Killer Skies

- Homework 7 due tonight
- Solar Observing this week
- Exam 2 Friday
- Last time: Gamma Ray Bursts Effects
- Today: Compact Objects

"No, dear. I don't think the star on the Christmas tree will implode, and suck our living room into a black hole."

Music: *Black Hole Sun* – Soundgarden

Solar Observing This Week

Happens now:

M-Th, 10:30am-1:30pm, weather permitting

At Campus Observatory

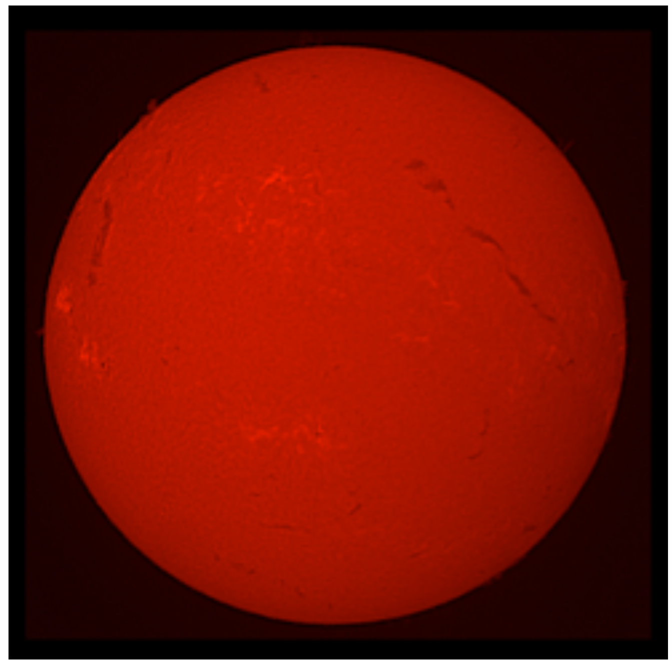
(behind building)

Assignment details and report form on class website

Report due Nov 22nd

Subscribe to Solar Observing Status Blog for weather-related notices

http://illinois.edu/blog/view/414



Hour Exam 2

Hour Exam 1 Friday, Nov 8th, in class

- information on course website
- 40 questions (cover material from Oct 7th to Nov 1: Lect 14-24)

May bring 1-page of notes

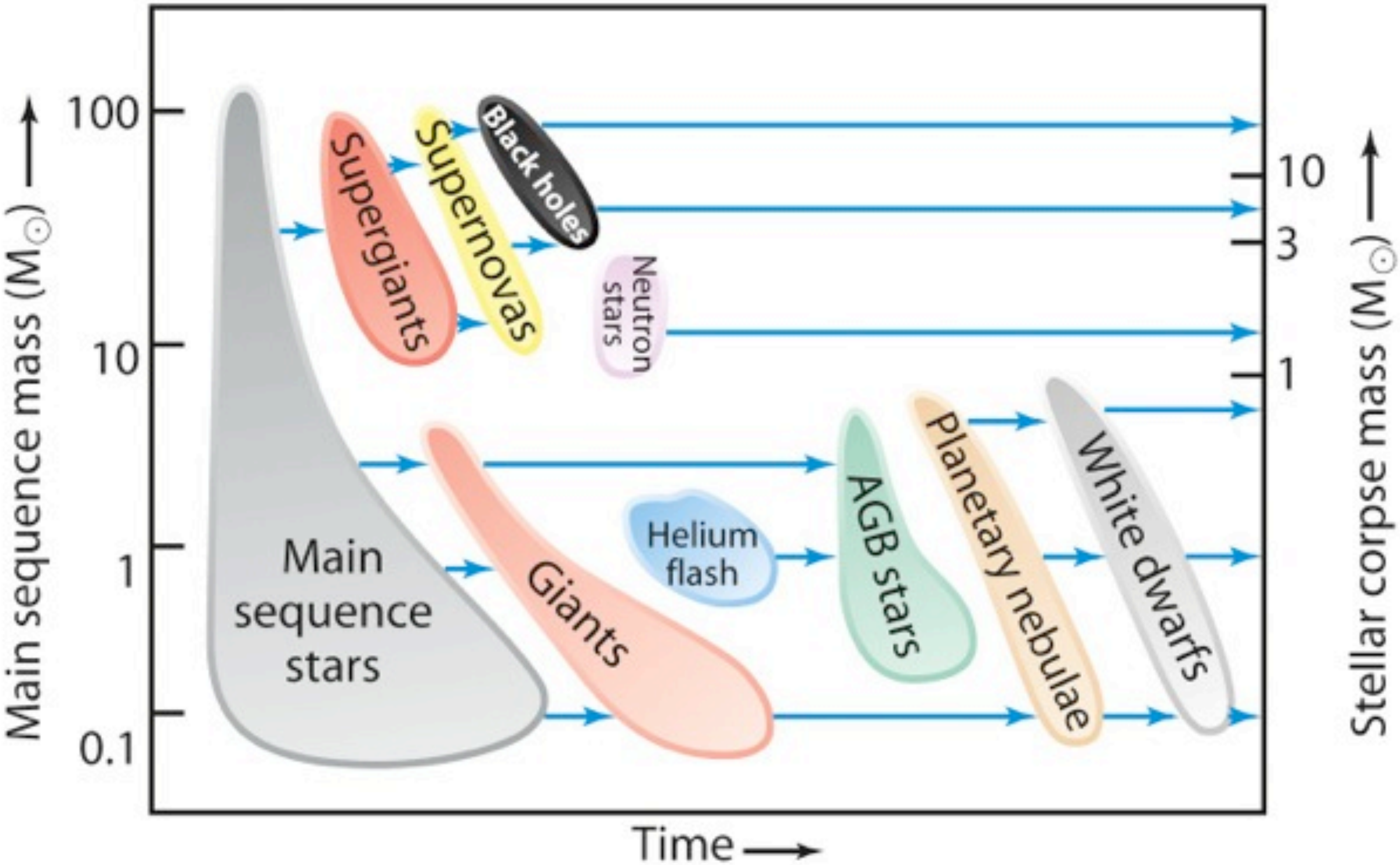
- both sides
- printed, handwritten, whatever

Most useful study materials

- class notes
- iClicker questions
- study guide
- homework questions
- old exam

Focus on concepts, main ideas

Stellar Evolution Recap



Actually any compact object can cause issues when they get too close, but remember these compact objects are compressed, i.e. small and hard to see.

Review: Thought Question

List the stellar corpses in order of their masses (lowest to highest)?

A. White Dwarf, Black Hole, Neutron Star
B. Black Hole, Neutron Star, White Dwarf
C. Neutron Star, White Dwarf, Black Hole
D. White Dwarf, Neutron Star, Black Hole
E. Neutron Star, Black Hole, White Dwarf

Answer D

What is a neutron star?

