Lives of the Stars Lecture 8: Stellar graveyards

– *white dwarfs, neutron stars and black holes*

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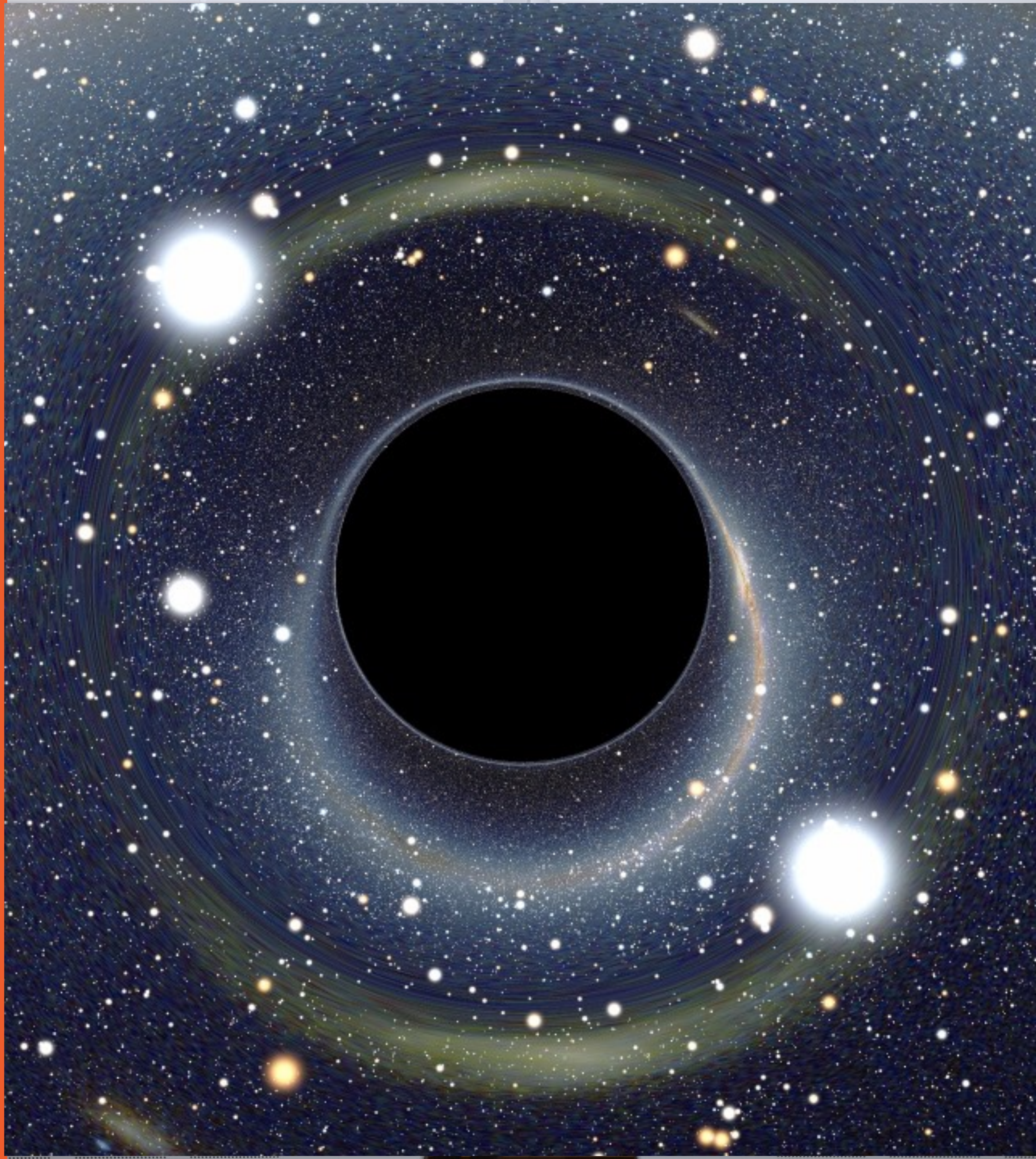
THE UNIVERSITY OF SYDNEY



In tonight's lecture

- white dwarfs
  - *the end-point for low- and intermediate mass stars*
- neutron stars
  - *the end-point for high-mass stars*
- Black holes
  - *the end of the highest-mass stars?*

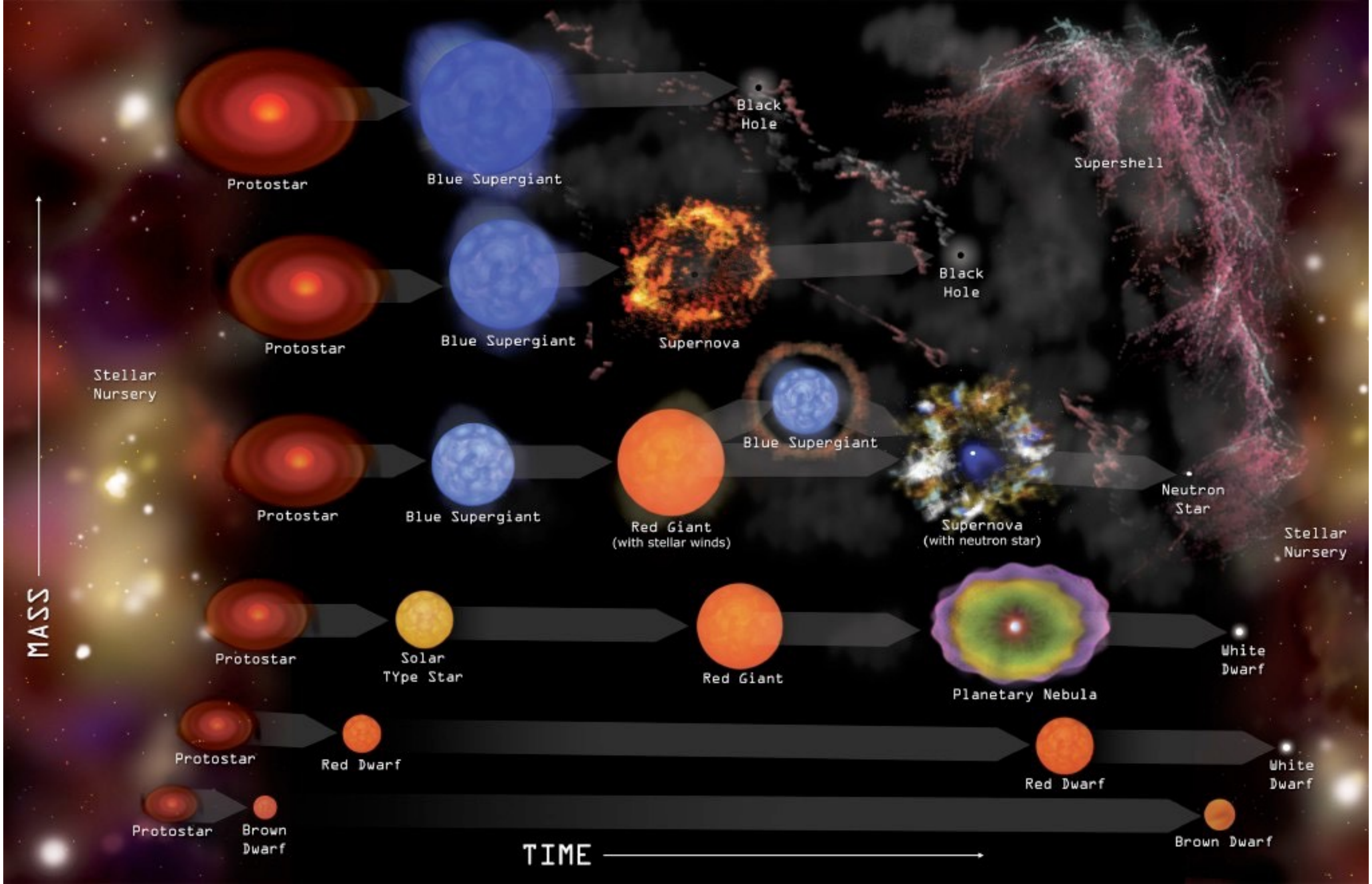
After the end

We have discussed in great detail how stars live and evolve, and how they end their lives. This lecture, we're going to look at the remnants that are left after a star finishes its evolution, the truly stable states of a star's existence.

The end-state that a star reaches depends on its mass. Roughly speaking, they are:

- less than ~8 solar masses: white dwarf
- 8– ?25? solar masses: neutron star
- more than ?25? solar masses: black hole

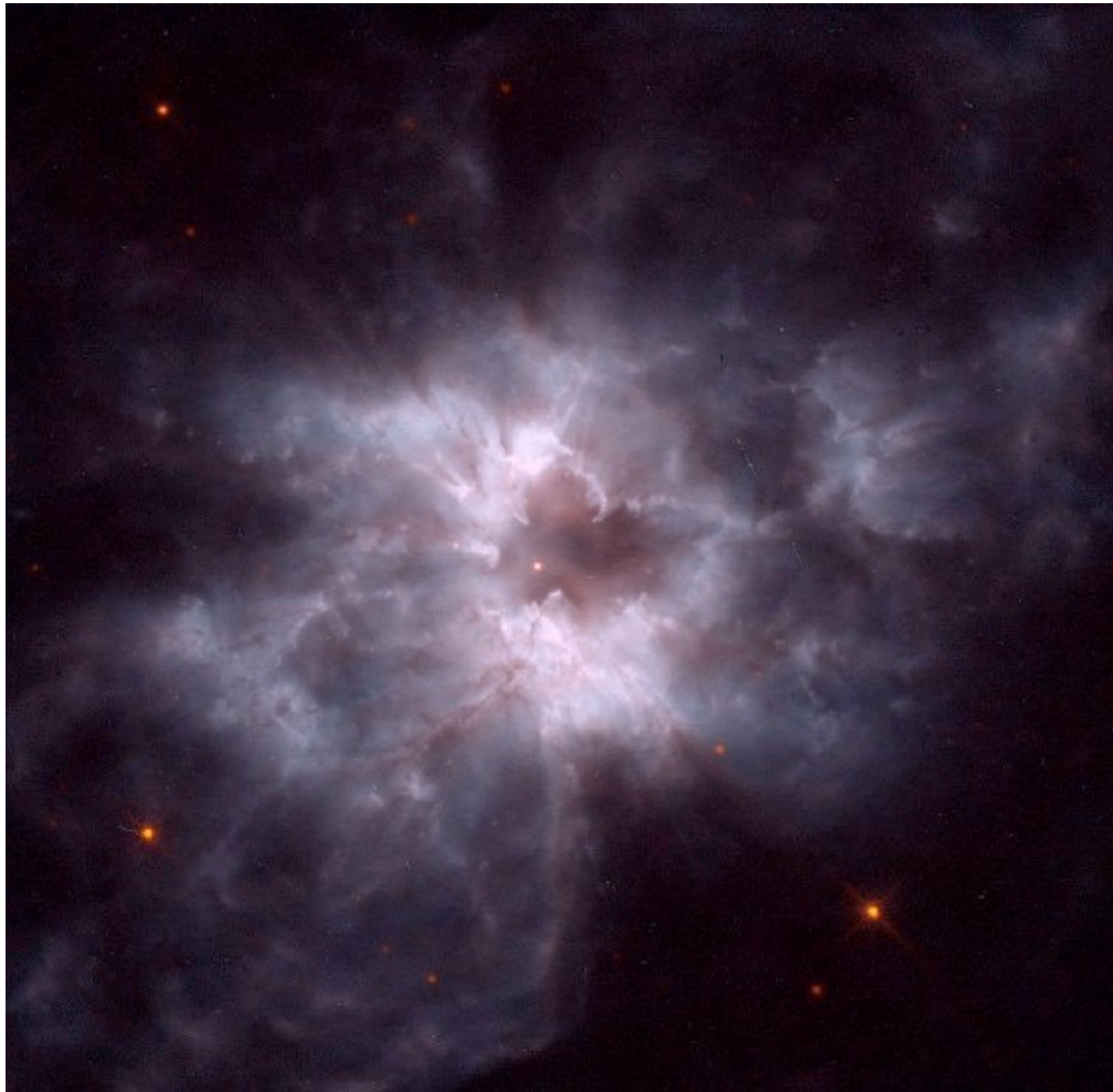
This is illustrated in the following diagram.


Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
TIME

White dwarfs

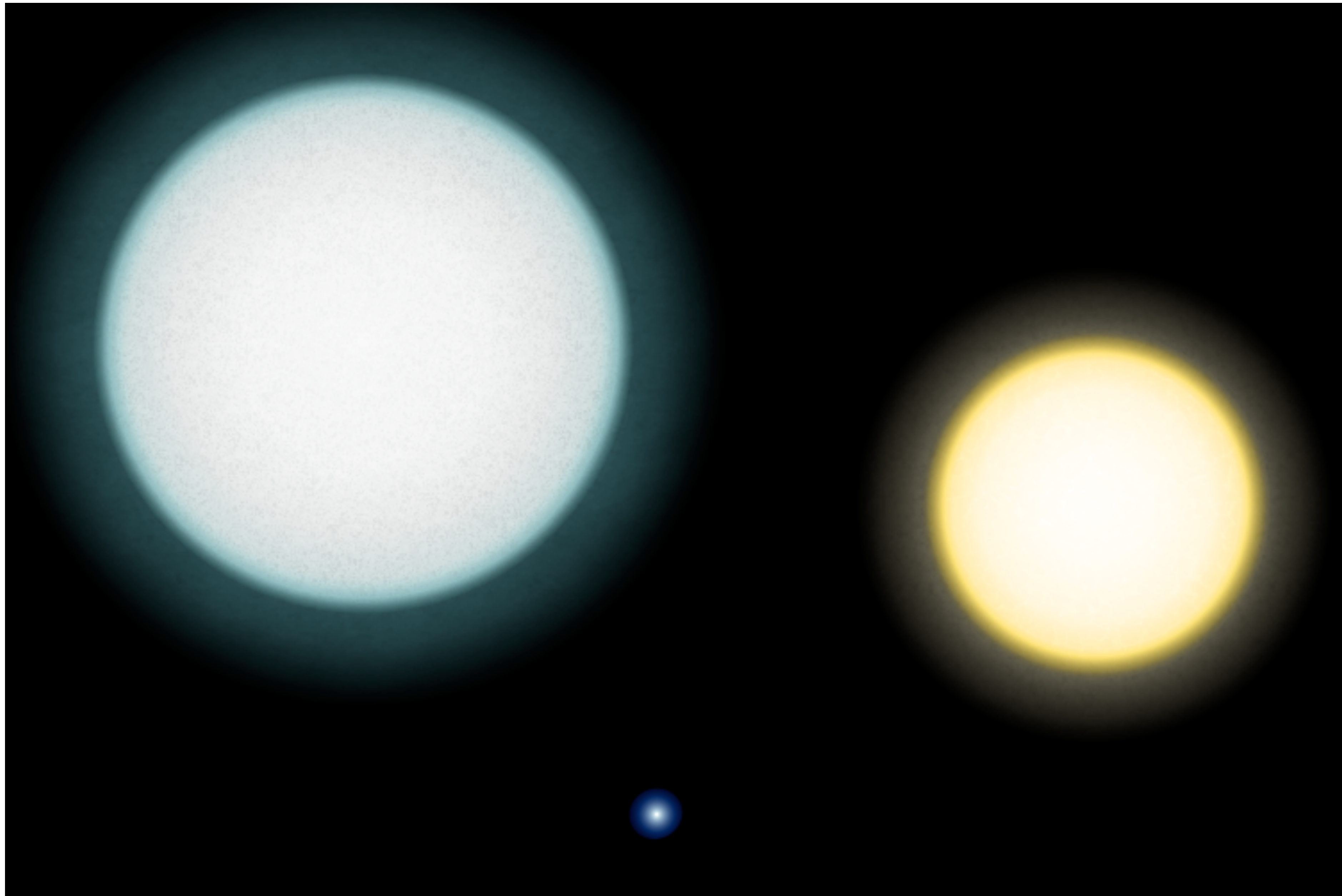
It is estimated that there are about 35 billion white dwarfs in the Galaxy, possibly as many as 100 billion. They are by far the most common stellar remnant in the Galaxy. However, they are hard to find because they are so faint.

As we have seen, white dwarfs are the end-points of evolution for stars like the Sun, left behind after a spectacular planetary nebula is ejected.



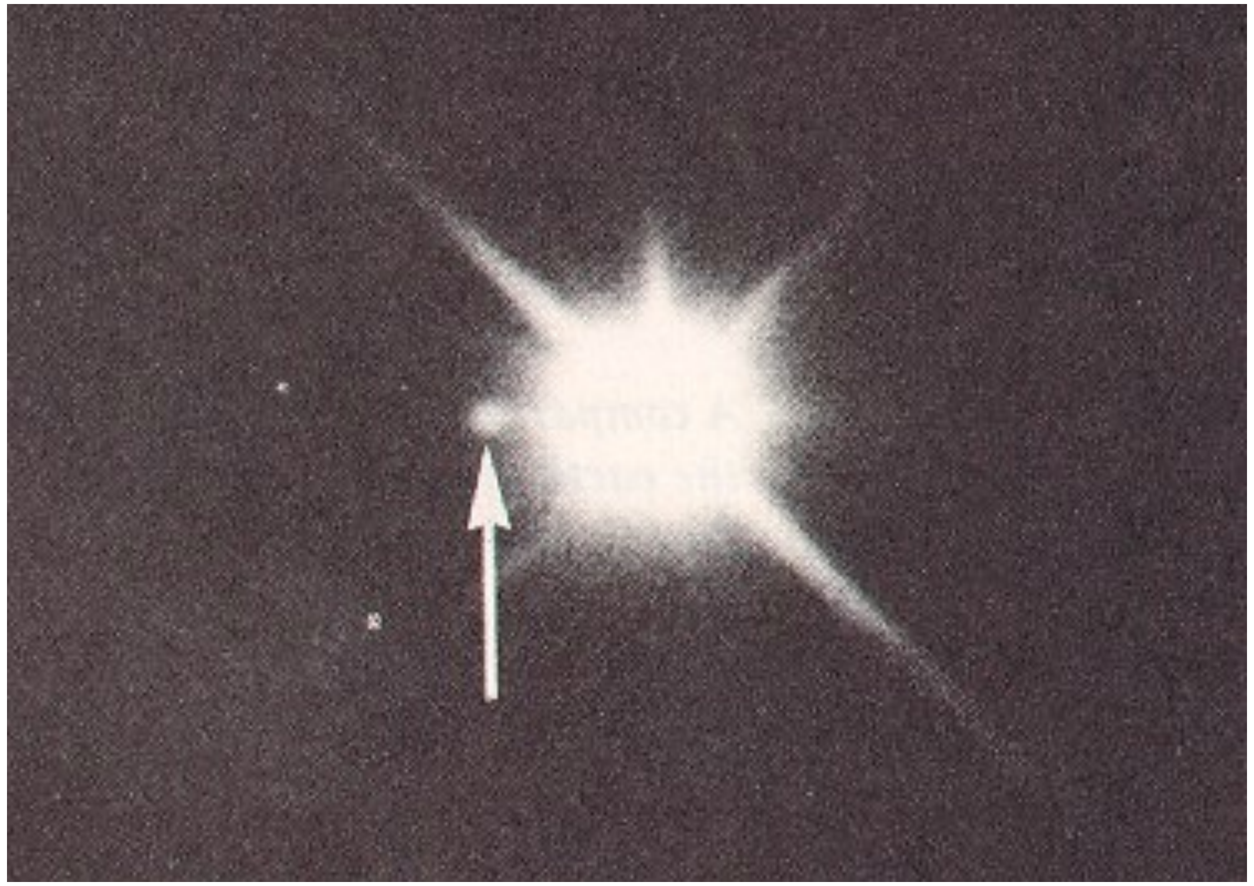
HST image of NGC 2440; the white dwarf, visible at the centre, is one of the hottest white dwarf stars known.

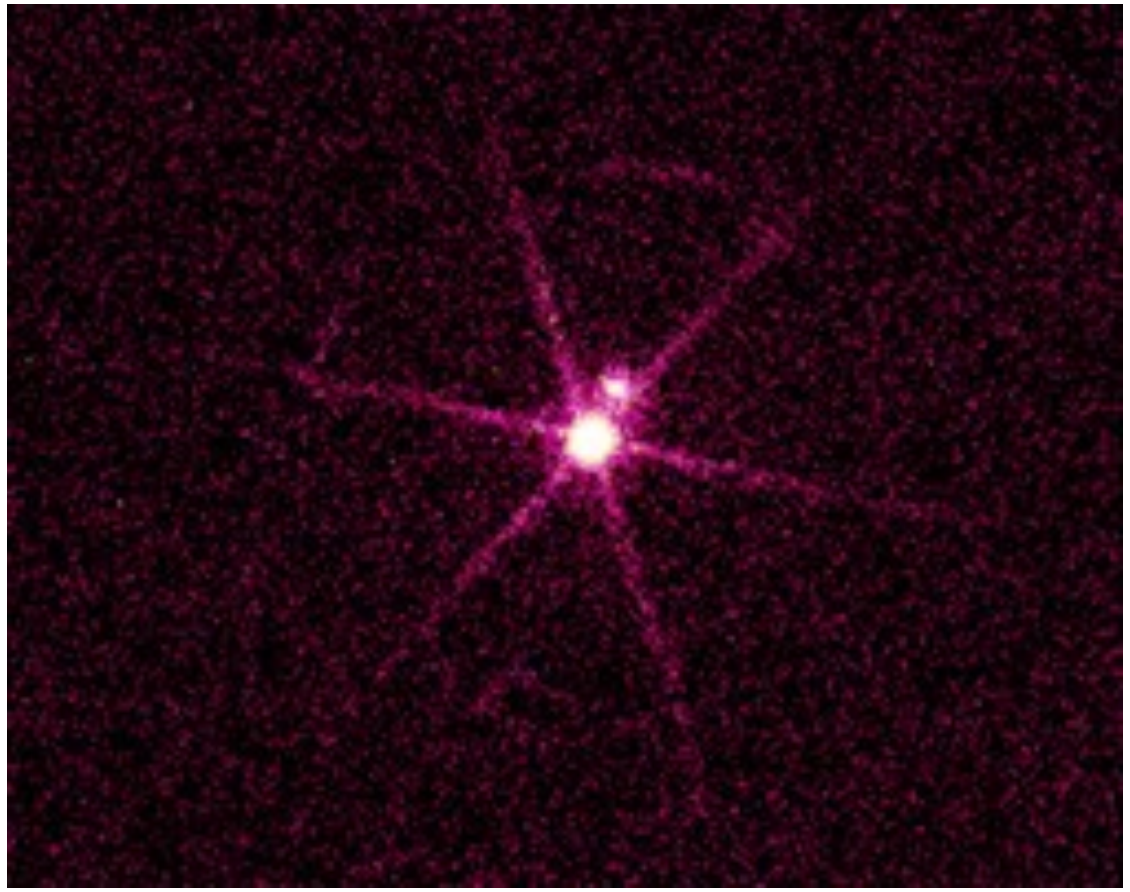
White dwarfs have radii between 0.8% and 2% of the size of the Sun, comparable to the size of the Earth.



