Astronomy 1 – Fall 2019

Are black holes real science?

Or just really cool science fiction?

Lecture 13; November 25, 2019

iClicker Question

Which of the following best describes the evidence for black holes?

A. The General Theory of Relativity predicts the existence of black holes, but there is no way to test this theory because light does not escape from black holes.

B. The General Theory of Relativity predicts the existence of black holes, and astronomers have detected them by measuring the orbits of particles near the black holes.

C. The General Theory of Relativity predicts the existence of black holes, and astronomers have detected merging black holes via the ripples they send through space.

D. The General Theory of Relativity predicts the existence of black holes, and astronomers have imaged a few of them.

E. B, C, and D are all true.

Previously on Astro 1

- Late evolution and death of intermediate-mass stars (about 0.4 $M_\odot$ to about 4 $M_\odot$):
  - red giant when shell hydrogen fusion begins,
  - a horizontal-branch star when core helium fusion begins
  - asymptotic giant branch star when the no more helium core fusion and shell helium fusion begins.
  - Then alf of the mass of the star is ejected exposing the CO core of the star. The core is a white dwarf the envelope a planetary nebula.
- Late Evolution and death of High-Mass Star (>4 $M_\odot$)
  - Can undergo carbon fusion, neon fusion, oxygen fusion, and silicon fusion, etc
  - The highest mass stars eventually find themselves with a iron-rich core surrounded by burning shells (>8 $M_\odot$). The star dies in a violent cataclysm in which its core collapses and most of its matter is ejected into space: a supernova!! 99% of the energy can come out in neutrinos!
  - Predicted to leave behind a neutron star or a black hole remnant; the outcome depends on the mass of the core.

Today on Astro-1

- Introduction to special relativity
  - Practiced in discussion sections last week!
- Introduction to general relativity
- Introduction to black holes
  - stellar mass black holes [U: 21]
  - Supermassive black holes [will cover in U: 24]

What is special about Special Relativity?

Einstein's *special theory* of relativity (1905)

1. No matter what your constant velocity, the laws of physics are the same.

Einstein in 1905

How Can You Tell If This Airplane is Moving?

You are on a windowless airplane and cannot see outside. The ride is extremely smooth. Is it possible to make a measurement inside the airplane to determine whether you are moving or are stationary?

A. Yes. Drop an object and see if it falls vertically or is deflected backward.
B. Yes. Shine a light forward up the aisle and backward down the aisle and measure the difference in their speeds.
C. Yes. Throw one ball forward down the aisle and throw a second ball backward down the aisle. Then determine which one went further.
D. No. There is no experiment that you can do inside the train to determine whether the train is moving at constant speed or is stationary.

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B. Yes. Shine a light forward up the aisle and backward down the aisle and measure the difference in their speeds.

C. Yes. Throw one ball forward down the aisle and throw a second ball backward down the aisle. Then determine which one went further.

D. No. There is no experiment that you can do inside the train to determine whether the train is moving at constant speed or is stationary.

The speed you measure for ordinary objects depends on how you are moving.

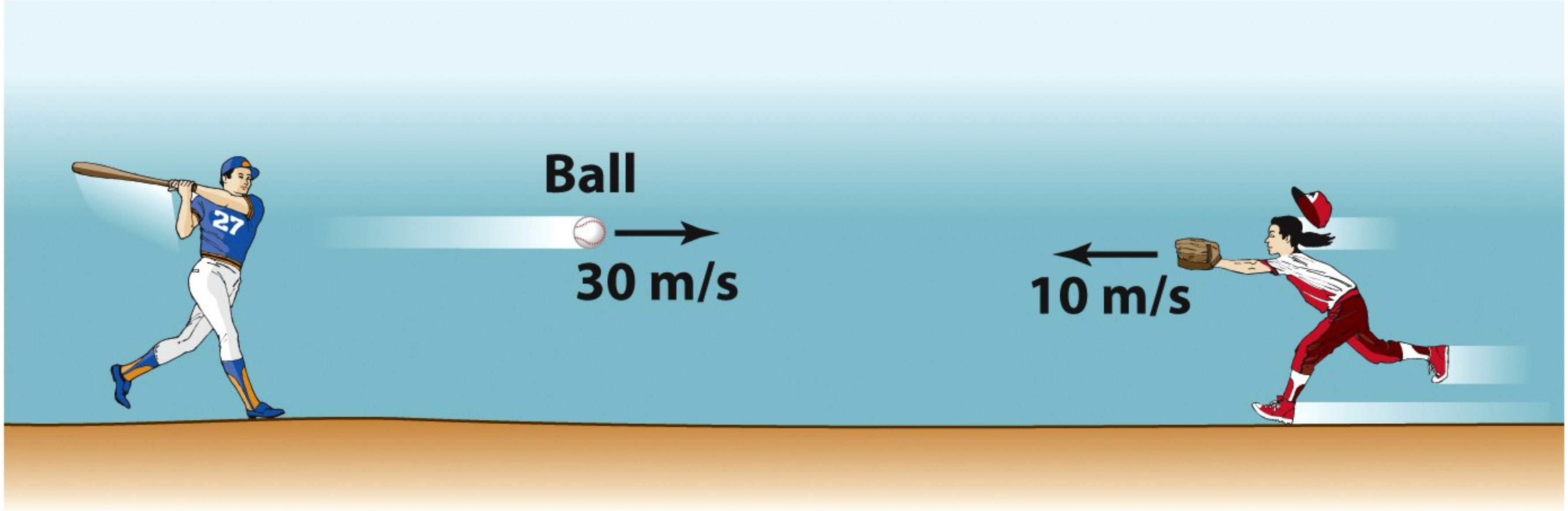
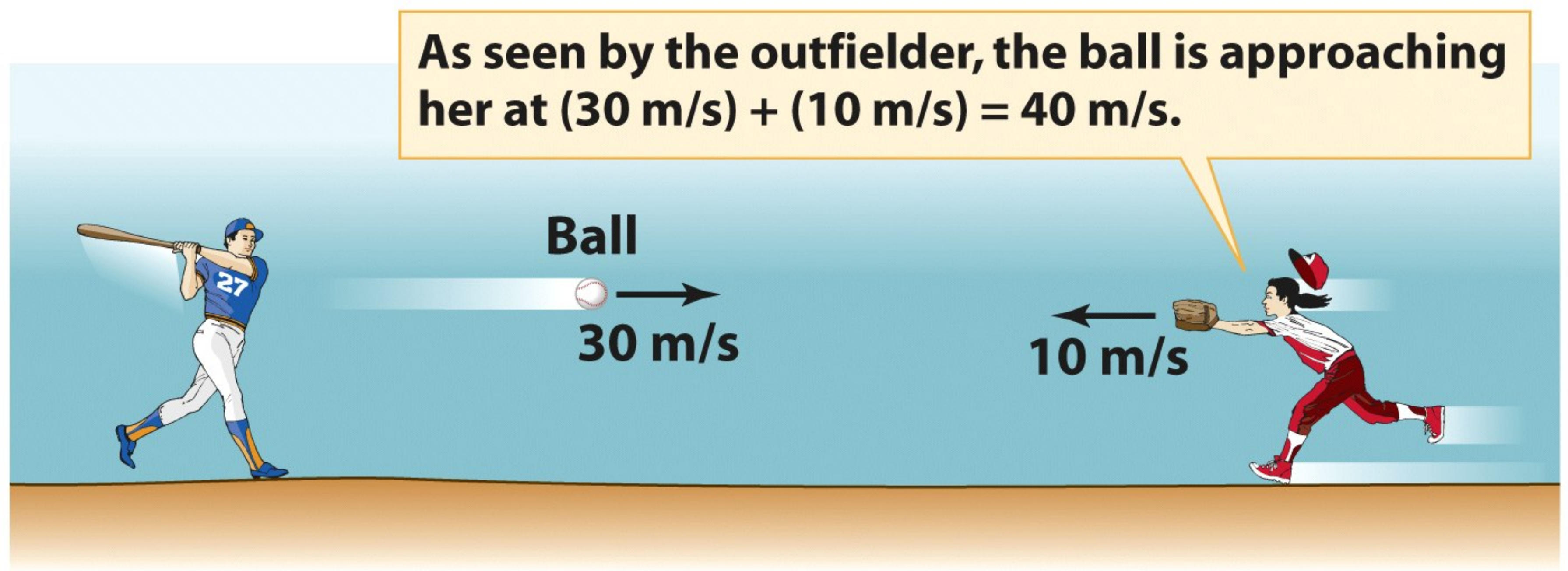


Figure 22-1a
Universe, Eighth Edition

The speed of the ball is 40 m/s ***relative to*** the outfielder.



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

Figure 22-1a
Universe, Eighth Edition

Einstein's special theory of relativity (1905)

1. No matter what your *constant velocity*, the laws of physics are the same.
2. **No matter what your constant velocity, the speed of light in a vacuum is the same.**

Einstein in 1905

What speed of light does each astronaut measure?

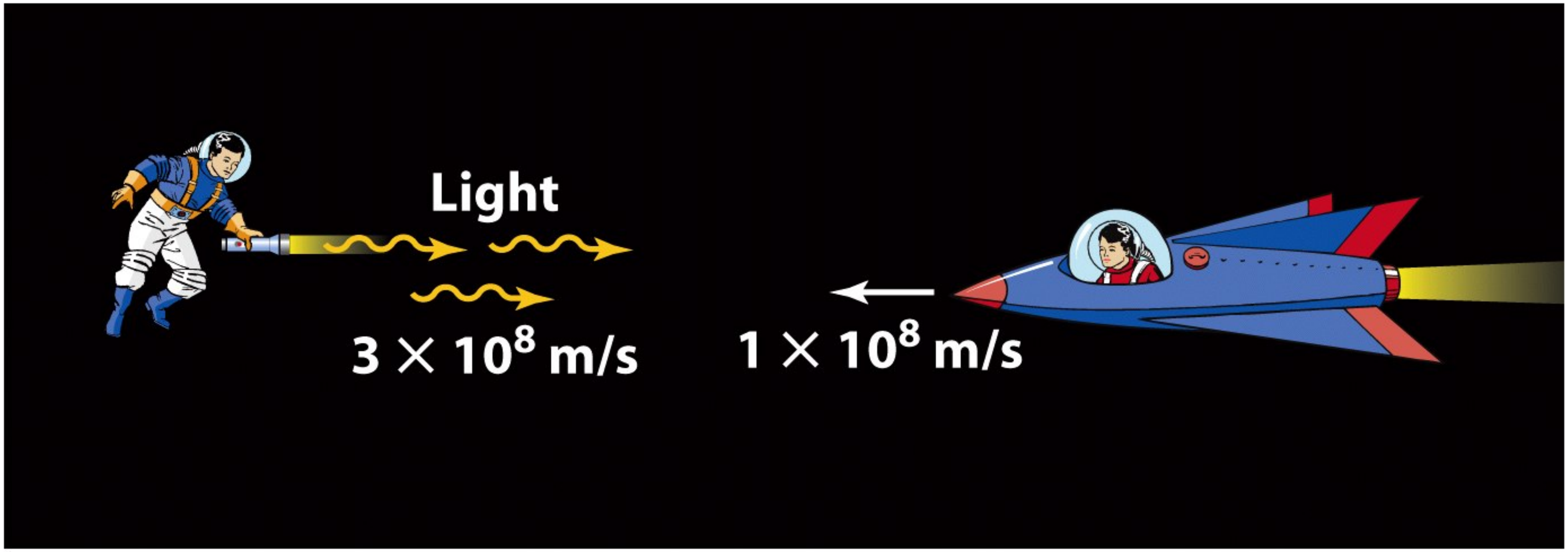
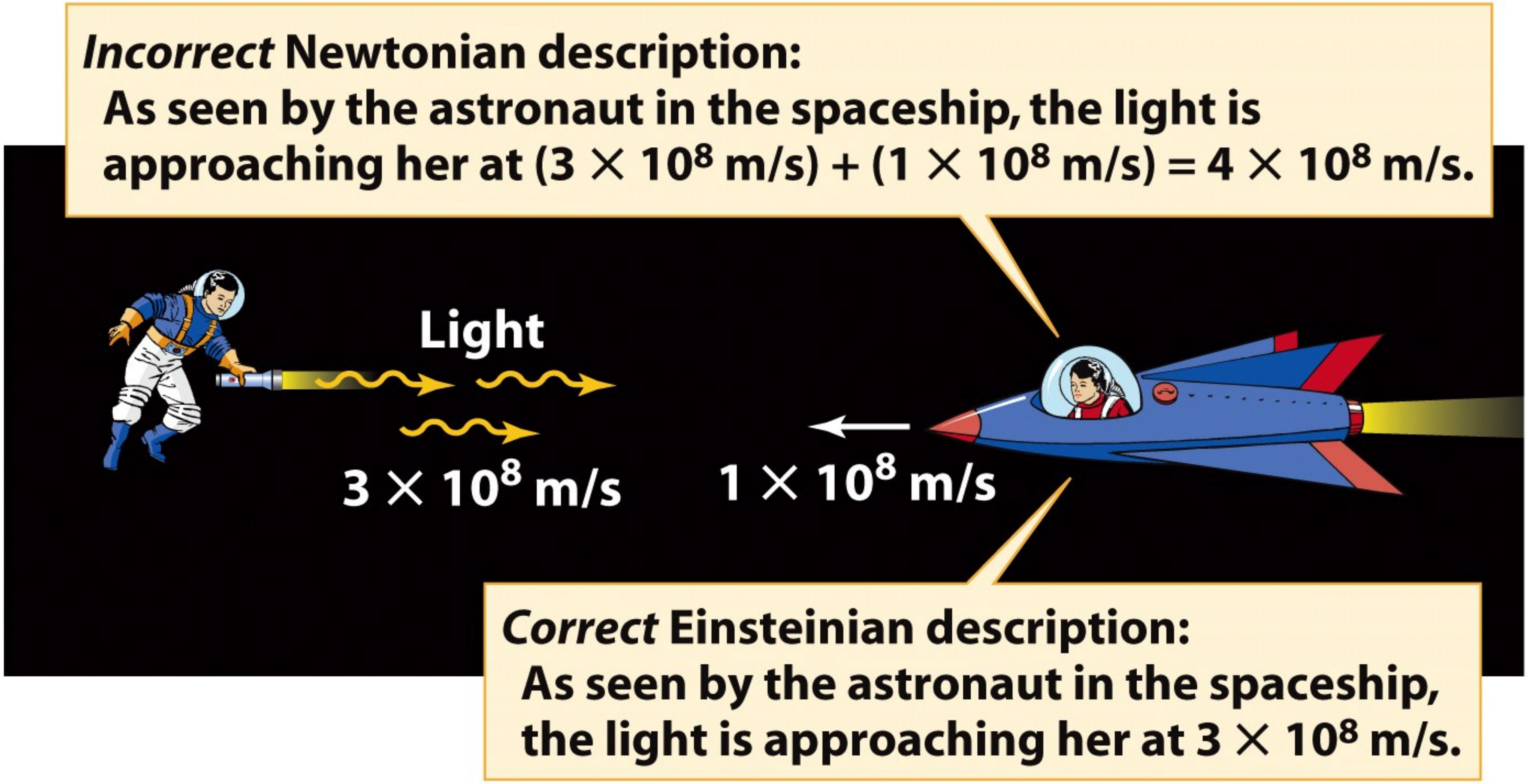


Figure 22-1b
Universe, Eighth Edition

Einstein’s hypothesis does not match your common sense.



Incorrect **Newtonian description:**
As seen by the astronaut in the spaceship, the light is approaching her at (3 × 10^8 m/s) + (1 × 10^8 m/s) = 4 × 10^8 m/s.

Correct **Einsteinian description:**
As seen by the astronaut in the spaceship, the light is approaching her at 3 × 10^8 m/s.

