

Title: Juan Maldacena - Black Holes and the Structure of Space Time

Date: Oct 02, 2004 11:00 AM

URL: <http://pirsa.org/04100001>

Abstract: Black Holes and the Structure of Space Time <kw> Juan Maldacena, blackholes, space-time, gravitation, gravity, special relativity, quantum mechanics, Einstein, equivalence principle, redshift factor, universality, white black holes, quantum gravity, string theory, general relativity, Penrose, Hawking, thermodynamics, entropy </kw>

Newton's Gravity

“Everything that goes up comes down again”

Only if it goes slower than $v_e = 11\text{Km/s}$!

Why?

Gravitational force decreases with distance. If the velocity is large enough \rightarrow we can escape, e.g. spacecrafts sent to other planets, etc.



v less than v_e



v greater than v_e

Black Holes in Newton's Gravity

What if the escape velocity were the velocity of light?

$$v_e^2 = \frac{2 GM}{R}$$

Laplace ~ 1800

If v_e greater than c the object would look black, no light could come out of it. This happens if there is a lot of mass in a small region.

It is convenient to define the “black hole radius” of an object as

$$R_h = \frac{2 GM}{c^2}$$

This is the size it would need to be in order to be a black hole:

$$R_{h, \text{sun}} = 3 \text{ Km}$$

$$R_{h, \text{earth}} = 1 \text{ cm}$$

$R_{h, \text{us}}$ = smaller than any distance we can experimentally measure today.

Special Relativity

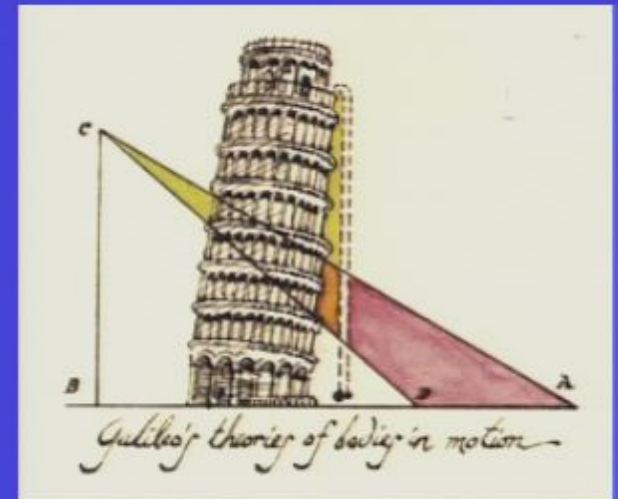
Einstein 1905

- ✓ The speed of light is the maximum speed at which information travels.
- ✓ Physics is the same no matter how fast an observer is moving. In particular, all observers measure the same speed of light.
- ✓ Time flows differently for observers that are moving relative to each other.
- ✓ Space and time are related. How we perceive time depends on how fast we move.

Equivalence Principle

Aristotle: Heavy objects fall faster.

Galileo: All objects fall in the same way once we remove the effects of the air resistance.

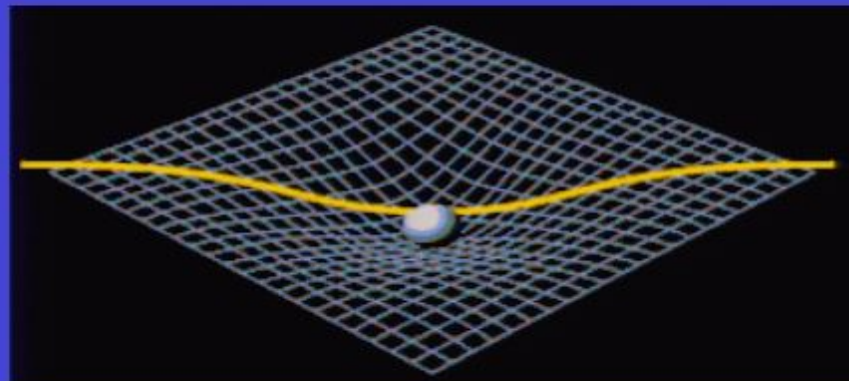


✓ The motion of a particle in a gravitational field is independent of the mass of the particle.

General Relativity

Einstein 1915

- ✓ Newton's theory does not obey special relativity.
- ✓ Einstein: space-time is curved.
- ✓ A heavy mass curves space-time and the motion of a light particle just follows the “shortest” line along that space-time.
- ✓ Gravity is due to space-time curvature.



Gravity changes the flow of time

If we have two observers in a curved space-time, time can flow differently for each of those observers.

