Black Holes

Evolution of stars

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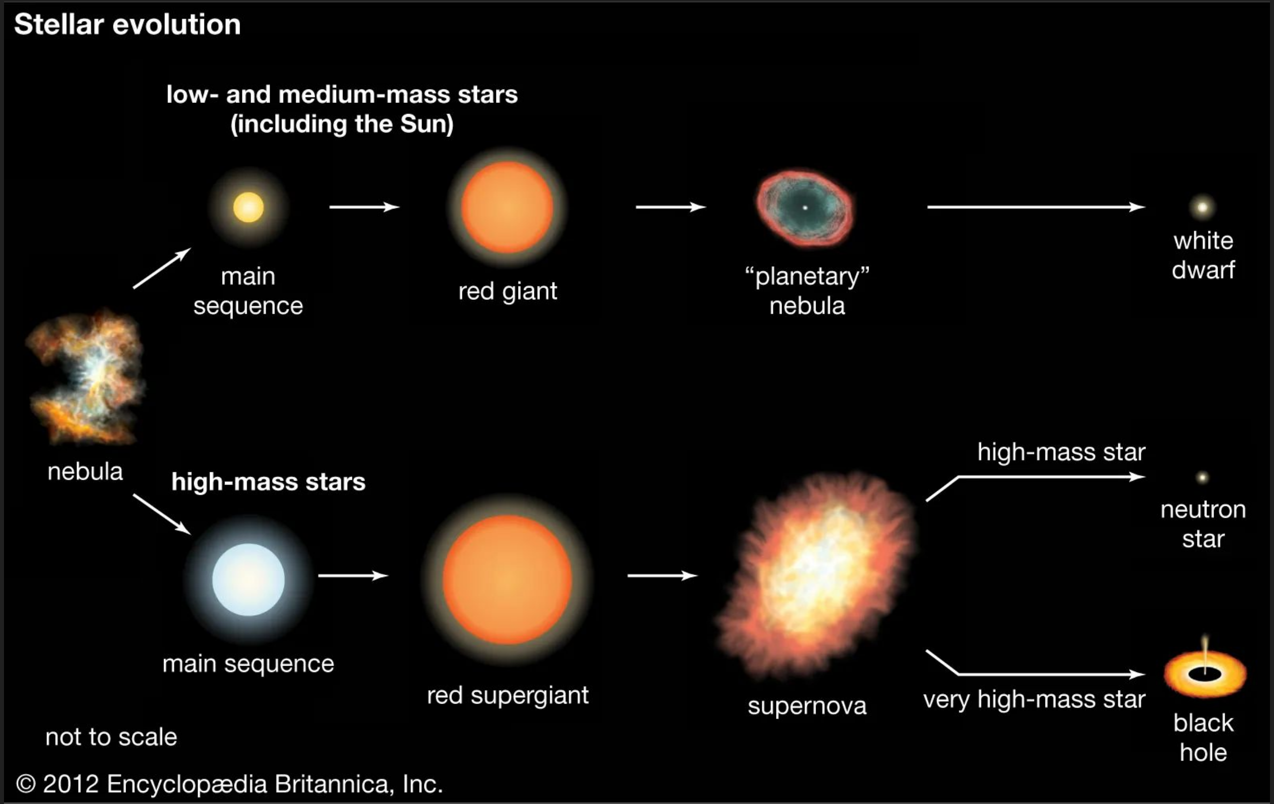
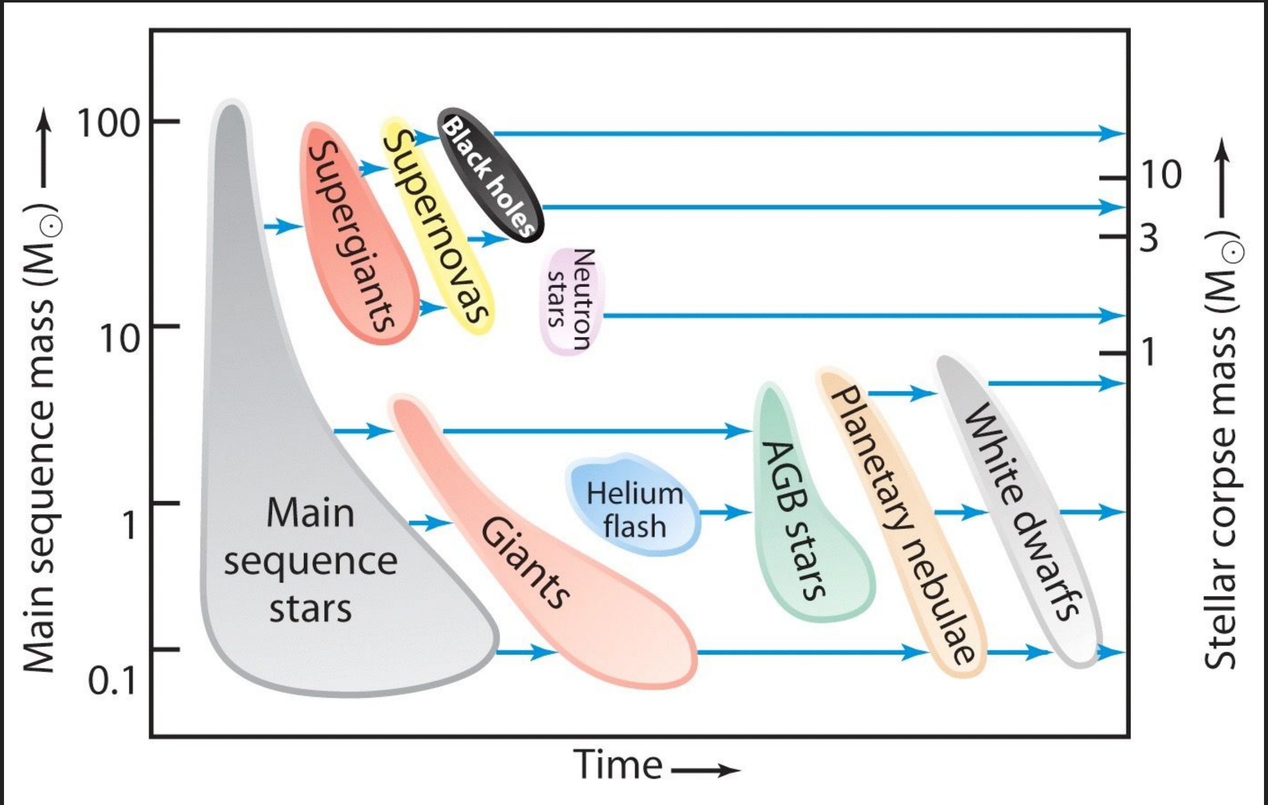


