Black Holes

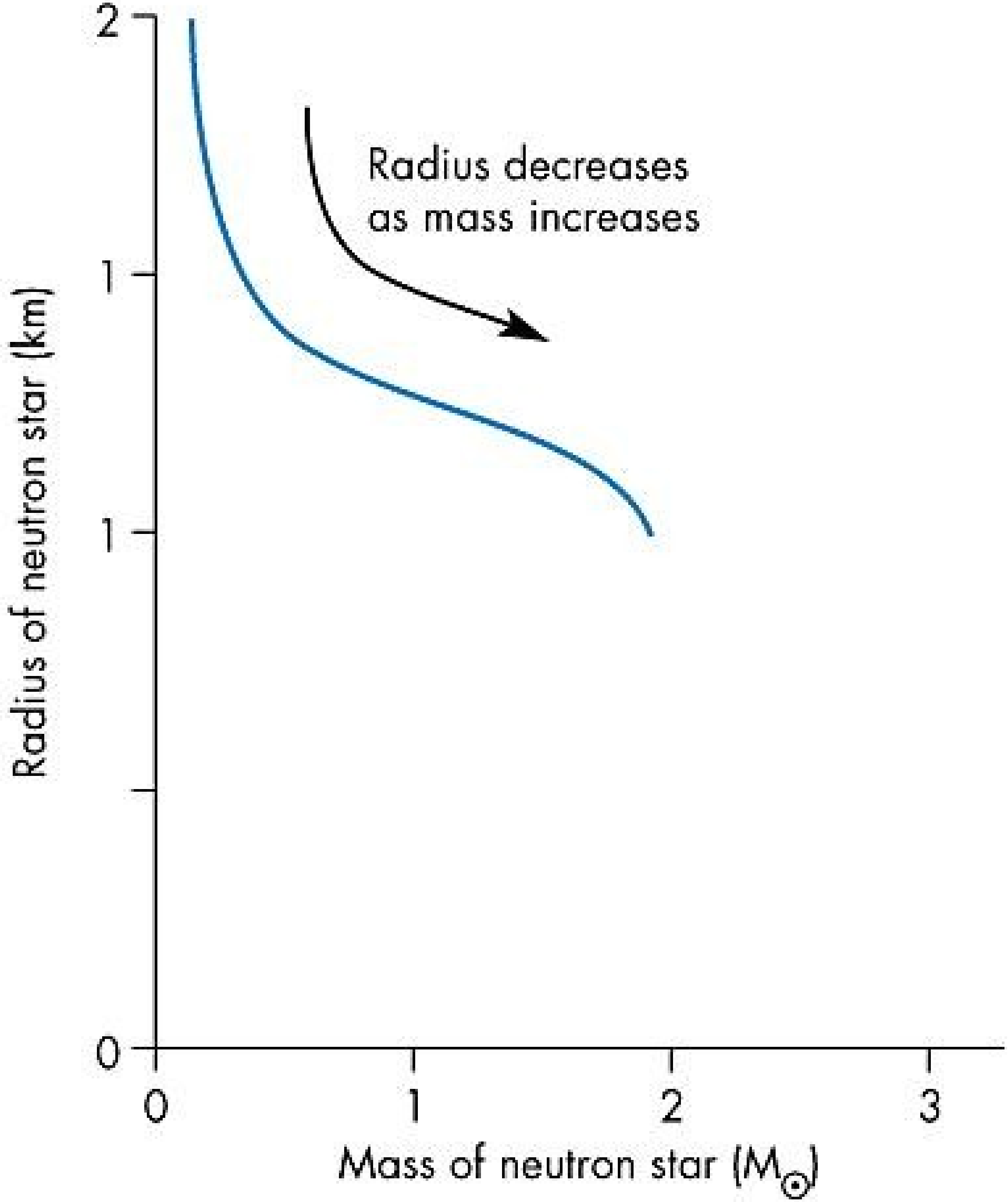
- Formation
- Spacetime
- Curved spacetime
- Event horizon
- Seeing black holes

Demo: 1L10.50 - Gravity Well - Black Hole

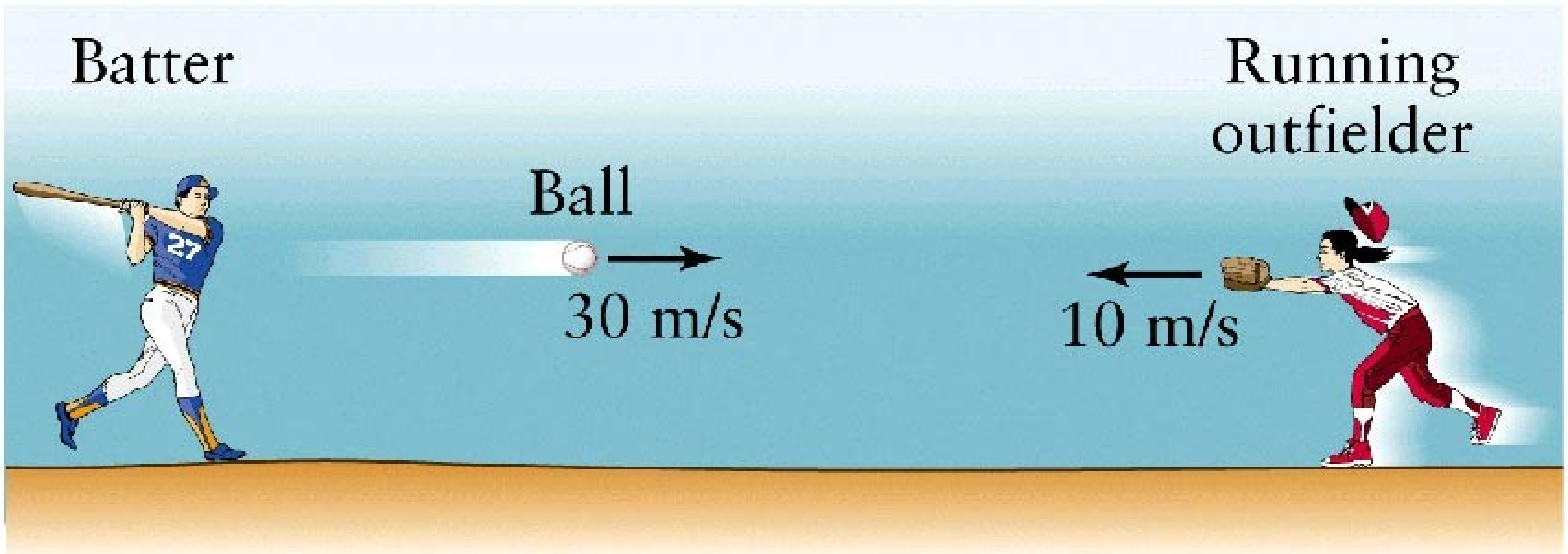
A more massive neutron star has

A) A smaller radius
B) A larger radius
C) Radius is independent of mass
D) No radius

Mass versus radius for a neutron star



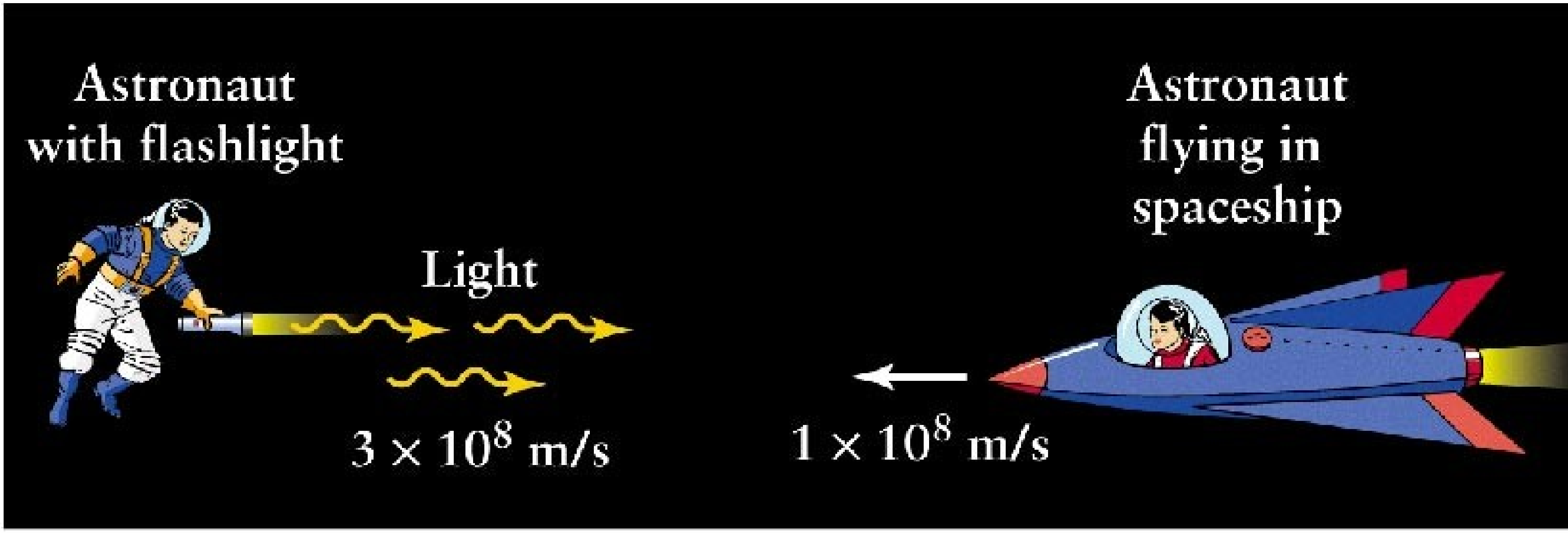
Objects too heavy to be neutron stars collapse to black holes



As seen by outfielder, ball is approaching her at
(30 m/s) + (10 m/s) = 40 m/s

a

Speed of light is constant



Incorrect Newtonian description:

As seen by astronaut in spaceship, light is approaching her at $(3 \times 10^8 \text{ m/s}) + (1 \times 10^8 \text{ m/s}) = 4 \times 10^8$ m/s

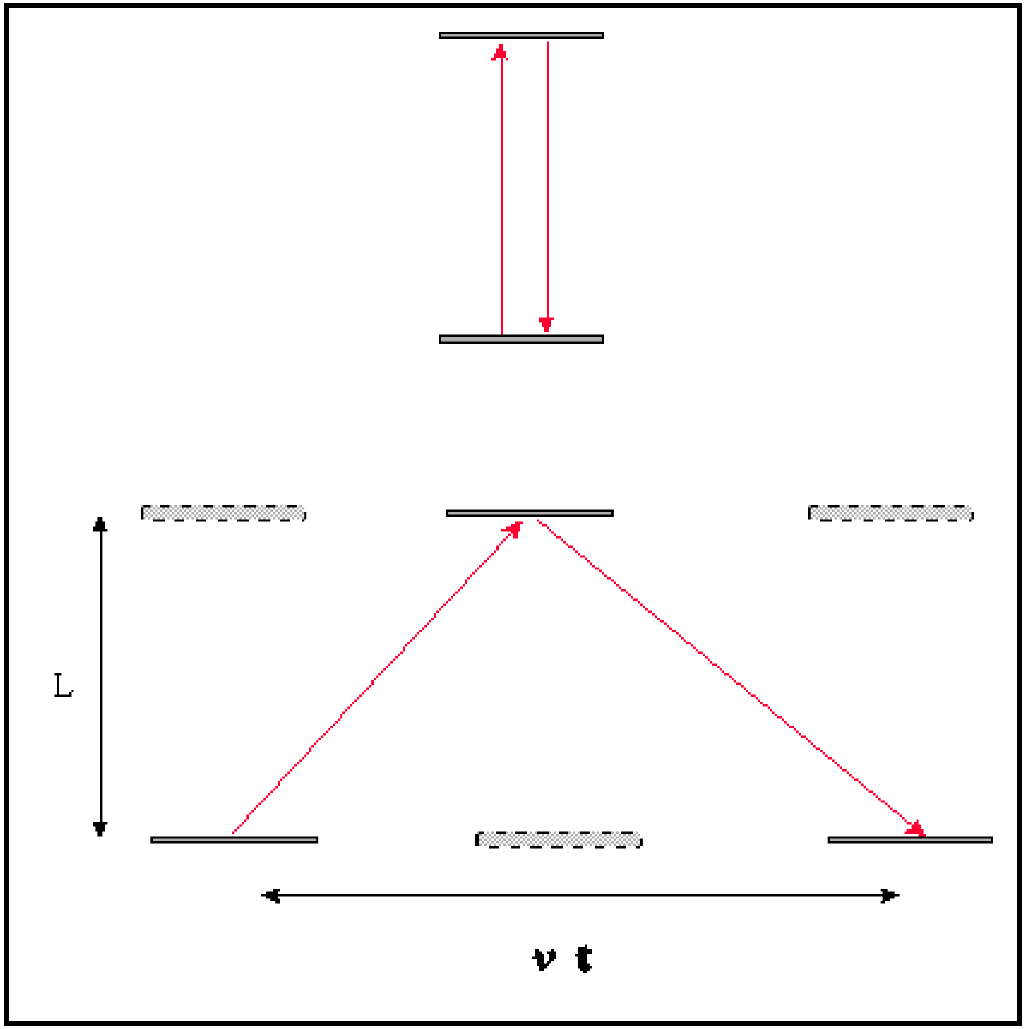
Correct Einsteinian description:

As seen by astronaut in spaceship, light is approaching her at 3×10^8 m/s

Our conceptions of space and time has to be changed.

