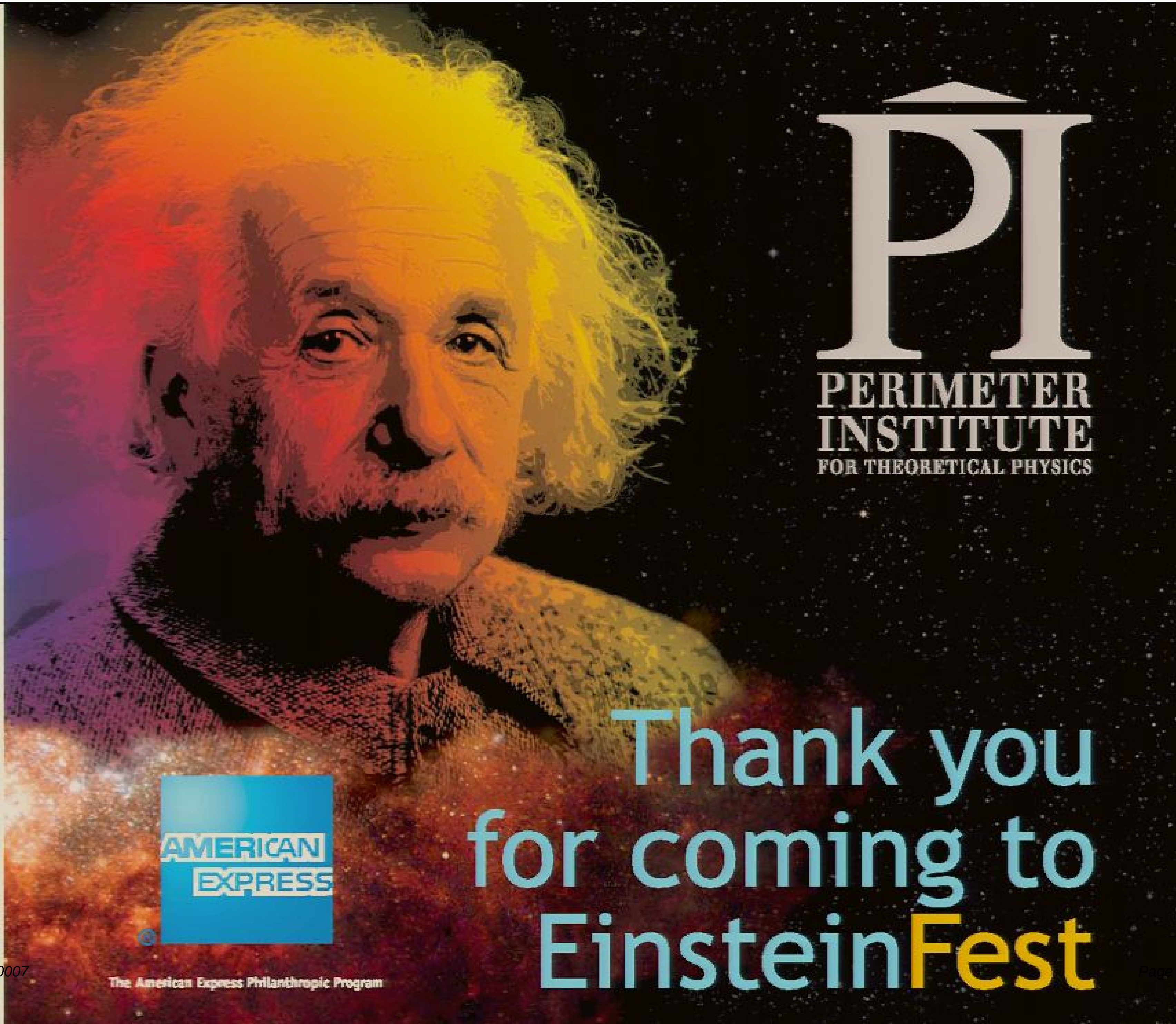
Title: Strange Views of Space and Time: From Einstein to String Theory