Evolution of stars



Neutron stars

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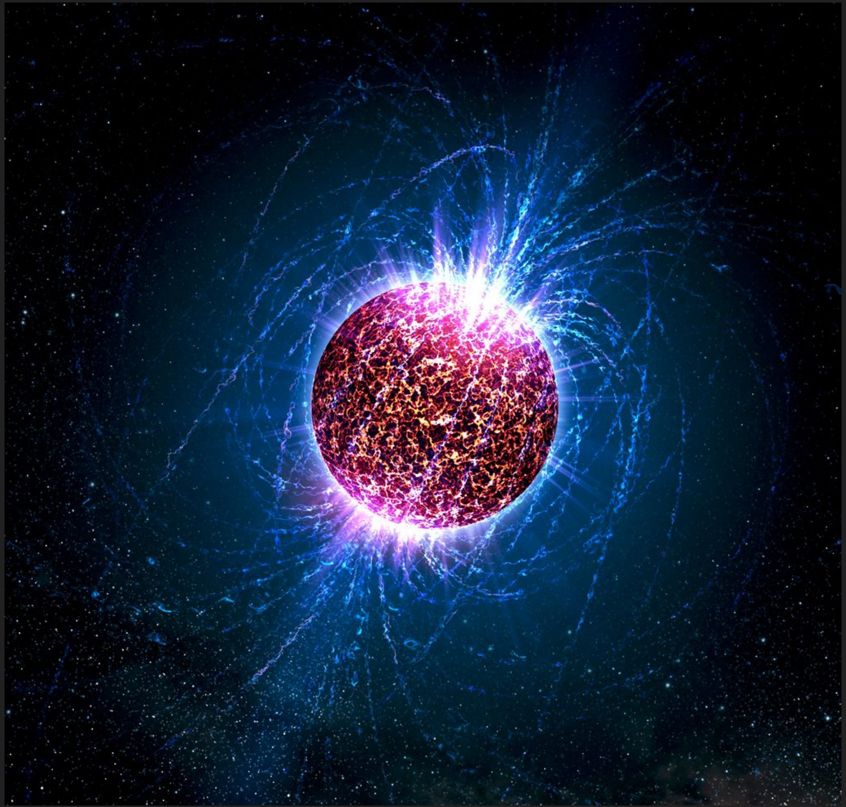
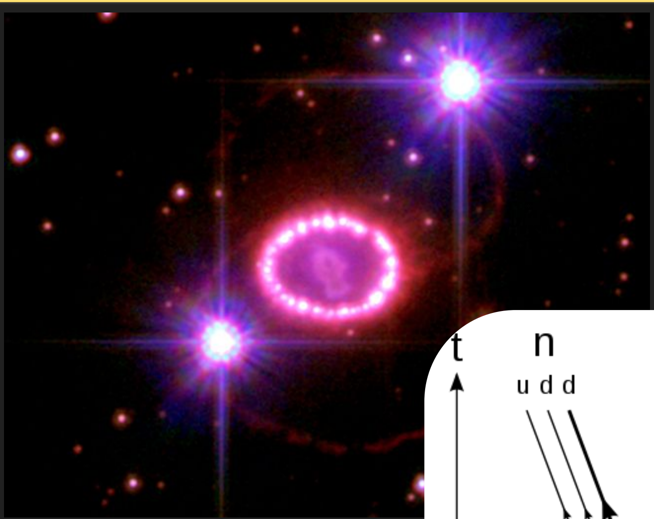
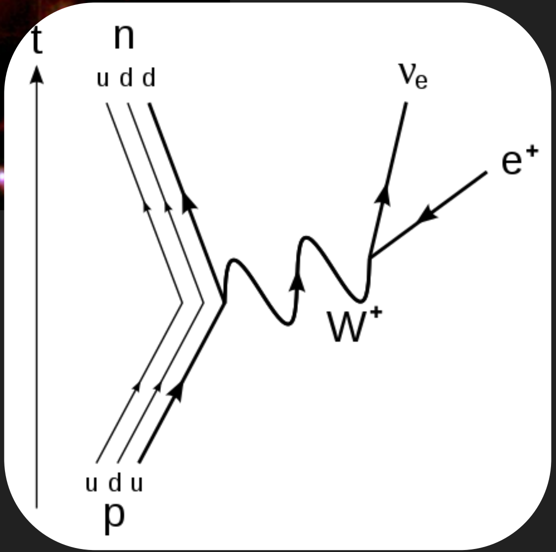


