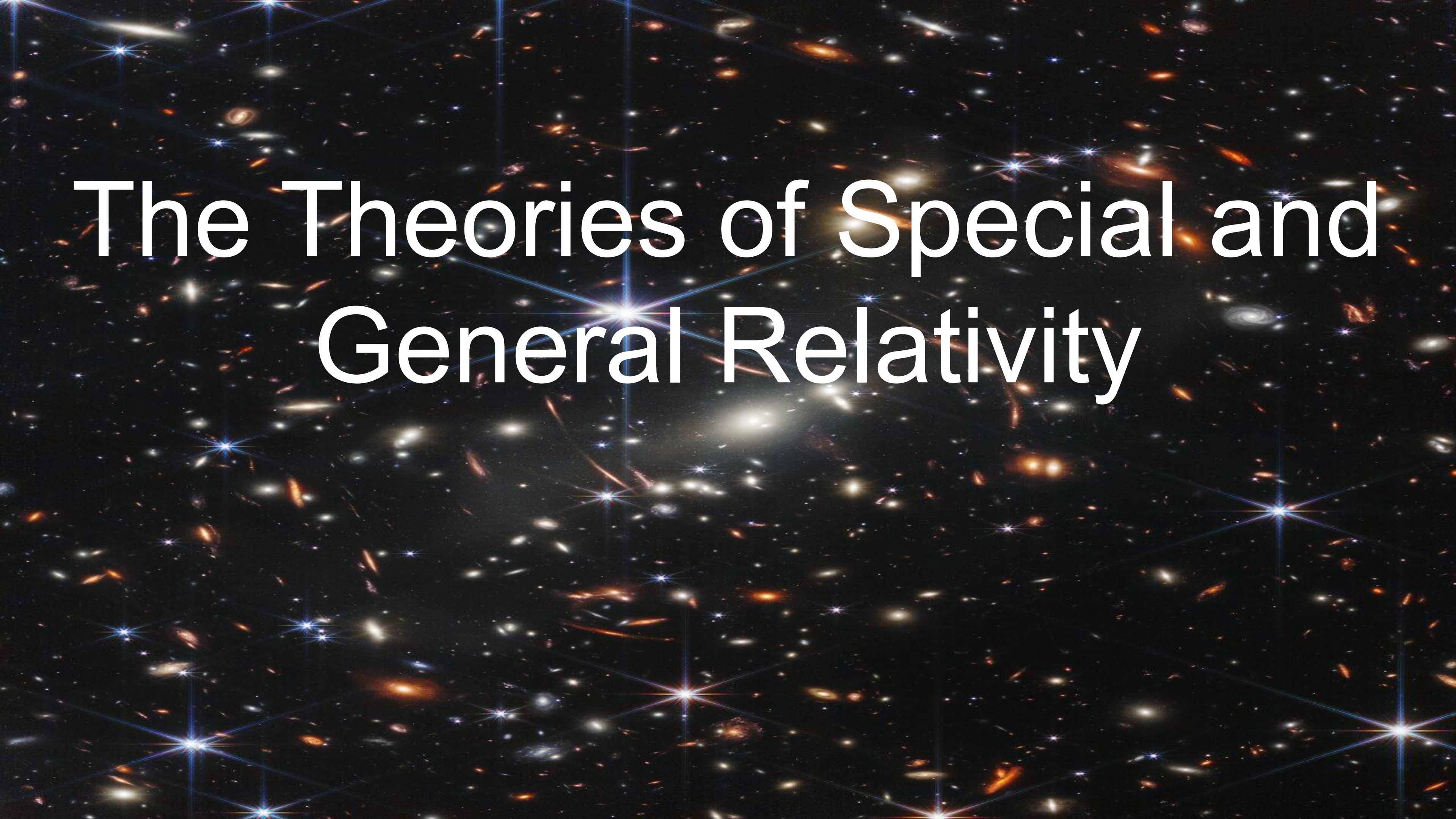
The Theories of Special and General Relativity



