Astronomy 210

This Class (Lecture 35):

General Relativity

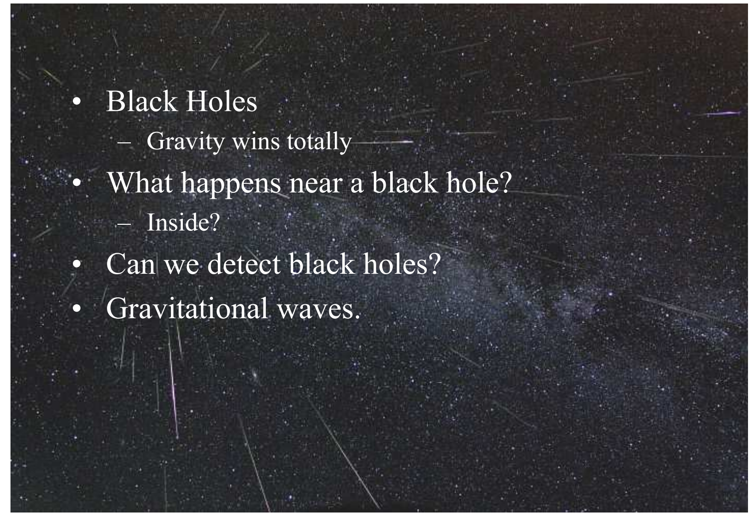
Next Class:

Black Holes

Stardial 2 is available.

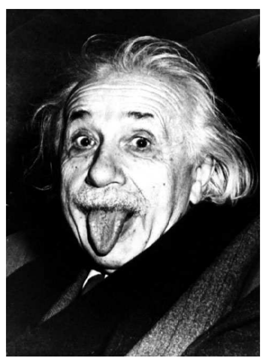
HW 10 due Friday.

Outline



- Black Holes
  - Gravity wins totally
- What happens near a black hole?
  - Inside?
- Can we detect black holes?
- Gravitational waves.

The Theory of 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**
  - Gravity is not a force, but a curvature
  - Matter tells spacetime how to curve
  - Curved spacetime tells matter how to move

Back to Black Holes

- Laplace (1790s) using Newton's gravity and the escape velocity of a body
- Postulated about a special case of escape velocity

$$\sqrt{\frac{2GM}{R}} > c$$

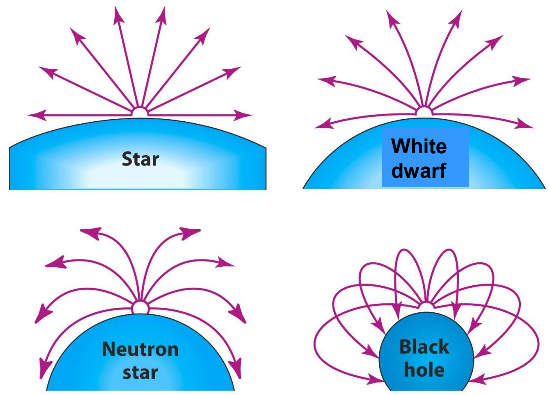
$$\Rightarrow v_{esc} > c$$

Light can not escape $\Rightarrow$ black hole

Right answer, wrong argument

Now, Back to Black Holes

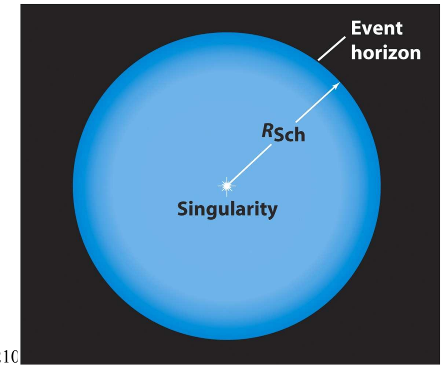
- When matter gets sufficiently dense, it causes spacetime to curve so much, it closes in on itself
- Photons flying outward from such a massive object arc back inward!