- Facts:
  - Regardless of speed or direction, observers always measure the speed of light to be the same value.
  - Speed of light is maximum possible speed.
- Consequences:
  - The length of an object decreases as its speed increases
  - Clocks passing by you run more slowly than do clocks at rest

Time dilation: Clocks passing by you run more slowly than do clocks at rest

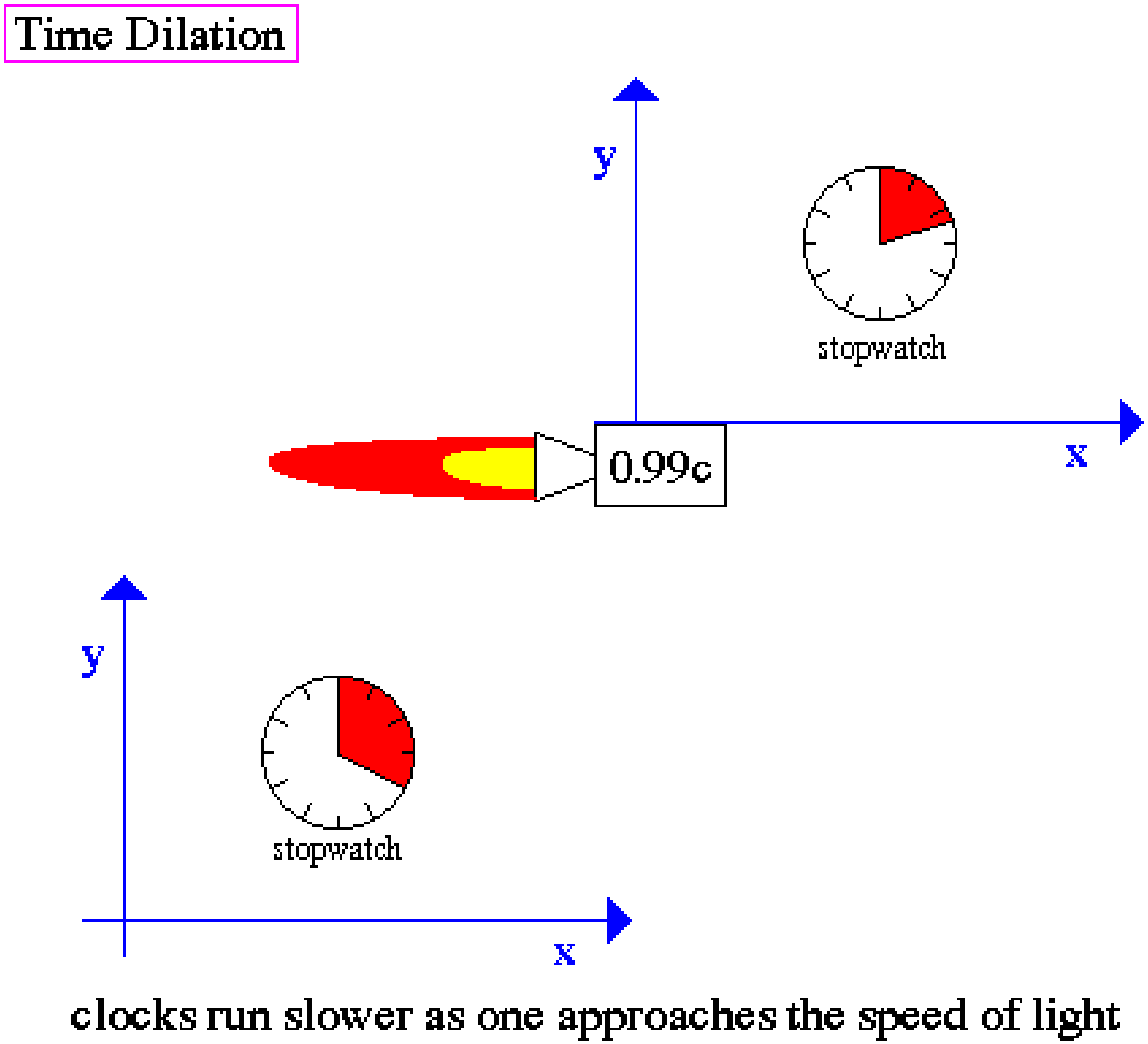


Red shows path of light.

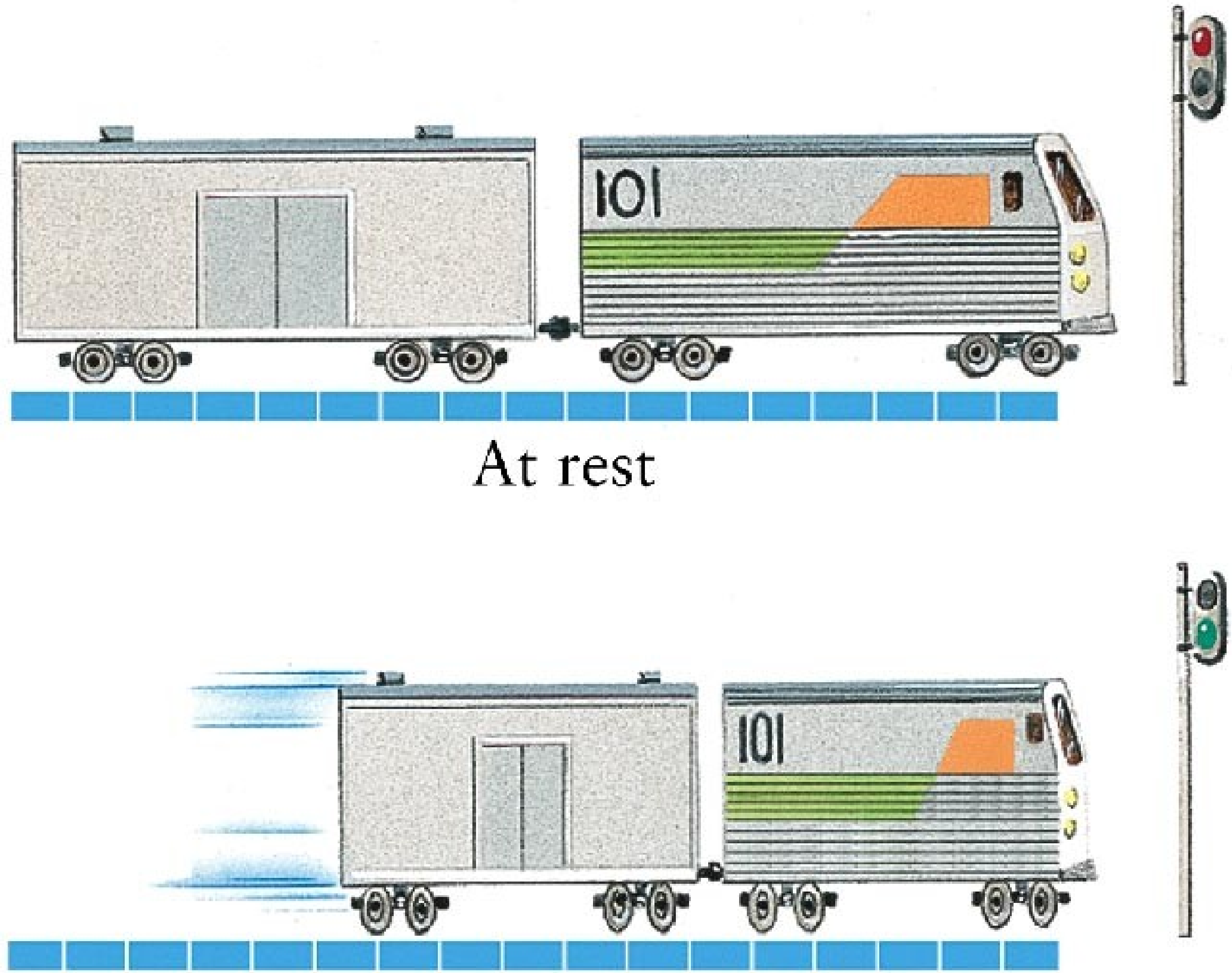
In stationary clock, light travels distance 2L between ticks of clock.

In moving clock, light travels a longer distance between ticks of clock – takes longer to travel the longer distance – clock runs slower.

