The Warpings of Spacetime

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Einstein revolutionized our notions of space, time, and gravity.

Space and time are unified; gravity is the curvature of this unified spacetime.

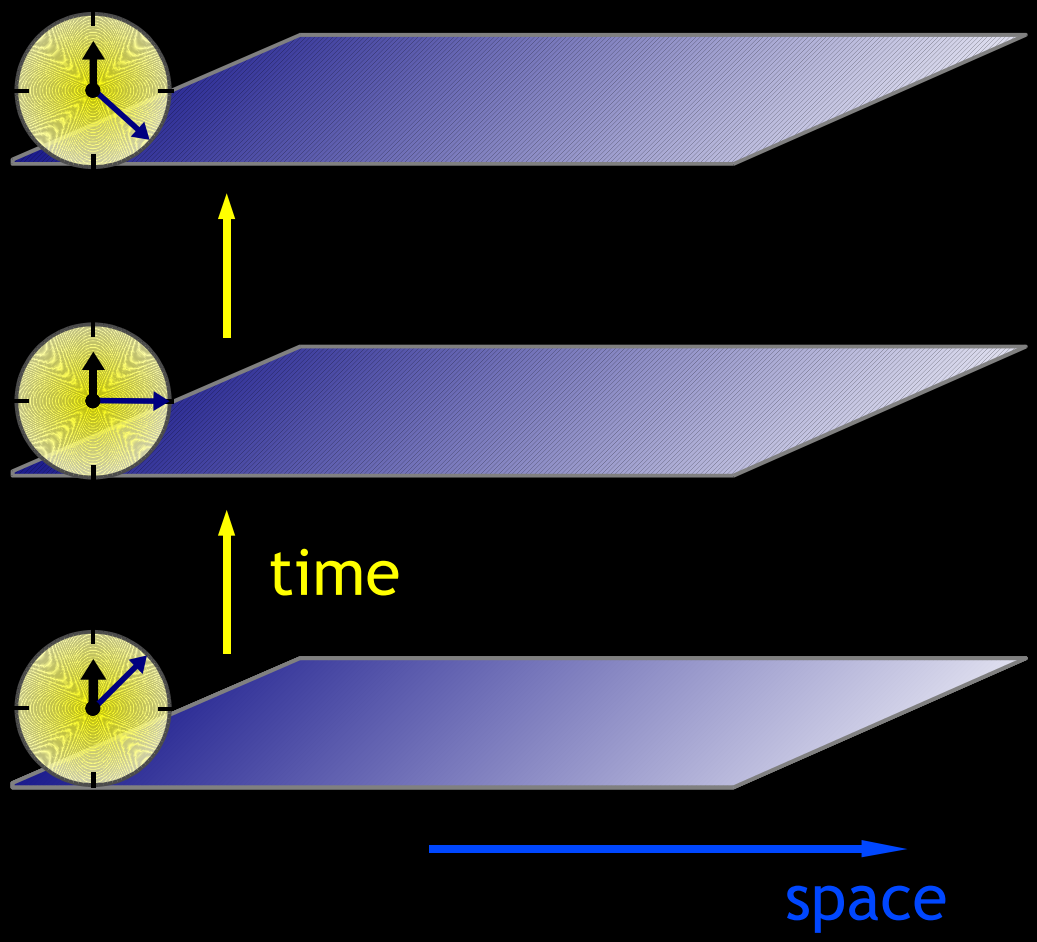
Let's start with time.

How important is time? Consult Google.

Number of search results returned for:

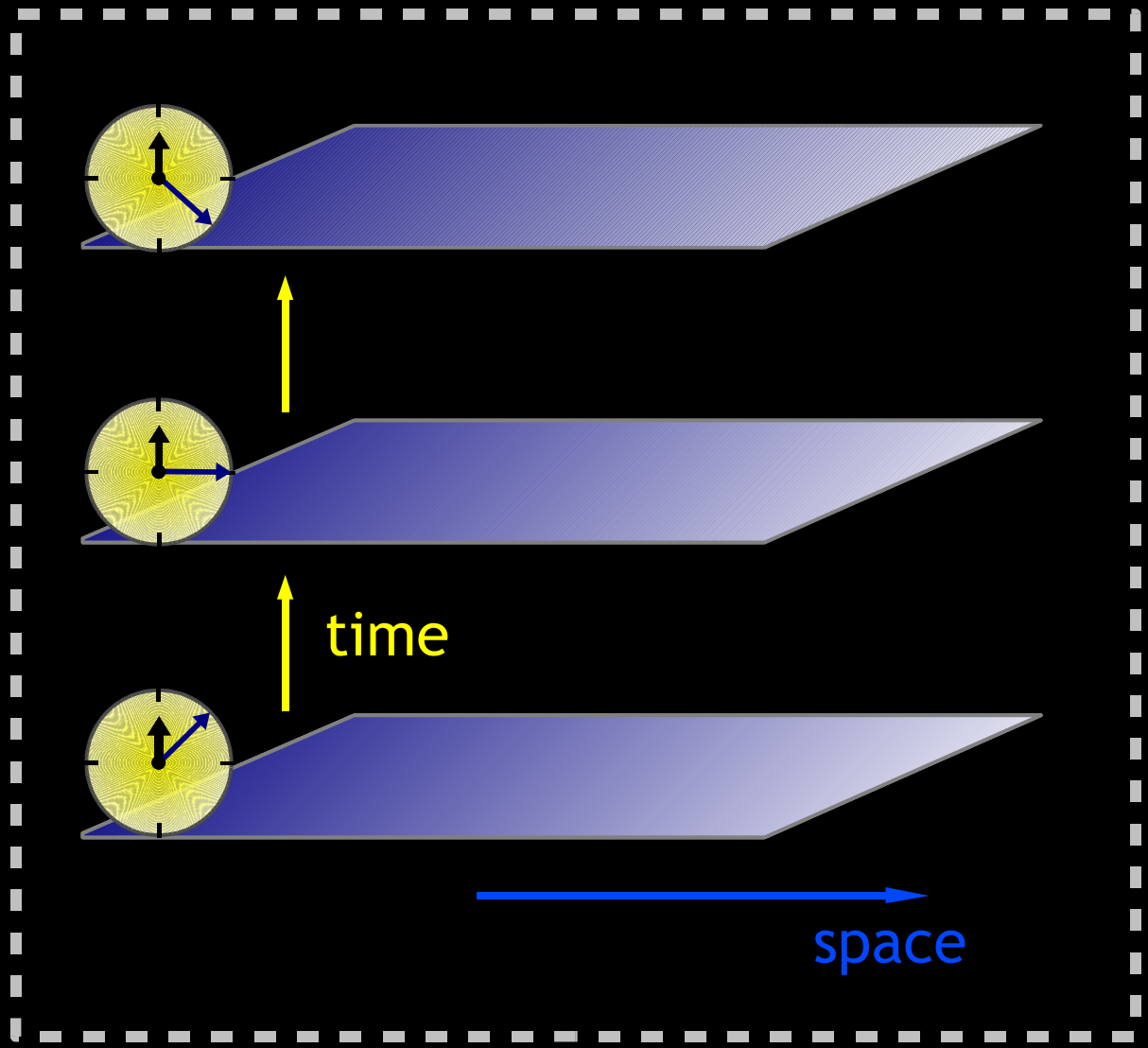
space	422,000,000 pages found
money	262,000,000 pages found
fun	173,000,000 pages found
love	170,000,000 pages found
sex	76,400,000 pages found
peace	89,900,000 pages found
war	179,000,000 pages found
harry potter	20,900,000 pages found
time	972,000,000 pages found

Time in Sir Isaac Newton's universe: absolute, universal.



“Space” (the three-dimensional world in which we live) happens over and over again, and “time” labels the different moments.

We need <u>four numbers</u> (3 for position in space, one for time) to specify any specific "event."

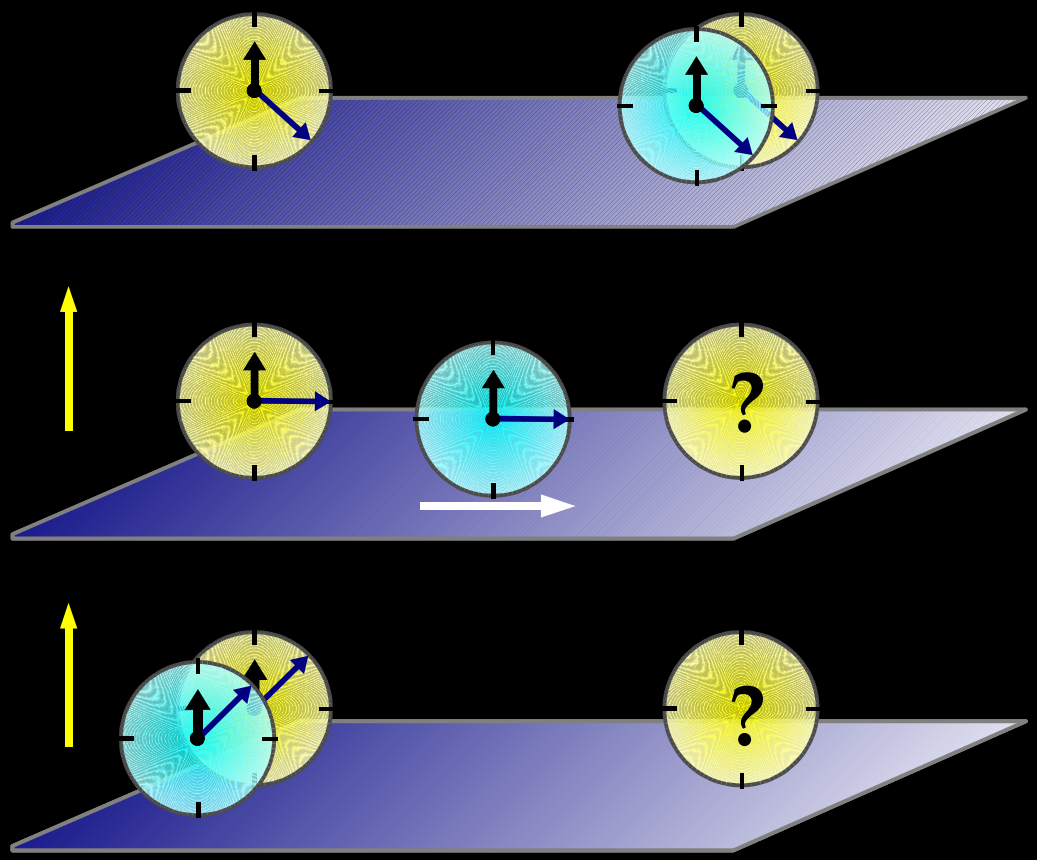


spacetime

It is therefore okay to label the whole shebang a four-dimensional spacetime.

On the other hand, space and time are completely different, so why bother?

