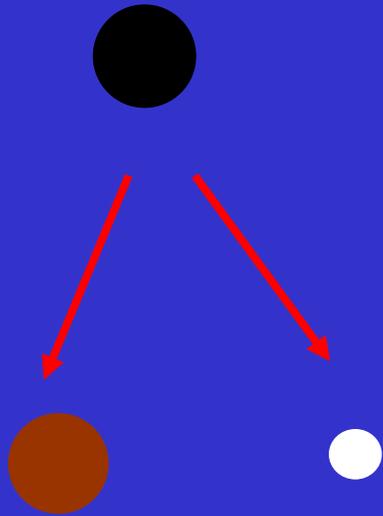


I do not think so...



They are unavoidable



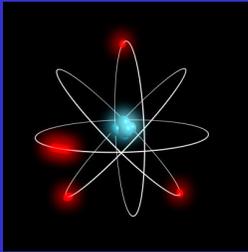


They are not black

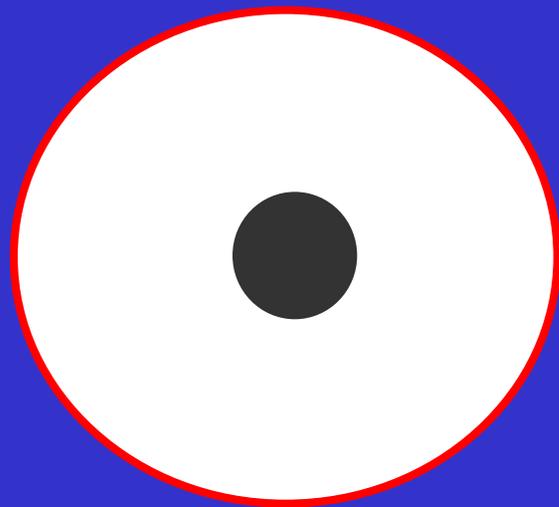
They imply that quantum mechanics is incompatible with gravity



Incompatible ?



String theory



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

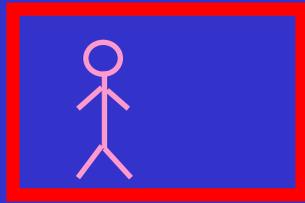
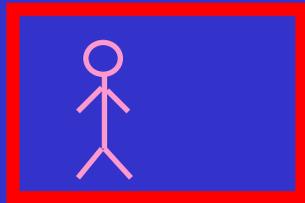
Relation between quantum mechanics and spacetime geometry

Still several puzzles with the interior



Principle of Relativity

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



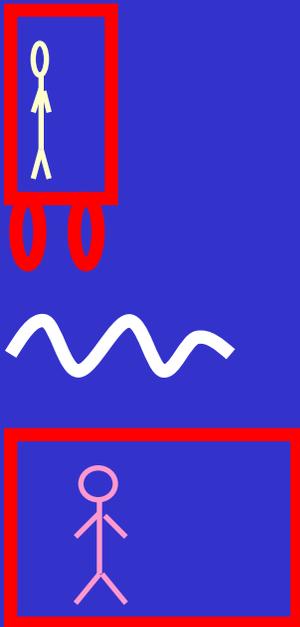
Special Relativity

- 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 basic 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

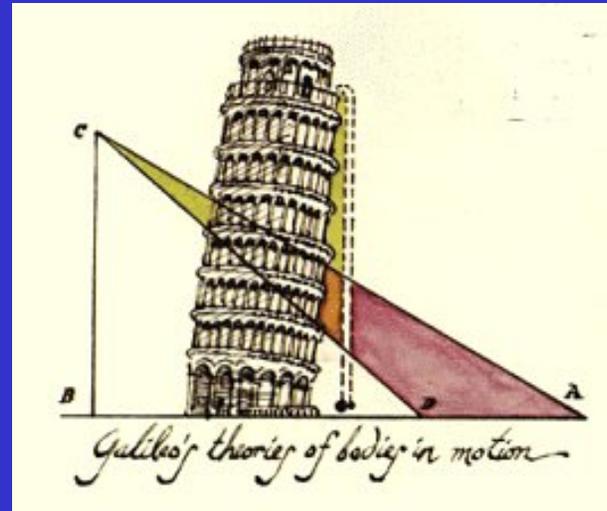
The time we measure depends on how we move.

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 resistance)



Einstein's happy thought:

When you fall freely gravity ``disappears''

New physics law: ``Equivalence principle''

Going with the flow feels easier

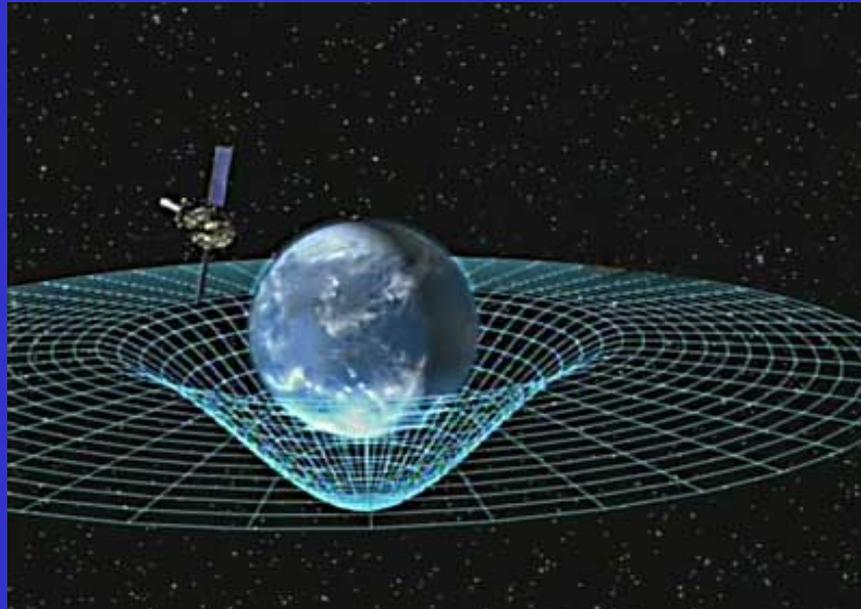
Feels weightless



General Relativity

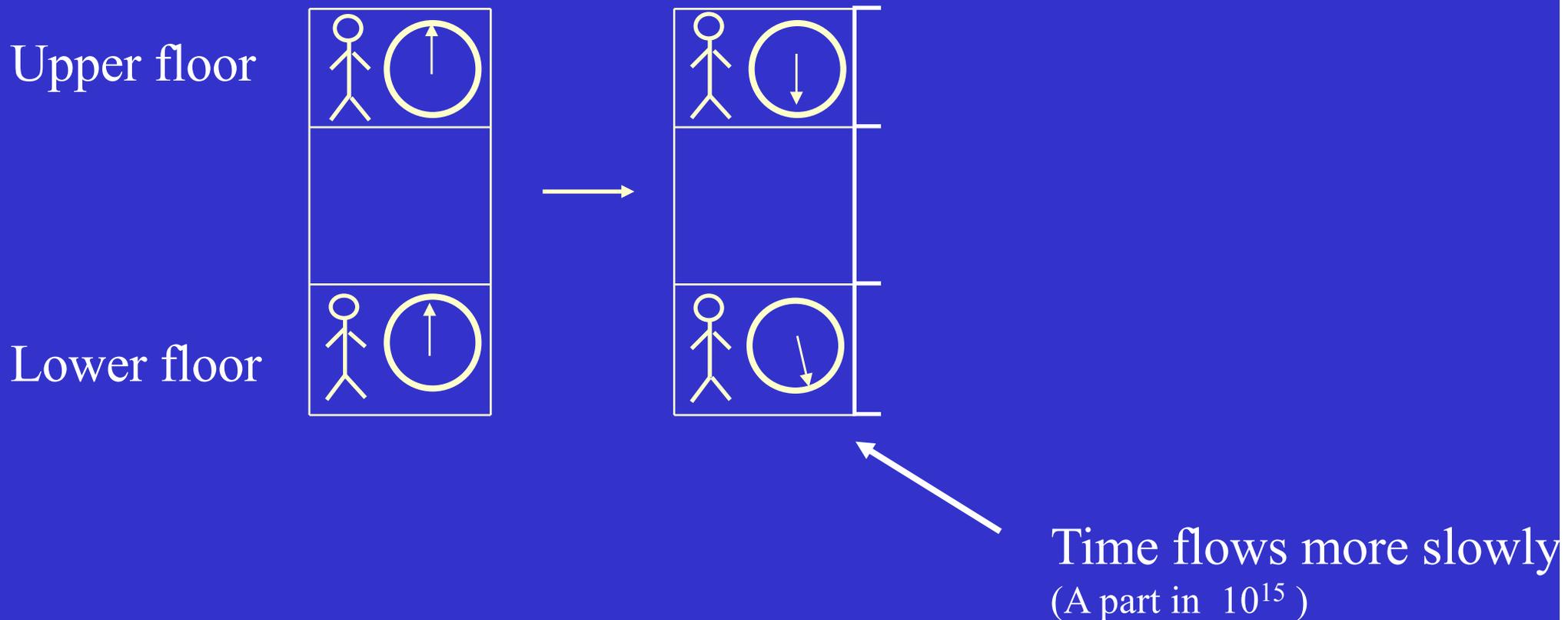
Einstein 1915

- ✓ 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.

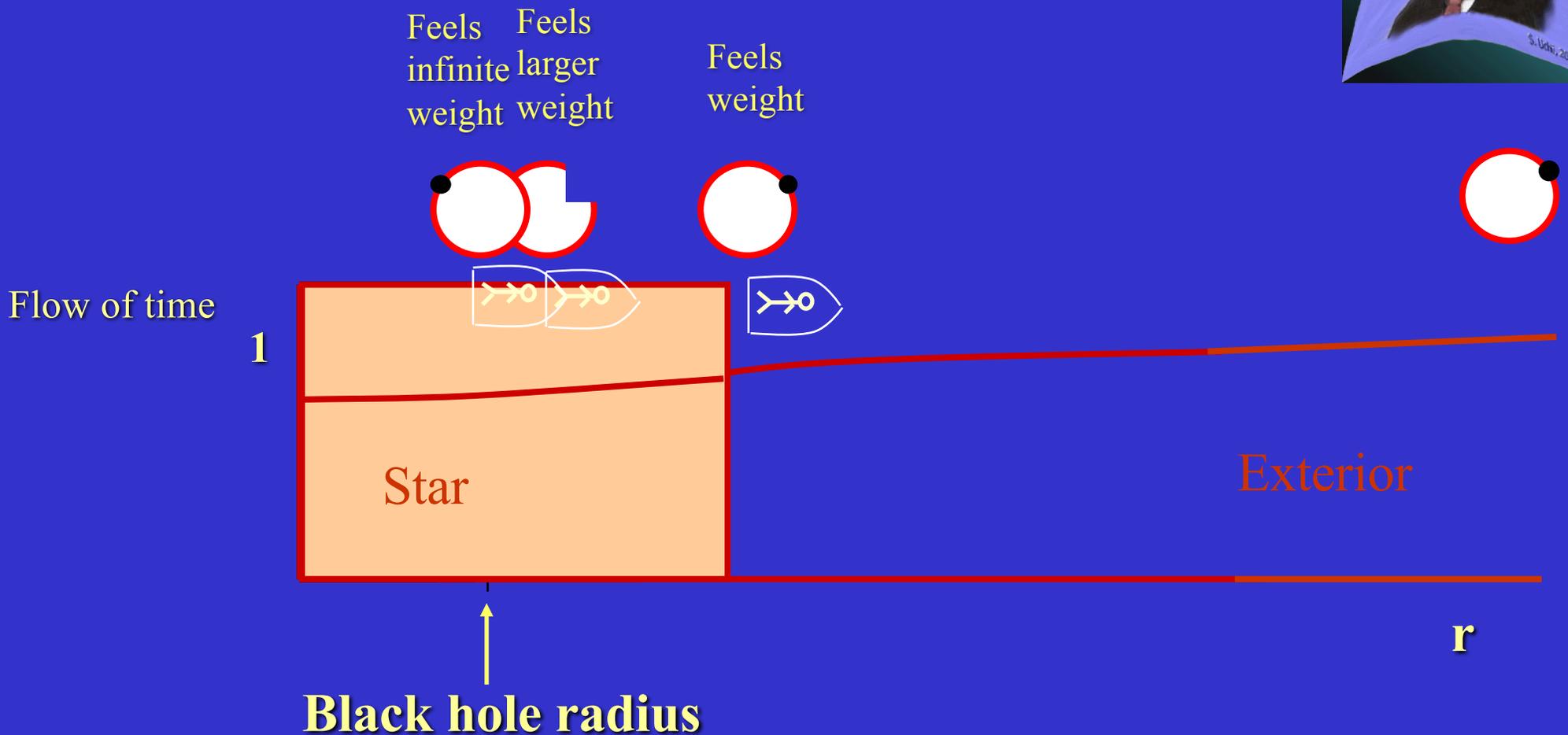
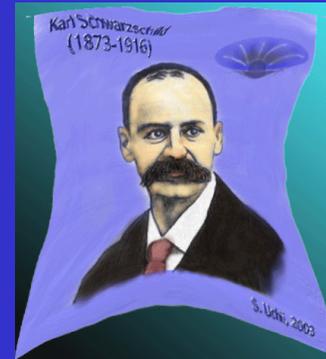




Massive
body

Karl Schwarzschild found the spacetime geometry outside a massive spherical body

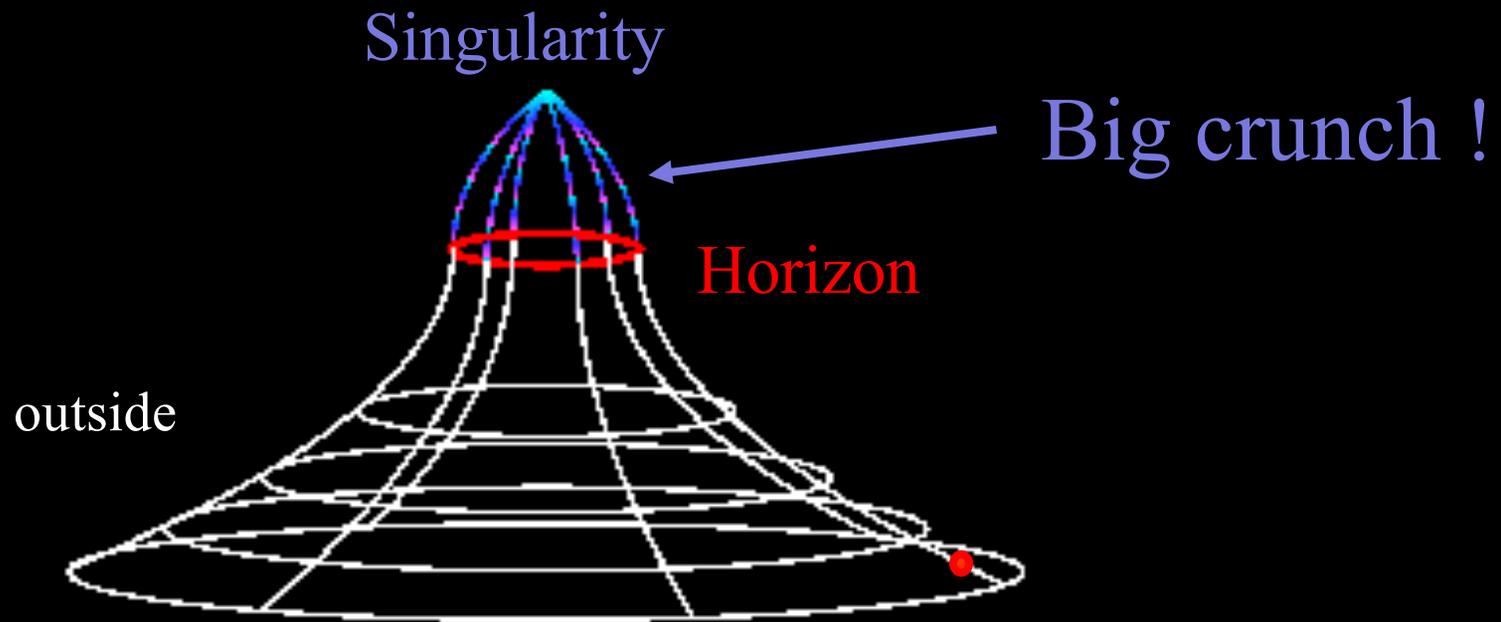
This geometry tells us how time flows.