The collapsed core of a massive star

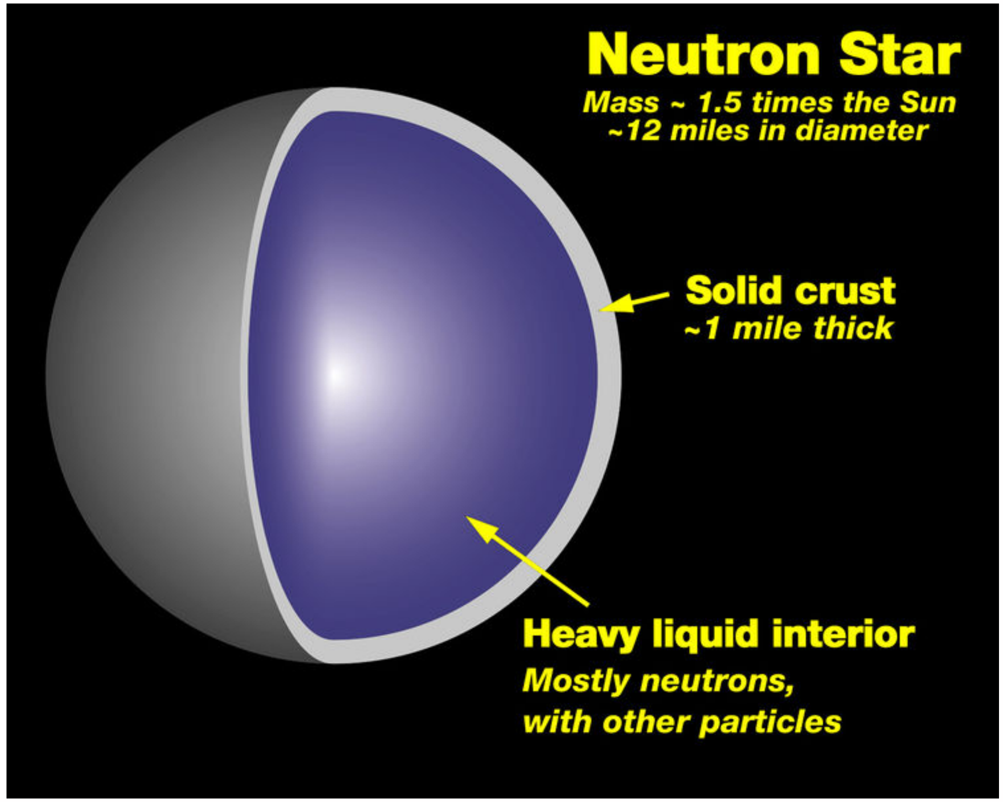
Consists almost entirely of neutrons

As dense as an atomic nucleus

- large mass around 1.5 M_{sun}
- in tiny radius around 30 km

Think of it as matter with all the empty space squeezed out of it

Originally thought to be too small to ever see

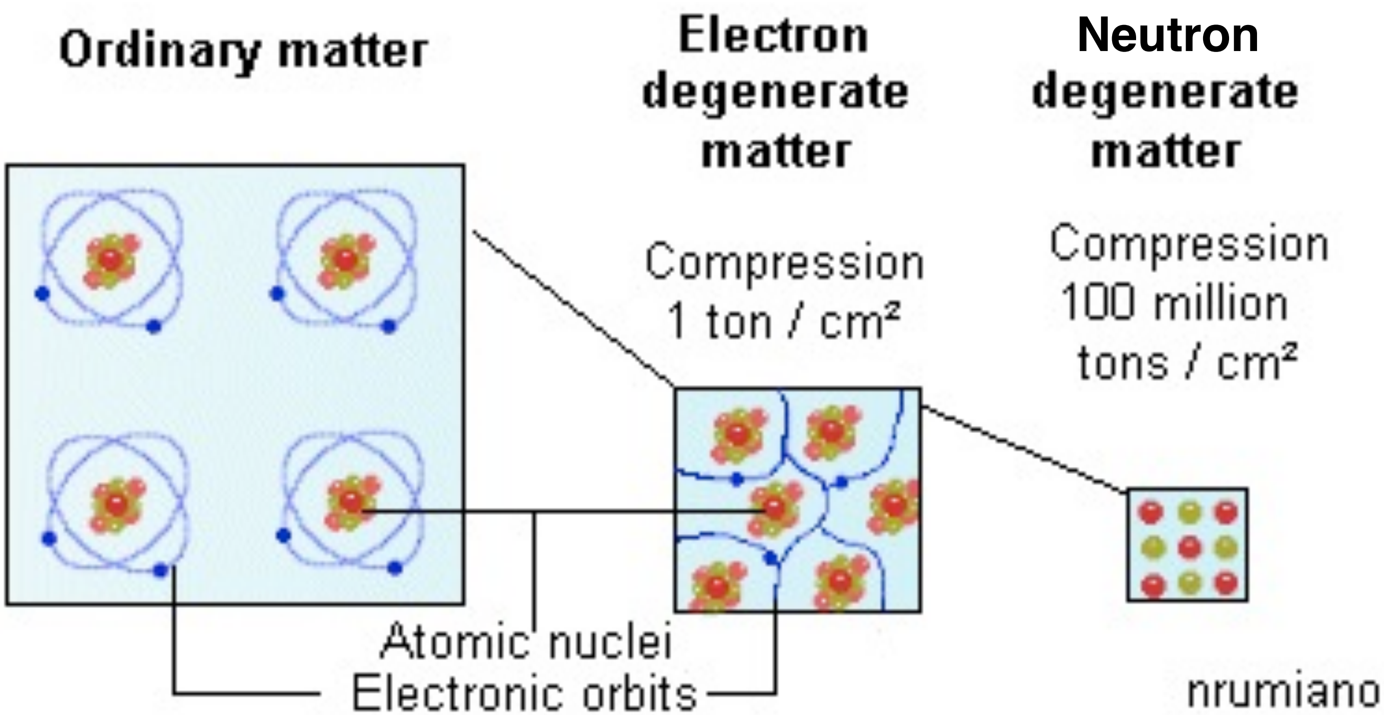


A model of a neutron star's internal structure

Neutron stars are compact objects that are created in the cores of massive stars during supernova explosions. The core of the star collapses, and crushes together every proton with a corresponding electron turning each electron-proton pair into a neutron. The neutrons, however, can often stop the collapse and remain as a neutron star.

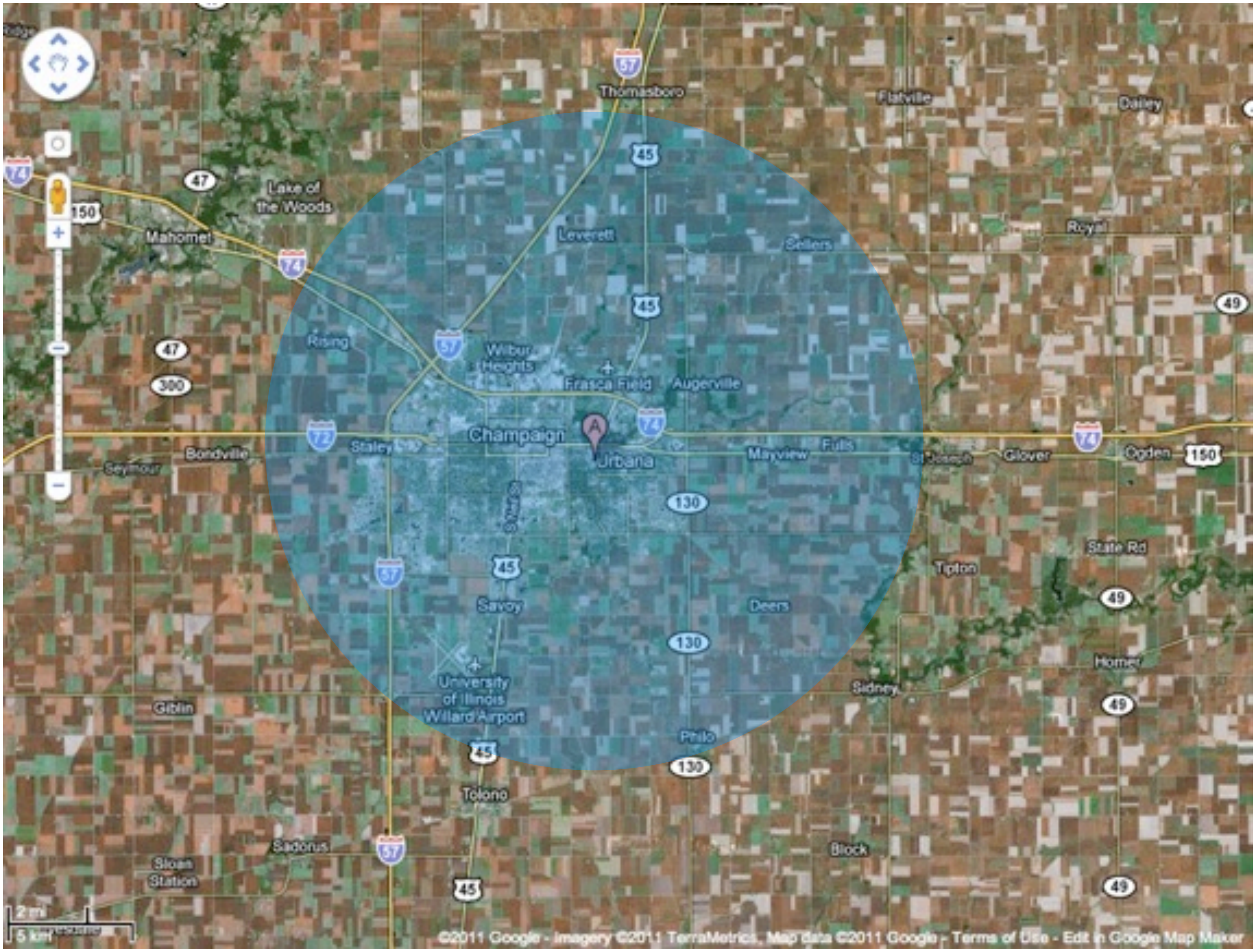
Although their surface temperatures can be nearly 1 million K, they are are very dim due to their small size

What supports a neutron star against gravity?



In a neutron star, protons and electrons merge into neutrons. When neutrons run out of room, they resist further collapse.

Electron degeneracy can't support masses higher than 1.4 solar masses. So, object collapses to small size. But, neutrons have a similar degeneracy, so they now are to support against further collapse at much higher densities!