Date: Nov 15, 2005 03:00 PM

URL: http://pirsa.org/05110007

Abstract: In honour of the hundredth anniversary of Einstein\'s \'miraculous year\', I will describe the modern view of space and time. I will start with special relativity, then describe how space and time are modified in Einstein\'s general theory of relativity, and end with recent ideas coming out of string theory. In all cases, the view of space and time arising from modern physics is radically different from our everyday experience, yet many of their strange properties have already been confirmed by experiment. <kw> Einstein, space, time, general relativity, special relativity, string theory, dimension, simultaneity, gravity, black hole, singularity, big bang, space-time</kw>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Strange Views of Space and Time :

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Mysteries of Time

1) Does time have a beginning?

2) Can it end?

3) Can you make time go faster or slower?

4) Is time travel possible?

Dimension:

How many numbers do you need to specify a location?

- The equator is one-dimensional (longitude)
- The surface of the earth is two-dimensional (latitude, longitude)

- The space above the earth is three-dimensional (latitude, longitude, altitude)

An event is an occurrence that happens in a small region of space at a definite time.

The collection of all events is *four-dimensional* (time, latitude, longitude, altitude).

Einstein's special theory of relativity

1) Nothing can travel faster than light

Maximum
Speed

300,000
km/sec

Fermilab National Accelerator

Protons are pushed to .999999 the speed of light

2) If two events occur at the same time for one person, they will occur at different times for another person in motion relative to the first.

The notion of simultaneity is relative.

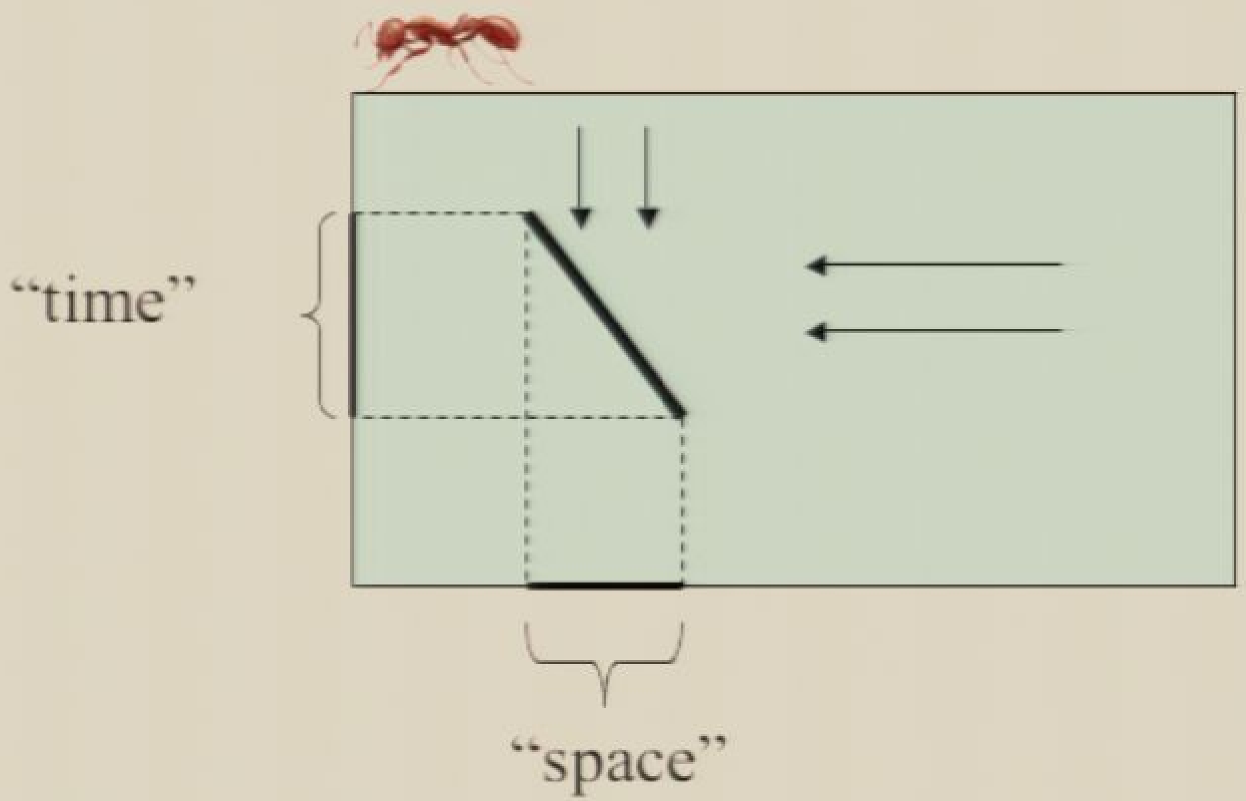
More generally, the elapsed time between two events depends on who is measuring it.