Figure 22-1b
Universe, Eighth Edition

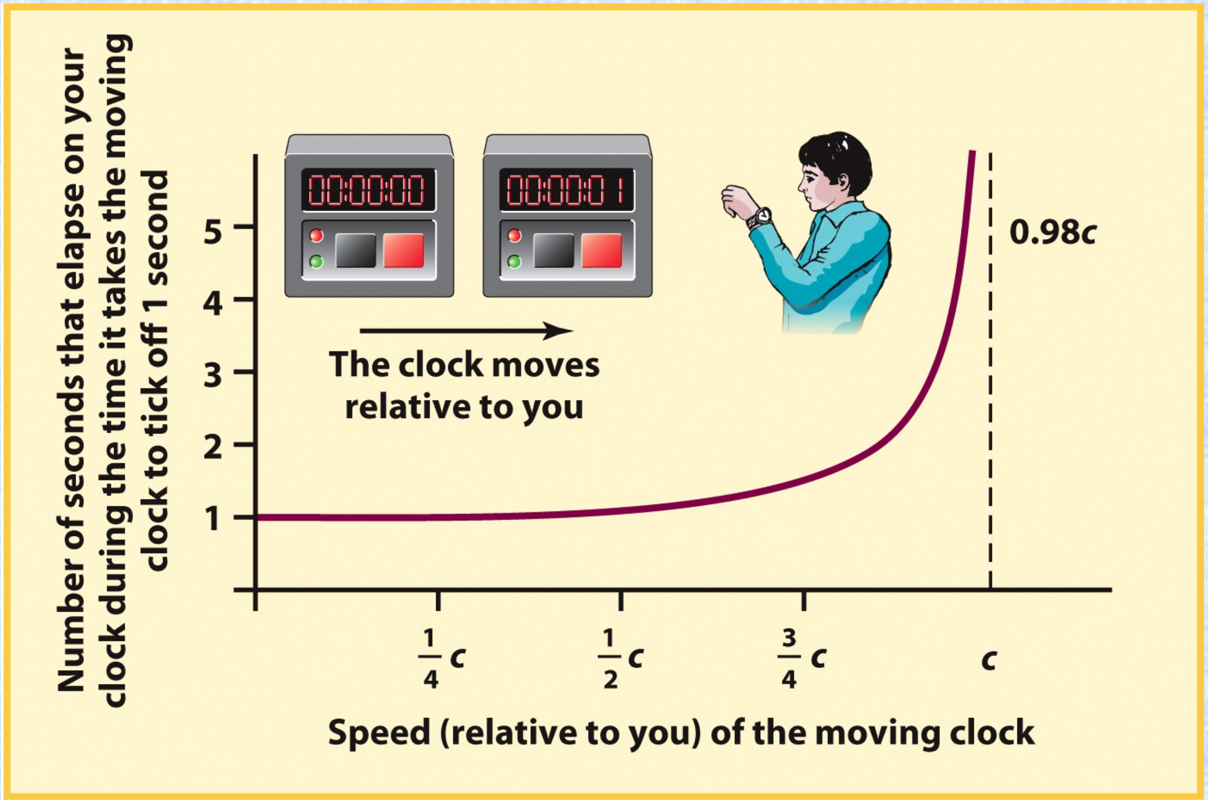
The constant speed of light has some very interesting consequences.

- Space and time are intertwined.
  - ➔Time dilation
  - ➔Length contraction

- How does this work?

Spacetime = 3 spatial dimensions + time

Implication #1. Moving Clocks Run Slow.



Time dilation

Figure 21-2b
Universe, Tenth Edition

HW8 (2 problems): Let's check that you have the concept before we introduce the math.

A friend takes a ride on a spaceship to a distant star and returns to Earth. You and your friend were the same age when your friend left on the spaceship. When your friend returns she

A. will be the same age as you.
B. will be younger than you.
C. will be older than you.
D. will be two times older than you.
E. could be older or younger than you depending on the speed during the journey.

A friend takes a ride on a spaceship to a distant star and returns to Earth. You and your friend were the same age when your friend left on the spaceship. When your friend returns she

A. will be the same age as you.

B. will be younger than you.

C. will be older than you.

D. will be two times older than you.

E. could be older or younger than you depending on the speed during the journey.

We call this effect **time dilation**.

$$T = \frac{T_0}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

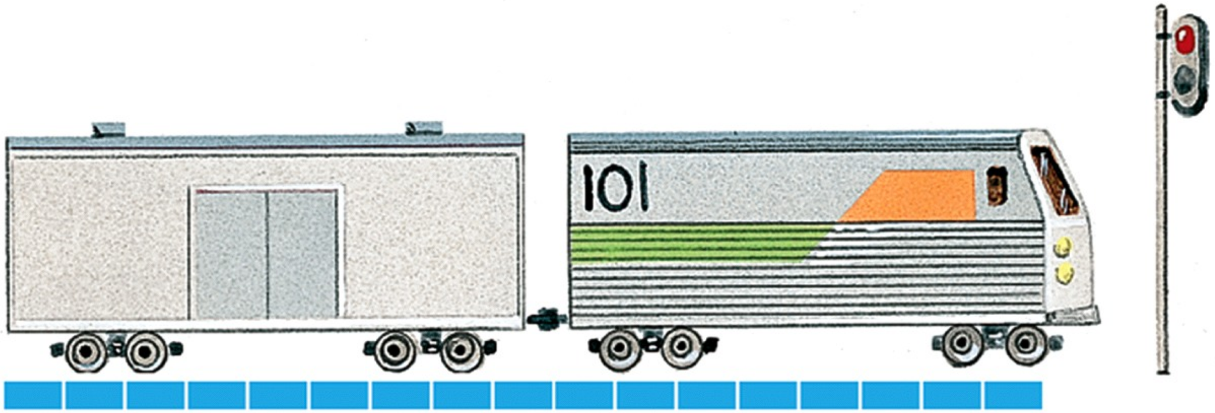
T = time interval measured by an observer moving relative to the phenomenon

T_0 = time interval measured by an observer not moving relative to the phenomenon (**proper time**)

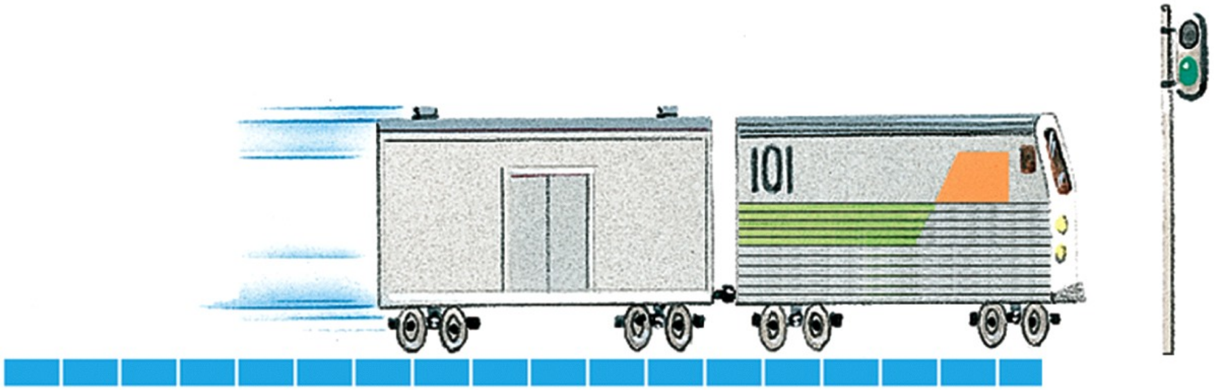
v = speed of the moving observer relative to the phenomenon

c = speed of light

Implication #2. Length Contraction.



This train is at rest relative to you.



The same train is now moving relative to you.

Length contraction

Figure 21-2a
Universe, Tenth Edition

Consequence: LENGTH CONTRACTION

$$L = L_0\sqrt{1 - (v/c)^2}$$

L = length measured (along the direction of motion) by an observer moving relative to the phenomenon

L_0 = length measured by an observer not moving relative to the phenomenon (**proper length**)

v = speed of the moving observer relative to the phenomenon

c = speed of light

Question (iclickers!)

- **Suppose you are in a spaceship traveling toward Earth at 95% of the speed of light. Compared to when your ship was at rest on Mars, you measure the length of your ship to be:**
  - A) The same as when it was on Mars
  - B) Longer than when it was on Mars
  - C) You can't tell. Your life processes have slowed down too much for you to measure the length
  - D) Shorter than when it was on Mars

Question (iclickers!)

- **Suppose you are in a spaceship traveling toward Earth at 95% of the speed of light. Compared to when your ship was at rest on Mars, you measure the length of your ship to be:**
  - A) *The same as when it was on Mars*
  - B) Longer than when it was on Mars
  - C) You can’t tell. Your life processes have slowed down too much for you to measure the length
  - D) Shorter than when it was on Mars

Special Relativity

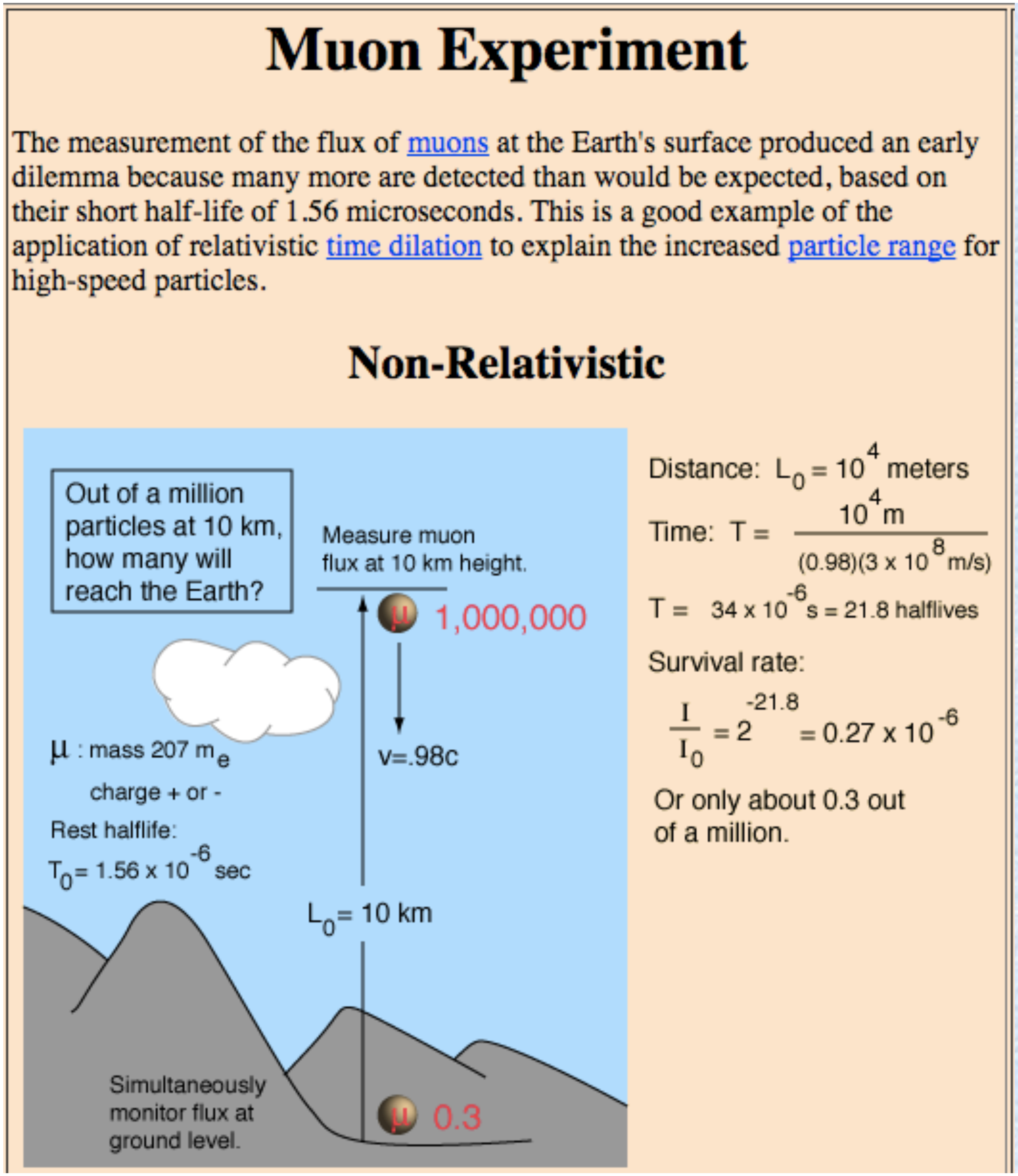
The predicted effects time dilation and length contraction sound cool, but can Special Relativity be tested?

YES! And it is everyday.

Let's examine a terrestrial example.

Example of Special Relativity: Muon Decay in Earth’s Atmosphere

- An unstable particle called a muon is produced when fast moving protons from interstellar space collide with atoms in Earth’s upper atmosphere.
- The muons move at speeds close to the speed of light.
- Special relativity helps us understand the high flux of muons that reach Earth’s surface.



Muon Experiment

The measurement of the flux of muons at the Earth's surface produced an early dilemma because many more are detected than would be expected, based on their short half-life of 1.56 microseconds. This is a good example of the application of relativistic time dilation to explain the increased particle range for high-speed particles.

Non-Relativistic

Distance: $L_0 = 10^4$ meters

Time: $T = \frac{10^4\,\text{m}}{(0.98)(3 \times 10^8\,\text{m/s})}$

$T = 34 \times 10^{-6}$ s = 21.8 halflives

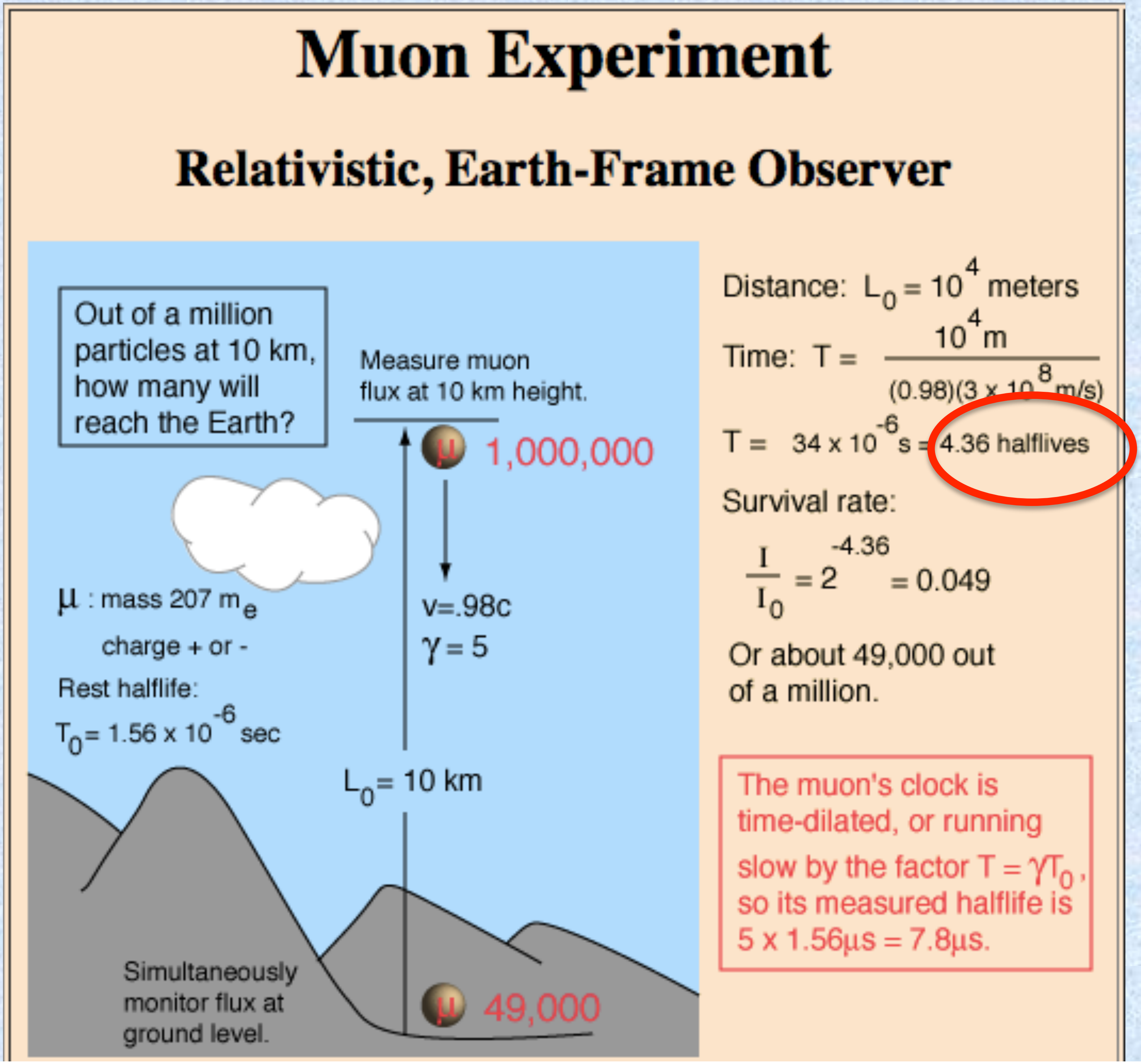
Survival rate:

$$\frac{I}{I_0} = 2^{-21.8} = 0.27 \times 10^{-6}$$

Or only about 0.3 out of a million.

Number of half lives = travel time / half life = 34e-6 s / 1.56e-6 s = 21.8

$I = I_0\,(1/2)^{[\#\text{ half lives}]}$



Muon Experiment

Relativistic, Earth-Frame Observer

Out of a million particles at 10 km, how many will reach the Earth?

Measure muon flux at 10 km height.

μ : mass 207 m_e

charge + or -

Rest halflife:

$T_0 = 1.56 \times 10^{-6}$ sec

Simultaneously monitor flux at ground level.

