Astronomy 122

HW8 due on Friday.

Mar Lecture report due in discussion class tomorrow.

Nightlab report due in discussion class on April 12th.

Nightlab makeup assignment available online (see assignments), also due on April 12th.

This Class (Lecture 20):

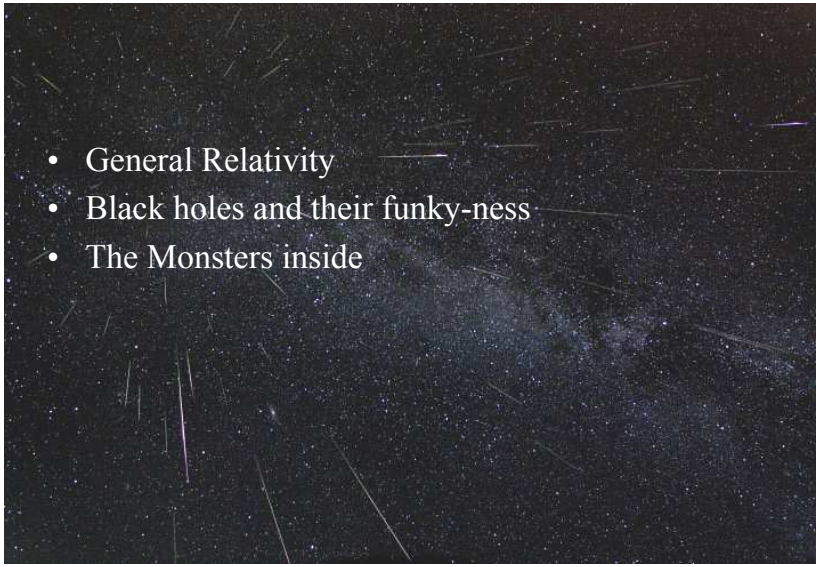
Black Holes

Next Class:

The Milkyway

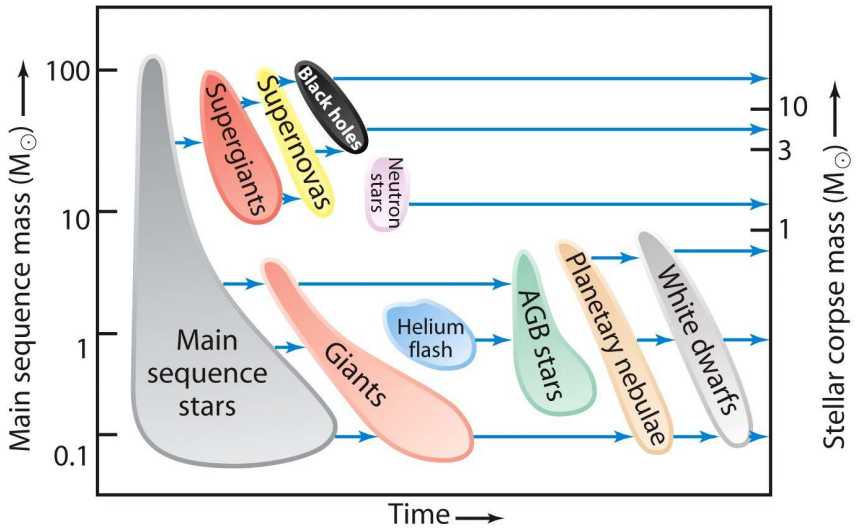
Music: *Rocket Man* – Elton John

Outline



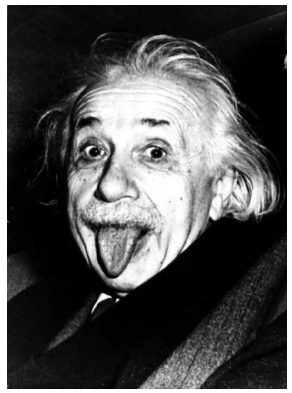
- General Relativity
- Black holes and their funky-ness
- The Monsters inside

Stellar Evolution Recap

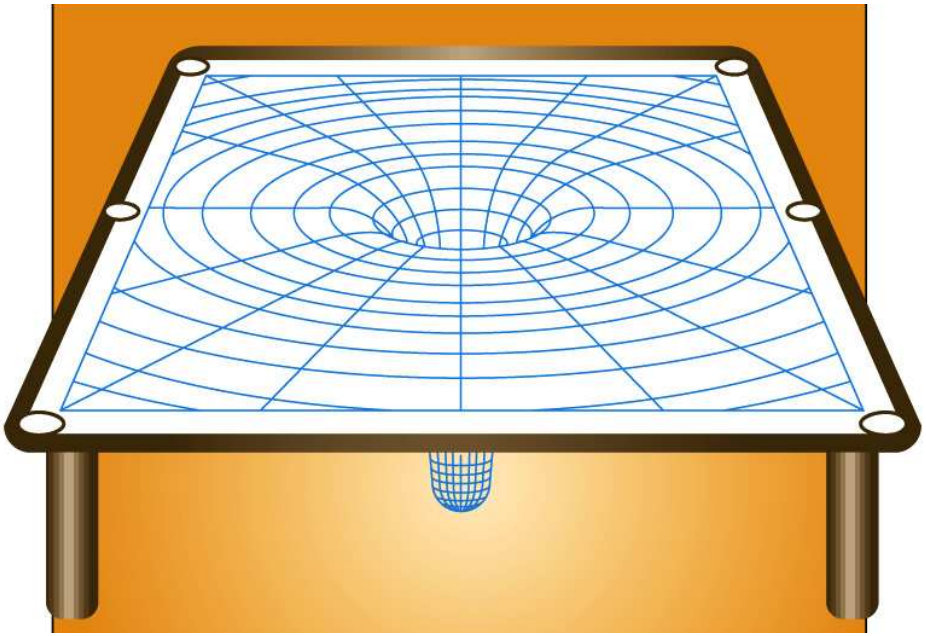


The Theory of General Relativity

- Einstein's Theory of Relativity tells us how gravity works
  - Space and time are not distinct
  - They are bound together in 4-dimensional **spacetime**
  - Matter tells spacetime how to curve
  - Curved spacetime tells matter how to move