They are not falling freely!

What if they fell ?

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



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 .

- 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)

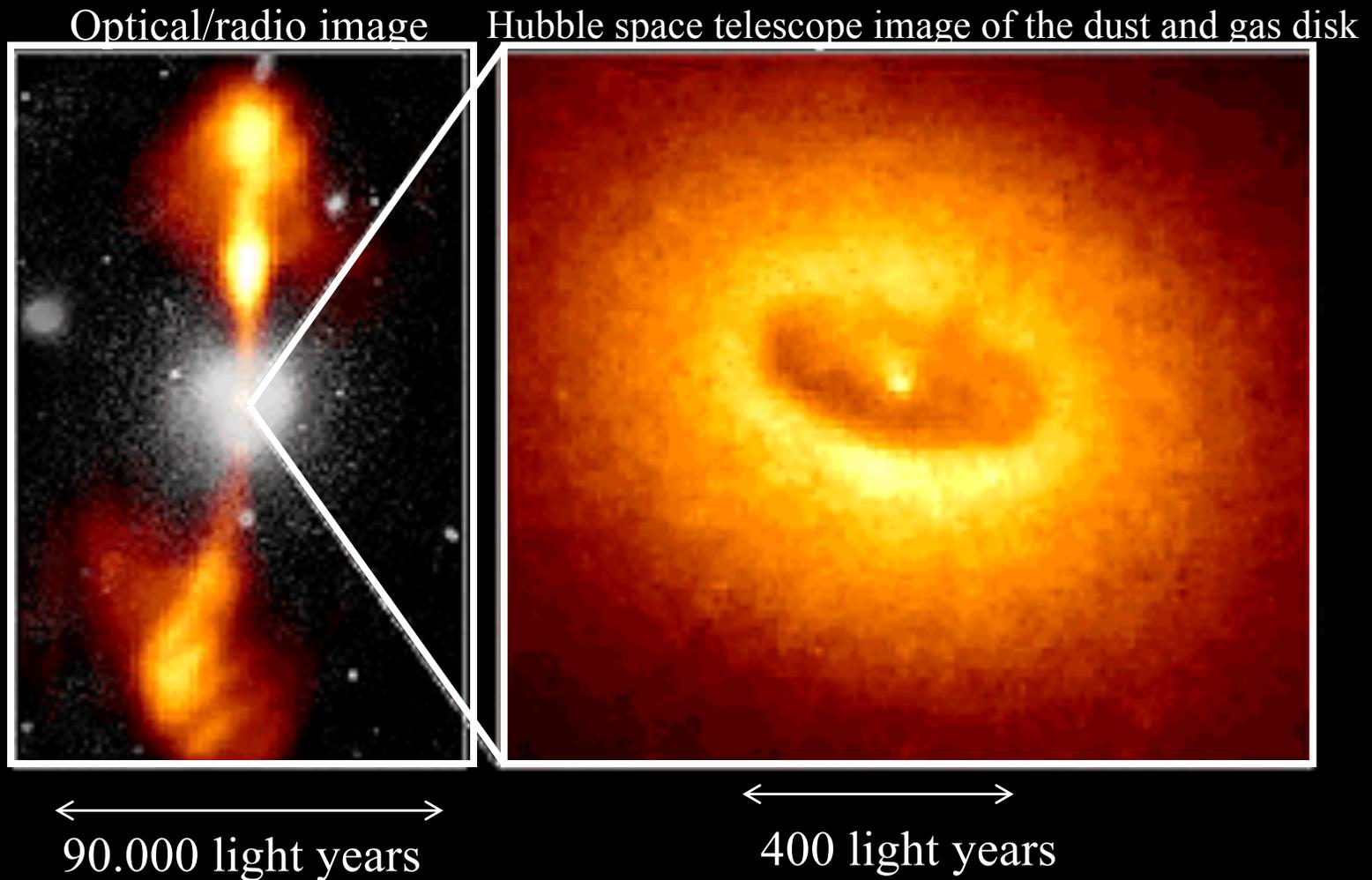
2) Black holes at the center of galaxies

(size ~ size of the solar system)

How do we see them?

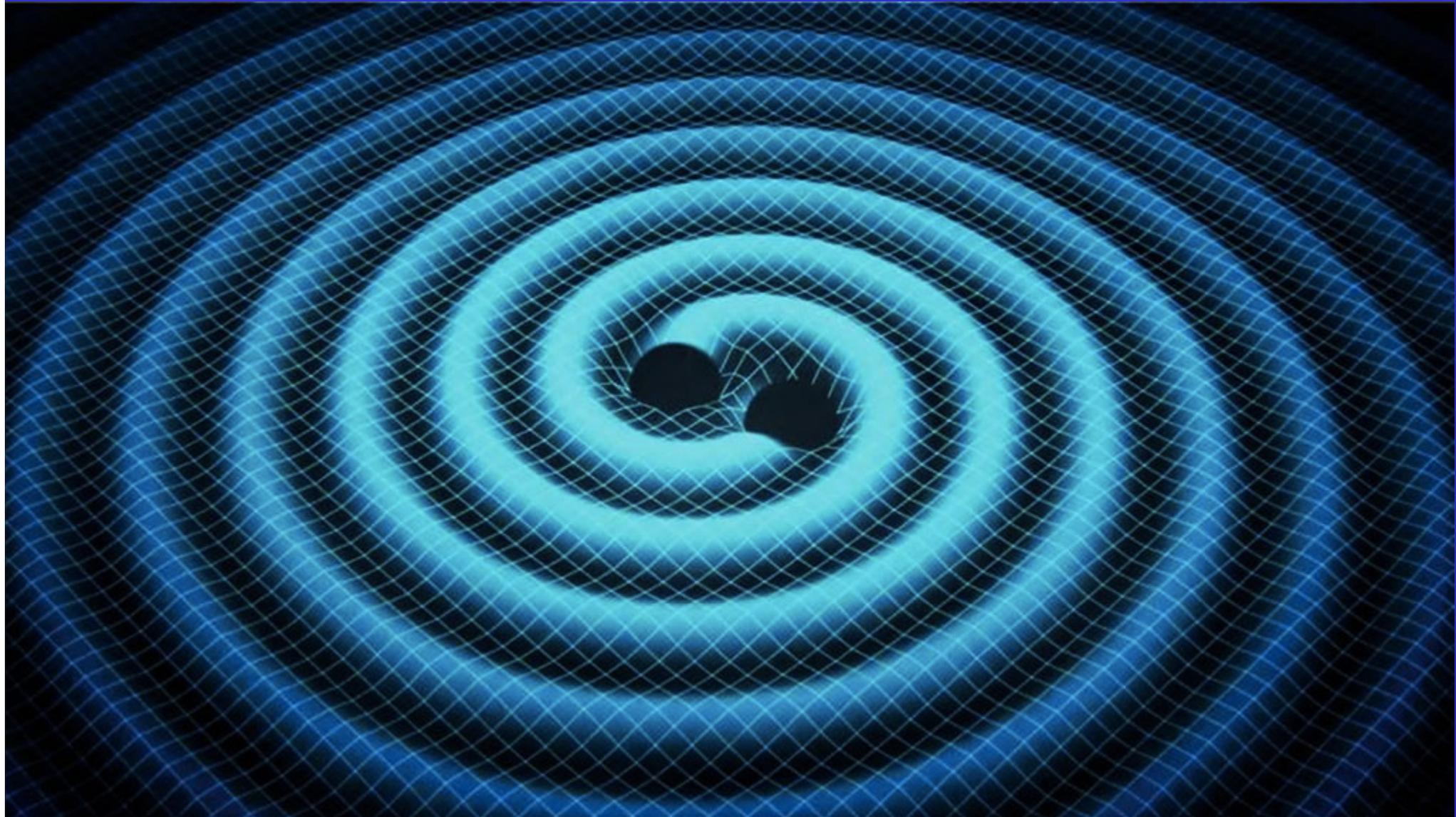
- Matter falls in, heats up and emits light or other radiation.

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



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

Black hole collisions produce gravity waves



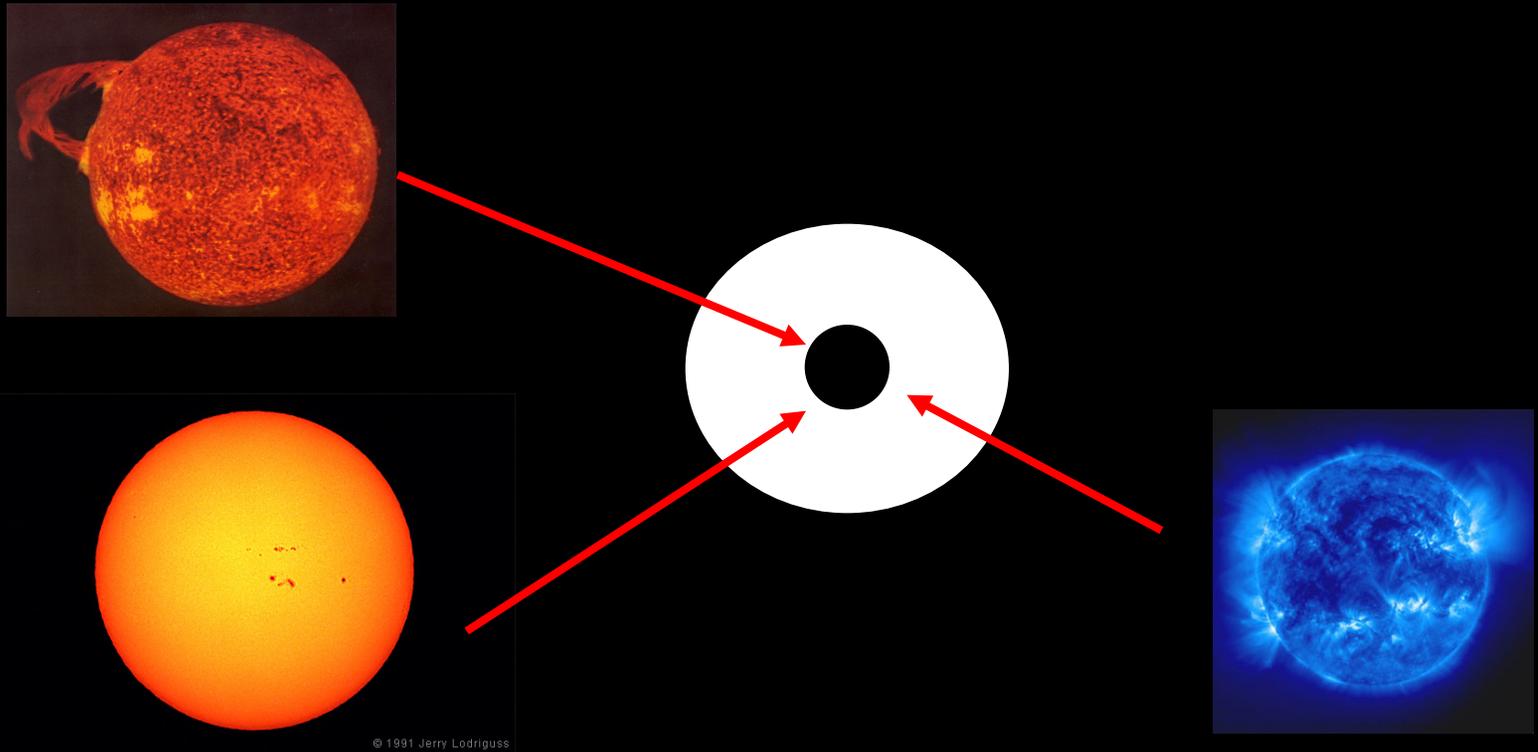
Interesting theoretical aspects

Interesting conceptual aspects

Interesting properties

Universality:

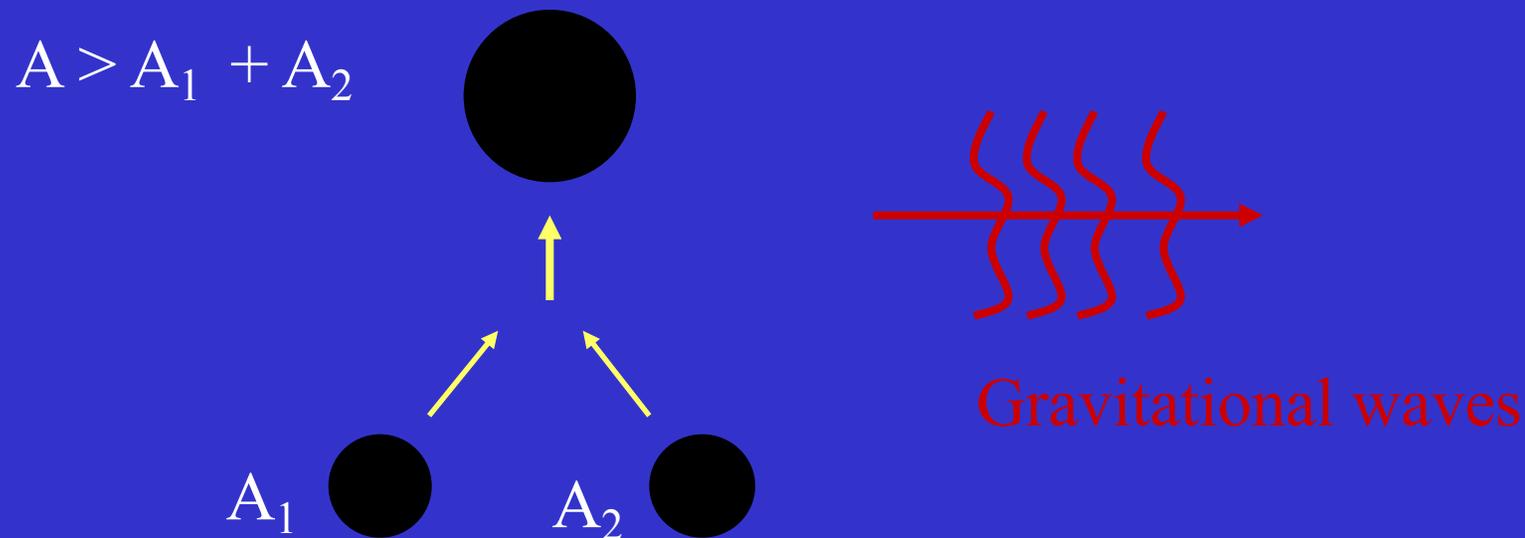
The final shape of the black hole is independent on how it formed. It is only characterized by its mass, its angular rotation velocity and its charge.



