Announcements

- Today is the **last day for news summary** extra credit – email submissions accepted until 5 pm today
- Next **midterm**: Wednesday after spring break, March 26
- Midterm will cover Chapter 3 and Chapters 9-12
- Will be extremely similar to quizzes
- Review in class Monday March 24
- **Quiz 8** on Chapter 12 due Monday March 24

The **event horizon** of a black hole

A is the physical surface of the black hole

B defines the outer edge of an accretion disk

C is the point from within which light cannot escape

D extends for millions of miles into space

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Black Holes

The mass of a neutron star cannot exceed about 3 solar masses. If a core remnant is more massive than that, nothing will stop its collapse, and it will become smaller and smaller and denser and denser.

Eventually the gravitational force is so intense that even light cannot escape. The remnant has become a black hole.

The radius at which the escape speed from the black hole equals the speed of light is called the event horizon.

An Earth-mass black hole has an event horizon of about a centimeter; for the Sun it is about 3 km.

OBSERVING BLACK HOLES

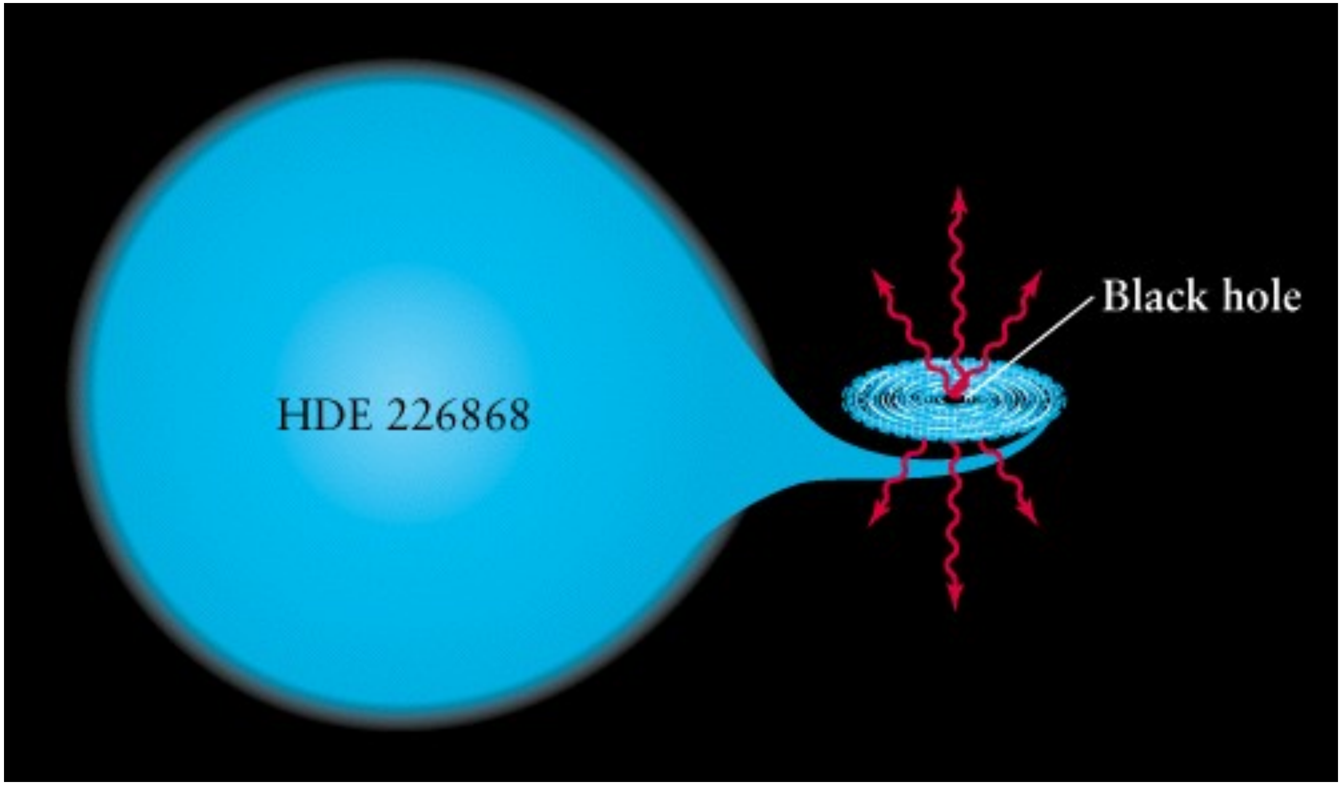
Black holes are black, so how do we see them?

If a black hole is in a binary system with a companion star that is close enough for some of its matter to be caught by the black hole, the matter spirals in at speeds close to the speed of light, heats up by its own enormous friction, and emits energetic x-rays.

But matter spiraling in to neutron stars also emits x-rays. How do we know we're looking at a black hole and not a neutron star? From the energy of x-rays, we know about how fast the infalling matter is moving and can conclude that it is caught by either a neutron star or a black hole.

Matter falling on a black hole from its companion in a binary system

Diagram of the same system



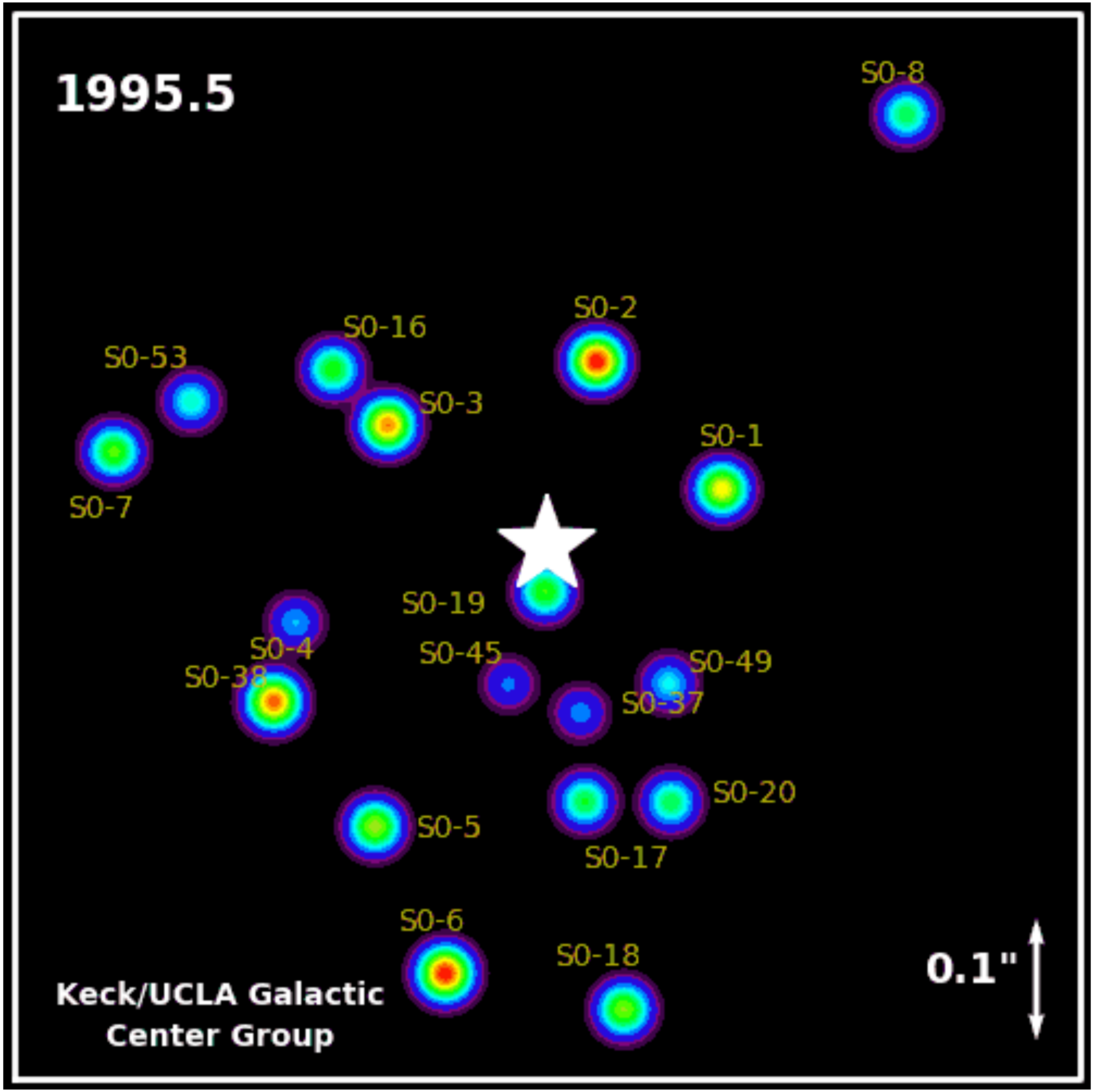
Supermassive Black Holes

- As we'll learn later, there are also **supermassive black holes**, with masses 10^6-10^9 times the mass of the Sun, at the centers of galaxies – including our own galaxy, the Milky Way
- Some of our best observational evidence for the existence of black holes involves black holes at the centers of galaxies
- This is done more or less the same way we find the masses of stars by observing binaries: we find stars orbiting the black hole, measure their orbits, and use Kepler's laws
- In the case of the Milky Way, the mass being orbited is so large and the volume containing it so small that it can only be a massive black hole!