3) The spatial distance between two events also depends on which person is measuring it. The length of an object is observer-dependent.

Everyone agrees on a certain combination of spatial distance and elapsed time. There is only one well-defined “distance” between events.

Space and time are truly unified into a single entity called space-time.

Analogy



A remarkable consequence of the unification of space and time: the time you experience depends on your state of motion!

Your watch runs slower and you age less when you are in motion.

(Unfortunately this effect is tiny unless you are moving close to the speed of light.)

This has been tested in many experiments:

- Take two synchronized atomic clocks. Put one in an airplane and fly it around the earth. When it returns, it will no longer agree with the other clock.
- The kaon, an unstable particle, only lives for a short time. When it is created in a particle accelerator, its lifetime is longer when it travels close to the speed of light.

A way to travel into the future:

Board a spaceship and travel close to the speed of light for one year. When you return, it will be ten years later on earth!

But this is a one-way trip.

Einstein's General Theory of Relativity

This is a theory of gravity.

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Answer: Newton's theory was incompatible with special relativity.

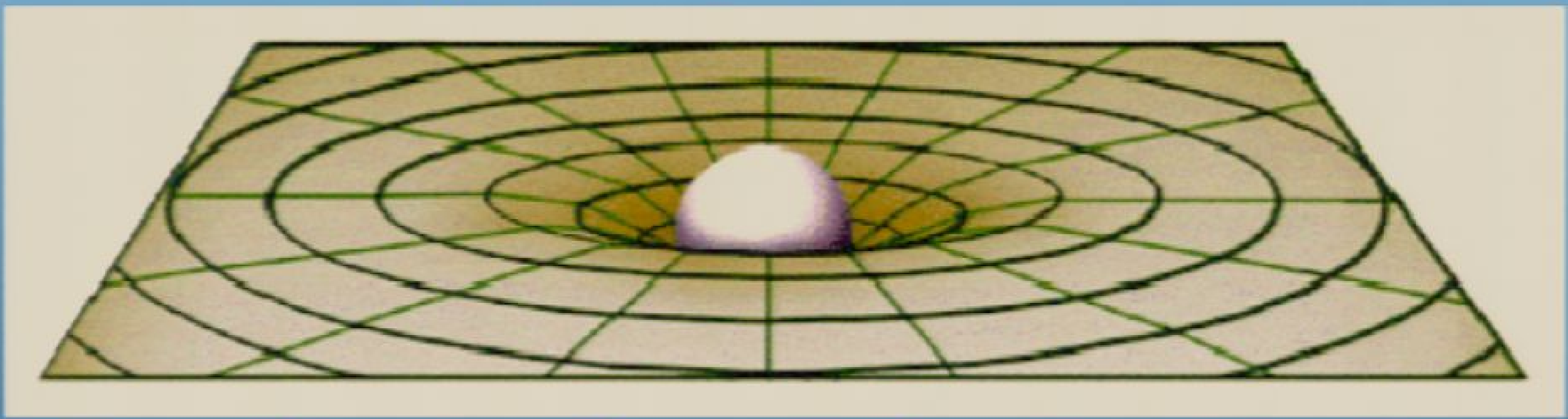
Key idea of general relativity:

Matter causes space-time to stretch or warp.