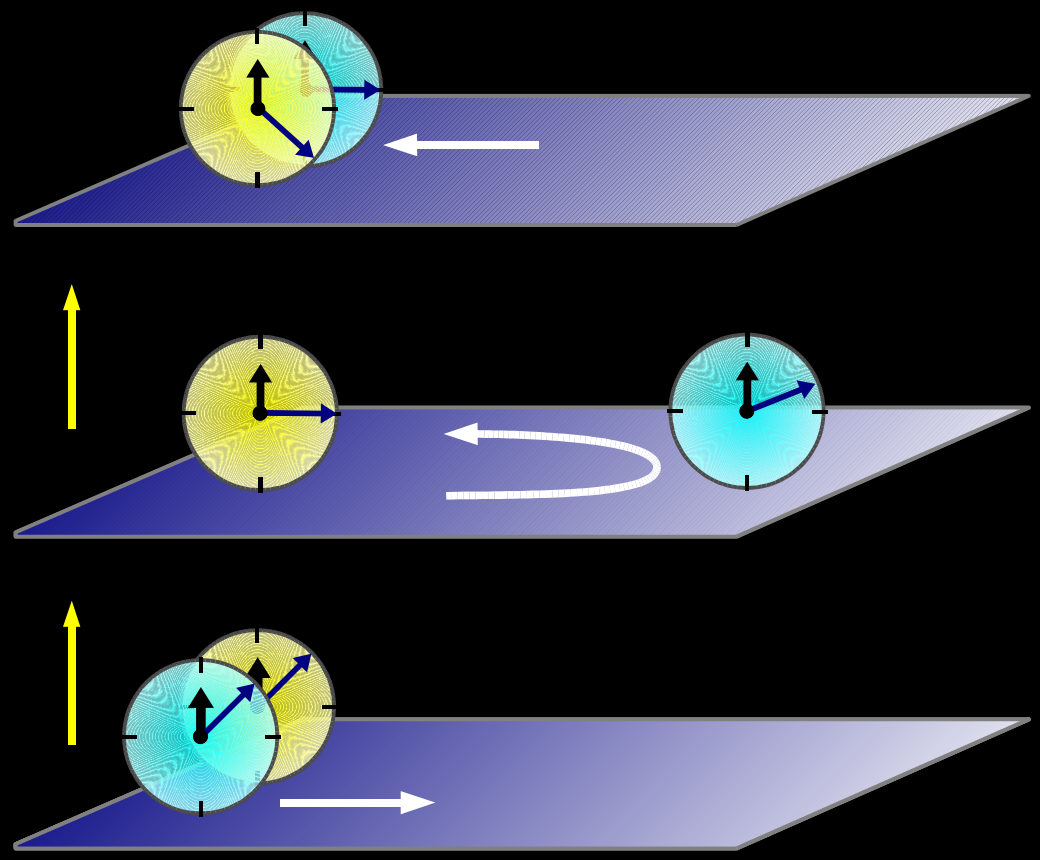
Synchronizing time: how do you know when is “right now” some distance far away?



Answer: synchronize clocks locally, then send one far away.

Of course, you need good clocks! They must <u>remain</u> synchronized -- “flow” at the same rate.

Einstein, 1905: moving clocks don't “flow” at the same rate. Absolute synchronization is impossible!



Spacetime isn't “sliced” into moments of simultaneous time.

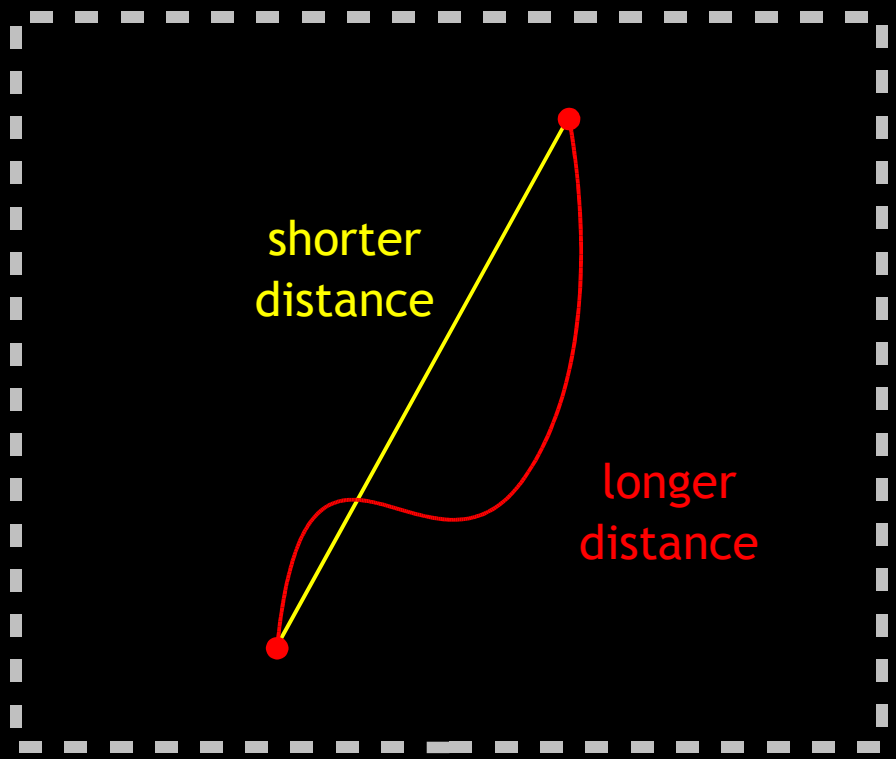
Instead, time measures the distance traveled through spacetime along a trajectory. (Accelerated clocks tick more *slowly*.)

Time is <u>individual</u>, not universal. The amount of time you experience depends on how you move.

This is less crazy than it sounds.

The distance between two points in space depends on the path you take between them (obviously).

Time is like that! The elapsed time between two events in spacetime depends on the path you take.



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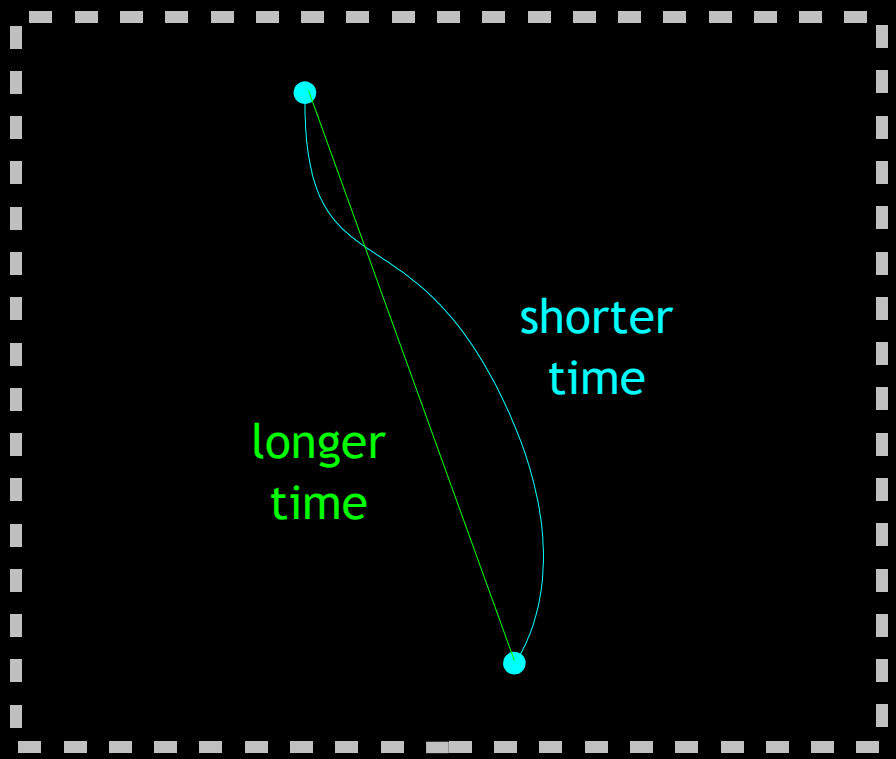
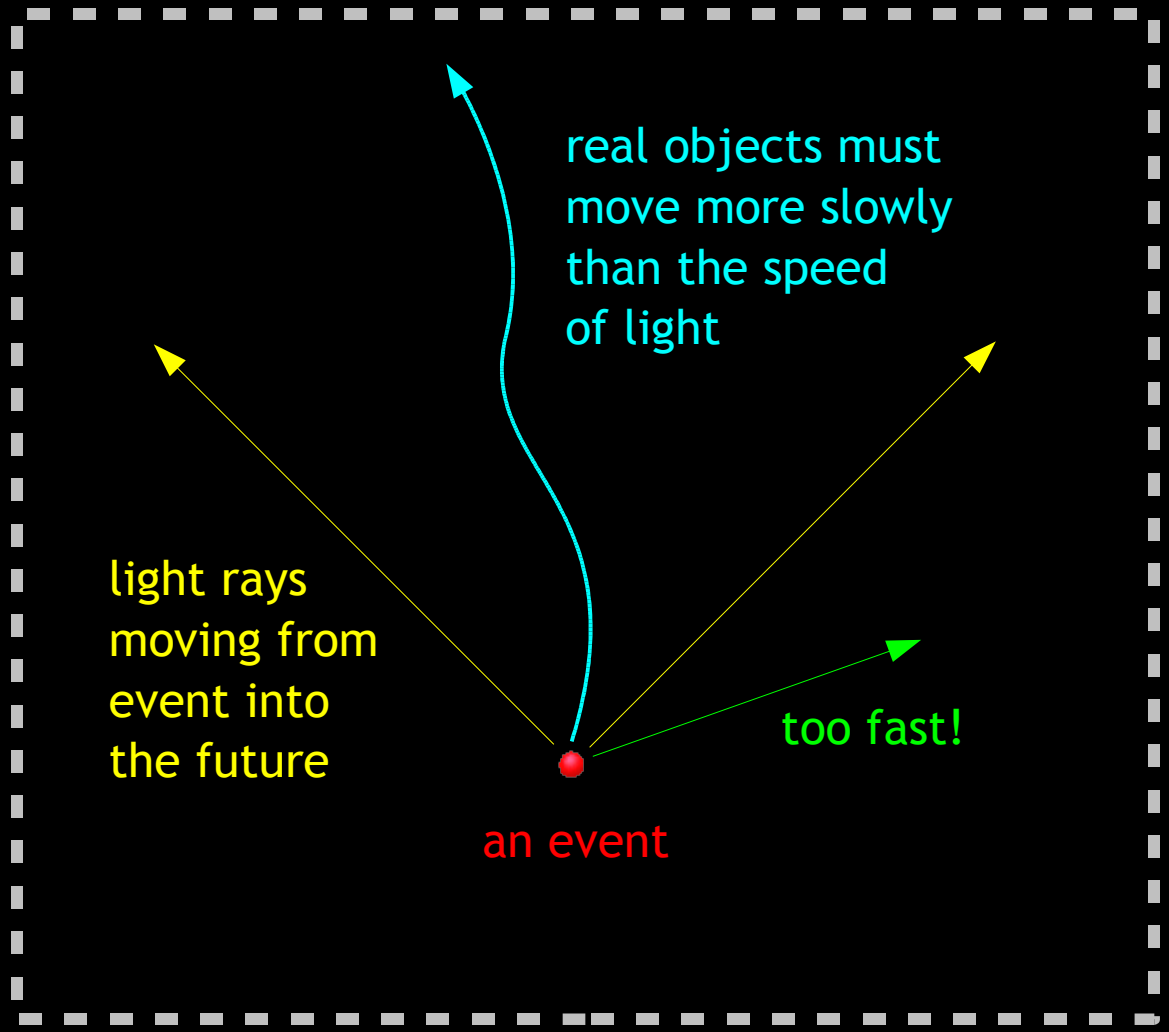


spacetime

In Einstein's universe, there is no unique notion of "right now" at all points throughout space. Instead, there is a speed limit: the speed of light.