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

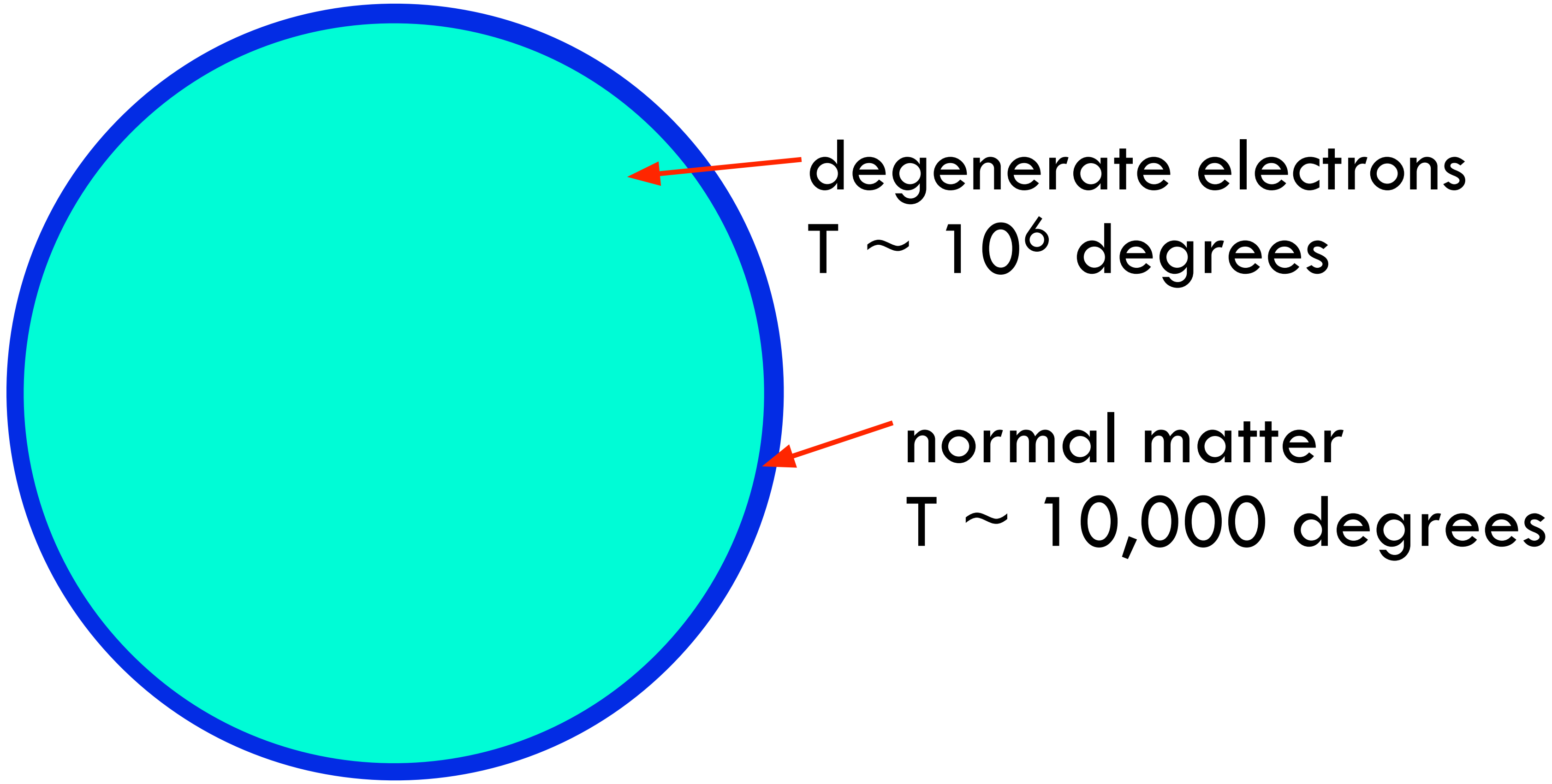
The most famous white dwarf, and the first to be discovered, is Sirius B.





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.

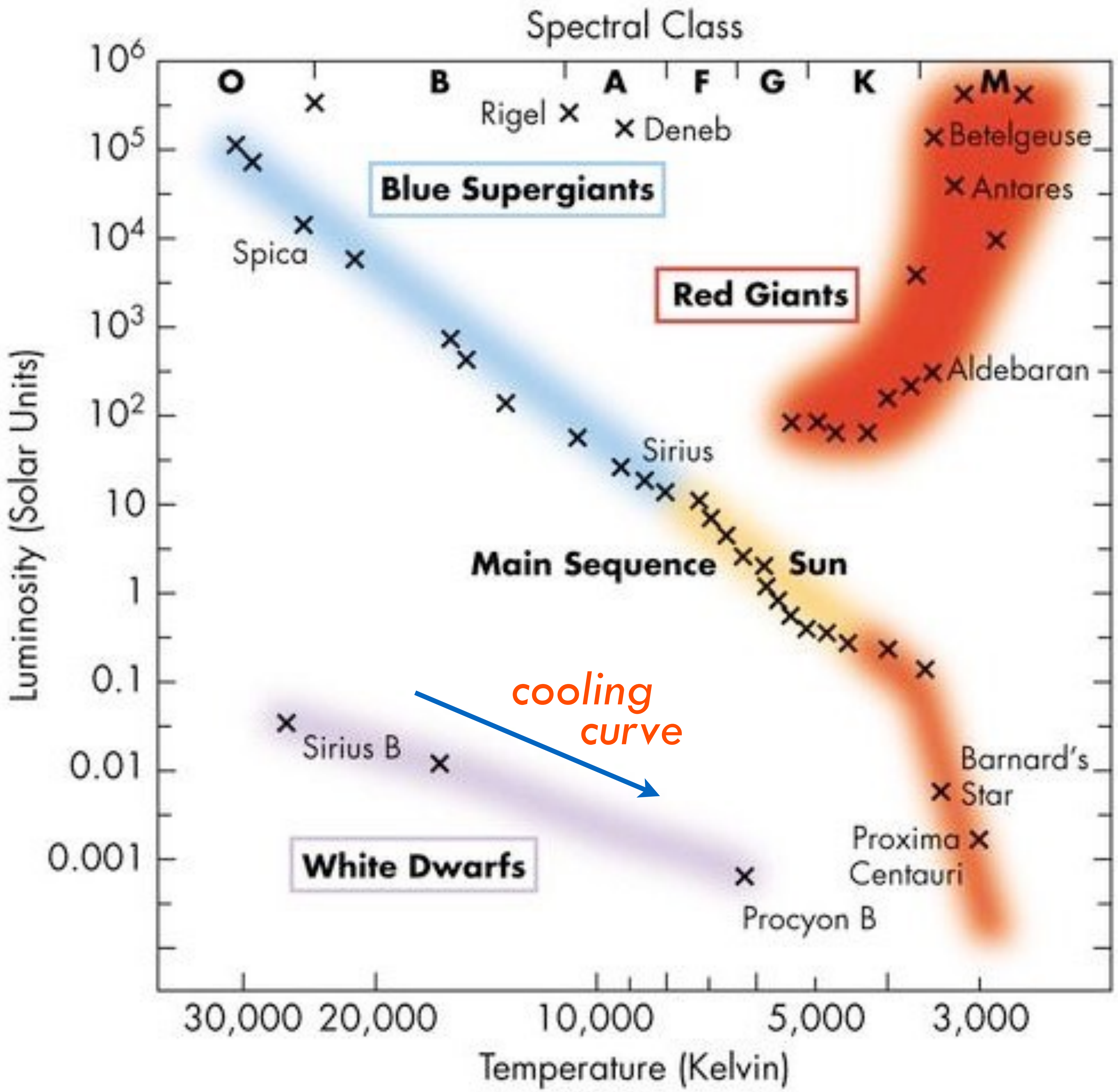
The structure of a white dwarf is extremely simple. As we have discussed, it is held up by the quantum pressure of degenerate electrons. The electrons are excellent conductors, so the interior has an almost uniform temperature throughout its whole volume, which is about the size of the Earth.



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.

At first the interior of the white dwarf is so hot that any remaining hydrogen and helium is rapidly fused to carbon and oxygen. These reactions generate large numbers of neutrinos, which drain the star of energy and allow it to cool rapidly.

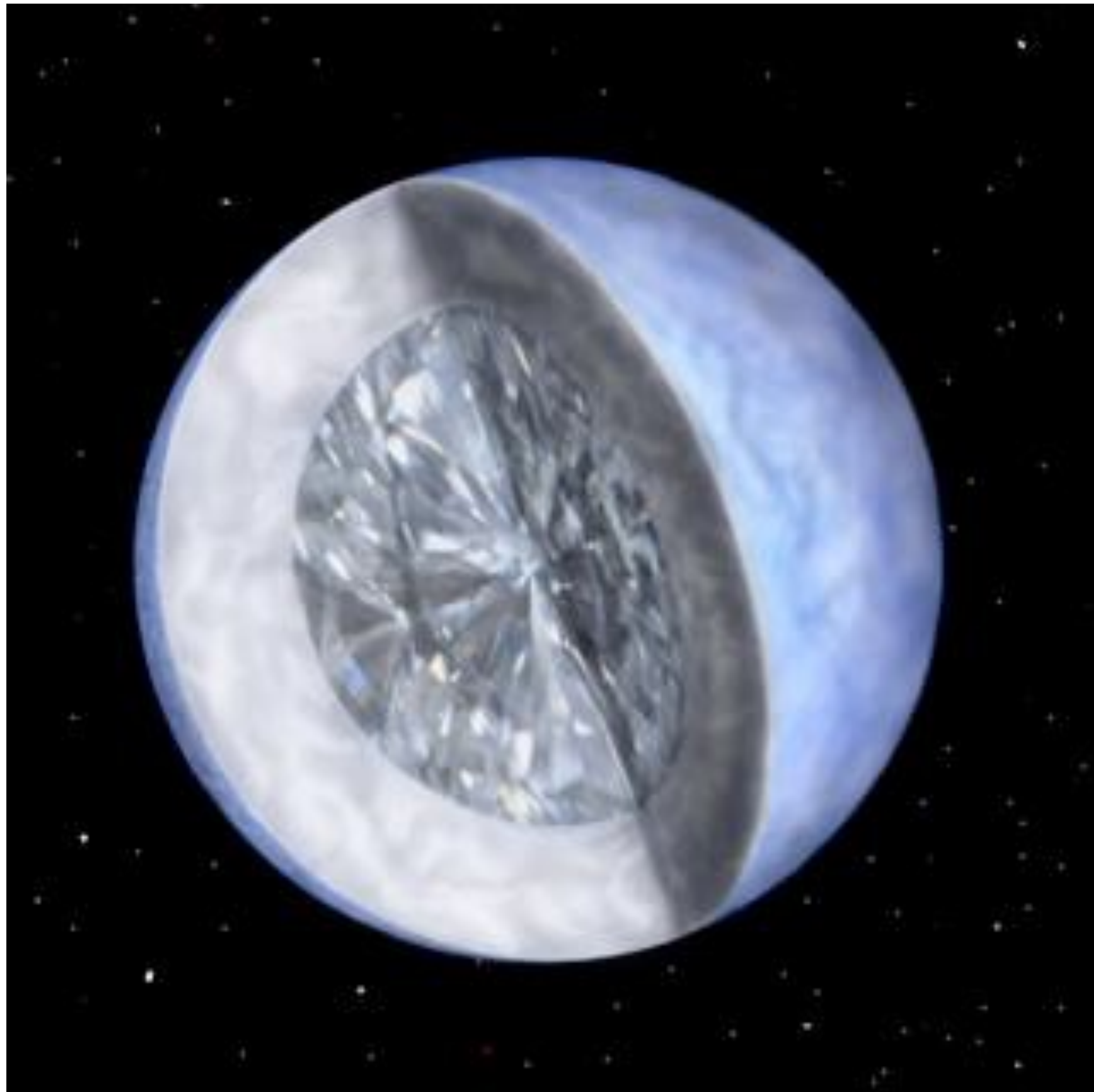
After about 10 million years, the interior has cooled to about 30,000 K and is no longer producing neutrinos. Now the star can cool only by radiation, and the effective insulation of the surface layer means that the time taken is extremely long: billions of years. The oldest white dwarfs in our Galaxy have only reached 3500 K – a bit cooler than the Sun.



The white dwarf sequence in the Hertzsprung-Russell diagram is basically a *time* sequence: as white dwarfs age and cool, they move down and to the right.

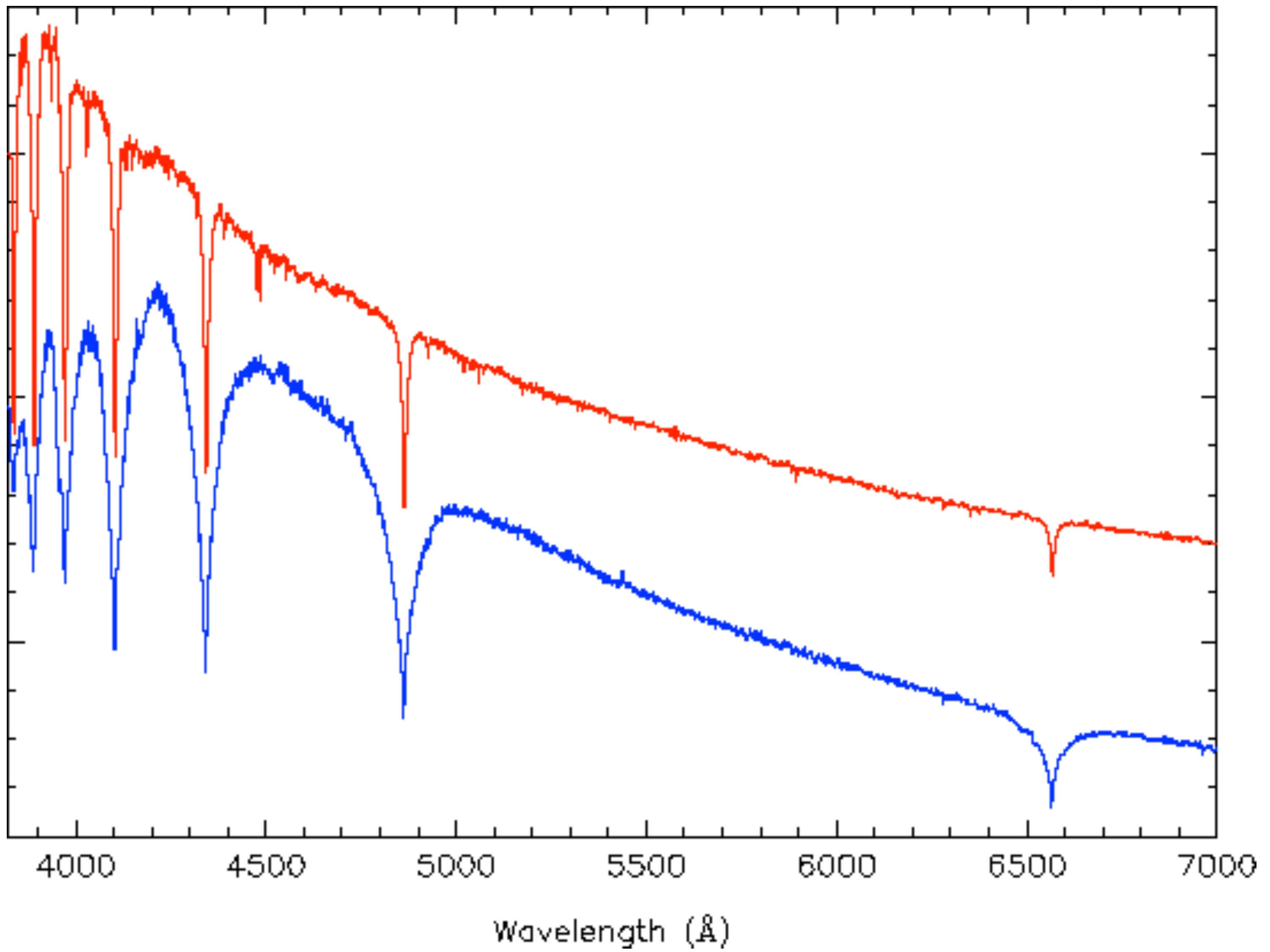
As they cool down, white dwarf cores eventually crystallise, with the nuclei (mostly carbon) forming a lattice surrounded by a sea of electrons.

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.

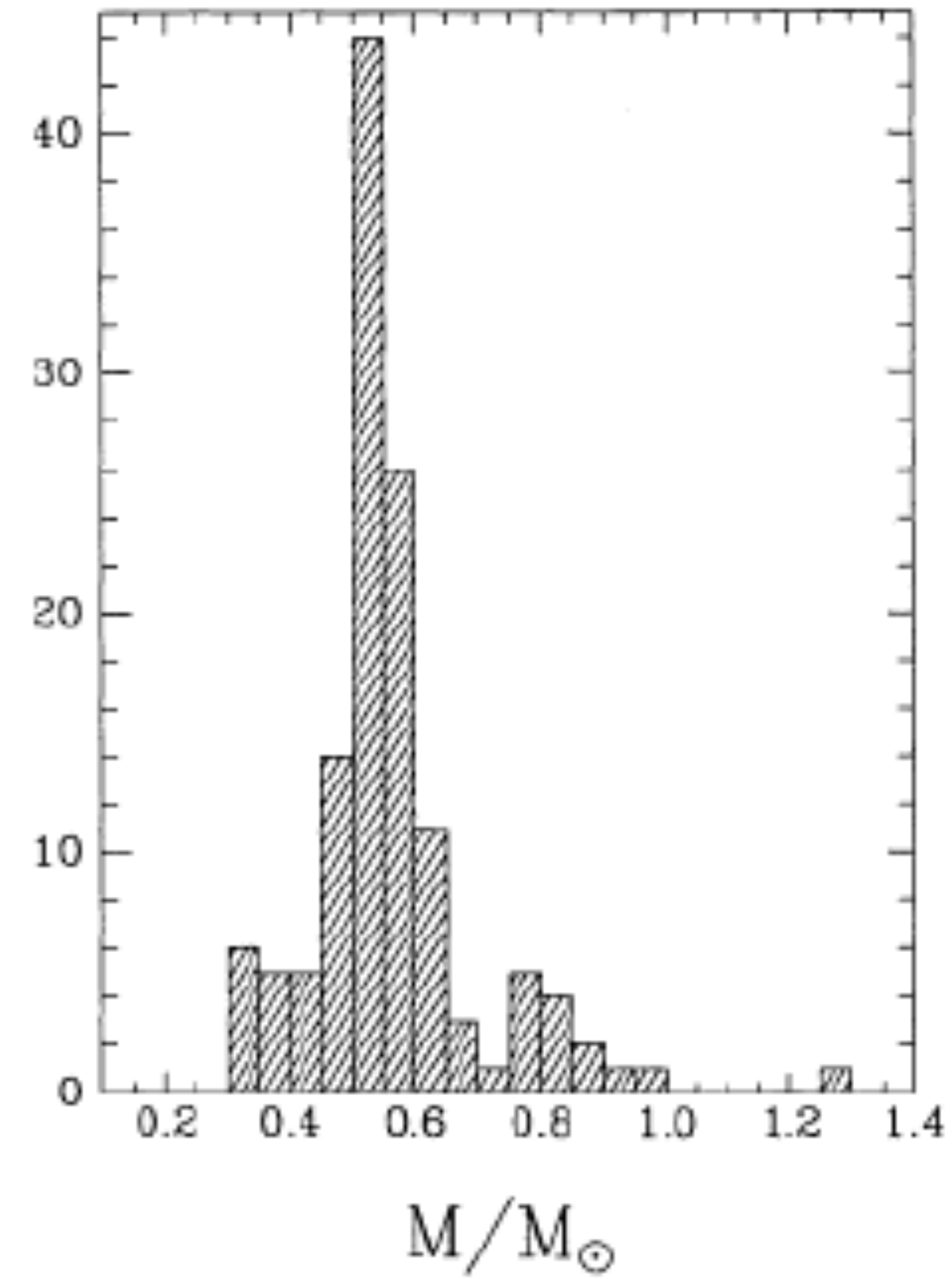


The media reported this as “a 10 billion trillion trillion carat diamond”.

The spectra of white dwarfs typically show only one element: usually hydrogen, but helium in about 20% of stars. The huge gravity at the surface means that heavier elements diffuse downwards in very short times (decades). The lines are extremely broad, because of the high surface gravity: we can measure the gravity from the shapes of the lines.

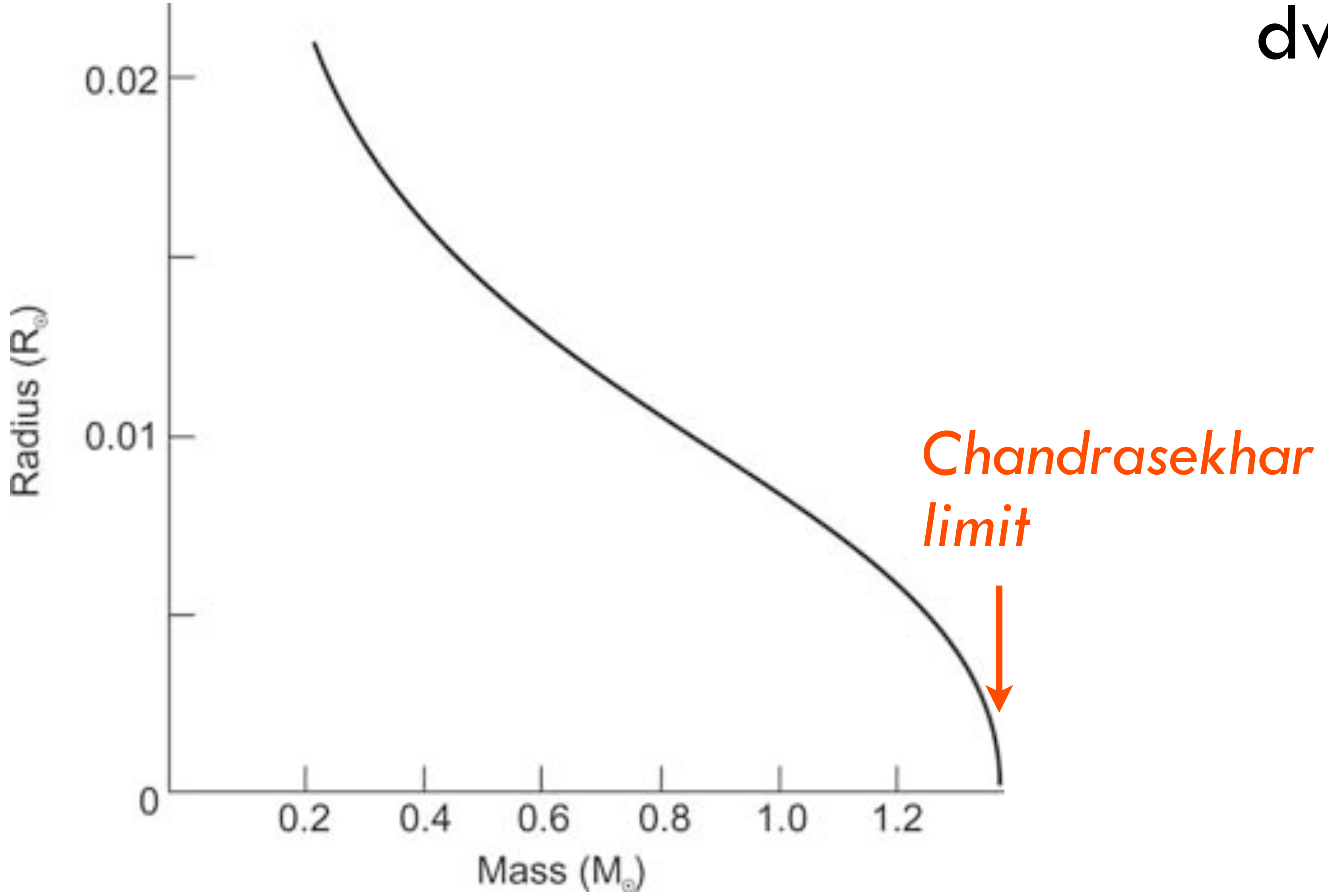


The spectrum of a white dwarf (top) compared to the spectrum of an A type star of similar temperature. The white dwarf lines are much broader, and show only lines of hydrogen.



