Black Holes and the structure of space time

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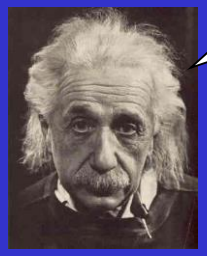
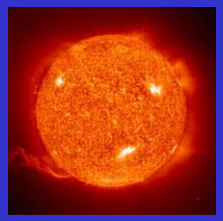
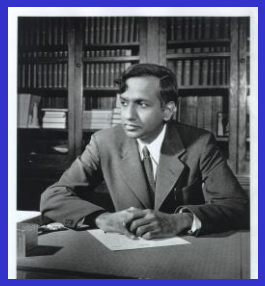
General relativity

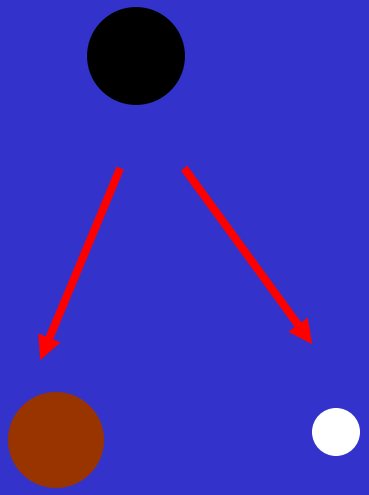
I do not think so…







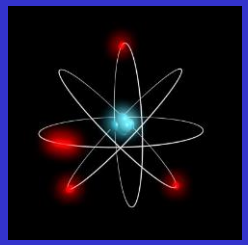
They are unavoidable



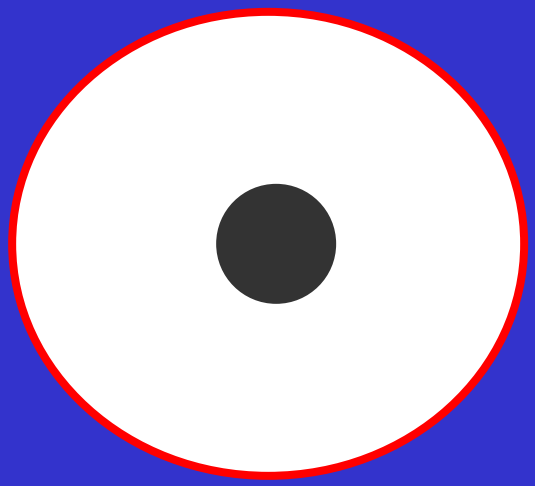
They are not black

They imply that quantum mechanics is incompatible with gravity

Incompatible ?



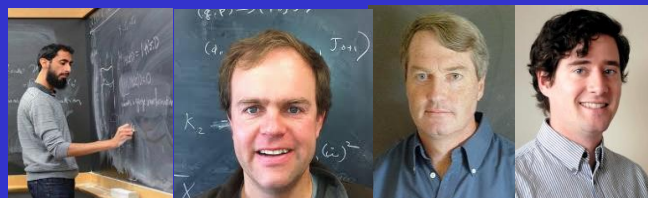
String theory



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

Relation between quantum mechanics and spacetime geometry

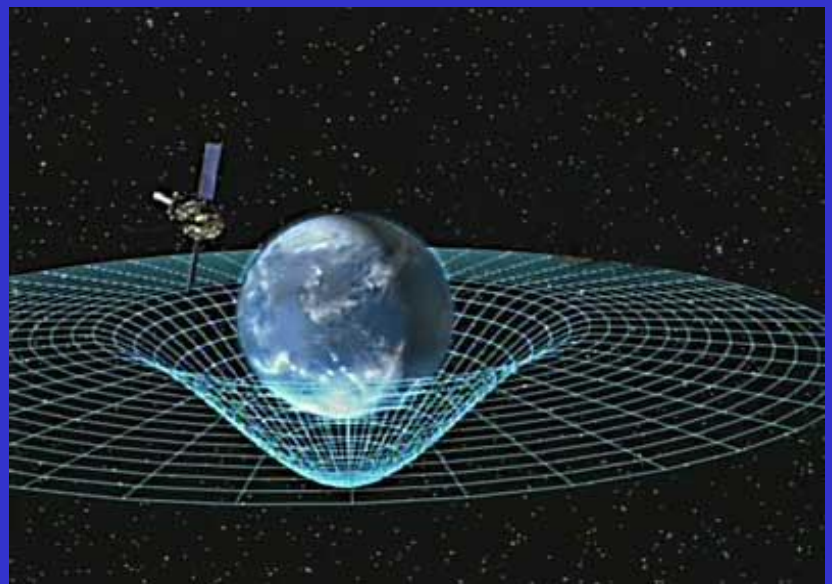
Still several puzzles with the interior



General Relativity

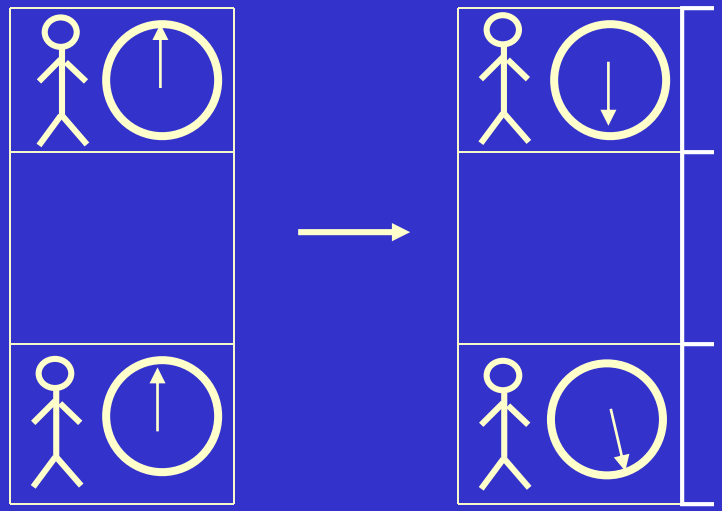
Einstein 1915

- ✓ 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

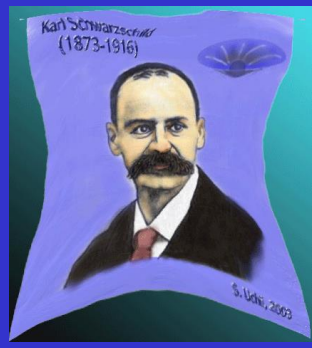
Time flows differently for two observers in a gravitational field.



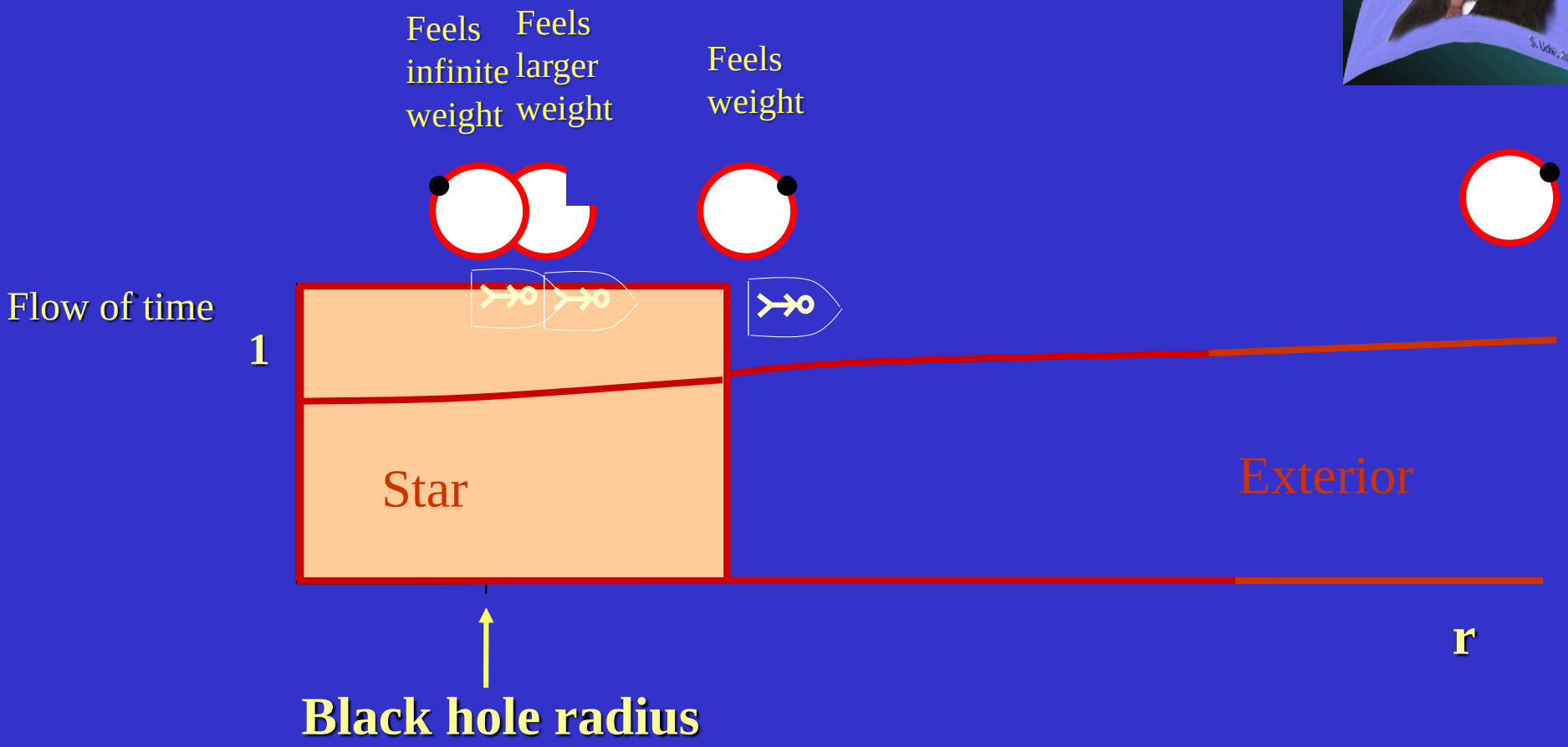
Time flows more slowly

(A part in 10^{15})

Karl Schwarzschild found the spacetime geometry outside a massive spherical body



This geometry tells us how time flows.

