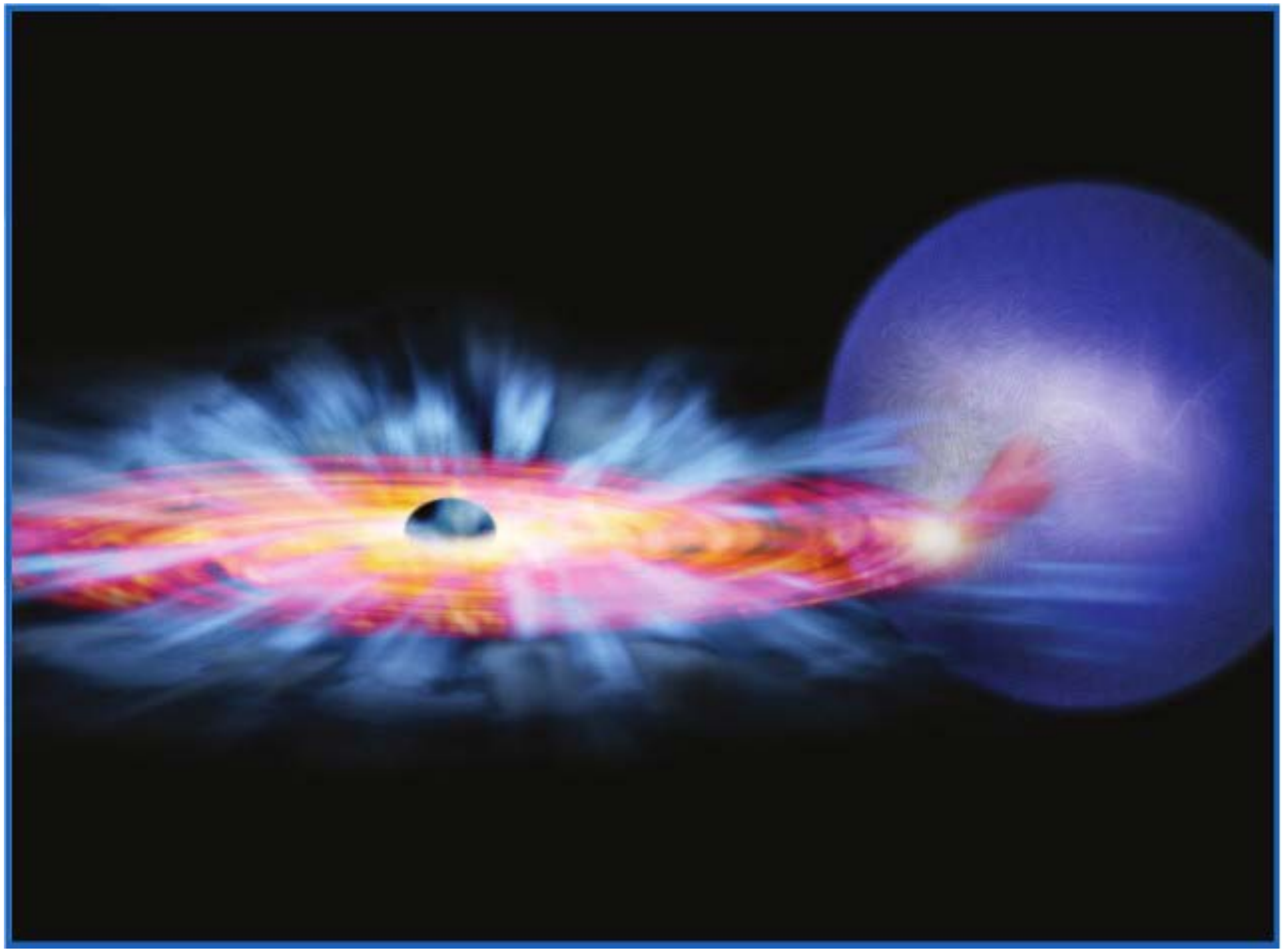
Black Holes



Syllabus and Schedule for ASTRO 210 (Black Holes)

The syllabus and schedule for this class are located at:

http://chartasg.people.cofc.edu/chartas/Teaching.html

Gravity is Universal

Gravity is everywhere. It is Universal.

Newton first described it as an **attractive force** between any objects with mass. His **theory of gravity** explained the orbits of the planets and it **allows us to determine the mass of objects** like planets, the Milky Way, the BH in the center of our Milky Way, and the mass of other distant galaxies.

Gravity is one of the four **fundamental forces** in the Universe. It is not that important at relatively small scales but it dominates at scales greater than the size of ~ planets.

Gravity is strongest near compact objects like white dwarfs, neutron stars and black holes.

Black Holes

During the final stages of a massive stars evolution the star runs out of fuel and is unable to support itself against gravity. The star collapses into a singularity and forms a **black hole**.

Einstein reluctantly predicted their existence and astronomers have indirectly confirmed their existence.

Black Holes (BH) capture the imagination of many people because of their strange and exotic properties.

Strange Properties of Black Holes

- BHs have masses ranging from a few times the mass of the sun ($M_{\odot}$) to several billion (10^9) times $M_{\odot}$. Current theories predict that this mass is concentrated in a **singularity**!

- **time dilation** (the slowing down of time) and the shifting of colors towards the red (**gravitational redshift**) is very significant near a black hole.

- **black holes spin and drag the space** around them. Could a future civilization find a way to extract energy from a spinning black hole?

- black holes consume material that comes within their gravitational attraction. This material is lost **forever**…

Topics Covered in this Course

- Einstein's theory of special and general relativity.

- Stellar Evolution and the fate of stars

- Detection of stellar mass black holes

- Accretion onto black holes

- Galaxies and their Nuclei

- Dark Matter and how to detect it.

- Quasars and Jets

Topics Covered in this Course

- Gamma Ray Bursts, The most powerful explosions in the Universe

- The black hole in the center of the Milky Way

- Gravitational waves

- Feedback between black holes and their environments

- Miniholes and the Hawking Effect

- Inside Black Holes (Singularities)

- Black holes in the laboratory?

Presentation for course

Every student will be expected to contribute to a **20-minute presentation** on a topic related to material covered in the course. You will work in groups of two to prepare and present the research talk.

The presentation may be in PowerPoint, Keynote, PDF or blackboard. It should include a **list of references** and each student should present a portion of the talk.

There will be several dates near the end of the semester allocated to these research presentations.

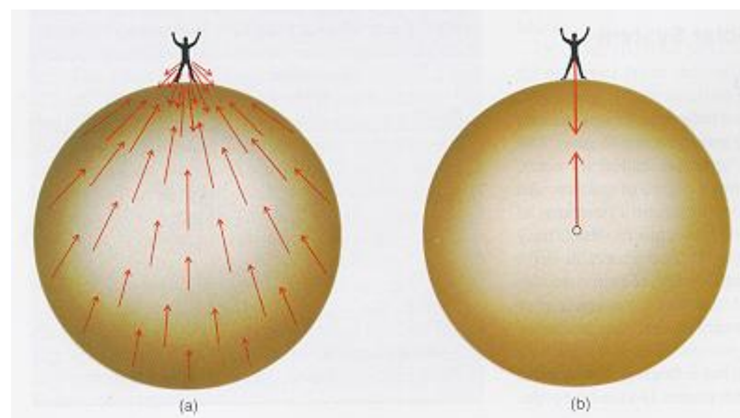
Newton's Law of Gravity

There is an attractive force between two bodies called **gravity**. The force of gravity depends on the masses of the two bodies, and their separation (squared); the larger the mass, the greater the attraction; the larger the separation, the smaller the attraction.

Isaac Newton

Note that the word "separation" means the distance between the *centers* of the two bodies.

$$F = G\frac{M_1 M_2}{r^2}$$



The Gravity Probe B EXPERIMENT

Gravity in Newton's Universe

Einstein's Gravity

Mass and energy tells space how to curve and curvature tells matter how to move.

Einstein's equations are a set of ten equations that describe the interaction of gravitation as a result of spacetime being curved by matter and energy.

Spacetime curvature is expressed by the symbol $G_{\mu\nu}$ called the **Einstein tensor**.

Energy and momentum are represented by the symbol $T_{\mu\nu}$ called the **energy stress-tensor**.

$$G_{\mu\nu} + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

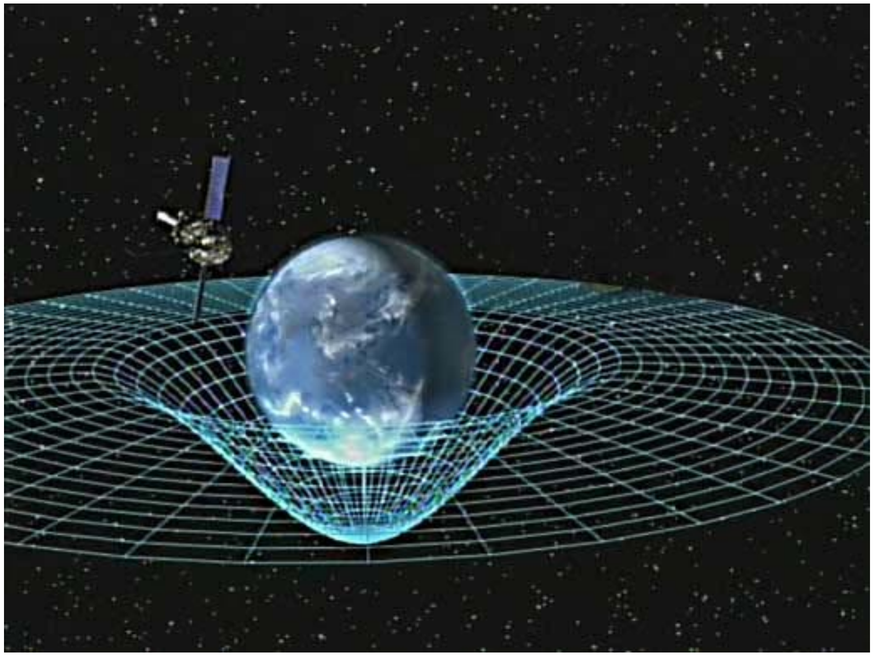
Curvature of spacetime

Mass and energy

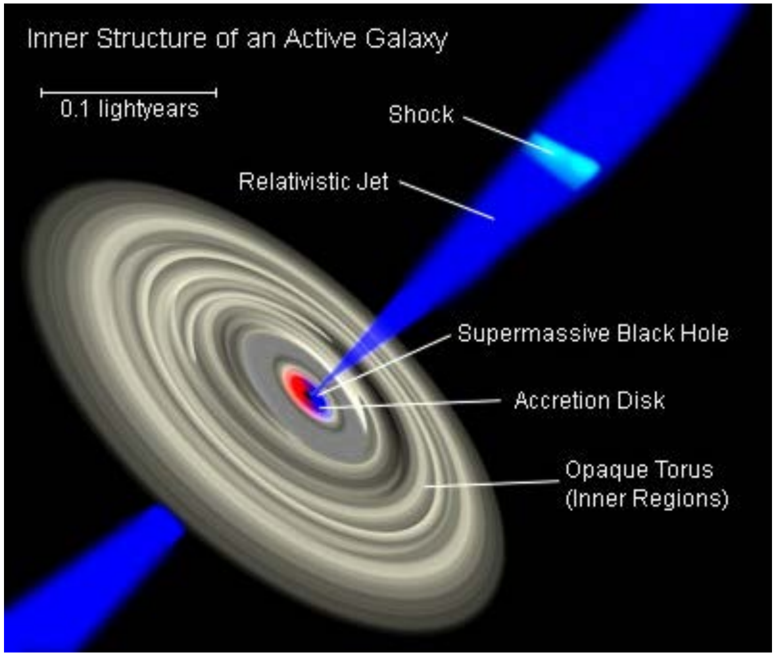
In 1915 Einstein published his equations of general relativity that describe gravity.