Neutron stars

- What's left after a Type II supernova—core collapse
- About 1.4–3 $M_{\odot}$
- Composed of a sea of neutrons
  - The protons and electrons are squished together and forced to become neutrons
- Neutron star supported by neutron degeneracy pressure
- A teaspoon of a neutron star on Earth would weigh almost 1 billion tons
- Surface gravity—200 billion g
- Escape velocity—half the speed of light





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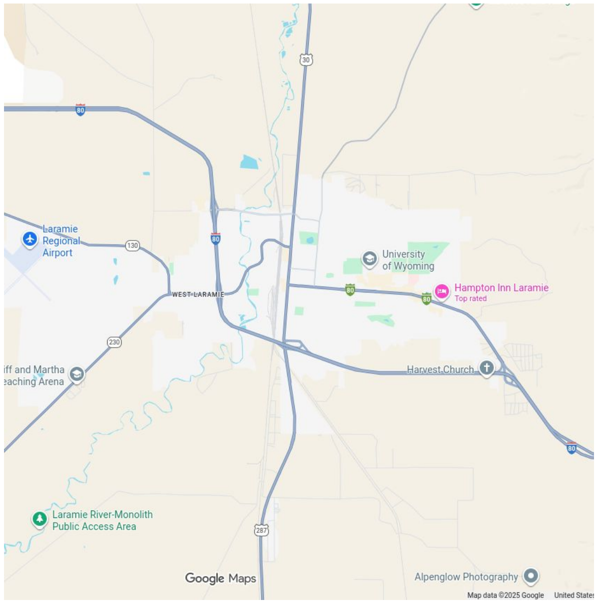
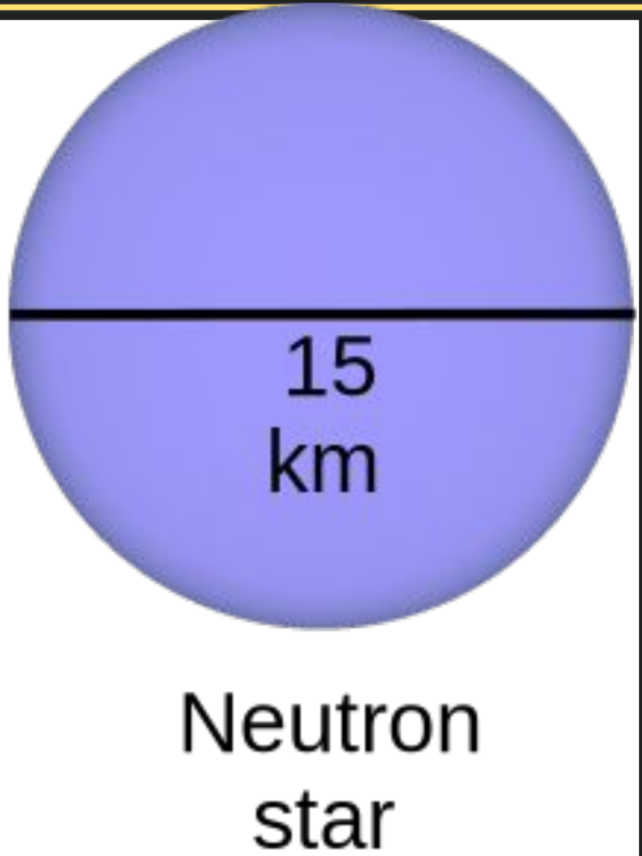
Neutron star size

