Introduction to Astronomy Lecture 5: Stellar graveyards

– white dwarfs, neutron stars and black holes

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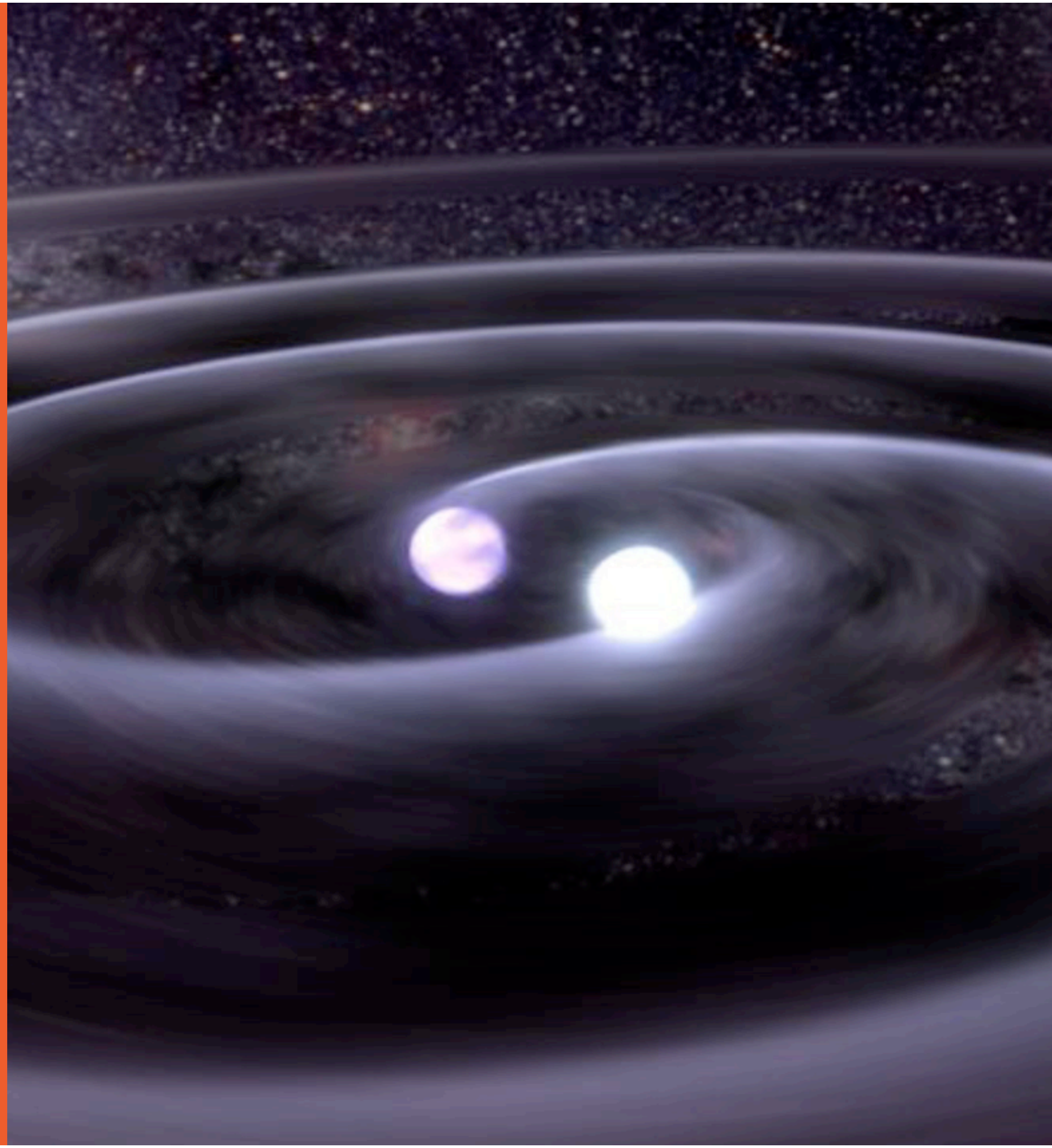
THE UNIVERSITY OF SYDNEY



In tonight's lecture

- White dwarfs
  - *the end-state for low-mass stars*
- Neutron stars
  - *pulsars, X-ray binaries and millisecond pulsars*
- Black holes
  - *General relativity and general weirdness*

White dwarfs

Stability at last!

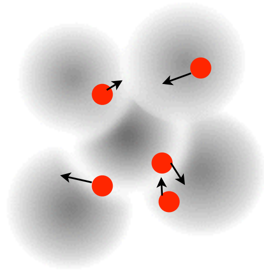
Last lecture, we learned that stars are supported by the pressure created by fusing hydrogen to helium in the core.

When the source of this pressure is removed, the star collapses.

To halt the collapse, something else is needed to provide the pressure.

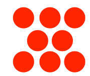
This turns out to be a peculiar property called *degeneracy pressure* – perhaps better thought of as *quantum pressure*.

- **white dwarf:** electrons run out of room and halt the collapse of the star



maximum mass
1.4 solar masses

- **neutron star:** neutrons run out of room and halt the collapse of the star

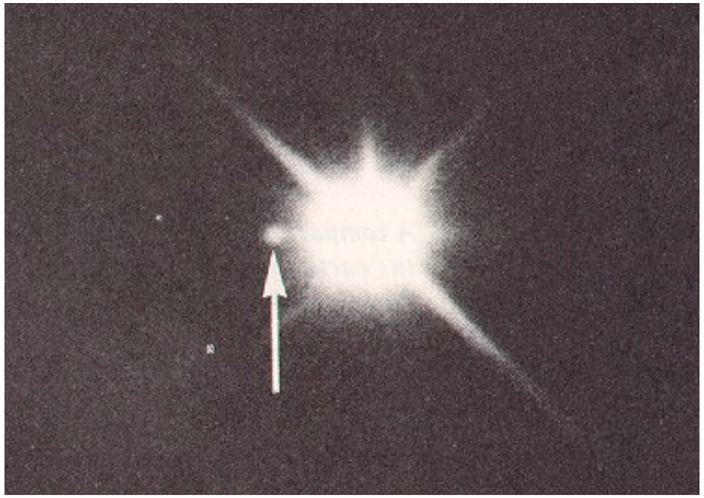


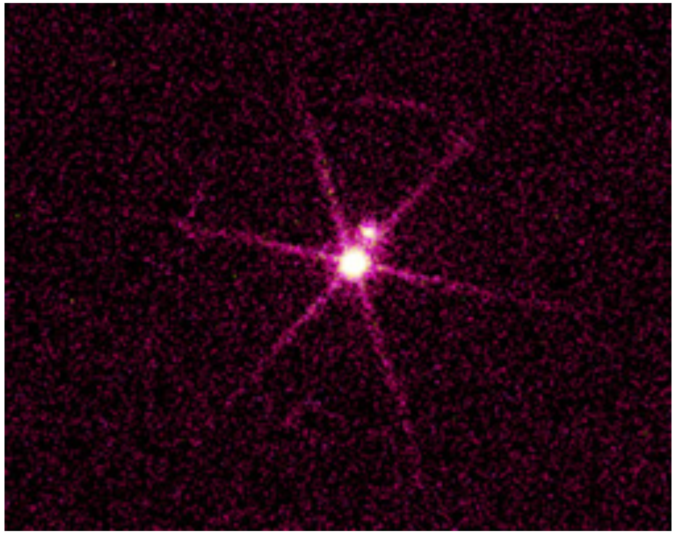
maximum mass
~3 solar masses

- **black hole:** gravity wins: collapse continues

?

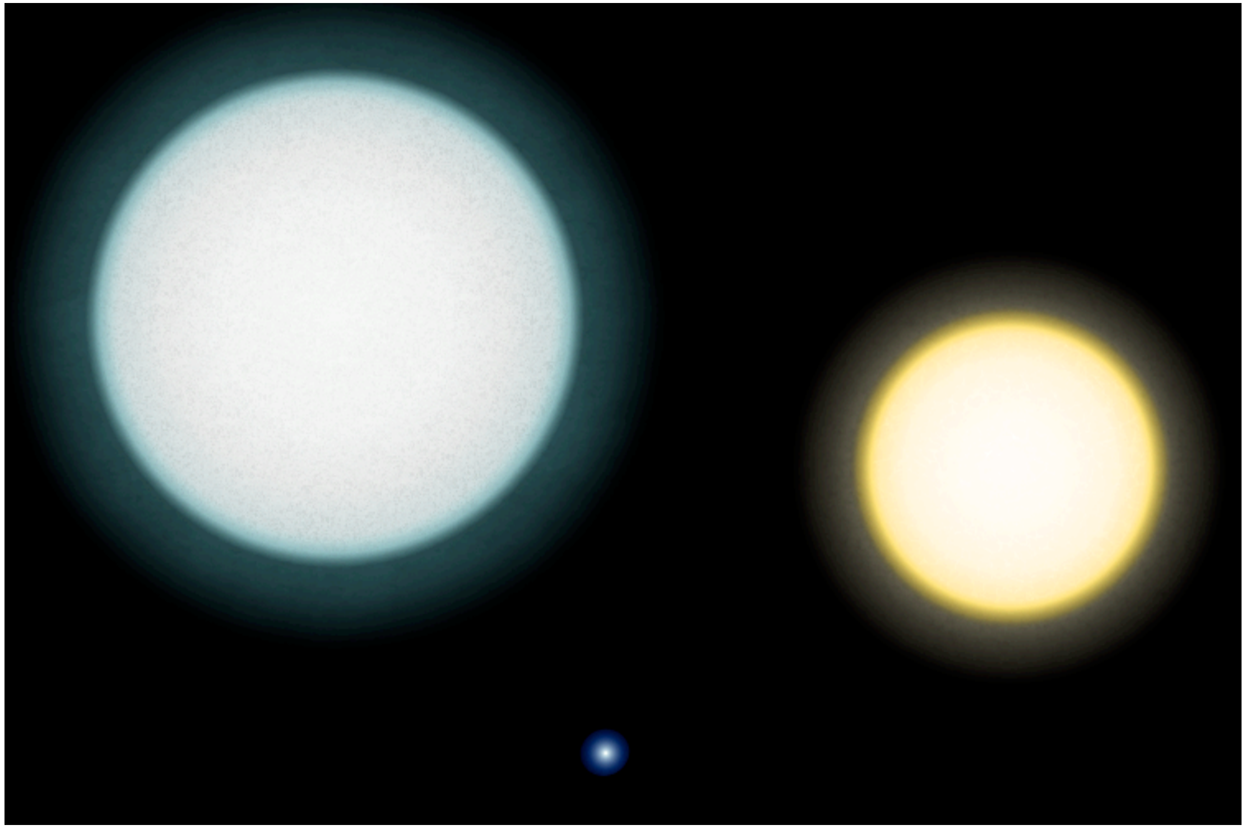
The most famous white dwarf, and the first to be discovered, is *Sirius B*.



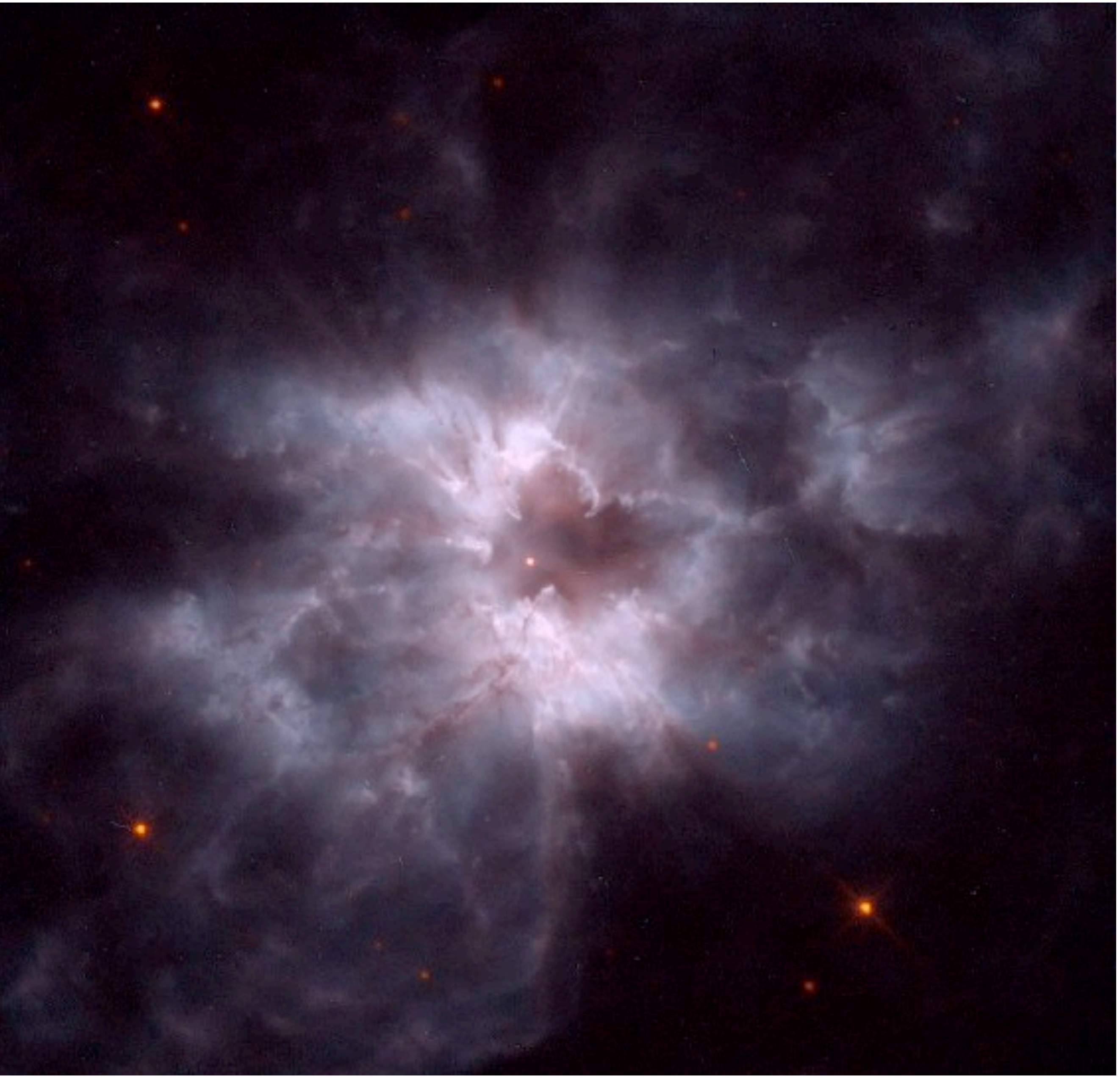


A comparison between optical (left) and X-ray (right) images of Sirius A and B, which are an A-type star and a white dwarf. The optical image is dominated by the main sequence star, the X-ray image by the white dwarf.

White dwarfs are extremely hot but extremely faint, meaning they must be *small*. They have radii between 0.8% and 2% of the size of the Sun, comparable to the size of the Earth.



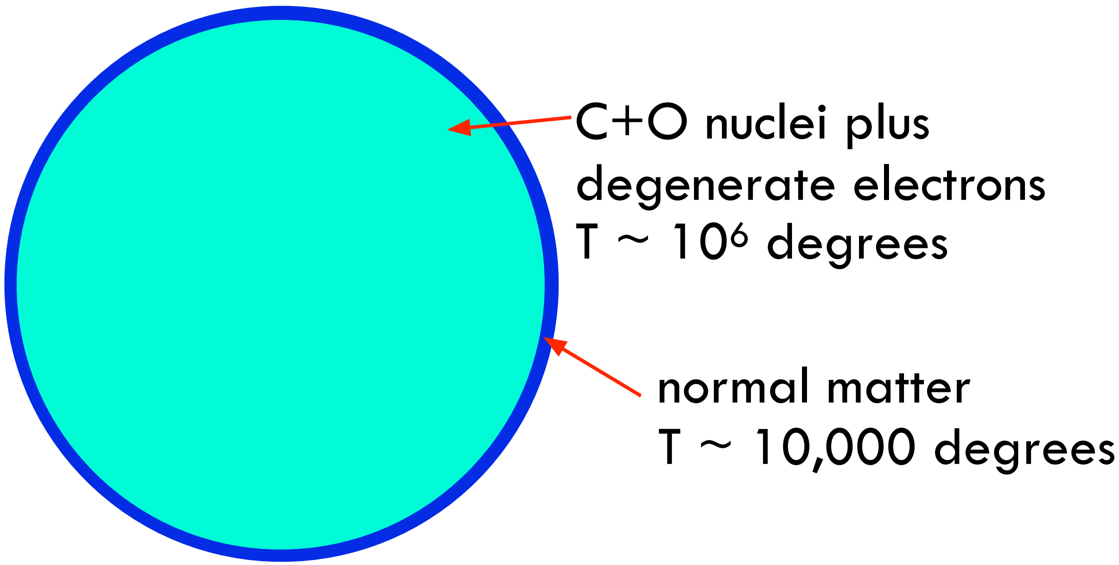
Size of the white dwarf IK Pegasi B (center) compared to its A-class companion IK Pegasi A (left) and the Sun (right).



White dwarfs are no longer producing energy. Instead, as we saw last week, they are the remnant core of a star like the Sun, left behind after a spectacular planetary nebula is ejected.

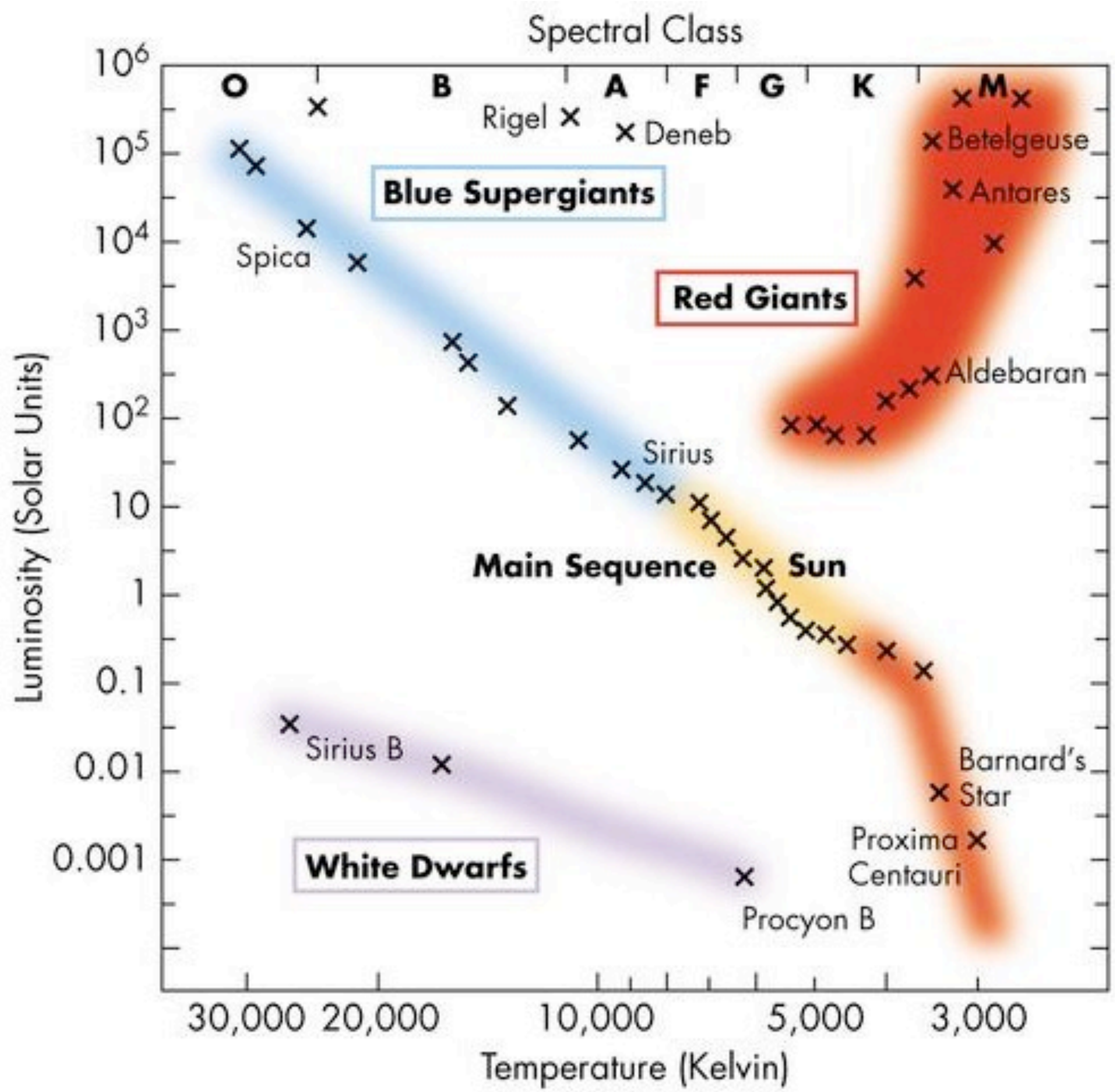
HST image of NGC 2440; the white dwarf, visible at the centre, is one of the hottest white dwarf stars known.

Because they are the remaining cores of stars, white dwarfs are usually made of carbon and oxygen — or sometimes helium (from lighter stars) or oxygen-neon-magnesium (from heavier stars). The electrons from the atoms are squeezed very tightly together so they become degenerate, and their quantum pressure stops the star from collapsing any further.



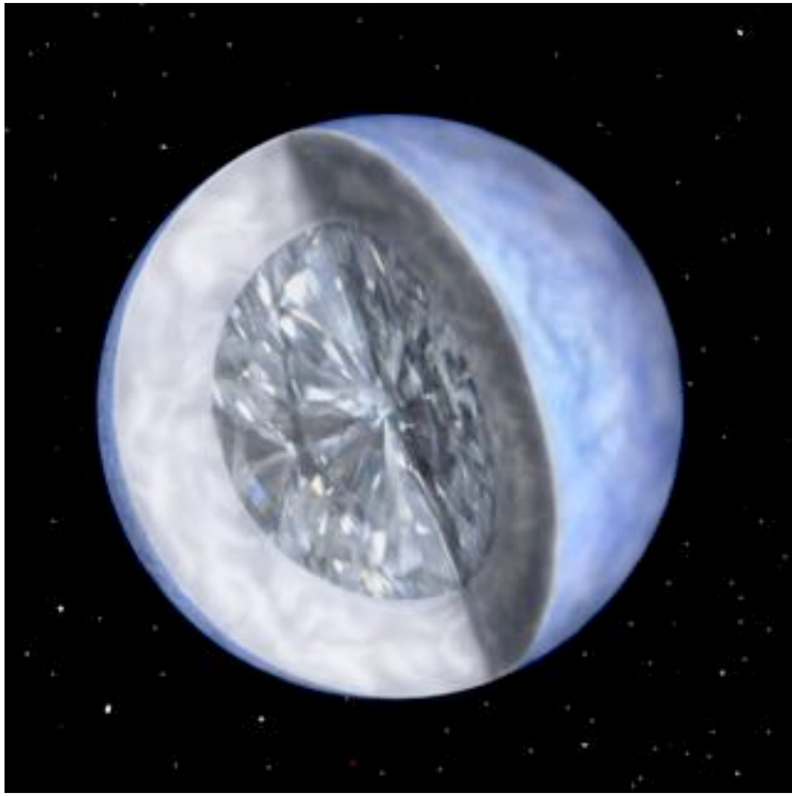
On the surface is a thin layer, about 50 km thick, of normal matter. It is an extremely good insulator, so the white dwarf takes a long time to cool down.