Dragging of Space

Albert Einstein's theory of general relativity predicts that rotating bodies drag spacetime around themselves in a phenomenon referred to as **frame-dragging**.



Recent experimental tests (ie. Gravity Probe B) have errors that are too large to convincingly test frame-dragging.

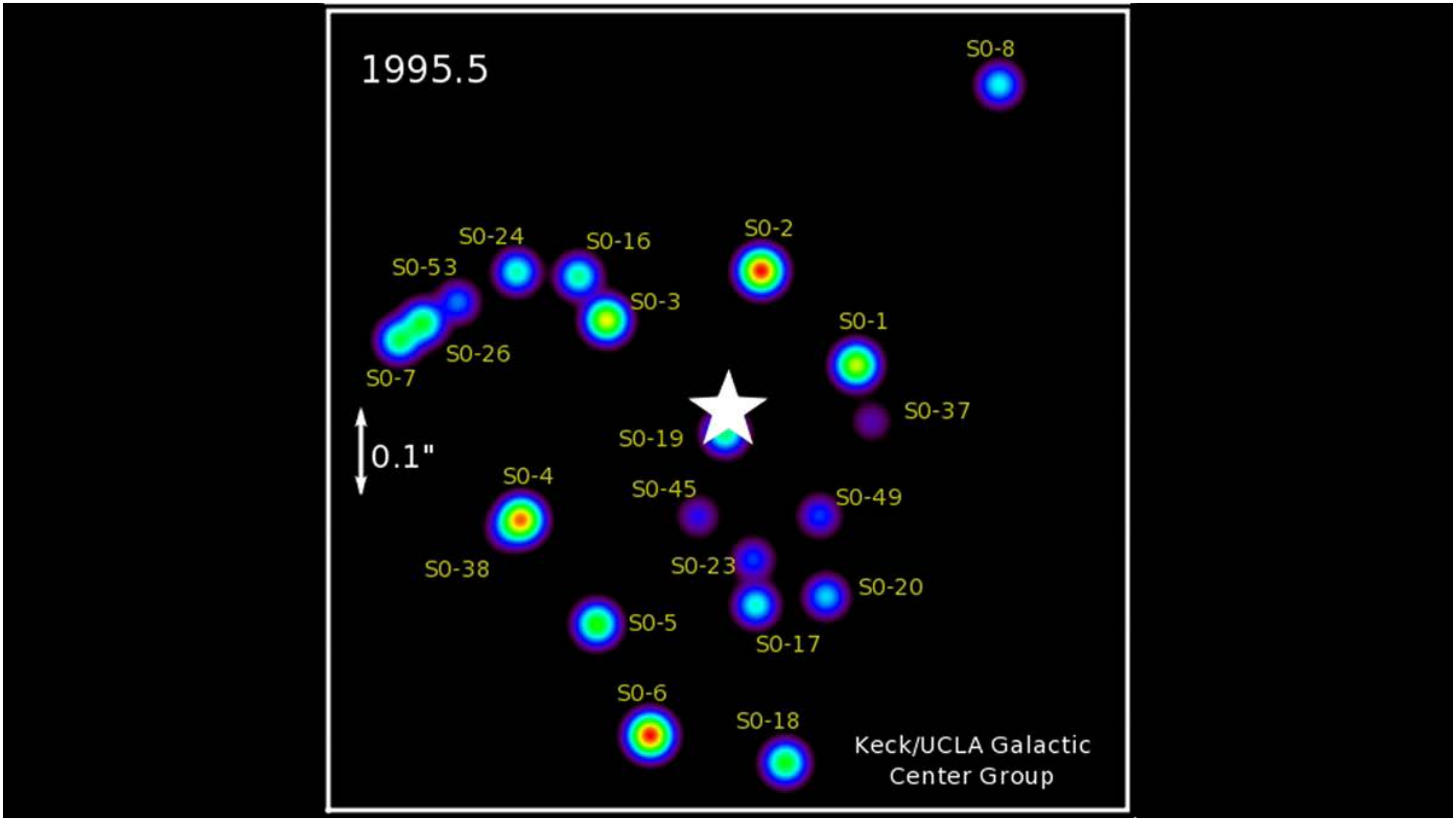


Relativistic jets may provide evidence for the reality of frame-dragging

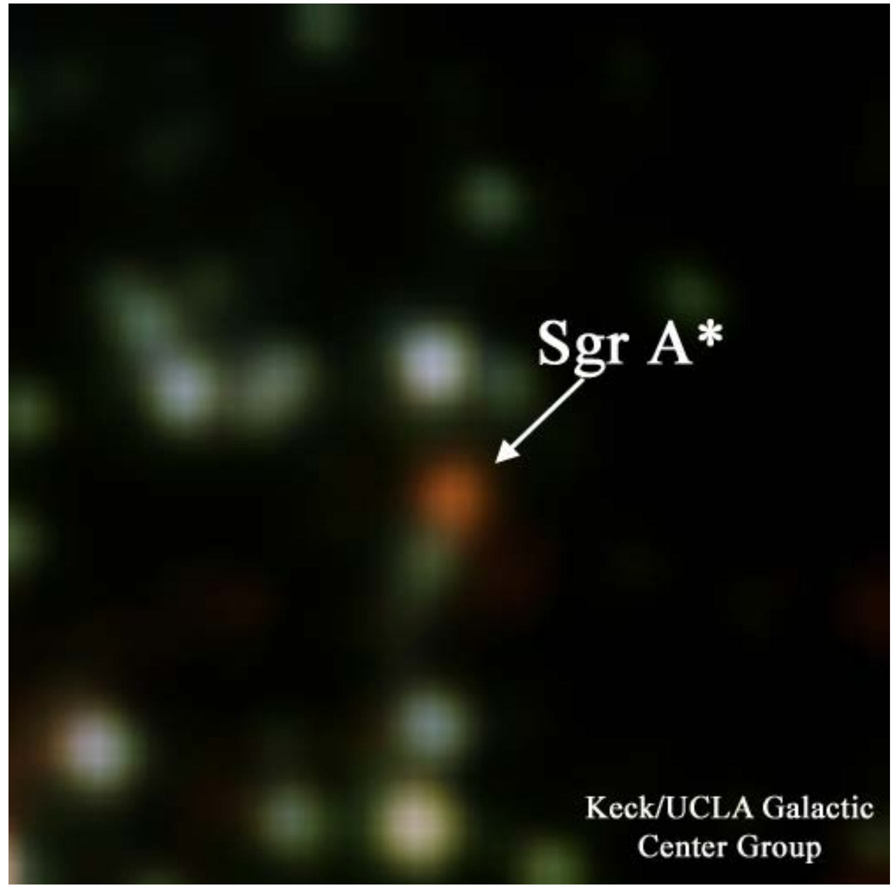
The Gravity Probe B EXPERIMENT

Measuring the Warping & Twisting of Spacetime with Gyroscopes

A supermassive black hole in our neighborhood



A supermassive black hole in our neighborhood

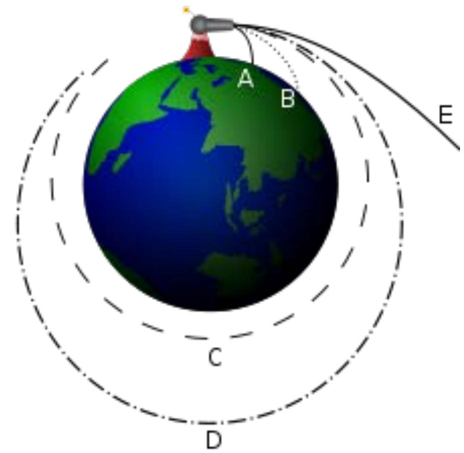


This three color animation, centered on Sgr A*-IR shows, the broadband color of Sgr A*-IR throughout an outburst. The image is 1 arcsec on a side and covers about two hours of observations. H (1.8 microns) = blue, K' (2.1 microns) = green, and L' (3.8 microns) = red. Data obtained at the W. M. Keck Observatory.

Escape Speed

An object on any planet or massive body has to have a speed larger than a certain value to escape the gravitation pull of that massive body.

For a body to escape the gravitational pull of the Earth and escape into space it has to have a speed greater than the **escape speed**. On Earth it is about 40,000 km/h = 11.2 km/s ~ 25,000 mph.

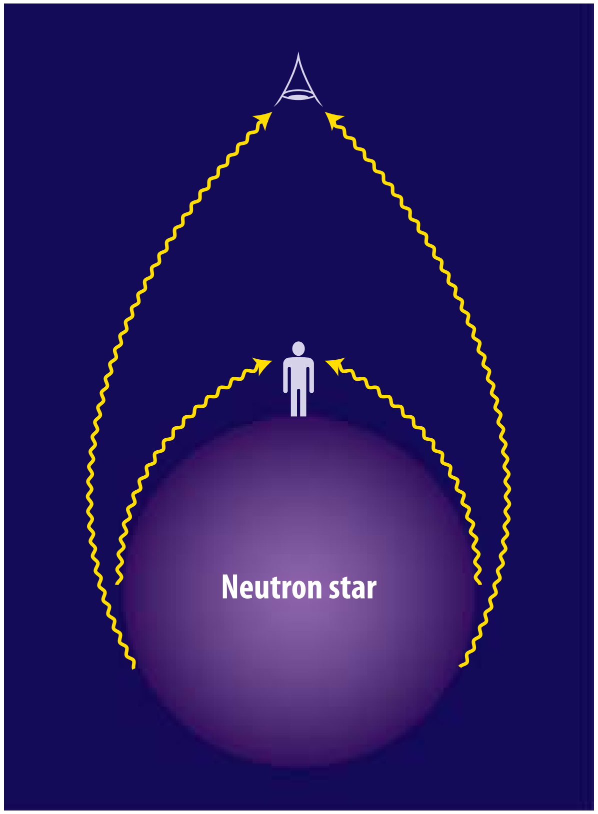


Luna 1, launched in 1959, was the first man-made object to achieve escape velocity from the Earth.