Top floor



First floor



Redshift Factor

An observer far from a heavy mass sees time going faster than an observer close to it.

$$\text{Redshift factor} = \frac{(\text{flow of time at some position})}{(\text{flow of time far away})}$$

Examples: Redshift factor at:

Surface of the sun: $1 - 2 \cdot 10^{-6}$

Surface of the earth: $1 - 8 \cdot 10^{-10}$

Surface of a neutron star: 0.7

We can find the space-time outside a massive object.

One finds precisely how time slows down:

$$\text{Redshift} = \sqrt{1 - \frac{r_h}{r}}$$

$$r_h = 2G \frac{M}{c^2}$$



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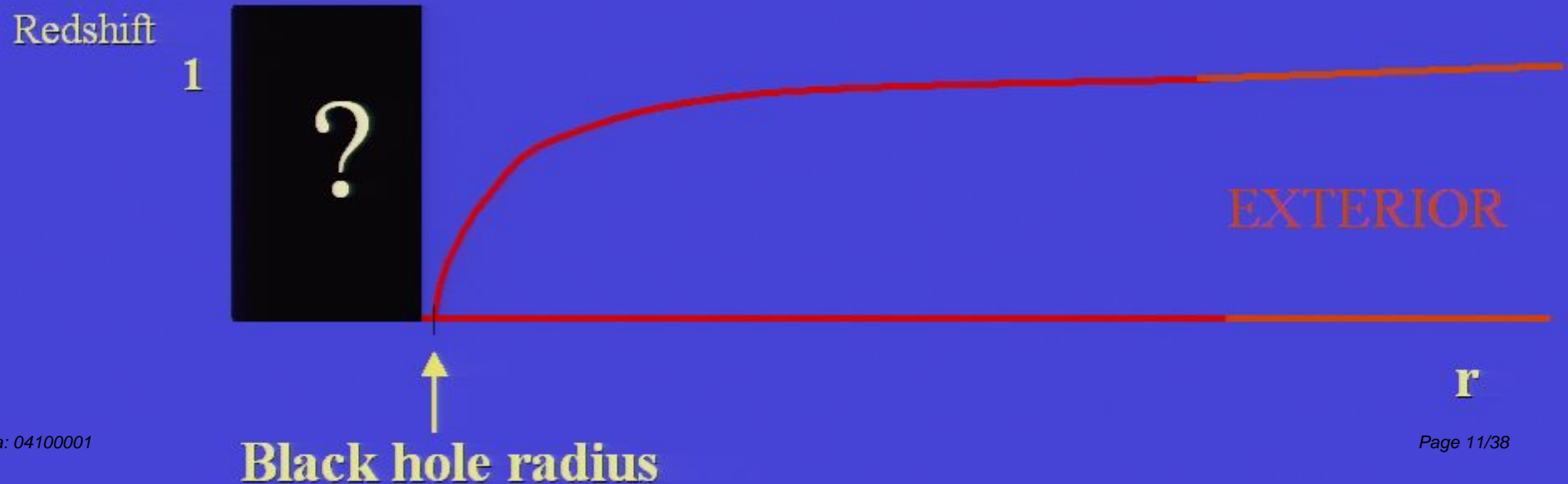


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Black Holes

Can an object have a size smaller than the black hole radius?

When this was first discovered it was thought that it was something unphysical, that maybe objects could never become that small.

Later it was understood that:

- 1) Some stars can collapse into a black hole.
- 2) An observer who is falling into the black does not feel anything special as he crosses the horizon
- 3) There are some objects in the sky that are probably black holes

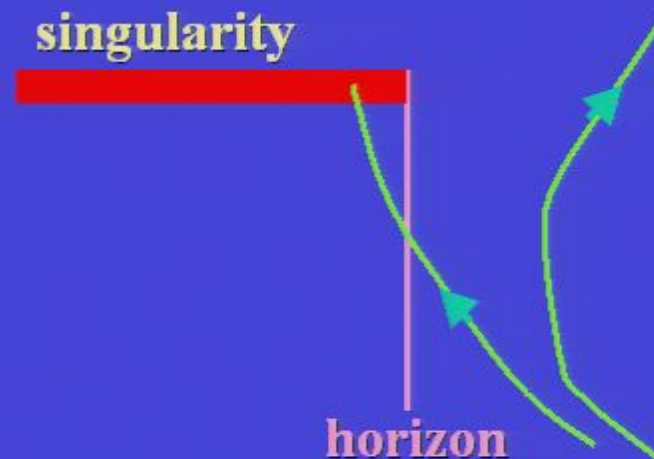
The Horizon and Beyond

The surface where time slows to a halt is called a horizon.