Time dilation



Special Relativity: Length Contraction



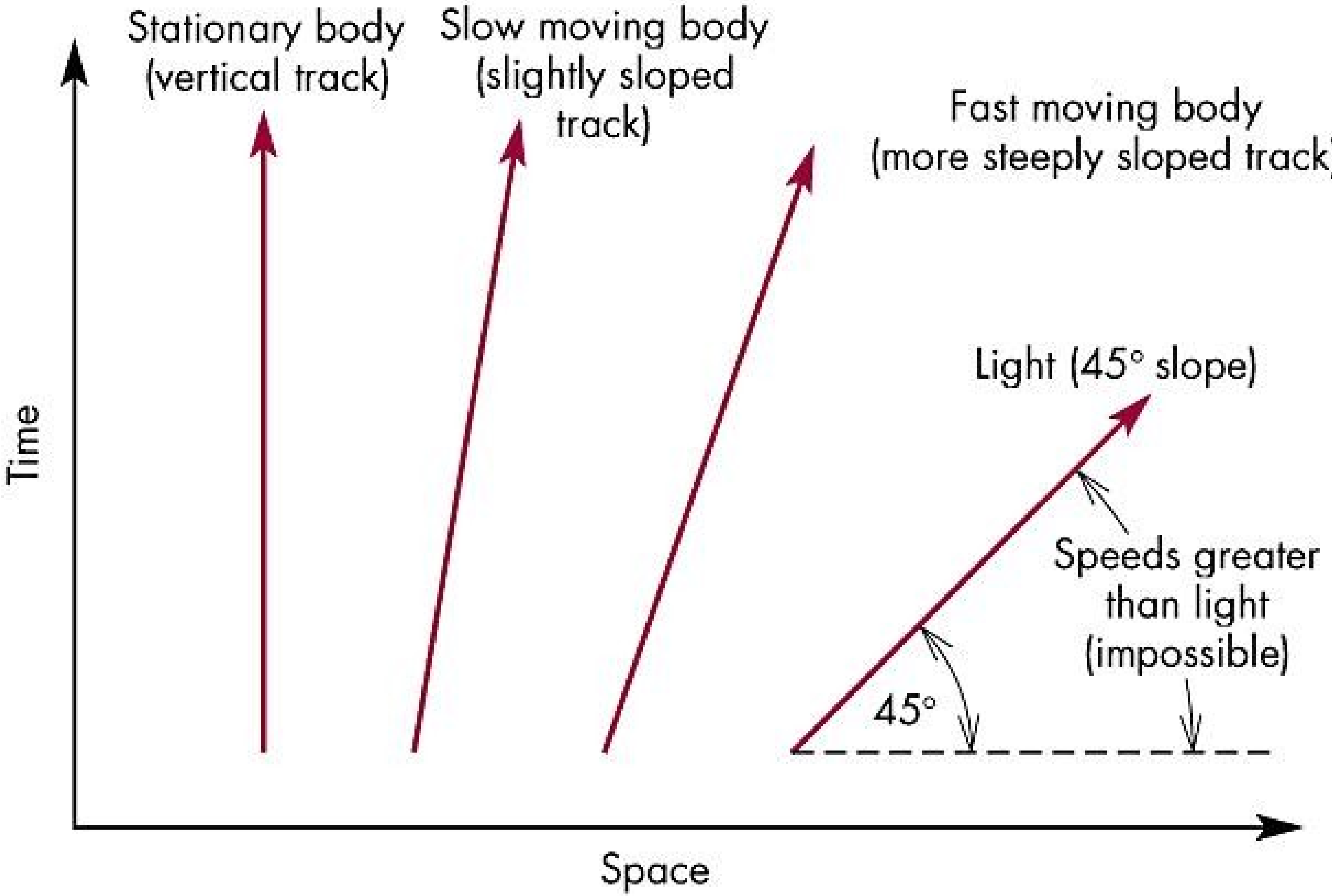
At rest

In motion

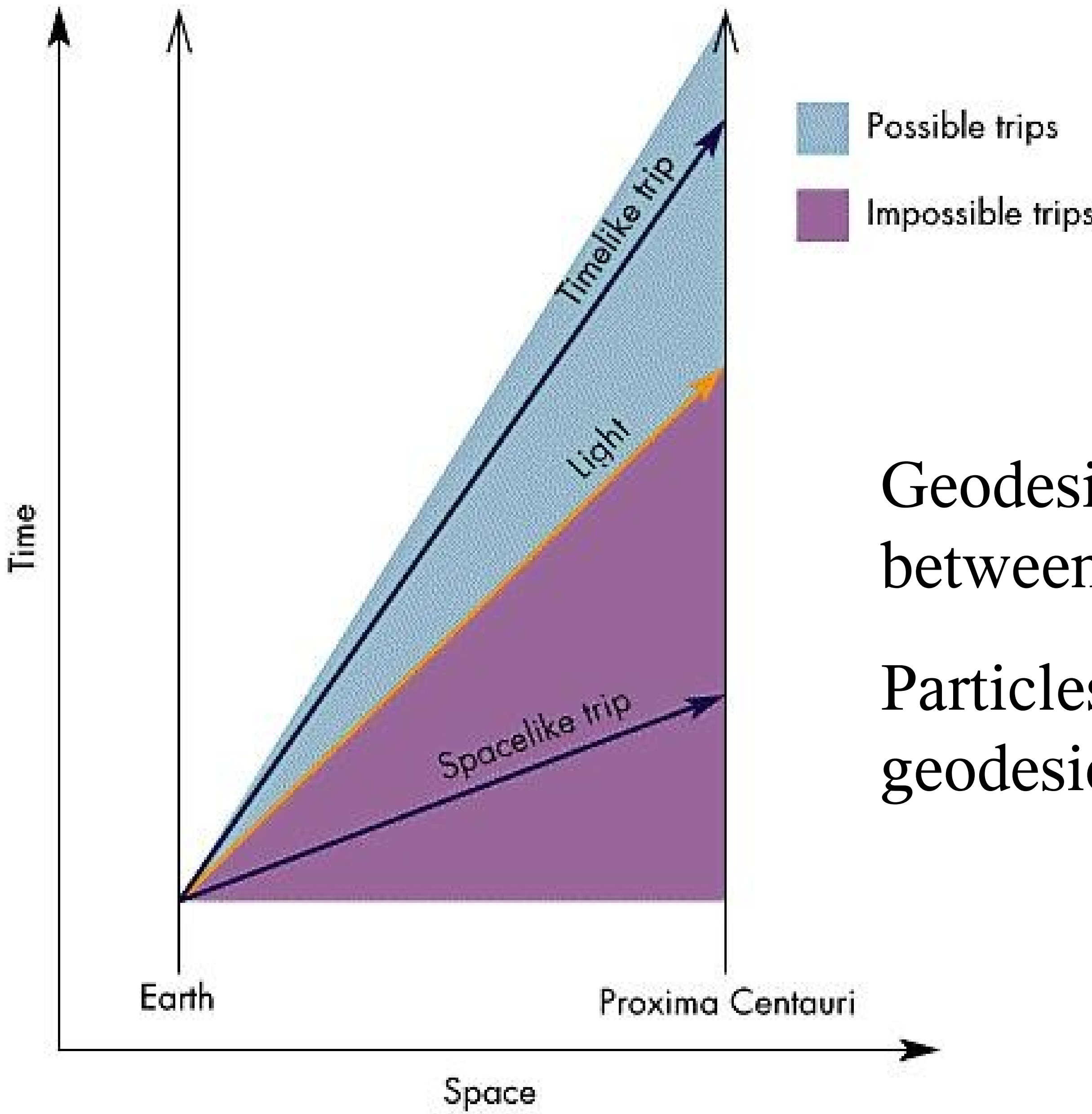
As an object speeds up, an observer at rest would see

A) It get longer and its clock run faster
B) It get shorter and its clock run faster
C) It get longer and its clock run slower
D) It get shorter and its clock run slower

Spacetime Diagram



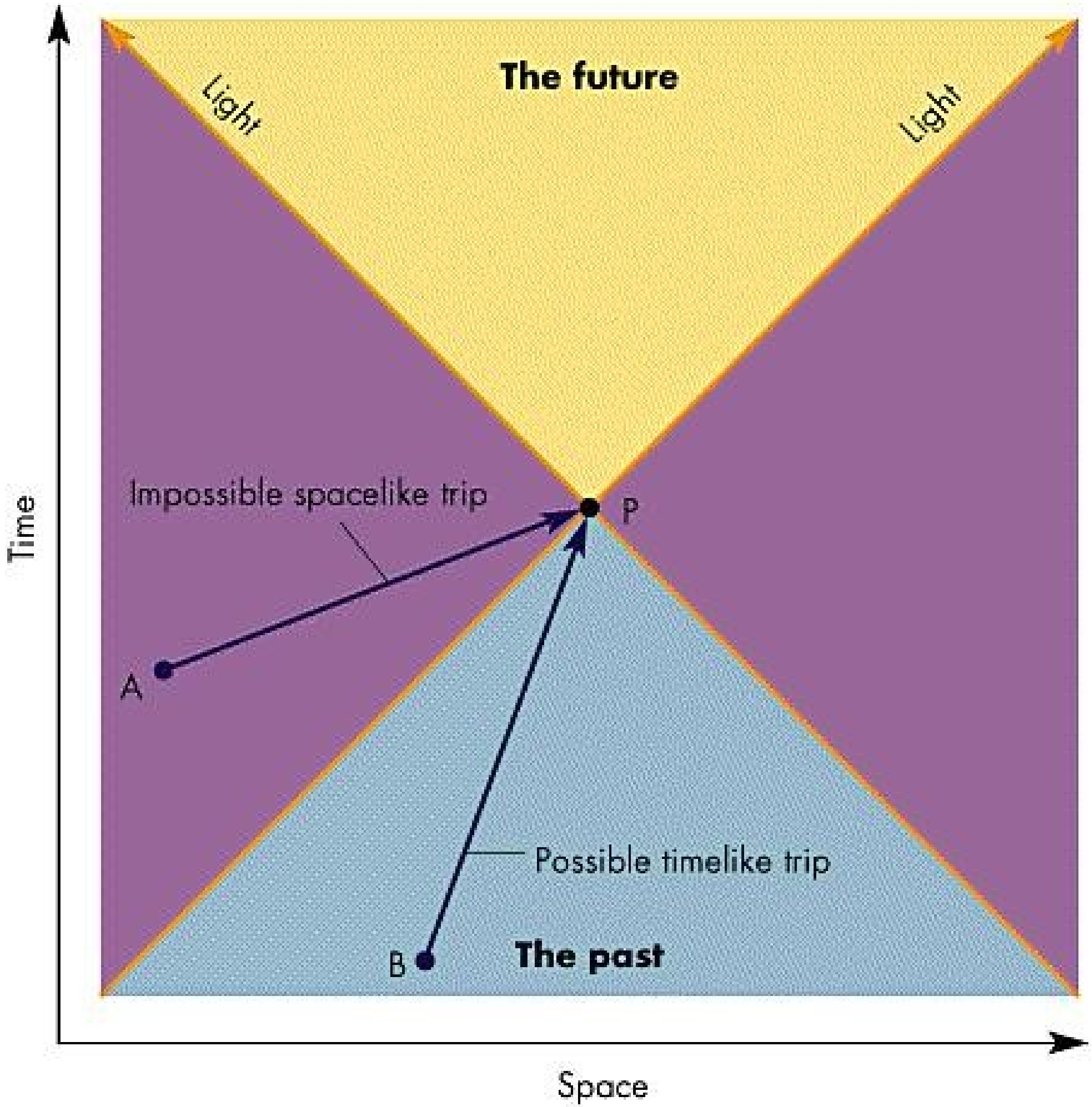
Spacetime Diagram



Geodesic = shortest path between two points.

Particles follow geodesics in spacetime.

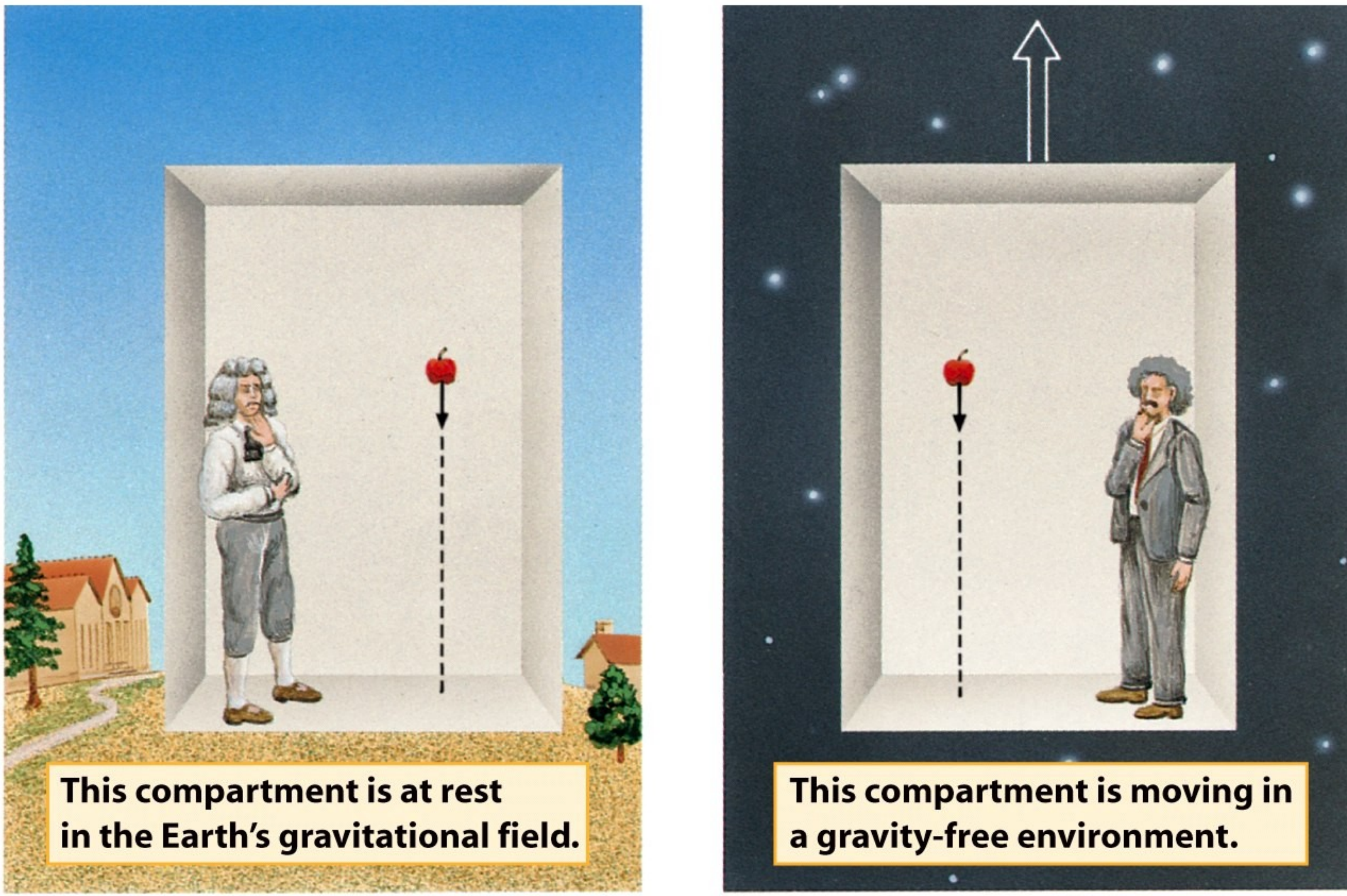
Spacetime Diagram



If Alpha Centauri exploded 3 second ago, could there be any effect now on Earth?