Bending of Light

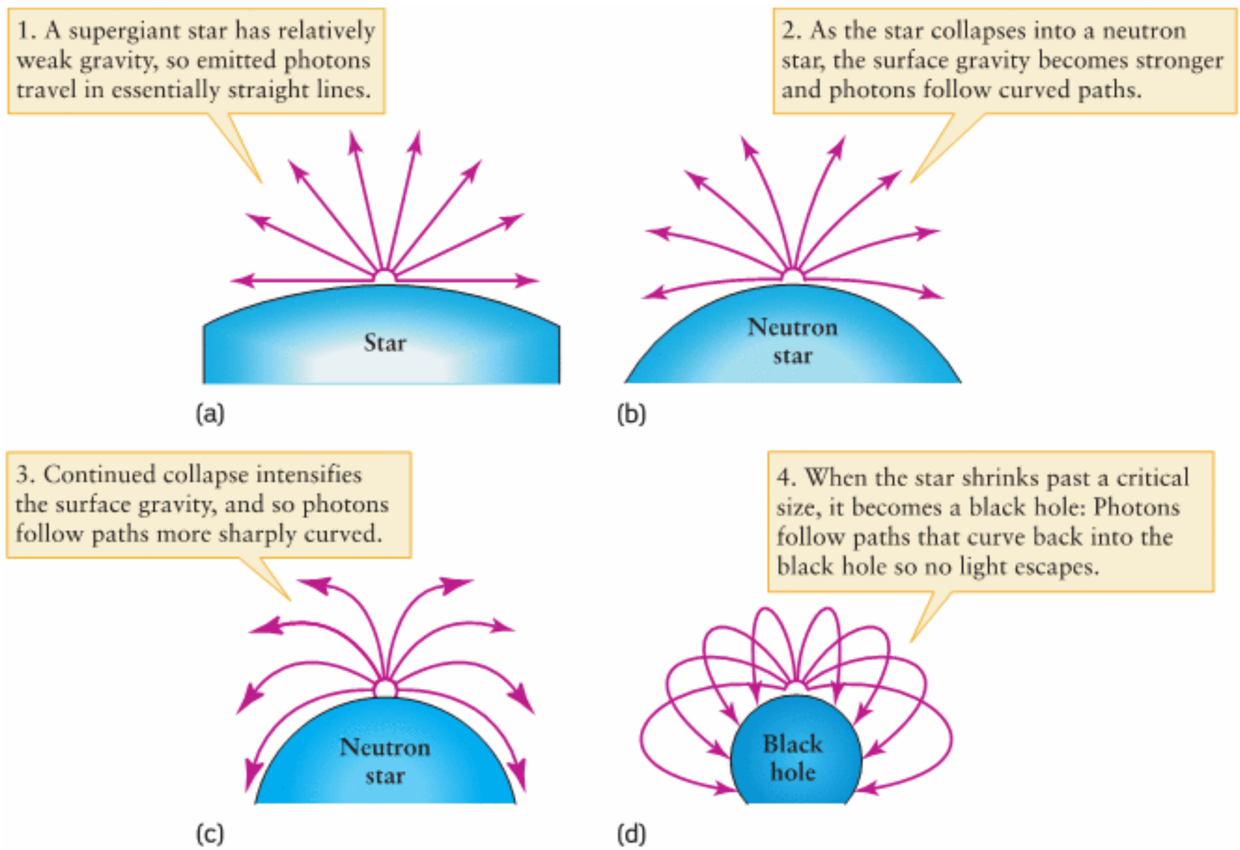
One way of characterizing the strength of an objects gravity is by the speed needed to escape from the objects surface.

For a **neutron star** that is slightly heavier than the Sun but with a radius of about 10 - 20 km one needs a speed of about half the speed of light to escape.



The severe bending of light by gravity means that an observer on the surface of a neutron star can see farther to the horizon. An observer high above the star can see more than half the surface.

Einstein's General Relativity Predicts Black Holes



When a star becomes a black hole, not even photons emitted directly upward from the surface can escape; they undergo an infinite gravitational redshift and disappear.

Comparison Between Newton's and Einstein's Theories of Gravity

Newton's Law states that the force between 2 bodies of mass is **instantaneous**.

Einstein's theory states that matter curves space around it. Particles follow the straightest possible path in curved space-time. Gravitational waves travel at the speed of light.

Observations that confirmed Einstein's theory:
-GR used to explain the orbit of Mercury
-GR used to explain the *deflection of light* during a solar eclipse.

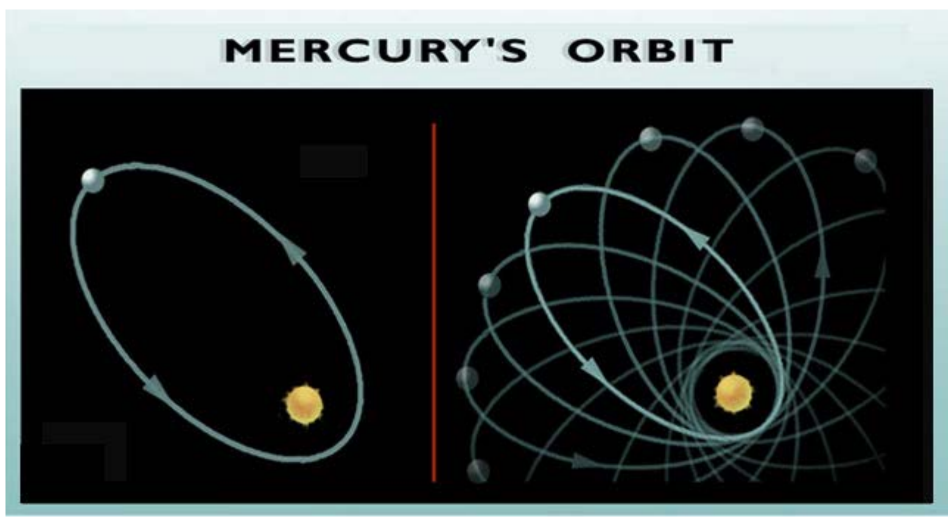
The strength of a gravitational field can be characterized by the ratio of the escape speed to the speed of light.
For $(v_{escape}/c)^2 << 1$ Newtonian physics works ok.
For $(v_{escape}/c)^2 \sim 1$ one needs to use Einstein's general relativity.

Testing the General Theory of Relativity

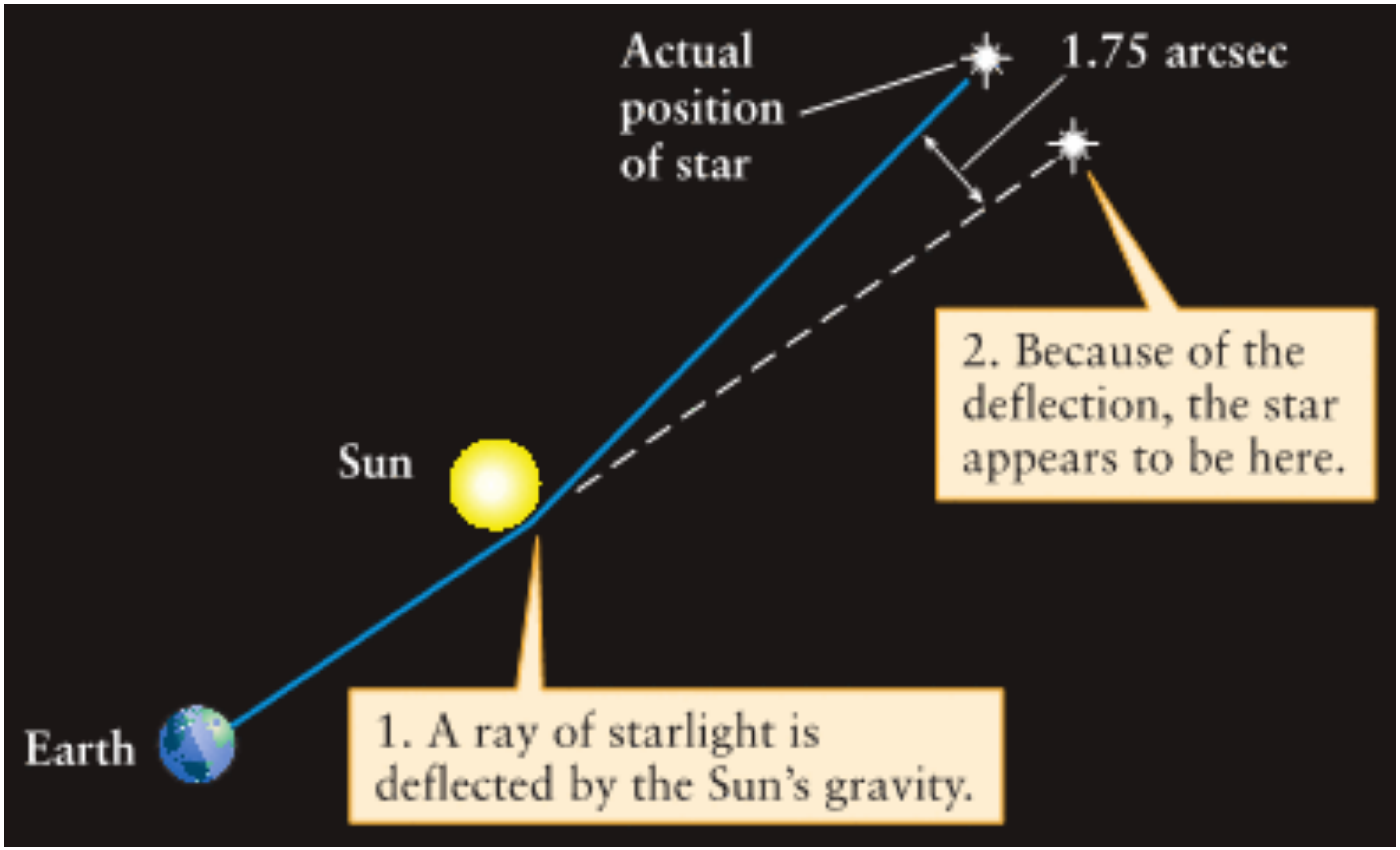
Newton's law of gravity predicts that the **orbits of planets** around the Sun **are closed ellipses**.