Area law

The area of the horizon always increases.

Hawking



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 classical theory.

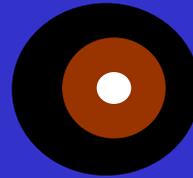
When we include quantum mechanics we find a new surprise:

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:

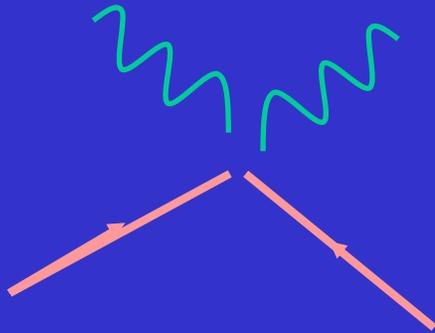
$$T_{\text{sun}} = 0.000003 \text{ } ^\circ \text{ K}$$

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

Why?

Relativistic quantum mechanics

- Particles can be created and destroyed.



The vacuum

→ Energies should be positive.

Negative energy



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

Positive energy



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

negative "energy"



positive energy

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 less than a millisecond. Worse than a nuclear bomb!
- ✓ A black hole of a mass of 10^{12} Kg produced at the beginning of the Big Bang would be evaporating now.
- ✓ There could be very small black holes produced in particle accelerators → would decay very quickly

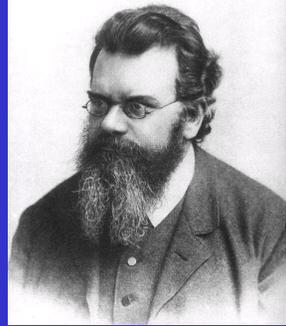
Theoretical problems with black hole temperature

The thermal properties of black holes mix quantum mechanics and gravity. This leads to puzzles

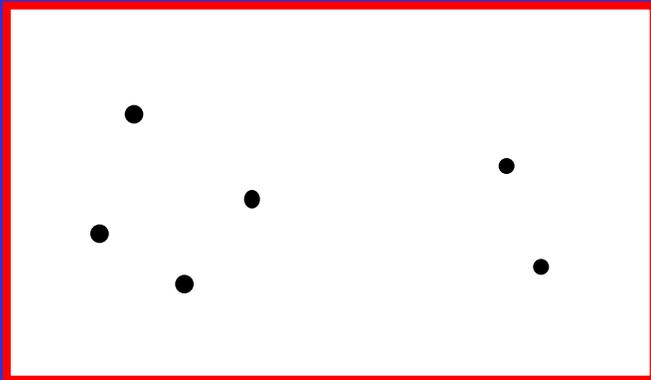
Puzzles:

- ✓ Why are black holes hot?
- ✓ Information loss.

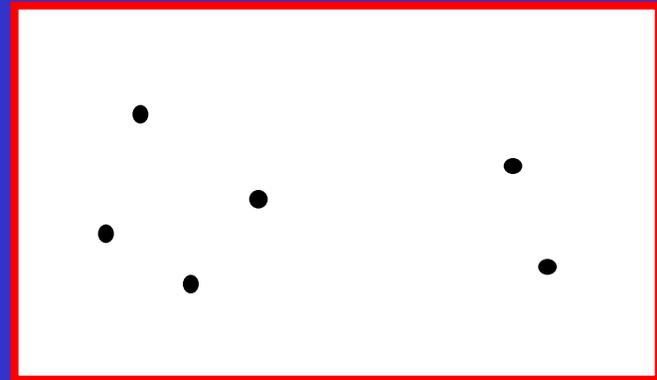
Temperature



Boltzmann
1866



Cold



Hot

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

Heat and entropy (disorder)

Entropy \rightarrow number of configurations of the constituents

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

Bekenstein, Hawking

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

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

Area law \rightarrow second law of thermodynamics (entropy increases)

What are the constituents of a black hole?

- Microscopic constituents of spacetime
- Structure and nature of spacetime

Information loss

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



Quantum mechanics \rightarrow precise description. 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.

We need a theory that puts together quantum mechanics and gravity

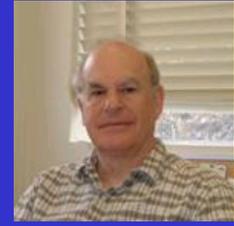
String theory



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).

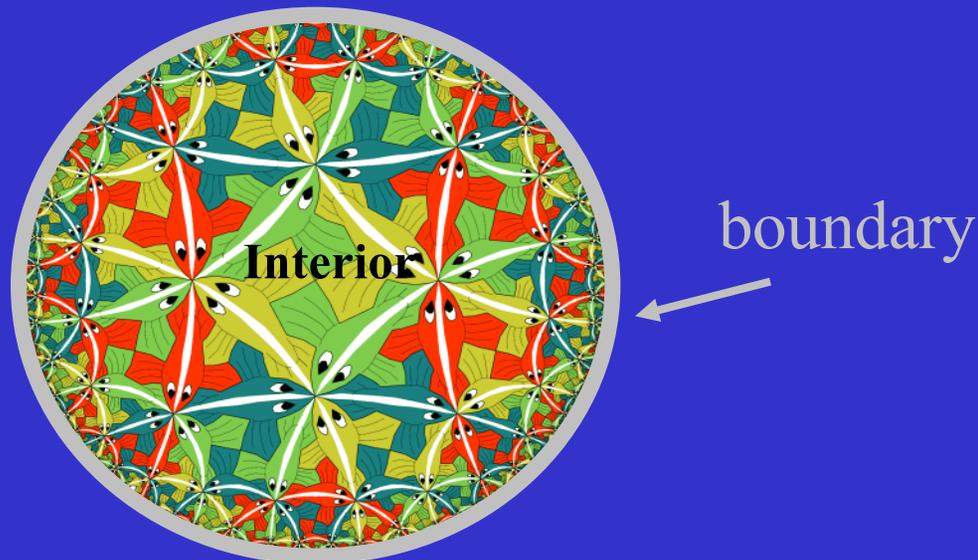
It can describe in a complete way certain simple universes
with negative curvature.

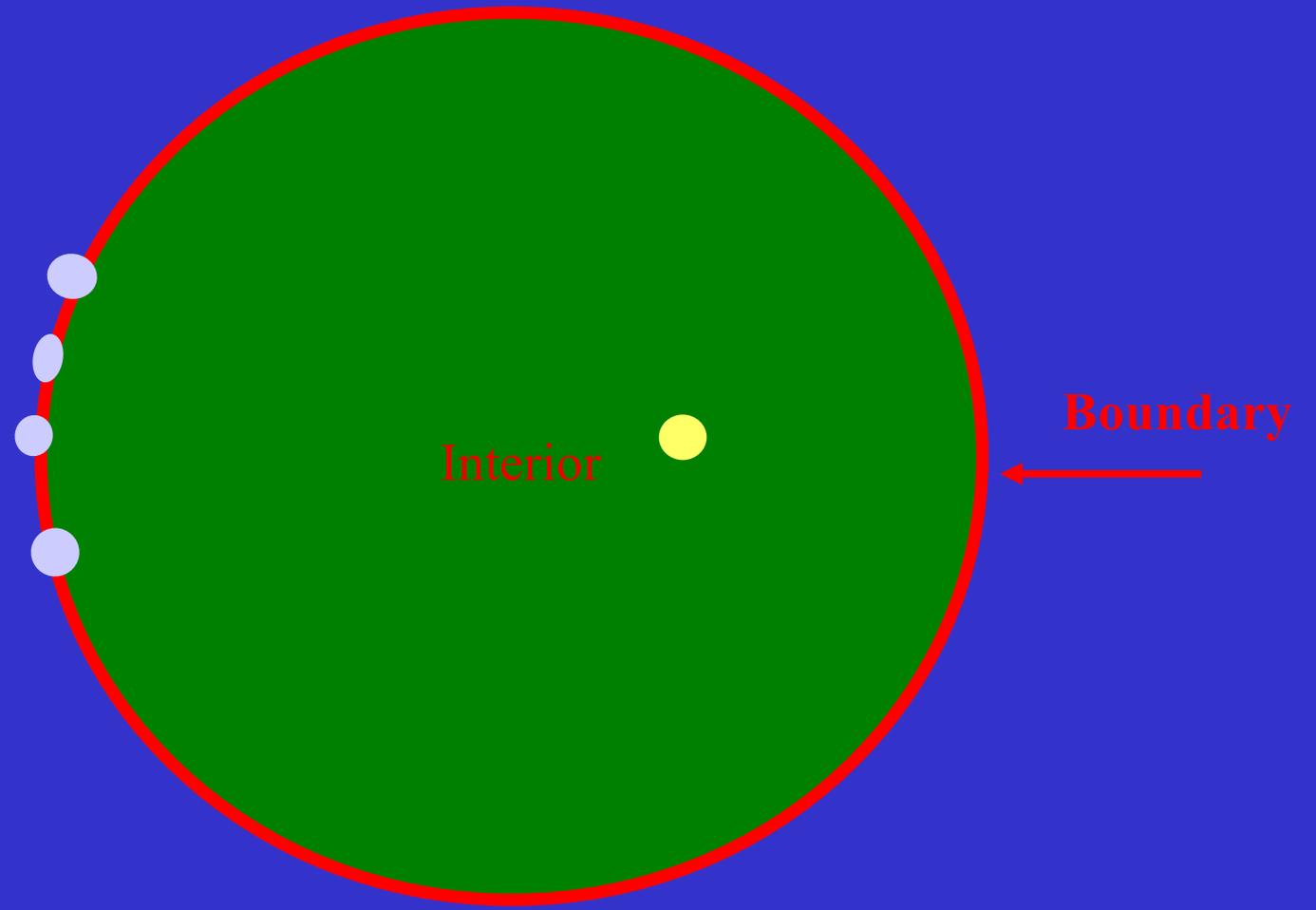


Holography

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.





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

Black holes correspond to a
large number of states
on the boundary

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.

Emergent geometry



Emergent geometry

A verbal analogy

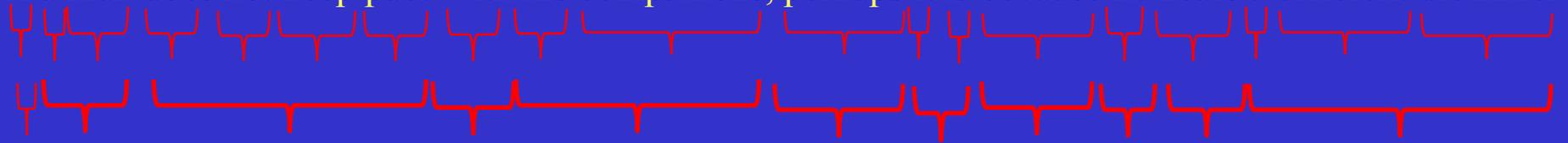
If a man does not keep pace with his companions,
perhaps it is because he hears a different drummer