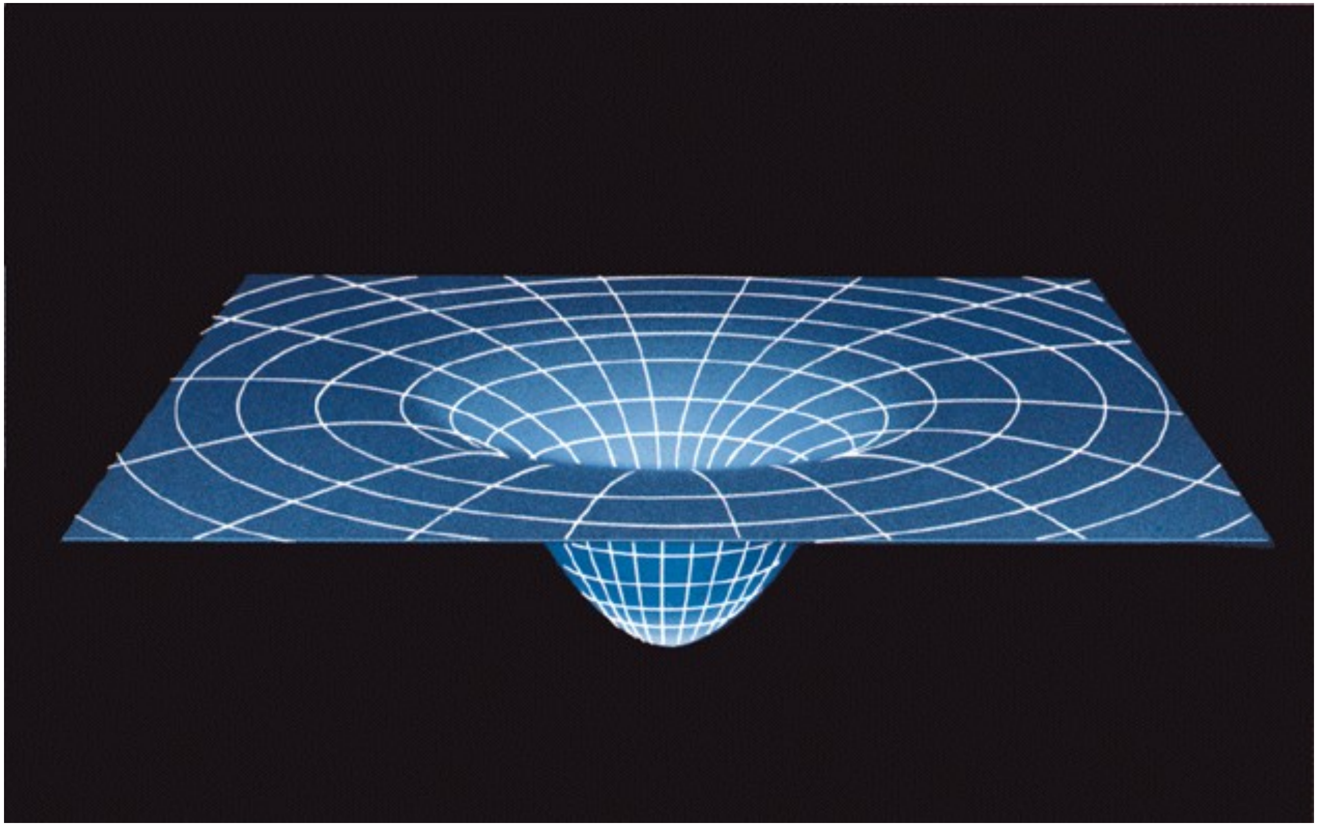
Animation of the orbits of stars around the supermassive black hole at the center of the Milky Way

Observations are made in the **infrared** to see through all the dust at the Galactic Center, and use **adaptive optics** to get enough spatial resolution to see the orbits of individual stars

Recall previous discussions of adaptive optics, and of reddening by dust!



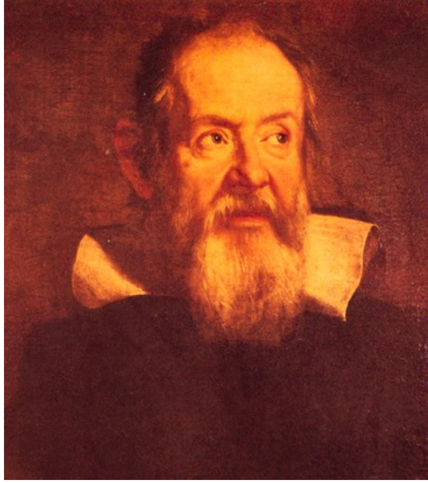
SPACE, TIME, AND SPACETIME



Recall the Galilean view of the universe…

GALILEAN

Meaning of the Copernican Revolution



- The Earth is curved
- Up depends on where you are
- The Earth is moving.

  We no longer have an absolute, unmoving reference point.
- Time is absolute:

  You know what it means for two events to occur at the same time
- Space is flat

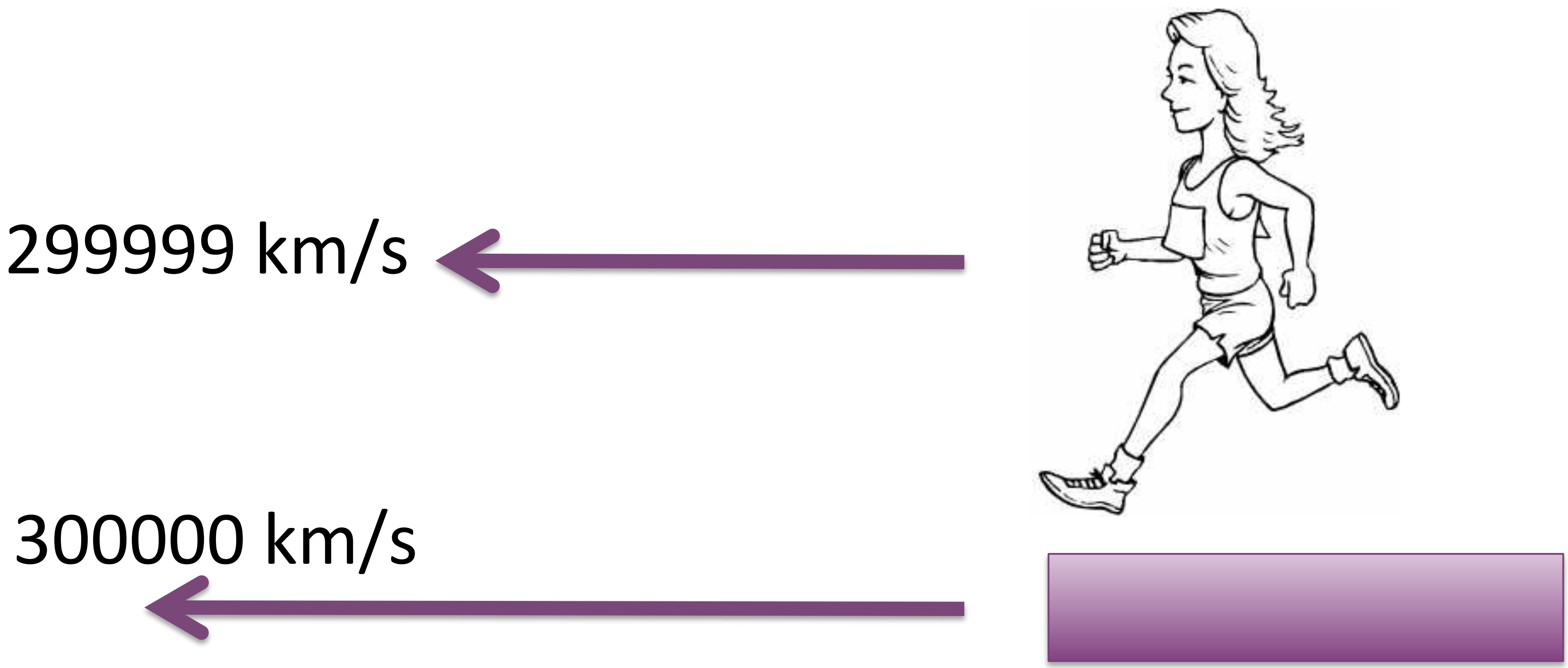
Special Relativity

People knew that light was an electromagnetic wave in the 19th century. But they thought that like all waves, it had to have a medium to move through. Thus, the speed of light would be different depending your motion relative to this absolute medium.

However, all the experiments showed that the speed of light was constant no matter what!

Also the equations that describe light say this explicitly, but no one made the giant conceptual leap until Einstein.

Einstein performed a thought experiment. Suppose you and a light beam are in a race. Your friend is watching you. What your friend sees is this



So your friend would say that that the light beam is moving just 1 km/s faster than you.

But you see this

300000 km/s

You see the light beam moving at the speed of light. It's almost as if you aren't even moving!

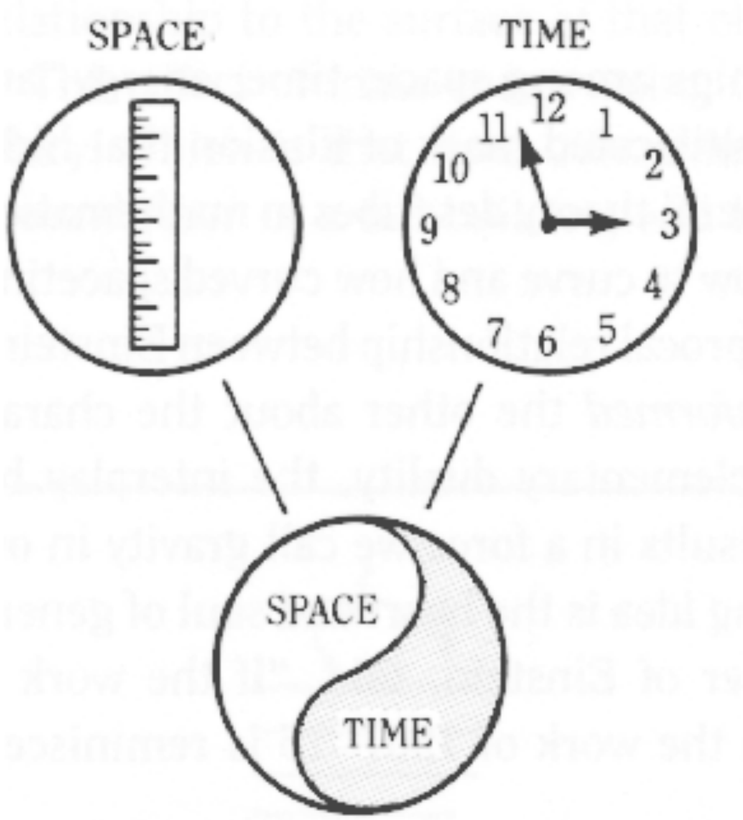
At the end of the race, you and your friend compare notes.

Friend: You were fast. You almost had the light beam nailed. Just 1 km/s faster!