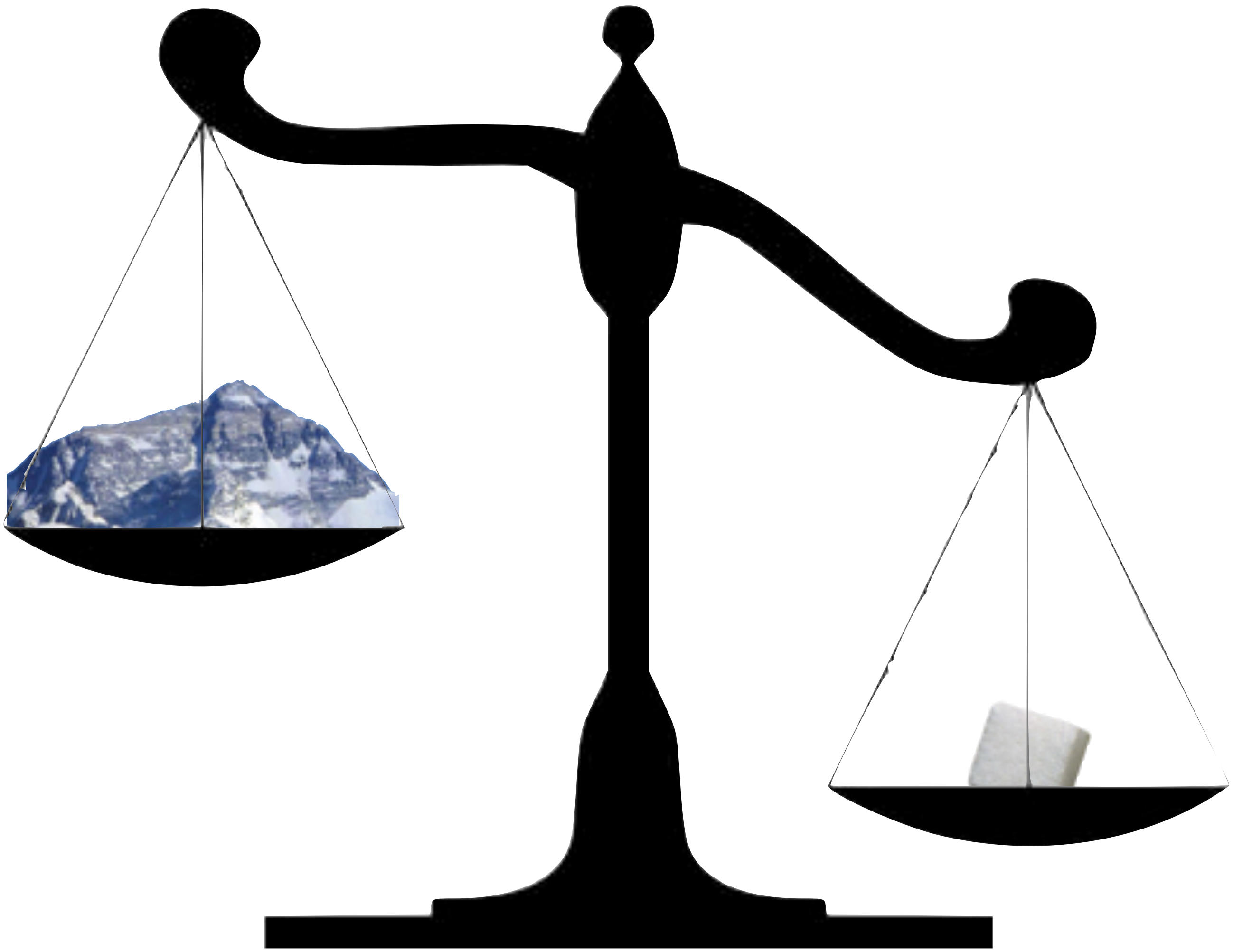


A neutron star is about the same size as a small city, with 500,000 times the mass of the Earth!

8

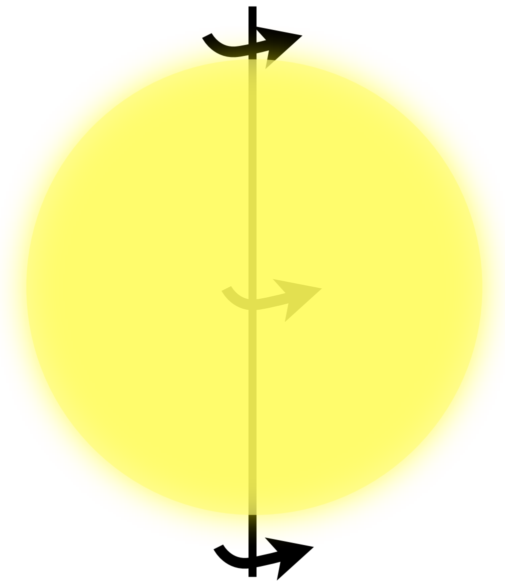
The size of C-U, but about 500,000 times the mass of the Earth (1.5 M_{Sun}). Due to their small size, but large mass, the surface gravity is 100 billion time greater than the Earth's. To escape from a neutron star's surface, one would have to travel at a velocity of 100,000 km/s, that is about one third of the speed of light. And what if it had more and more mass?

A sugar cube of neutron star has more mass than a mountain!



Neutron stars are fascinating objects because they are the most dense objects known. They are only about 10 miles in diameter, yet they are more massive than the Sun. One sugar cube of neutron star material weighs about 100 million tons, which is about as much as a mountain.

Why does a neutron star spin so fast?



Regular star: Large size and slow spin. Weak magnetic field.

Neutron star: Very small size and very fast spin. STRONG magnetic field.

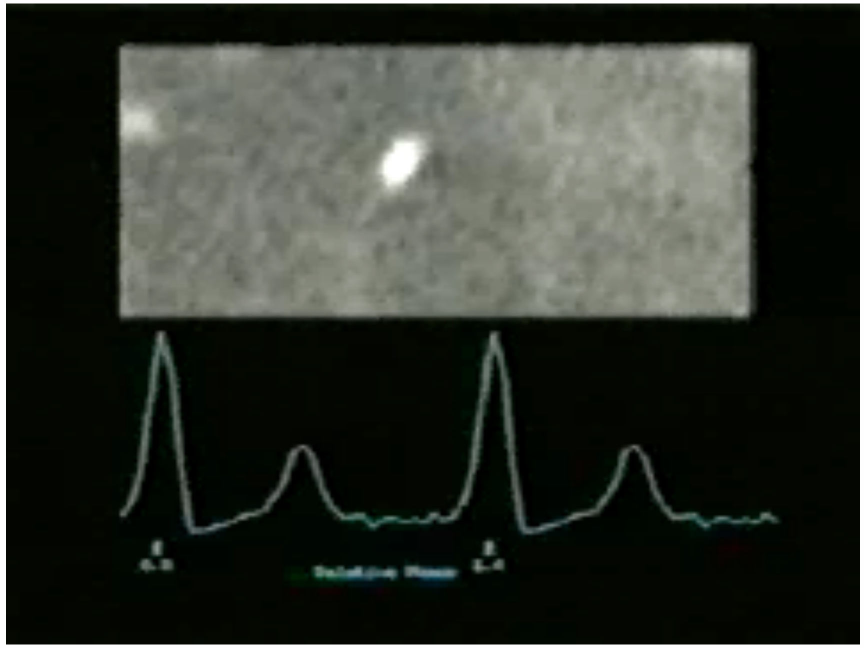
When the stellar core collapsed, the rotation rate and magnetic field strength both increased

Just as a spinning ice skater can spin very fast by pulling in his/her arms and legs tight about the center of her body, a star will spin faster when it brings its material closer to its center. The magnetic field is frozen into the star, so when the core collapses, the magnetic field is compressed too. The magnetic field becomes very concentrated and much stronger than before.