A white dwarf does nothing but cool down, which takes an *extremely* long time. The oldest white dwarfs in our Galaxy have only reached 3500 K – a bit cooler than the Sun.



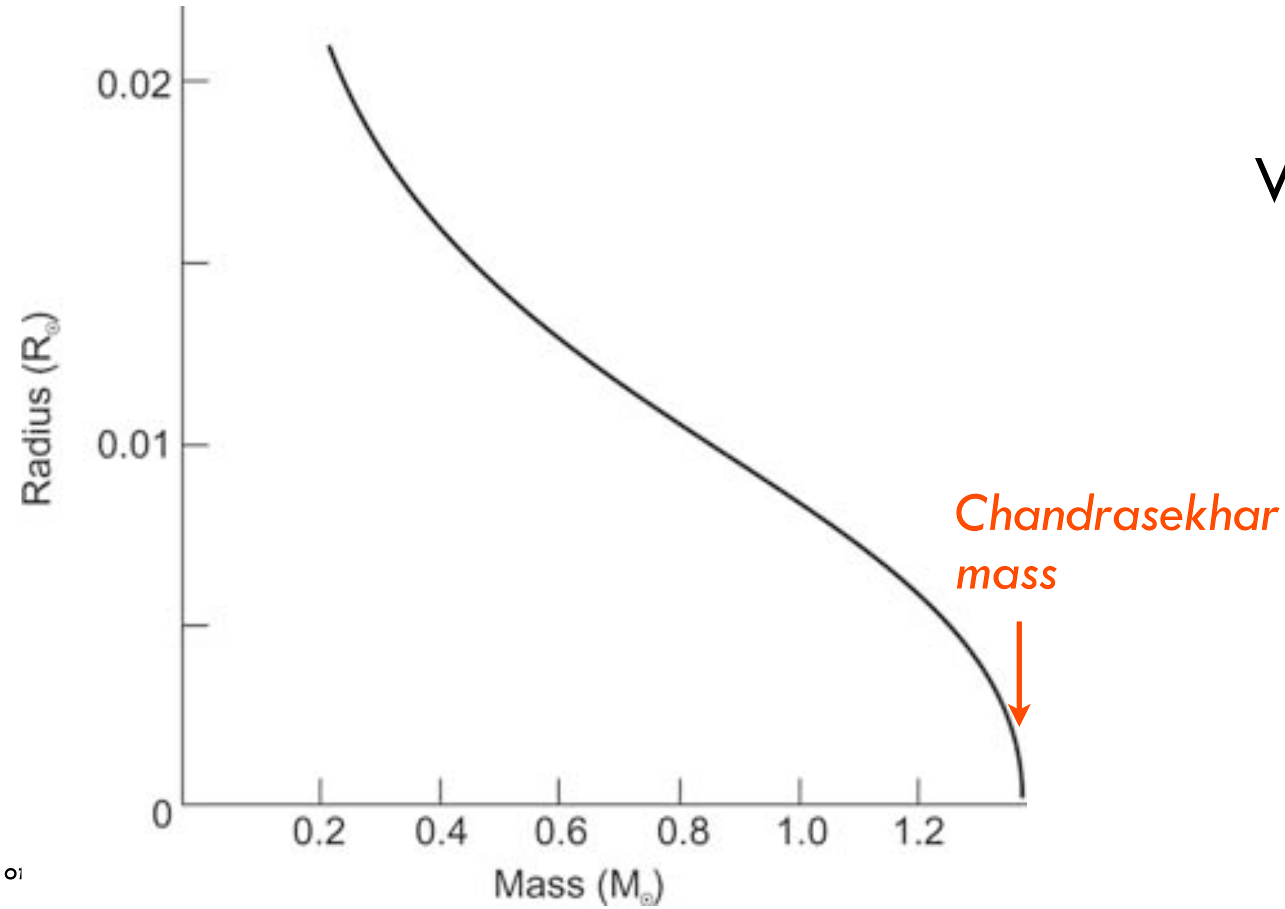
As they cool down, white dwarf cores eventually crystallise, with the nuclei (mostly carbon) forming a lattice surrounded by a sea of electrons.

In 2004, scientists measuring miniscule light variations caused by pulsations in the white dwarf announced that they had detected a white dwarf with a crystallised core.

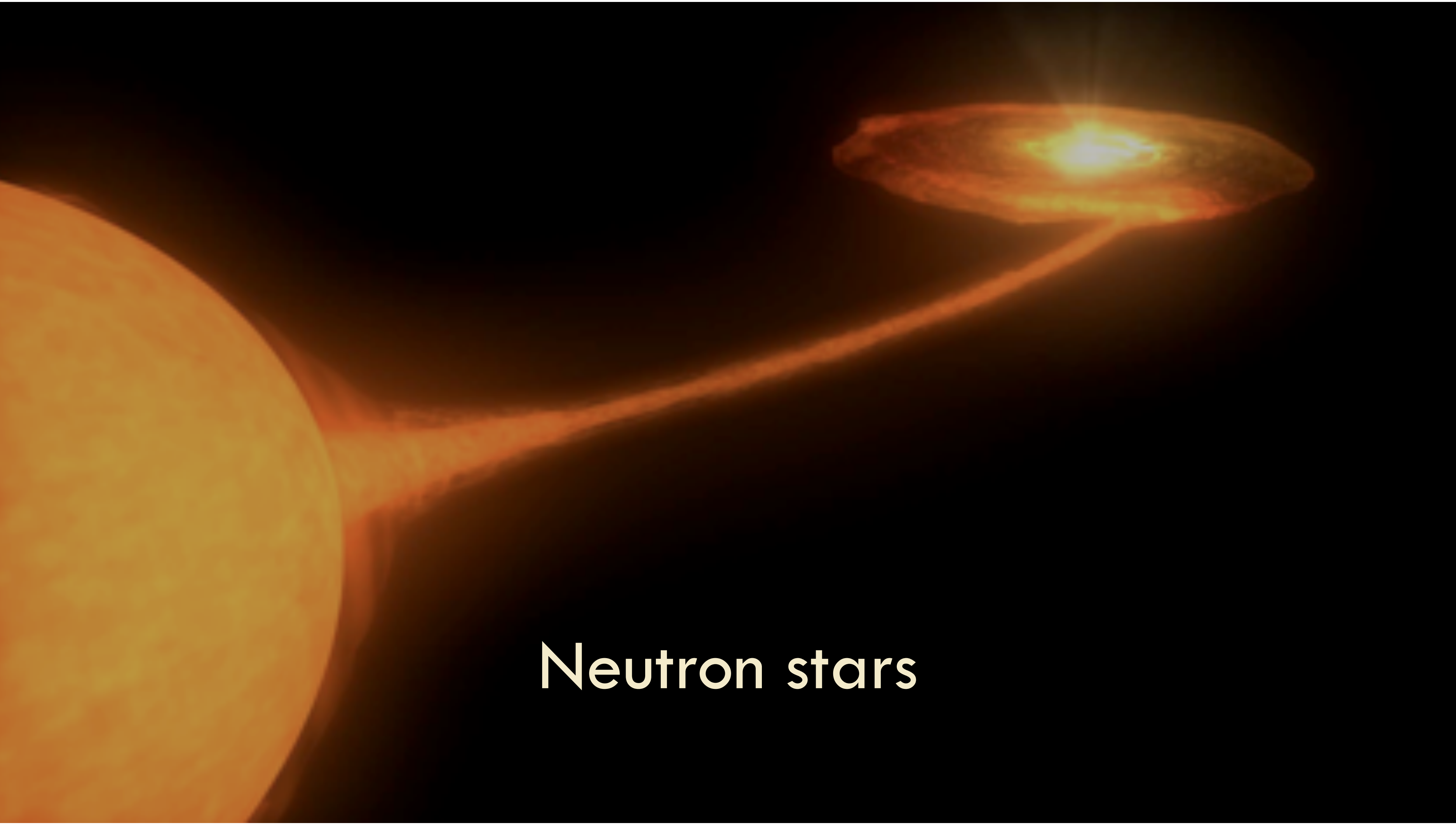


The media reported this as “a 10 billion trillion trillion carat diamond”.

With white dwarfs, the more massive they get, the smaller they get. The limiting mass (where the radius would be zero) is the Chandrasekhar mass (~1.4 solar masses).



What happens next?

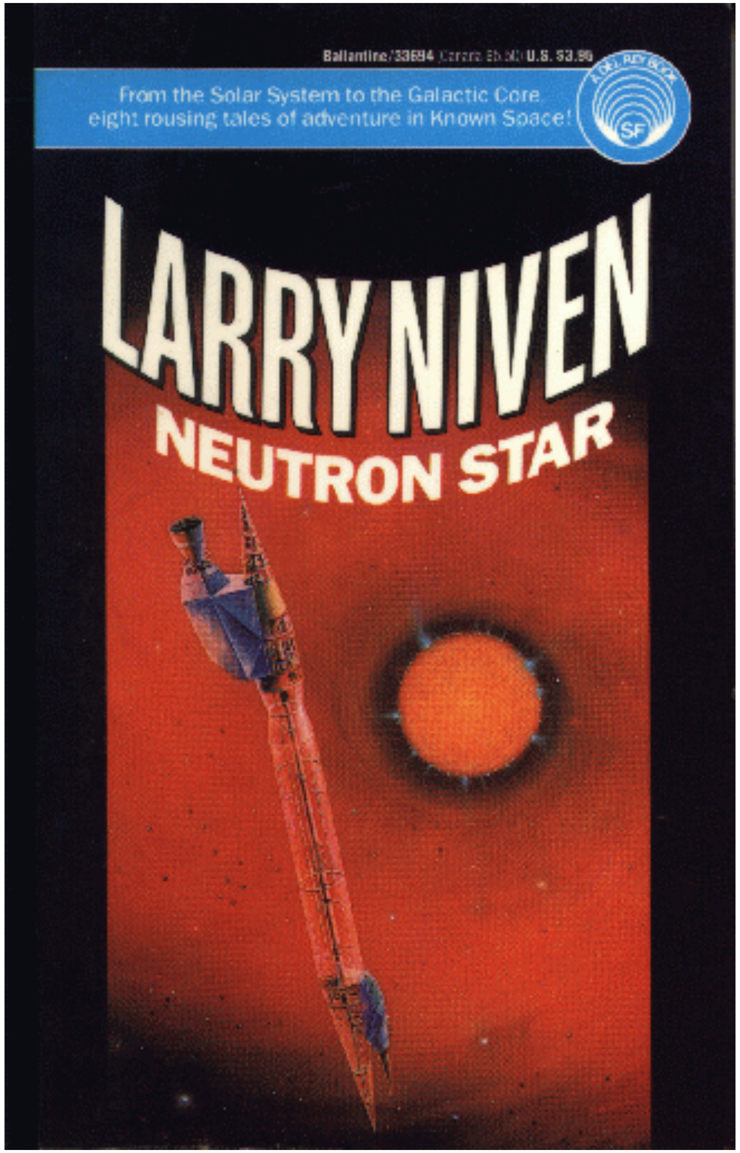

Neutron stars

A star which starts of bigger than ~6–8 solar masses leave a core bigger than this mass: these stars can't leave behind a white dwarf. Instead, during the supernova explosion the electrons and protons in the core of the collapsing star are squeezed together to form neutrons, and we are left with a *neutron star*.

But this neutron star is only 10 km across. How do we ever detect such a small remnant from the Earth? Even if it were extremely hot, its tiny size would make it so faint as to be essentially invisible.

In 1966, Larry Niven won a "Hugo" award for best science fiction short story, for his story "Neutron Star". This describes a trip very close to the only neutron star known.

In 1966, this must have seemed a very good bet.



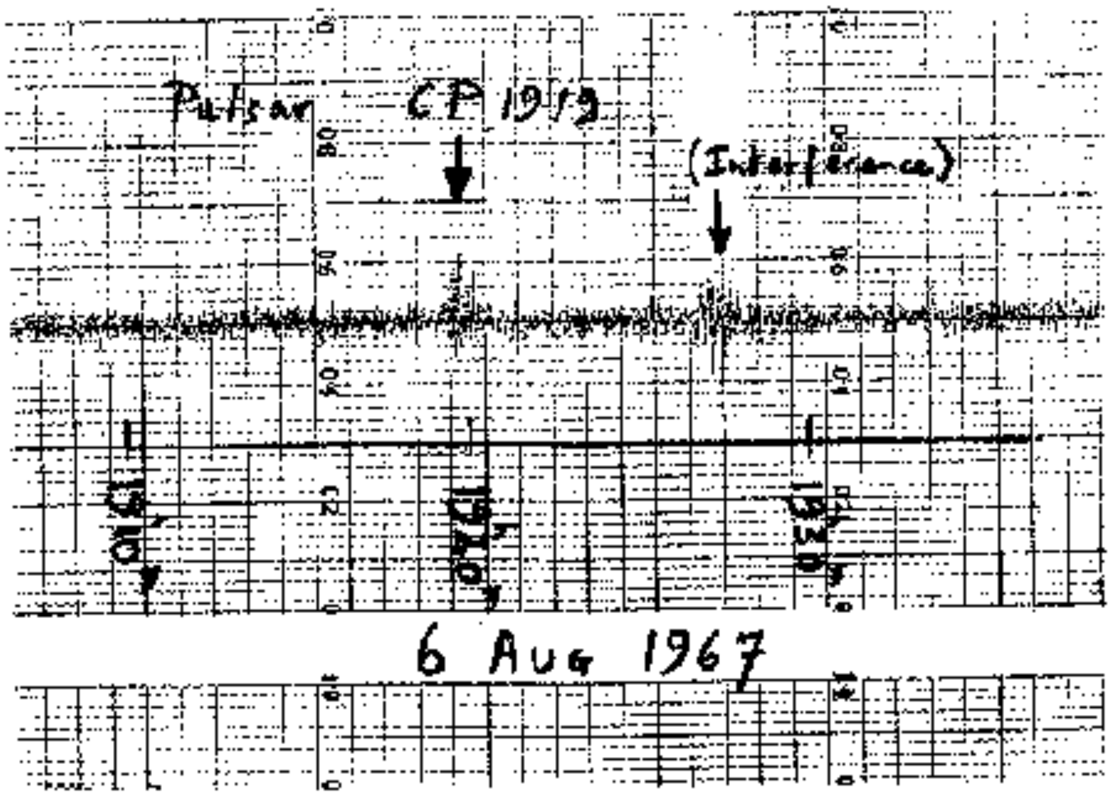
Pulsars

In 1967, Jocelyn Bell and Tony Hewish were using a special radio telescope to look for radio scintillation to find quasars.

Bell had responsibility for operating the telescope and analysing the data, looking at 96 feet of chart paper per day.

Bell found repeated patches of "scruff" which seemed to follow the sky.

Closer scrutiny showed the "scruff" consisted of extremely regular pulses, occurring every 1.337 seconds like clockwork. The source was initially dubbed "LGM" – standing for Little Green Men.

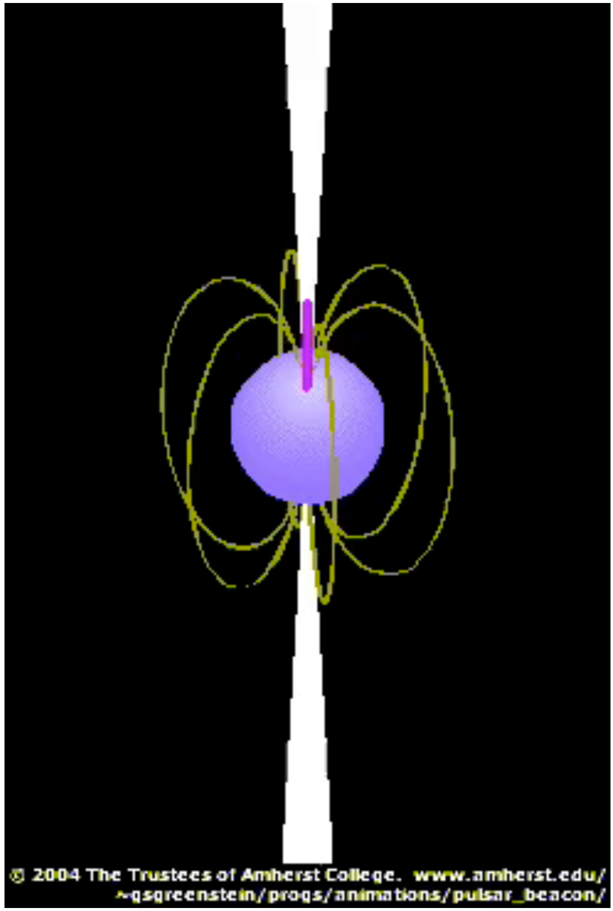


After a few weeks three more rapidly pulsating sources were detected, all with different periods. They were named *pulsars*.

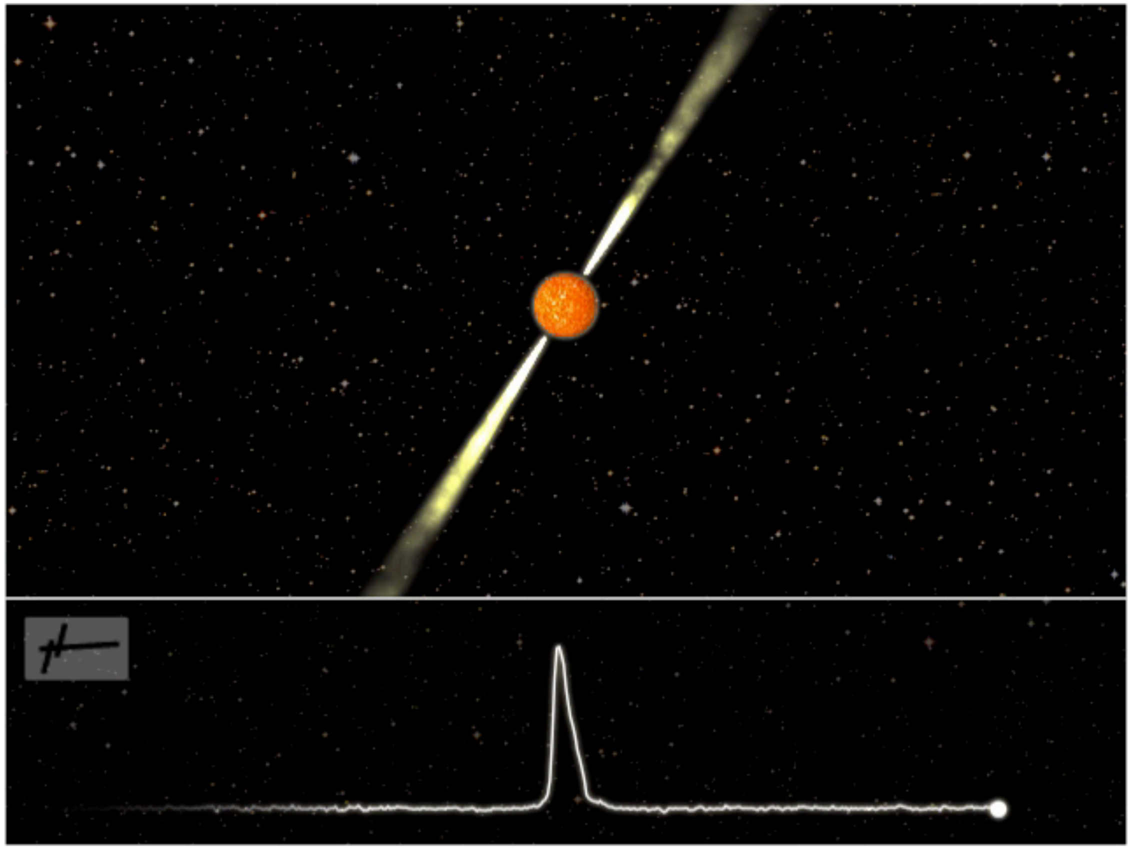
Fast pulses must mean a very *small* object. Even a white dwarf would tear itself apart if it rotated in any less than about 4 seconds.

Oppenheimer had suggested neutron stars as a theoretical possibility. In 1968 Thomas Gold suggested that pulsars are rotating neutron stars with powerful magnetic fields.

The neutron star produces radiation in a narrow beam: the *lighthouse model*.



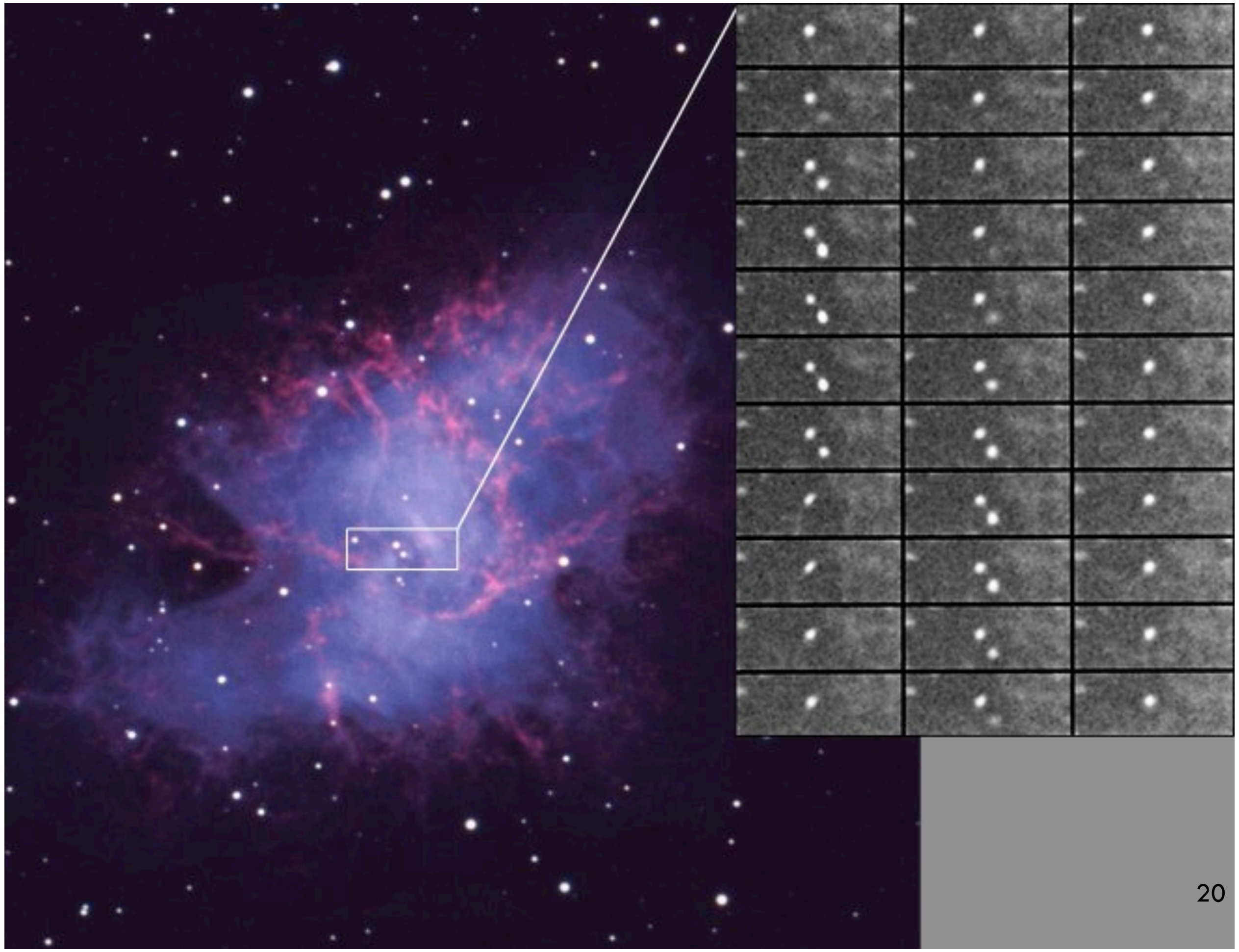
We see a burst of radio waves each time the neutron star's magnetic pole is pointed at us.



animation by Joeri van Leeuwen
http://www.astron.nl/pulsars/animations/

A pulsar was discovered in the centre of the Crab nebula, and the optical star was flashing at the same period: 0.33 seconds.

