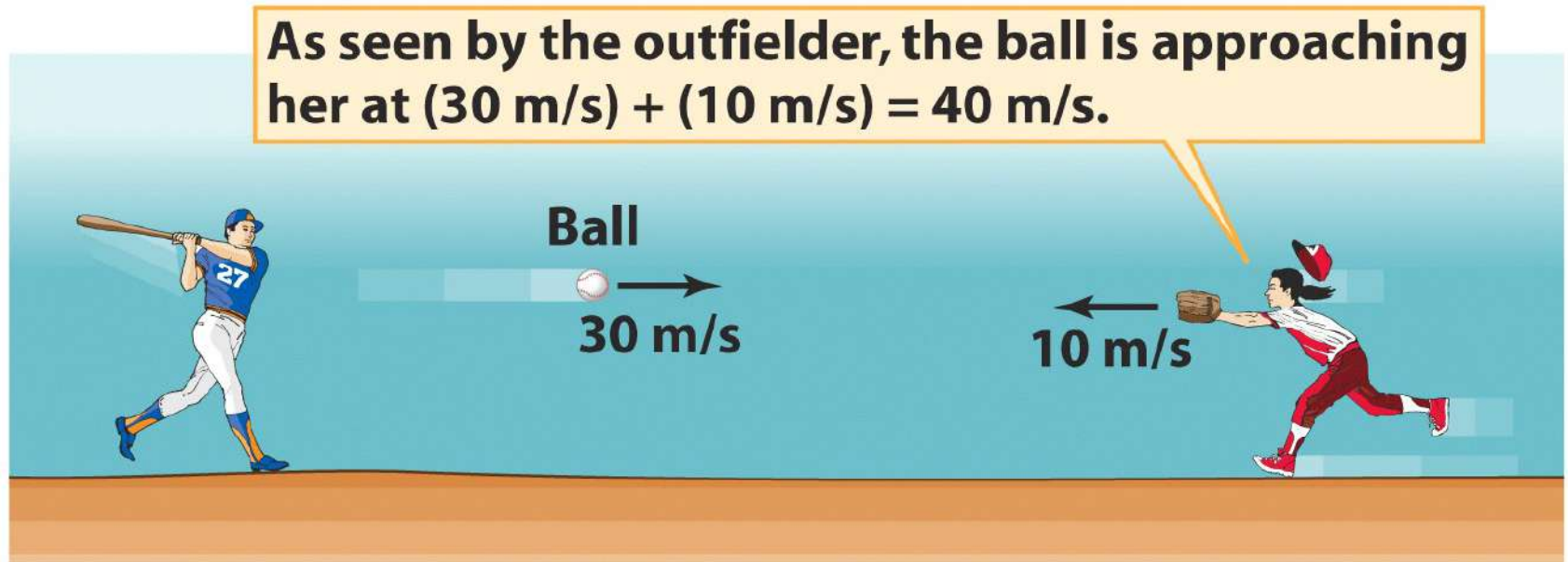


A detailed illustration of a black hole in space. The central black hole is surrounded by a glowing accretion disk with concentric rings of blue and white light. Two powerful jets of blue and orange energy are being emitted from the poles of the black hole, extending into the surrounding space. The background is a deep blue space filled with numerous white stars.

Black Holes

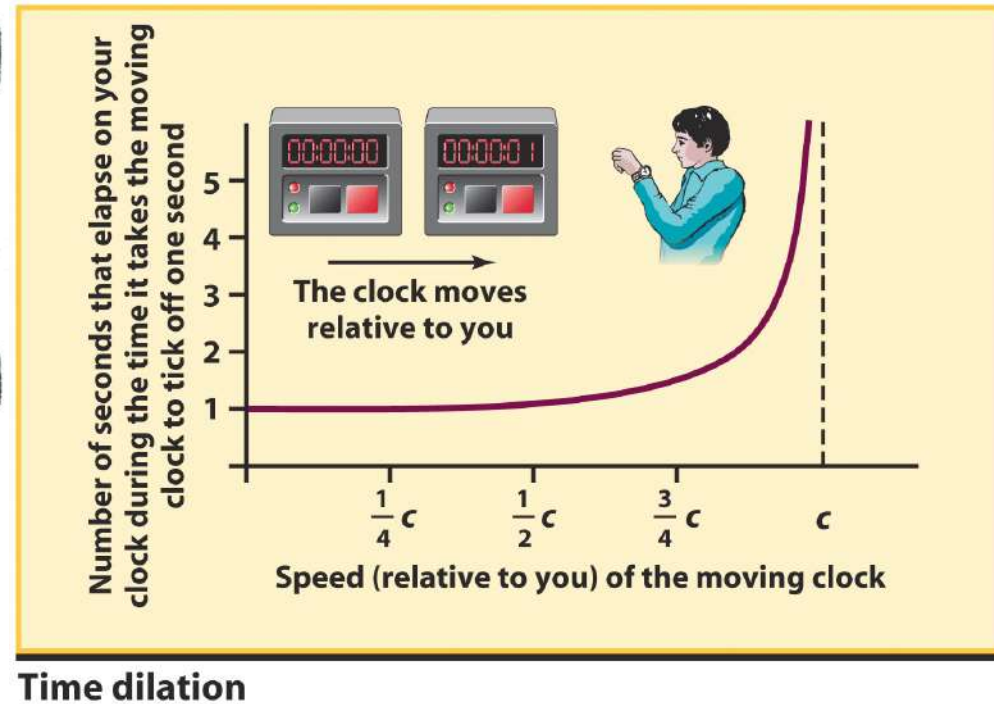
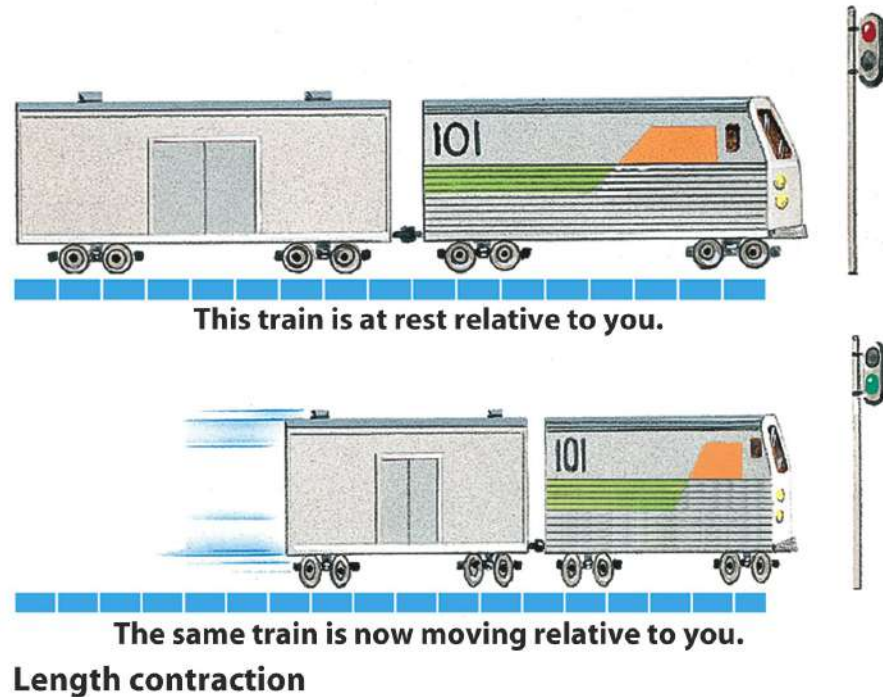
Chapter Twenty-Four

The special theory of relativity changes our conceptions of space and time



- This theory, published by Einstein in 1905, is based on the notion that there is no such thing as absolute space or time
- Space and time are not wholly independent of each other, but are aspects of a single entity called spacetime

An observer will note a slowing of clocks and a shortening of rulers that are moving with respect to the observer



This effect becomes significant only if the clock or ruler is moving at a substantial fraction of the speed of light

The speed of light is the same to all observers, no matter how fast they are moving

Incorrect Newtonian description:

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



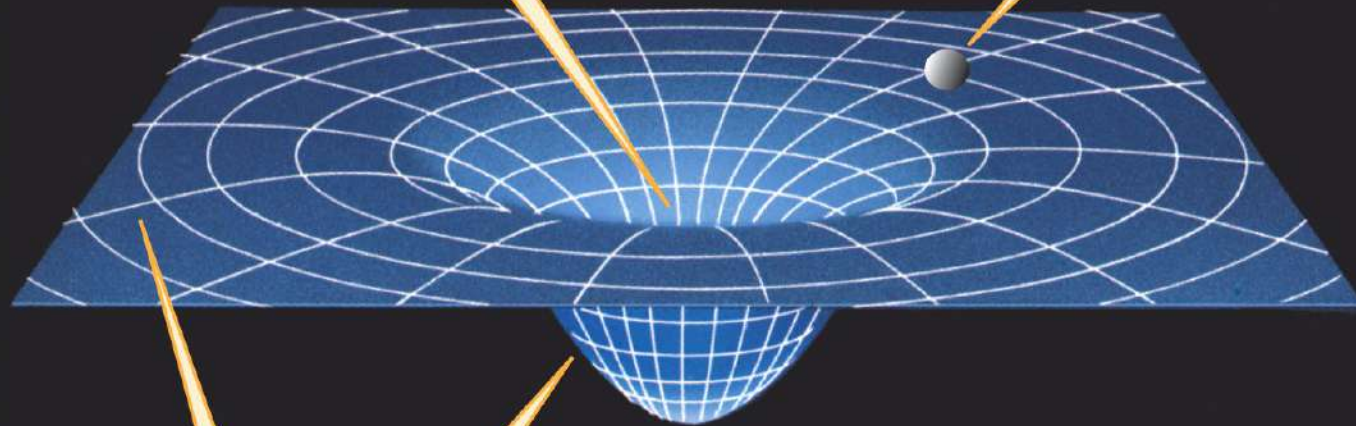
Correct Einsteinian description:

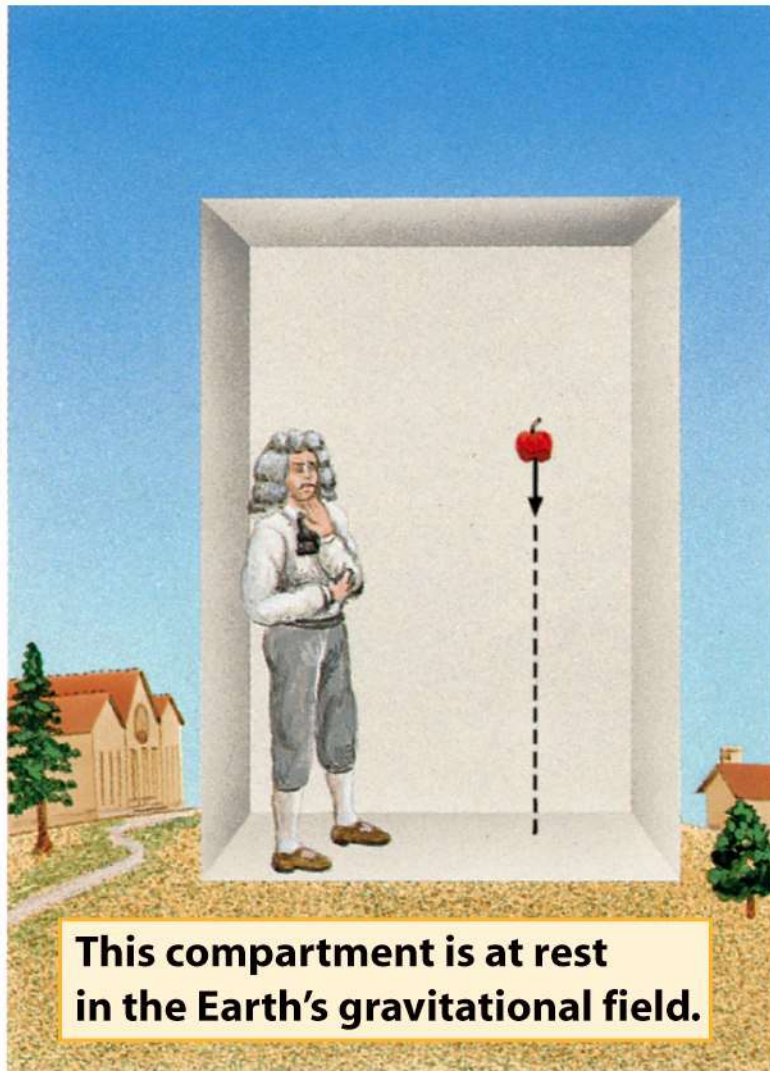
As seen by the astronaut in spaceship, the light is approaching her at $3 \times 10^8 \text{ m/s}$.

1. A massive object curves the spacetime around us.

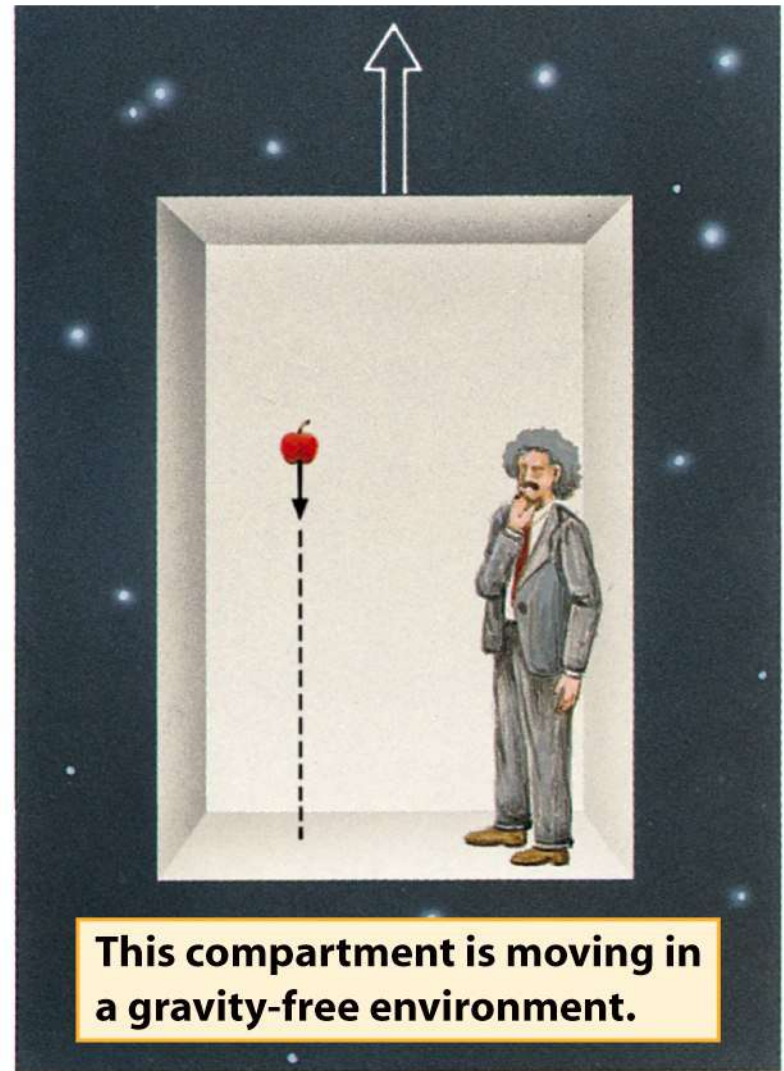
3. In Einstein's picture of gravity other objects sense the curvature and are drawn into the "well."

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

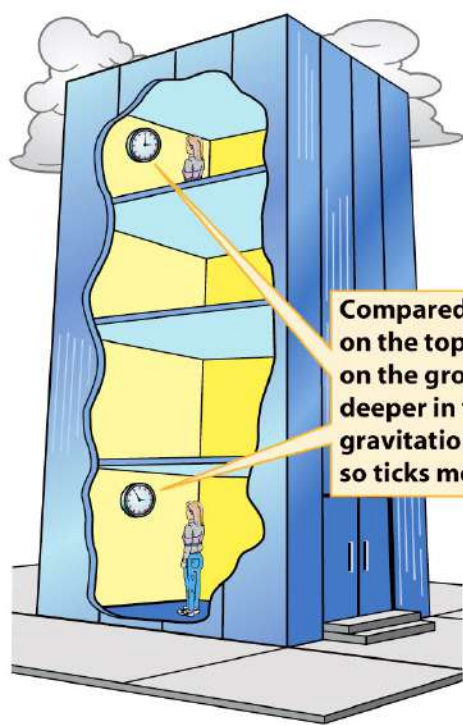




(a) The apple hits the floor of the compartment because the Earth's gravity accelerates the apple downward.

