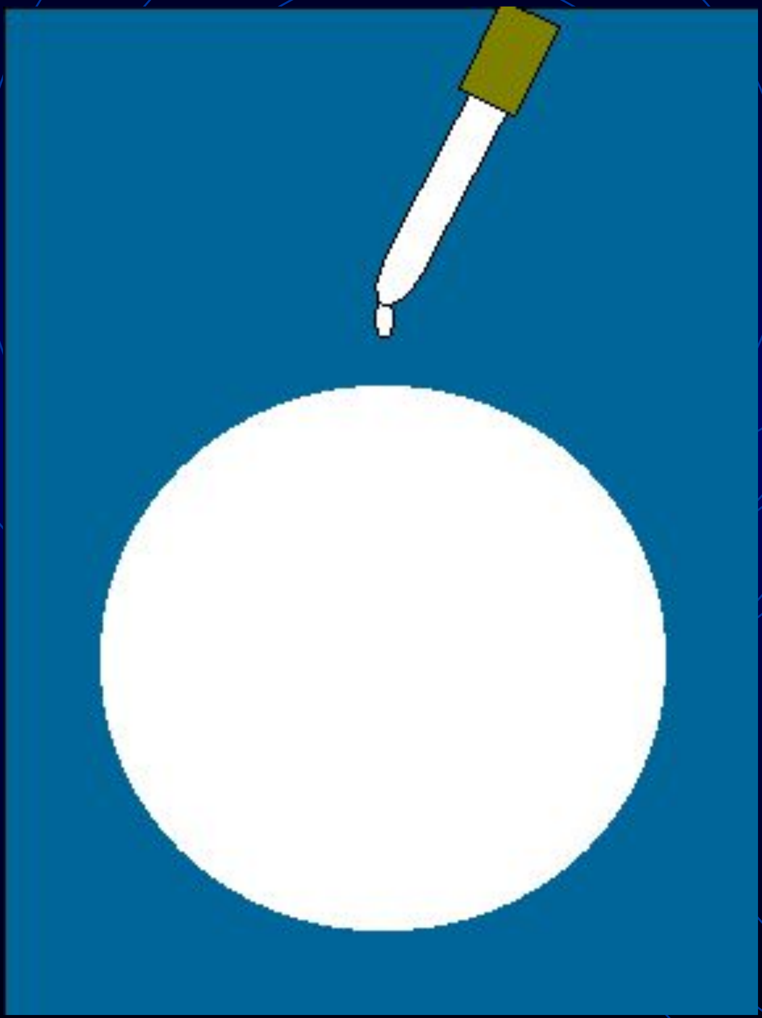
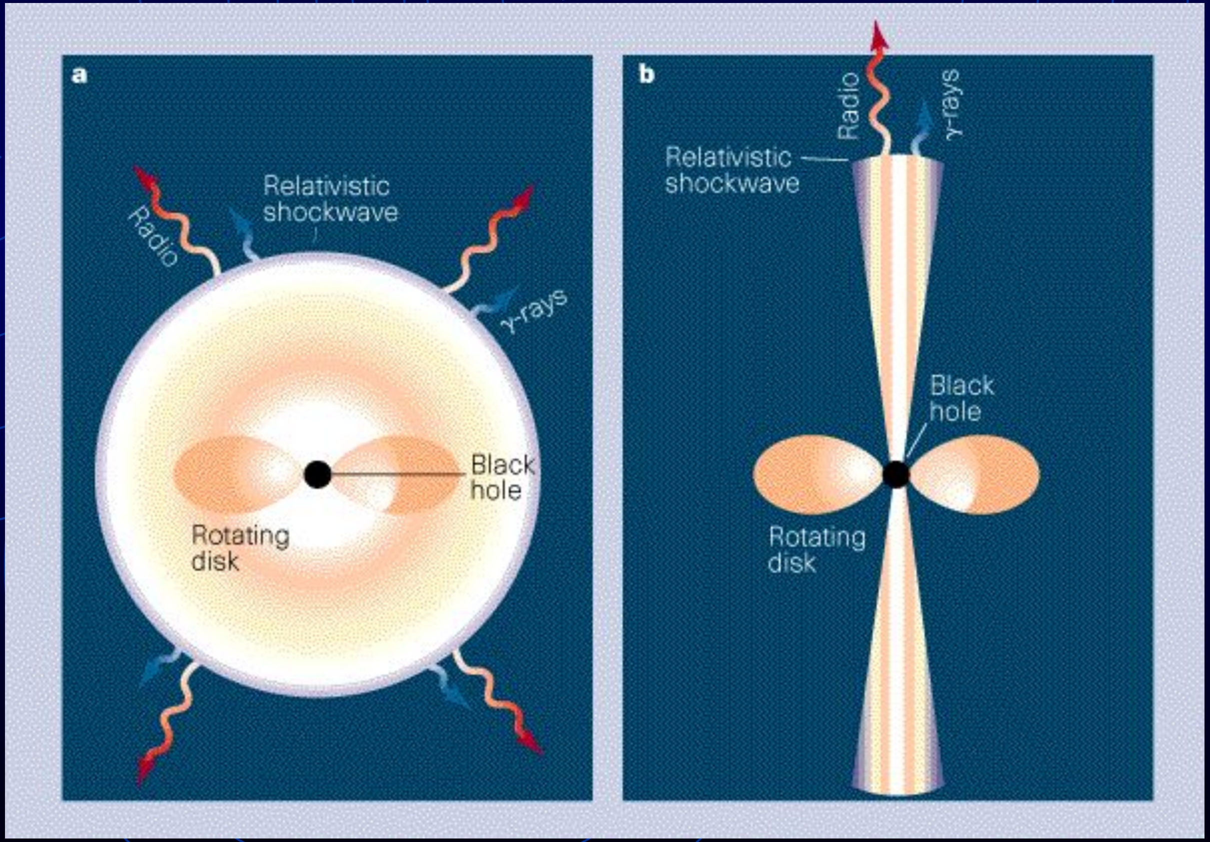
Relativity and Black Holes

Since neutron stars are degenerate, what is their maximum mass?

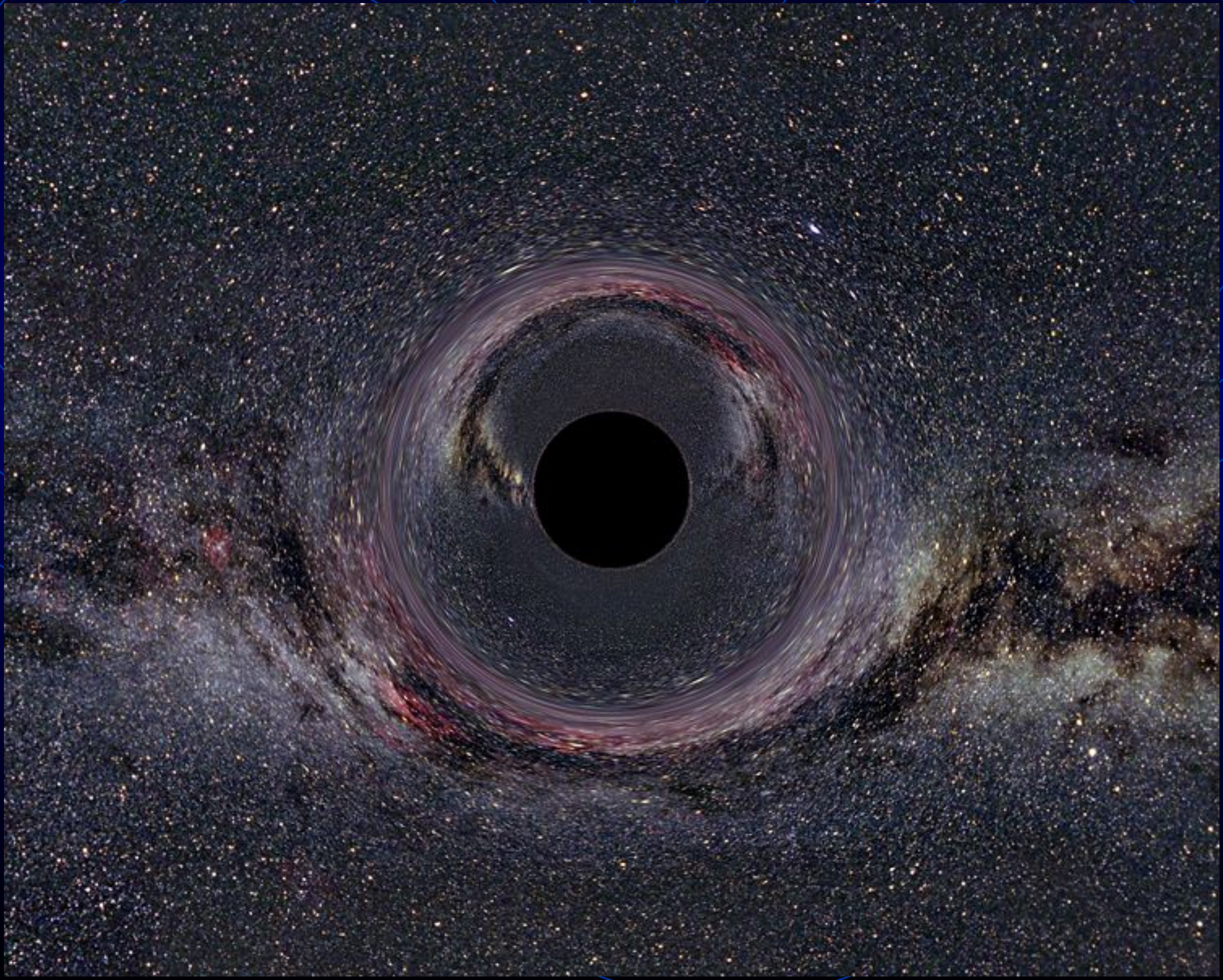


If a white dwarf star in a binary system exceeds its mass limit (1.4 M_{sun}) it blows up in a Type Ia supernova. What happens if a neutron star in a binary system exceeds its mass limit?

It is possible for the core of a massive star to exceed the mass limit before collapsing



A black hole is the ultimate collapsed star



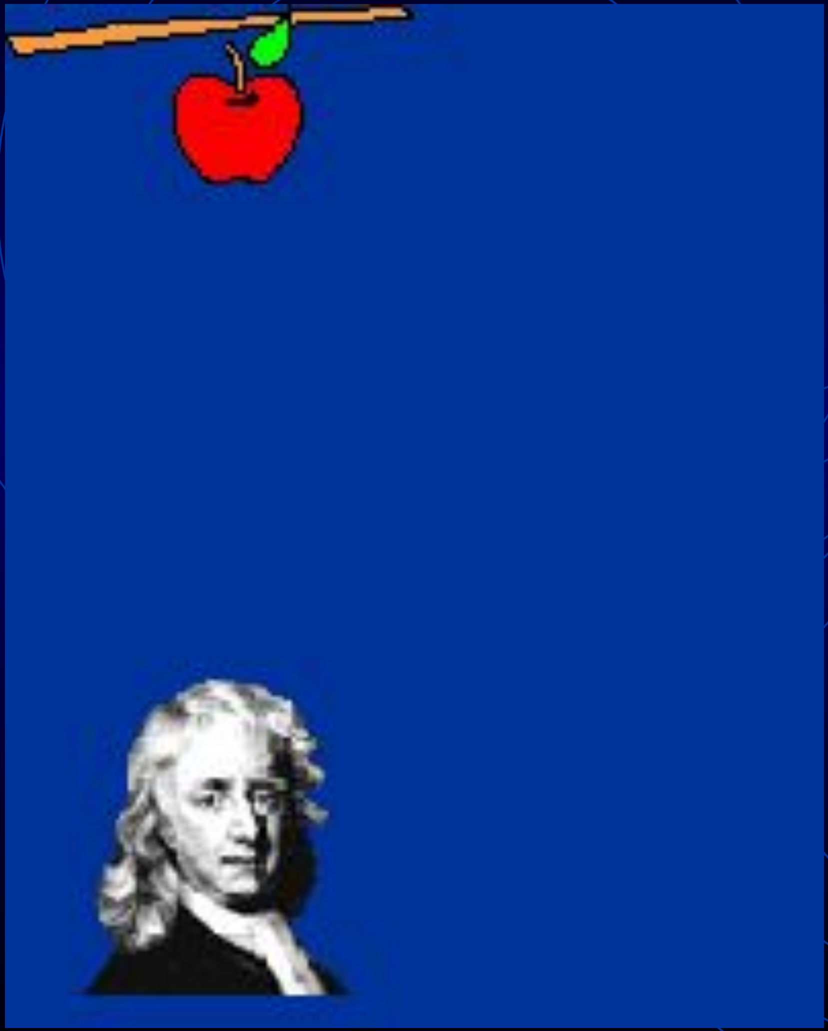
Let’s check the video

https://www.youtube.com/watch?v=kOEDG3j1bjs

Questions

If photons have no mass how are they affected by gravity?