The Crab pulsar is also slowing down, as the pulsar converts its energy of rotation into high energy particles.



The Crab pulsar' period increases by 38 nanoseconds per day.

A rapidly-spinning core with a large magnetic field is exactly what you would get if you shrank a star like the Sun down.

Sun: size 1.4×10^6 km

rotation period 27 days = 2.3×10^6 s

Neutron star: size 14 km = 1 million times smaller

☞ rotation period 1 million times shorter = 2.3 s

Magnetic field is compressed as the star shrinks

☞ a billion times stronger

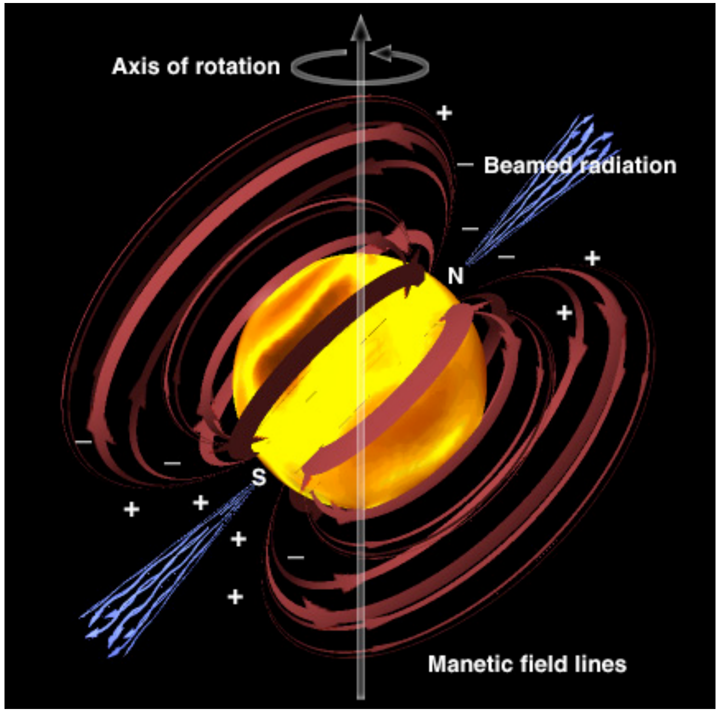
Why do pulsars pulse?

Pulsars emit radio waves because electrons ripped from their surface are accelerated by their strong magnetic fields, producing beams aligned with their poles.

Because pulsars are slowing down, this means

- The youngest pulsars should be the fastest pulsars (they have not had a chance to slow down yet!)

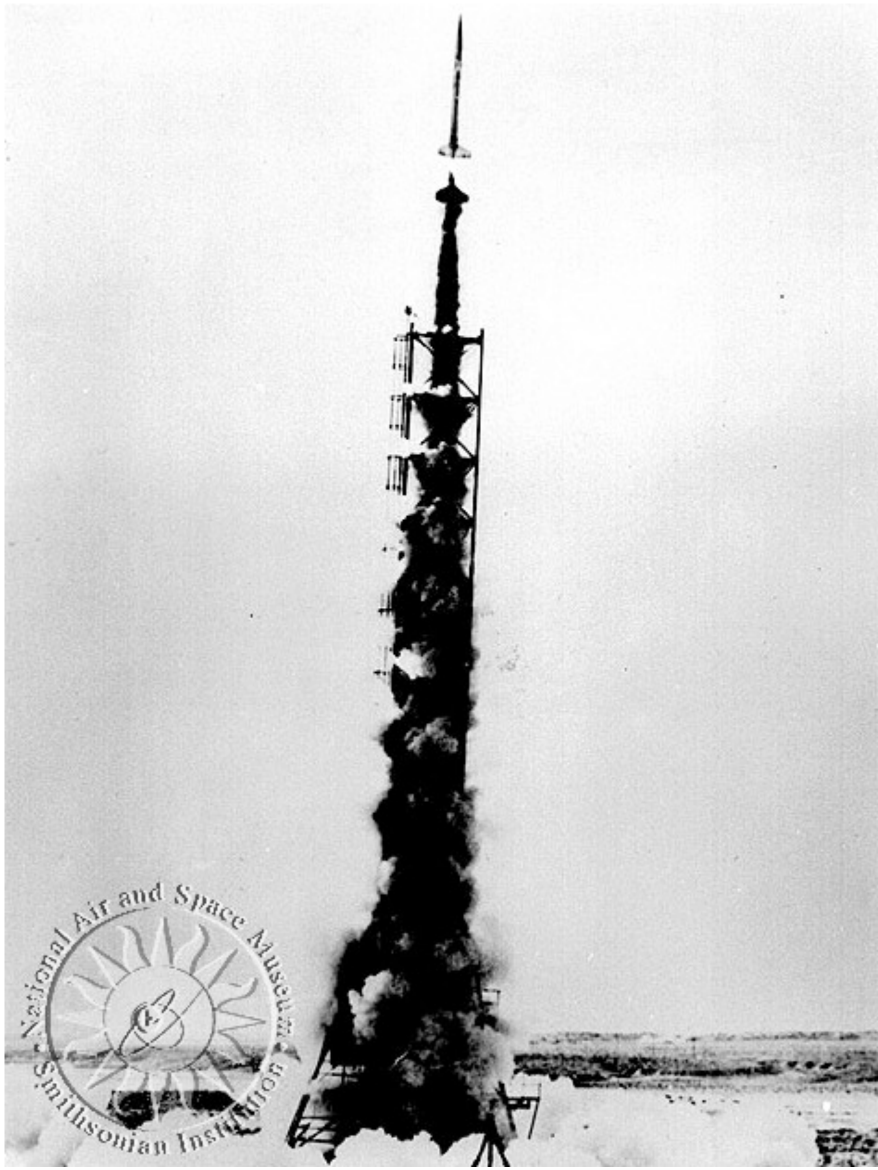
- Pulsars don't stay pulsars forever: eventually they slow down so much that the "lighthouse" switches off.



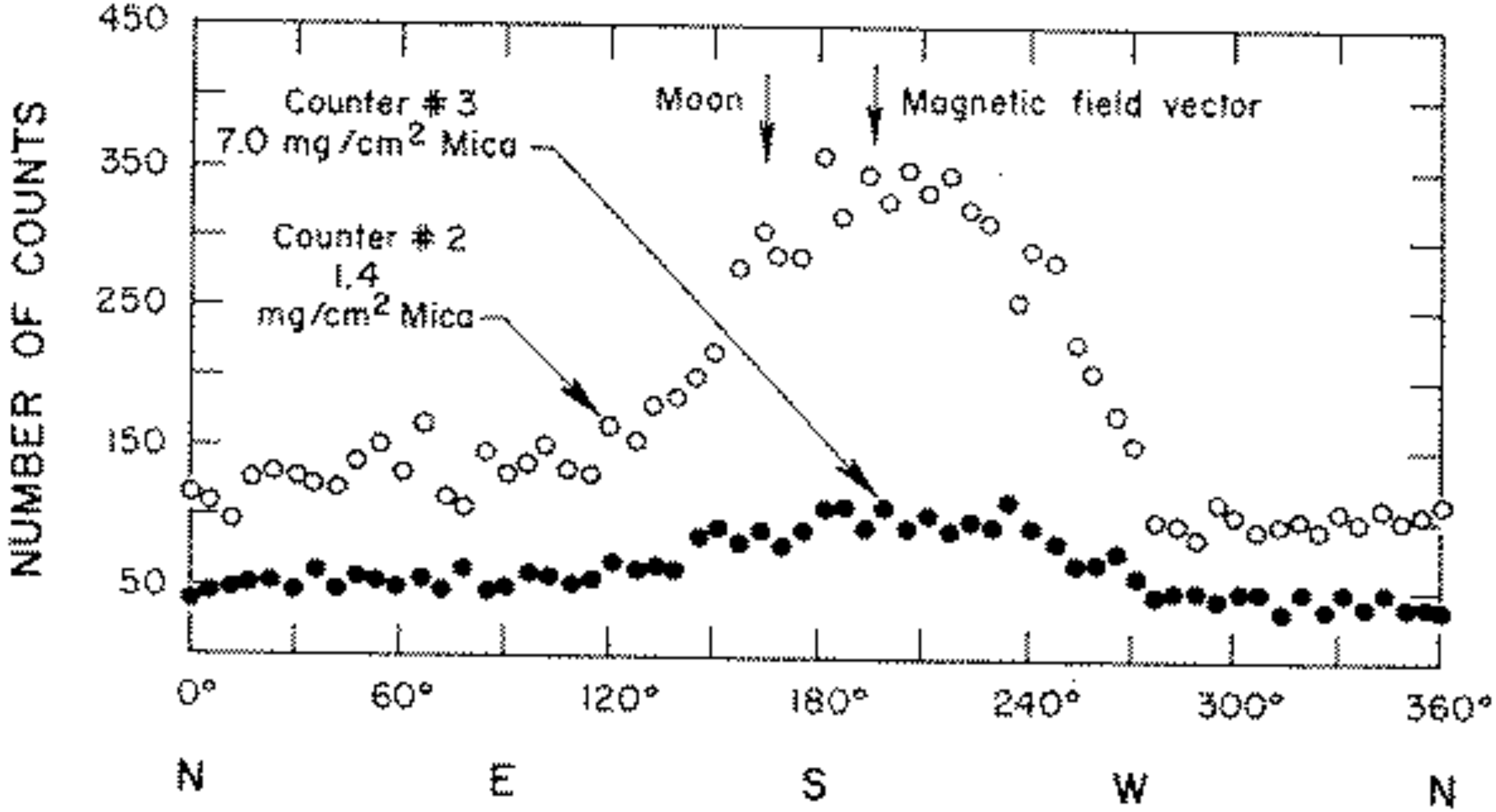
Discovery of X-ray binaries

The first X-ray source outside the solar system was discovered in an *Aerobee* rocket flight in 1962.

Based on how many X-rays the Sun produced, it was thought there was no hope of detecting X-rays from other stars. Rocket flights were launched with the stated aim of detecting solar X-rays reflected from the Moon.



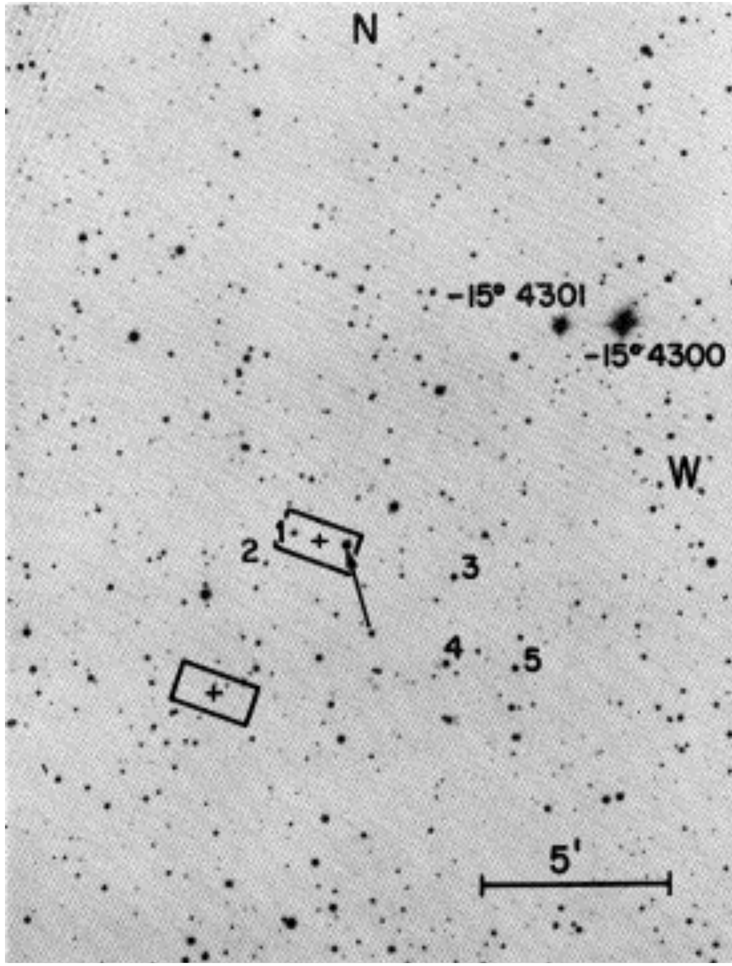
During the 350s rocket flight, a source was detected in the direction of Scorpio, which was 100,000,000 times brighter than the Sun! But the position error was huge: 5°x5°



"So we got a star atlas and opened it up... and discovered that there are a lot of stars in the sky; so we closed it again."

– Herbert Gursky (1995)

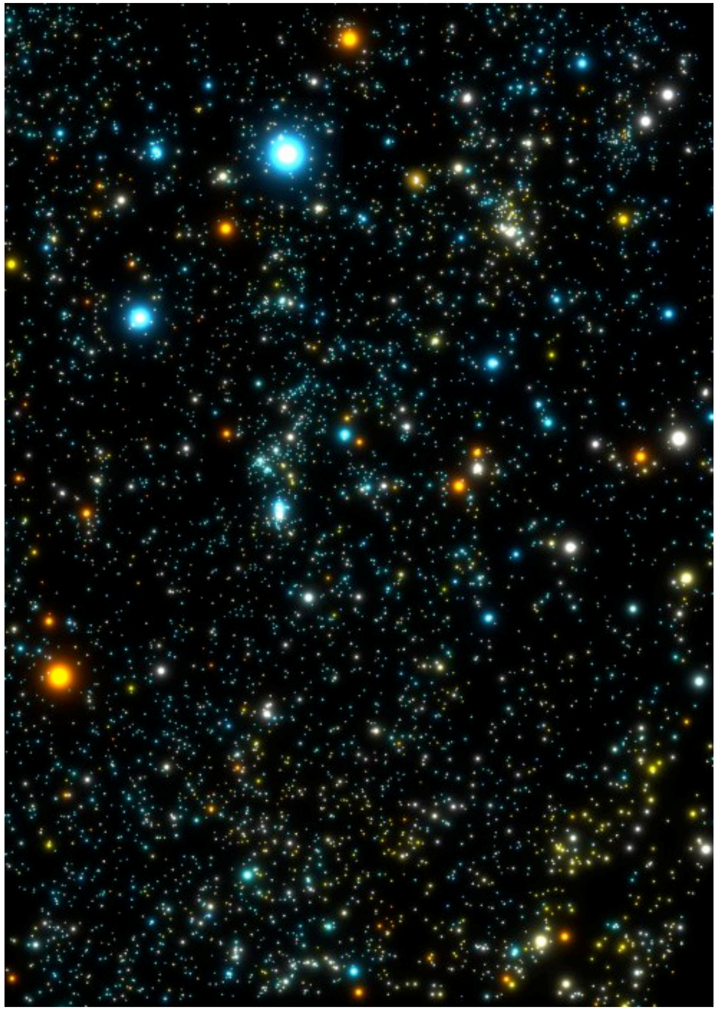
A better X-ray position led to the optical identification of the source: a faint (13th mag) blue star, which showed rapid intensity variations and strong emission lines.

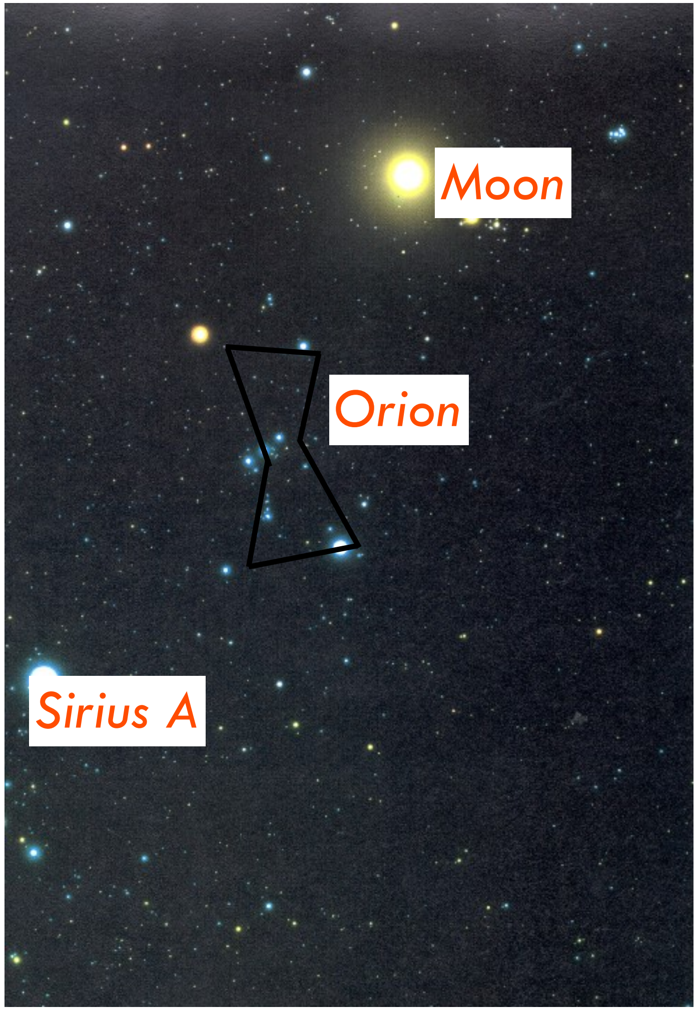


Many people realised simultaneously that accretion onto a neutron star could produce the massive amounts of energy seen.

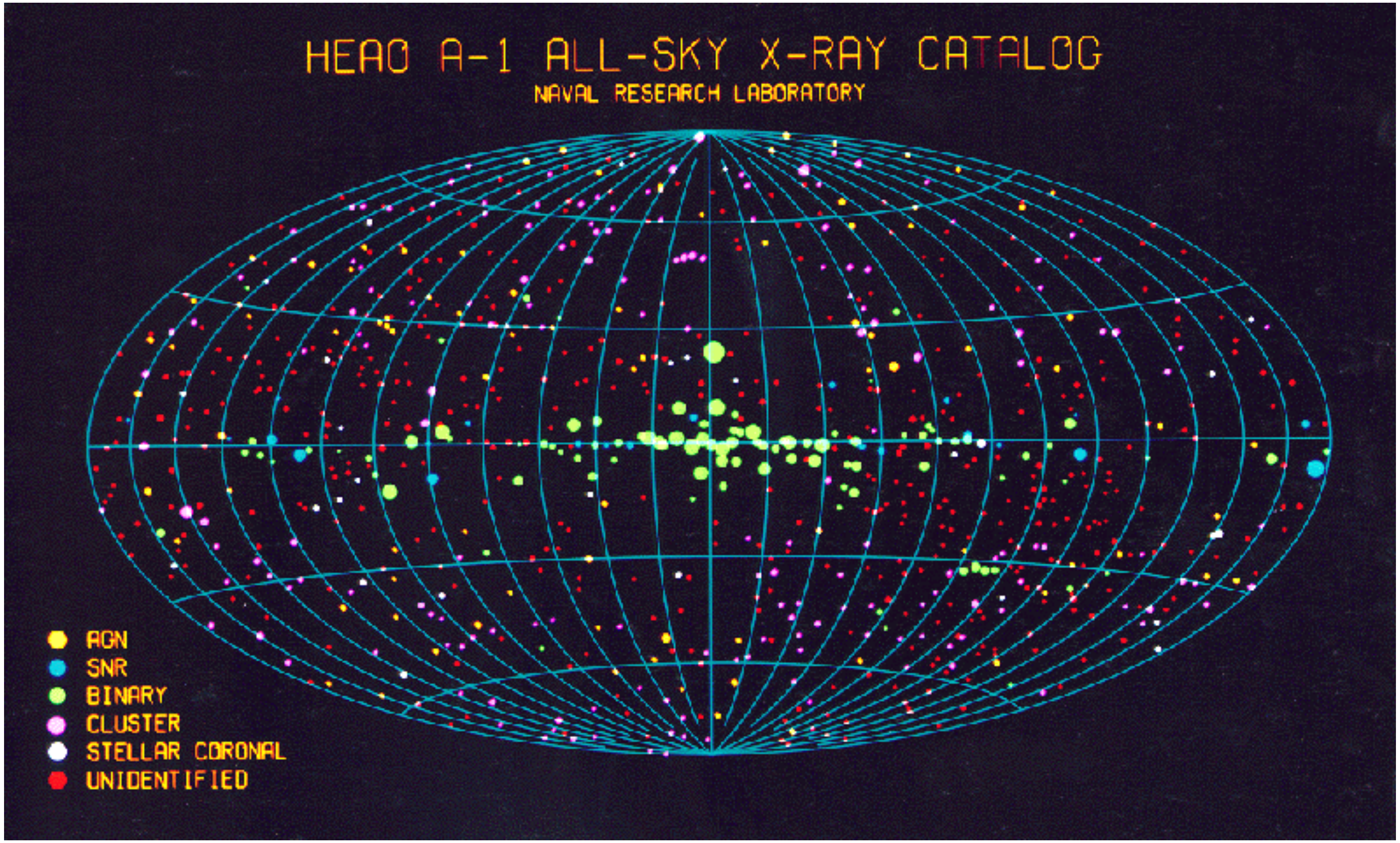
Since then, there have been a dozen X-ray telescopes in orbit.

The X-ray sky is very different to the optical sky.





We now know of several hundred X-ray sources in the Galaxy. Most of them are X-ray binaries.



The X-rays – very high-energy electromagnetic radiation – come from matter falling onto a neutron star.

