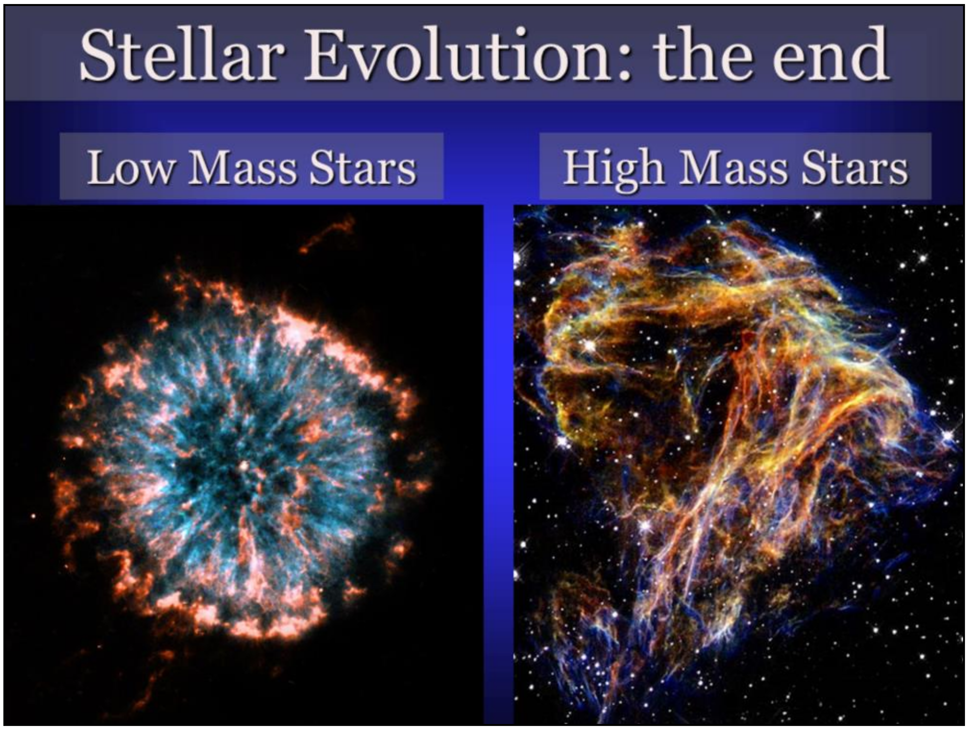
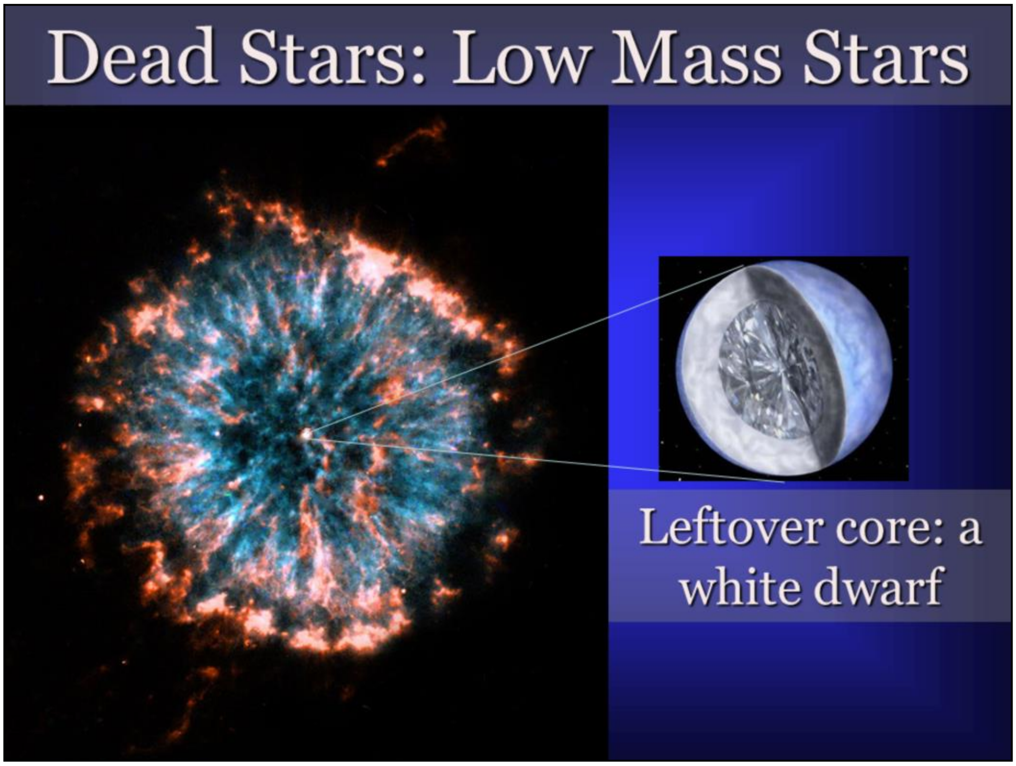


Left: “Glowing Eye Nebula” HST image, planetary nebula

Right: N49, Type II supernova remnant


Dead Stars: Low Mass Stars
Leftover core: a white dwarf

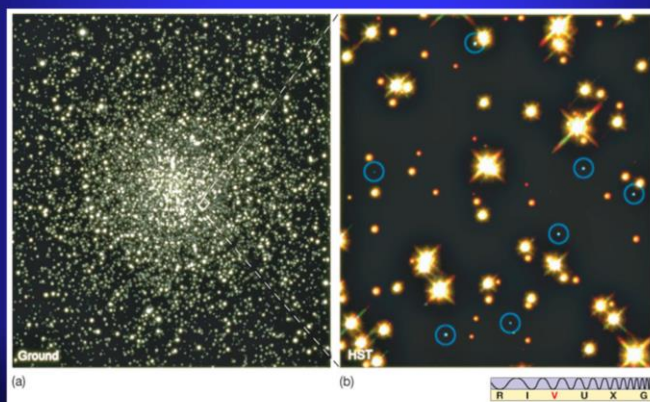
White Dwarfs

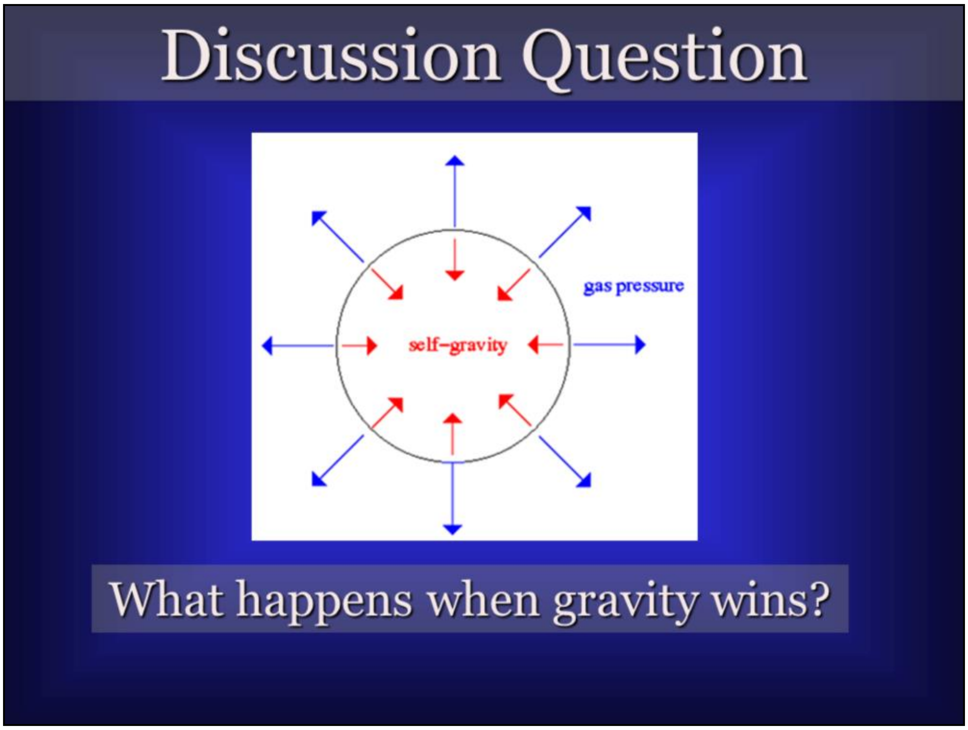
1. How do they form?
2. What are they made of?
3. What stops them from collapsing?
4. How big are they?
5. What's their size/mass relationship?
6. What is a nova?
7. What is a type I supernova?

Weird Stuff

White Dwarfs:

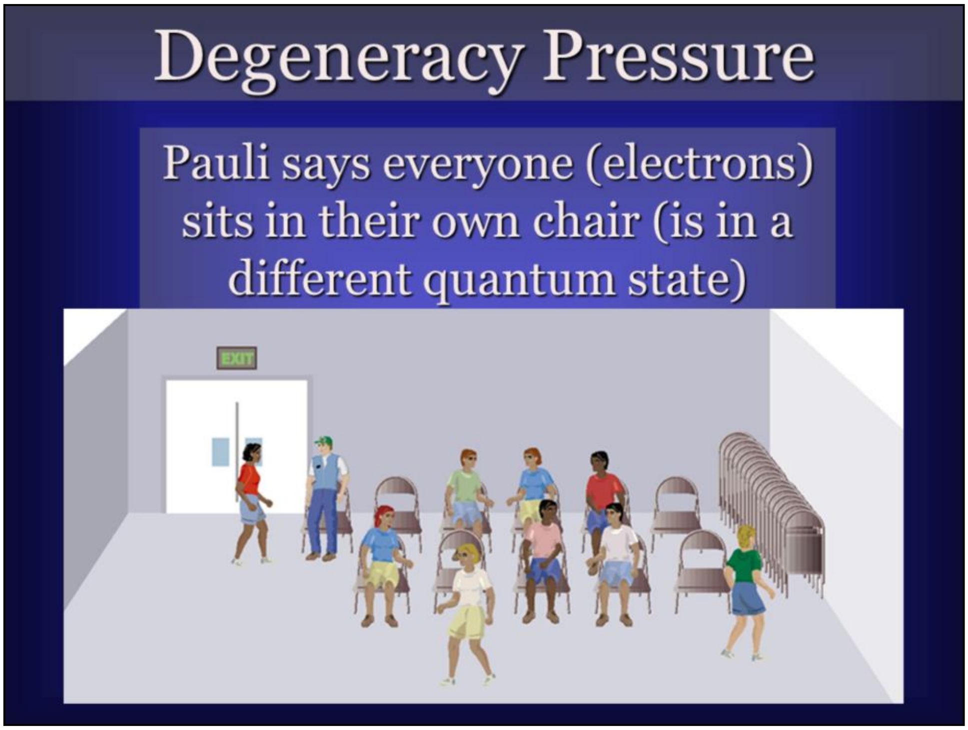
the dead stellar core left over after the low mass puff off their outer layers





What is the “gas” made of?