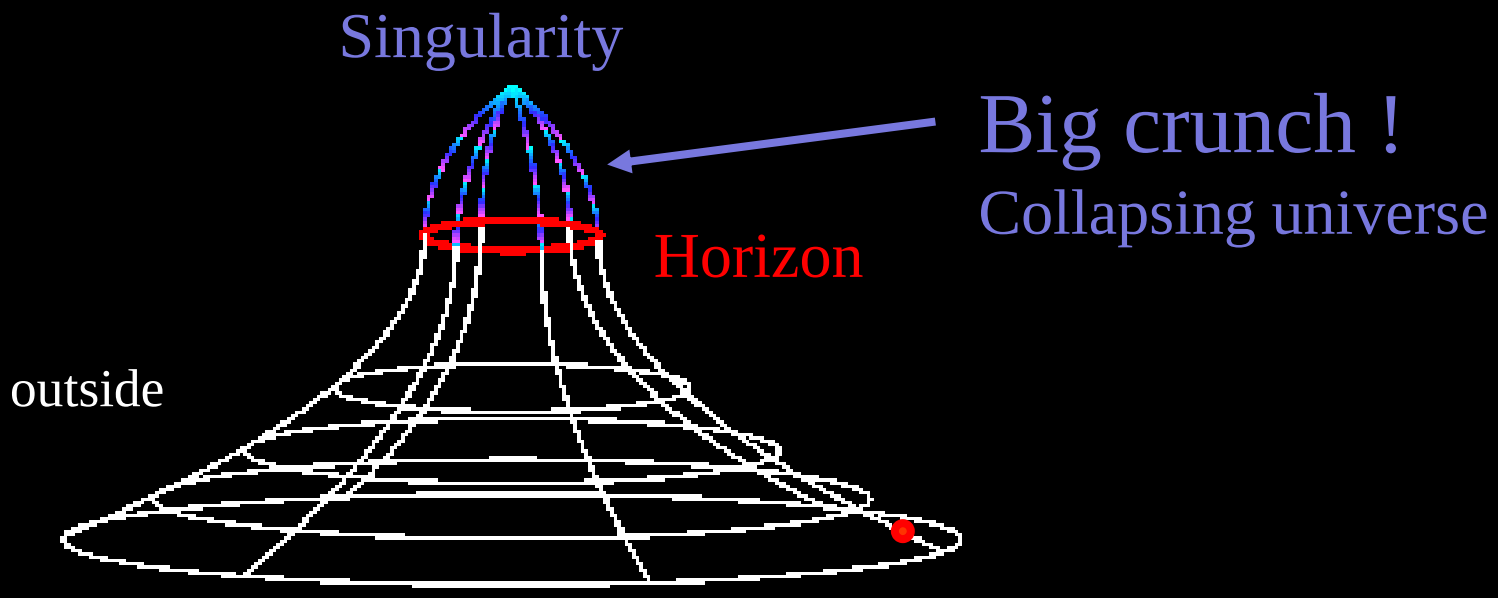


Equivalence principle:

If you fall freely, gravity “disappears”

It is also true at the horizon !

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

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.

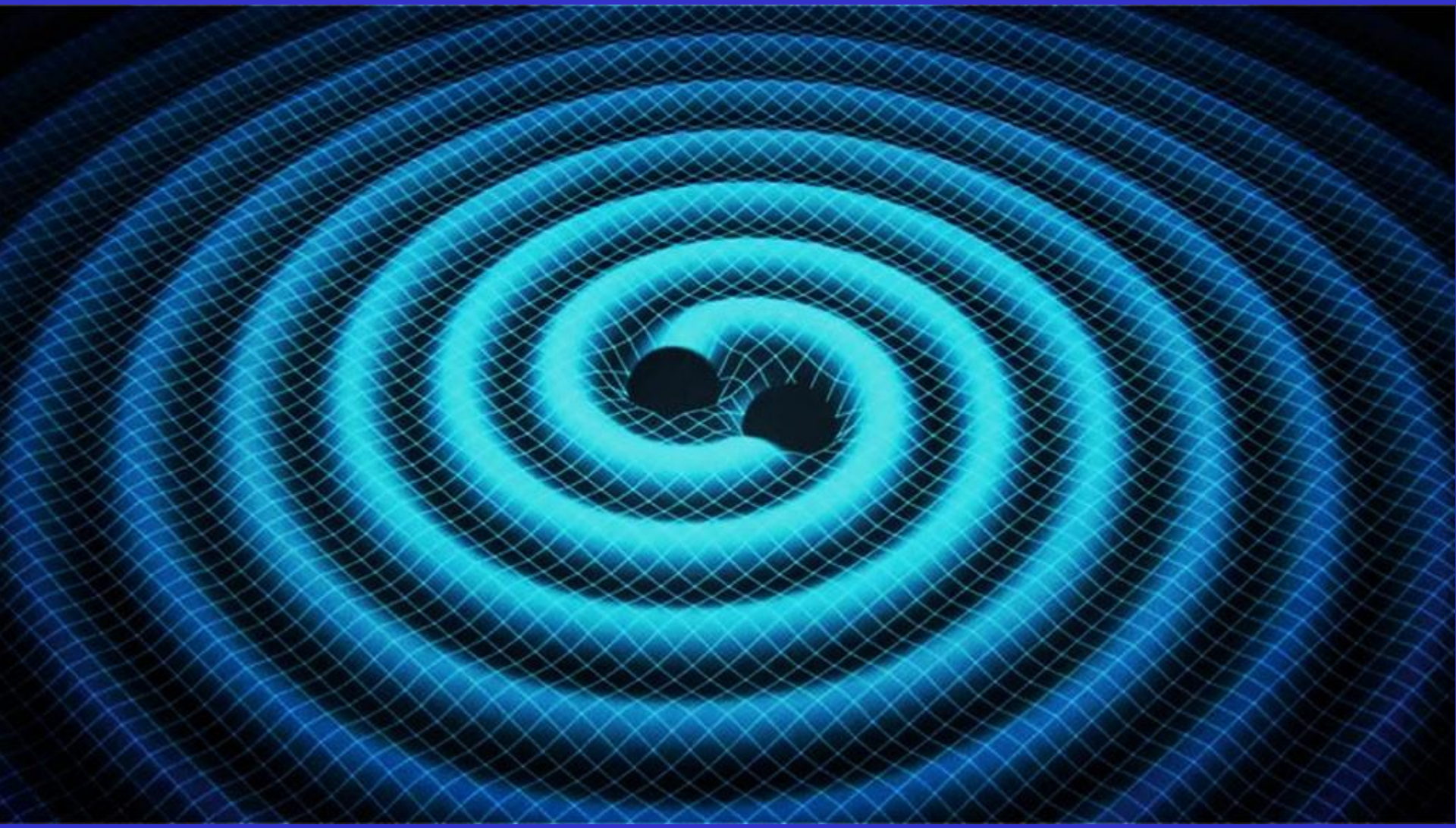
1) Once you cross the horizon, you cannot get out!

2) A star can collapse into a black hole.

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

We can ``hear'' black holes when they collide

Ligo/Virgo 2016

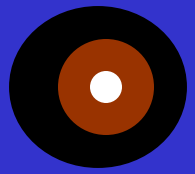


Quantum Mechanics leads to a new surprising prediction

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:

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

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

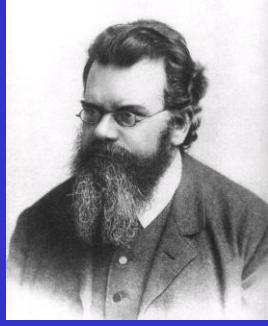
Theoretical problems with black hole temperature

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

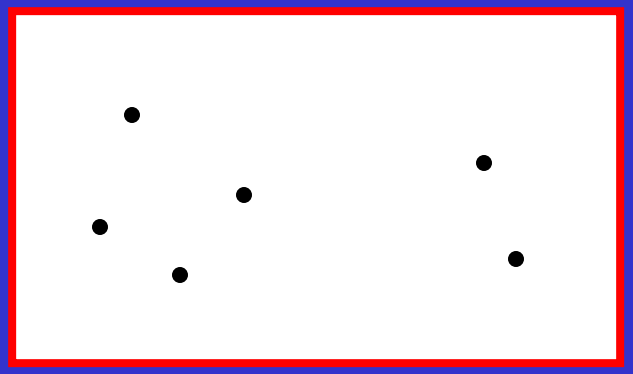
Puzzles:

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

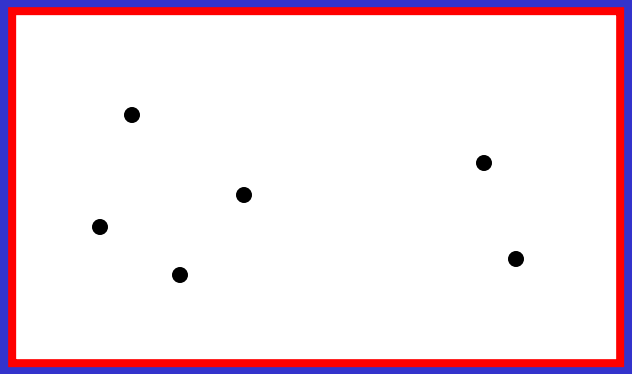
Temperature



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

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

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

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

Hawking ‘70

Information loss

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

Quantum mechanics → 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 fully quantum description of spacetime