Pulsars

Joyceln Bell

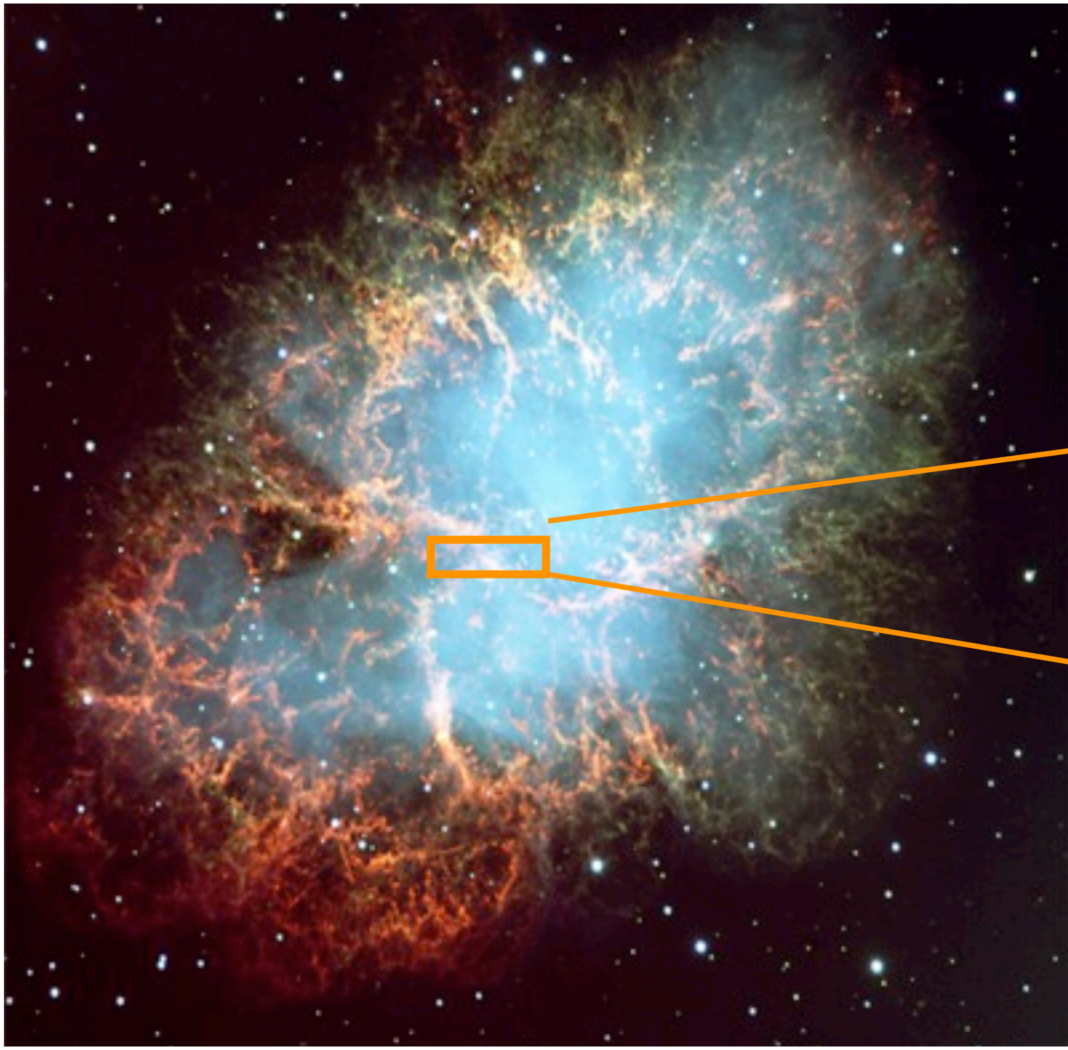
- In 1967, Jocelyn Bell discovered radio pulses from the constellation Vulpecula that repeated regularly
- Every 1.337… seconds
- What could it be?
- Perfect timing, but no real encoding of signal
- Jokingly called LGMs
  - beacons from space aliens--“little green men”
- Then pulsars (pulsing star)

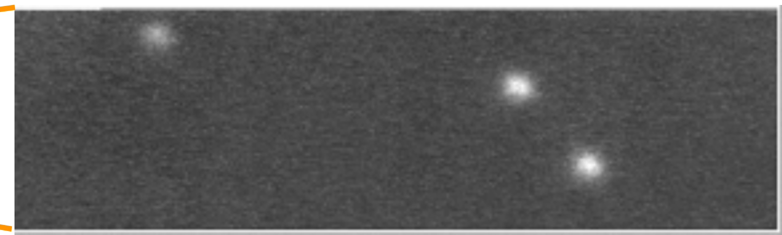


The signal from a pulsar is a series of regular pulses

Initially baffled as to the seemingly unnatural regularity of its emissions, they dubbed their discovery LGM-1, for "little green men" An object cannot change its brightness significantly in an interval shorter than the time light takes to cross its diameter. If pulses from pulsars are no longer than 0.001 seconds, then the objects cannot be larger 300 km in diameter. That makes neutron stars the only reasonable explanation. Her advisor (Antony Hewish) won the nobel prize for this discovery, not Joyceln.

"Pulsing star" at the center of Supernova 1054





The 'pulsar' at the center of the Crab Nebula pulses *30 times per second!*

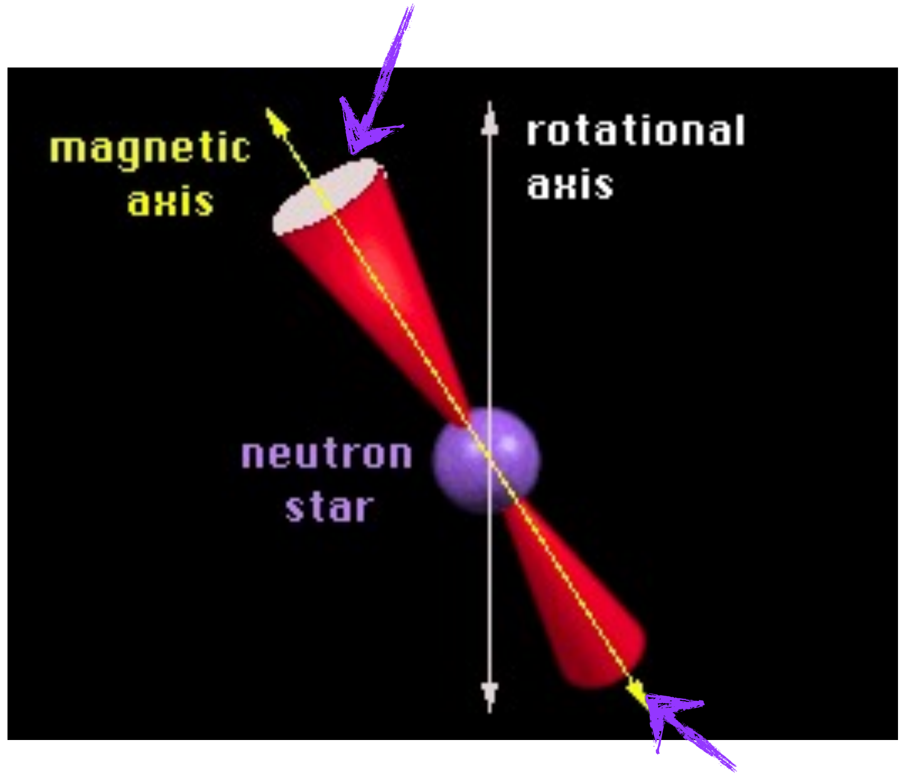
Lesson: Supernovae are the spawn of pulsars.

The Crab Nebula is a supernova remnant – The remains of a supernova explosion that occurred in 1054. Pulsars are often associated with remnants of supernova explosions. What could it be? Pulses were too fast to be a star pulsing in size. Could it be spinning? Would have to be small to be spinning that fast. Perhaps a spinning neutron star?!? Anything larger in size would be torn to pieces!

A pulsar is a spinning neutron star

- Neutron star's intense magnetic field creates beams of radiation
- Rapid rotation sweeps beams around the sky
- If the beam sweeps over Earth, see a flash of light (else nothing)
- Like a lighthouse!

Light comes out here



and here

If the beam sweeps past Earth, you see a flash of light

When the core collapses, its spin and magnetic field strength increases. Conservation of angular momentum!

Typically

Surface field strength over 1 trillion times that of the Earth.
Rotation rate up to 1000 times per second – 20% the speed of light!