What determines the size of the ball?



The Pauli exclusion principle states that subatomic particles like electrons, neutrons, and protons may not occupy the same quantum state.

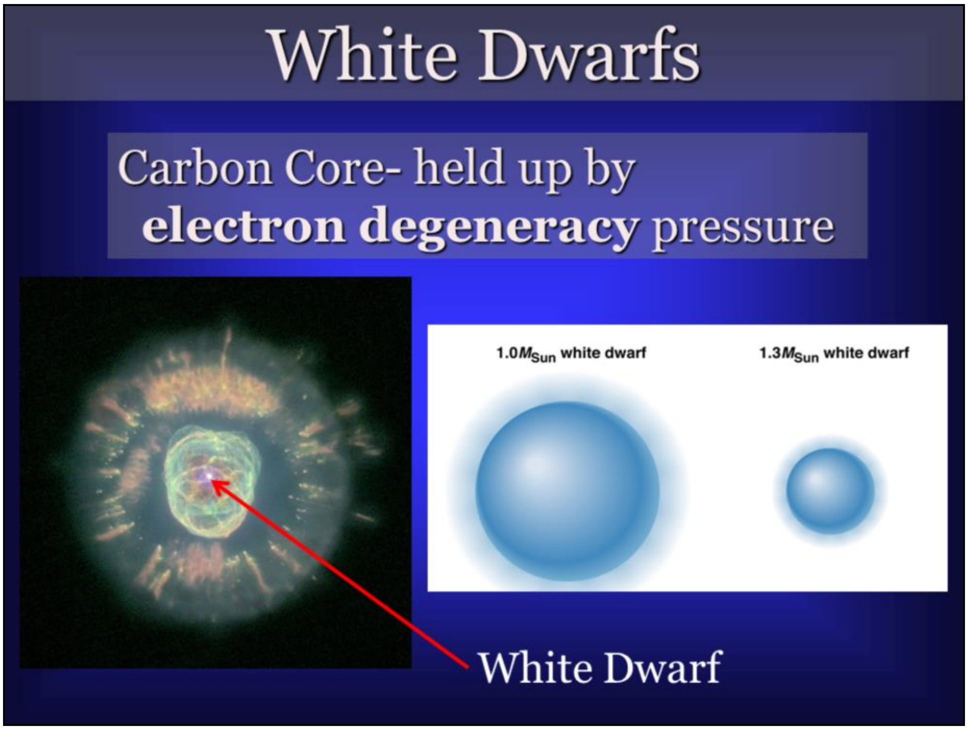
When you try to make them, they start to fight.

If you keep packing people in, they will eventually sit on each others laps. Or something…

Pressure no longer depends on temperature. It depends instead on how closely packed the electrons are.

According to the uncertainty principle, if you squish electrons down into a small space, their momentum gets more and more out of control. Thus the 'pressure'

Degeneracy refers trying to make them occupy the same quantum state. They resist degeneracy.



They are not fusing… only cooling off. Verrrrrrrrrry slowly

Since there is no longer an internal energy source, gravity crushes the material down until it is being held up by electron degeneracy pressure.

Since degeneracy pressure doesn't depend on temperature, white dwarfs never change size once they are created.

In fact, white dwarfs actually get smaller the more massive they are because degeneracy pressure depends on the distance between particles.

On the HR diagram, they follow a line of constant radius, slowly cooling off and getting dimmer.

Degenerate matter is VERY dense. Approximately 10 tons per cubic inch.

They are dead core of a low mass star. When the star dies (creating a planetary nebula), the nebula eventually disperses leaving behind the white dwarf

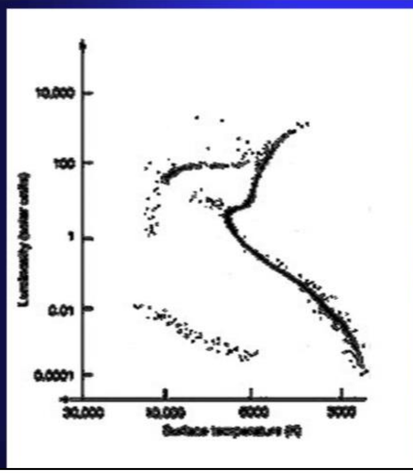
Therefore, White dwarfs are made up mostly of carbon nuclei and electrons.

In fact, it is believed that there is a layer of crystalline carbon near the surface.

This means that there diamonds beneath the surface of a white dwarf!

What happens then?

After a white dwarf forms, all it can do is cool…

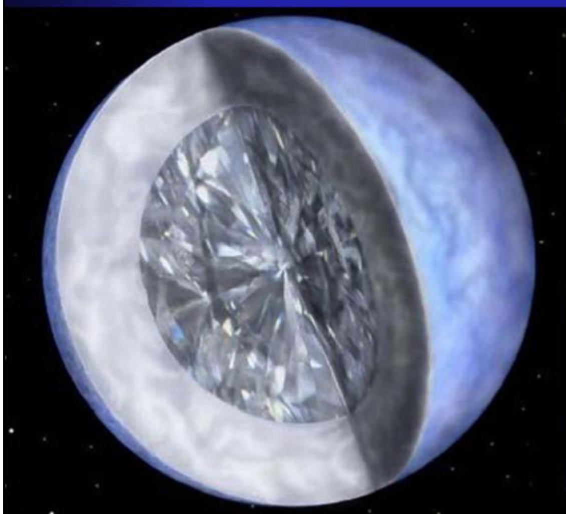


The vertical spread is radius

Horizontal spread is temperature

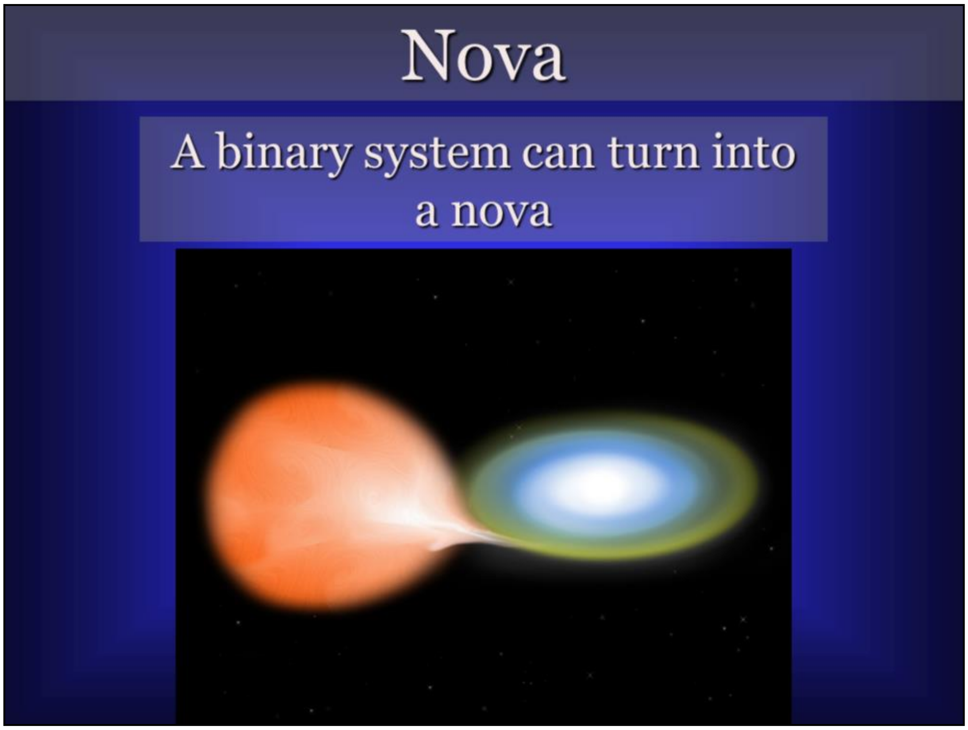
The star’s luminosity changes due to the quakes, which we use to figure out the structure of the interior (just like helio-seismology, this is astero-seismology).

White Dwarf



... and crystallizes...

Making the biggest diamonds in the universe!



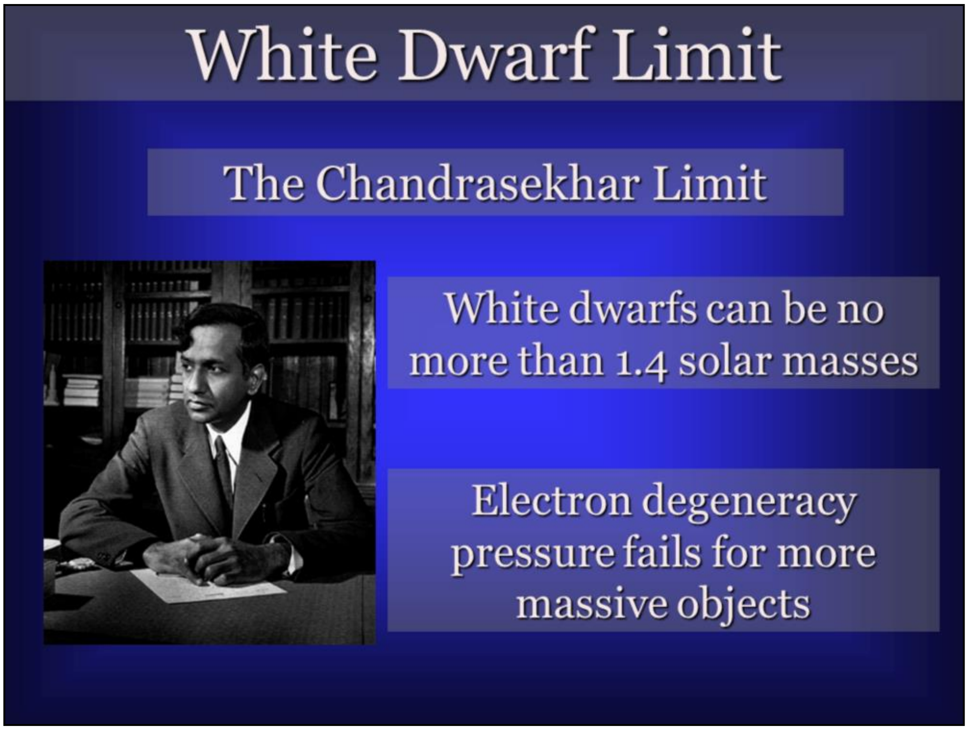
How do we get more mass onto a white dwarf? It's already dead….