A) Yes
B) No

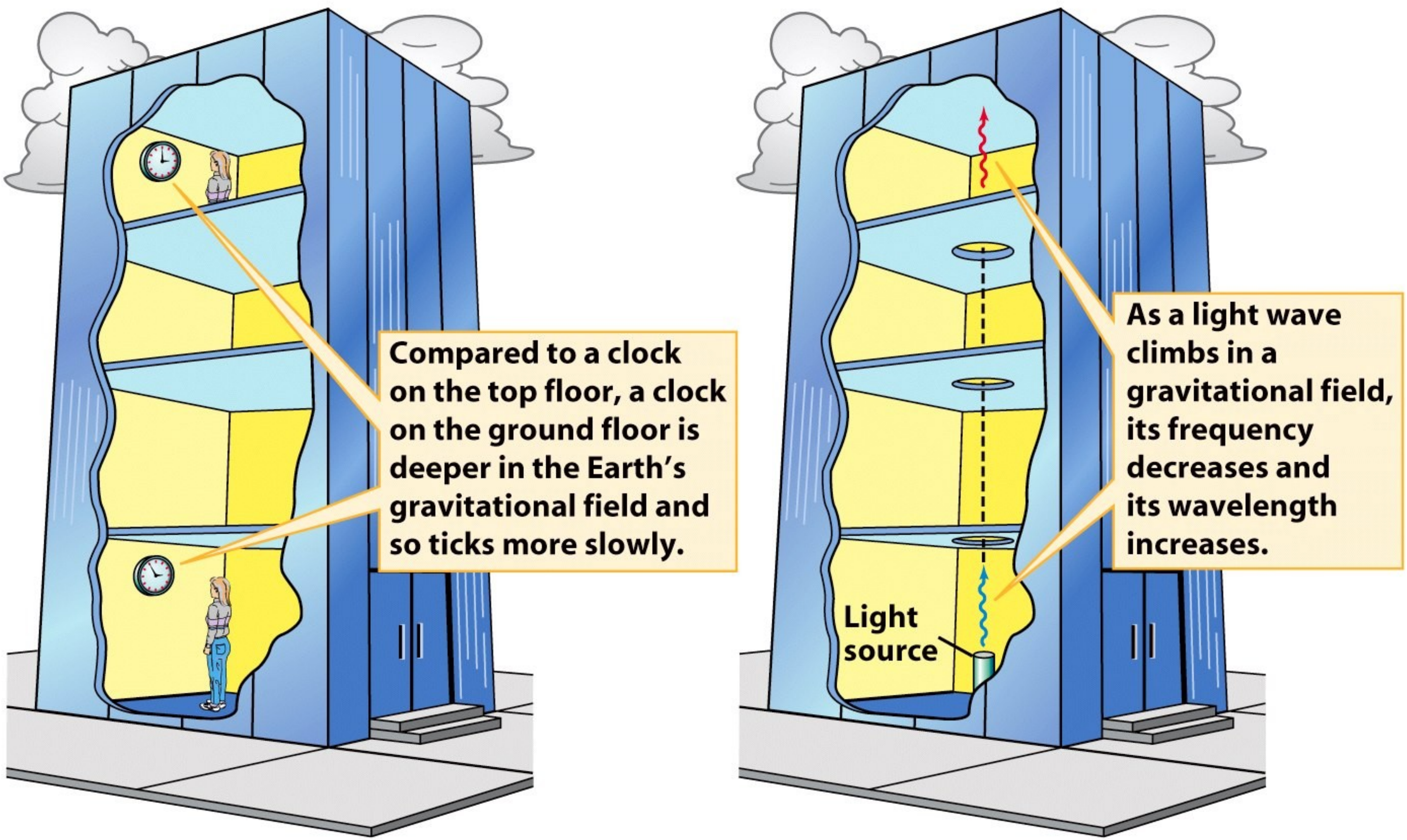
Equivalence principle



(a) The apple hits the floor of the compartment because the Earth's gravity accelerates the apple downward.

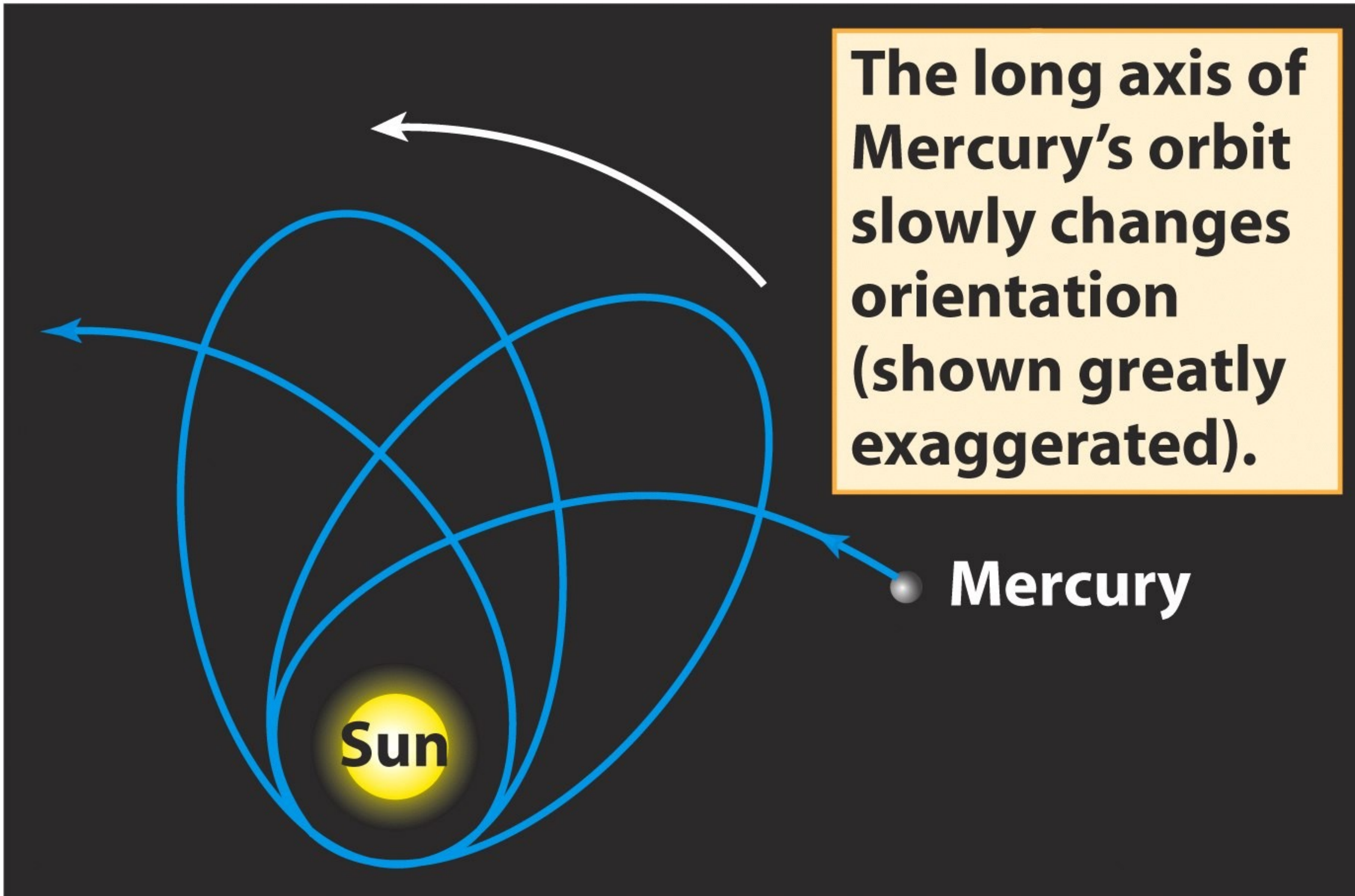
(b) The apple hits the floor of the compartment because the compartment accelerates upward.