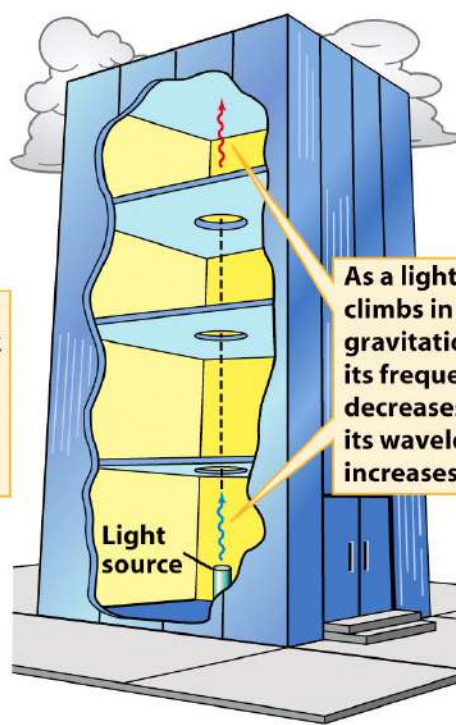


(b) The apple hits the floor of the compartment because the compartment accelerates upward.



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.

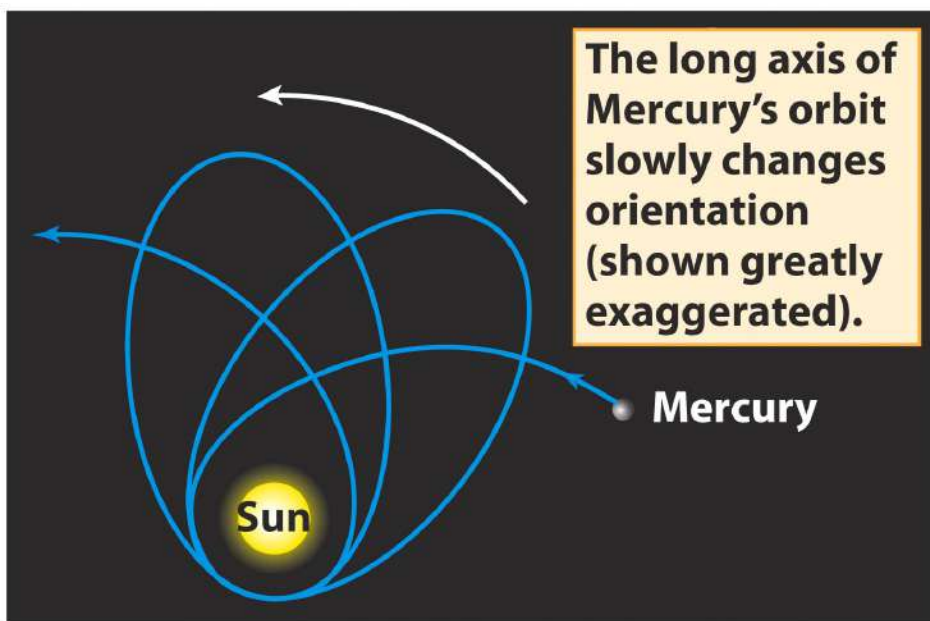
(a) The gravitational slowing of time



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

(b) The gravitational redshift

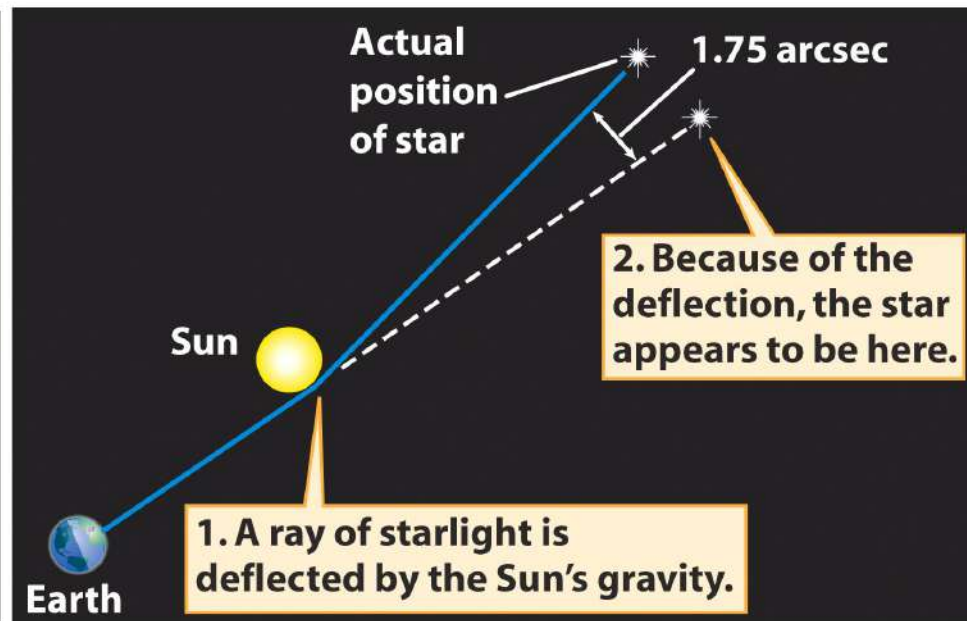
The theory of relativity predicts a number of phenomena, including the bending of light by gravity and the gravitational redshift, whose existence has been confirmed by observation and experiment



The long axis of Mercury's orbit slowly changes orientation (shown greatly exaggerated).