Einstein's theory predicts that the orbits are not closed and that the major axis of the ellipse should gradually rotate.

This small rotational effect (precession of perihelion) has been detected in Mercury's orbit.



Testing the General Theory of Relativity



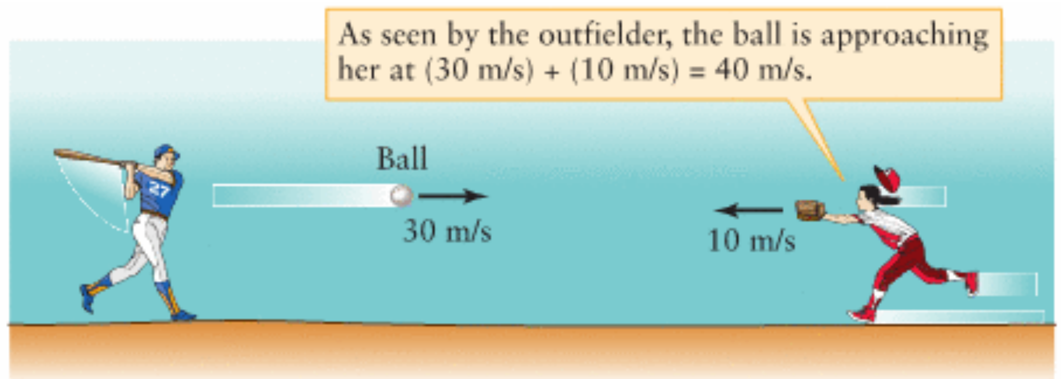
Special Relativity

Principles of Special Relativity:
1. The laws of physics are the same for all inertial observers.

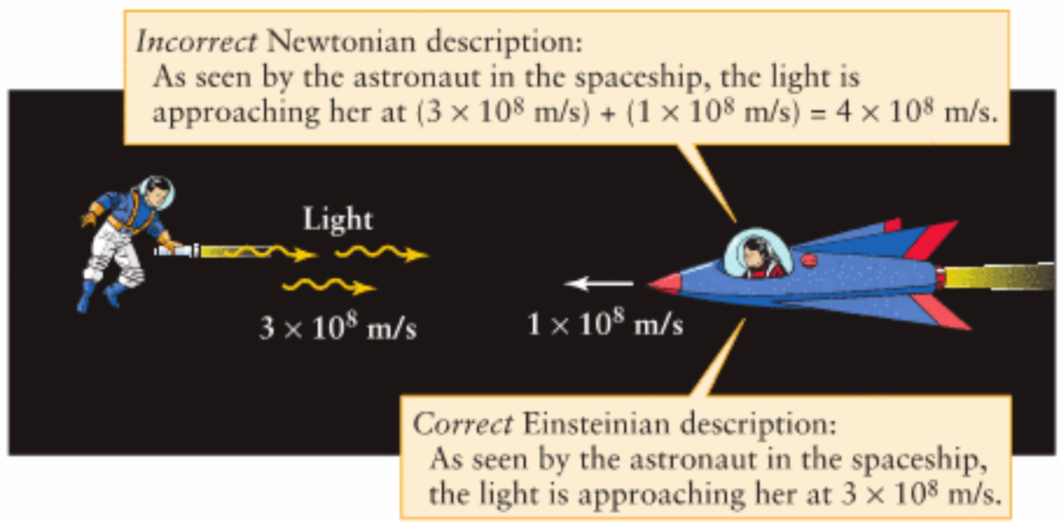
2. The speed of light is the same for all **inertial** observers regardless of the state of motion of the source.

An **inertial observer** is one that is not accelerating.

Special Relativity



(a)



(b)

Special Relativity

The length you measure an object to have depends on how that object is moving; the faster it moves, the shorter its length along its direction of motion. This phenomenon is called **length contraction.**

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

L = observed length of object along direction of motion

L_0 = length of object at rest (proper length)

v = speed of object with respect to observer

c = speed of light

Special Relativity

A clock runs slower when observed by someone moving relative to the clock than someone not moving relative to the clock. This phenomenon is called **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

v = speed of phenomenon relative to observer

c = speed of light

Special Relativity

Special relativity also predicts the famous relationship:

$$E = mc^2$$

In fusion reactions mass is converted to energy and this released energy is what powers the stars.

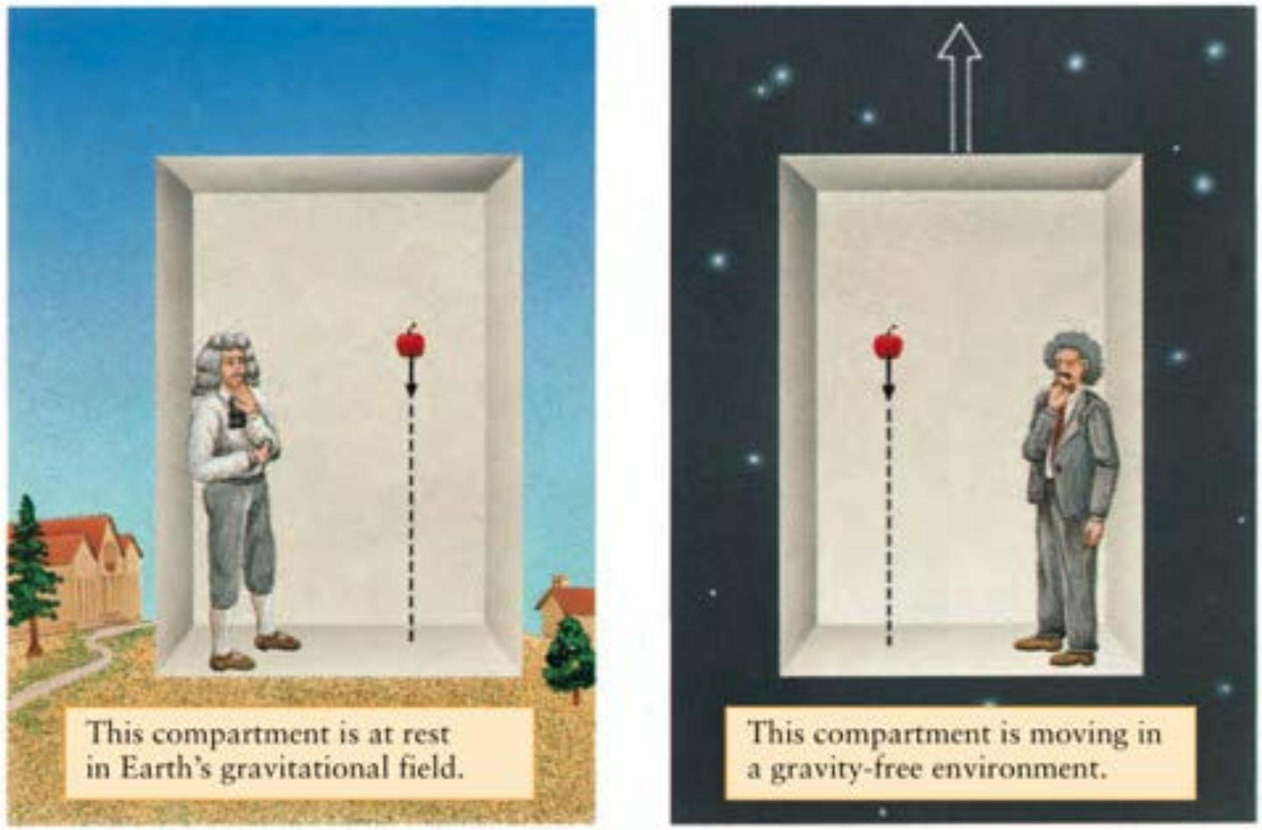
General Theory of Relativity

The **equivalence principle** asserts that you cannot distinguish between :

(a) being at rest in a gravitational field and

(b) being accelerated upward in a gravity-free environment.
This idea was an important step in Einstein's quest to develop the general theory of relativity.

