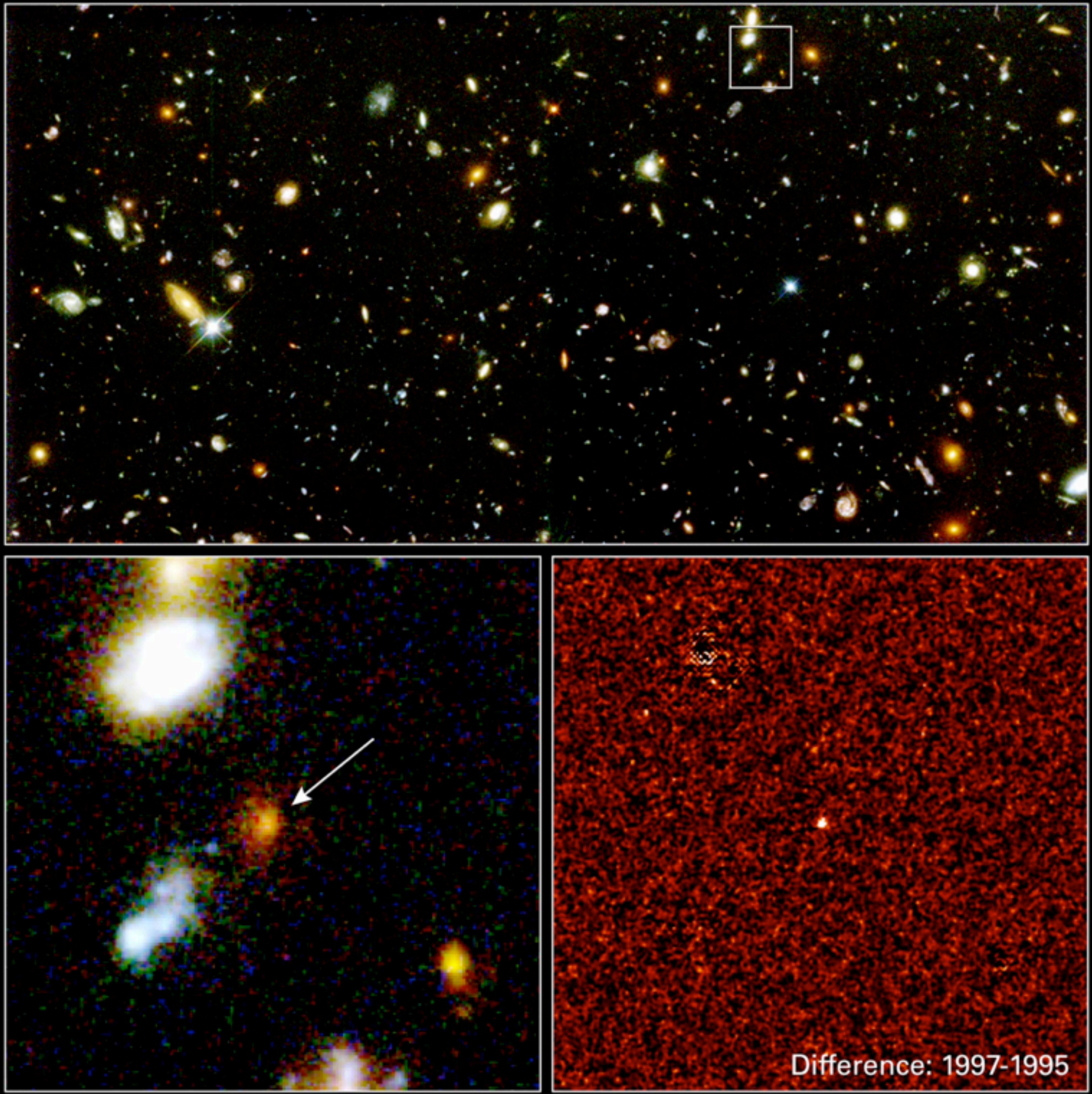
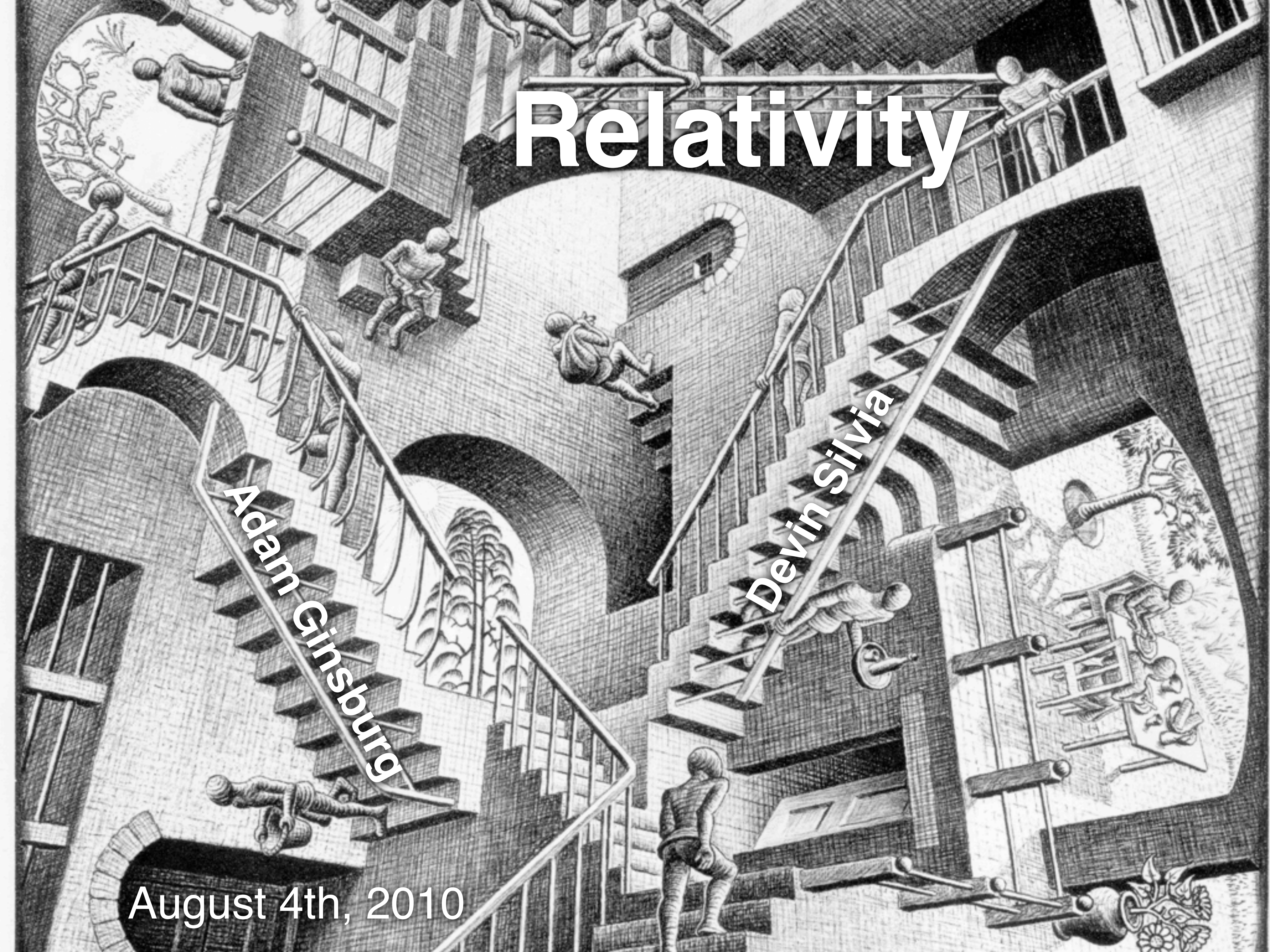

Difference: 1997-1995

Study Guide

- Study guide is available on CU Learn
- Tomorrow is review & pizza


Relativity
Adam Ginsburg
Devin Silvia
August 4th, 2010

Outline

- Special Relativity
  - Thought experiments
- General Relativity
  - curvature of spacetime
  - Around black holes
  - inside black holes
  - strange behaviors
- Other oddball topics

Relativity

Two major tenets:

1. The laws of nature are the same for everyone (the same everywhere)
2. The speed of the light is the same for everyone

What are the key facts on which special relativity is based?

A. The speed of light is the same for all observers.

B. The laws of nature look the same to all observers.

C. There is no preferred “up” or “down” in space.

D. all of the above

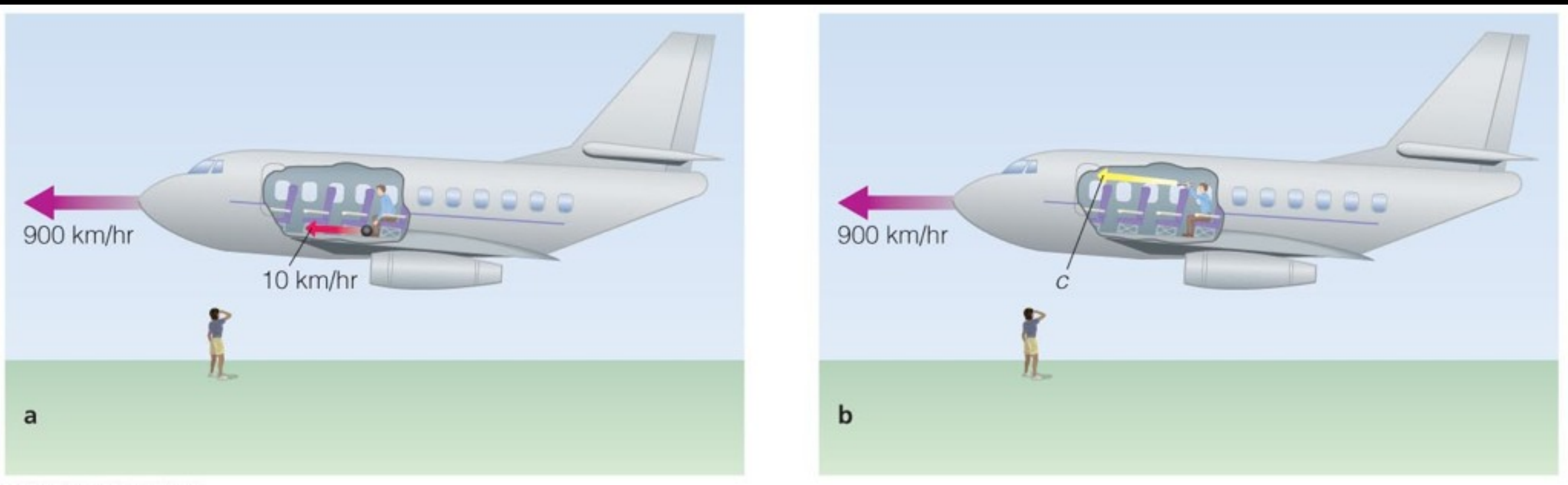
E. A and B

Einstein it up

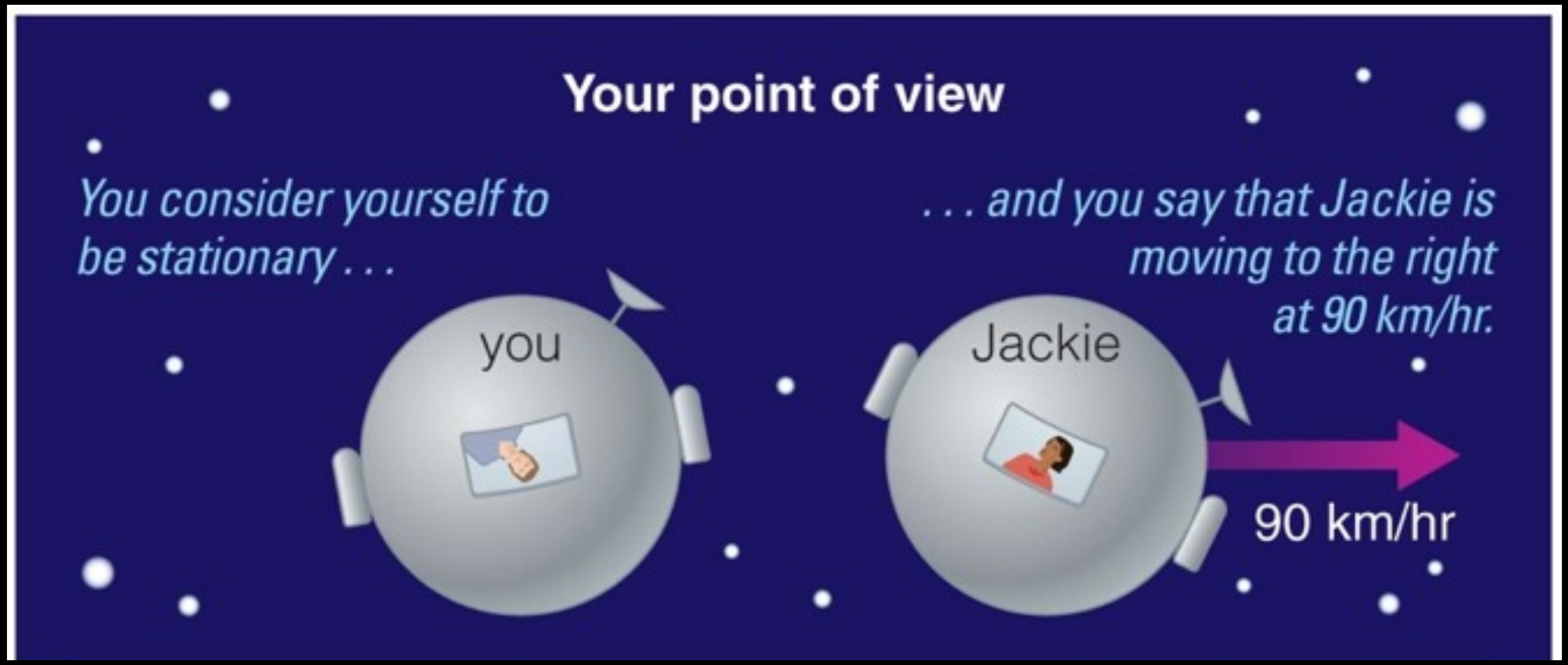
- Albert Einstein, everyone's favorite crazy-haired genius, performed a series of "thought experiments" to come up with the laws of relativity
- A thought experiment is a test of physical laws based entirely on hypothetical situations. The idea is to set up an experiment and predict its results without having to perform the experiment, perhaps because it is impractical (rather than impossible)

Start simple...

- If you roll a ball along the floor of an airplane, you see it rolling at 10 km/hr
- An observer from the ground would see it going at 910 km/hr (speed of plane + speed of ball)
- If you shine a flashlight, both you and the ground observer see the light traveling at c, the speed of light



Thought Experiment 1:
You fly your spacecraft past Jackie's at 90 km/hr
What do you observe? What does Jackie observe?