Suppose we have a white dwarf around a red giant.

The giant can feed hydrogen onto the surface of the white dwarf.

Eventually, enough piles up that the hydrogen fuses in a large and sudden detonation (called a *nova*)

Then the process starts all over again.



Chandrasekhar did this work between his undergraduate and graduate academic careers.

When he presented the work to the Royal Society, they balked.

Later he won the Nobel Prize in physics for his work on degeneracy.

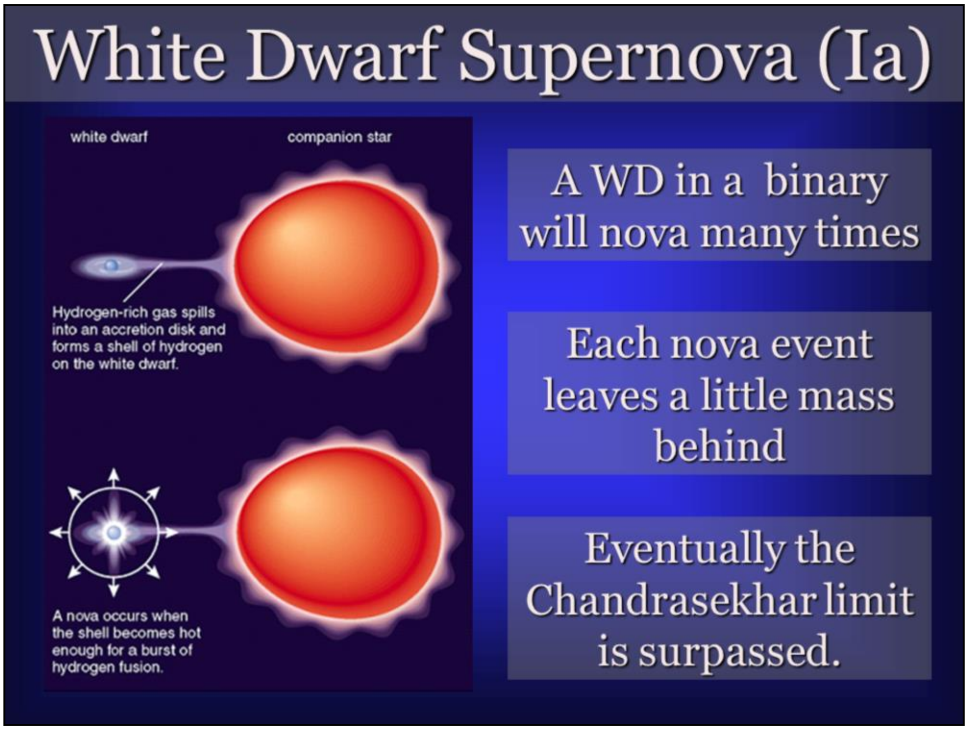
So… What happens when a white dwarf exceeds the Chandrasekhar Limit?

It turns into a neutron star!

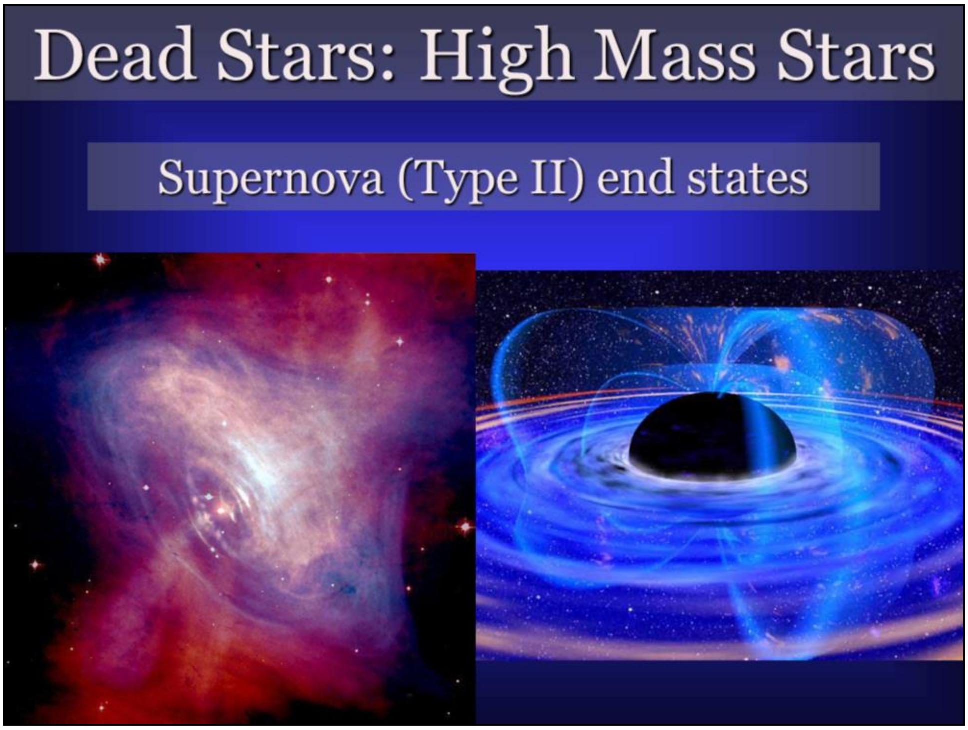
Question

After MANY white dwarf novas, the white dwarf

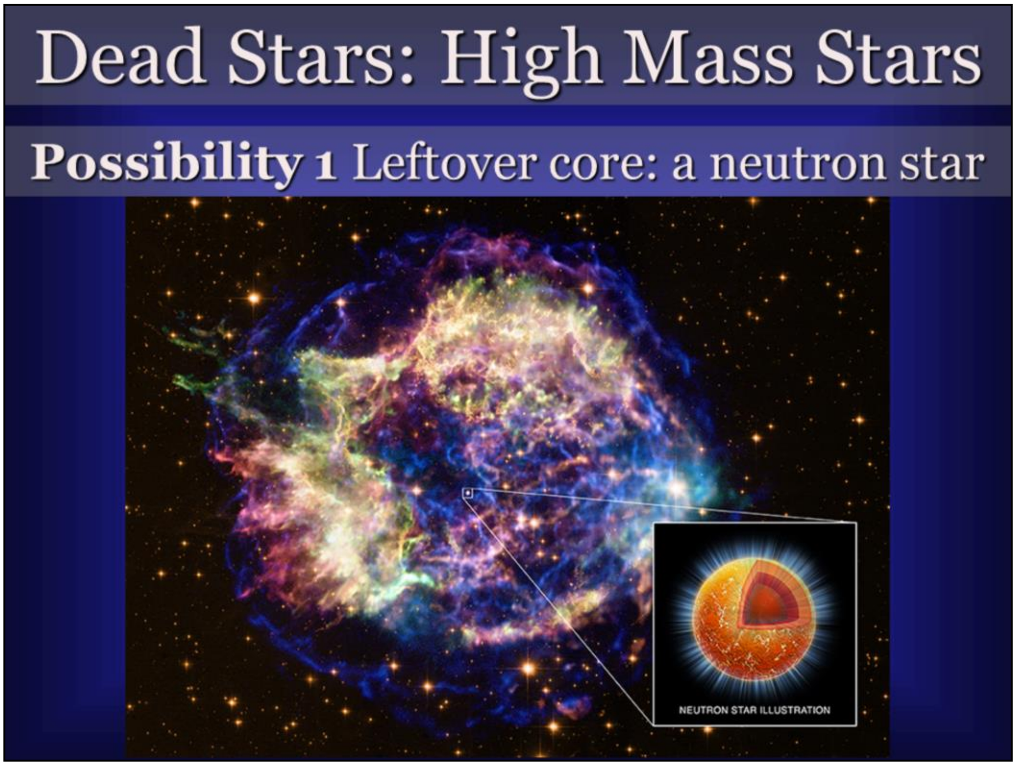
A. gets more massive and slowly shrinks to a single point
B. uses up the fuel of its red giant companion and becomes a “normal” white dwarf.
C. collapses suddenly and explodes violently
D. The novae keep happening forever



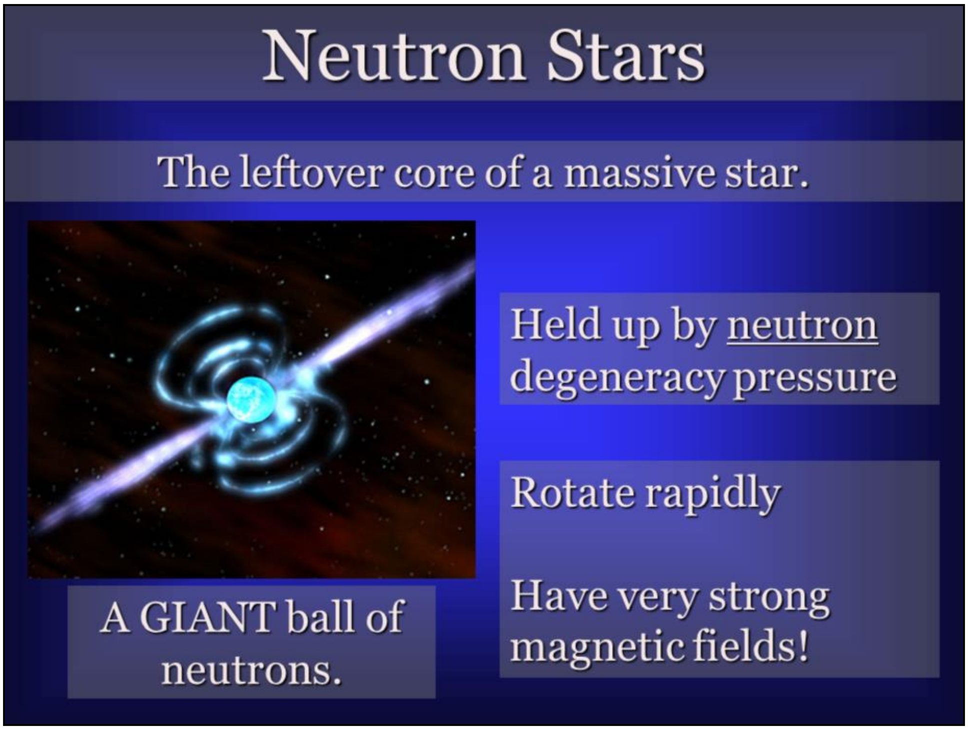
Eventually you build up so much material that the white dwarf reaches the Chandrasekhar limit. And THEN a big explosion happens. The WD collapses and detonates, exploding completely.