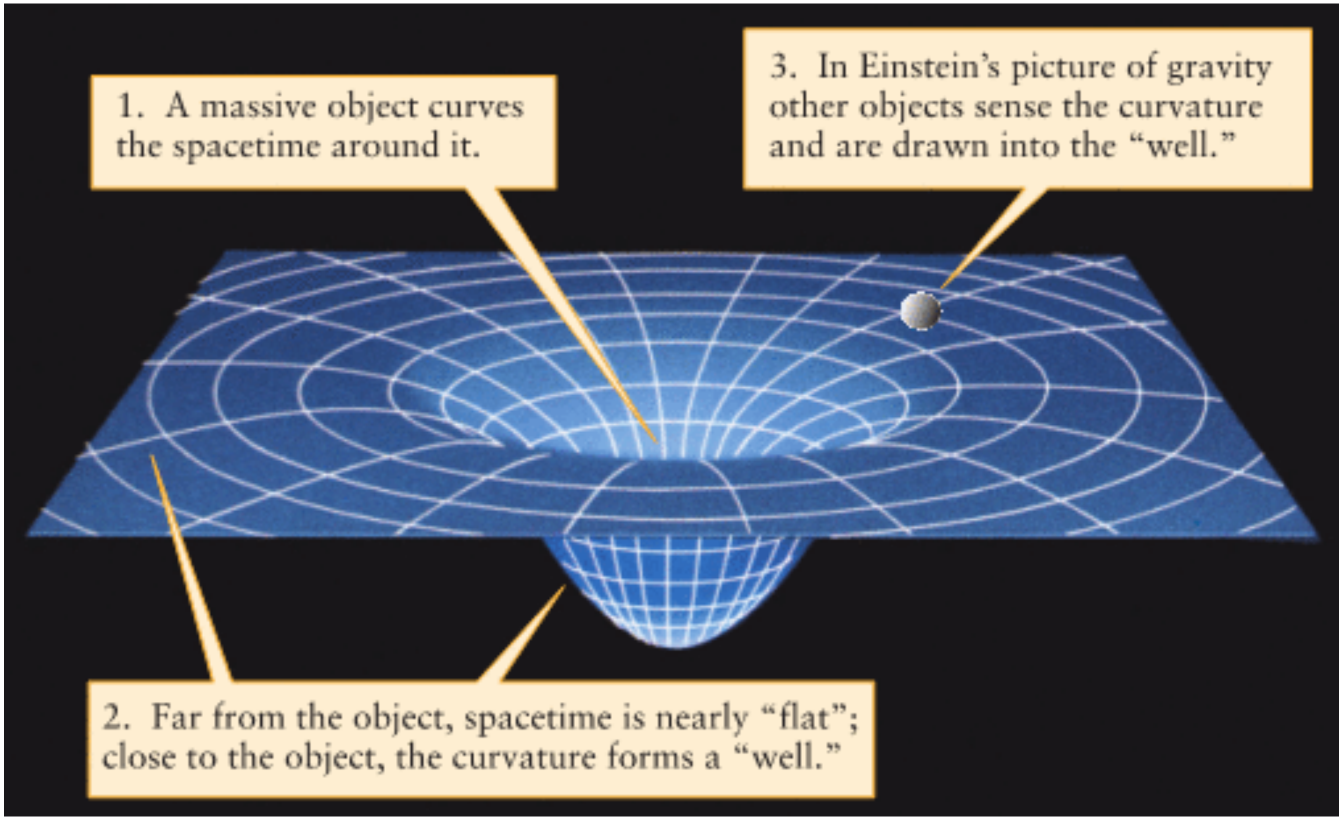
General Theory of Relativity



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

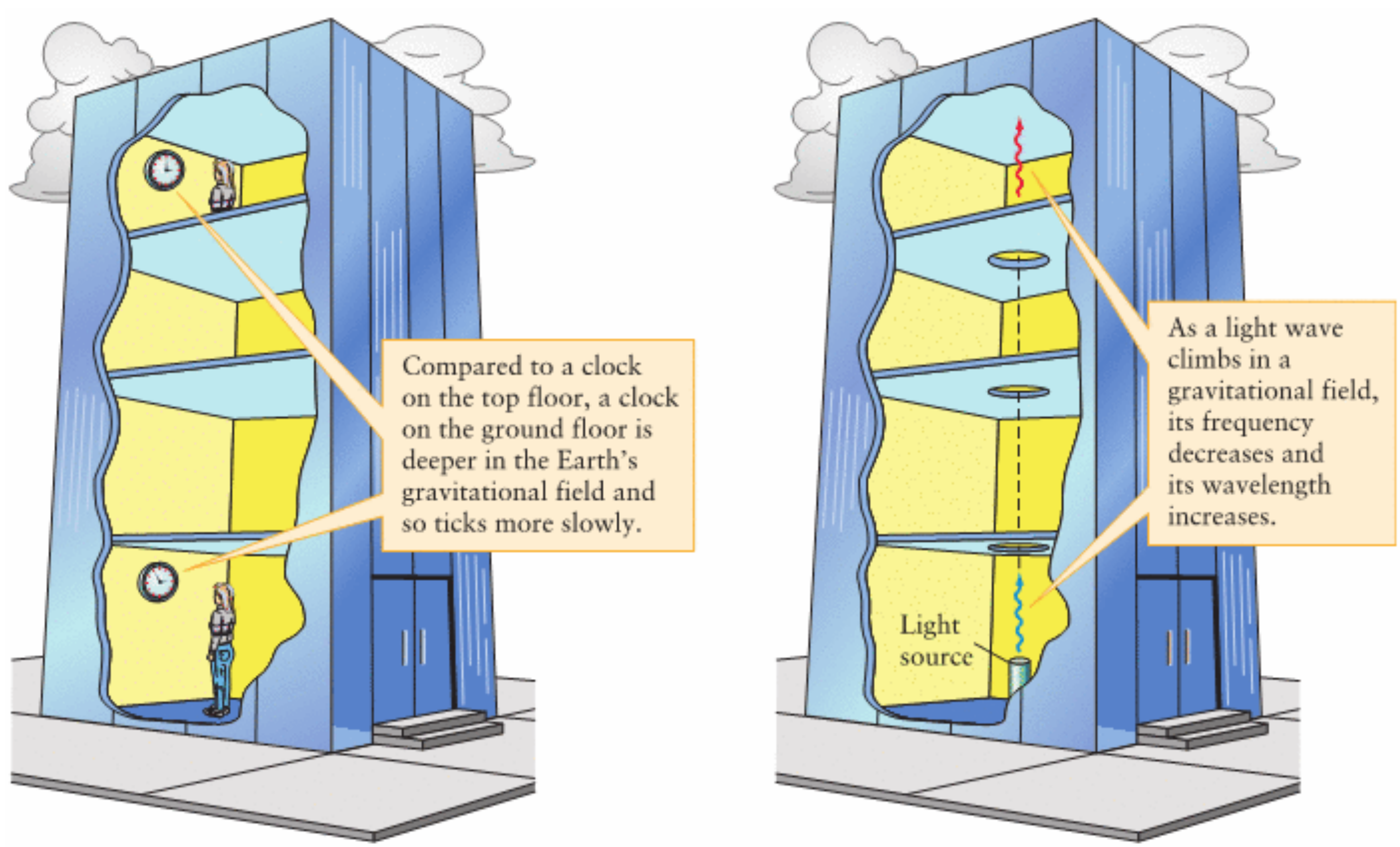
(b) The apple hits the floor of the compartment because the compartment accelerates upward.

General Theory of Relativity



Einstein envisioned gravity as being caused by curvature of space. Above is a two dimensional analogy to help understand the curvature of four-dimensional spacetime.

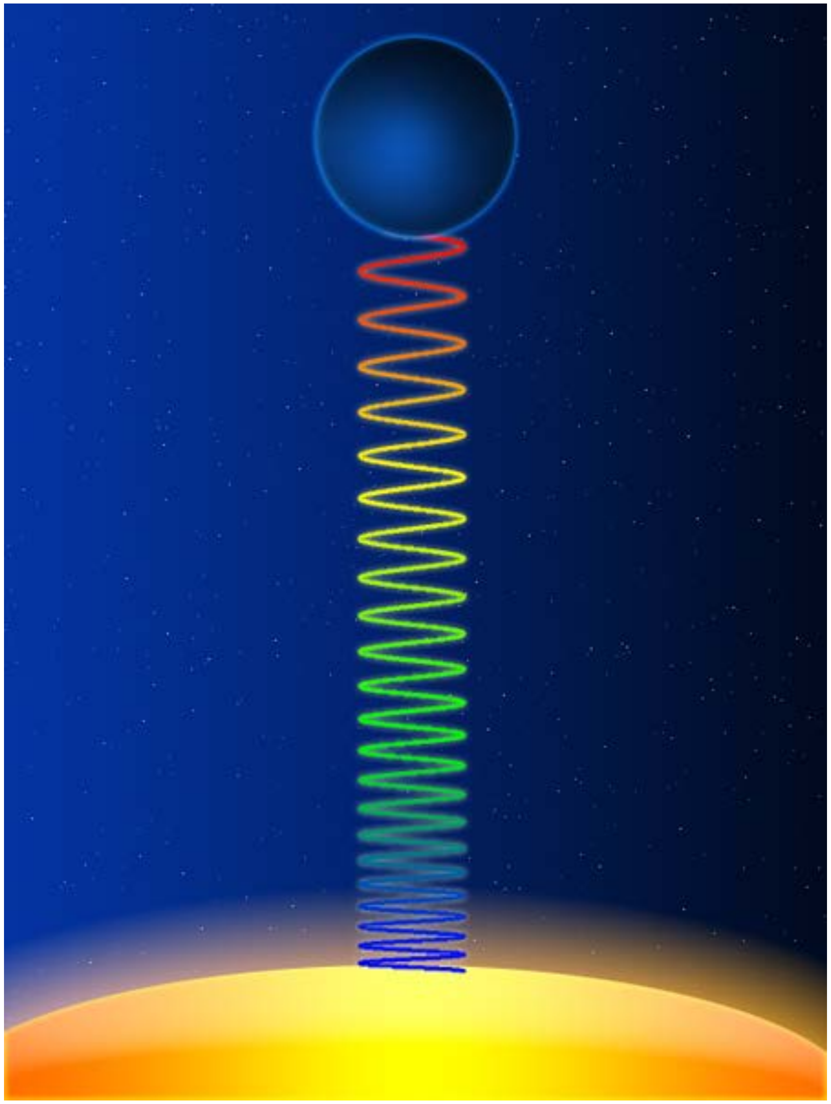
Gravitational Slowing of Time and Gravitational Redshift



(a) The gravitational slowing of time

(b) The gravitational redshift

Gravitational Redshift

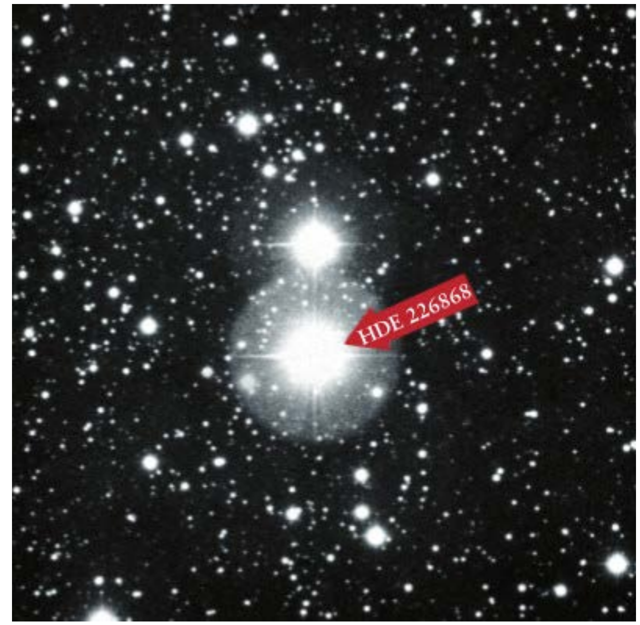


Black Hole Candidates

Cygnus X-1 is thought to be a black hole in a binary system with a companion supergiant B0 star. The X-ray emission of Cygnus X-1 changes significantly within 0.01 sec. This places a limit on the size of the object.