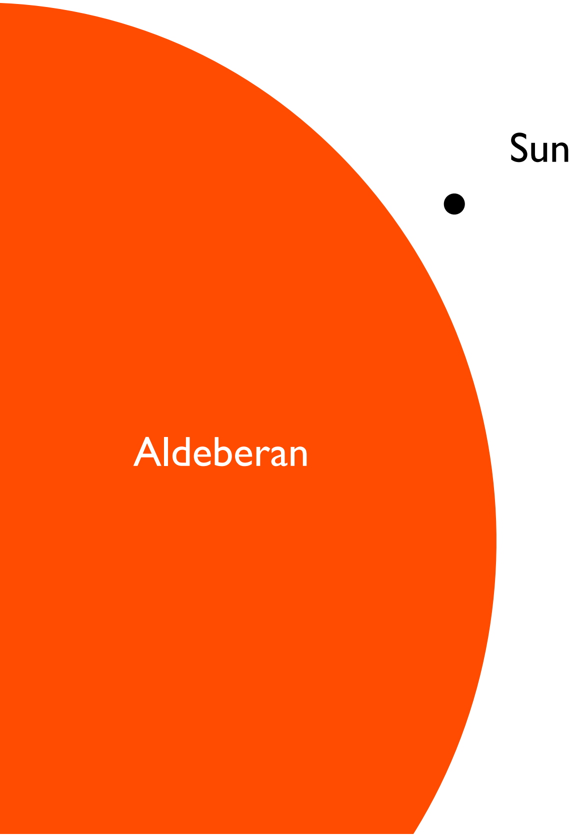
Where does this accreted matter come from?

There is not enough matter in interstellar space.

It must come from a *binary companion*: 2/3 of stars are in a binary system.

We know a star undergoes massive expansion during the late stages of its life.

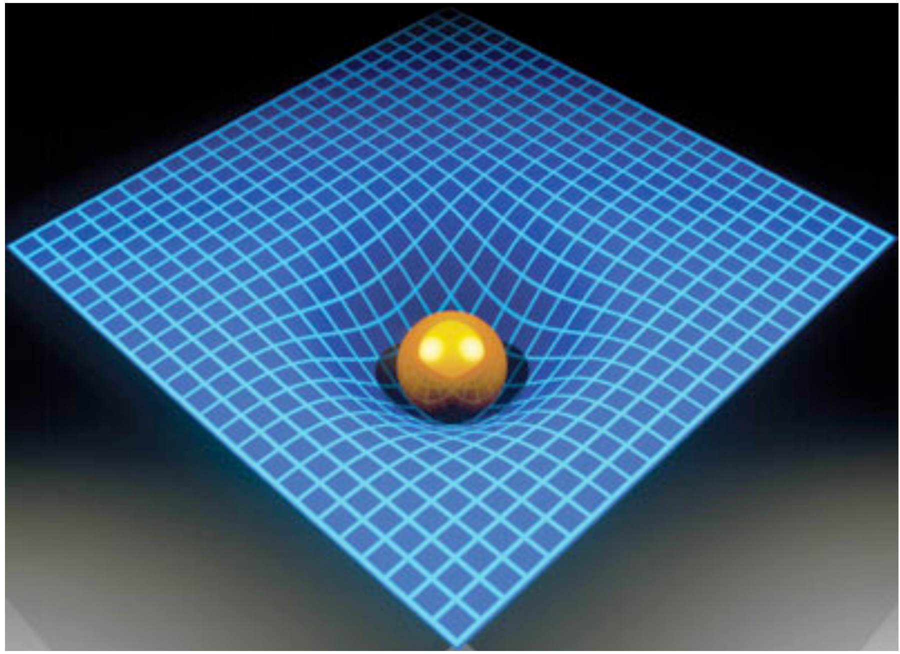
What happens when the star is not alone?



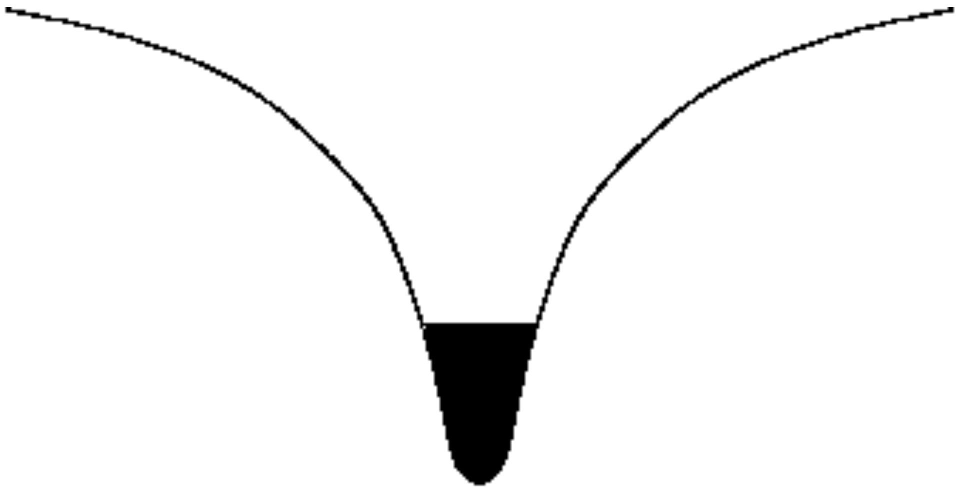
Potential wells

We need to think about the way matter reacts to the gravity from a pair of stars.

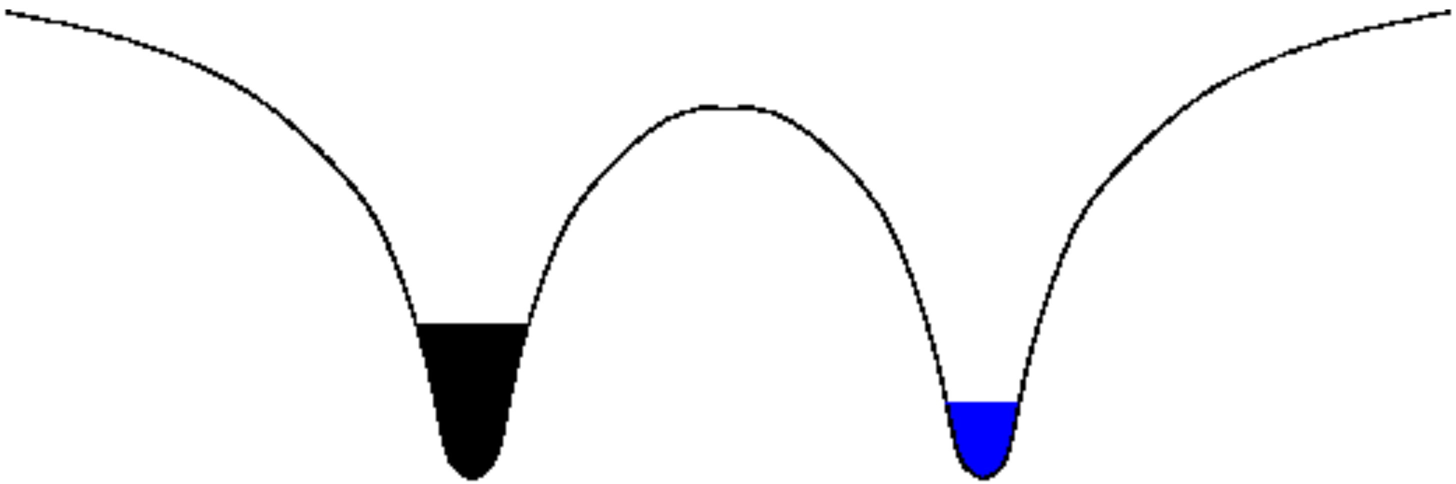
The best way of visualising this is to consider *potential wells*, which shows how gravity behaves near an object.



A graph of the gravitational potential energy around a single object looks like this. A particle put near the object will be attracted to it, just as a marble would roll down the hill to the centre.



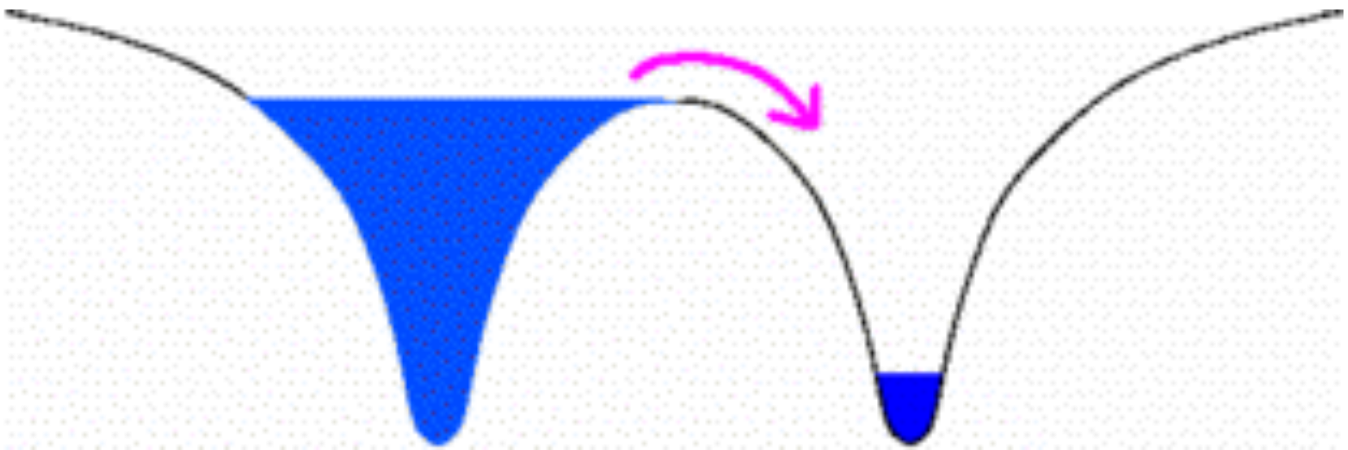
In the case of a binary star, each star has its own well representing its gravitational field. The two wells overlap at some point: in the centre if the stars have equal masses, otherwise closer to the heavier star.



In order to get X-rays from accreting material, we are going to need to get matter from one well to the other. How?

– move wells closer together *(hard to do)*

– move matter inside the well upwards

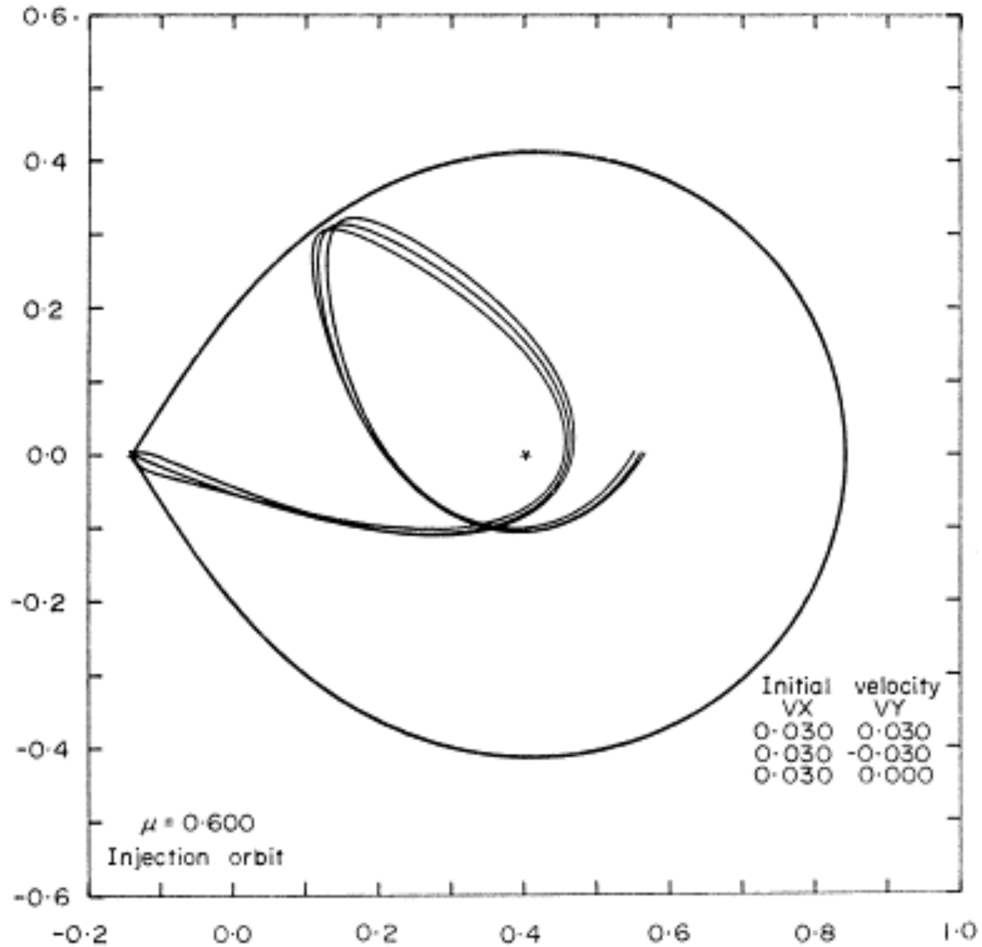


This is exactly what stellar evolution does. The same amount of mass suddenly gets much less dense and expands away from the centre. For a single star, this is the end of the matter, but if the star is in a binary, this expansion might push some material over the edge into the neighbouring well

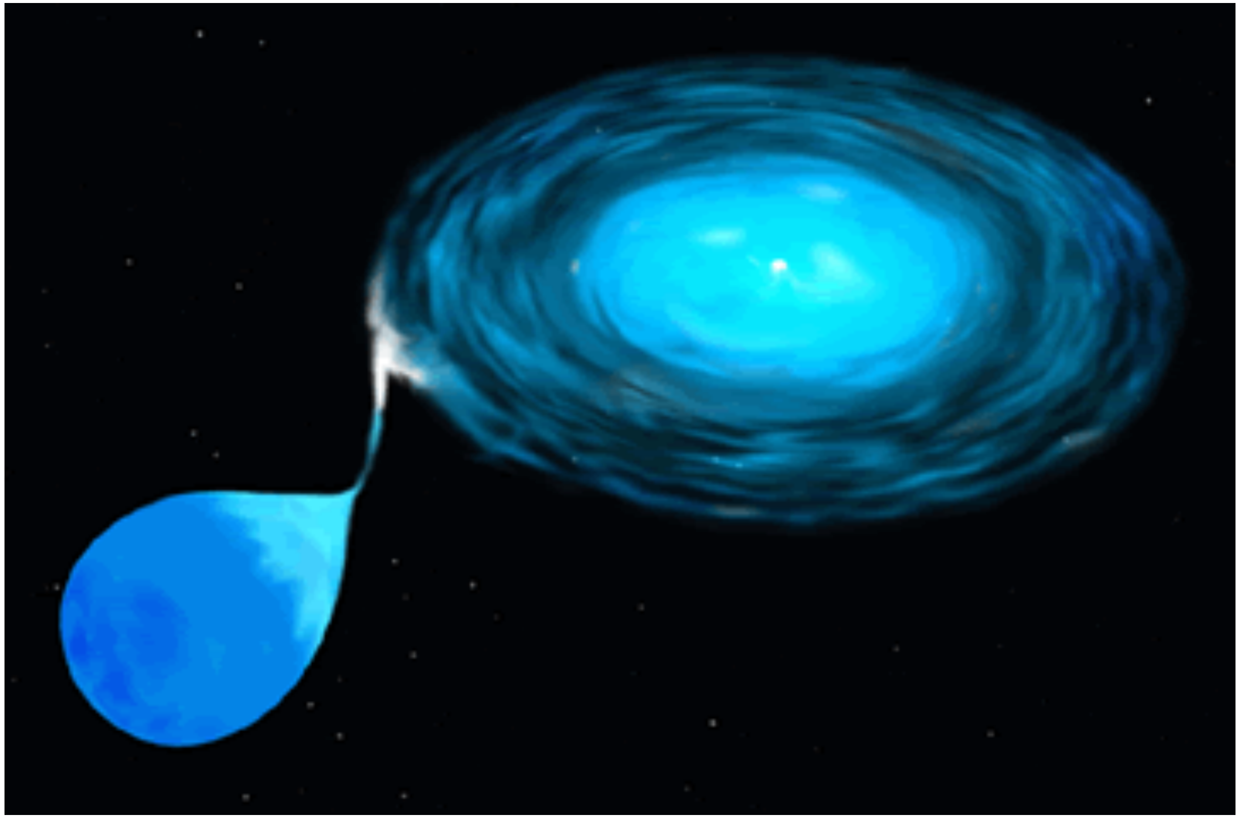
☞ material lands on neighbouring star

☞ if the star is compact, we can get X-rays.

Matter does not actually fall straight down, because it has angular momentum. This tends to make it go *around*.



Friction lets angular momentum be transported out while matter is transported in (where it can accrete onto the neutron star). The disk spreads into an *accretion disk*.



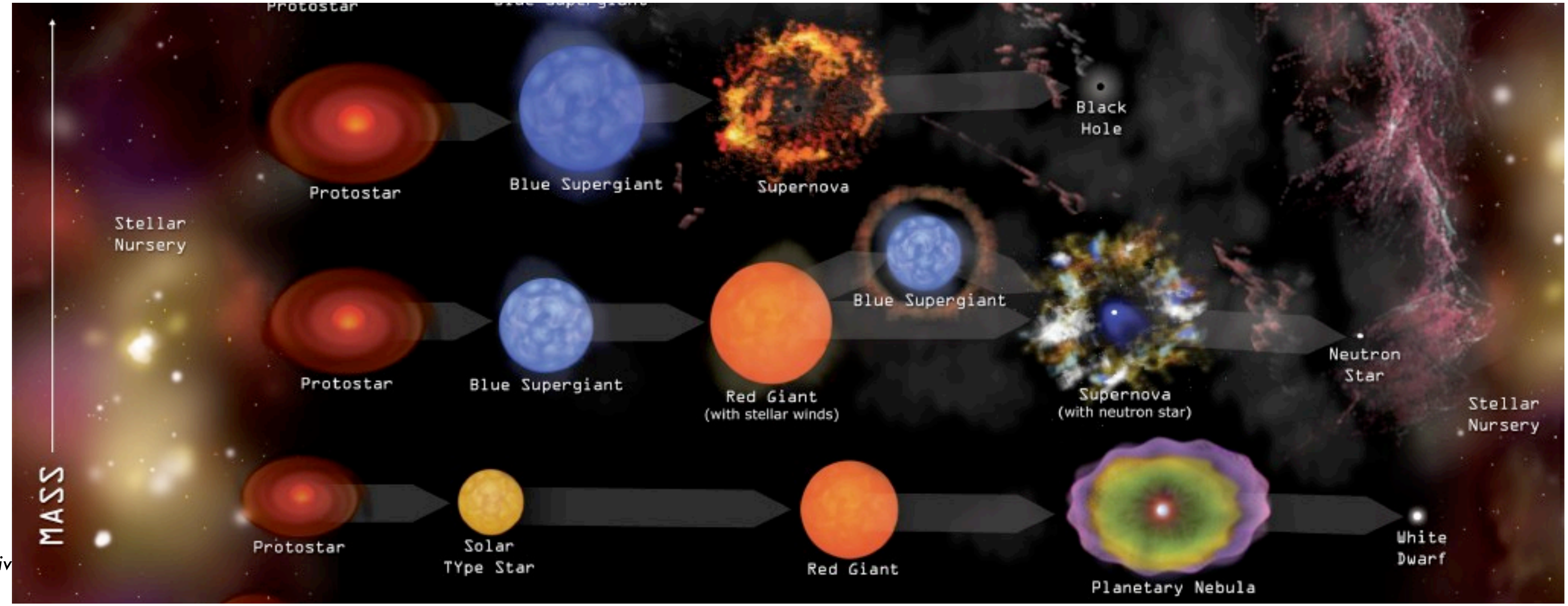
Surprisingly, X-ray binaries fall into two distinct groups:

- some systems have *massive* star companions (O or B stars), very *elliptical* orbits, and *long* orbital periods of months or years
- some systems have *low-mass* companions (M or K stars), *circular* orbits, and very *short* orbital periods – days or hours (the shortest is 11 minutes!)

Nearly all X-ray binaries fall into these categories: there are essentially none in between.

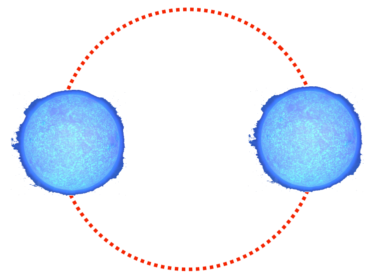
Why should this be? It all hinges on the fact that in order to end up with a neutron star, you have to start out with a star at least 6 times as massive as the Sun.

Let's consider how these two sorts of binaries could come about.

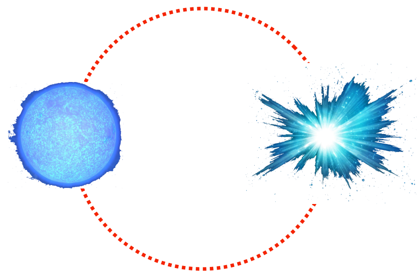


Forming a binary containing a massive star and a neutron star isn't too hard.

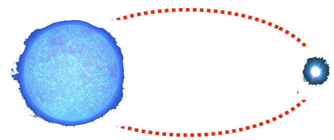
Begin with two massive stars.



Then one goes supernova

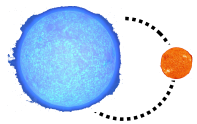


… leaving the other in an elliptical orbit with a neutron star

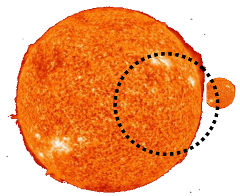


Forming a binary containing a low-mass star and a neutron star turns out to be much harder.

Begin with a massive star and a light star.



How does the giant star fit inside the orbit?



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After the supernova explosion,

the binary will be unbound.