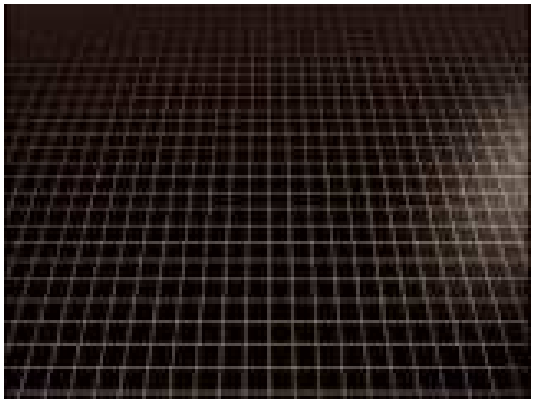


Curved Space



Curved Spacetime

- No matter = Flat Spacetime
- Massive object = Dent in Spacetime
  - Everything follows curvature of spacetime including light (photons)



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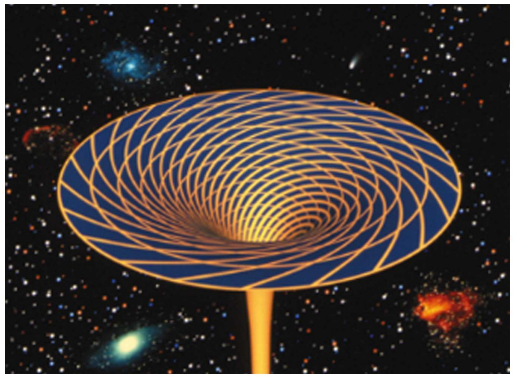
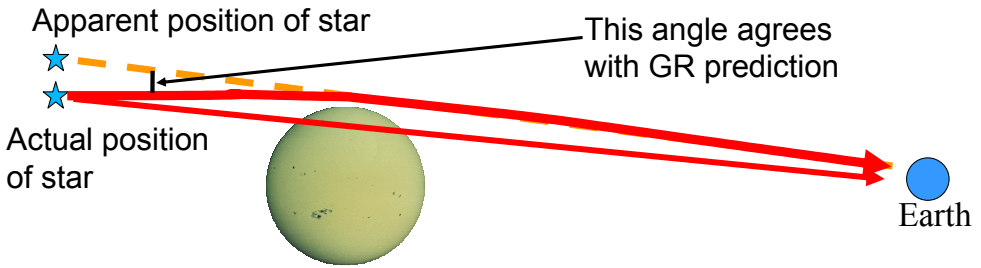
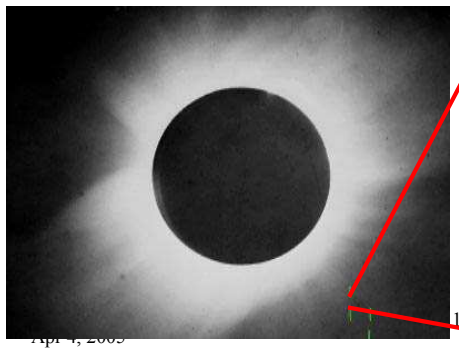
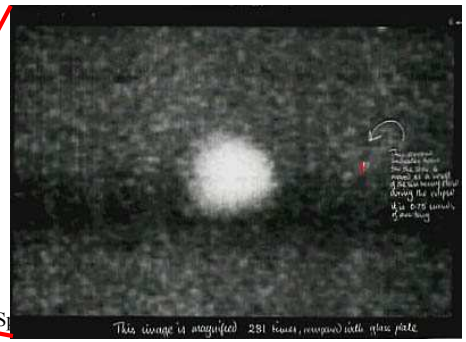


Eddington and the 1919 Eclipse

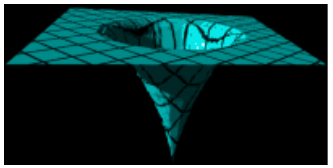


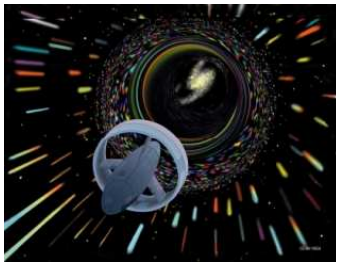




General relativity

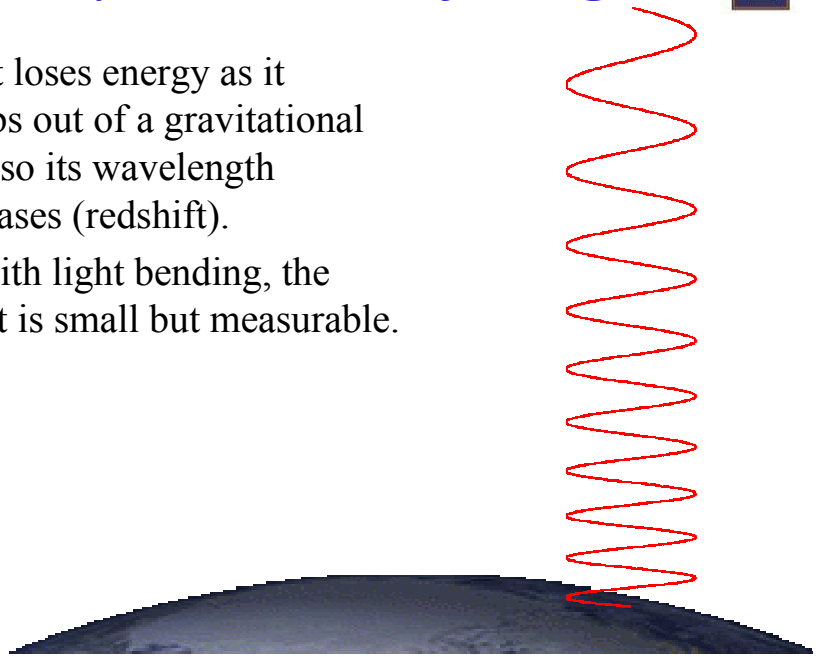
- Gravitational fields can also change space and time
  - A clock runs more slowly on Earth than it does in outer space away from any mass, e.g. planets.
- Einstein revealed that gravity is really 'warped' space-time.
- A black hole is an extreme example.