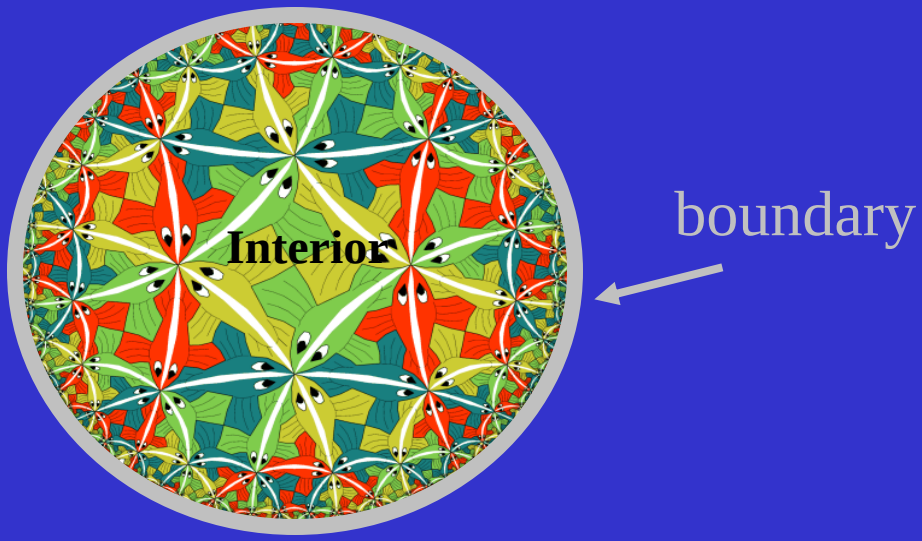
We have one in some special cases

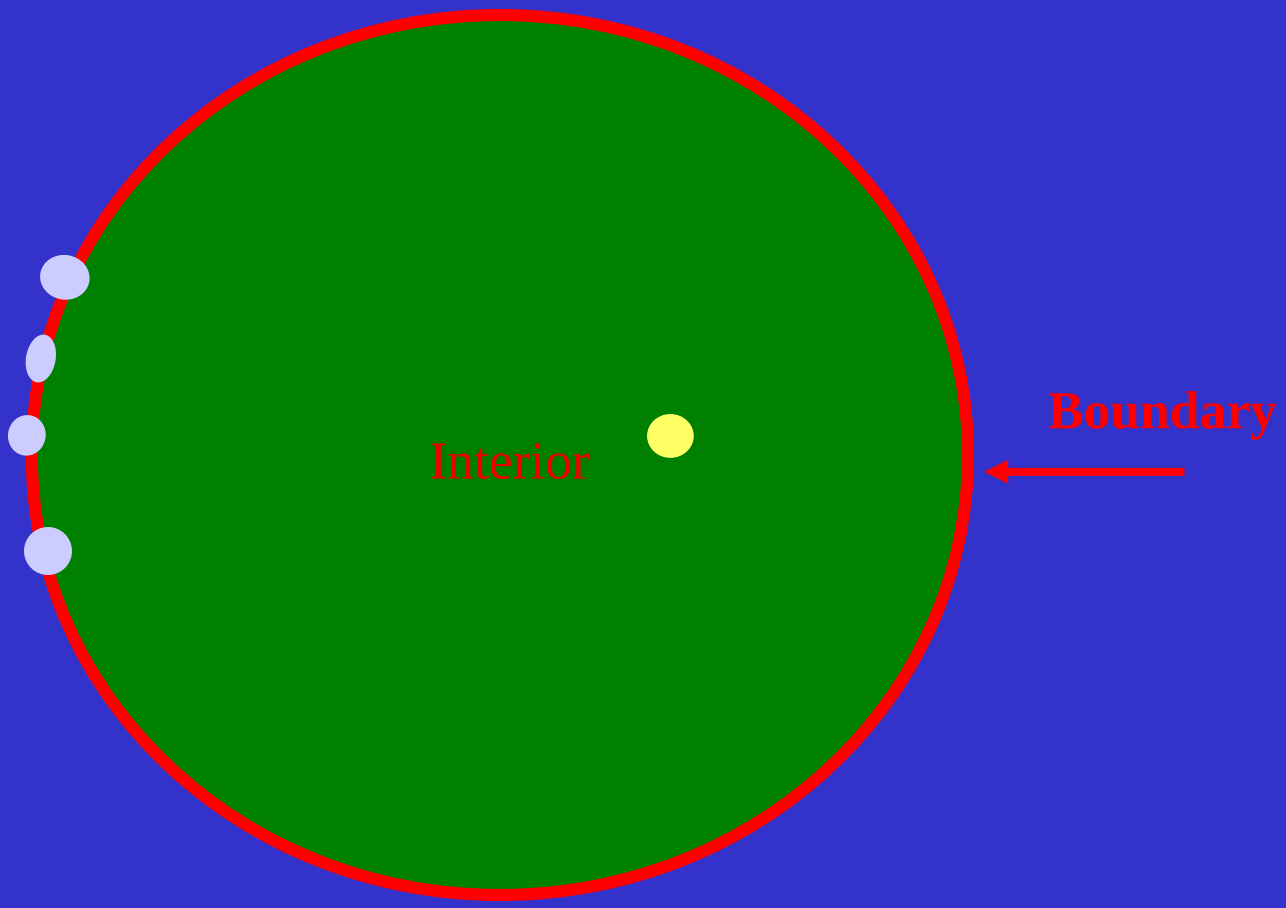
Holography, gauge/gravity duality, AdS/CFT

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

JM 1997

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 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.

Emergent geometry

Emergent geometry

A verbal analogy

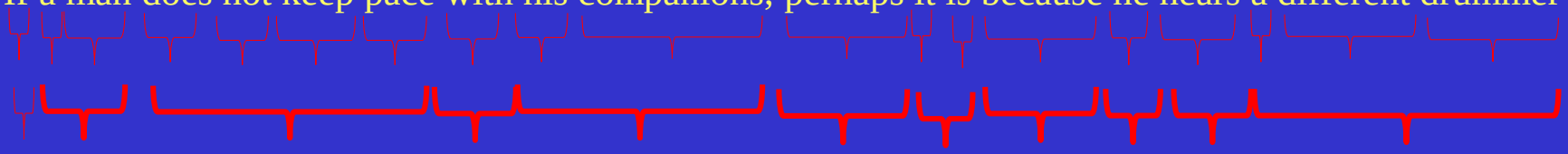
If a man does not keep pace with his companions,

perhaps it is because he hears a different drummer

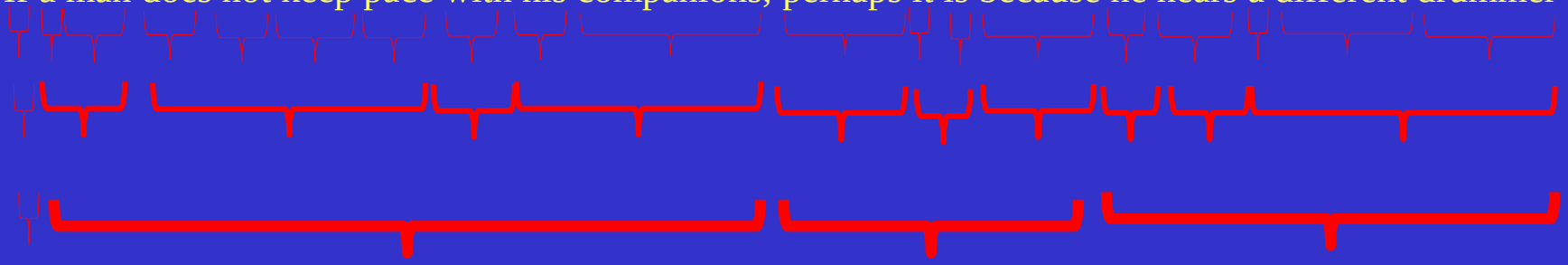
If a man does not keep pace with his companions, perhaps it is because he hears a different drummer