Knowing the surface gravity, we can determine the mass of the star. The masses of white dwarfs are usually around 0.6 solar masses, with some smaller and some larger. This distribution of masses is still not well understood.

However, the most astonishing thing about white dwarfs is the relationship between mass and radius. Unlike main sequence stars, where adding mass increases the size of the star, increasing the mass of a white dwarf *decreases* the size. At a mass of 1.4 solar masses, the radius would shrink to zero: this is the upper limit to the mass of a white dwarf, the *Chandrasekhar limit*.

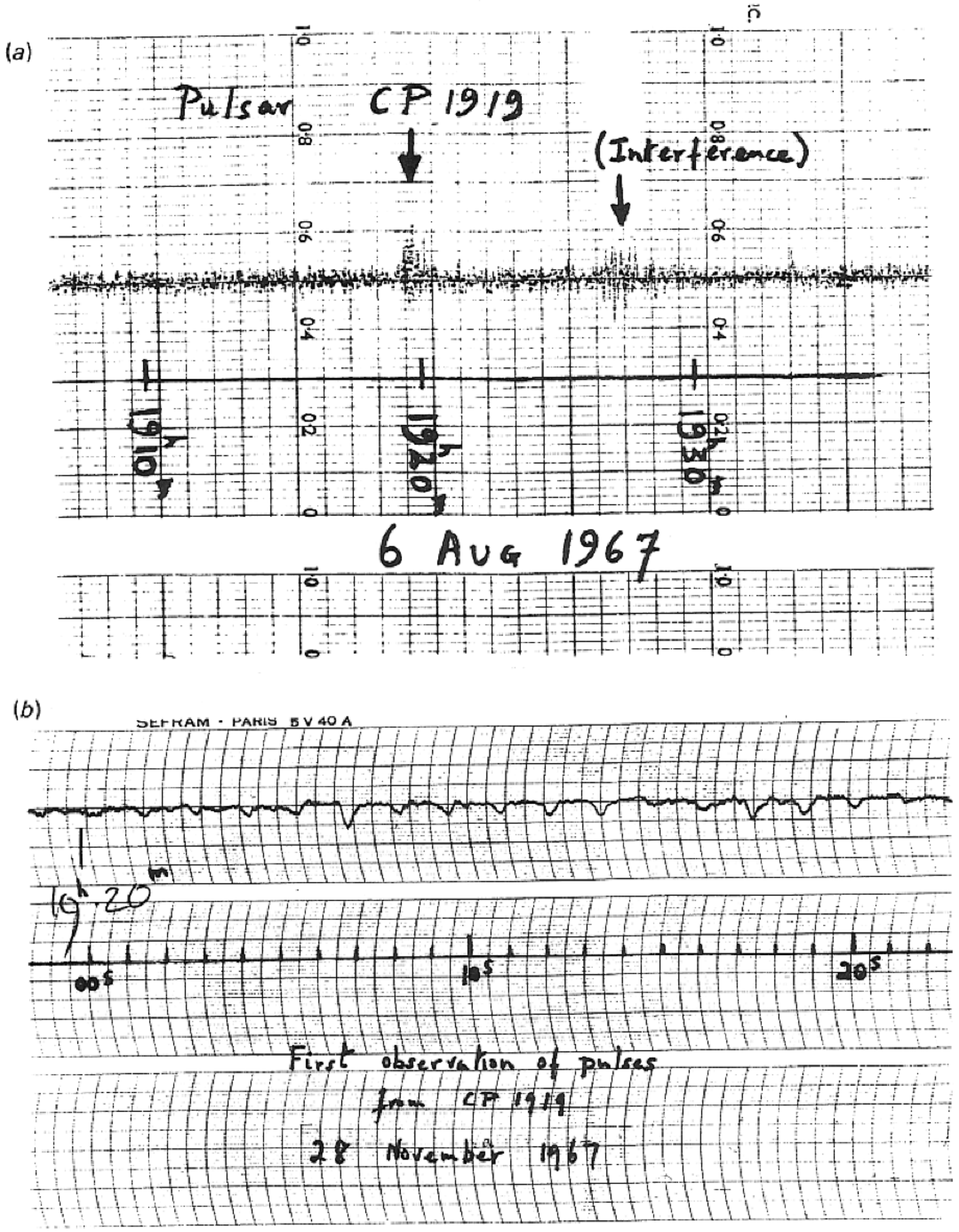


Neutron stars

We have already discussed what happens when a white dwarf exceeds the Chandrasekhar mass. The degenerate pressure which is holding the star up against gravity breaks down, and the star collapses to a neutron star (or, in the case of a Type I thermonuclear supernova, blows itself to smithereens).

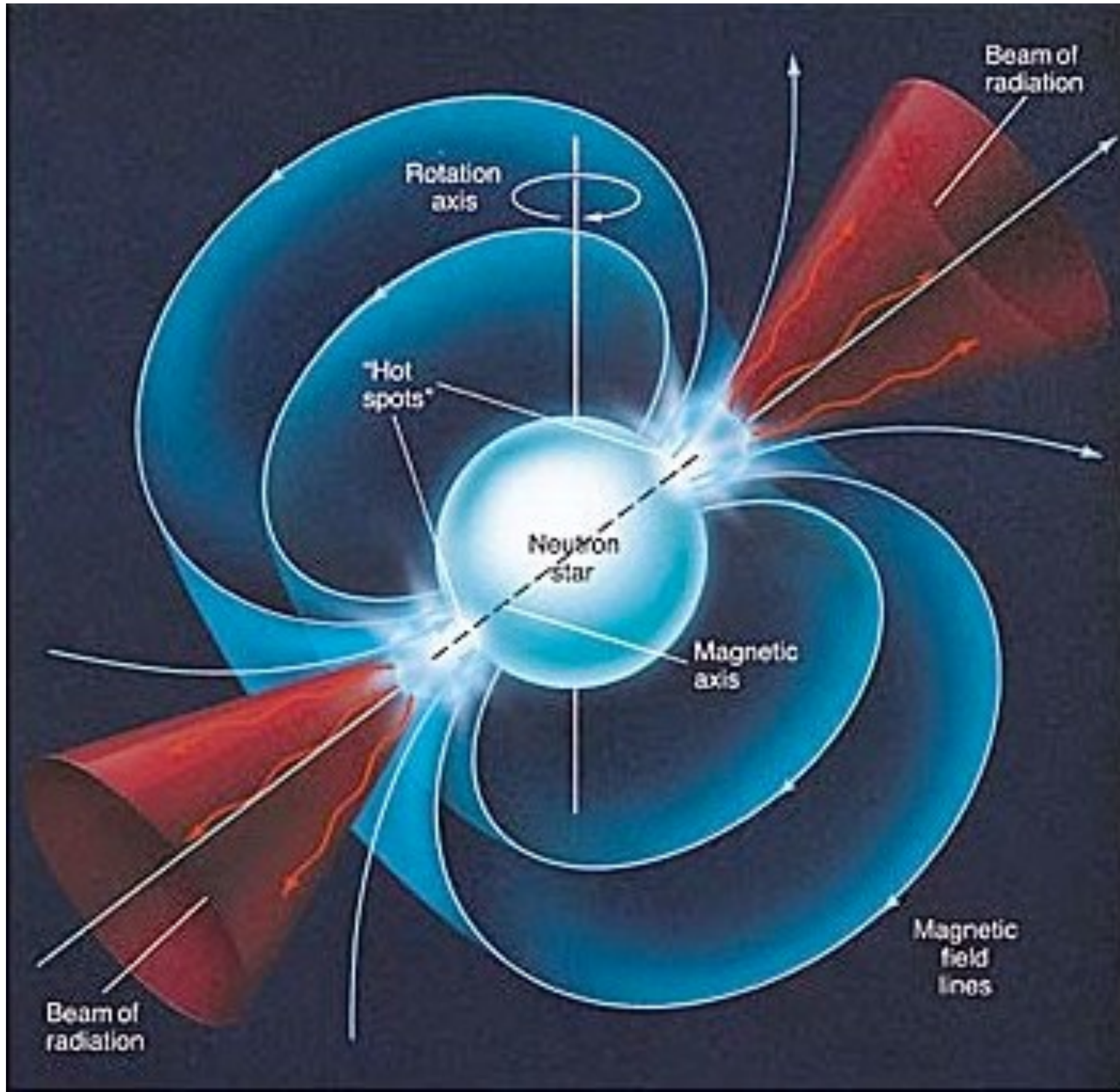
Neutron stars were actually predicted theoretically long before they were eventually observed.

Their detection was a surprise: sources of rapid radio pulsations called *pulsars*.



Jocelyn Bell (First pulsar detection, 1967). The first pulsar appeared as "scruff", but a higher-speed chart recording showed it was actually a regular series of pulses.

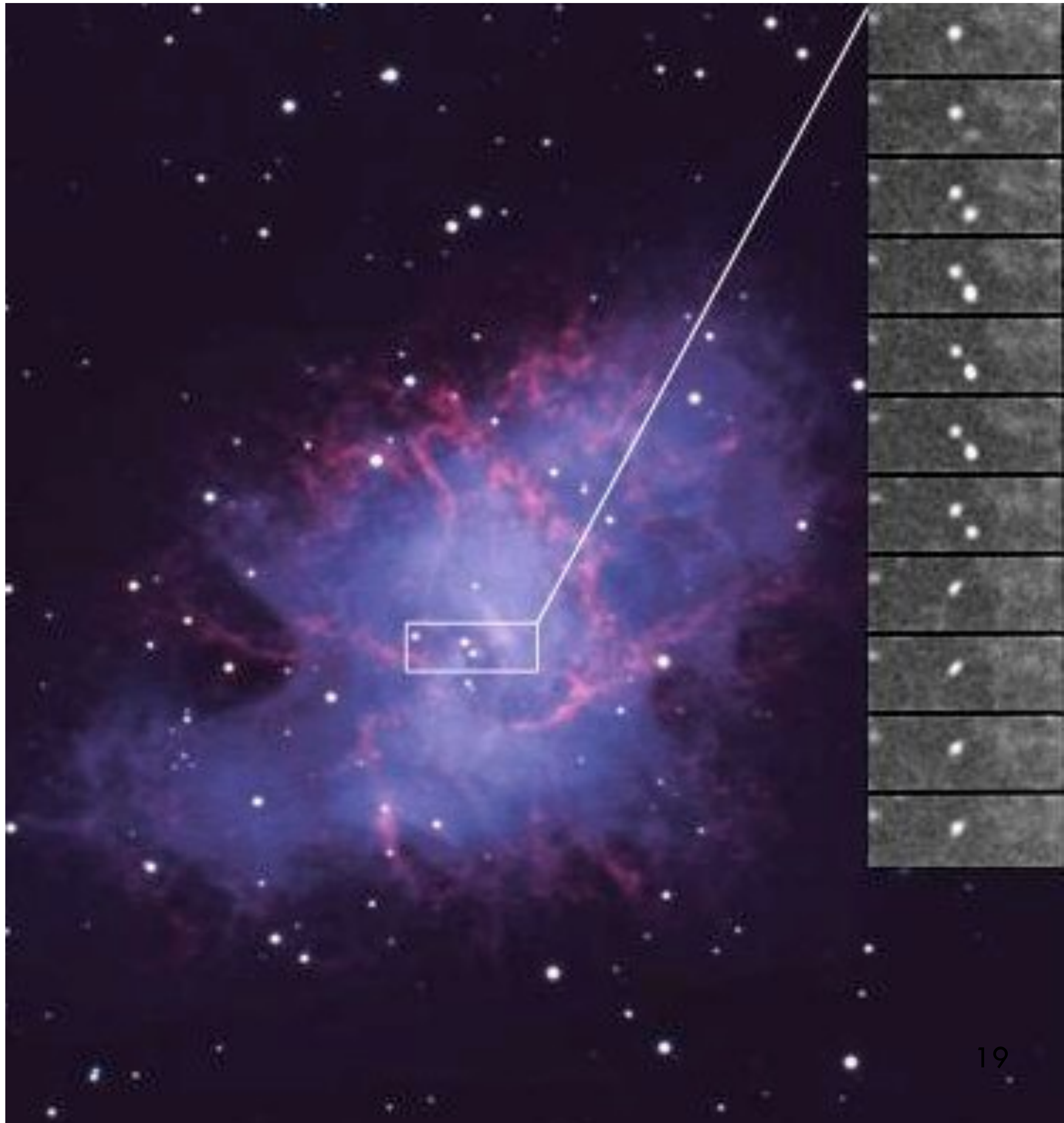
The rapid pulsations arise from spinning neutron stars. A strongly magnetised star accelerates charged particles to enormous speeds, producing a beam of intense radio waves which whips around like a beacon, producing a pulse every time the beam sweeps past us.



Why do pulsars spin so fast? Conservation of angular momentum means that when an ordinary star collapses, its rate of spin has to increase. If the Sun were to shrink to neutron star size, it would be rotating once every few seconds, just about right for a pulsar. Similarly, the collapse also explains the strong magnetic field: the magnetic field lines already present in the star are compressed, leading to a much stronger surface magnetic field.

Animation showing the flash of light every time the pulsar beam sweeps past us.

In 1968 an extremely rapid pulsar (0.033 seconds) was found in the Crab nebula, remnant from an explosion in 1054 – hence confirming the link with supernova explosions. The central star of the nebula was found to be flashing in visible light as well.

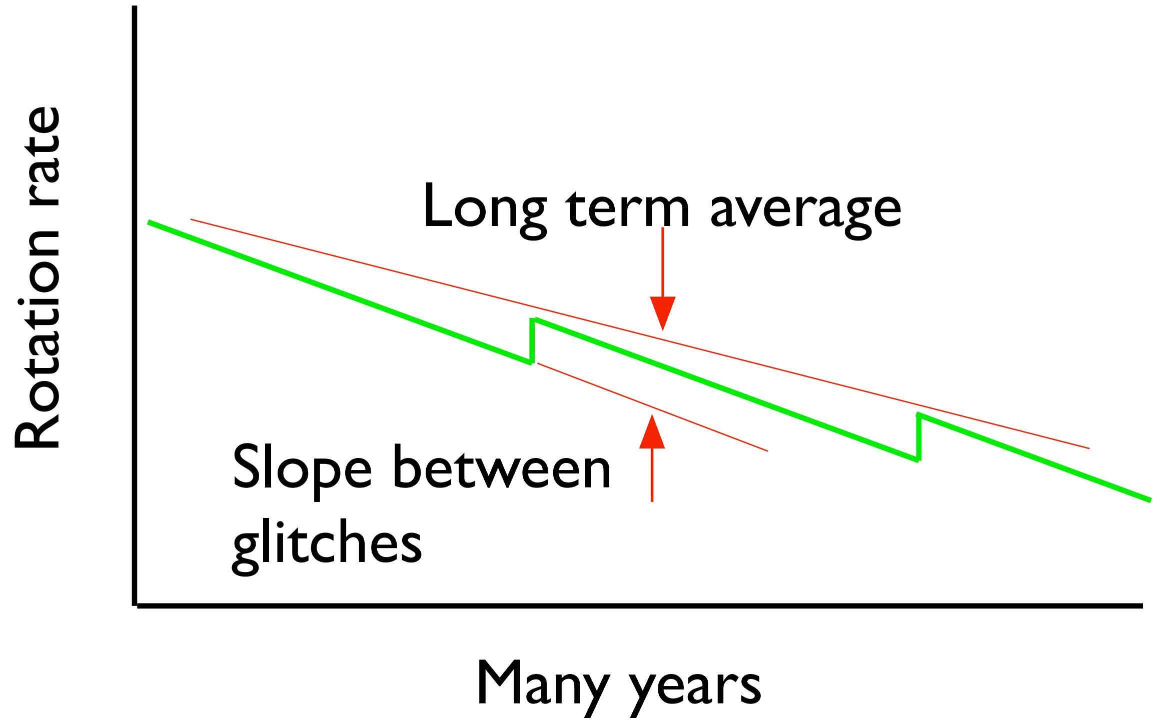


One prediction of the model for pulsars was that a rotating neutron star ought to slow down. By 1969, measurements carried out using the thousand-foot dish antenna at Arecibo found that the pulse rate from the Crab pulsar was indeed slowing down, by about a millionth of a second per month.

Further, the amount of energy the pulsar was losing each year was just the energy required to keep the Crab Nebula shining.

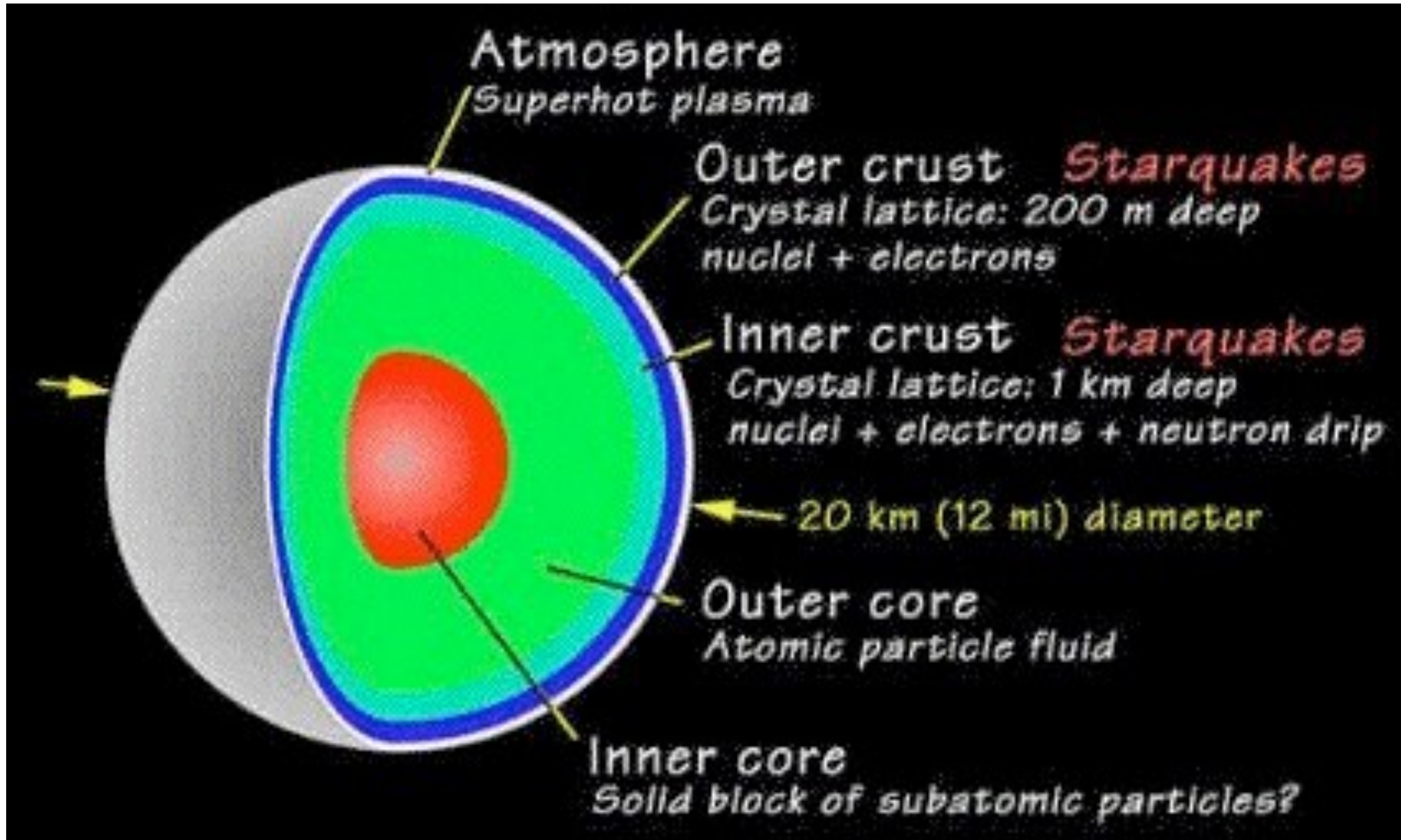
Glitches

Most pulsars are extremely good timekeepers: their periods slow down at very constant rates. However, some young pulsars show *glitches*, where the rotation rate suddenly increases, then reverts to its original slow-down rate, taking a month or so to return to its original period.

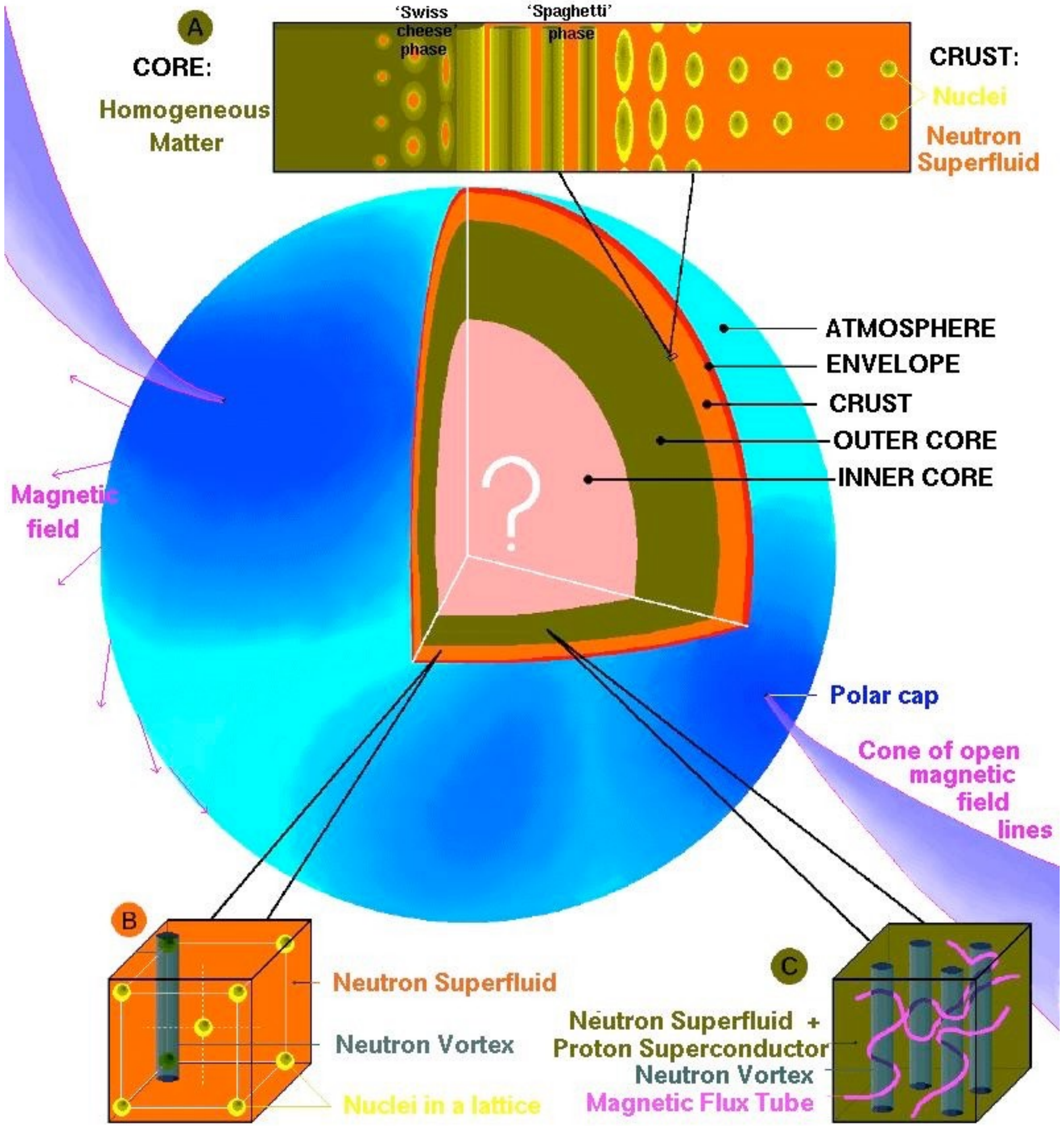


It is from modelling glitches that we have our best evidence for the interior structure of neutron stars. We believe the outer solid crust is made of iron. Below this is a lattice of neutrons, at the density of an atomic nucleus. Even deeper, the neutrons form a *superfluid*. It is possible that there is a solid core, but we have no idea what such material would be like.