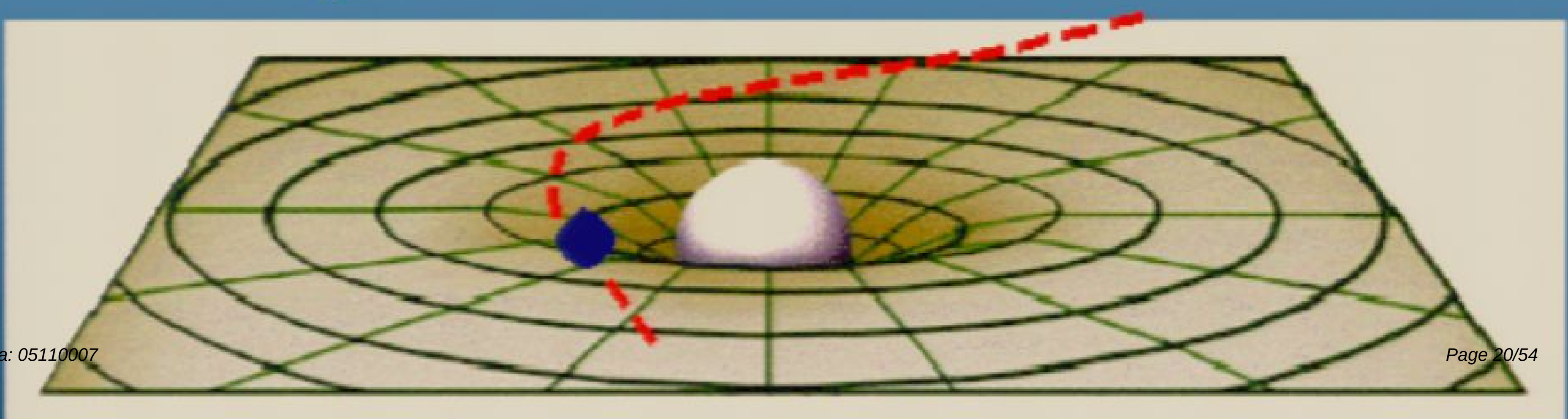
Gravity is nothing but objects responding to the curved space-time.