Gravitational redshift

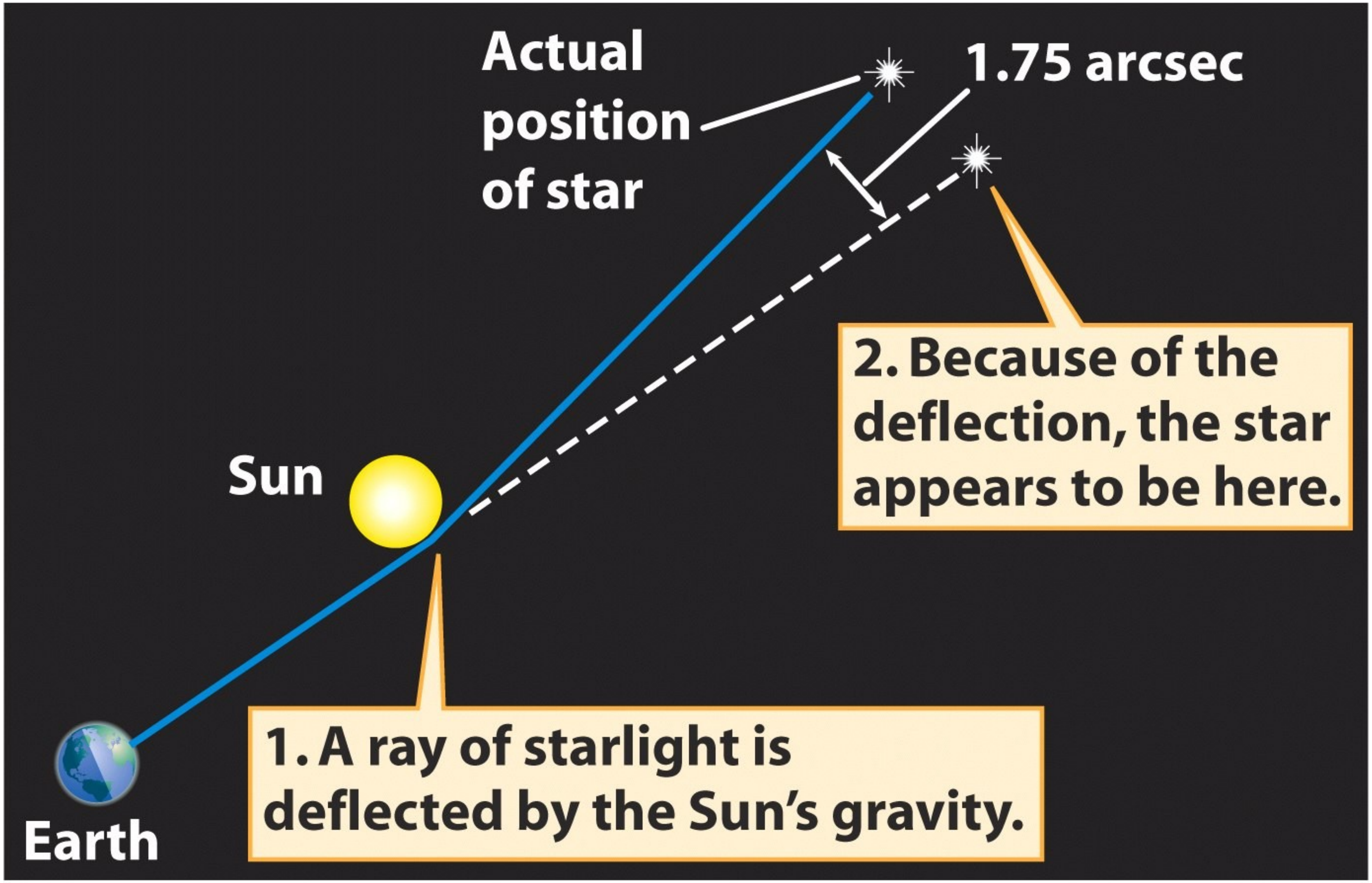


(a) The gravitational slowing of time **(b)** The gravitational redshift

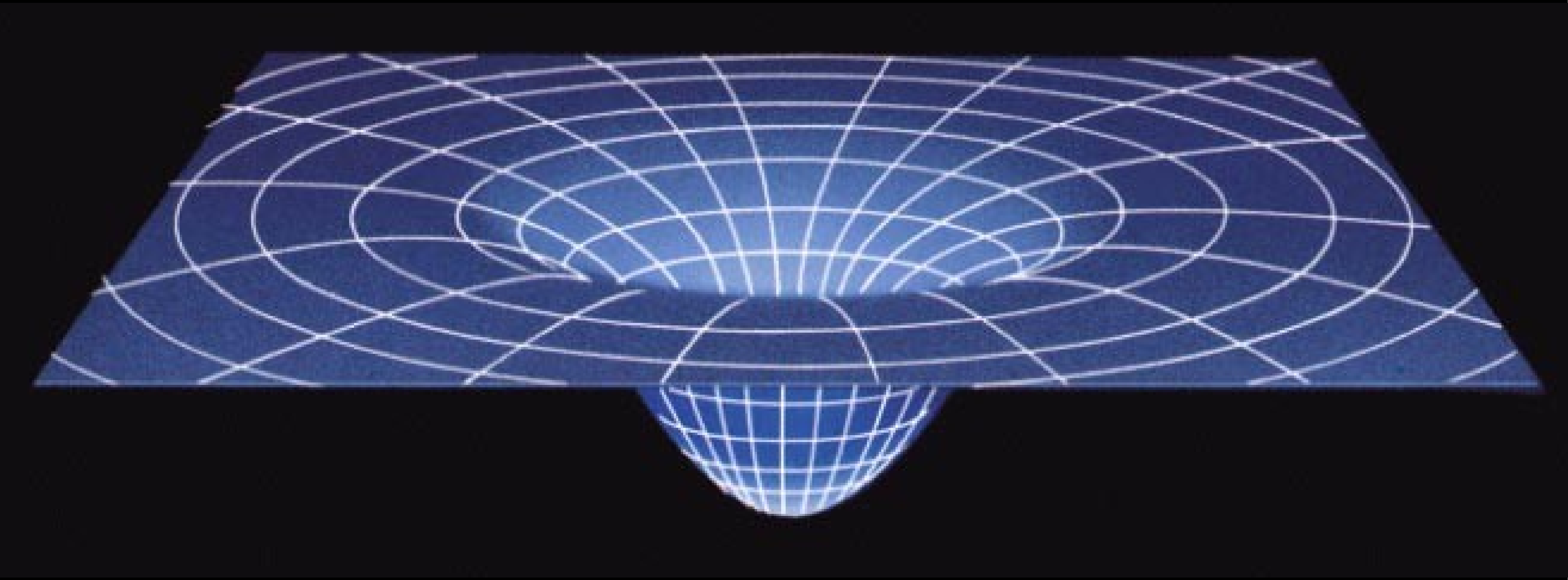
Precession of Mercury’s orbit



Gravity bends the path of light



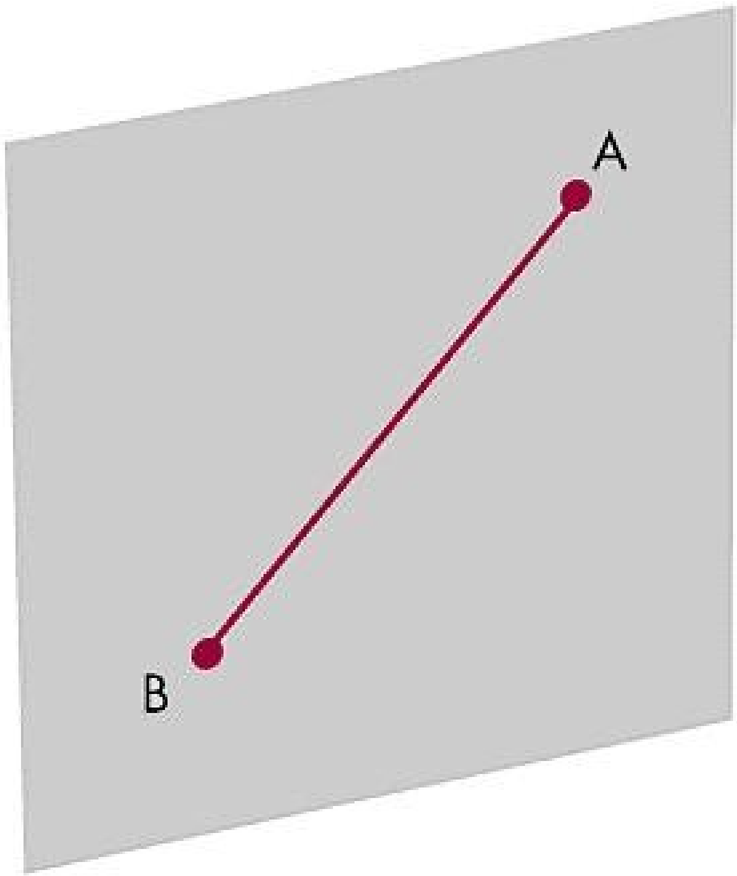
Gravity deforms space-time



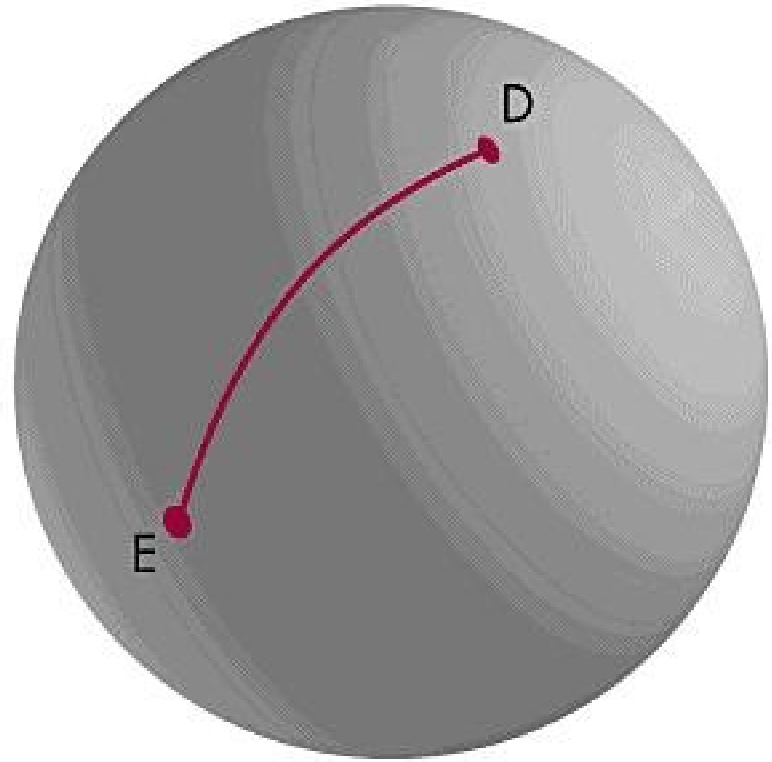
Einstein's theory of gravity is built on the principle that

A) The speed of light is constant.
B) As an object speeds up its clock runs faster.
C) The effects of gravity cannot be distinguished from the effects of acceleration in the absence of gravity.
D) Everyone's a relative.