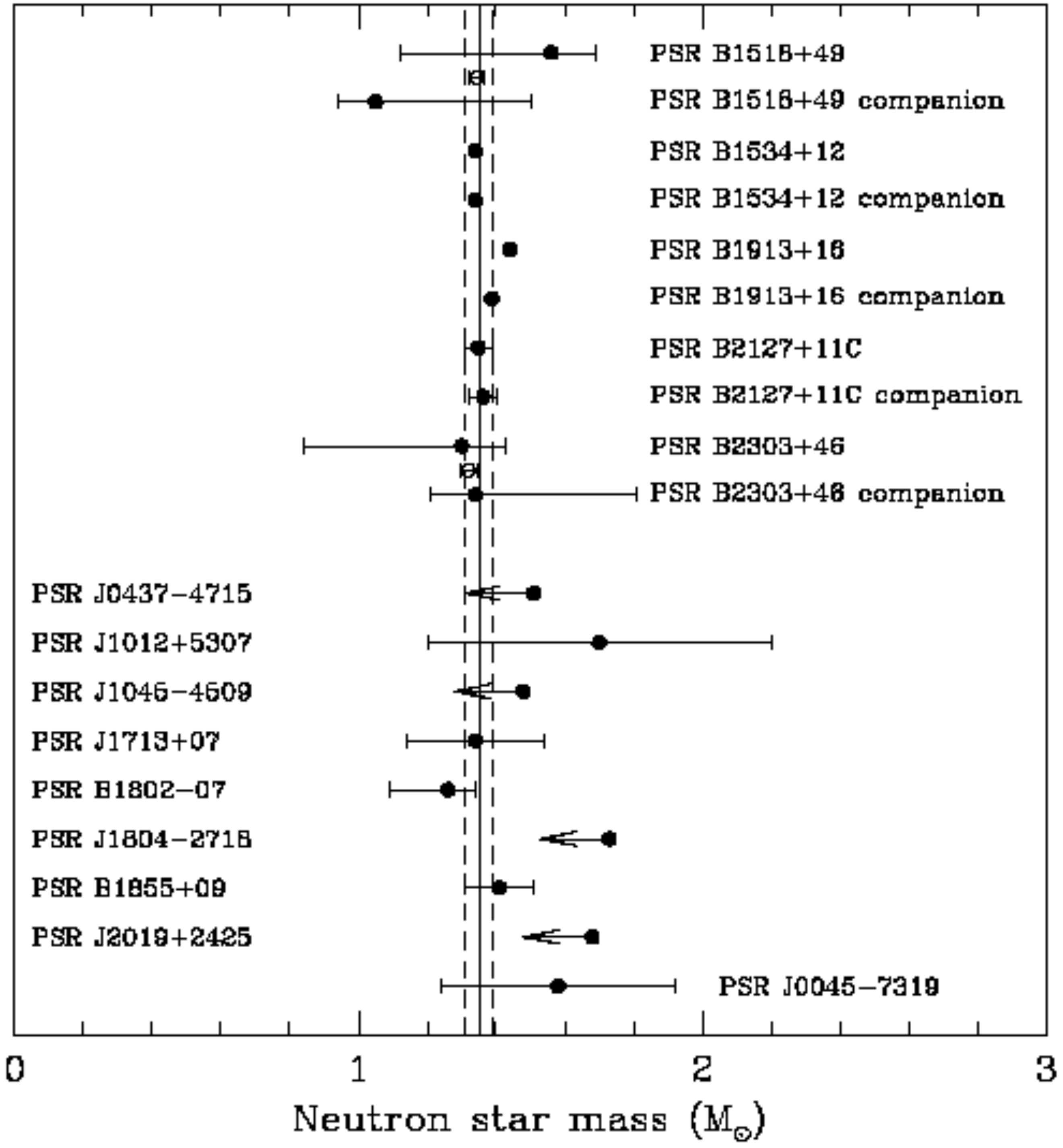
Glitches are *starquakes*, an adjustment between the superfluid core and the crust as the neutron star slows down.



A NEUTRON STAR: SURFACE and INTERIOR

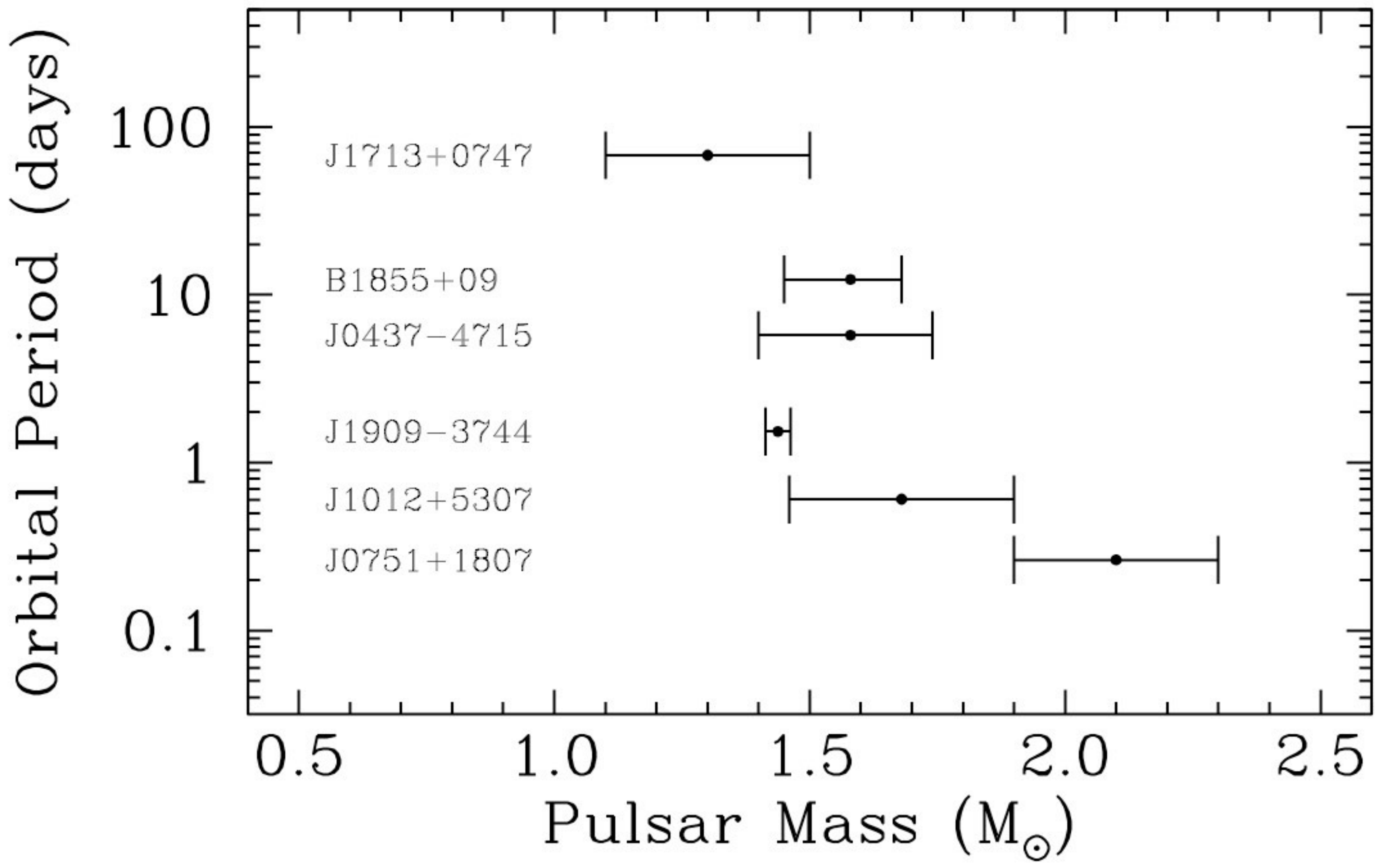


The measured masses for pulsars (measured from pulsars in binary systems) are all remarkably consistent, and all very close to the Chandrasekhar mass. This is despite the fact we think it is *possible* for a neutron star to have a mass up to 2 or 3 solar masses.



(Actually, it now appears that it is just pulsars in neutron star–neutron star binaries which all have masses of 1.4 solar masses. Neutron stars with white dwarf companions appear to be heavier.

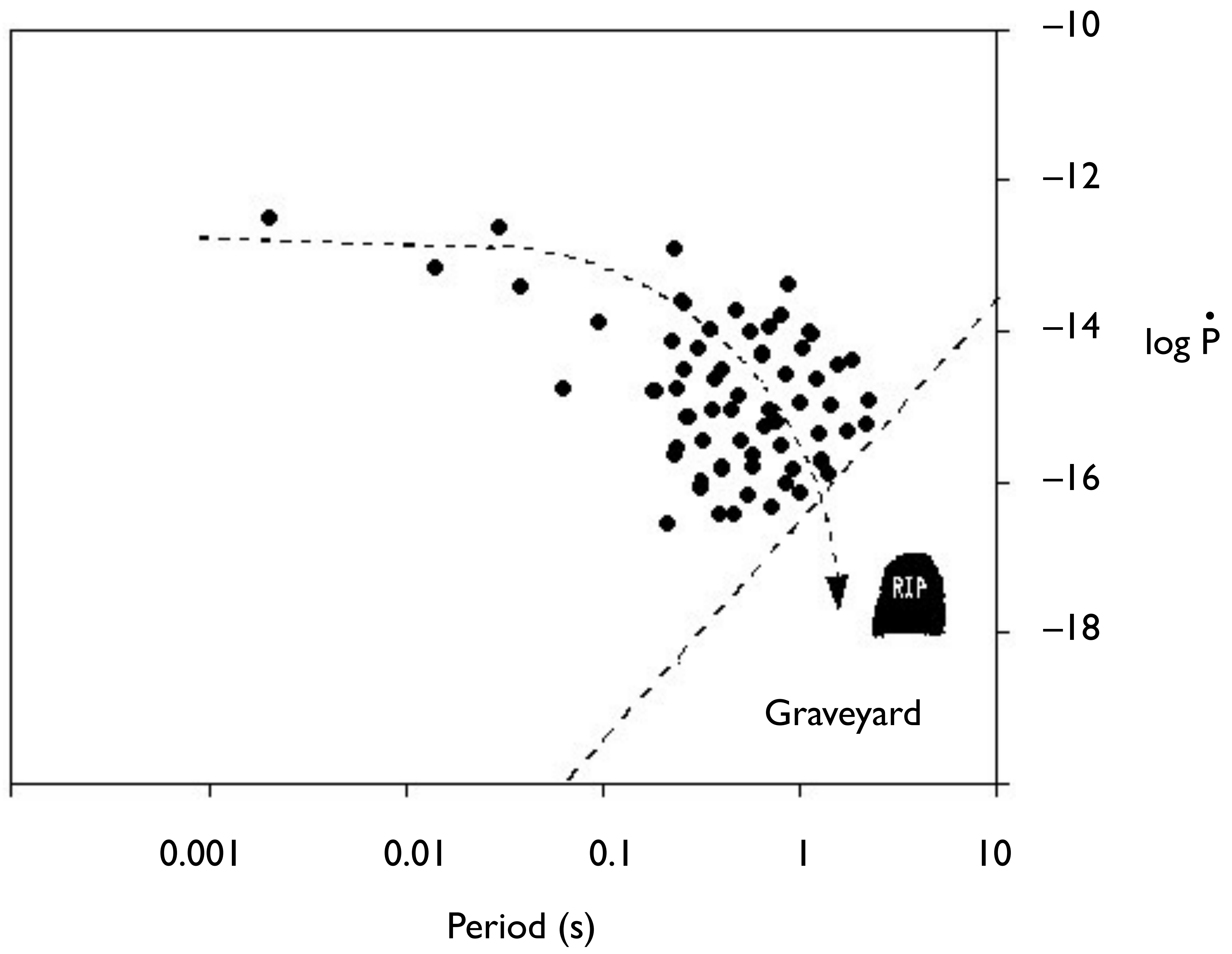
The record is now held by PSRJ0751+1807, a pulsar in a 6-hour orbit with a white dwarf companion, which has a mass of 2.1 solar masses.)



Masses of neutron stars with white dwarf companions.

Pulsar ageing

A pulsar is probably born spinning fast, possibly as fast as 100 times per second, and its magnetic field is very strong. As it converts its rotational energy into radiation, it gradually slows down and its magnetic field grows weaker. Eventually, it reaches a period (about 10 seconds) where the "lighthouse" switches off: the electric field generated by the neutron star's rotation is no longer strong enough to rip electrons from the surface. The average pulsar is a few million years old, and the oldest is about 10 million years old.

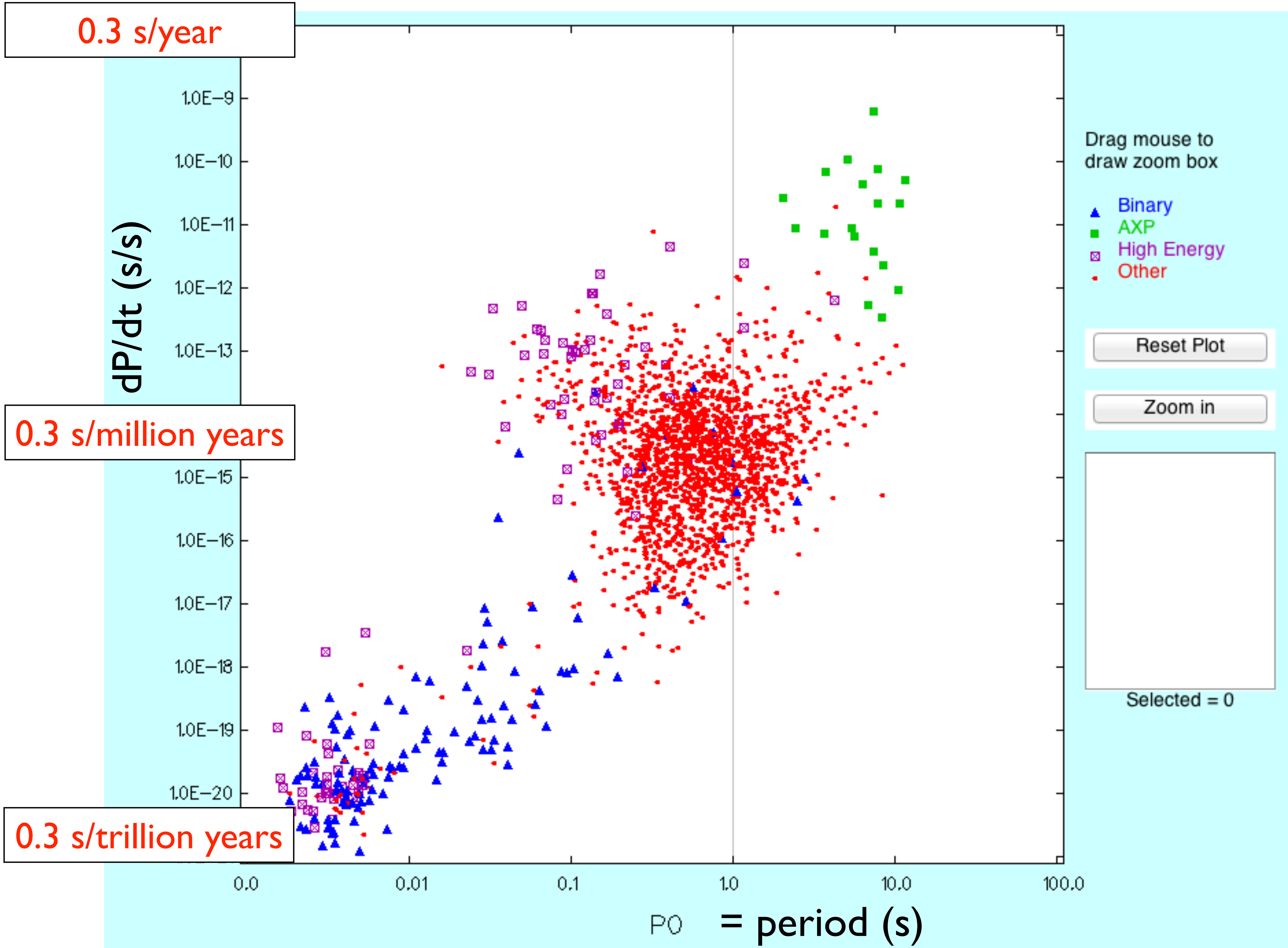


How a pulsar ages: it slows down, loses its magnetic field, and enters the "pulsar graveyard".

Not all neutron stars are pulsars. For some, the "lighthouse beam" is not pointed at us, so we don't see the pulses. In addition, all neutron stars older than about 10 million years have stopped emitting as pulsars, so are no longer visible to us.

There are now about 2536 pulsars known. Most are common-or-garden pulsars, with periods of around 1 second; but there are a couple of special ones which have been found.

* see http://www.atnf.csiro.au/people/pulsar/psrcat/


0.3 s/year
0.3 s/million years
0.3 s/trillion years
dP/dt (s/s)
1.0E−9
1.0E−10
1.0E−11
1.0E−12
1.0E−13
1.0E−15
1.0E−16
1.0E−17
1.0E−18
1.0E−19
1.0E−20
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P0 = period (s)
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Binary
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Reset Plot
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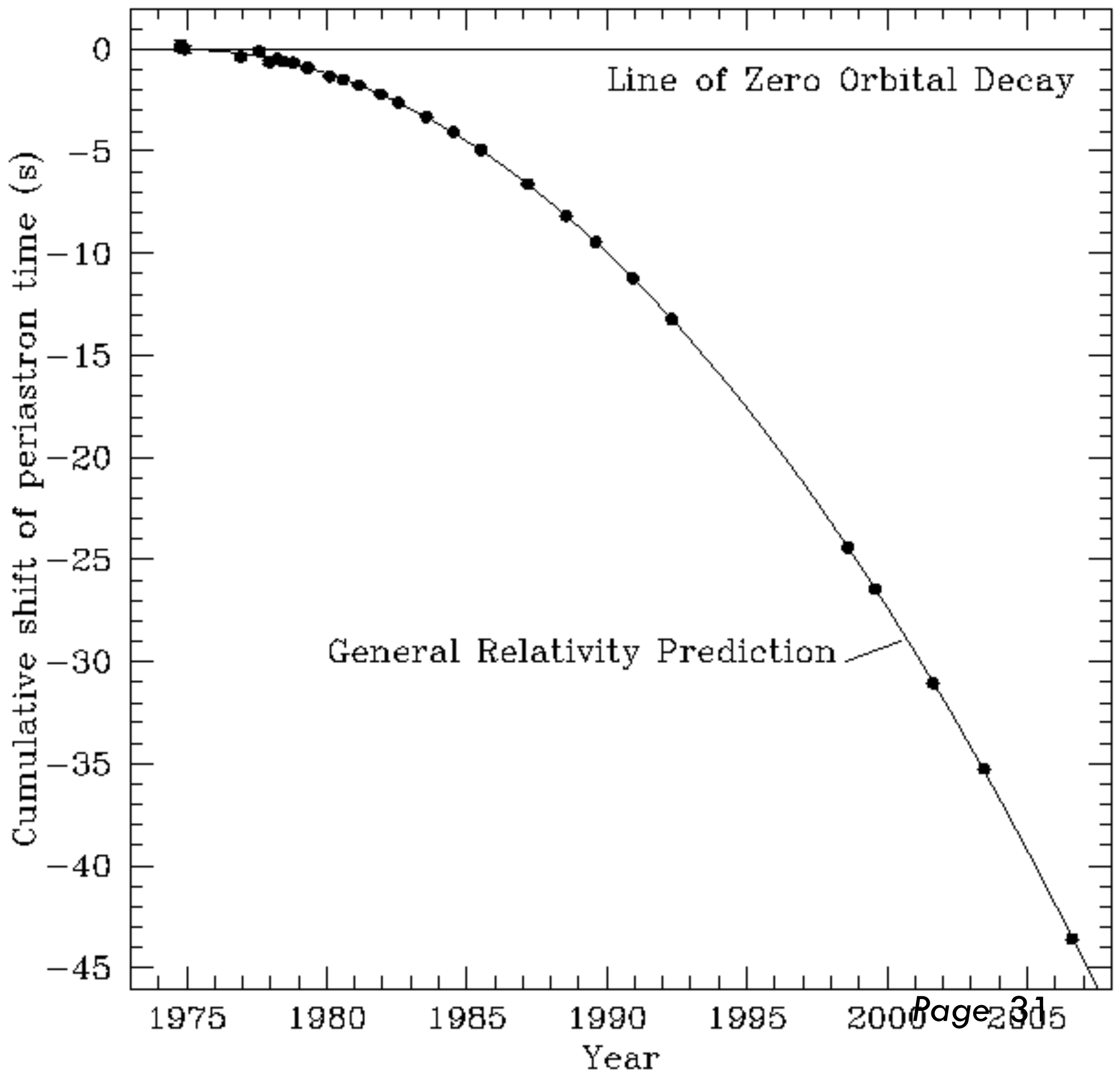
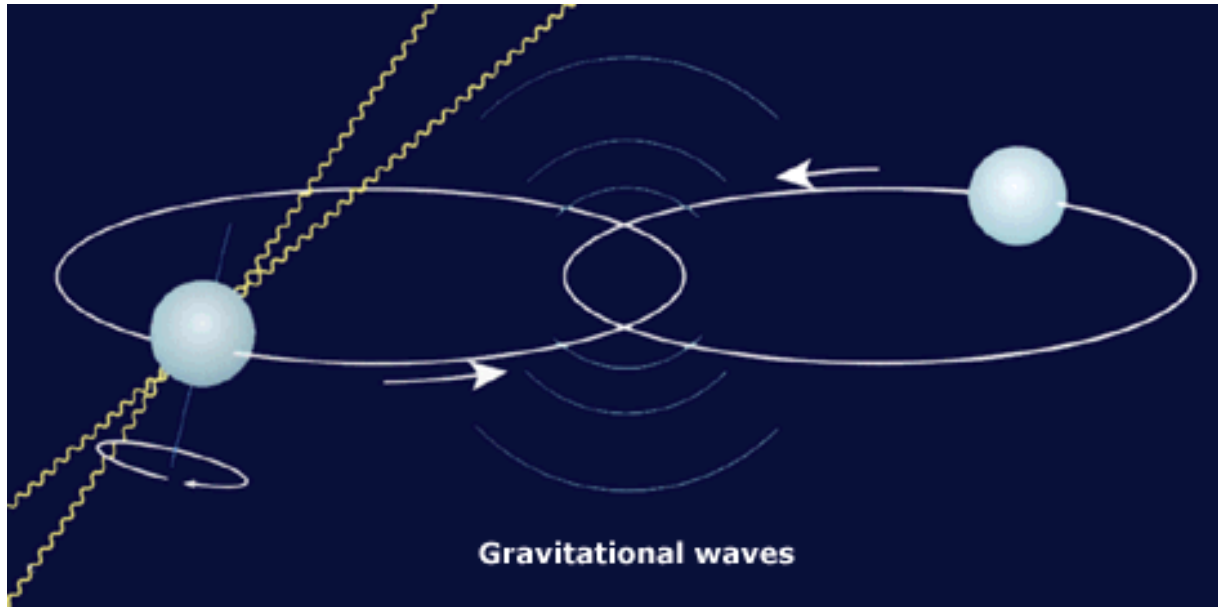
Binary pulsars

In 1974, Joe Taylor and his student Russell Hulse discovered the first pulsar in a binary orbit: a 59 ms pulsar in an elliptical 8 hour orbit with another neutron star (not pulsing). Careful timing of the orbit over the next decade showed that the orbit is decaying: the two neutron stars are slowly spiralling together. They are losing energy to *gravitational radiation*, as predicted by General Relativity.





