Astronomy 210

This Class (Lecture 34):

Supernovae and Neutron Stars

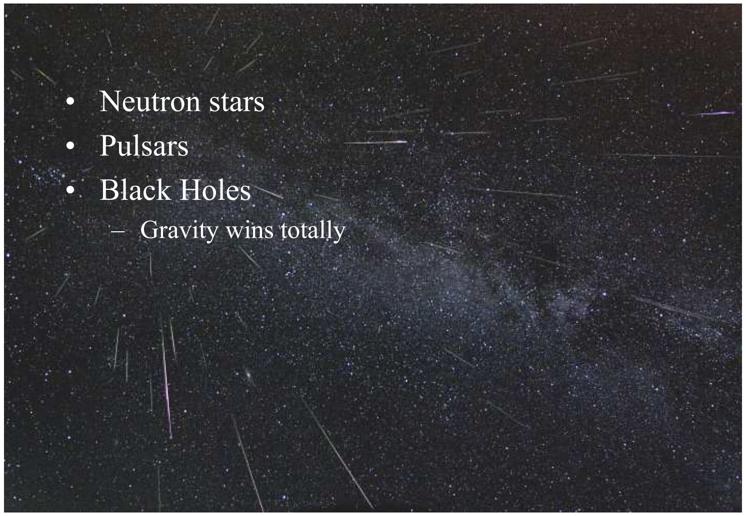
Next Class:

General Relativity

Stardial 2 is available.

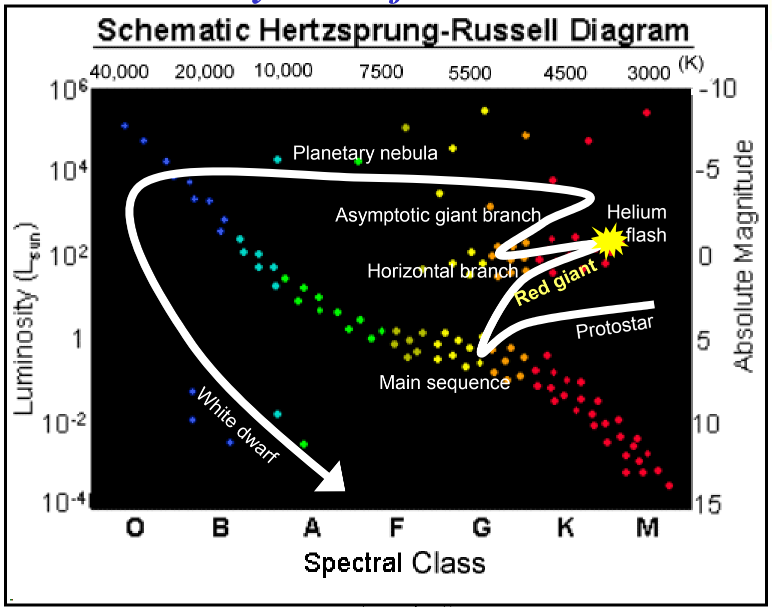
HW 10 due Friday.