In addition to WD novae, Type II supernovae can make neutron stars directly (and also black holes).

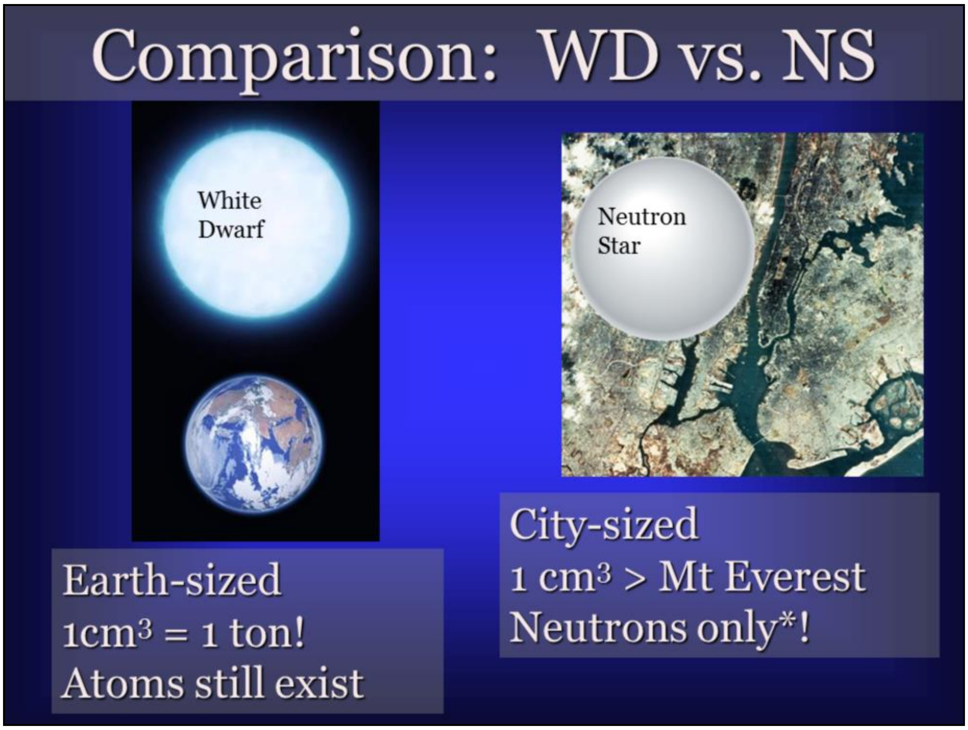


White Dwarf (and planetary nebula) on the left; Type II supernova on the right



About the size of Manhattan Island but more massive than the Sun.

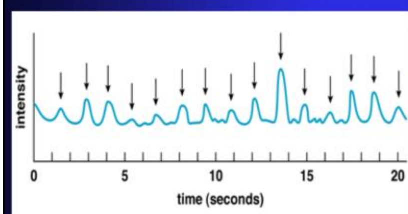
A cubic inch weighs more than Mt. Everest.



*mostly. Though maybe not entirely.

Little Green Men

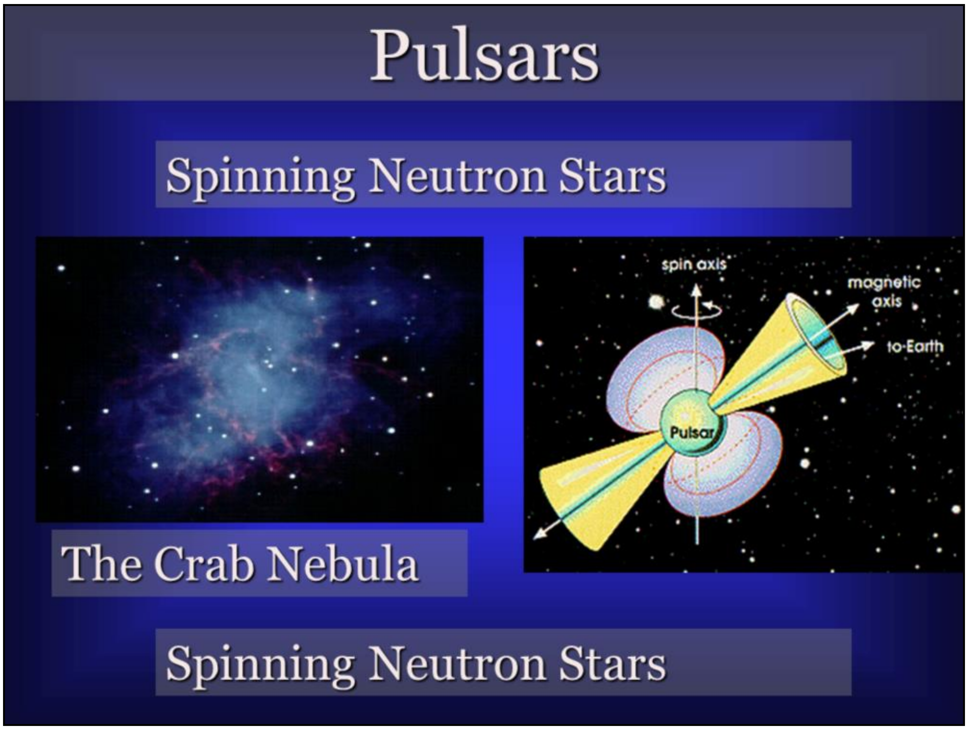
Jocelyn Bell- 1967



A 4 ½ acre radio telescope designed to find quasars

Found a very regular radio signal.

They called the source LGM-1



After a lot of puzzling, they turned out to be spinning neutron stars.

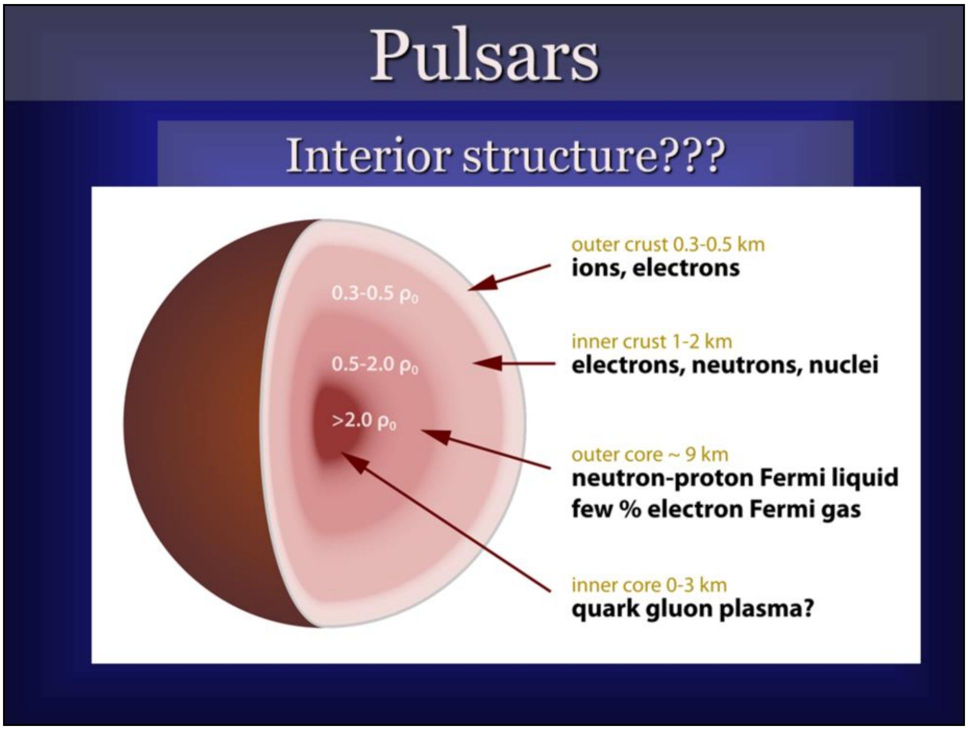
The magnetic field is offset from the axis of rotation.

Light is being beamed out of the poles of the magnet.

When the light sweeps past us, we see a pulse. The period of the pulsation is the rotation period of the neutron star.

All pulsars are neutron stars. The light is from charged particles (electrons) moving very fast around the magnetic fields. The emission is concentrated into a beam that comes out at the magnetic poles.

We only see the pulse if the beam sweeps past us.



Yeah so like, what even?

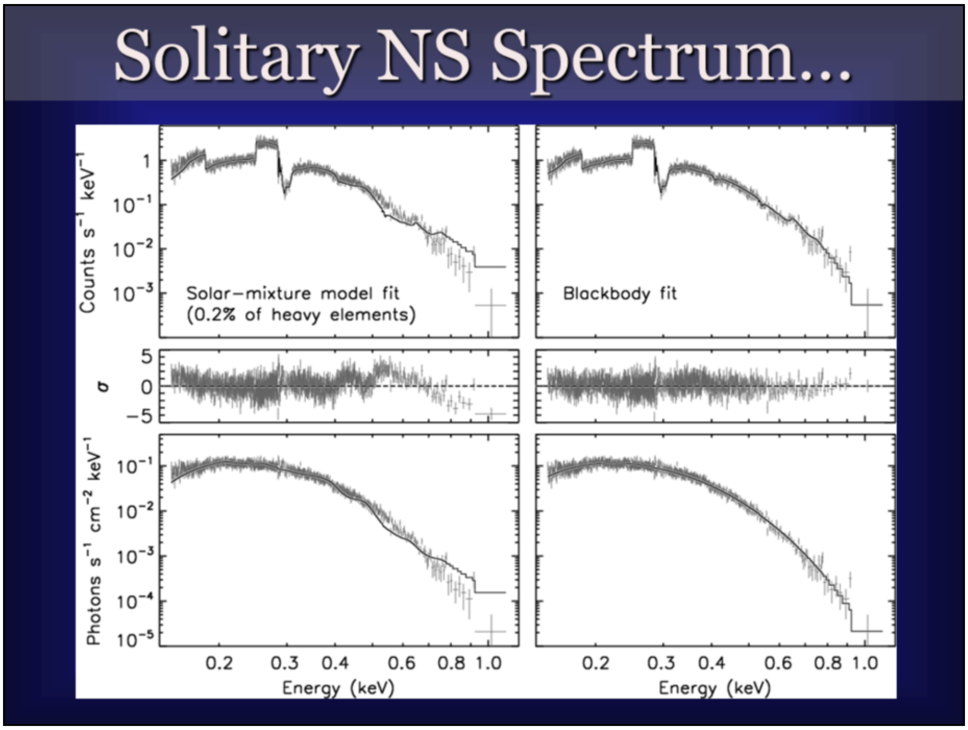
Definitely the outside has regular ions. (see spectrum next page)

And certainly inside is a superfluid.