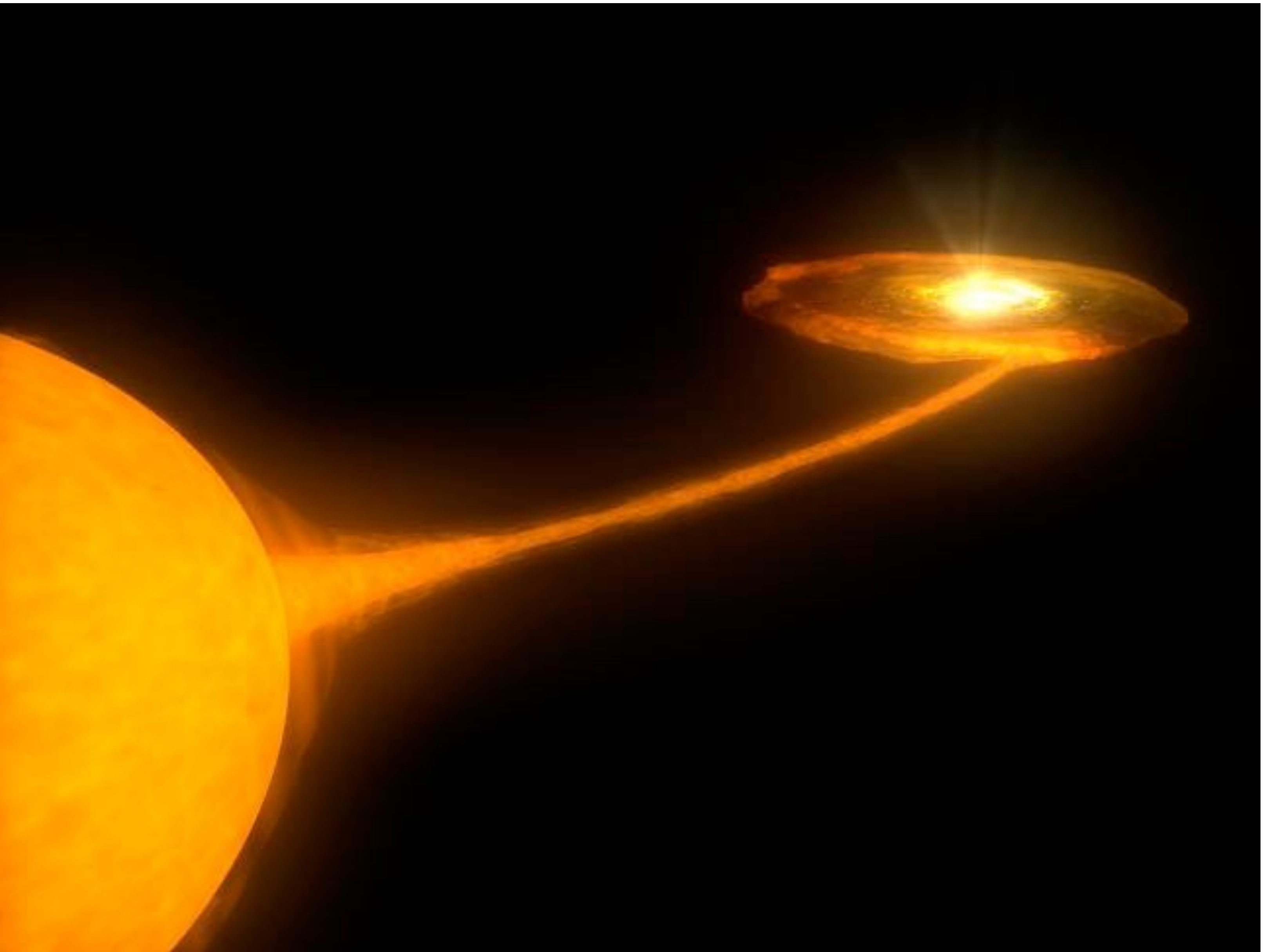
Millisecond pulsars

In 1982, an *extremely* fast pulsar was discovered, rotating 642 times per second (period 1.55 ms). At this speed, a point on the equator is travelling at about 25% of the speed of light!

Most surprisingly, the millisecond pulsar (and others discovered later) was found to be *old*, unlike other short-period pulsars like the Crab, which is young. Further, most (~80%) millisecond pulsars are in binary systems, compared to <1% of regular pulsars.

Why?

To answer that, we have to take a look at the other guise in which we find neutron stars: the *X-ray binaries*. These are a class of accreting binaries: binary star systems where one star is transferring material to its companion. In the case of X-ray binaries, the accreting star is a neutron star.



The millisecond pulsar connection

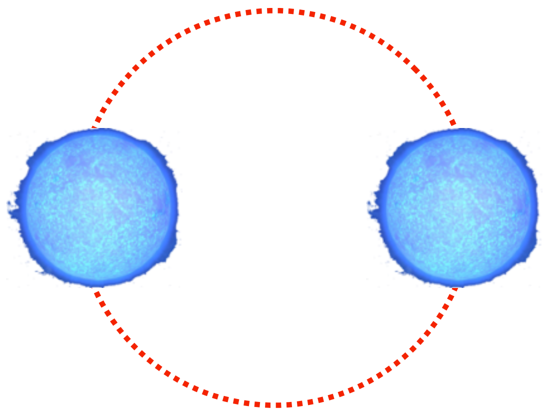
X-ray binaries are endlessly interesting in their own right. However, there is a connection with the question of how to make a millisecond pulsar.

It turns out that millisecond pulsars are *recycled* pulsars. Unlike ordinary pulsars, which form from a supernova explosion, pulse for a while, then fade into oblivion, millisecond pulsars get a new lease of life by being recycled through a binary system which is transferring matter.

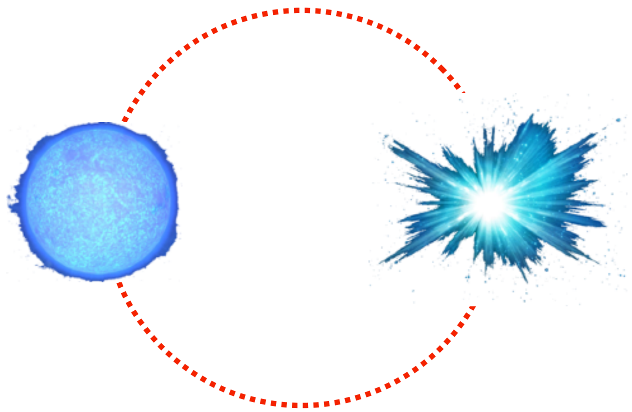
But we know these systems by another name: *X-ray binaries*.

How to make a millisecond pulsar

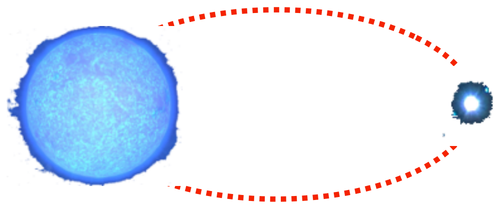
Start with a two stars in a
binary system



The more massive star undergoes a supernova explosion

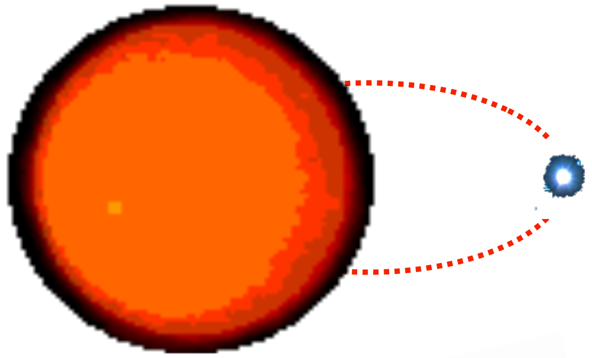


… leaving a neutron star in a binary with another star.

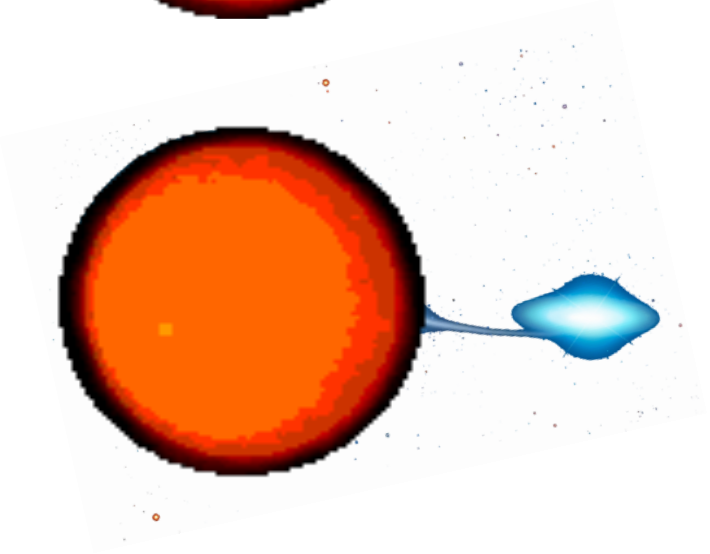


How to make a millisecond pulsar

The second star expands and begins transferring mass

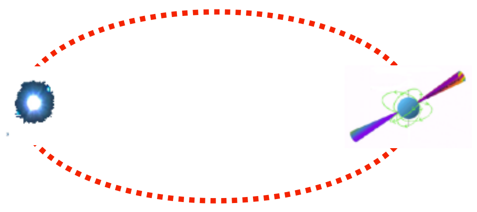


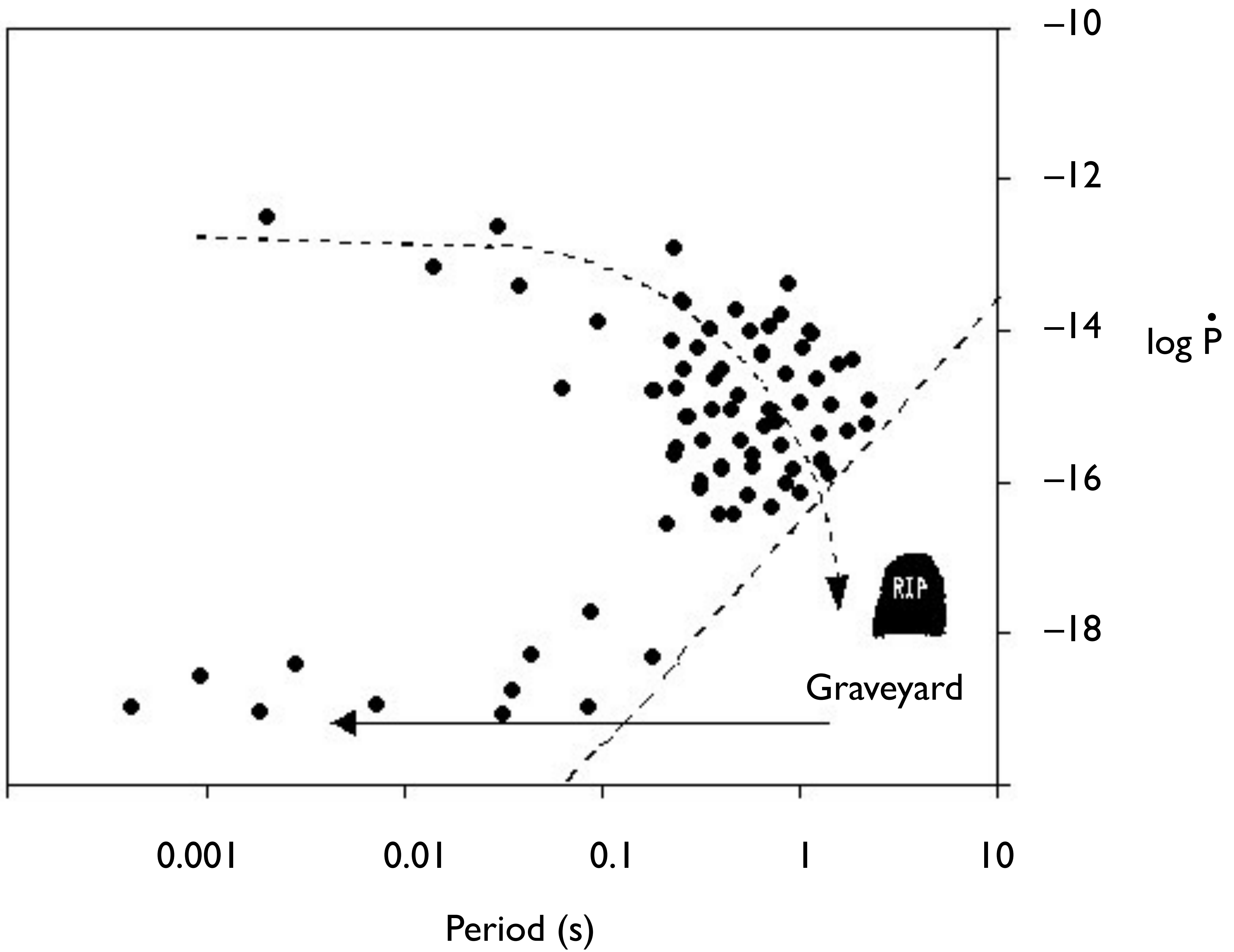
... so the system becomes visible as an X-ray binary. It accretes not only matter, but also angular momentum, so it *spins up*.



Then the second star undergoes a supernova explosion

... leaving a very fast pulsar in orbit with another neutron star.

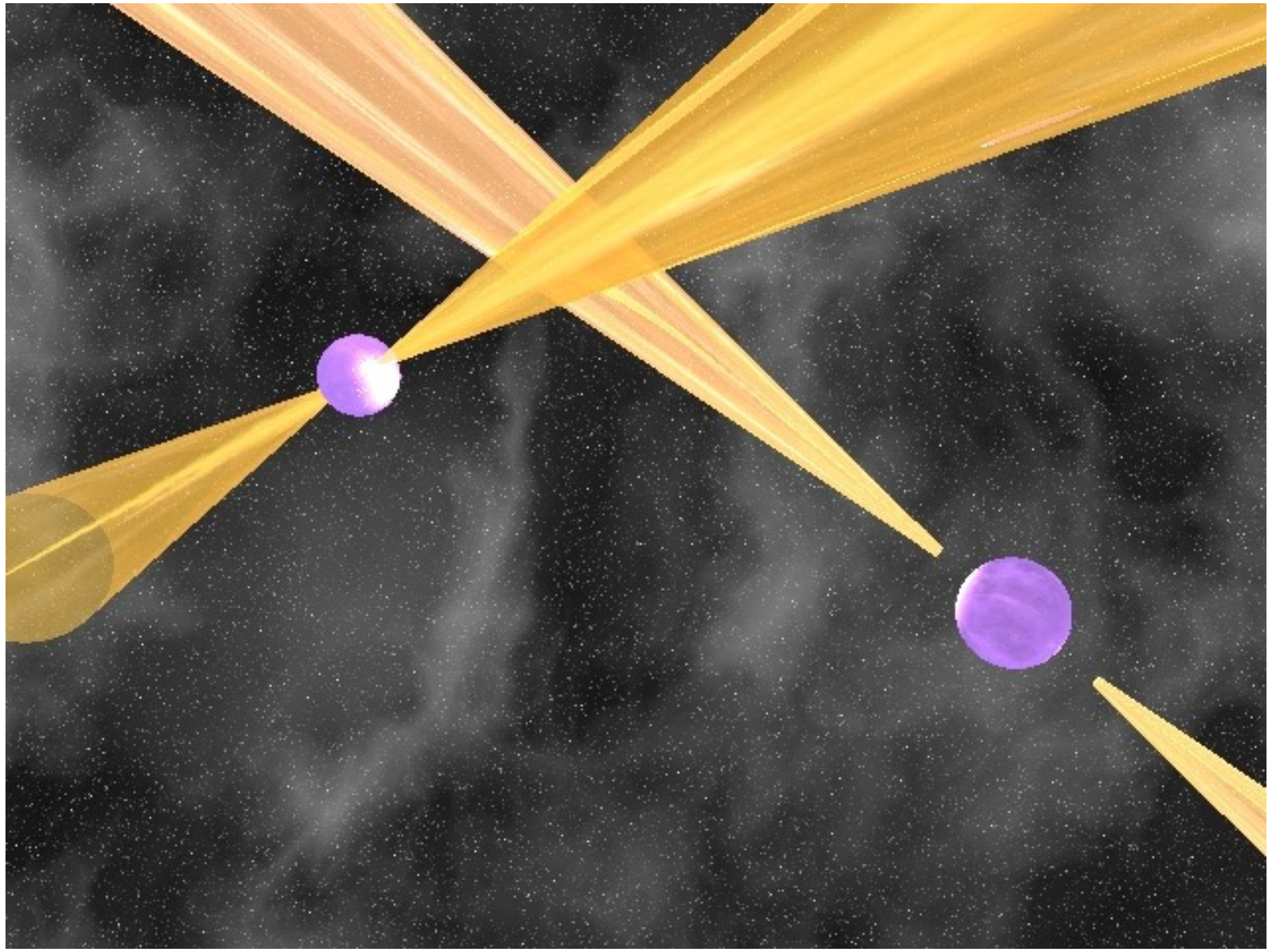




Recycled pulsars leave the graveyard by being *spun up*: they reach very short periods but have low magnetic fields.

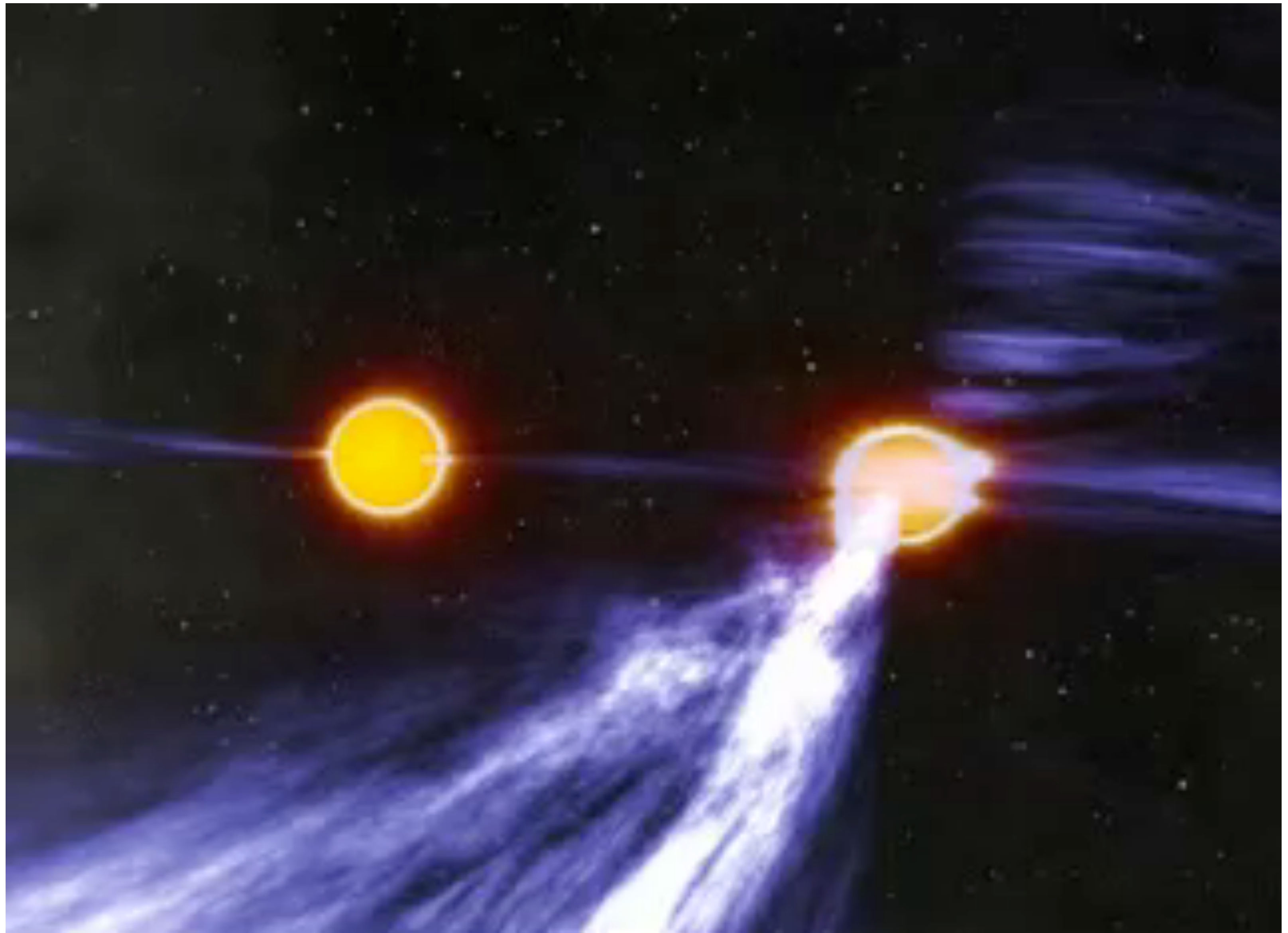
The first double pulsar

In 2004, the first (and so far only) *double* pulsar was discovered: a binary where both neutron stars are pulsars!