Distance: $L_0 = 10^4$ meters

Time: $T = \dfrac{10^4\,\mathrm{m}}{(0.98)(3 \times 10^8\,\mathrm{m/s})}$

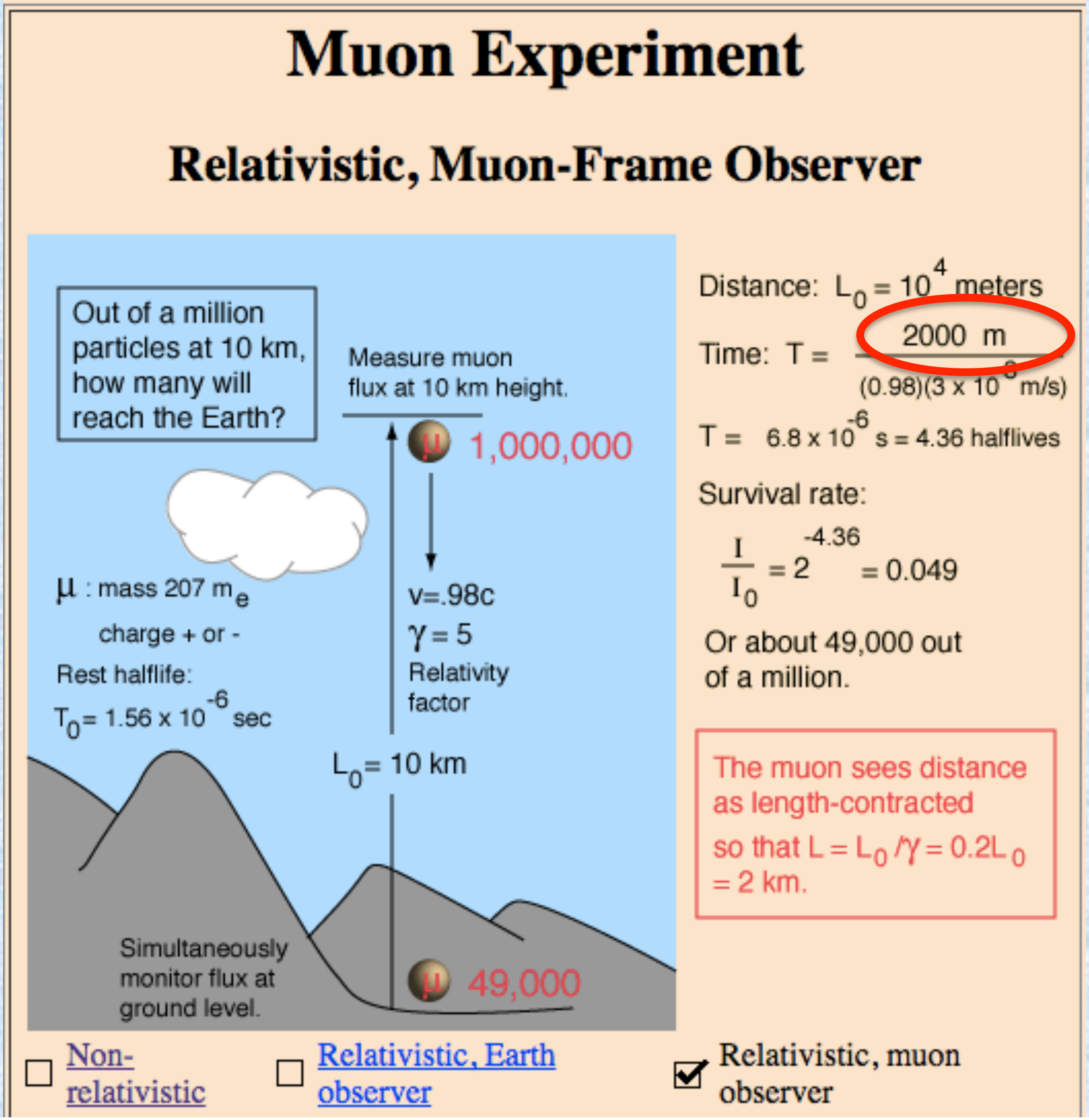
$T = 34 \times 10^{-6}\,\mathrm{s} =$ 4.36 halflives

Survival rate:

$$\frac{I}{I_0} = 2^{-4.36} = 0.049$$

Or about 49,000 out of a million.

The muon's clock is time-dilated, or running slow by the factor $T = \gamma T_0$, so its measured halflife is 5 x 1.56μs = 7.8μs.



Muon Experiment

Relativistic, Muon-Frame Observer

Out of a million particles at 10 km, how many will reach the Earth?

Measure muon flux at 10 km height.

Simultaneously monitor flux at ground level.

Distance: $L_0 = 10^4$ meters

Time: $T = \frac{2000\ \text{m}}{(0.98)(3 \times 10^8\ \text{m/s})}$

$T = 6.8 \times 10^{-6}$ s = 4.36 halflives

Survival rate:

$$\frac{I}{I_0} = 2^{-4.36} = 0.049$$

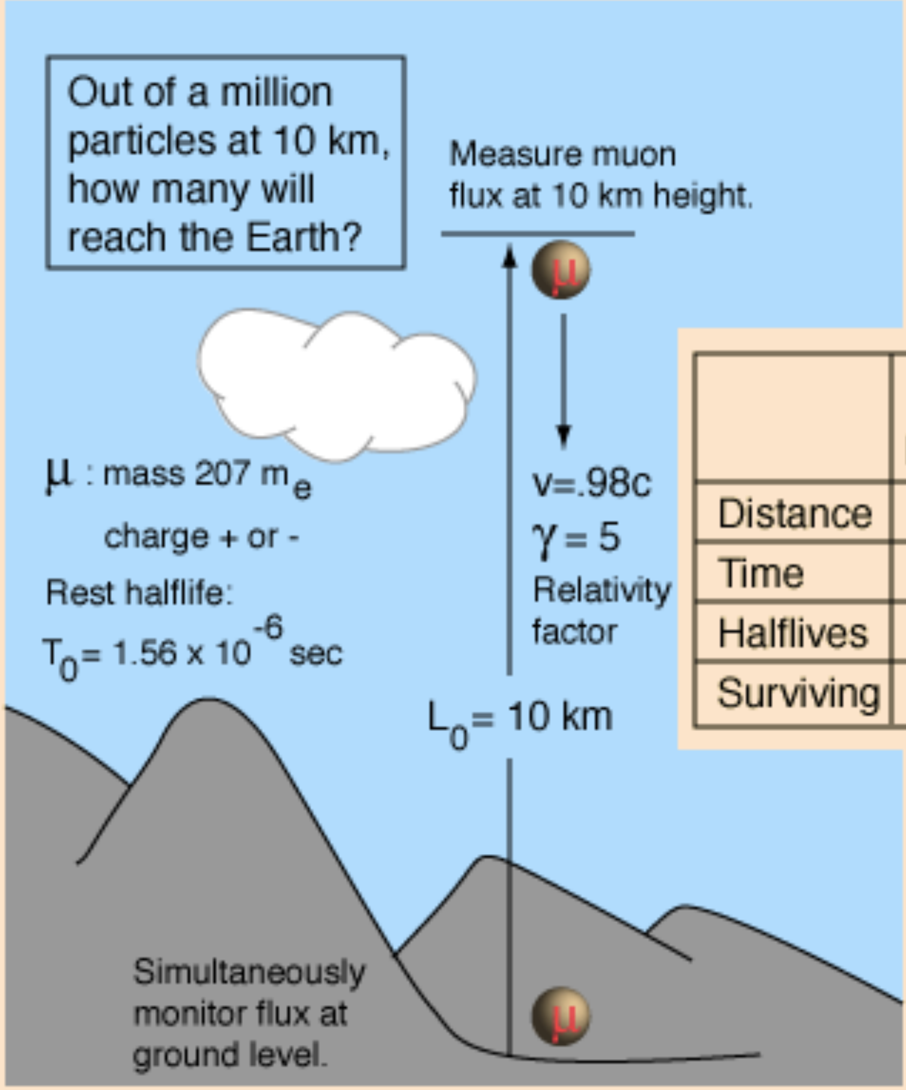
Or about 49,000 out of a million.

The muon sees distance as length-contracted so that $L = L_0/\gamma = 0.2L_0 = 2$ km.

☐ Non-relativistic ☐ Relativistic, Earth observer ☑ Relativistic, muon observer

Muon Experiment

Comparison of Reference Frames



Out of a million particles at 10 km, how many will reach the Earth?

Measure muon flux at 10 km height.

μ : mass 207 m_e

charge + or -

Rest halflife:

$T_0 = 1.56 \times 10^{-6}$ sec

v=.98c

$\gamma = 5$

Relativity factor

$L_0 = 10$ km

Simultaneously monitor flux at ground level.

By the basic principle of relativity, all valid descriptions must agree on the final result.

	Relativistic		Non-Relativistic
	Muon	Ground	
Distance	2 km	10 km	10 km
Time	6.8μs	34μs	34μs
Halflives	4.36	4.36	21.8
Surviving	49000	49000	0.3

Comparison of the three approaches to the muon survival rate.

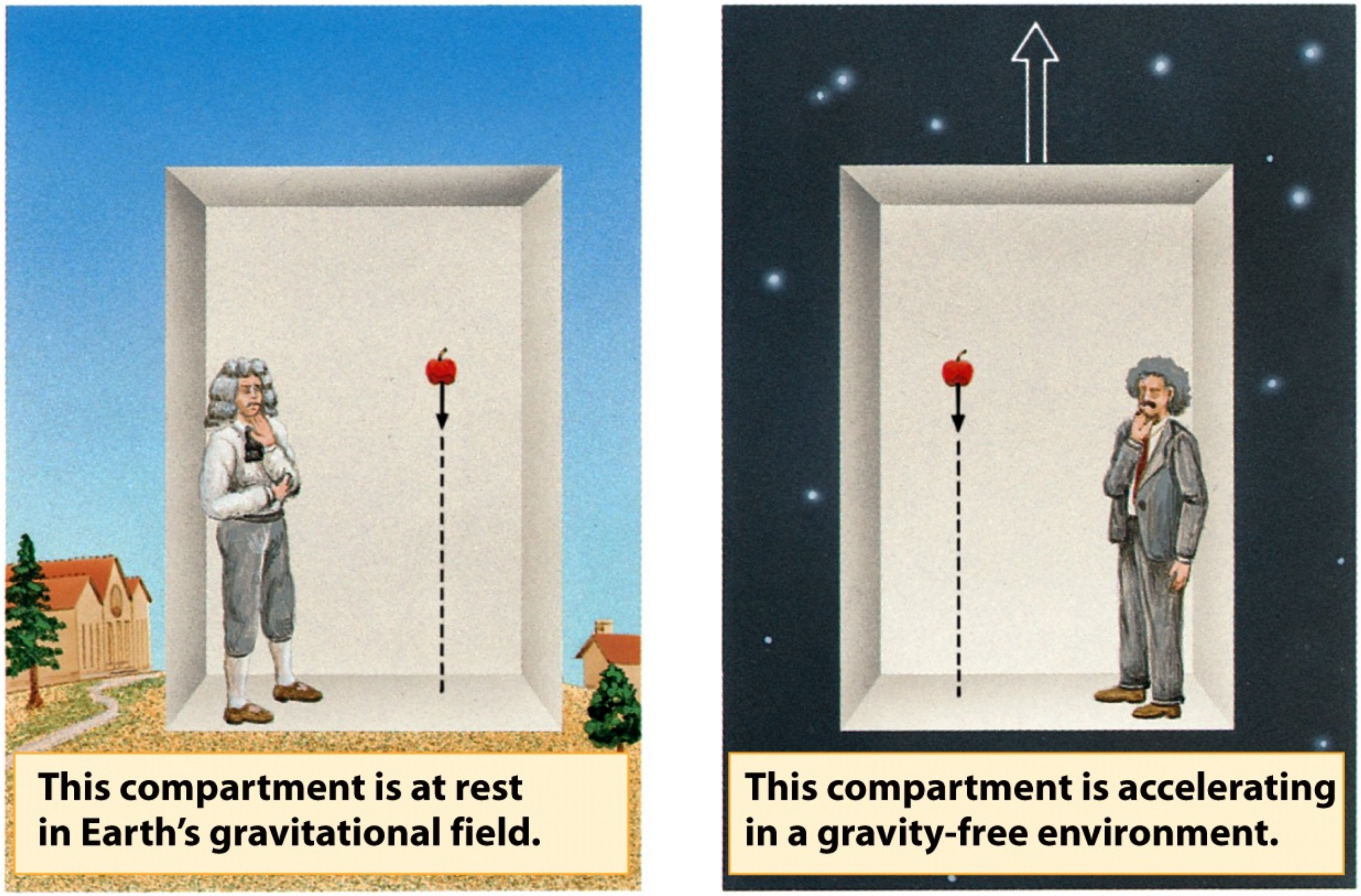
Introduction to General Relativity

Acceleration (Gravity)

The Equivalence Principle (1915)

1. The downward pull of gravity can be accurately and completely duplicated by an upward acceleration of the observer.

2. Gravity can be described as a property of spacetime!



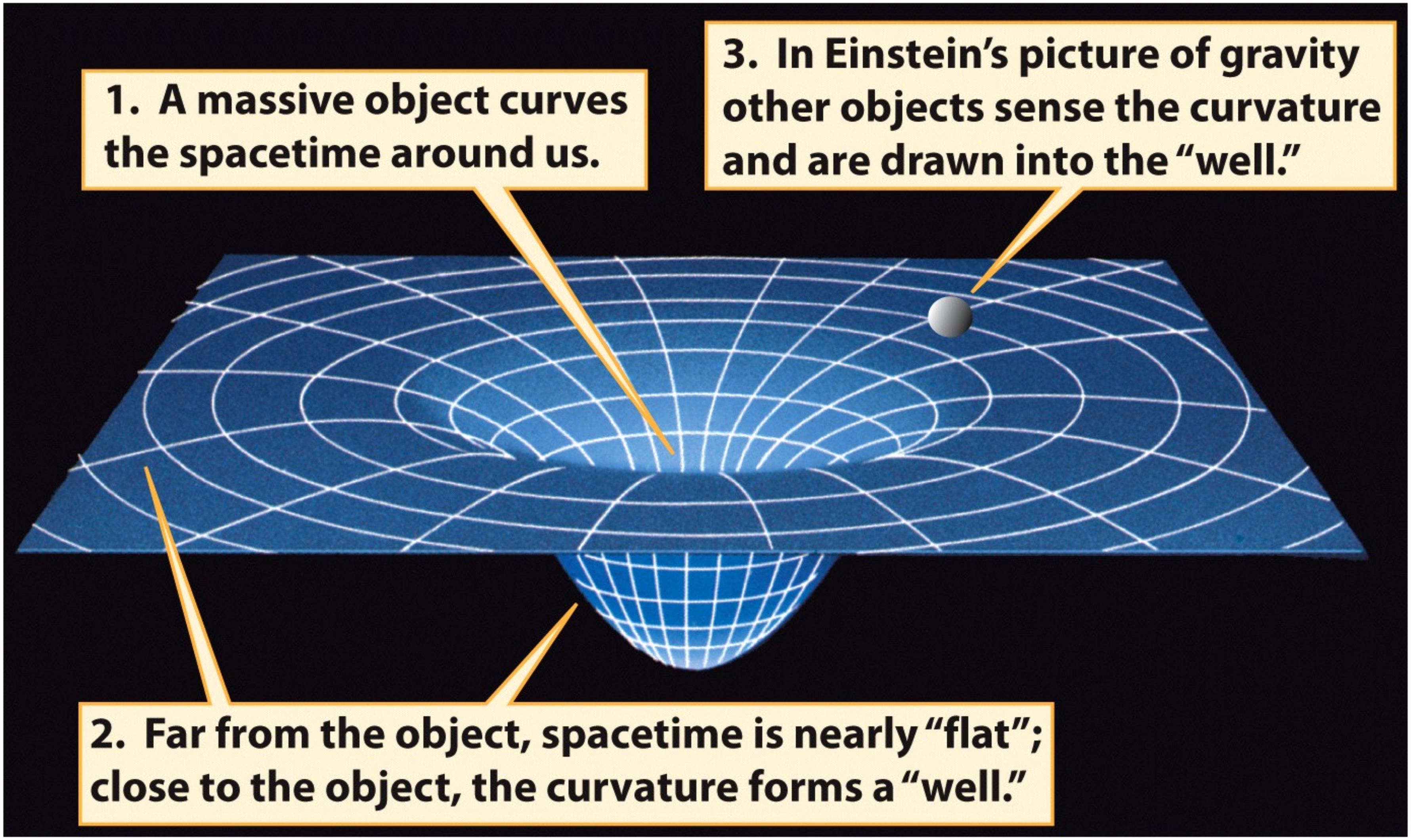
This compartment is at rest in Earth's gravitational field.