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



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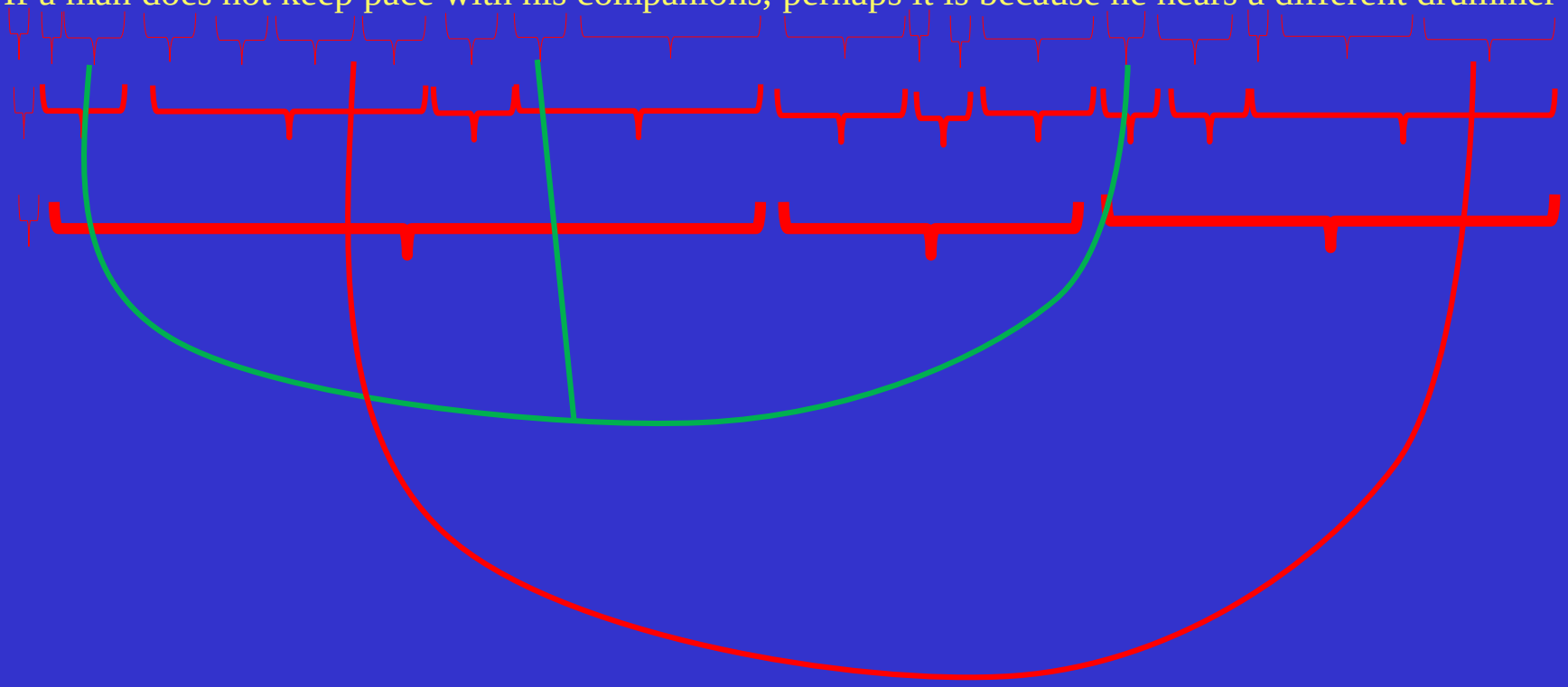
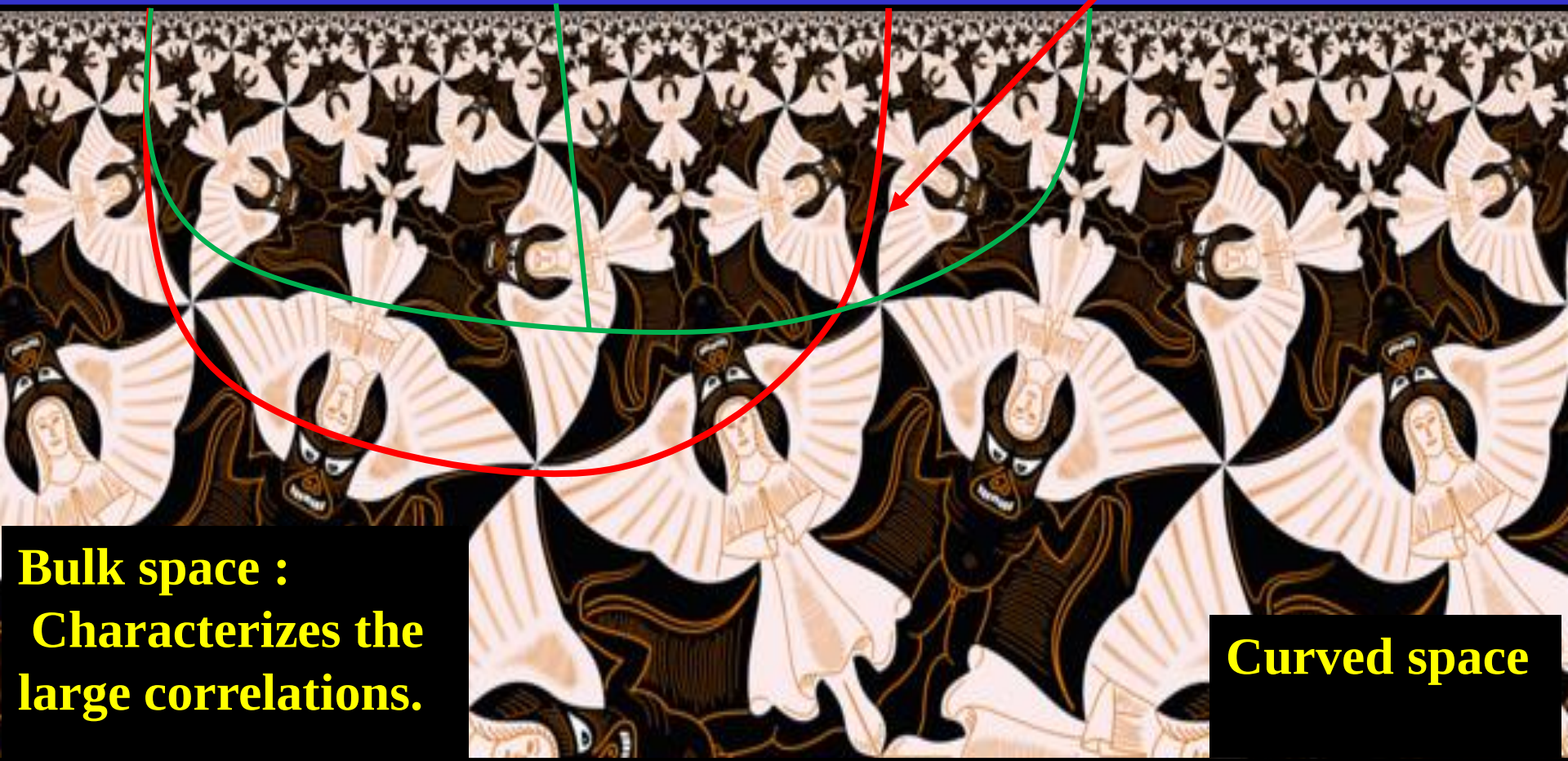


State of the quantum system.

Extra long distance correlations → particles

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



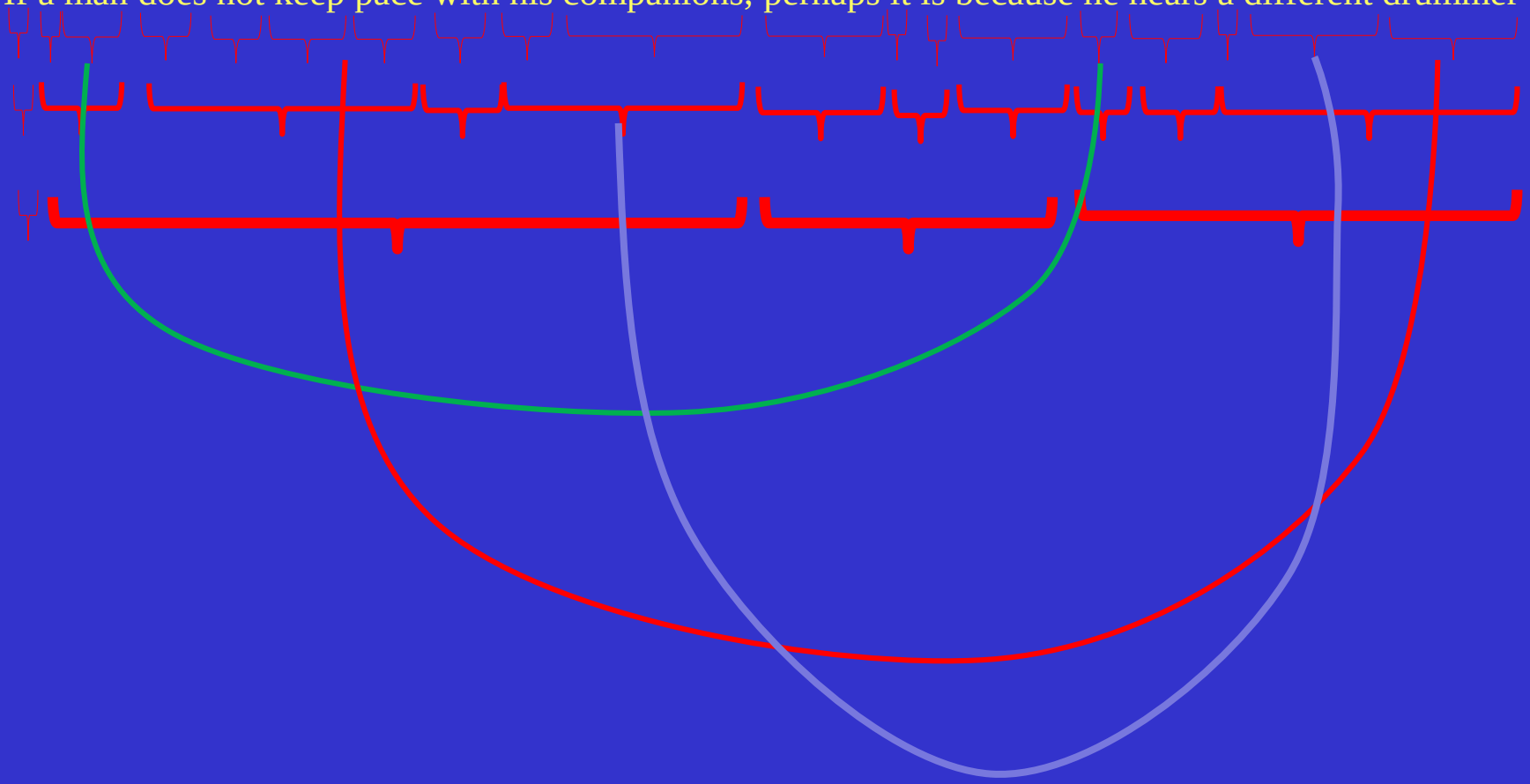
Bulk space : Characterizes the large correlations.

Curved space

What is a black hole in the spacetime ?