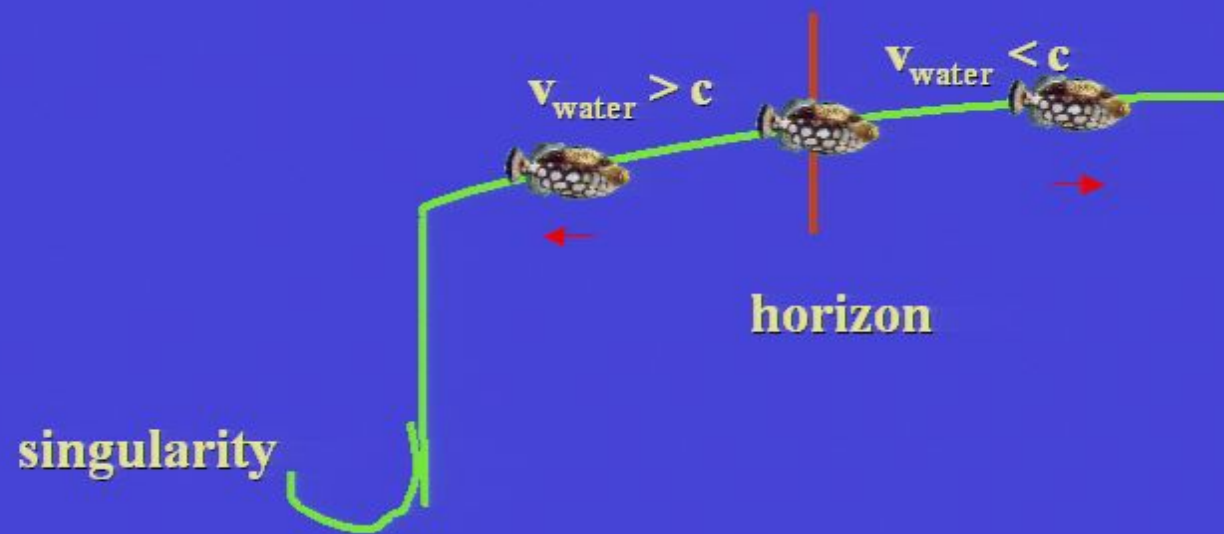
If you cross it you do not feel anything special, but you cannot come back out again.

Once you cross the horizon, you continue to fall in and you are crushed into a “singularity.” This is a region of very high space-time curvature that rips you apart.

Penrose



Spacetime as a river



The fish swim with maximum velocity $= c$. If the fish cross the region where the river velocity becomes greater than c , then they will end up in the waterfall.

These fish do not see anything special when they cross the region where the velocity of the water is c .

Real Black Holes

Black holes can form in astrophysical processes. Some stars are so massive that collapse into black holes.

Black holes produced through these processes are of the following types:

1) Black holes that collapse from stars with masses of the order of a few times the mass of the sun

$$(r_h \sim 10 \text{ km})$$

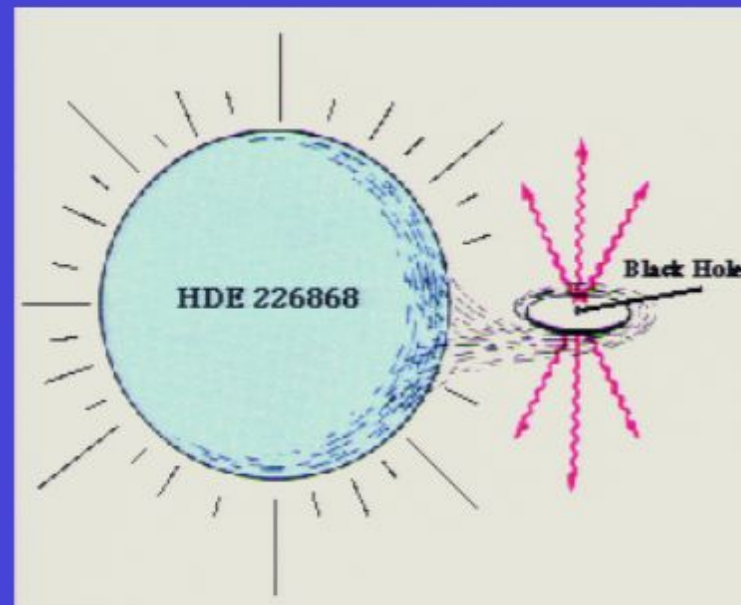
2) Black holes in the center of galaxies with masses of the order of a billion times the mass of the sun.

$$(r_h \sim 3 \cdot 10^9 \text{ km} \sim \text{size of the solar system})$$

How Do We See Them?