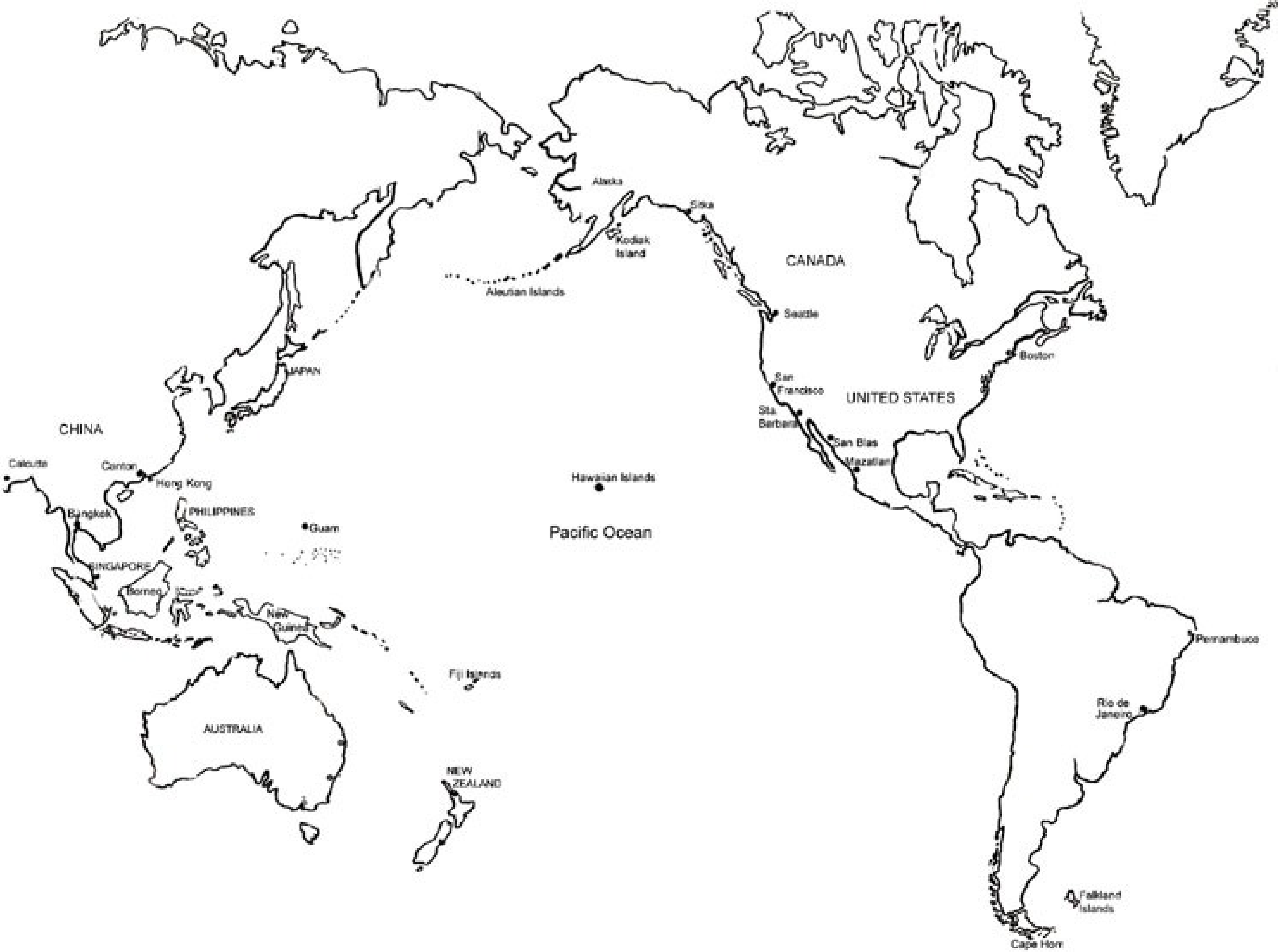
Geodesics in curved spacetime



A Flat two-dimensional space



B Curved two-dimensional space

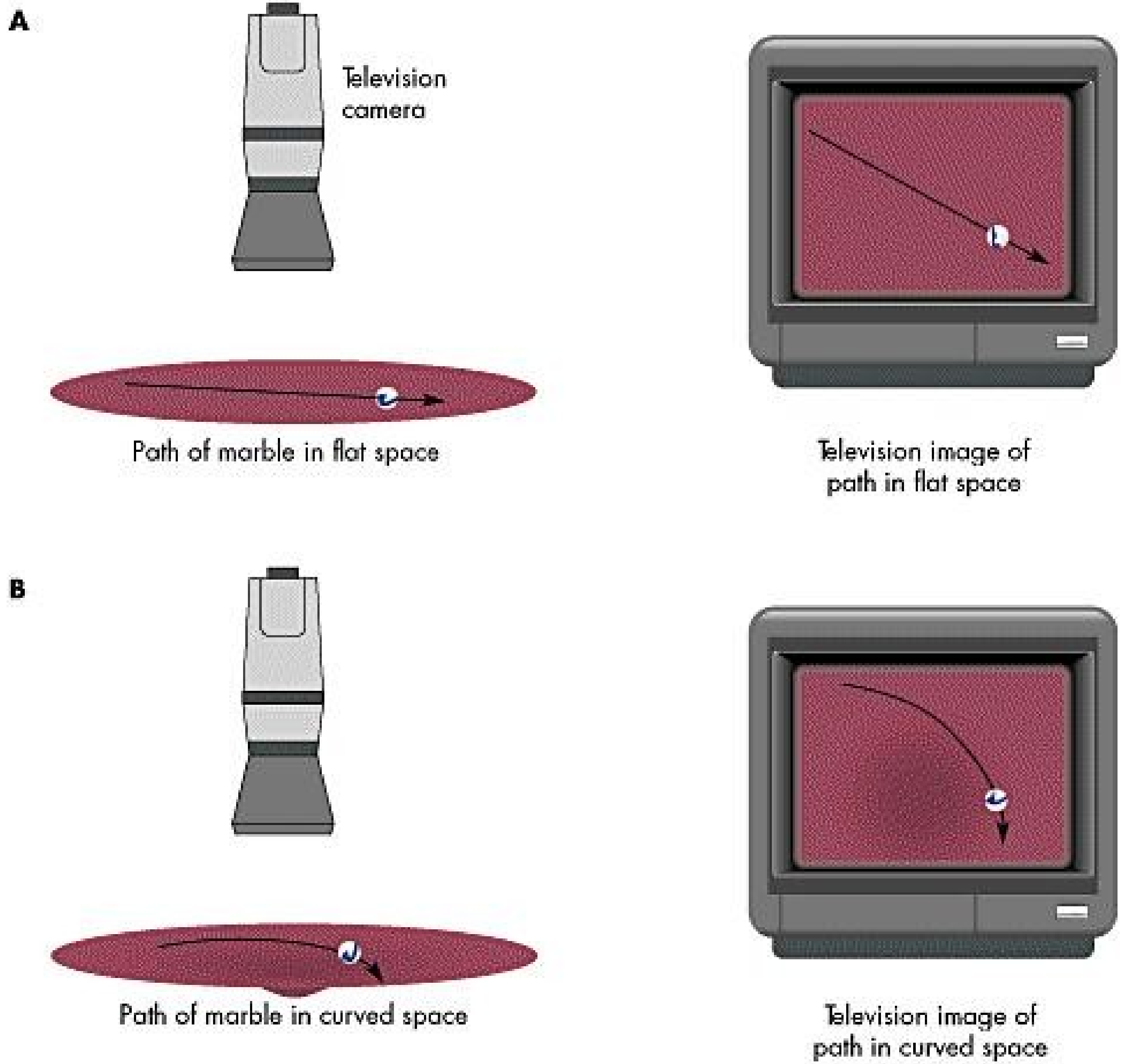


Adapted from *Greyhounds of the Sea The Story of the American Clipper Ship*
Carl C. Cutler (New York:G.P. Putnam's Sons, 1930)

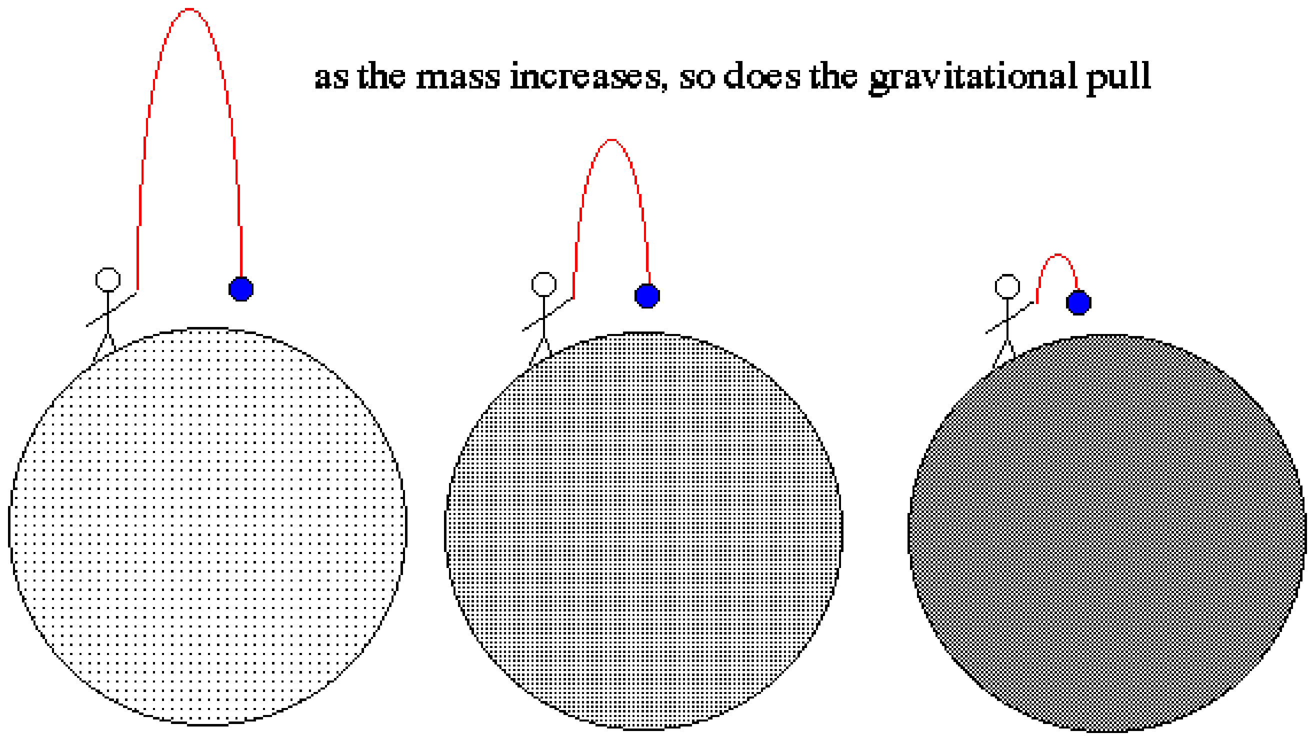
An airplane flies from Chicago to Beijing following the shortest possible route

A) The path of the airplane will appear as a straight line on a normal map
B) The airplane will fly over Alaska
C) The airplane will fly over Hawaii
D) The plane will fall off the end of the Earth and never reach China

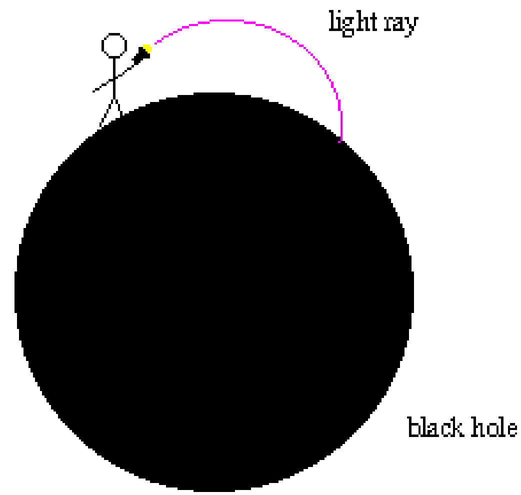
Geodesics in curved spacetime



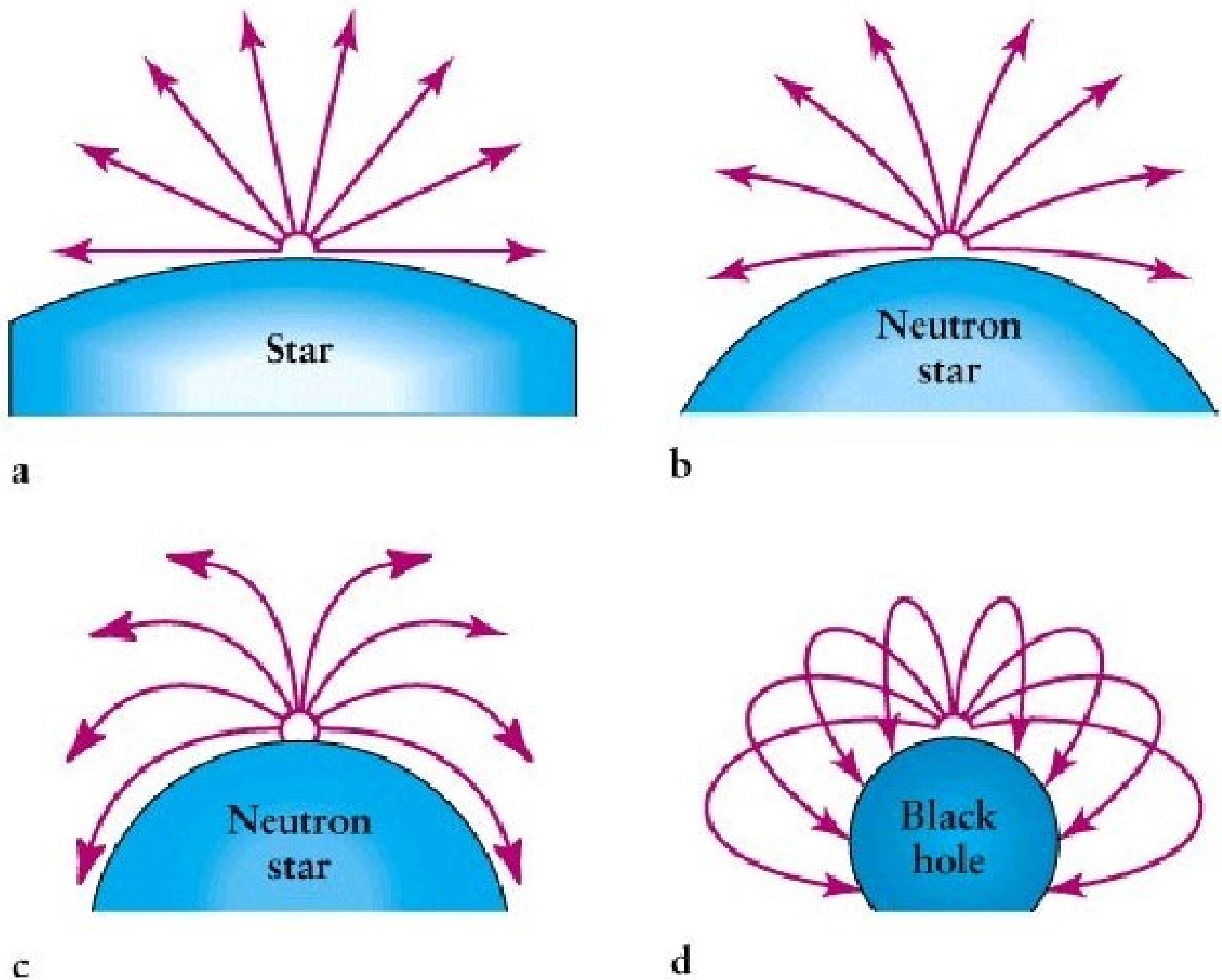
as the mass increases, so does the gravitational pull