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

Black 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
- Turns out this radius is what Laplace calculated, now called the Schwarzschild radius

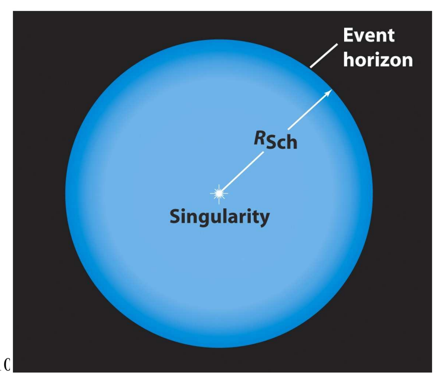


Black Hole

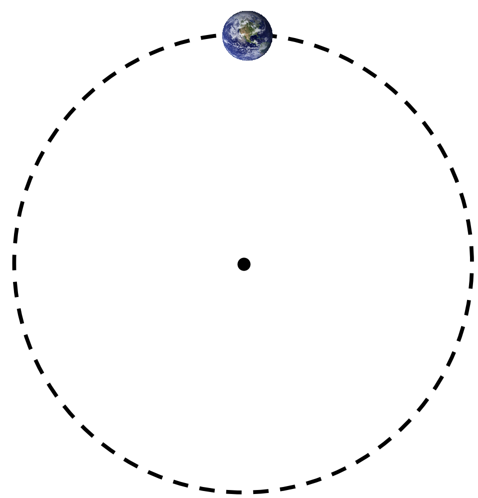
- The Schwarzschild radius is

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

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



Well outside of a black hole?



Major Tom

- Astronaut Major Tom is lowered toward a black hole. His distance from the singularity is $R_{ast} > R_{Sch}$ but near.
- If we communicate with Tom via light waves

$$\frac{\lambda_{obs}}{\lambda_{ast}} = \sqrt{\frac{1 - \frac{R_{Sch}}{R_{obs}}}{1 - \frac{R_{Sch}}{R_{astr}}}}$$

Major Tom

- What do we see, when Tom communicates?
- If $R_{obs} \Rightarrow \infty$

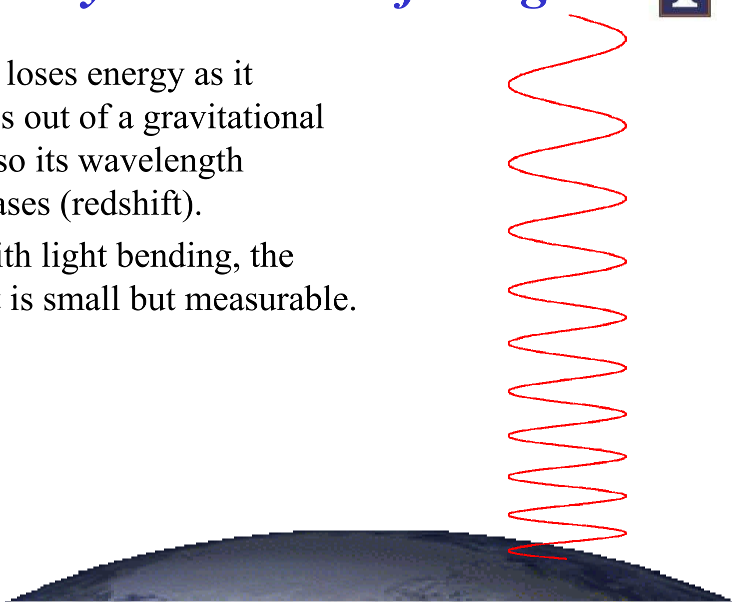
$$\frac{\lambda_{obs}}{\lambda_{ast}} = \sqrt{\frac{1 - \frac{R_{Sch}}{R_{obs}}}{1 - \frac{R_{Sch}}{R_{astr}}}}$$

$$\frac{\lambda_{obs}}{\lambda_{ast}} = \frac{1}{\sqrt{1 - \frac{R_{Sch}}{R_{ast}}}} > 1 \qquad \lambda_{obs} > \lambda_{ast}$$

- **Gravitational redshift!**

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.



Major Tom

- What about Tom's watch? Light is basically the tick here, so

$$\Delta t = P = \frac{1}{\upsilon} = \frac{\lambda}{c}$$

$$\frac{\Delta t_{obs}}{\Delta t_{ast}} = \frac{\lambda_{obs}}{\lambda_{ast}}$$

$$\Delta t_{obs} > \Delta t_{ast}$$

- We would see Tom's watch tick slow
- **Time dilation! Time slowed by strong gravity.**

What Does Tom See?