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

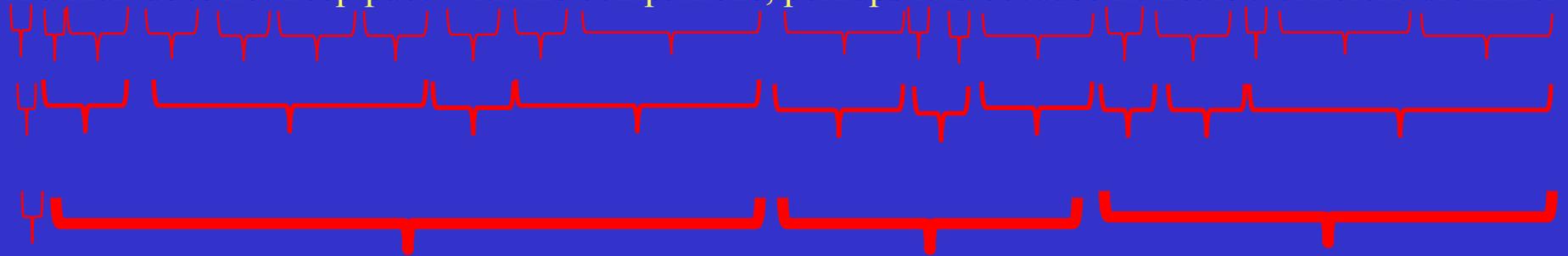
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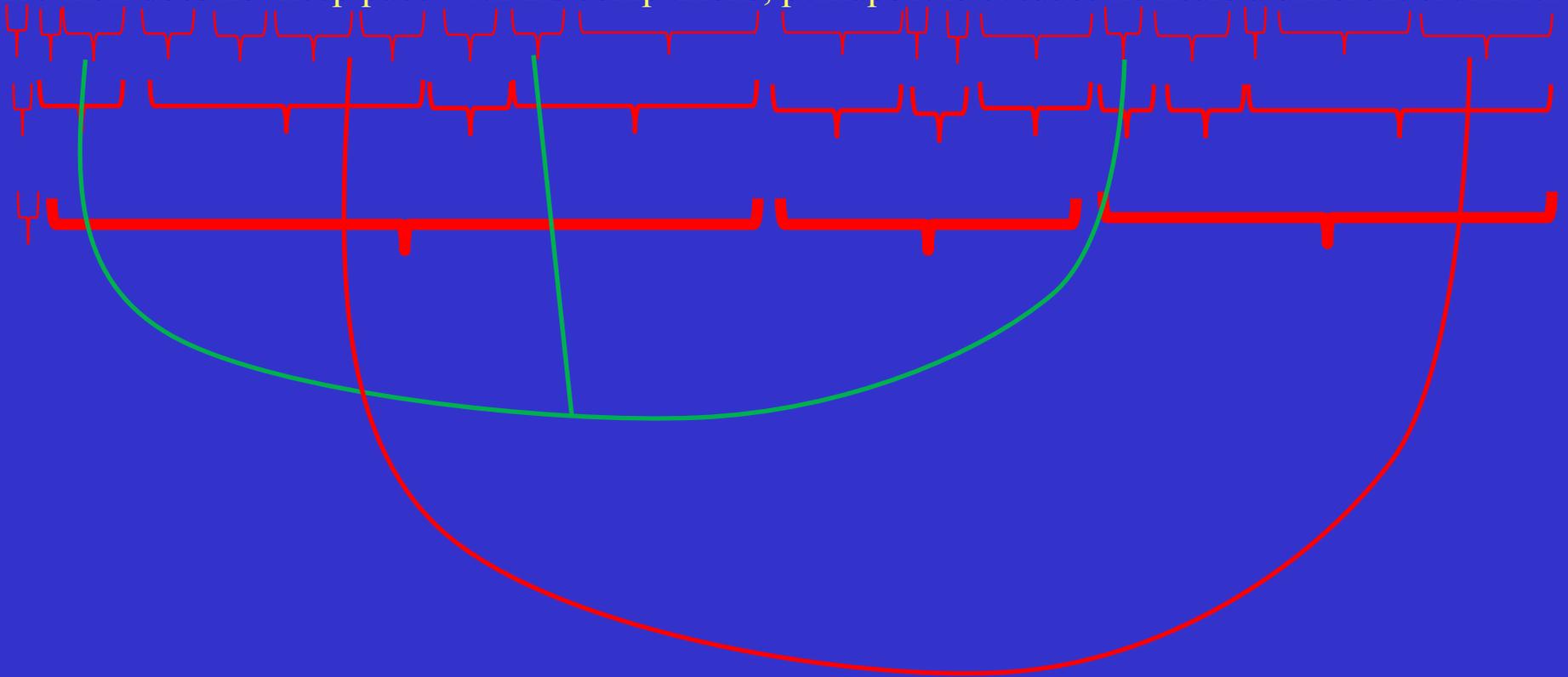
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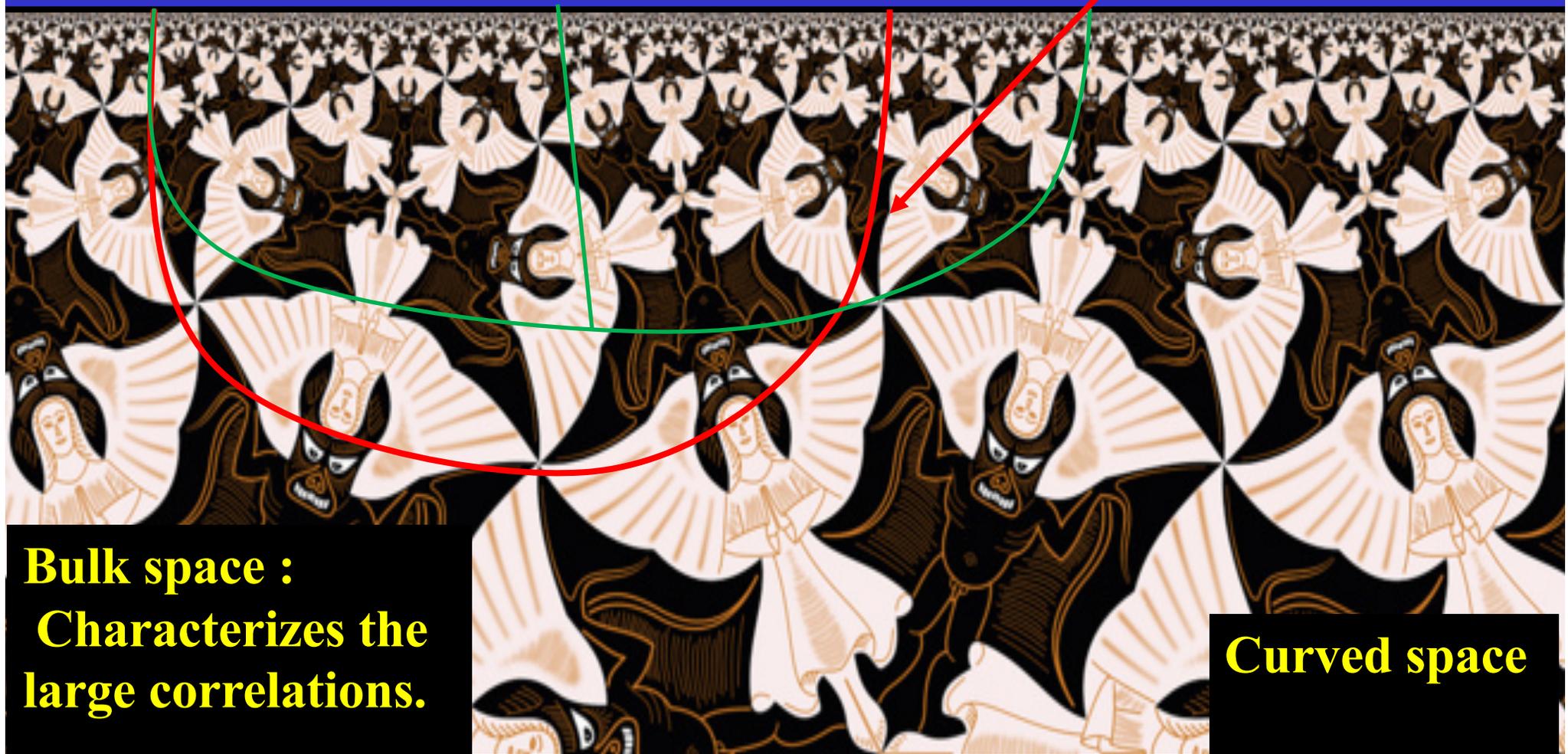
If a man does not keep pace with his companions, perhaps it is because he hears a different drummer



State of the quantum system.

Extra long distance correlations \rightarrow particles

We study various aspects of wormholes that are made traversable by an interaction between 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



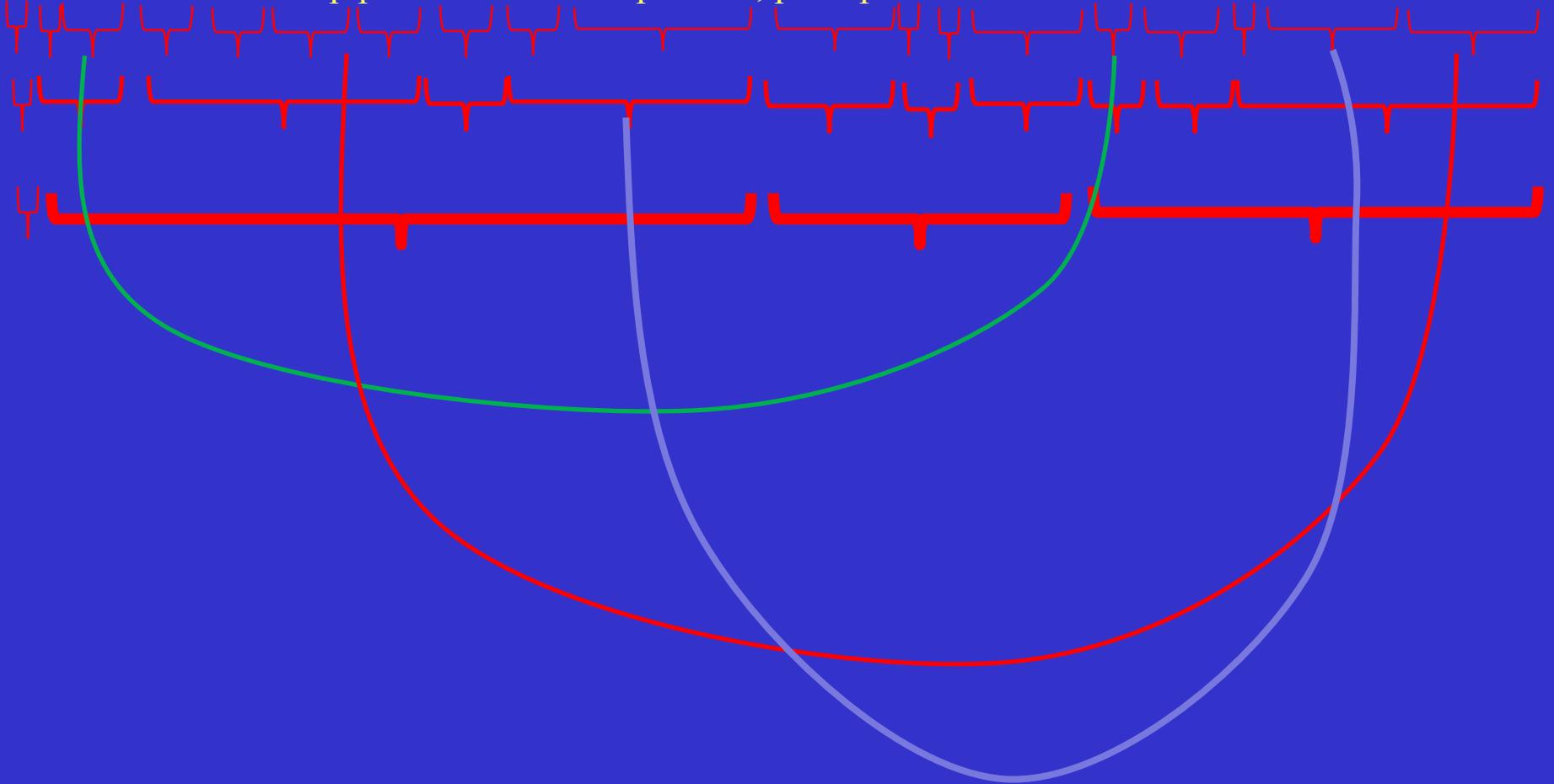
Bulk space :
Characterizes the large correlations.

Curved space

What is a black hole in the
spacetime ?

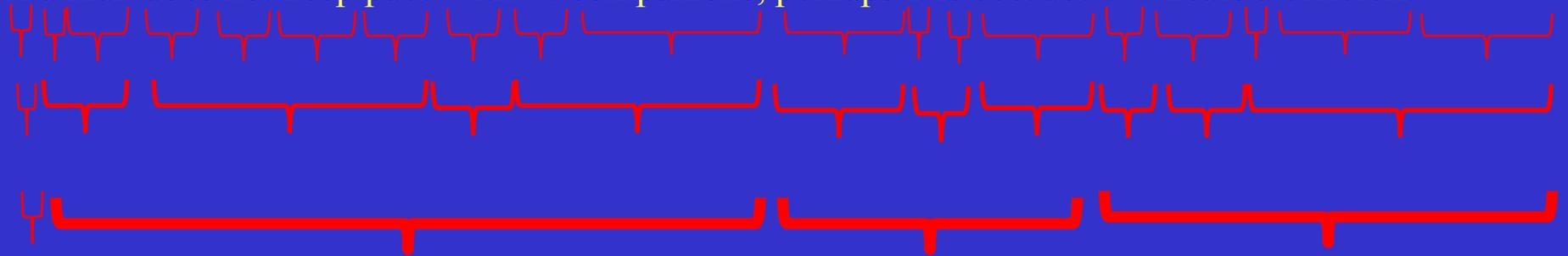
Back to the sentence

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



Make a couple of changes

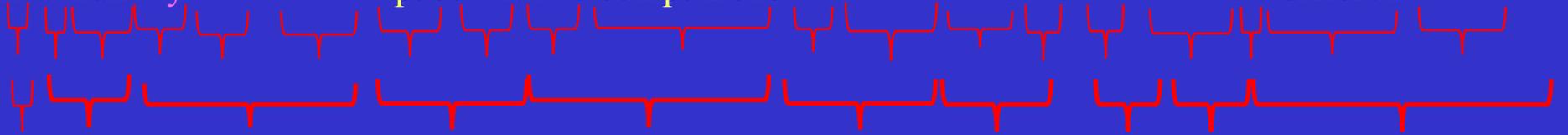
If a man does not keep pace with *its* companions, perhaps it is because *she* hears a different *lecture*



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 dlfi 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 dlfiel 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 \rightarrow 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.

Using holography to learn about strongly interacting theories:

Boundary theory: Particles in our spacetime

Interior: Some curved five dimensional universe.

Getting information out of black holes !

Black holes as sources of information

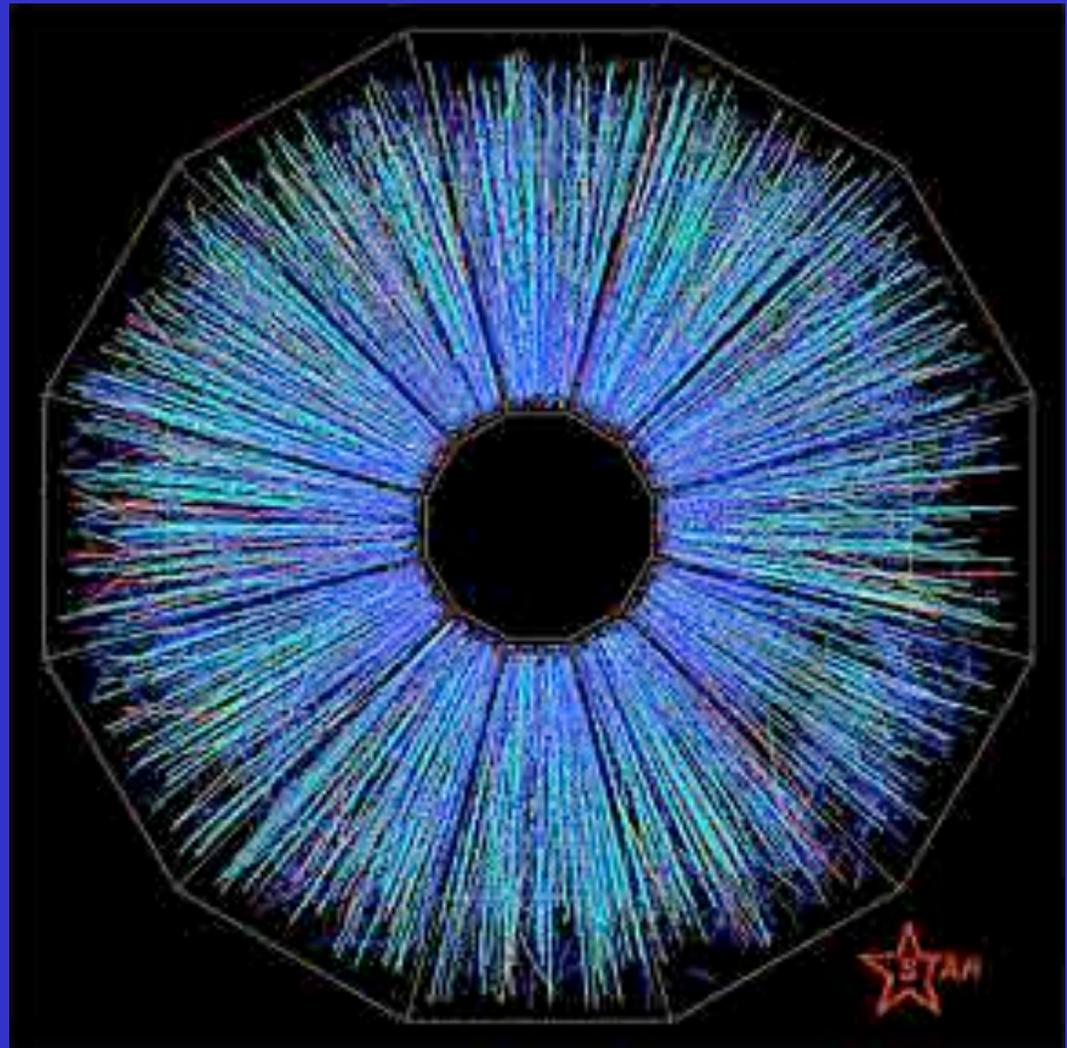
Model heavy ion collisions at RHIC or LHC (Large Hadron Collider)

→ View the collision as creating a new phase of matter

or

→ As creating a black hole in a weird five dimensional space

→ Black hole horizons and hydrodynamics.