This compartment is accelerating in a gravity-free environment.

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

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

Figure 21-3
Universe, Tenth Edition



1. A massive object curves the spacetime around us.

2. Far from the object, spacetime is nearly "flat"; close to the object, the curvature forms a "well."

3. In Einstein's picture of gravity other objects sense the curvature and are drawn into the "well."

Figure 21-4
Universe, Tenth Edition

GR Predicts the Deflection of Light

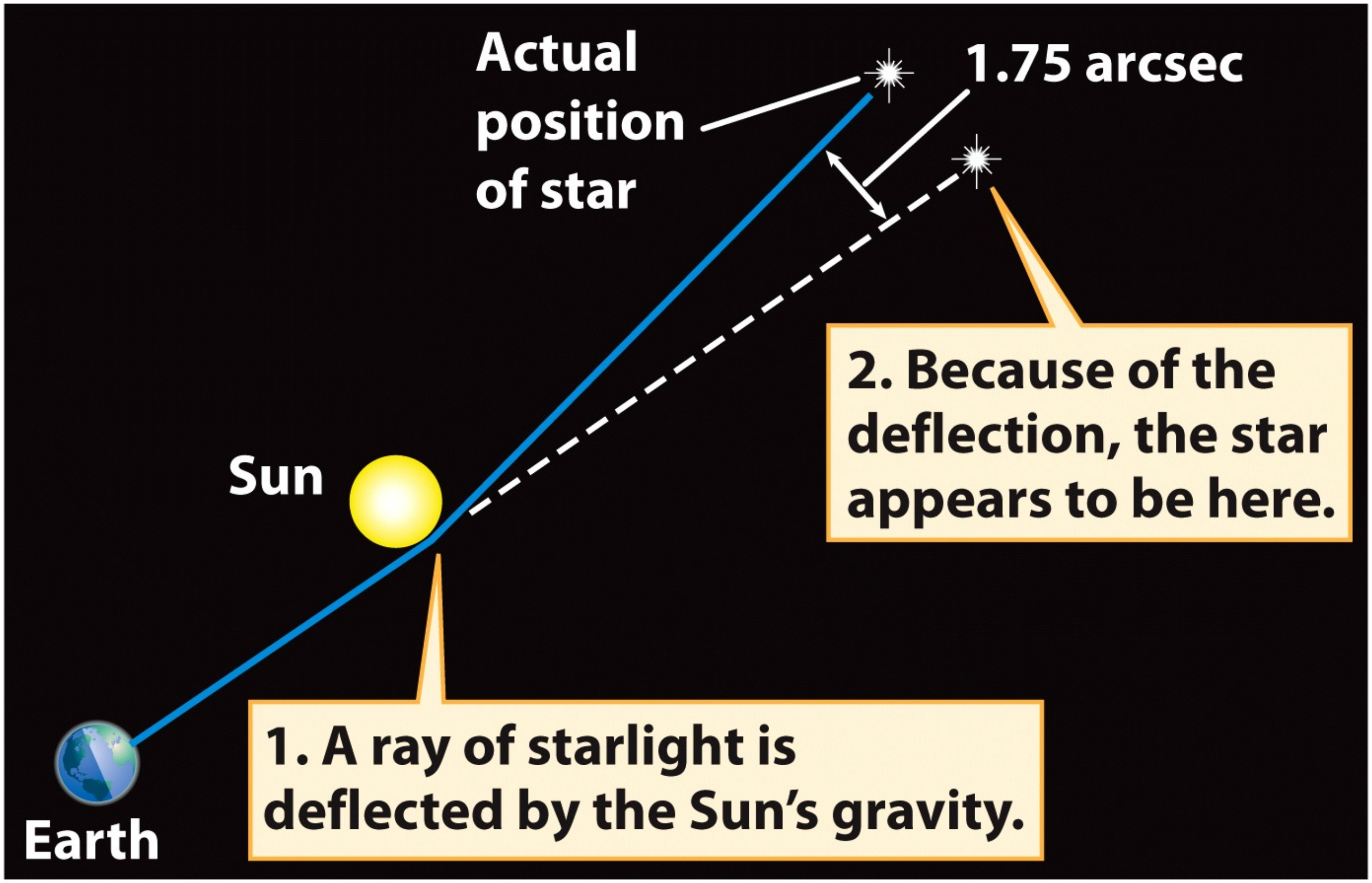


Figure 21-5
Universe, Tenth Edition

Explains the Precession of Mercury's Orbit

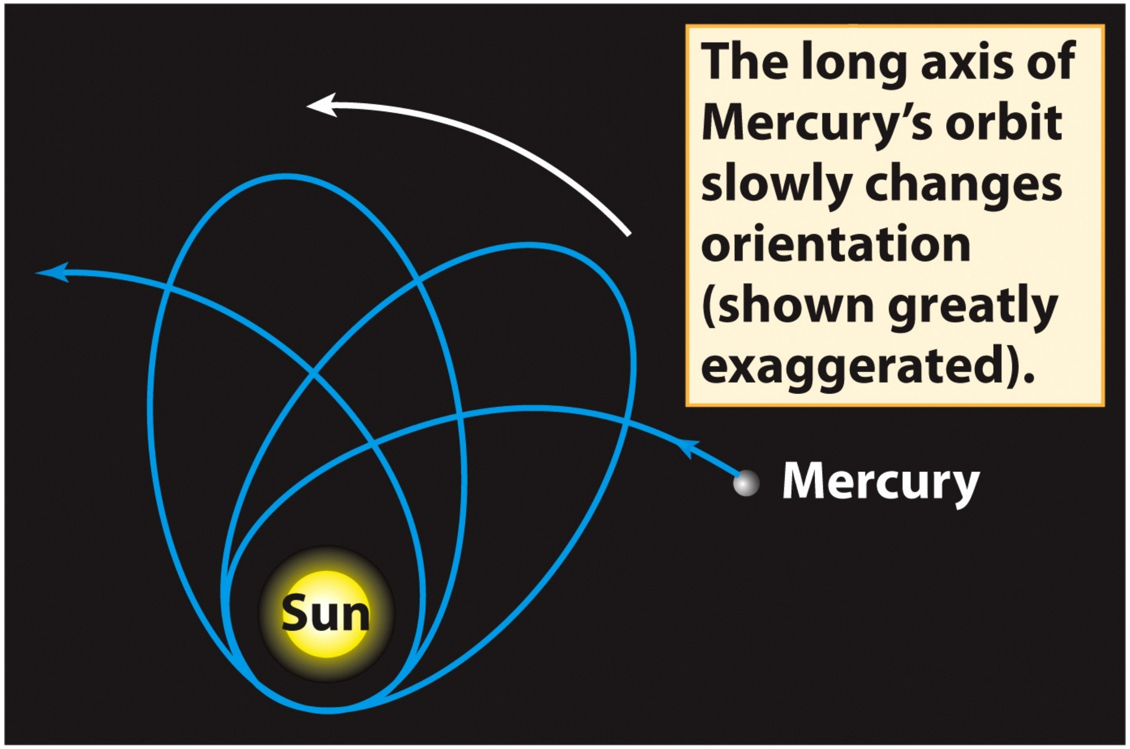
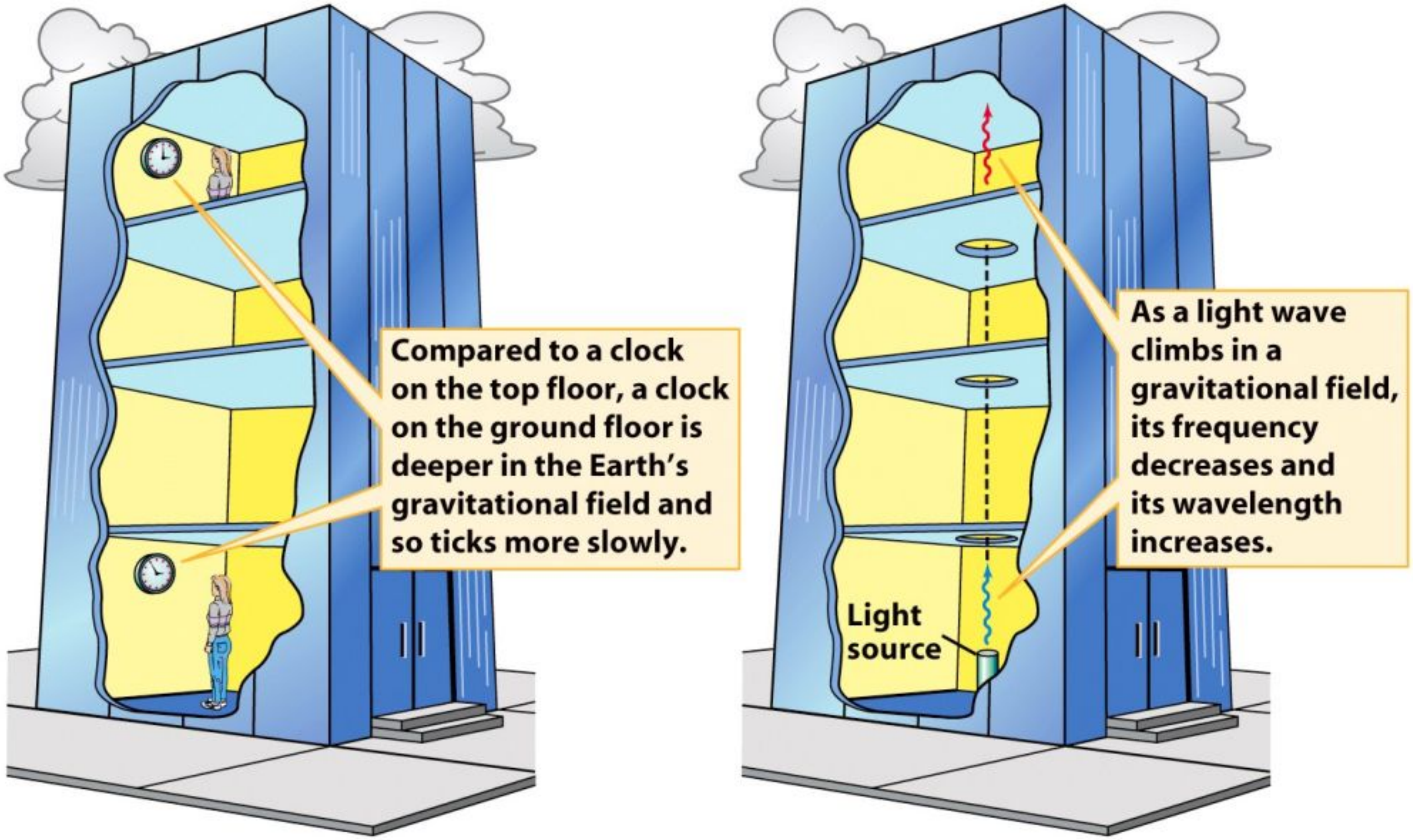


Figure 21-6
Universe, Tenth Edition

Predictions of Einstein's general theory of relativity



Compared to a clock on the top floor, a clock on the ground floor is deeper in the Earth's gravitational field and so ticks more slowly.

As a light wave climbs in a gravitational field, its frequency decreases and its wavelength increases.

(a) The gravitational slowing of time

(b) The gravitational redshift

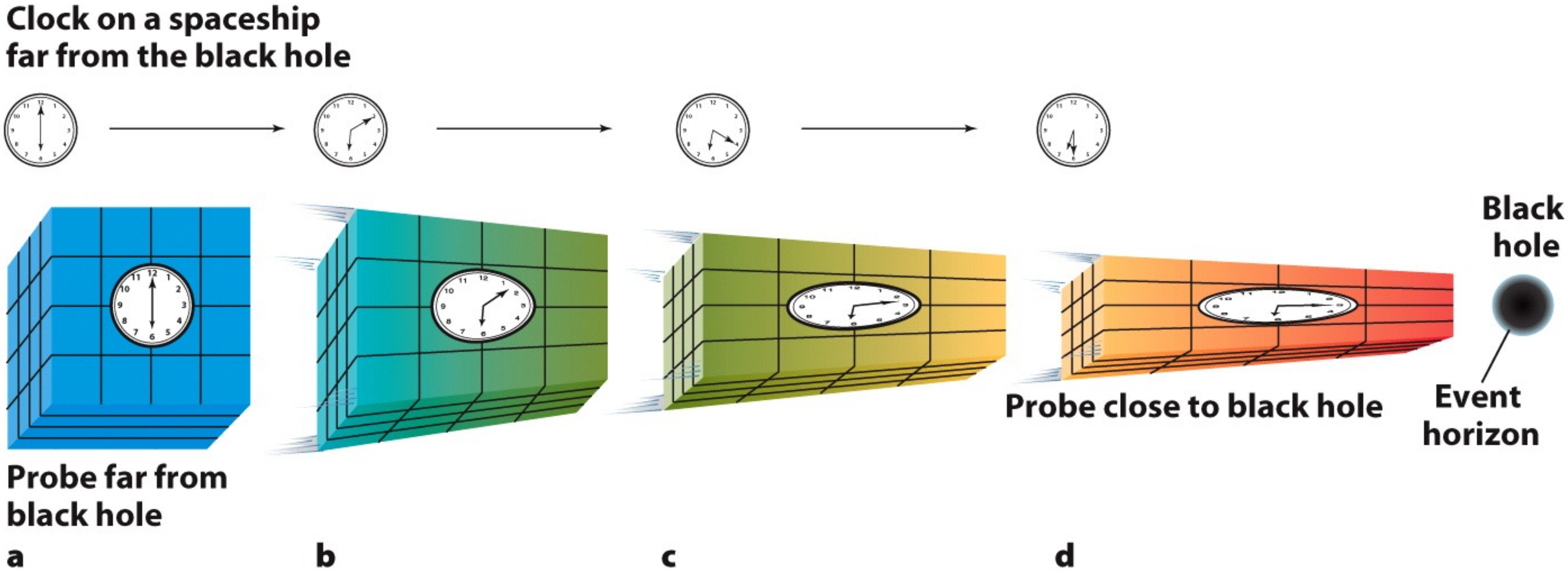
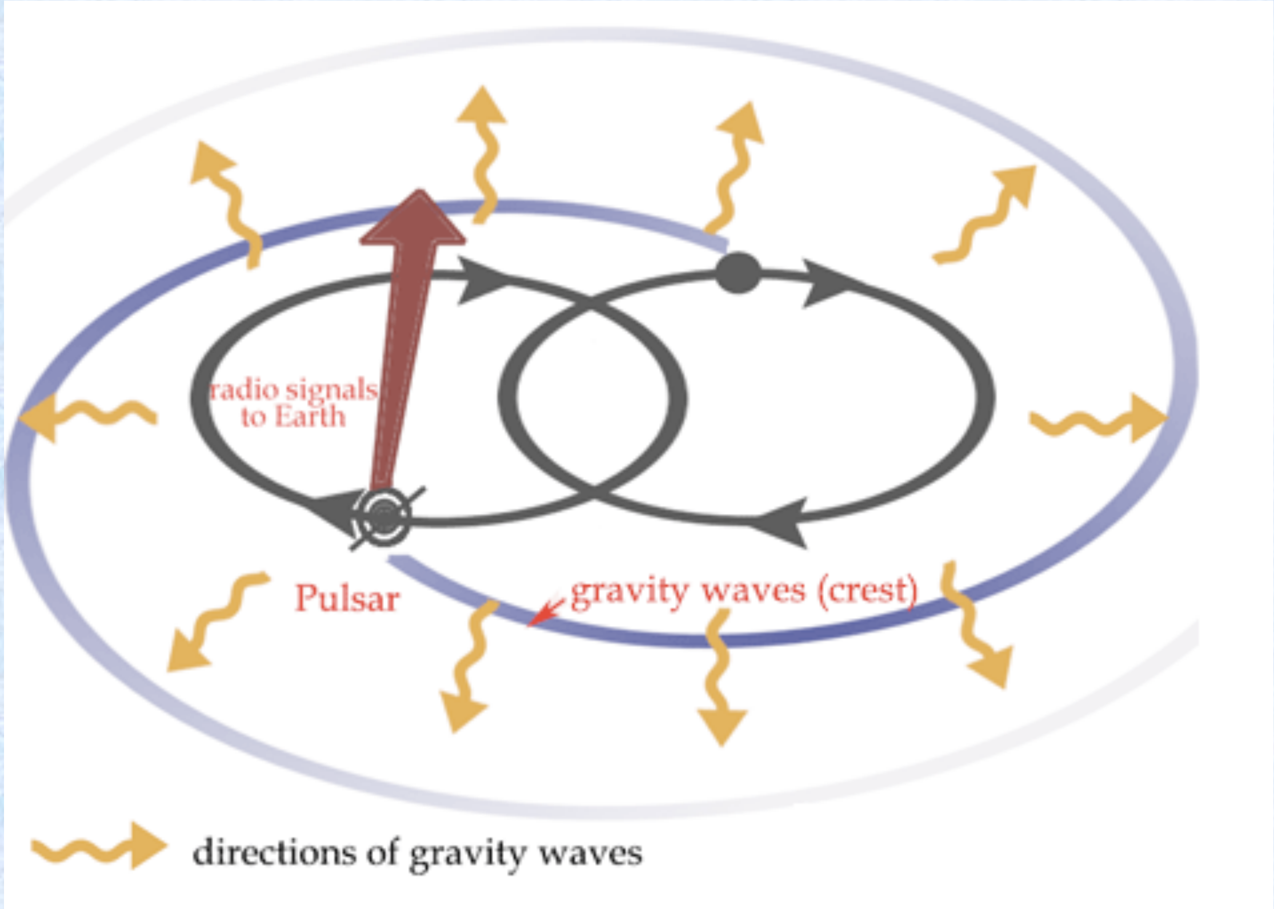


Figure 21-21

Universe, Tenth Edition

Another prediction: Gravitational Waves (Ripples in Spacetime)



Question (iclickers!)