Magnetic field beams radiation into space

A pulsar is a spinning neutron star

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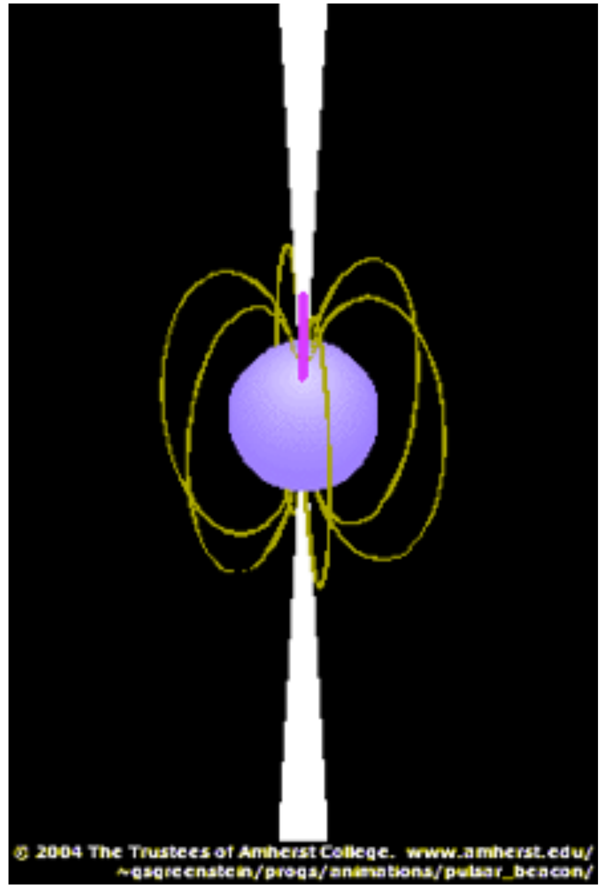
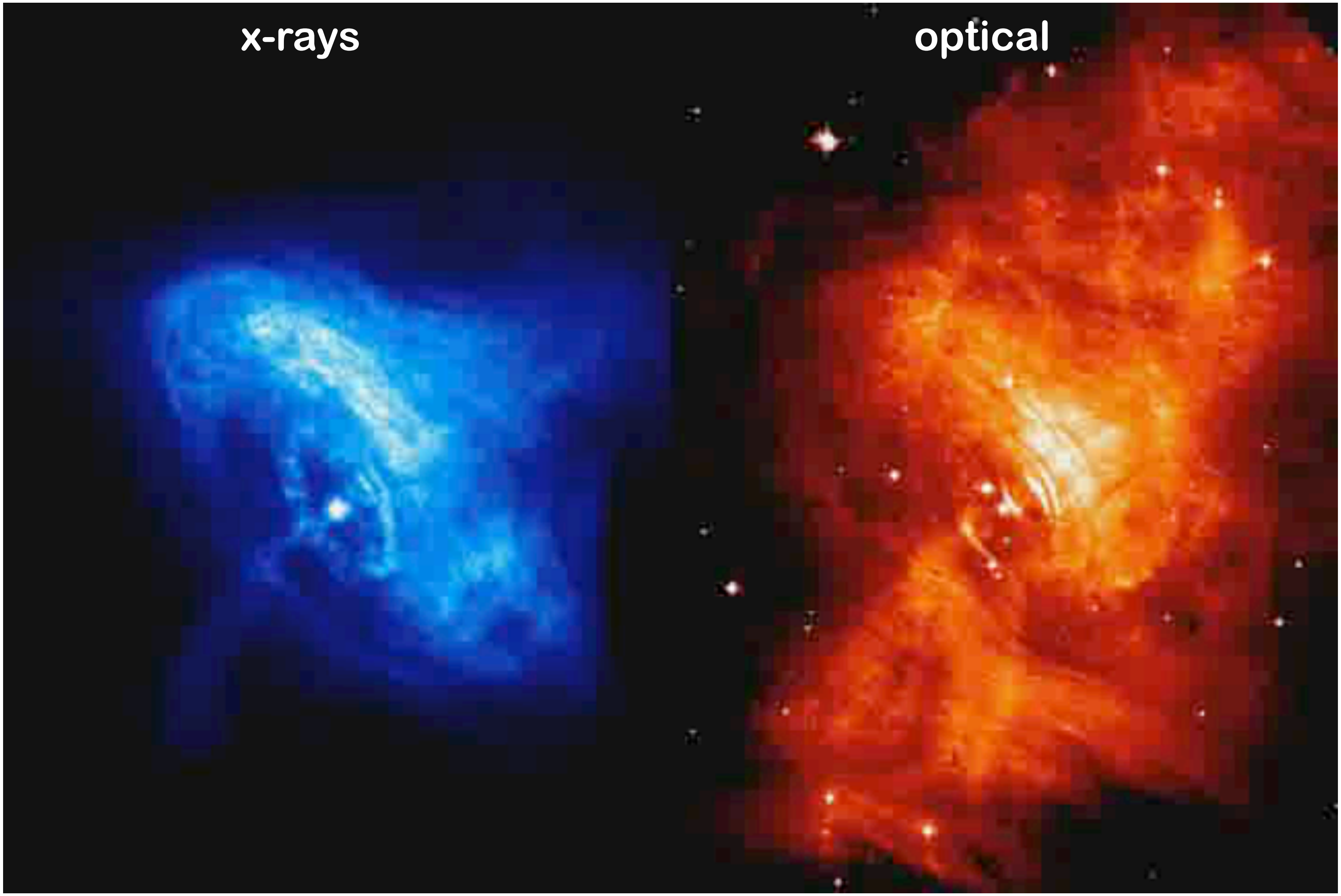


If the beam sweeps past Earth, you see a flash of light

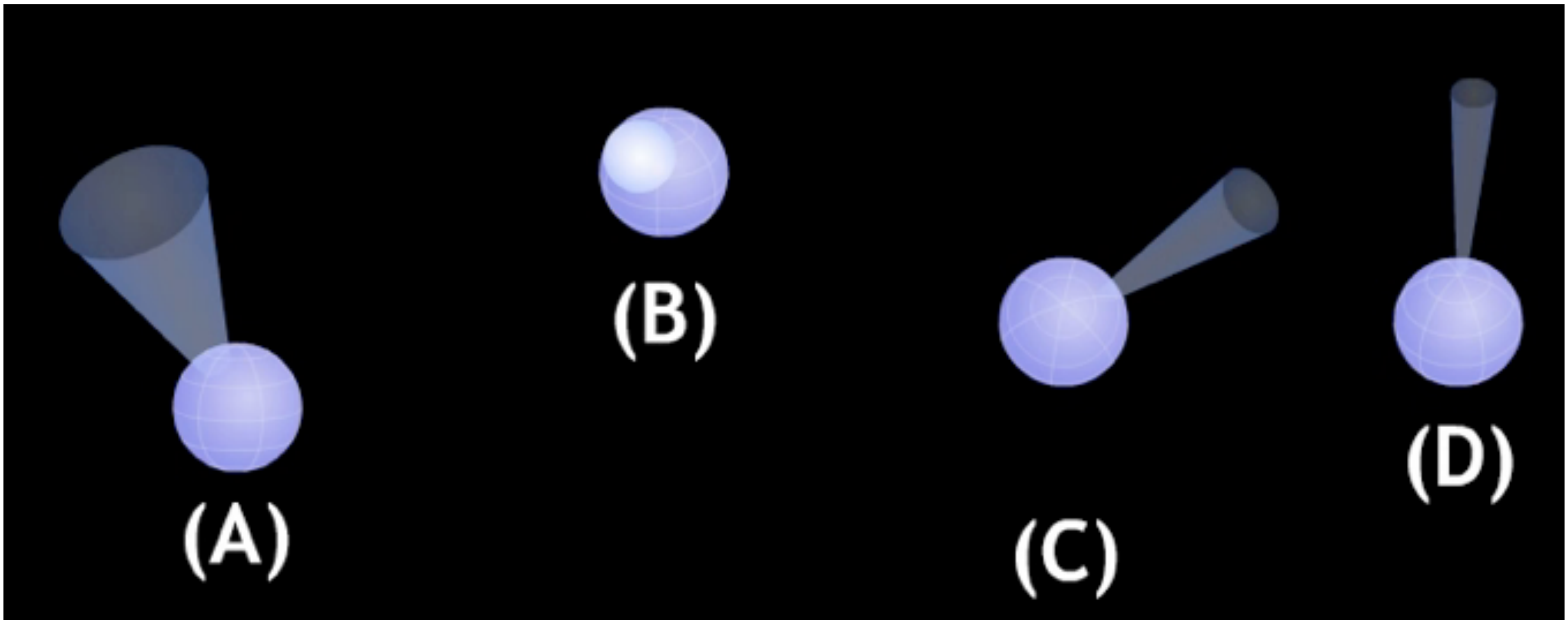
Close-up of the Crab's Neutron Star



This movie shows dynamic rings, wisps and jets of matter and antimatter around the pulsar in the Crab Nebula as observed in X-ray light by Chandra (left, blue) and optical light by Hubble (right, red).

Thought Question

Which of these neutron stars would be observed as a pulsar?



Answer B: The one that intercepts your line of sight.