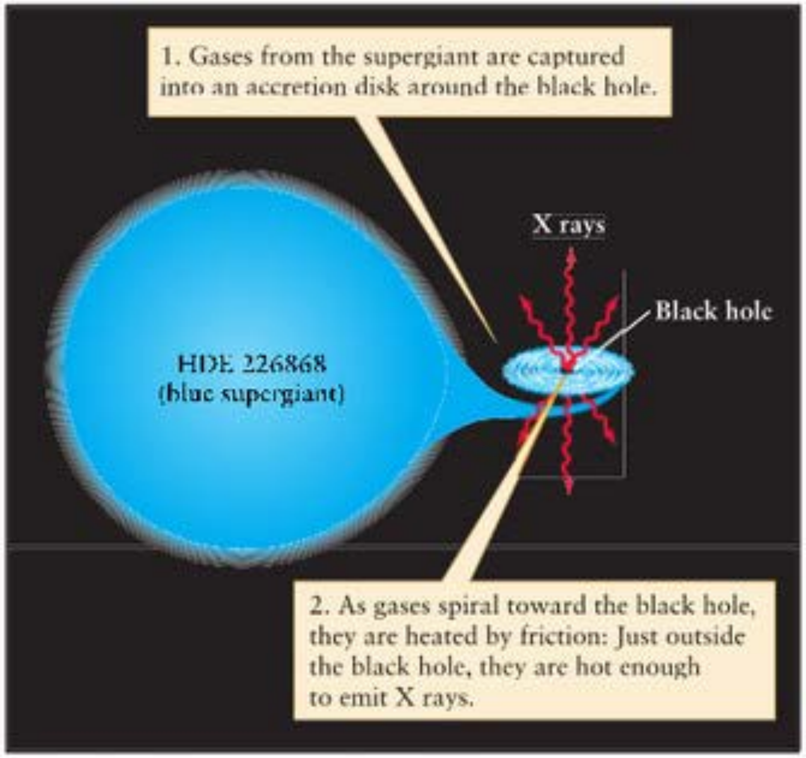
The shortest variation time in the flux of an object of size D is the time that light takes to travel across the object (t_{lc}).

$t_{variation} > t_{lc} = D/c \rightarrow D < ct_{variation} \rightarrow$
$\rightarrow D < 3\times10^5$ km/sec $\times$ 0.01 sec
$\rightarrow D < 3{,}000$ km



HDE 226868 is a B0 star with an estimated mass of 30 $M_\odot$ and the other object in the binary is estimated to have a mass of ~ $7M_\odot$ implying that it is a black hole.

Black Holes



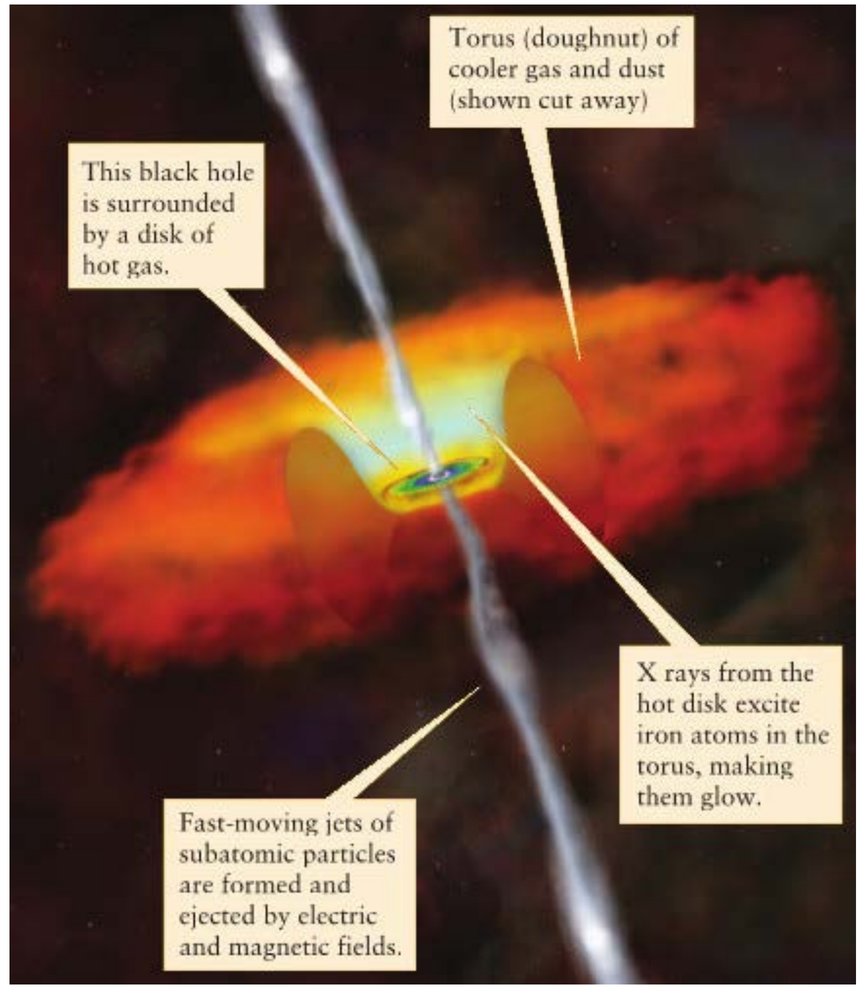
(a) A schematic diagram of Cygnus X-1

(b) An artist's impression of Cygnus X-1

Jets from Stellar Mass Black Holes

Jets of charged particles moving at near the speed of light are observed in stellar mass black hole systems.

It is thought that magnetic fields collimate material from the accretion disc into these narrow beams.



Supermassive Black Holes

Astronomers have discovered black holes with masses ranging from 10^6 to 10^{10} $M_\odot$ in the centers of most galaxies. It is not clear how **supermassive black holes** (SMBH) form and how they grow so large so early.

SMBH's are usually detected from radio, optical, UV and X-ray emission originating from material surrounding the black hole.

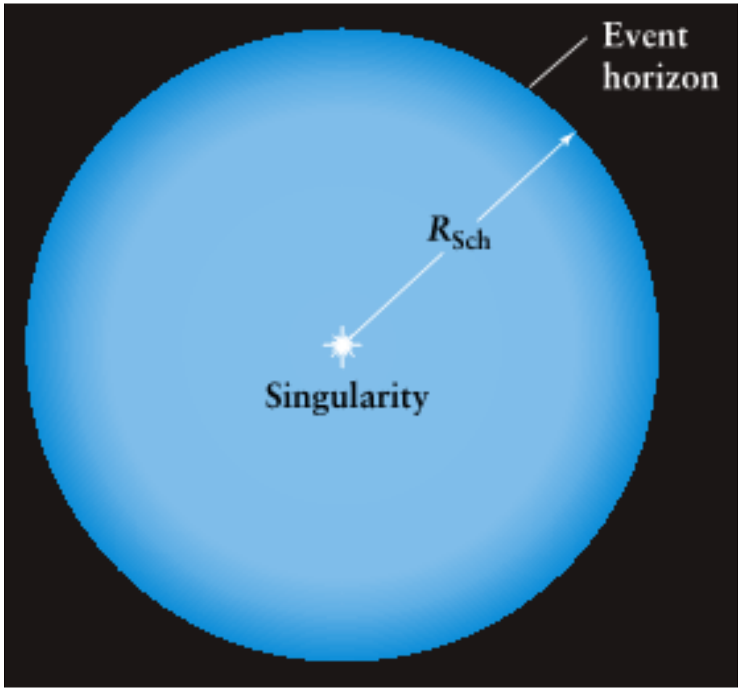
Another way of detecting SMBH's is from their gravitational influence on material in their near vicinity.

Non Rotating Black Holes

The **event horizon** of a BH is a sphere surrounding it where the escape speed is equal to the speed of light. Anything that crosses the event horizon cannot escape and exit the black hole.

For a non-rotating BH the distance from the center to the event horizon is called the **Schwarzschild radius.**

The star's entire mass is crushed to a single point, known as the singularity, at the center of the black hole.



$$R_{Sch} = \frac{2GM_{BH}}{c^2}$$

R_{Sch} = Schwarzschild radius

$G = 6.67 \times 10^{-11}$ N m^2/kg^2

c = 3×10^8 m/s

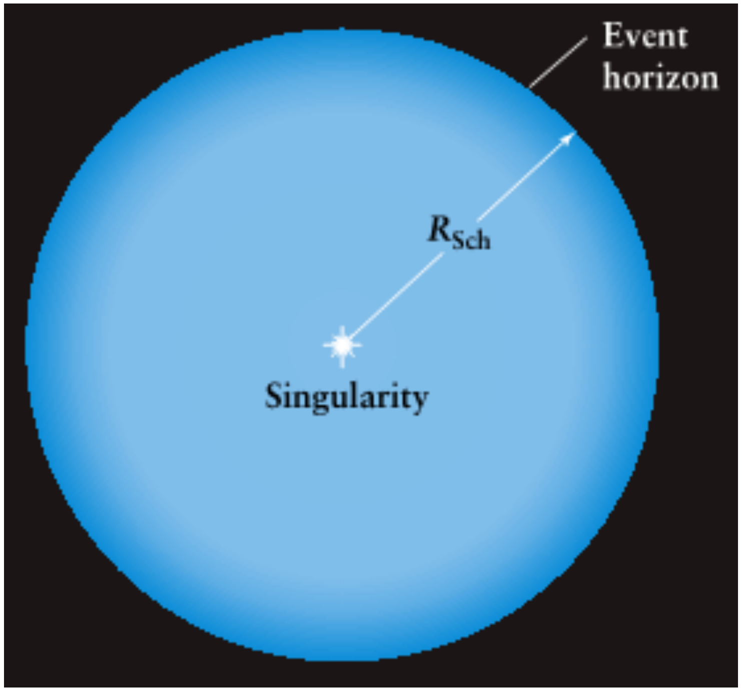
M_{BH} = mass of black hole

Non Rotating Black Holes

Example: What is the Schwarzschild radius of a mass of $M_\odot \sim 2 \times 10^{30}$ kg ?

The Schwarzschild radius is directly proportional to the mass of the black hole.

Without using a calculator estimate the Schwarzschild radius of a billion solar mass black hole.



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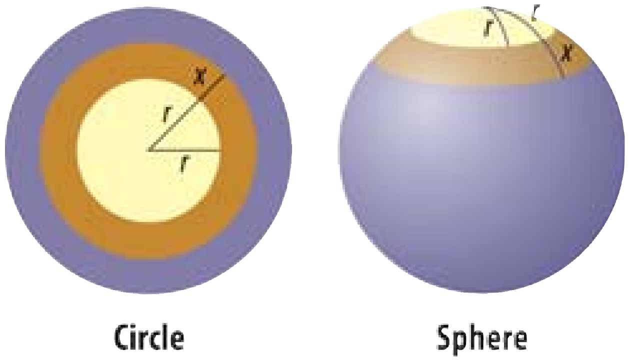
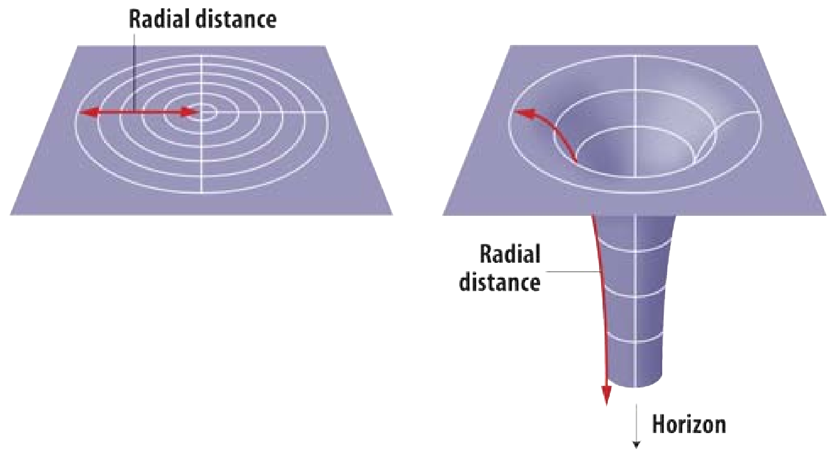
Curvature of Space





How to test if you live on a curved surface:
Concentric circles drawn on a plane differ in circumference by $2\pi x$. Concentric circles drawn on the curved surface of sphere differ in circumference by an amount smaller than $2\pi x$.