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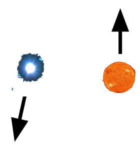


Solutions:

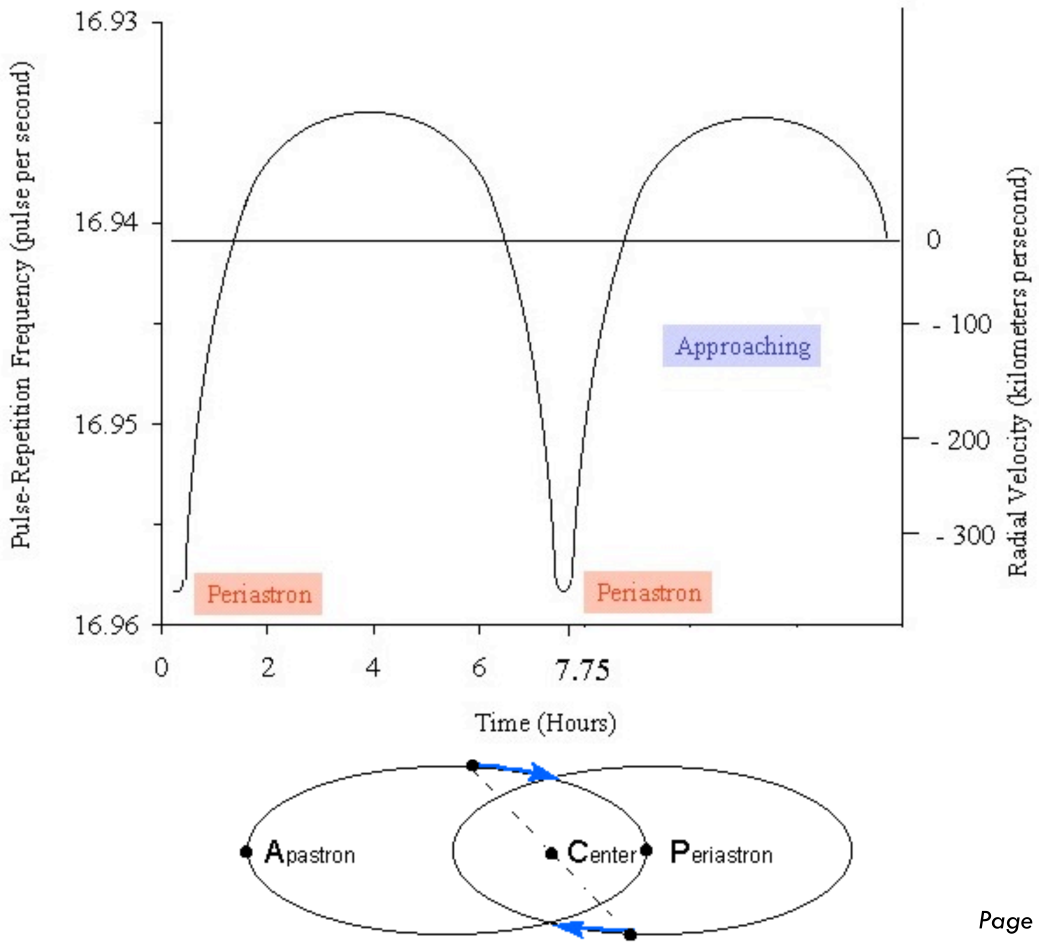
- The red giant was not inside the current orbit: the orbit has shrunk dramatically since both stars were on the main sequence. There was a period of *common envelope evolution*, where the low mass star was actually inside the giant envelope, and helped strip it away.

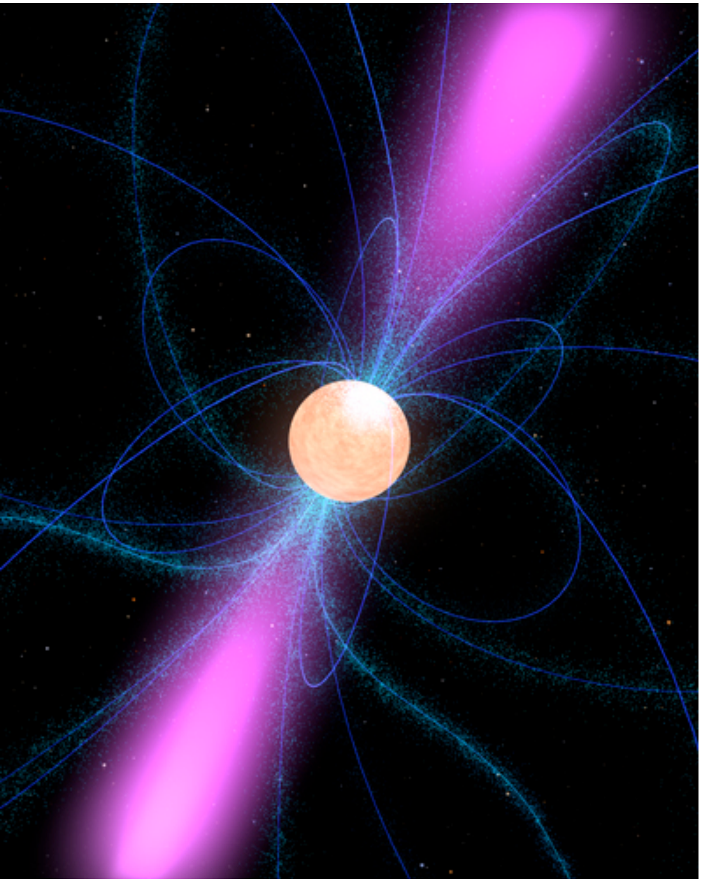
- The supernova must have been asymmetric, with a "kick" in one direction. If this kick is in exactly the right direction, the orbit can remain bound (and the whole binary will get a velocity).

Millisecond pulsars: the link with X-ray binaries

In 1974, Joe Taylor and Russell Hulse discovered a pulsar in a binary system.

The pulsar was pulsing 17 times per second; the orbital period was 7.75 hours. Both stars are neutron stars, though only one is a pulsar.





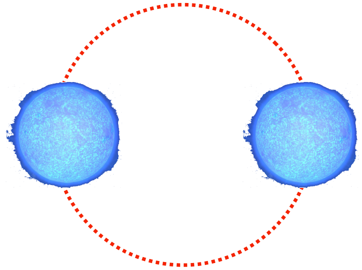
In 1982, an *extremely* fast pulsar was discovered, rotating 640 times per second.

More *millisecond pulsars* were discovered, and 80% are in binary systems (compared to <1% of regular pulsars)

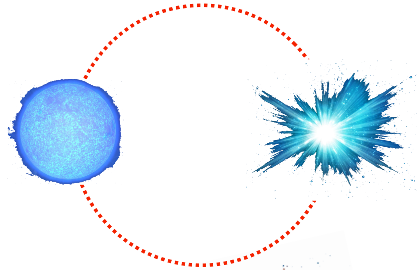
Millisecond pulsars are *old*: other fast pulsars (like the Crab pulsar) are young.

Millisecond pulsars are *recycled* pulsars.

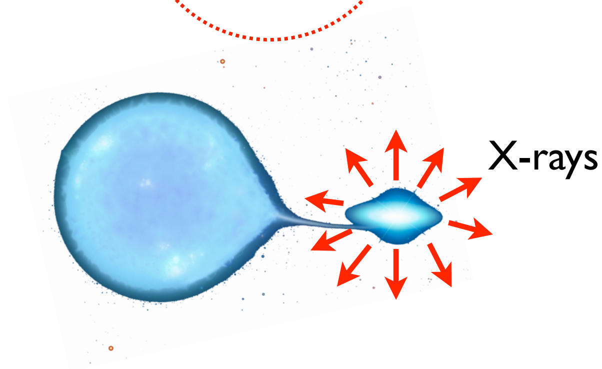
Born in a binary system,



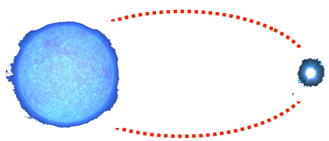
one star goes supernova, then the other evolves and leaves a neutron star.



The second star starts spilling matter onto the neutron star, which accretes matter and angular momentum, which spins it up: an *X-ray binary*.

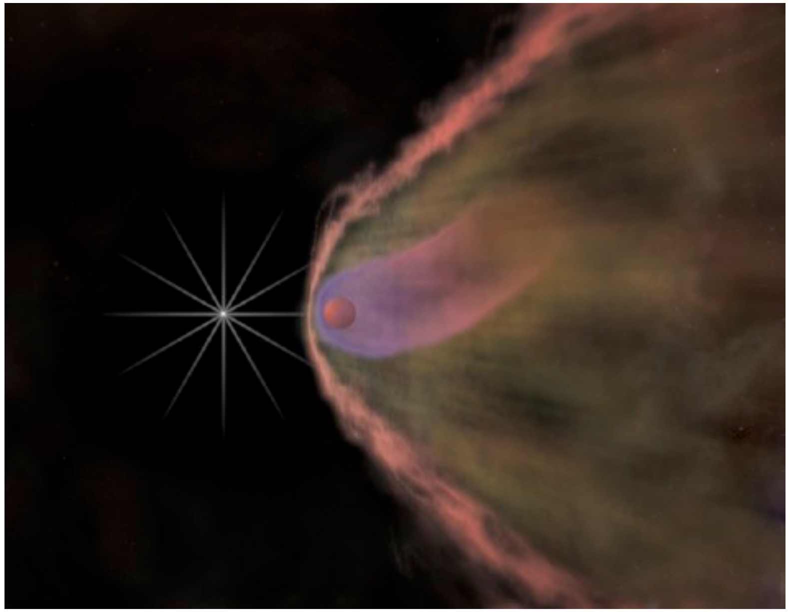


When accretion stops, we have a very fast pulsar in orbit with a neutron star or white dwarf.



Why are some millisecond pulsars single?

Missing link: the “Black Widow” pulsar, which appears to be evaporating its companion.

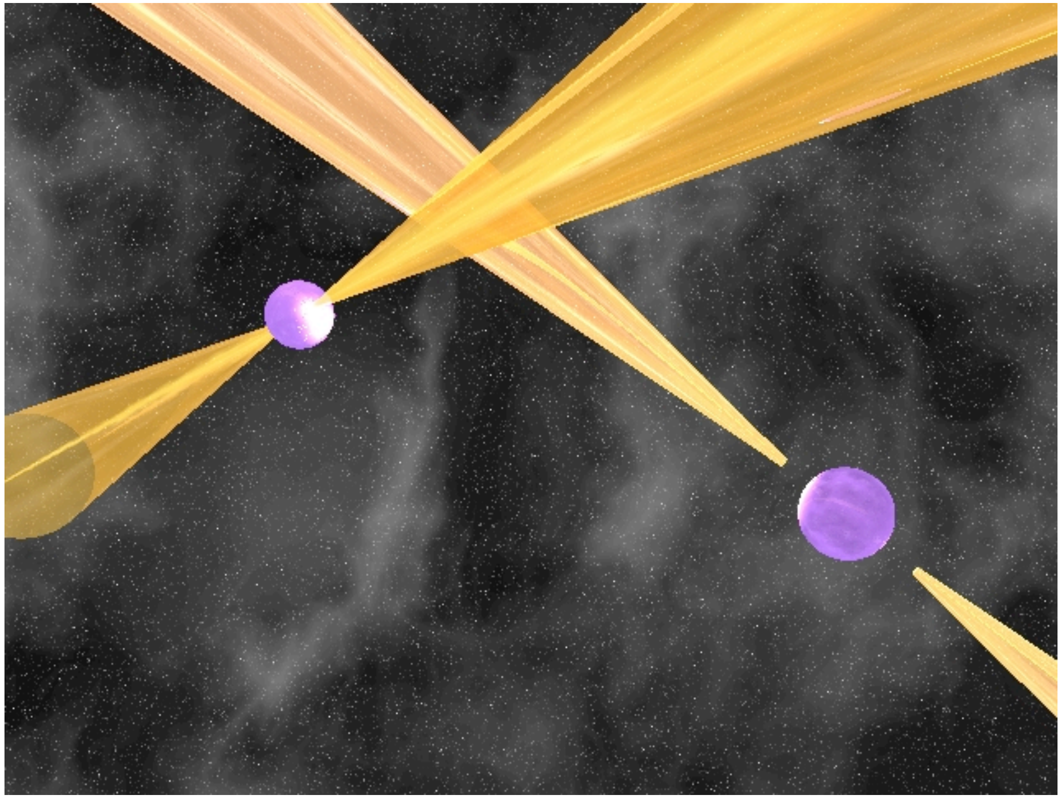


Artist’s impression of PSR B1957+20 and its companion, showing the pulsar's powerful wind blasting the companion, stripping it of gas and steadily evaporating it, shown by the purple trail of material streaming away from the companion star.

Here’s an animation showing the whole evolution of a single millisecond pulsar.

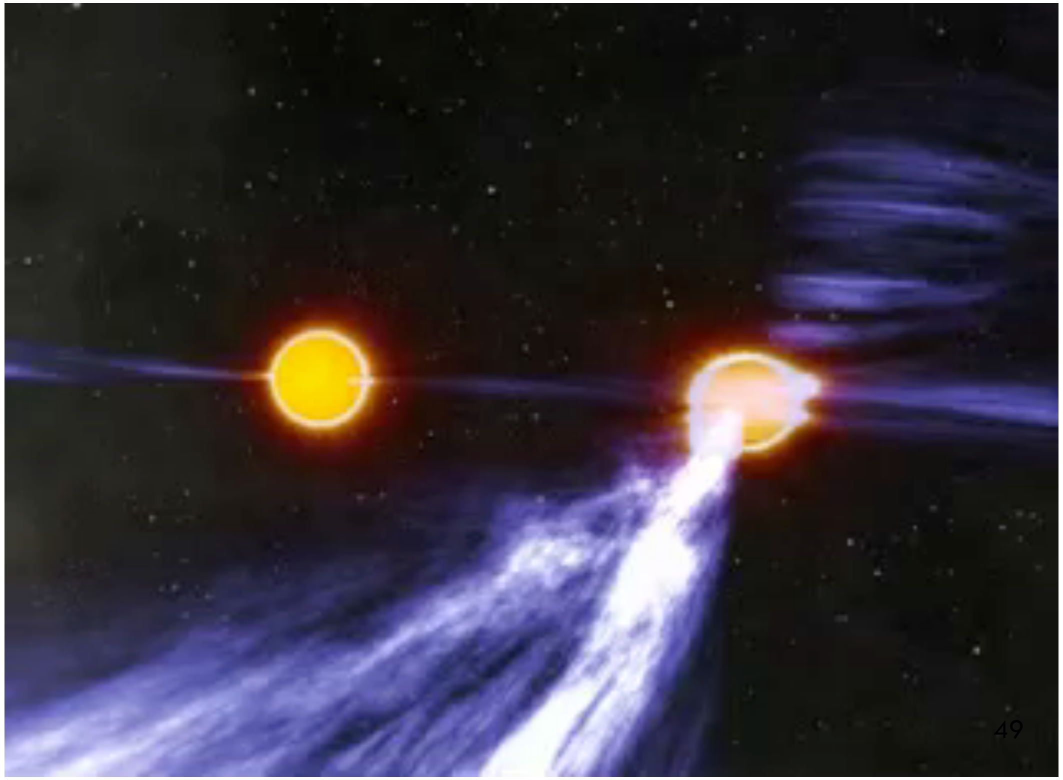
The first double pulsar

In 2004, the first double pulsar was discovered: a binary where *both* neutron stars are pulsars!



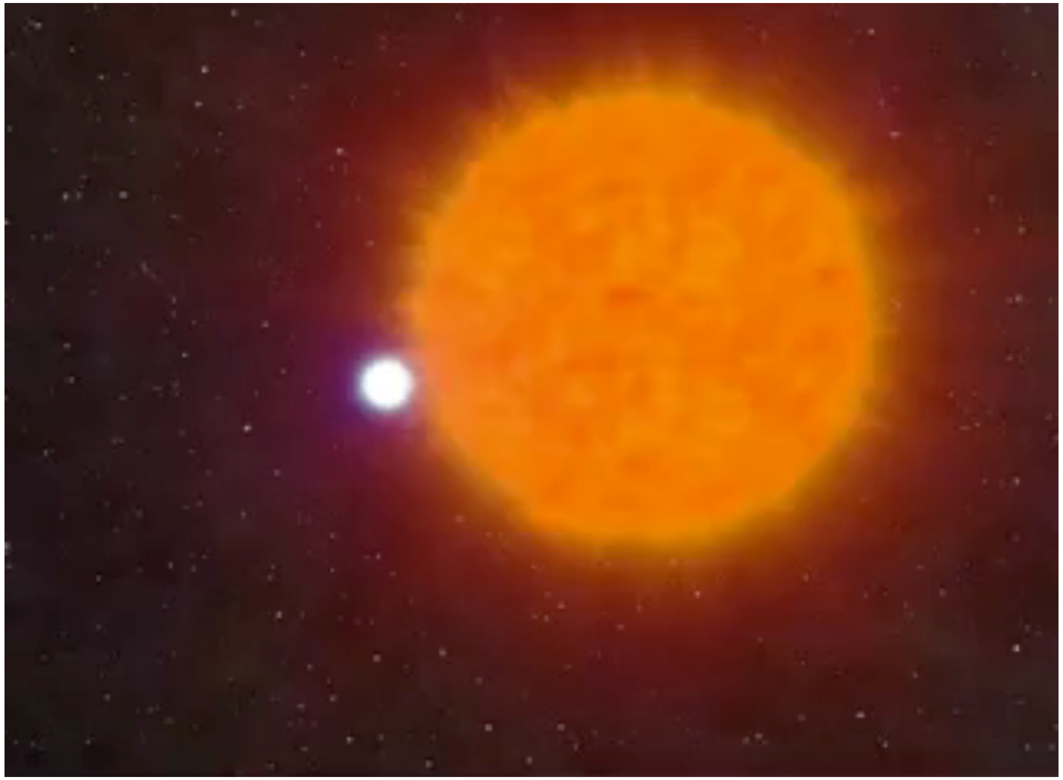
The binary consists of a pulsar with a spin-period of 23 ms – the millisecond pulsar – orbiting a 2.8 s pulsar in a 2.4 h orbit (which means the size of the orbit is the diameter of our Sun). The mean orbital velocity is about 0.1% of the speed of light.

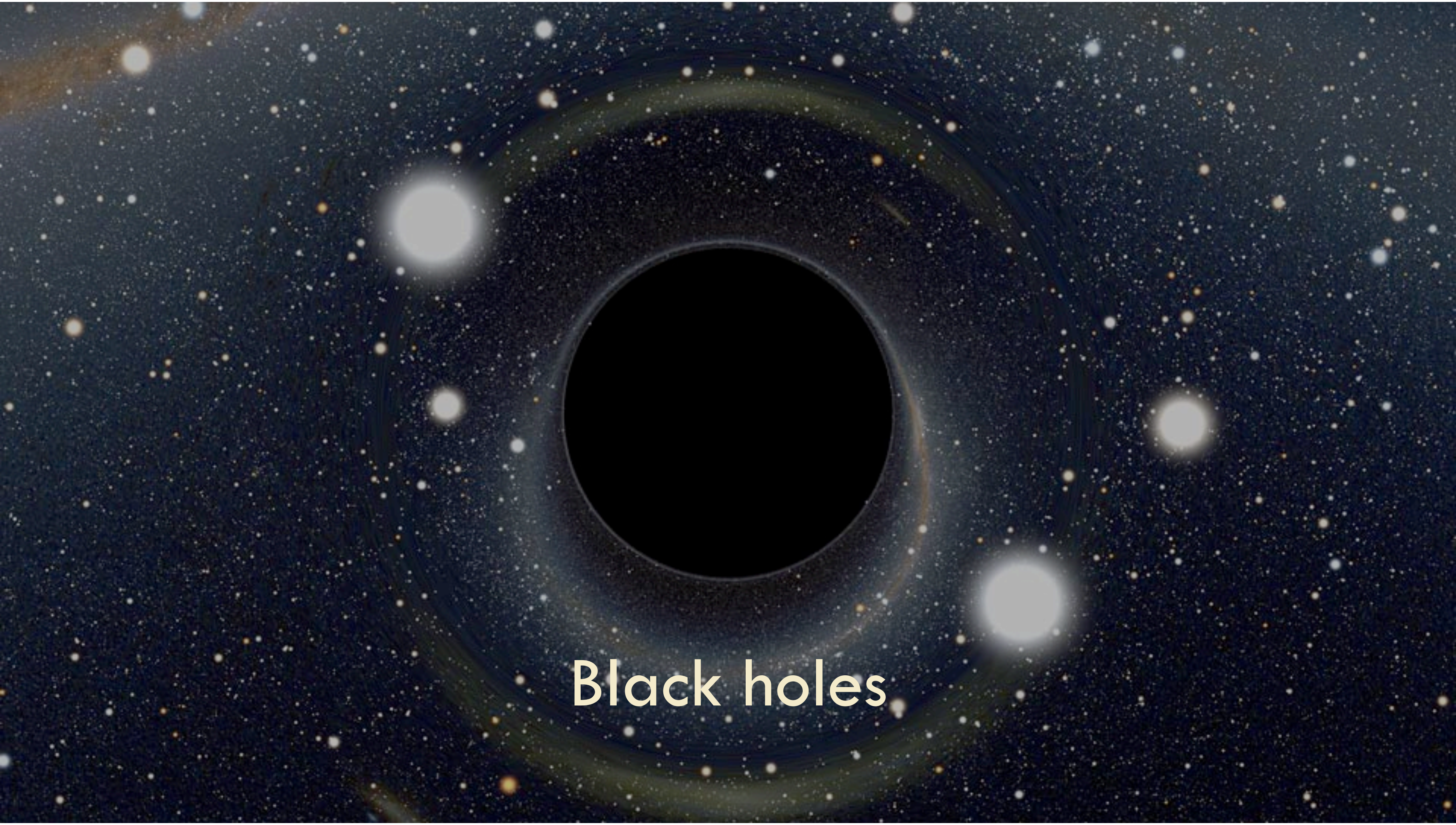
Furthermore, the orbit is almost exactly edge-on, so both pulsars are actually eclipsed each orbit.



The millisecond pulsar must have initially been the more massive star; the slower pulsar resulted from the second supernova, so is much younger than the other.

The chance of finding such a binary is remote, since both pulsars have to be pointing in our direction and the younger pulsar must still be alive.