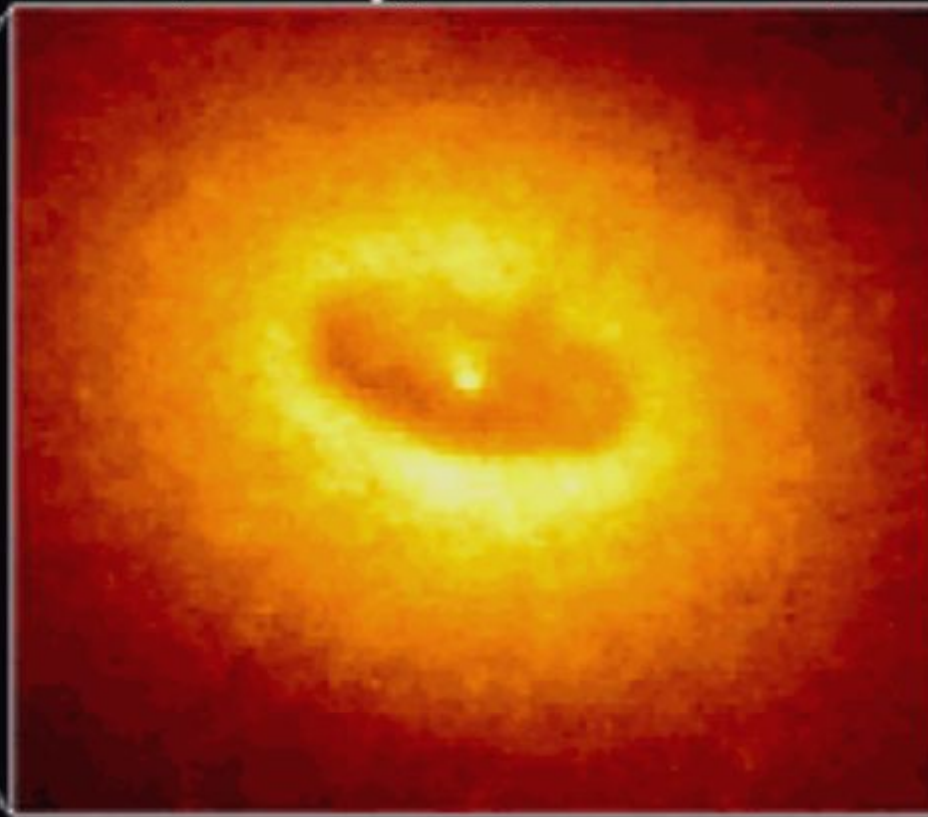
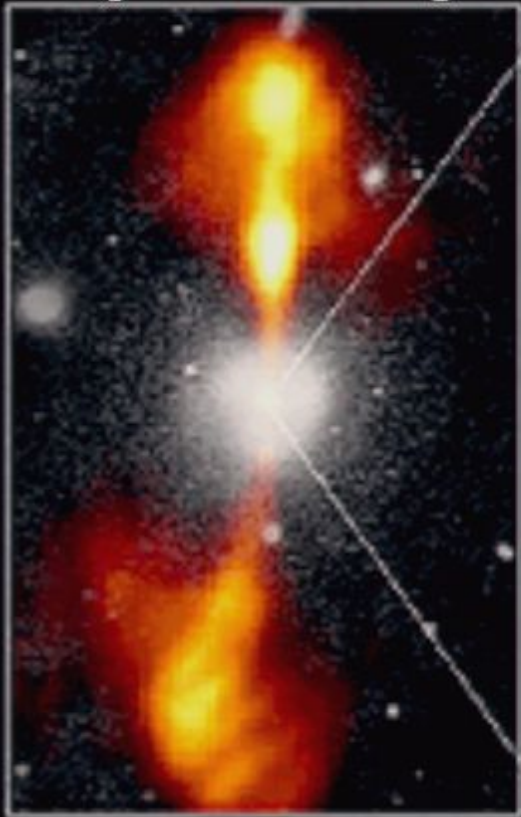
In principle we could see them by seeing how they deflect light, etc.

In practice these black holes are surrounded by some gas and this gas heats up in a characteristic way as it falls in and astronomers see the radiation coming from this hot gas.

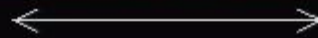


Optical/radio image

Hubble Space Telescope image of a dust and gas disk



380 arcseconds
88.000 light years



1,7 arcseconds
400 light years



Universality

The final shape of a black hole as seen from the outside is independent of how we make it (up to the total mass, charge and angular momentum).

Area law:

Hawking

Total area of the horizon always increases. Total mass of black holes does not necessarily increase.

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White Black Holes!