Schwarzschild's equations predict the circumference of a circle around a point mass as a function of the radial distance from the point mass.
Something remarkable happens when you get close to the point mass:
When the radius reaches 3 M km, where M is the mass of the object in solar masses the circumference reaches a constant value. To a distant observer an object falling towards the point mass will never appear to get any closer than 3M km.

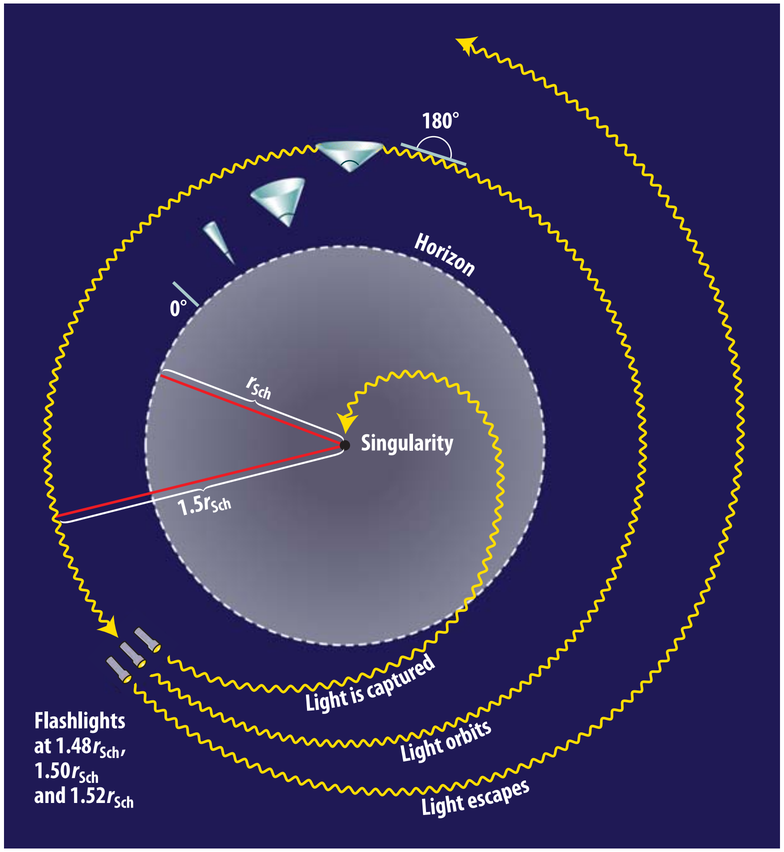
Non Rotating Black Holes

Trajectories of light rays become curved close to a black hole.

At 1.5 R_{sch} radii a carefully aimed light ray can orbit the hole indefinitely.

At the horizon the escape cone closes up.

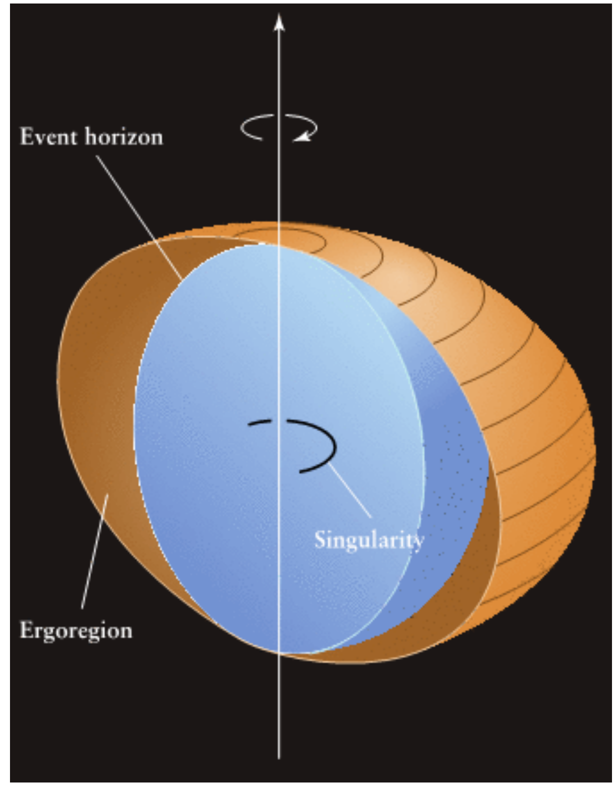
Radiation from just outside the event horizon would reach a distant observer with a larger shift in wavelength, and a clock near the hole would appear to run slow.



Rotating Black Holes

When the matter that collapses to form a black hole is rotating, that matter does not compress to a point. Instead, it collapses into a ring-shaped singularity located between the center of the hole and the event horizon.

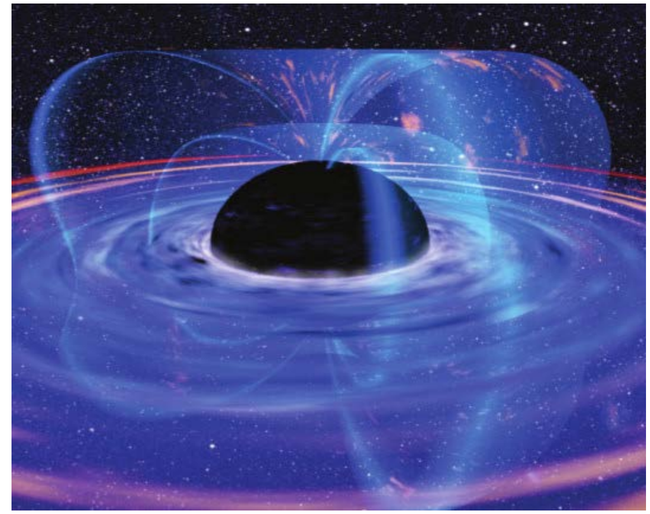
The structure of such rotating black holes was first worked out in 1963 by the New Zealand mathematician Roy Kerr.



Outside the spherical event horizon is the doughnut-shaped ergoregion, where the dragging of spacetime around the hole is so severe that nothing can remain at rest.

Properties of Black Holes

1. Mass: One can estimate the mass of a BH by measuring the size and period of an object that orbits the BH and using Newton's form of Kepler's third law.



An artist's impression of the accretion disk around the supermassive BH at the heart of the galaxy MCG–6-15-30. The arching magnetic field allows the accretion disk to extract energy and angular momentum from the black hole.

2. Electric Charge: BH's are expected to have some electric charge.

3. Angular Momentum: Conservation of angular momentum implies that when a rotating star collapses to form a BH the resulting BH will be spinning much faster since the material is crushed to a much smaller radius.

Falling Into a Black Hole

Imagine sending a probe into a black hole equipped with a camera to send you images of what its sees.

-As the probe approaches the BH the severe bending of light will make stars that are almost behind the BH form multiple images and stars exactly behind form rings.

-The probe itself will initially appear to be speeding up but as it approaches the BH time dilation will make it appear moving slower and **eventually will appear not to be moving.**

-The color of the probe will appear to increase in wavelength due to gravitational redshift.

-As the probe gets closer the strong tidal forces stretch the probe along the line pointing towards the center and also make it squeezed together along the perpendicular direction.

Falling Into a Black Hole

Any explorer travelling with the probe will have a different experience from a distant observer.

Explorers will notice nothing unusual as they travelled through the horizon. They would however realize that no matter how hard they fired their engines they could no get out of the horizon.

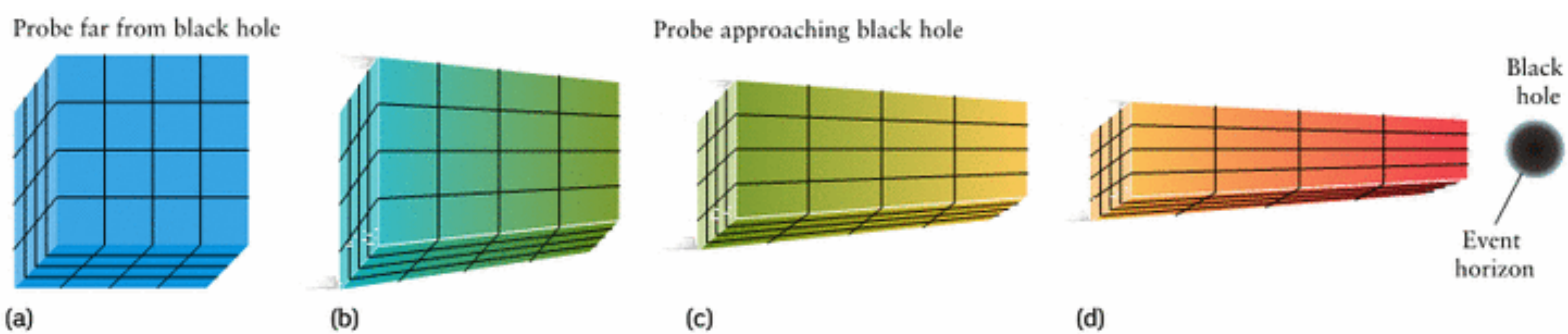
As the explorers are drawn towards the singularity they are stretched ("**spagettified**") due to tidal forces.