Mercury

Sun



Actual position of star

1.75 arcsec

2. Because of the deflection, the star appears to be here.

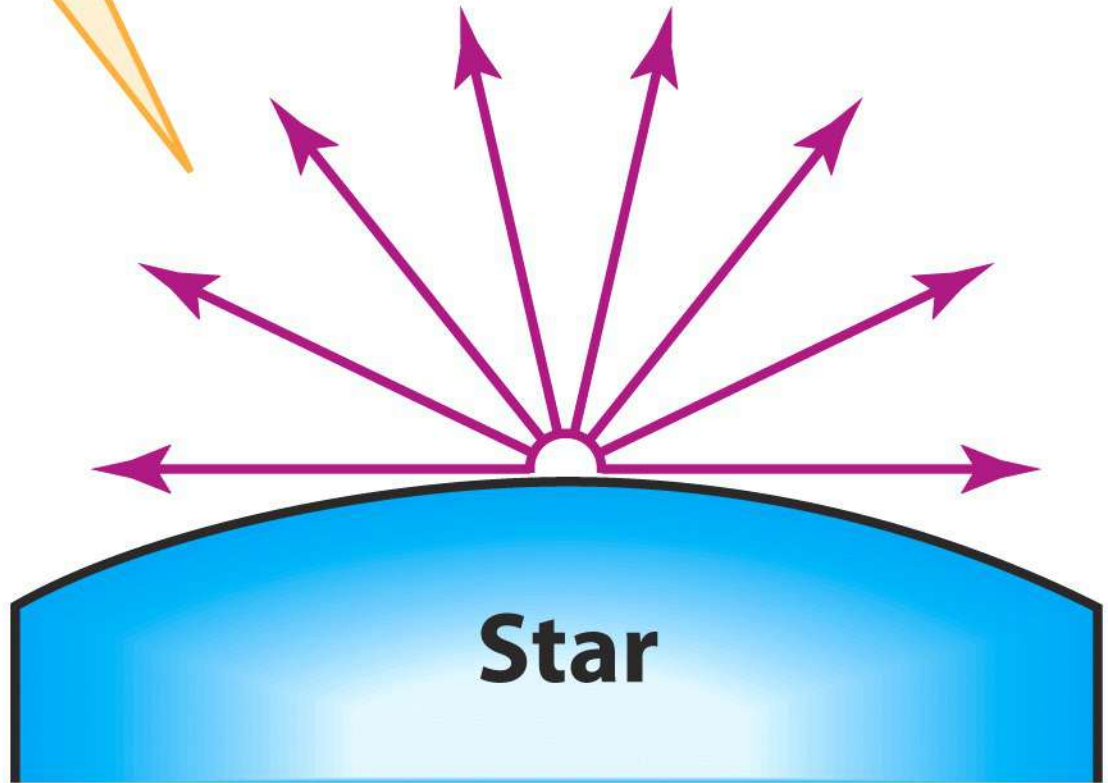
Sun

1. A ray of starlight is deflected by the Sun's gravity.

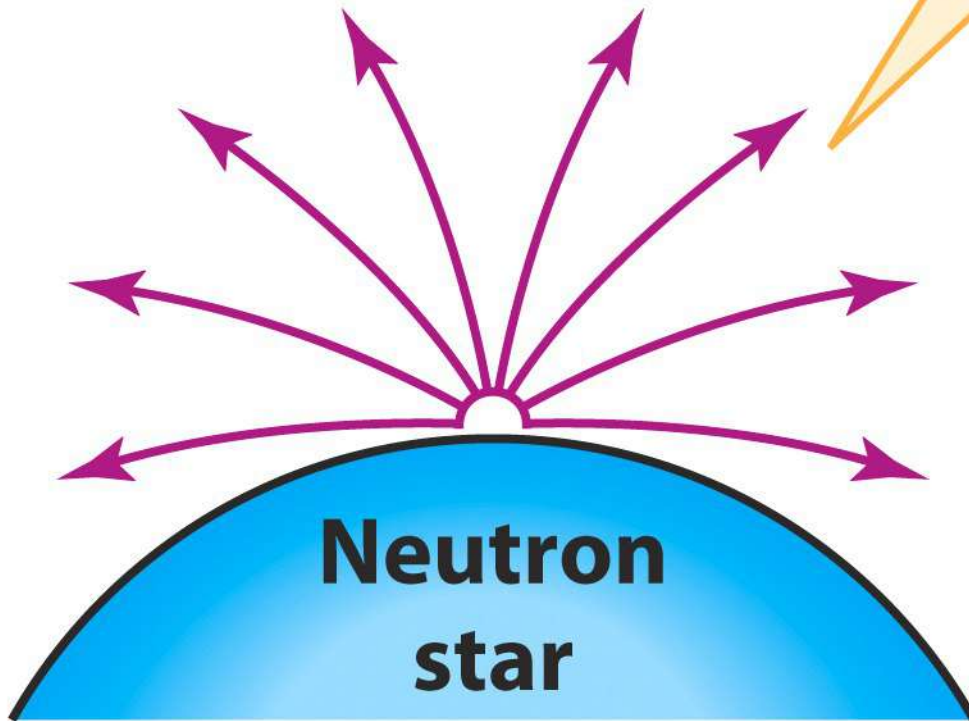
Earth

The general theory of relativity predicts black holes

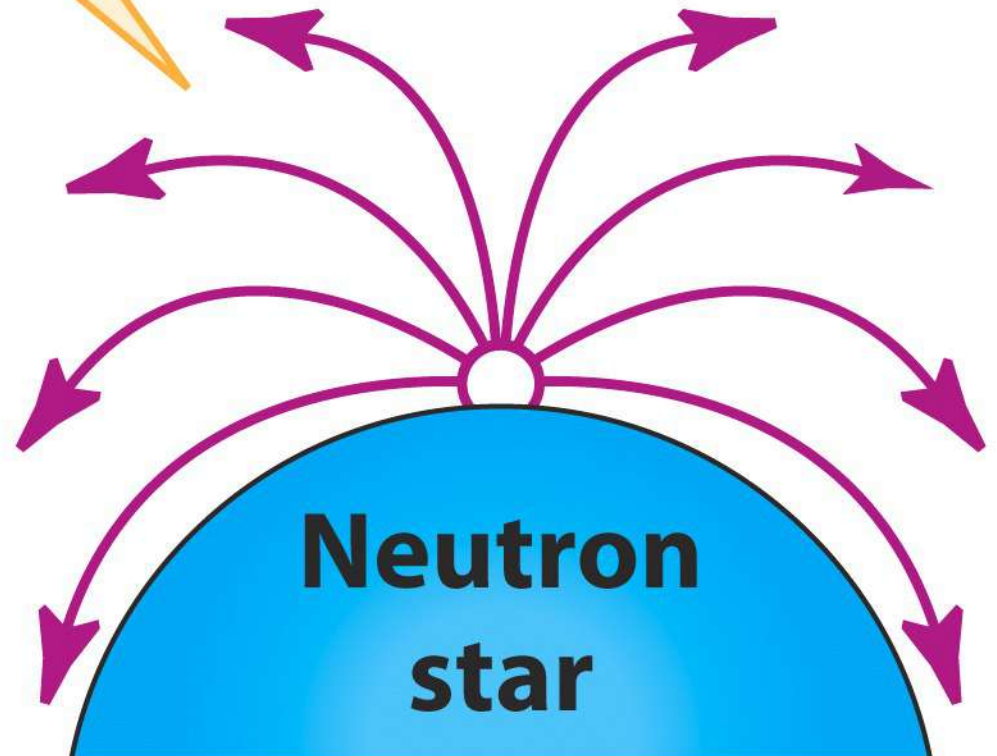
1. A supergiant star has relatively weak gravity, so emitted photons travel in essentially straight lines.



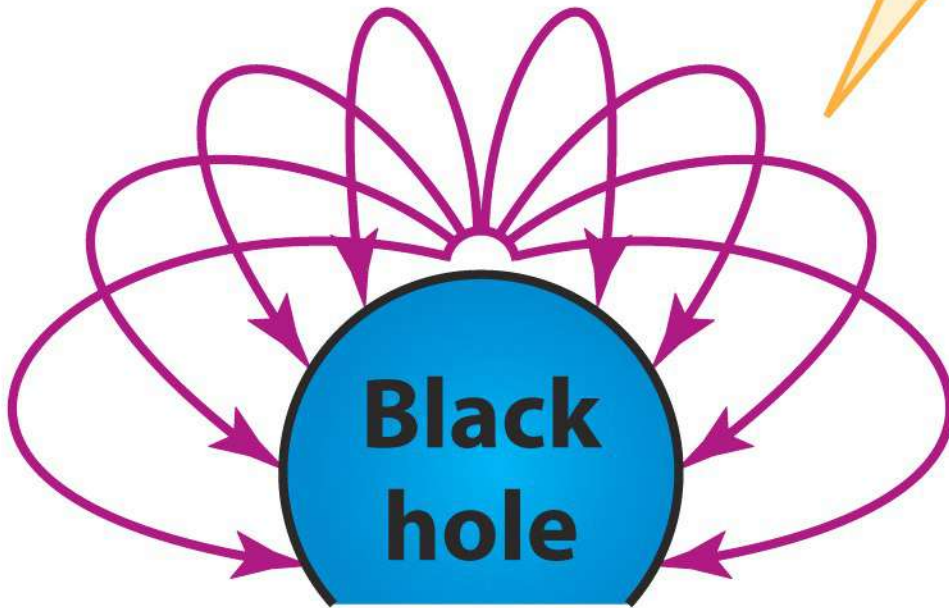
2. As the star collapses into a neutron star, the surface gravity becomes stronger and photons follow curved paths.