- **Suppose you are far from a planet that has a very strong gravitational field, and you are watching a clock on the surface of the planet. During the time in which your own clock ticks out a time of 1 hour, how much time does the clock on the planet tick out?**
  - A) More than 1 hour
  - B) No time at all
  - C) Exactly 1 hour, the same as your clock
  - D) Less than 1 hour

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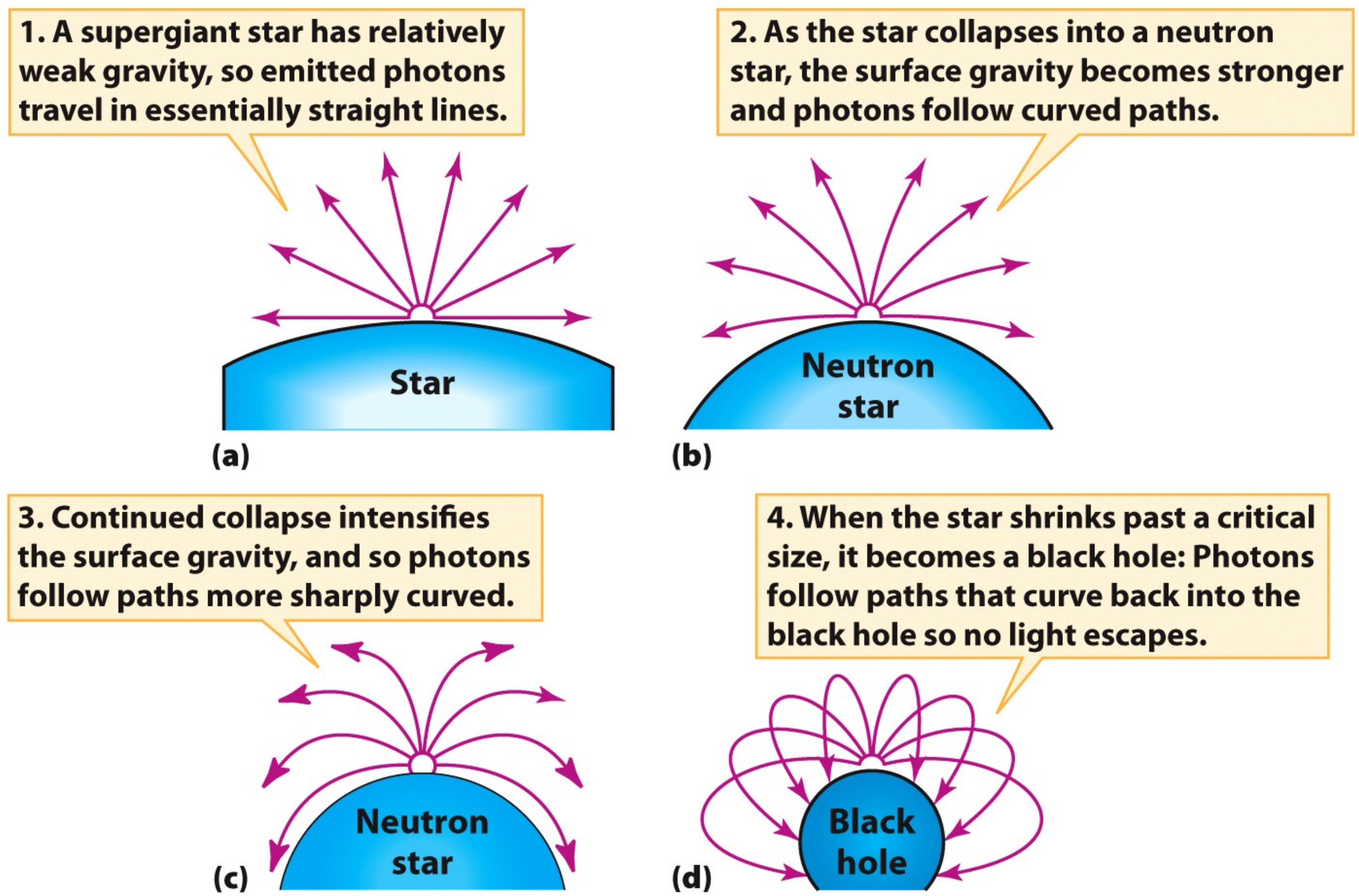
- **Suppose you are far from a planet that has a very strong gravitational field, and you are watching a clock on the surface of the planet. During the time in which your own clock ticks out a time of 1 hour, how much time does the clock on the planet tick out?**
    - A) More than 1 hour
    - B) No time at all
    - C) Exactly 1 hour, the same as your clock
    - D) *Less than 1 hour*

General Relativity Predicts Black Holes

Do They Really Exist?

Formation of a Black Hole



1. A supergiant star has relatively weak gravity, so emitted photons travel in essentially straight lines.

2. As the star collapses into a neutron star, the surface gravity becomes stronger and photons follow curved paths.

3. Continued collapse intensifies the surface gravity, and so photons follow paths more sharply curved.

4. When the star shrinks past a critical size, it becomes a black hole: Photons follow paths that curve back into the black hole so no light escapes.

Figure 21-8
Universe, Tenth Edition

Structure of a Black Hole

The event horizon is the point where the escape velocity equals the speed of light. It is the "point of no return."

Schwarzschild radius

$$R_{\mathrm{Sch}} = 2GM/c^2$$

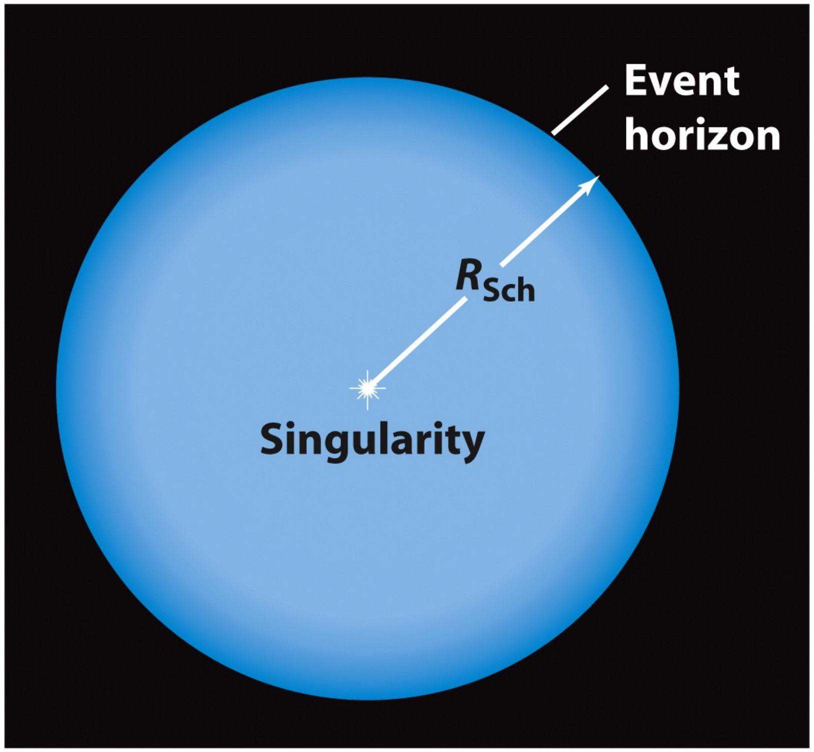
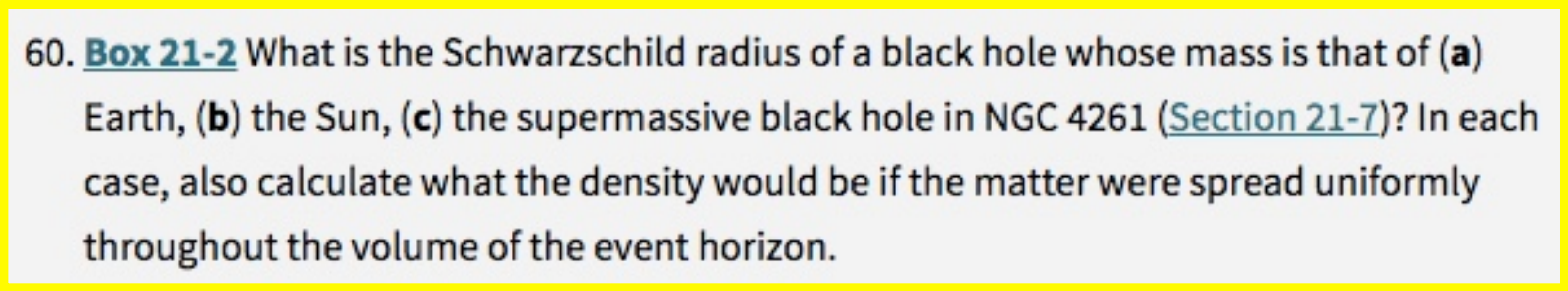
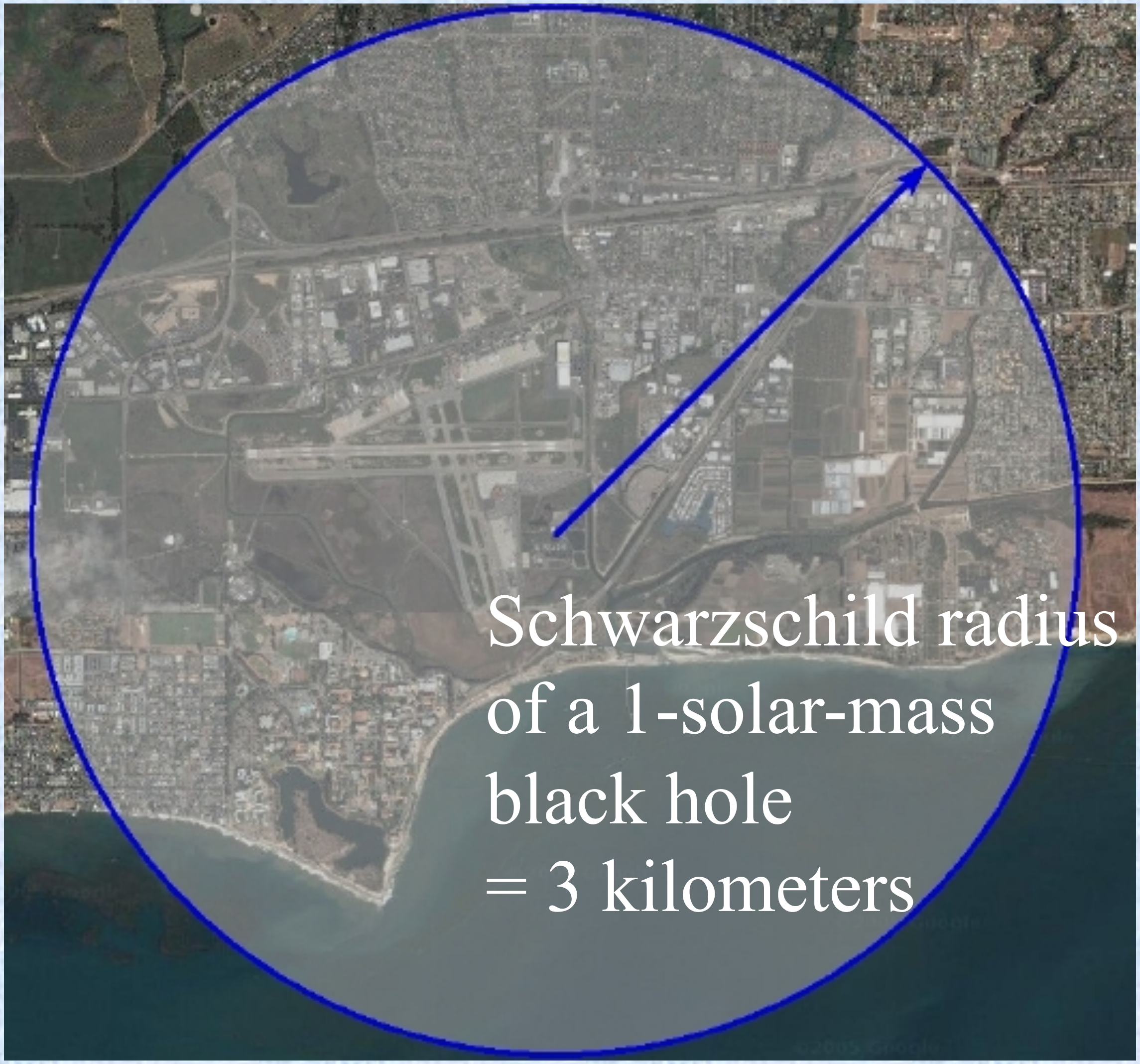


Figure 22-18
Universe, Eighth Edition
© 2008 W. H. Freeman and Company



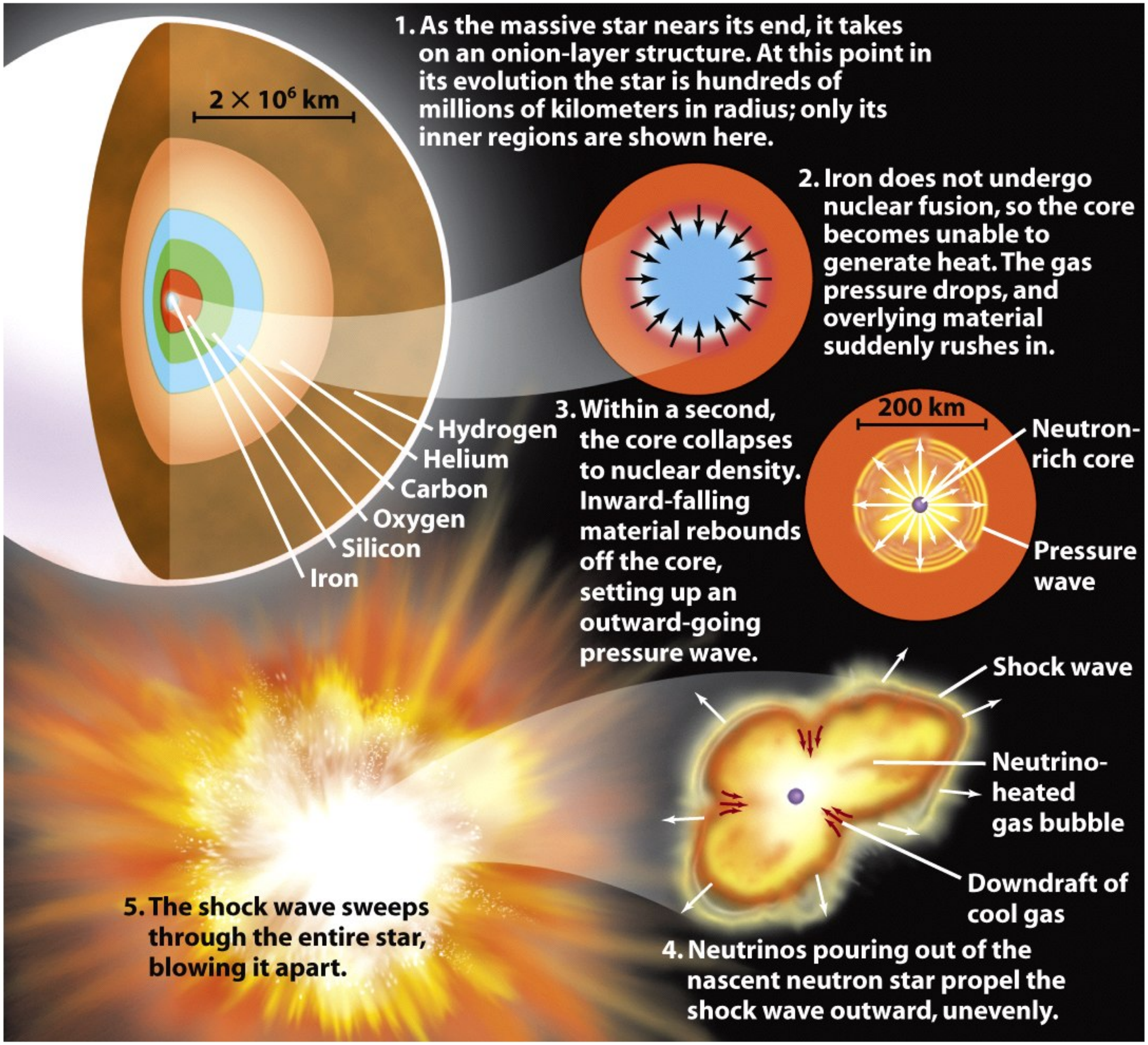
60. Box 21-2 What is the Schwarzschild radius of a black hole whose mass is that of (**a**) Earth, (**b**) the Sun, (**c**) the supermassive black hole in NGC 4261 (Section 21-7)? In each case, also calculate what the density would be if the matter were spread uniformly throughout the volume of the event horizon.