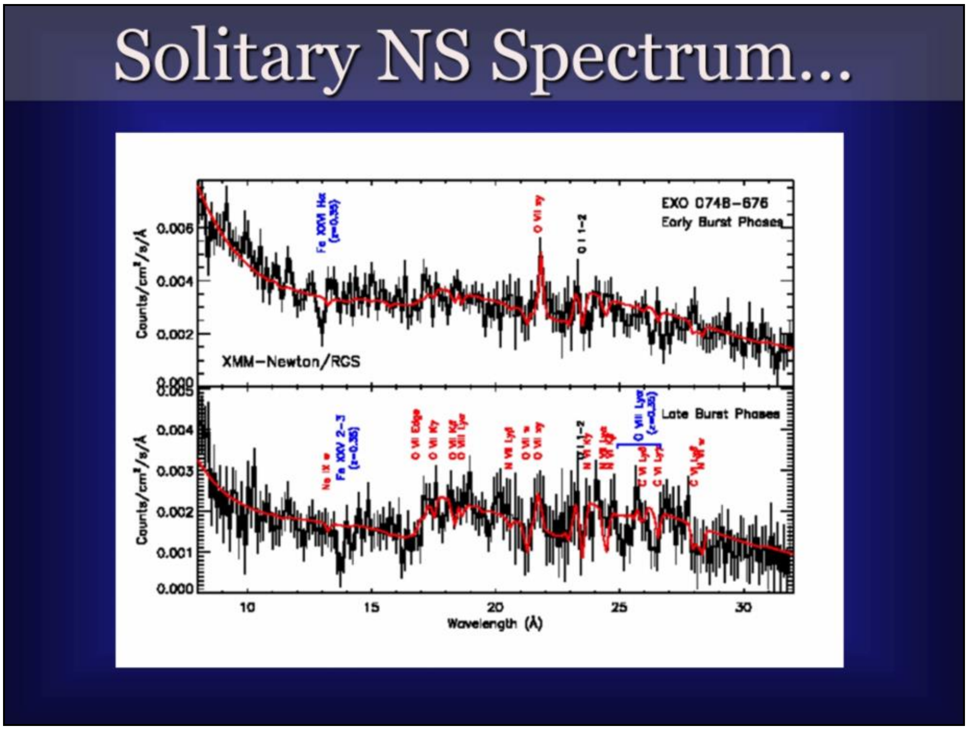
So probably some kind of superconducting superfluid somewhere in there → spinning charges make for magnetic fields

What's the deal with that quark and gluon plasma? IF it exists, then it will make a really big magnetic field (quarks are charged). This could explain it but we really don't know.

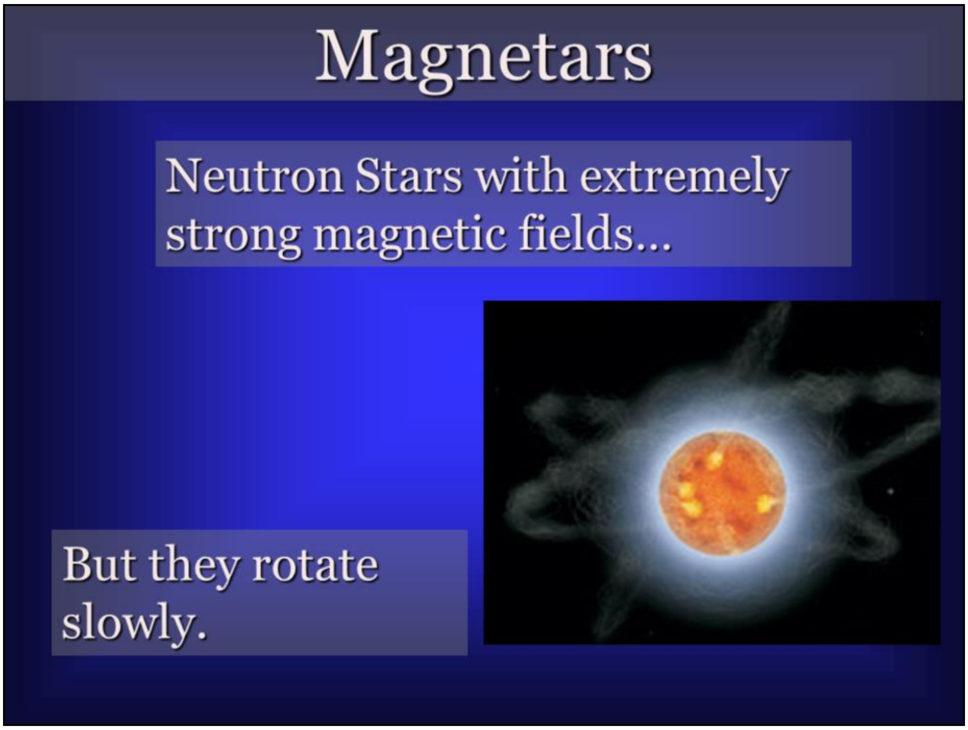
also: at least *some* neutron stars have atmospheres made of carbon! Weird! So it's clear that not *all* elements get crushed into neutrons. It will be interesting to see how our ideas of neutron stars change over the next 5-10 years.



Mostly a blackbody spectrum. This was 500ks observation (5.78 days staring at the same object in space… that's a LONG time!!) The odd jumps are due to iron lines, mostly.



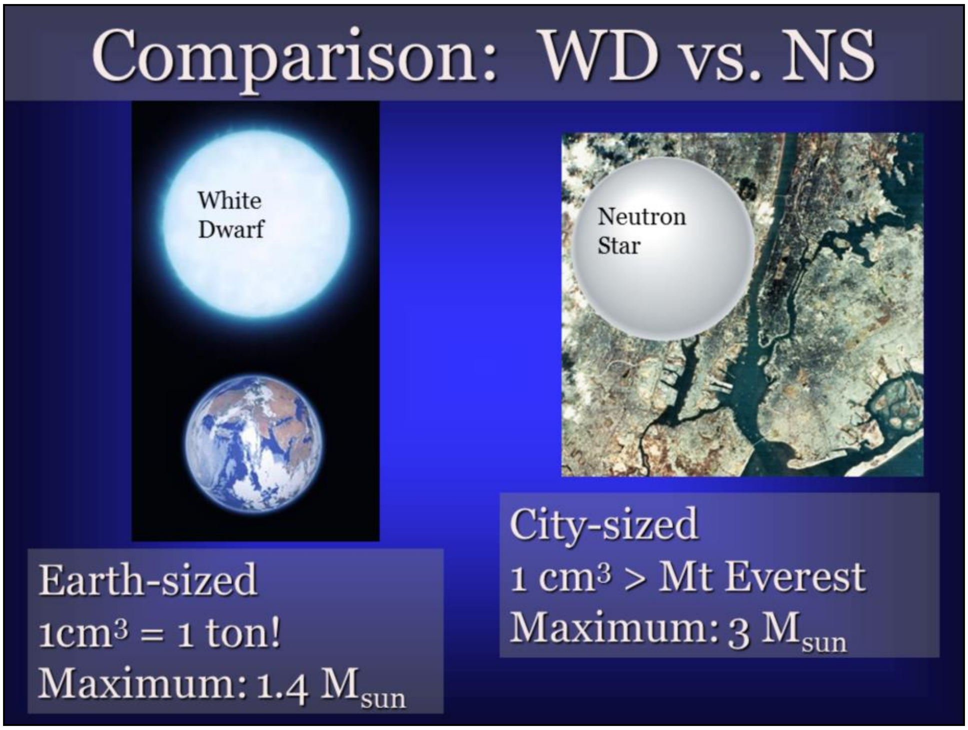
You can observe some leftover bits that aren't neutrons (after the core collapse and bounce, some of the overlying material falls back to the star). By these lines we can tell the size of the neutron star (since their width depends on the gravity felt by the atom). This neutron star is made of neutrons and not something weirder (like strange quarks)



Pulsars with very strong magnetic fields are relatively rare. The magnetic fields can stress the neutron star's crust and cause it to crack suddenly, causing huge starquakes… and a huge burst of energy.

There are a lot of questions about magnetars…

1) How do they have such big magnetic fields?
2) How do they form?
3) Do all pulsars have a magnetar phase?
4) We have observed a rapidly spinning pulsar slowing down quickly… and suddenly quaking in a way similar to a magnetar. Is it possibly on its way to turning into one as it loses rotational energy?



*mostly. Though maybe not entirely.

Neutron Stars

The force of gravity 1 AU from a 10 Solar Mass black hole is:

A. The same as the force gravity from a 10 solar mass star.
B. Greater than the force of gravity from a 10 solar mass star
C. Less than the force of gravity from a 10 solar mass star.
D. Infinite

Neutron Stars

The force of gravity 1 AU from a 1 Solar Mass black hole is:

A. The same as the force gravity from a 10 solar mass star.
B. Greater than the force of gravity from a 10 solar mass star
C. Less than the force of gravity from a 10 solar mass star.
D. Infinite

A super massive star goes supernova leaving behind a particularly large core.

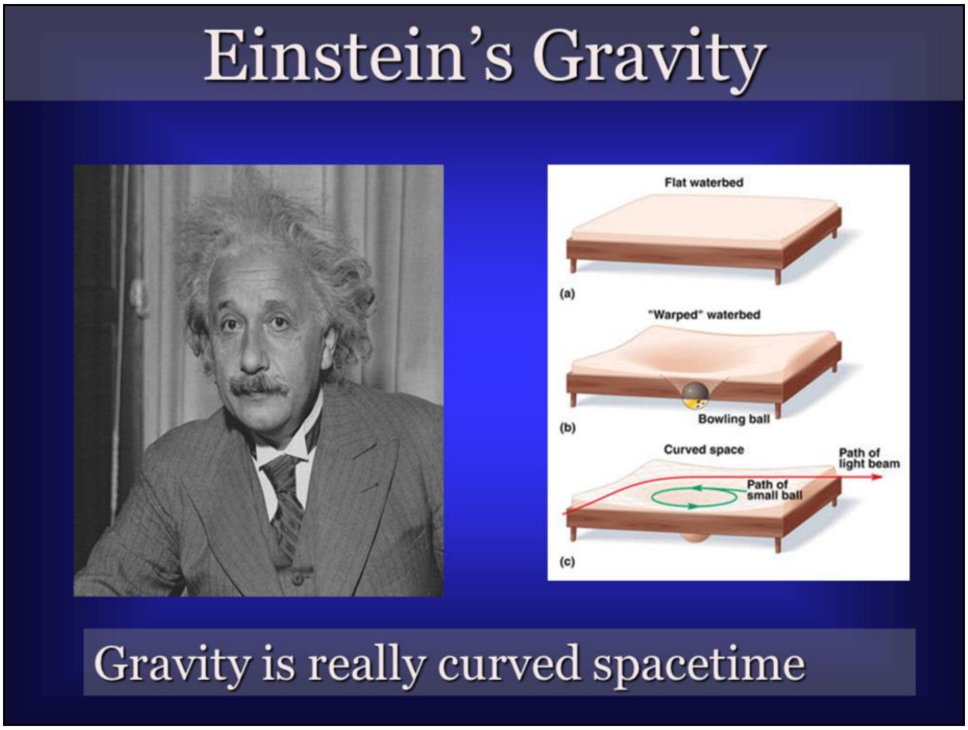
The release of gravitational potential energy that used to halt the collapse further strengthens it.