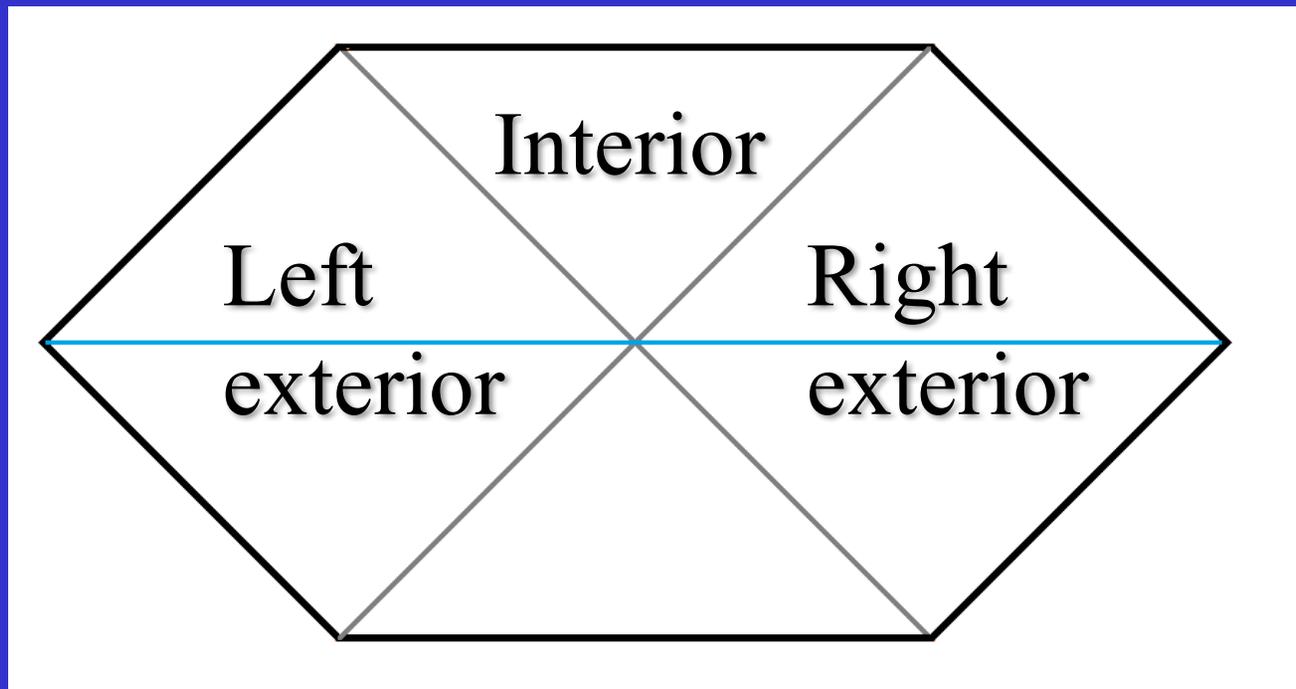


Entanglement and geometry

Entanglement and geometry

- The quantum mechanical property of entanglement plays an important role in constructing the spacetime geometry.
- We will discuss just one example.

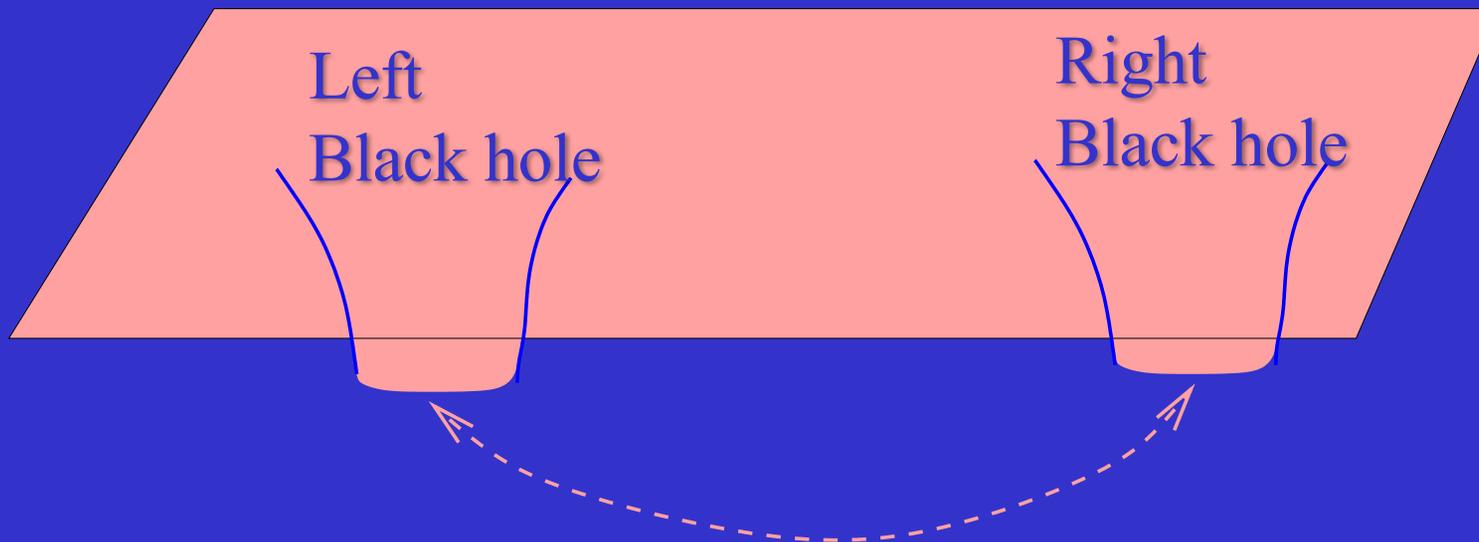
Two sided Schwarzschild solution



Eddington, Lemaitre,
Einstein, Rosen,
Finkelstein
Kruskal

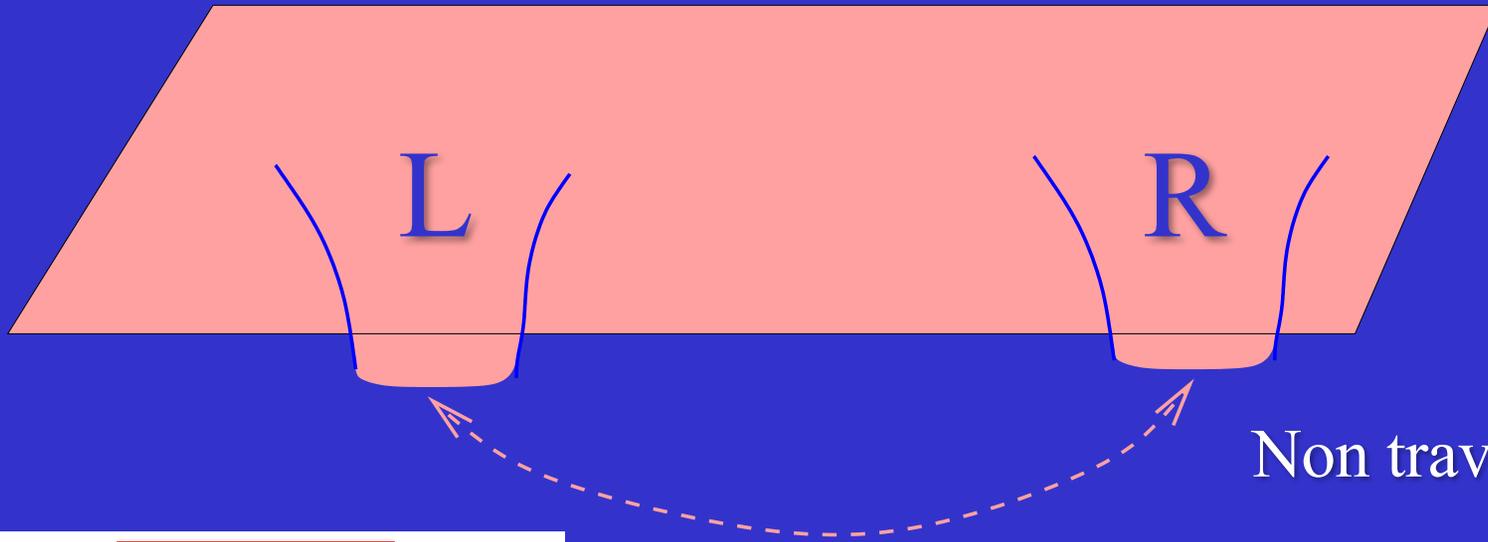
Simplest spherically symmetric solution of pure Einstein gravity
(with no matter)

Wormhole interpretation.



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

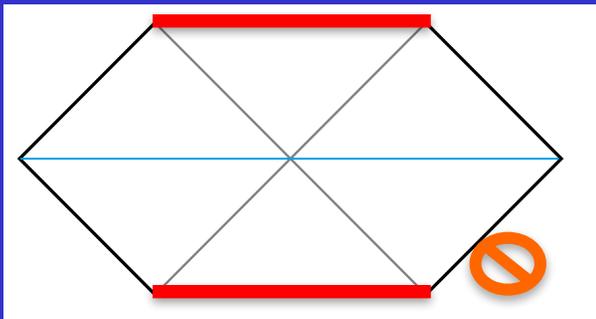
Not the typical science fiction wormhole



Non traversable

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

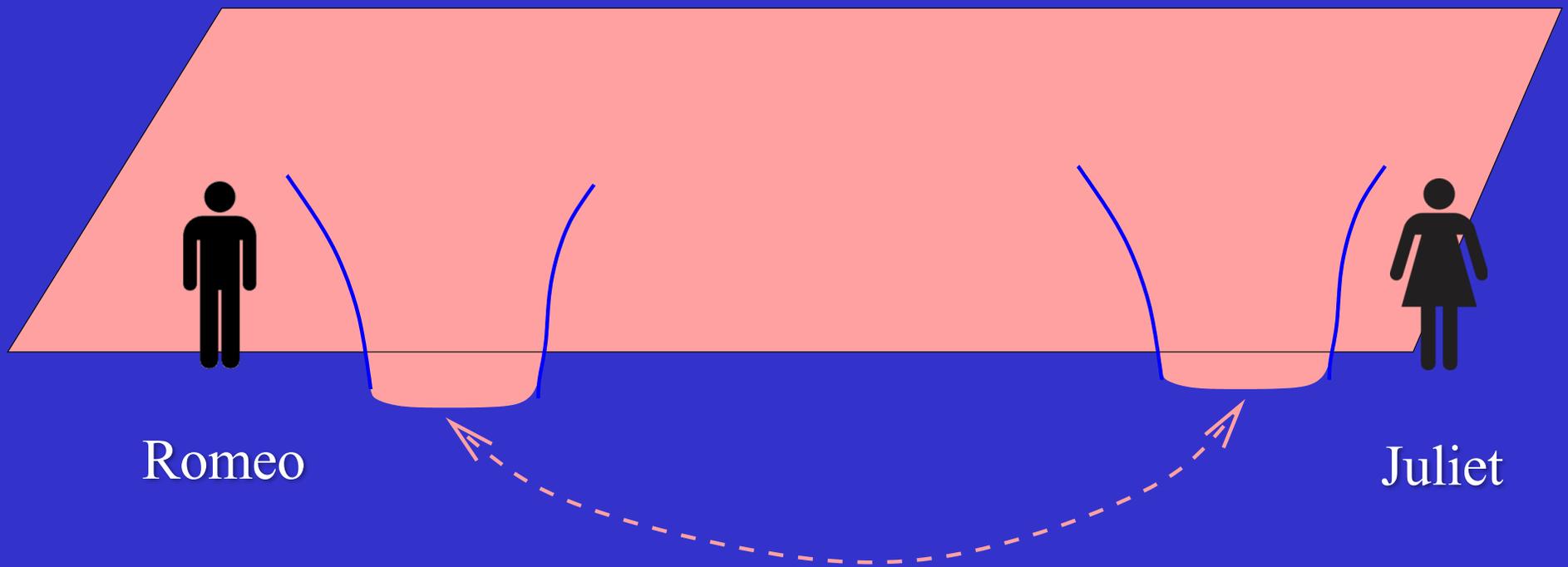
Analogy

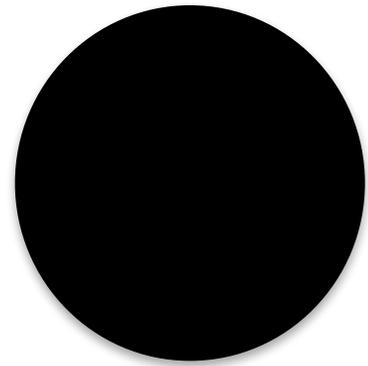
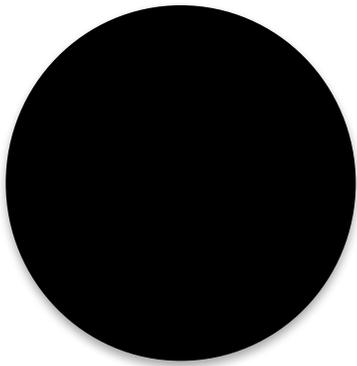
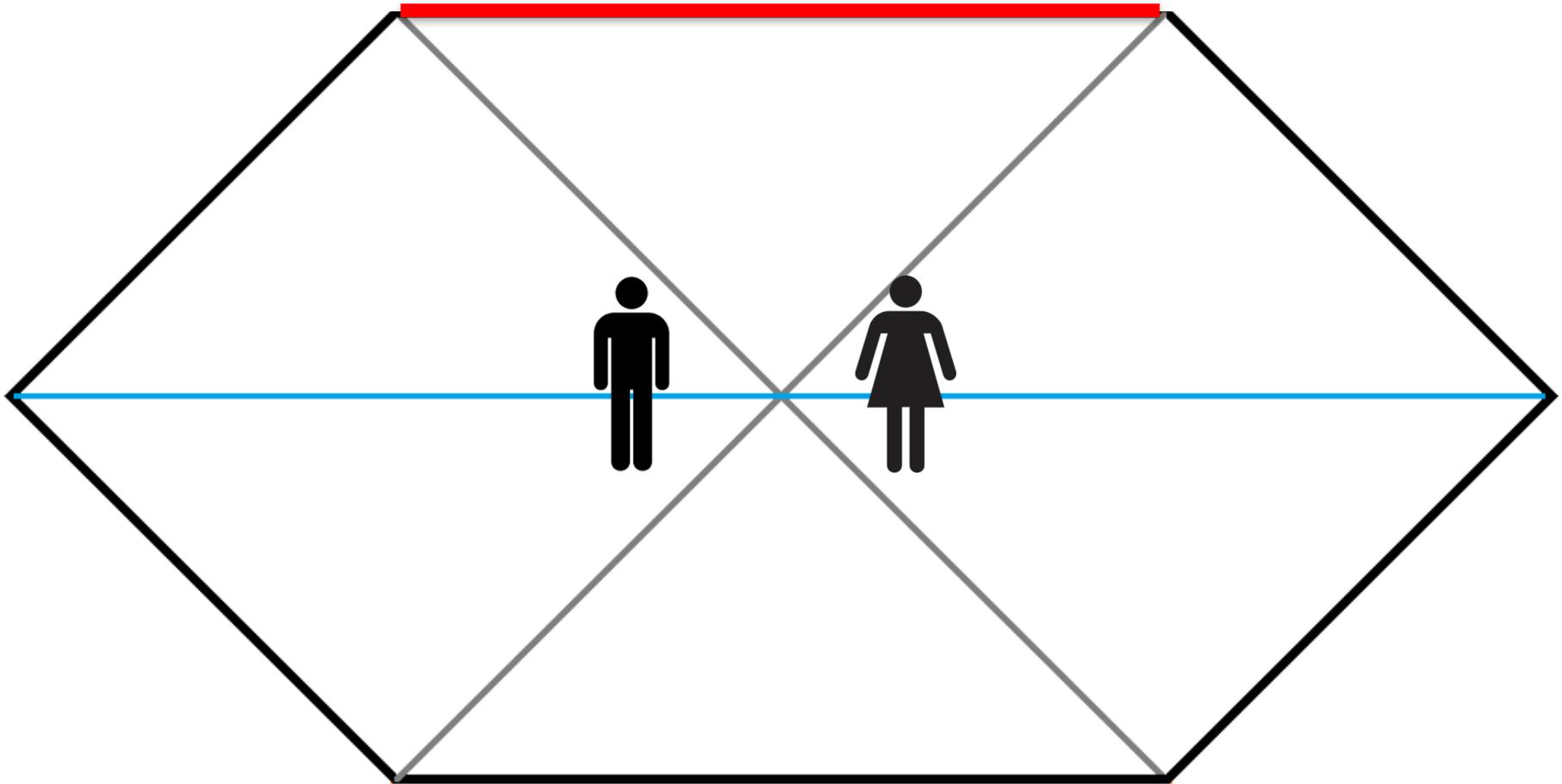
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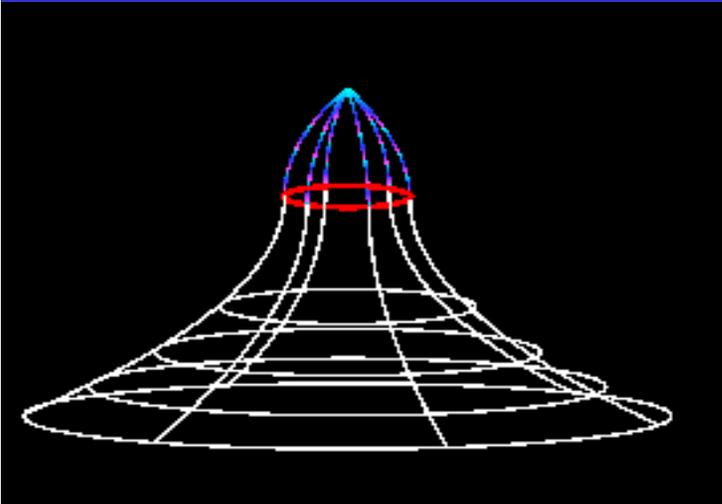
Si alguien no lleva el paso de sus compañeros, quizás sea porque está escuchando otro tamborista