To understand black holes we need some new physics



So far we have used Newton’s gravity. Near a black hole Newton’s gravity doesn’t give the right answer anymore. We need a new way to describe gravity.

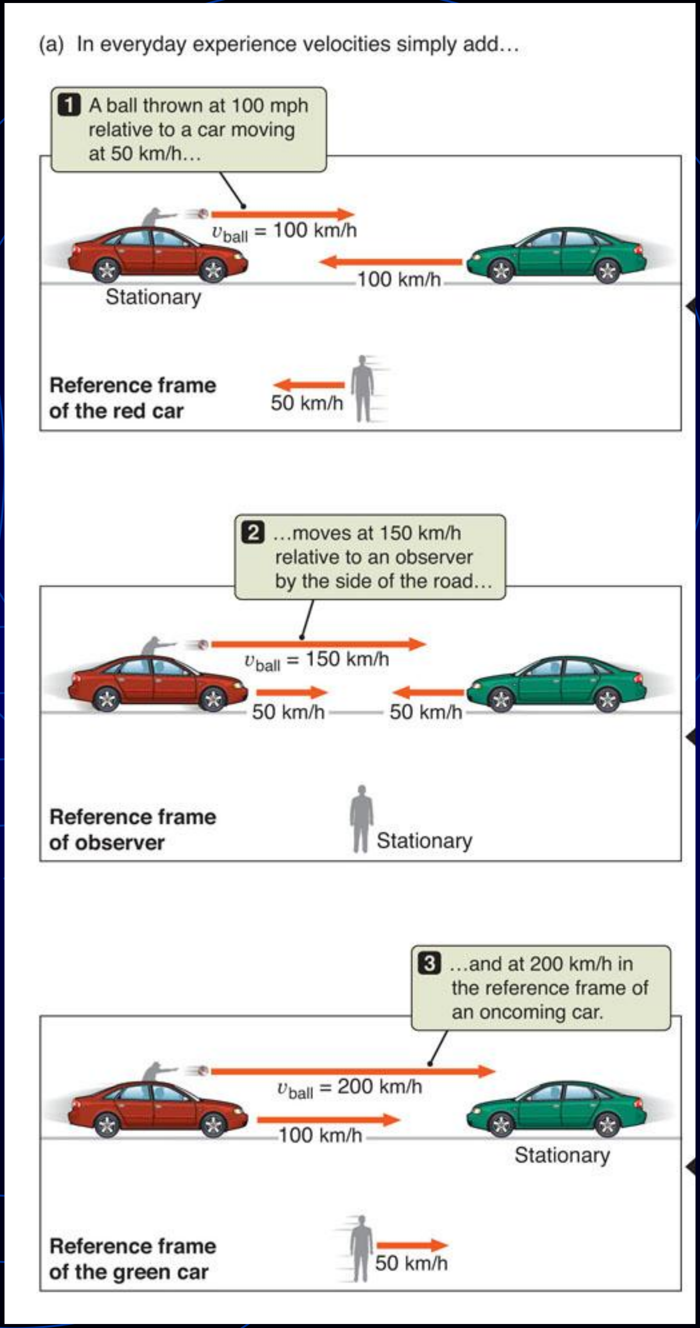
Problem 1: The speed of light in vacuum is always the same

Regardless of the wavelength being measured or the speed of the source, everyone always measures the same value for the speed of light in a vacuum

300,000 $^{km}/_{s}$

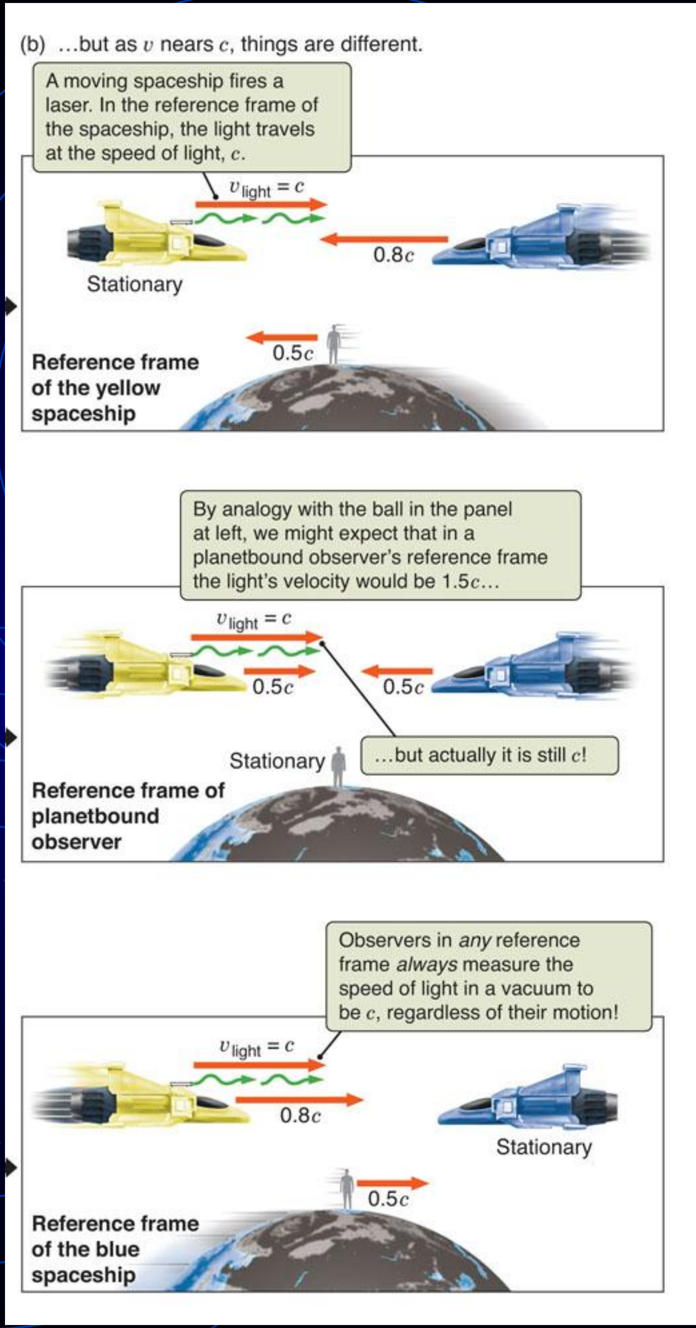
What's so special about the speed of light?

Galileo figured out how to add and subtract speeds to determine what each observer sees if the speeds are "slow". You just add or subtract the speeds. That makes sense.

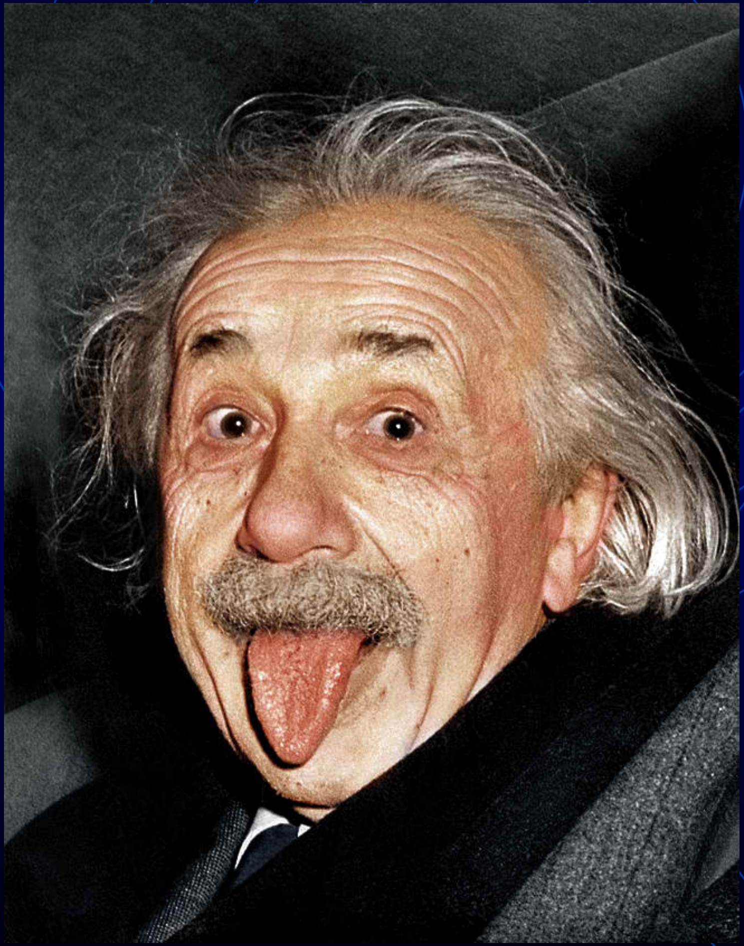


Light doesn’t add up!

Everyone always sees the laser beam’s speed as c. The speeds of the two spacecraft don’t add up right, either! In this example ½ plus 1 doesn’t equal 1.5, it equals 1! Likewise, ½ + ½ doesn’t equal 1 it equals 0.8!



THIS DOESN’T MAKE SENSE!!!



Albert Einstein puzzled over the question of why light doesn’t add up and eventually came up with a theory to explain it: Special Relativity

Einstein's Postulates of Special Relativity

1. Light always travels at 300,000 $^{km}/_{s}$ regardless of the speed of the source.
2. The laws of physics are the same in all inertial reference frames. As a result, it is impossible to determine absolute motion. You cannot tell who is moving and who is stationary, all that matters is relative motion.

Results: strange things happen when relative velocities are close to the speed of light.

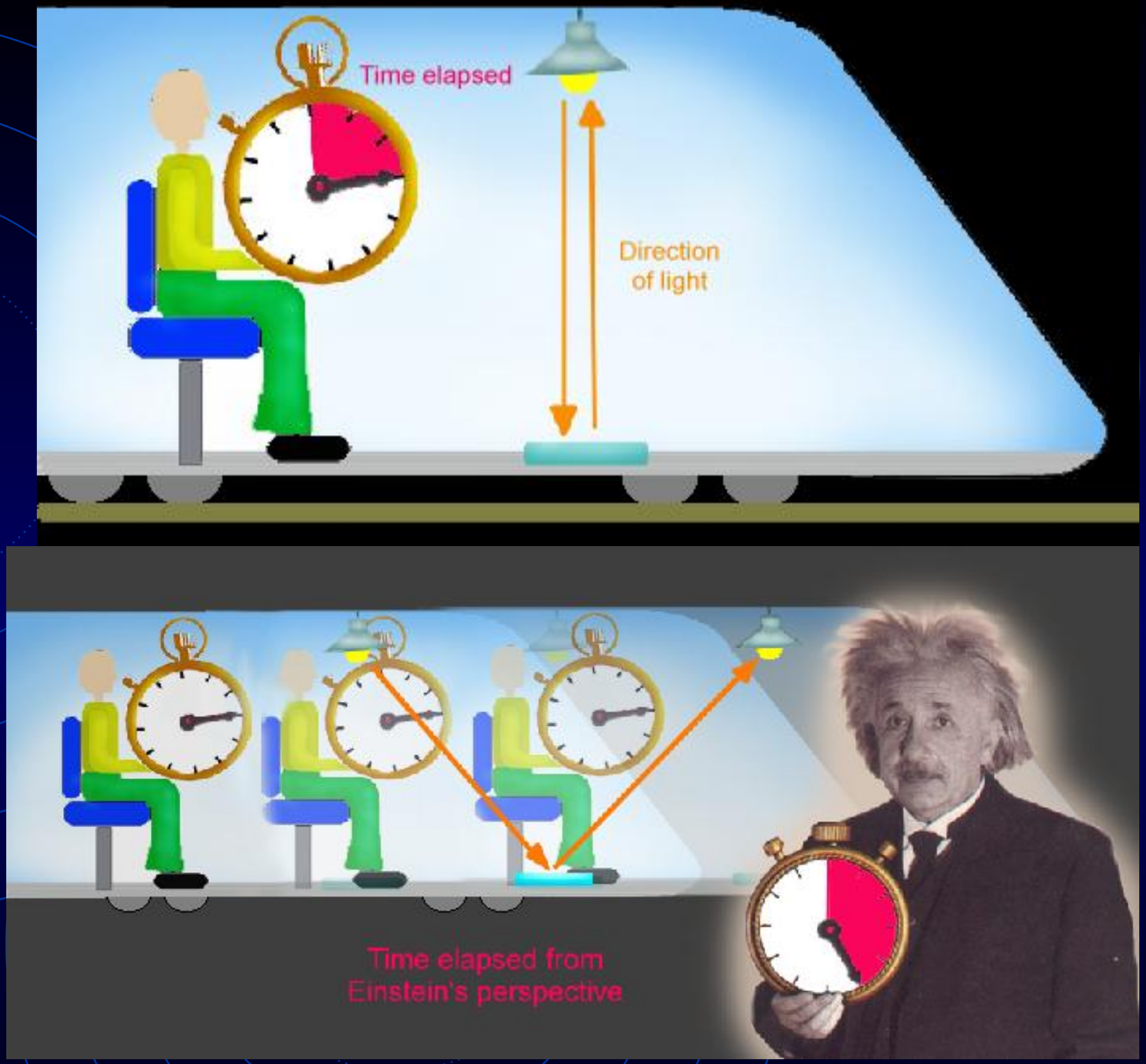
The most famous equation to come from Special Relativity

$$E = mc^2$$

This equation says that mass and energy are one and the same thing. Mass can be converted into energy as we have seen in the core of stars. Likewise, energy can be converted into mass.