- Now the observer is Tom, and we are at $R_{us} \Rightarrow \infty$

$$\frac{\lambda_{obs}}{\lambda_{us}} = \sqrt{\frac{1-\frac{R_{Sch}}{R_{obs}}}{1-\frac{R_{Sch}}{R_{us}}}}$$

$$\frac{\lambda_{obs}}{\lambda_{us}} = \sqrt{1-\frac{R_{Sch}}{R_{obs}}} < 1 \qquad \lambda_{obs} < \lambda_{us}$$

- **Our communication is blue shifted!**

What Does Tom See?

- What about our watch from Tom's perspective?

$$\Delta t = P = \frac{1}{\upsilon} = \frac{\lambda}{c}$$

$$\frac{\Delta t_{obs}}{\Delta t_{us}} = \frac{\lambda_{obs}}{\lambda_{us}}$$

$$\Delta t_{obs} < \Delta t_{ast}$$

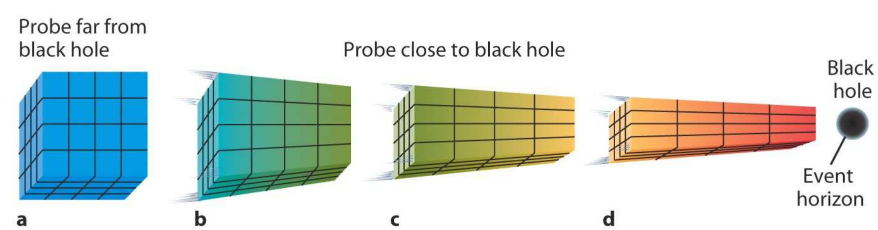
- Tom would see our clocks tick fast
- **Our movements would be sped up.**

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.

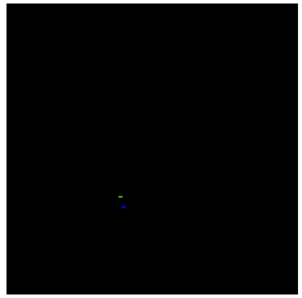
Probing a Black Hole

- 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



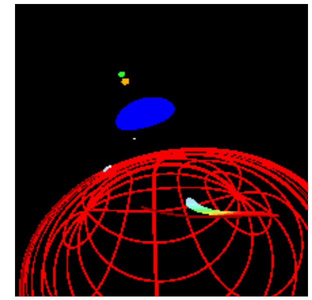
Approaching a Black Hole

- 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.



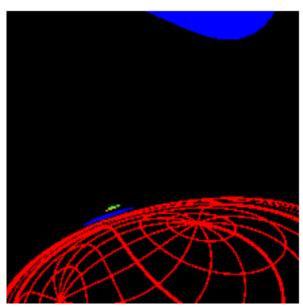
Orbiting the Black Hole: Our POV

- 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.



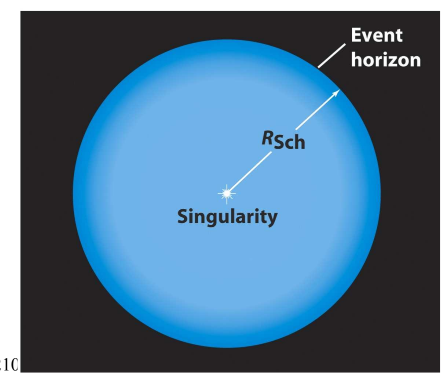
Going In

- 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.



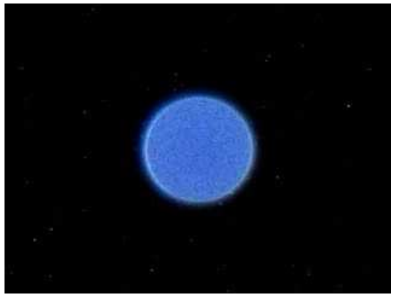
Life inside a Black Hole?

- 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!