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

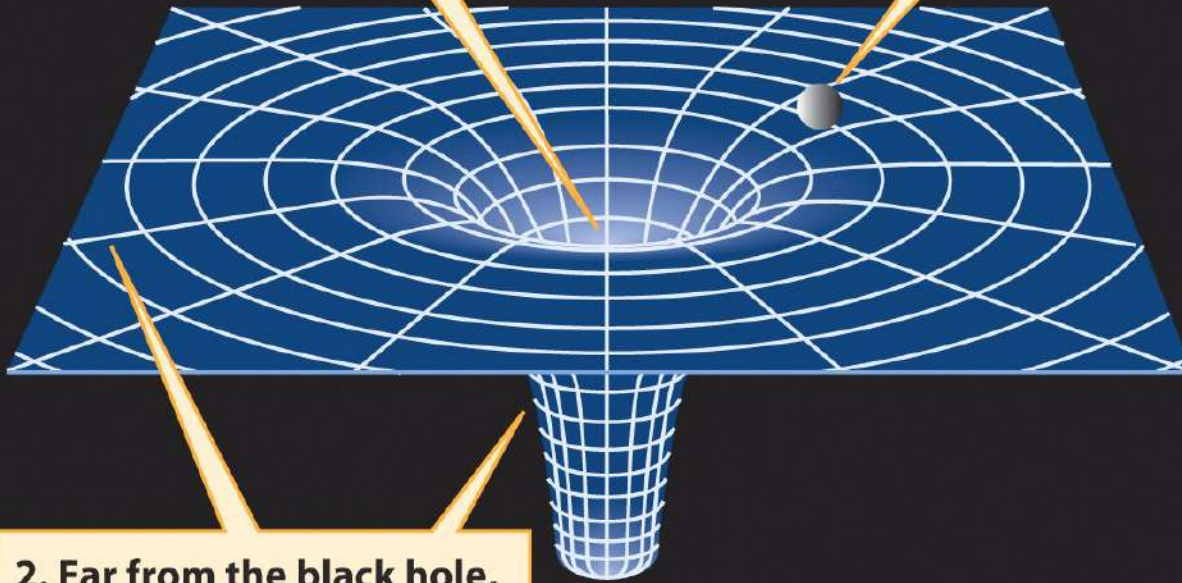


4. When the star shrinks past a critical size, it becomes a black hole: Photons follow paths that curve back into the black hole so no light escapes.

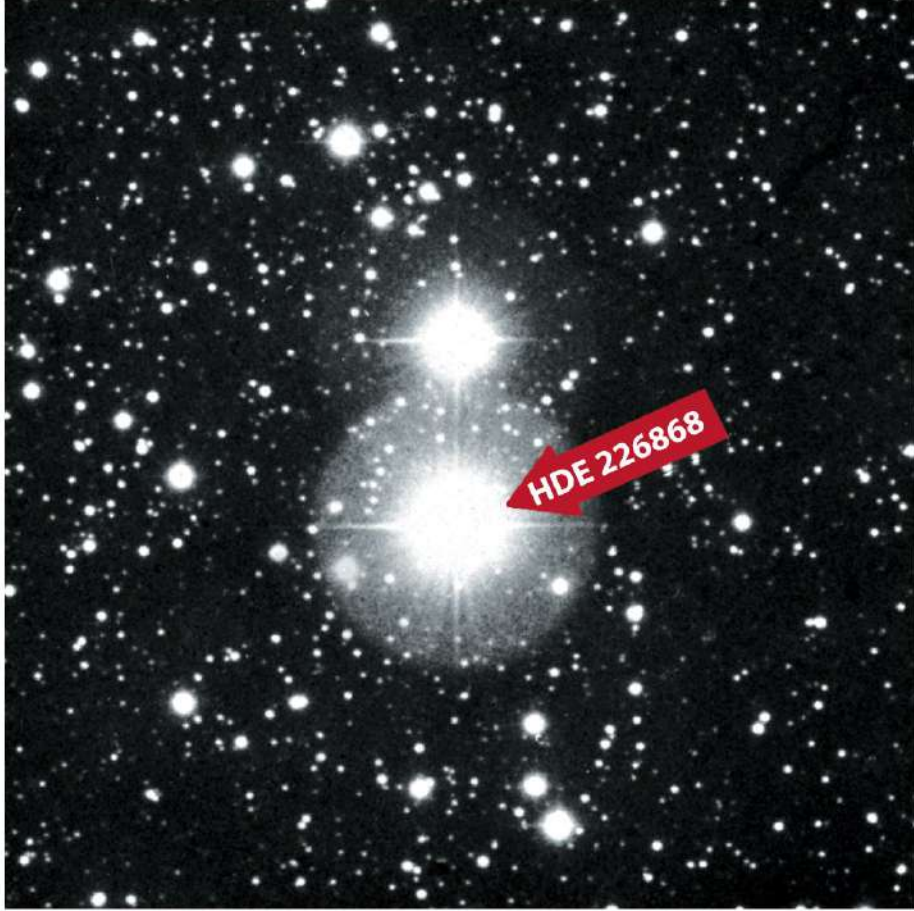


1. A black hole sharply curves the spacetime around it.

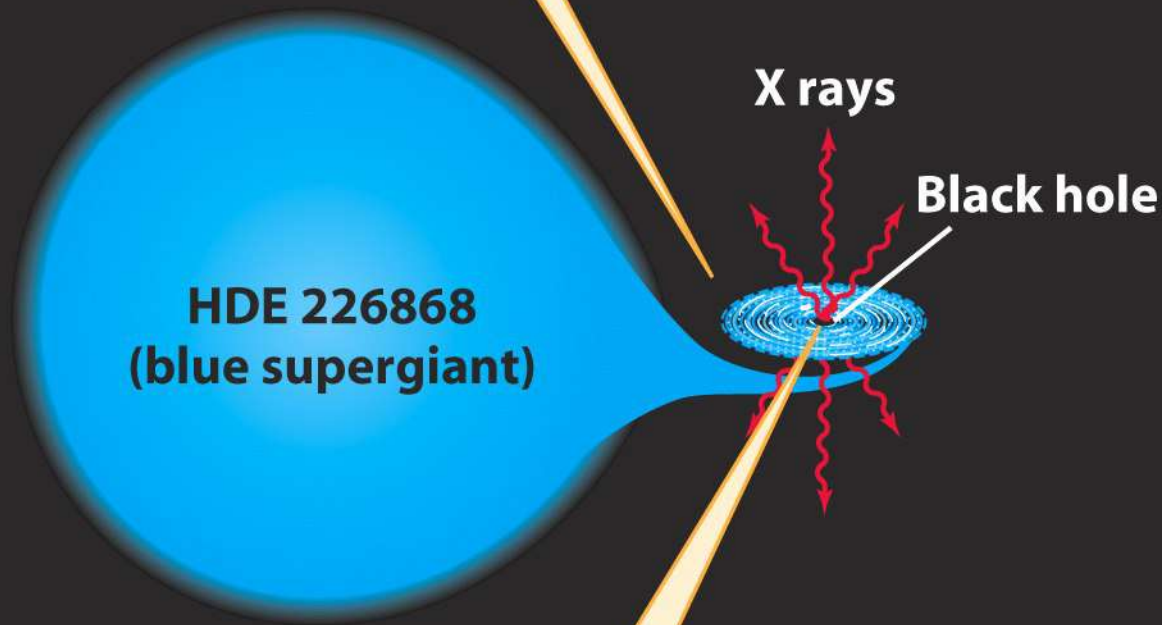
3. Objects that venture too close to the black hole cannot escape from the "well."



2. Far from the black hole, spacetime is nearly "flat"; close to the black hole, the curvature forms a "well" that is infinitely deep.