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

Smaller black holes have a higher temperature.

$$k T = \frac{\hbar}{r_h}$$



What is this temperature for black holes of different masses?

$$T_{\text{sun}} = 3.6 \cdot 10^{-7} \text{ K}$$

$$T_{\text{earth}} = 0.1 \text{ K}$$

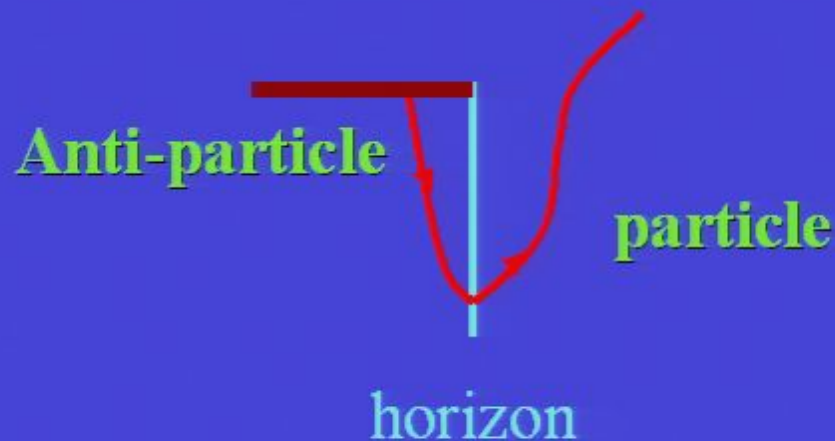
$$T_{M=10^{18} \text{ Kg}} = 7000 \text{ K (would look white)}$$

Why? \rightarrow Pair creation

In flat space



In the presence of a horizon



The Life and Death of a Black Hole

- ✓ Black hole emits radiation → loses energy → has a finite lifetime (if no additional matter is falling in)

Lifetime for various black holes:

- ✓ Mass of the sun → much longer than the age of the universe
- ✓ Our mass (100 Kg) → a millisecond.
- ✓ Mass of 10^{12} Kg (mass of a mountain) → age of the universe.
Could be observed if it was formed at the big bang.

Theoretical Puzzles with Black Holes

Thermal properties of black holes mix quantum mechanics and gravity. It is hard to mix these two theories.

Puzzles:

- ✓ Entropy of the black holes.
- ✓ Information loss.

Heat and Entropy

Heat \rightarrow motion of the microscopic components of the system.

We can measure the number of microscopic degrees of freedom by the “entropy” of the system

First law of thermodynamics \rightarrow relates entropy and the specific heat.
the more energy needed to raise the temperature \rightarrow the more entropy

How does the heat of the black hole arise? What is “moving” on a black hole? **Compute entropy from the first law:**

Bekenstein, Hawking

$$S = \frac{\text{Area of the horizon}}{4G_N \hbar}$$

$$S = \frac{\text{Area of the horizon}}{(10^{-33} \text{ cm})^2}$$

Black holes and the Structure of Space-time

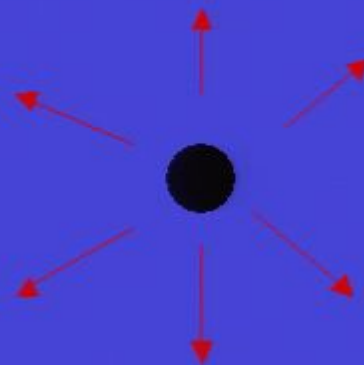
Black holes are independent of what forms them. Their thermal properties only depend on gravity and quantum mechanics. This should be explained by a theory of quantum gravity.

Roughly speaking, the black hole entropy should come from the motion of the “space-time quanta,” from the elementary quanta (or atoms...) that make space and time.

Understanding precisely these thermal aspects of black holes, we learn something about the quantum structure of space-time.

Information Loss

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



The principles of quantum mechanics imply that there should be a precise description of black holes.

There should be subtle differences in what comes out of a black hole, depending on how we made it.

String theory

- Theory of quantum gravity
- Gravitons = quanta of spacetime geometry → tiny loops of string
- Other objects → D-branes
- Precise mathematical rules governing their behavior



Black holes in string theory

- We understand some simple black holes

Strominger, Vafa



$g \rightarrow 0$



Collection of D-branes
And strings.

Entropy: Number of ways to arrange the strings and D-branes.

Holography and Black Holes

Entropy = Area \neq volume

Usual optical hologram: 2d surface encodes the information about the three dimensional shape of an object

Holography in quantum gravity:

't Hooft, Susskind

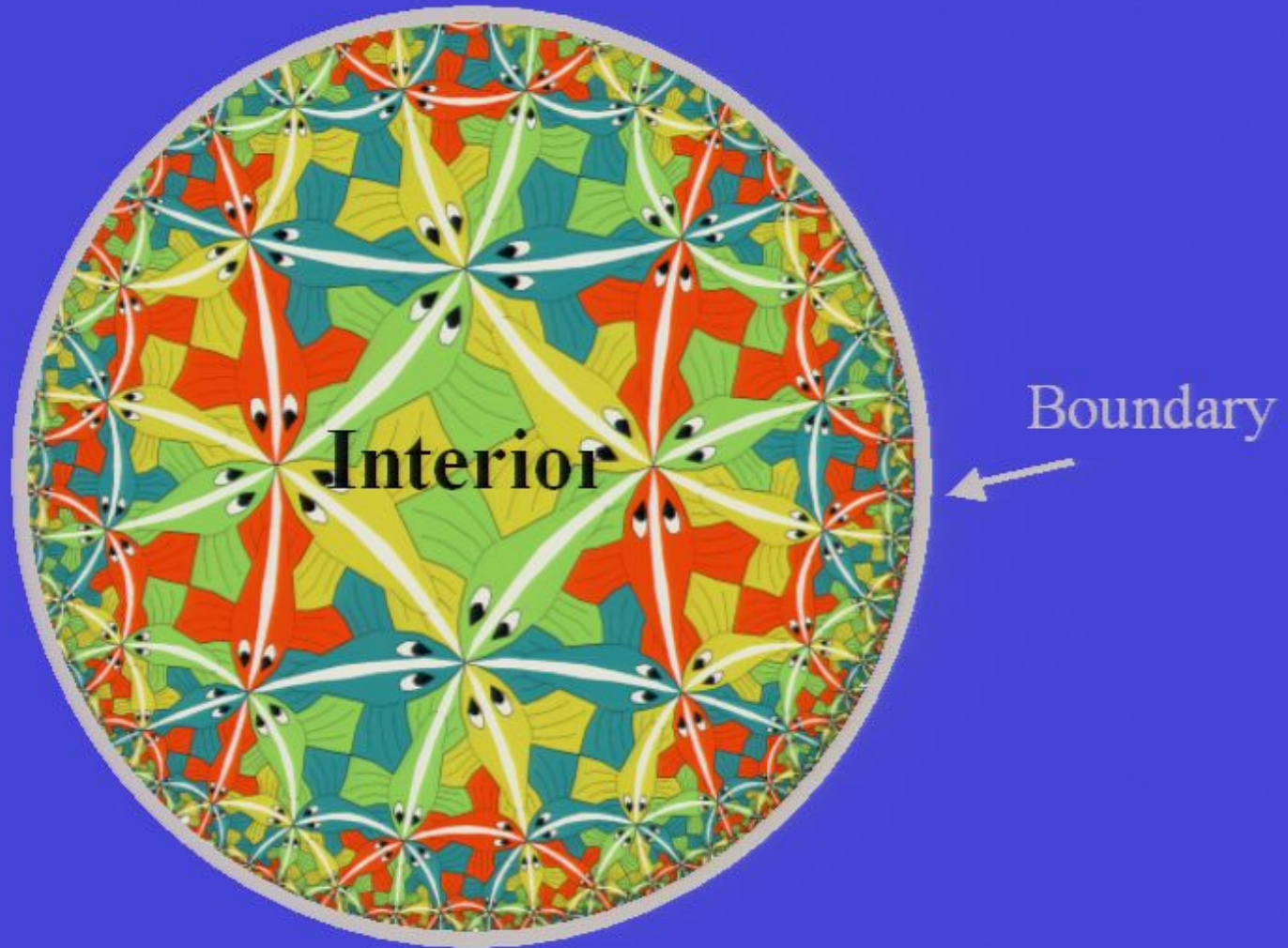
Number of degrees of freedom to describe a region grows like the area of the region