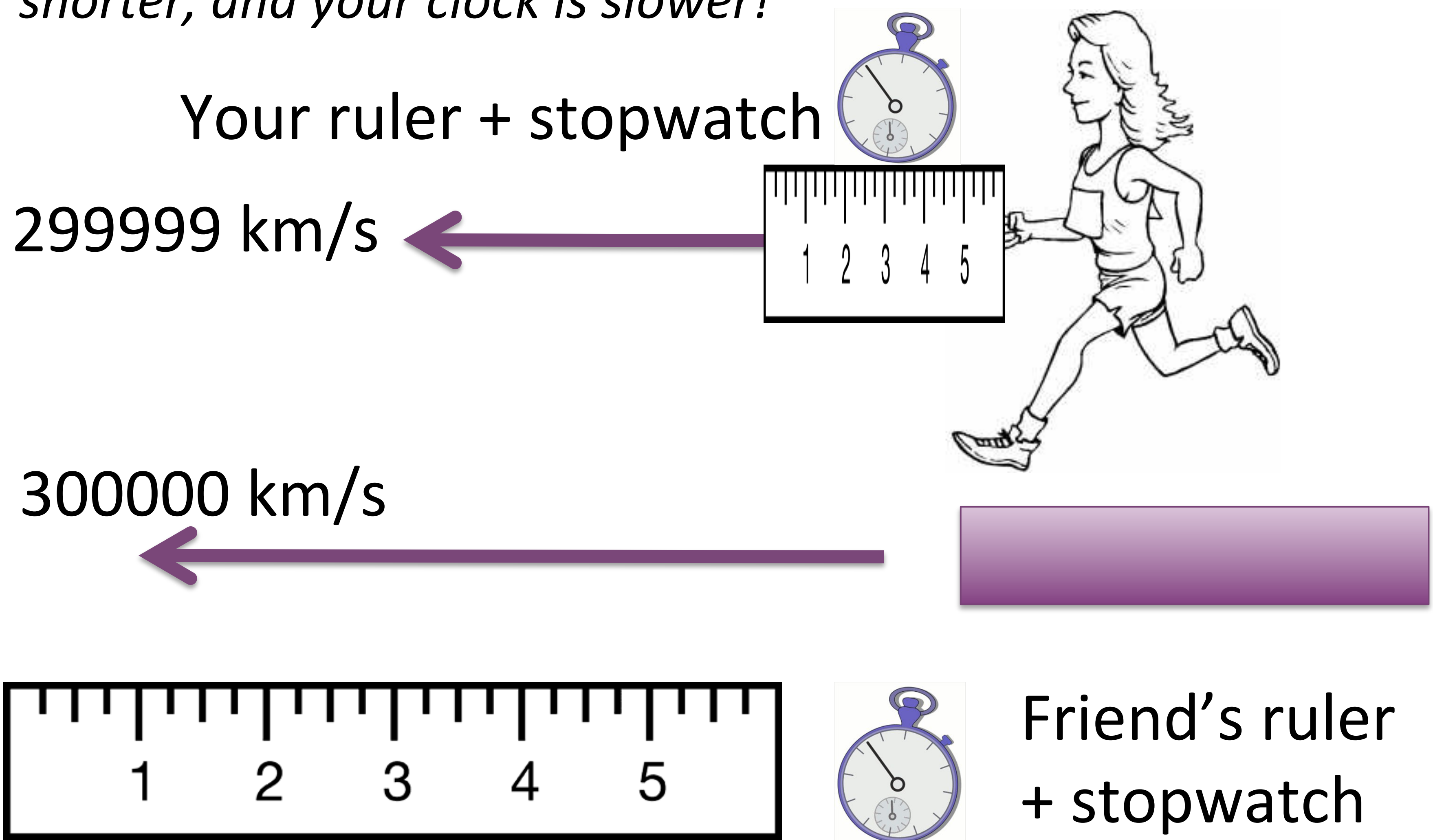
You: I was slow. It was as if I wasn't even moving!

How can both of you be right? The only way is that **space and time are relative and not absolute**.

Measurements of distance and time depend on how you are moving relative to the things you are measuring.



You and your friend do the experiment again, but this time you are holding a ruler and a stopwatch, both of which your friend can see. Your friend has an identical ruler and stopwatch. Now this is what your friend sees: *your ruler is shorter, and your clock is slower!*



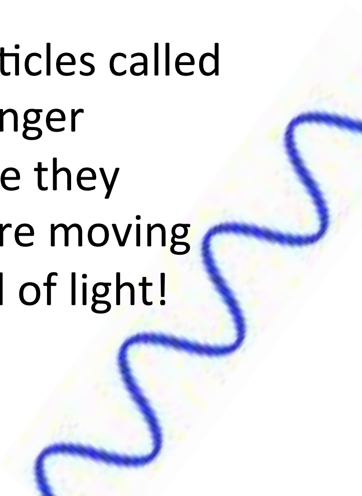
Einstein's theory of special relativity says

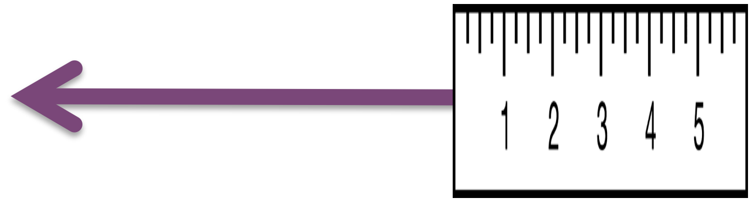
- objects moving near the speed of light are contracted in the direction of their motion
- time runs more slowly for an observer traveling near the speed of light (*time dilation*)
- events that happen at the same time according to me may not happen at the same time according to you, if we are moving relative to each other
- so the speed of light is always the same – the rulers and clocks we use to measure it are not!

These effects are real and experimentally verified!

Muon, former resident cat at the Institute of Astronomy in Cambridge, England

Subatomic particles called *muons* have longer lifetimes before they decay if they are moving near the speed of light!



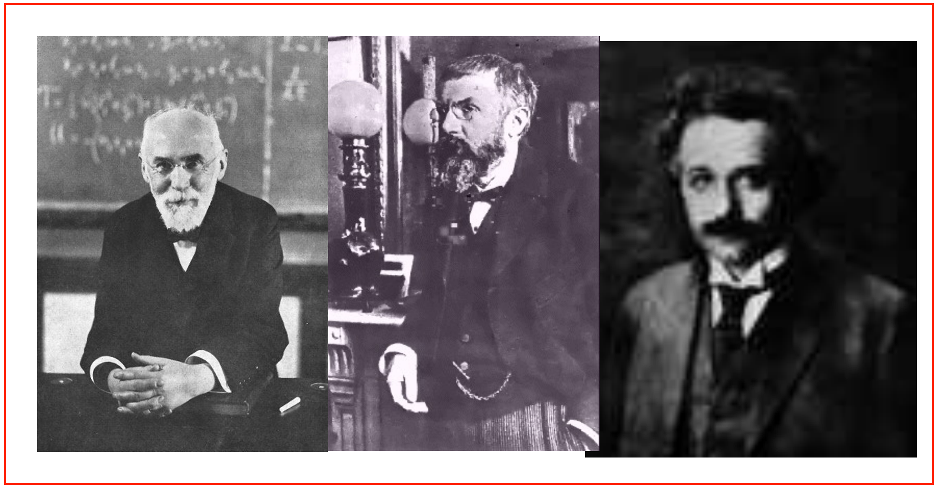


This is the meaning of relativity. **Time and space (or measurements of time and distance) can only be described relative to an observer and are not absolute quantities!** Two things that happen at the same time according to me may not happen at the same time according to you.

Time and space can't be considered independently: they are each parts of *spacetime*. There is **no absolute time**: clocks run at different rates depending on the relative speeds of the observers. There is **no absolute space**: how long you measure something to be depends on how fast it is moving relative to you.

SPECIAL RELATIVITY

The speed of light is the same to all observers



- The Earth is curved
- Up depends on where you are
- The Earth is moving.
- Space and time are mixed up with one another into *spacetime*, which depends on the observer

- Space-time is flat

If Einstein had stopped there, he would be considered one of the greatest physicists ever. But he didn't. He asked what this meant for the laws of motion.

Newton said that if an object feels no force, then it moves in a straight line.

Einstein thought long and hard about this and he realized that there was a hole in this way of thinking. He perform what is known as a "thought" experiment.

1. Suppose you are in a windowless ship in outer space. There is nothing nearby and you feel no forces acting on you.

Newton would say that you would continue to move in a straight line.

2. Now suppose your windowless ship is in orbit around the Earth. You again feel no forces acting on you.

But Newton wouldn't say you are moving in a straight line, but instead in a circular orbit.

Since your ship has no windows and you feel no forces in both cases, you can't tell the difference! What's going on?

There is no difference between 1 and 2 in terms of what you experience (no forces). Yet somehow you have to know which law to obey!

Einstein concluded that both situations are the same or equivalent. This became known as the equivalence principle.

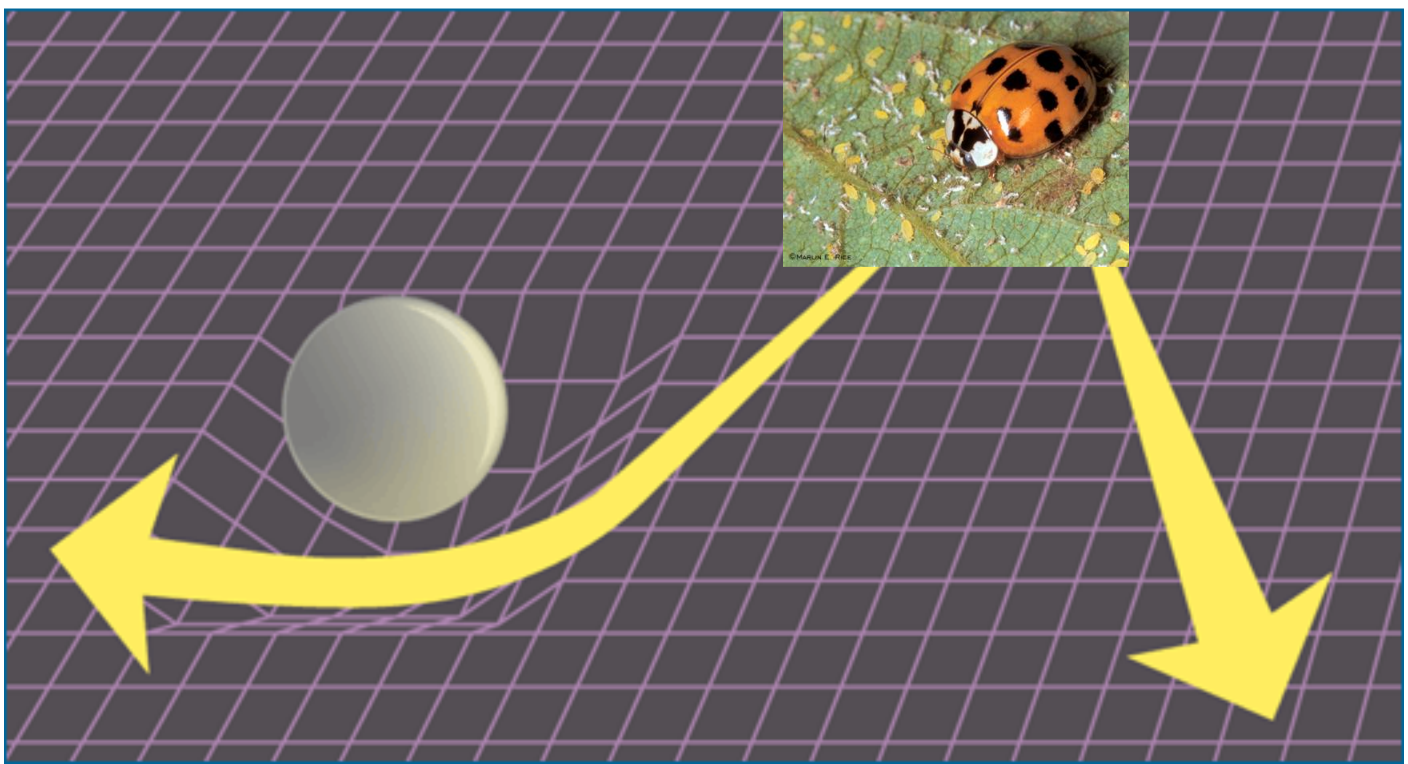
To reconcile this dilemma, he concluded that in both situations, you must move in a straight line, but *straight was not always straight*.

When is straight not straight?

Imagine you are watching a blind beetle walk along a flat piece of paper. It only moves forward in what it perceives as a straight line. On a flat piece of paper, it will trace out a straight line.