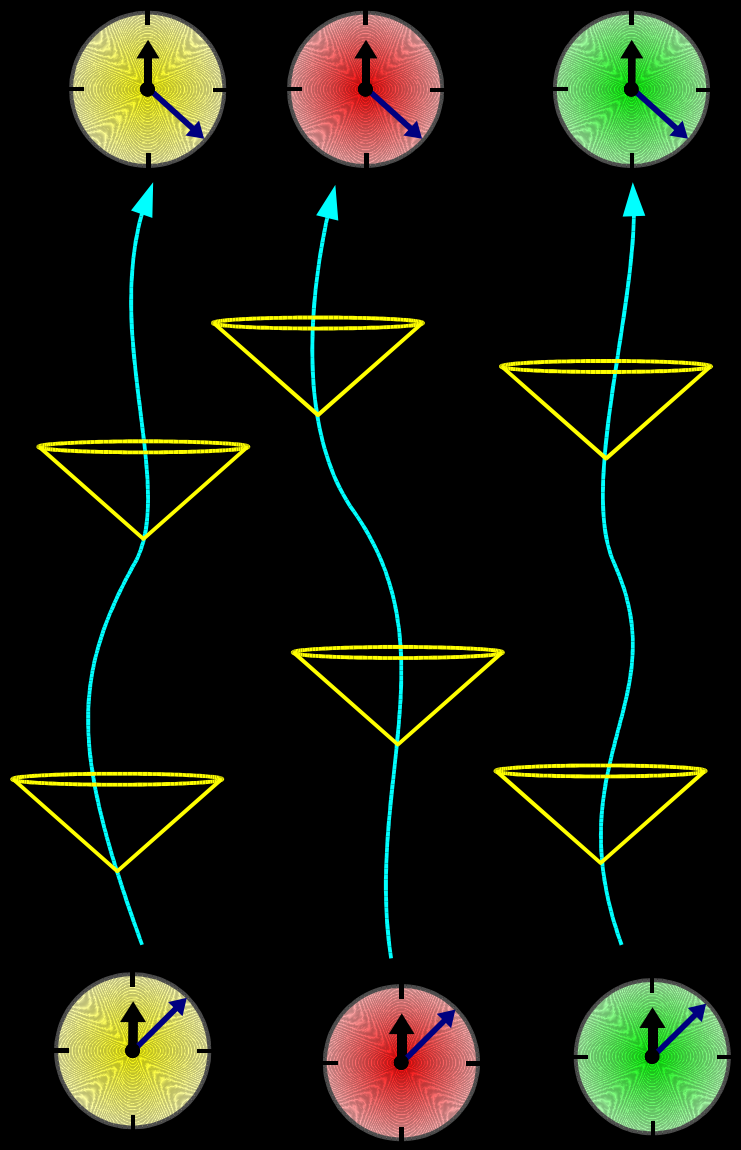
This idea is the basis of special relativity, which replaces Newton's idea of an absolute space and time.



spacetime

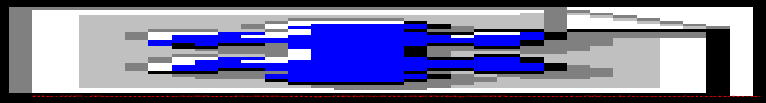
Associated to each event in spacetime is a light cone, and physical objects must move on trajectories that stay inside the light cones.

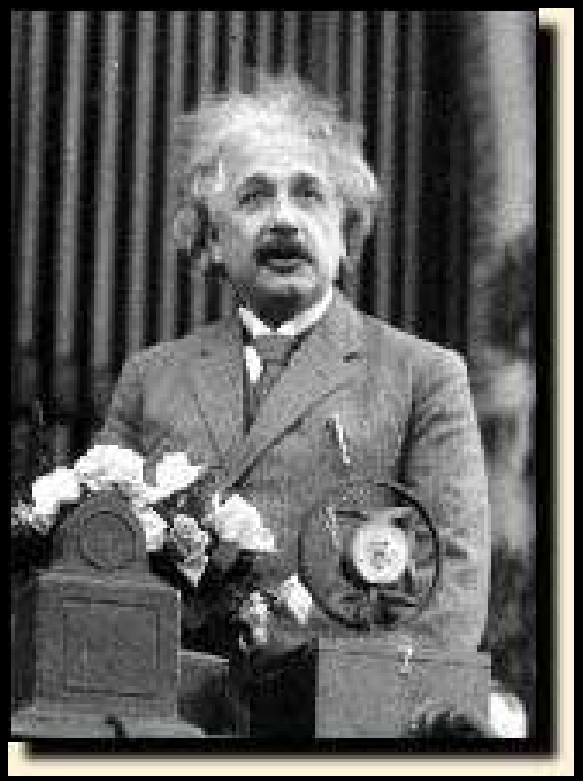
We are tricked into believing in absolute time (simultaneity) because most objects move slowly compared to light, so clocks remain very close to synchronized.



Unification of space and time came with an unintended consequence: unification of mass and energy!

$$E = mc^2$$

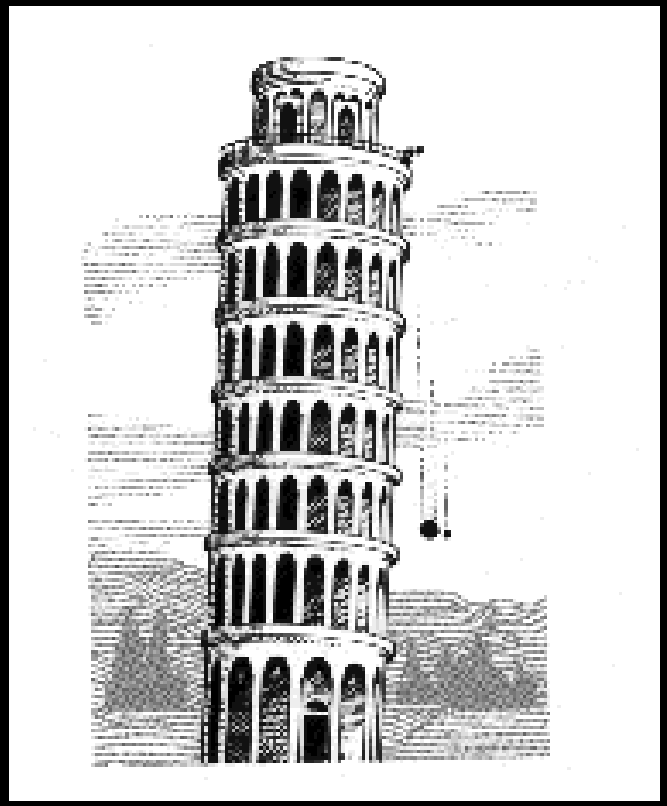




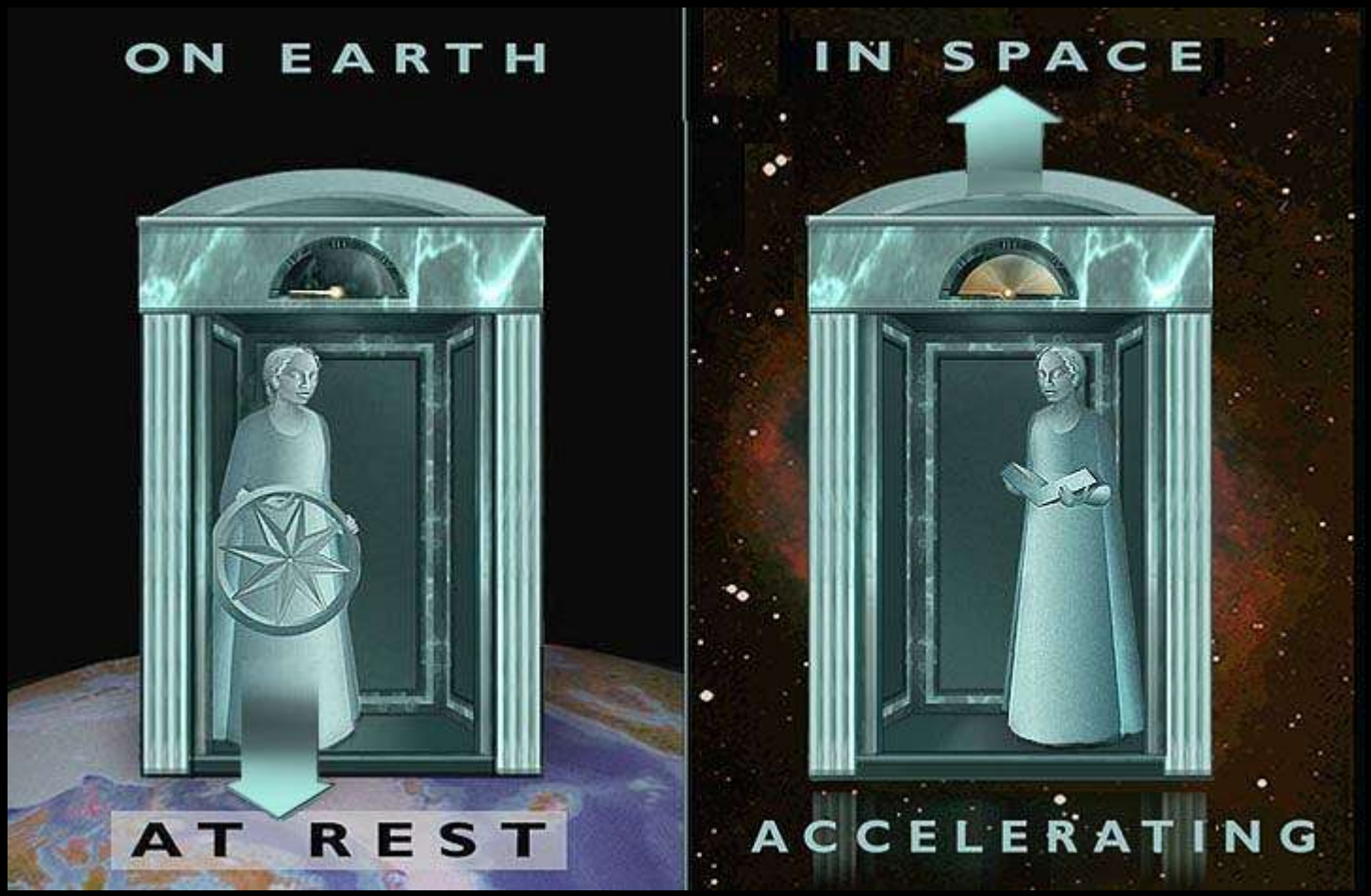
"It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing -- a somewhat unfamiliar conception for the average mind. Furthermore, the equation E is equal to m c-squared, in which energy is put equal to mass, multiplied by the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned before. This was demonstrated by Cockcroft and Walton in 1932, experimentally."

One force doesn't fit into the framework of special relativity: gravity. Einstein realized that there was something else special about gravity: it is universal. Everything reacts the same way to gravity.