Time Dilation

The time between two ticks of the clock depends on how fast you are moving with respect to the clock. My clock always runs at the right rate. It's always the other guy that has the



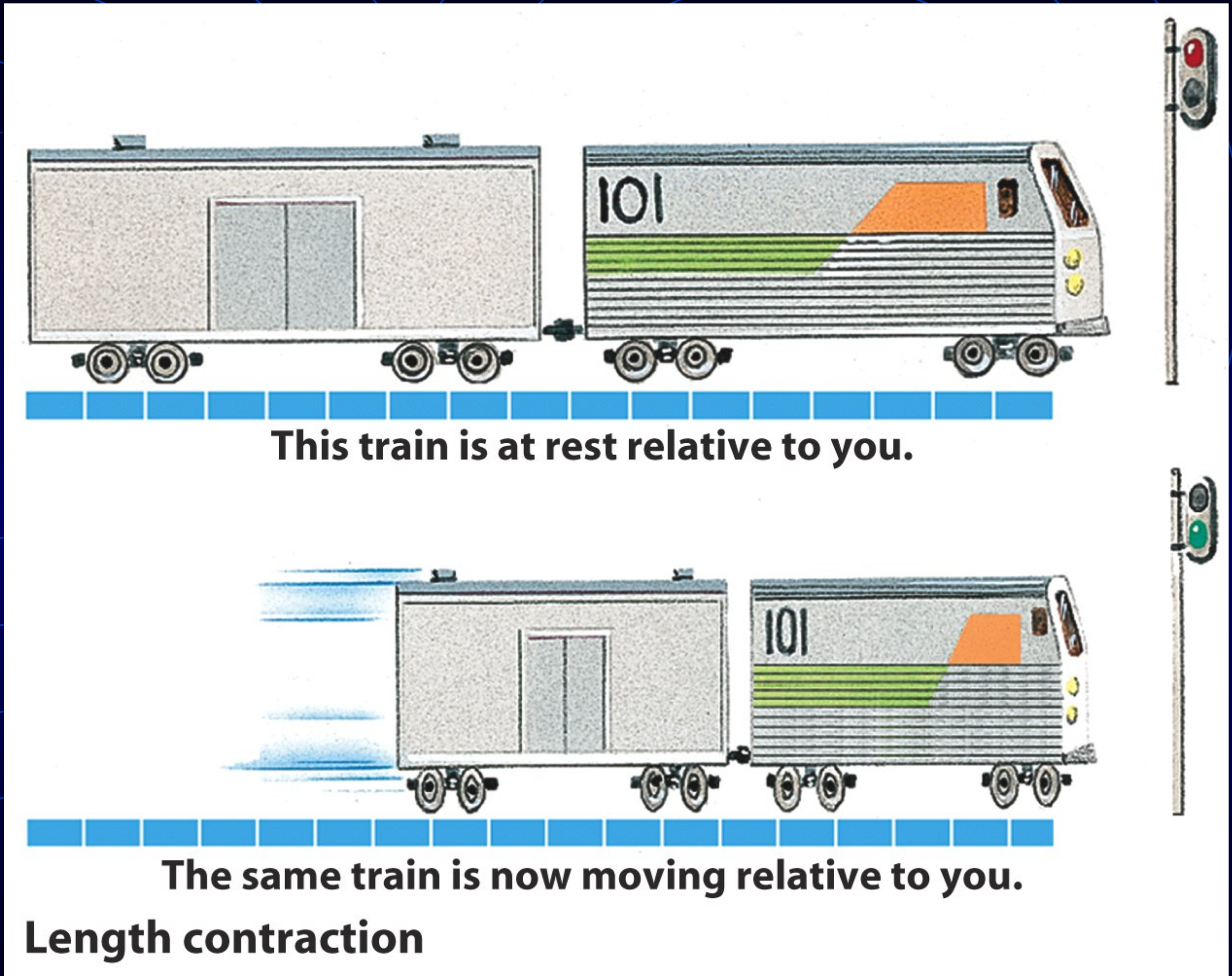
slow clock. No one ever sees someone else's clock running fast! Watch Time Dilation video

Since time is relative, what you see as simultaneous events might not be to another observer

Watch Simultaneity in Relativity video

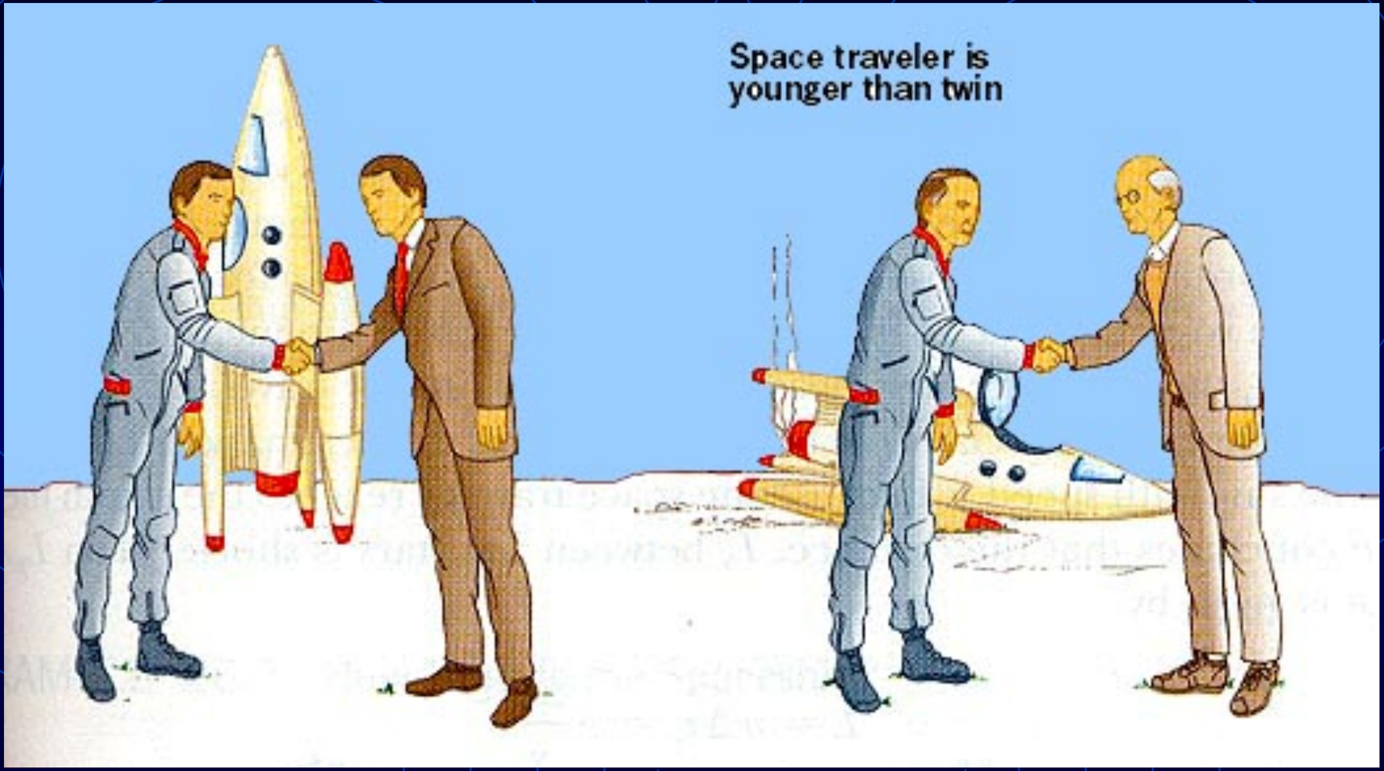
Length Contraction

To someone on the train the length of the train is always the same. To someone on the ground the length of the train depends on how fast it is moving.



The distance in the direction of motion is different for different observers

A paradox of Special Relativity: The Twin Paradox



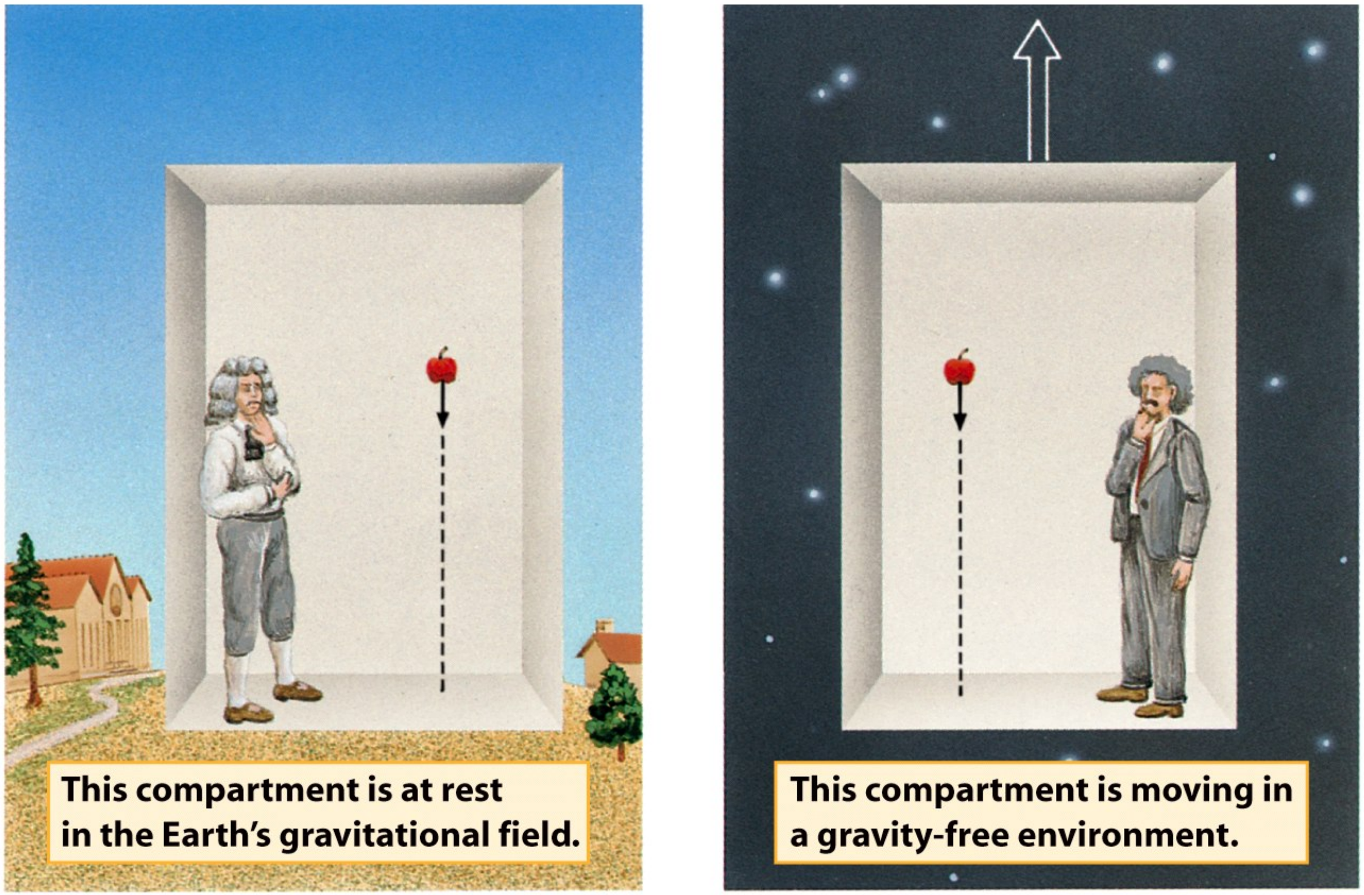
The "Special" of Special Relativity is that it only applies to things moving at constant speed