A forbidden meeting





Black hole interior ?



Equivalence principle:
No problem when crossing the horizon.

Mystery: How do we describe the interior using the same variables that make quantum mechanics manifest for the outside observer ?

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

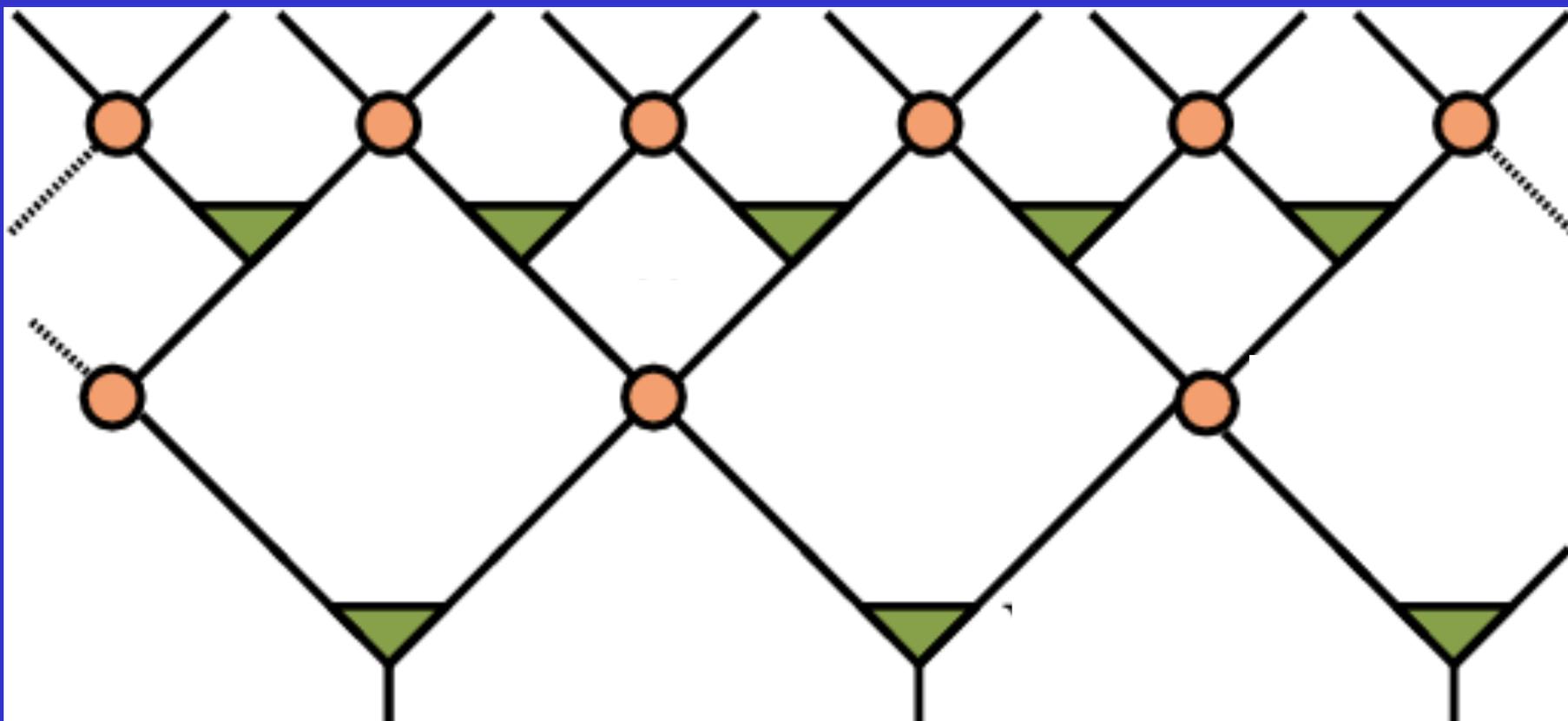
Thank you !



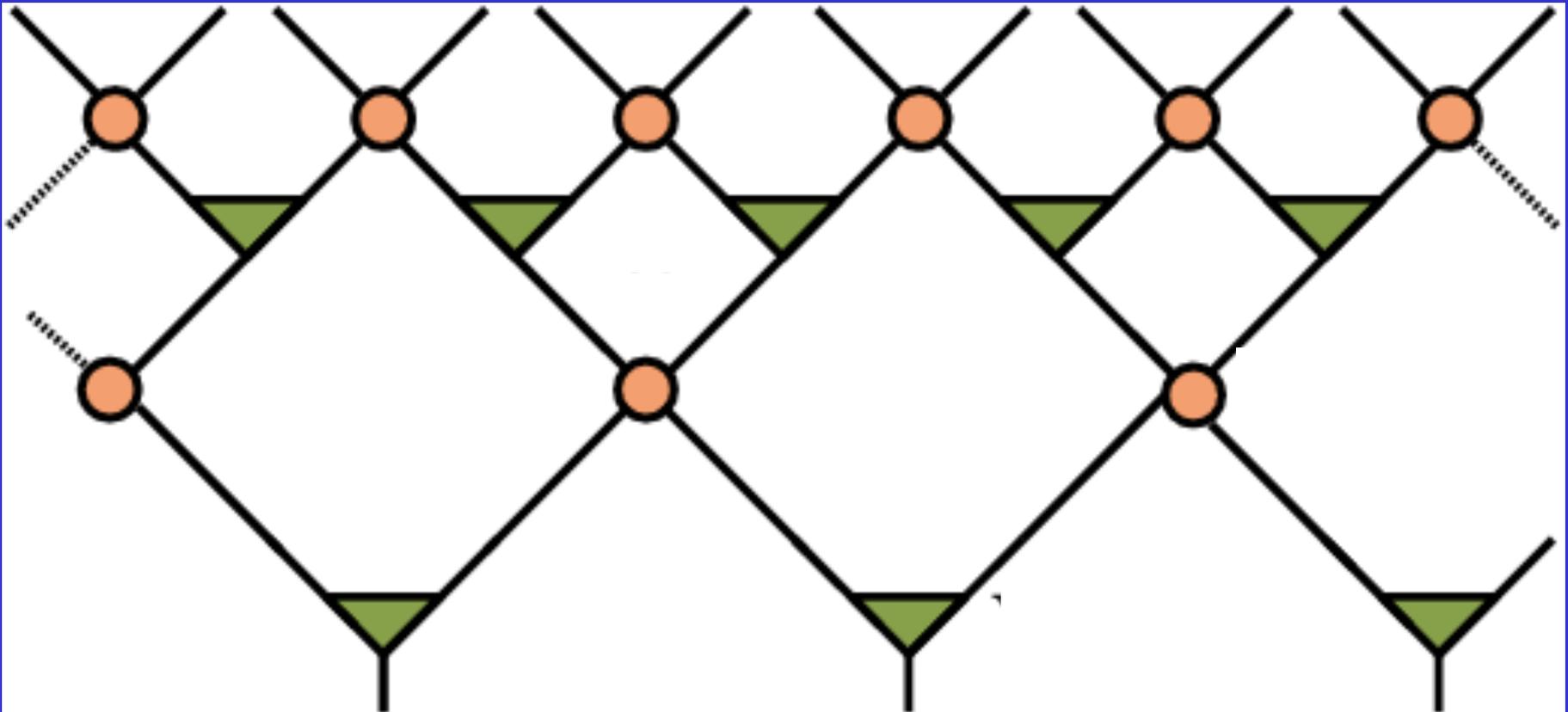


Extra slides

Tensor networks

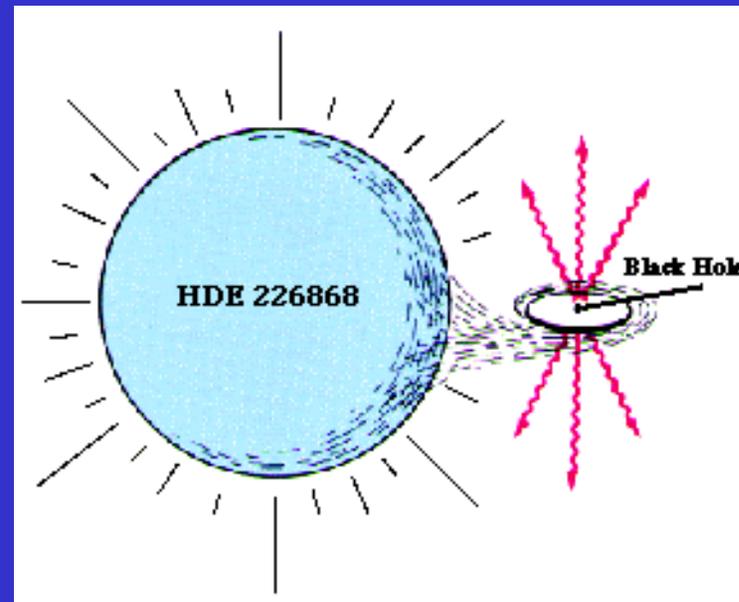


Artificial neural networks → deep learning



How do we see them?

- Watching matter fall in and heating up.
- Seeing the gravity waves produced by their collisions.