When is straight not straight?

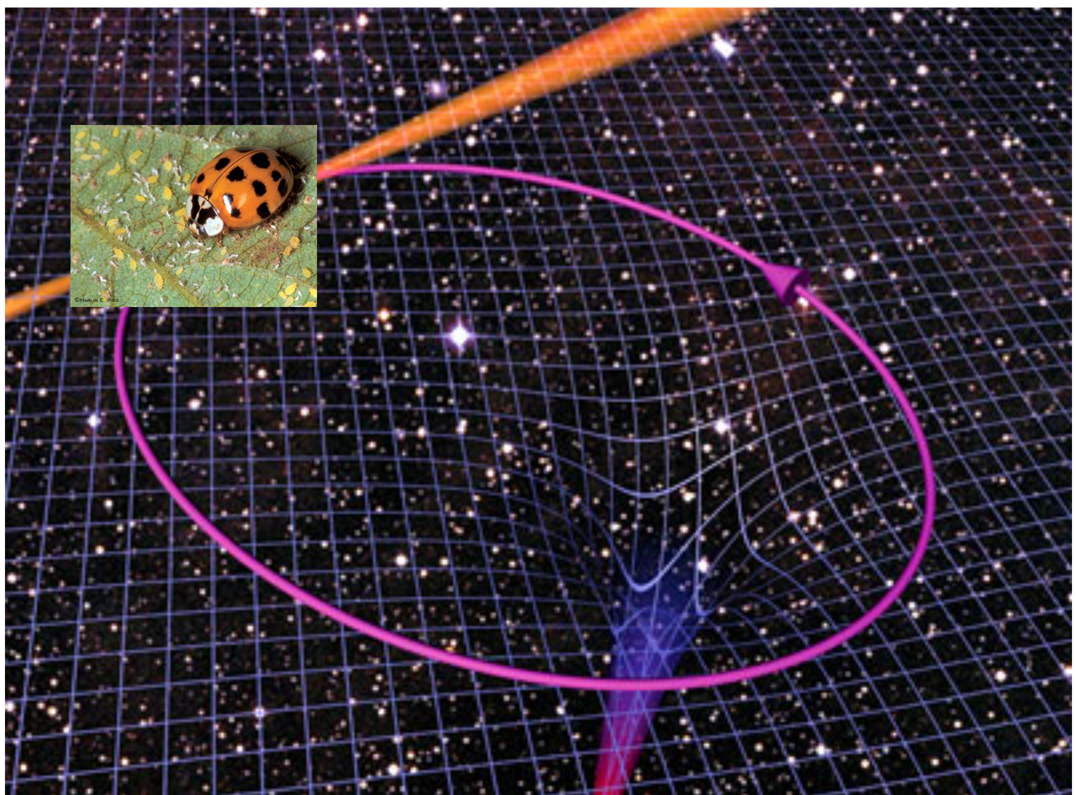
Now imagine you are watching a blind beetle walk along a curved piece of paper. It still tries to move in a straight line, but because of the curvature of the paper it doesn't move in a straight line (from our point of view above the paper).



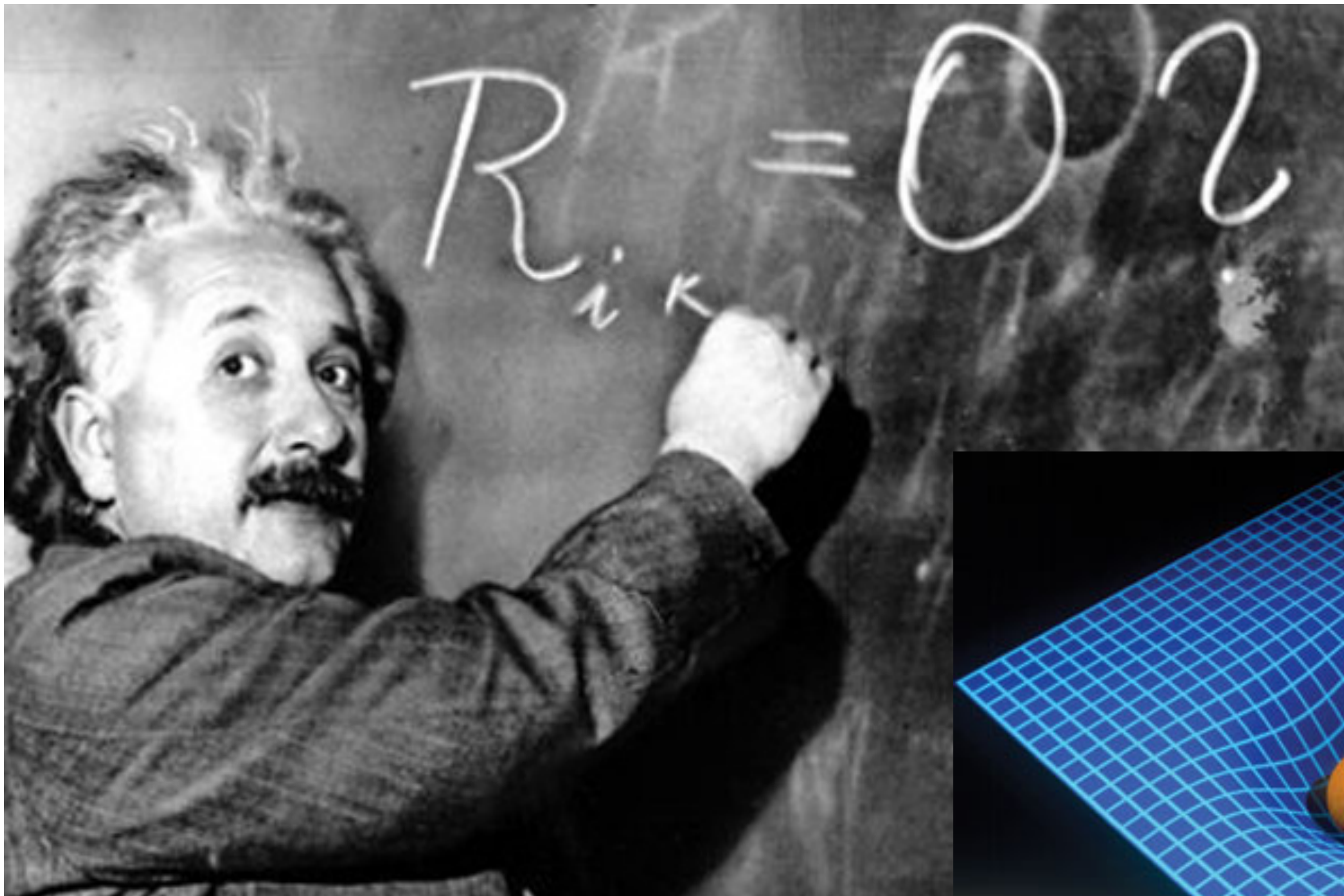
When is straight not straight?

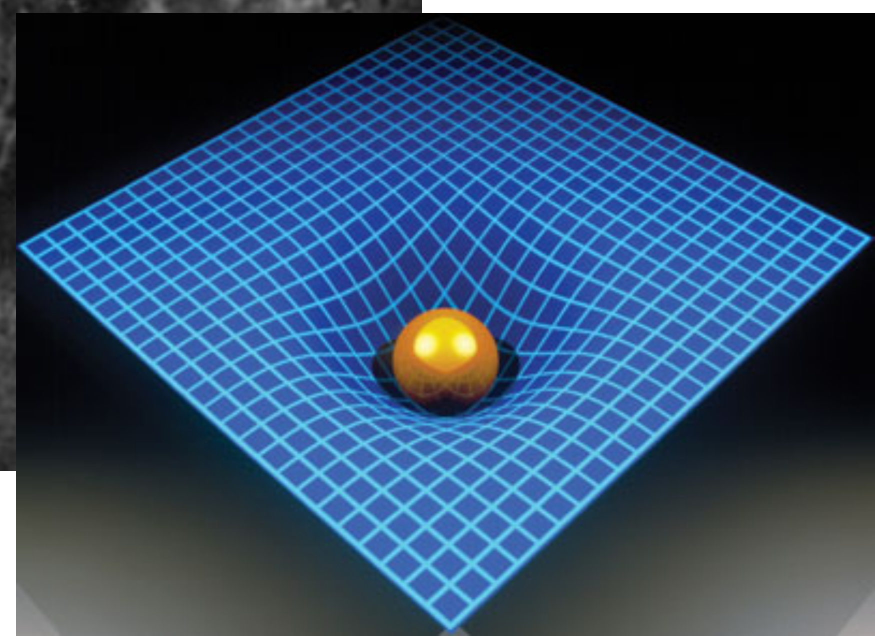
Now make the paper more and more curved.
Eventually its straight line becomes a circle.

This is starting to look like an orbit!