Outline

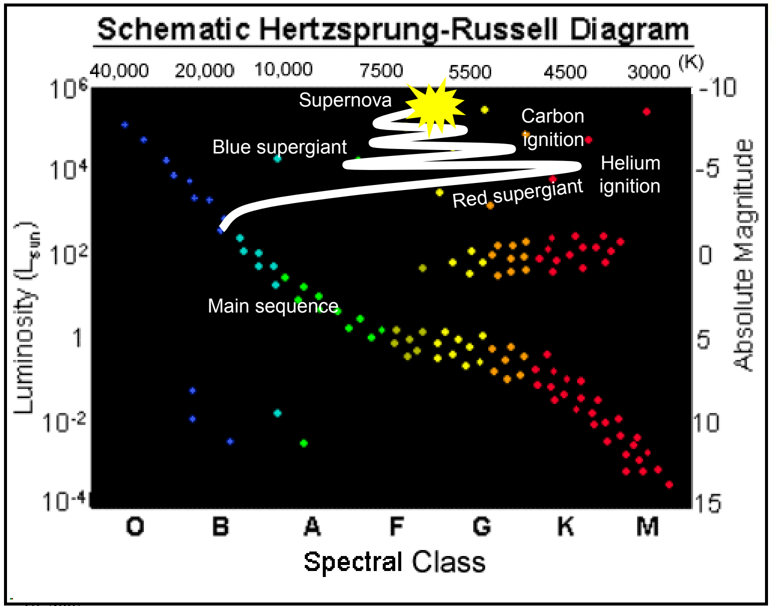


- Neutron stars
- Pulsars
- Black Holes
  - Gravity wins totally

Evolutionary Path of a Solar-Mass Star



Evolutionary Path of a High-Mass Star



Death throes

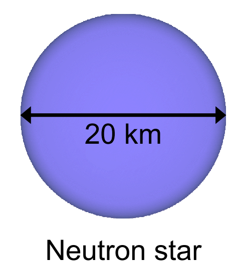
- What triggers a supernova?
  - Hydrostatic equilibrium is lost, gravity wins
  - Iron core with $M > M_{Chandra}$
- What happens?
  - Quick core collapse overcoming electron degeneracy pressure.
  - Rebound off the core, explosion of envelope
- What are end products?
  - Enriched ejecta and compact neutron star (if core mass < 3 solar masses)

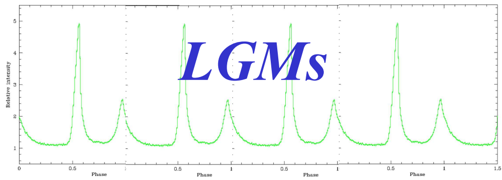
Supernova!

Supernova Leftovers

- What's left of the star's core after a Type II supernova?
- A **neutron star**
  - About 1.4 – 2 solar masses
  - Very small diameter – around 20 km!
  - Composed of a sea of neutrons
    - Supported by *neutron degeneracy pressure!*
    - Teaspoon of neutron star material on Earth would weigh almost 1 billion tons!!!!
  - Surface gravity – 200 billion times that on Earth
  - Escape velocity – of half the speed of light

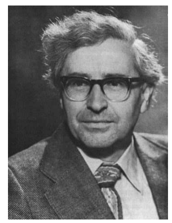
Relative Sizes of Stellar Corpses





LGMs

Jocelyn Bell Burnell



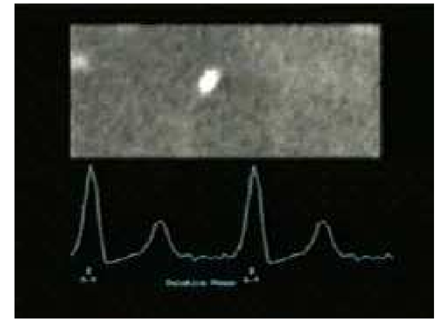
Anthony Hewish

- In the late 1960s, Jocelyn Bell discovered radio pulses from the constellation Vulpecula that repeated regularly
  - Every 1.337… seconds
- What could it be?
- Perfect timing, but no real encoding of signal.
- Jokingly called LGMs, then Pulsars.

http://www.radiosky.com/rspplsr.html

Pulsars

- What could it be?
  - Pulses were too fast to be a variable star
- A rotating star?



Rotating Star?

Max possible rotation rate at equator: when gravity balances centripetal acceleration.

$$v_c = \sqrt{\frac{GM}{R}}$$

But

$$v_c = \frac{2\pi R}{P}$$

so

Rotating Star?

Solve for P

$$= \frac{4\times 10^5 \text{ s}}{\sqrt{\rho}} \quad \rho \text{ in kg/m}^3$$

Rotating Star?

For shortest possible pulsar known of P = 1 ms

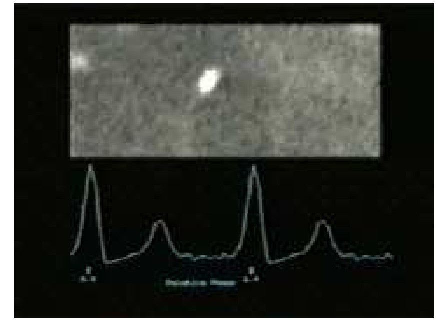
$$P = \frac{4\times10^{5}\ \mathrm{s}}{\sqrt{\rho}} \qquad \rho \text{ in kg/m}^{3}$$

$$\Rightarrow \rho_{\min} \geq\ 10^{17}\ \mathrm{kg/m}^{3}$$

Must be a neutron star! V_{esc} > 1/3 c!