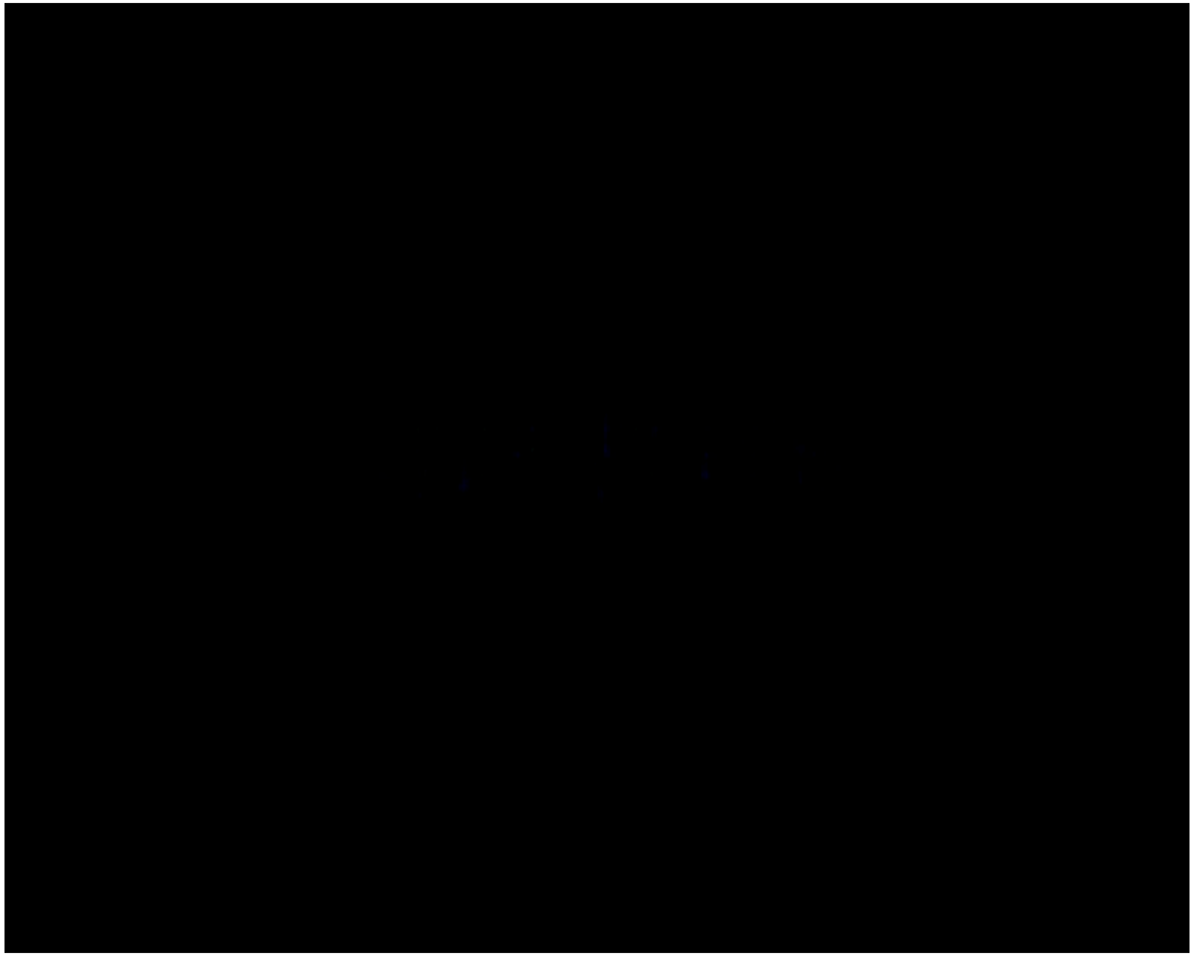


Black holes

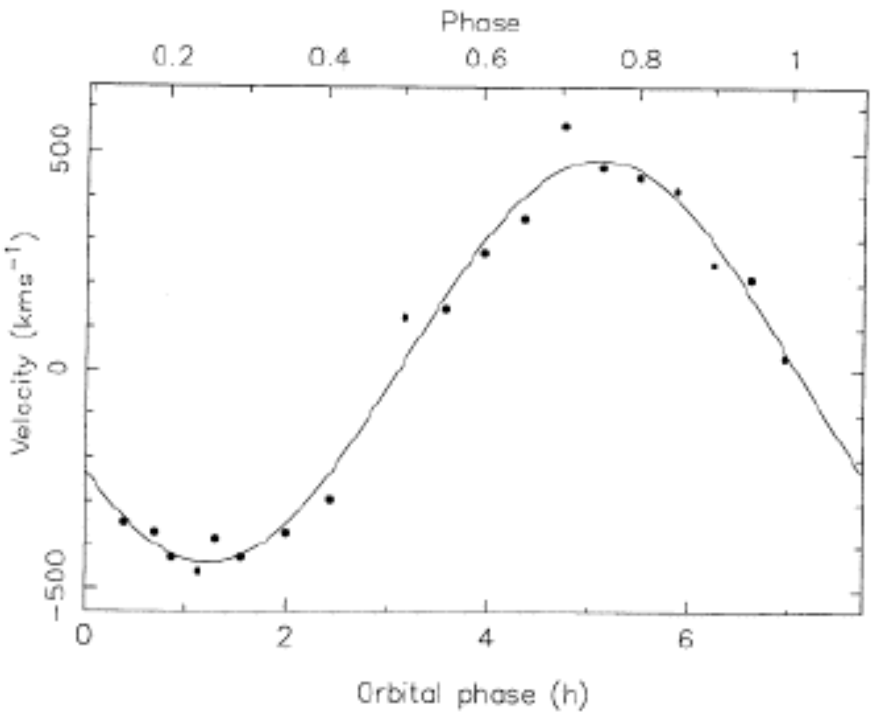
Black holes

When the collapsing core of the star is larger than the maximum mass a neutron star can have, there is nothing else which can resist the relentless pull of gravity. The result is a black hole.

Of course, if we thought finding neutron stars was hard…



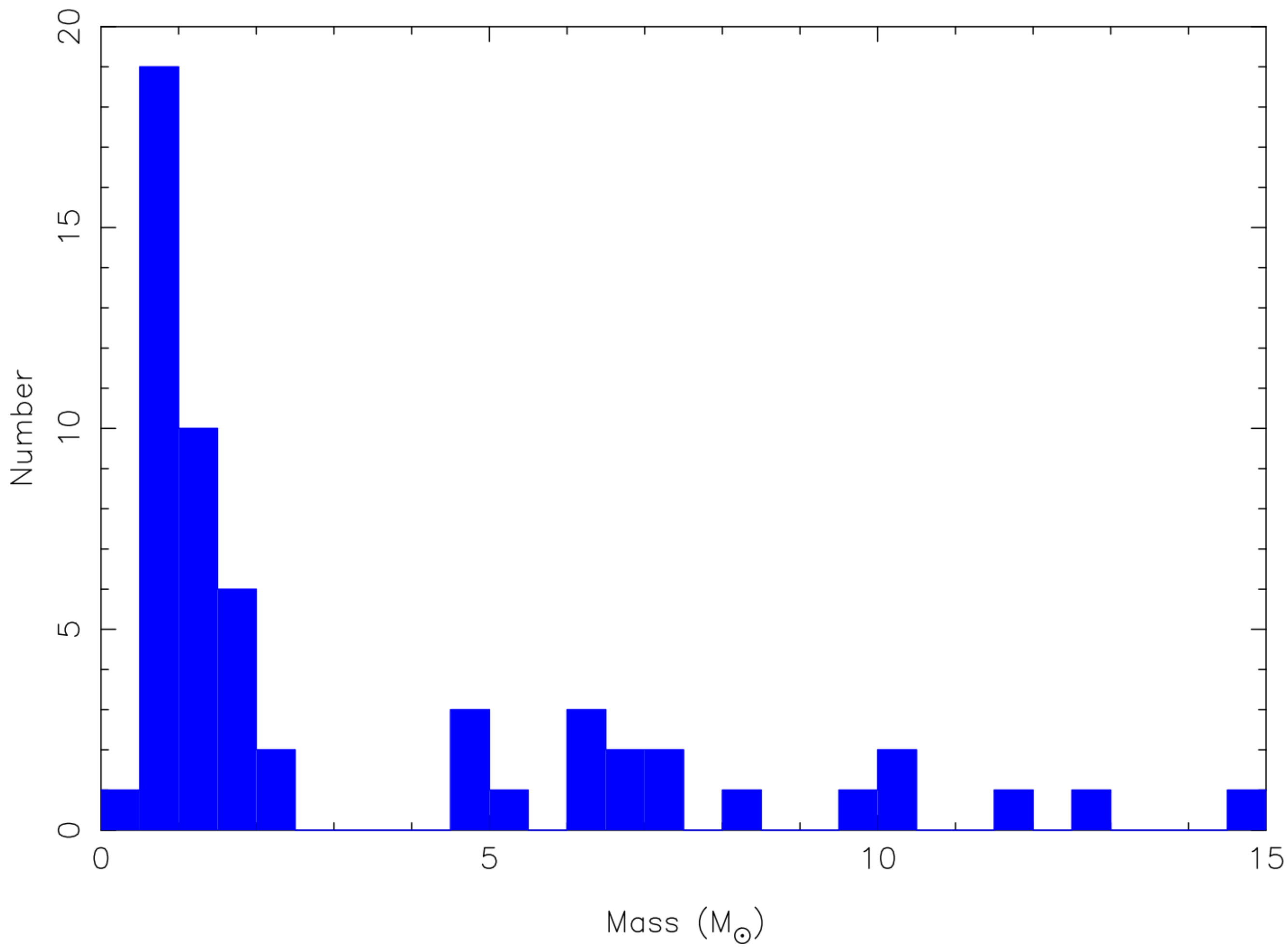
With X-ray binaries, we can measure the velocity of the companion star, and hence the mass of the unseen star it is orbiting.



The velocity of the companion star in the X-ray binary A0620–00. From the large velocity swing,

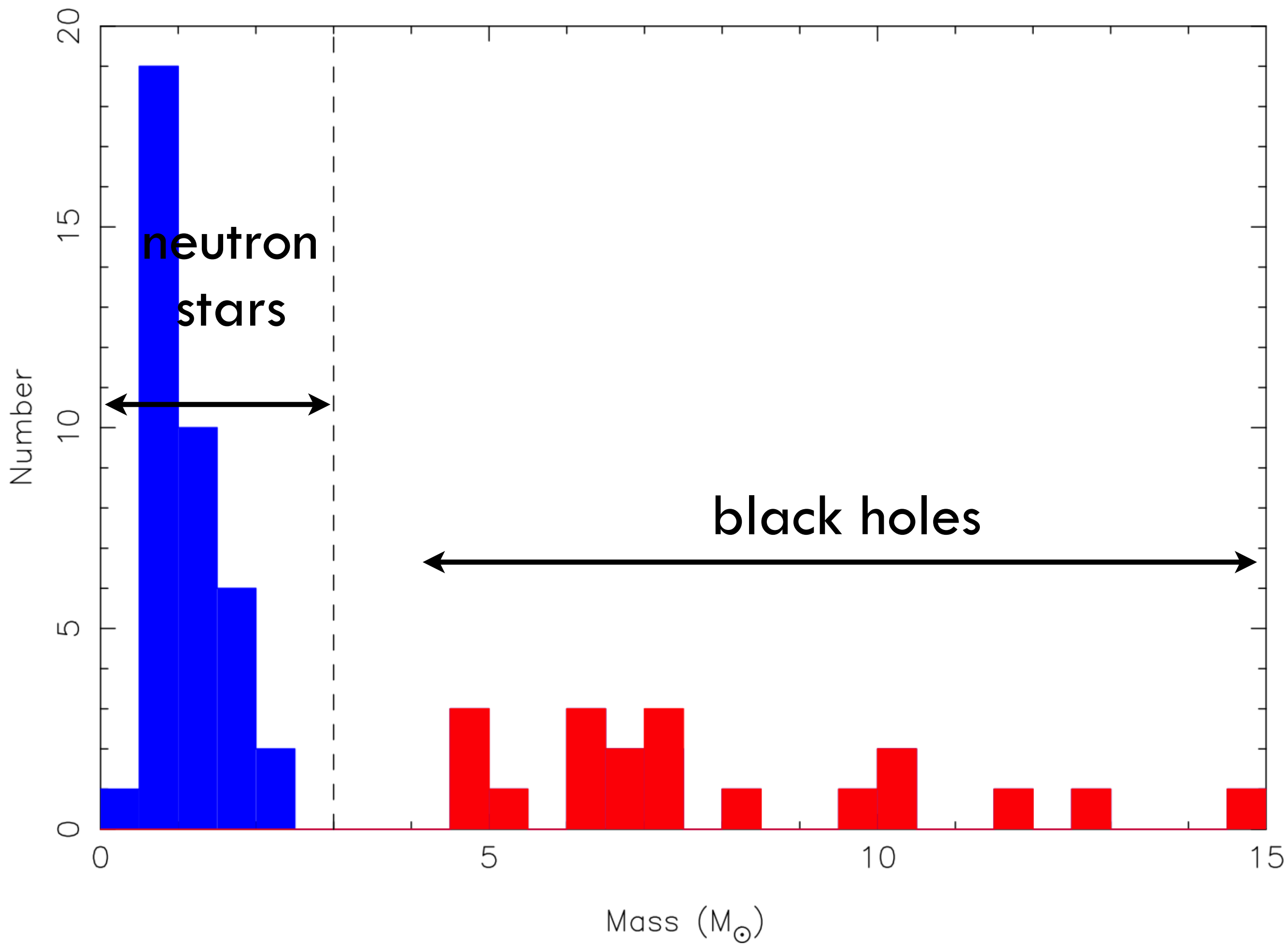
Th *we derive a minimum mass for the accreting object of 3.3 solar masses.*

Look at the masses of the object we can't see.



data from https://stellarcollapse.org/

Some of the invisible objects are too heavy to be a neutron star: these must be black holes.



data from
https://stellarcollapse.org/

As we will see later, astronomers have also found evidence for supermassive black holes (more than a million times the mass of the Sun) in the cores of many galaxies, including the Milky Way.

What we know astronomically about black holes is more or less restricted to this: we have located objects which are so heavy that they must be black holes. We don't really know anything more about them.

So let's take a look at what the theorists tell us about black holes.

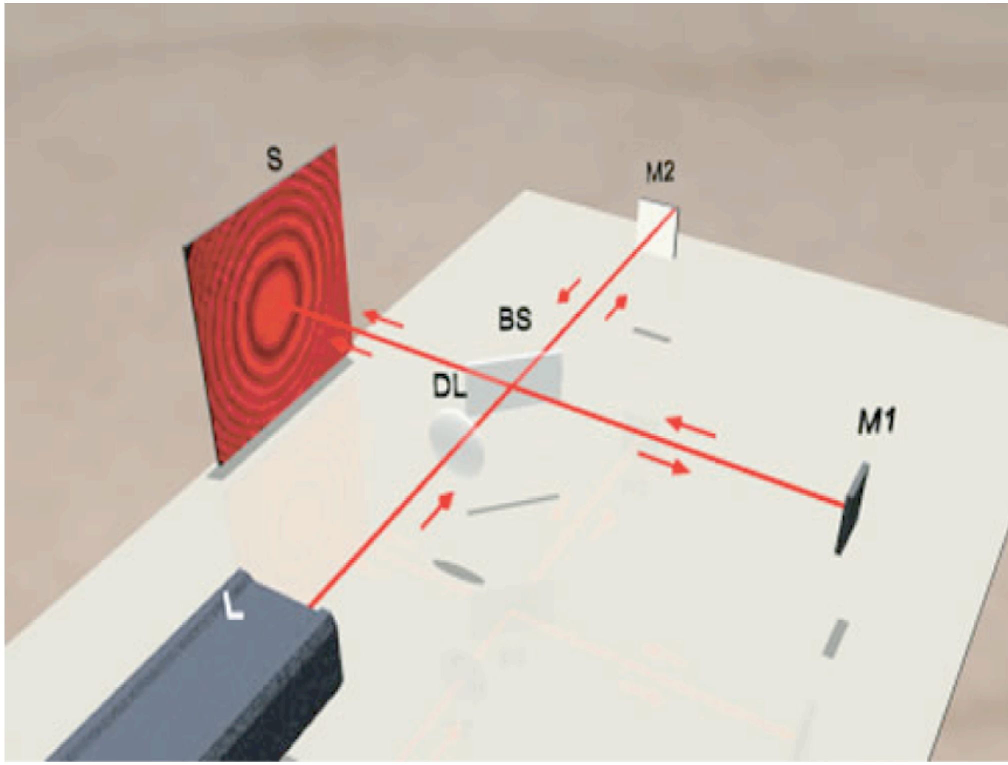
Relativity

If light is a wave, what is it waving in?

Scientists assumed there must be a substance, permeating the whole universe, through which light "waved": the *aether*.

Michelson and Morley made an experiment to measure the speed of light relative to the aether.

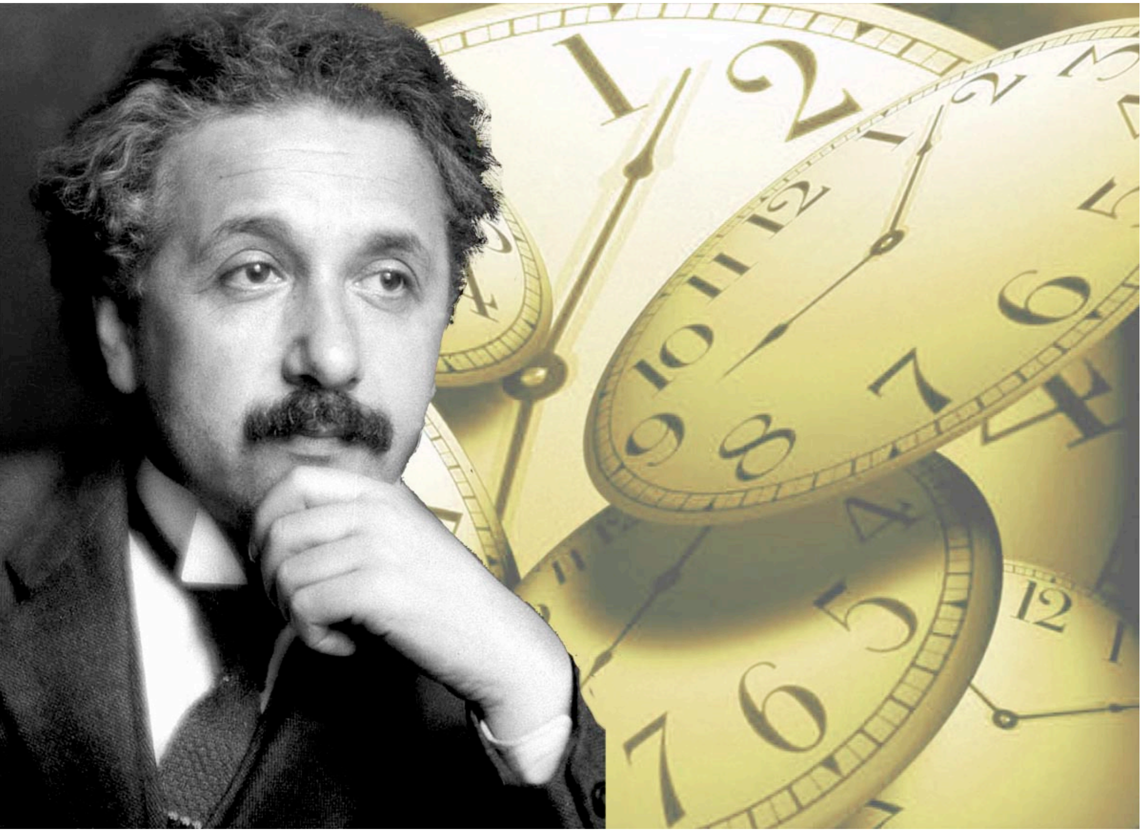
They found... nothing!



Einstein's answer

In a landmark paper in 1905, Einstein formulated the *special theory of relativity*. Starting from the assumption that, providing you're not accelerating, *the laws of physics look the same to all observers*, he showed that the speed of light must always be c, no matter how fast you're moving.

Einstein showed that one of the consequences of this is that *how fast time passes* depends on the speed of the observer. An observer travelling fast will measure less elapsed time than a stationary observer.

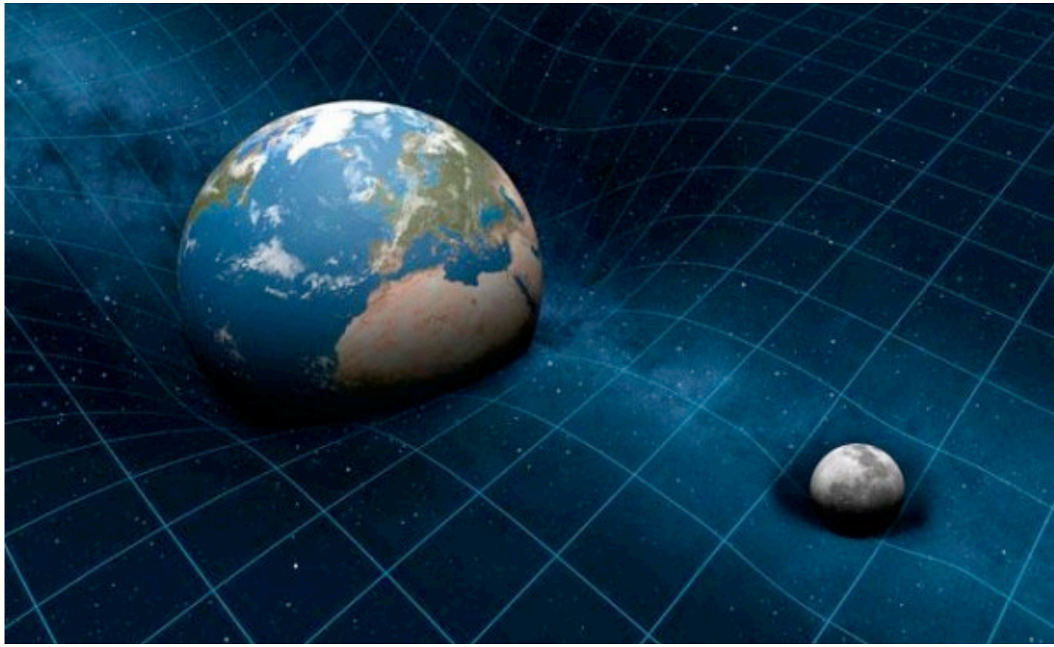


This flies against our everyday experience, but has since been demonstrated to hold in a number of very solid experiments. GPS receivers need to take into account relativistic effects in order to be able to calculate positions accurately.

In 1916 Einstein expanded his Special Theory to include the effect of gravitation on the shape of space and the flow of time.

This theory, referred to as the *General Theory of Relativity*, proposed that *matter causes space to curve*.

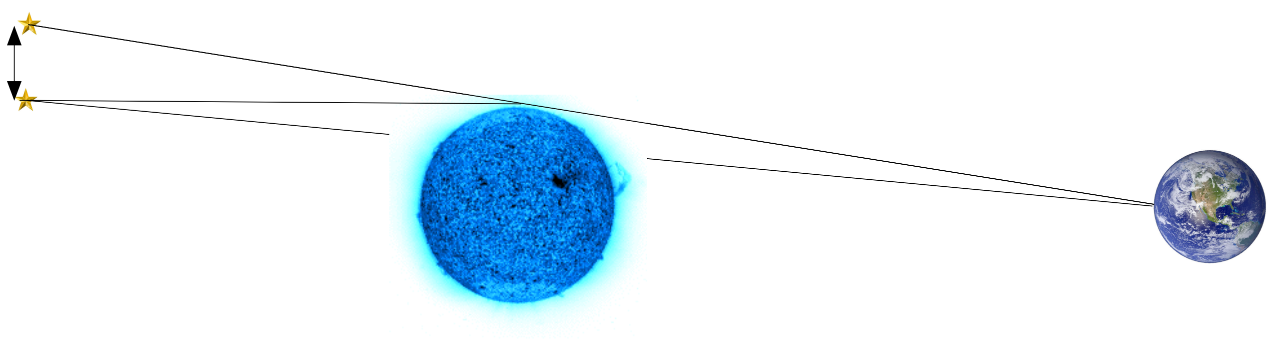
Gravity is no longer envisaged as a force that acts at a distance: matter is deflected by another mass because the space around it is curved.



General Relativity predicted that light itself would be bent by a massive object.

Thus the position of a star ought to be different when it is near the Sun than when it is far away.