There is no form of pressure that we know of to stop gravity once neutron degeneracy fails.

The star collapses into oblivion. Gravity finally wins once and for all.

The star becomes infinitely small, reduced to a point that mathematicians call a singularity.

These objects are so compact and have such an immense gravitational field that Newton's gravitational law fails completely and we must turn to Einstein.

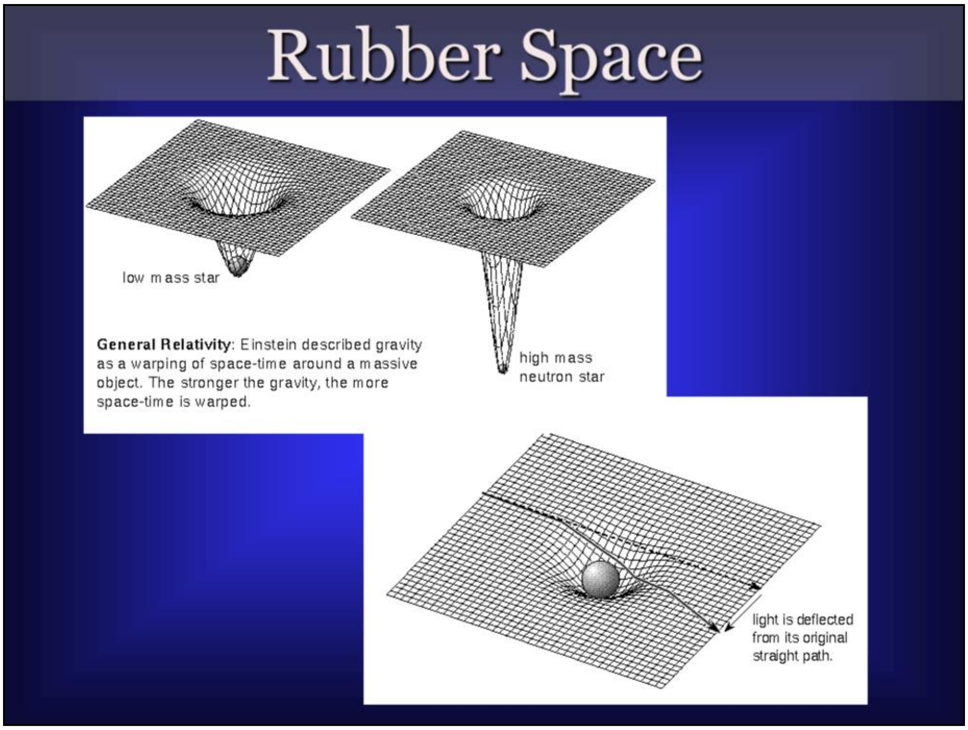


Massive objects always take the shortest possible path between point A and point B.

In flat space, the shortest path is a straight line.

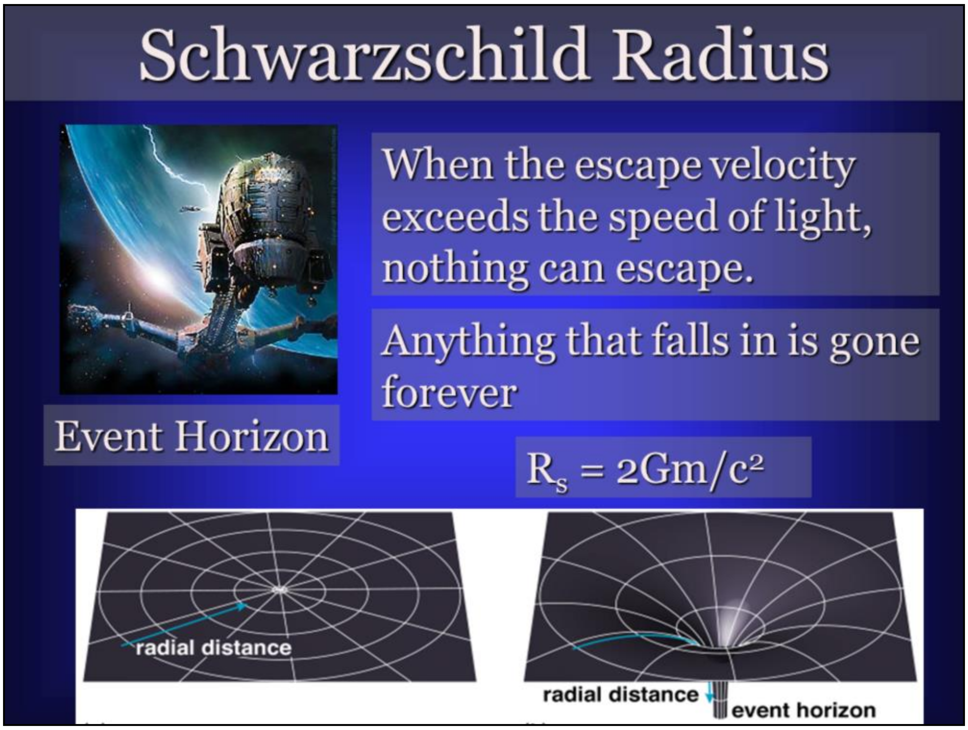
Spacetime gets warped by massive objects, so the shortest possible path is curved.

Light follows these curved paths as well. Light is effected by gravity.



Light itself actually goes into orbit around the black hole at the event horizon. If you could position yourself there, you could see the back of your own head!

$R_s = 2Gm/c^2$



Light itself actually goes into orbit around the black hole at the event horizon. If you could position yourself there, you could see the back of your own head!

$R_s = 2Gm/c^2$

Light itself actually goes into orbit around the black hole at the event horizon.
If you could position yourself there, you could see the back of your own head!

Black Holes

The force of gravity 1 AU from a 10 Solar Mass black hole is:

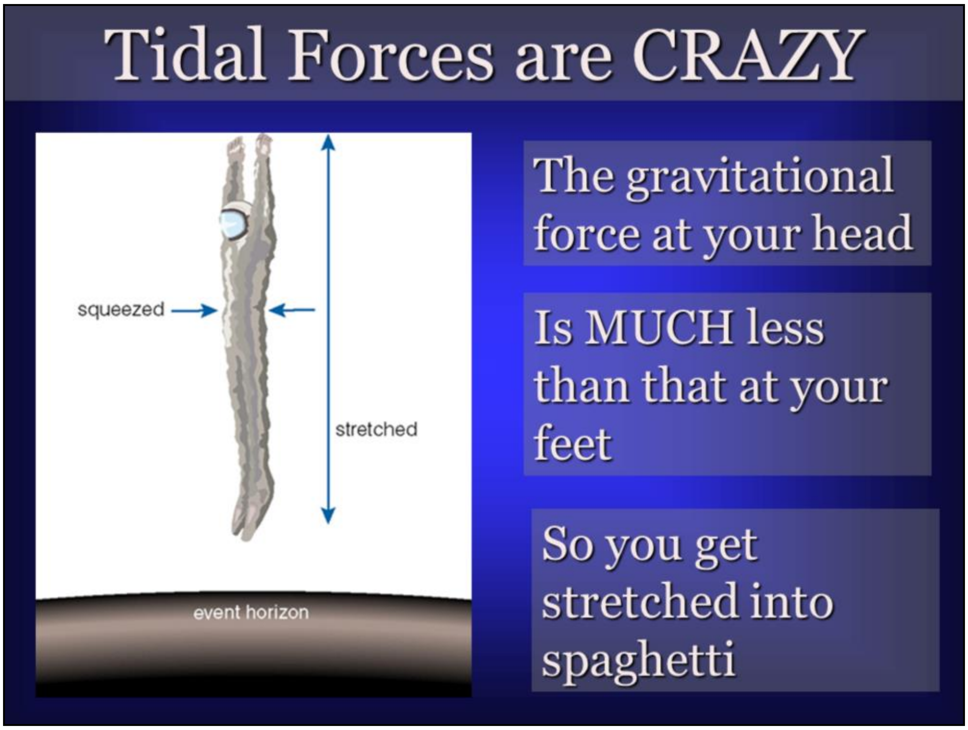
A. The same as the force gravity from a 10 solar mass star .
B. Greater than the force of gravity from a 10 solar mass star
C. Less than the force of gravity from a 10 solar mass star.
D. Infinite

Black Holes

If the Sun were replaced by a 1 Solar Mass black hole:

A. The Earth and all the planets would be sucked in.
B. We would get very cold but our orbit would be unaffected.
C. The inner planets would get sucked in.
D. Everything would be exactly the same as now.

B: Because black holes ***don't suck***!