Pulsars

- What could it be?
  - Pulses were too fast to be a variable star
- Very precise, better than atomic clocks.
- P from 1s to 1ms!
- Could they be something spinning?
  - Would have to be small to be spinning that fast
- They must be spinning neutron stars!



What are Pulsars?

- When the core collapses, its spin and magnetic field strength increases
- Typically
  - Surface field strength over 1 trillion times that of the Earth
  - Rotation rate up to 1000 times per second
- Magnetic field beams radiation into space
- If the Earth is in the beam's path, we see the pulsar

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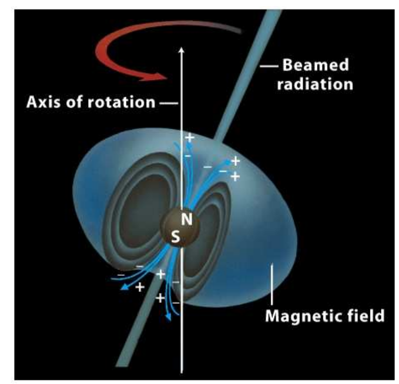
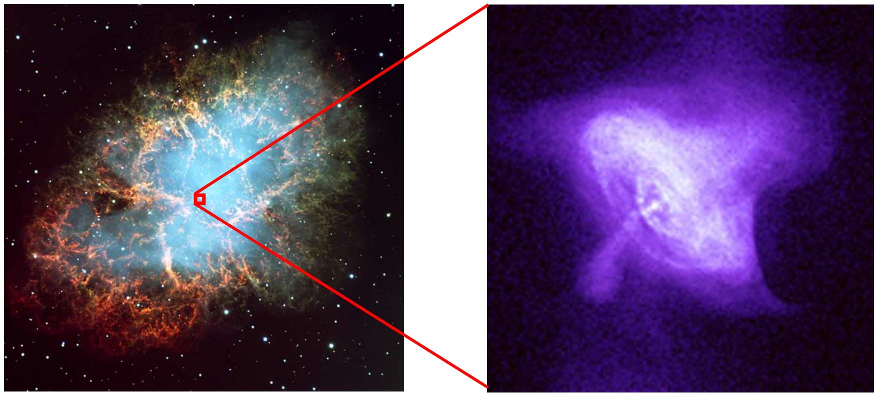


Crab Nebula – Remnant of the Supernova of 1054



Optical - ESO

X-ray - Chandra

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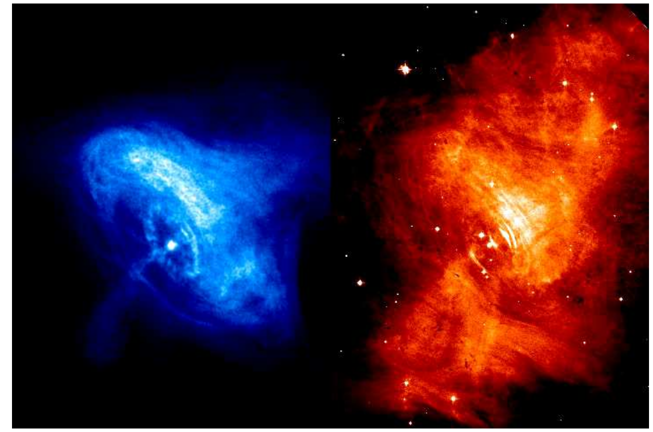
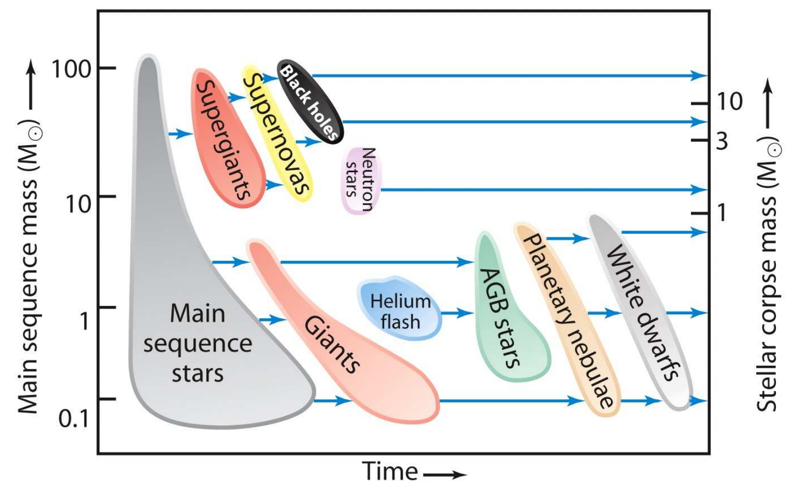