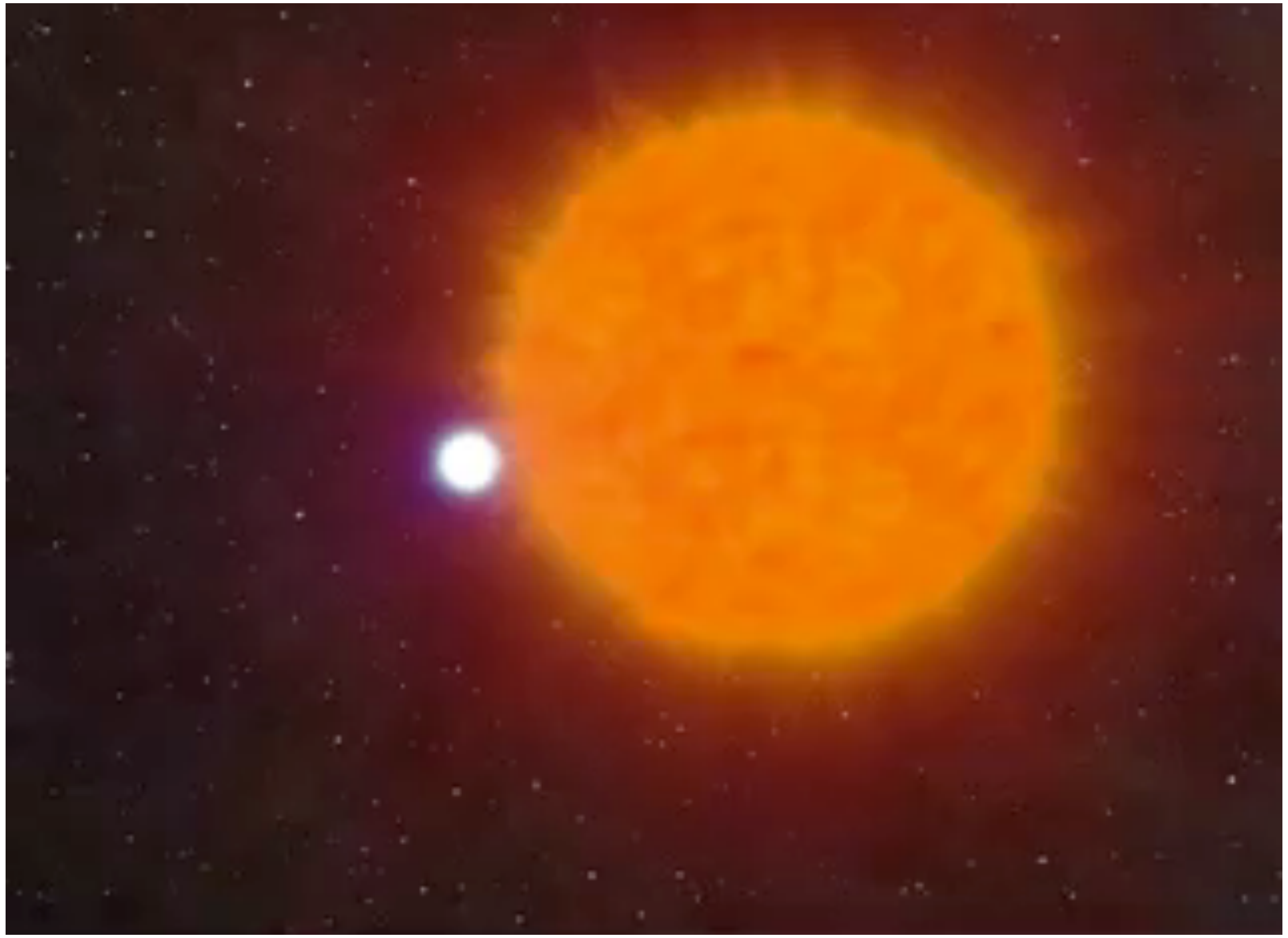


The binary consists of a pulsar with a spin-period of 23 ms – the millisecond pulsar – orbiting a 2.8 s pulsar in a 2.4 h orbit (which means the size of the orbit is the diameter of our Sun). The mean orbital velocity is about 0.1% of the speed of light.

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



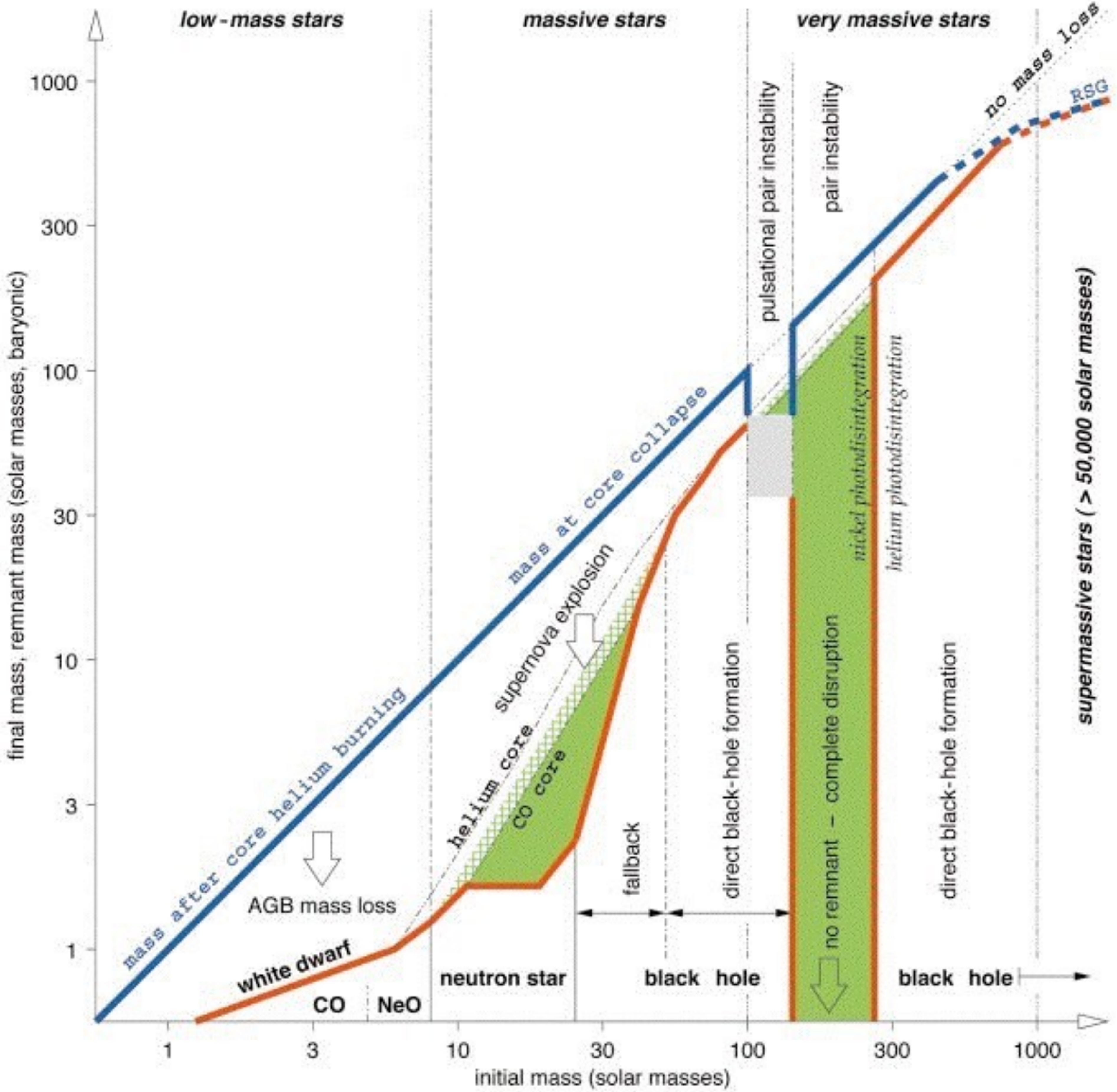
The millisecond pulsar must have initially been the more massive star; the slower pulsar resulted from the second supernova, so is much younger than the other.



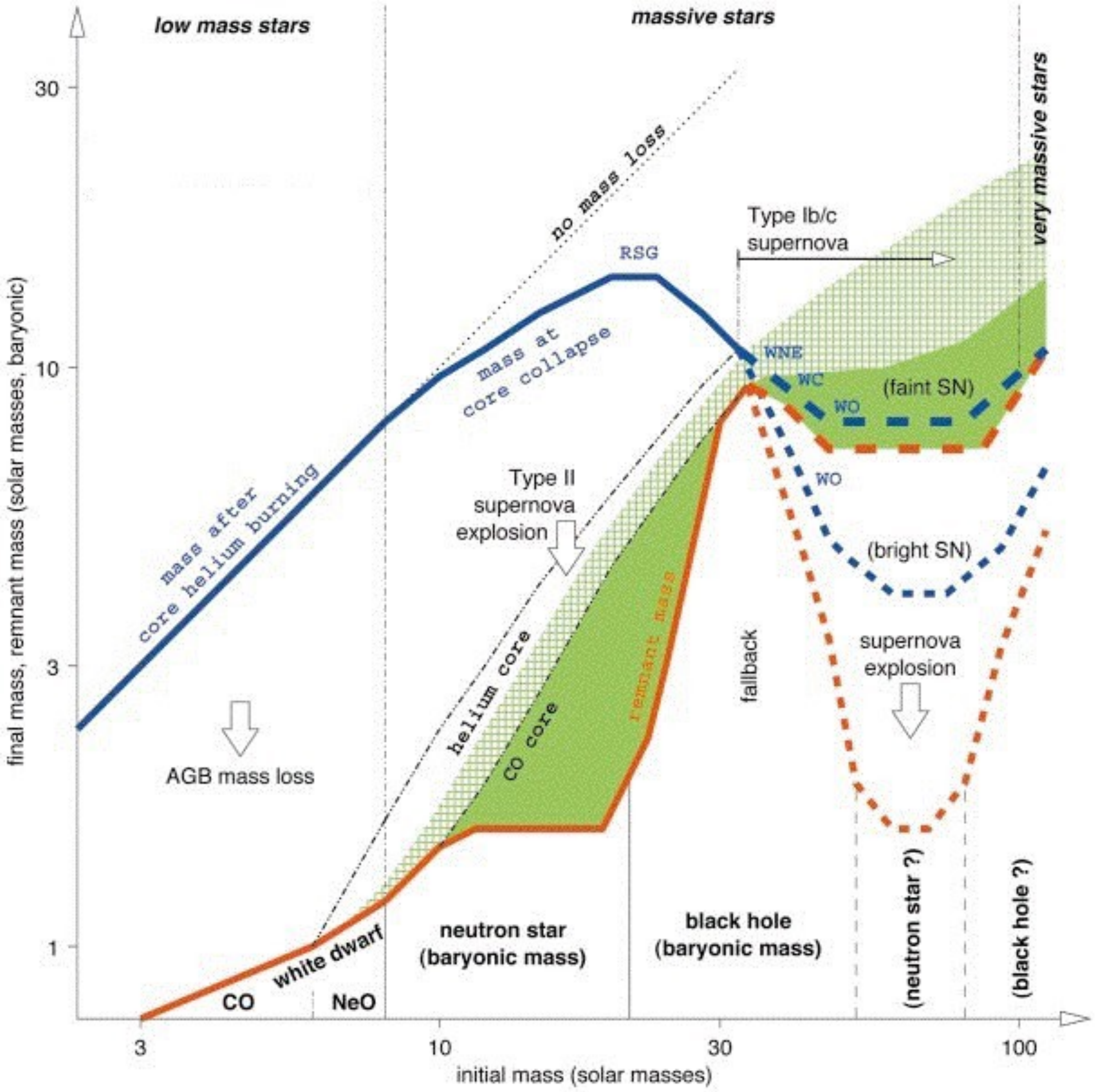
The chance of finding such a binary is remote, since both pulsars have to be pointing in our direction and the younger pulsar must still be alive.

This system was enormously important in testing the theory of General Relativity – we'll see how in a little while.

Recall that when we talked about the evolution of massive stars, we said that we didn't know just how much mass was lost in the later stages of a massive star's life. This has a major effect on its ultimate fate. When the star loses little mass, everything over about 25 solar masses forms a black hole.



For our best guess at how much mass stars with similar metallicity to the Sun lose, the fates can be very different. Since the amount of mass lost depends strongly on the luminosity, and hence mass, of the star, it is even possible that above about 50 solar masses there is a “window” where the star loses so much mass that neutron stars are formed instead of black holes.

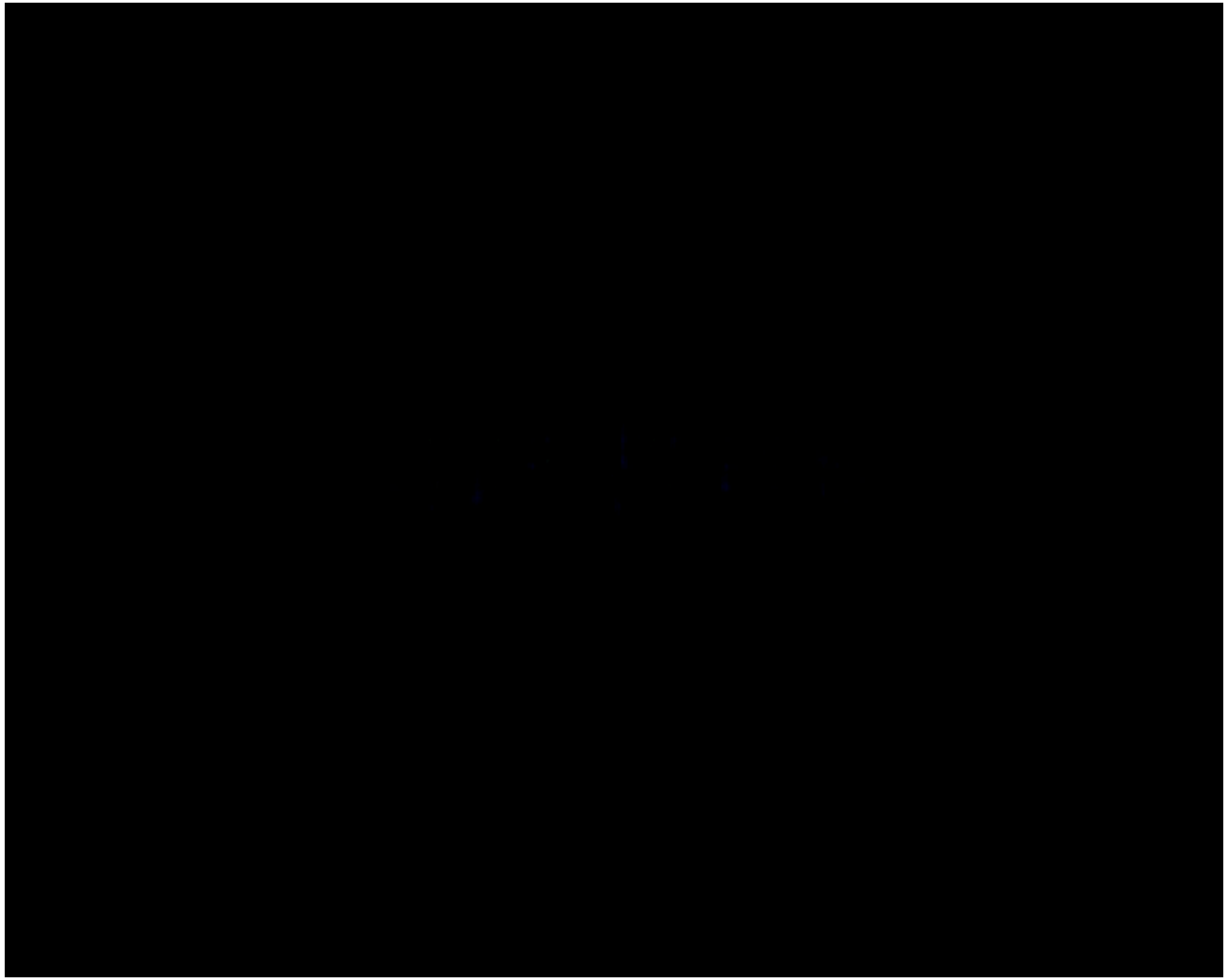


Black holes

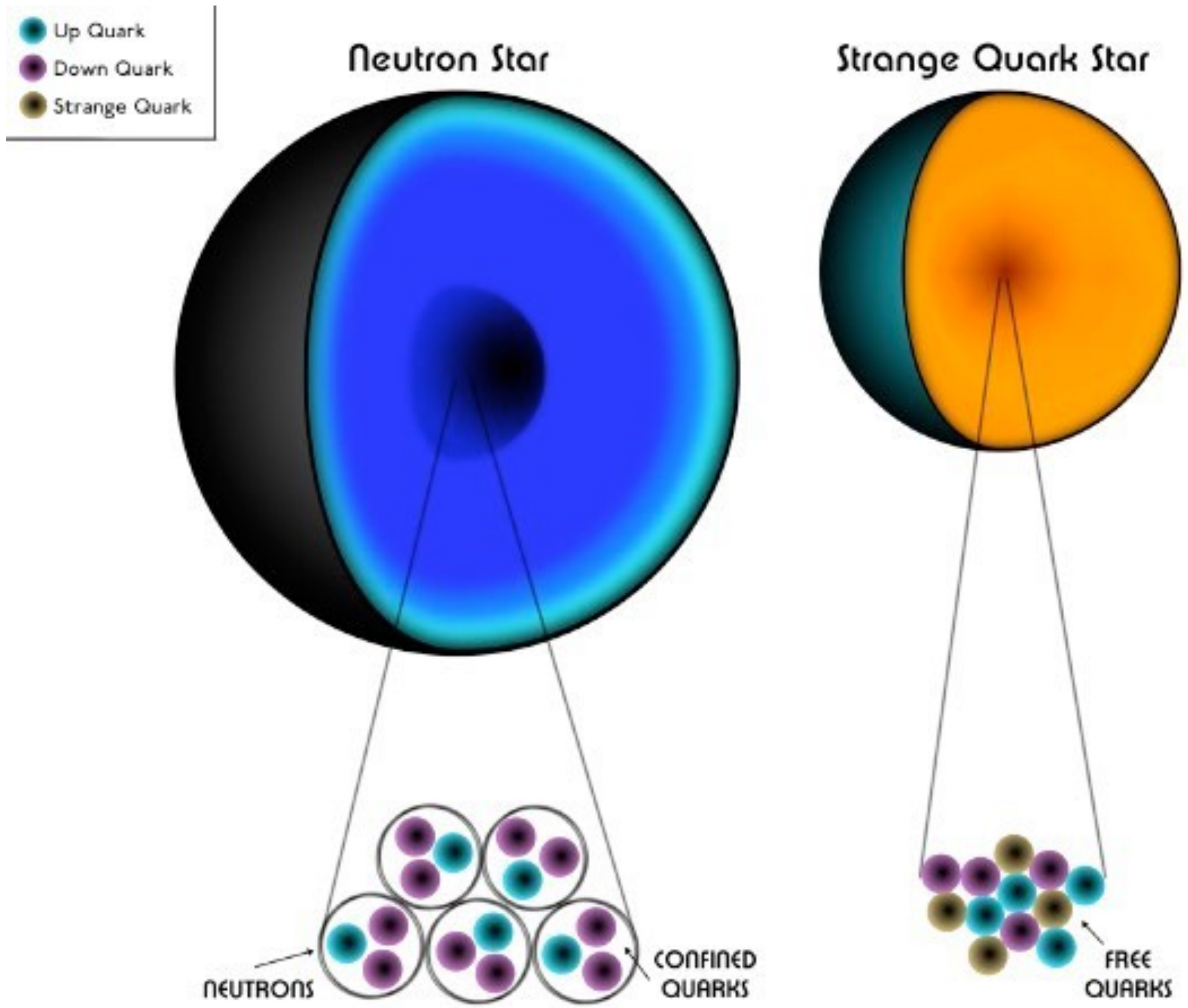
Just as white dwarfs have a maximum allowed mass, so do neutron stars. There comes a mass when even the outward pressure provided by degenerate neutrons cannot counterbalance the inward pull of gravity.

And after that, there is no force left which can balance it.* Gravity has won: the star must collapse to a black hole.

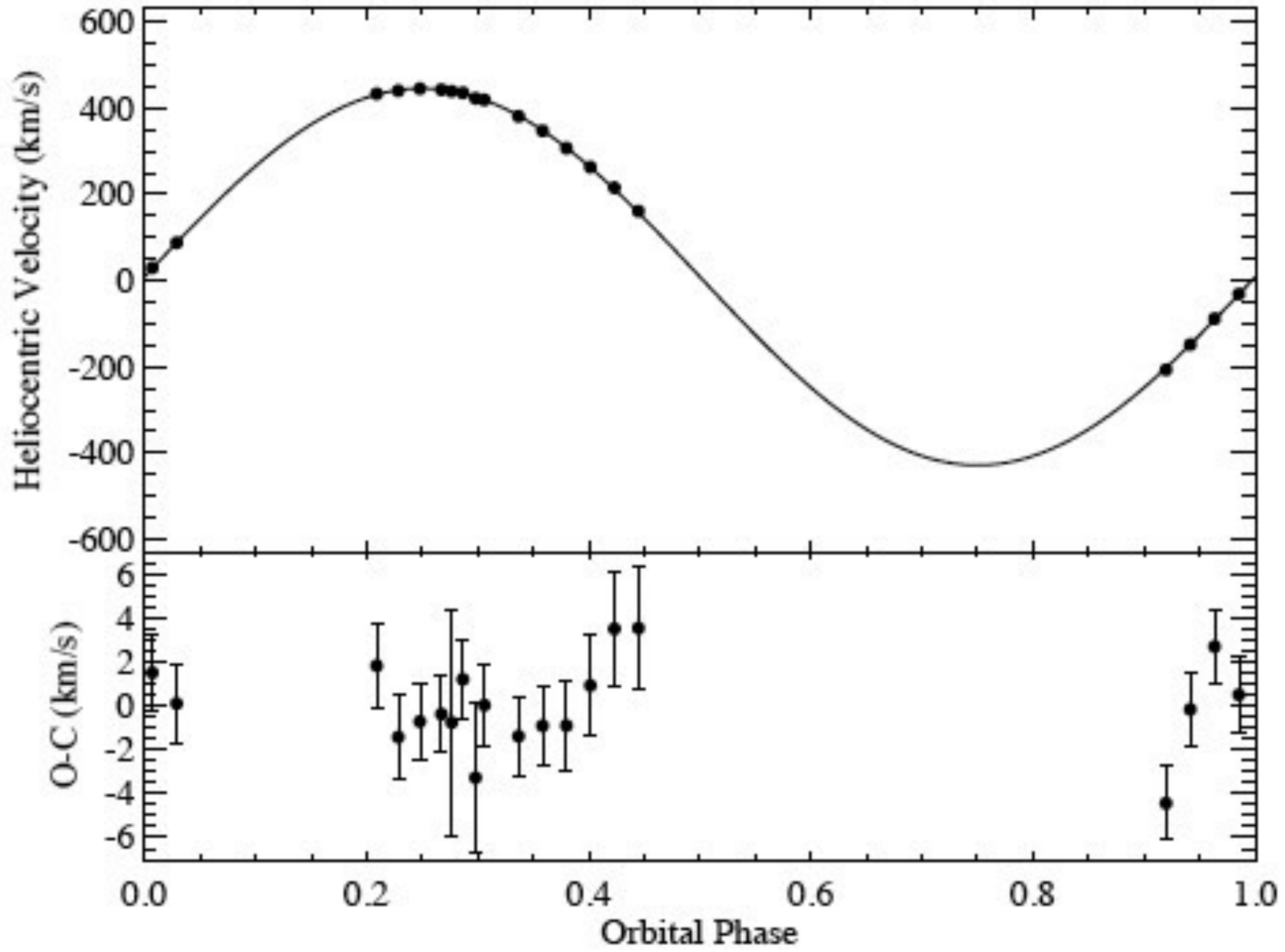
But how do we find black holes?