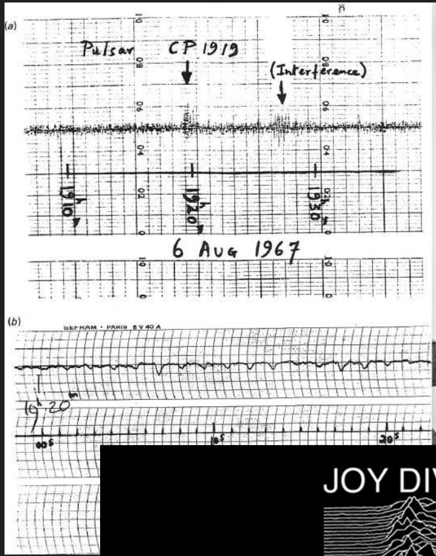




Pulsars

Pulsars

- In 1967, Jocelynn Bell and Anthony Hewish found radio pulses in the constellation Vulpecula that repeated precisely every 1.337 seconds
- Called LGM-1 (Little Green Man 1) because of how precise it was
- Soon realized this was actually spinning neutron stars



What are pulsars?

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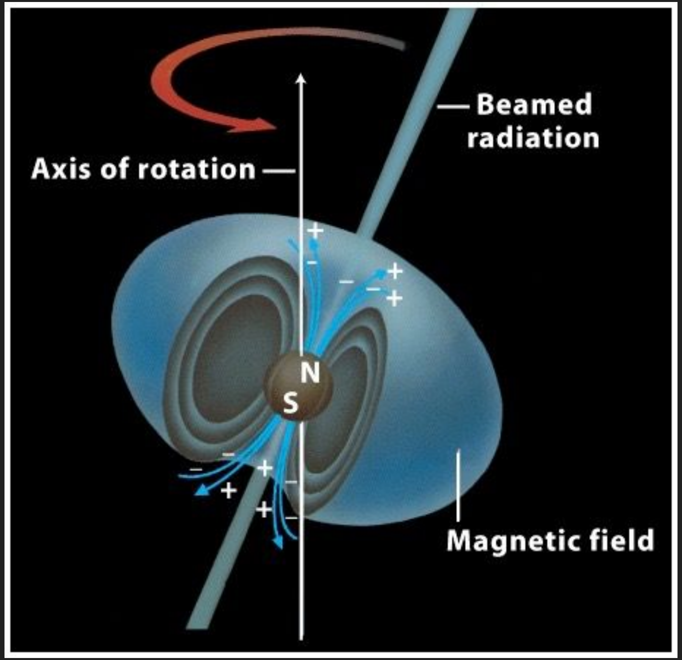
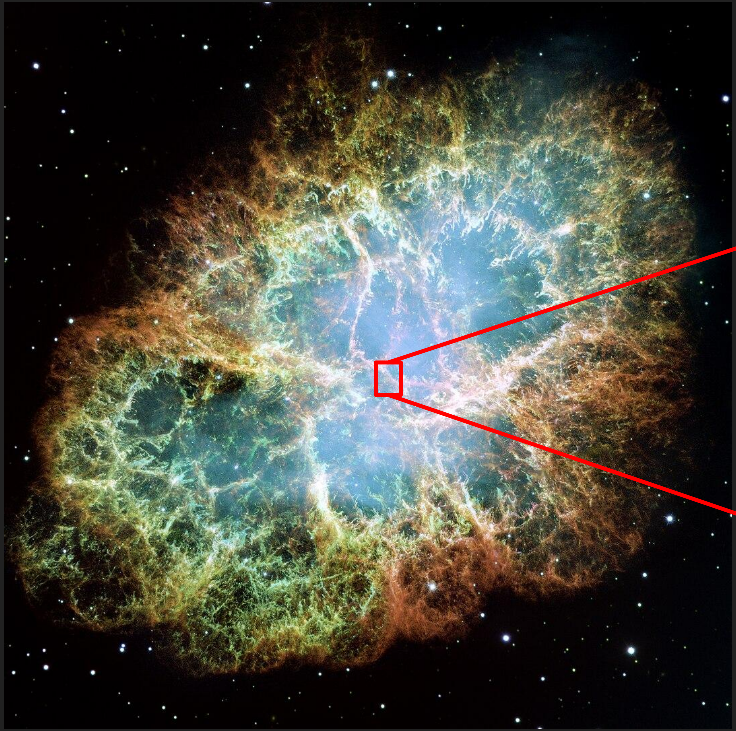
- When the core collapses, its spin and magnetic field strength increase dramatically
- Surface B field strength over 1 trillion times that of Earth
- Rotate 1000 times per second
- Magnetic field beams radiation into space
- Like a rapidly spinning radio lighthouse
- If the Earth is in the beam’s path, we see a pulsar