Rooftop observing

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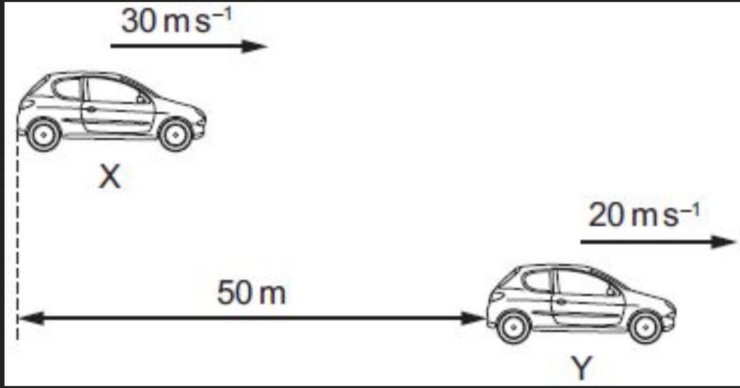
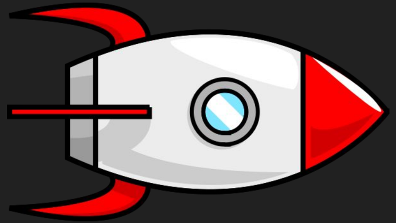
Thanks to all those who came!

Relative motion

- What happens when a stationary observer and a moving observer see a fast-moving car?
- The stationary observer measures the fast car to be moving at 30 m/s, while the moving car measures 10 m/s
- What happens when we move at 99% the speed of light? Does light move slower?
- Classical physics says yes





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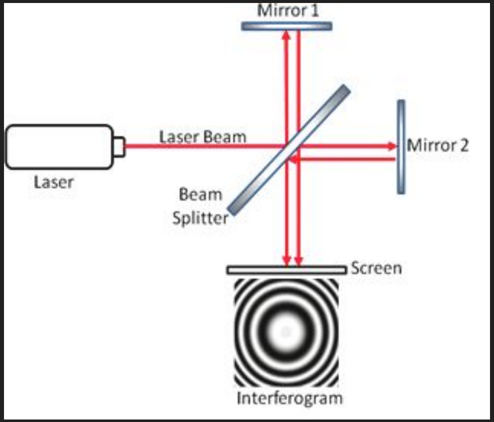
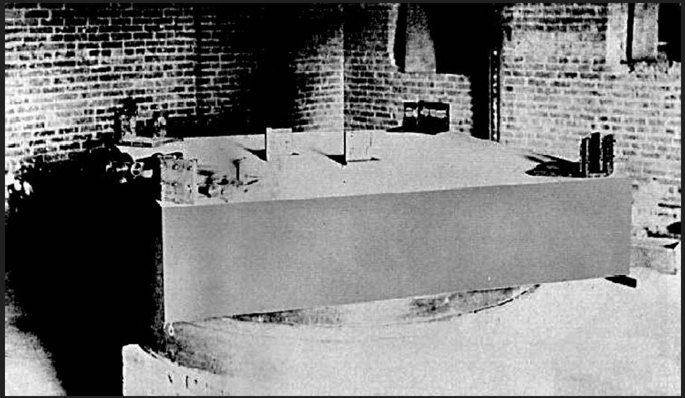
Michelson-Morley experiment

- Using interferometry, Michelson and Morley attempted to measure this difference in speeds
- Null result
- There was absolutely no difference in the speed of light in any direction
- Light moved at the same speed in all directions





Special Relativity

- Two postulates:
    1. The laws of physics are identical for everyone, regardless the velocity at which they are moving.
    2. The speed of light, c = 3×10^8 m/s, is constant for everyone. It is the fastest possible speed in the universe, and nothing travels faster than light.
- Time and space change with an observer's velocity
- Valid only for constant velocity
- This can entirely be described with high school-level math.

Time dilation

- Clocks tick differently for different observers
- Rest frame: Δt
- Moving frame: Δτ
- One second is not the same as one second for an observer on the rocket ship mentioned earlier!

$$\Delta t = \gamma \Delta \tau$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Poll everywhere

A clock on a rocket ship moving at 99% the speed of light measures a time interval of one second. What does an observer on Earth measure?