The answer to the paradox is
General Relativity: Einstein's Law of Gravity

The Equivalence Principle is the basic postulate of General Relativity

It is impossible to tell the difference between gravity and an acceleration

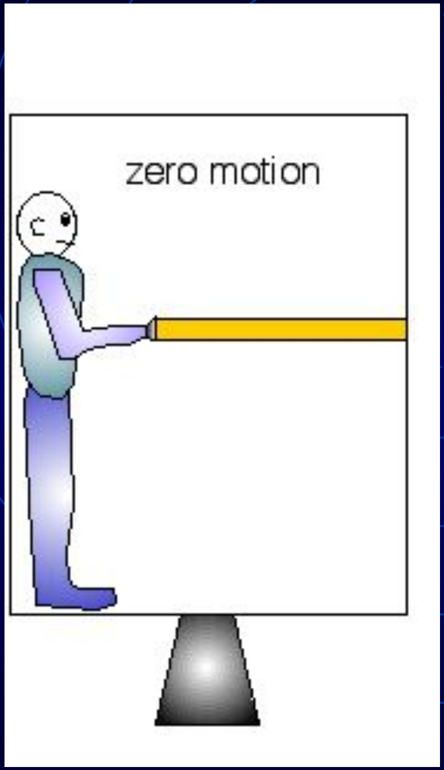
The Equivalence Principal in action



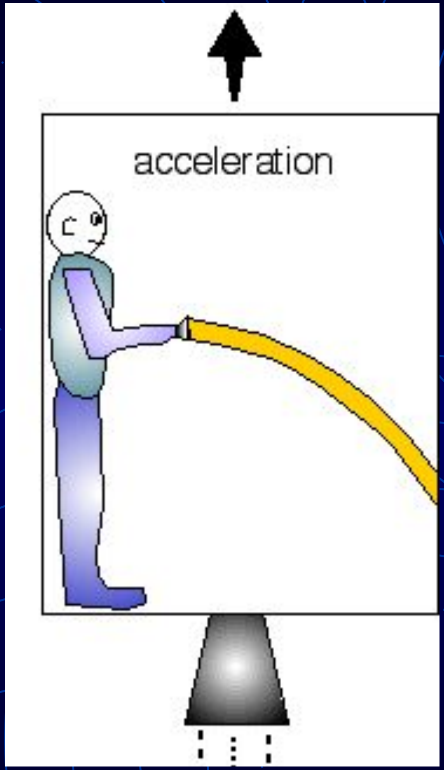
(a) The apple hits the floor of the compartment because the Earth's gravity accelerates the apple downward.

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

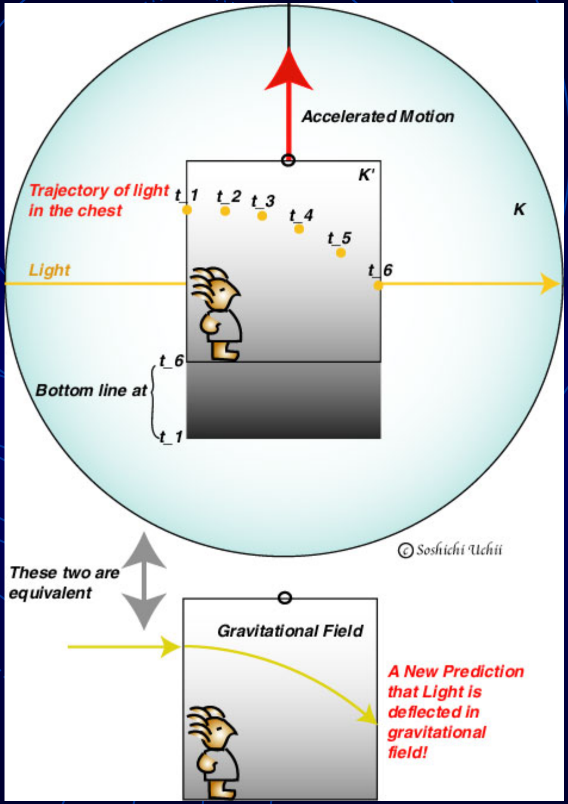
The Equivalence Principle means that light can be bent by gravity



If the rocket is stationary the beam goes straight across the room to hit the opposite wall.

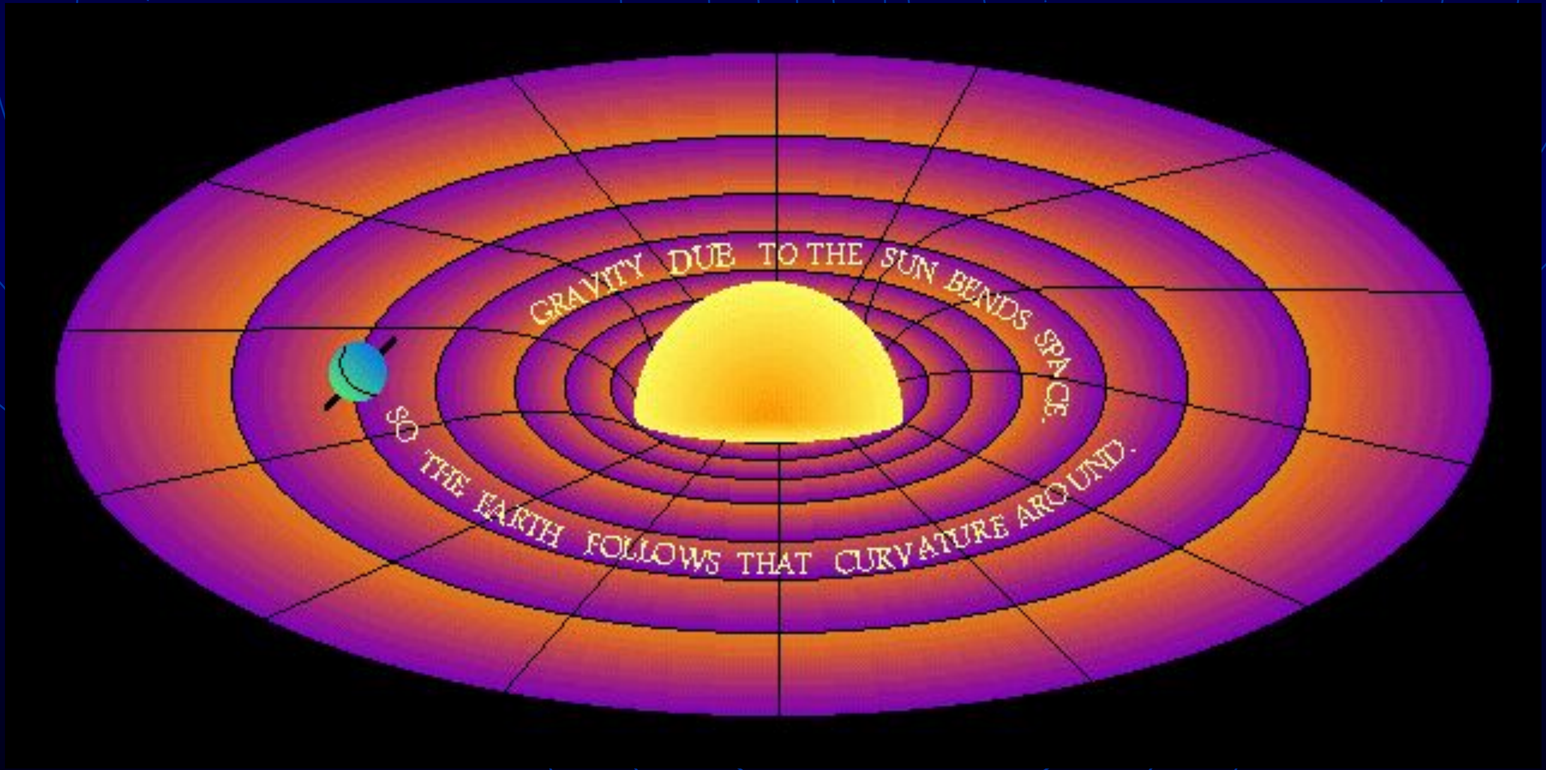


Due to the acceleration, the beam curves downward and hits the opposite wall near the floor.



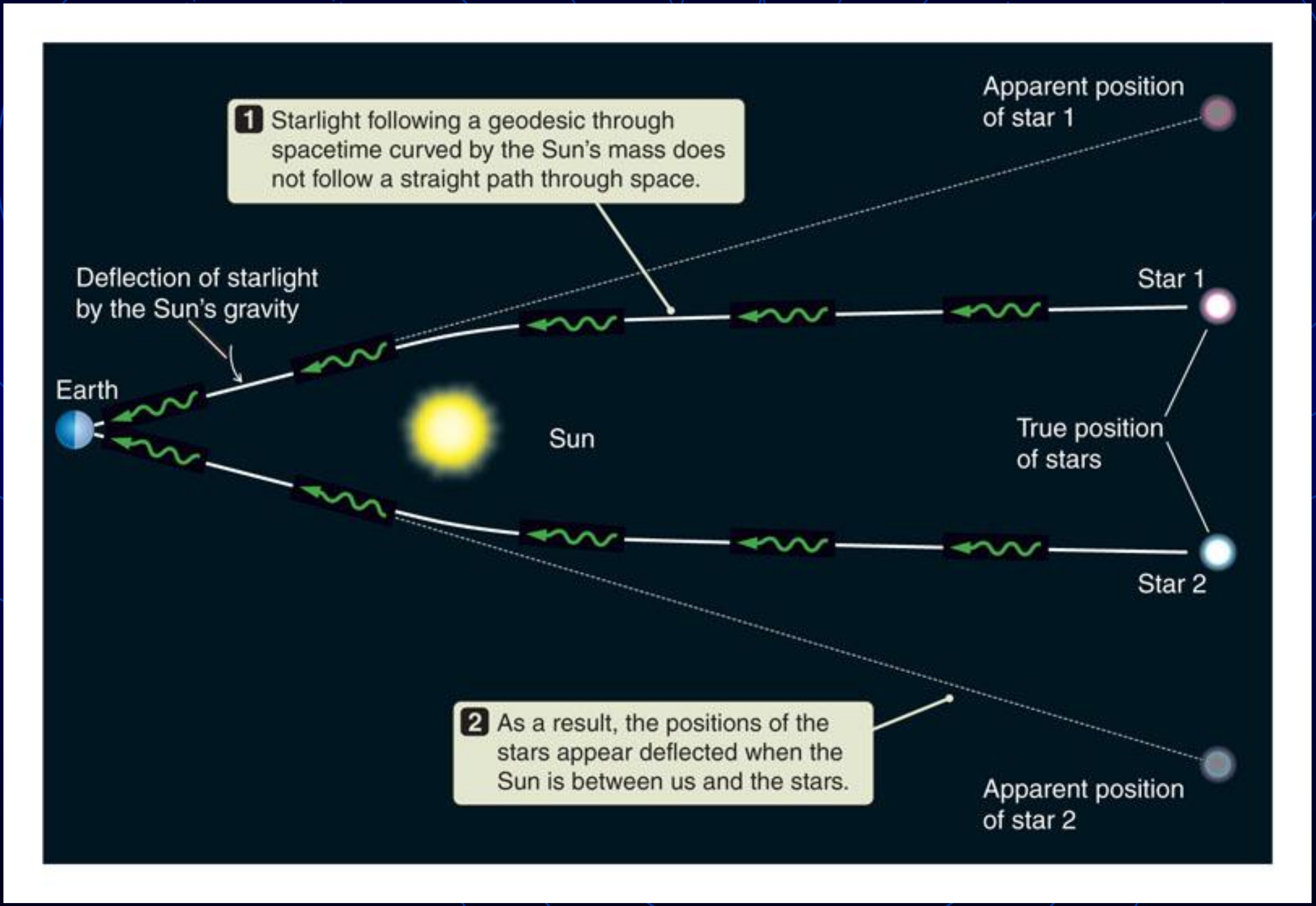
Since the rocket acceleration bends light, gravity must bend it, too