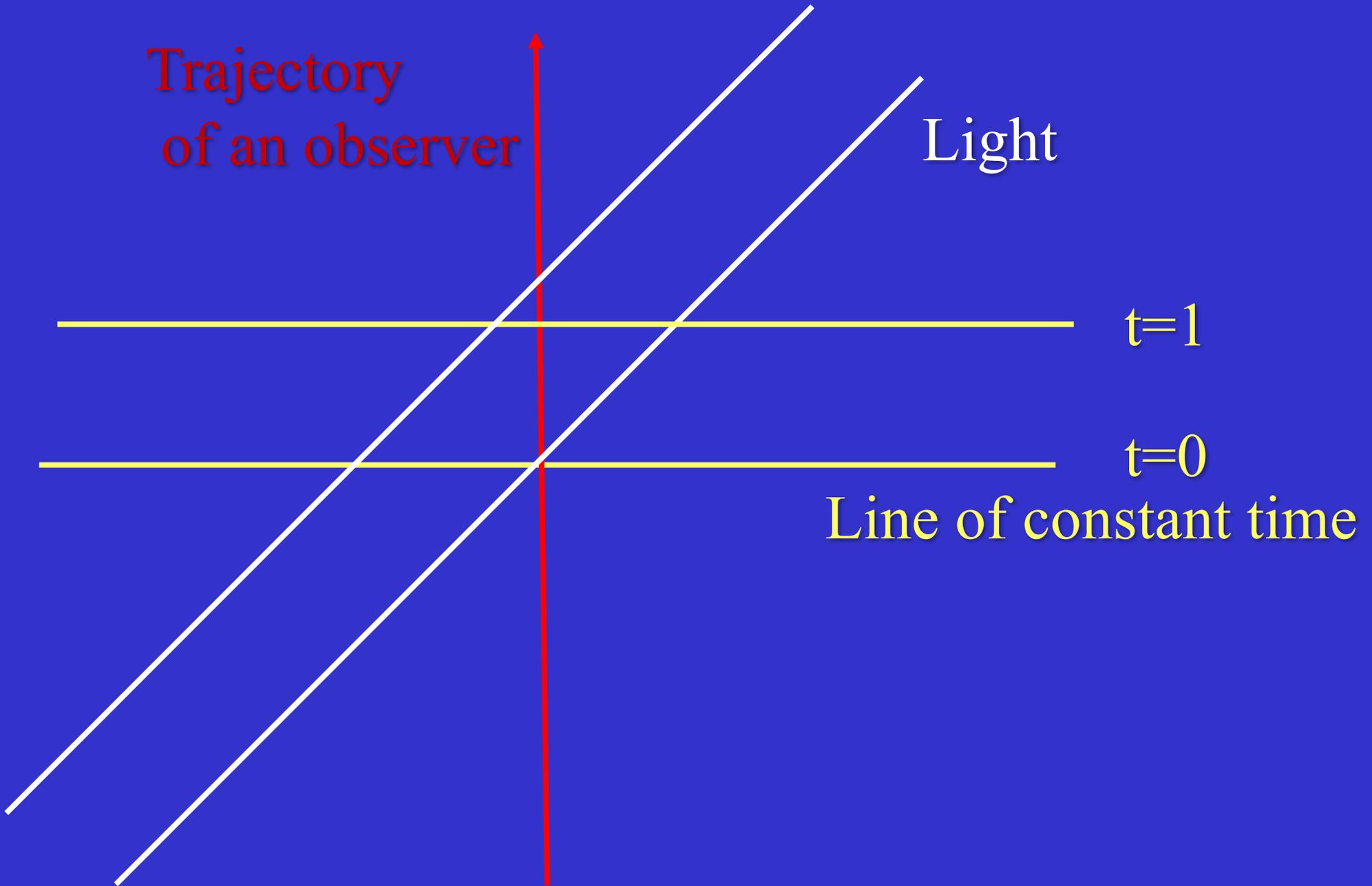
Trajectory
of an observer

Light

$t=1$

$t=0$

Line of constant time

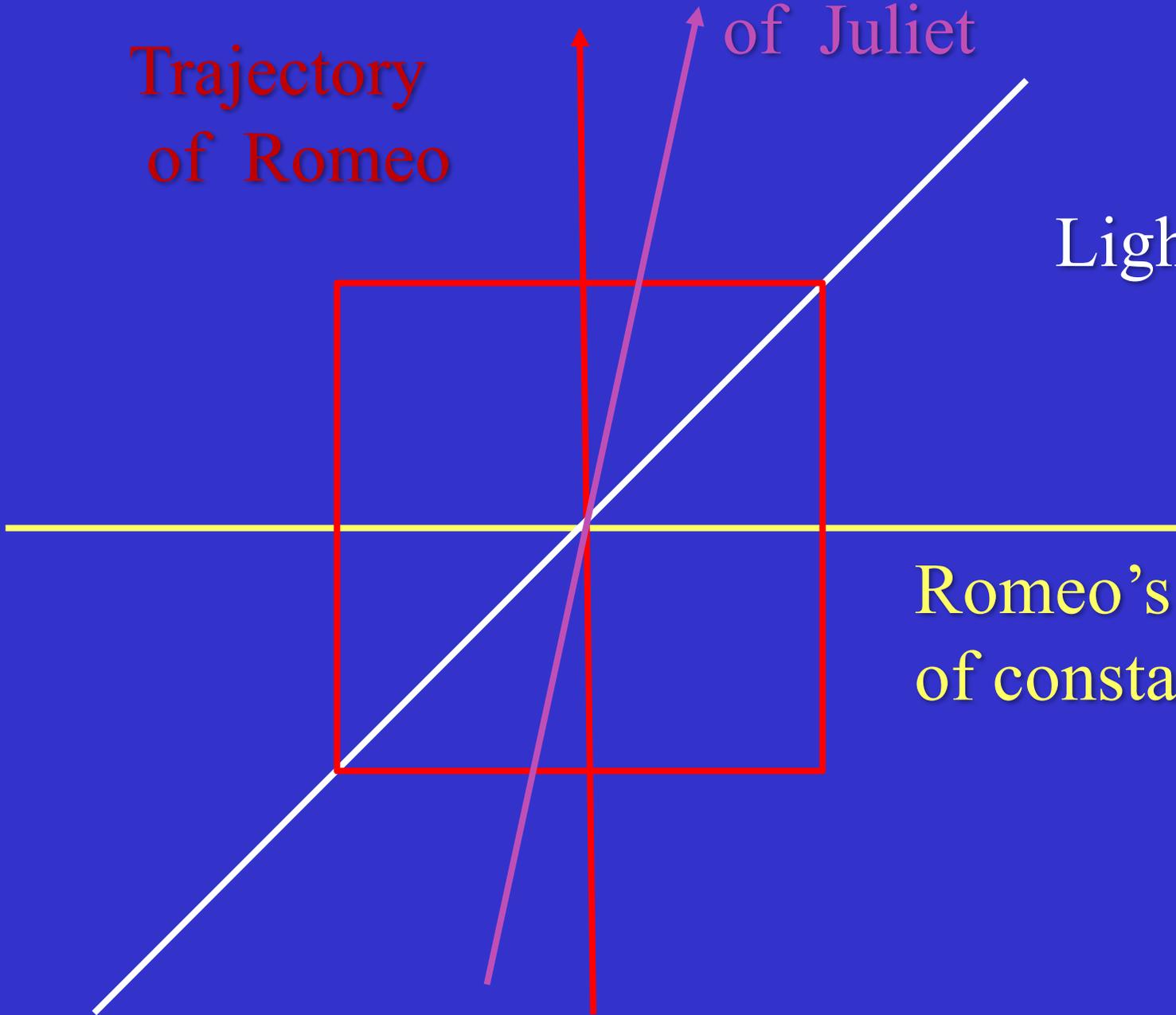


Trajectory
of Romeo

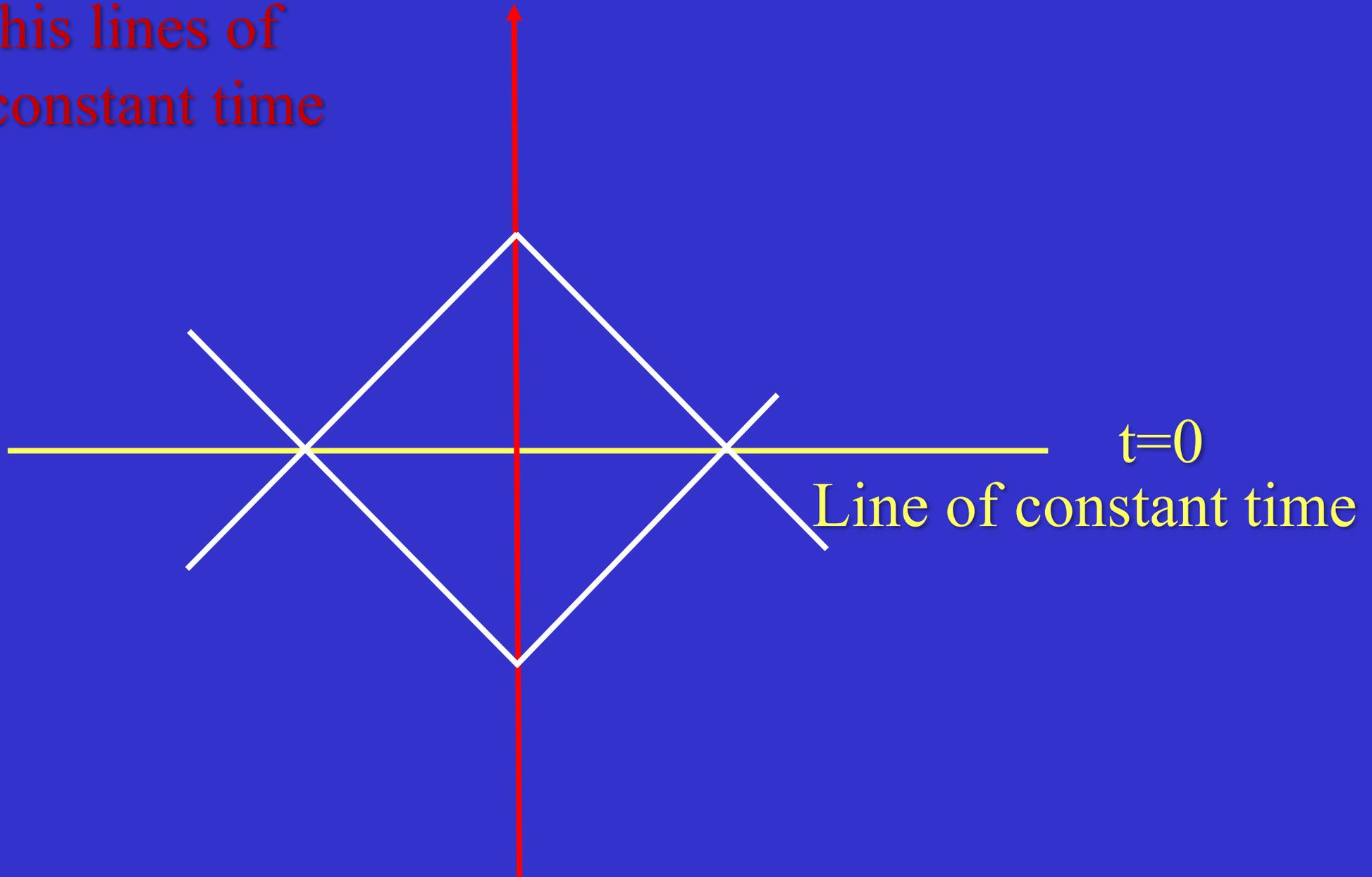
Trajectory
of Juliet

Light

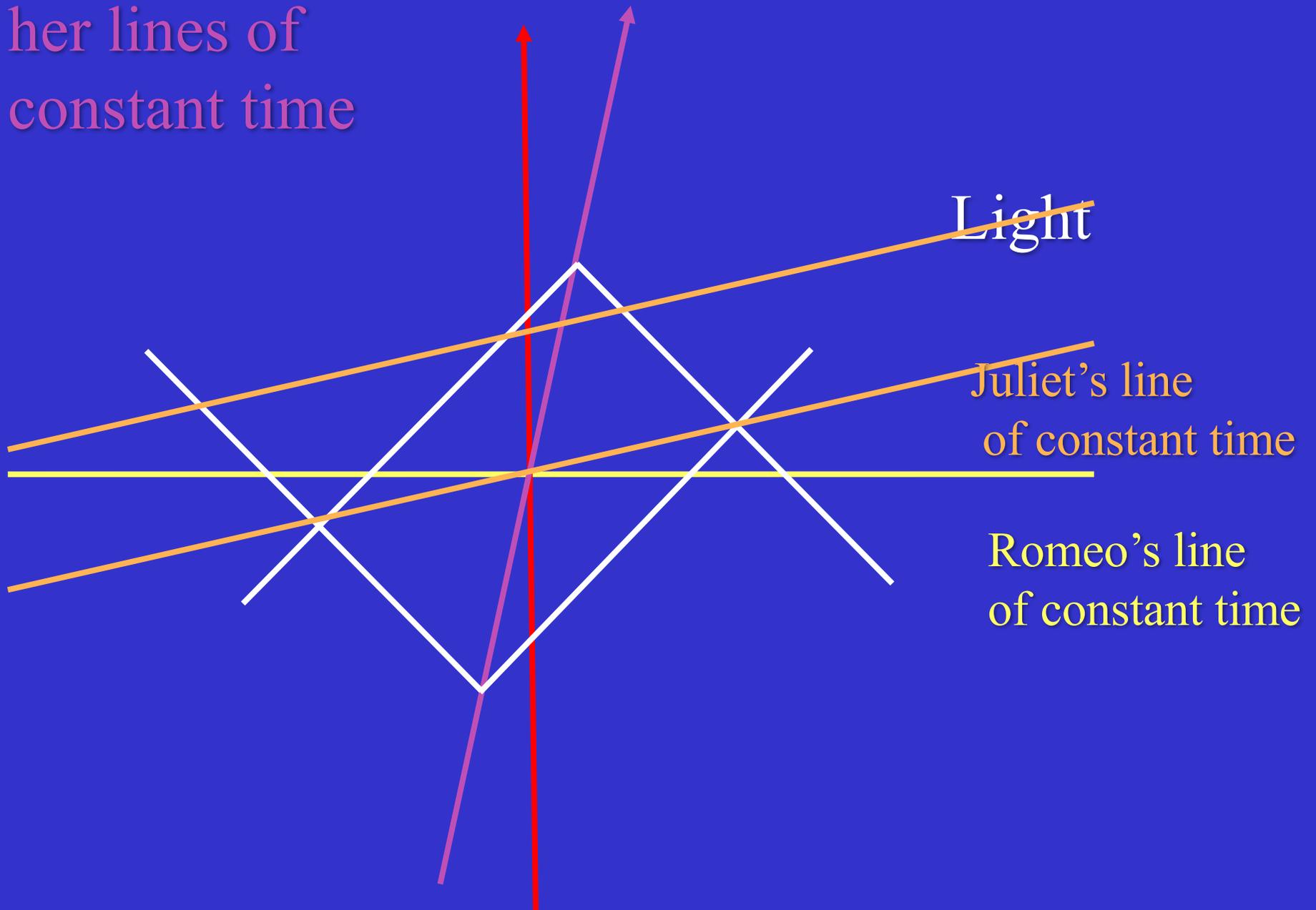
Romeo's lines
of constant time



Romeo's determines
his lines of
constant time



Juliet determines
her lines of
constant time



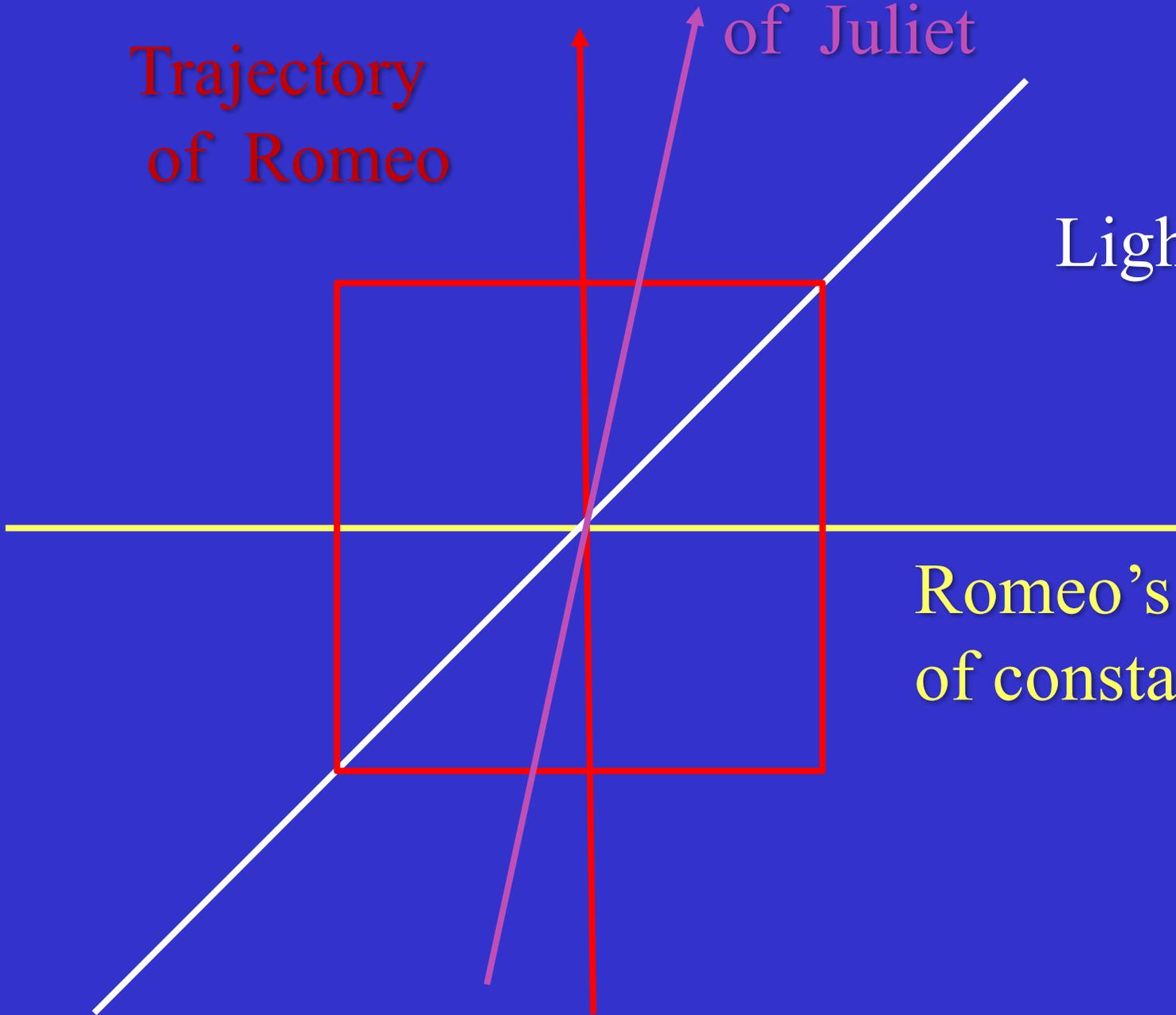
The twin “paradox”