1. Gases from the supergiant are captured into an accretion disk around the black hole.

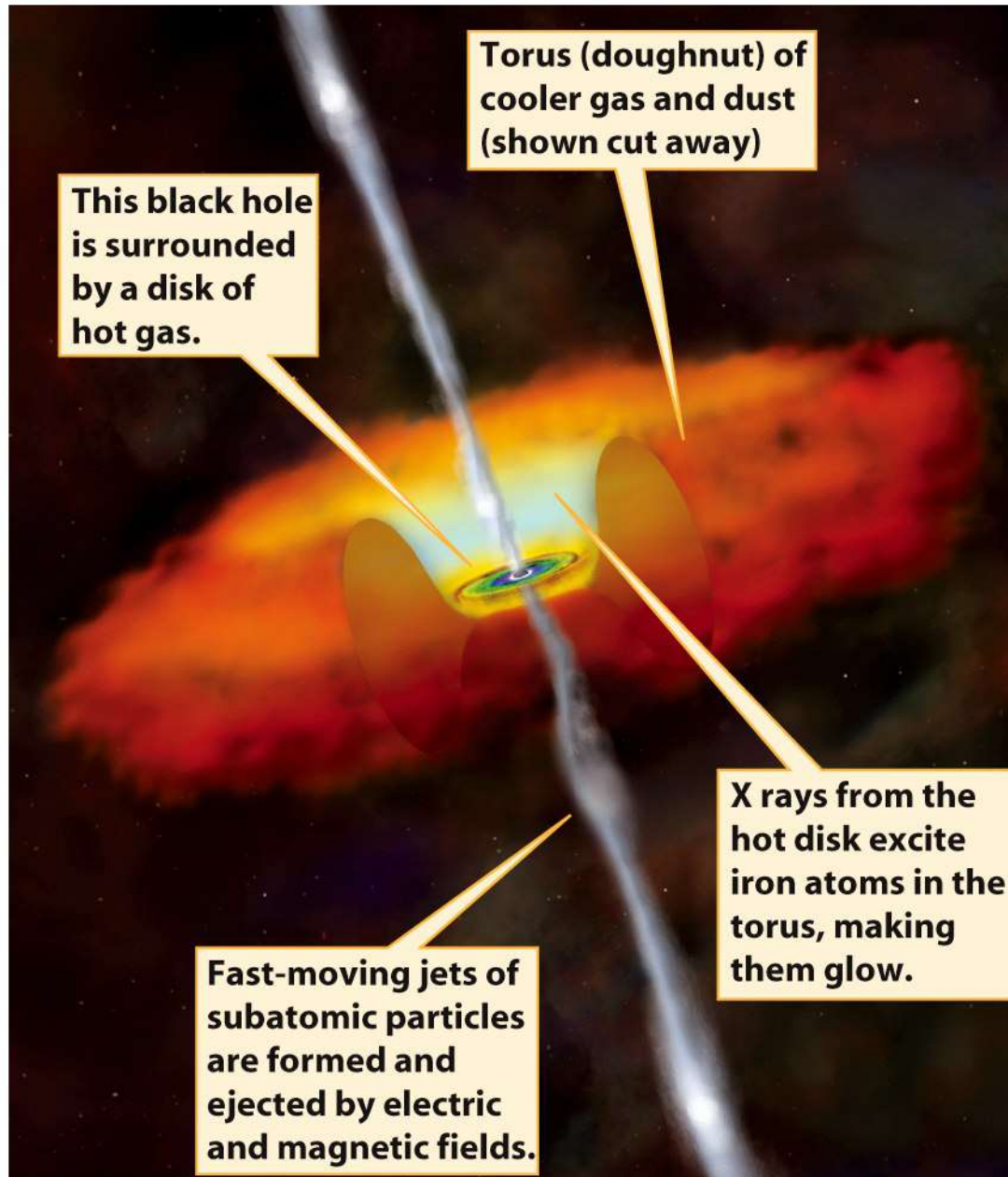


2. As gases spiral toward the black hole, they are heated by friction: Just outside the black hole, they are hot enough to emit X rays.

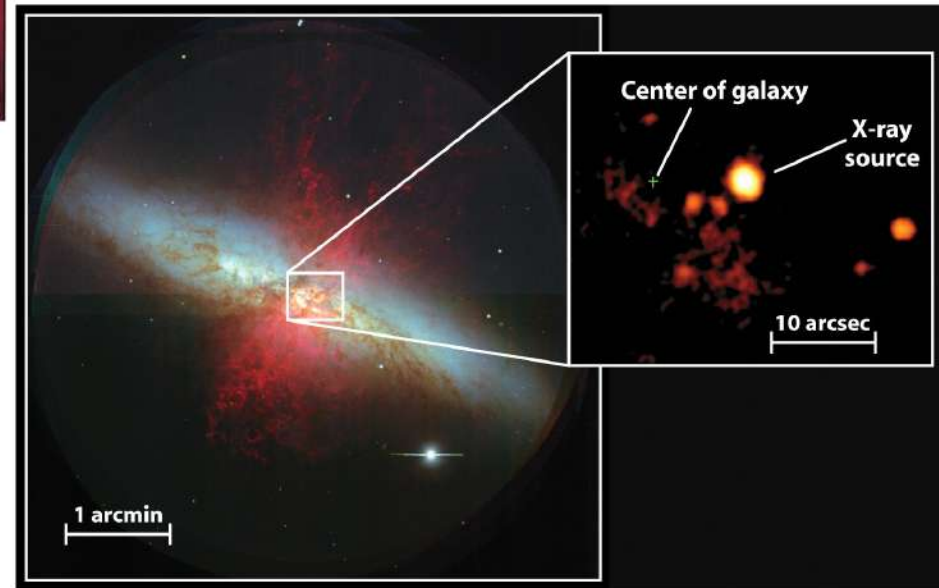
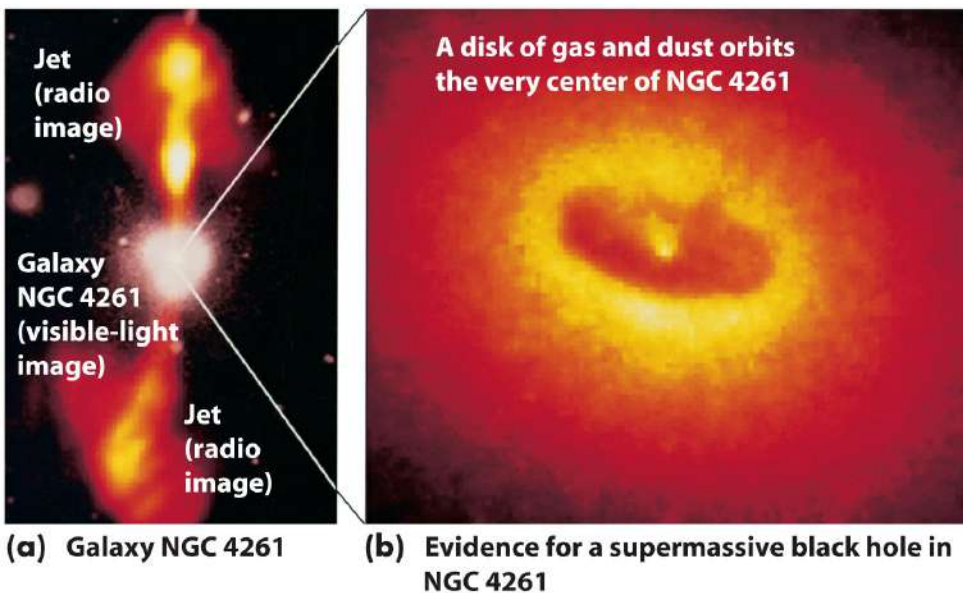
A schematic diagram of Cygnus X-1