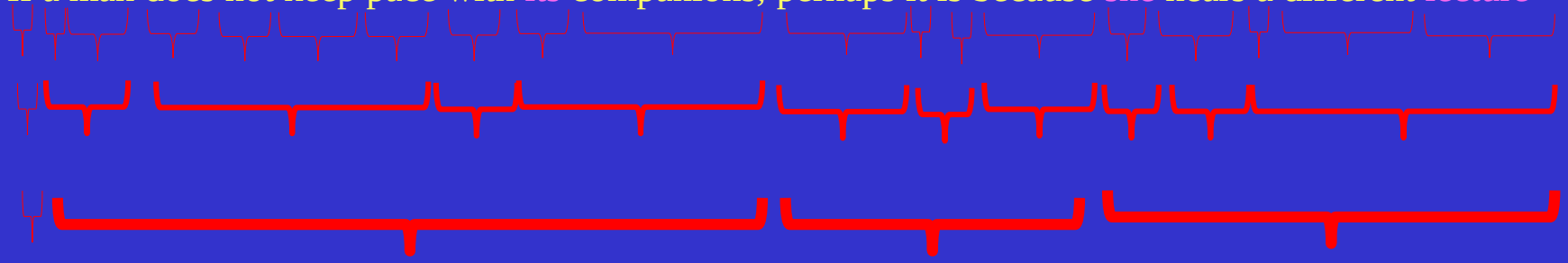
Back to the sentence

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



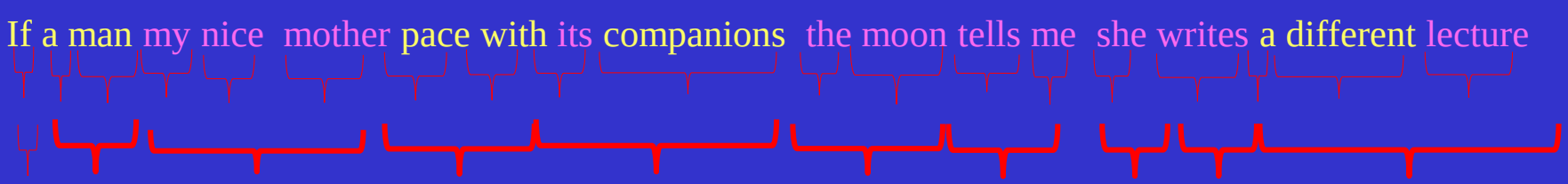
Make a couple of changes

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…



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 = amount of disorder = entropy.

2^{nd} law =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.

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

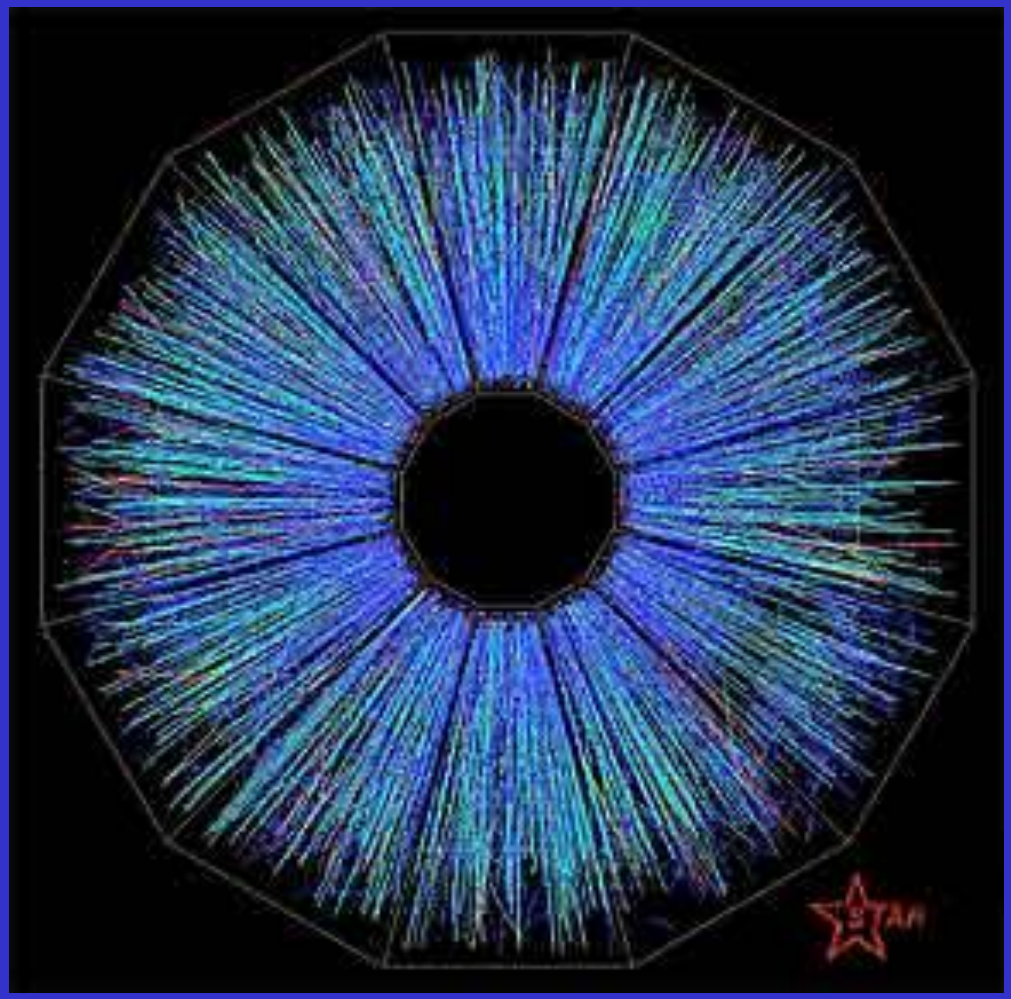
Model heavy ion collisions at RHIC or LHC (Large Hadron Collider)

→ 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.



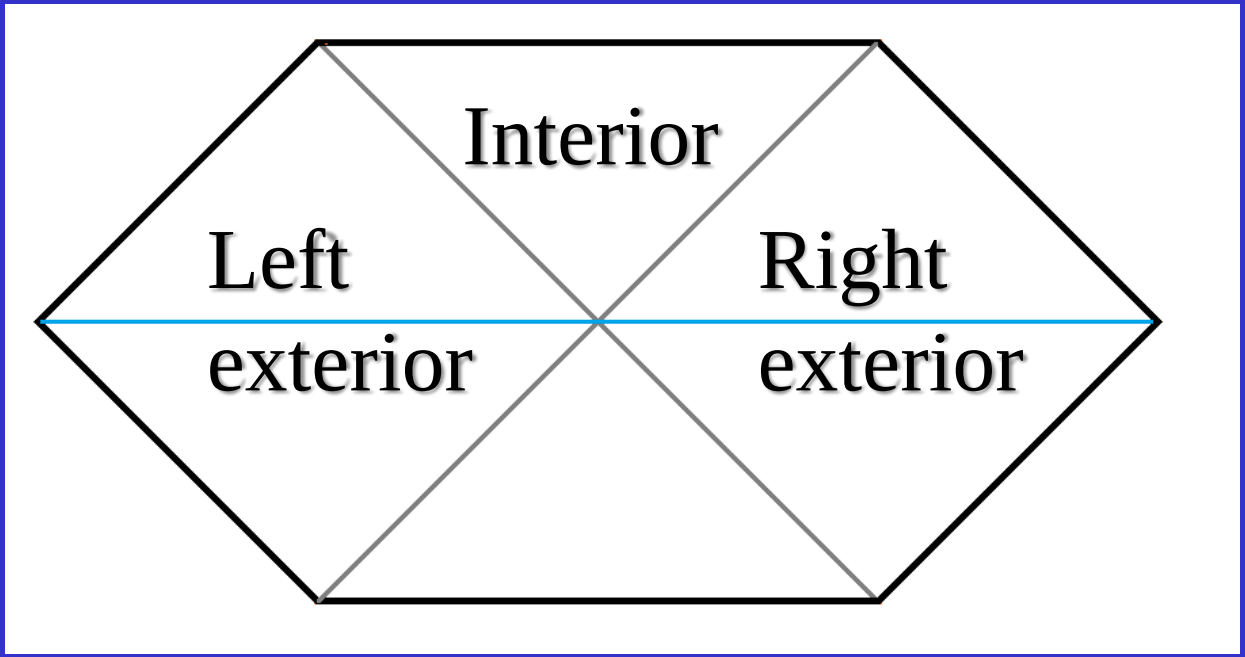
Entanglement and geometry

Entanglement and geometry

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

- We will discuss just one example.