Gravity: Space as a Rubber Sheet

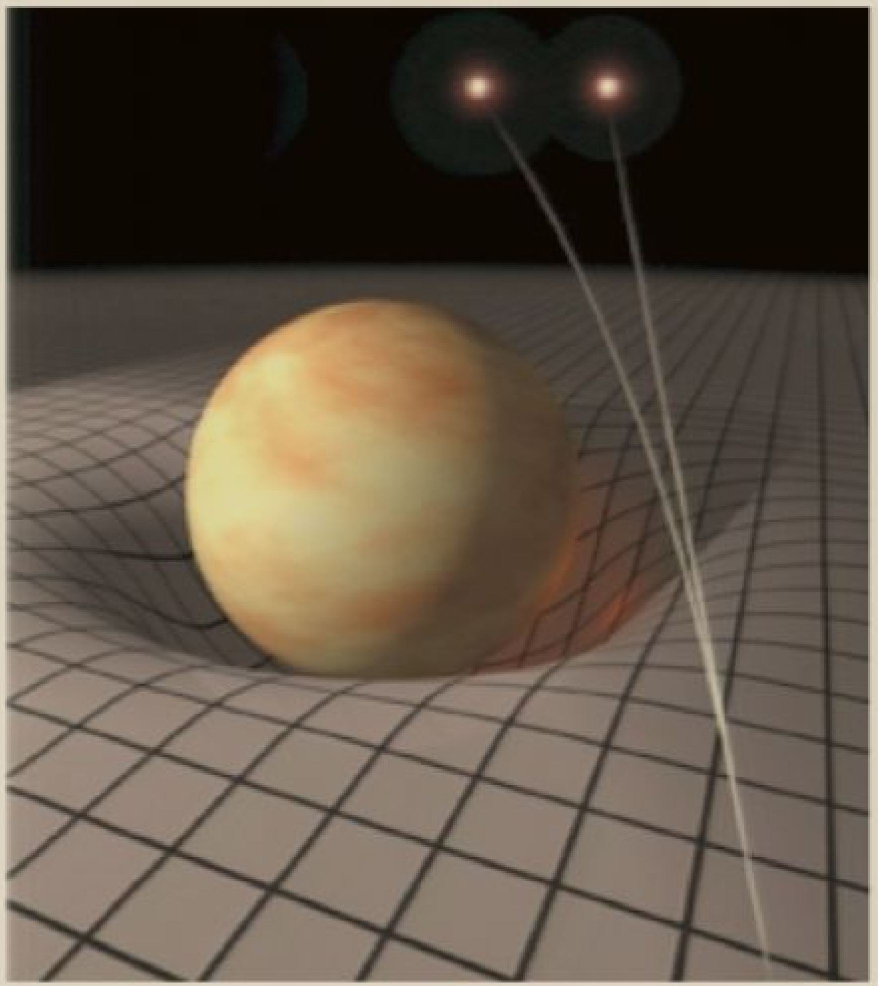
- Matter tells space how to curve



- Curved space tells matter how to move



Light is bent by gravity

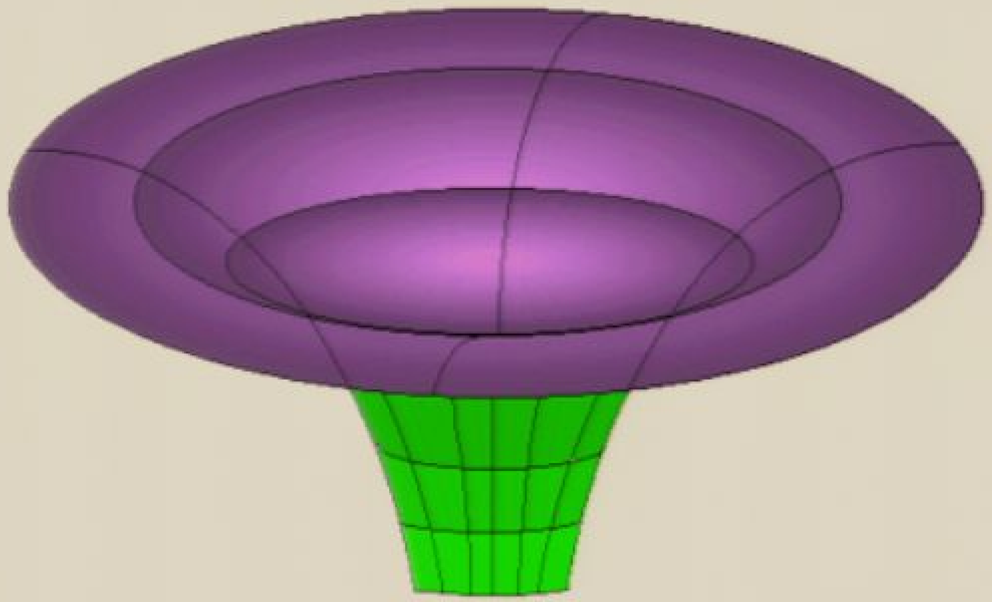


Black holes:

After billions of years, stars use up their nuclear fuel and start to collapse.

For massive stars, nothing can stop this collapse. They shrink until gravity becomes so strong that nothing can escape, forming a black hole.

Space near a black hole:



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- In the center of our Milky Way galaxy, there is a huge black hole with a mass a million times larger than the sun.
- Inside the black hole, the matter continues to collapse to essentially zero size, forming a singularity.