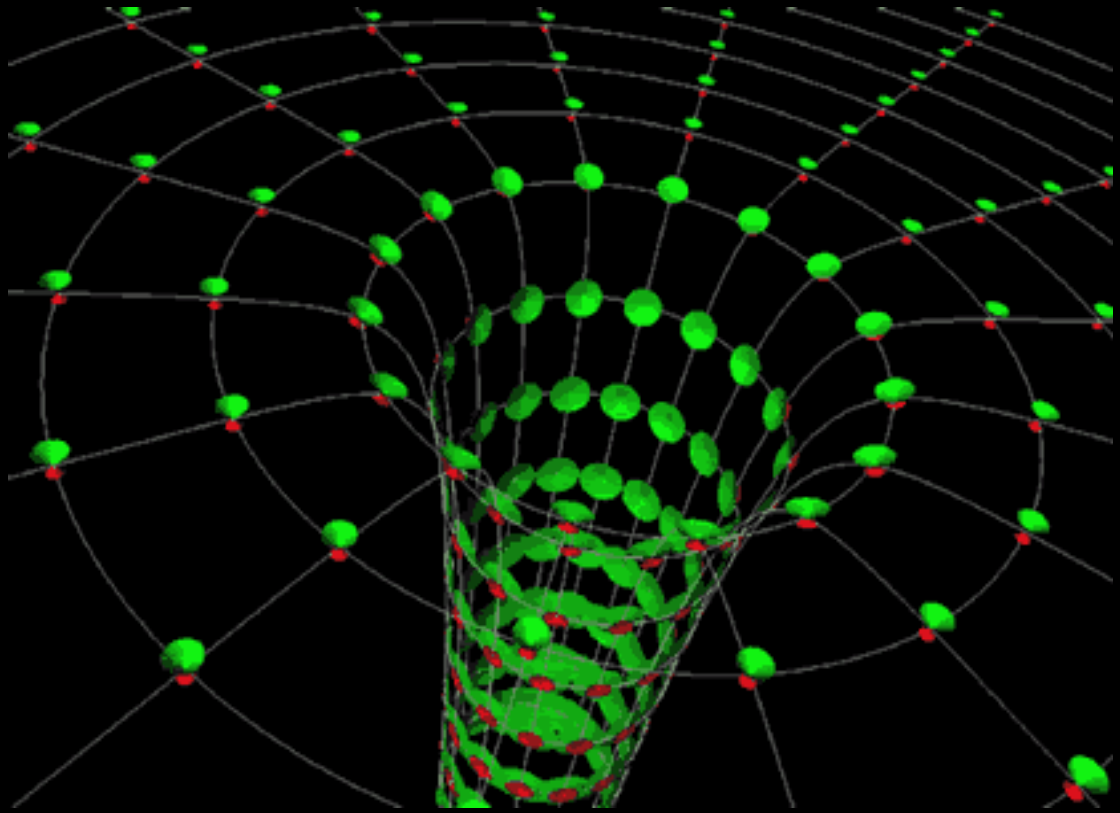
Galileo in Pisa: objects fall the same way in gravity, regardless of their mass or composition.



But if <u>everything</u> feels the <u>same</u> acceleration, this is equivalent to <u>nothing</u> feeling <u>any</u> acceleration. Gravity is <u>undetectable</u> in a small region of space. (The "principle of equivalence.")



Einstein's brilliant idea: if gravity isn't really a “force,” but instead a universal feature of spacetime, perhaps we can think of it as the curvature of spacetime itself.

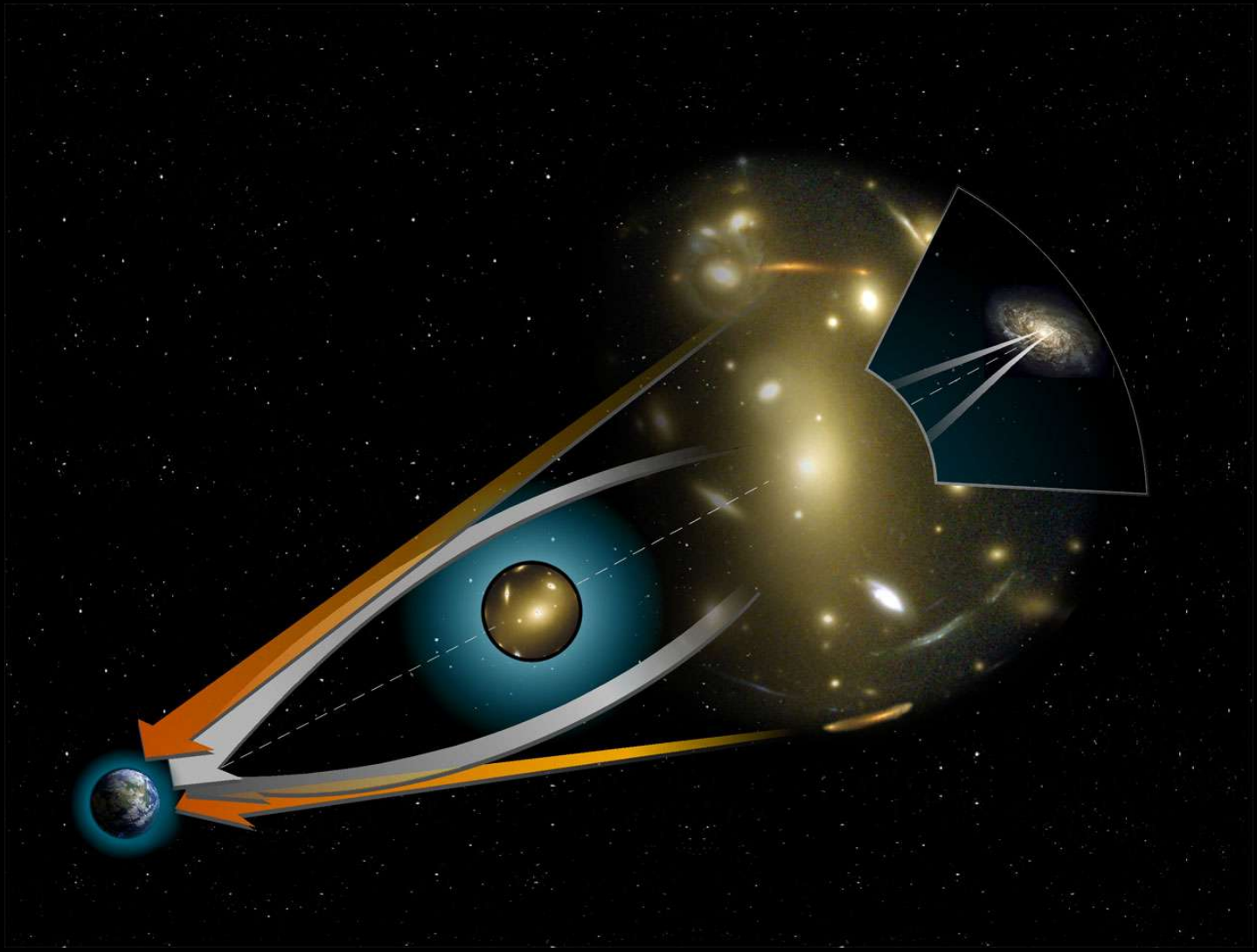


The content of general relativity is simply this: Gravity is a manifestation of the curvature of spacetime.

Curvature is created by energy, and affects everything in the universe.

We can put this idea to work:

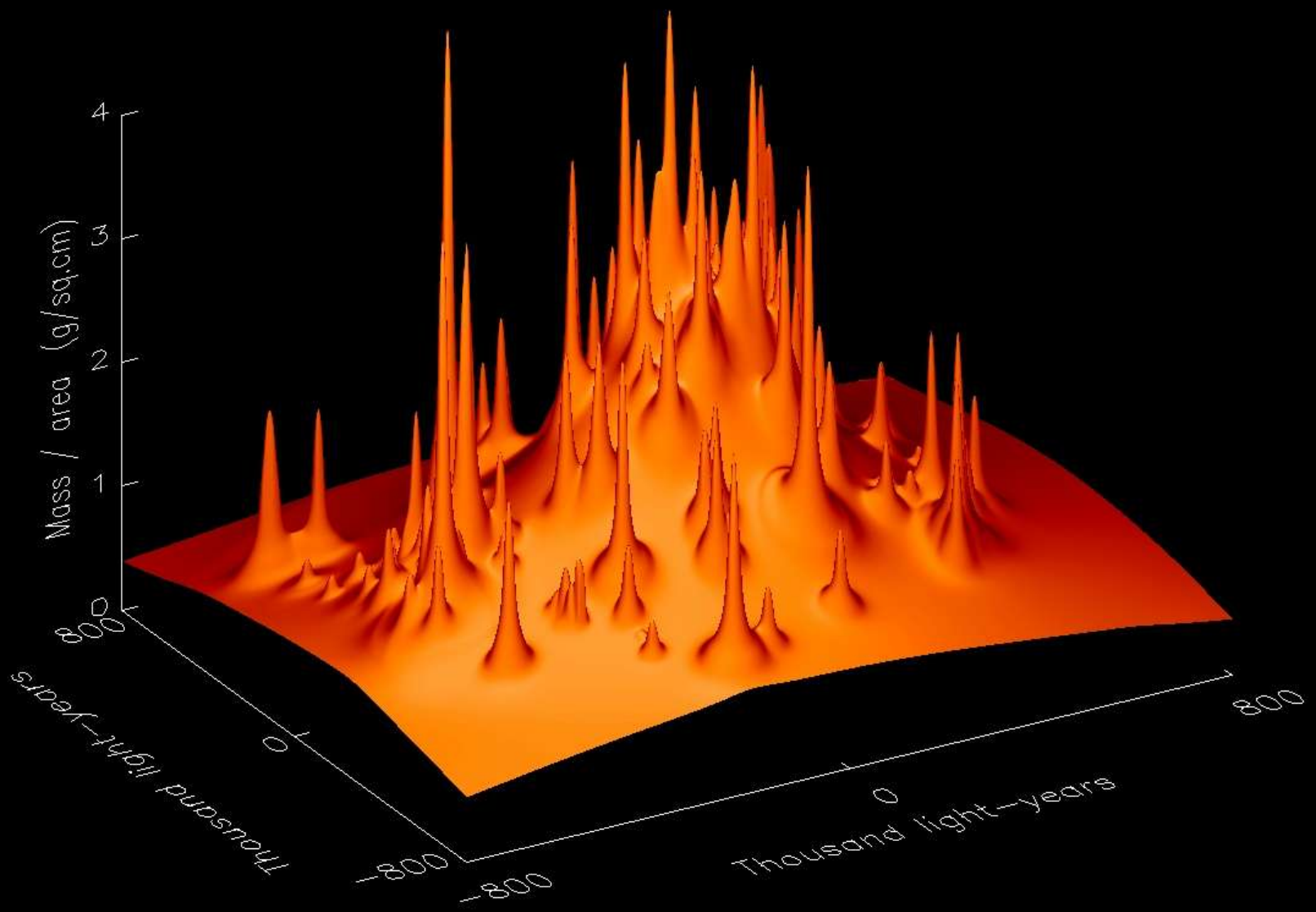
gravitational lensing.



The gravitational field of a galaxy (or cluster of galaxies) deflects passing light; the more mass, the greater deflection.