[* Actually, some people suggest there could be one more intermediate step between a neutron star and a black hole: a *quark star*, where the neutrons themselves have dissolved into their constituent quarks. However, no-one has ever seen one; nor is it clear you could actually tell the difference between a quark star and a black hole]

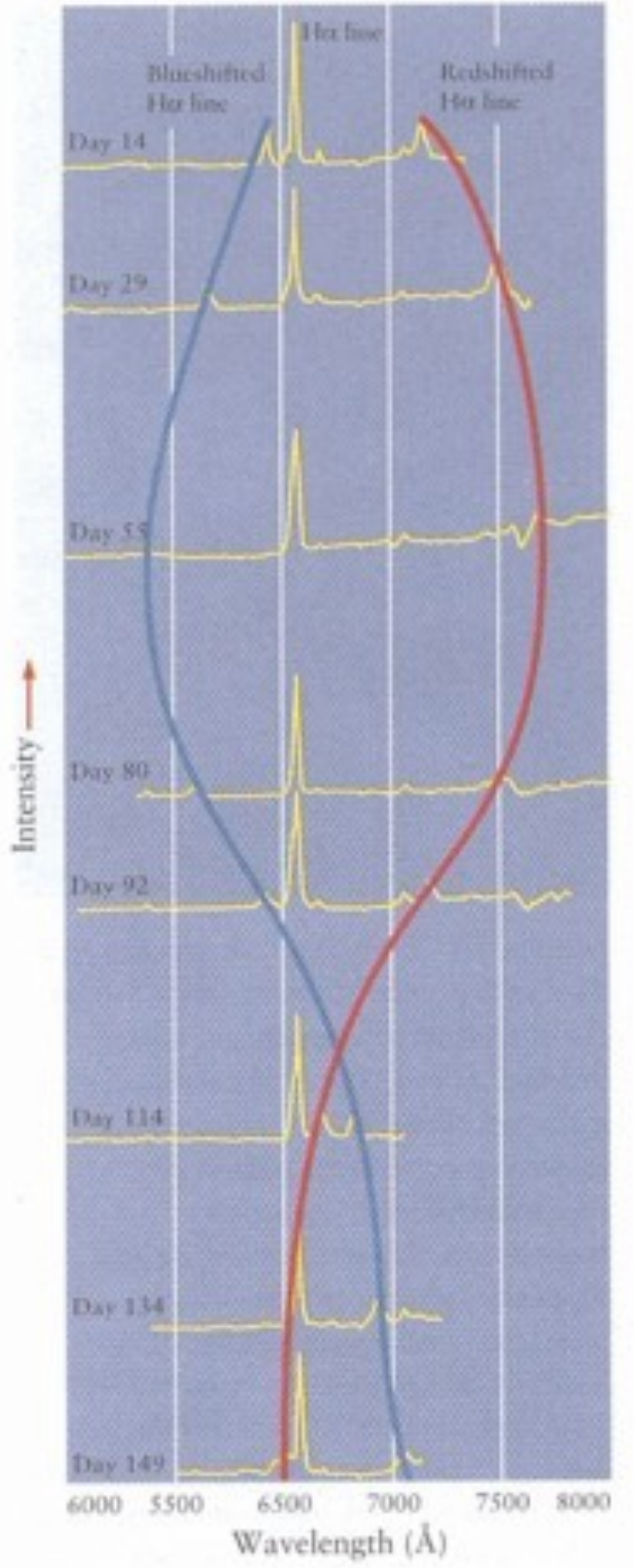


As it happens, we are not completely bereft: we might not be able to see black holes, but we can still detect them by their mass. It turns out that the X-ray binaries are an excellent hunting ground for black holes. We want to find an X-ray binary whose accreting star is more massive than any neutron star could *possibly* be: then by elimination, it must be a black hole.

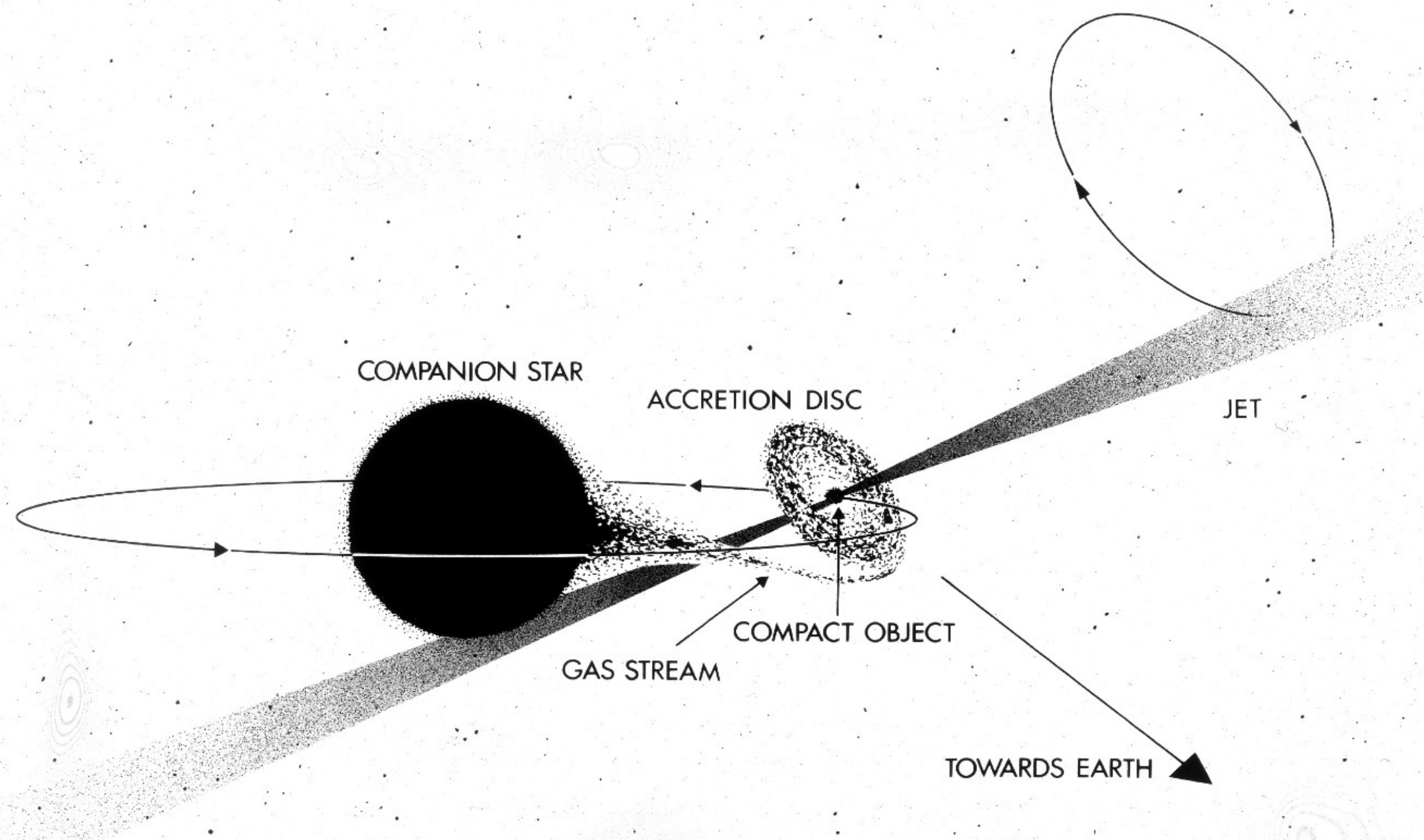


The Doppler shift of the companion star in the X-ray binary A0620–00. Knowing its mass (K dwarf, <0.8 solar masses) and how fast it's moving (500 km/s), we can calculate the mass of the unseen primary star: we derive a lower limit of 5 solar masses, well above the maximum allowed mass for a neutron star.

There are other, weirder signs that there are probably black holes lurking in our neighbourhood. One of the weirdest is SS 433, which was thought to be an unremarkable blue star, until Bruce Margon took spectra showing *three* sets of hydrogen lines, one stationary, one redshifted, and one blueshifted. What's more, the lines changed places over a 164-day period. The star seemed to be coming, going, and standing still, all at the same time!



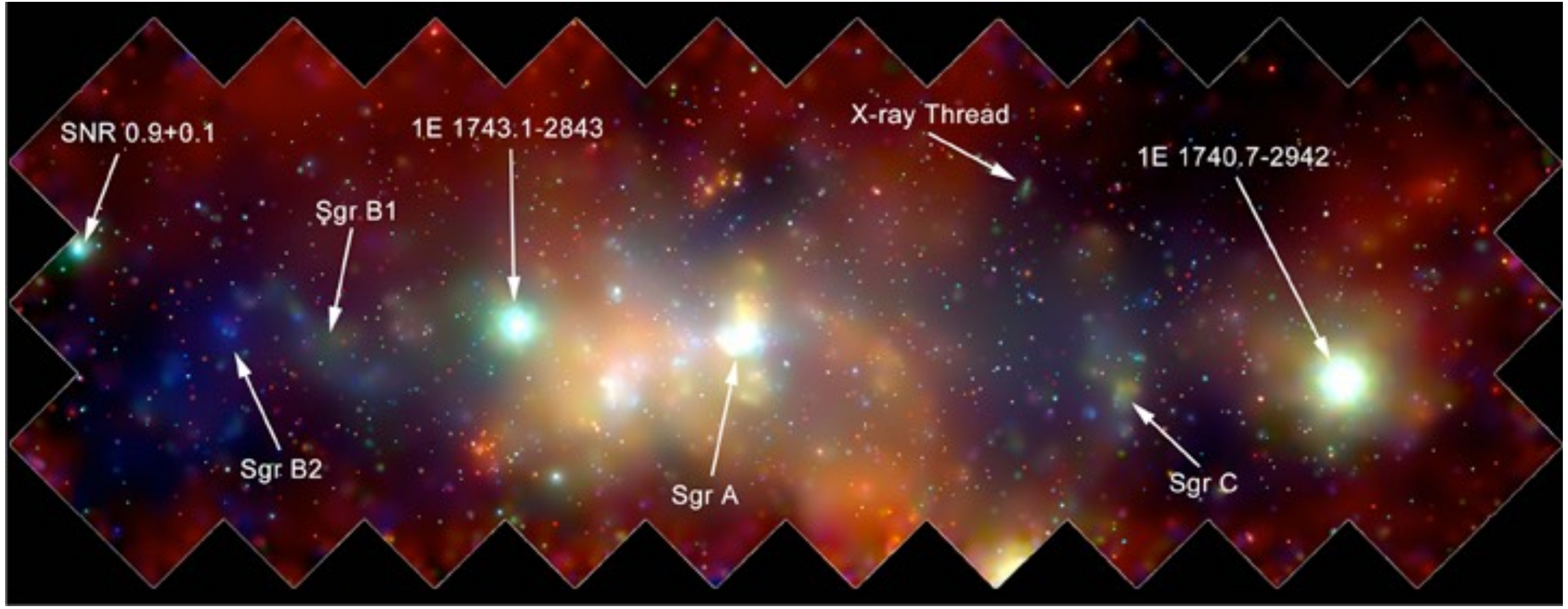
The answer seems to be that the central star is squirting out two high velocity jets of gas in opposite directions, like water from a high-pressure sprinkler. The jets precess around, wobbling around the axis of the binary, so we see the lines from each jet first approaching us, then receding from us.



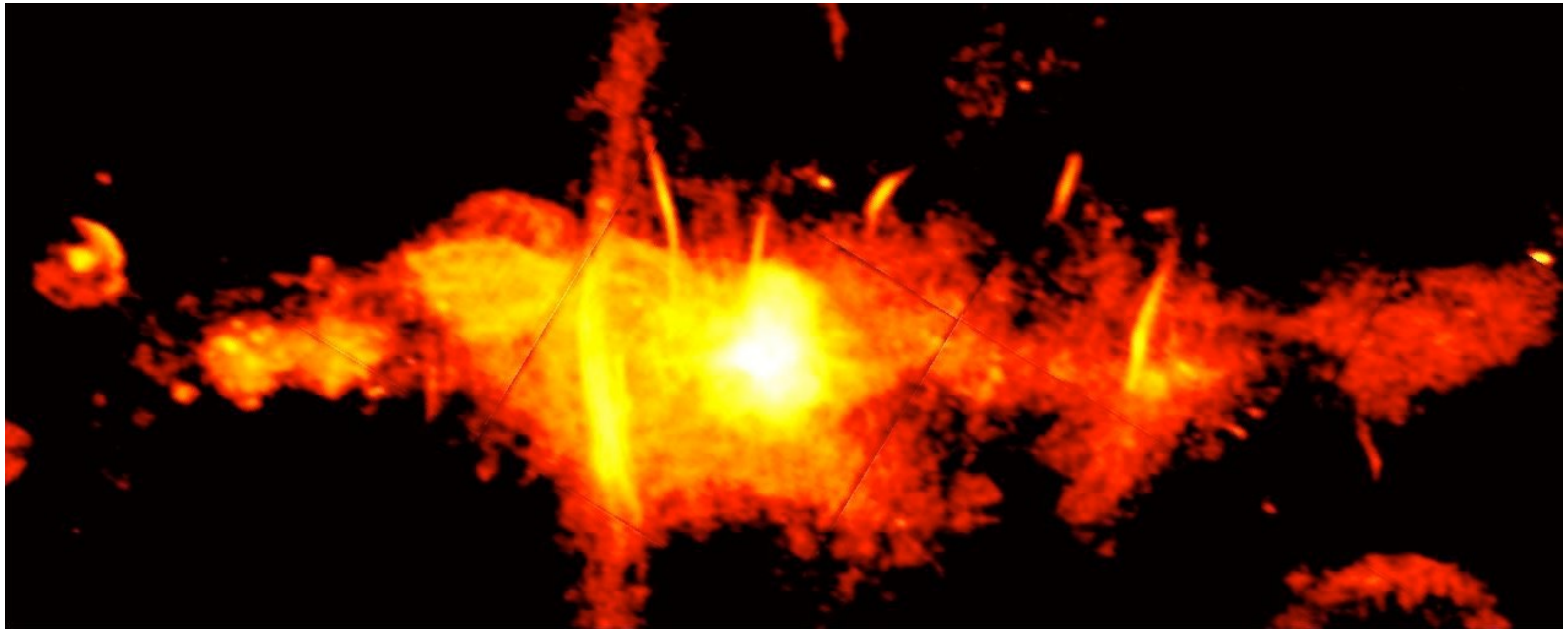
The SS-433 System

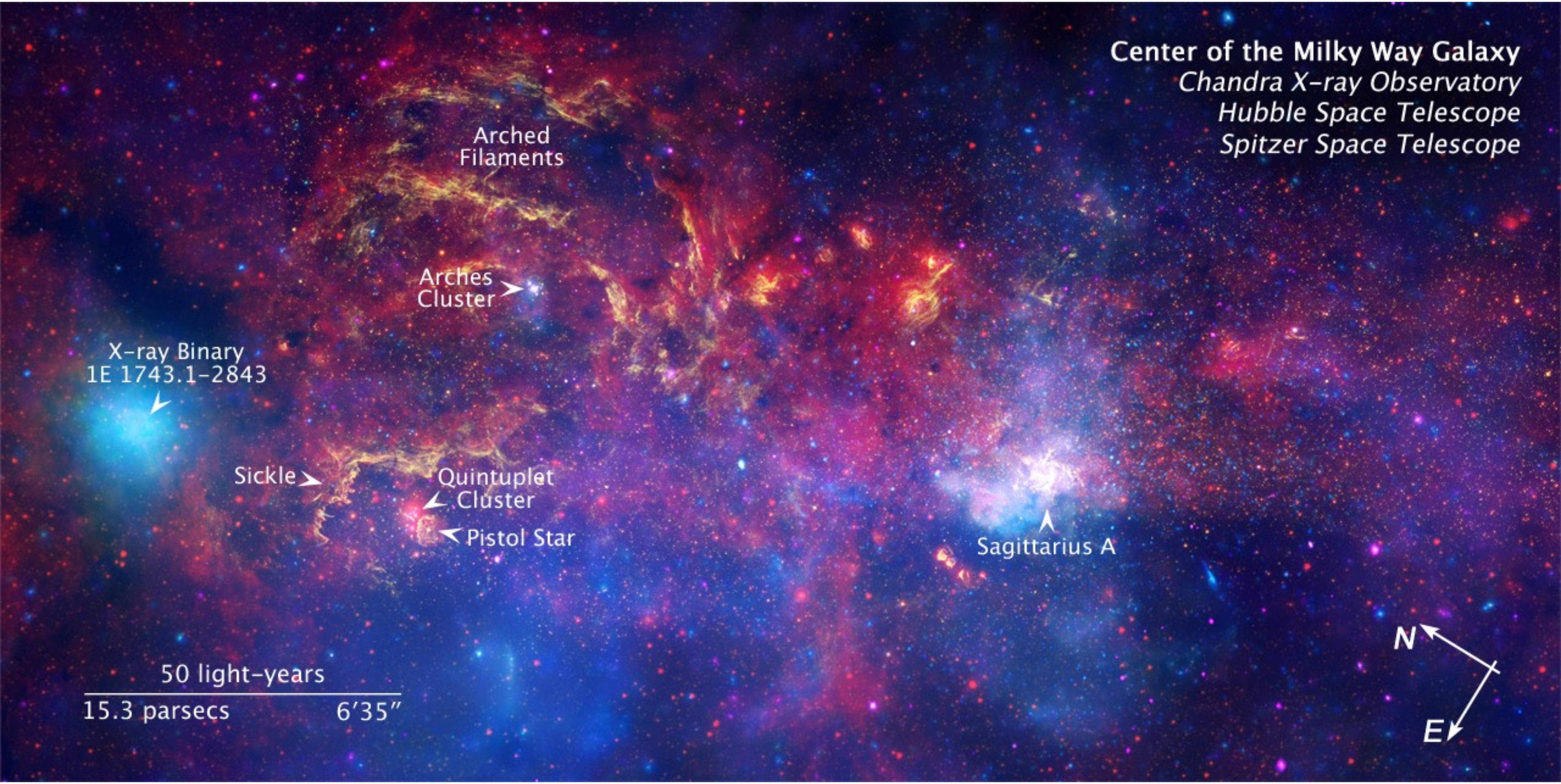
We have other evidence of black holes: the centres of many galaxies, including our own, show signs that they contain giant black holes, millions of solar masses in size.

The following is a comparison between X-ray and radio pictures of the centre of our Galaxy. We suspect the complex labelled “Sagittarius A” harbours a giant black hole.

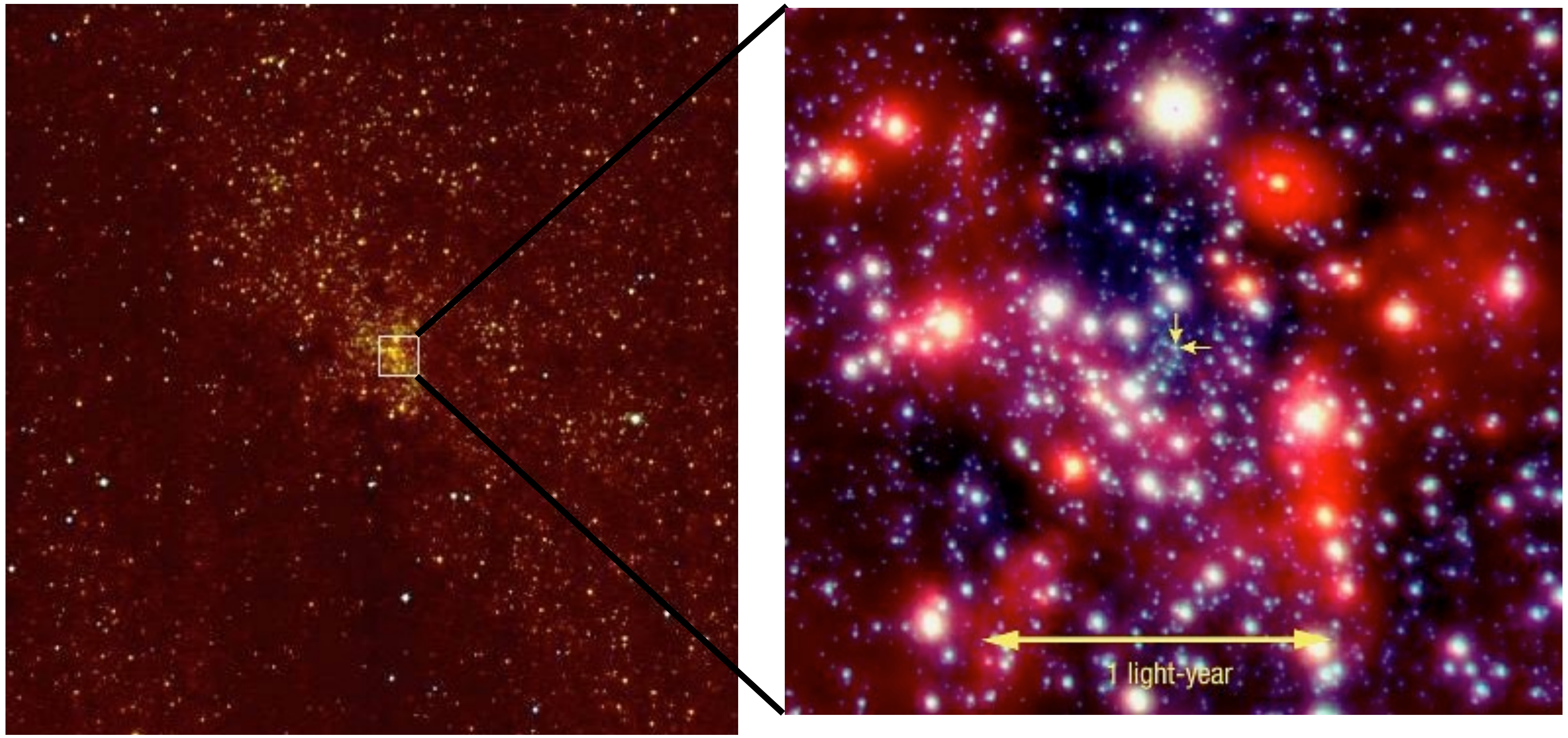


X-ray (top) and radio (bottom) images of the Galactic centre region: a violent place with supernovae, X-ray binaries, and a giant black hole hidden in Sagittarius A.