Schwarzschild Radius



Schwarzschild radius
of a 1-solar-mass
black hole
= 3 kilometers

Stellar Mass Black Holes



1. As the massive star nears its end, it takes on an onion-layer structure. At this point in its evolution the star is hundreds of millions of kilometers in radius; only its inner regions are shown here.

2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in.

3. Within a second, the core collapses to nuclear density. Inward-falling material rebounds off the core, setting up an outward-going pressure wave.

4. Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly.

5. The shock wave sweeps through the entire star, blowing it apart.

Figure 20-14
Universe, Eighth Edition

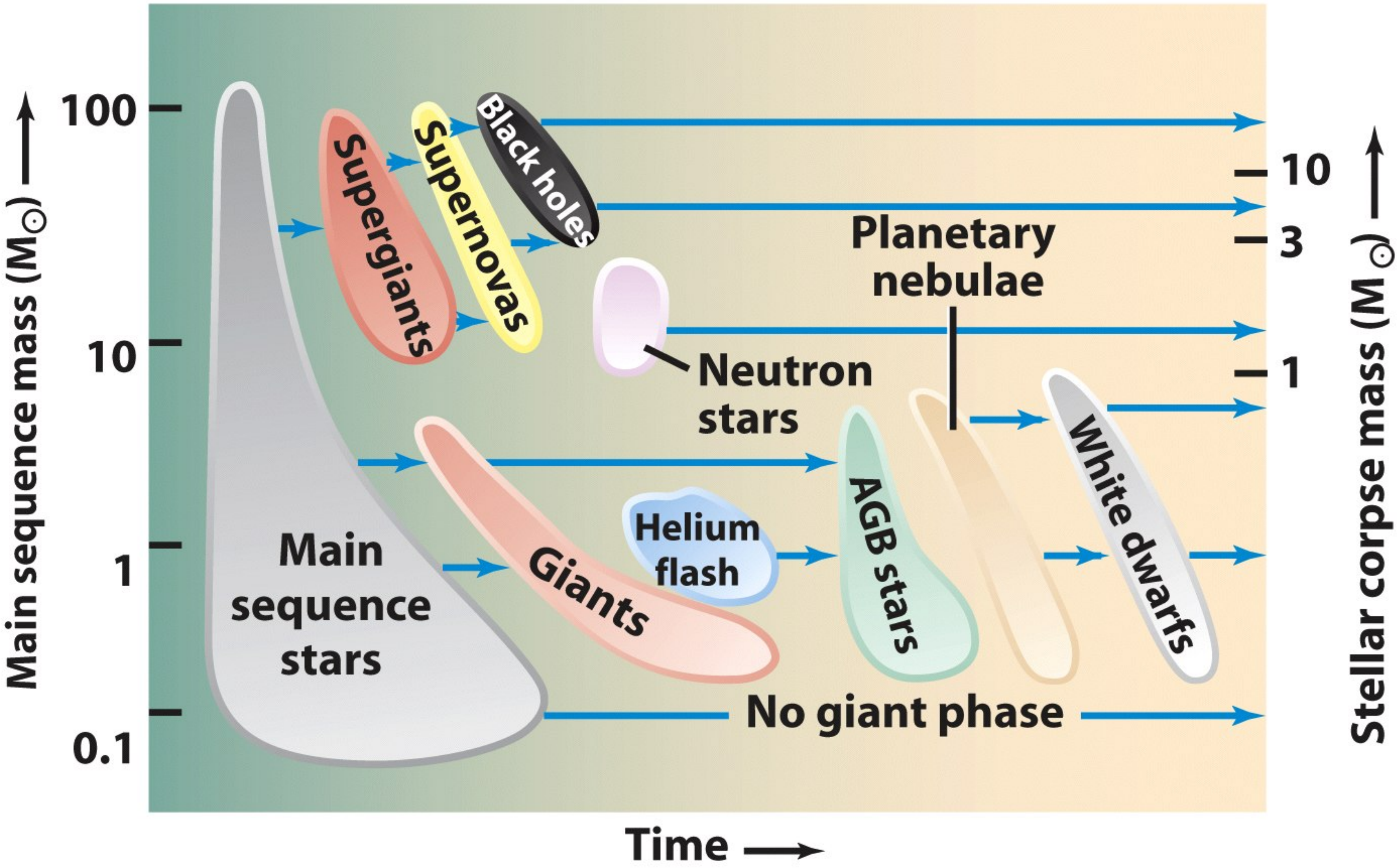
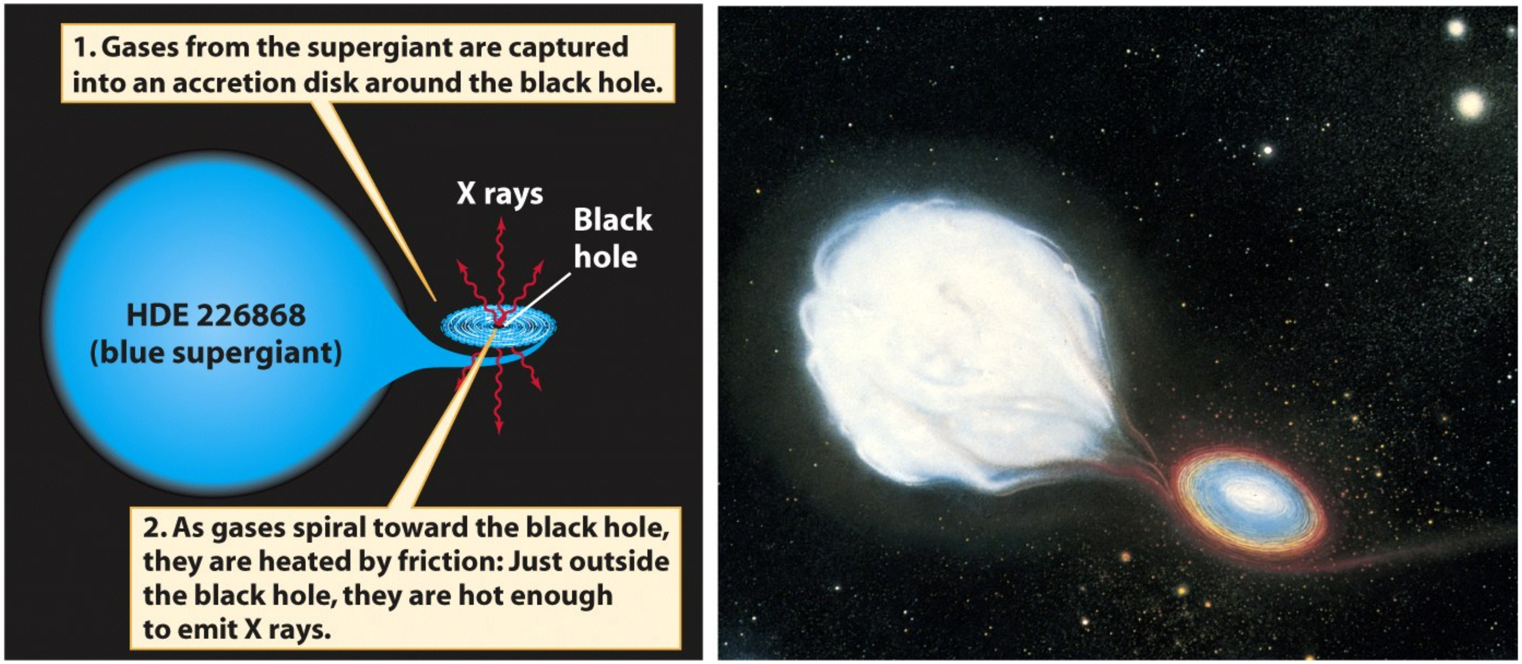


Figure 20-26a

Universe, Eighth Edition

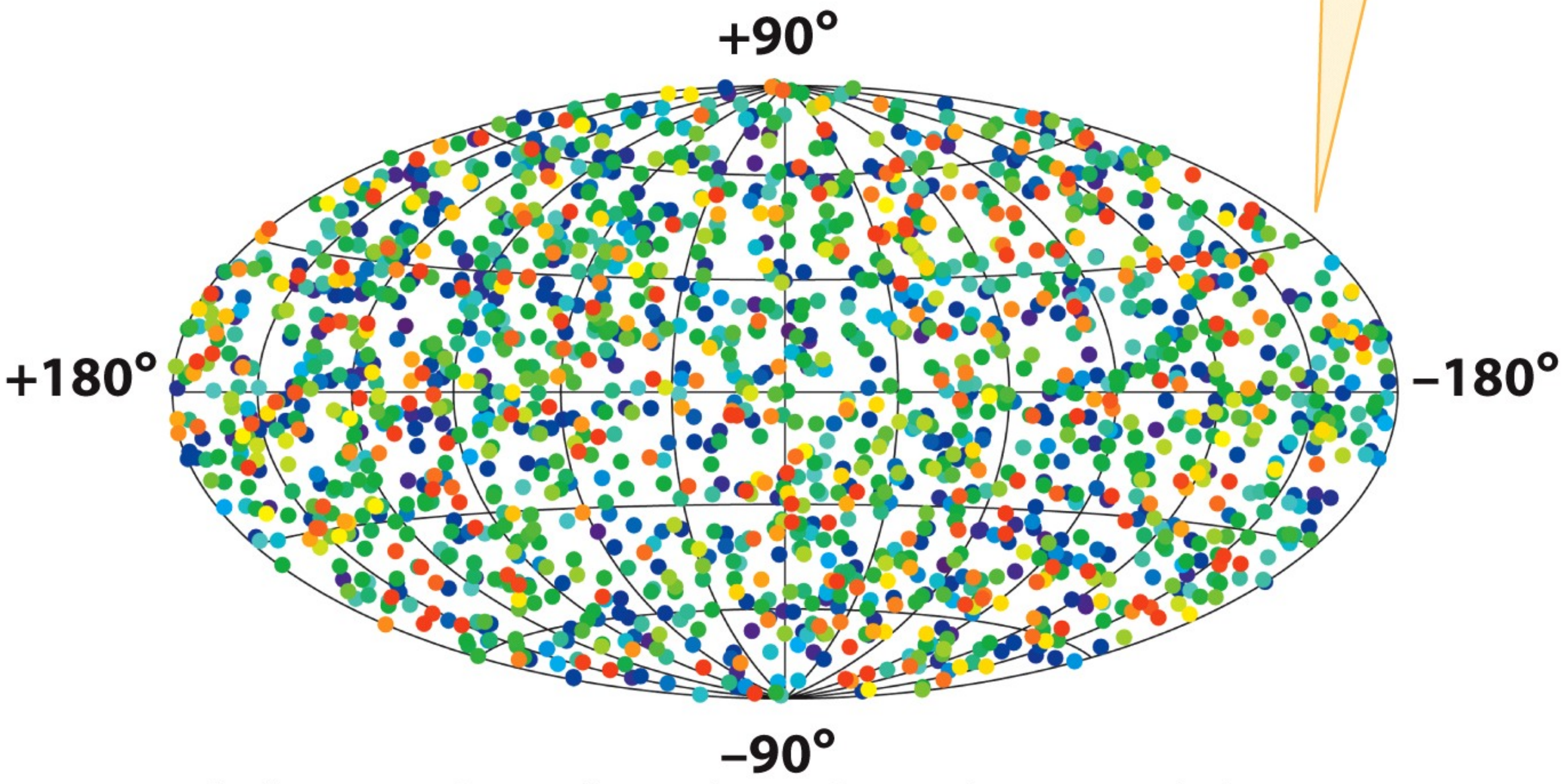


(a) A schematic diagram of Cygnus X-1 (b) An artist's impression of Cygnus X-1

Figure 22-11
Universe, Eighth Edition

The larger member of the Cygnus X-1 system is a B0 supergiant of about 30 M. The other, unseen member of the system has a mass of at least 7 M and is probably a black hole.

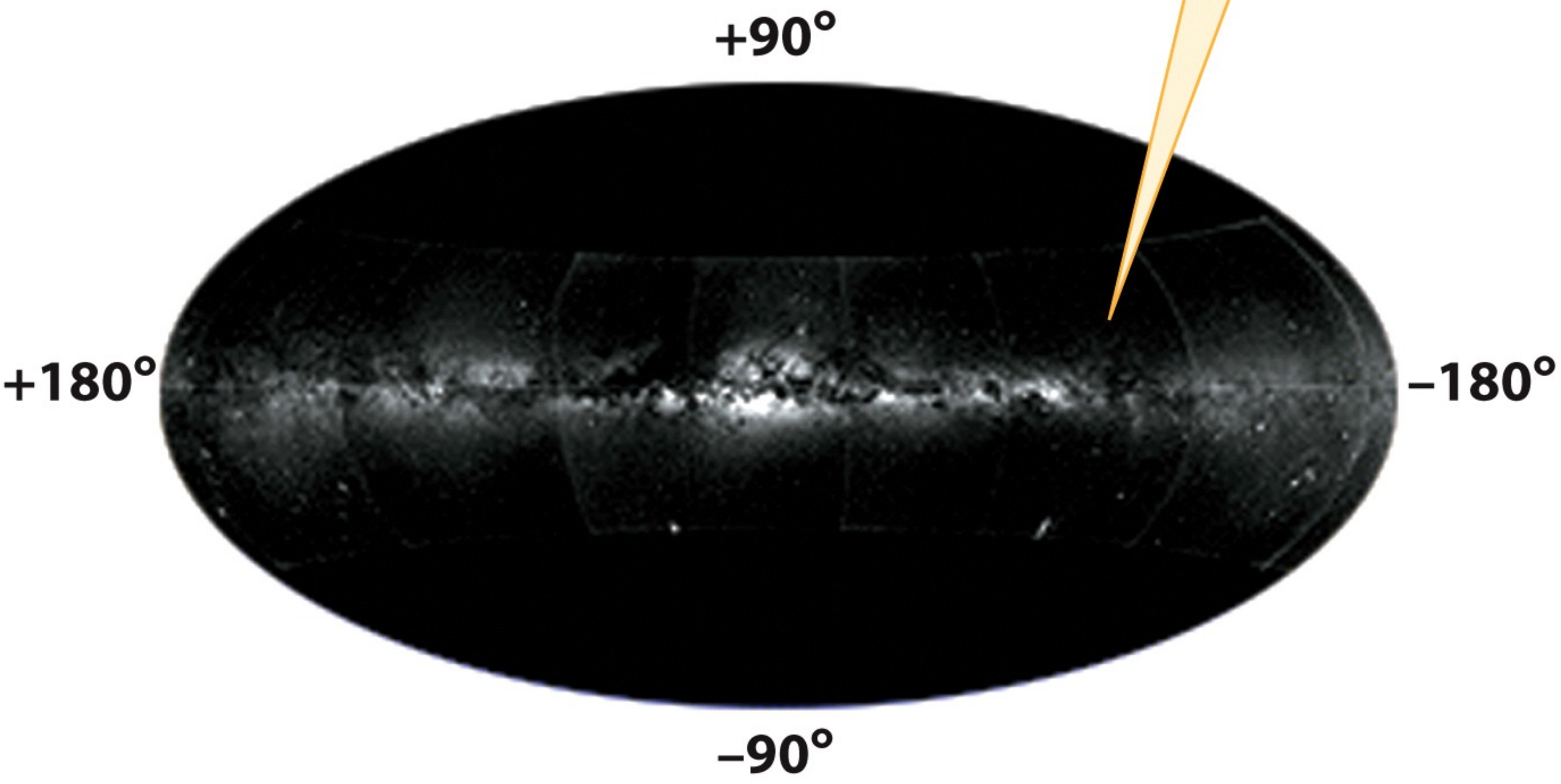
Gamma-ray bursts are found in all parts of the sky...



Map of the entire sky showing the positions of gamma-ray bursts

Figure 21-12a
Universe, Tenth Edition

... and are *not* concentrated in the plane of the Milky Way Galaxy.