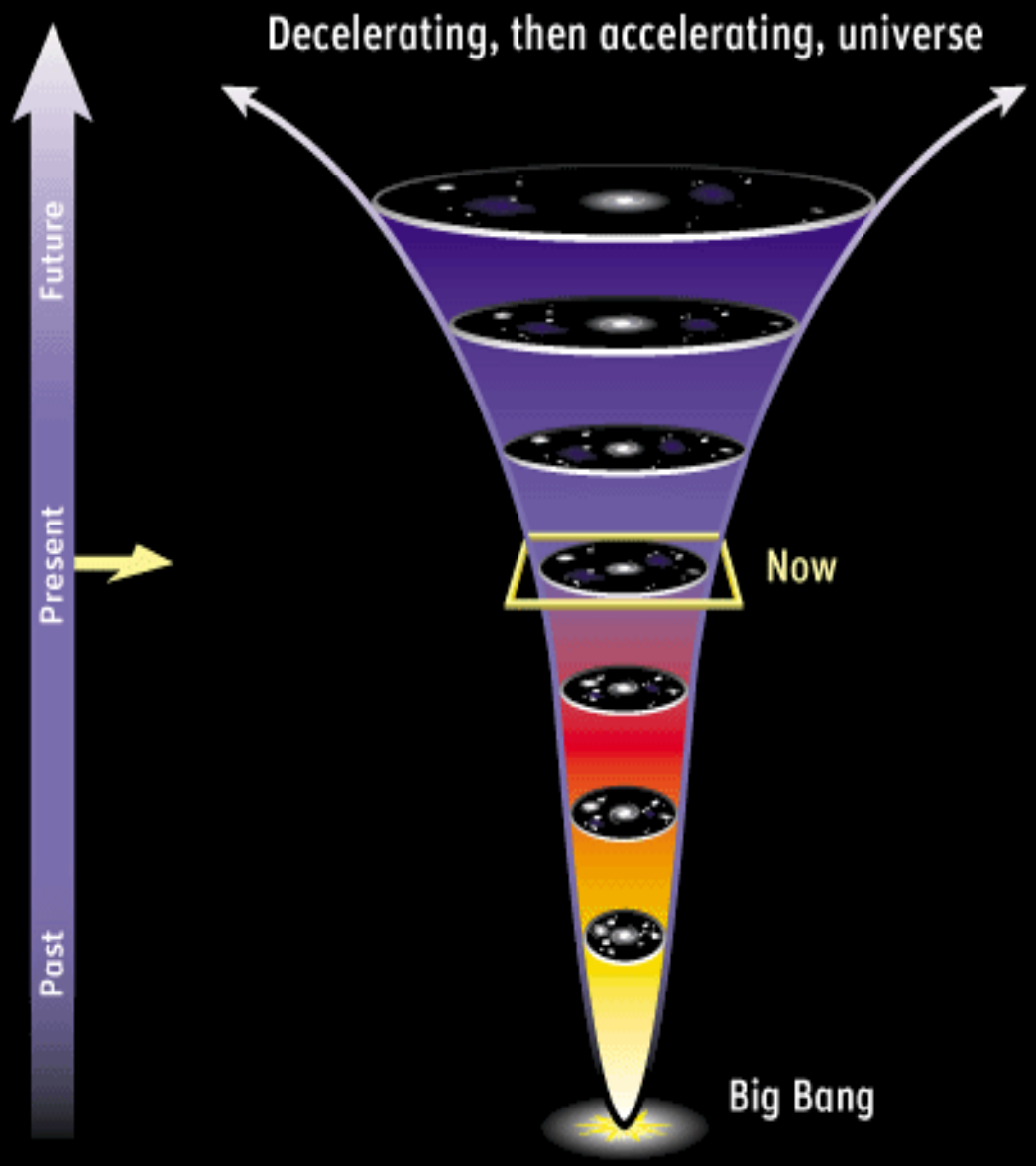
So we can infer the existence of matter even if we can't see it.

Hubble Space Telescope image of a cluster of galaxies.
An irregular blue galaxy in the background is multiply-imaged.



Mass reconstruction of the cluster. Note the large, smooth distribution of (apparently invisible) matter -- that's the dark matter!

Another manifestation of spacetime curvature: the expanding universe.



Galaxies are distributed smoothly through space, and the amount of space between them is growing.

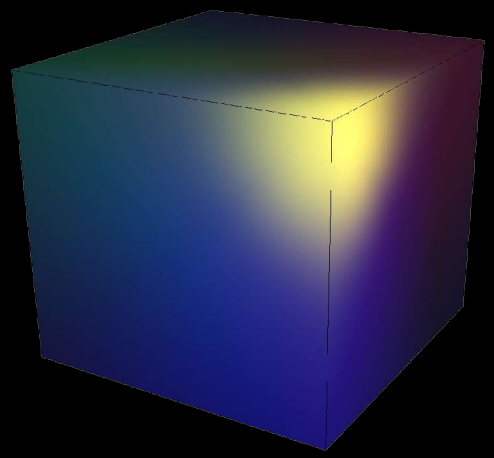
That's what “expansion” really means.

We now know that the universe is accelerating, which we attribute to dark energy.

What is this Dark Energy stuff?

- Smoothly distributed through space: doesn't fall into galaxies and clusters.

- Constant density (or changing very slowly) through time. Not diluted by expansion.



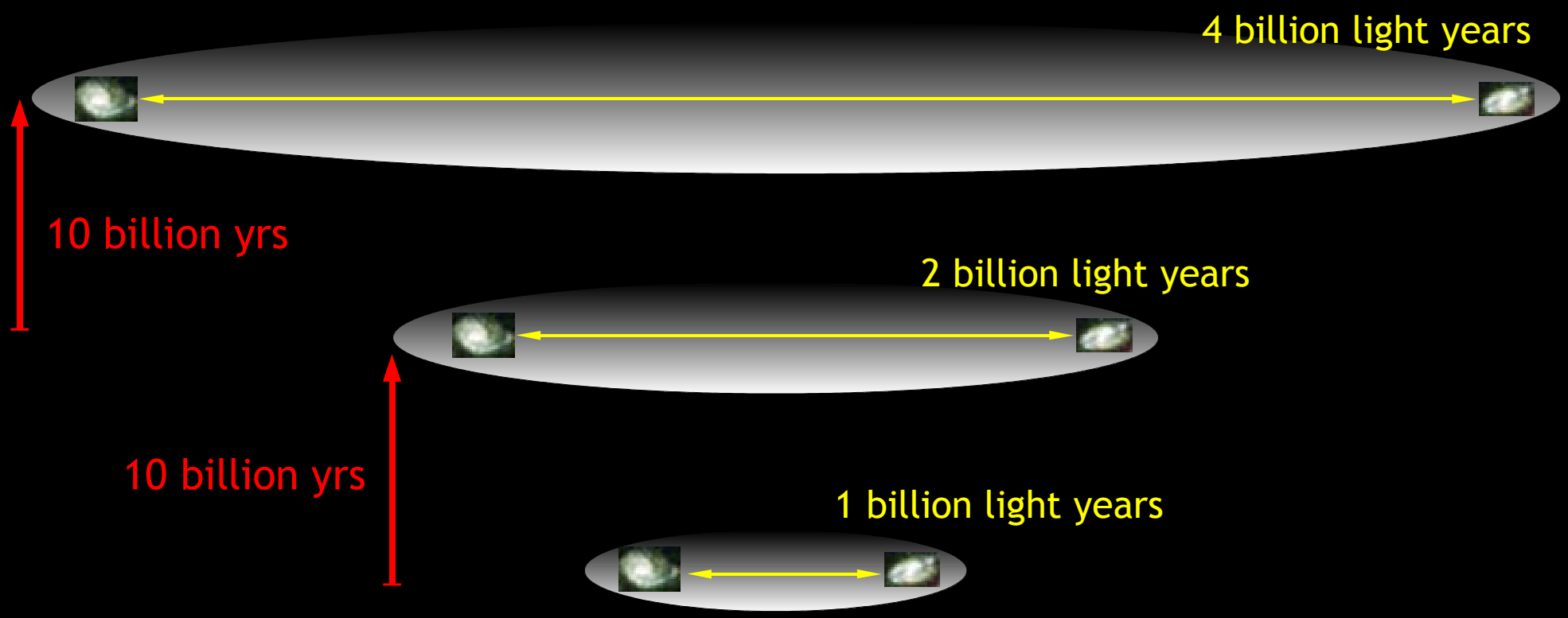
(artist's impression of vacuum energy)

- Invisible to matter. Only detected via gravity.

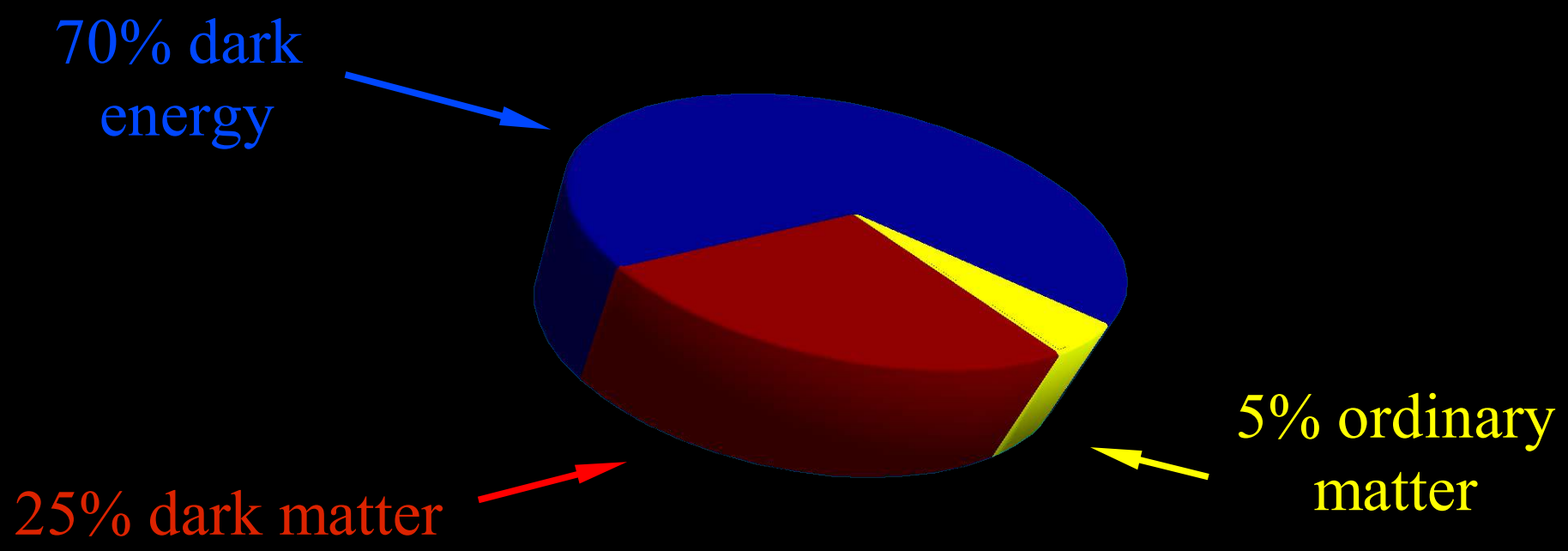
Leading candidate: vacuum energy, or the "cosmological constant." The intrinsic energy of empty space itself.

Why does dark energy with constant density make the expansion rate appear to accelerate?

Constant density -> persistent expansion -> apparent acceleration of distant galaxies.