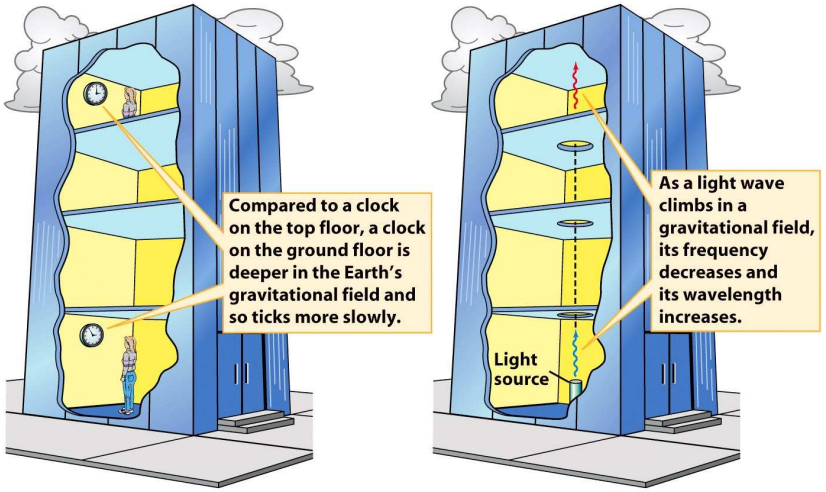


Gravity Also Redshifts Light

- Light loses energy as it climbs out of a gravitational field so its wavelength increases (redshift).
- As with light bending, the effect is small but measurable.



Gravity Redshifts Light



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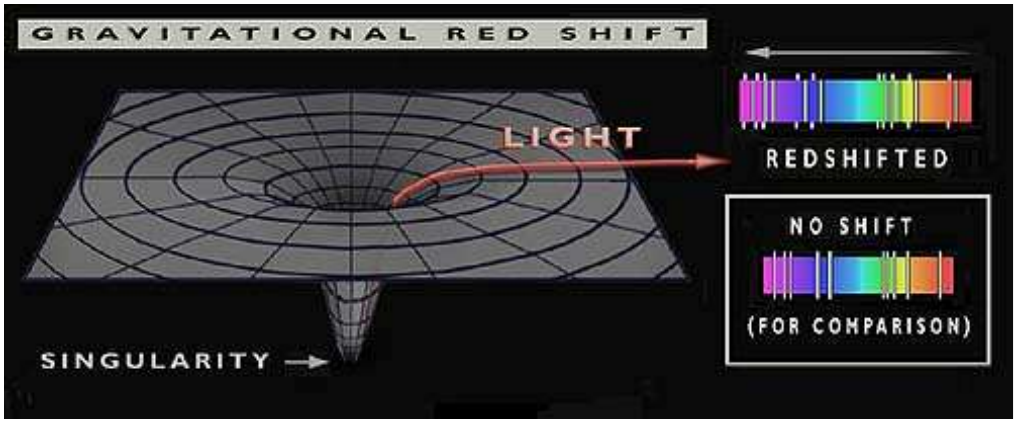
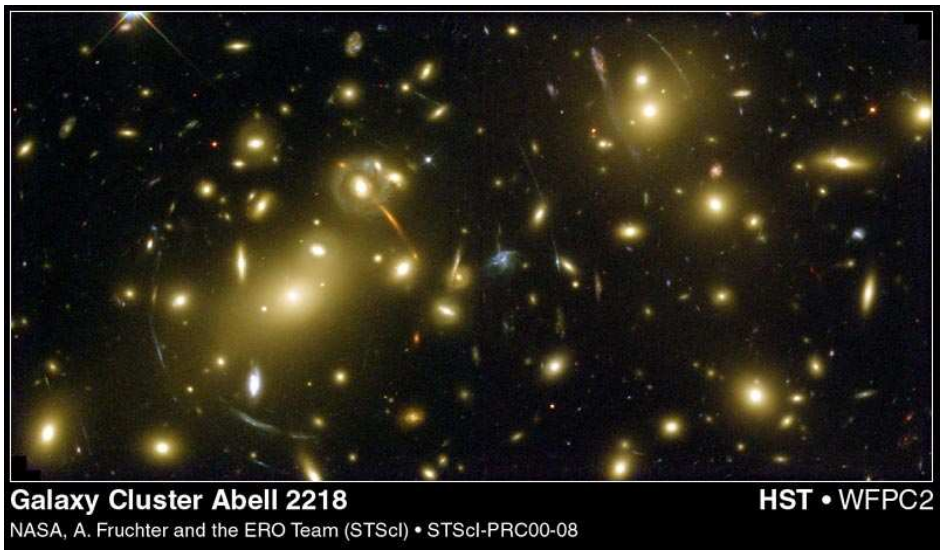