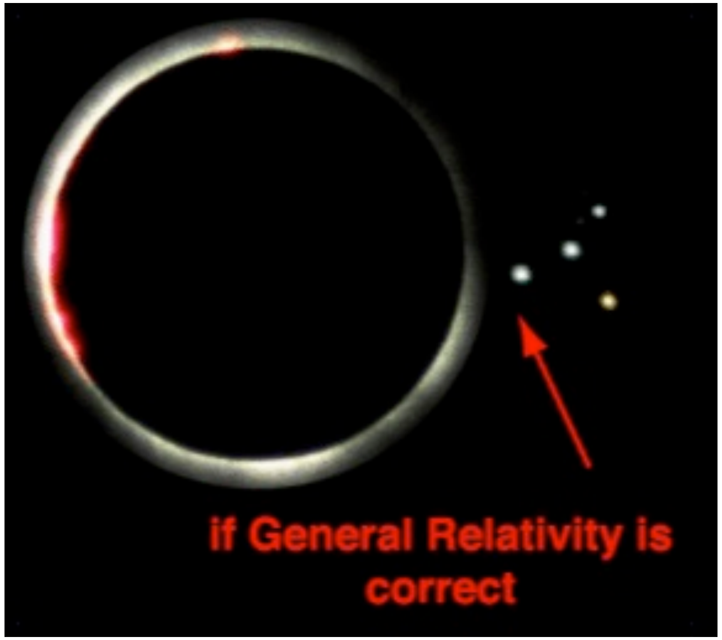
apparent shift of star



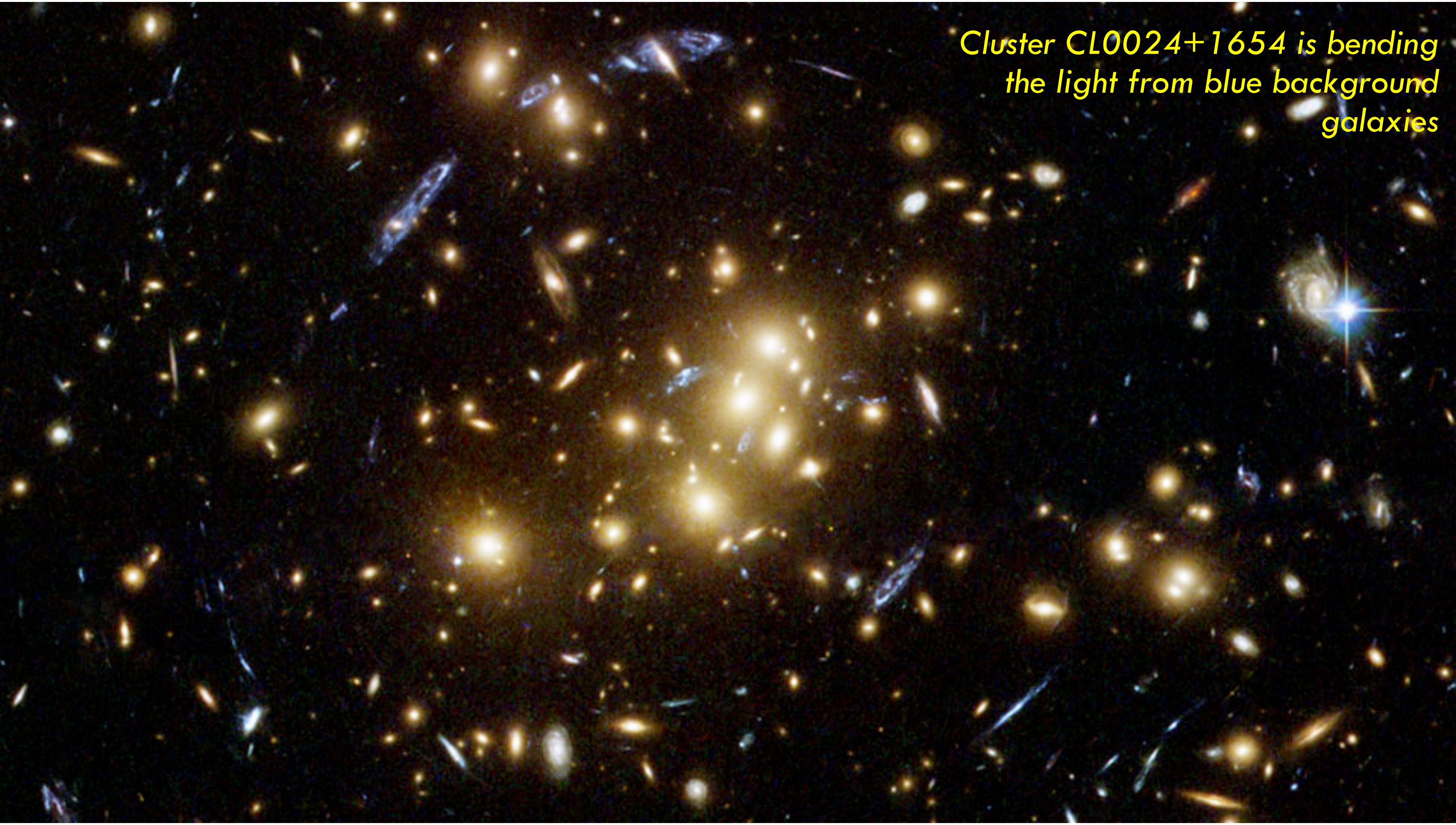
Of course, it is hard to see stars when they are near the Sun!

Eddington measure the positions of stars in the Hyades cluster during the solar eclipse of 1919.

The light from several stars was bent as it grazed the Sun, exactly as Einstein predicted.

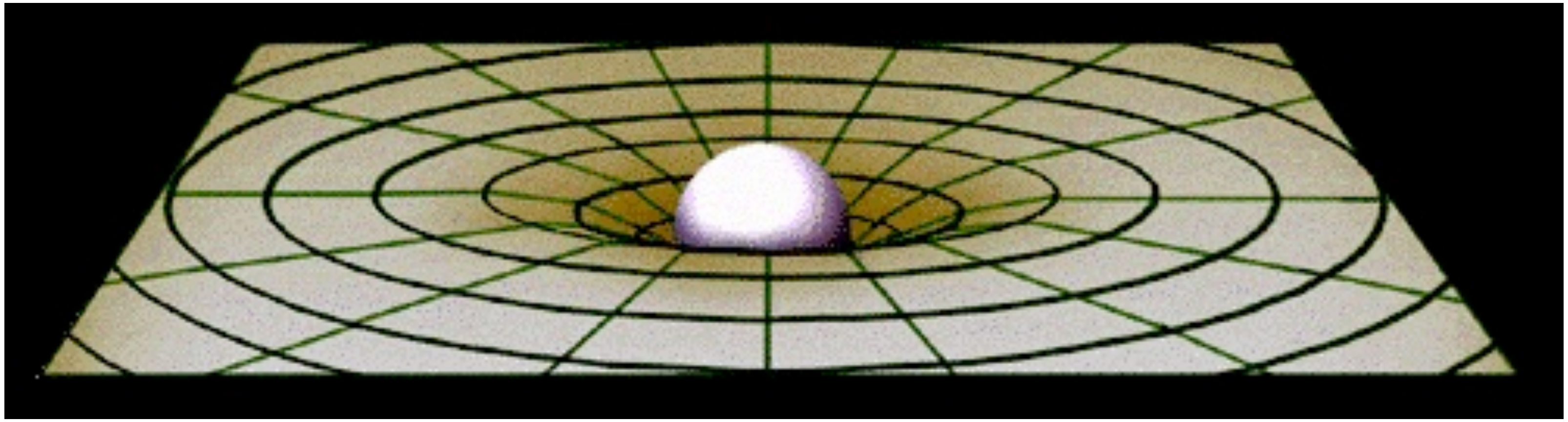


The bending of light by matter has since been demonstrated far more dramatically, in the discovery of gravitational lensing, where a massive cluster of galaxies bends the light from background objects into strange shapes.


Cluster CL0024+1654 is bending
the light from blue background
galaxies

What direction is spaced curved into? All three of the dimensions we know about are taking part in the curvature: space is being curved into *another dimension entirely*.

One way to represent this warping of space by matter is to display the three dimensions of our universe as a two-dimensional sheet in three-dimensional space. Mass warps the sheet (space) into the third dimension.

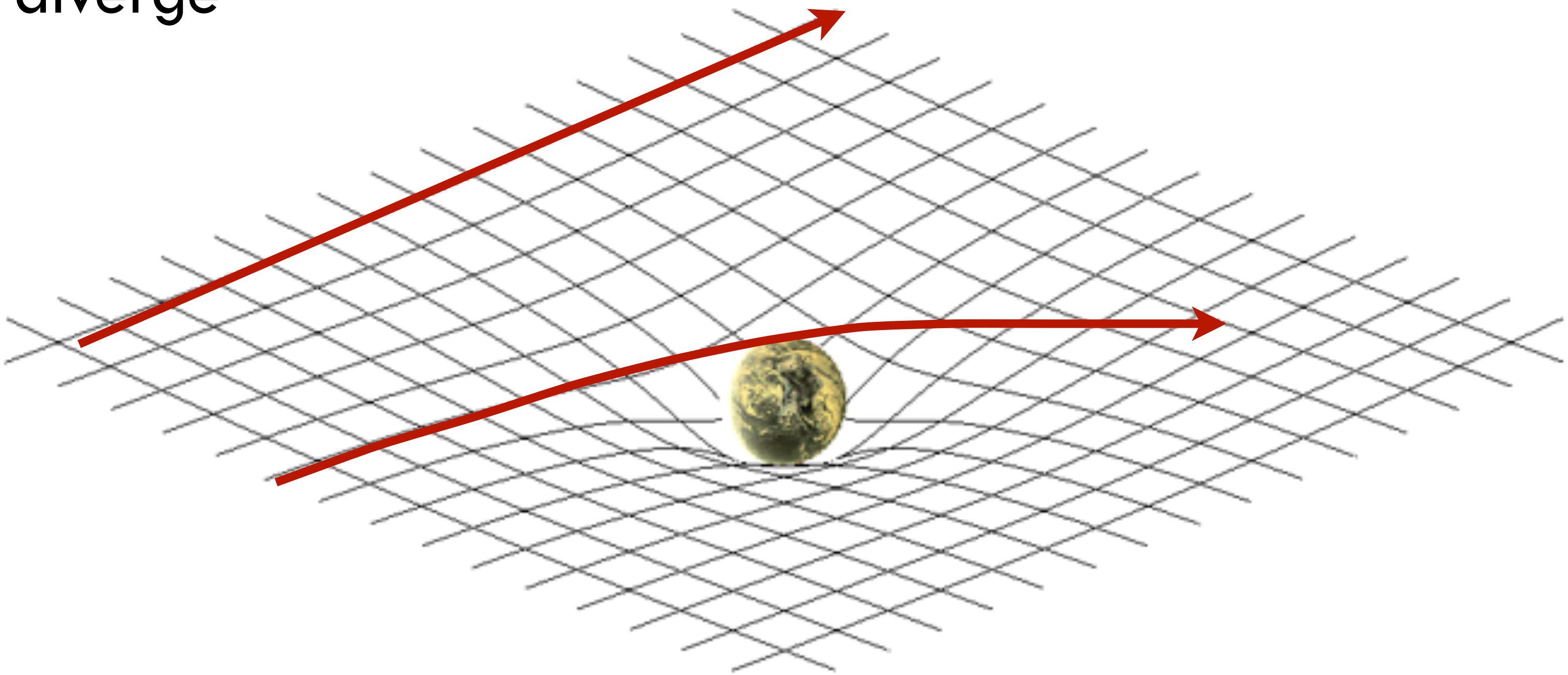


But remember! In this picture, we are two-dimensional beings: we can only know about things that happen *in the sheet*. Only a hyperspace observer could actually see the curvature of space.

Since we ourselves are embedded in the 2D sheet, we have no way of ever seeing this extra dimension. We can only measure its effect on our two-dimensional universe.

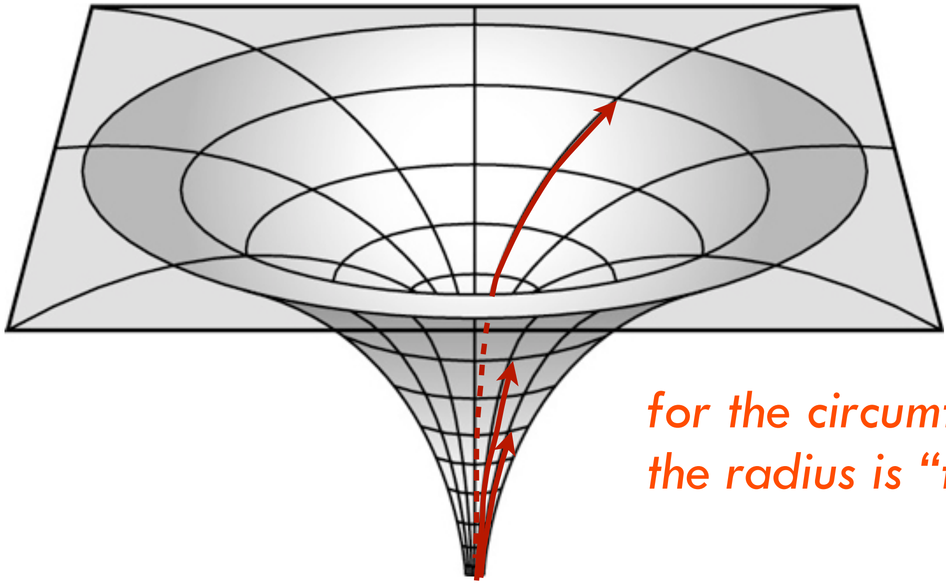
So how does a two-dimensional scientist find out that space is curved?

She could find lines which are initially parallel and always straight, but which later diverge



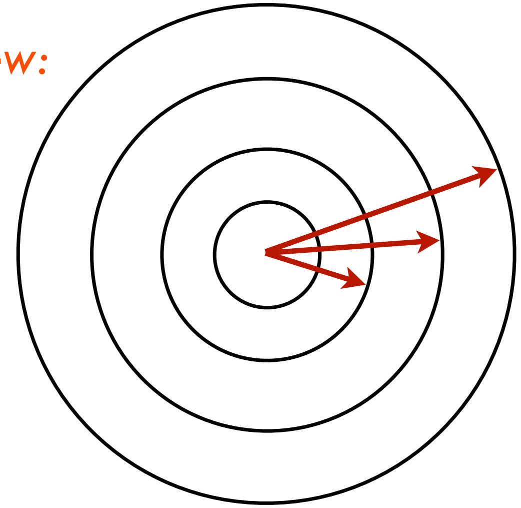
This corresponds to the shift in position of stars in 3-D space.

She could find circles whose circumference is less than 2π times their radius



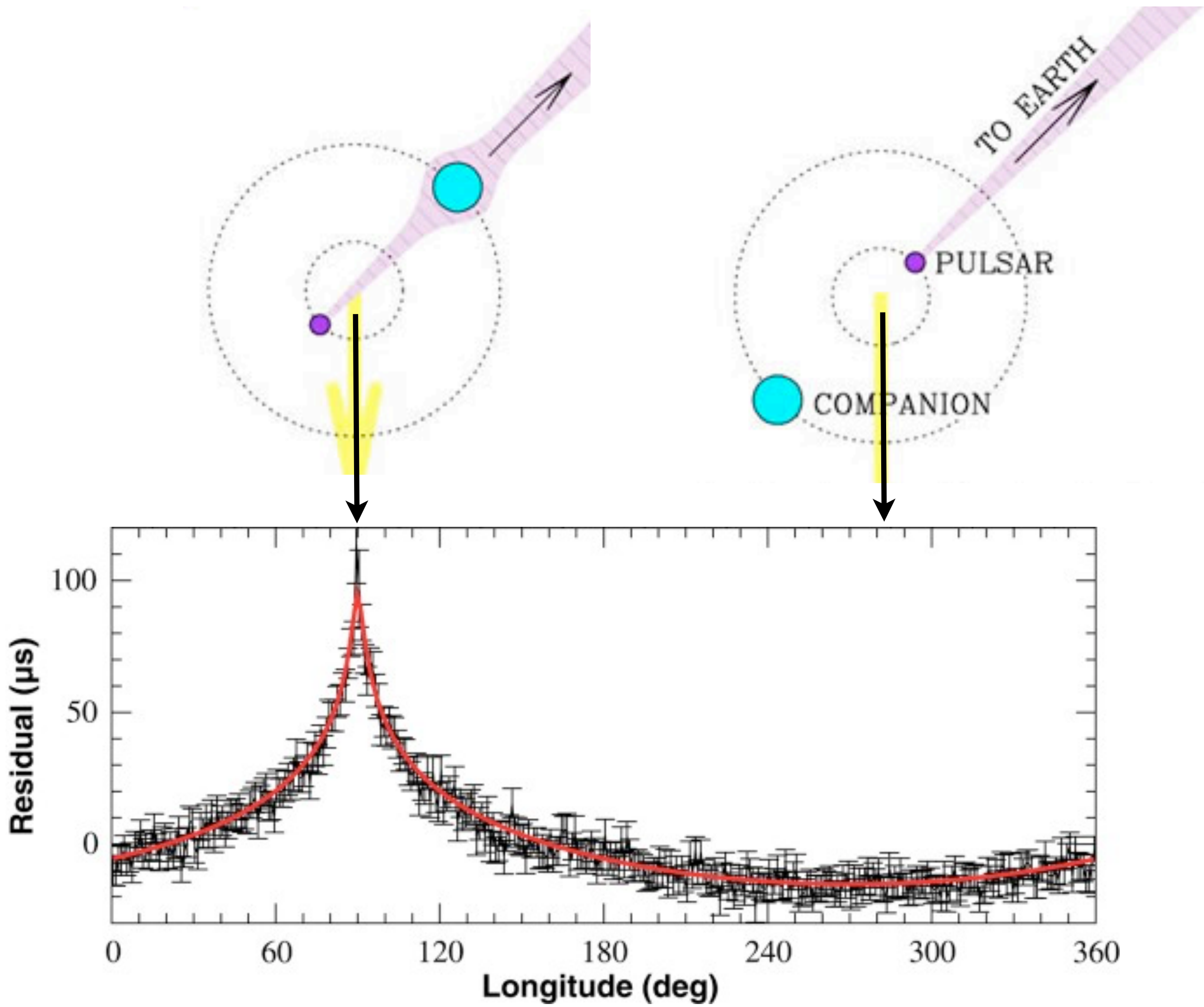
for the circumference of each circle the radius is "too big"

top view:

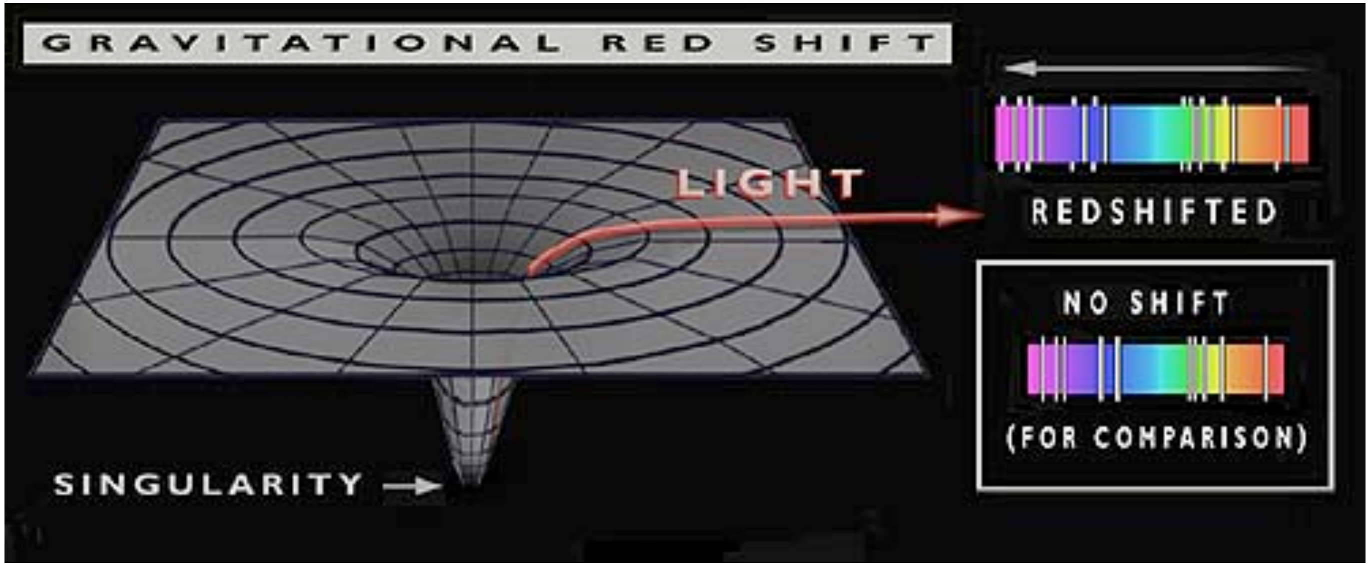


This corresponds to finding a sphere whose volume is less than 4/3π times its radius.

With the binary pulsar, we can actually measure this extra distance across the sphere containing the companion neutron star.



Gravity also produces a gravitational redshift: a photon leaving a gravitational field loses energy and becomes redshifted.



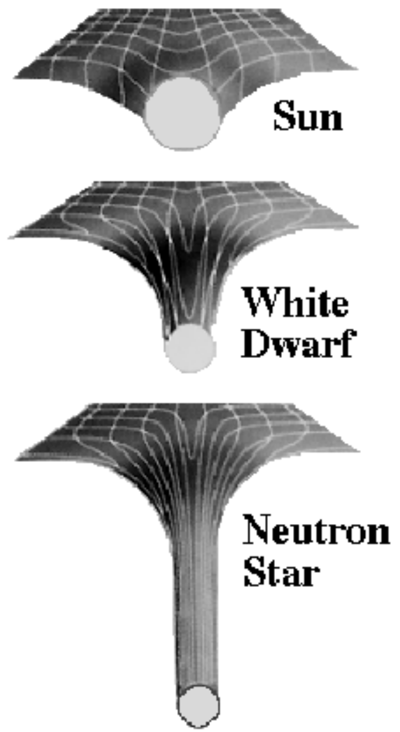
This gravitational redshift is easily measurable in the spectra of white dwarfs.

Black holes at last!

Let's consider what happens if we take a star and crush it.

As the star gets smaller the surface gravity increases → space-time is getting more curved.

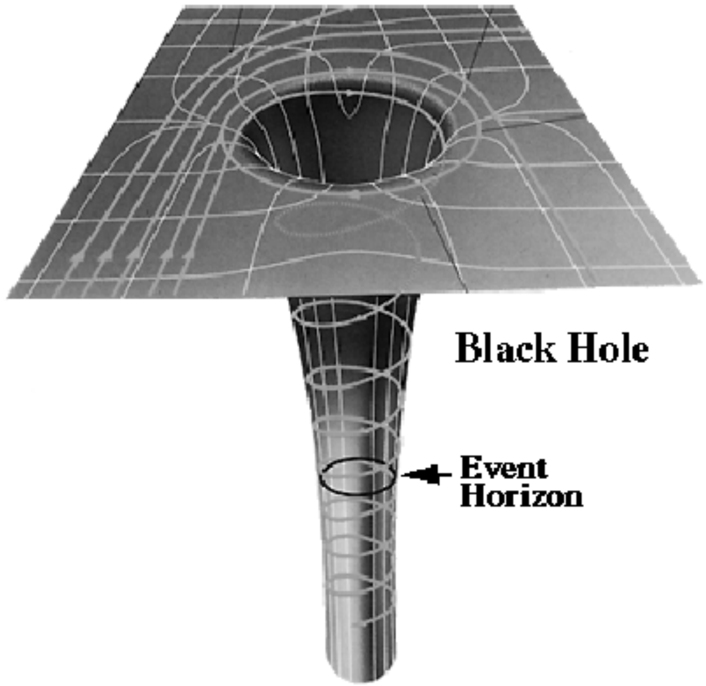
The gravitational redshift near the surface increases.