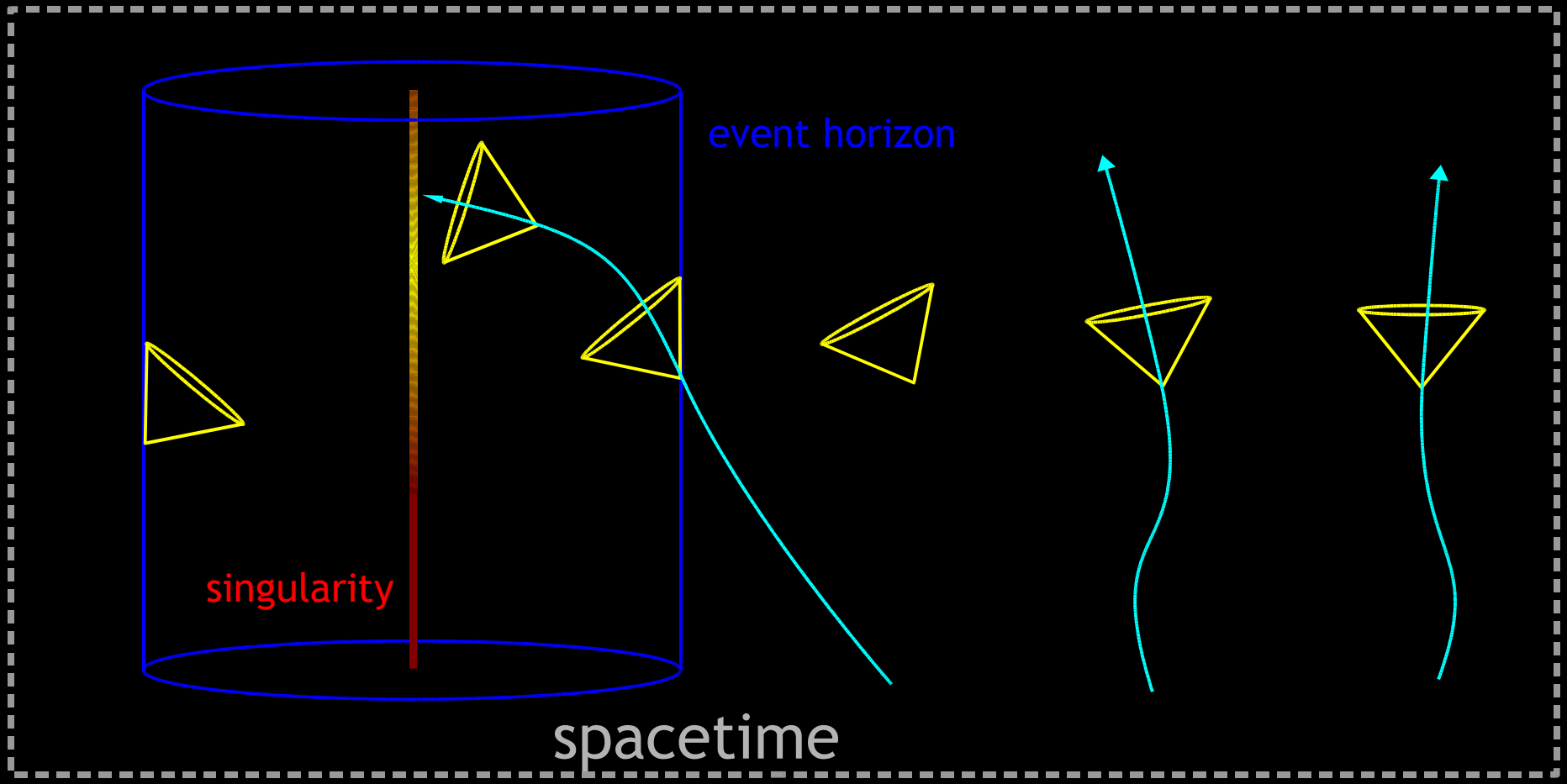


Good news: we have a complete inventory of the constituents of the universe.



Bad news: it makes no sense to us!
Although even that is a kind of good news.

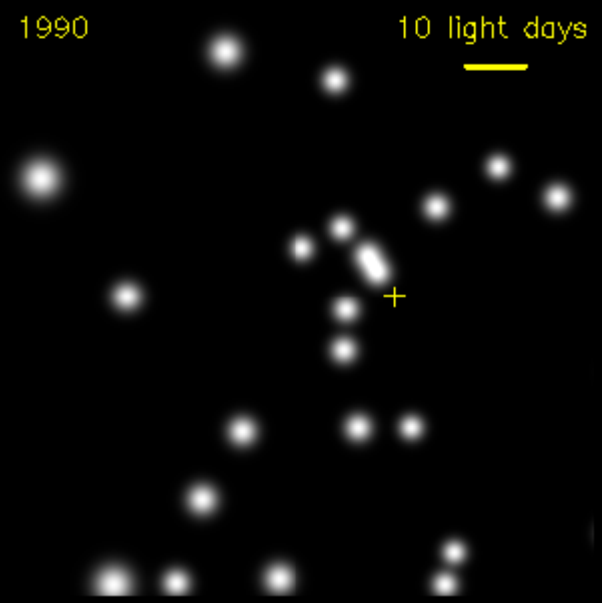
Spacetime curvature can force light cones to tilt. This is the origin of black holes: regions where spacetime is so curved that light can't escape.



Falling into the singularity is as inevitable as moving forward in time (it *is* just moving forward in time).

We have good evidence that black holes really exist!

Matter spinning around a supermassive black hole in galaxy NGC 7052.

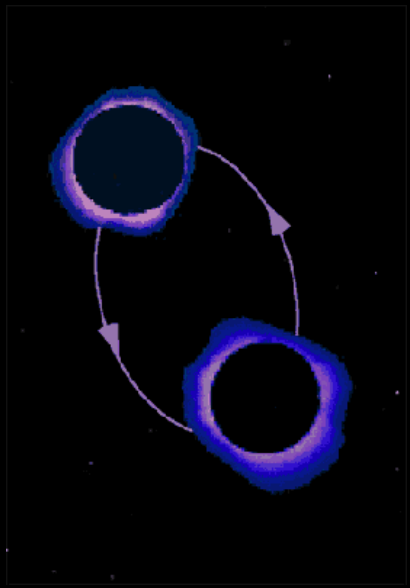


[Genzel et al.]

There is also a supermassive black hole (1 million solar masses) at the center of our Milky Way galaxy. We can “weigh” it by observing motions of nearby stars.

General relativity is being tested as we speak.

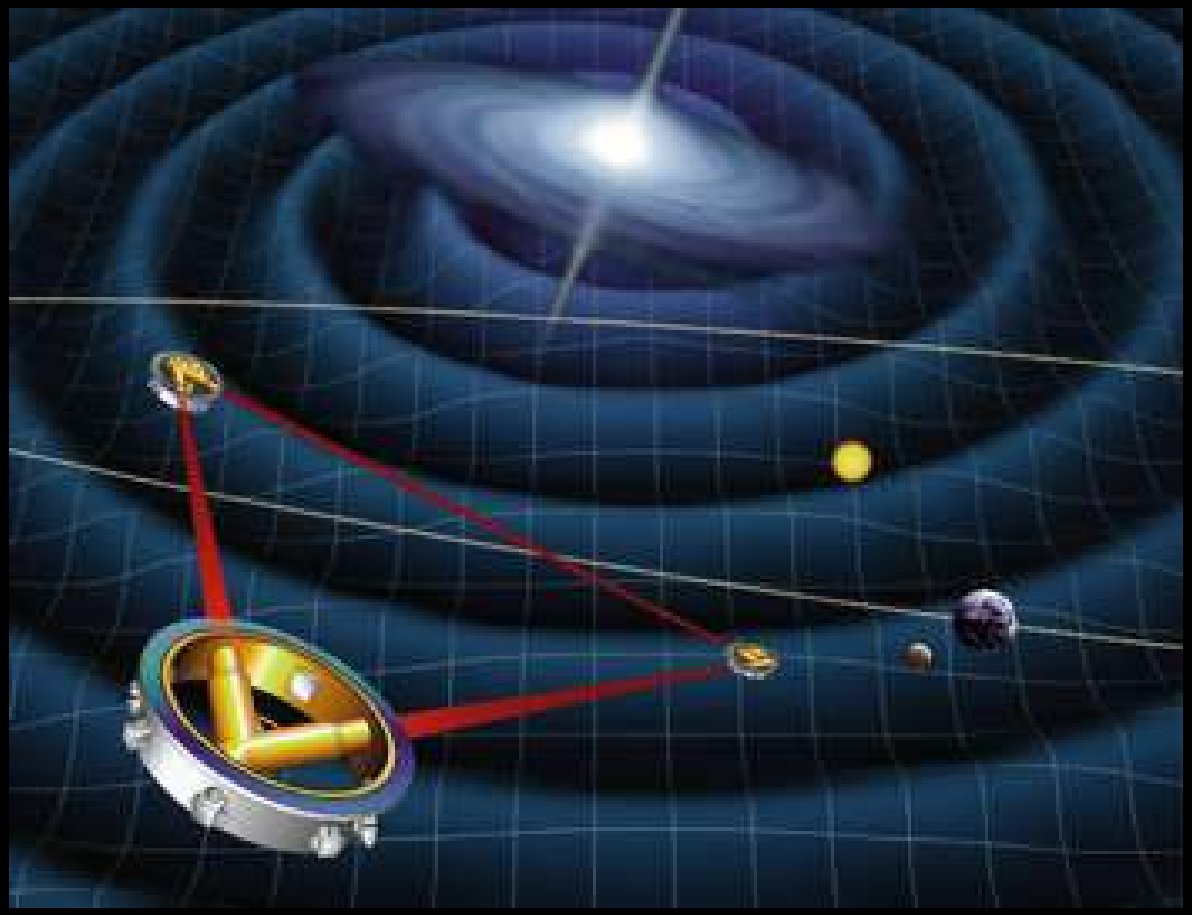
Example: the search for gravitational waves from orbiting black holes. The LIGO observatory includes two 4-km evacuated tubes, with lasers bouncing off suspended mirrors at each end.



Challenge: a passing wave will jiggle the mirrors by only about 10^{-16} cm – a thousandth of the diameter of an atomic nucleus!

Future gravitational-wave observatories offer even more intriguing challenges. The LISA observatory will be an array of three satellites, separated by 5 million km.

LISA will search for gravitational waves from the coalescence of supermassive black holes in distant galaxies (among other things).

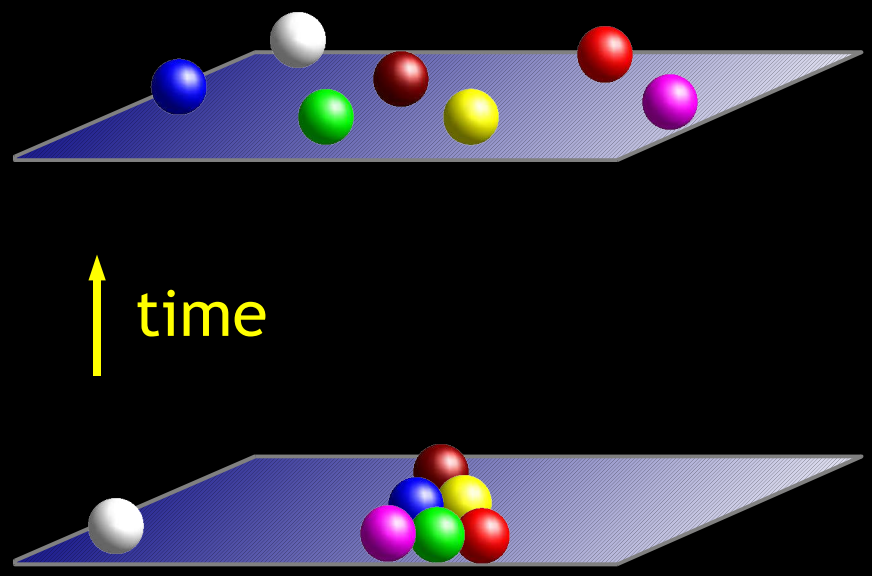


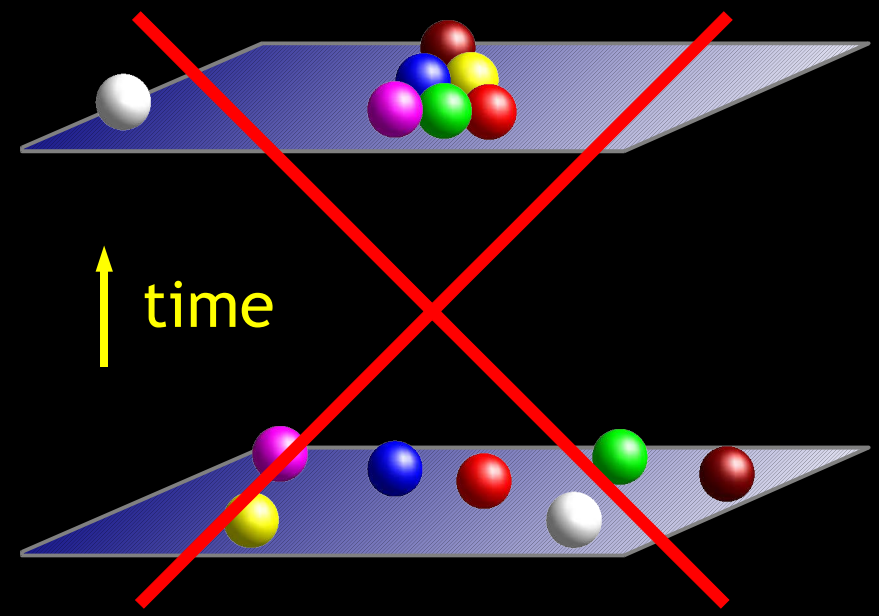
Down-to-Earth GR: Global Positioning System (GPS)

A system of satellites using clocks to help you find exactly where you are, and locate the nearest Starbucks.