Crab Nebula — A supernova remnant

Optical—HST



X-Ray—Chandra

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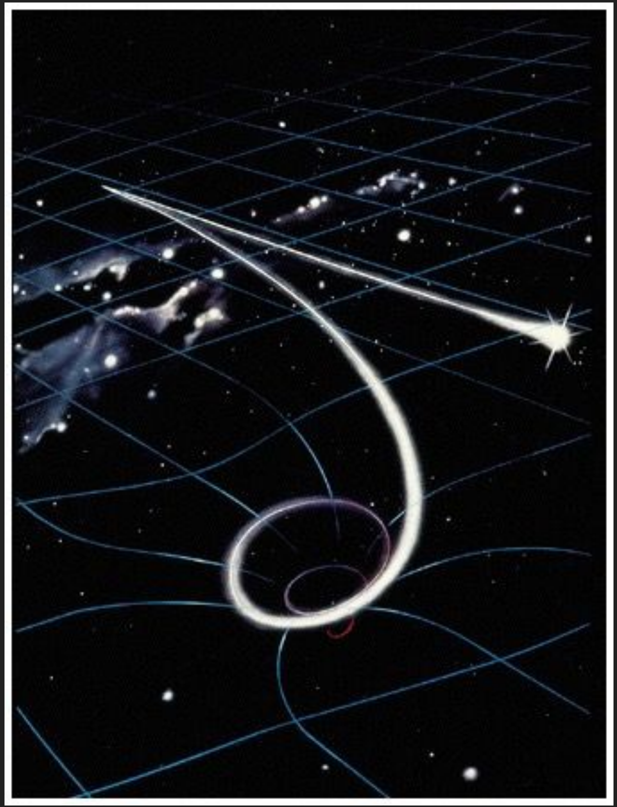
When neutron degeneracy isn't enough

- The maximum neutron star mass is about 3.0 $M_\odot$
- Above this mass, neutron degeneracy cannot stop gravity
- There is nothing left to stop the total collapse into a black hole
- The point at which even light can't escape gravity (General Relativity)



How do we see a black hole?

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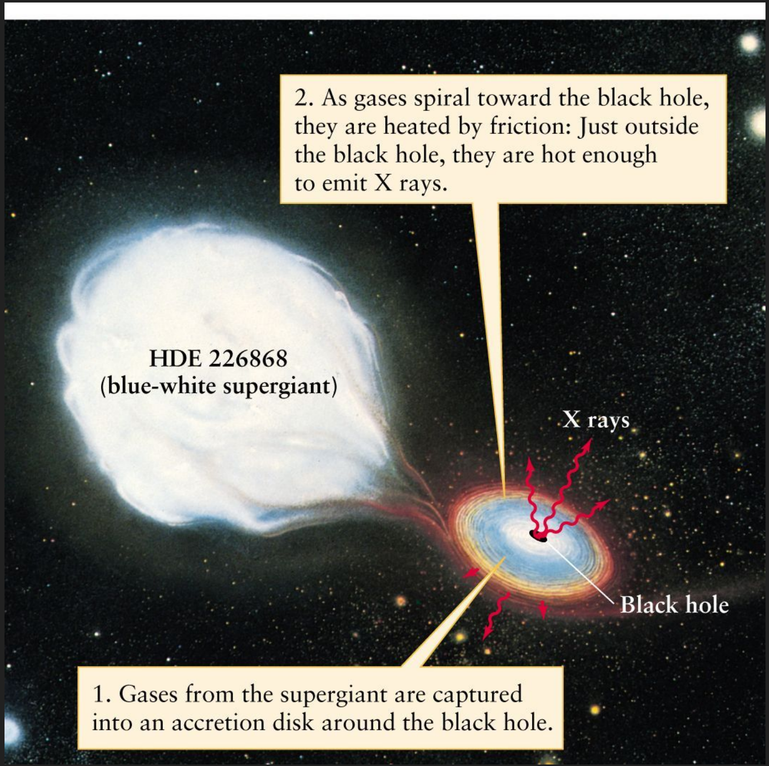
- Similar to measuring the mass of stars in a binary system, we can measure the mass of an invisible object from the orbit of another star
- If a black hole is in a binary system, it can steal mass from its companion
- Matter falling in towards a black hole forms an accretion disk, which slowly deposits matter onto the black hole