Einstein Lens



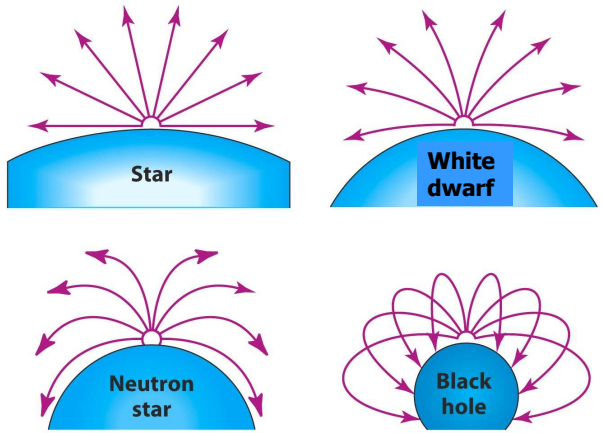
 http://antwrp.gsfc.nasa.gov/apod/ap000201.html

To each ones own

- From each other's view, things would appear normal, time and colors.
- That's the theme of relativity: if I only measure things nearby, I see normal things. Weirdness only happens at distance from observer or moving at great speeds relative to observer.

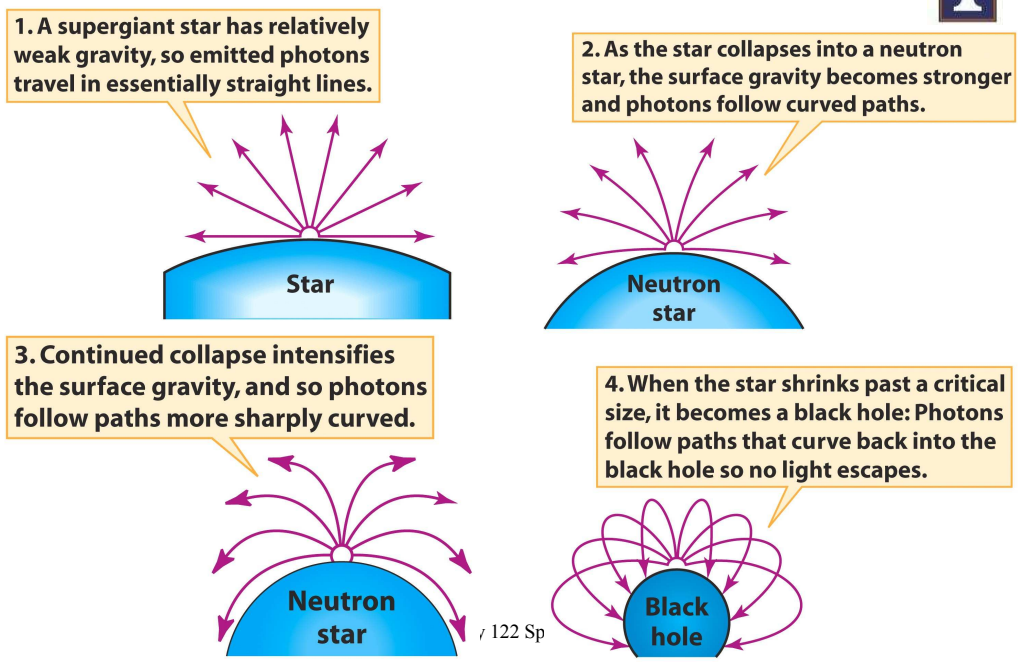
Back to Black Holes

- When matter gets sufficiently dense, it causes spacetime to curve so much, it closes in on itself
- Photons flying outward from such a massive object arc back inward!



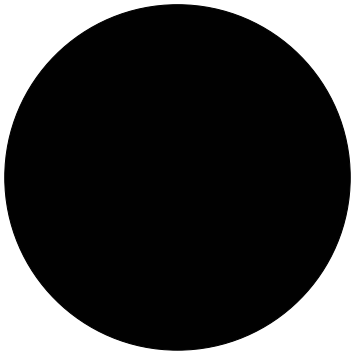
- Neither light or matter can escape its gravity, it is a **black hole!**

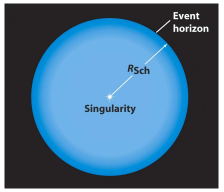
Black Holes



Black Holes Are Very Simple

They can have only
- Mass
- Electric charge
- Rotation (spin)

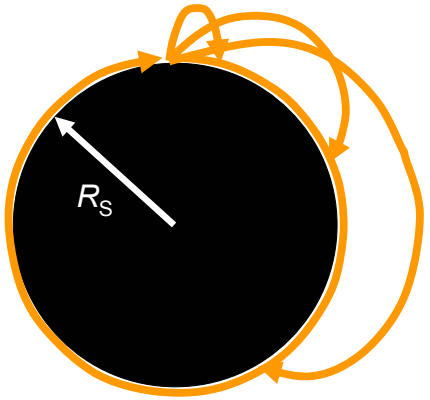




Black Hole

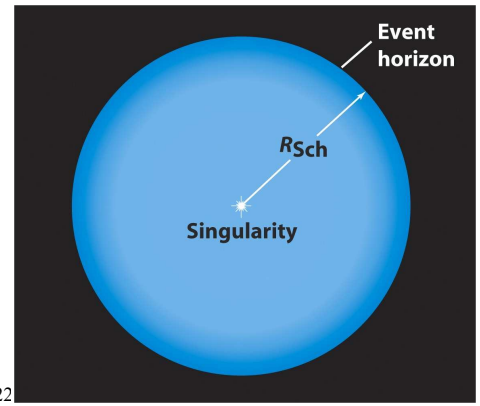
$$R_{Sch} = \frac{2GM}{c^2}$$

- The Schwarzschild radius
- More massive black hole = larger the event horizon
  - $R_{Sch} = 3\ (M/M_{\odot})$ km
  - If object's mass in radius < R_{Sch} then it's a BH
  - For Earth R_{Sch} = 1cm
- The radius of no return
- Cosmic roach hotel