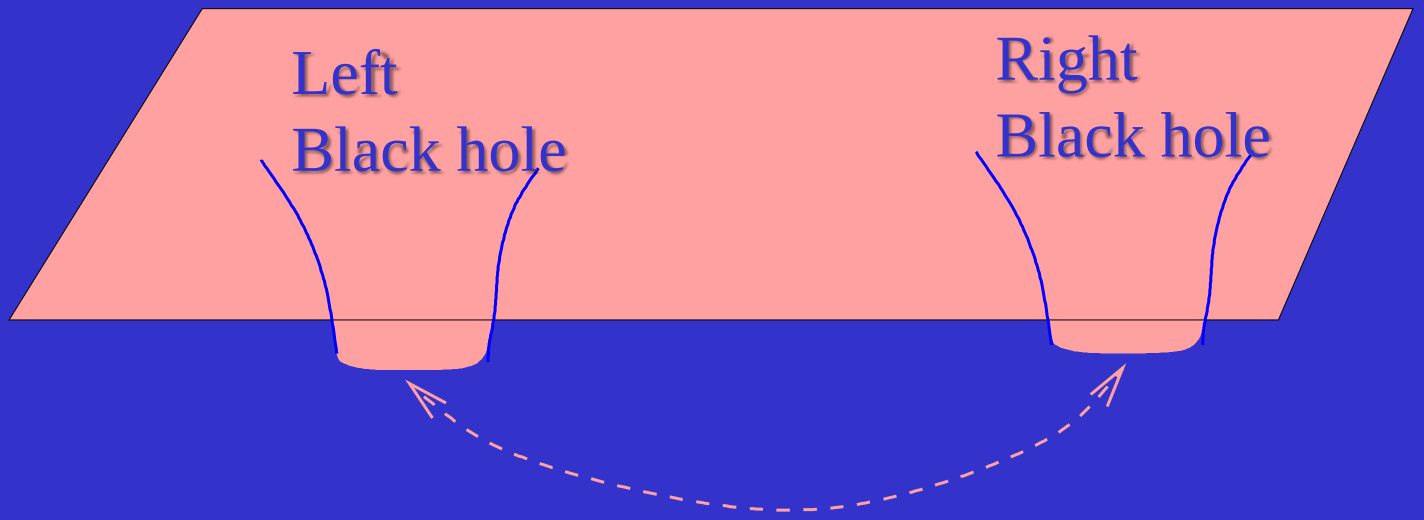
Two sided Schwarzschild solution



Eddington, Lemaitre,
Einstein, Rosen,
Finkelstein
Kruskal

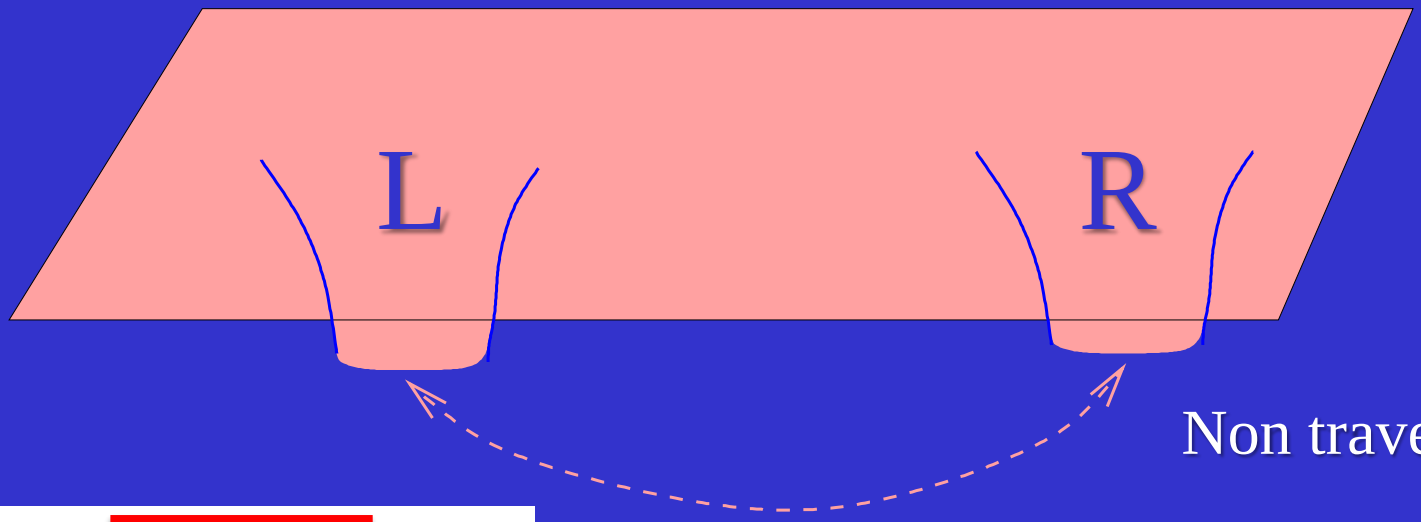
Simplest spherically symmetric solution of pure Einstein gravity (with no matter)

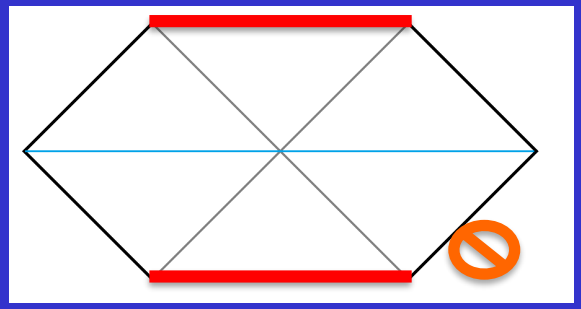
Wormhole interpretation.



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 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.

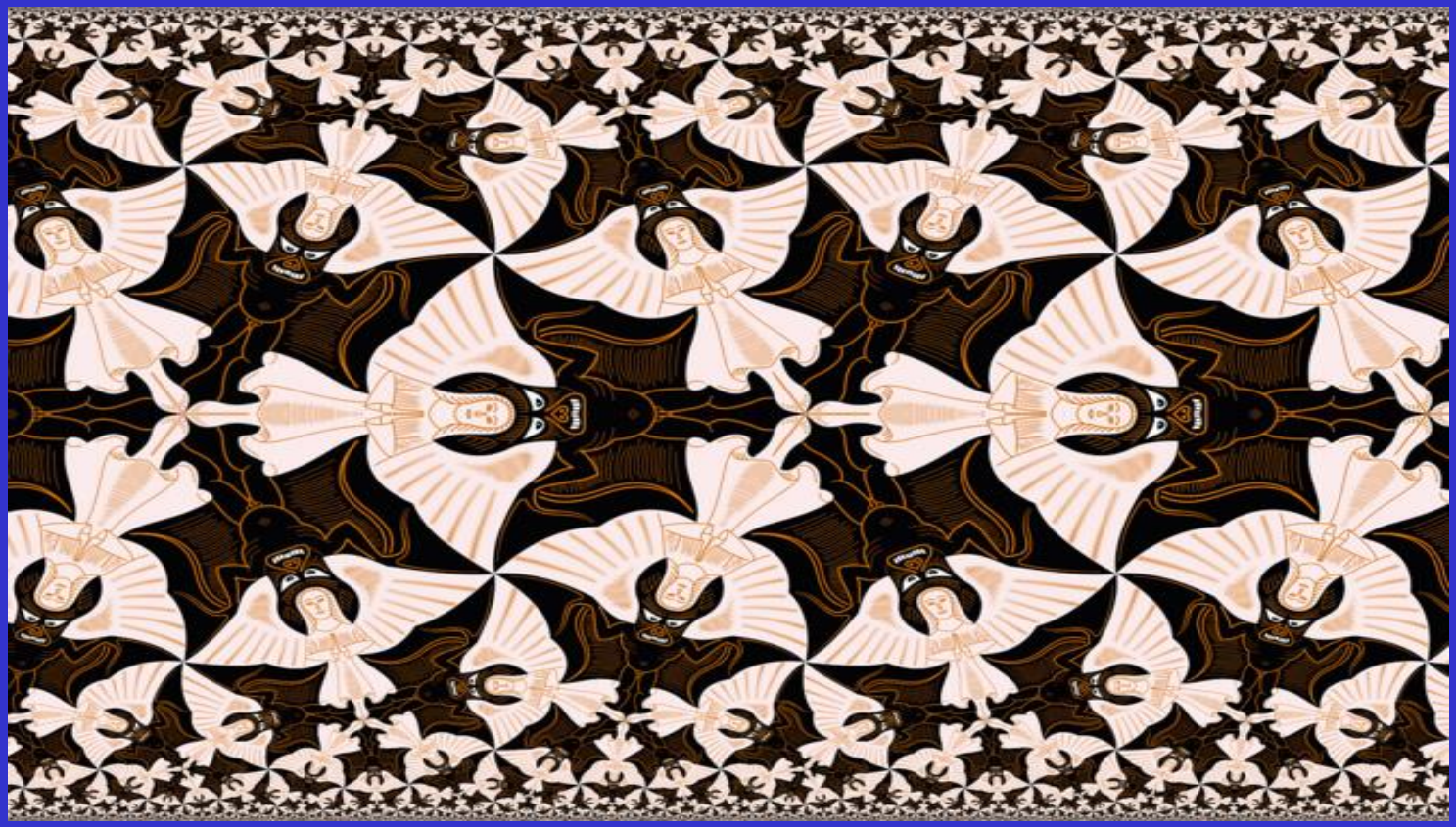
Geometric connection
from entanglement.