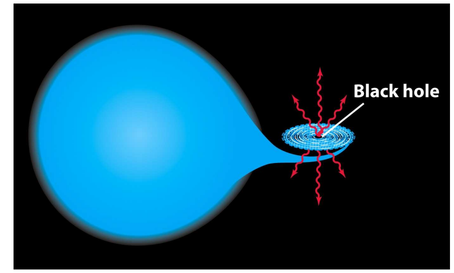
How To See A Black Hole

- 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



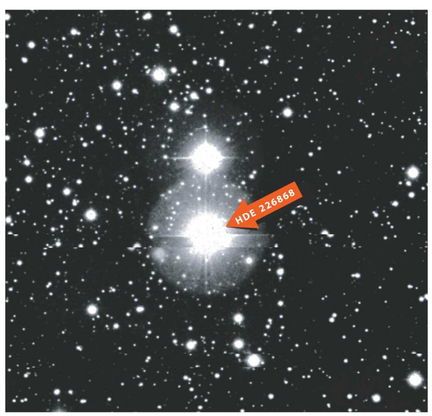
How To See A Black Hole

- 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

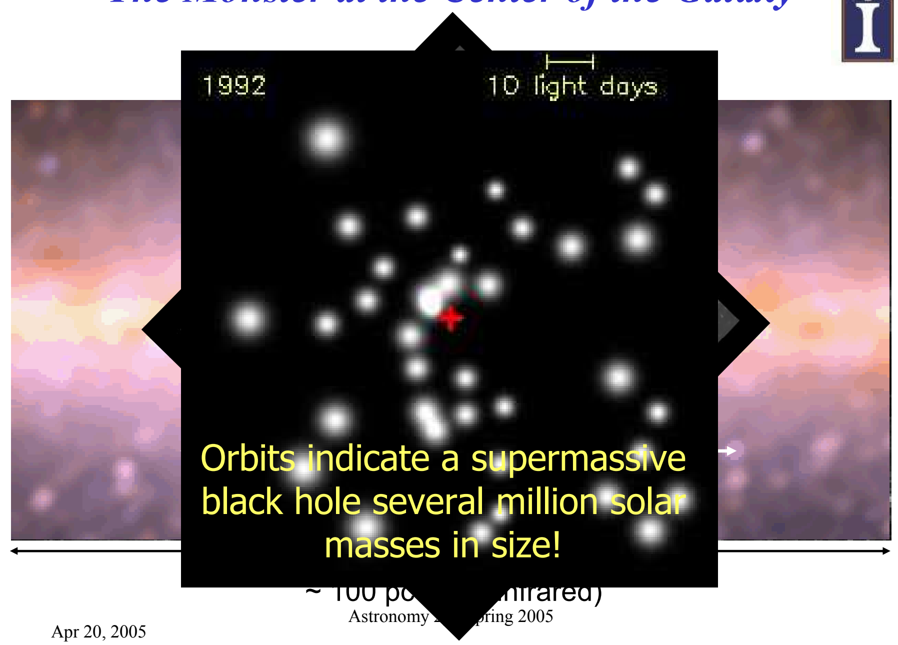


Cygnus X-1

- 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

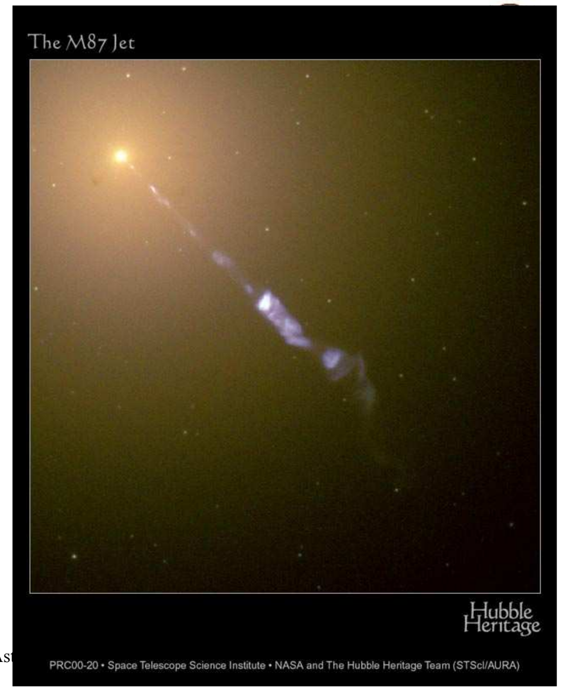


The Monster at the Center of the Galaxy



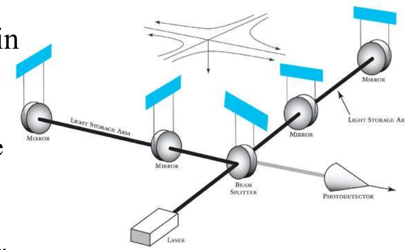
The Jet of M87

- 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