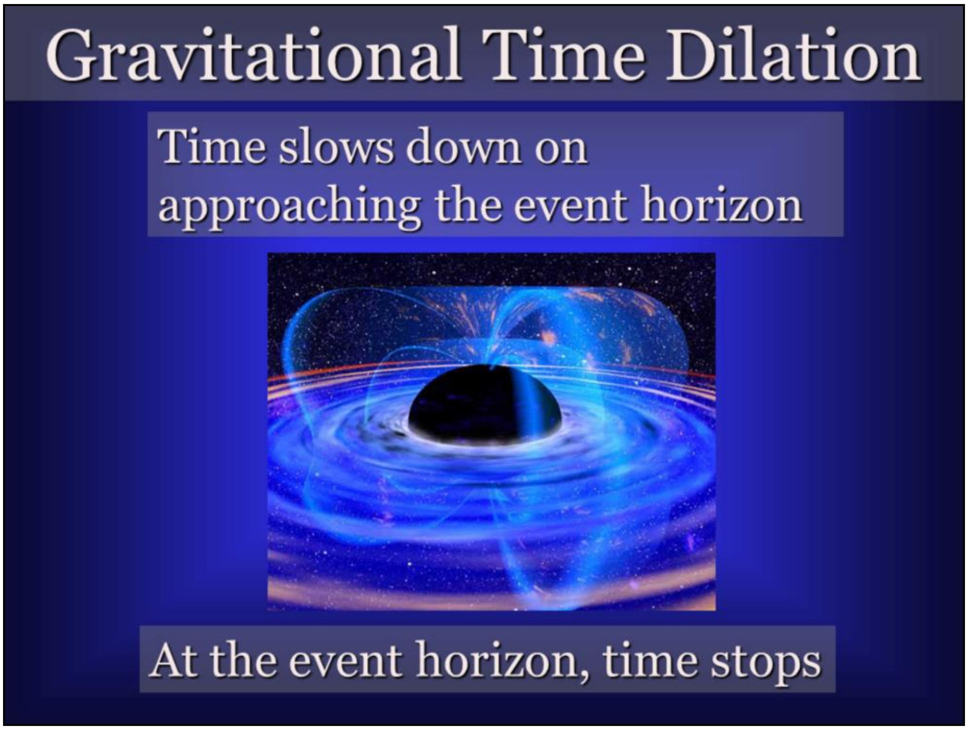


Bigger the black hole, the **less** tidal force there is at the surface

Tidal Forces are CRAZY

Mass	Rs	Tidal Force (g's)
10 M_{sun}	1/200 R_e	10^9
100 M_{sun}	1/20 R_e	10^7
10^6 M_{sun}	4 R_{sun}	0.1
10^9 M_{sun}	4,000 R_{sun}	10^{-7}

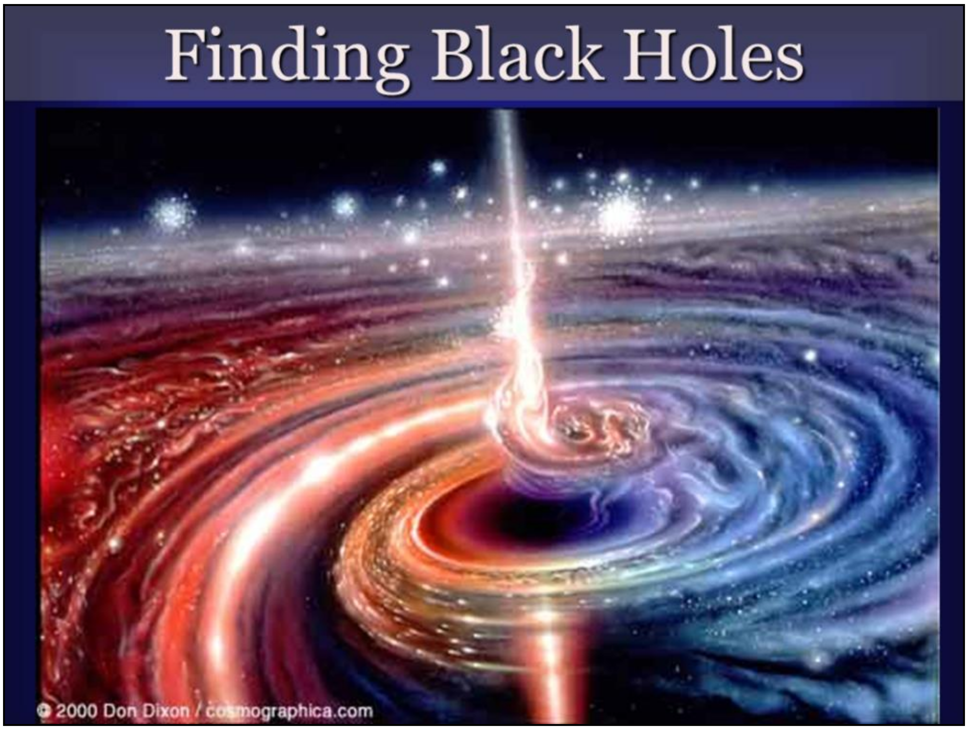
Bigger the black hole, the **less** tidal force there is at the surface



At least from our perspective. Not from the perspective of the person falling into the black hole.

Light also red shifts and at the event horizon, the wavelength becomes infinite.

Objects become unobservable to us.



Discussion: If we can’t see the black hole itself, how could we find them?

We must look at their effects on other objects:

- Binary stars: accretion (like with the novae)
- Gravitational lensing
- Accretion disks
- Infalling material (x-rays from)
- Huge jets
- Antimatter fountains

- Binary stars: accretion (like with the novae)

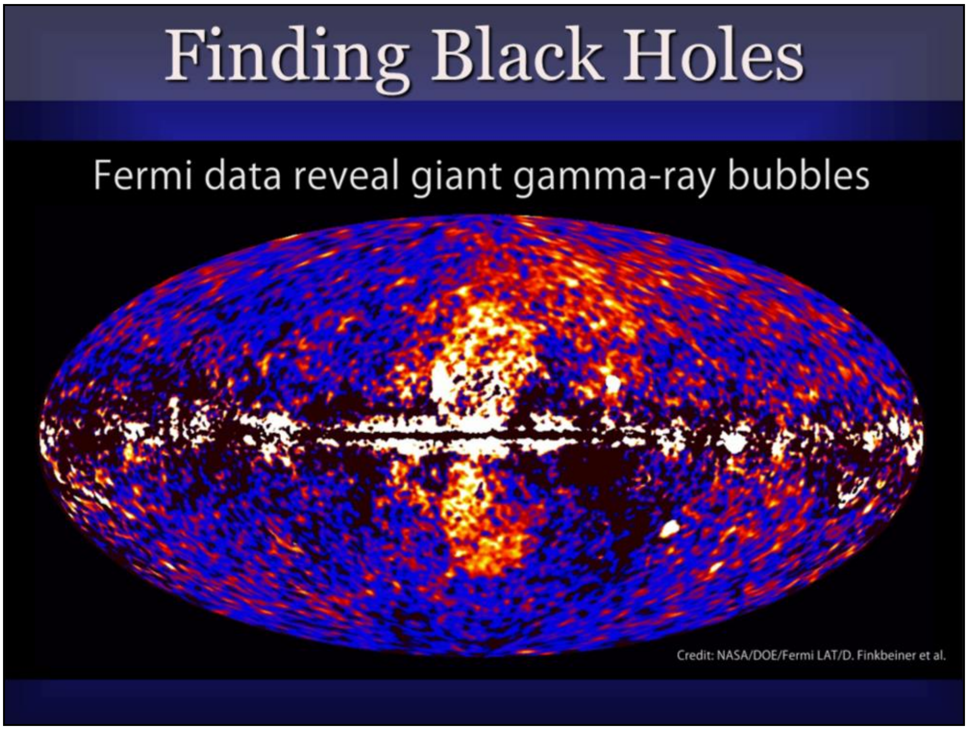
Hard to see apart from point source X-ray images though, because even the accretion disk around this is so small (the black hole “size” is a city block, maybe”)

At the center of our galaxy is a 3.6 million solar mass object that is an excellent candidate for a super massive black hole.

It has been observed in the past as a radio source and named Sagittarius A.

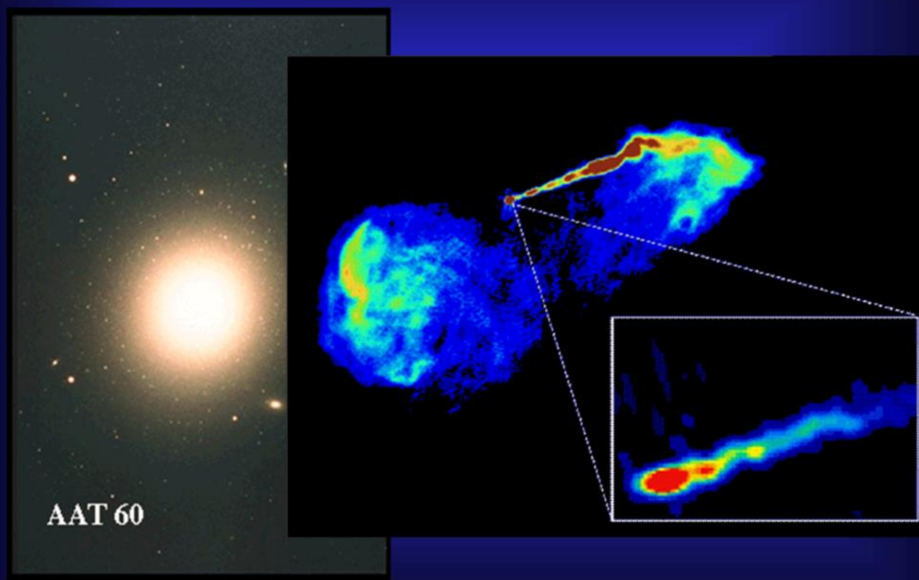
Observations of the positions of several stars in the neighborhood suggest something of the correct mass is there. It could be a dense cluster however.

There was a flare observed in 2003 within 10 Schwarzschild of the location of Sgr A. It is characteristic of a flare from an accretion disk.