Mass Warps Space-time and the curvature of space-time tells mass how to move



This illustrates only two dimensions. Space-time warps in all four dimensions: three space and one time

Consequences of General Relativity



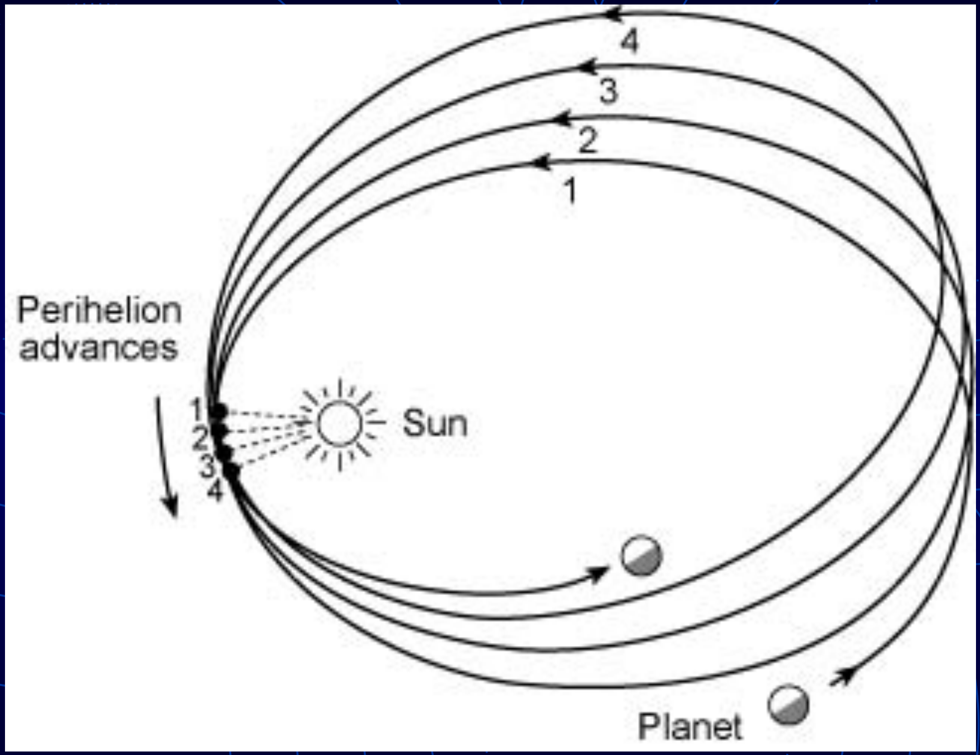
The path of light is bent by massive objects. This was first verified during the total eclipse of 1919.

We have seen gravity lenses with HST

Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

General Relativity explained the unusual orbit of Mercury

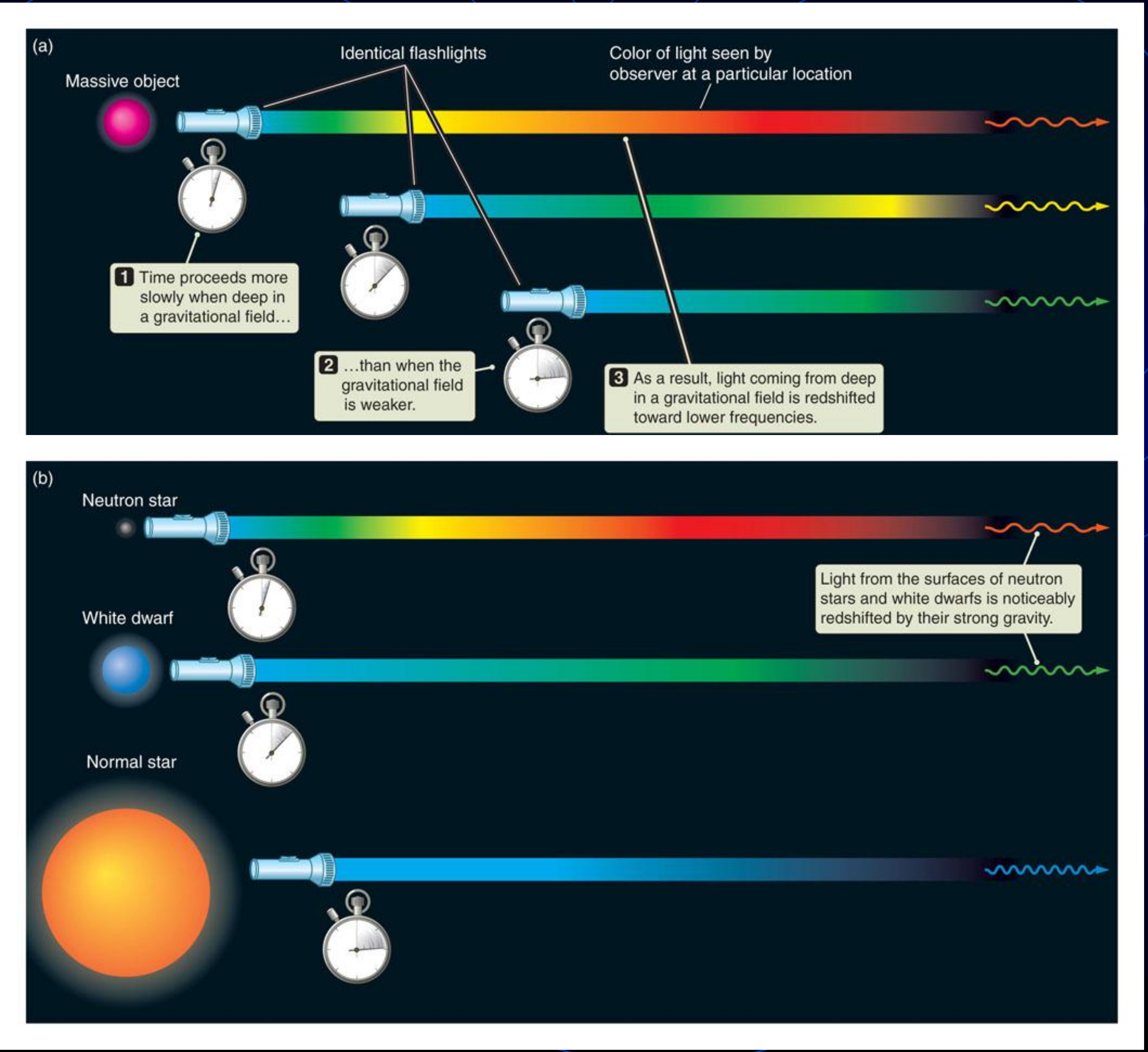


The "Anomalous Precession of the Perihelion of Mercury" was a problem that had been know about since the mid 1800's.

Gravity Warps Time, Too

Imagine each person is holding a clock and you are at the center. If you are standing at the center, they are all moving with respect to you so Special Relativity says you see a time dilation of their clocks. Since you can't tell the difference between acceleration and gravity, gravity must also cause clocks to run slow: gravitational time dilation.

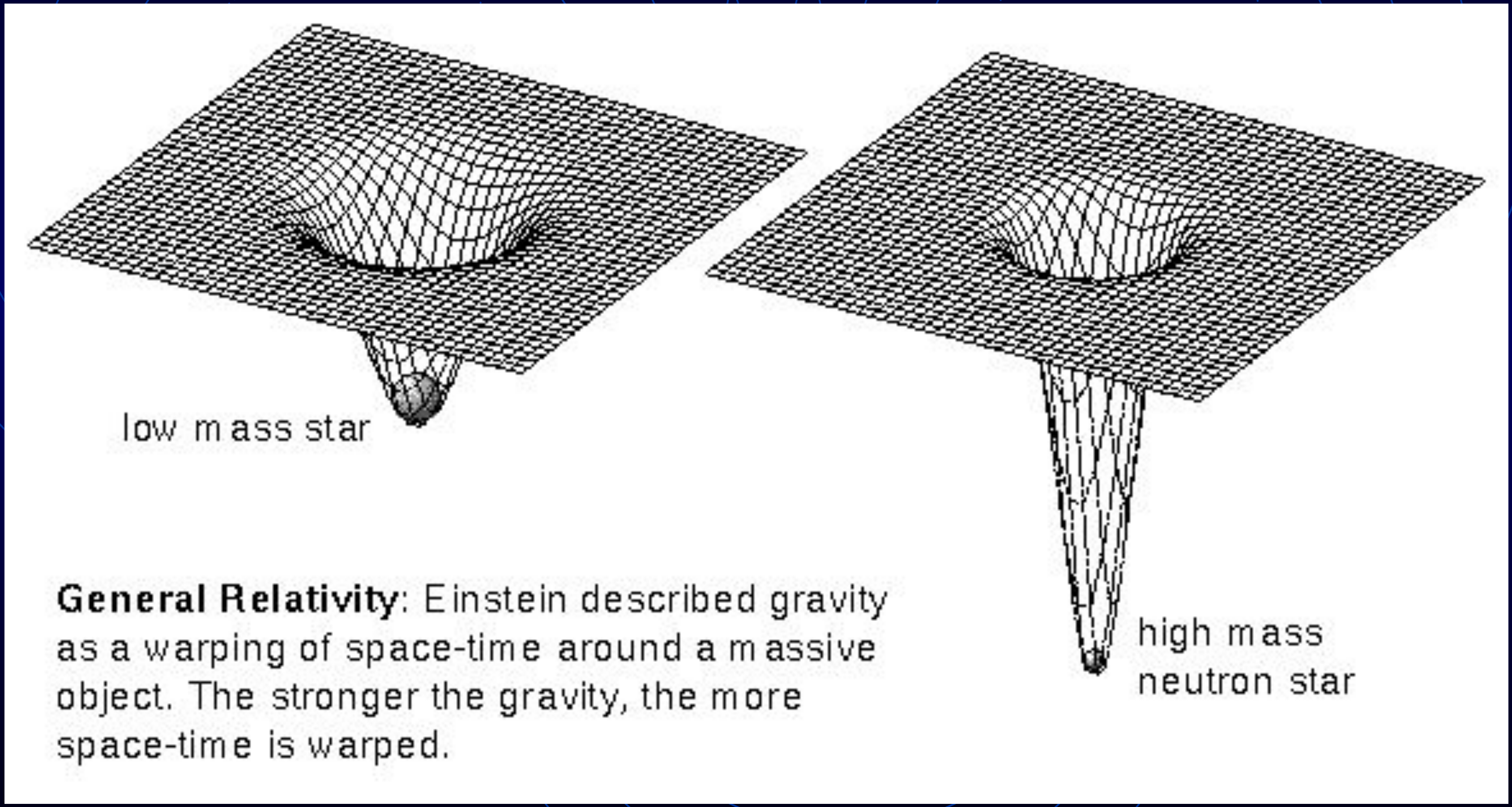
Gravitational Redshift



- Can an observer ever see something fall into a black hole?

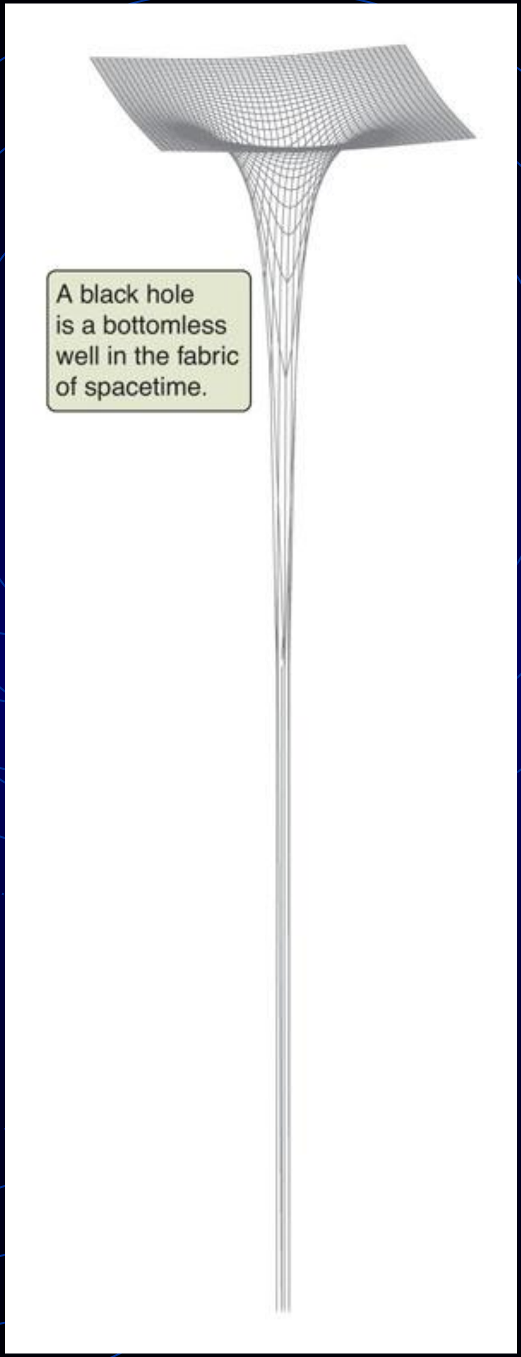
As an object falls toward the event horizon of a black hole, it will redden in appearance. It will also appear to emit light more slowly, and thus will become dimmer. The combination of these two effects are that an external observer will see the object redden and fade out of sight, but they will never see it cross the event horizon.