Other effects of curved space-time

1) Time slows down near massive objects.

You age more slowly here on earth than you would out in space. Near a black hole, time almost stands still.

Global Positioning System (GPS)

This would not work if relativity was not taken into account.

2) Matter in motion produces ripples in space-time called gravitational waves

LIGO: An experiment to detect these gravitational waves

3) Time machines are not obviously impossible

There are space-times in general relativity which describe time travel. But these time machines have always existed. It is very difficult to build a time machine.

Cosmology

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The universe is expanding.

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In the past they must have been closer together. General relativity tells us that about 13 billion years ago, all the matter in the universe was squeezed to essentially infinite density. This is called the Big Bang.

What happened before the Big Bang?

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According to general relativity, this question is meaningless.

Time, itself, begins at the Big Bang. If there is no time, nothing can happen.

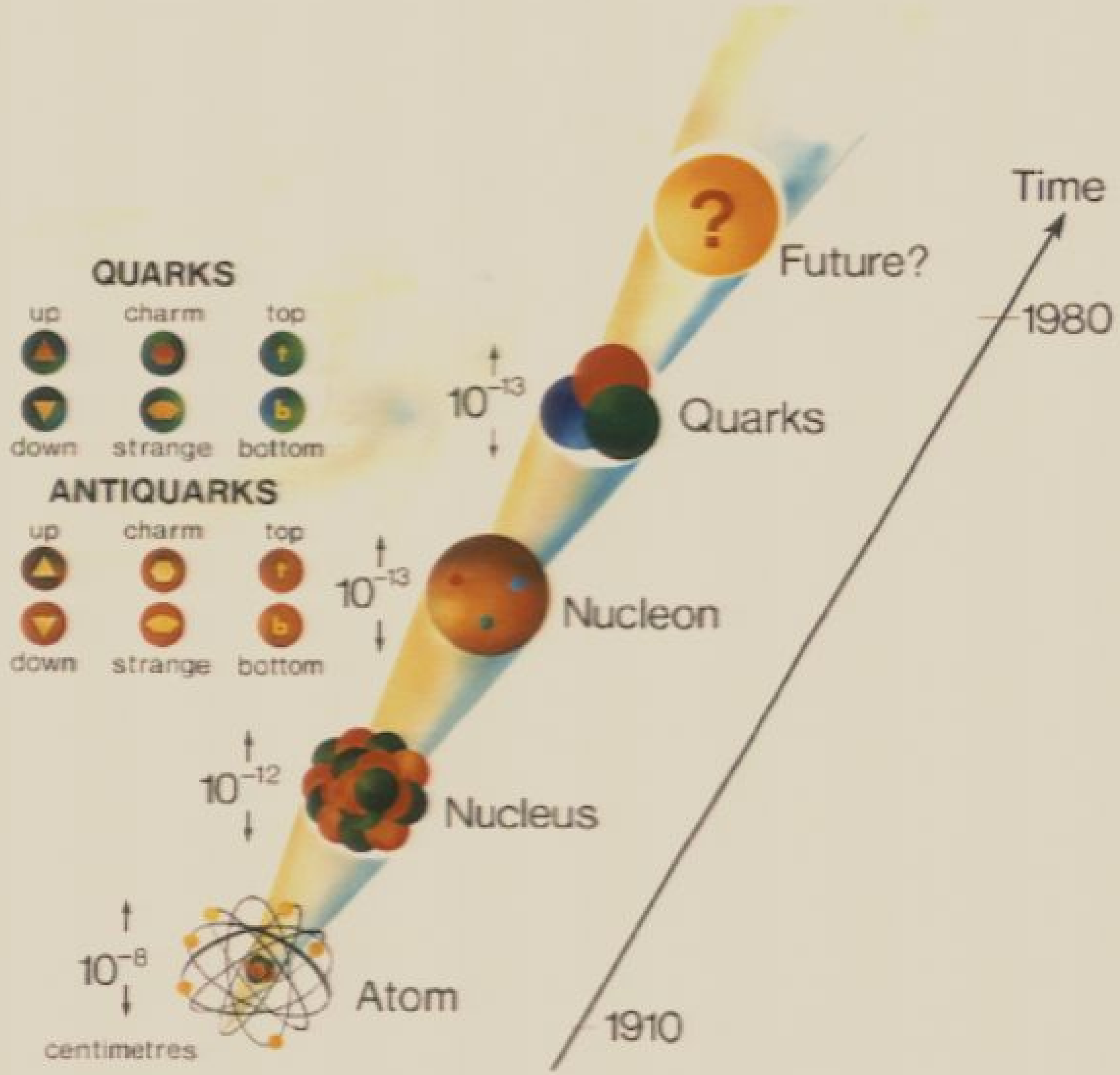
The Big Bang and the center of black holes are both examples of singularities: regions of infinite gravitational field. Space and time end at singularities.