When Neutron Degeneracy Isn't Enough

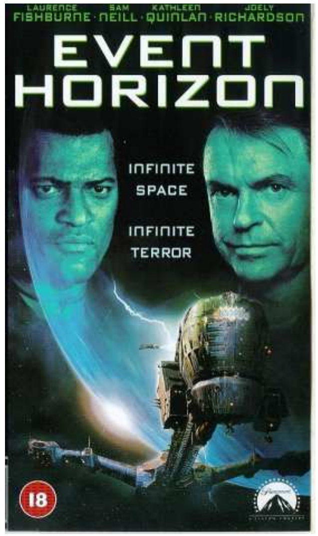
- Maximum neutron star mass
  - About 3.0 $M_{\odot}$
  - Original star around 30$M_{\odot}$
- Beyond this mass, neutron degeneracy cannot stop gravity
- Nothing left to stop, so total collapse– gravity rules!
- **A black hole**

Stellar Evolution Recap

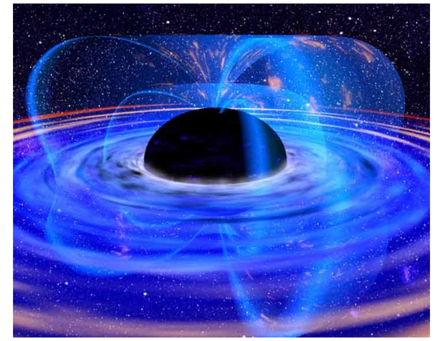


Black Holes

- Black holes inspire fear, awe, uncertainty, and bad science fiction
- Many people think that black holes are dangerous
  - That they suck matter in like "cosmic vacuums"
- Black holes follow the same laws of gravity as everything else



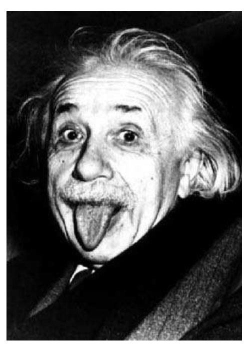
Physics of Black Holes



- Black holes are simple, yet strange objects
- Intense gravity due to compactness
- Newton's Laws cannot describe what happens in the presence of such an intense gravitational field
- We need Einstein's *Theory of Relativity*

The Theory of General Relativity

- Recall Galileo: for free body motion is straight line, constant speed
- Important to note that ALL free bodies move this way. straight line, constant speed, INDEP of size, mass
- Q: Why?
- A: That's the way it is!
- Q: Be more specific: that's the way WHAT is?
- A: Einstein: that's the way space and time are if nothing else going on (no forces) space and time constructed so that free bodies move in straight lines at constant speed independent of nature of the object
- **That's the way space and time are**



Free Fall

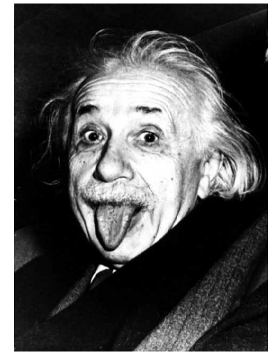
- Recall Galileo's experiment.
- The objects in the gravity field, move independent to mass or even object.
- For Newton, the object mass cancels out of the gravity equation.