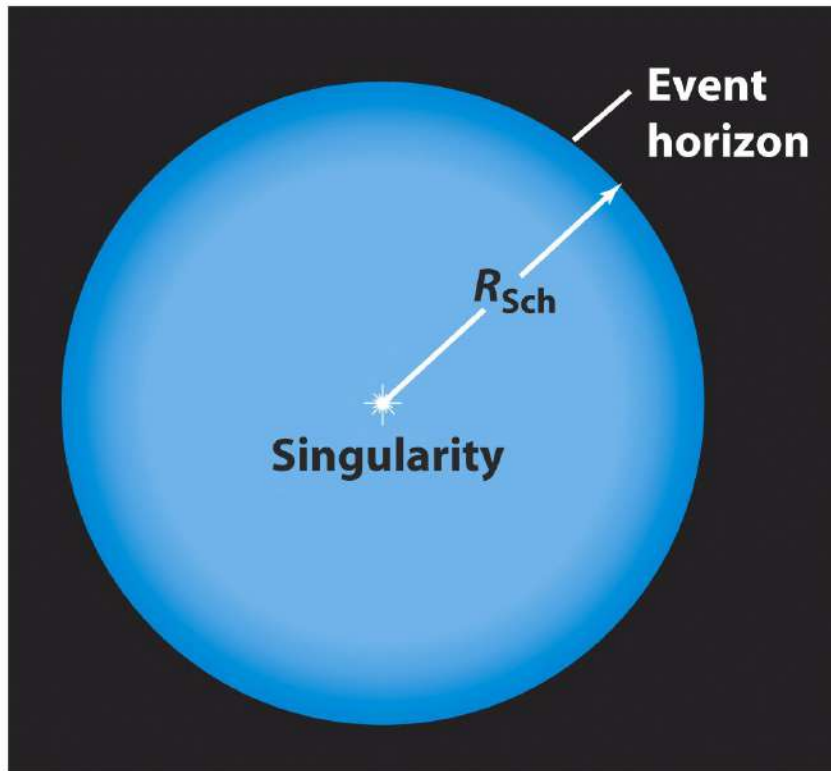
An artist's impression of Cygnus X-1

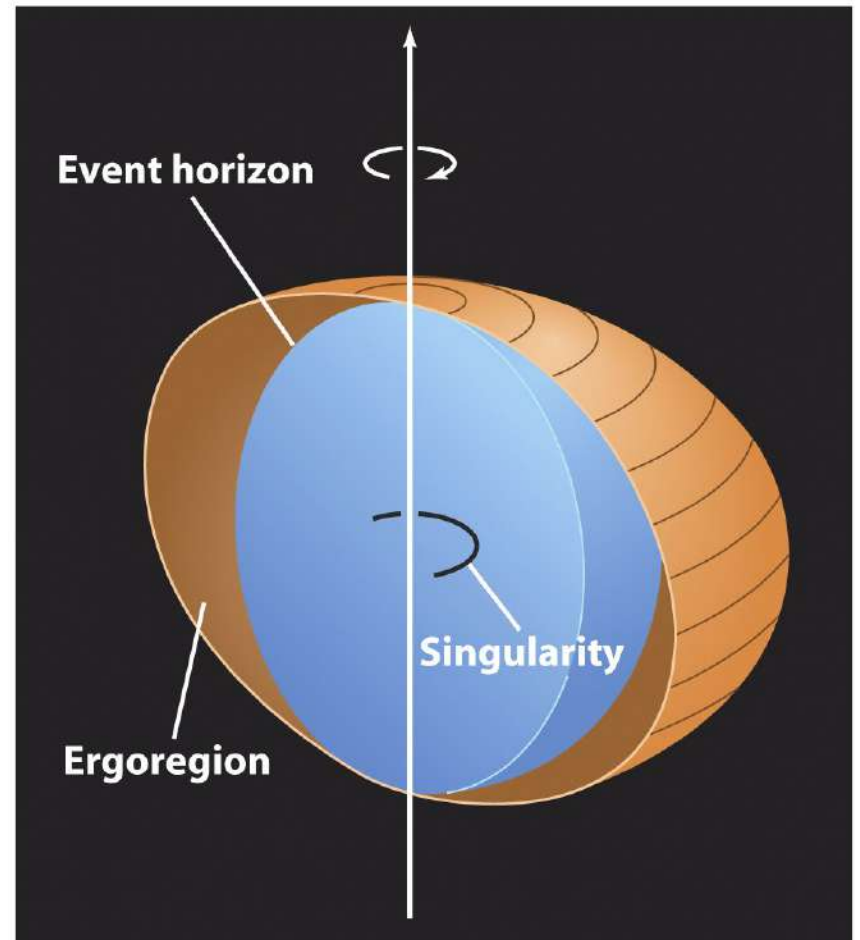


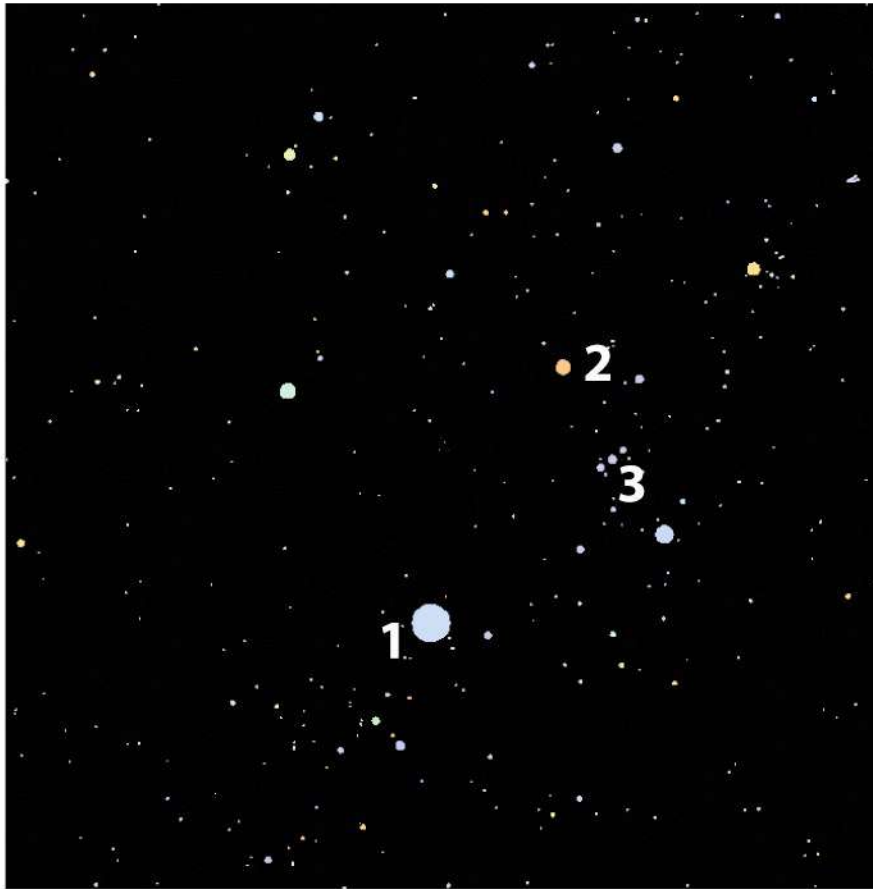
Supermassive black holes exist at the centers of most galaxies



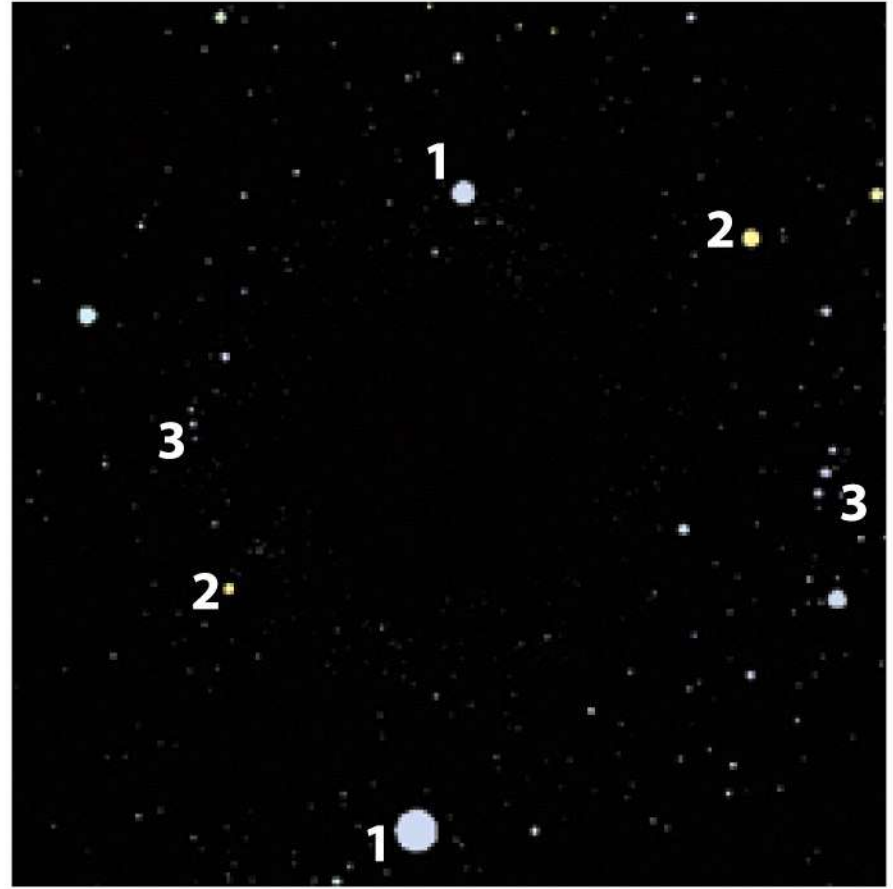
These are detected by observing the motions of material around the black hole







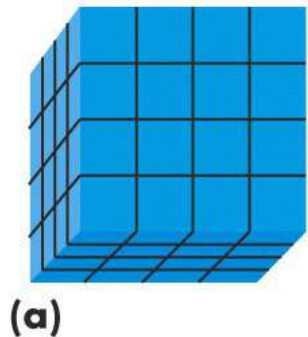
(a) Looking directly toward the black hole from a distance of 1000 Schwarzschild radii: Note positions of stars 1, 2, and 3.