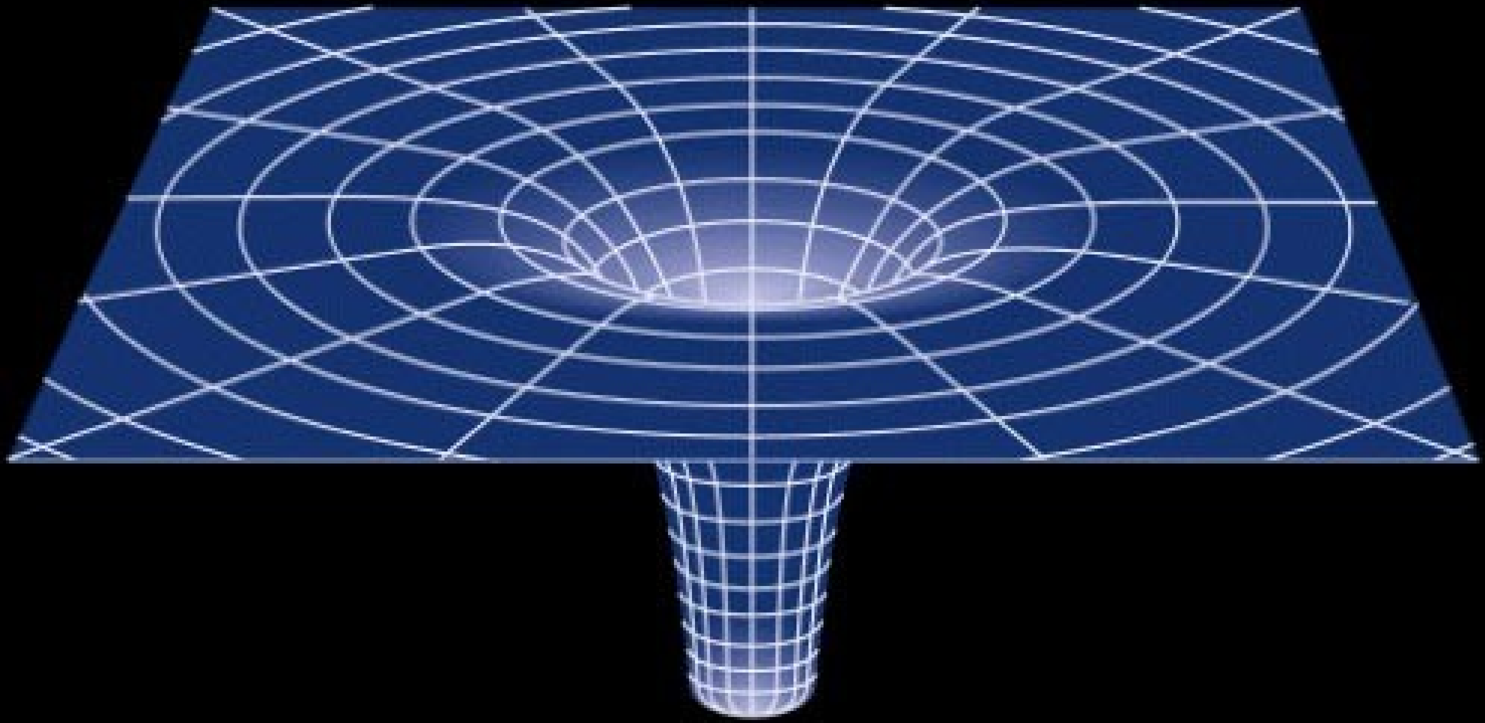
if the gravitational pull is such that even light cannot escape, then a black hole forms



Gravity bends the path of light



Spacetime should be distorted into an infinite well by a dense black hole

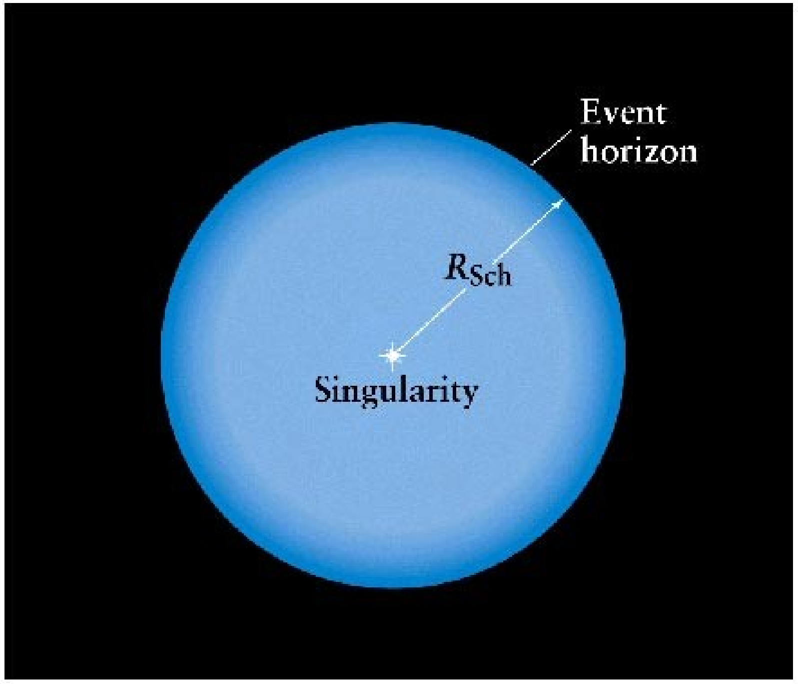


A nonrotating black hole has only a "center" and a "surface"

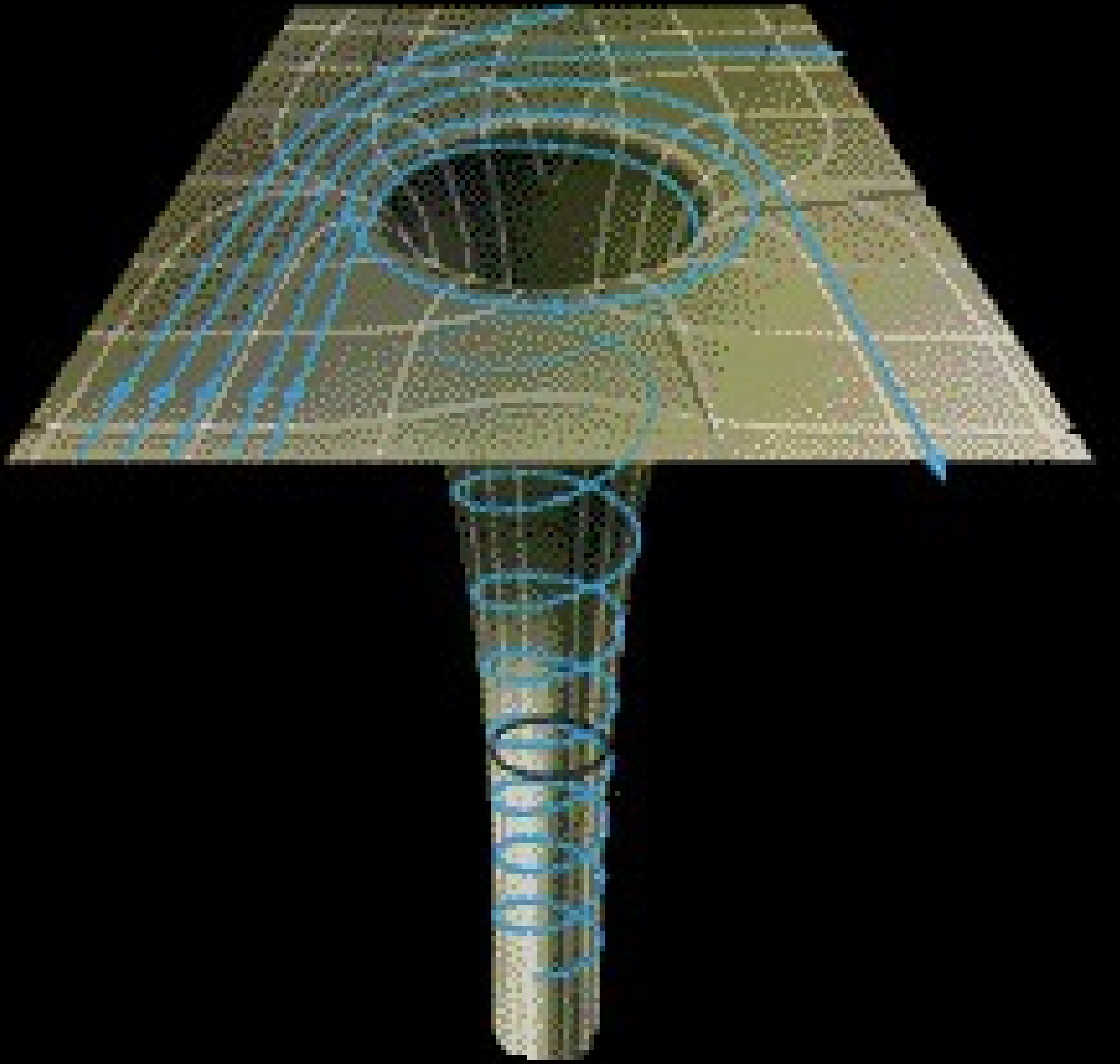
The black hole is surrounded by an *event horizon* which is the sphere from which light cannot escape

The distance between the black hole and its event horizon is the *Schwarzschild radius* ($R_{Sch} = 2GM/c^2$)

The center of the black hole is a point of infinite density and zero volume, called a *singularity*



Event horizon



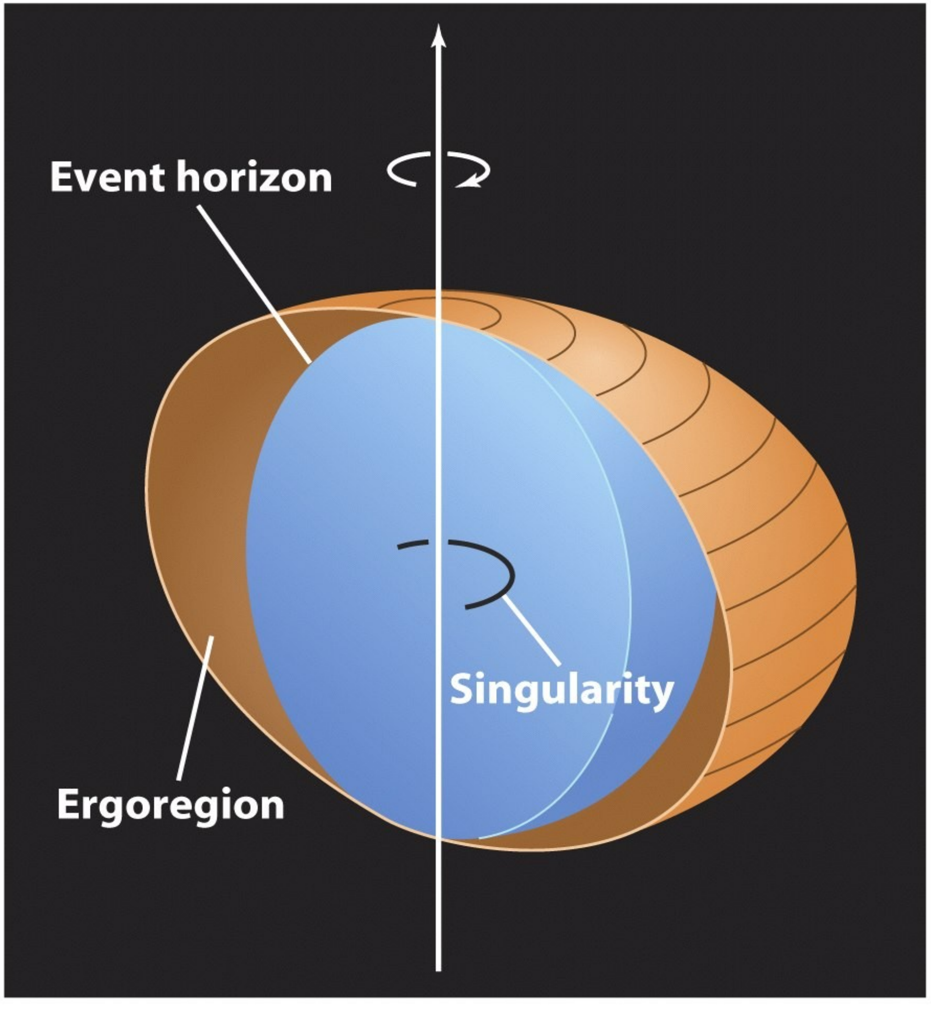
Three parameters completely describe the structure of a black hole