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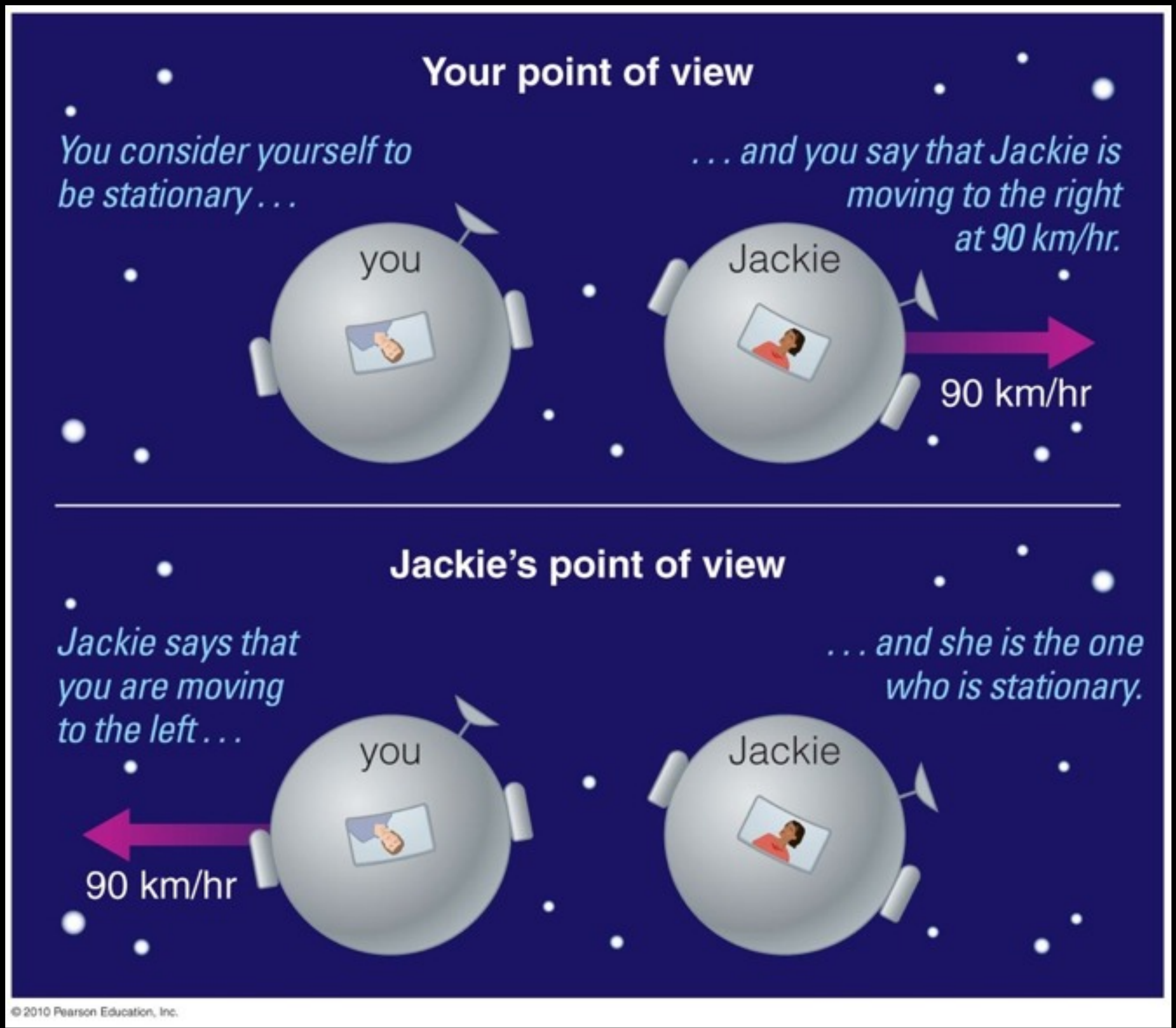
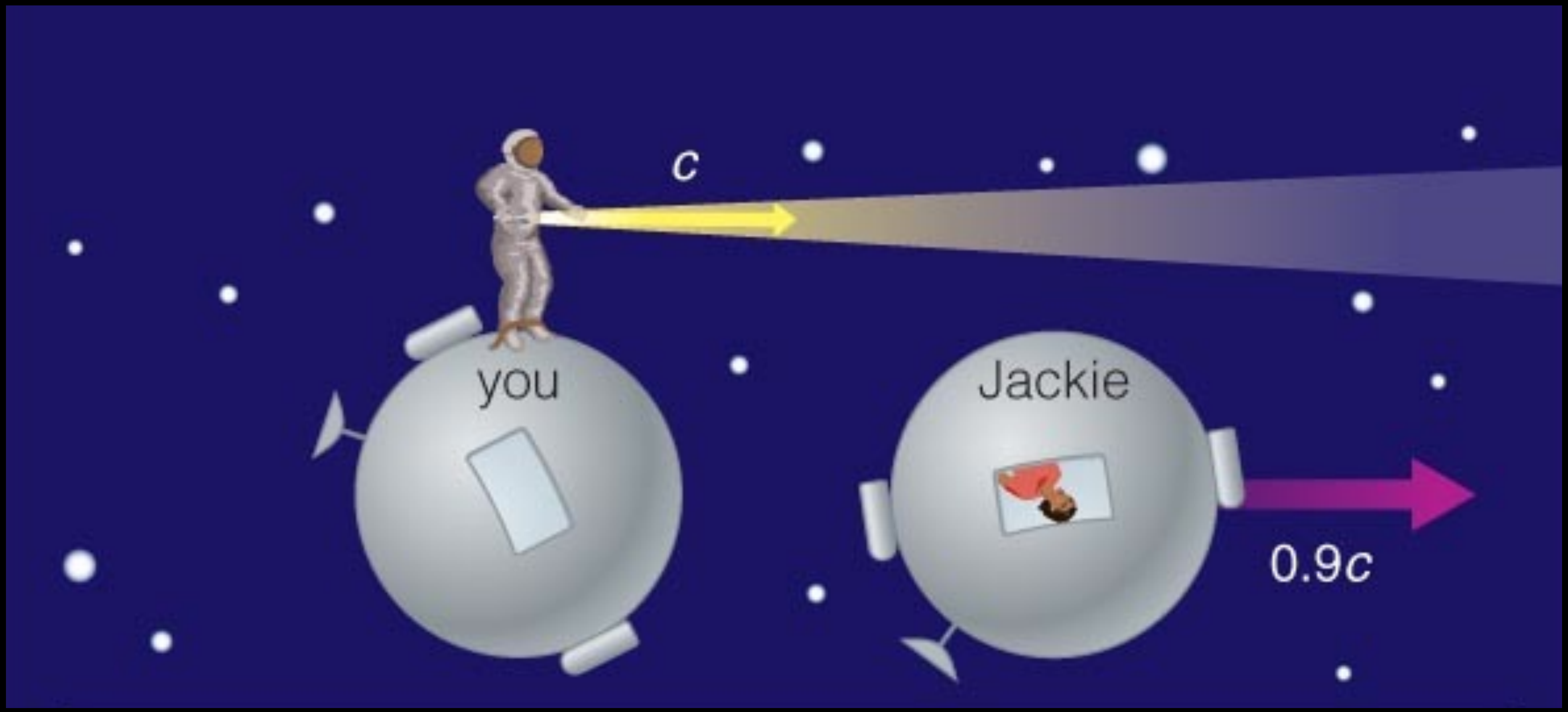
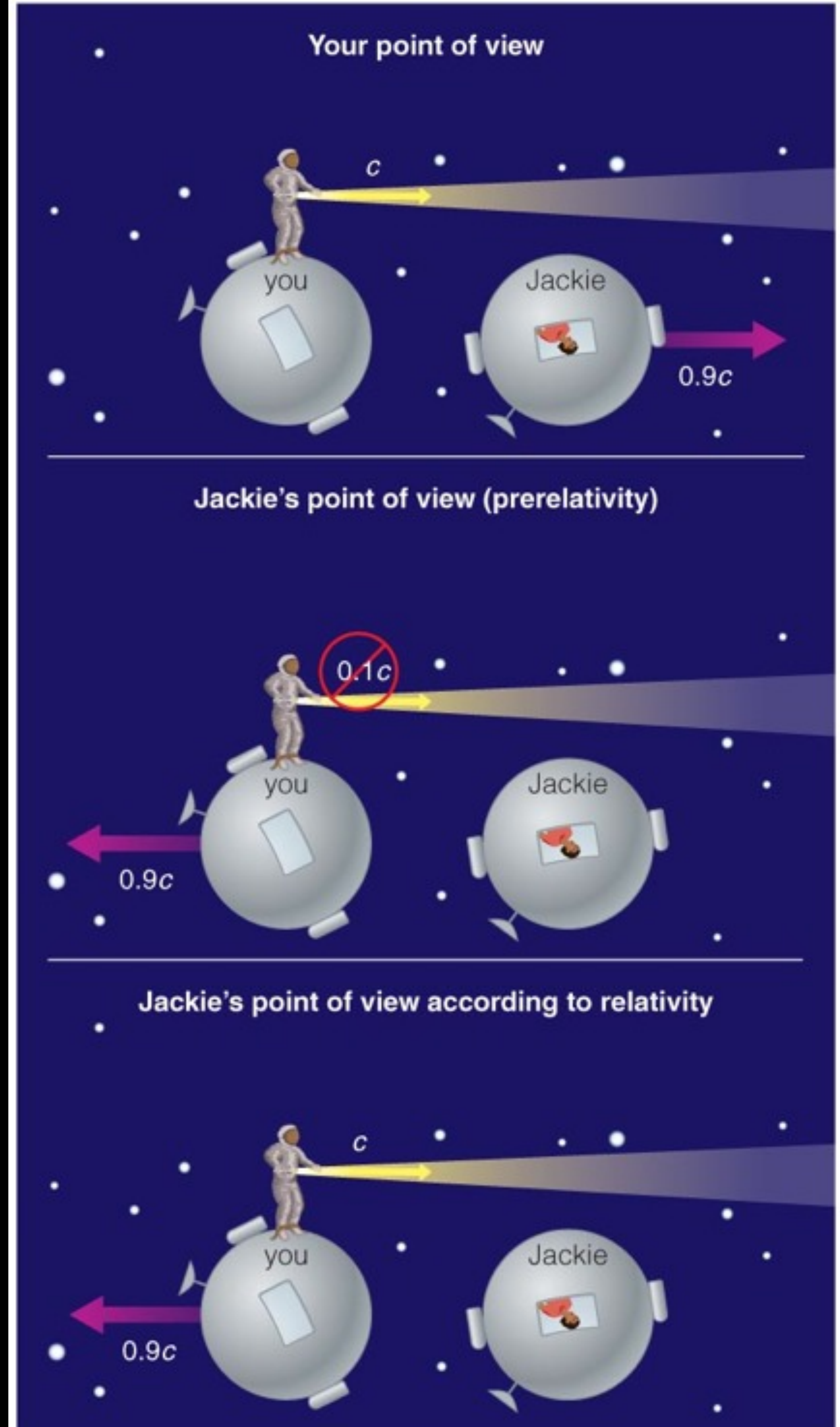


Thought Experiment 2:
You shine a light at Jackie as she is moving away at 0.9c. How fast does she see the light coming towards her?



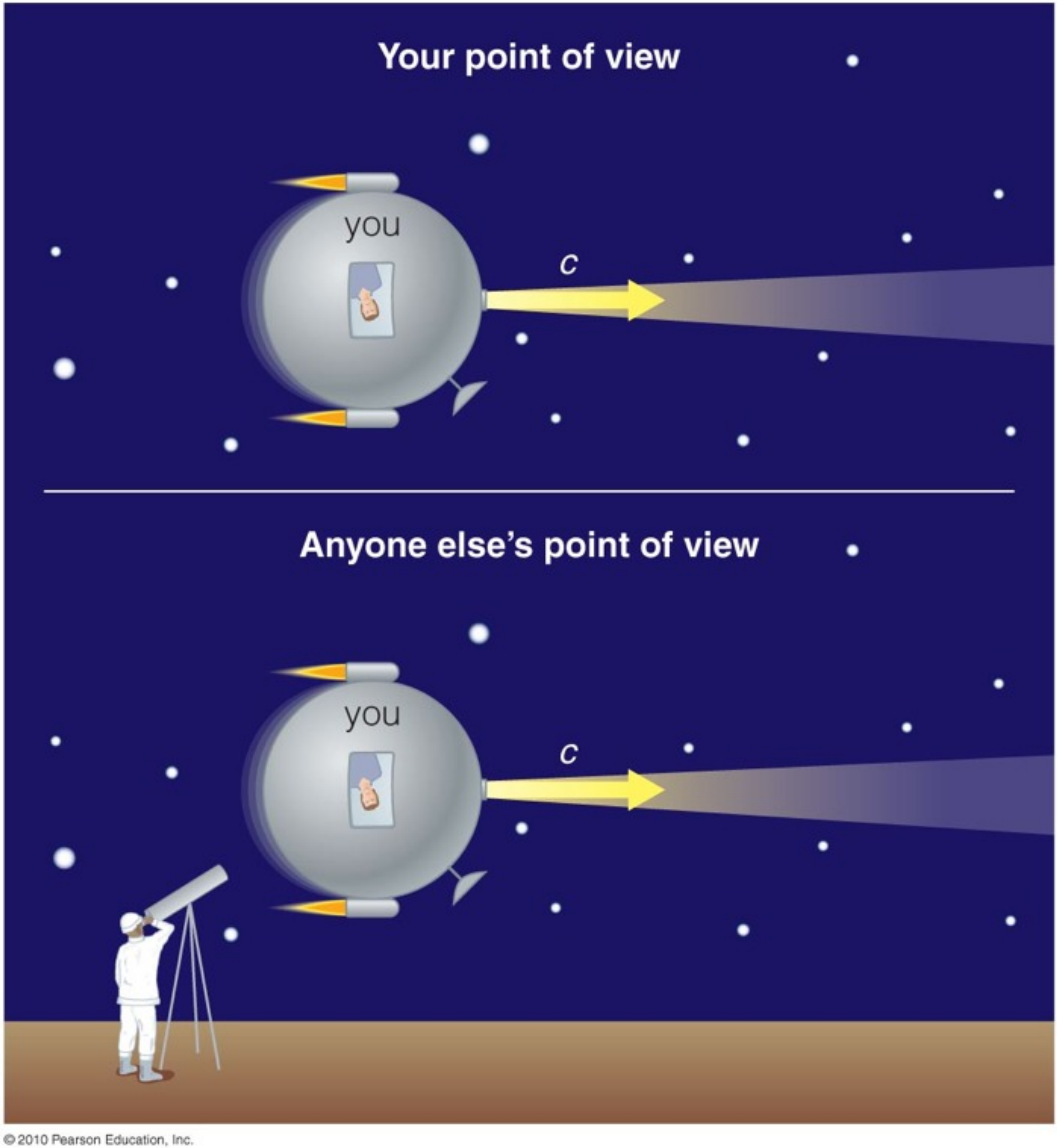
Without relativity, you'd say that Jackie sees the light coming at 0.1c = 1c - 0.9c. But relativity says the speed of light is *always* c.



Thought Experiment 3: You are flying at 0.9999c and trying to go faster.

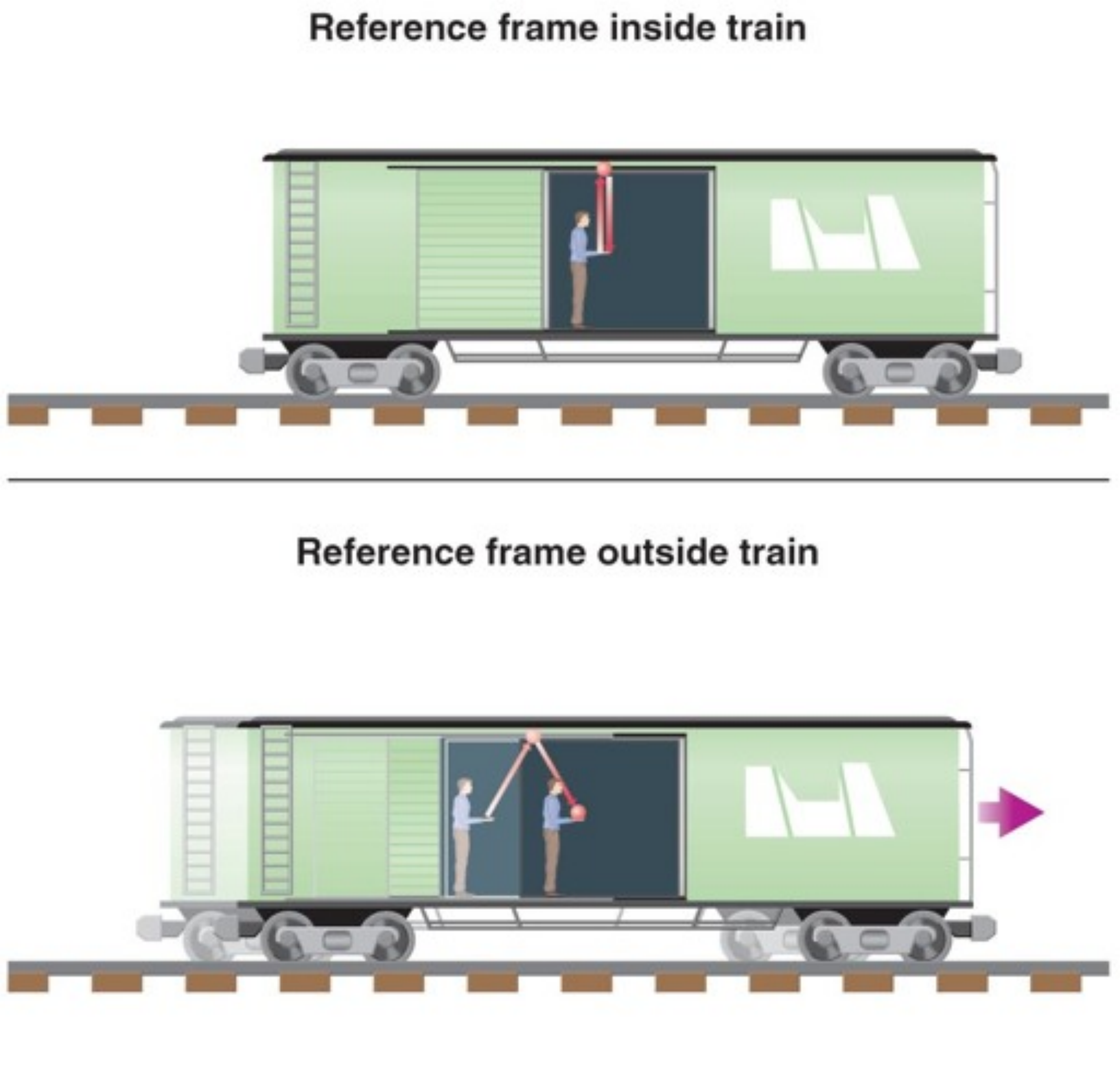
Will you ever reach the speed of light? Will you catch up to your headlights?

What would a "stationary" observer see?