The Theory of General Relativity

- Since objects move the same in a gravity field, INDEPENDENT of object, then gravity is not a force, but also a feature of space-time!
- Objects due their best to move in a straight line.
- **Newton:** Matter causes force (gravity) $\Rightarrow$ particles follow curved lines in “flat” (Euclidean geometry) space
- **Einstein:** Matter causes spacetime to be “curved“ $\Rightarrow$ particles follow straight lines (“geodesics”) in curved space

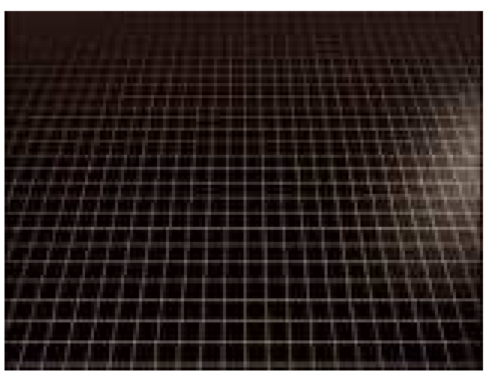
The Theory of Relativity

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



Curved Spacetime

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



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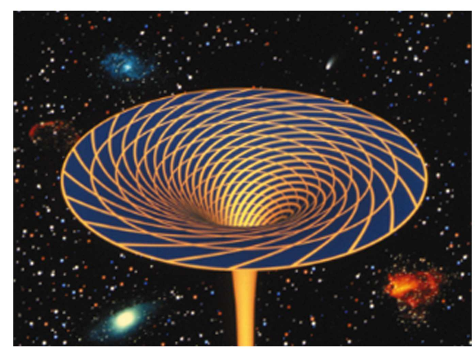
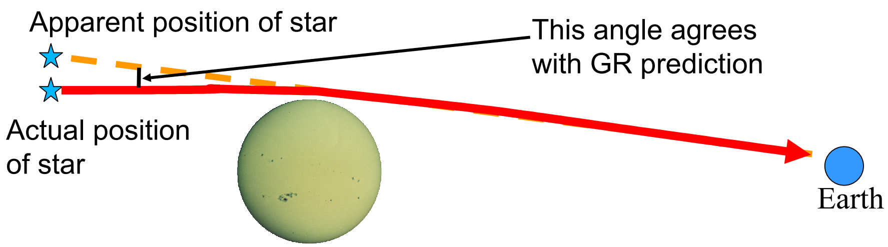
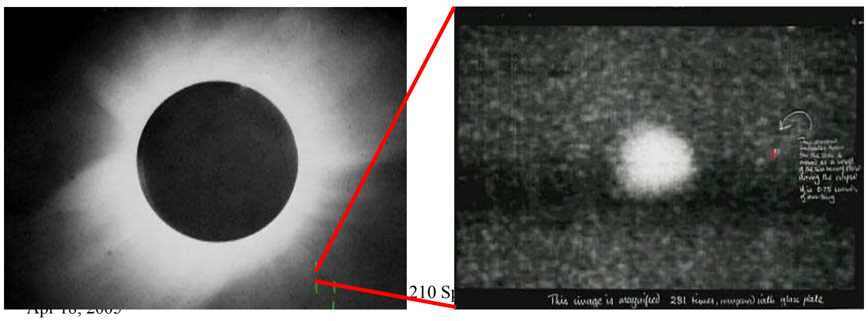
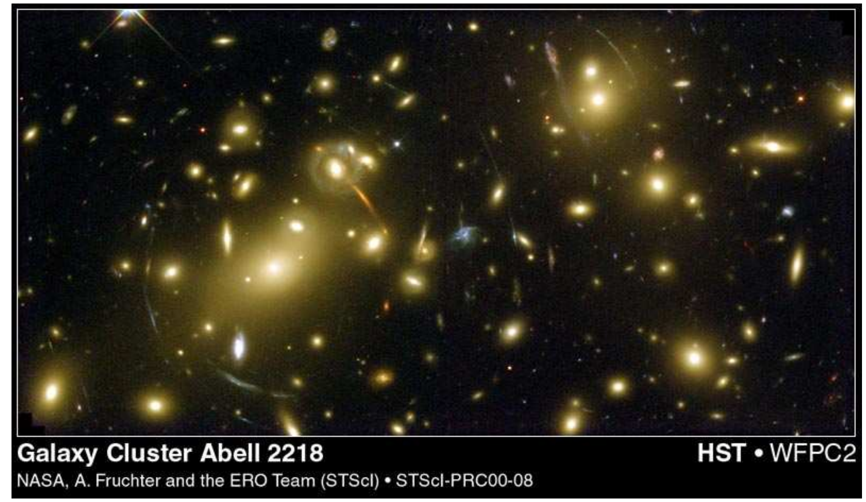