When poll is active respond at **PollEv.com/nikhilpatten355**

Send **nikhilpatten355** to **22333**

$$\Delta t = \gamma \Delta \tau$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Poll everywhere

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[results]

Length Contraction

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- Two observers measure the same speed of light
- Time dilation means an observer's time interval is larger than a stationary time interval
- Length must decrease to maintain constant velocity
- Rest frame: L_0
- Moving frame: L

$$L = \frac{L_0}{\gamma}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

General Relativity

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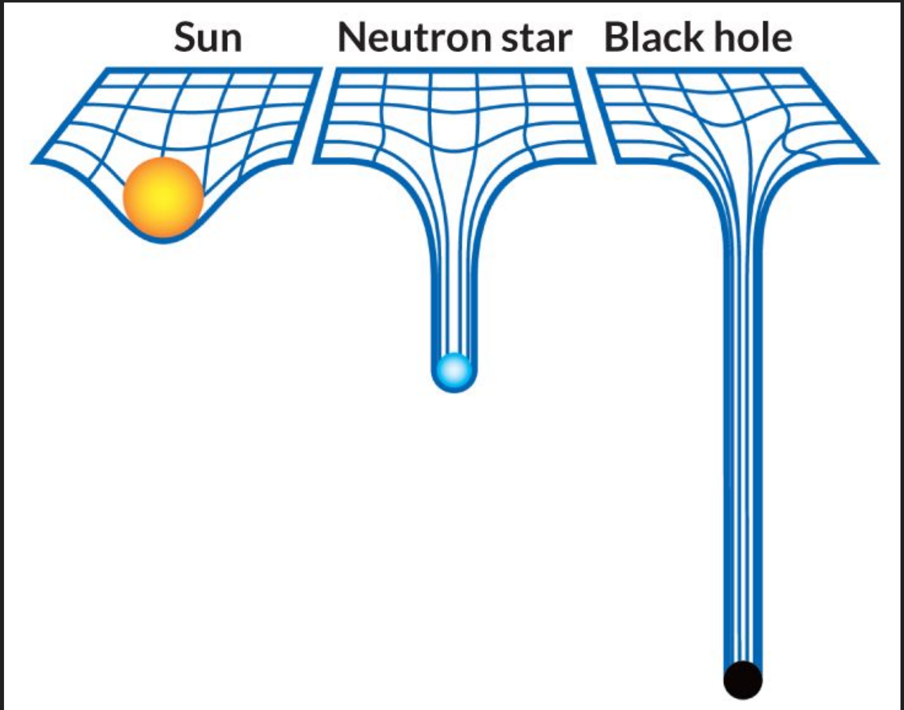
- SR only valid for constant v
- Things hardly ever move at constant v. Gravity (and other forces) cause objects to accelerate
- Einstein needed to incorporate gravity into SR
- Led him to understand gravity not as a force, but a geometric effect, a curvature of spacetime



General Relativity

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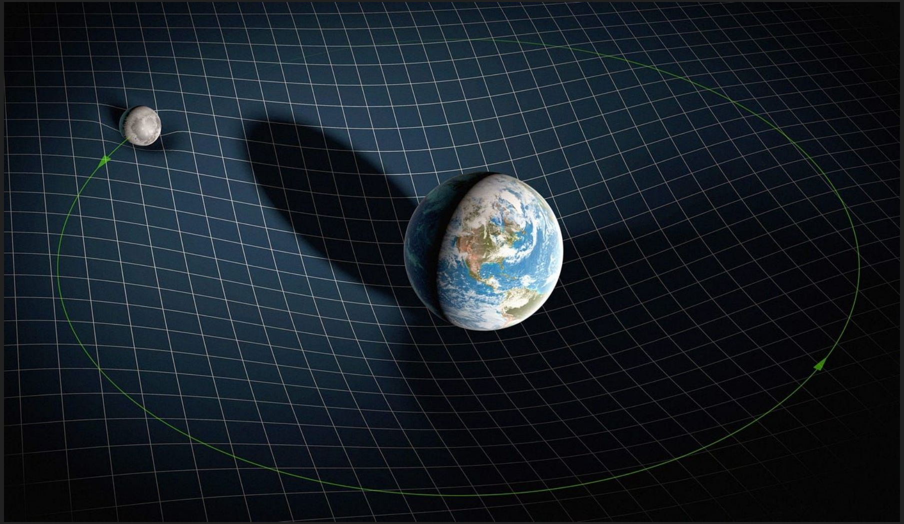
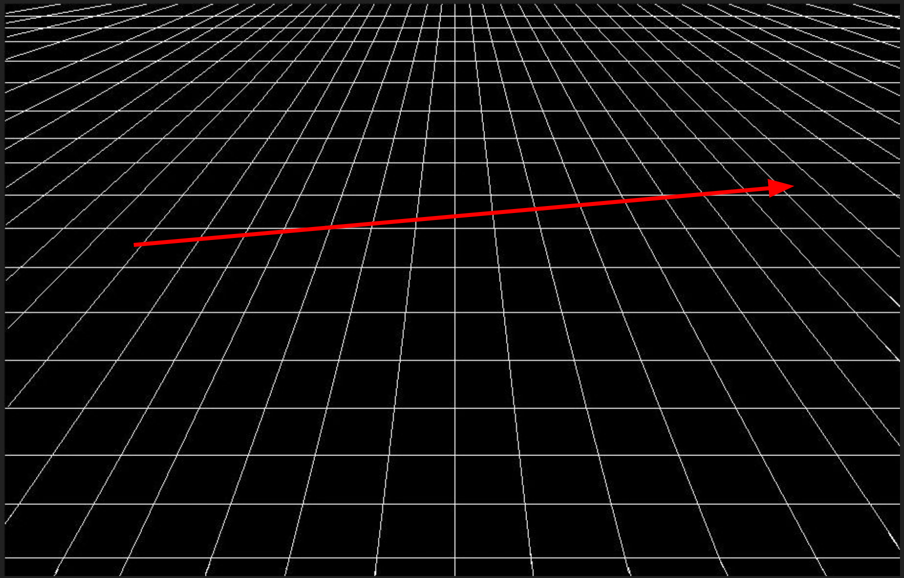
- Einstein's GR tells us how objects in spacetime are accelerated by gravity
- Objects tell spacetime what shape it is
- Curved spacetime tells objects how to move
- Gravity is a geometric effect, it is the curving of space time around masses