Israel
JM

Susskind JM

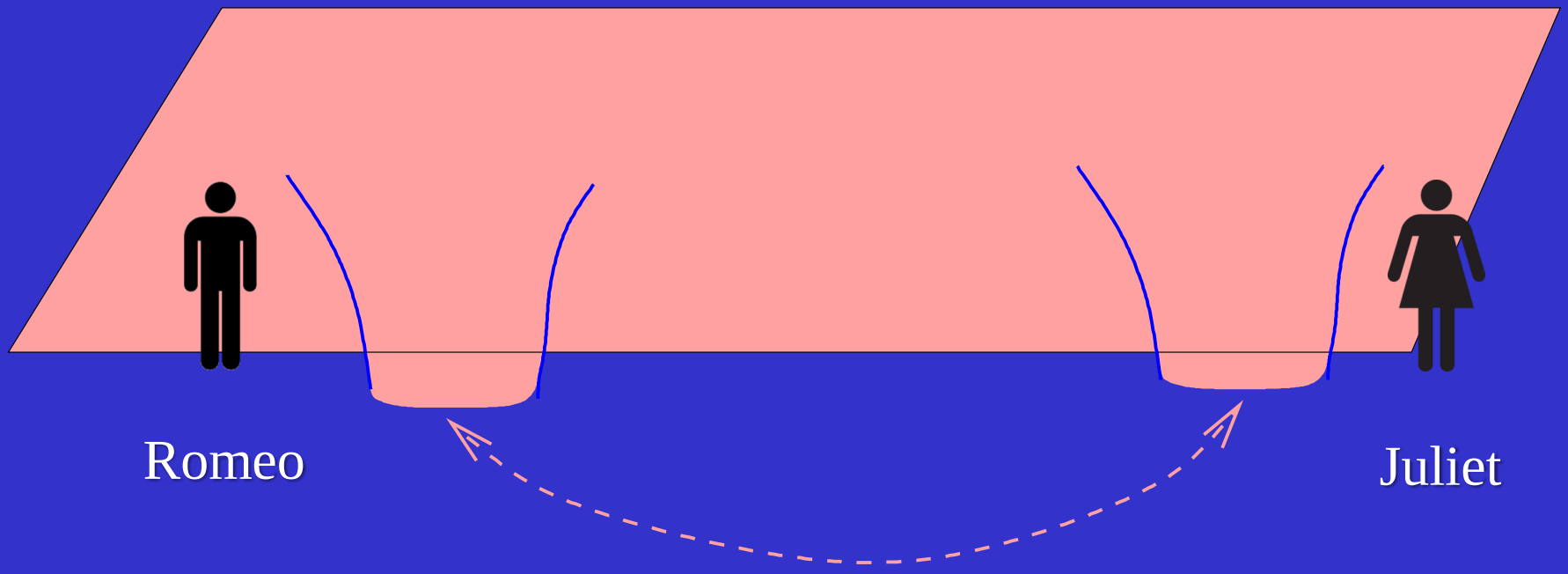
Analogy

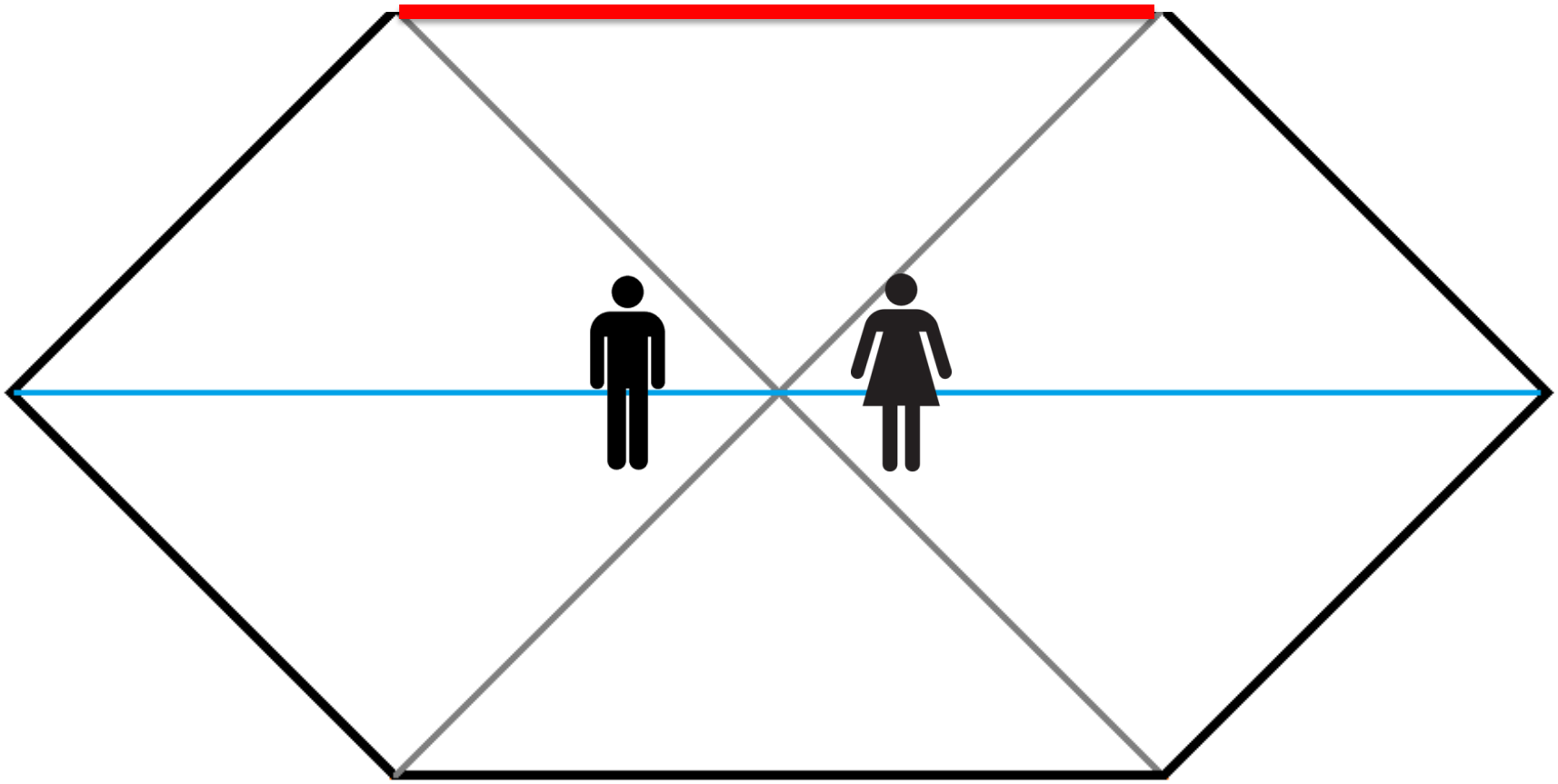
If a man does not keep pace with his companions, perhaps it is because he hears a different drummer

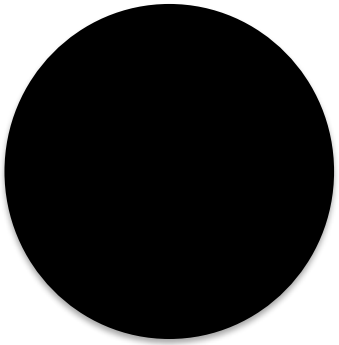


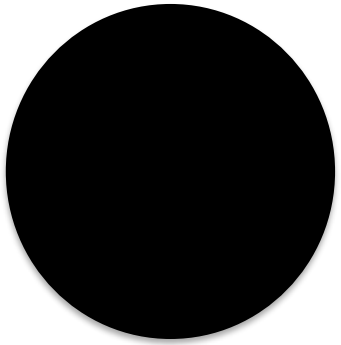
Si alguien no lleva el paso de sus compañeros, quizas es porque está escuchando a otro tamborista

A forbidden meeting









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.

✓There are many questions we do not understand → how to describe the “singularity”.

I would now like to discuss some aspects of cosmology

Two stunning predictions of General Relativity

- Black holes
- Expanding universe

"Your math is great, but your physics is dismal"

(Einstein to LeMaitre)

Both involve drastic stretching of space and/or time

Lemaitre's paper: 1st published value for the rate of expansion of the universe

UN UNIVERS HOMOGÈNE DE MASSE CONSTANTE ET DE RAYON CROISSANT, RENDANT COMPTE DE LA VITESSE RADIALE DES NÉBULEUSES EXTRA-GALACTIQUES

Note de M. l'Abbé G. LEMAÎTRE

1. GÉNÉRALITÉS.

La théorie de la relativité fait prévoir l'existence d'un univers homogène où non seulement la répartition de la matière est uniforme, mais où

Utilisant les 42 nébuleuses figurant dans les listes de Hubble et de Strömberg (1), et tenant compte de la vitesse propre du soleil (300 Km. dans la direction $\alpha = 315°$, $\delta = 62°$), on trouve une distance moyenne de 0,95 millions de parsecs et une vitesse radiale de 600 Km./sec, soit 625 Km./sec à 10^6 parsecs (2).

Nous adopterons donc

$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3{,}08 \times 10^{18} \times 3 \times 10^{10}} = 0{,}68 \times 10^{-27}\ \text{cm}^{-1} \qquad (24)$$

Cette relation nous permet de calculer R_o. Nous avons en effet par (16)

$$\frac{R'}{R} = \frac{1}{R_o\sqrt{3}}\sqrt{1 - 3y^2 + 2y^3} \qquad (25)$$

Friedman: 1924

Lemaitre: 1927

H = 625 Km/s /Mpc

Used Hubble's distance data

Hubble: 1929:

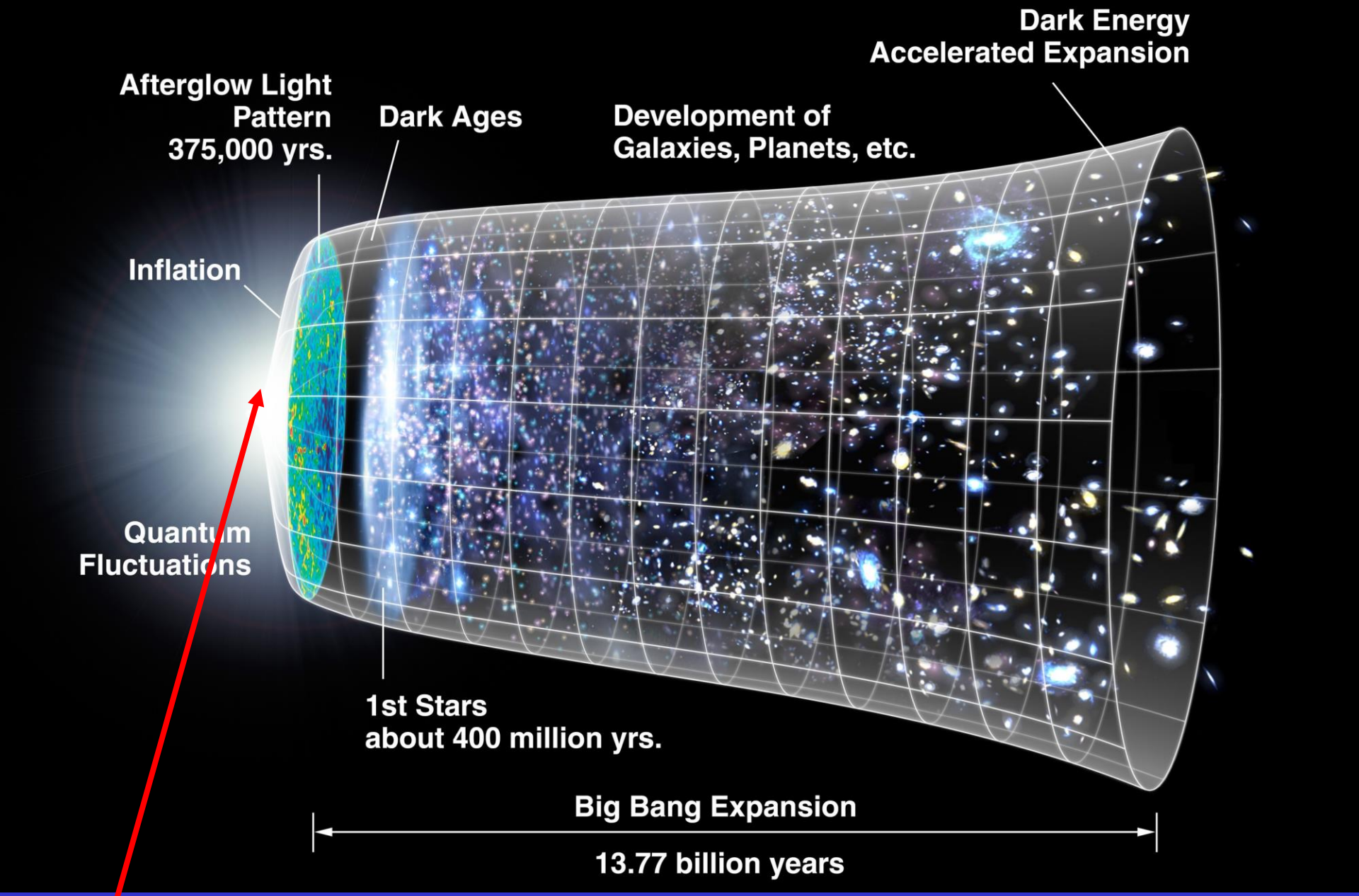
500 Km/s/Mpc

Current: 70 Km/s/Mpc

Lemaitre and pope Pius XII

- Pope Pius XII wanted to interpret initial singularity of the Big Bang as proof of the creation.
- Lemaitre convinced him not to make statements like this.
- Lemaitre said that religion is closer to psychology than to cosmology.
- Seeing God in our neighbor and not in the initial singularity.