Black Hole

- The matter in a black hole collapses to a point – called a **singularity**
- A black hole is separated from the rest of the Universe by a boundary, the **event horizon**
- Nothing can escape from within its radius
- This radius is called the Schwarzschild radius

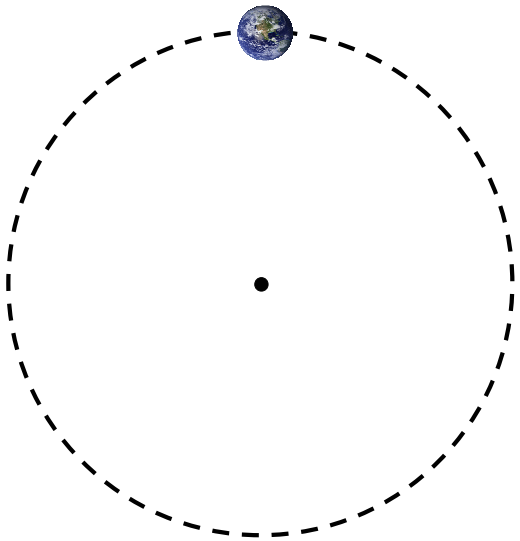


Thought Question

What do you think would happen to the Earth if the Sun collapsed into a black hole?

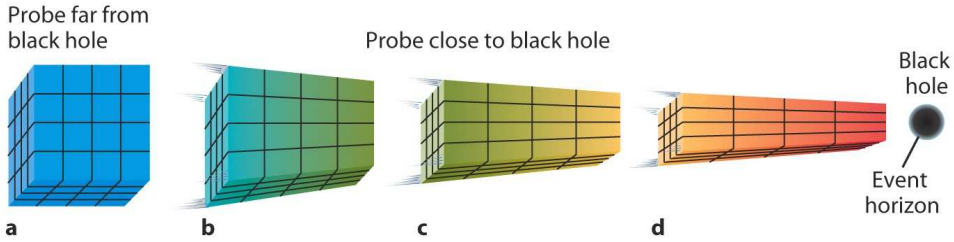
1. Fall in directly
2. Slowly spiral in
3. Stay in its orbit
4. Slowly spiral away
5. Fly away in a straight line

Well outside of a black hole – It looks just like any other mass



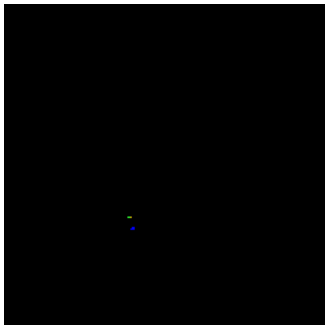
Probing a Black Hole

- We send a glowing blue cube into a black hole… What happens?
  - As the probe approaches the black hole, it gets stretched by the gravity of the black hole
  - The light it emits redshifts more and more as it gets closer to the black hole
  - Eventually, tidal forces rip it apart



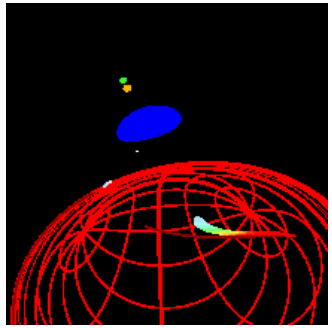
Example: Approaching a Black Hole

- A quad system with a black hole (30 $M_\odot$), a blue star (60 $M_\odot$), a yellow star, and a green star.
- Schwarzschild radius is marked in red.
- Up to last stable orbit $3R_{Sch}$



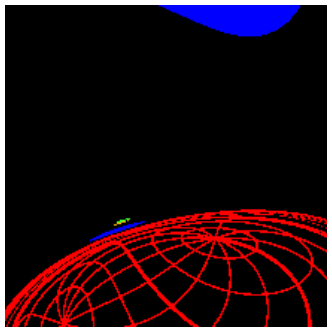
Orbiting the Black Hole: Our POV

- Orbiting (unstable) at 2 R_{Sch}, we fire a white probe.
- The probe appears to freeze at the horizon of the black hole, joining the frozen images of probes fired on previous orbits. If we could see a probe clock, it would appear to halt.
- The changing colors of the probe show how it becomes more and more redshifted, from our point of view.
- From the probe point of view, it neither freezes nor redshifts, but careers on through the horizon toward the singularity of the black hole.



Going In

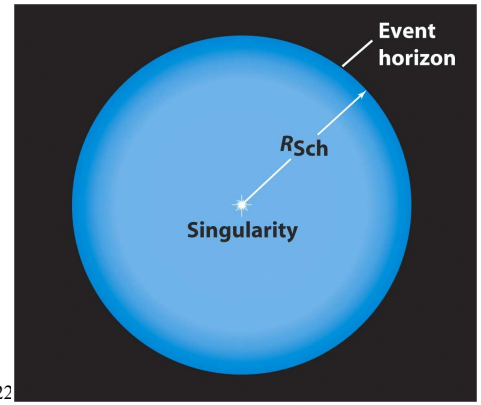
- Start out at 1.5 R_{Sch}, the last orbital position, requiring light speed.
- Inside of that, orbits go inside R_{Sch}
- Tidal forces at R_{Sch} for this object is about 1 million g's along a human.
- As we fall in, we free-fall quickly to the singularity
- The blue-shifted Universe is mostly x and γ-rays.
- The tidal force has become so strong that all images are concentrated into a thin line about (what is left of) our waist.



http://casa.colorado.edu/~ajsh/singularity.html

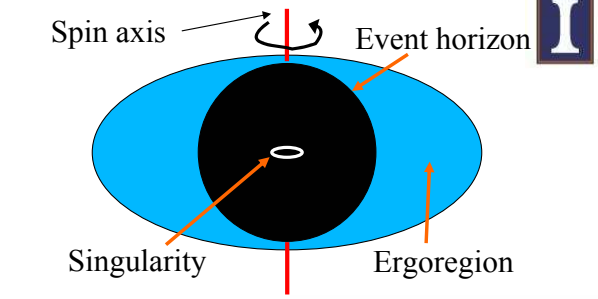
Life inside a Black Hole?