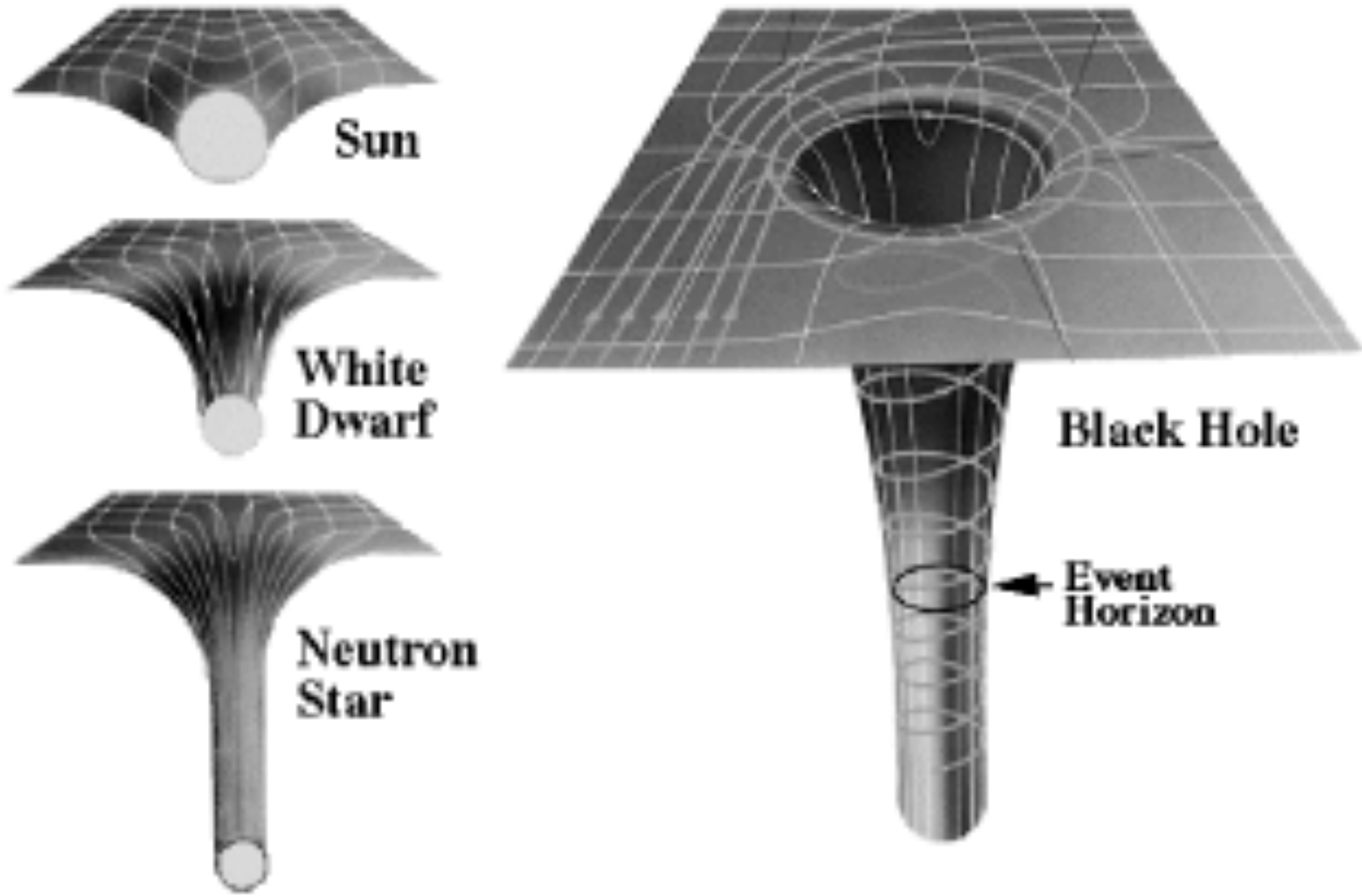


This is the **theory of general relativity**, Einstein's great triumph. He realized this around 1908-11, but it took him until 1915 to work out the math.

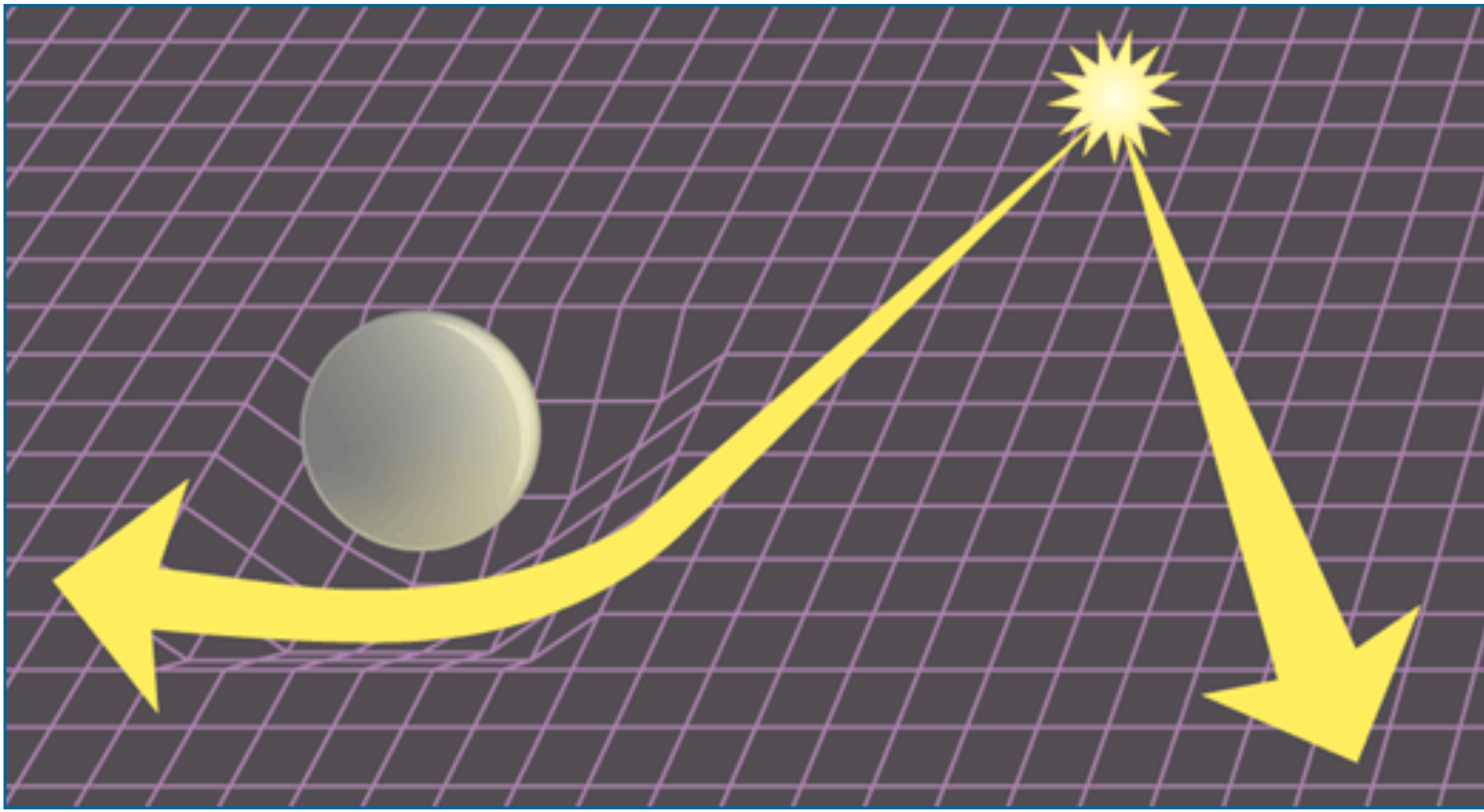




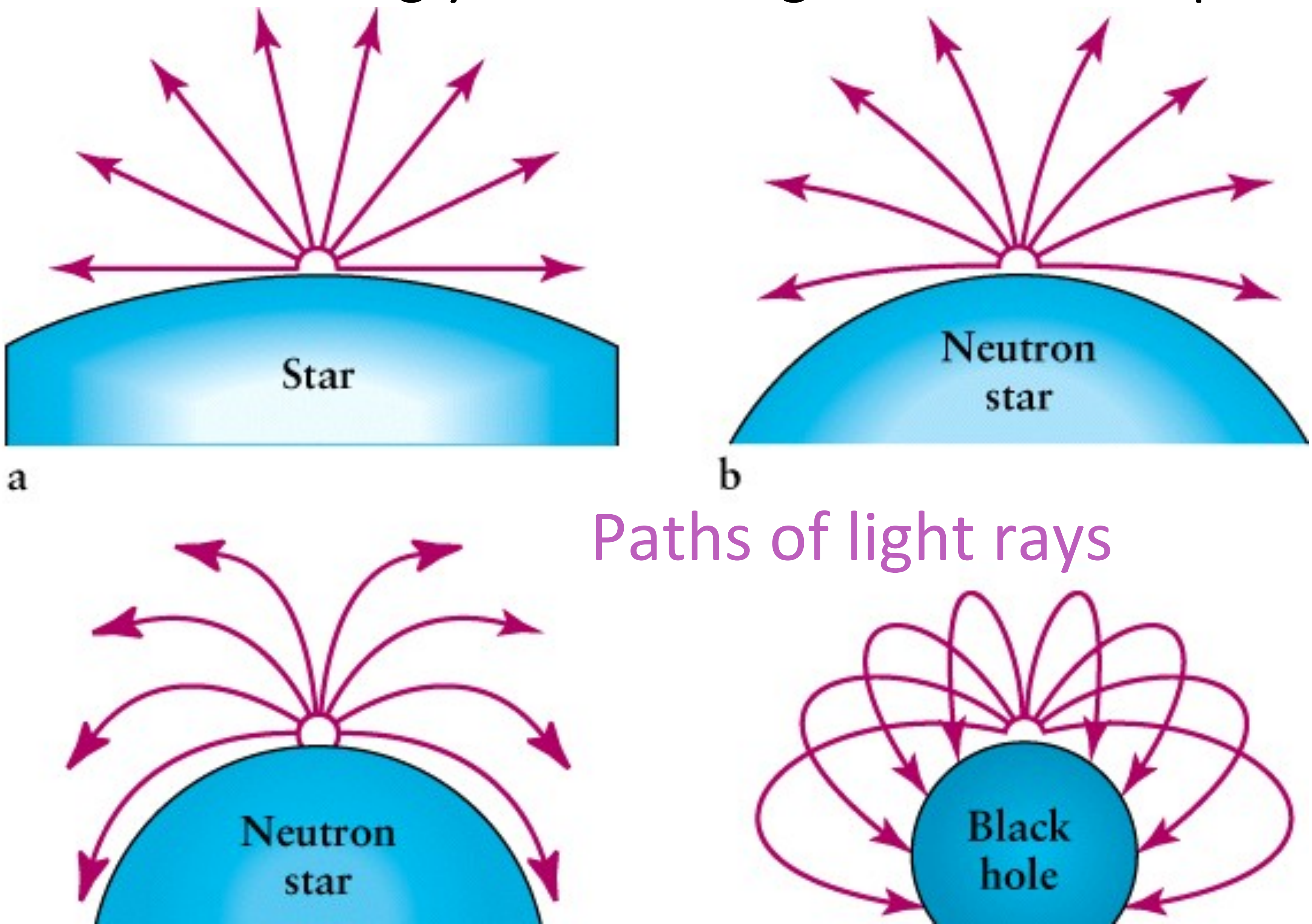
Mass warps spacetime. As we get to more and more massive and dense objects, the curvature gets greater and greater.



Because spacetime itself is curved, an object or a ray of light passing near a massive object and following a "straight" path will actually have a curved trajectory.



Black holes are regions of spacetime that are curved so strongly that even light cannot escape.



Paths of light rays

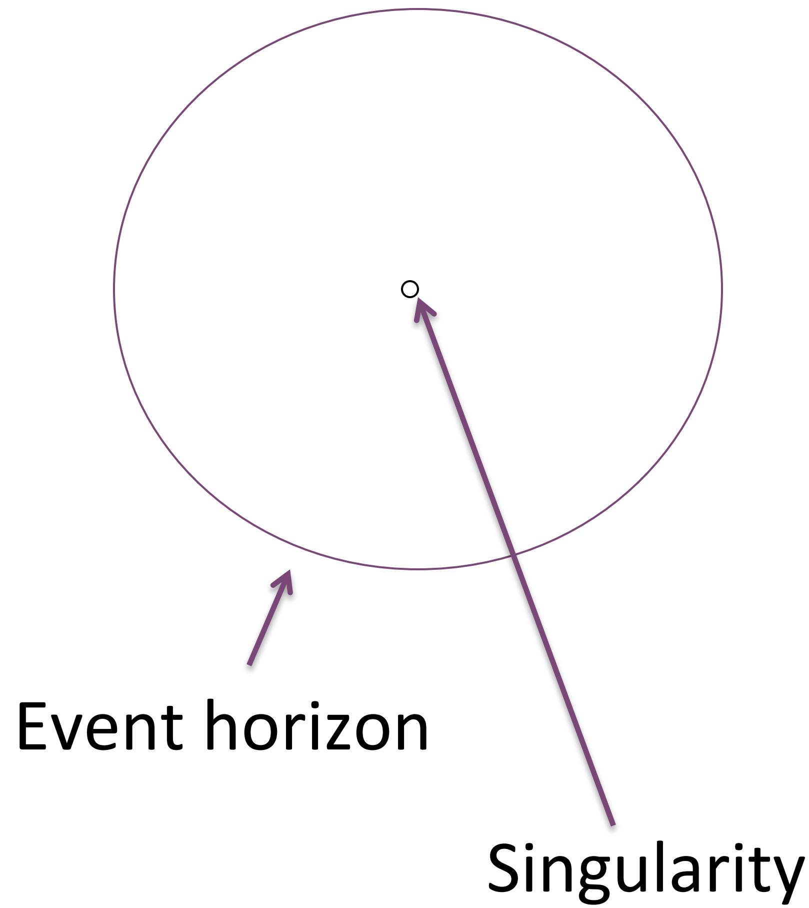
What happens if you fall into a black hole?