- Today we have great evidence for the Big Bang cosmology.
- Simplicity of the initial conditions.
- The universe was almost uniform, with very small fluctuations in the density. Very simple chemical composition. + dark matter.
- Self assembling universe.
- Relatively simple laws of physics, uniformly valid across the observable universe.



We do <u>not</u> understand how to describe this.

- Why ?
- When the universe is very small, quantum gravity effects are very large.

- We are investigating aspects of quantum gravity via string theory.

- String theory is a theory under construction we do not know how to describe the initial singularity, yet...

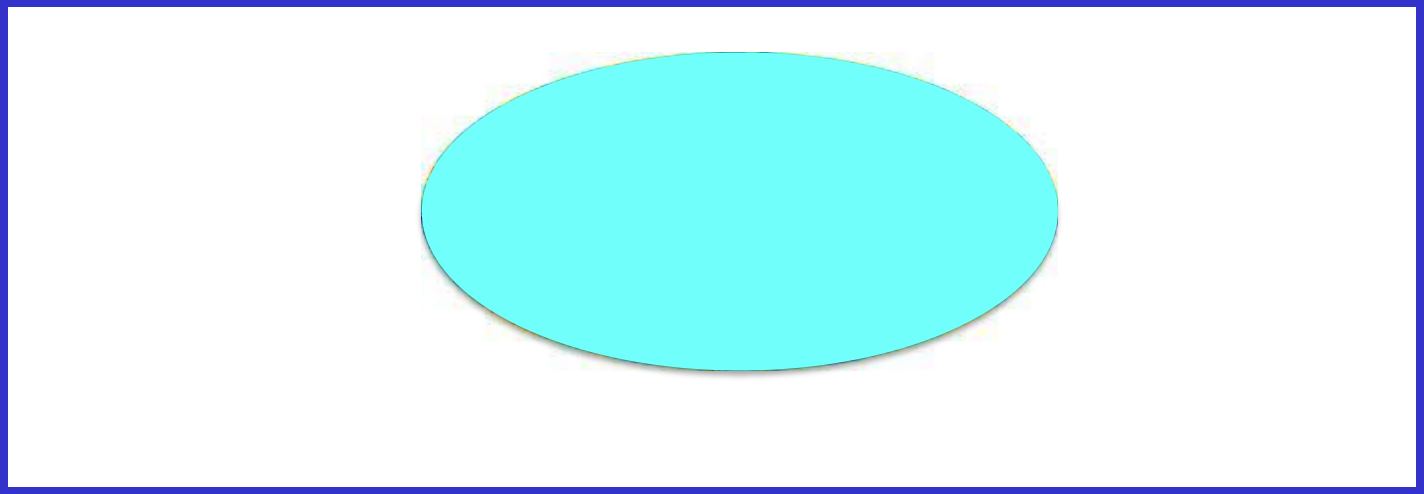
- Hope: Understanding the black hole singularity → initial singularity

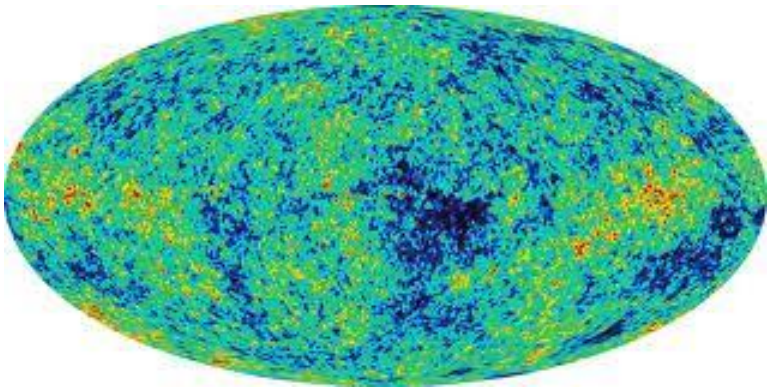
- There is one interesting piece of evidence for quantum mechanics in the early universe:

Inflation

Starobinski, Mukhanov, …
Guth, Linde,
Albrecht, Steinhardt, …

- Period of expansion with almost constant acceleration.
- Produces a large homogeneous universe





Quantum mechanics is crucial for understanding the large scale geometry of the universe.

The randomness of quantum mechanics manifest itself at a cosmic scale

- The further back we go → more random
- But larger scales.
- Largest scales → ``constants of nature''

- Maybe this explains special values of the constant of nature:

Cosmological constant = dark energy $\quad \frac{\Lambda}{l_p^4} \sim 10^{-120}$

$\frac{m_H^2}{l_p^2} \sim 10^{-34} \quad (\text{or} \quad 10^{-2})$

Higgs mass
(or scale of electroweak symmetry breaking)

Quark masses, etc.

The Multiverse = the universe at very long scales

Credit: Florida State University

- The more fundamental laws of physics could allowvarious values for the ”fundamental constants”.
- (In the same way that from the same chemical elements we can form different materials.)
- Inflation can “populate” these various possibilities.
- Multiverse = totality of the universe, including regions outside our observable universe.
- In regions where the constant are different life is not possible. An observer can only observe values which are consistent with life.
- → Anthropic explanation of the “fine tuning”.

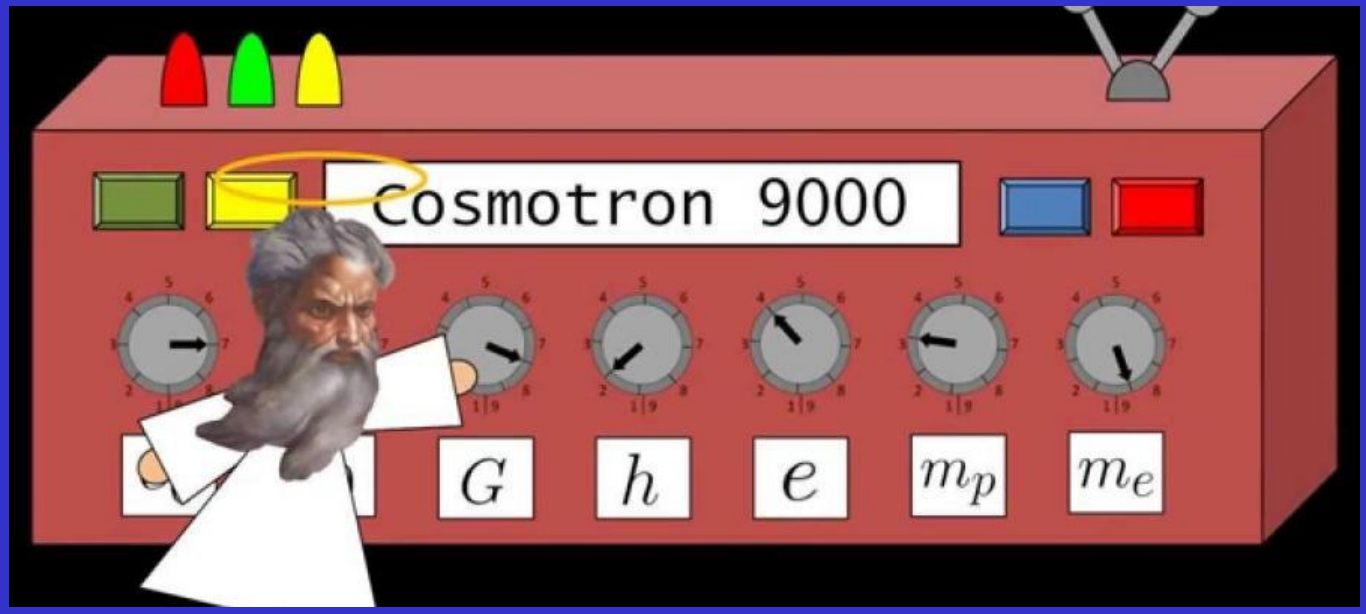
This reasoning had a major success:
it predicted a non-zero value for the cosmological constant

Weinberg 1987

Observed: 1998 Riess et al. ; Perlmutter et al.

Unfortunately, the fundamental theory is not understood well enough to make any other prediction.
(some have been made, but I consider them based on very weak theoretical grounds).

- Some have claimed that the fine tuning is evidence of God, or intelligent design.



They are making the same error as Pius XII


GOD
OR
MULTIVERSE
WHICH PROVIDES A BETTER EXPLANATION
FOR FINE TUNING

- This is a wrong dichotomy.
- Saying that God did it that way is not a scientific explanation. The multiverse is a plausible (though uncertain) one.
- If God can create a universe, why cannot God create a multiverse ?
- In any case, the “creation” has to be done outside of time, since time is part of spacetime and the fabric of the universe itself.

  St. Agustine ~ 400
- Certainly we have a multitude of “worlds” already, not a single “world”. I am referring to exoplanets.

Conclusions

- Understanding the quantum mechanics of spacetime should lead us to describe the beginning of the universe in terms of well defined physical laws.

- We are not there, yet…

- Even the simpler problem of the black hole interior has not been solved, yet...

The end

Thank you !