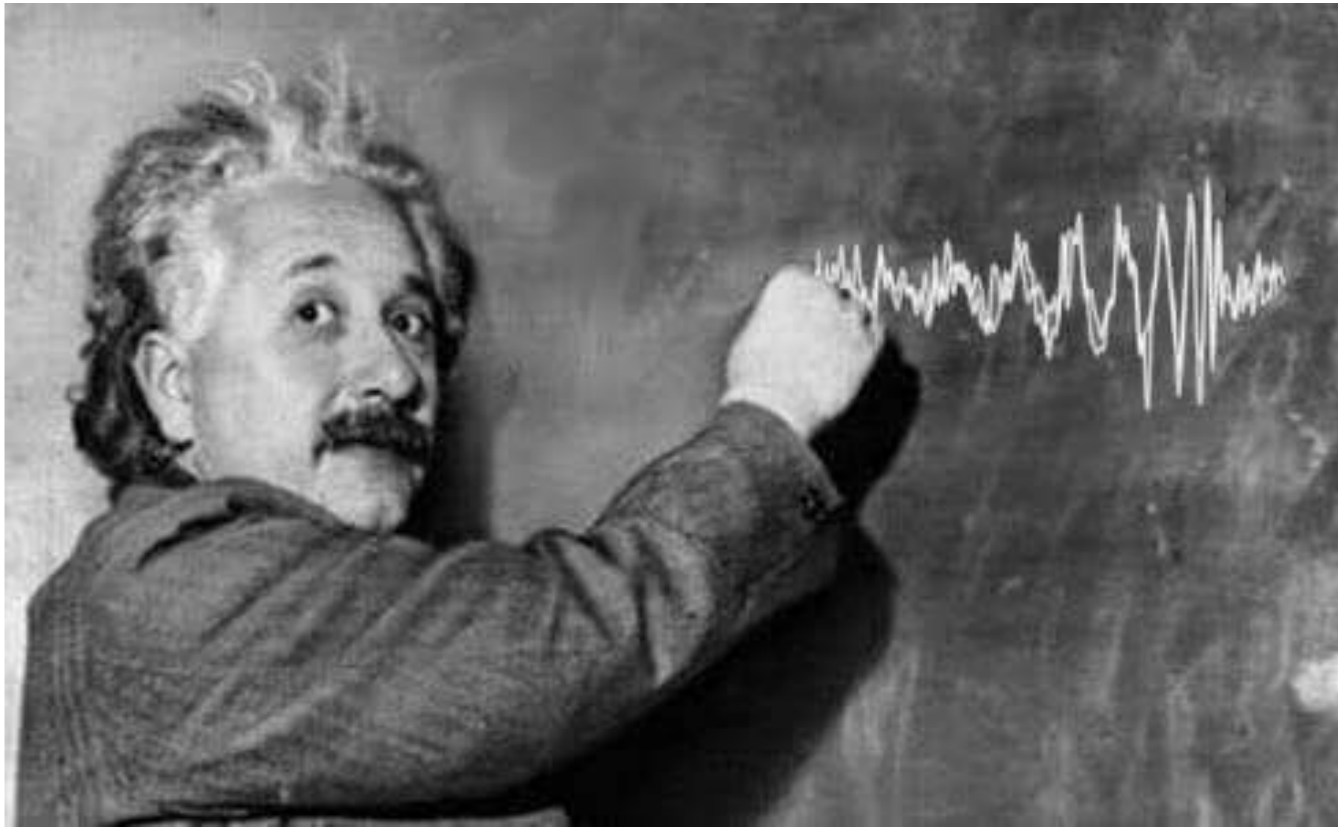
When the star is only 3 km across, the redshift from its surface is infinite: no light can escape at all.

The star has become a black hole.

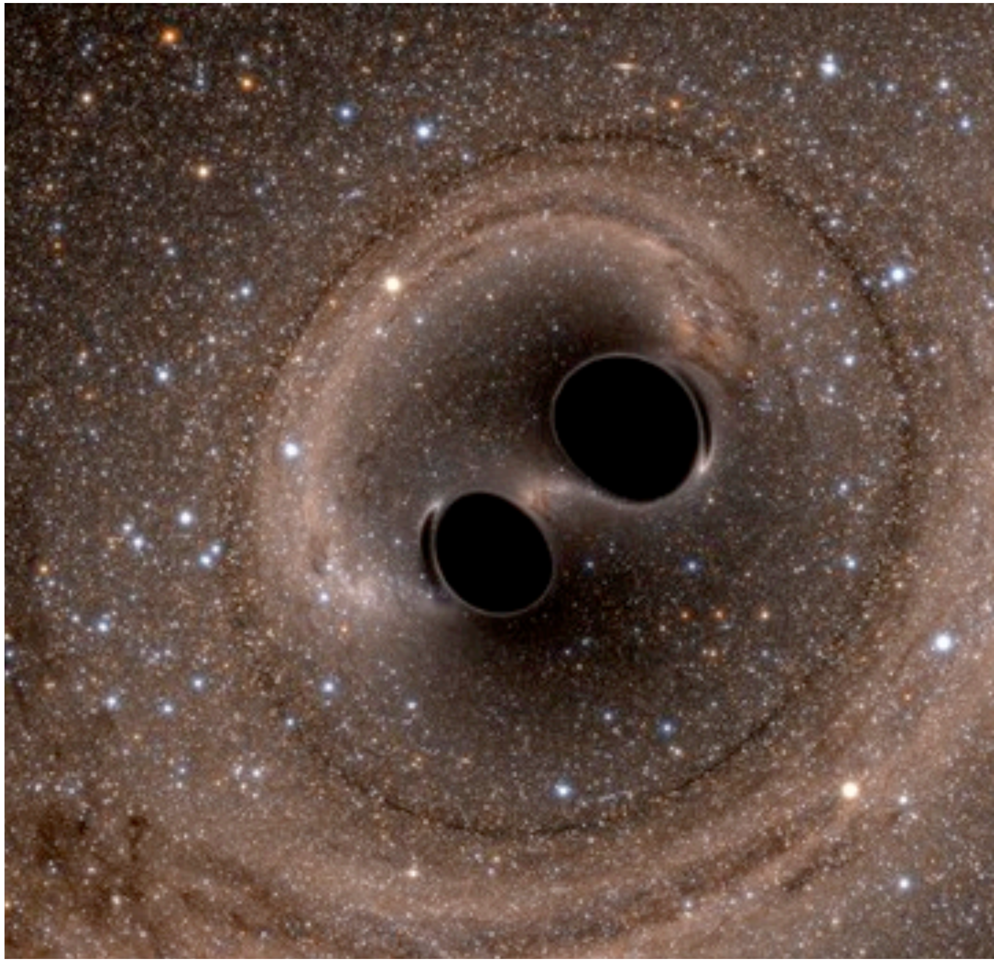
The “dent” in space-time is so deep that it forms a bottomless well.



Einstein also predicted that two masses orbiting each other would produce *gravitational waves* – ripples in space-time. These waves are strongest for very *heavy* objects orbiting very *close* to one another – so the "loudest" gravitational waves will come from the moments just before two black holes spiral together and merge.



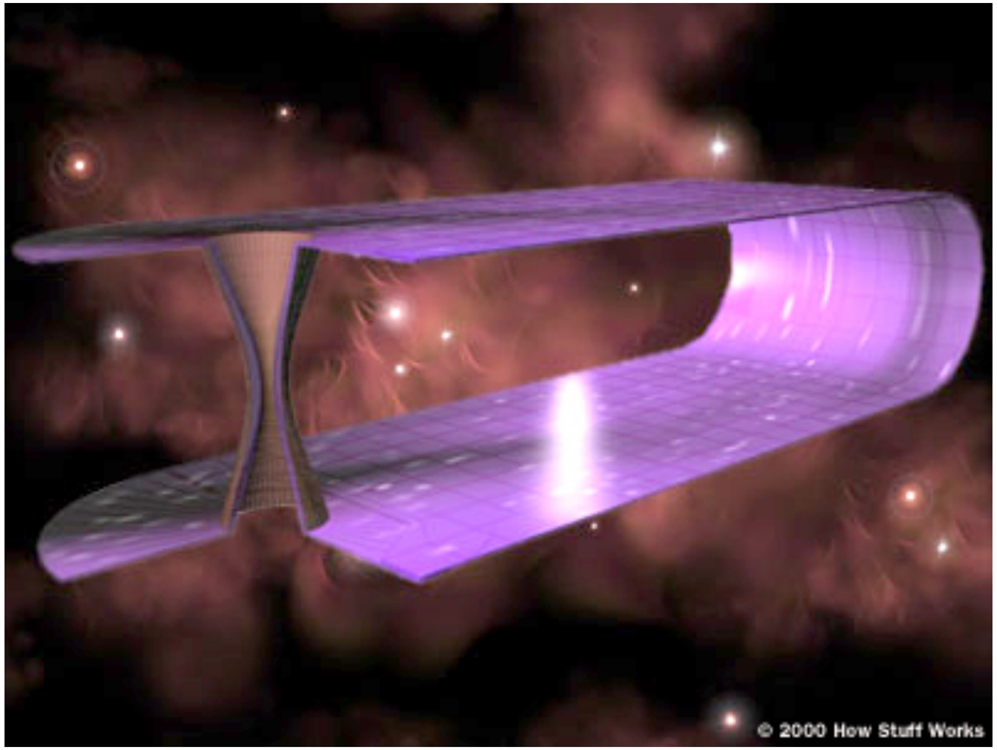
On 14 September 2015 a gravitational wave signal was detected by the two arms of the Laser Interferometer Gravitational-Wave Observatory (LIGO).



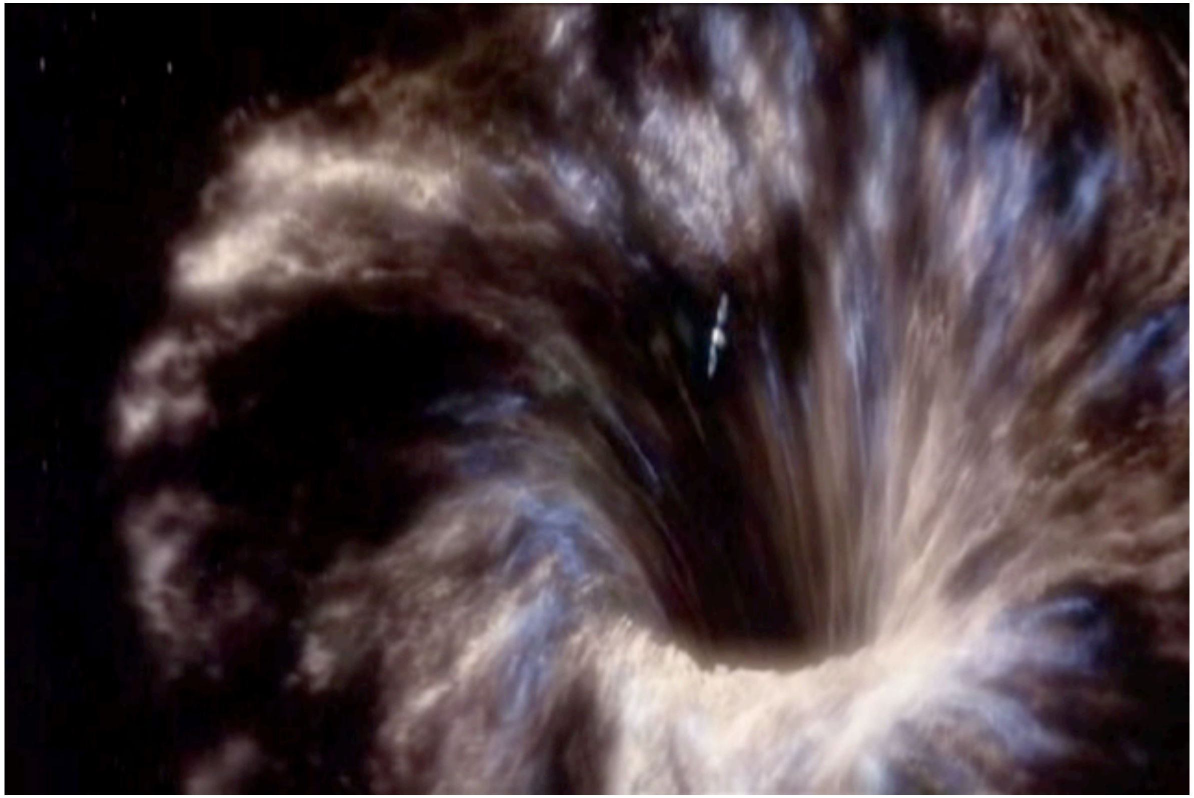
We'll talk about this event, and the birth of gravitational wave astronomy, in the last lecture.

And even stranger...

Some people suggest it could be possible for a black hole to join with a white hole (an anti-black hole) to form a wormhole, which could transfer matter billions of light years away.



Wormholes have become very popular in science fiction (*remember that distance problem*!). A wormhole would be *spherical* to our eyes: it only looks like a funnel to a hyperspace observer of a two-dimensional universe.



Next week

...we'll look at a whole grab-bag of things that we haven't touched on yet: binaries, clusters and variables.

We'll also be doing some star viewing from our new rooftop observatory

Further reading

- Jocelyn Bell Burnell's description of her discovery of pulsars is available on line, in the form of the transcript of an after-dinner speech she gave, at http://www.bigear.org/vol1no1/burnell.htm. There's a somewhat longer account at http://www3.interscience.wiley.com/cgi-bin/fulltext/118807400/PDFSTART (in PDF form)
- "**Cosmic Catastrophes: supernovae, gamma-ray bursts, and adventures in hyperspace**" by J. Craig Wheeler (Cambridge UP, 2000) is a wonderful description of the violent end of stars. He has a very good overview of stellar evolution first (this book could actually have been recommended for last week's lecture), and one of the best explanations (and use) of the "rubber sheet" diagrams which are so often used when talking about black holes. An excellent read, though not always easy.
- If you want to get really serious about black holes, you can't do better than "**Black Holes and Time Warps: Einstein's outrageous legacy**" by Kip Thorne (Picador, 1994). One of the world's leading black hole theorists, Thorne has written a book which starts with the discovery of black holes as a concept, and ends with really wild speculations about the possibilities for wormholes and time machines. It purports to be written for the layperson, but the concepts are so extreme that you shouldn't be put off if you don't get it all at once; it's seriously mind-blowing stuff.

- If you'd really like to get your mind around higher dimensions, you should start off with reading "**Flatland**" by Edwin Abbott. Written in 1880, it's about a two-dimensional being who gets to experience life in three-dimensional space. A. K. Dewdney (who wrote a mathematics column for Scientific American for some years) wrote a similar book called "**The Planiverse**". Both of these books give insight into what exactly a higher dimension, outside current experience, would mean. Not one, but two movies were recently made about Abbot's book: I have "**Flatland the Movie**" (to distinguish it from "**Flatland the Film**" (!)), and it's very enjoyable. Short, too: only 35 min long.
- There's an excellent site on general relativity at "**Spacetime Wrinkles**" at the National Center for Supercomputing Applications, http://archive.ncsa.uiuc.edu/Cyberia/NumRel/NumRelHome.html. It has lots of stuff we didn't have time to discuss, including discussion about gravitational waves and how to detect them, and illustrations of how light gets bent near a black hole.
- NASA has a nice booklet for teachers about black holes: "**The Anatomy of Black Holes**" http://imagine.gsfc.nasa.gov/educators/blackholes/imagine/cover.html.
- We didn't get into the question of what happens if you fall into a black hole, etc. Check out the animations at "**Inside Black Holes:** What really happens inside black holes?" http://jila.colorado.edu/~ajsh/insidebh/
- The story of the Sco X-1 and the start of X-ray astronomy is told at "**The Story of SCO X1: Days and Rockets in the White Sands**" http://chandra.harvard.edu/xray_sources/sco/sco1.html

Sources for images used:

- Gravitational waves: from "Gravitational Waves: The Big Bang's Smoking Gun", http://www.space.com/25088-gravitational-waves.html
- Optical image of Sirius: from Stars and Galaxies by Richard McCray, http://cosmos.colorado.edu/stem/courses/ASTR1120-3/documents/chapter5/lesson5.html; Chandra X-ray image from Astronomy Picture of the Day, 2000 October 6, http://apod.nasa.gov/apod/ap001006.html
- Sizes of white dwarfs: from Wikipedia http://en.wikipedia.org/wiki/White_dwarf
- NGC 2440 and its white dwarf: from Astronomy Picture of the Day, 2004 January 11, http://apod.nasa.gov/apod/ap040111.html
- HR diagram: from Explorations: an Introduction to Astronomy by Thomas Arny, Fig. 12.17, http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch12/1217.html
- Crystallised white dwarf: from "Diamond in the Sky" by Travis Metcalfe, http://cfa-www.harvard.edu/~tmetcalfe/diamond.html
- X-ray binary: from http://xraypulsars.aip.de/
- "Neutron Star" by Larry Niven: cover of edition by Ballantine Books (1989)
- Jocelyn Bell at Mullard Observatory: from http://cosmos.colorado.edu/cw2/courses/astr1120/text/chapter7/Bell.html
- Pulsar "scruff": from "A Tutorial on Radio Pulsars" by Jon Bell, http://www.jb.man.ac.uk/~pulsar/Education/Tutorial/tut/node3.html
- Rotating pulsar: from Pulsar beacon animation, http://www.amherst.edu/~gsgreenstein/progs/animations/pulsar_beacon/
- Crab Pulsar: from "Optical images of the Crab Pulsar" from the SEDS M1 page: http://www.seds.org./messier/more/m001_pulsar.html
- Pulsar radiation: from Astronomy 122: Birth and Death of Stars by Jim Schombert, Lecture 16: Neutron stars http://zebu.uoregon.edu/~js/ast122/lectures/lec16.html
- Aerobee rocket launch: from Space Race, http://www.nasm.si.edu/exhibitions/gal114/SpaceRace/sec200/sec231.htm
- First X-ray source discovered: from the original paper by Giacconi et al. 1962, "Evidence for Rontgen-rays from sources outside the solar system", Phys. Rev. Lett. 9, 439
- Optical ID of Sco X-1: from original paper by Sandage et al. 1966, "On the optical identification of Sco X-1", Ap. J. 146, 316.
- Images of the X-ray and optical sky: from Five Years of ROSAT, http://wave.xray.mpe.mpg.de/rosat/five_years/survey
- HEAO X-ray source catalogue: from Chandra resources, http://chandra.harvard.edu/resources/illustrations/heaoA1.html
- Comparison of Aldebaran with the Sun: from Astronomy 122: Birth and Death of Stars by Jim Schombert http://abyss.uoregon.edu/~js/ast122/lectures/lec09.html
- Rubber sheet diagram: from "Zero Point Energy and Relativity" http://www.setterfield.org/ZPE_and_relativity/ZPE_and_Relativity.html
- Material falling around: from Flannery 1975, "The location of the hot spot in cataclysmic variable stars as determined from particle trajectories", MNRAS 170, 325
- Artist's impression of an accretion disk: from Astronomy Picture of the Day 1999 December 19, http://apod.nasa.gov/apod/ap991219.html
- Pulsar: from "Astronomical whirling dervishes hide their age well" http://www.astronomynow.com/090610Astronomicalwhirlingdervisheshidetheiragewell.html
- Binary pulsar: from http://astrosun.tn.cornell.edu/courses/astro201/psr1913.htm
- Black widow pulsar: from Chandra Photo Album, http://chandra.harvard.edu/photo/2003/b1957/index.html
- Animation of the formation of a millisecond pulsar: from RXTE: Snazzy Science http://heasarc.gsfc.nasa.gov/docs/xte/Snazzy/Movies/millisecond.html

- Double pulsar image and animations: from "First-known double pulsar opens up new astrophysics", Jodrell Bank Press Release 2004/01, http://www.jb.man.ac.uk/news/doublepulsar/
- Black hole image: from APOD 2014 October 26 http://apod.nasa.gov/apod/ap141026.html
- Velocity of companion to A0620–00: from original paper by Johnston, Kulkarni and Oke 1989, ApJ 345, 492
- Supermassive black hole: painting by Don Dixon http://cosmographica.com/gallery/portfolio/portfolio301/pages/326-QuasarB.htm . Artwork copyright 2003 by Don Dixon/cosmographica.com, used with permission.
- Michelson interferometer: from http://blitiri.blogspot.com.au/2013/10/coherence-3-michelson-interferometer.html
- Einstein: from Fermilab Today http://www.fnal.gov/pub/today/archive/archive_2014/today14-04-18_NutshellReadMore.html
- Spacetime curvature: painting by Mark Garlick, from "Putting Einstein to the Test" http://scienceblogs.com/startswithabang/2013/05/01/putting-einstein-to-the-test/
- Eclipse test of GR: from "Out with a Bang": a web version of the VSU planetarium show presented in April 2001, http://www.valdosta.edu/phy/astro/pl_shows/bh_2001/bh/index.html
- Gravitational lensing in the galaxy cluster Abell 2218: from Astronomy Picture of the Day, 2001 October 7 http://apod.nasa.gov/apod/ap011007.html
- Cluster CL0024+1654: Hubble image, from APOD 2015 August 23, http://apod.nasa.gov/apod/ap150823.html
- "Rubber sheet" diagram: from "Spacetime Wrinkles: General Relativity" http://archive.ncsa.uiuc.edu/Cyberia/NumRel/GenRelativity.html
- Parallel lines: from https://en.wikipedia.org/wiki/General_relativity#/media/File:Spacetime_curvature.png
- Radius vs circumference in a warped sheet: redrawn from "Cosmic Catastrophes" by J. Craig Wheeler, Figure 9.6
- Shapiro delay: from "Astronomers Weigh "Recycled" Millisecond Pulsar", NRL Press Release 2-06r http://www.nrl.navy.mil/pressRelease.php?Y=2006&R=2-06r
- Gravity waves: from "Explorations: an Introduction to Astronomy" by Thomas Arny, Fig. 14.16 http://www.mhhe.com/physsci/astronomy/arny/instructor/graphics/ch14/1416.html
- Gravitational redshift: from "Spacetime Wrinkles: Putting Relativity to the Test" http://archive.ncsa.uiuc.edu/Cyberia/NumRel/EinsteinTest.html
- Squashing a star: from "The Anatomy of Black Holes", http://imagine.gsfc.nasa.gov/docs/teachers/blackholes/imagine/contents.html
- Wormhole: from "How Stuff Works: How time travel will work" by Kevin Bonsor http://www.howstuffworks.com/time-travel.htm
- Binary stars: from "How To Find A Binary System's Habitable Zone" http://www.iflscience.com/space/how-find-binary-stars-habitable-zone