Thought Experiment 4: Time Dilation

a) You watch someone throw a ball into the air while on a train



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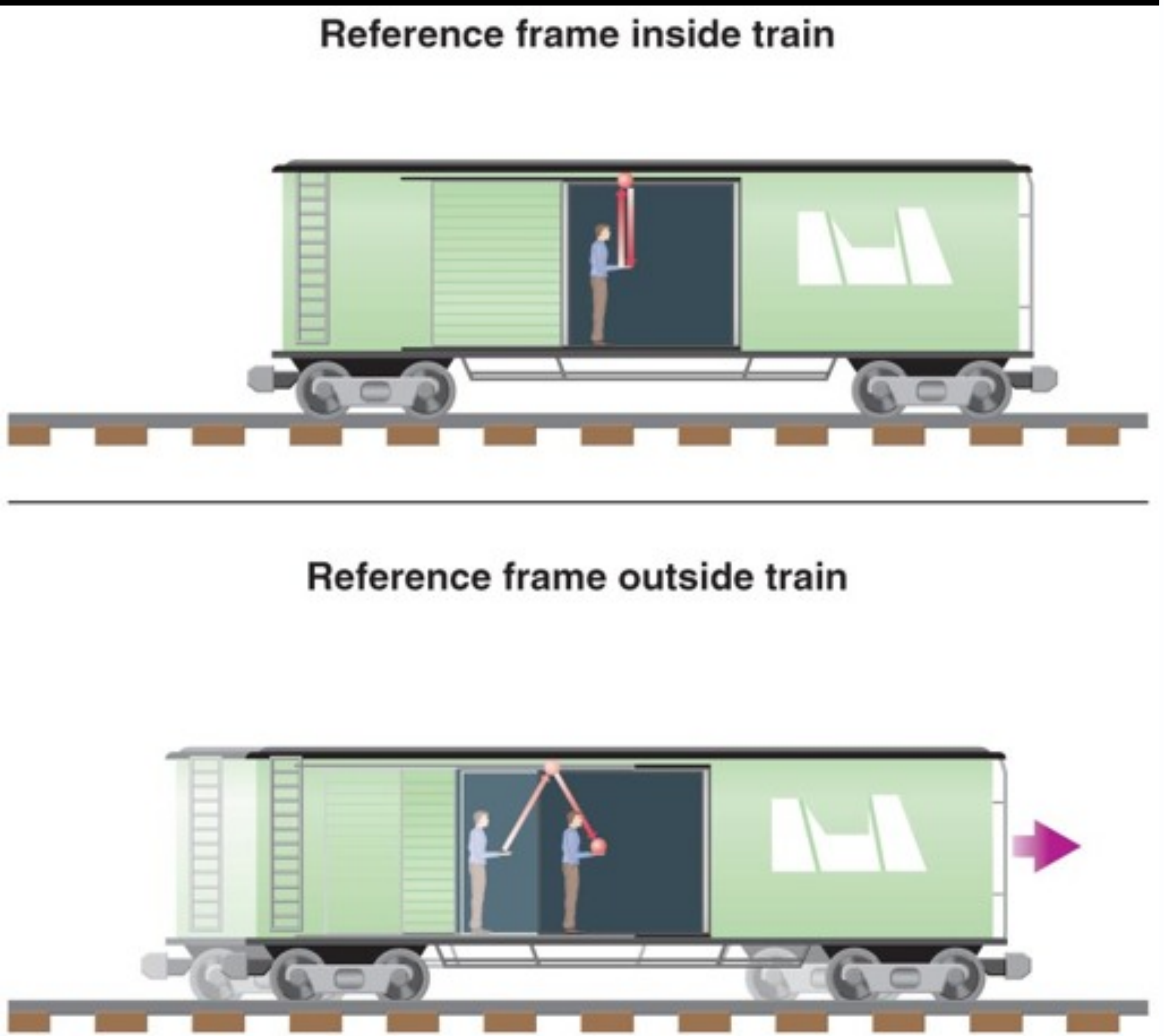
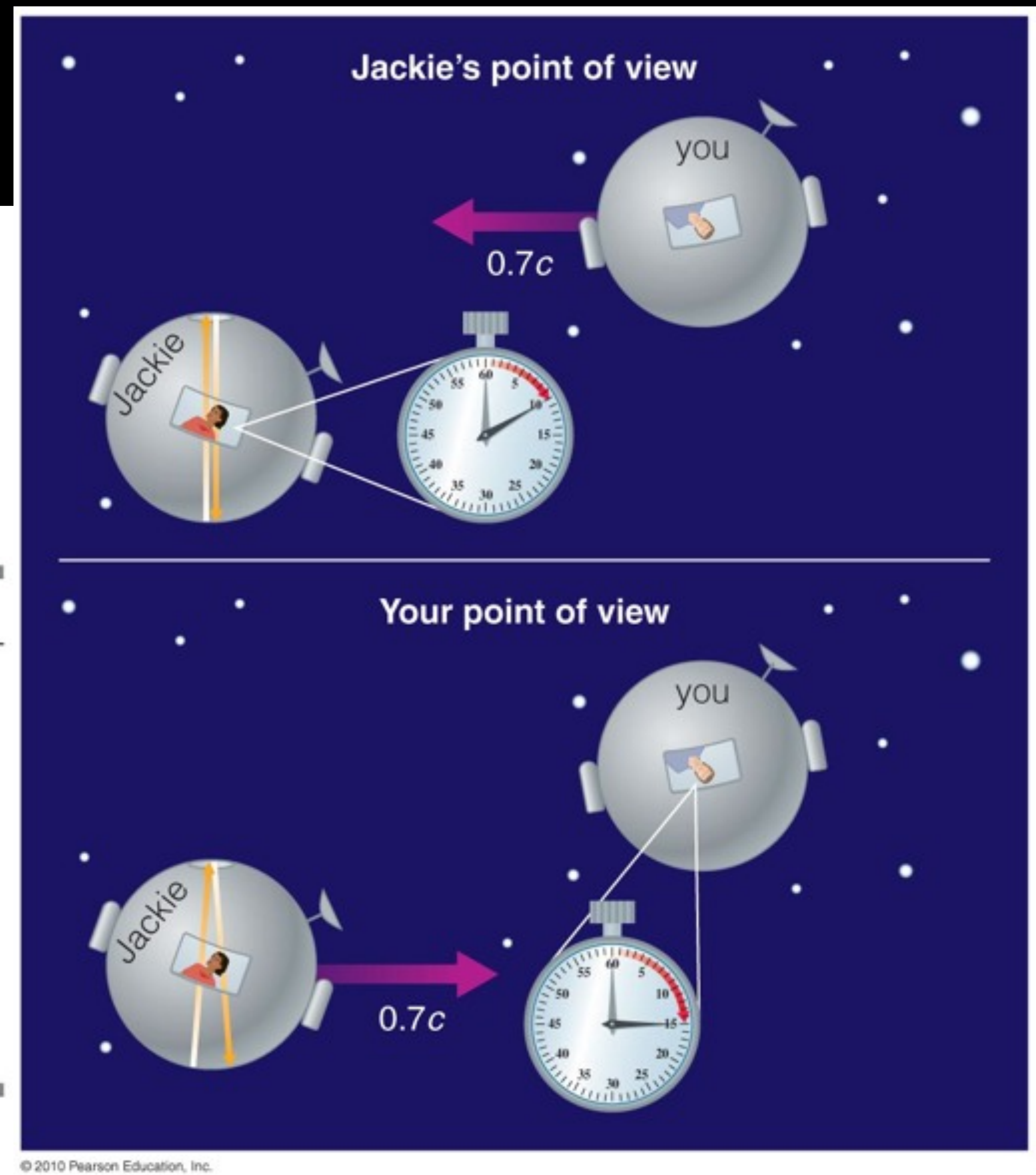
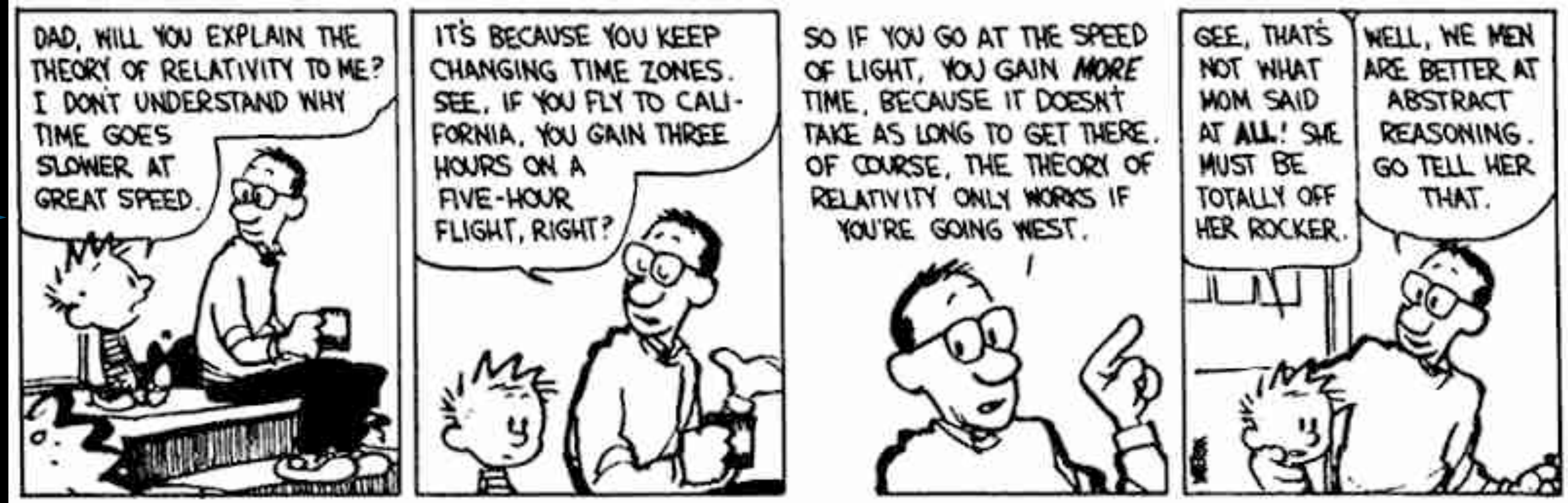


b) Jackie bounces light off a mirror while flying past you





If someone were to pass you at 90% the speed of light,

A. time would appear to be running slower for them, and they would think that time is running slower for you.

B. time would appear to be running slower for them, but they will think time is running *faster* for you.

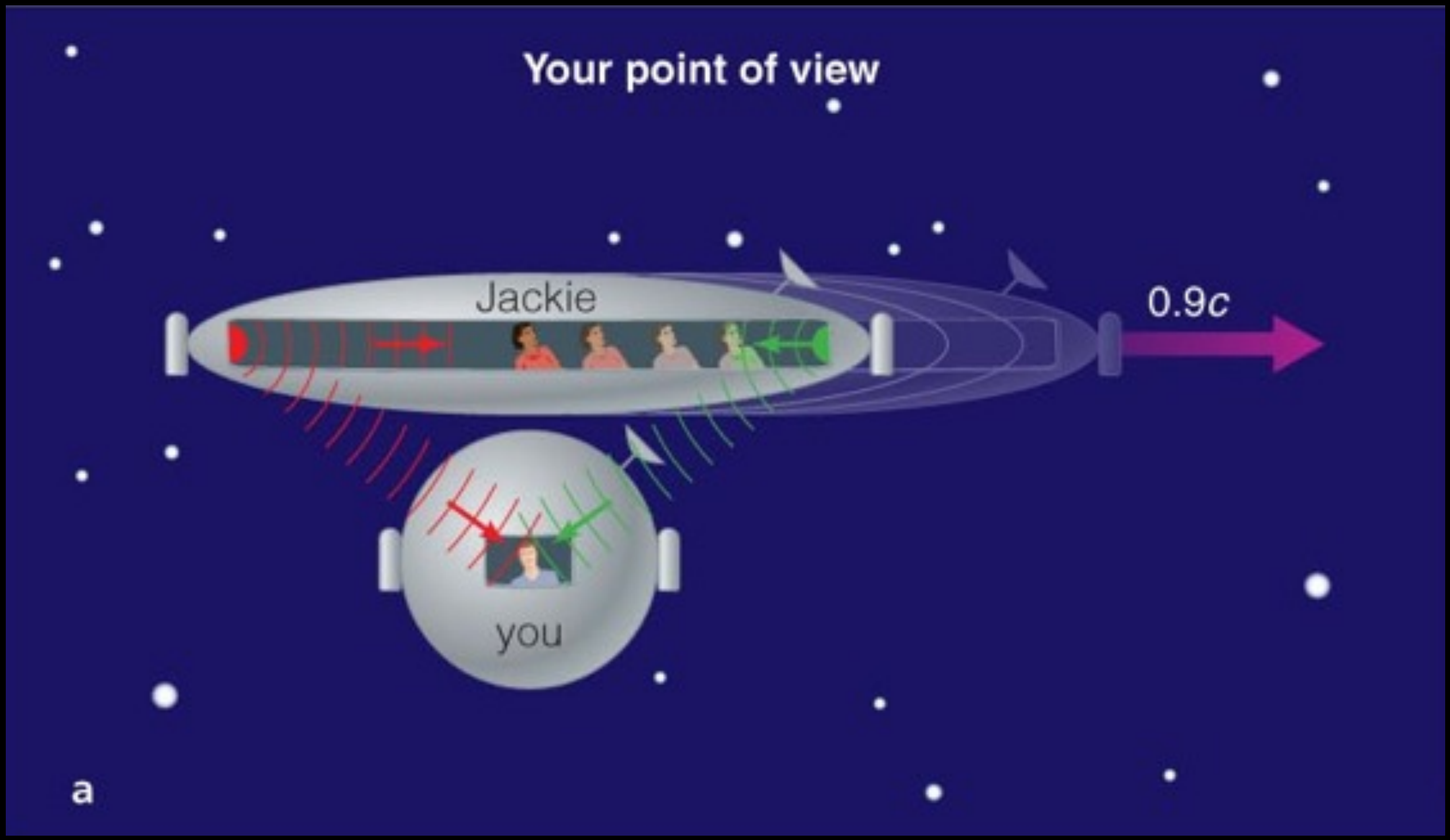
C. time would appear to be running slower for them, but they will see your time unchanged.

D. depends on whether you're flying east or west

E. none of the above

Thought Experiment 5: Simultaneity

You and Jackie are moving by each other at 0.9c. You see the red and green light blink at exactly the same time. What does Jackie see? Who is correct?