Eddington and the 1919 Eclipse





Einstein Lens



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

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

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

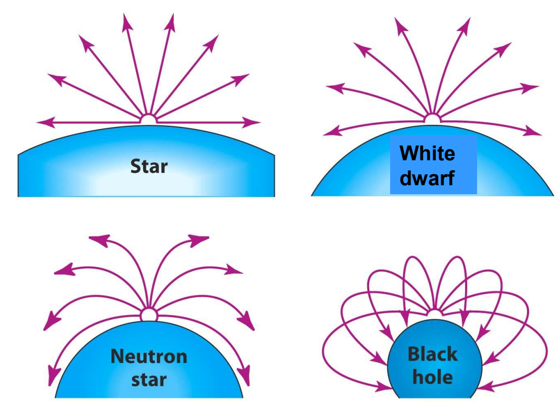
$$\Rightarrow v_{esc} > c$$

Light can not escape
$\Rightarrow$ black hole

Right answer, wrong argument

Now, Back to Black Holes

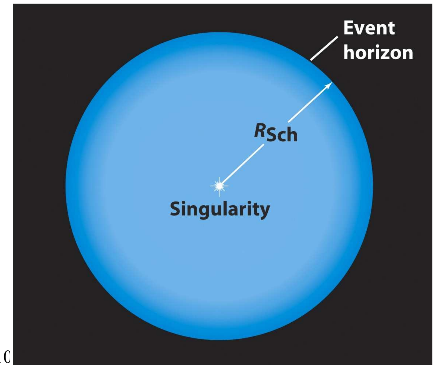
- When matter gets sufficiently dense, it causes spacetime to curve so much, it closes in on itself
- Photons flying outward from such a massive object arc back inward!



- 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

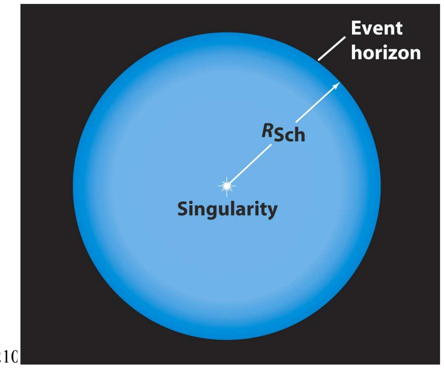


Black Hole

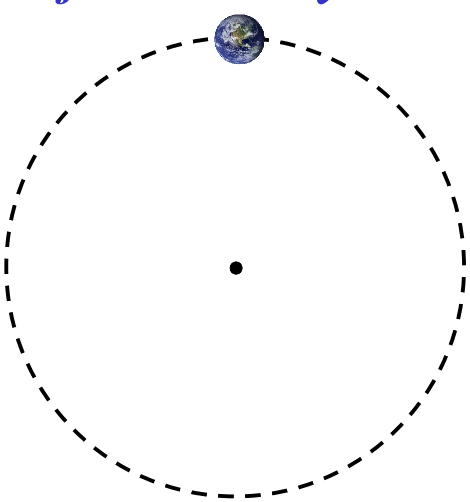
- The Schwarzschild radius is

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

- 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 $R_{Sch} = 1$cm
- The radius of no return
- Cosmic roach hotel



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



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 $R_{obs} \Rightarrow \infty$