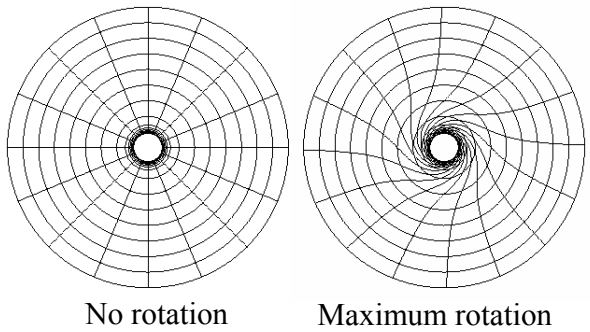
- Once inside R_{Sch}, no getting out
- All matter ⇒ center ⇒ point (?) "singularity"
- Known laws of physics break down
- A few points to make:
  - We know that all observers travel to center
  - Don't know what happens there
  - Regardless, certain that you die if you go in
  - In a way, it's not a relevant question, since can't get info out even if went in
  - Active subject of research!



Rotating Black Holes

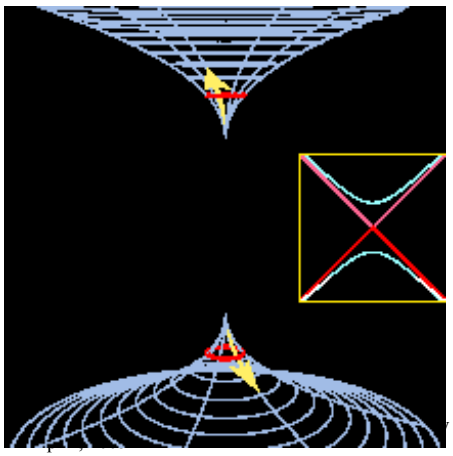
- First studied by Roy Kerr in the early 1960s
- Region just outside horizon where you are dragged along by spacetime
- Can't stand still in ergoregion without falling in
- Singularity is a torus





Wormholes

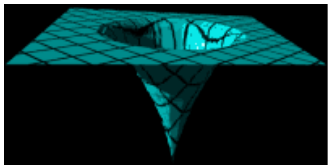
- Tunnel to another universe, or another part of our own?
- **No:**
  - Wormhole throat is unstable, and pinches off
  - Once you fall through one horizon, you can't come out through another
- **Also:** Stellar collapse to a black hole does not produce a wormhole
- **So:** mathematically allowed, but unphysical in general relativity

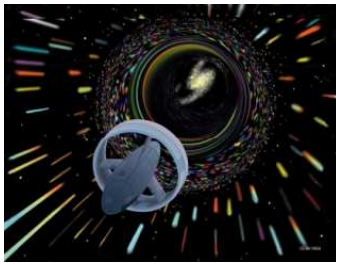


Sorry… not any time soon

General relativity

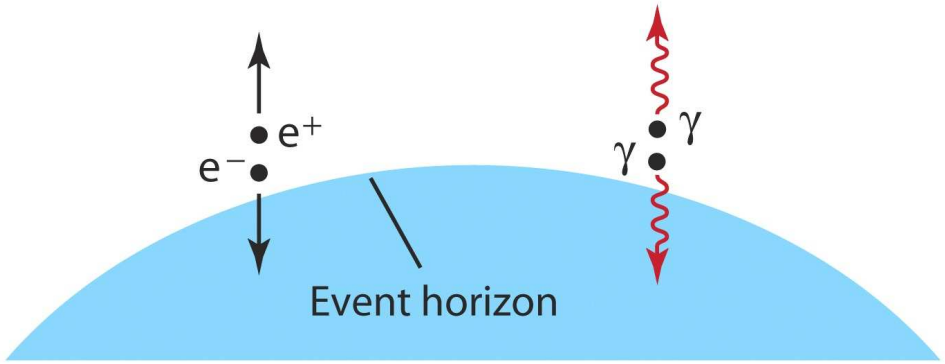
- Rotating black holes may form wormholes to "elsewhen" but they are thought to be short-lived.
- Researchers are considering stabilizing them with exotic matter.
- What if it were possible to create a localized region in which space-time was severely warped?
  - A car has a speed limit on a road, but what if you compress the road itself?





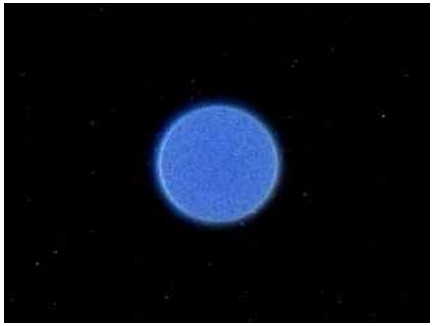
Hawking Radiation

- Black holes are not truly black!
- Quantum mechanical effects near event horizon cause them to produce blackbody-like radiation
- Temperature **increases** as mass **decreases**
- Too dim/cool to see for stellar-mass black holes