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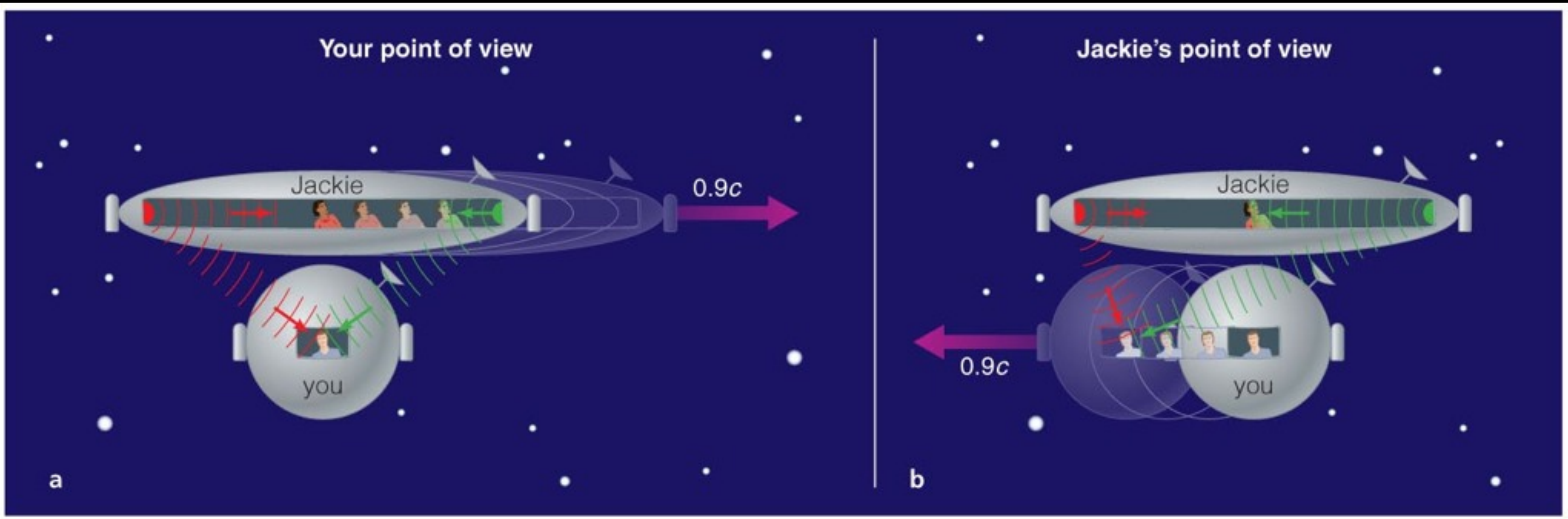
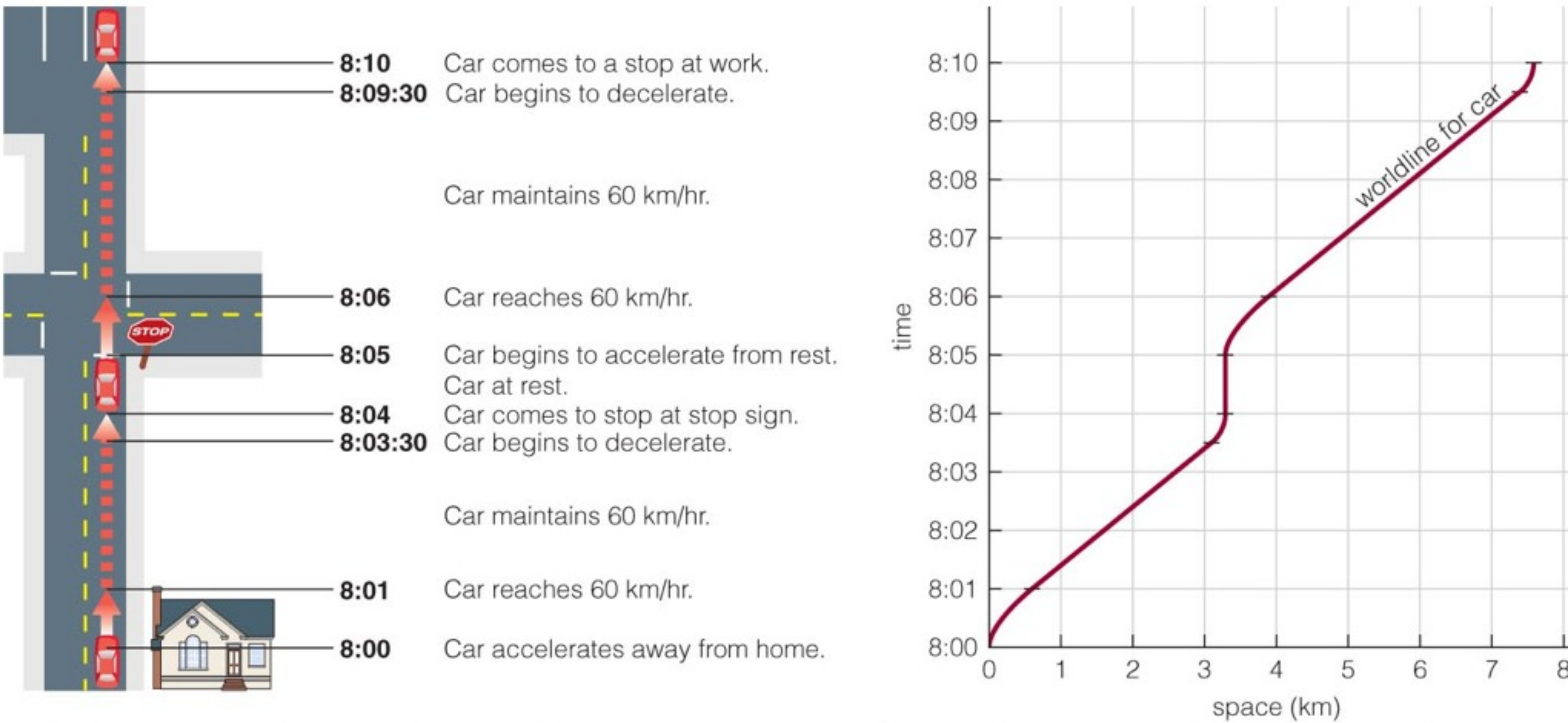


Spacetime

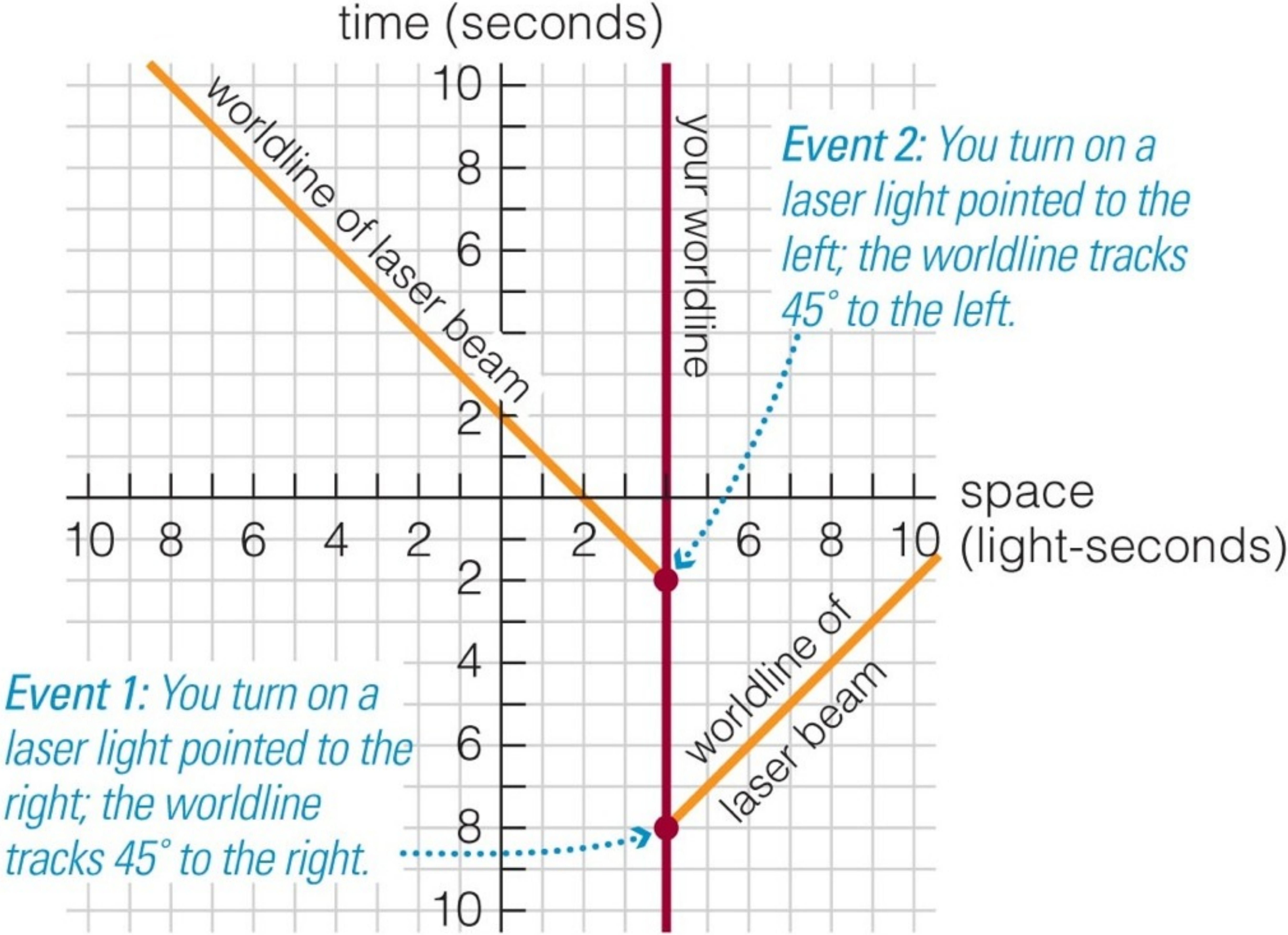
- Space and Time are really a 4-dimensional volume
- We perceive things in 3D, though: it's very difficult (impossible?) to visualize a full 4 dimensions
- We rely on "projections" of the full 4D reality into simpler abstractions, like two-dimensional plots of space vs time

Spacetime & Worldlines

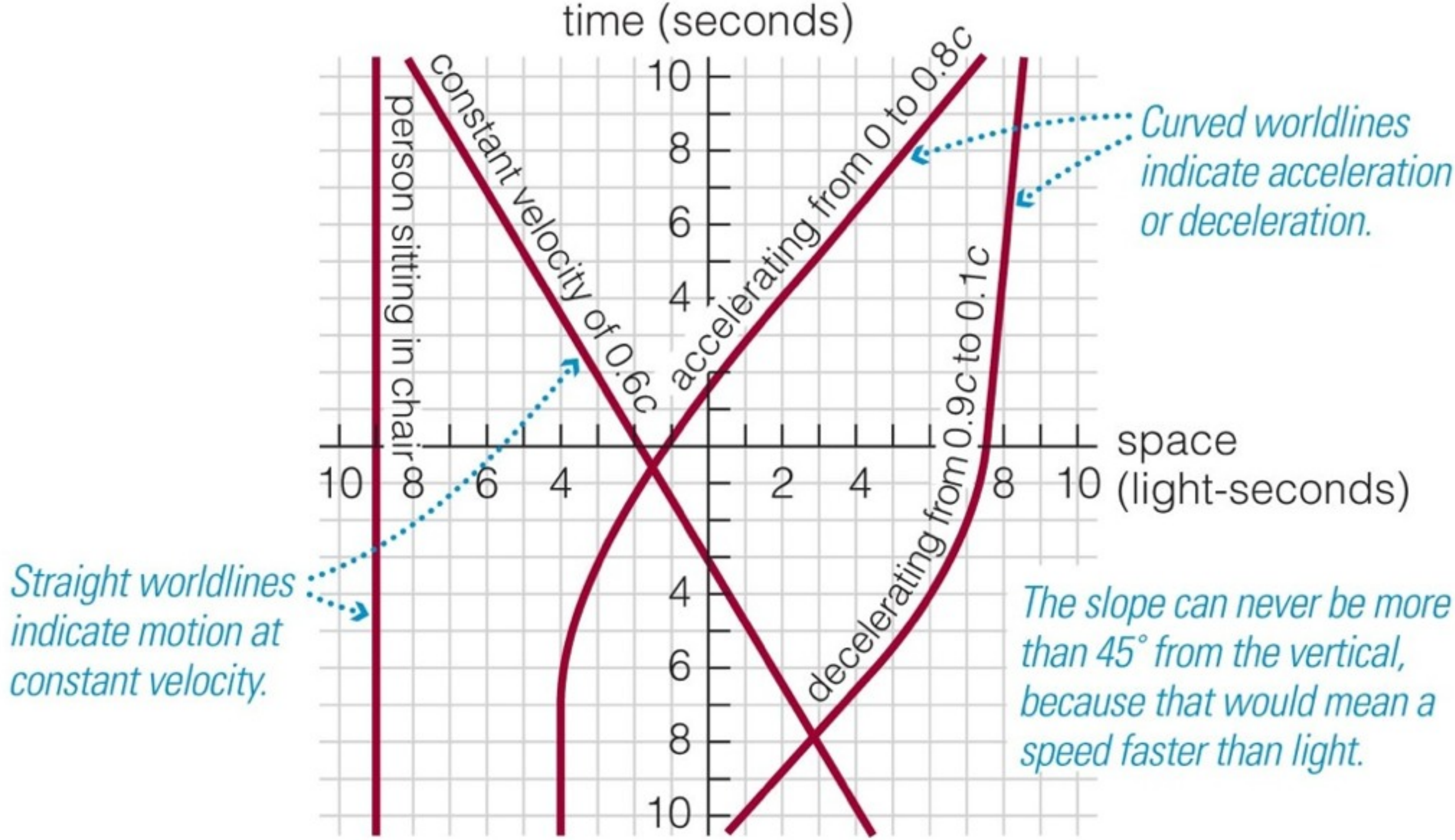


a This diagram shows the events that occur during a 10-minute car trip from home to work on a straight road.

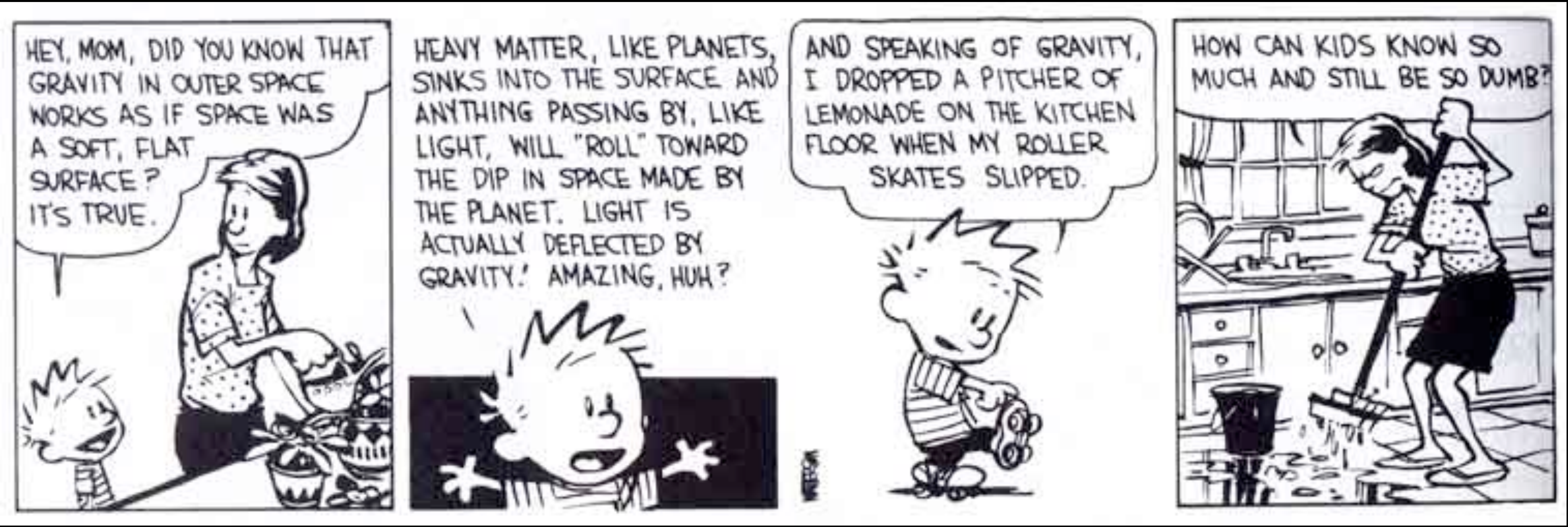
b We make a spacetime diagram for the trip by putting space (in this case, the car's distance from home) on the horizontal axis and time on the vertical axis.


time (seconds)
10
8
6
2
2
4
6
8
10
space (light-seconds)
10 8 6 4 2 2 6 8 10
worldline of laser beam
your worldline
Event 2: You turn on a laser light pointed to the left; the worldline tracks 45° to the left.
worldline of laser beam
Event 1: You turn on a laser light pointed to the right; the worldline tracks 45° to the right.