- Mass
  - As measured by the black hole's effect on orbiting bodies, such as another star
- Total electric charge
  - As measured by the strength of the electric force
- Spin = angular momentum
  - How fast the black hole is spinning

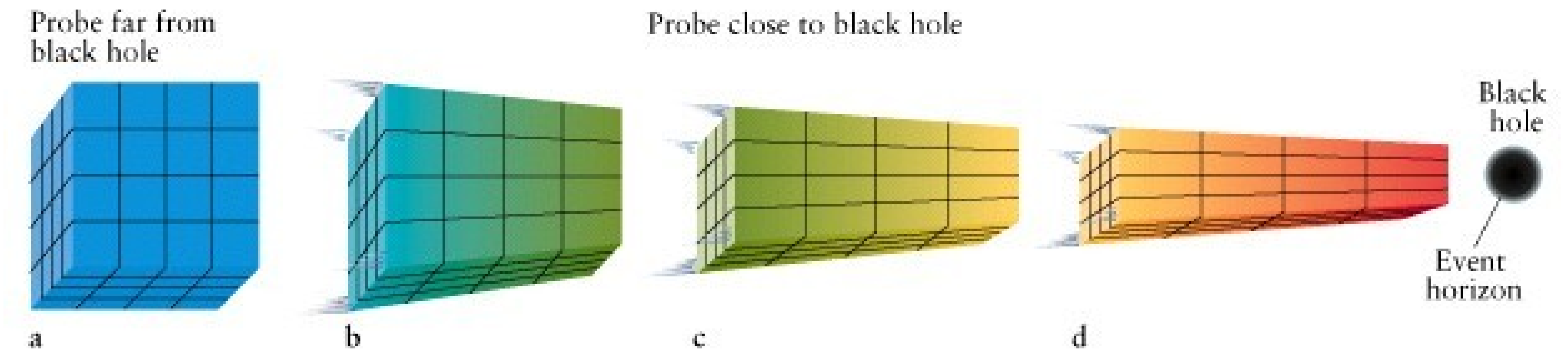
Most properties of matter vanish when matter enters a black hole, such as chemical composition, texture, color, shape, size, distinctions between protons and electrons, etc

Rotating black holes

- A rotating black hole (one with angular momentum) has an ergosphere around the outside of the event horizon
- In the ergosphere, space and time themselves are dragged along with the rotation of the black hole



Falling into a black hole



Falling into a black hole gravitational tidal forces pull spacetime in such a way that time becomes infinitely long (as viewed by distant observer). The falling observer sees ordinary free fall in a finite time.

Falling into a black holes

- With a sufficiently large black hole, a freely falling observer would pass right through the event horizon in a finite time, would be not feel the event horizon.
- A distant observer watching the freely falling observer would never see her fall through the event horizon (takes an infinite time).
- Falling into smaller black hole, the freely falling observer would be ripped apart by tidal effects.

Falling into a black hole

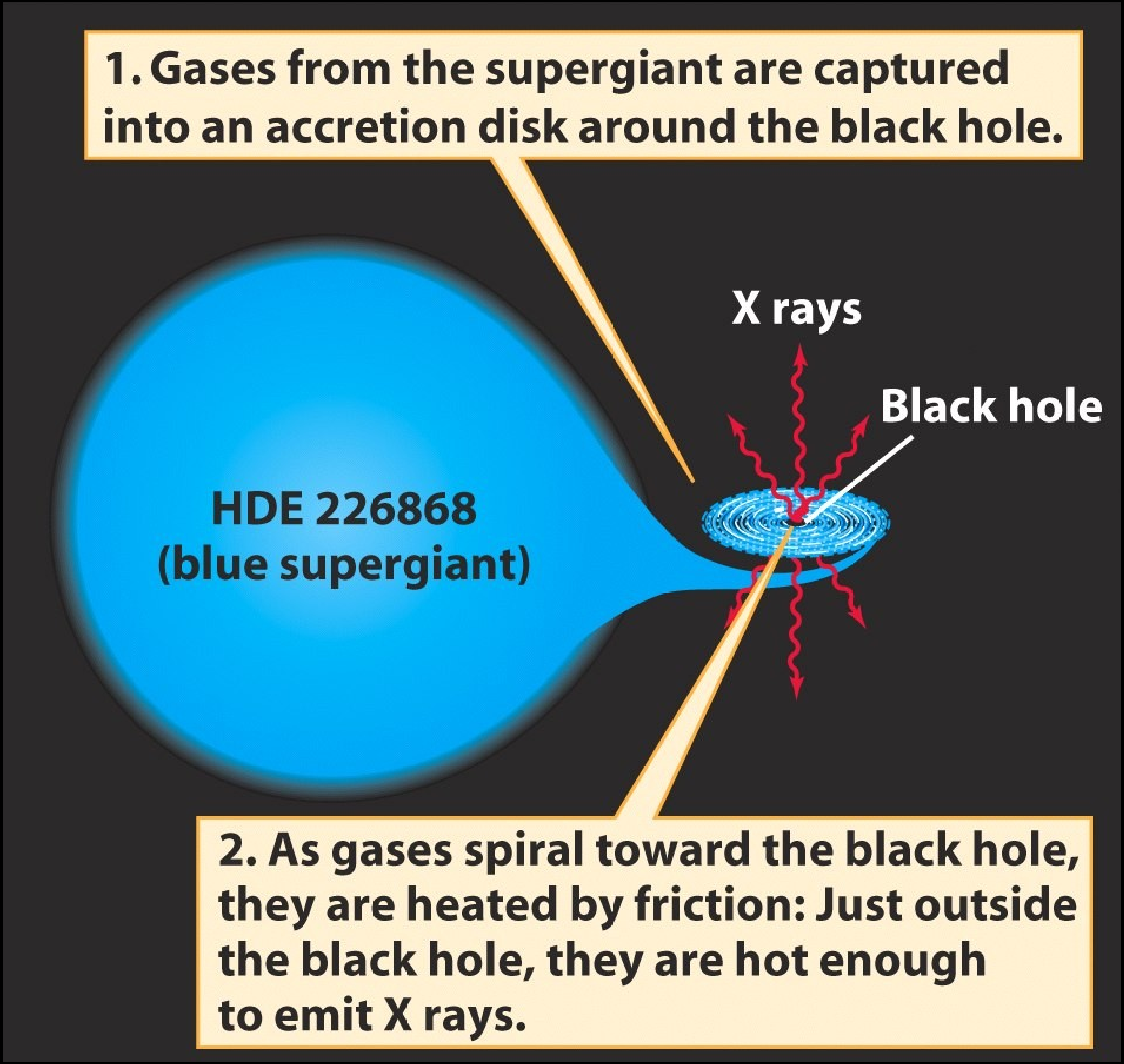
- Signals sent from the freely falling observer would be time dilated and redshifted.
- Once inside the event horizon, no communication with the universe outside the event horizon is possible.
- But incoming signals from external world can enter.

- A black hole of mass M has exactly the same gravitational field as an ordinary mass M at large distances.

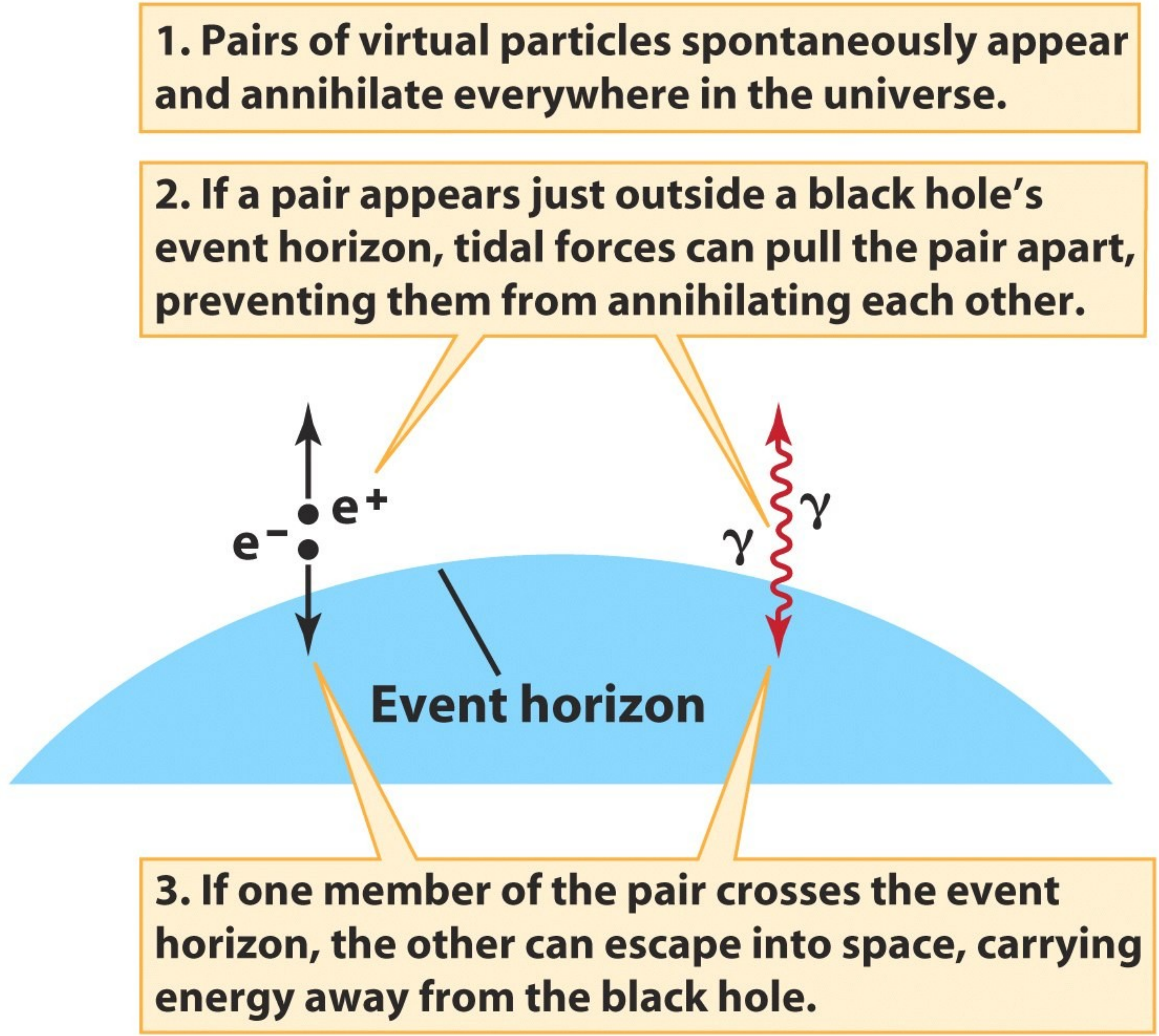
As you fall into to a black hole, you shine a blue flashlight at a friend exterior to the hole, she sees

A) blue light
B) blue light at first, then turning red
C) blue light, then red, then nothing
D) nothing

Seeing black holes


1. Gases from the supergiant are captured into an accretion disk around the black hole.
X rays
Black hole
HDE 226868 (blue supergiant)
2. As gases spiral toward the black hole, they are heated by friction: Just outside the black hole, they are hot enough to emit X rays.

Black holes evaporate



Review Questions

1. What are the two facts which caused Einstein to invent the special theory of relativity?
2. What are two key consequences of special relativity for how we observe moving objects?
3. What effect does gravity have on spacetime?
4. How do astronomers search for black holes?
5. In what sense is a black hole “black”?
6. How are black holes actually simpler than any other objects in astronomy?
7. What happens to an object that falls into a black hole?
8. Do black holes last forever?