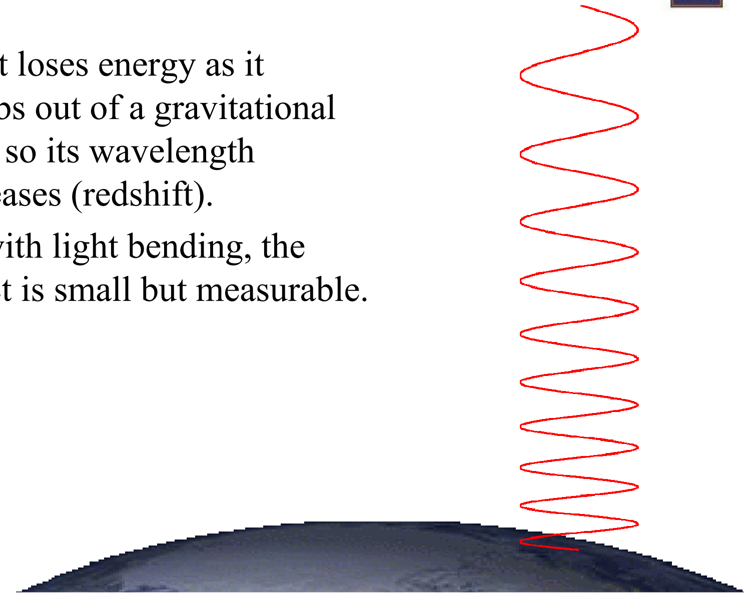
$$\frac{\lambda_{obs}}{\lambda_{ast}} = \sqrt{\frac{1-\frac{R_{Sch}}{R_{obs}}}{1-\frac{R_{Sch}}{R_{astr}}}}$$

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

- **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?

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

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

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

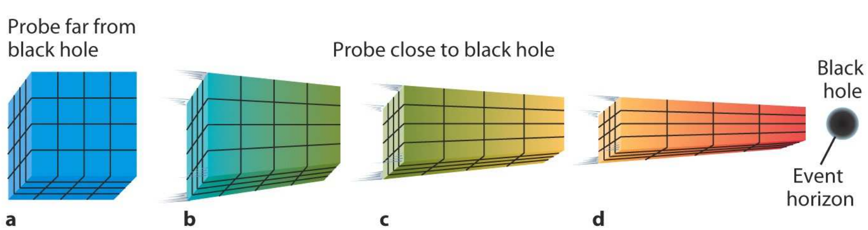
- Tom would see our clocks tick fast
- **Our movements would be sped up.**

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.

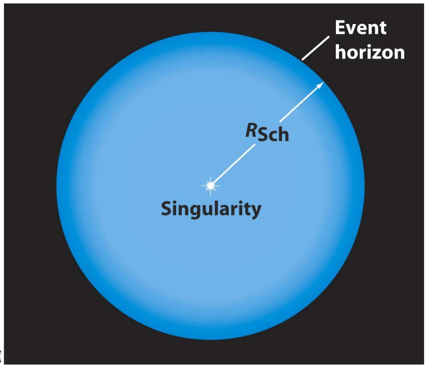
Probing a Black Hole

- 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



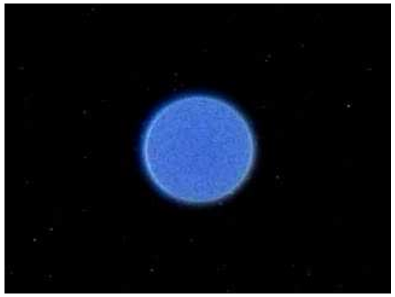
Life inside a Black Hole?

- 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
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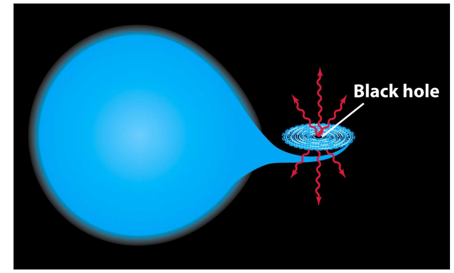
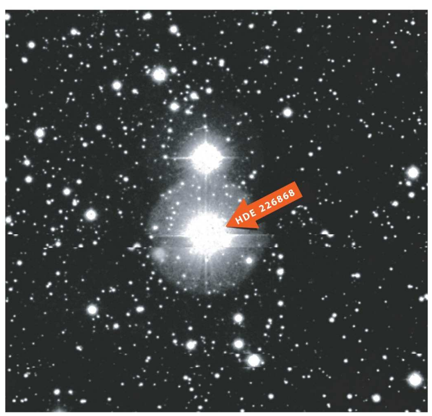


Cygnus X-1

- 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