Cygnus X-1

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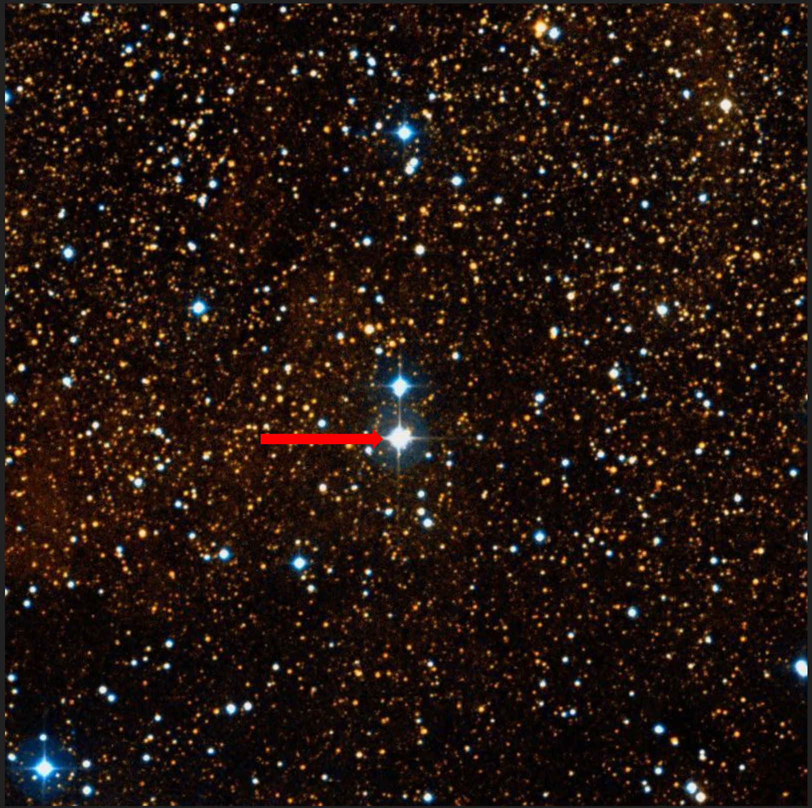
- A binary system with an unseen 15 $M_\odot$ companion
- Spectrum of X-ray emission consistent with material rapidly orbiting a black hole
- Rapid X-ray fluctuations suggest the object is only a few km in diameter
    - Nothing can travel faster than light, so time fluctuations tell you maximum size



Types of black holes

- Primordial: Formed from overdense regions of the early universe. Masses range from grams to planetary mass
- Solar-mass: Formed by the collapse of a massive stellar core. A few solar masses
- Intermediate-mass: Formed by collisions of stars at the dense center of clusters. Masses of hundreds to thousands of solar masses.
- Supermassive: Probably formed from the first generation of ultra-massive stars. Millions or billions of solar masses.

Sgr A*

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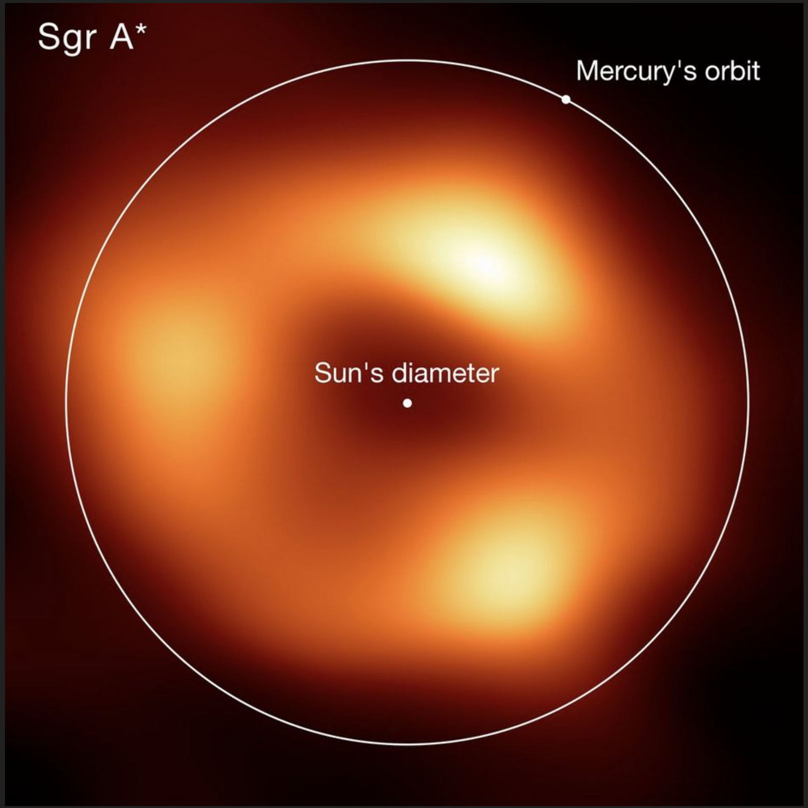
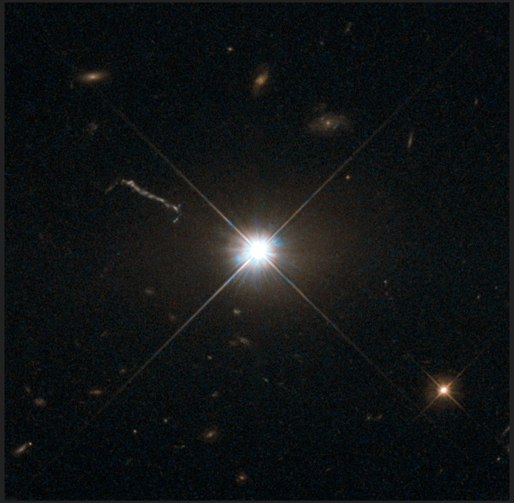