There are two places in a black hole that are special:

- Event horizon
- Speck in the center (*singularity*)

There is nothing actually at the event horizon – if you cross it you might not even notice. But your doom is sealed at this point: there is nothing you can do to escape.

The singularity is a point of infinite density – you are destroyed here.



What happens if you fall into a black hole?

But in fact, since you aren't a tiny speck, you probably won't survive even as far as the event horizon. The force of gravity is so strong, and changing so fast as you get closer and closer to the black hole, that it is much stronger on your feet than it is on your head. A gravitational forces that changes across the length of an object is called a **tidal force**, and in the case of a black hole, it will pull you apart.

What happens if you fall into a black hole?

This process is called *spaghettification*, since anything falling into a black hole will be stretched out like a piece of spaghetti!

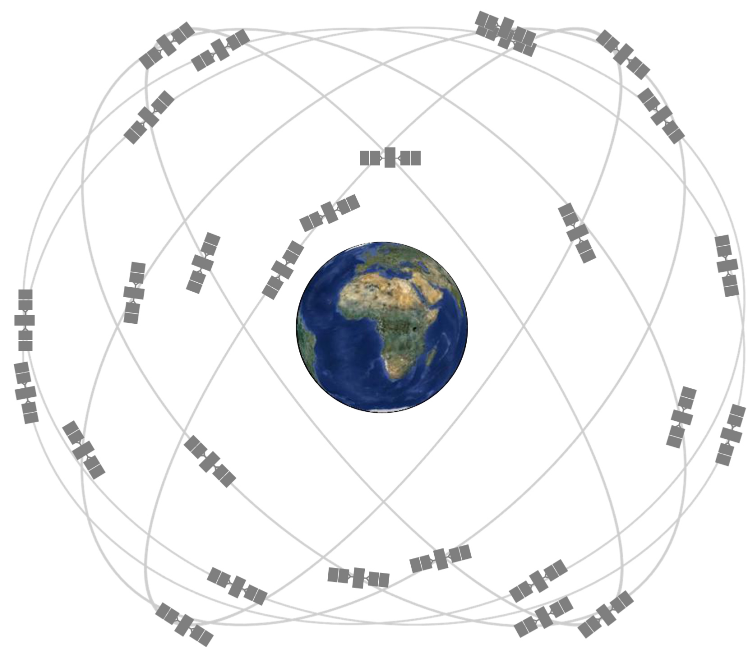
GENERAL RELATIVITY

- The Earth is curved
- Up depends on where you are
- The Earth is moving.
- Spacetime depends on the observer

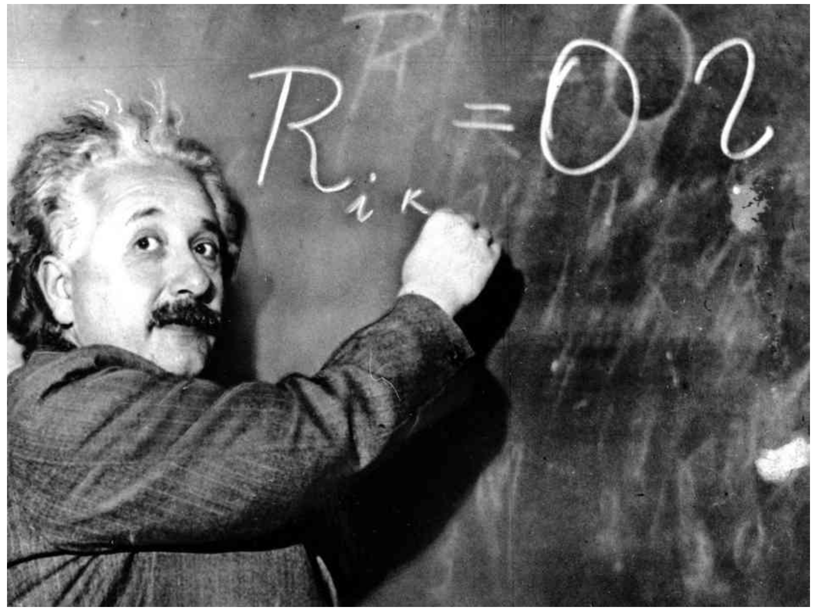
- Spacetime is curved

Relativity in the Real World

- GPS: how does it work?
  - Each satellite continually transmits message: time message was sent, position of satellite when message sent
  - Receiver records time messages received, uses speed of light to calculate distance to satellite
  - Messages from four or more satellites then used to determine position



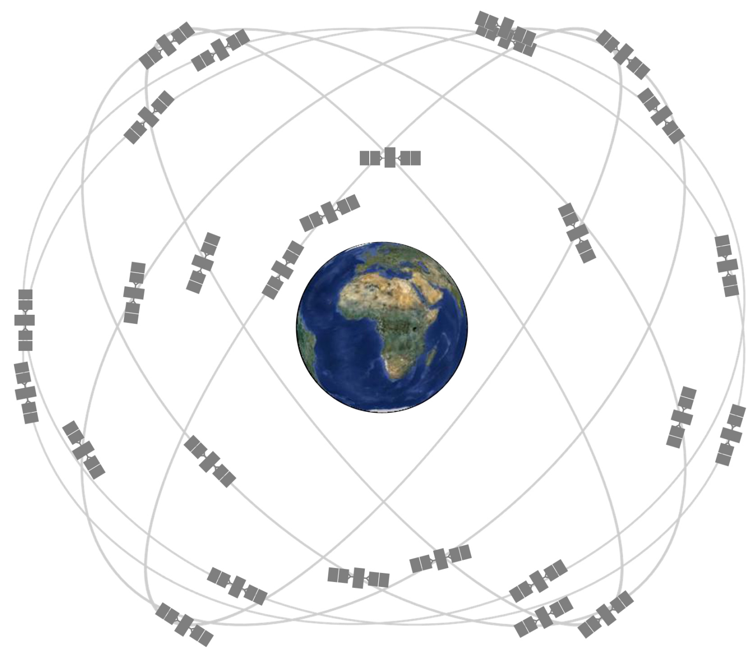
Relativity in the Real World



- Special relativity: clocks run slower at high speeds
- General relativity: clocks run slower in a strong gravitational field

Relativity in the Real World

- GPS satellites: need to correct clocks on satellites!
  - Special relativity: clocks run slow because satellites move fast
  - General relativity: clocks run fast because satellites are farther from Earth
- Without these corrections, GPS positions would be wrong after 2 minutes, and errors would accumulate at a rate of 10 km per day!



Relativity in the Real World

Gravitational waves

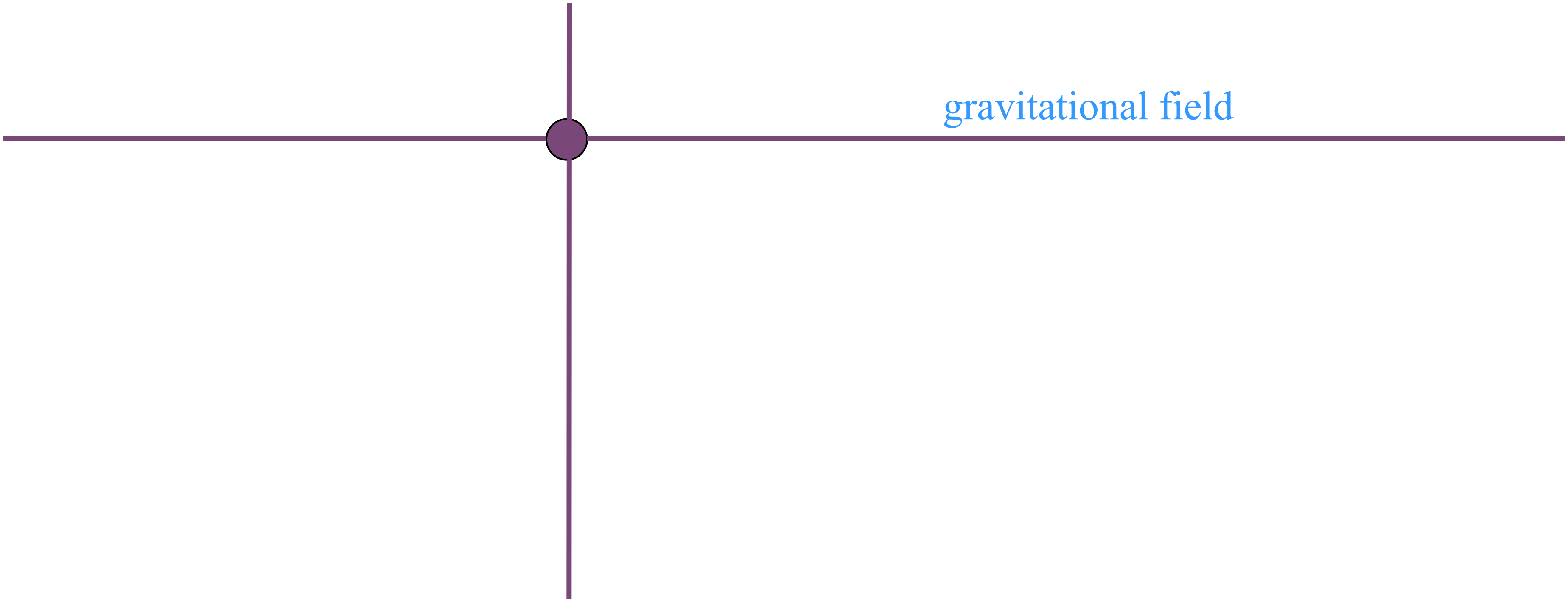
When Einstein derived the theory of general relativity, he found that the equations allowed for the existence of gravitational waves.