Map of the entire sky at visible wavelengths

Figure 21-12b
Universe, Tenth Edition
NASA

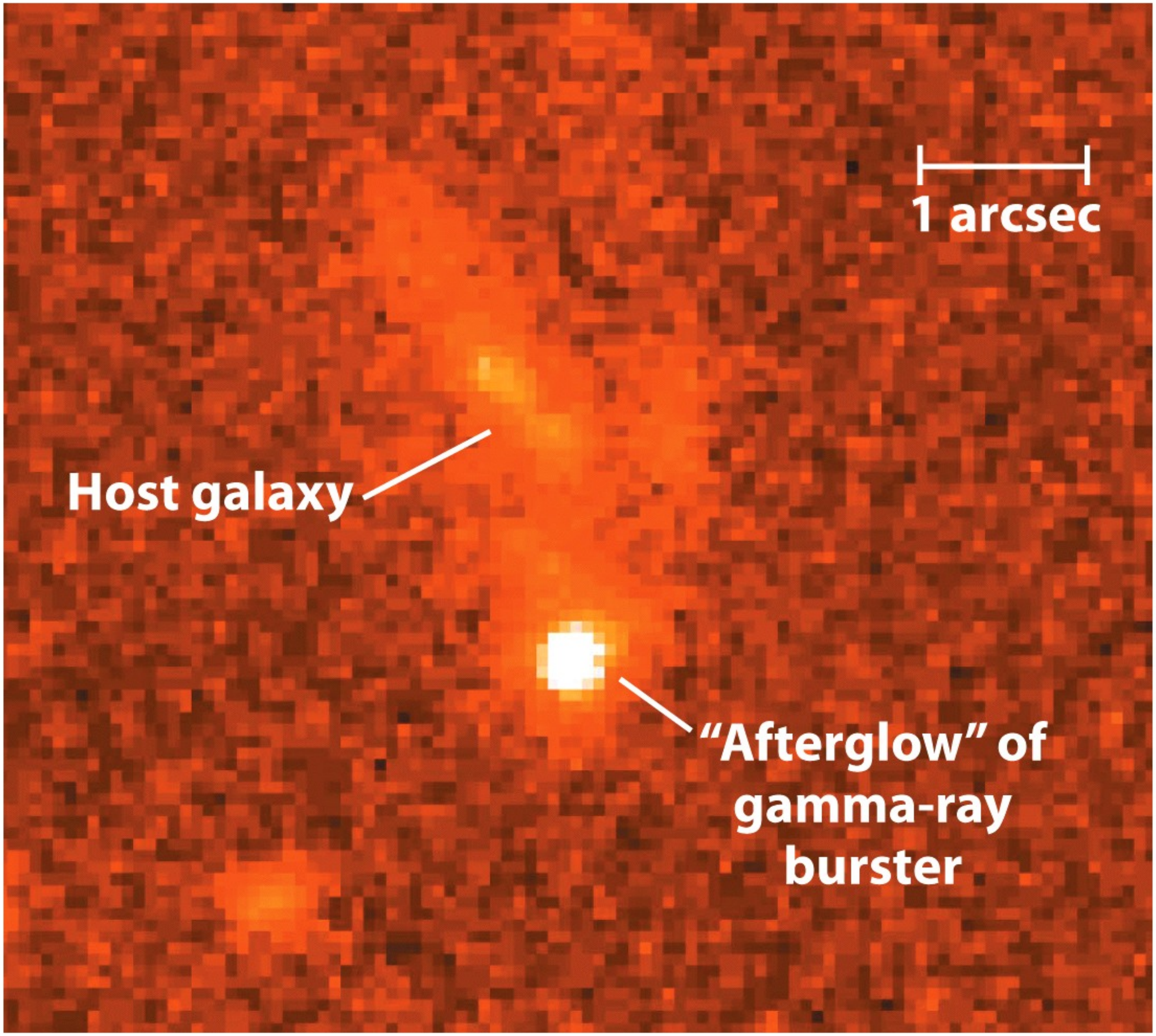
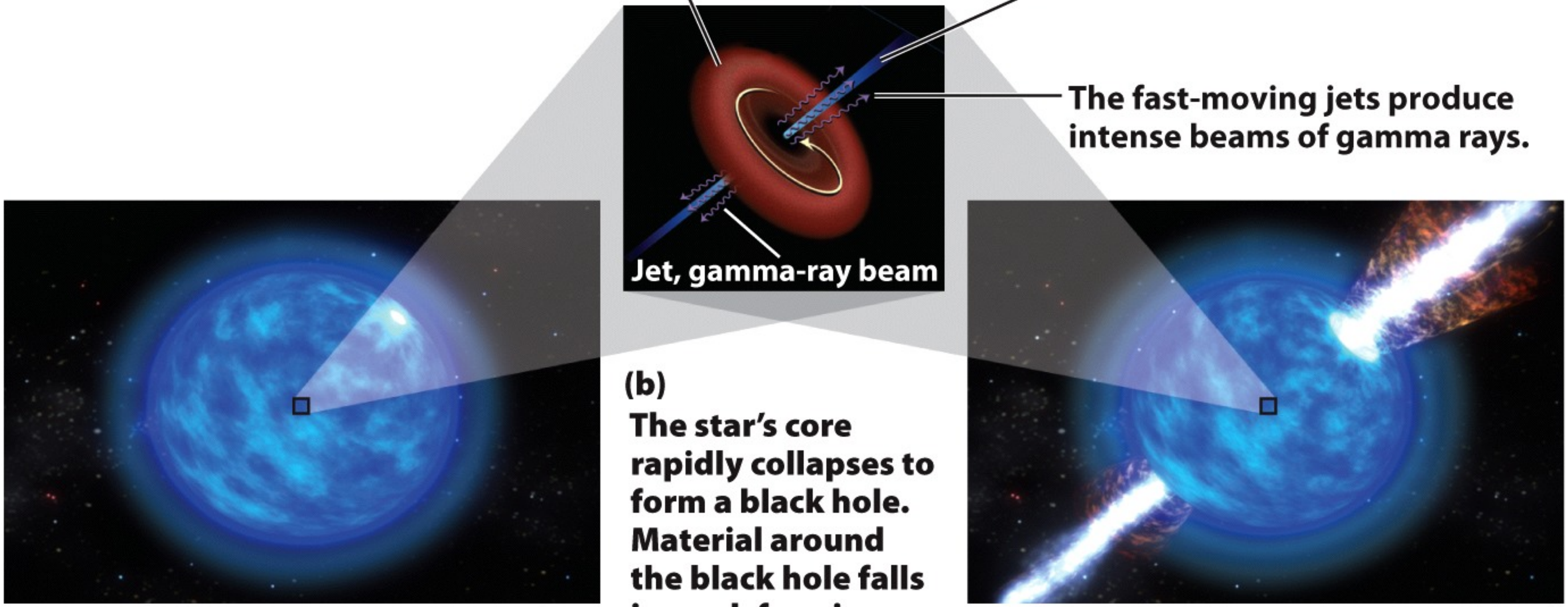


Figure 21-13
Universe, Tenth Edition
Andrew Fruchter, STScI; and NASA

Torus with a black hole and accretion disk at its center.

Two oppositely-directed jets of fast-moving particles emerge along the star's rotation axis.

The fast-moving jets produce intense beams of gamma rays.



(b) **The star's core rapidly collapses to form a black hole. Material around the black hole falls inward, forming an accretion disk and jets.**

(a) **After shedding its outer layers of hydrogen and helium, a rapidly rotating supergiant star of more than 30 $M_\odot$ reaches the end of its lifetime.**

(c) **The jets blast through what remains of the supergiant star. If one of the jets and its beam is directed toward Earth, we see a gamma-ray burst.**

Figure 21-14
Universe, Tenth Edition
a, c: NASA/Sky Works Digital; b: NASA and A. Field, STScI

According to general relativity, a beam of light bends as it passes close to a massive object because

A. the massive object exerts an electromagnetic force on the photons.

B. the photons exert an electromagnetic force on the massive object.

C. it follows the curvature of the space around the massive object.

D. the speed of light increases.

E. the speed of light decreases.

According to general relativity, a beam of light bends as it passes close to a massive object because

A. the massive object exerts an electromagnetic force on the photons.
B. the photons exert an electromagnetic force on the massive object.
C. it follows the curvature of the space around the massive object.
D. the speed of light increases.
E. the speed of light decreases.

Gravitational Waves

- What kind of waves are you familiar with?
  - What is oscillating in each case?
- Gravitational waves are ripples in space-time.
  - Reveal cosmos that has never been perceived before.
  - They *do not* map onto one of our sensory experiences (e.g., electromagnetic waves → sight, sound waves → hearing).

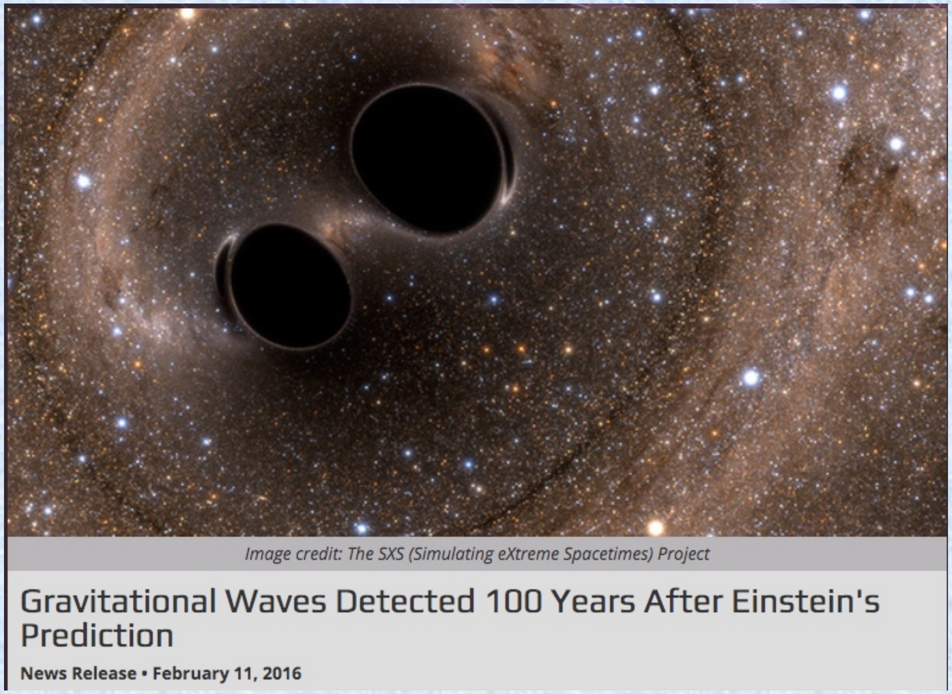


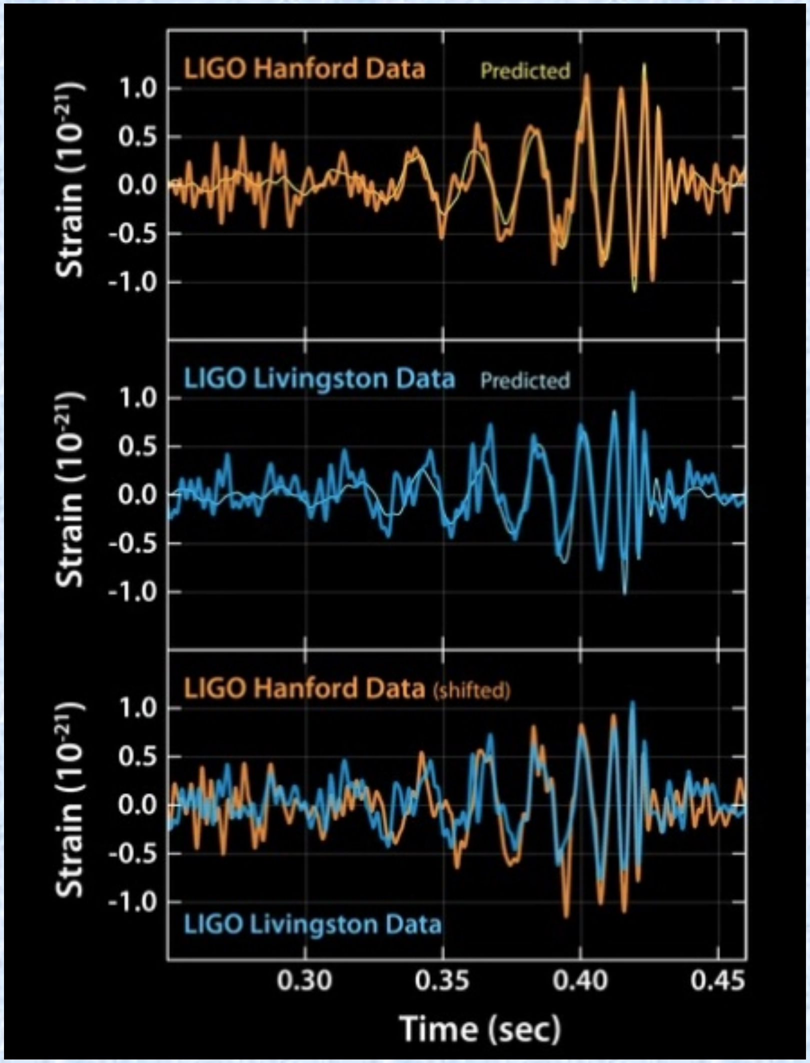
Image credit: The SXS (Simulating eXtreme Spacetimes) Project

Gravitational Waves Detected 100 Years After Einstein's Prediction

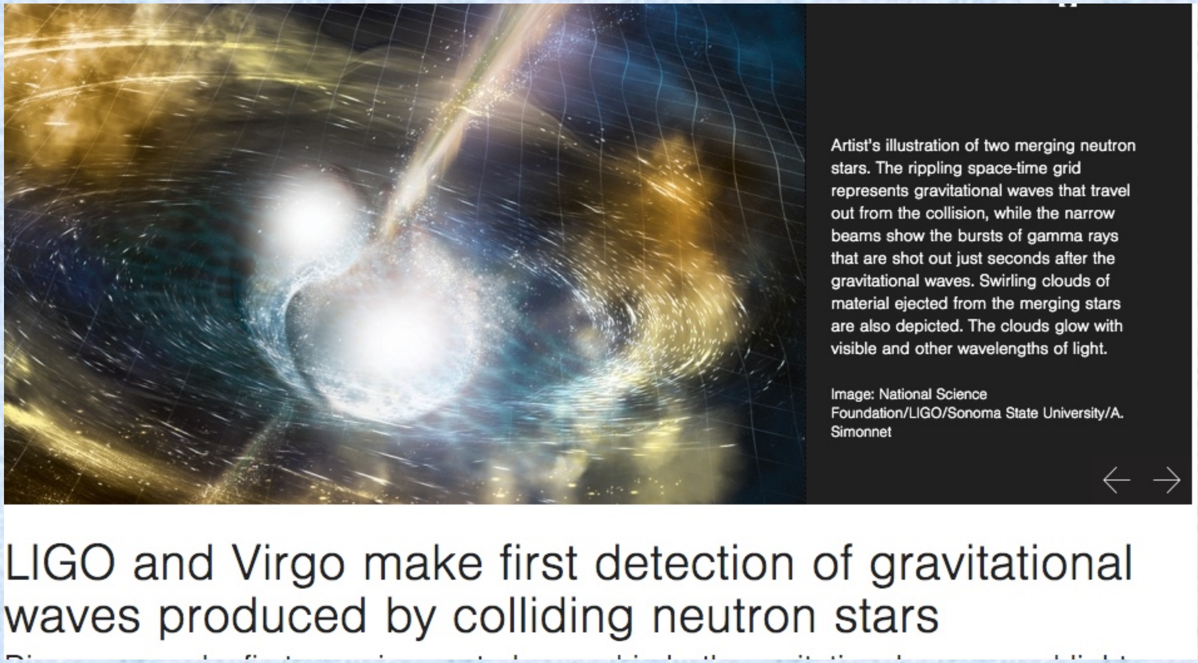
News Release • February 11, 2016

Gravitational Waves. First Detection (LIGO)

- Signal from the first gravitational wave detection.
  - Merging of two black holes, each roughly 30 times the mass of the Sun.
- New ways of looking at the universe may reveal loopholes in traditional thinking.
- Where do you think these black holes came from?
  - How could this discovery help us understand stellar evolution?