General relativity breaks down at singularities. It must be extended to a quantum theory of gravity.

String Theory

This is a promising candidate for a quantum theory of gravity. It may also unify all of the known particles and forces in nature.

Building blocks of matter (as of 1980)



By 1980, physicists had found that all matter was made up of electrons, quarks, and a few other particles.

String theory begins with the idea that on very small scales, all these particles are really little loops of string. They appear different simply because they correspond to different vibrations of the string.

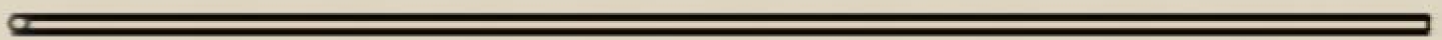
String theory predicts that space has nine (or maybe ten) dimensions.

Where are they?

Everywhere. Even here in this room.

Why can’t we see them?

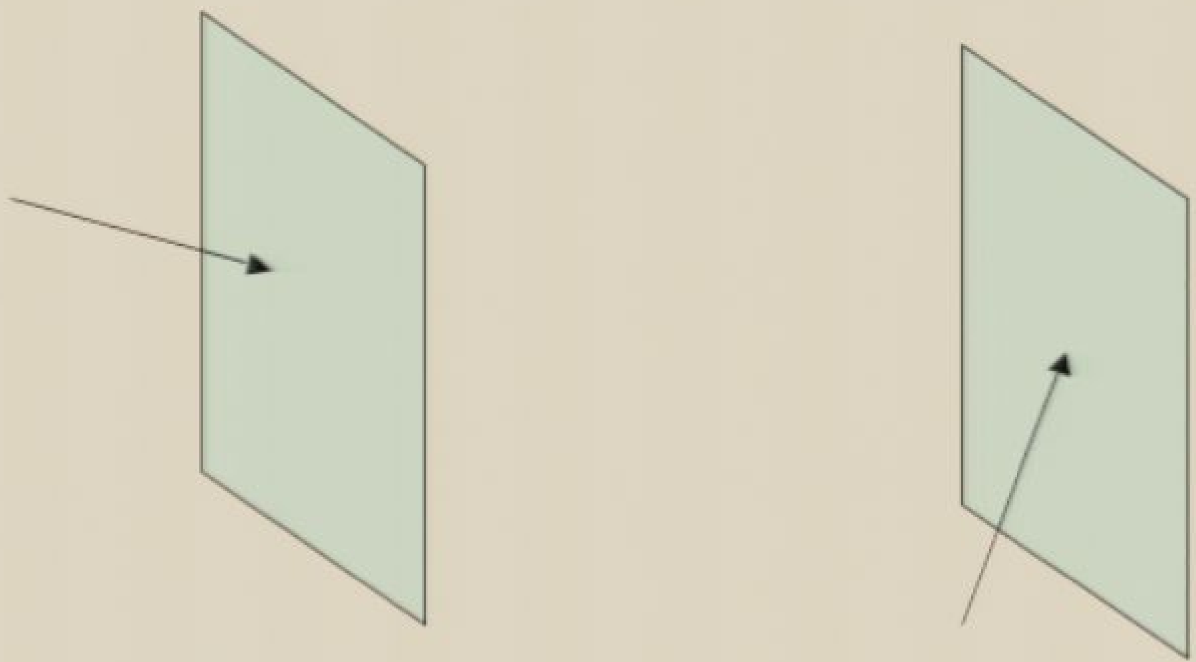
The extra dimensions may be curled up into small circles.