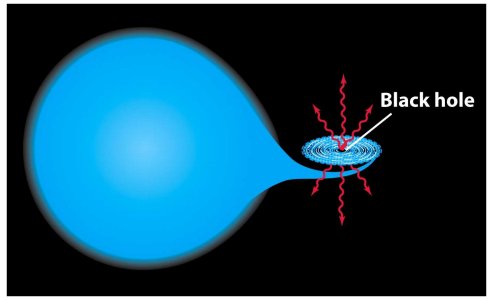
How To See A Black Hole

- Light cannot escape a black hole, how do we see it?
- We look for interactions between the black hole and a companion
  - Black hole pulls mass from the companion which forms a disk
  - The gas in the disk is compressed and heated so that it gives off X-rays



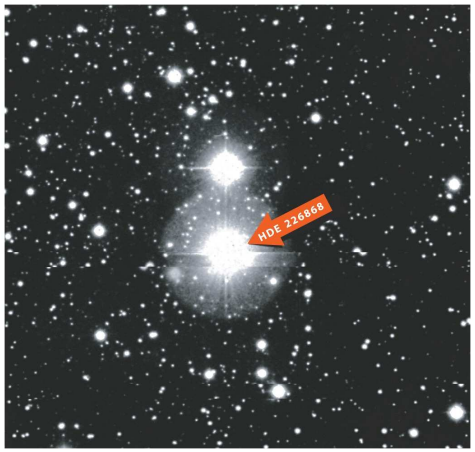
How To See A Black Hole

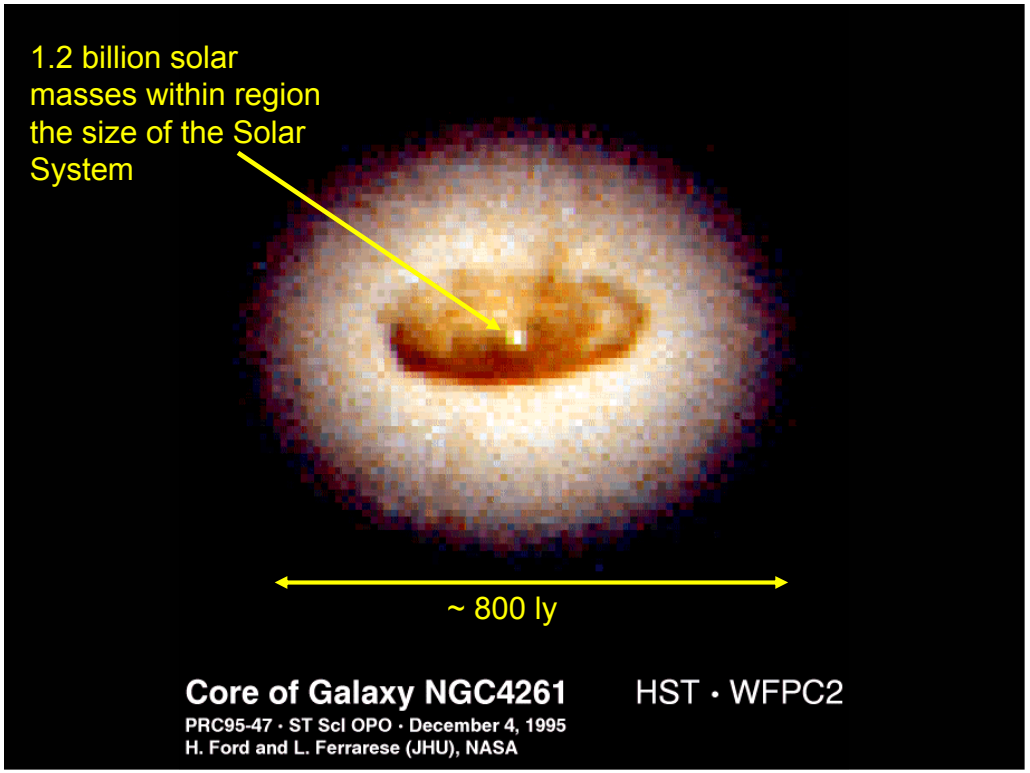
- If a black hole emits no light, how do we see it?
- We look for interactions between the black hole and a companion
  - Black hole pulls mass from the companion which forms a disk
  - The gas in the disk is compressed and heated so that it gives off X-rays



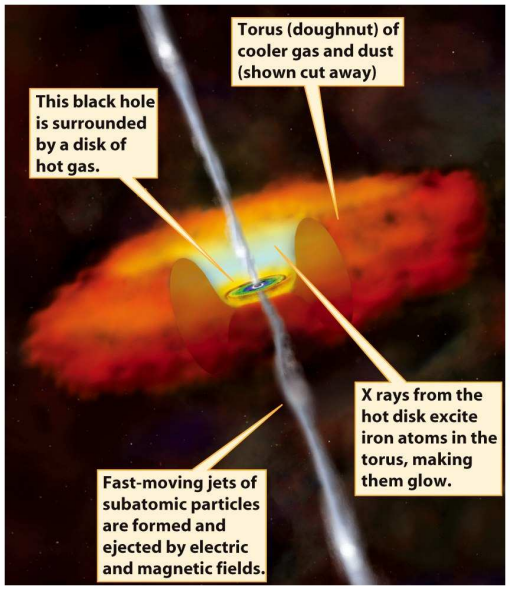
Cygnus X-1

- Binary system with unseen 7 solar mass companion
- Spectrum of X-ray emission consistent with that expected for a black hole
- Rapid fluctuations consistent with object a few km in diameter