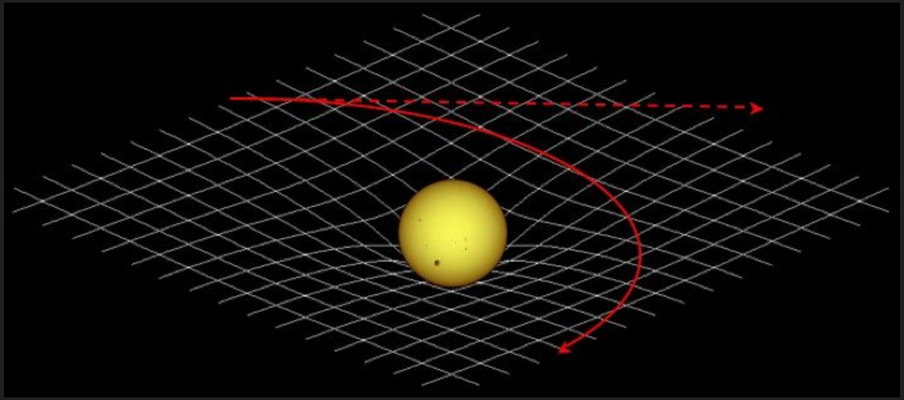
Flat spacetime

- No matter = flat spacetime
- Things roll along at constant speed, nothing speeds up, slows down, no change in direction



Curved spacetime

- Massive object = indentation in spacetime
- The underlying space an object is passing through is curved by placing a mass in it
- Because gravity is really curved spacetime, a mass can even accelerate a massless object (such as light)



Gravitational lensing

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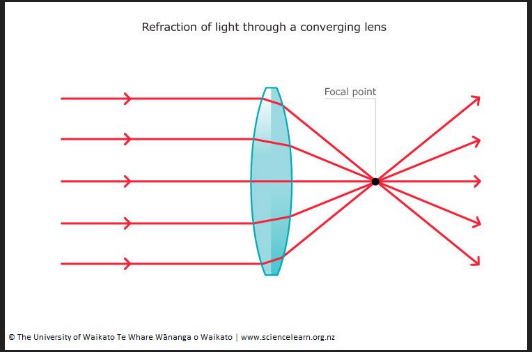
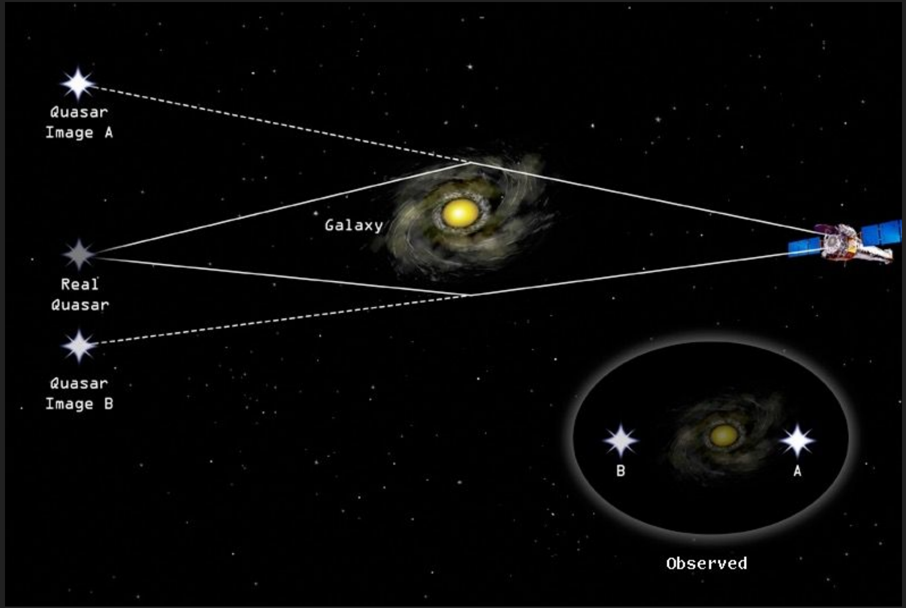
- If a distant object is behind a massive object, light from the background object is bent around the foreground object, and can create multiple images
- Similar to a lens