Worldlines & Acceleration

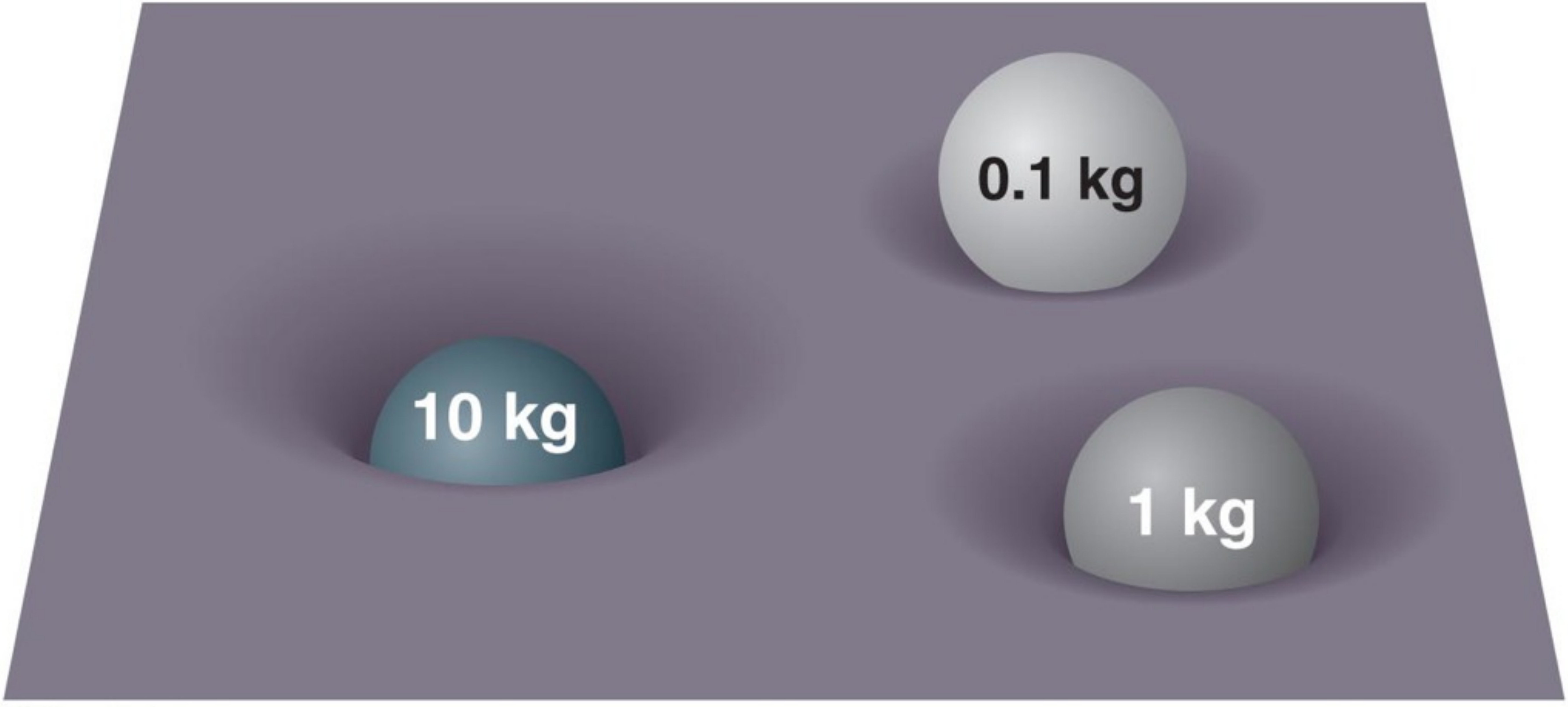


Gravity

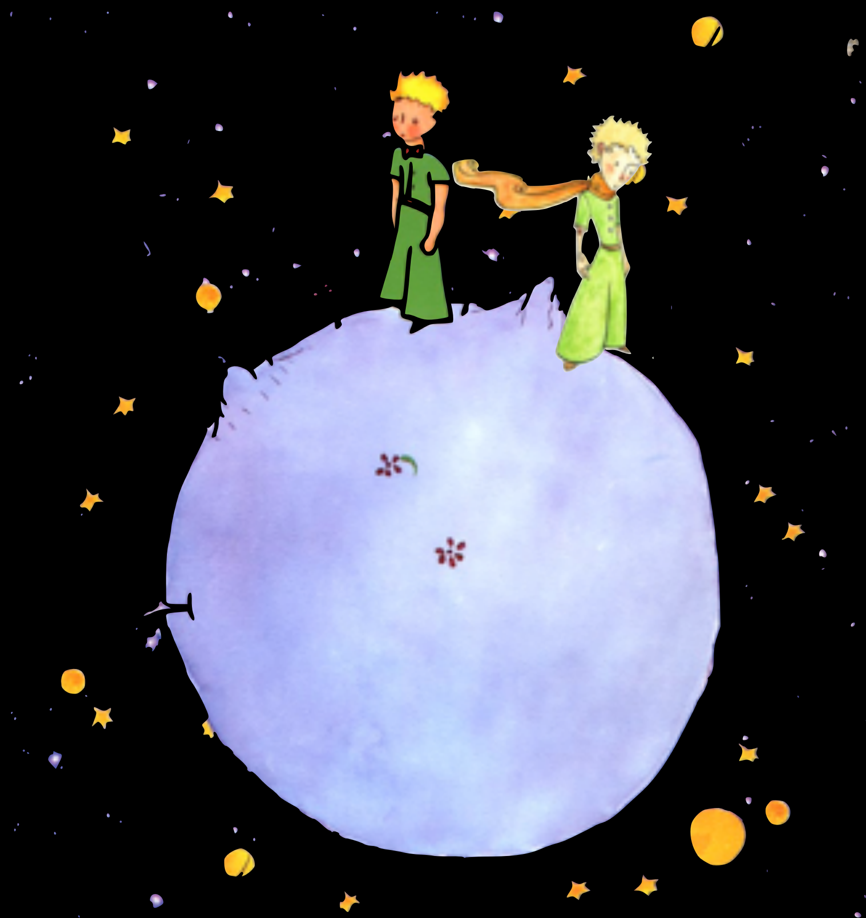

HEY, MOM, DID YOU KNOW THAT GRAVITY IN OUTER SPACE WORKS AS IF SPACE WAS A SOFT, FLAT SURFACE? IT'S TRUE.
HEAVY MATTER, LIKE PLANETS, SINKS INTO THE SURFACE AND ANYTHING PASSING BY, LIKE LIGHT, WILL "ROLL" TOWARD THE DIP IN SPACE MADE BY THE PLANET. LIGHT IS ACTUALLY DEFLECTED BY GRAVITY! AMAZING, HUH?
AND SPEAKING OF GRAVITY, I DROPPED A PITCHER OF LEMONADE ON THE KITCHEN FLOOR WHEN MY ROLLER SKATES SLIPPED.
HOW CAN KIDS KNOW SO MUCH AND STILL BE SO DUMB?

Gravity

New interpretation: mass distorts spacetime

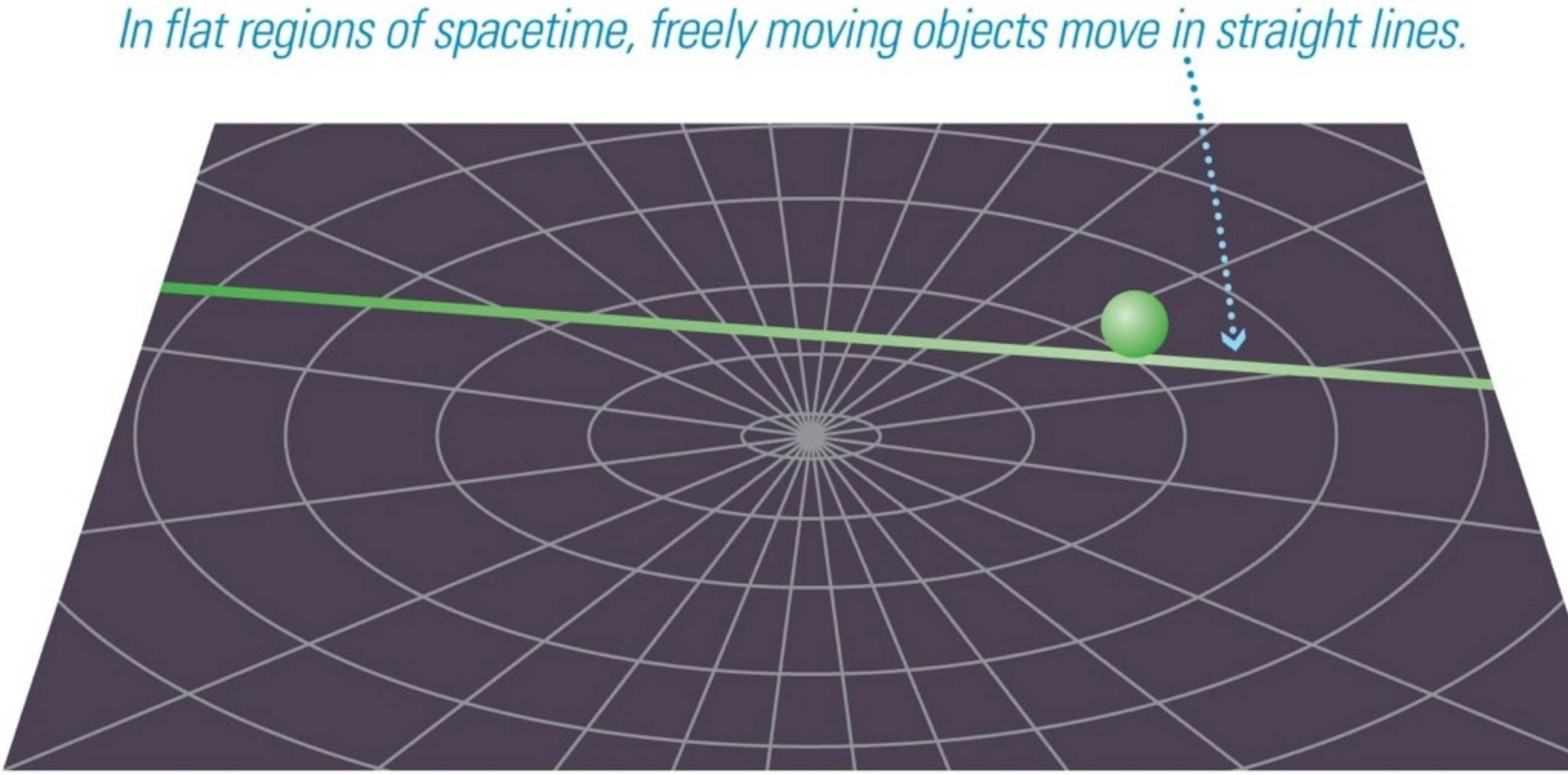


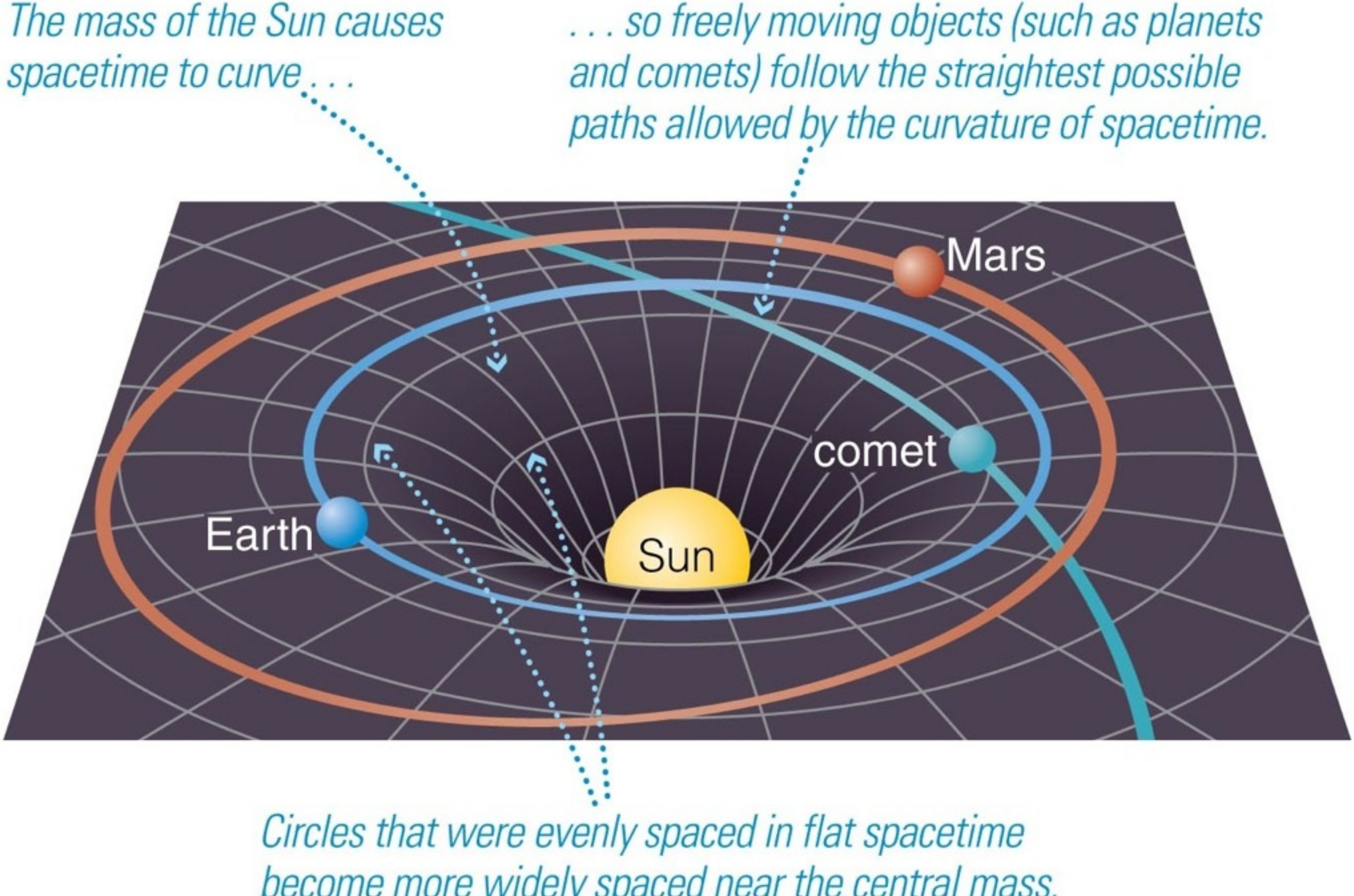
General Relativity



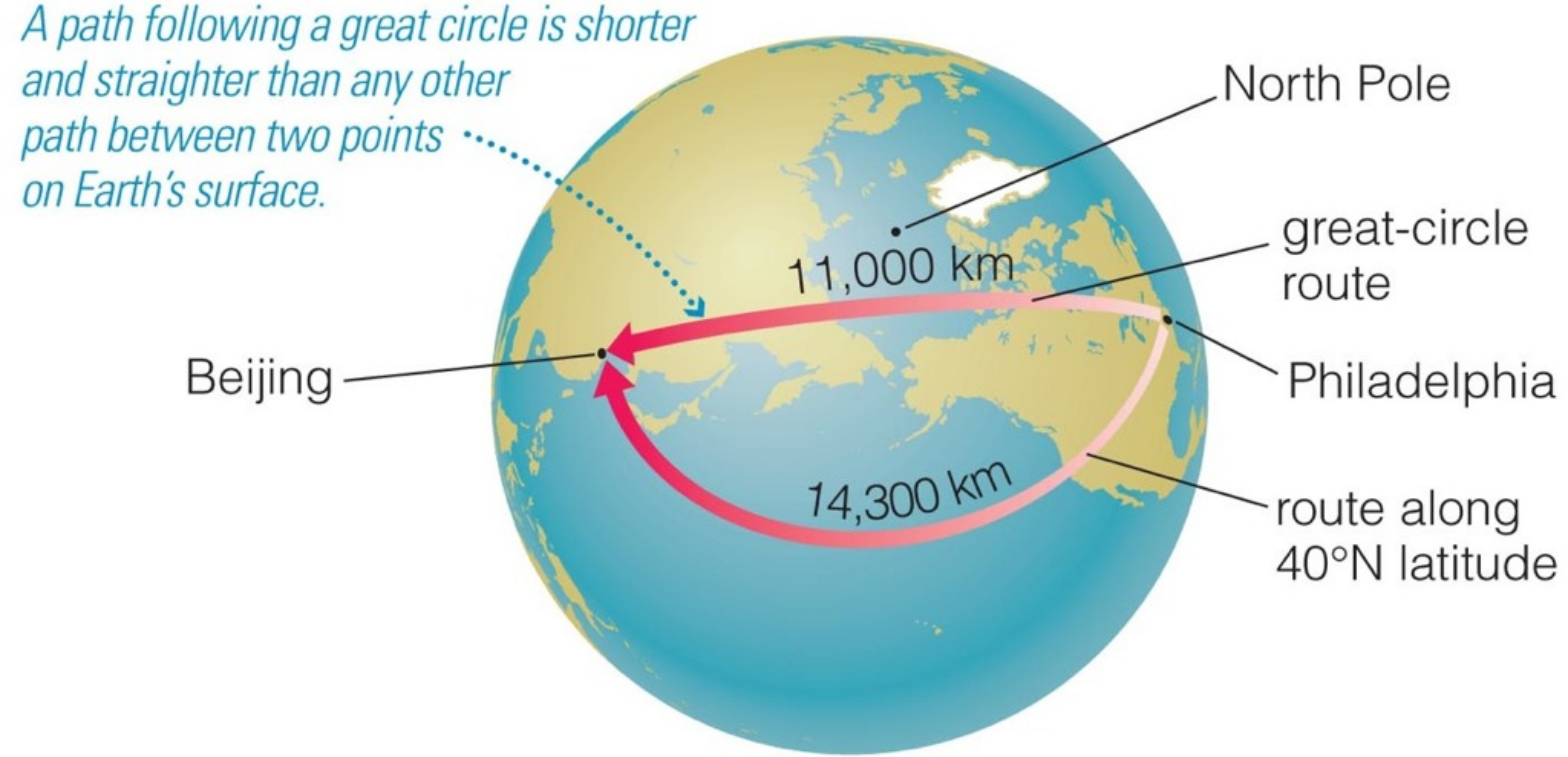
- Analogy:
  - The surface of the Earth is curved. If two people start walking in exactly opposite directions along a straight line, they'll bump into each other on the other side
  - What happens if you launch two balls in opposite directions out of a spacecraft orbiting a planet? The same thing! They'll hit each other. *Space is curved.*

Flat Spacetime




The mass of the Sun causes spacetime to curve. . . .
. . . so freely moving objects (such as planets and comets) follow the straightest possible paths allowed by the curvature of spacetime.
Mars
comet
Earth
Sun
Circles that were evenly spaced in flat spacetime become more widely spaced near the central mass.

Analogy - flights around Earth



b The shortest and straightest possible path between two points on Earth is always a piece of a great circle.