Space-time near massive objects is warped

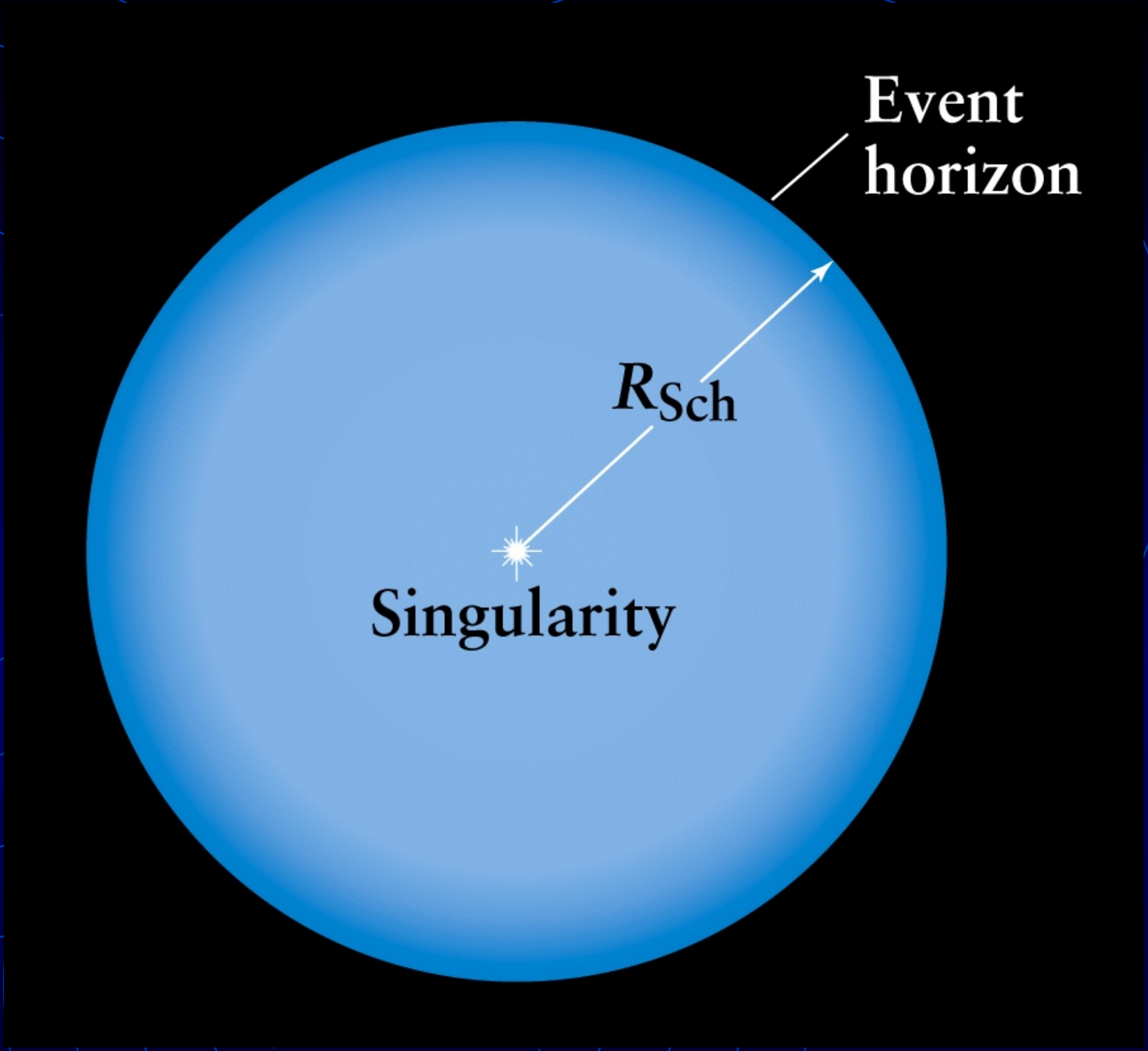


Space-time near a black hole is extremely warped

A black hole is an object whose escape velocity is the speed of light



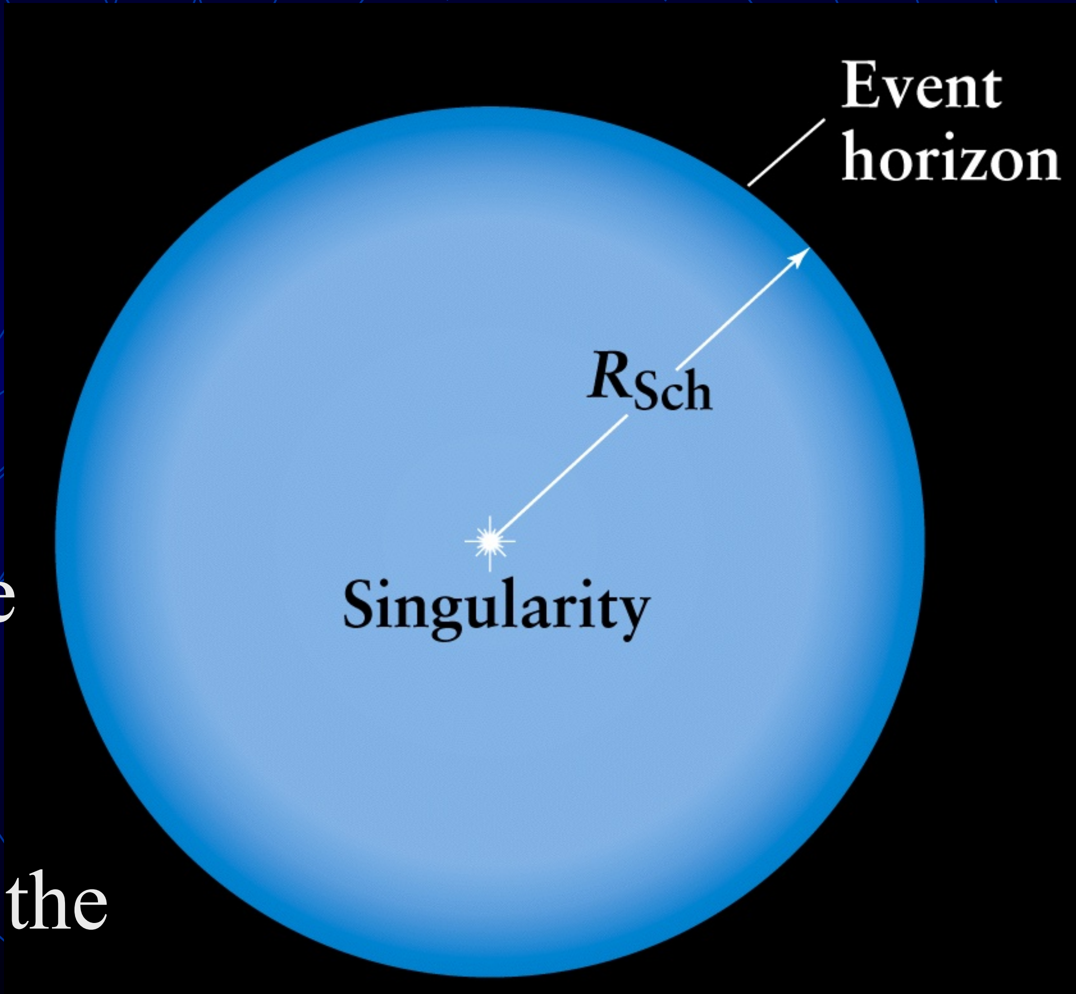
The Event Horizon is the point of no return for a black hole



R_{Sch} is the Schwarzschild radius which is half the diameter as measured from ***outside*** the black hole

The Schwarzschild Radius depends only on the mass

$$R_{Sch} = \frac{2GM}{c^2}$$



The radius at which the escape speed from the black hole equals the speed of light is called the **Schwarzschild radius.**

Schwarzschild radius

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

Since we are interested in a black hole and trapping of light by it, we put v_esc = c, the velocity of light,