If gravity is the warping of space and time, then gravitational waves are a warping of space and time that varies as a function of time – they are waves in spacetime itself

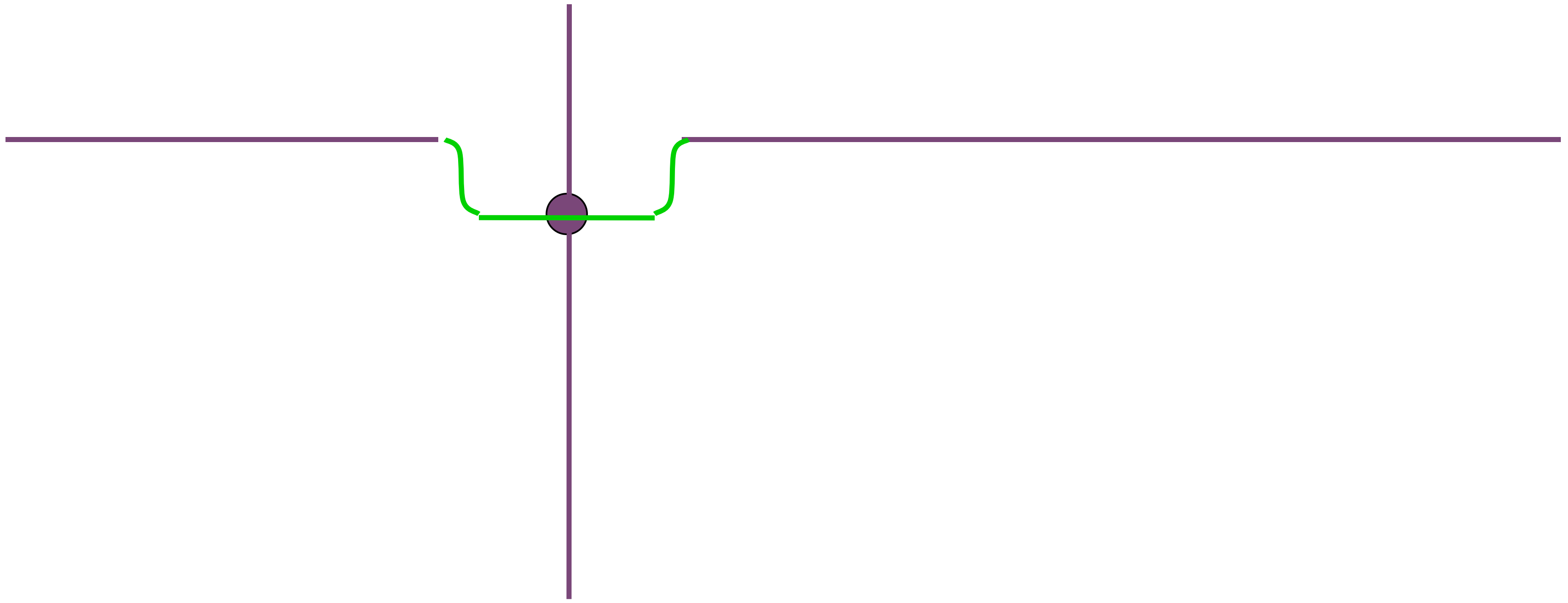
How do gravitational waves work?

Recall that electromagnetic waves are produced by moving charged particles. Similarly, gravitational waves are produced by ***moving massive particles.***

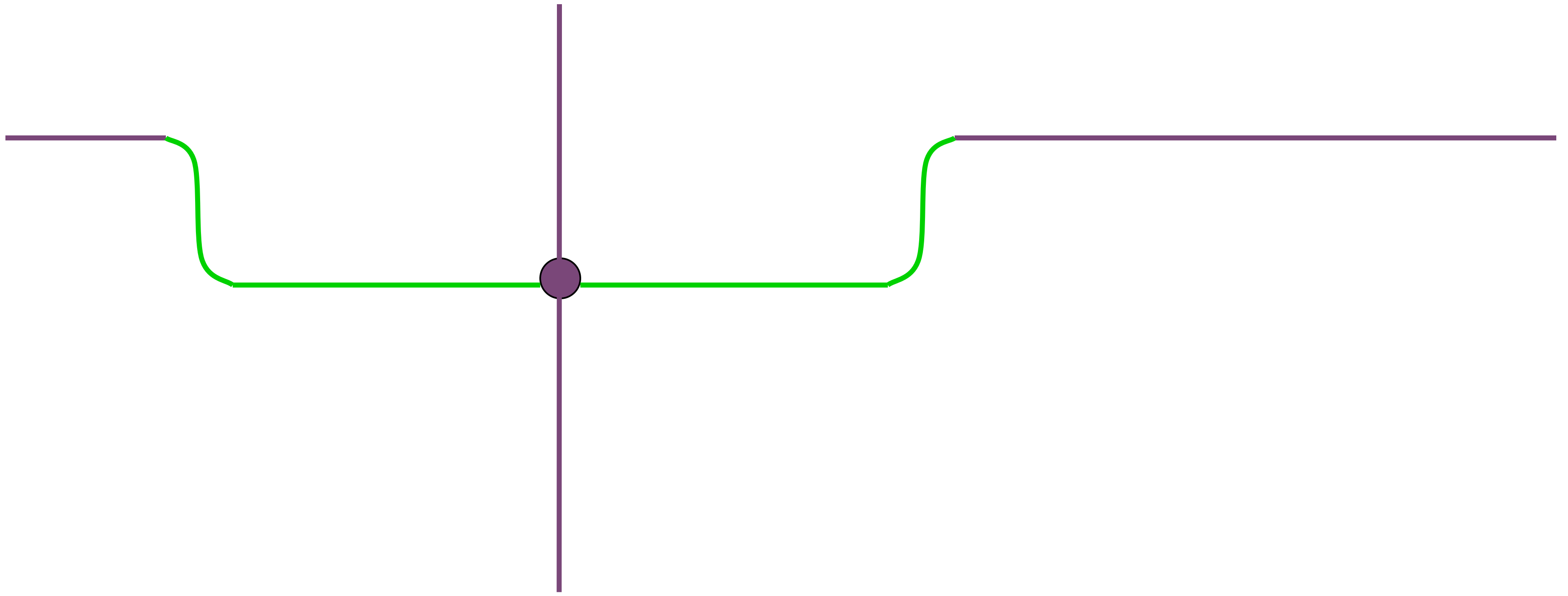
When a massive object moves, the information that it is at a new position travels outward at 300,000 km/s.



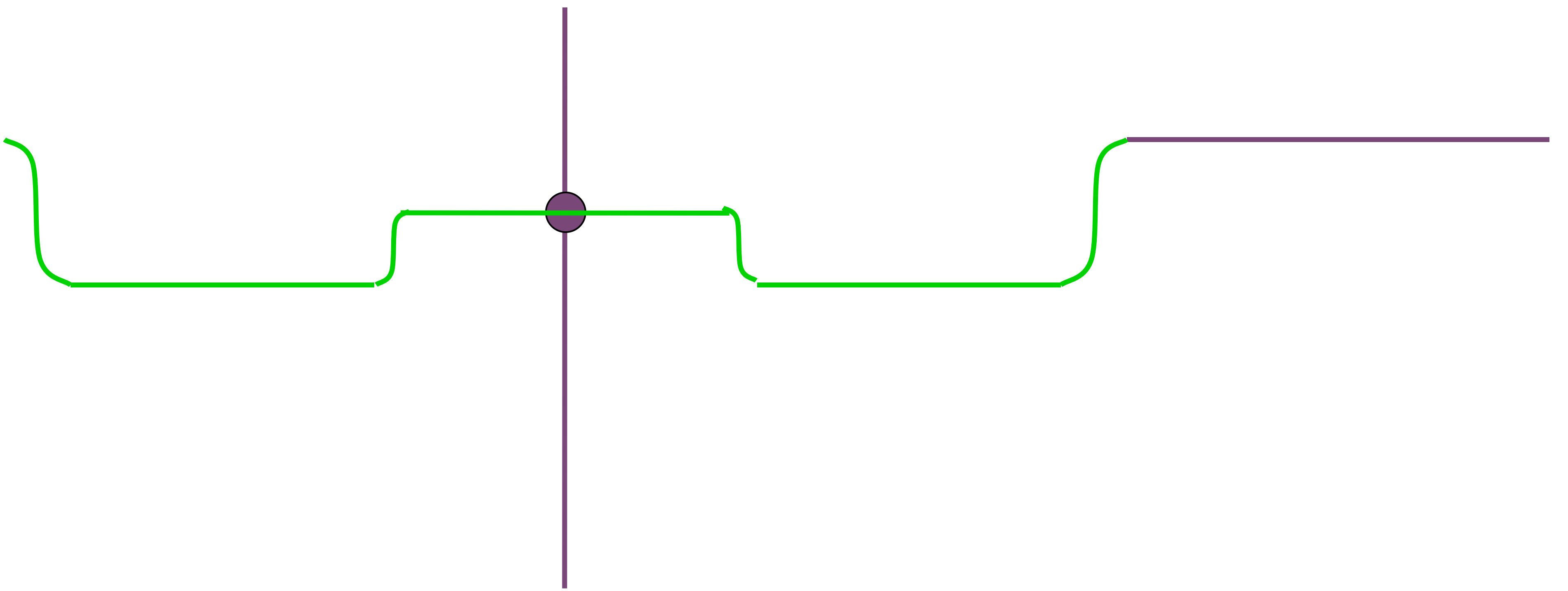
After 1 second, the gravitational field has changed only within a distance 1 light-second from the mass (about the distance from the Earth to the Moon).

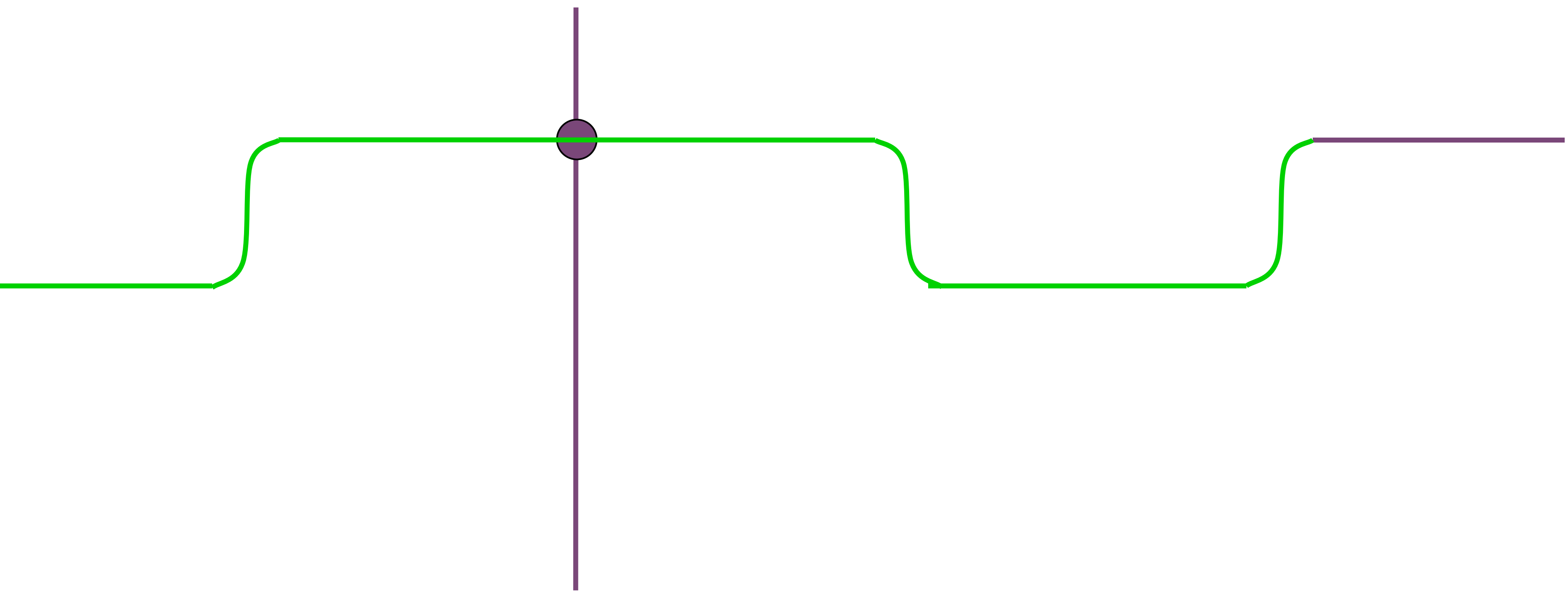


After 2 seconds, the gravitational field has changed within a distance 2 light-seconds from the mass.