Proof of GR 1: Precession of Mercury's perihelion

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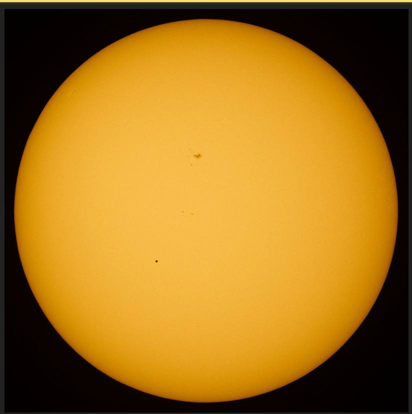
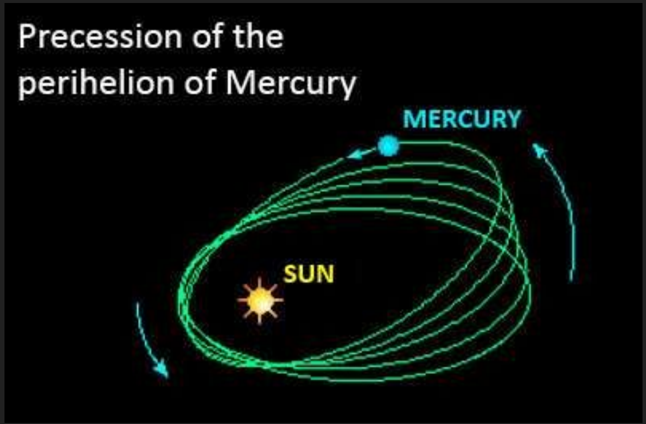
- Mercury perihelion precesses each orbit
- Exceeds Newtonian prediction
- Beautifully explained by General Relativity
- GR predicts elliptical orbits will precess
- GR predictions match up precisely with Mercury data, a beautiful confirmation





Proof of GR 2: Gravitational lensing

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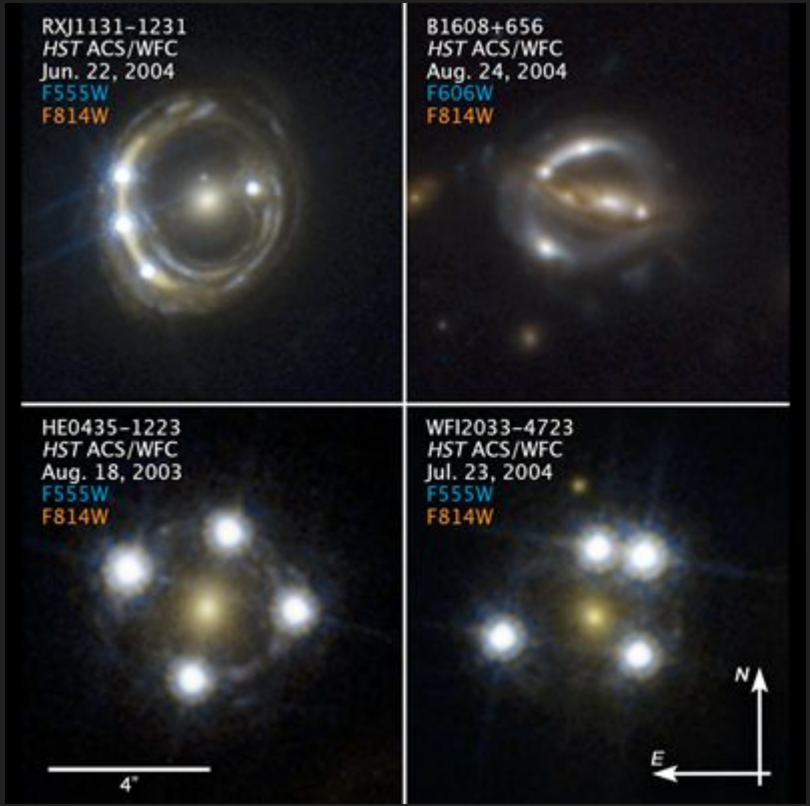
- There is only one background quasar in each system but there are multiple images of it
- Light travels in all directions from background quasar, but it is bent by the massive foreground galaxy
- Just as predicted by Einstein's Theory
- Different orientations lead to different images