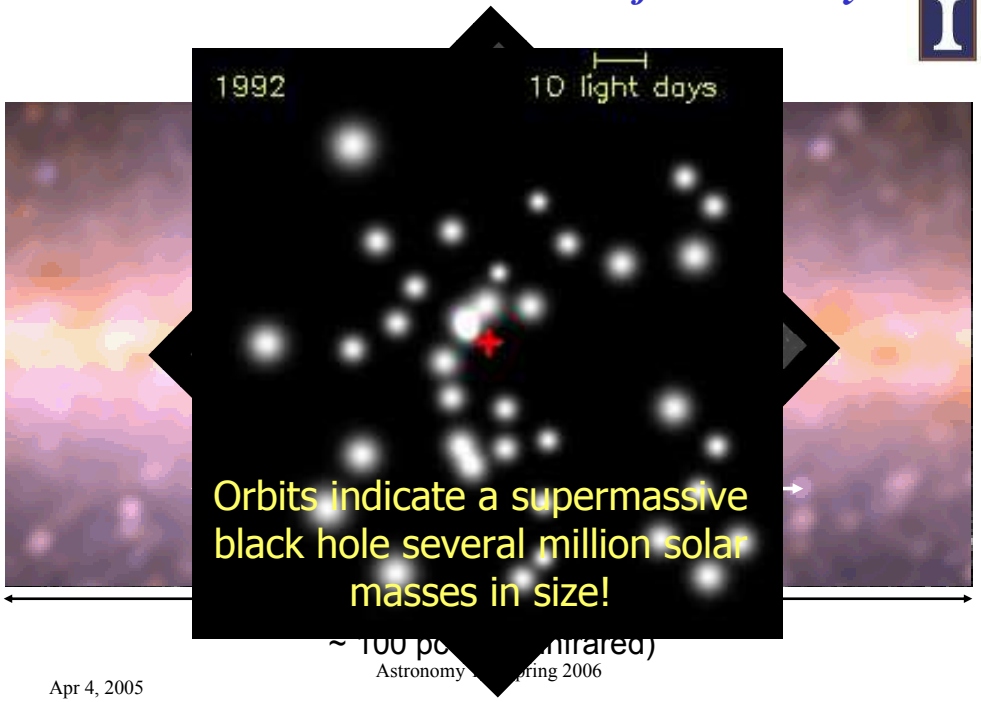


Black Holes



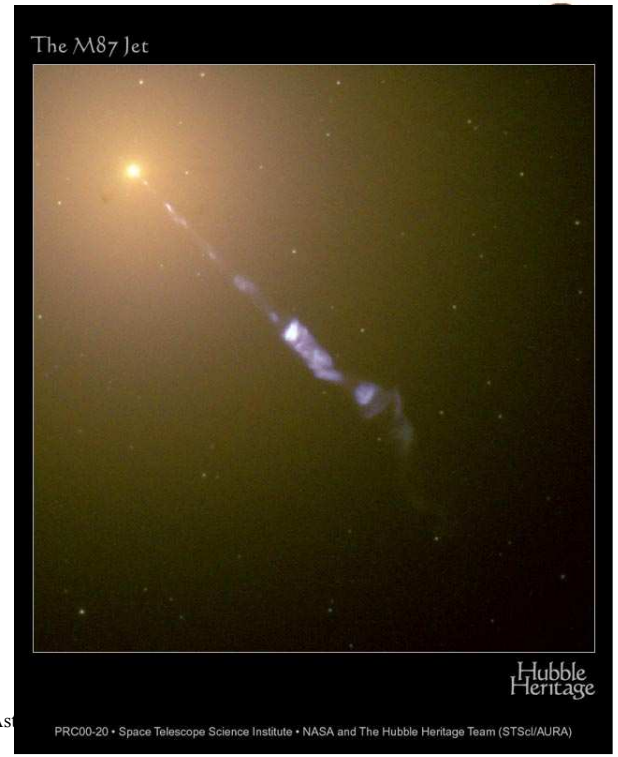
An artist's impression of Cygnus X-1

The Monster at the Center of the Galaxy



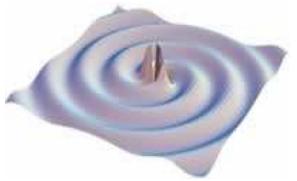
The Jet of M87

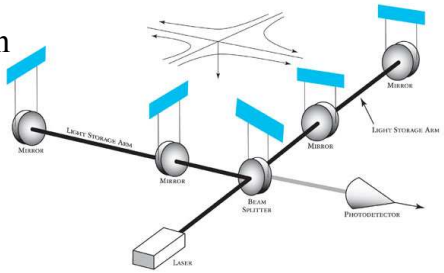
- Huge jet from the center of this galaxy (50 Mlyrs away).
- 5000 light years in length!
- The jet is probably created by energetic gas swirling around a massive black hole at the galaxy's center



Grav Waves

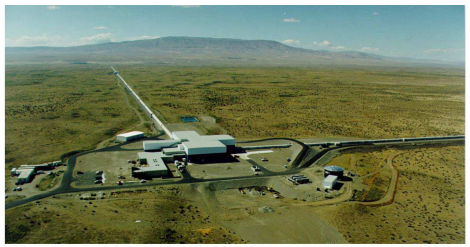
- Ripples in spacetime!
- Similar to EM radiation
- Recall rubber sheet analogy: if disturb, launch waves
- Larger disturbance ⇒ bigger waves
- Emitted in dynamic, strong gravity systems: neutron stars in pairs (binaries)
  - Orbit ⇒ emit gravity waves ⇒ lose energy ⇒ fall in ⇒ decrease period P





http://www.ligo.caltech.edu/LIGO_web/PR/scripts/facts.html

The Search



Four interferometers contribute data to LSC analyses:

•4 km and 2 km interferometers at LIGO Hanford Observatory

•4 km interferometer at LIGO Livingston Observatory

•GEO600

N.B.: No GEO data available for S2, but back on air for S3.

http://sciencebulletins.amnh.org/astro/f/gravity.20041101/index.php