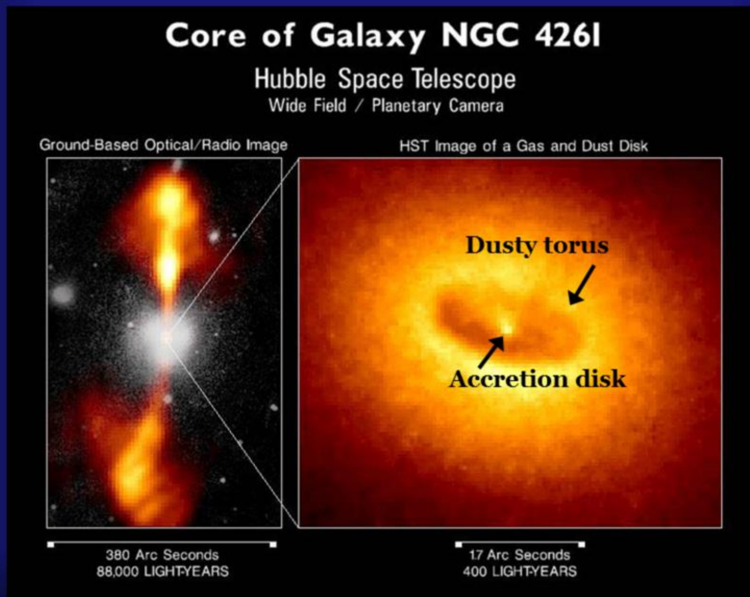


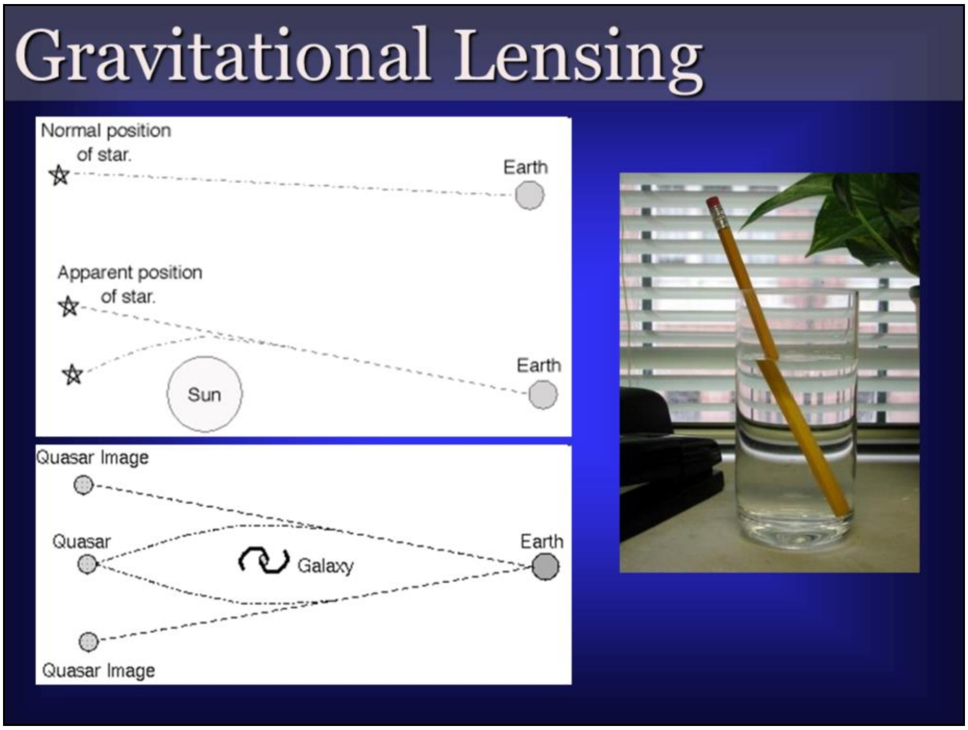
We also see an antimatter fountain from the center of our galaxy, which is fairly typical of supermassive black holes. 511 keV emission is from electron-positron annihilation!

Evidence for Black Holes



Evidence for Black Holes



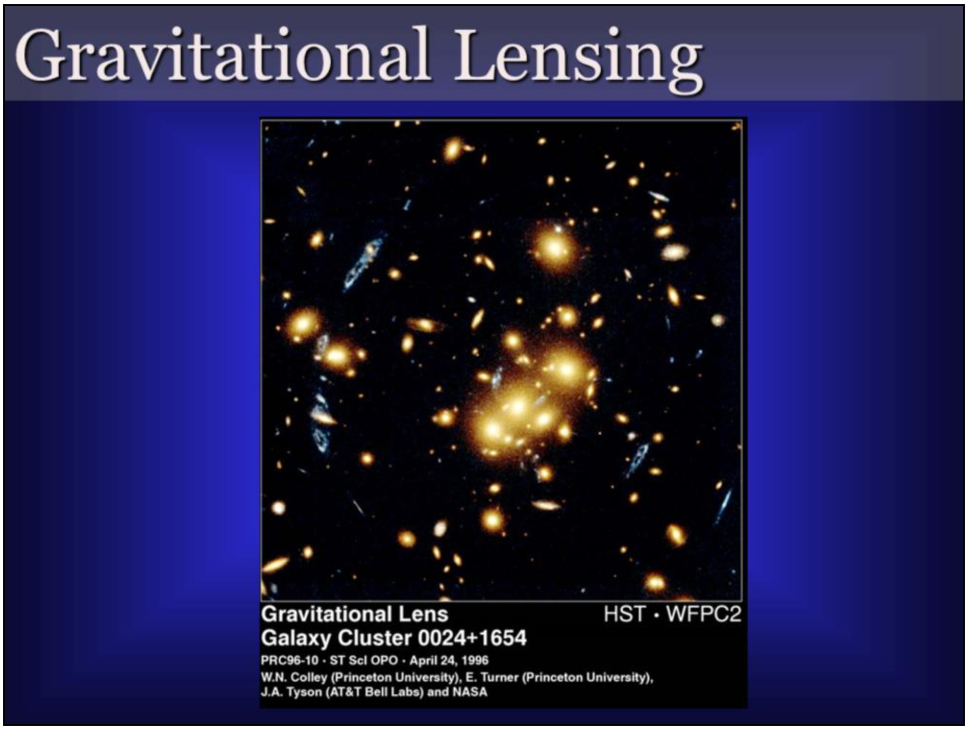


Massive objects bend the light path so that objects apparent position changes.

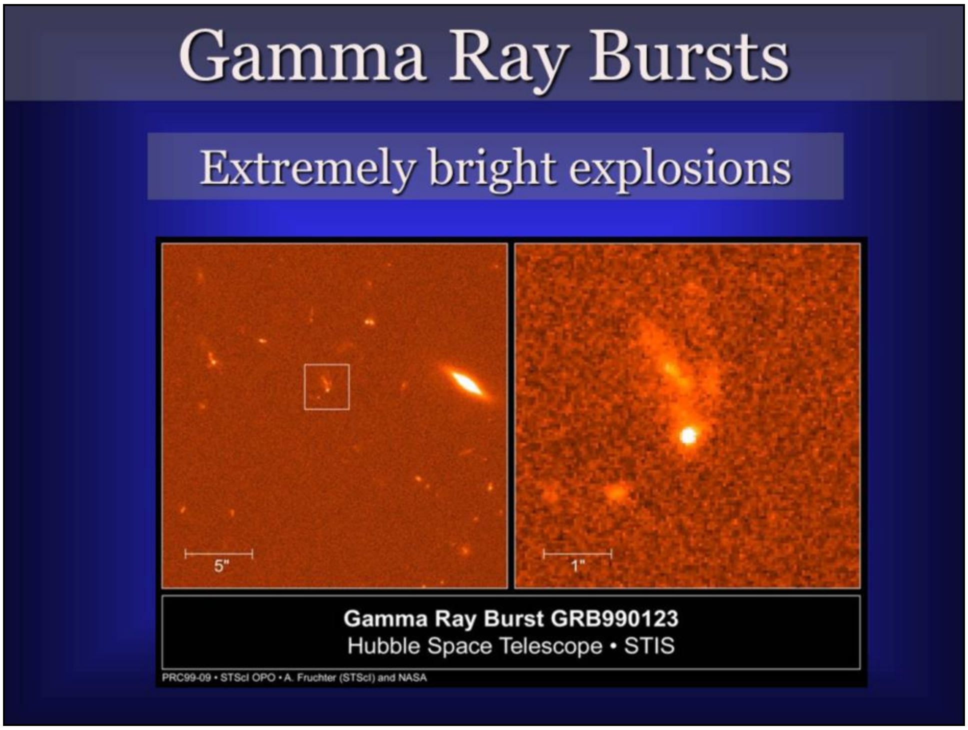
Just like looking at a pencil in a glass of water, the light bends (refracts) in the water making the pencil appear broken.

Starlight can get bent by the presence of a galaxy or the Sun so that the star appears somewhere else.

We can even see multiple copies of the same object.



We can see gravitational lensing of background galaxies due to the large cluster of galxies in the foreground.



In the 1960s, the US put satellites up to watch for gamma rays due to nuclear detonations.

They saw bursts of gamma rays coming from all over the place.

For a long time, we had no idea what or even where they were. We didn't know if they came from within the solar system, within the galaxy, or from distant extra-galactic sources.

GRB lasts a few seconds to a few minutes.

They are hundreds of times brighter than a typical supernova explosion.

Gamma rays are hard to focus, so pinpointing their location is difficult.

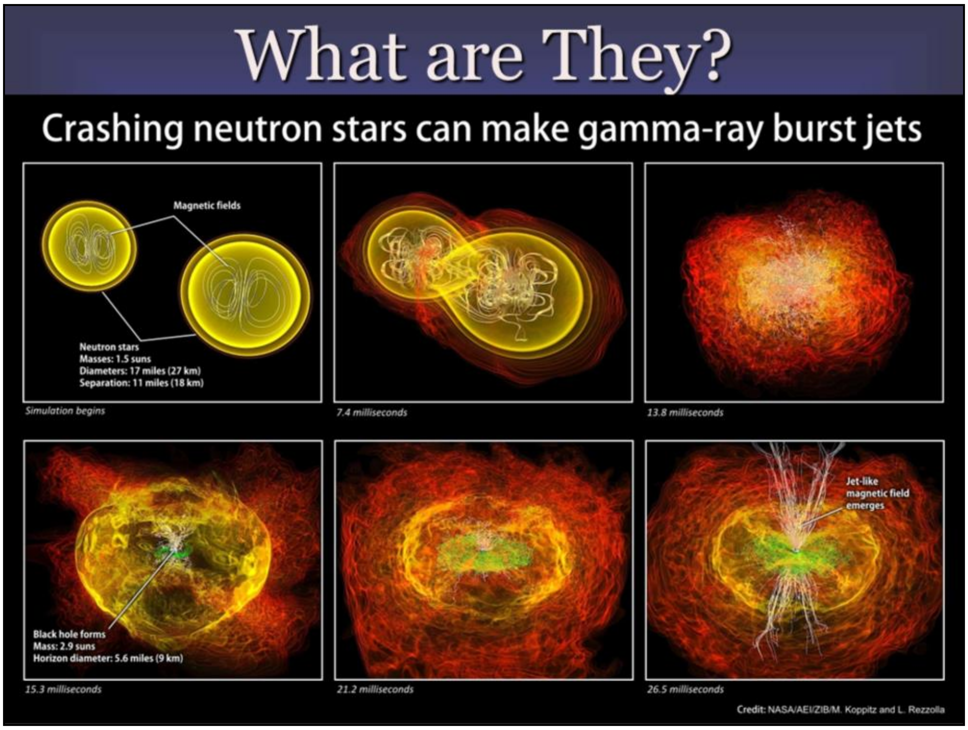
One has to look for lower energy counterparts, such as in the optical

They appear to be very far away, some near the edge of the observable universe.

Really big explosions of first or second generation stars.

It is inconceivable, given their distance, that the energy is spherically distributed.

The gamma rays are actually beamed at us. We don’t see the burst unless we are in the beam.



They appear to be very far away, some near the edge of the observable universe.

Some GRBs last for very short times, and these are due to mergers of neutron stars.

https://www.nasa.gov/topics/universe/features/gamma-ray-engines.html