Quasars

- A supermassive black hole that is accreting material
- Known as active galactic nucleus (AGN)



Physics of black holes

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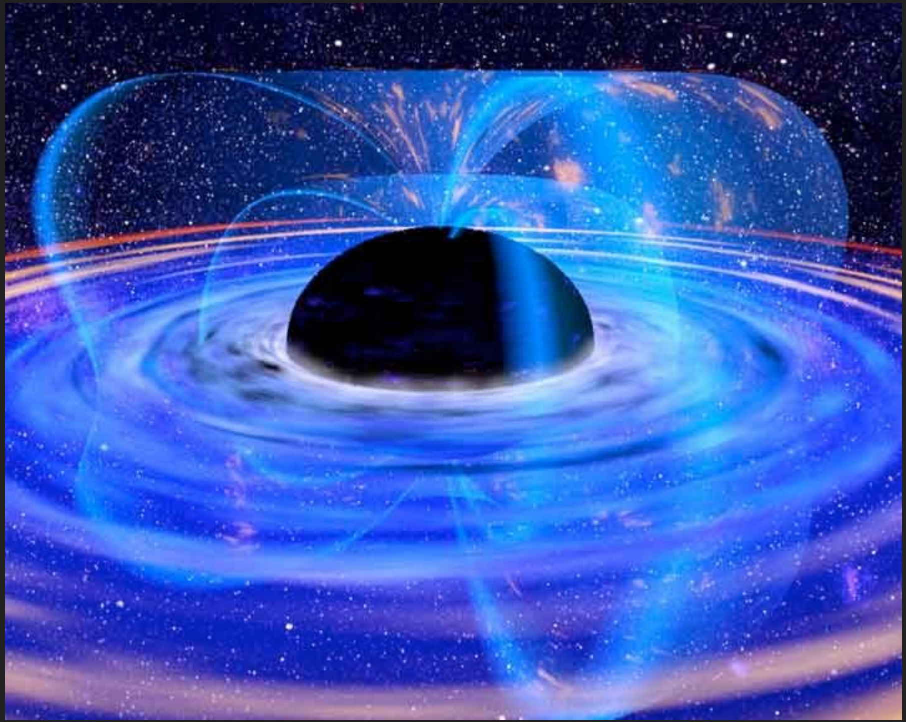
- Black holes are strange
- Intense gravity due to compactness
- Newton's Laws cannot accurately describe what happens in the presence of such intense gravitational field



General Relativity

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- To model black holes, you need Einstein's Theory of General Relativity (GR)
- GR is hard, you need tensor calculus
- This will be on the final
- Make sure you know how to do this, refresh on your own if you need

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

$G_{\mu\nu}$ is the Einstein tensor

Λ is the cosmological constant

$g_{\mu\nu}$ is the metric tensor

$T_{\mu\nu}$ is the stress-energy tensor

$$\kappa = \frac{8\pi G}{c^4}$$

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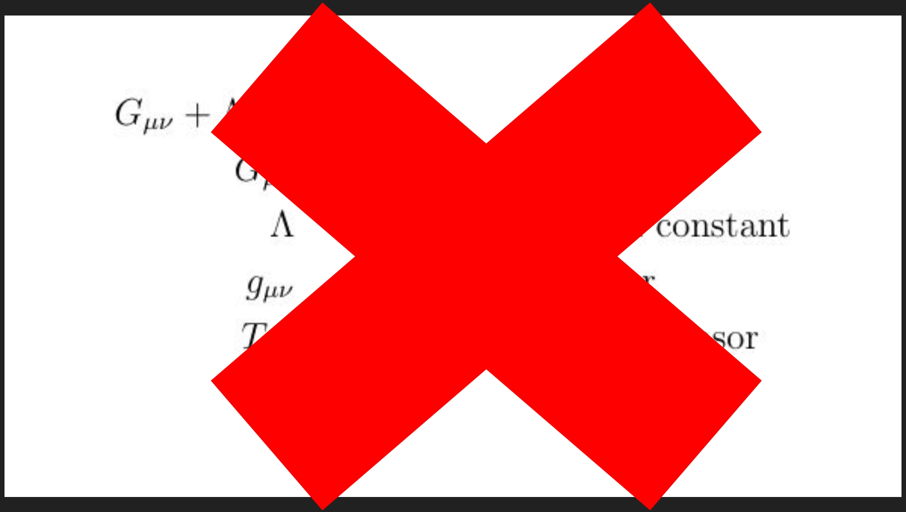