Small extra dimensions would be difficult to detect. It would take a lot of energy.

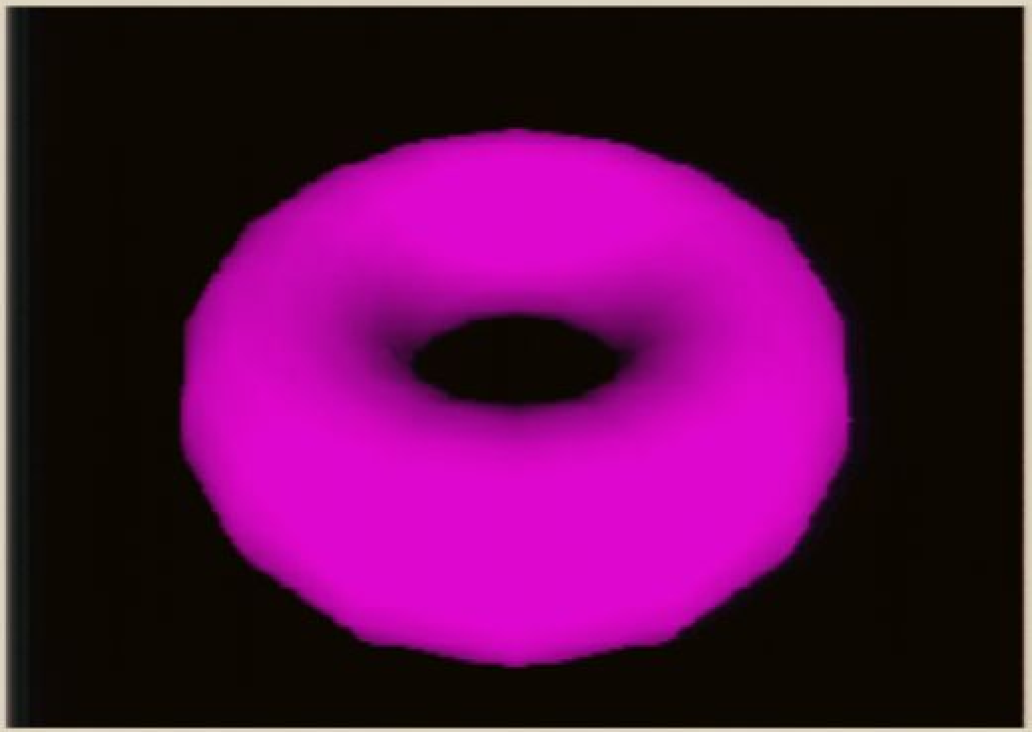
The extra dimensions may be large, but we live on a three-dimensional surface in this bigger space.

Our space



Another "parallel universe"?

In higher dimensions, black holes can be black rings.



Strings sense space-time differently than point particles. Space-times which are physically different in general relativity can be equivalent in string theory.

Example: If one direction of space is a circle, strings can wind around the circle.

In string theory, a circle of radius R is indistinguishable from a circle of radius 1/R!

Singularities

Since strings sense space-time differently, some singularities are removed in string theory:

a) Since strings are extended objects, they are not affected by some singularities.

b) Some singular space-times are equivalent to nonsingular space-times.

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1) There could be an earlier collapsing phase, so the Big Bang was really a Big Bounce.

2) Time (as we know it) really did begin at the Big Bang.

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Probably only into the future.