Weak lensing

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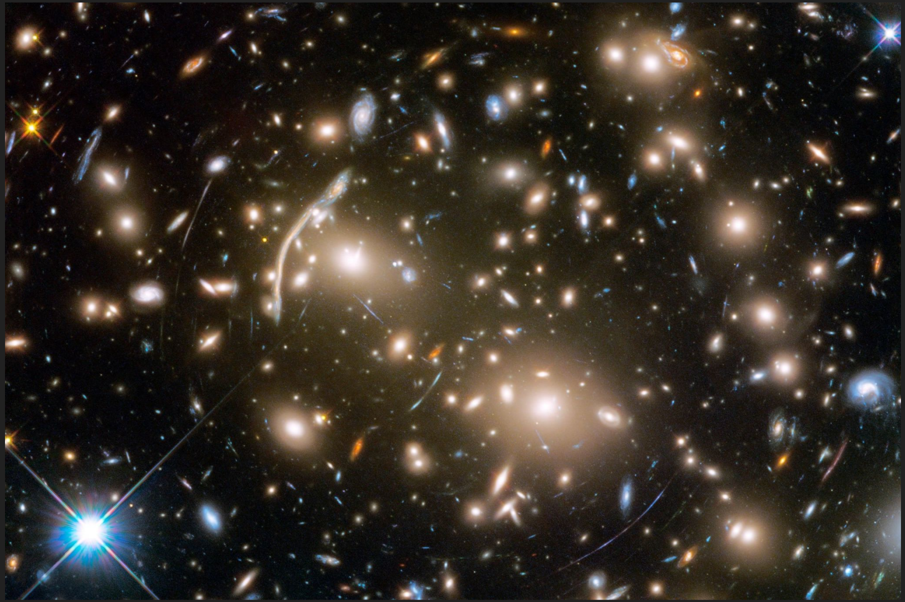
- Sometimes we don't get multiple images, we just get distorted images.
- Less mass
- The amount of distortion tells us the distribution of mass in the cluster that is warping spacetime