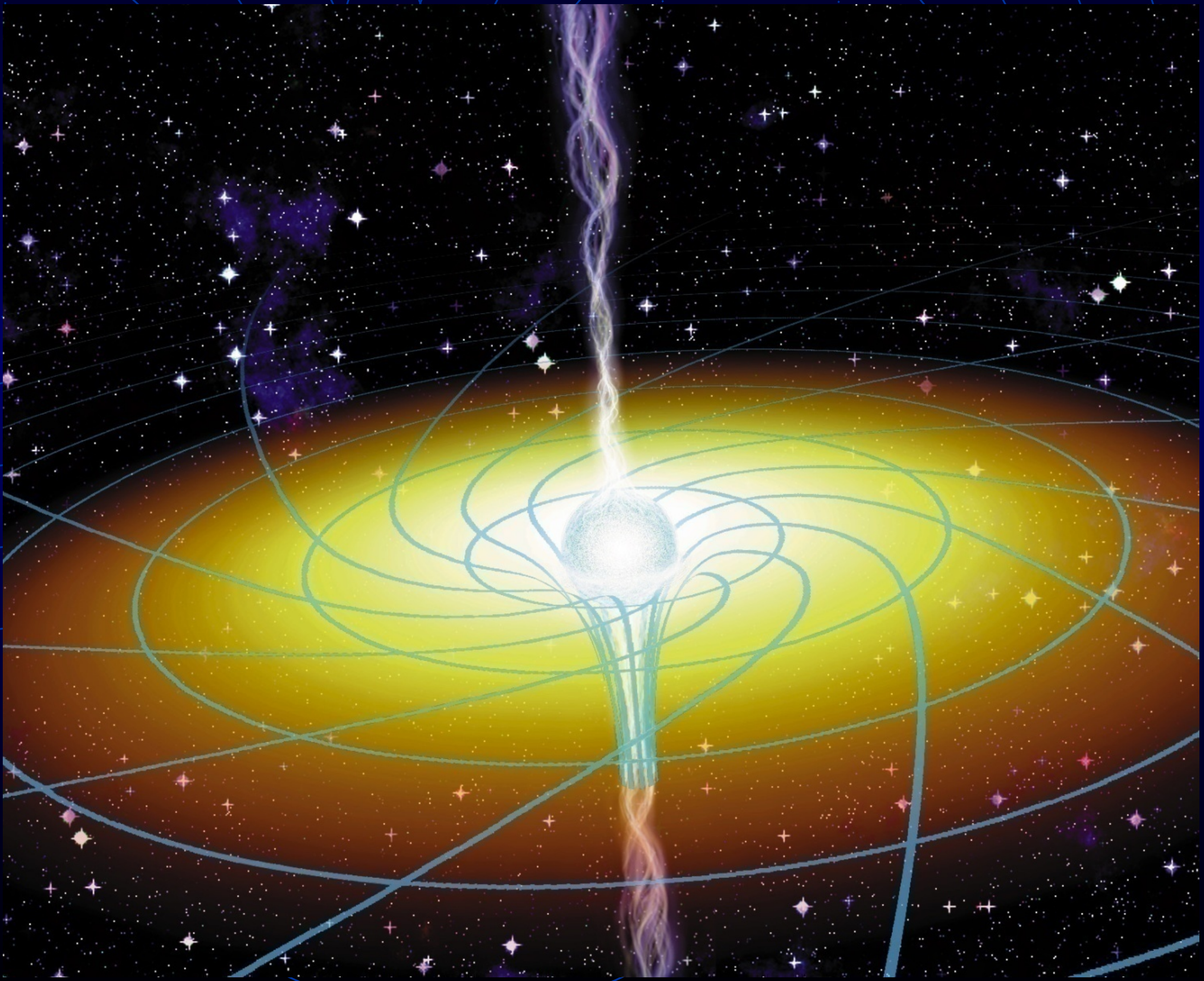
$$R_g = \frac{2GM}{c^2}$$

Problems

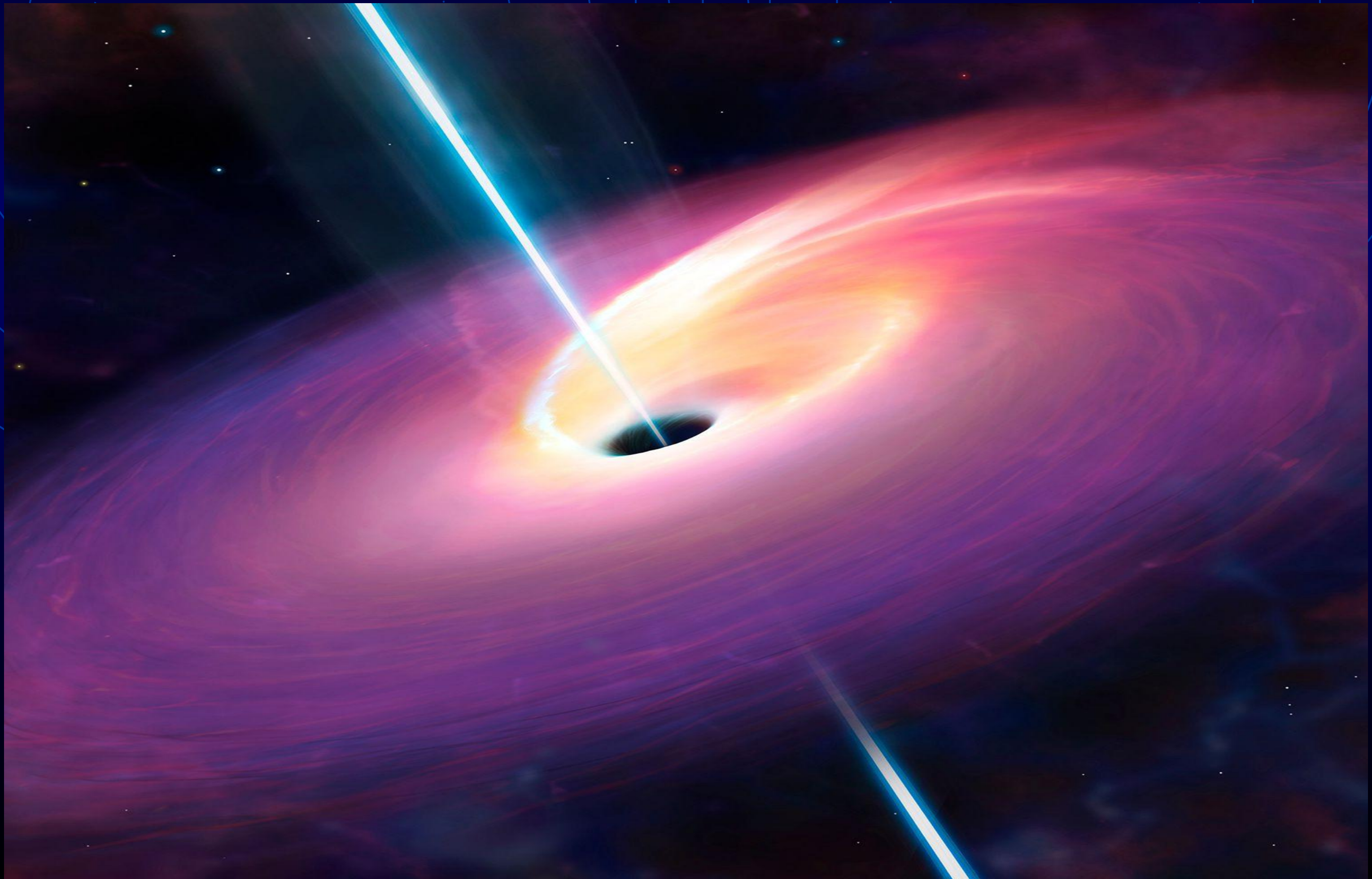
- Calculate the Schwarzschild radius, in centimeters, for Earth where $M = 5.7 \times 10^{27}$ grams. (Express answer to two significant figures)
- Calculate the Schwarzschild radius, in kilometers, for the sun, where $M = 1.98 \times 10^{33}$ grams. (Express answer to two significant figures)
- Calculate the Schwarzschild radius, in kilometers, for the entire Milky Way, with a mass of 250 billion suns. (Express answer to two significant figures)
- Calculate the Schwarzschild radius, in centimeters, for a black hole with a mass of an average human being with $M = 60$ kilograms. (Express answer to two significant figures)

A rotating black hole drags space-time around

"Now, here, you see, it takes all the running you can do, to keep in the same place."
from ***Through The Looking Glass*** by Lewis Carroll



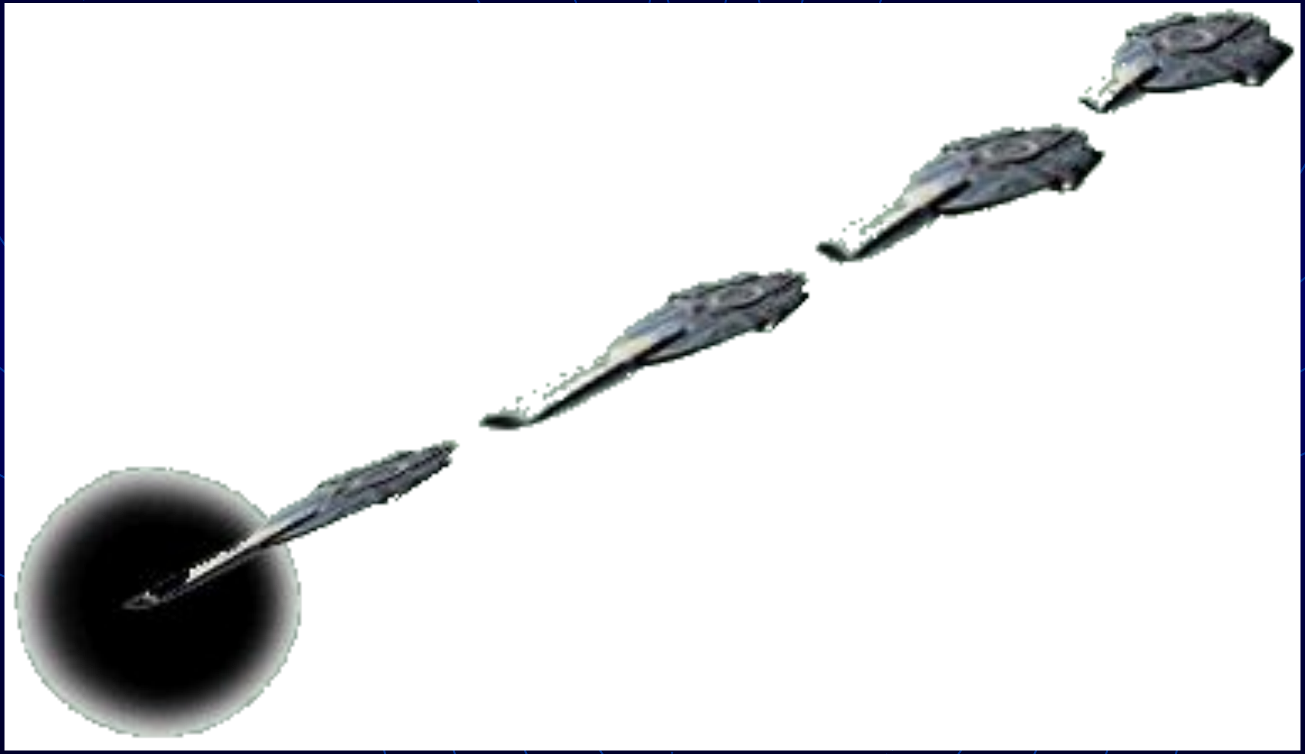
But black holes aren't just extremely massive, they're also incredibly fast rotators. Many black holes, from their measured spins, are spinning at more than 90% the speed of light.



While most stars themselves may spin relatively slowly, black holes rotate at nearly the speed of light. Why?

if you compress a massive object down, so that more of its mass is closer to the center of its axis-of-rotation, it will have to speed up in its rotational speed, making more revolutions-per-second, to keep angular momentum conserved.

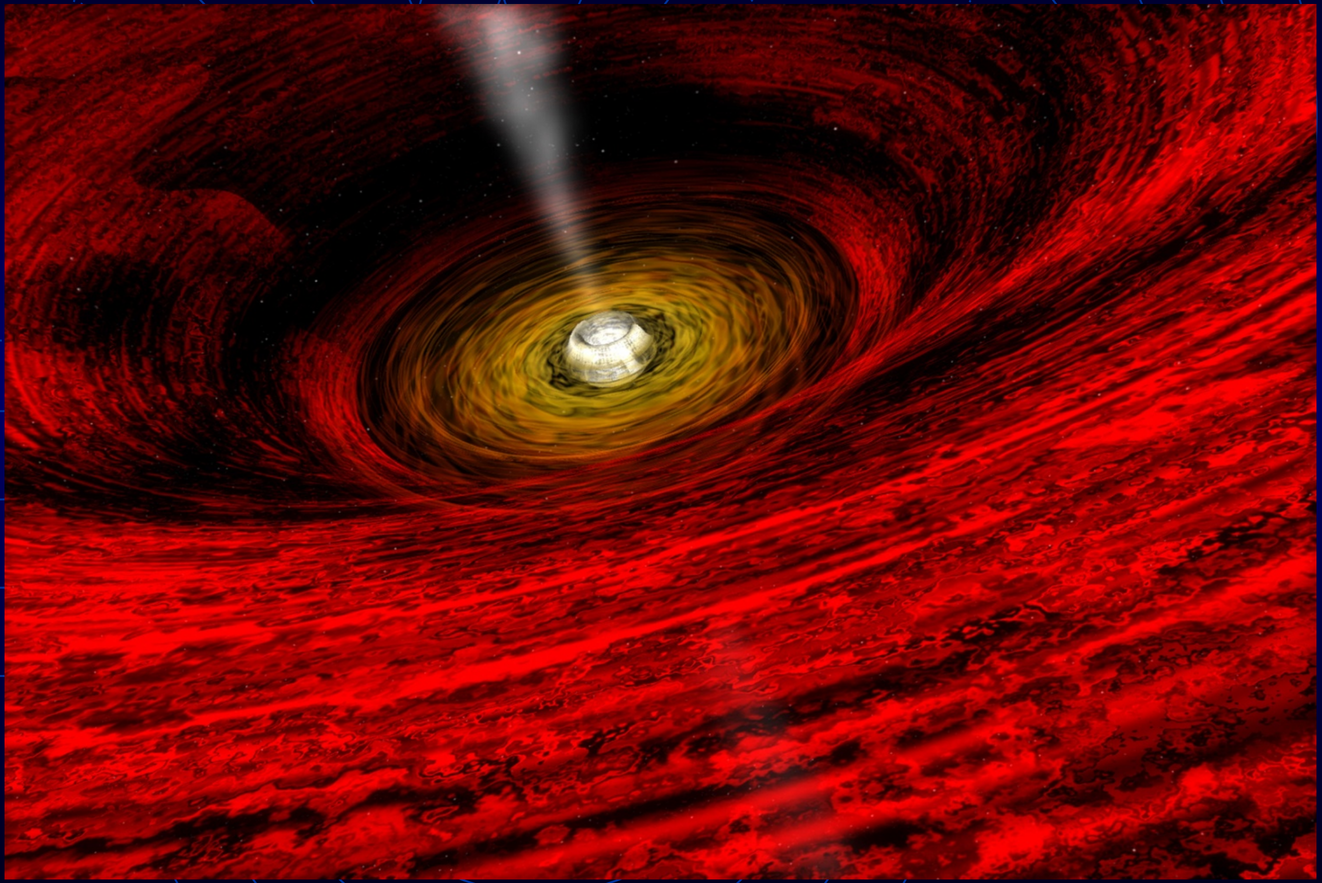
Falling into a black hole, tidal forces would rip you apart



Objects become spaghettified as they fall toward a black hole. Watch YouTube Spaghettification video