Holography in String Theory

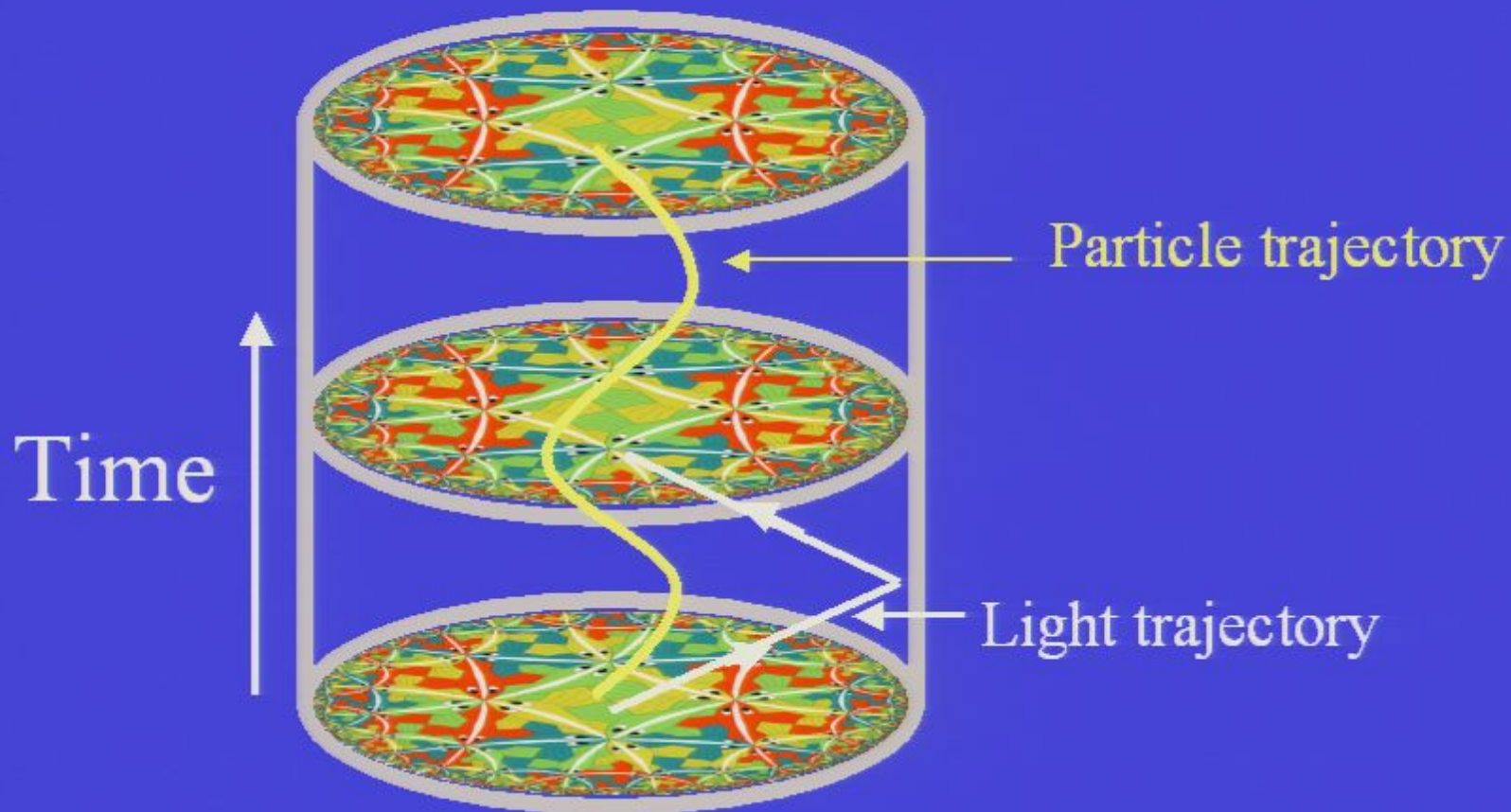
We can describe the interior of some space-times in terms of a theory at the boundary.