Proof of GR 3: Eddington and the 1919 eclipse

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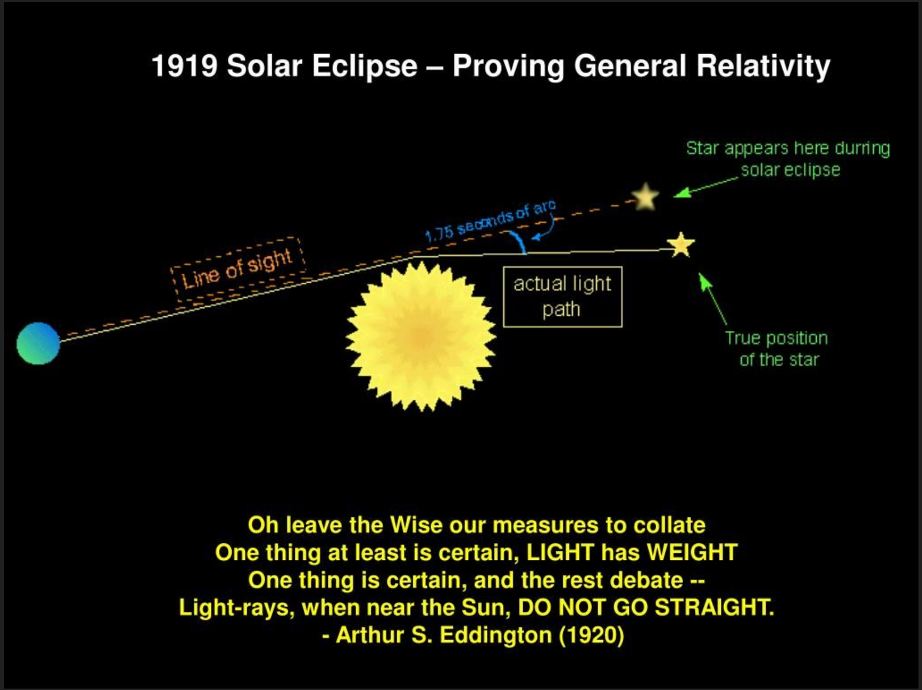
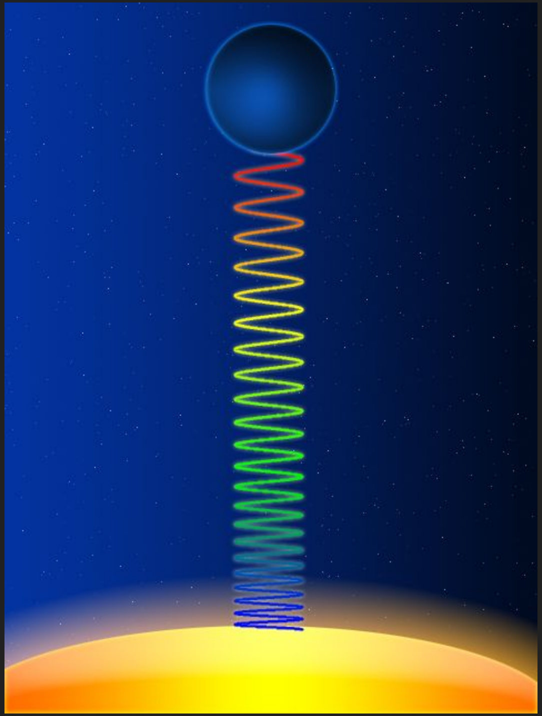
- Sun curves spacetime
- A star grazing the Sun should be deflected by the massive Sun
- Observers around the world measure the precise positions of stars during the 1919 total solar eclipse
- Deflection matches GR predictions precisely



Proof of GR 4: Gravitational redshift

- Light leaving highly curved spacetime will lose energy, ie. become redshifted
- Light entering highly curved spacetime will gain energy, ie. become blueshifted
- Spectroscopy of white dwarf Sirius B (very dense, curved spacetime) matches GR predictions exactly.
- First measured by Poundand Rebka in 1959



Proof of GR 5: Gravitational waves

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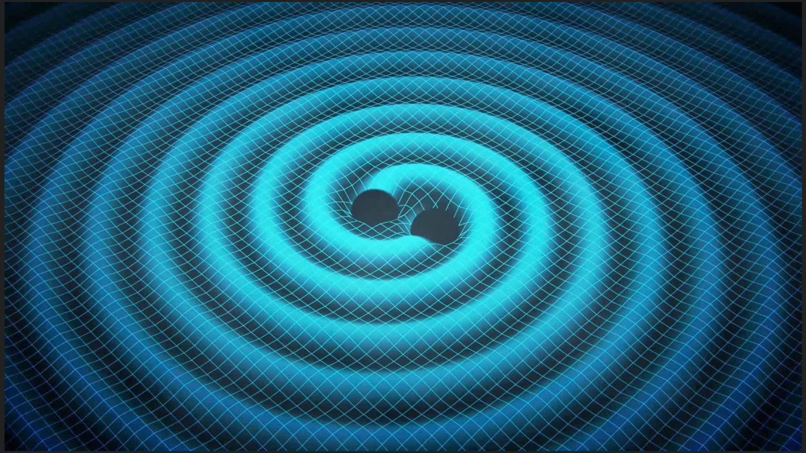
- Highly massive objects curve spacetime
- Two massive objects moving with respect to each other should propagate ripples in spacetime
- Merging massive compact objects lose energy in the form of gravitational waves
- We can detect this loss by the sudden change in gravitational waves
- First detected by LIGO in 2015