Clocks in orbit move more quickly than they would on Earth, due to the curvature of spacetime. General Relativity is necessary to make GPS work!

A puzzle: why does Time have a direction? – or,
"Why can we remember the past and not the future?"

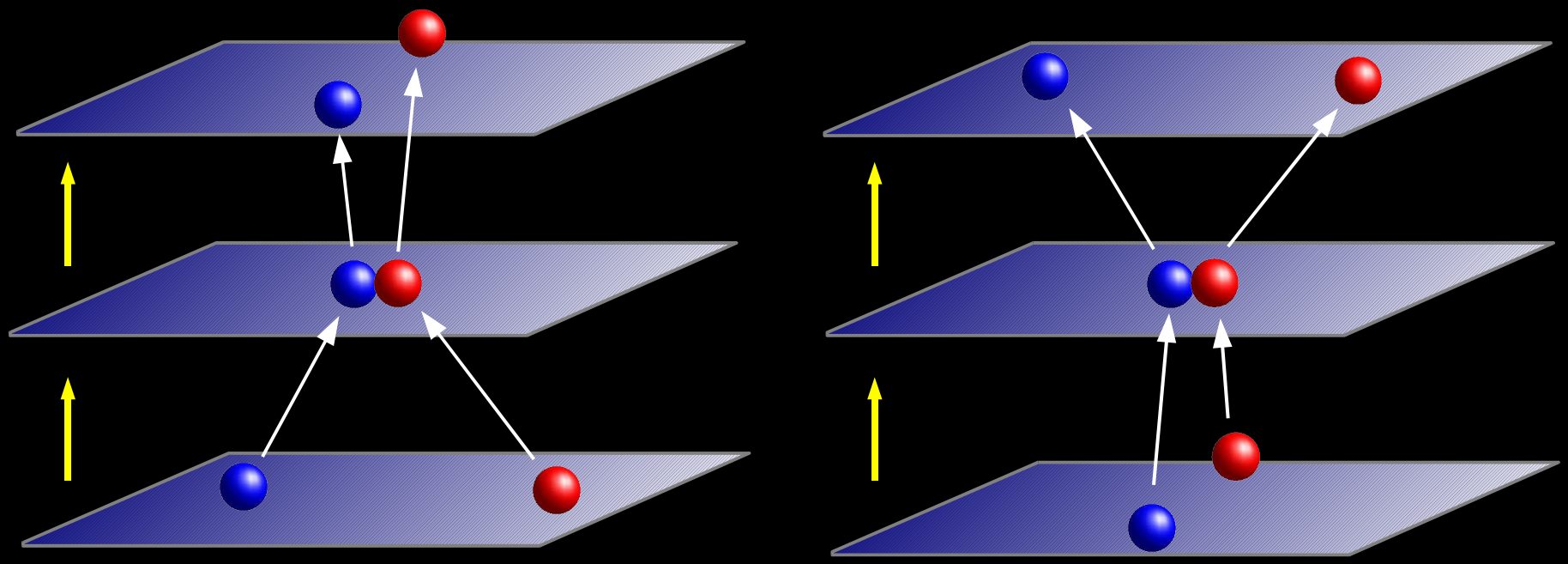




Evolution from <u>order</u> to <u>disorder</u> (increasing entropy) is easy and natural. Many more ways to be disordered.

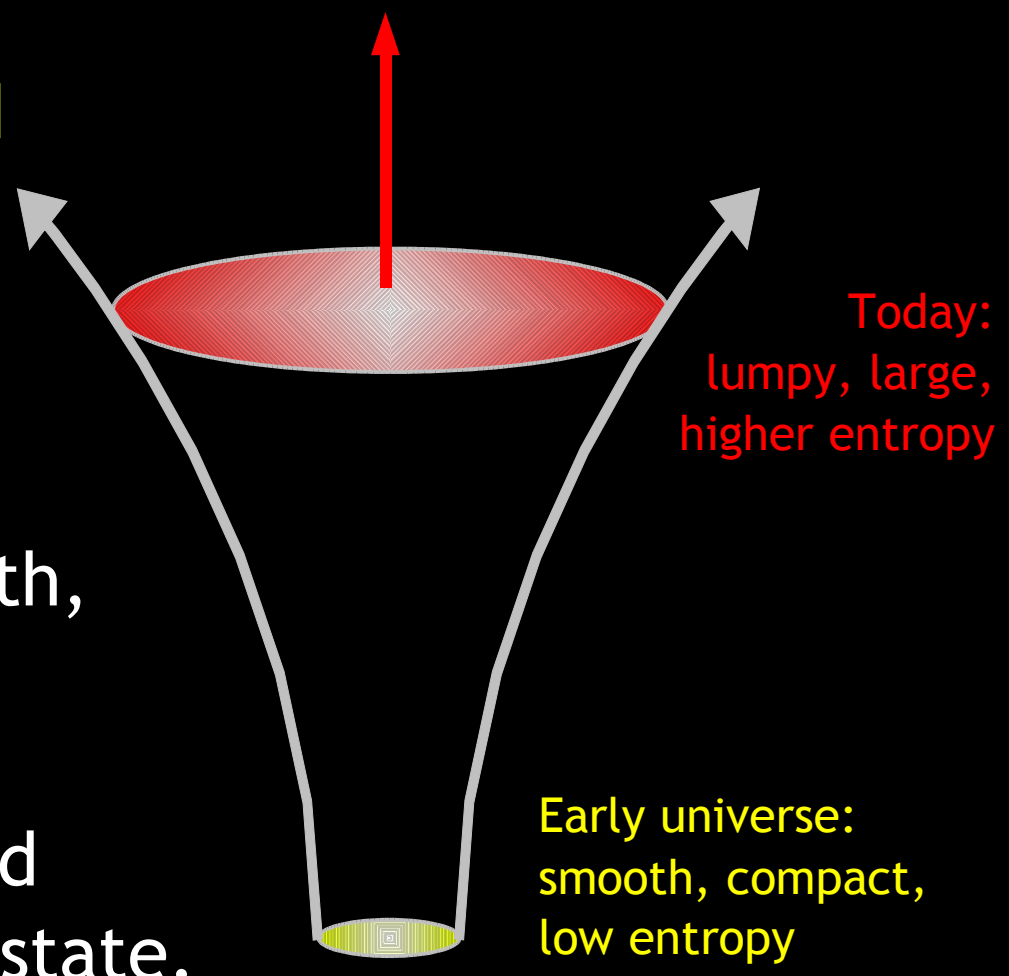
Evolution into order never happens (without outside help). The increase of entropy picks out an arrow of time.

But that's a puzzle. The microscopic laws of physics, governing the behavior of individual objects, are perfectly reversible – they work equally well running forwards and backwards in time.



Why is the collective behavior of macroscopic objects <u>irreversible</u>, while the behavior of the individual consitutents is perfectly <u>reversible</u>?

A partial answer: we see entropy (disorder) increase because at early times the universe was highly ordered (extremely low entropy).



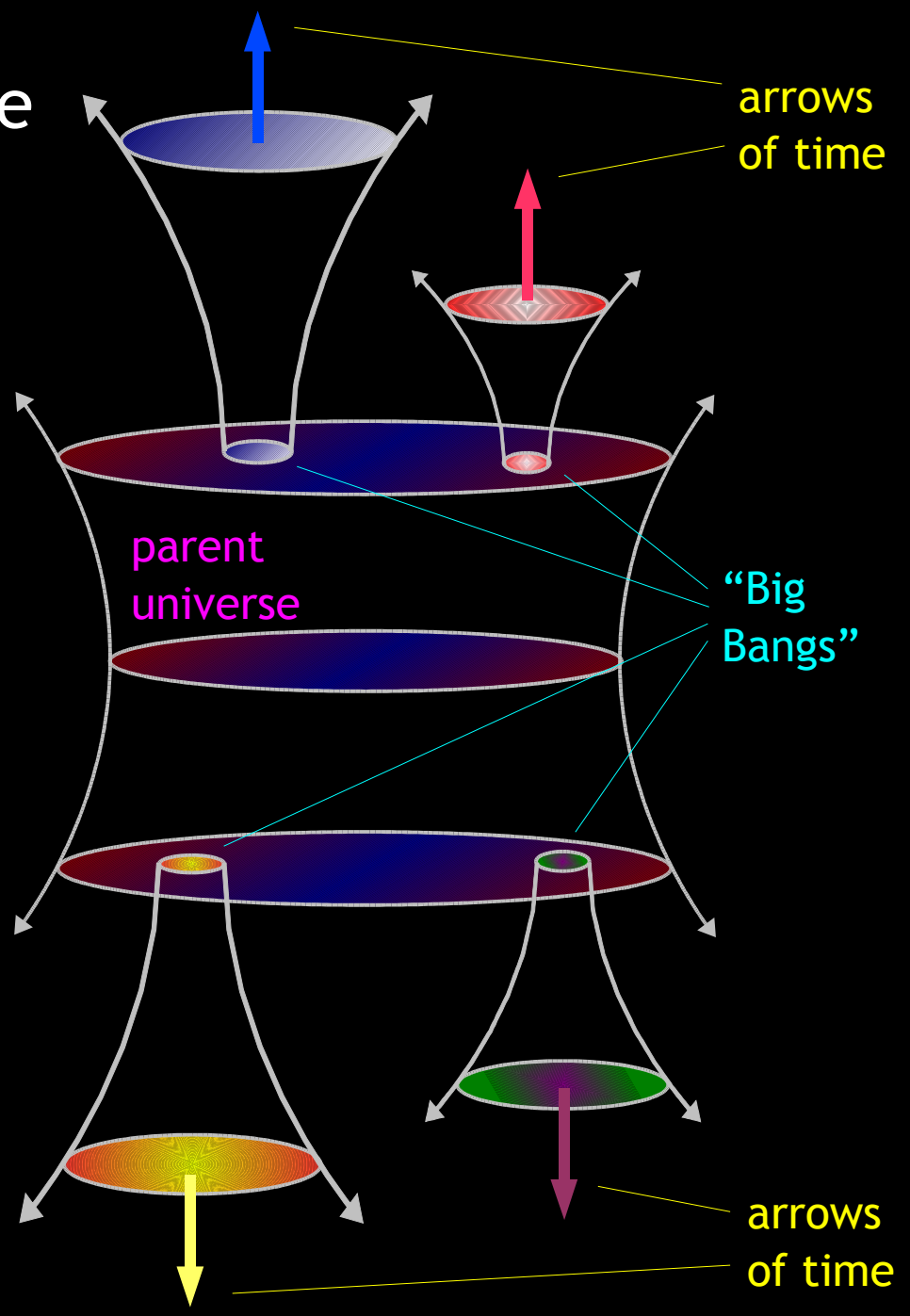
Everything we see was squeezed into a very tiny volume, and in a very smooth, featureless configuration. Entropy is growing today because the universe started in such an unlikely ordered state.