WARNING: Maps are *projections* and are therefore incorrect

According to general relativity, the presence of matter curves spacetime. This means that a planet in our solar system

A. feels a force of gravity coming from the Sun.

B. moves *as if* there was a force coming from the Sun.

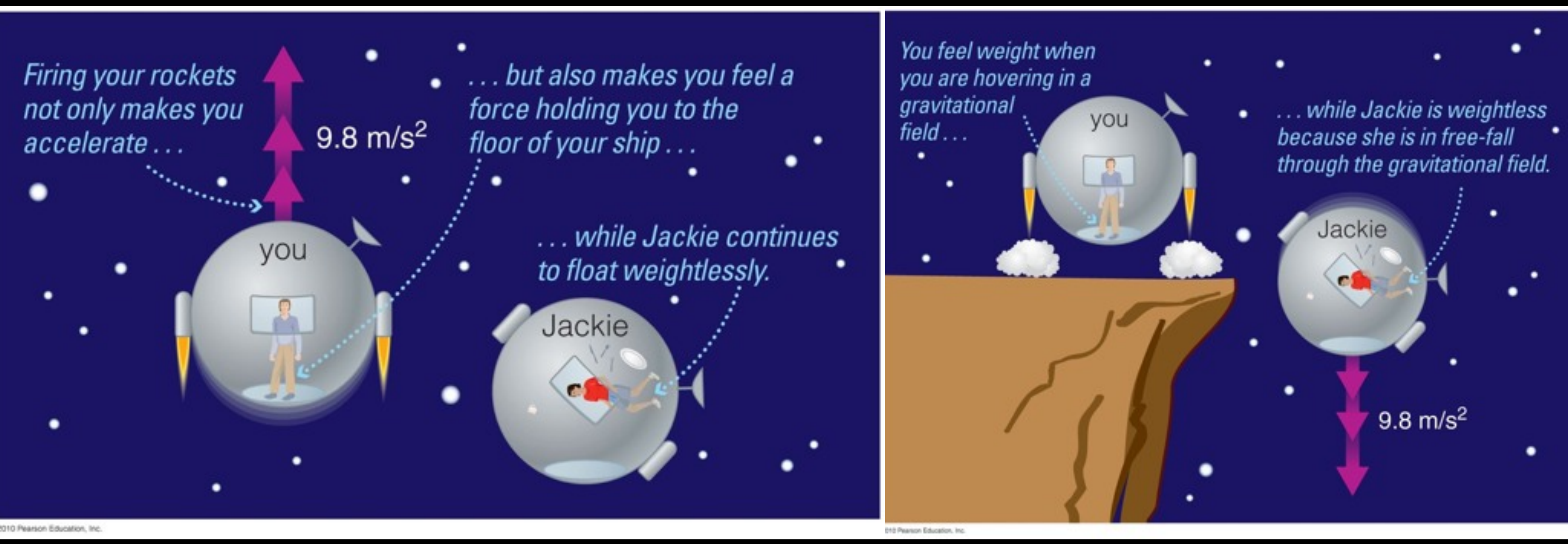
C. experiences free fall or free movement by moving in a curved orbit.

D. none of the above

E. B and C

General Relativity - Equivalence Principle

- These two scenarios are *equivalent*: there is no physical distinction between them in terms of physical effects on you and Jackie
- Gravity and Acceleration are equivalent



If you are in a spaceship that is sitting on the surface of a planet, you feel your weight. How does this compare to the weight you feel in an accelerating spacecraft?

A. One is real weight, the other is only apparent.

B. Both are the same; they are indistinguishable.

Gravity and Time

- Gravity curves spacetime. That means it affects time in addition to space.
- An accelerating aircraft will experience time slightly slower than an immobile observer on Earth
  - very slightly: 6 nanoseconds over 15 hours, tested on a plane in 1975

Why do people on Earth not each have their own definition of "now" according to relativity?

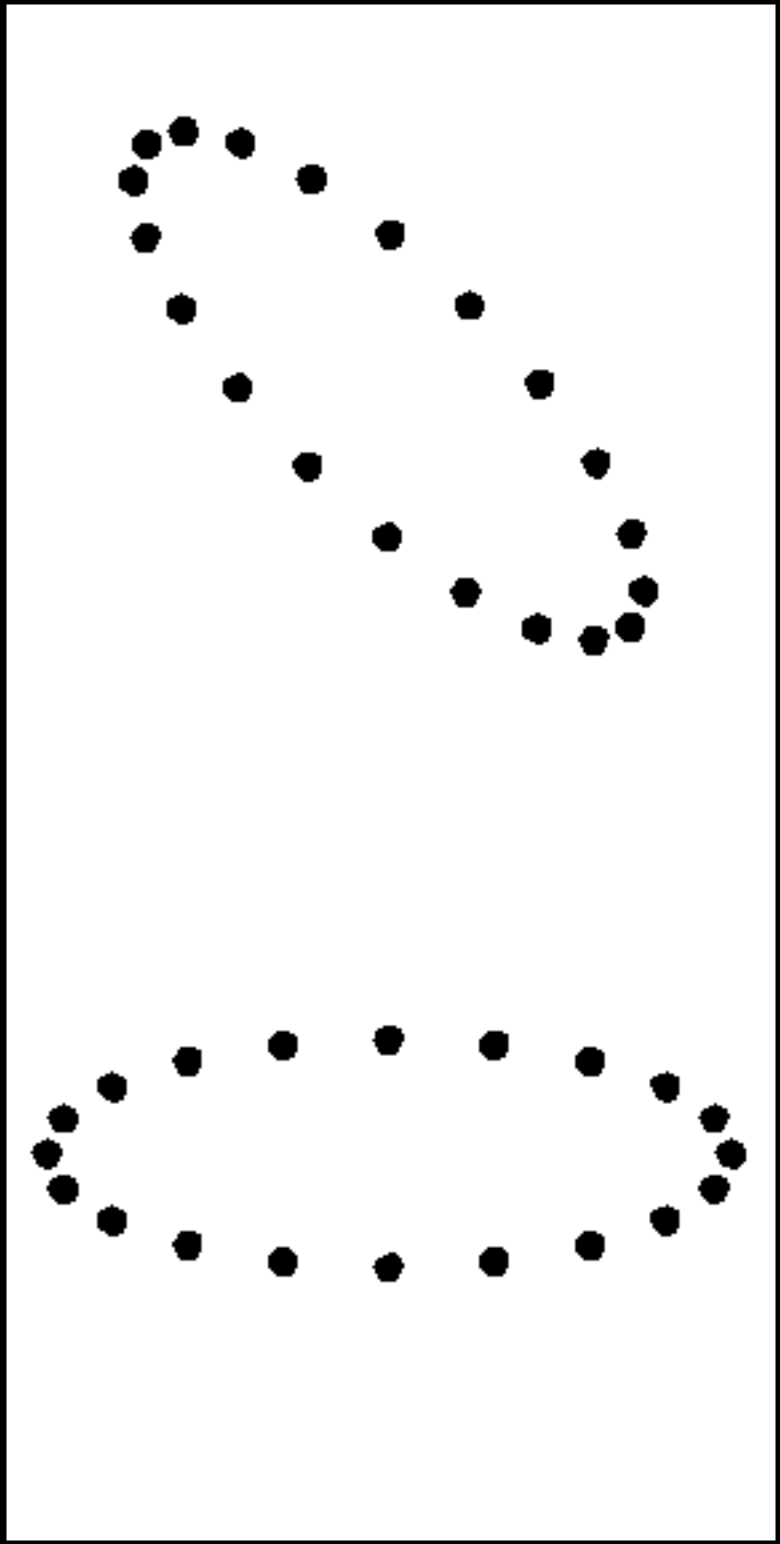
A. Relativity doesn't work on Earth, only in space

B. They do, but choose to ignore it.

C. We are all in nearly the same place – only light-microseconds apart – so "now" can only differ a few microseconds.

Gravitational Waves

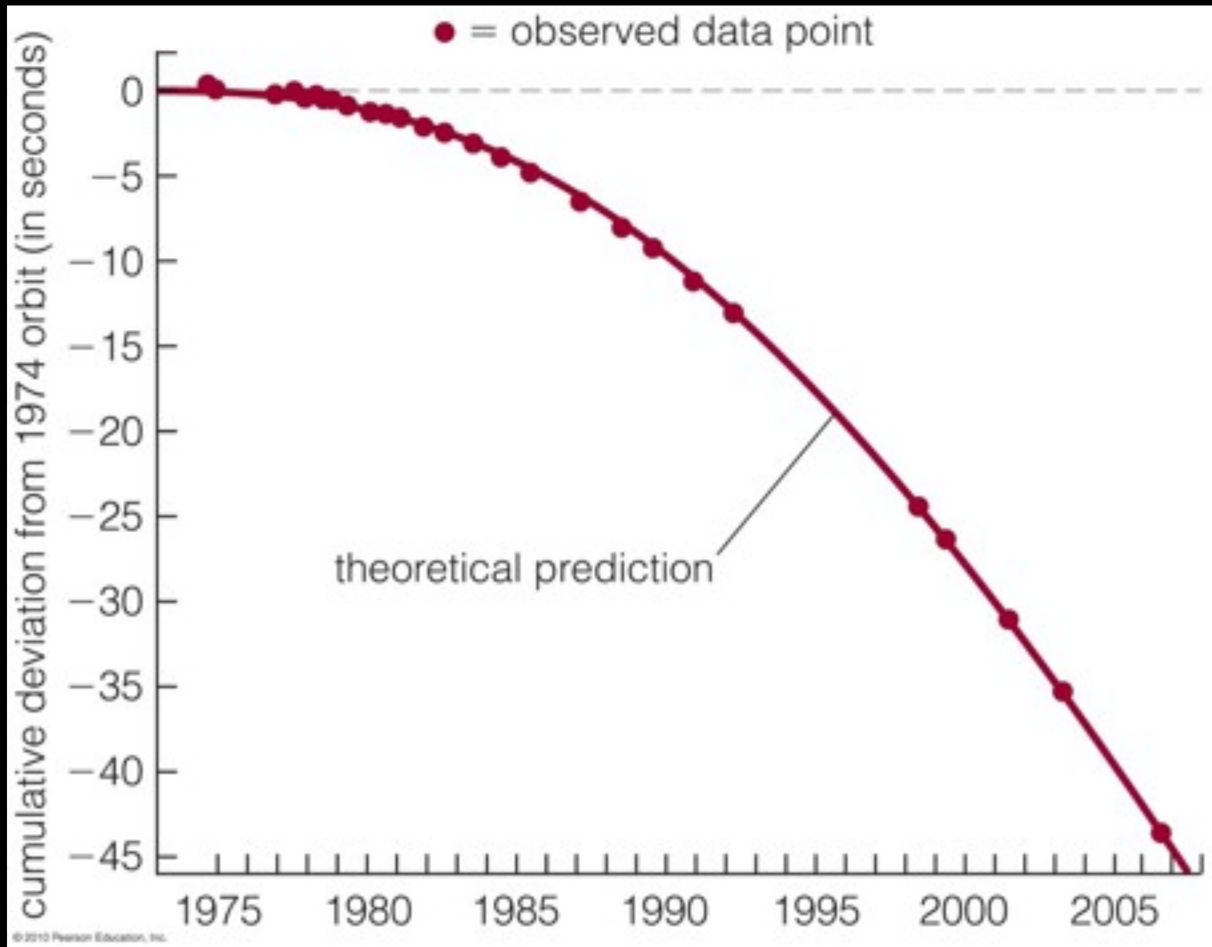
- Gravity can release energy in the form of waves
- This happens around tightly orbiting bodies and when massive objects (e.g. neutron stars, black holes) merge
- Predicted by General Relativity, not normal Newtonian gravity



Gravitational Waves

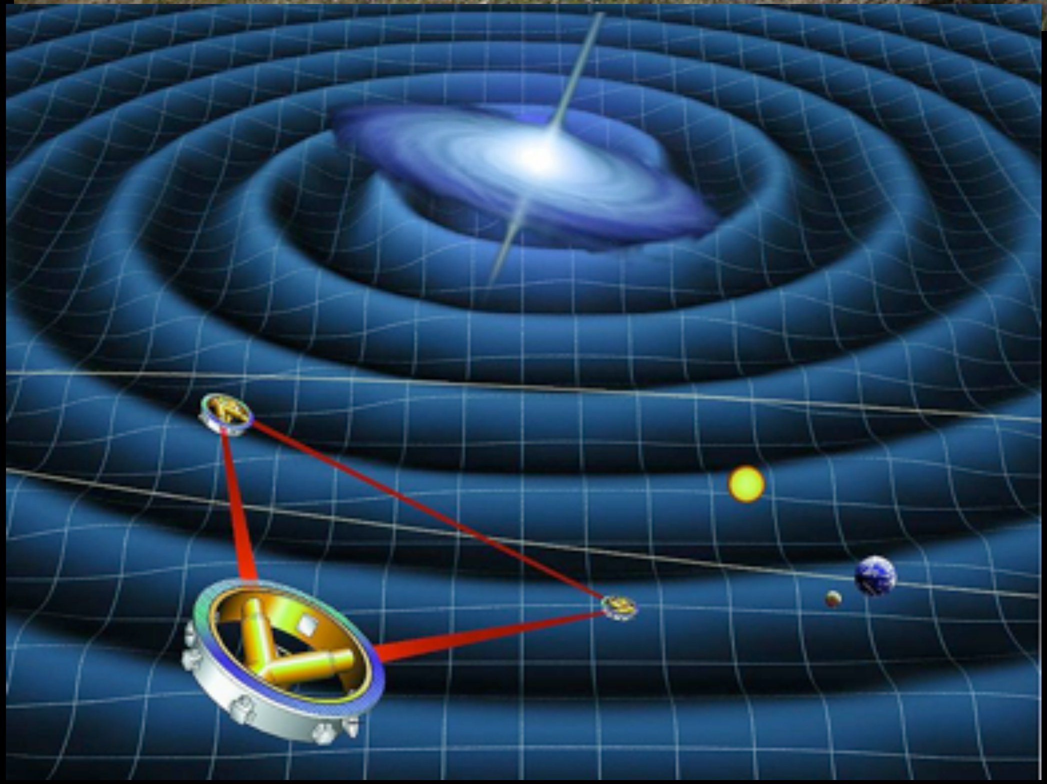
- Hulse & Taylor won 1993 Nobel Prize for the discovery of a binary pulsar system
- The system is losing energy by emitting gravitational waves
- Since pulsars are excellent clocks, it is possible to measure minuscule changes in their orbital period
- Proof of General Relativity!

Measurement of the decay in the orbital period of the binary pulsar



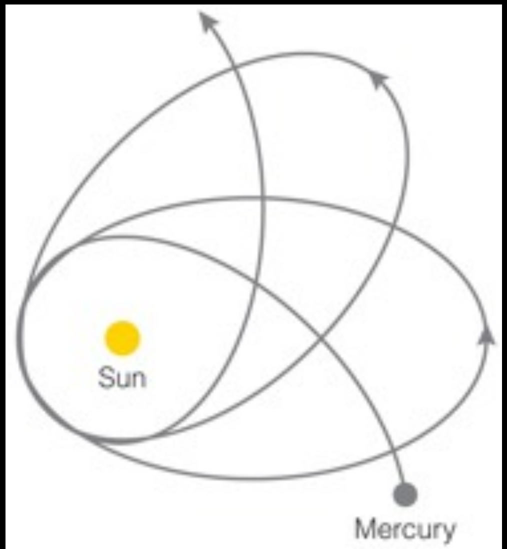
Gravitational Waves

- We are also trying to detect gravitational waves here on Earth
- LIGO is the Laser Interferometer Gravitational Wave Observatory
- LISA, the Laser Interferometer Space Antenna, is proposed to look at longer-wavelength gravitational waves

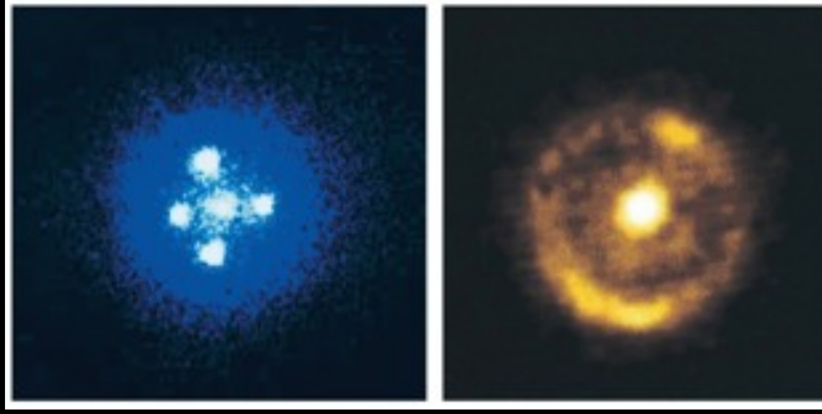


Proofs of GR

- Orbit of Mercury: Mercury precesses (its orbit "rotates") because time is slower when it's closer to the sun
    - Discovered in 1859 by Urban Le Verrier



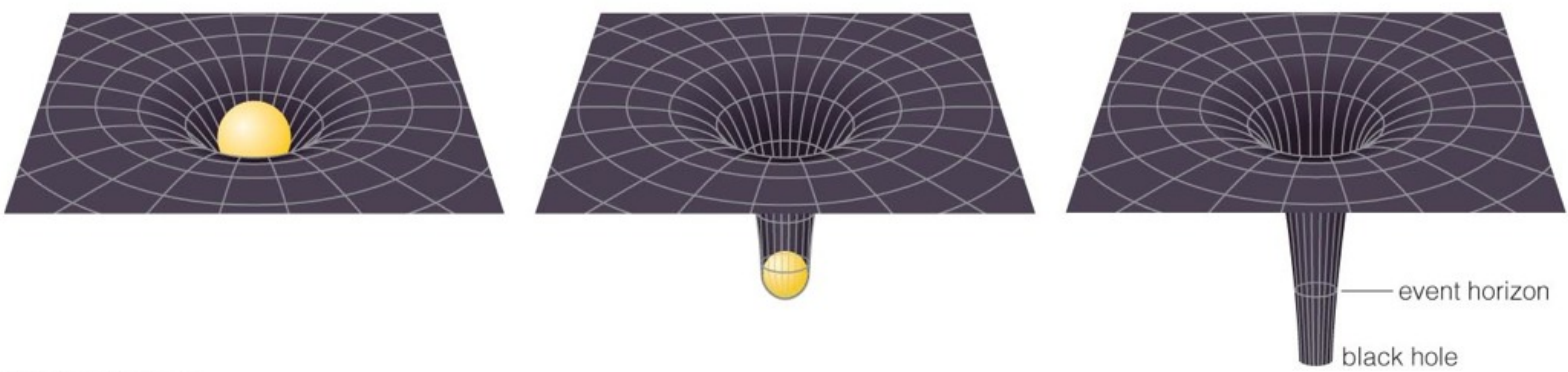
- Gravitational Lensing - discussed earlier in class



- Time dilation on aircraft. Time dilation has a measurable effect when using GPS satellites
- Gravitational Redshift - Light coming from near the surface of gravitating objects experiences slower time and is therefore redshifted
- Gravitational Waves

Black Holes

- As discussed previously, these are generated by collapse of neutron stars, or in the centers of galaxies
- What happens around a black hole?
  - Spacetime is distorted: In our analogy, the ball goes all the way through the sheet, leaving a hole at the bottom
  - The edge of the "hole" is called the Event Horizon, because no information or events escape it



Black Holes

What happens to objects thousands of kilometers away from the Event Horizon of a solar-mass Black Hole?