Falling into a black hole

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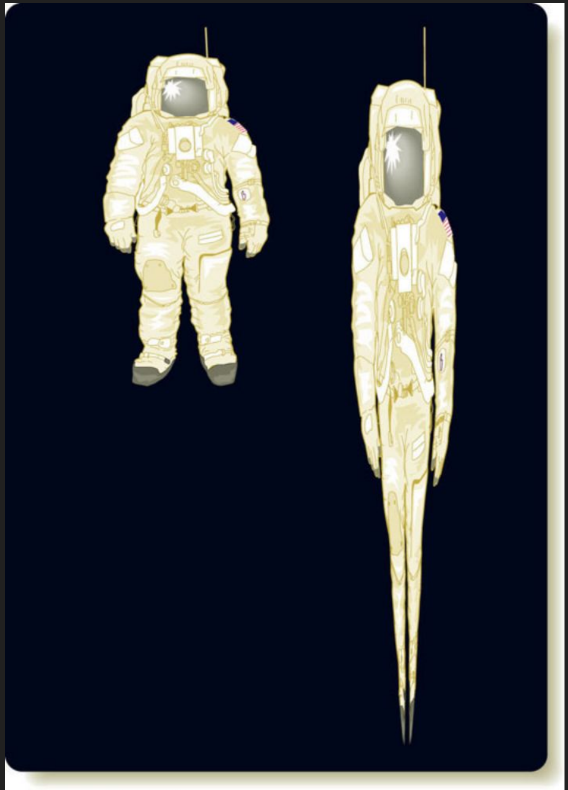
- Imagine that you are in free-fall into a 3 $M_\odot$ black hole from your rocket ship 1 AU from the black hole
- You would fall slowly at first, accelerating as you approach the black hole
- Your watch would show it took about 2 months for you to approach the event horizon

Spaghettification

- Near the event horizon, you would feel your feet being pulled more strongly than your head
- The relative difference in acceleration between your head and feet is about 100 million g
- The tidal force would kill you long before you cross the even horizon



From your rocket ship 1 AU away

- Imagine you have a blue light on your space suit blinking once per second
- As you approach the event horizon, the light will blink more slowly and look more red
- As you cross the event horizon, time is fully dilated and light fully redshifted
- The photons that leave you as you cross the event horizon are the last ones the rocket ship sees
- Your light would appear very red (radio waves) and you'd appear frozen forever at the event horizon

Looking out from the event horizon

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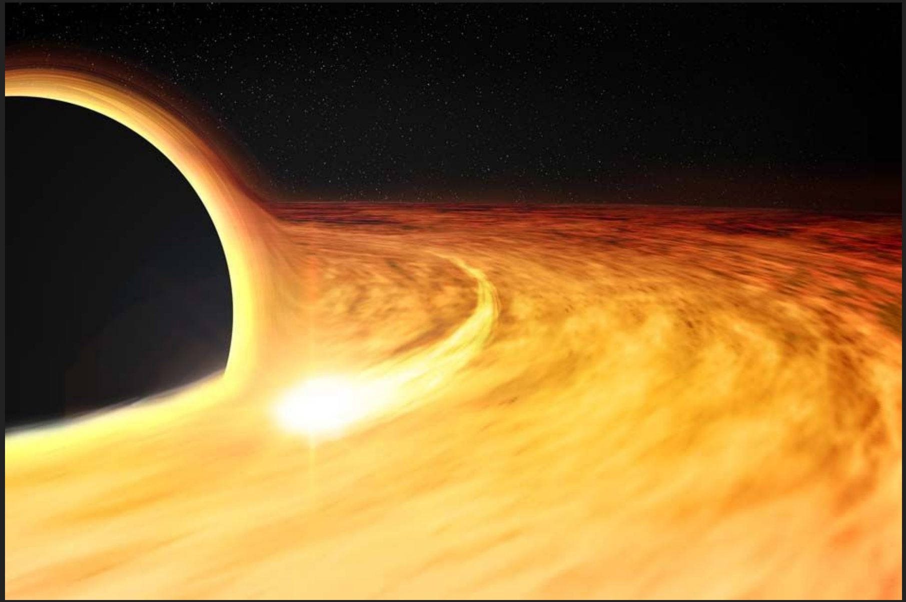
- Imagine you hover just above the event horizon
- Light from outside the black hole would appear perfectly blueshifted (gamma rays) and anti-dilated (sped up)
- You would watch all the remaining events in the universe play out. All the stars and galaxies in the universe die in an instant
- The universe would look infinitely blue and you would be incinerated by the high-energy gamma radiation the universe emits



Next time

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- The Great Debate