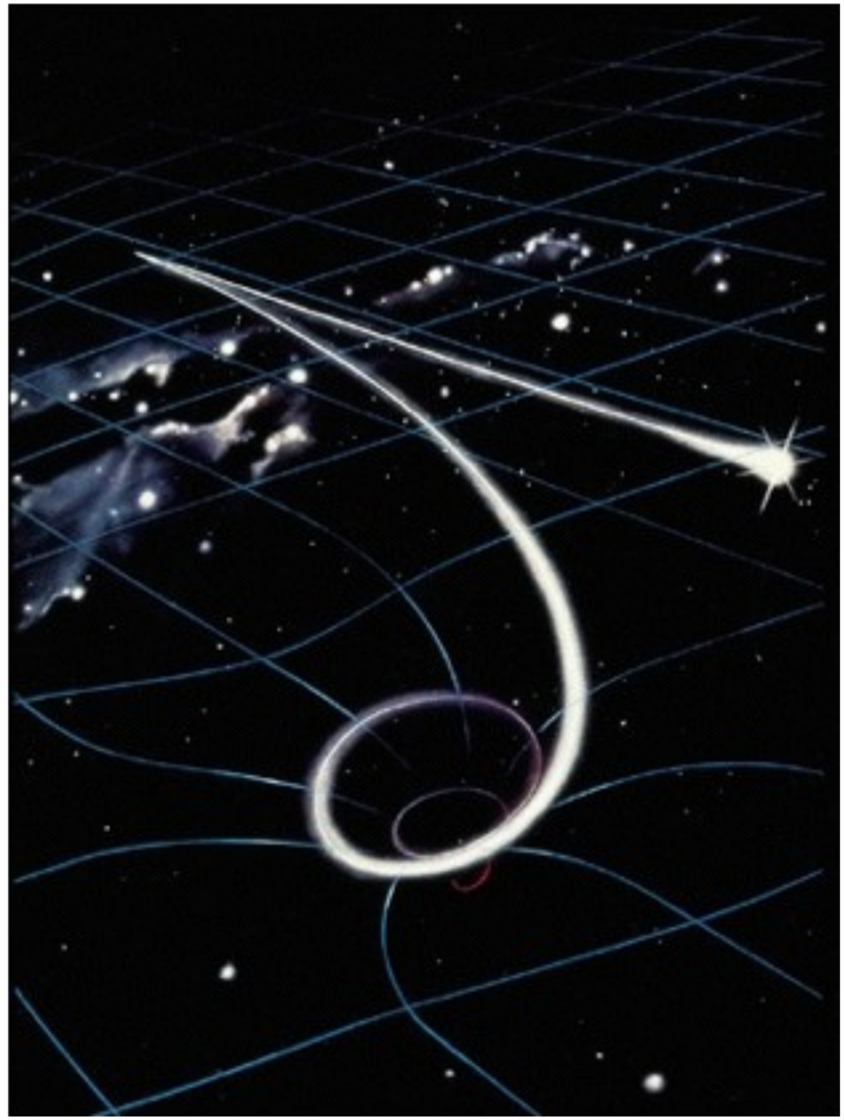
Neutron star limit

If star leading to supernova has M $\gtrsim$ 30 M_{Sun}

- Huge mass of star = huge gravity force on core
- Neutron pressure cannot stop the crush of gravity core Mass > 3 M_{Sun}
- Stellar core collapses

Leaves behind a black hole

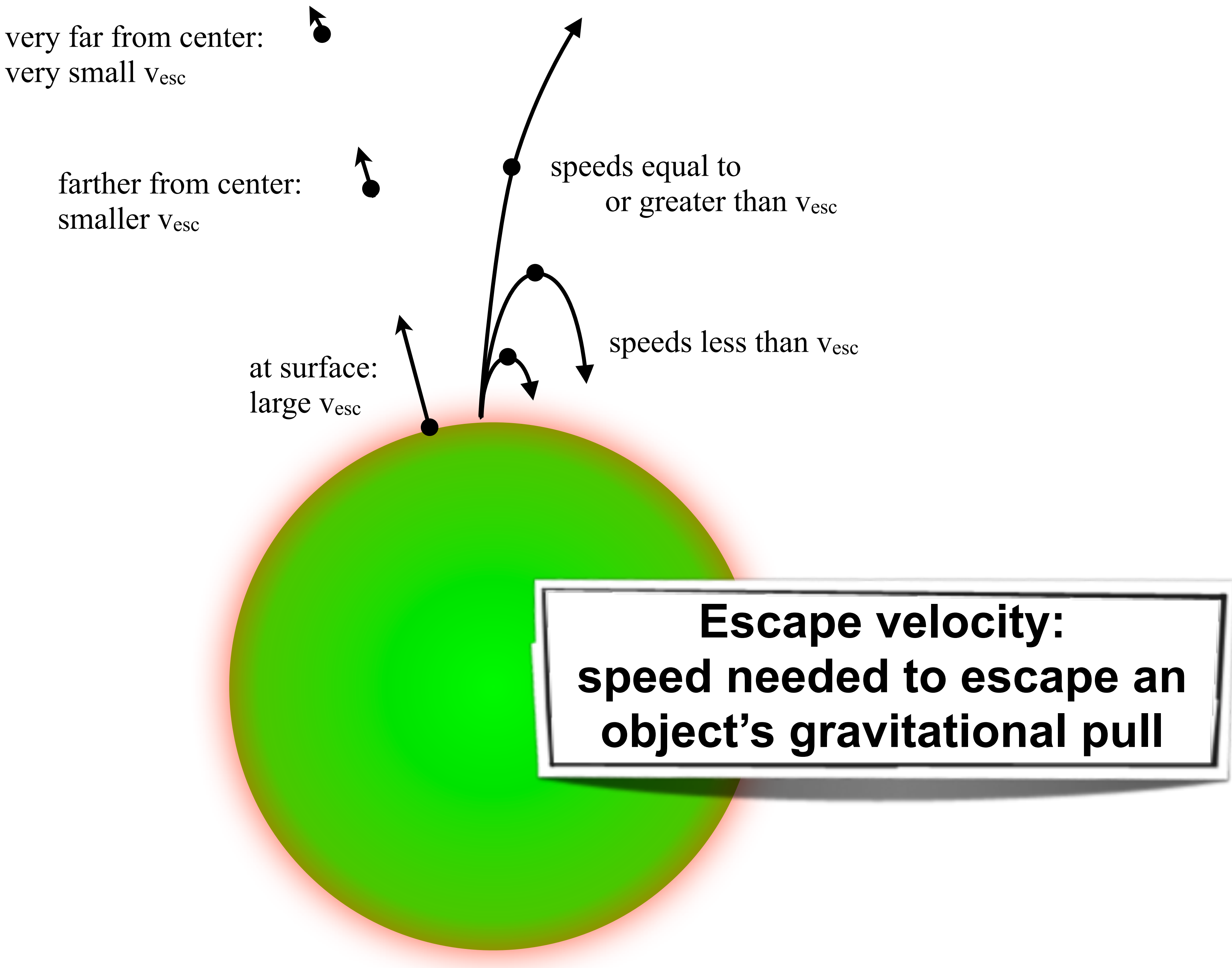
- like pulsars, expected to be rapidly spinning
- regions of extremely strong gravity



What is a black hole?

A black hole is an object whose gravity is so powerful that not even light can escape it.

To understand what we mean by “even light can not escape a black hole”, we have to understand escape velocities on other objects.



Escape velocity: speed needed to "break free" from a gravitational field. If speed is less than the escape speed, then you will will fall back onto the object. If speed is more than the escape speed, then you will leave the object, never to return. The farther you start from the center of the object, the lower the speed needed to escape its gravitational pull and vice-verse. The closer you start to the center of the object, the greater the escape speed.
The escape velocity from Earth's surface is about 40,000 km/hr, or 11 km/s. This is the minimum speed required to escape Earth's gravity for any object that starts near Earth's surface.

The speed of light - a universal speed limit

According to Einstein's theory of relativity, nothing can go faster than the speed of light

The speed of light - a universal speed limit

How fast is that?
Around the Earth over 7 times in a second
From Earth to the Moon in under 2 seconds
(it took the astronauts 4 days)
From the Sun to the Earth in a little over 8 minutes
From the Sun to Pluto in about 5½ hours
From the nearest star to Earth, about 4 years

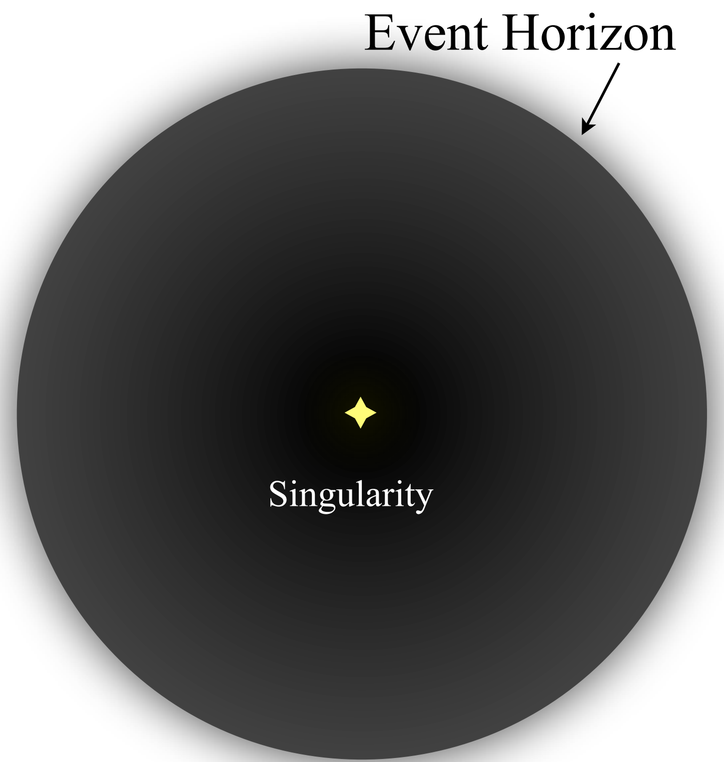
If escape velocity > speed of light, nothing can escape, even light

If you shrink the Earth to < 1cm, then the escape speed would be greater than the speed of light.
It would be a black hole!