Theory at the boundary is a relatively simple theory of particles

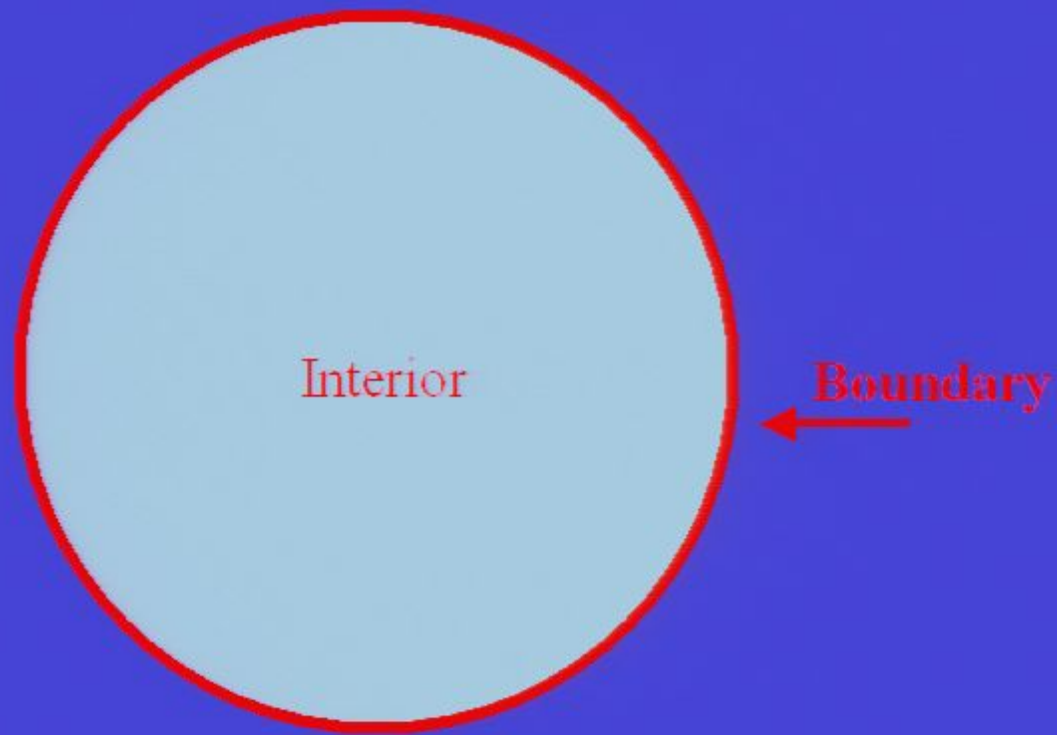
Negatively curved space



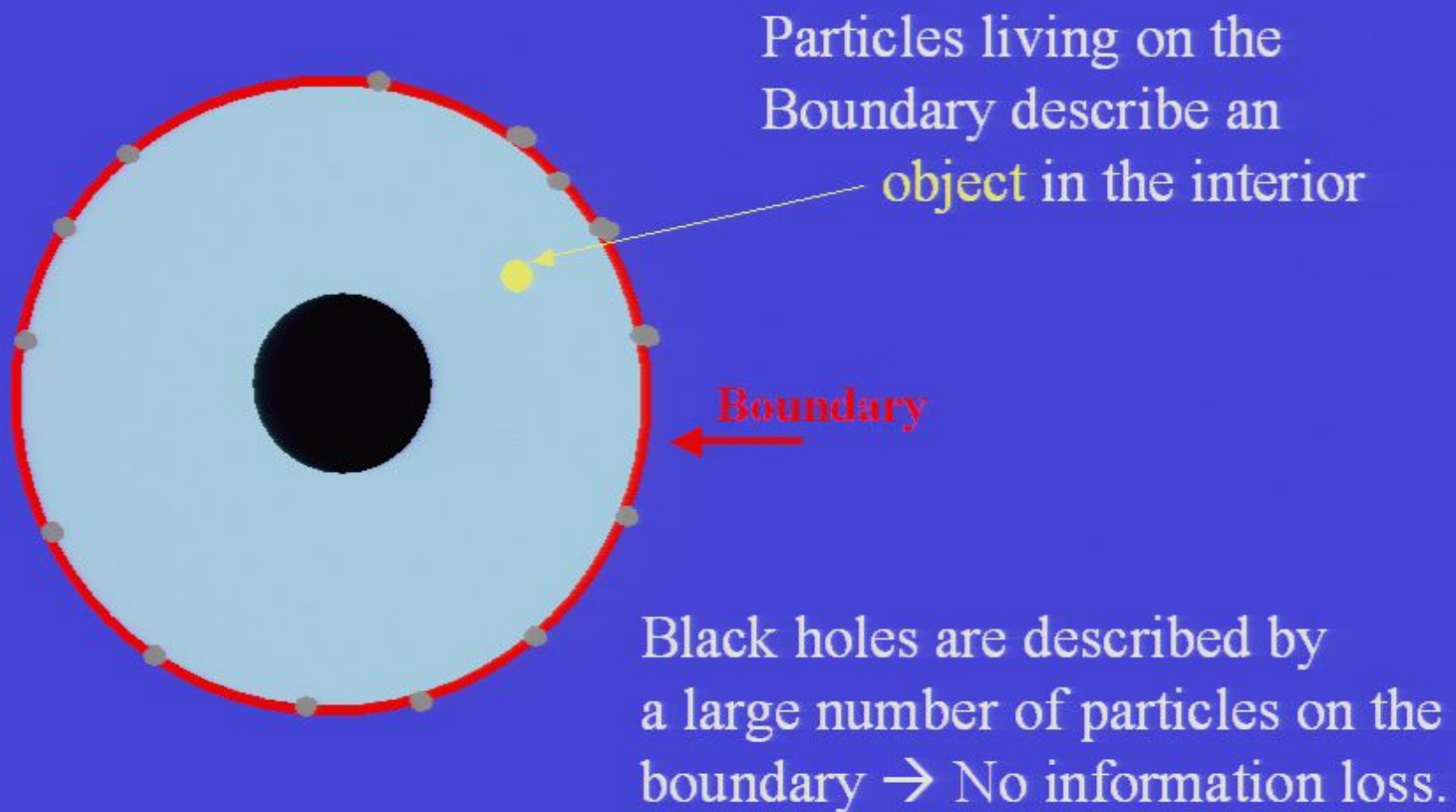
Negatively curved space-time



Pirsa: 04100001 Particles living in the interior → attracted to the center Page 32/38



Gravitational physics in the interior → Described in an alternative way by interacting particles living on the boundary.



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Particles on the boundary could describe very complex objects



Space-time and everything in it emerges dynamically out of the interaction of the particles living on the boundary.

Conclusions

- ✓ Black holes are fascinating objects where the effects of space-time curvature are dramatic.
- ✓ Black holes combined with quantum mechanics provide very interesting challenges to our understanding of space-time.
- ✓ String theory is capable of putting together the classical and quantum aspects of black holes. There is no information loss.

We are getting very novel and interesting ways of describing space time.