Multi-messenger Astronomy



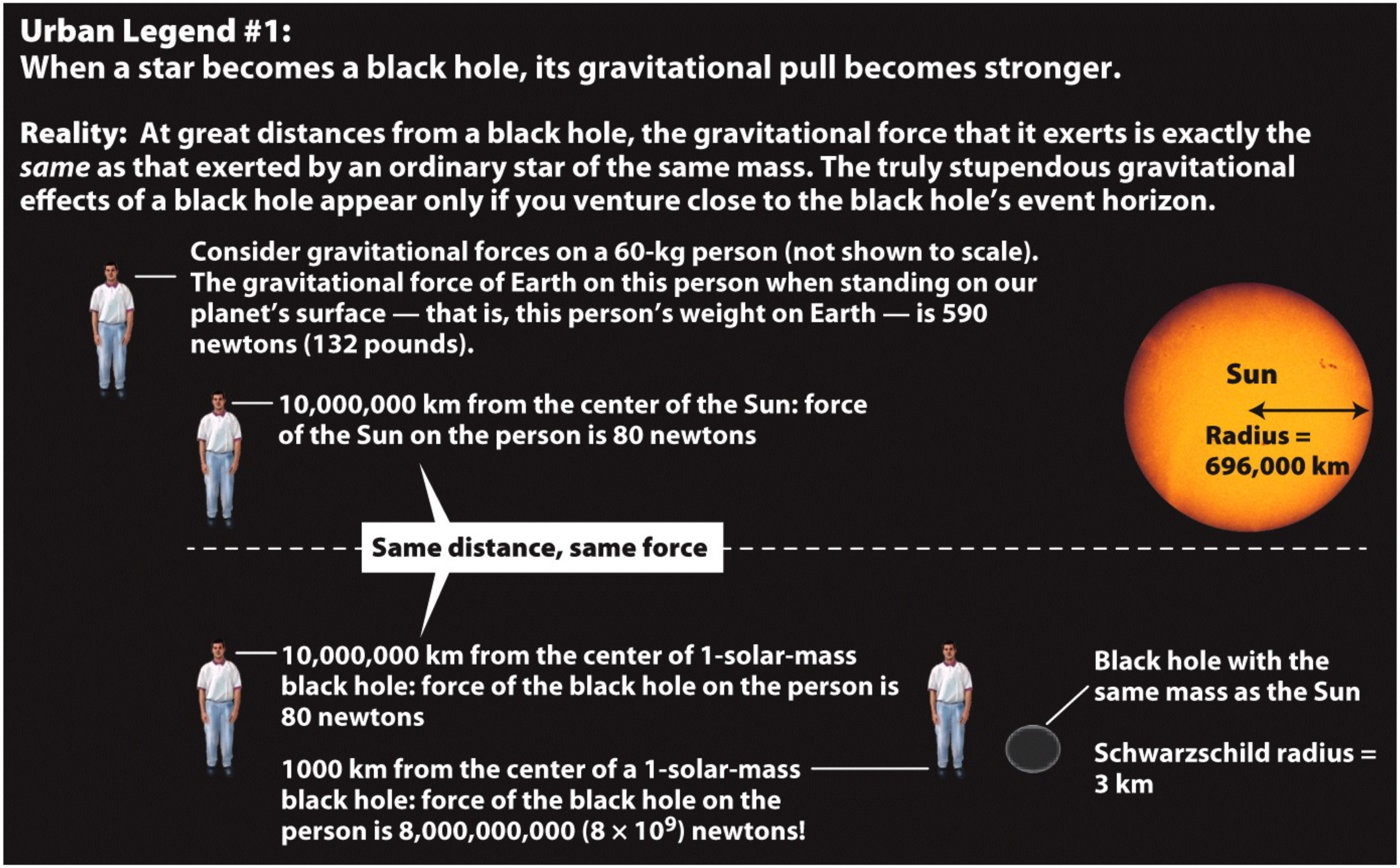
Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light.

Image: National Science Foundation/LIGO/Sonoma State University/A. Simonnet

LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars

- Merging stellar remnants estimated to be 1.1 to 1.6 times the mass of the Sun. Hence, neutron stars.
- Detection of gamma-rays very soon after the GW detection confirms theory that NS-NS mergers produce short gamma-ray bursts.
- Ejected material predicted to undergo r-process nucleosynthesis and create a bright glow, called a kilo-novae.

More Properties of Black Holes



Urban Legend #1:
When a star becomes a black hole, its gravitational pull becomes stronger.

Reality: At great distances from a black hole, the gravitational force that it exerts is exactly the *same* as that exerted by an ordinary star of the same mass. The truly stupendous gravitational effects of a black hole appear only if you venture close to the black hole's event horizon.

Consider gravitational forces on a 60-kg person (not shown to scale). The gravitational force of Earth on this person when standing on our planet's surface — that is, this person's weight on Earth — is 590 newtons (132 pounds).

10,000,000 km from the center of the Sun: force of the Sun on the person is 80 newtons

10,000,000 km from the center of 1-solar-mass black hole: force of the black hole on the person is 80 newtons

1000 km from the center of a 1-solar-mass black hole: force of the black hole on the person is 8,000,000,000 (8×10^9) newtons!

Cosmic Connections 21a
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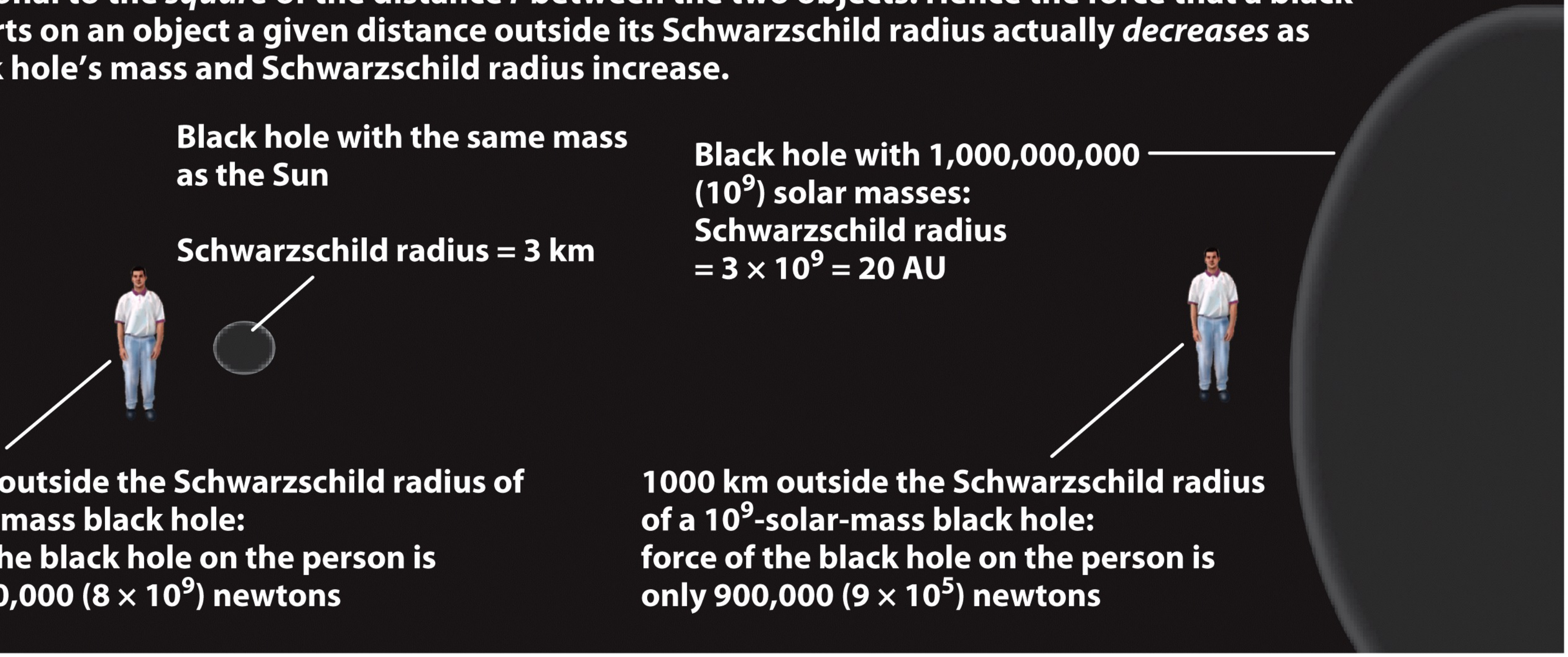
Urban Legend #2:
The larger a black hole, the more powerful the gravity near its Schwarzschild radius.

Reality: If you increase the mass of a black hole, its Schwarzschild radius increases by the same factor. Newton's law of universal gravitation, $F = Gm_1m_2/r2$, tells us that the force that an object of mass m_1 exerts on a second object of mass m_2 is directly proportional to mass m_1 but *inversely* proportional to the *square* of the distance r between the two objects. Hence the force that a black hole exerts on an object a given distance outside its Schwarzschild radius actually *decreases* as the black hole's mass and Schwarzschild radius increase.



Black hole with the same mass as the Sun

Schwarzschild radius = 3 km

Black hole with 1,000,000,000 (10^9) solar masses:
Schwarzschild radius
= 3 × 10^9 = 20 AU

1000 km outside the Schwarzschild radius of a 1-solar-mass black hole:
force of the black hole on the person is 8,000,000,000 (8 × 10^9) newtons

1000 km outside the Schwarzschild radius of a 10^9-solar-mass black hole:
force of the black hole on the person is only 900,000 (9 × 10^5) newtons

Cosmic Connections 21b
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Spinning Black Holes

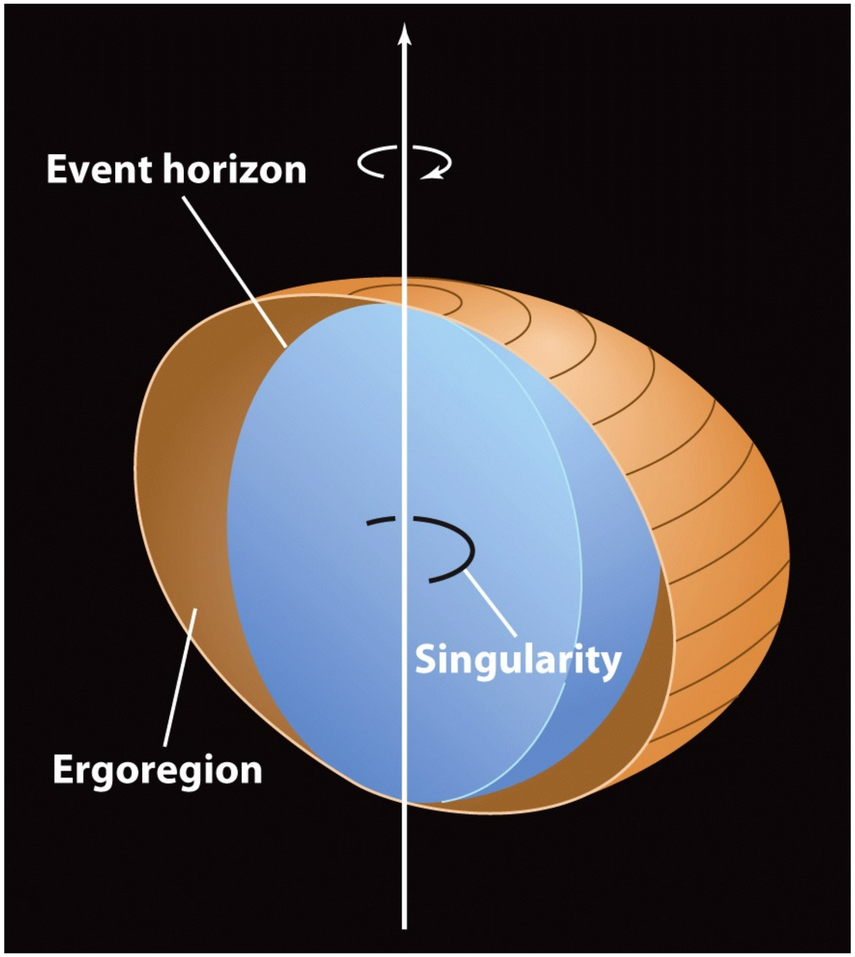

Figure 21-18
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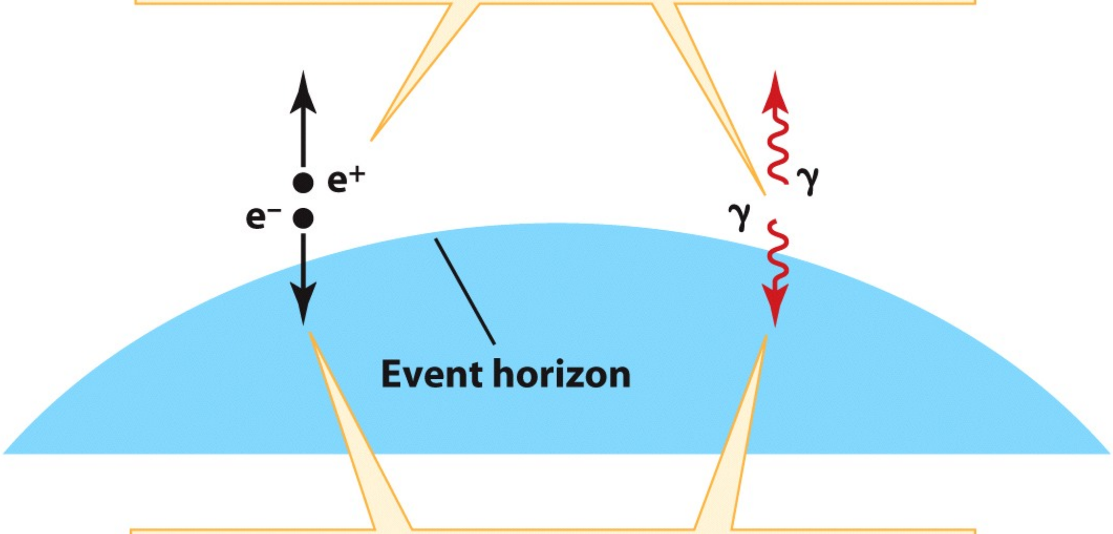
Hawking Radiation



1. Pairs of virtual particles spontaneously appear and annihilate everywhere in the universe.

2. If a pair appears just outside a black hole's event horizon, tidal forces can pull the pair apart, preventing them from annihilating each other.

3. If one member of the pair crosses the event horizon, the other can escape into space, carrying energy away from the black hole.

Figure 21-22
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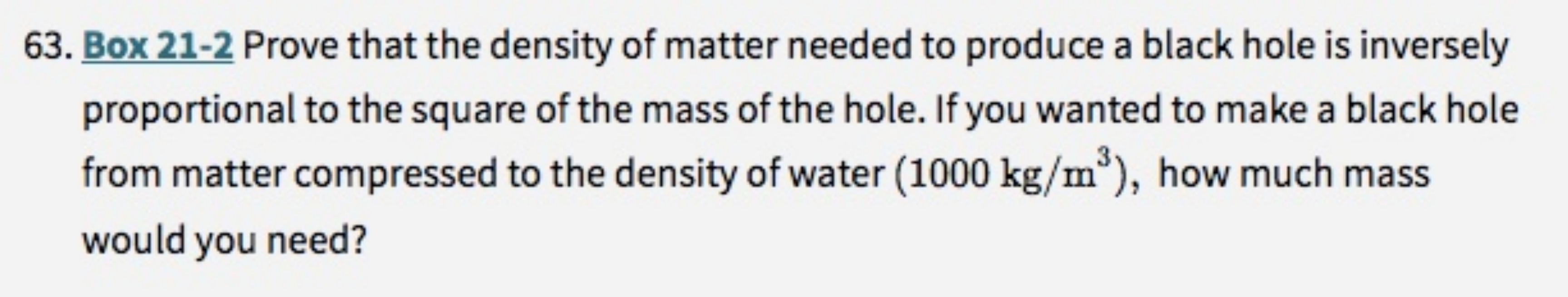
Homework Challenge Question



63. Box 21-2 Prove that the density of matter needed to produce a black hole is inversely proportional to the square of the mass of the hole. If you wanted to make a black hole from matter compressed to the density of water ($1000\ \mathrm{kg/m^3}$), how much mass would you need?

In other words, more massive black holes have lower density.

iClicker Question

Which of the following best describes the evidence for black holes?

A. The General Theory of Relativity predicts the existence of black holes, but there is no way to test this theory because light does not escape from black holes.

B. The General Theory of Relativity predicts the existence of black holes, and astronomers have detected them by measuring the orbits of particles near the black holes.

C. The General Theory of Relativity predicts the existence of black holes, and astronomers have detected merging black holes via the ripples they send through space.

D. The General Theory of Relativity predicts the existence of black holes, and astronomers have imaged a few of them.

E. B, C, and D are all true.

Summary

- **The Special Theory of Relativity:**
  - The laws of physics are the same in any (intertial) reference frame
  - The speed of light is the same to all observers
  - An observer will note a slowing of clocks and a shortening of rulers that are moving with respect to them.
  - Space and time are aspects of a single entity called spacetime.
- **The General Theory of Relativity:**
  - Inertial mass and gravitational mass are the same
  - Gravity = acceleration
  - Gravity is nothing but the distortion of spacetime by mass
  - Predicts bending of light by gravity, gravitational redshift and gravitational waves
- **Black Holes:**
  - A stellar corpse with mass greater than 3 ~$M_\odot$, will collapse under gravity. Will be so dense that not even light can escape.