As you shrink an object, Surface gravity gets stronger, Escape velocity increases. For example, if we shrink Earth, its escape velocity goes up. If escape velocity > speed of light, the object is a black hole. Not even light can escape.

"Parts" of a black hole

- Event horizon
  - Boundary around a black hole where the escape velocity = the speed of light
  - Nothing can escape from within it
- Singularity
  - All the matter that forms a black hole is crushed to an infinitely tiny and dense point at its center



For every 1 M_{Sun} of mass, a black hole's event horizon has a radius of 3 km

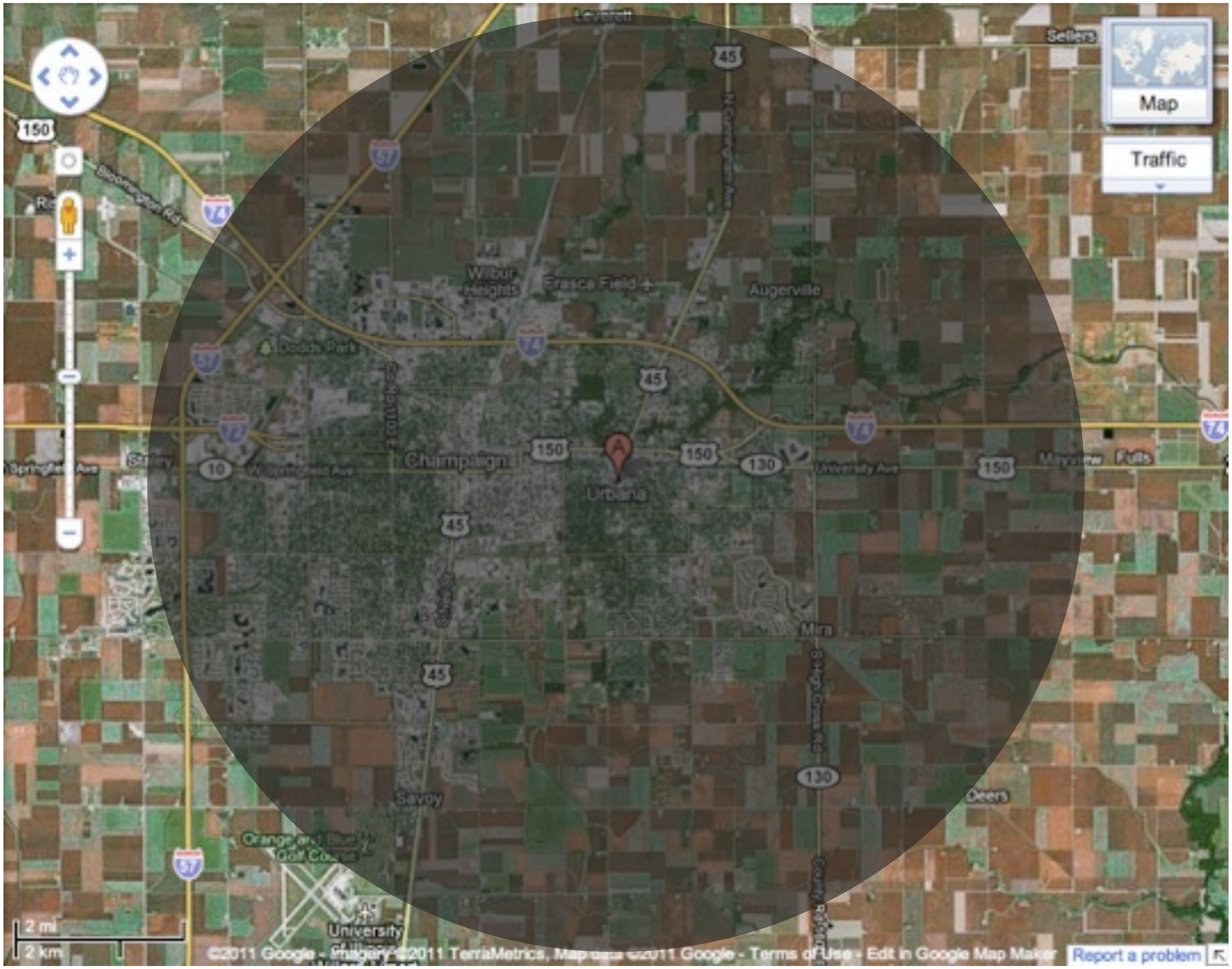
A collapsing object becomes a black hole when the escape velocity from its surface exceeds the speed of light. The event horizon is not a physical surface, just a distance from the center. Nothing can escape from within the event horizon because nothing can go faster than light. The event horizon gets its name because we have no hope of learning about any events that occur within it. Calculated by Karl Schwarzschild during WWI, while assigned to calculate artillery trajectories. The distance from the center to the event horizon is called the Schwarzschild radius.

Thought question

The radius of the event horizon of a 1 M_{Sun} black hole is 3 km. Thus, the radius of the event horizon of a 2 M_{Sun} black hole must be...

A. 1.5 km
B. 3 km
C. 6 km
D. 9 km
E. 12 km

Answer C: The radius of the event horizon increases directly with the mass of the black hole. If 1 M_{Sun} is 3km, then 2 M_{Sun} is 6km.



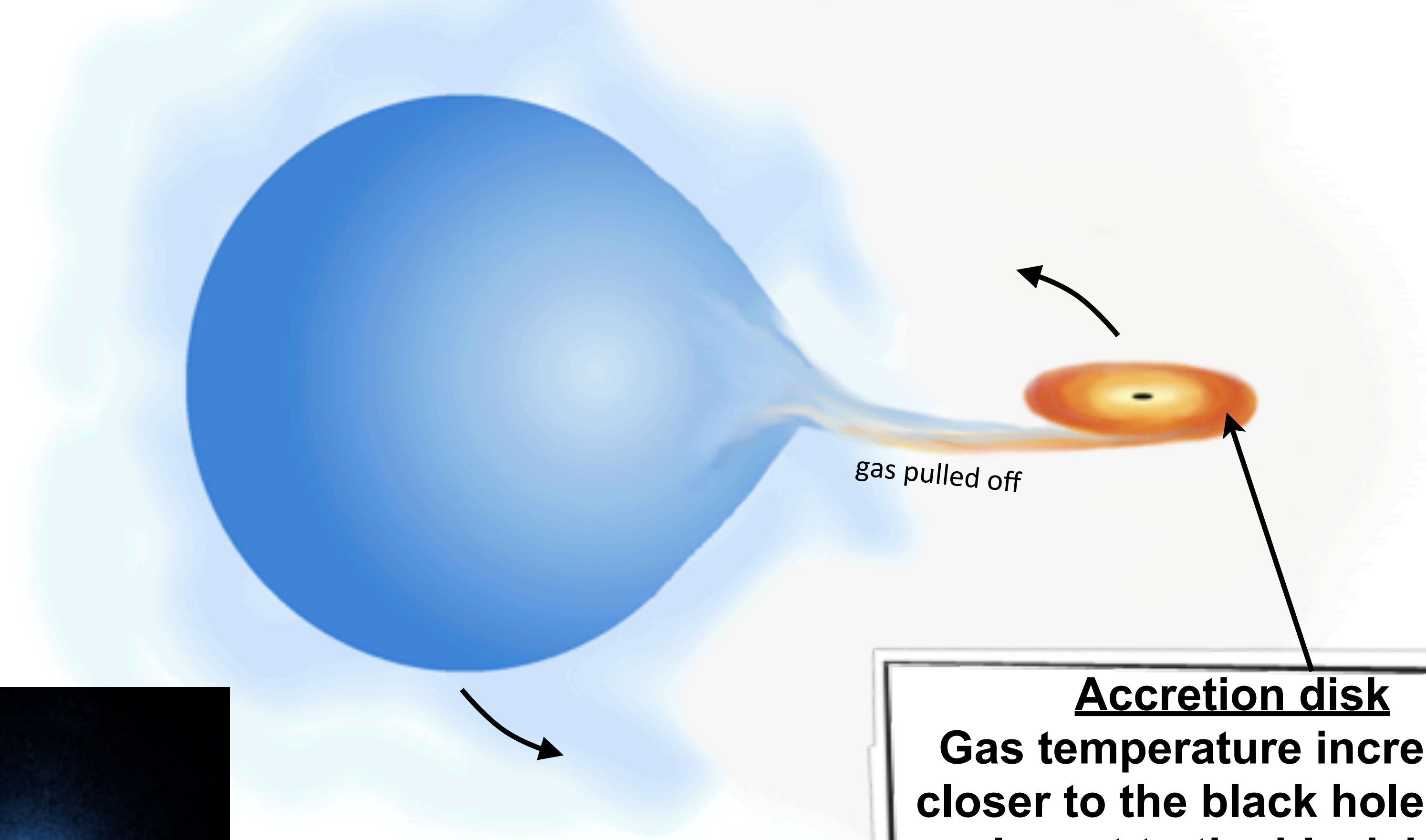
The event horizon of a 3 M_{Sun} black hole compared to Champaign-Urbana