After 3 seconds, the gravitational field has changed within a distance 3 light-seconds from the mass.





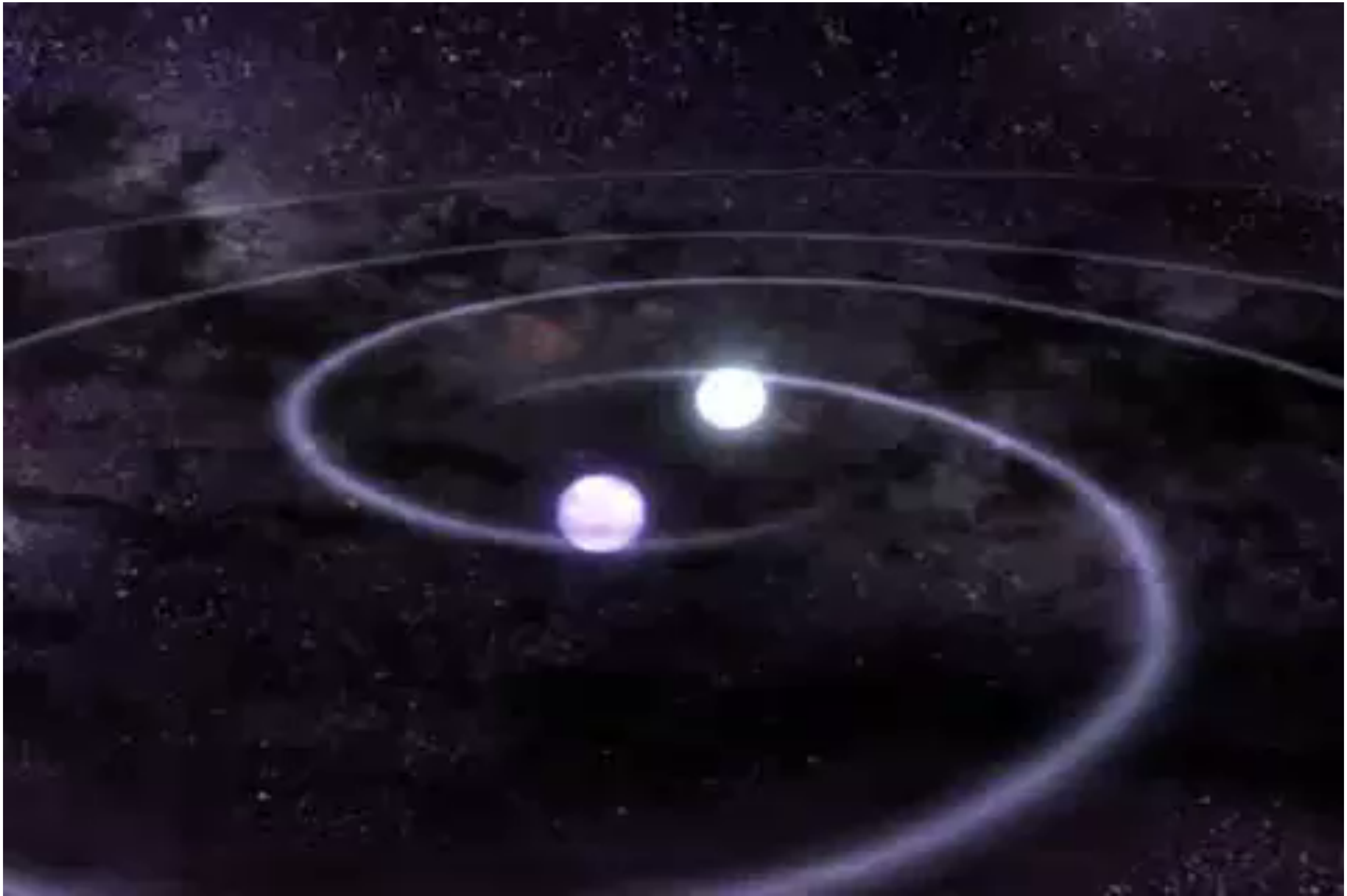
Gravitational waves

These waves are very very weak, because gravity is a weak force: the electromagnetic force between two protons is 10^{36} times stronger than their gravitational attraction.

This means that the only way to generate them is to take massive objects and move them really fast.

So we expect to see gravitational waves from neutron stars and black holes that are in a very tight and fast orbit.

An animation of gravitational waves

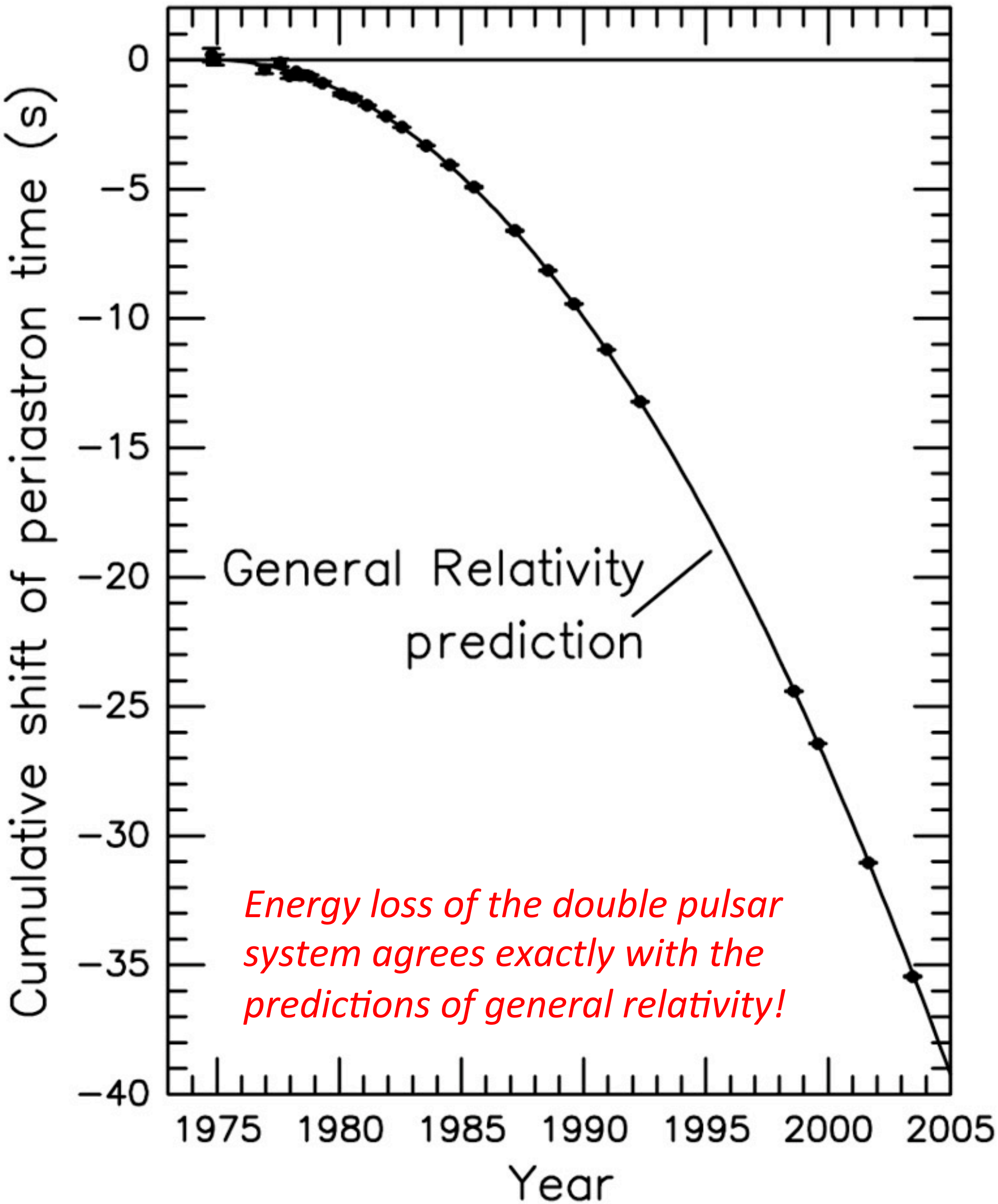


Gravitational wave astronomy

- The most violent events in the universe are also the most invisible.

- The merging of two black holes releases the maximum amount of energy possible ($E=mc^2$) in the shortest time possible (time it takes light to go across a black hole)

- But the energy is in gravitational waves, which are very hard to see



We have excellent *indirect* evidence for the existence of gravitational waves: two pulsars in a binary orbit are losing energy at exactly the rate predicted for their energy loss from gravitational waves.

But we have not yet seen the gravitational waves directly.

Gravitational-wave astronomy

So far all we have seen is the inspiral of the stars: The gravitational waves themselves have not been seen. But the waves from neutron stars that spiral together and coalesce are just barely strong enough to be able to detect them with the most sensitive instruments on Earth.

As a result, there is now a worldwide effort to detect gravitational waves , with first-generation gravitational-wave observatories now operating in Germany, Italy, Japan, and the US.

By sometime around 2017, the US observatory is expected to make the first direct detection, and you should be reading newspaper headlines saying that gravitational waves from a pair of neutron stars (or a neutron star-black hole binary) have been detected.

The US observatory is named **LIGO: Laser Interferometer Gravitational-wave Observatory**.

When a gravitational wave passes, it changes the distance between two mirrors, placed 4km apart, by a distance smaller than an atom - by about the size of an atomic nucleus.

That incredibly tiny change in distance is measured by bouncing a laser beam back and forth between two mirrors about 10,000 times, to magnify the change in distance traveled by about that many times.

LIGO’s two detectors:
4km vacuum tunnels
join pairs of mirrors
at Hanford , WA
Livingston, LA