General Relativity

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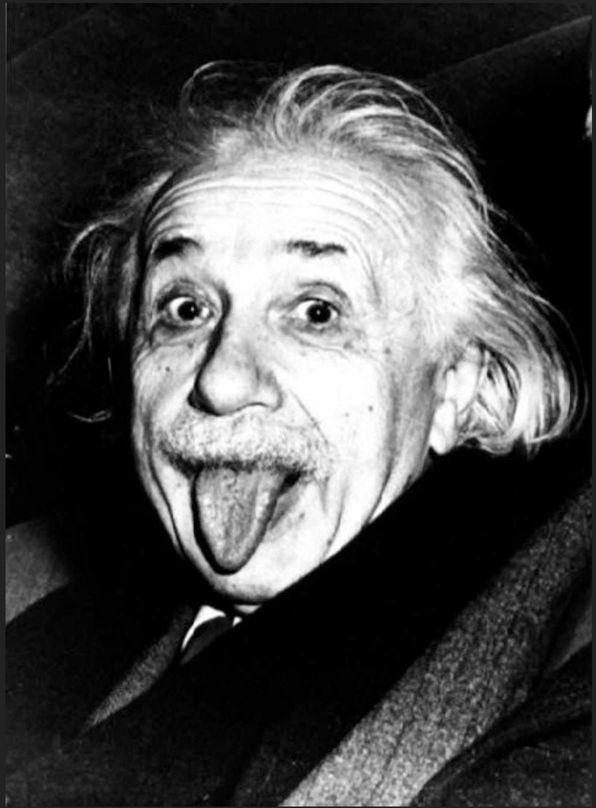
- Do not waste your time with GR
- I learned it only several years ago and forgot everything
- Just know that GR make cool predictions and results (more next class)



Schwarzschild radius

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- Matter bends space and time
- Intense gravitational fields cause time and space to alter, grouped together as spacetime
- All matter can form a black hole if compacted enough
- The Schwarzschild radius tells us the size of an object of mass m such that its surface is an event horizon—light cannot escape

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

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

$$c = 3 \times 10^{8}\ \mathrm{m\ s^{-1}}$$

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Poll everywhere

What size would you need to be to be made into a black hole? Take your mass to be 80 kg.

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

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

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

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

$$c = 3 \times 10^{8}\ \mathrm{m\ s^{-1}}$$

Poll everywhere

results

Far from a black hole, it looks like any other mass

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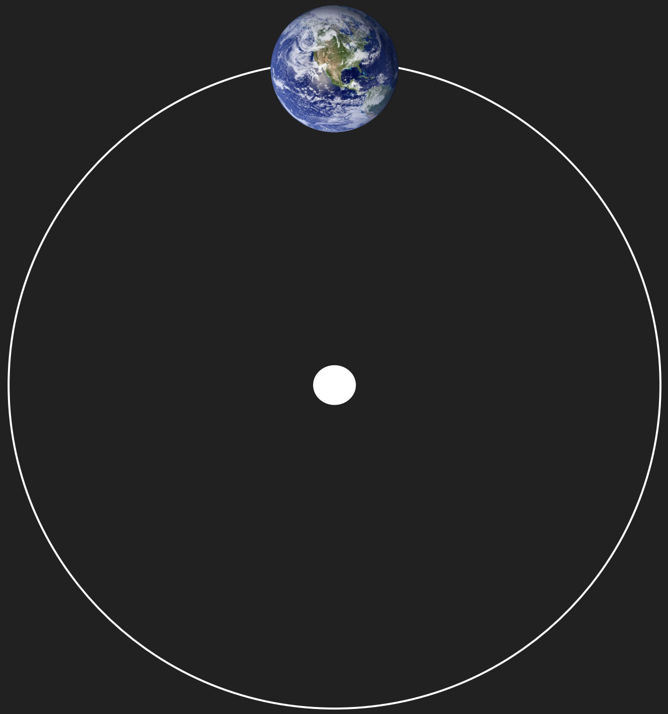

Rooftop observing

Tonight and Friday, 6:30–8:30 pm.

Meet near SW corner of PS





Next time

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- Black holes