A) They get sucked in

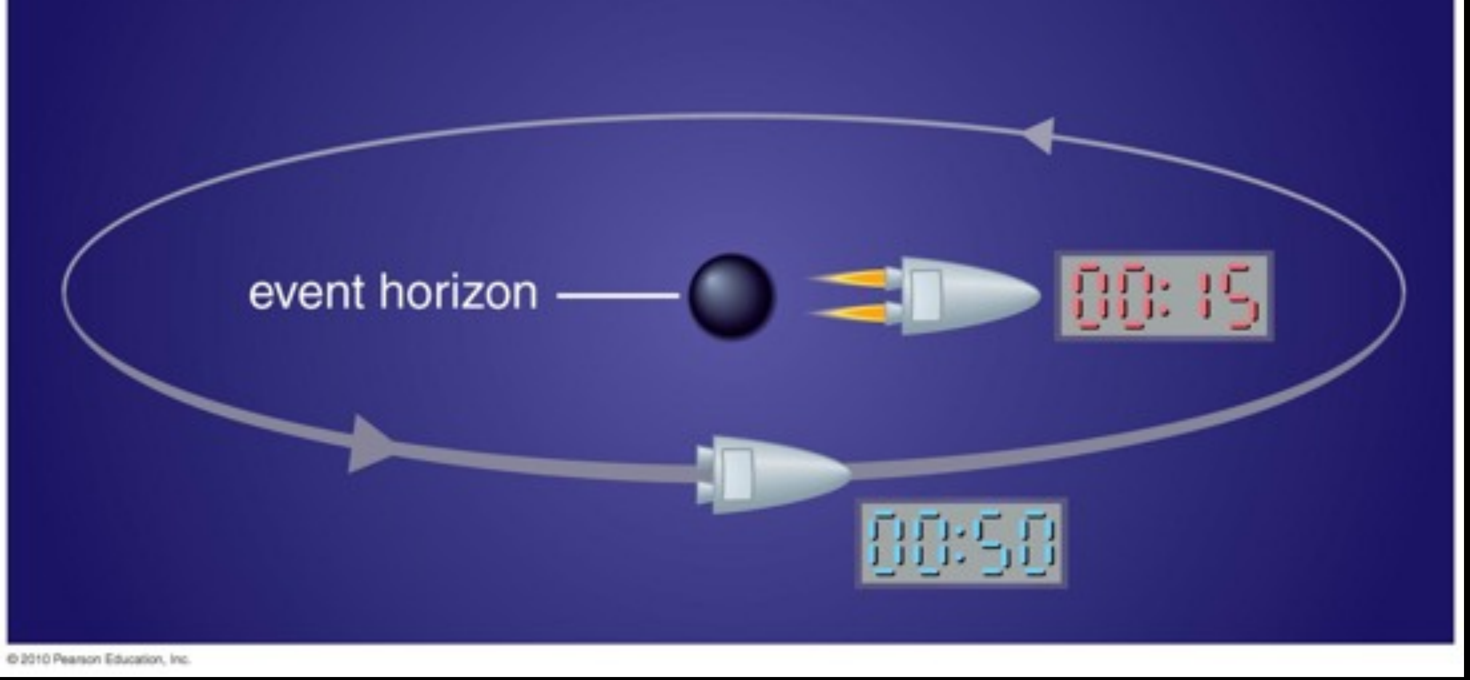
B) They freeze in time

C) They start to follow “straightest-line” orbits but eventually spiral in to the hole

D) They follow “straightest-line” orbits just like orbits around regular stars

E) They get zapped out of existence by black hole death rays

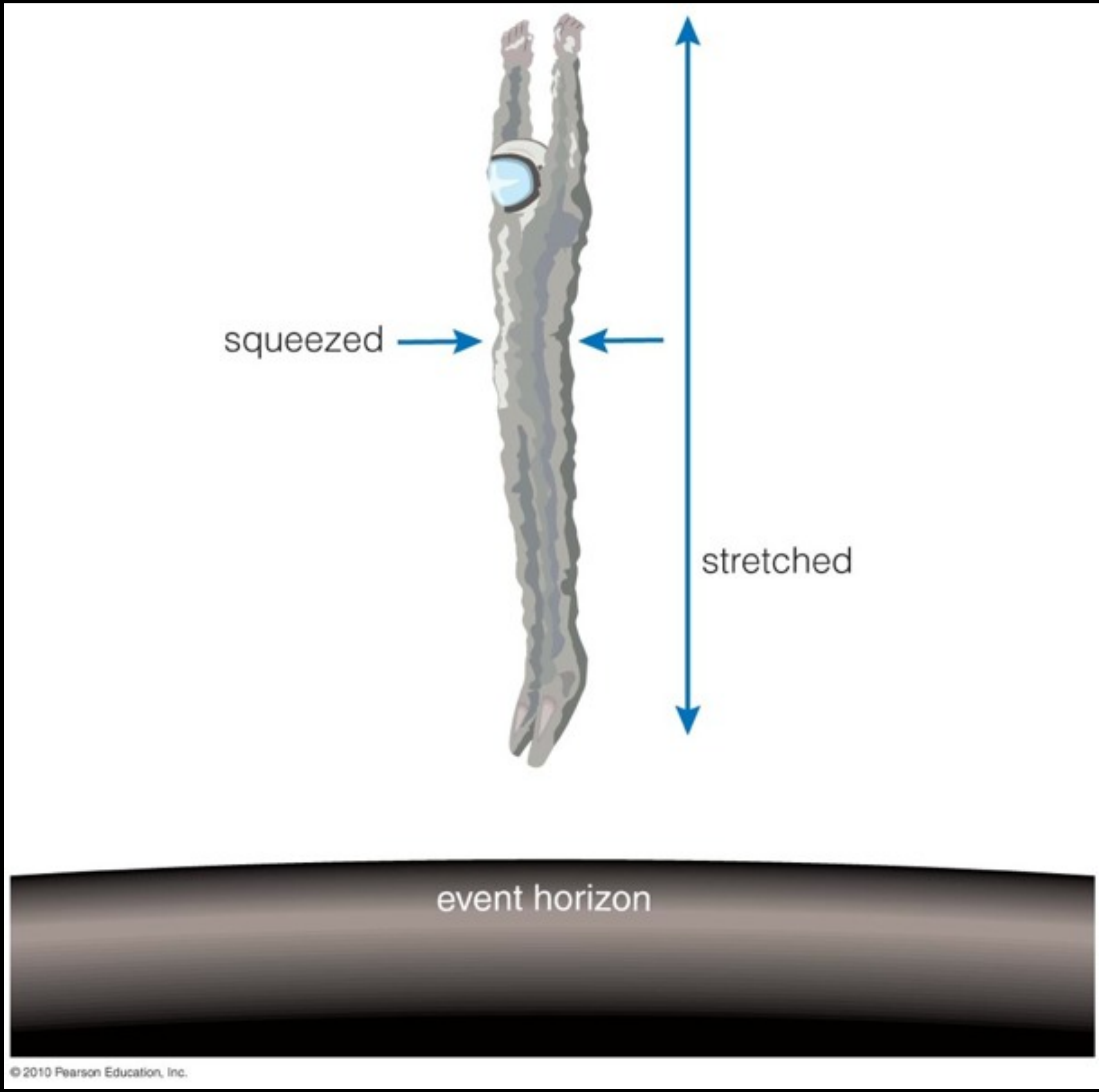
Black Holes



- What would happen if you fell into a black hole?
  - As you fell in, time would slow down relative to the outside world (from your perspective, time would go on as usual, but everything would appear to happen really fast outside)
  - Everything outside would become more and more blueshifted
  - Eventually you would cross the Event Horizon, but wouldn't notice anything particularly different

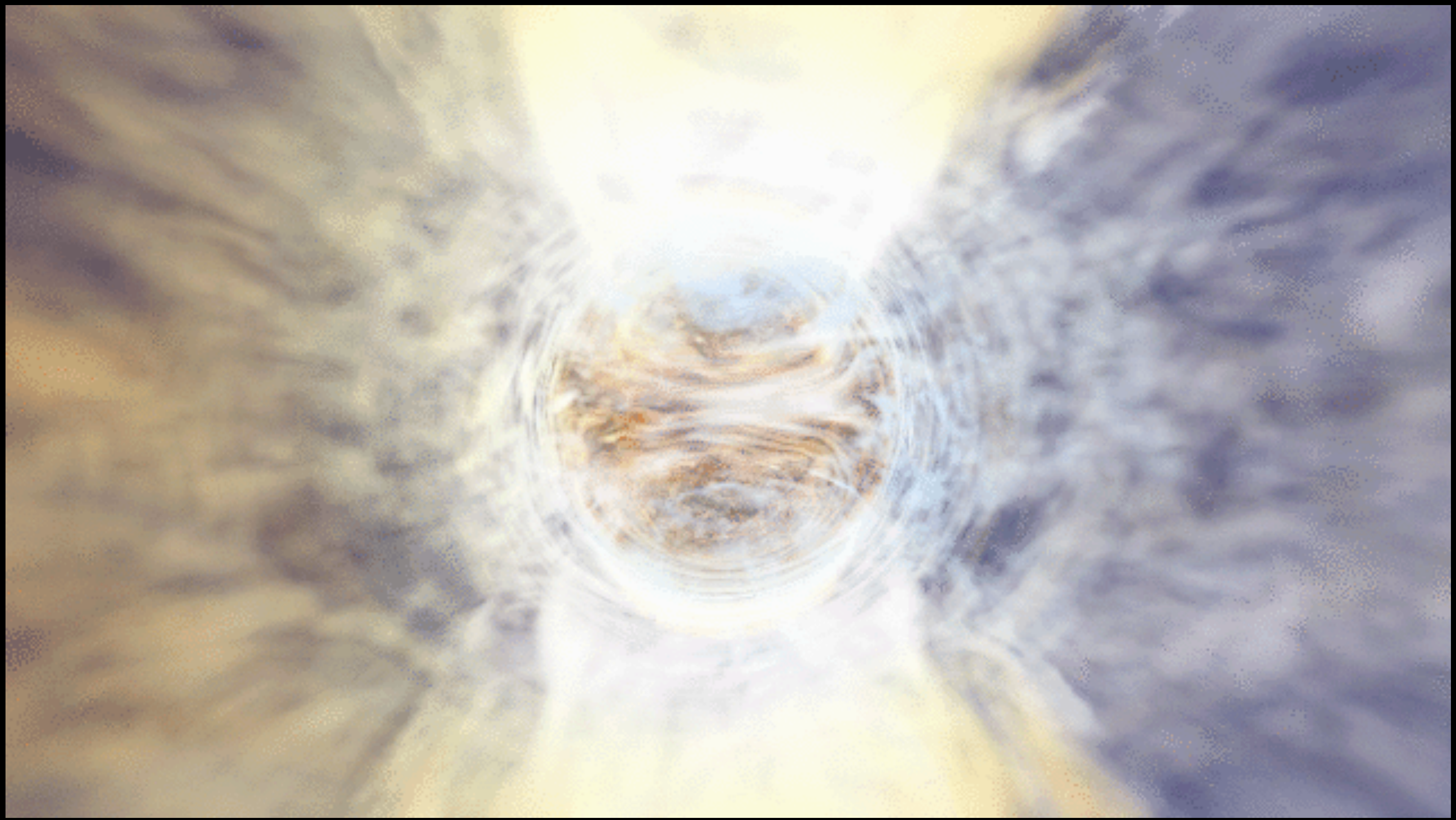
Black Holes

- But if you fell into a black hole the mass of the sun, you would be torn apart by tidal forces



Bigger!

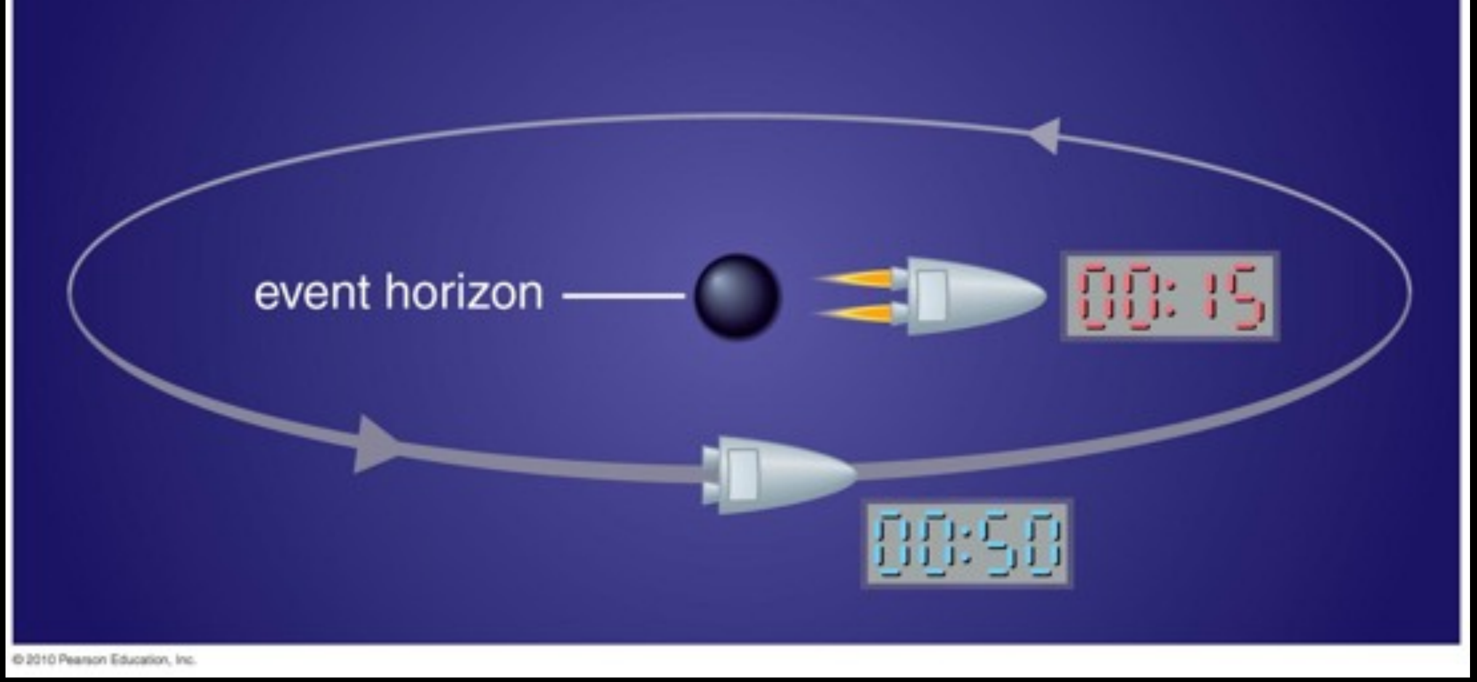
- A bigger black hole, such as a 10^9 solar mass black hole, has much weaker tides (though the strength of gravity at its event horizon is the same) so you could in theory survive past the event horizon
- This is a general relativistic visualization of a supercomputed magneto-hydrodynamic simulation of a disk and jet around a black hole.