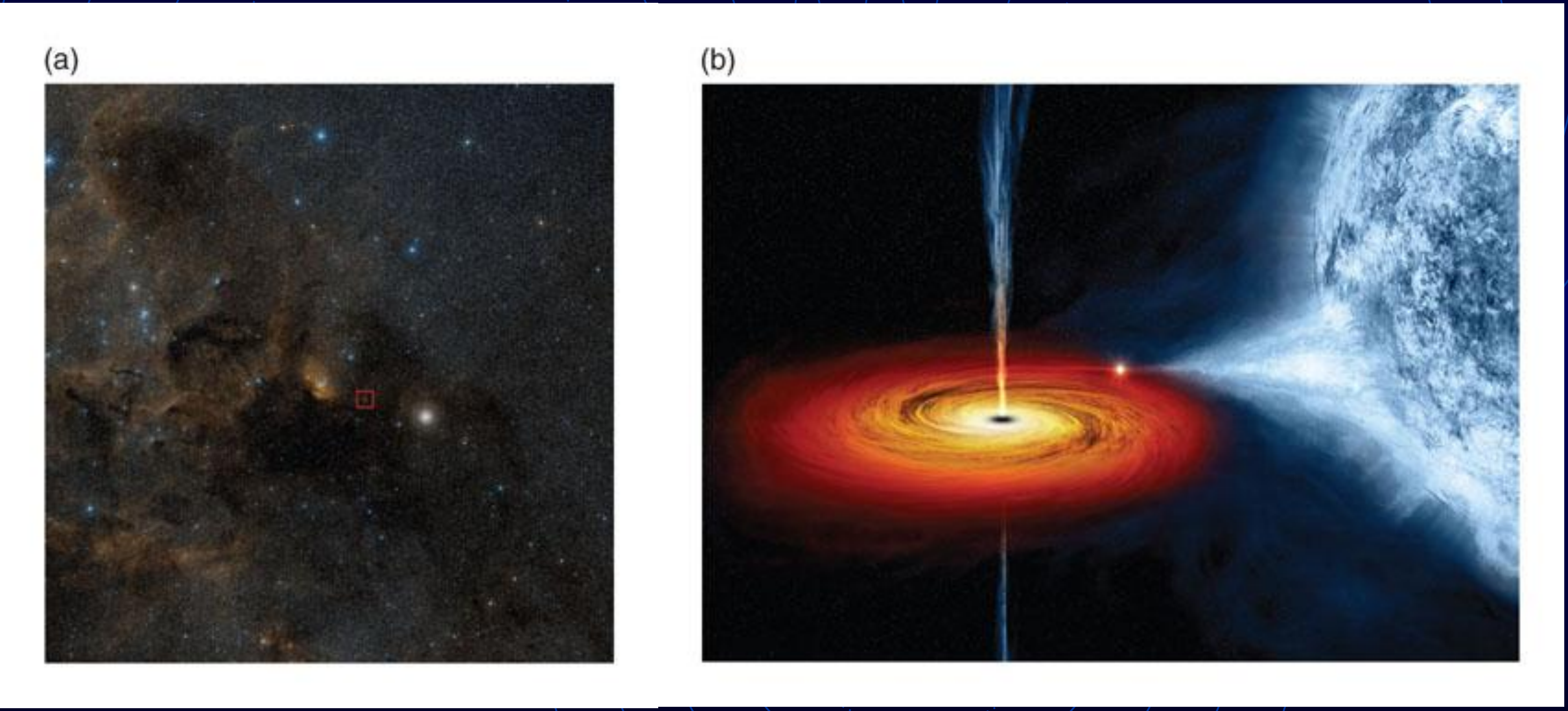
We “see” a black hole by the stuff falling into it

“You can’t see a black hole but you can hear the screams of things as it eats them.”



The jet doesn’t come from the black hole. It comes from the material near the black hole

Stellar Mass black hole candidates are in binaries



Questions

- **How black holes ‘shine’ ?**

https://www.youtube.com/watch?v=-OtUVDRL_wM

Gas falling toward a black hole initially orbits around it and then accumulates into a flattened disk. The gas stored in this disk gradually spirals inward and becomes greatly compressed and heated as it nears the center, ultimately reaching temperatures up to 20 million degrees Fahrenheit (12 million C), or some 2,000 times hotter than the sun's surface. It glows brightly in low-energy, or soft, X-rays.

For more than 40 years, however, observations show that black holes also produce considerable amounts of "hard" X-rays, light with energy tens to hundreds of times greater than soft X-rays. This higher-energy light implies the presence of correspondingly hotter gas, with temperatures reaching billions of degrees.

The new study involves a detailed computer simulation that simultaneously tracked the fluid, electrical and magnetic properties of the gas while also taking into account Einstein's theory of relativity. Using this data, the scientists developed tools to track how X-rays were emitted, absorbed, and scattered in and around the disk.

The study demonstrates for the first time a direct connection between magnetic turbulence in the disk, the formation of a billion-degree corona above and below the disk, and the production of hard X-rays around an actively "feeding" black hole.

Types of black holes

Stellar : When a star with more than eight times the Sun’s mass runs out of fuel, its core collapses, rebounds, and explodes as a supernova. What’s left behind depends on the star’s mass before the explosion. If it was near the threshold, it creates a city-sized, superdense neutron star. If it had around 20 times the Sun’s mass or more, the star’s core collapses into a stellar-mass black hole.

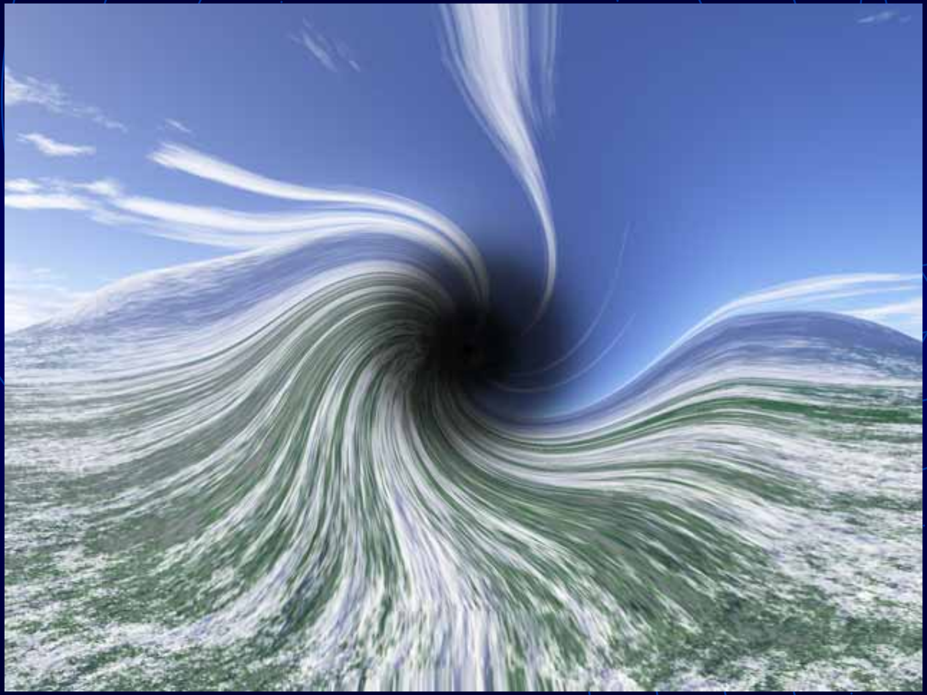
Supermassive:
Almost every large galaxy, including our Milky Way, has a supermassive black hole at its center. These monster objects have hundreds of thousands to billions of times the Sun's mass

Primordial
Scientists theorize that primordial black holes formed in the first second after the birth of the universe. In that moment, pockets of hot material may have been dense enough to form black holes, potentially with masses ranging from 100,000 times less than a paperclip to 100,000 times more than the Sun's. Then as the universe quickly expanded and cooled, the conditions for forming black holes this way ended.

Mass of black holes

stellar-mass black holes have masses ranging from about 3 times the mass of our sun to about 50 times the mass of our sun. In contrast, supermassive black holes have a mass greater than about 50,000 times the mass of our sun and are typically millions to billions times the mass of our sun

Does a black hole last forever?



Distortions of every day things with a small black hole passing in front

Quantum Mechanics and the Heisenberg Uncertainty Principle

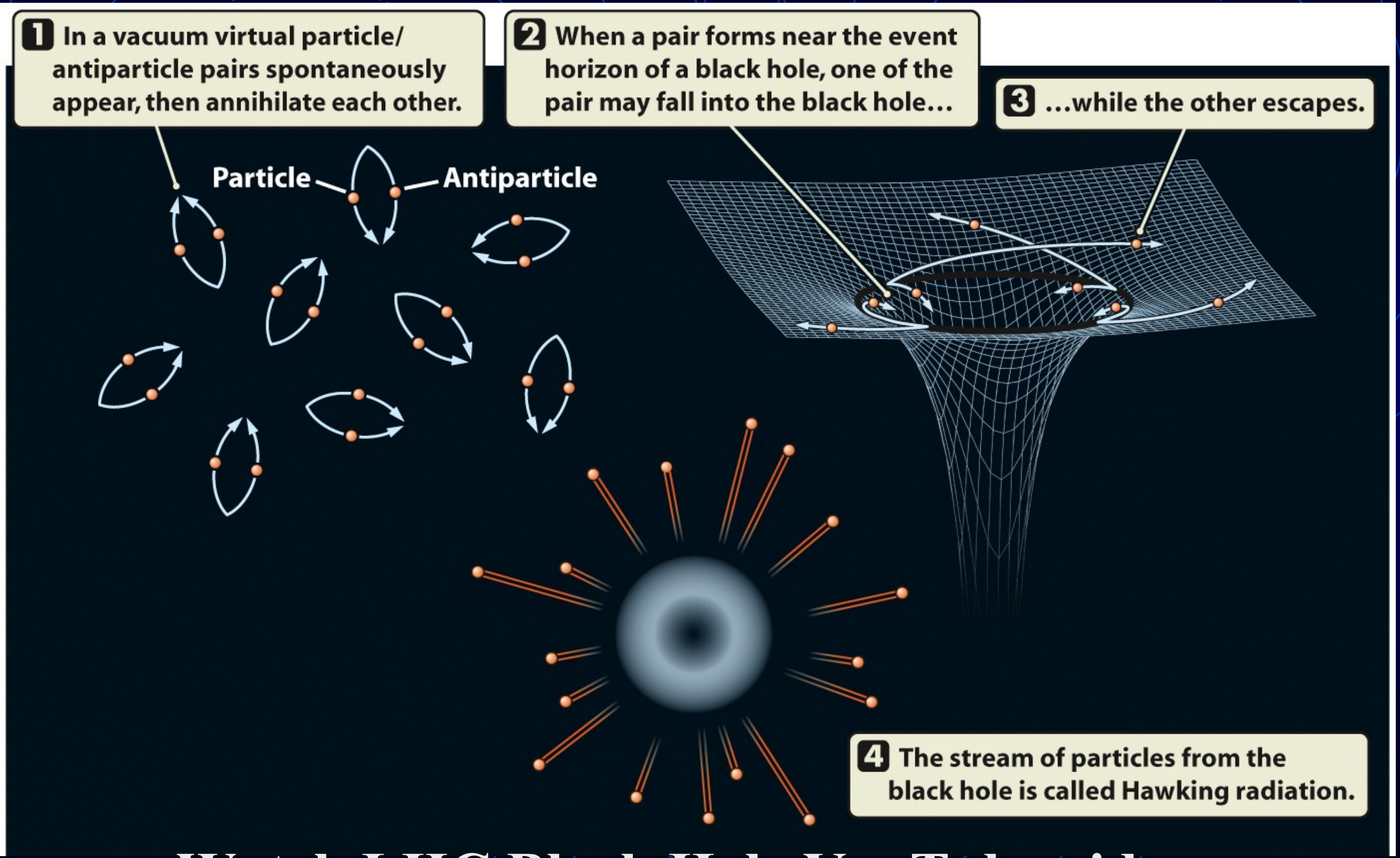
$$\Delta E \Delta t \approx h$$

$$h = 6.626 \times 10^{-34} J \cdot s$$

You can get something from nothing but you can't keep it for very long.

An electron-positron pair can exist for about 10^{-21} seconds before they annihilate each other

Black Holes evaporate by Hawking Radiation



Watch LHC Black Hole YouTube videos

A black hole of one solar mass (M ☉ = 2.0×10^{30} kg) takes more than 10^{67} years to evaporate—much longer than the current age of the universe at 1.4×10^{10} years. But for a black hole of 10^{11} kg, the evaporation time is 2.6×10^{9} years.