Trajectory
of Romeo

Trajectory
of Juliet

Light

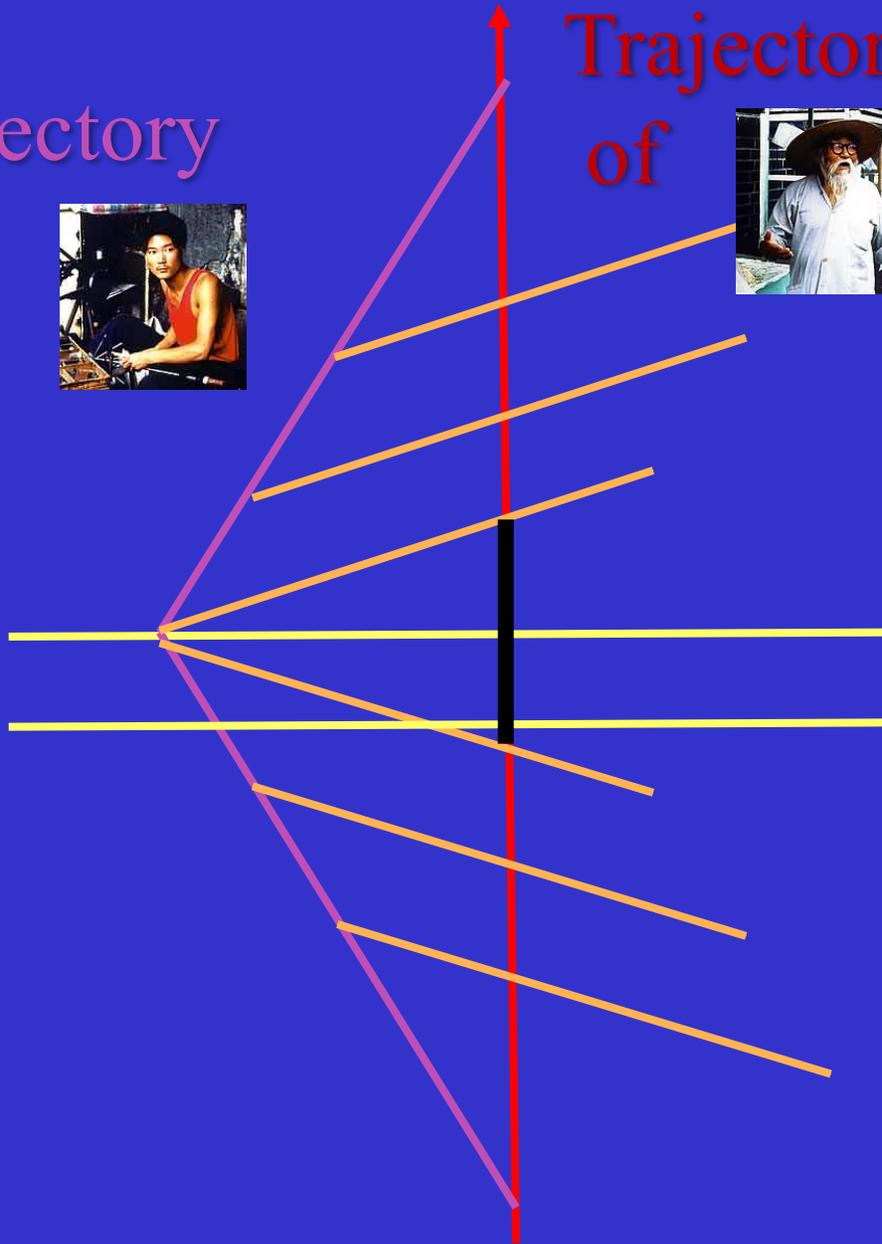
Romeo's lines
of constant time



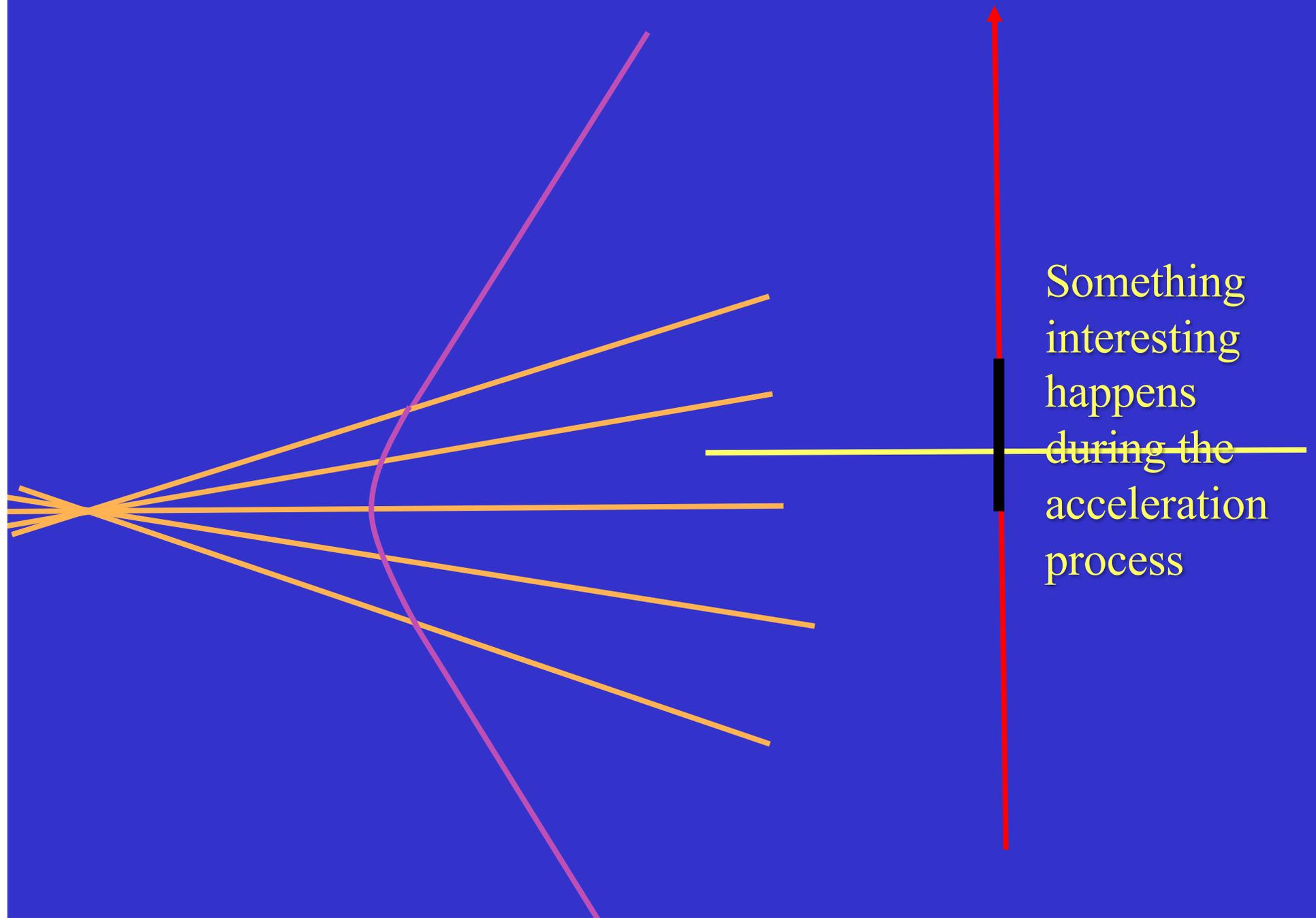
Trajectory
of



Trajectory
of



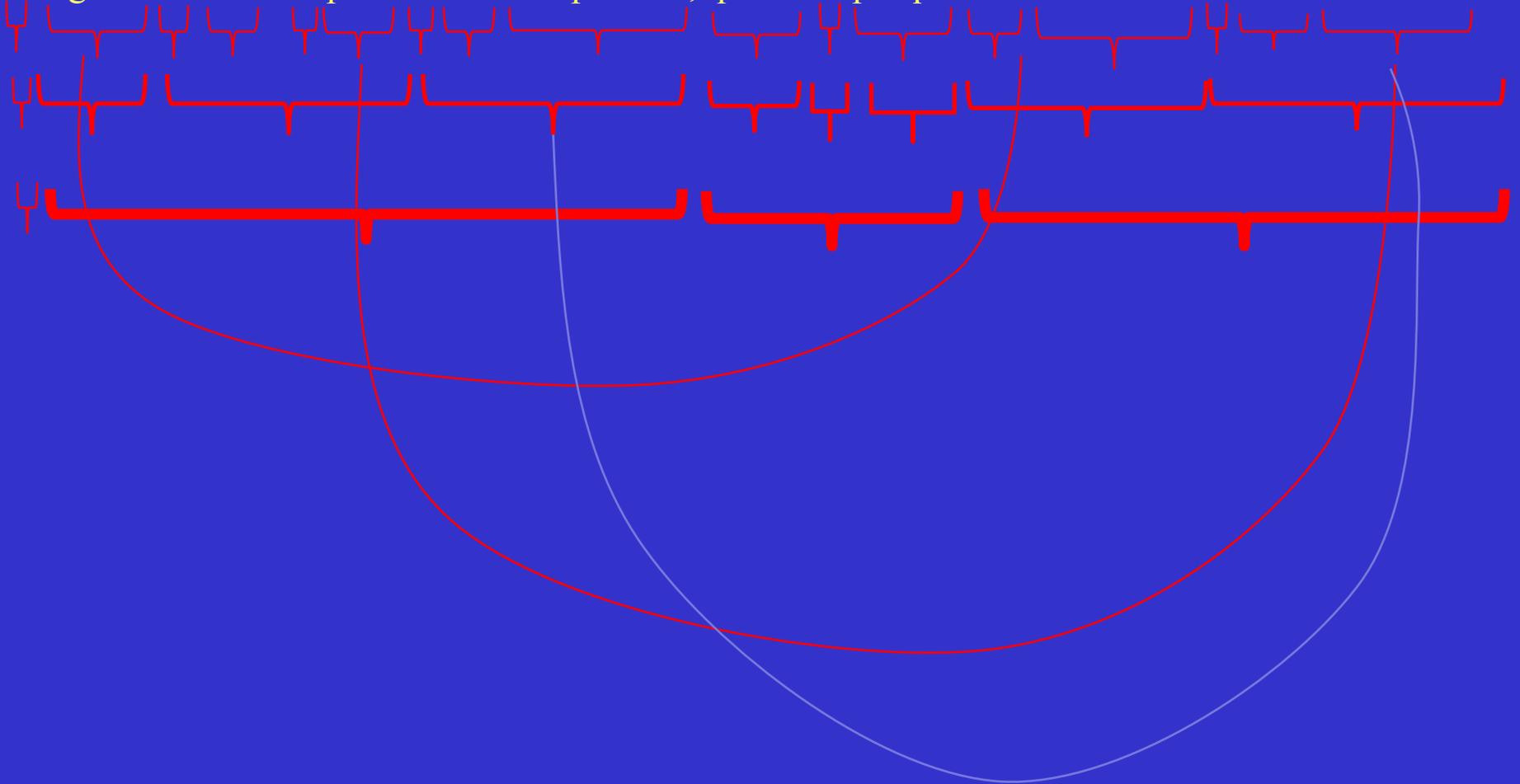
Something
interesting
happens
during the
acceleration
process



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, quizás es porque está escuchando a otro tamborista



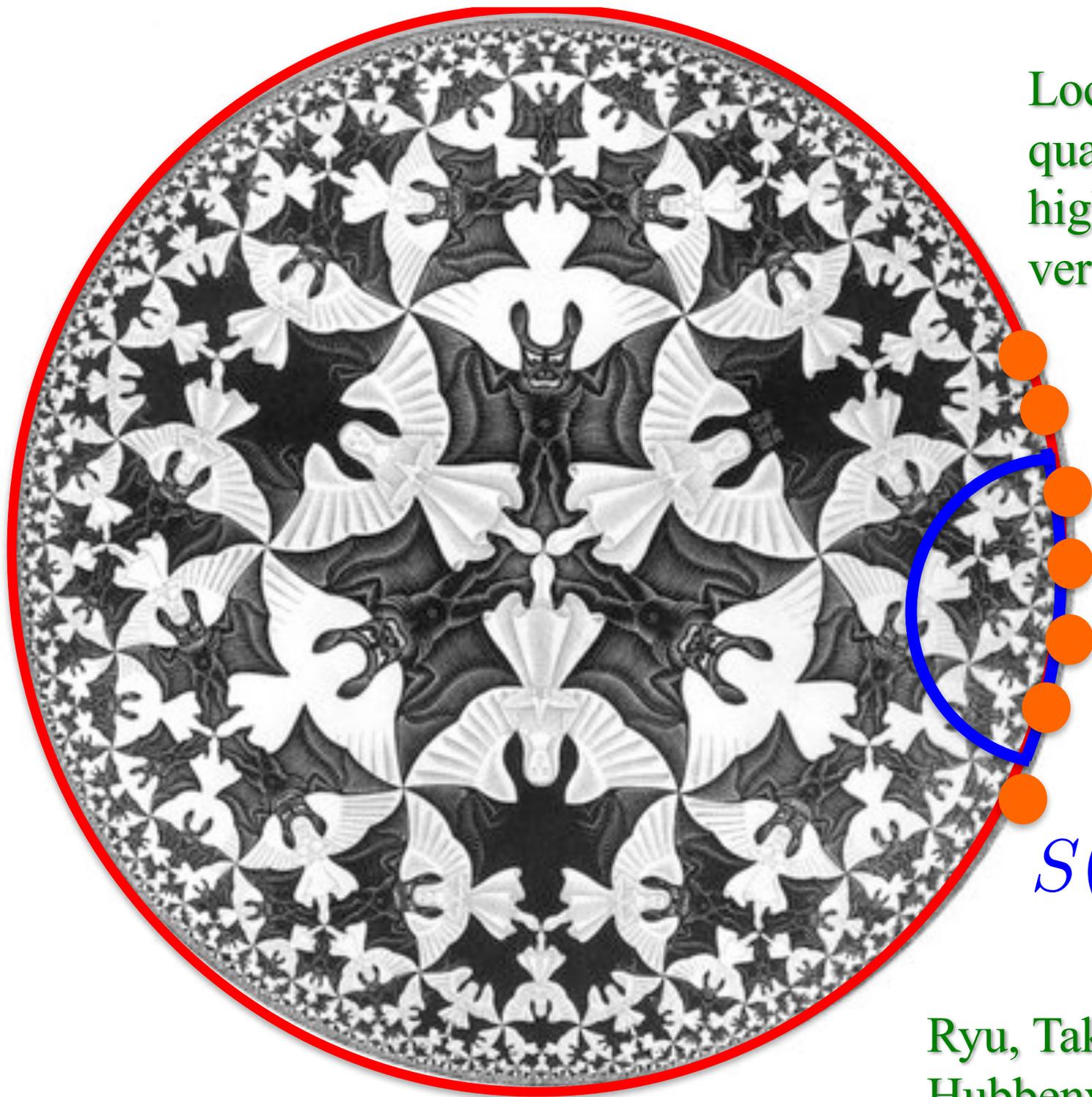
Different quantum systems in detail, that give the same long long distance structure

Spacetime different near the boundary

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Higher level “simplified”
description



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 ?