The question is: <u>why</u> did the universe start like that?

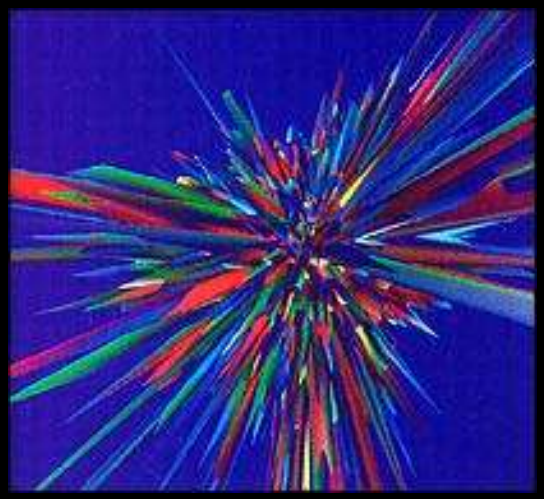
One possibility: our observable universe is just a tiny part of a much larger ensemble that is overall time-symmetric.

Baby universes created perpetually into the future, and also in the deep past with a <u>reversed</u> arrow of time.

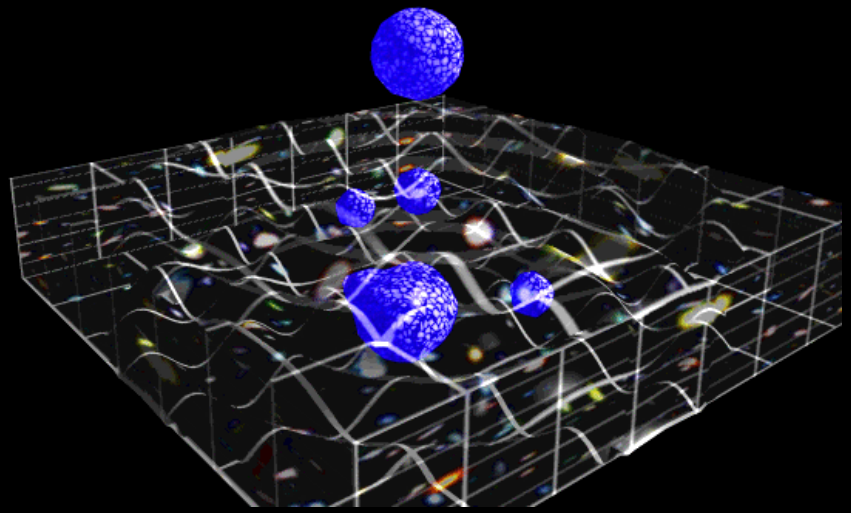
Isaac Newton could not have coped with "baby universes."



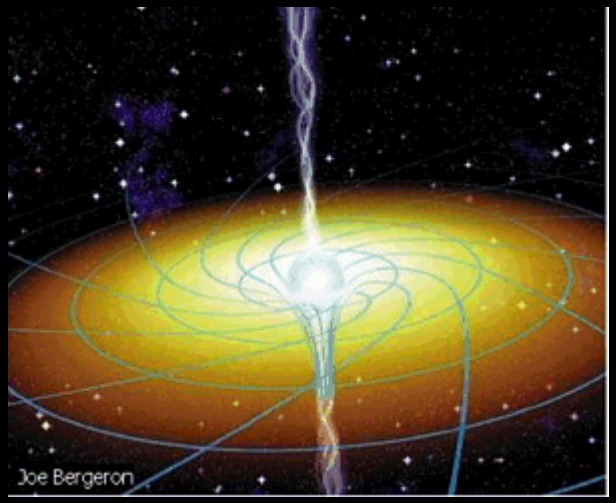
What's next? New theories.



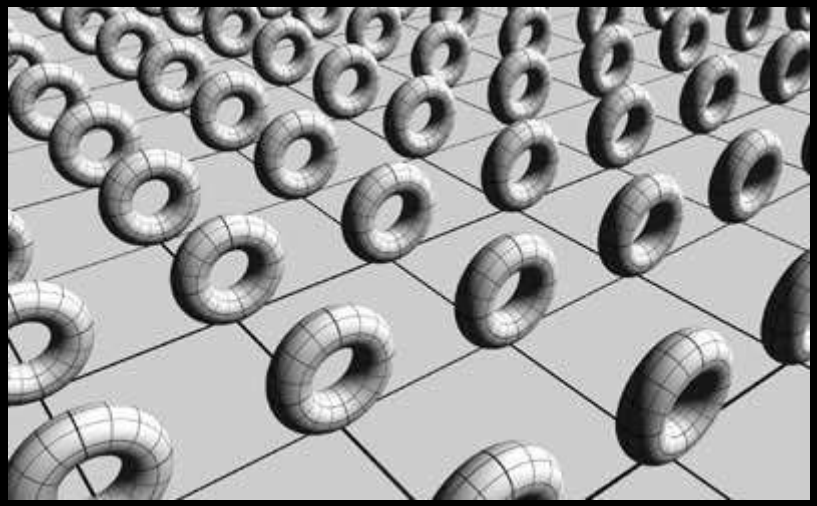
Inflation and multiple universes



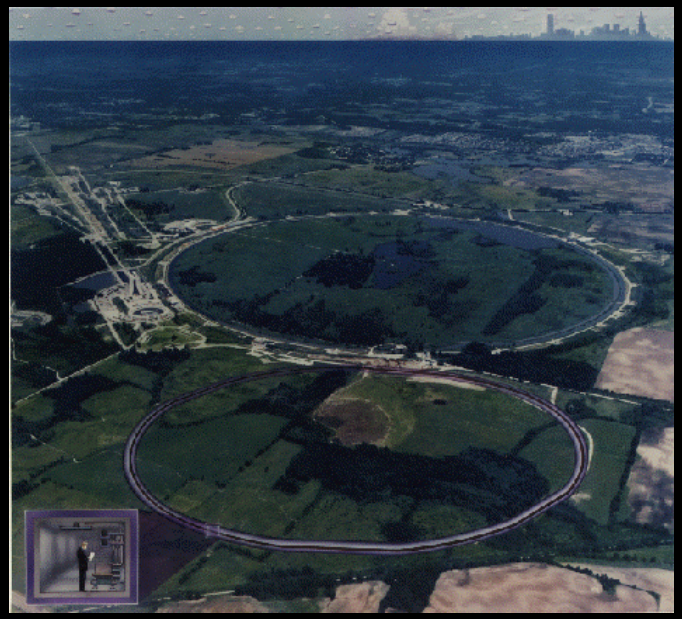
Superstrings, branes, and extra dimensions of spacetime



Black holes and quantum gravity

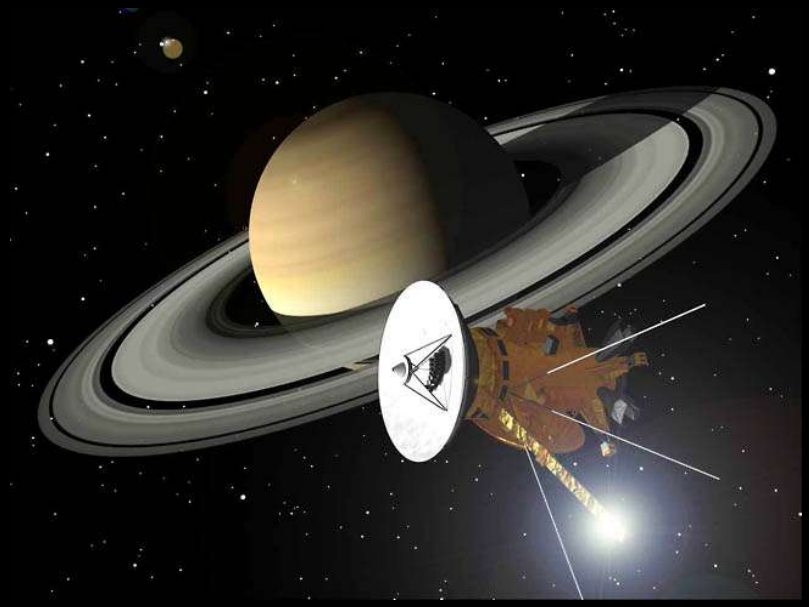


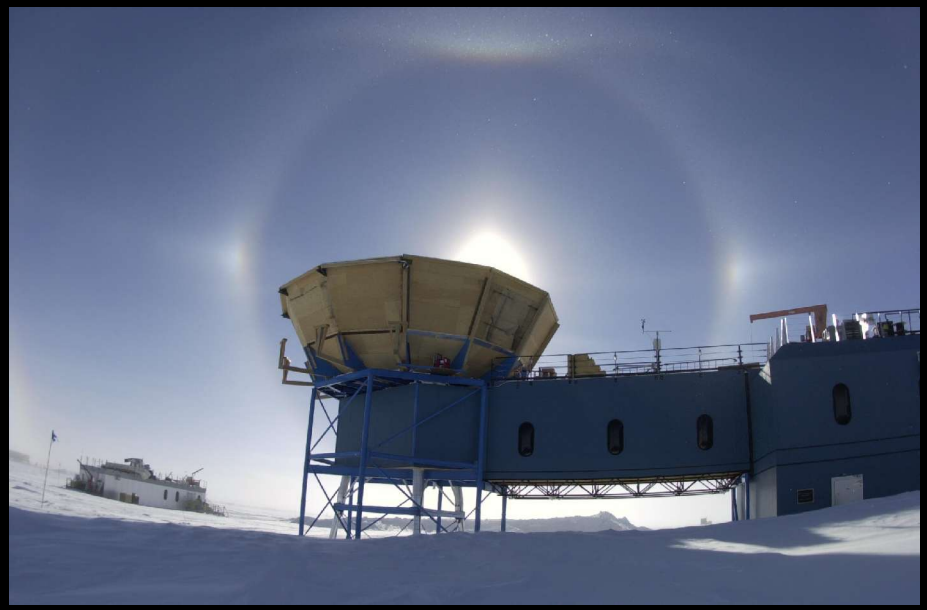
What's next? New experiments.



Particle accelerators

Satellites in the Solar System





Telescopes in space and on the ground

Precision laboratory experiments

We've learned a great deal about the universe in the last half-century: how particle physics works, what the universe is made of, and the key role played by dark energy.
We like to think that Einstein would be proud.

There is still a long way to go to fulfill Einstein's dream of a unified description of the laws of nature.

But the quest is half the fun.