For every solar mass, the event horizon has a radius of 3 km. 3 M_{Sun} black hole, 9 km radius event horizon

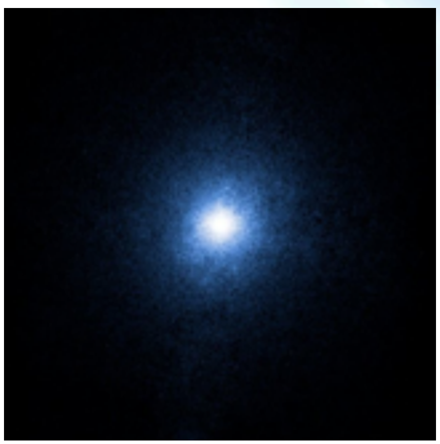
How do we “see” a black hole?

Can you find the black hole above?

How do we "see" a black hole?
Black holes in binary star systems!



<u>Accretion disk</u>
Gas temperature increases closer to the black hole. Gas closest to the black hole emits X-rays



<u>Cygnus X-1 the first x-ray detected black hole</u>

If a black hole is in a binary star system, it can steal matter from its sister star. This matter falling toward a black hole forms an accretion disk. The hot gas falling into the black hole emits strongly in X-rays.

iClicker Poll: Life Far Away From a Black Hole

Future industrial accident ("mistakes were made") causes Sun to be crushed to black hole without gain or loss of mass

What happens to Earth's orbit?

A. nothing: same orbit!

B. spirals in: aaargh!

C. stronger gravity, orbit closer, more elliptical but does not fall in

D. weaker gravity, orbit closer, more elliptical but does not fall in

Answer is A. Gravity is gravity. It is only close to a black hole that space time becomes different.

Black holes follow the same laws of gravity as everything else

Earth would have the same orbit around a 1 M_{Sun} black hole as it does around the Sun!

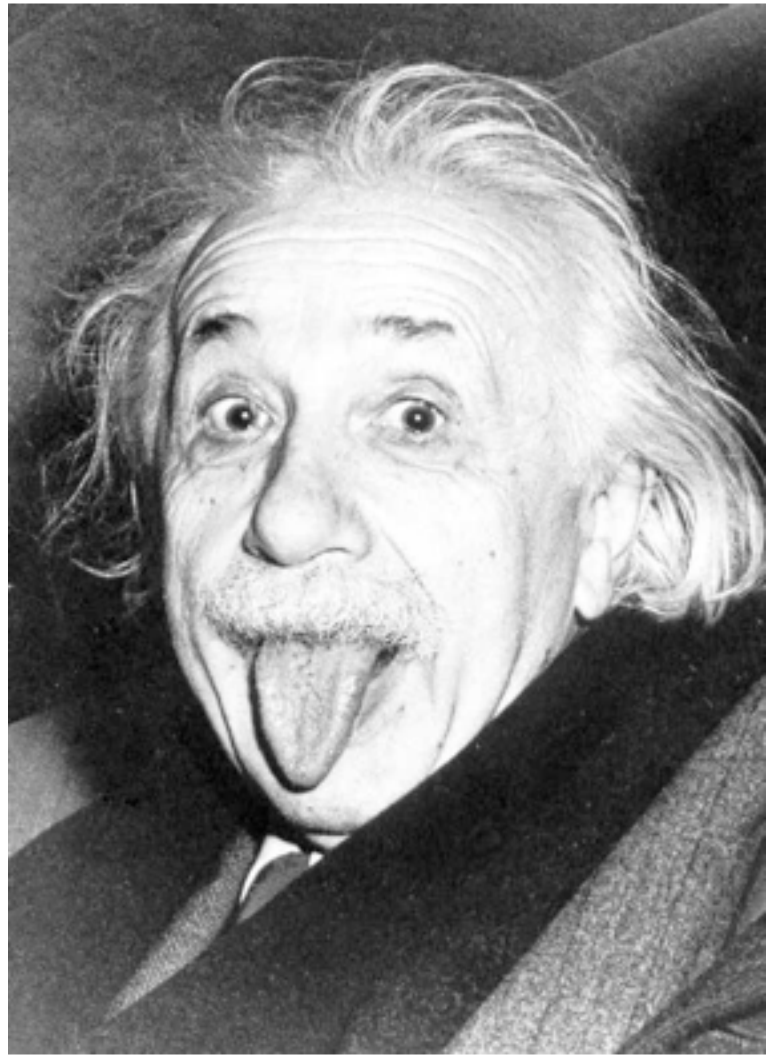
If the Sun shrank into a black hole, its gravity would be different only near the event horizon – and that's about 3 km. Black holes don't suck! Without sunlight, the Earth's surface would get extremely cold!

Physics of Black Holes

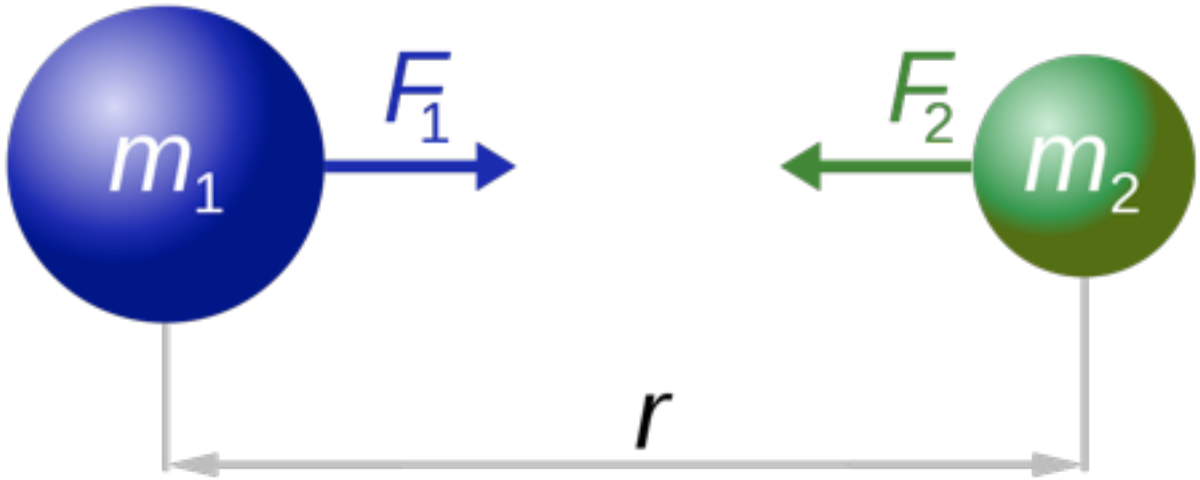
- Black holes are simple, yet strange objects
- Intense gravity due to compactness
- Newton's Laws cannot describe what happens in the nearby presence of such an intense gravitational field
- We need Einstein's Theory of Relativity

What happens to space and time near a black hole?

Einstein's Theory of Relativity tells us how a black hole affects space and time in its vicinity



How does a black hole's gravity stop light from escaping?

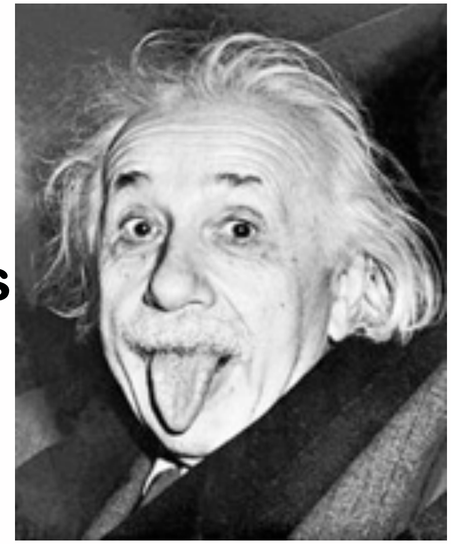


$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

Photons have no mass, so Newton's Law of Gravity says there should be no force on them!

Space, Time and Motion

Recall Galileo/Newton special cases of motion



Free Body

- object with no net forces acting
- motion is a straight line, constant speed

Important to note that all free bodies move this way. Straight line, constant speed, independent of size, mass

- Q: Why?
- Newton: That's the way it is!
- Q: Be more specific: that's the way what is?
- 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

Motion really reflects nature of space and time