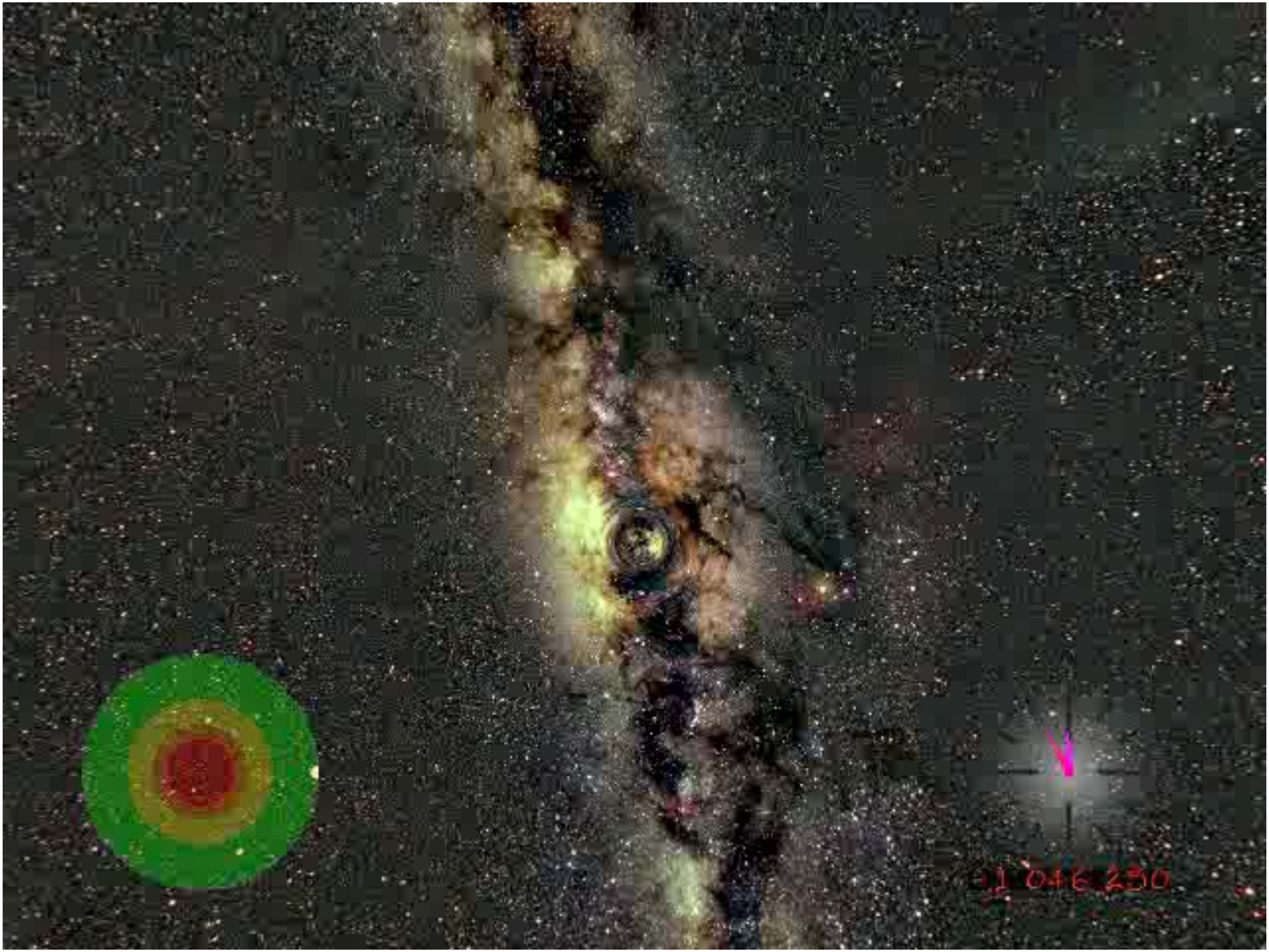
A distant observer would not see the explorers crossing the horizon since they see the explorers time freeze at the horizon.

Black Holes

(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.

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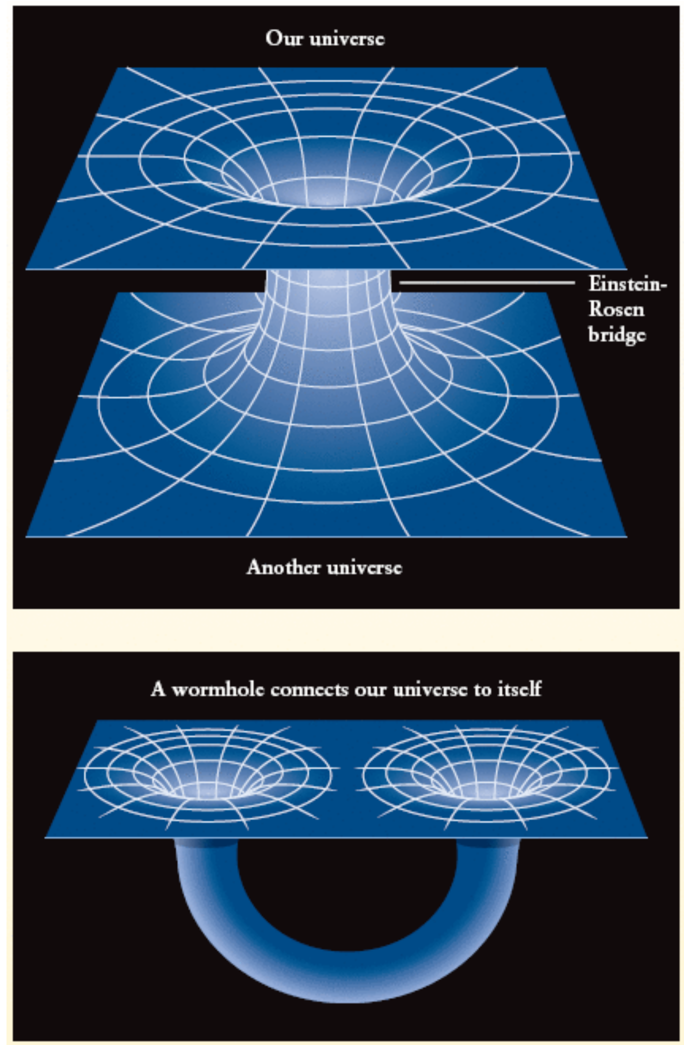
Black Holes



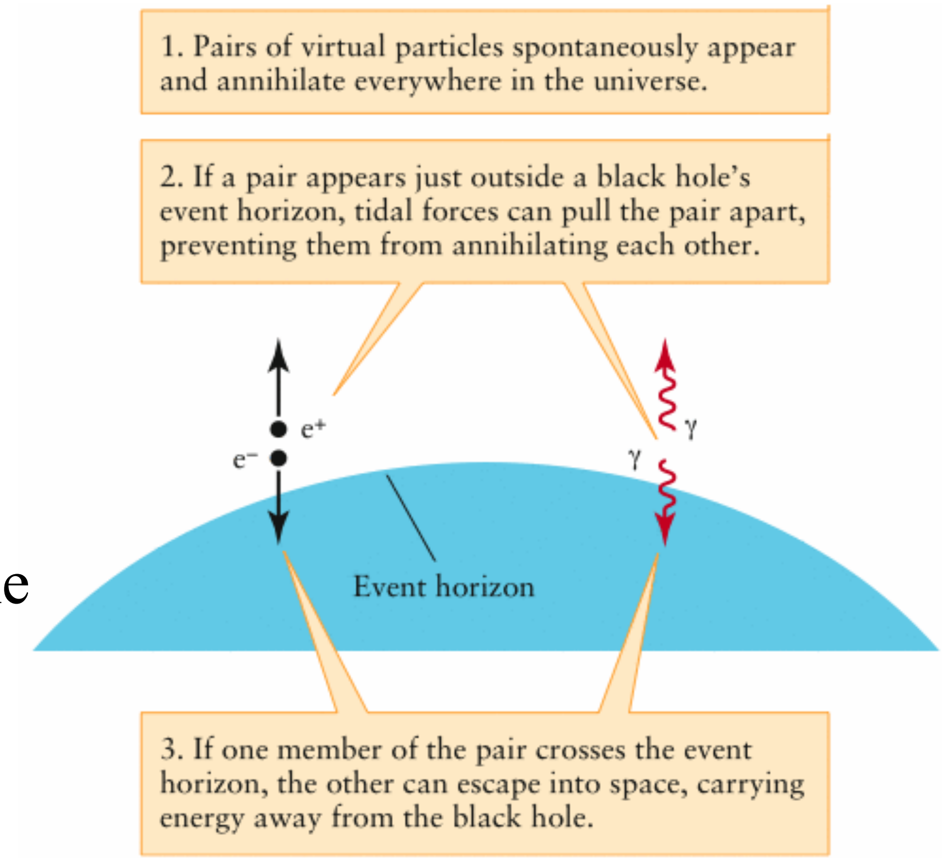
Our universe
Einstein-
Rosen
bridge
Another universe
A wormhole connects our universe to itself

Black Holes

Particles and antiparticles are constantly being created and destroyed out of vacuum fluctuations.

If a pair of **virtual particles** is created very close to the event horizon of a BH it is possible that one gets pulled into the BH and the other one escapes.

Since the particles were created from the Black Hole's gravitational energy the escaping particle has carries away some of the BH's mass.



Gravitational Equilibrium

Since gravity is only attractive one may ask why do we have structure in the Universe 13.7 Billion years after the big bang?

What forces are there that push matter away and prevent it from collapsing?

In stars there is an equilibrium between radiation pressure and gravity. When the fuel however runs out the star will collapse to form a White Dwarf or Neutron Star or Black Hole depending on the mass of the star.

Gravitational Equilibrium

One may ask why don't clusters of stars (globular clusters) collapse?

The amount of gravitational energy in a globular cluster is roughly equal to the energy needed to pull apart the cluster taking each star far apart from each other. This is called the **binding energy.**

The stars have **kinetic energy** due to their motion around the gravitational center. This motion is what keeps the star cluster from collapsing.

For **gravitational equilibrium** (no collapse) the kinetic energy of the cluster is equal to its binding energy.

47 Tucanae is a globular cluster in orbit around the center of the Milky Way. The random motion of its stars balance their mutual gravitational attraction, preventing the cluster from collapsing.

The Search for Black Holes Continues ..

A few reasons why scientists are still studying black holes:

1. One can study the properties of space-time in the strong gravity regime and further test Einstein's theory of general relativity.

2. Provide clues regarding the final stages of stellar evolution.

3. Supermassive black holes in the centers of galaxies may be crucial in the regulating the formation of the galaxies they reside in.

4. Once something (no matter how complex) crosses the horizon of a black hole it is lost forever. This concept of loss of information is still debated …

5. Currently GR does not apply to very small scales such as the singularity. Scientists are trying to extend GR to include quantum mechanics.

6. Exotic ideas such as extracting energy from BHs, travelling through wormholes inside BHs, time- travel and more … continue to capture are imaginations.