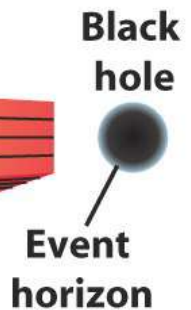
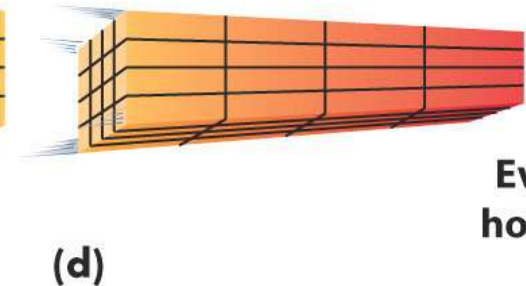
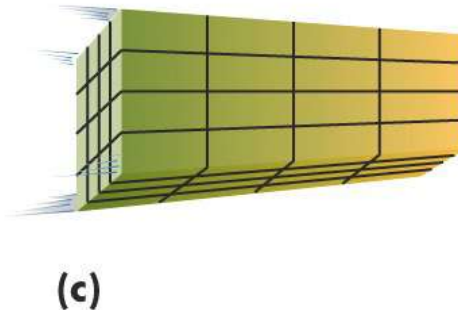
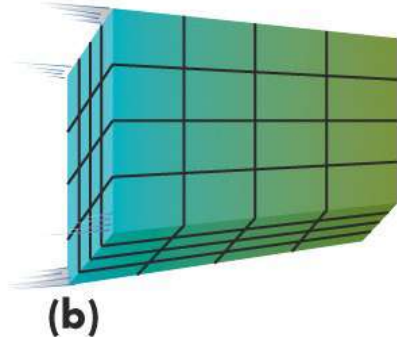
(b) Looking directly toward the black hole from a distance of 10 Schwarzschild radii: Light bending causes multiple images.

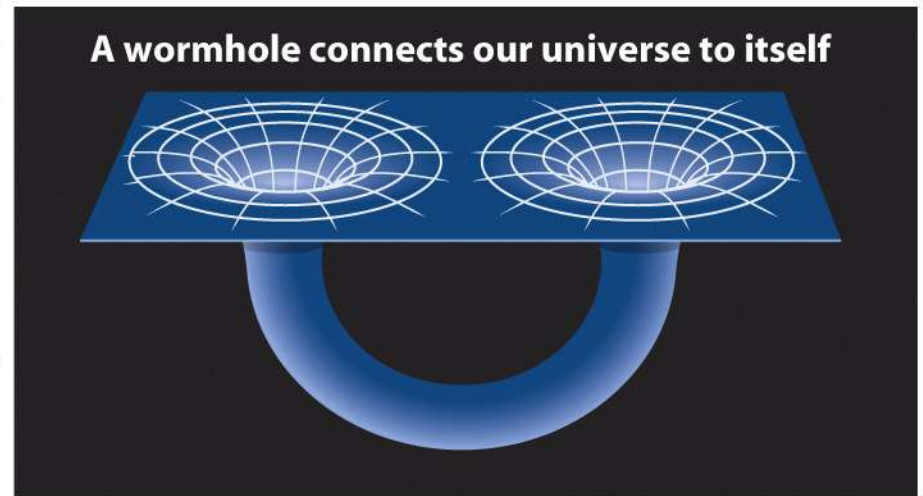
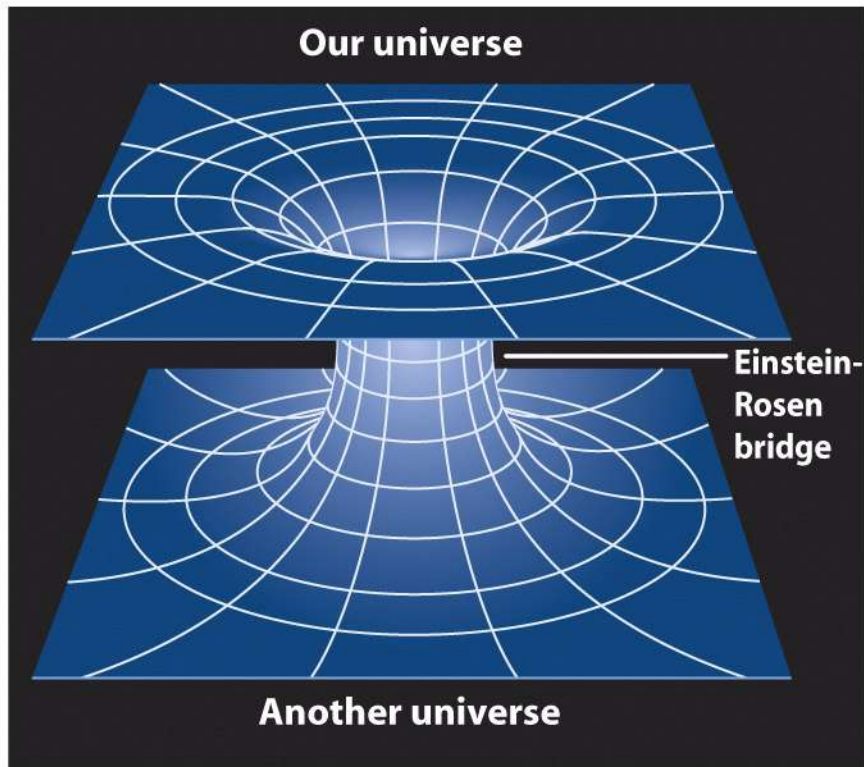
Falling into a black hole is an infinite voyage

Probe far from black hole



Probe approaching black hole



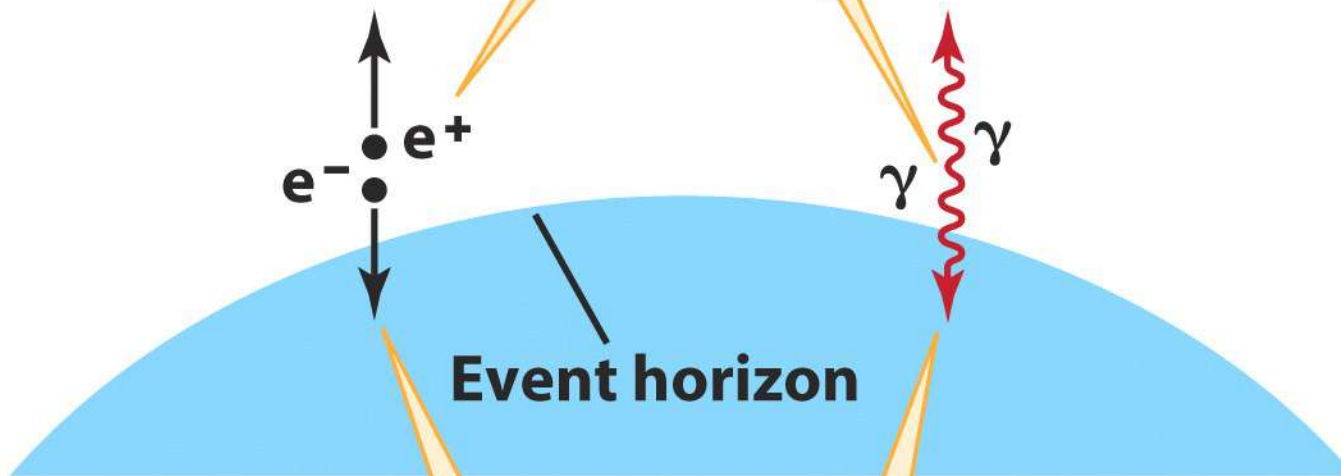


- Could a black hole somehow be connected to another part of spacetime, or even some other universe?
- General relativity predicts that such connections, called wormholes, can exist for rotating black holes

Black holes evaporate

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.