Black Hole Simulations

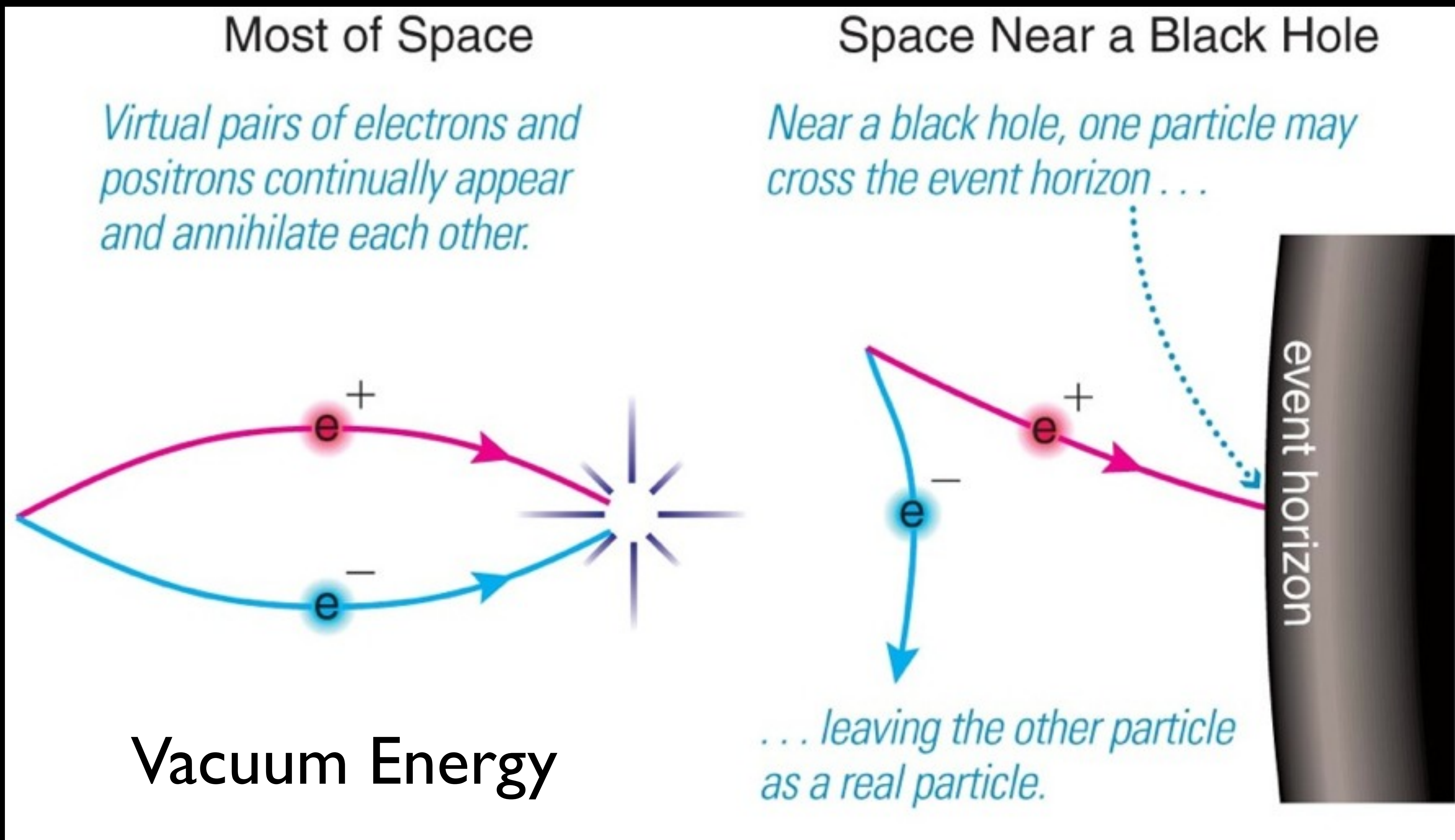
- Andrew Hamilton creates these simulations
- Check out his website for more information: http://jila.colorado.edu/~ajsh/insidebh/

Black Holes



- What would an outside observer see?
  - They would watch time get progressively slower for you
  - They would watch you get further and further redshifted until you became impossible to see even with radio telescopes
  - Eventually, they would see that time has stopped for you - from an outside observer's perspective, you'd never cross the event horizon

Black Holes - Other weird behavior



Hawking Radiation

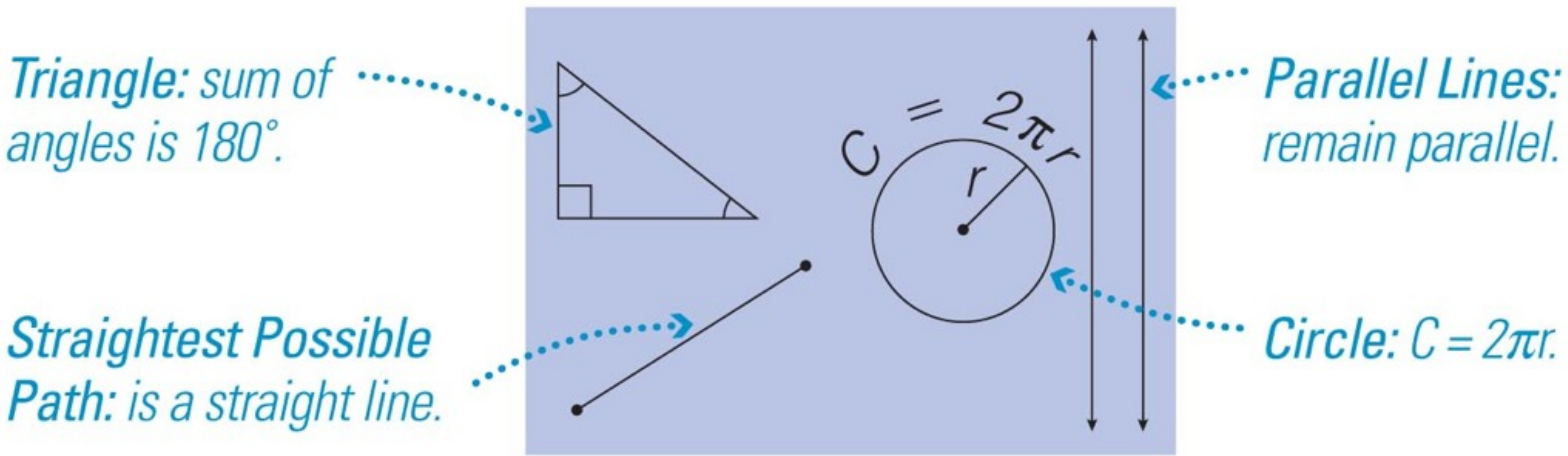
- In 1974, Stephen Hawking proposed that black holes may actually be emitting thermal radiation as blackbodies
- How the heck?!
    - Lots of models: pair creation, vacuum fluctuations, quantum tunneling
    - We haven’t directly observed it, so we’re not sure yet
- But it’s a black hole
    - A 1 solar mass black hole would have an effective temperature of 60 nano-Kelvin, which is as cold as the coldest gas ever created in laboratories on Earth.
        - It therefore absorbs even CMB radiation
    - A 2.7 K black hole would have the mass of the Moon, but it is not known how such a small black hole would form

Does light escape the black hole?

- No. Nothing escapes the black hole. It just happens that the black hole captures “negative mass” and lets a little bit of energy go
- The black hole slowly “evaporates” but never gives up its victims

Geometry of Spacetime: Flat

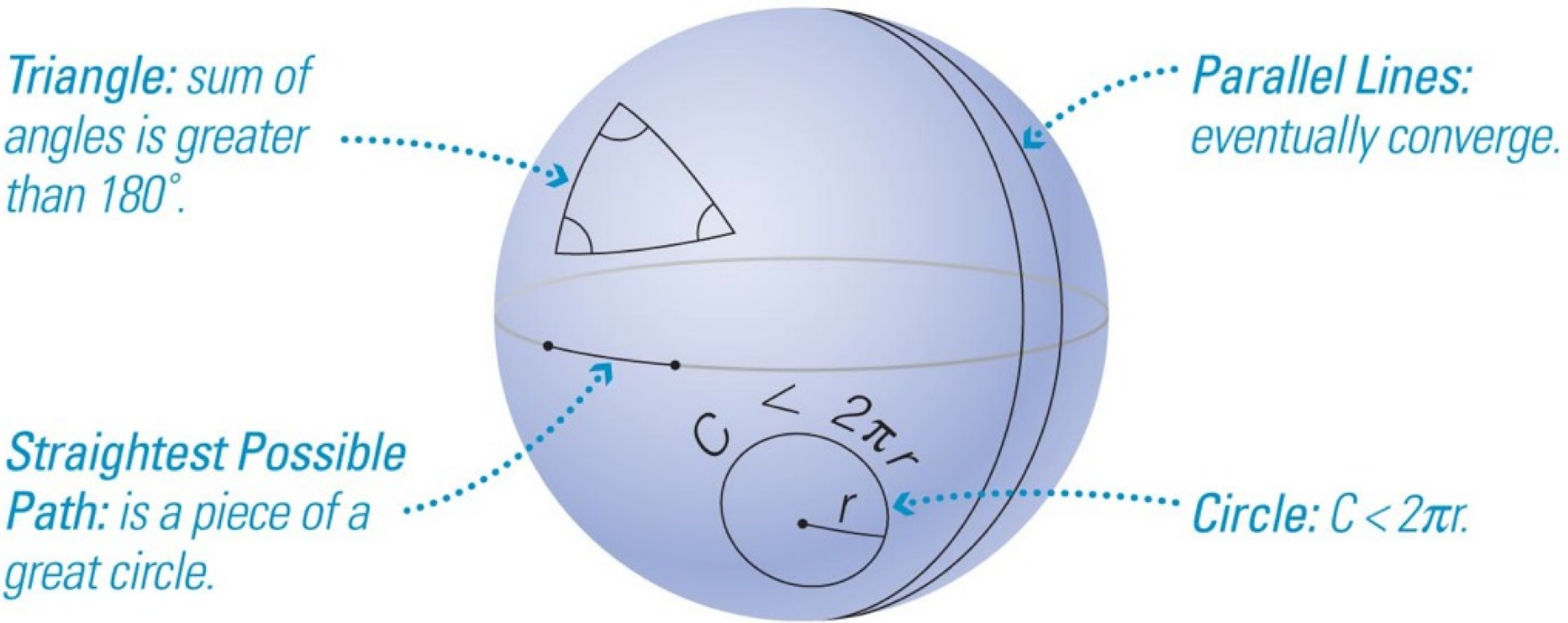
Our universe is "very flat" - we don't know that it's *exactly* flat but as far as we can measure, it is



a Rules of flat geometry.

Geometry of Spacetime: Closed

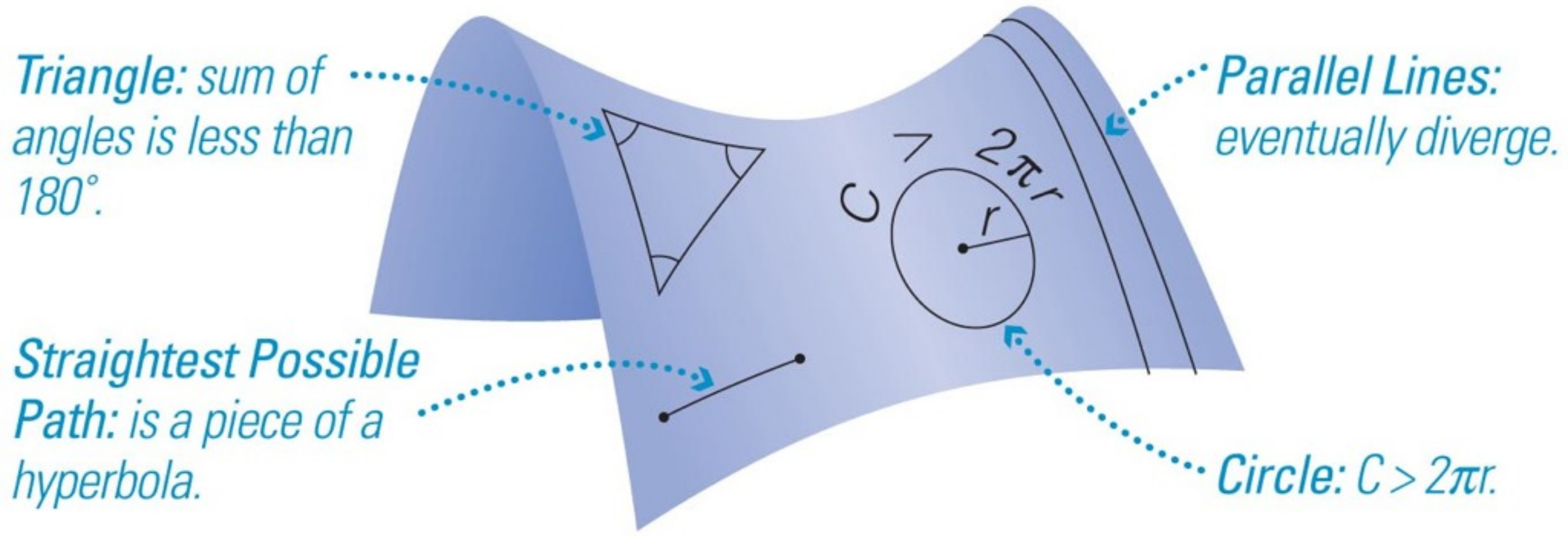
If the Cosmological Constant is zero, a closed universe will re-collapse in a Big Crunch



b Rules of spherical geometry.

Geometry of Spacetime: Hyperboloid

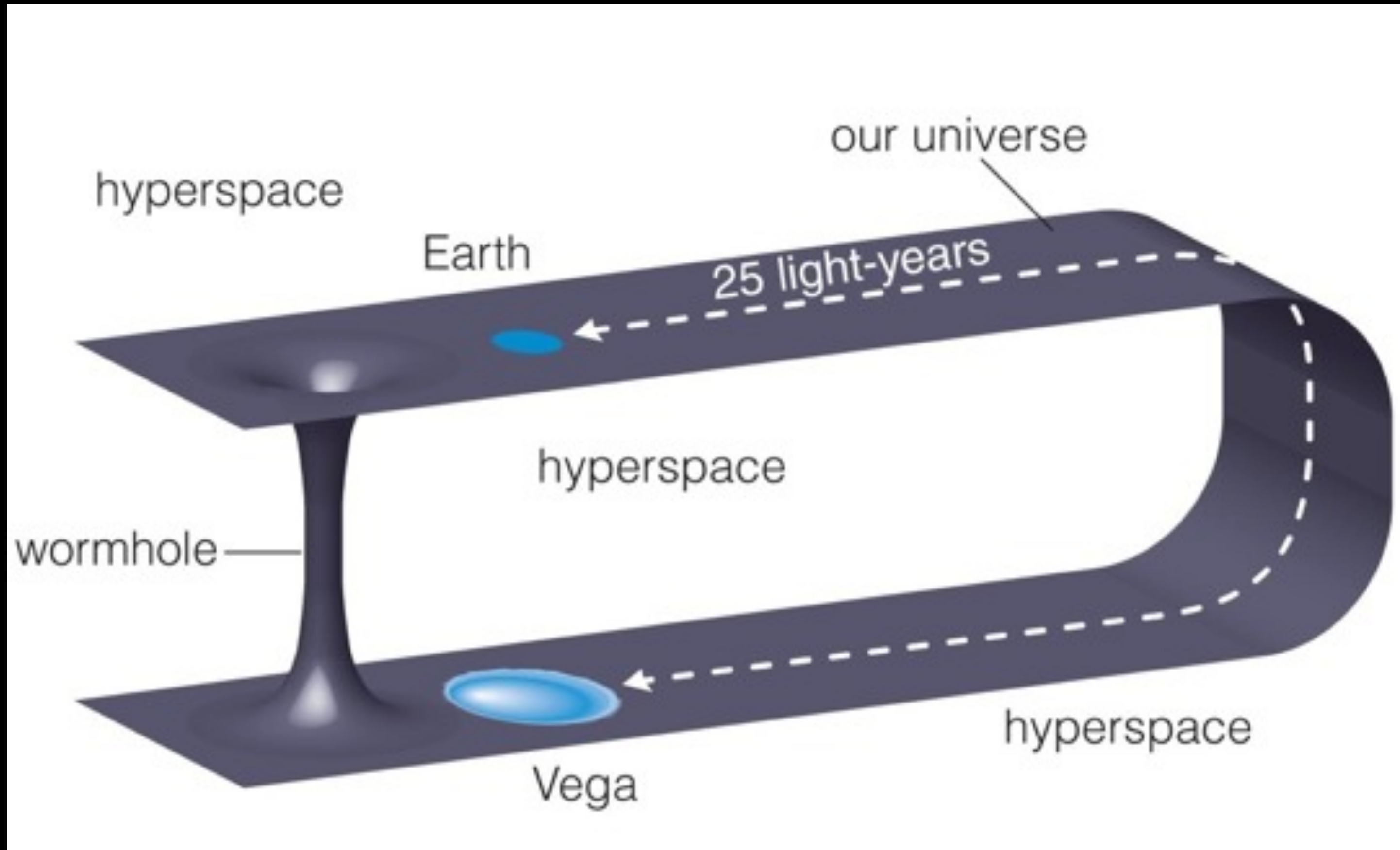
A saddle-shaped (hyperboloid) universe will expand forever



c Rules of saddle-shaped geometry.

Wormholes and Hyperspace

- Can you cheat the laws of relativity?
- There are no explicit physical laws (yet) forbidding the use of wormholes
- However, most physicists believe that we will discover laws that prevent the use of wormholes because jumping through spacetime can introduce un-resolvable paradoxes



Summary

- The universe is strange
- Relativity has some weird consequences
- Special and General relativity have both been experimentally verified