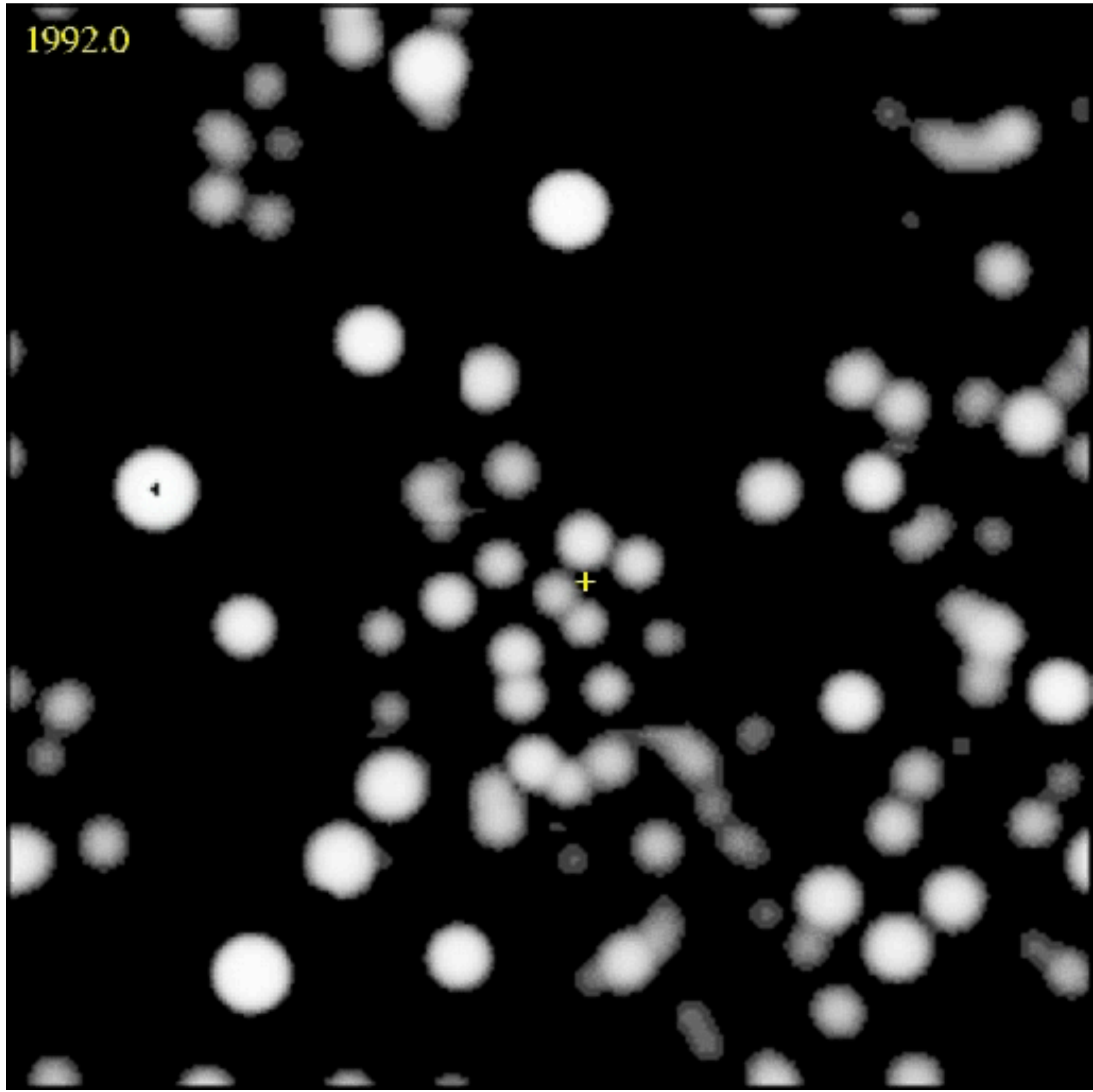



Center of the Milky Way Galaxy
Chandra X-ray Observatory
Hubble Space Telescope
Spitzer Space Telescope
Arched Filaments
Arches Cluster
X-ray Binary 1E 1743.1-2843
Sickle
Quintuplet Cluster
Pistol Star
Sagittarius A
50 light-years
15.3 parsecs
6′35″
N
E

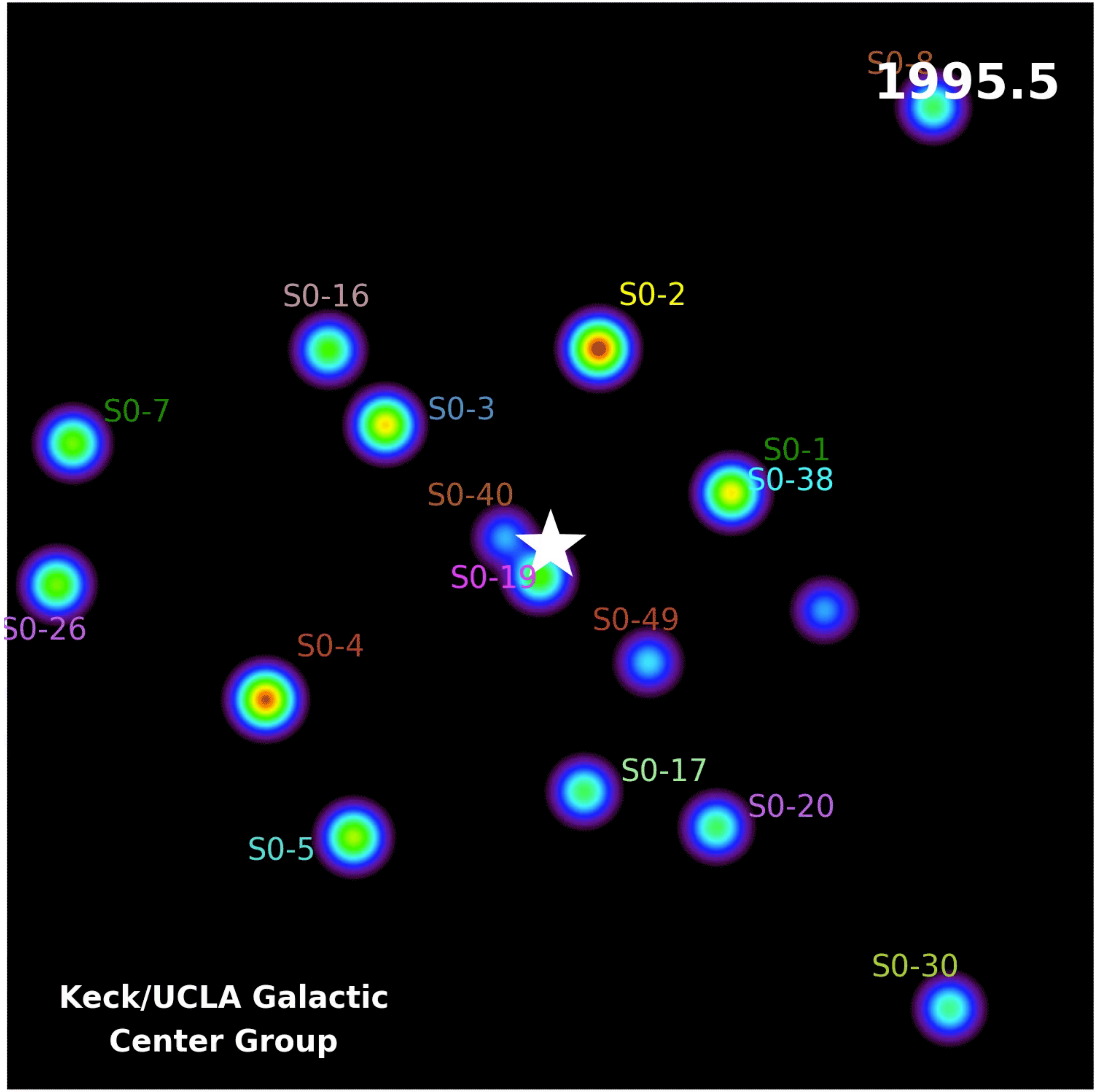
The best evidence for the mass of the black hole comes from very high resolution infrared images of stars at the very centre: images over several years show discernible motion, indicating the stars are being whipped around by a very large mass.



The star closest to Sgr A* can actually be seen to orbit the central mass; at its closest, it comes within 17 light-hours of the source (3 times the Sun-Pluto distance), at which time it is moving at 5000 km/s. The best estimate for the mass of the black hole is 2.6 million solar masses.



Infrared images of the central 2x2 arcsec around the black hole.


1995.5
S0-8
S0-16
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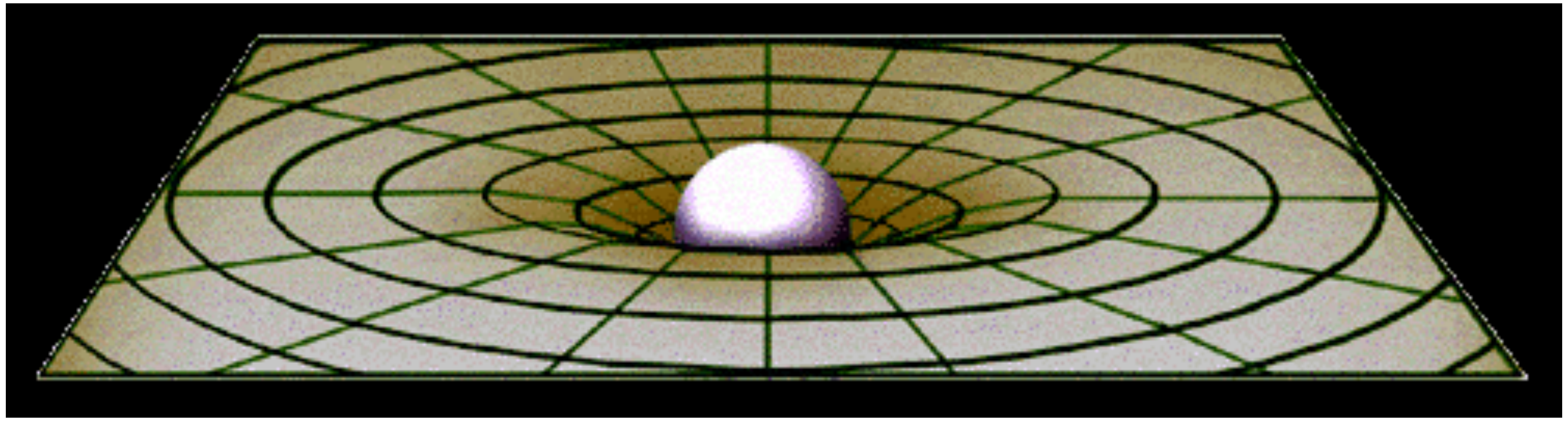
S0-19
S0-49
S0-26
S0-4
S0-17
S0-20
S0-5
S0-30
Keck/UCLA Galactic
Center Group

But what *is* a black hole? What do we mean when we say the star collapses all the way?

Let's start with Einstein. In his *Special Theory of Relativity*, he had already shown that space and time are fundamentally connected: that measurements of each depend on the speed of the observer. In 1916, he published his *General Theory of Relativity*, in which he postulated that mass causes space-time to curve, and it is this curvature that we perceive as gravity.

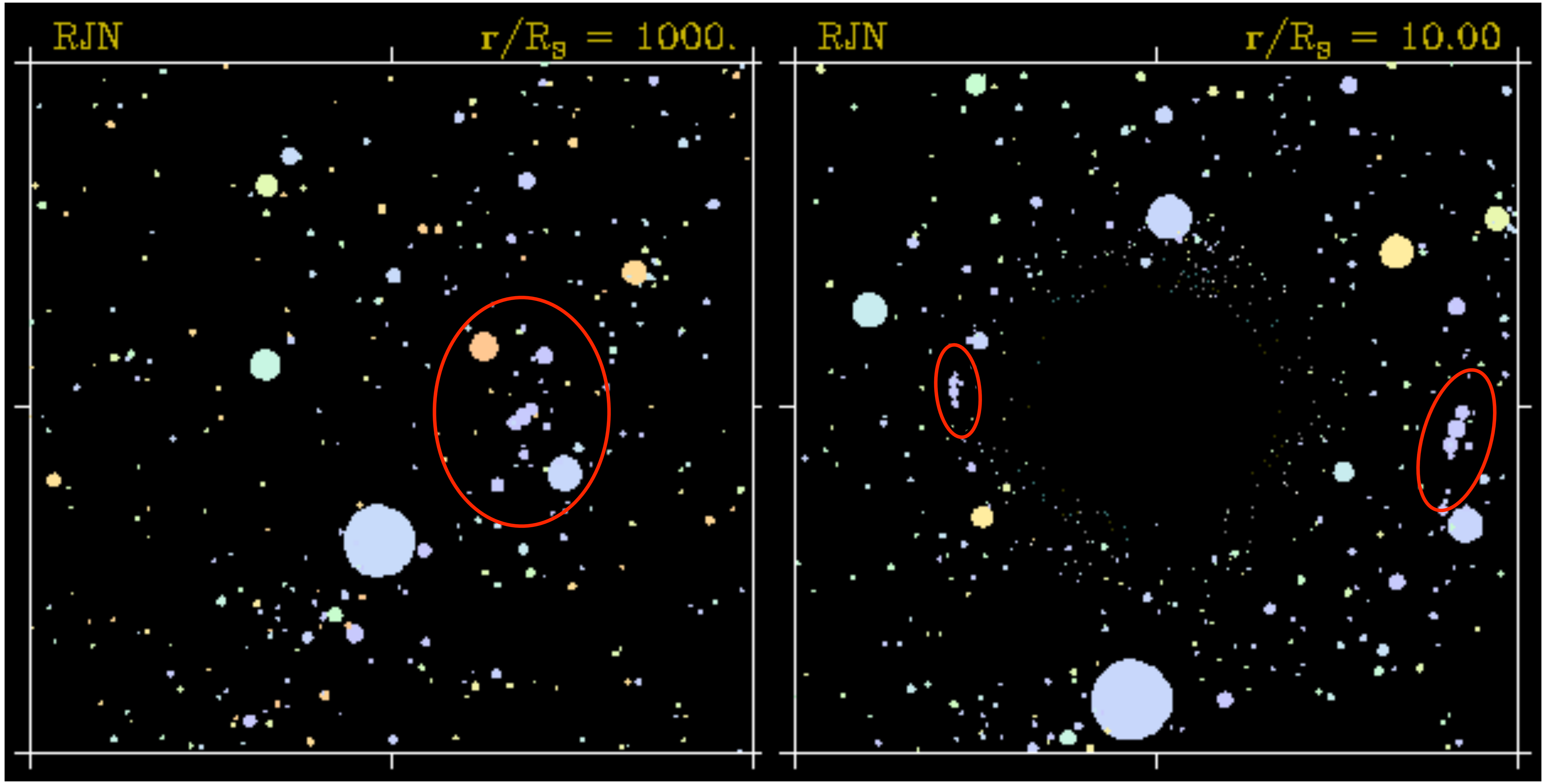


Gravity is no longer a mysterious force exerted at a distance by bodies. Instead, mass distorts space itself, and particles travelling through space get deflected by the distortions.

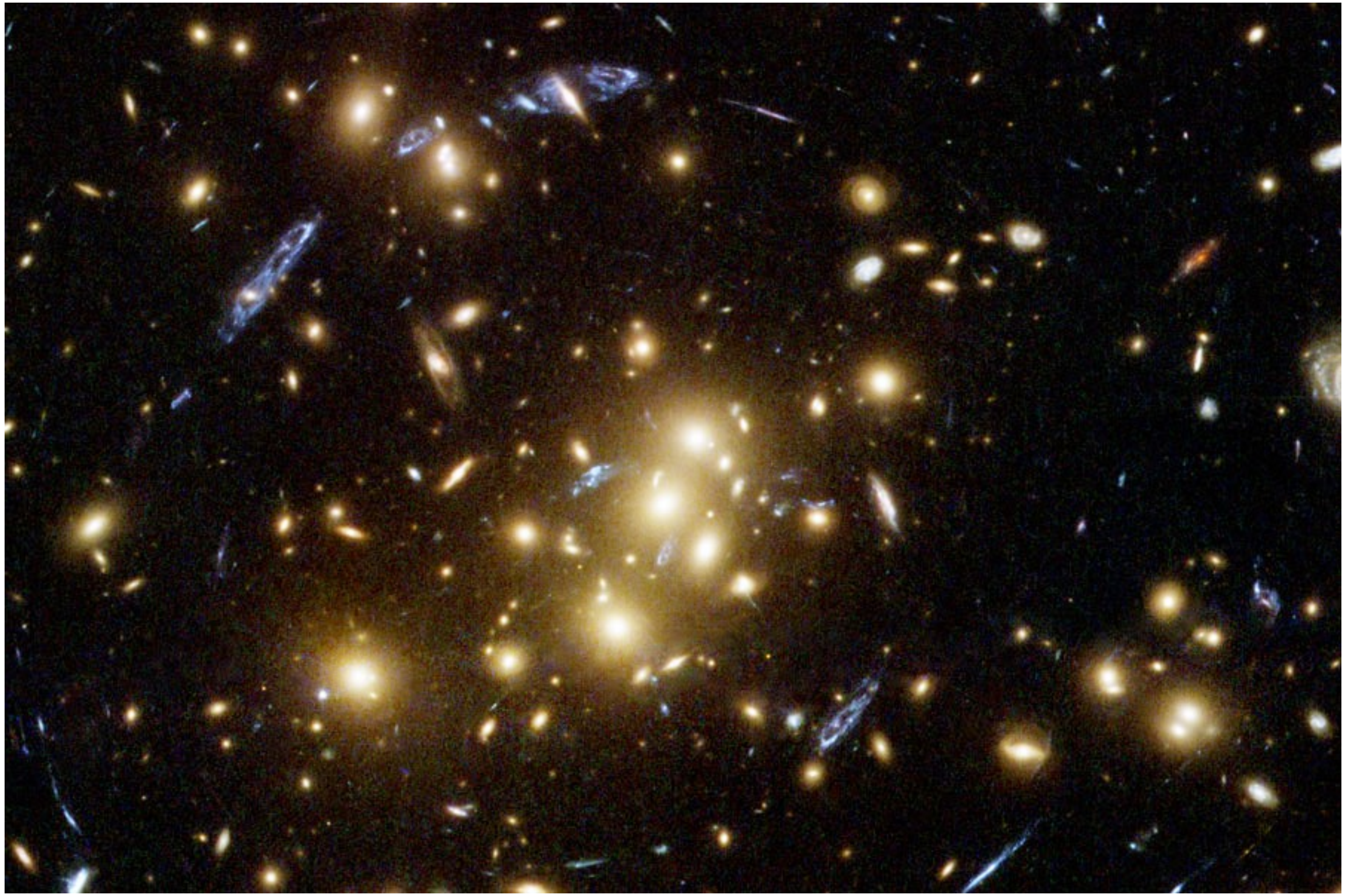
"Space tells matter how to move; matter tells space how to curve"

– John Archibald Wheeler

Light is bent by this curvature of space as well. Here is what a field of stars (left) would look like if a black hole was in front. Images are not only distorted, but double: light can reach us via multiple paths.

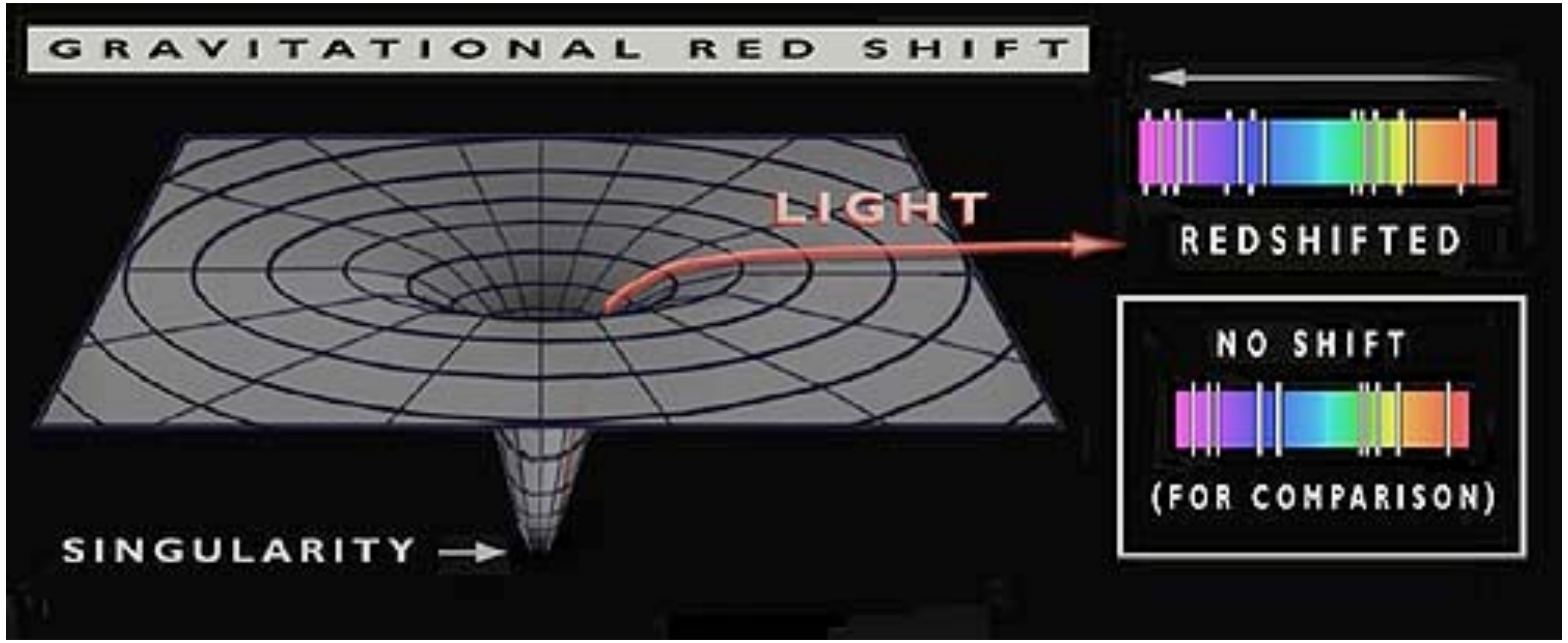


This bending of light has been seen, where a foreground cluster of galaxies acts as a *gravitational lens* bending the light of a more distant cluster into strange shapes.



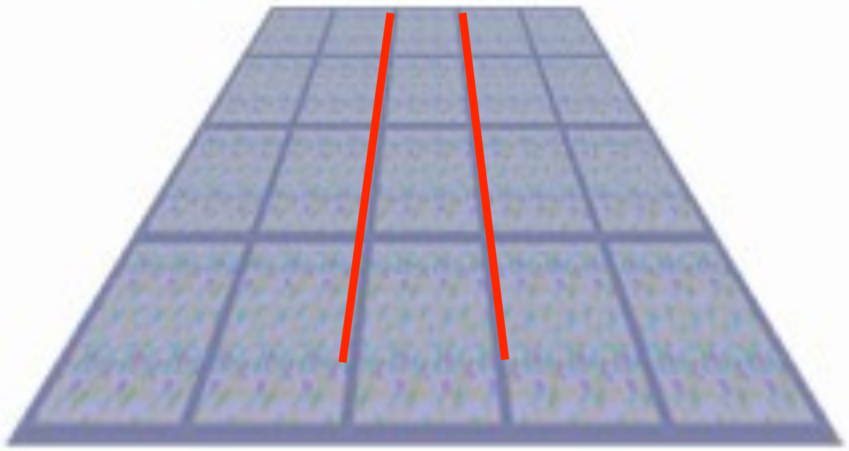
Another prediction of General Relativity is that light passing through a gravitational field will be *redshifted*. As the photon fights its way out of the gravitational field, it loses energy and its colour reddens.

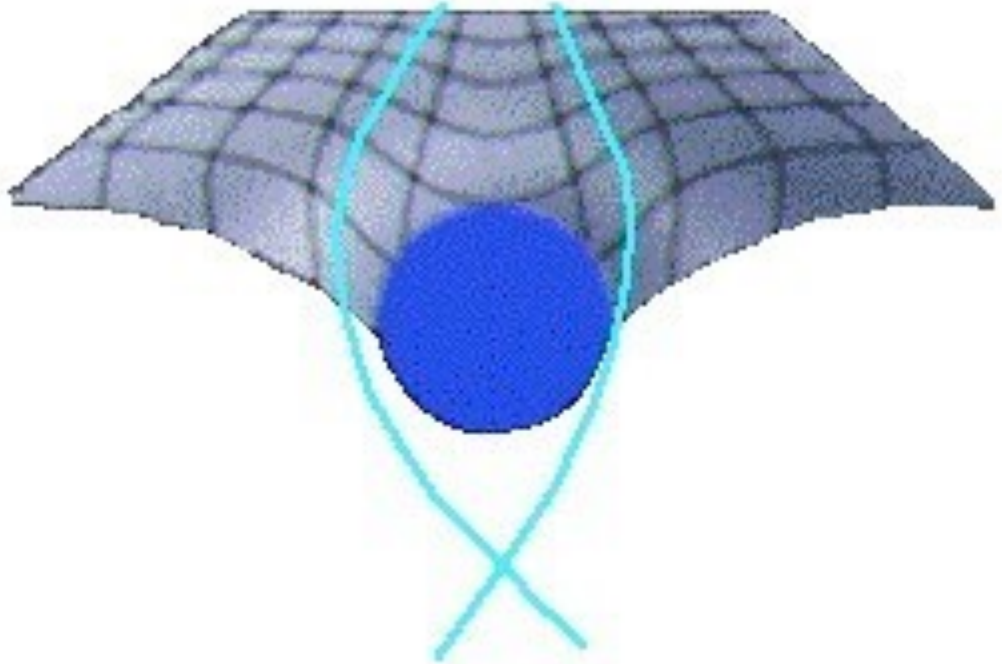
Gravitational redshift was first observed in the spectrum of Sirius B, the white dwarf companion to Sirius.



It is important to realise what these diagrams (called *embedding diagrams*) mean. They are representing our familiar *three*-dimensional universe as a *two*-dimensional surface in three-dimensional space. It allows us to see things like “curvature of space-time” which we can’t otherwise conceive of. But remember that everything we can measure in the real universe is also embedded in the 2D sheet, including *ourselves*. We have no way of ever seeing this third dimension, we can only *measure its effect* on our two-dimensional universe.

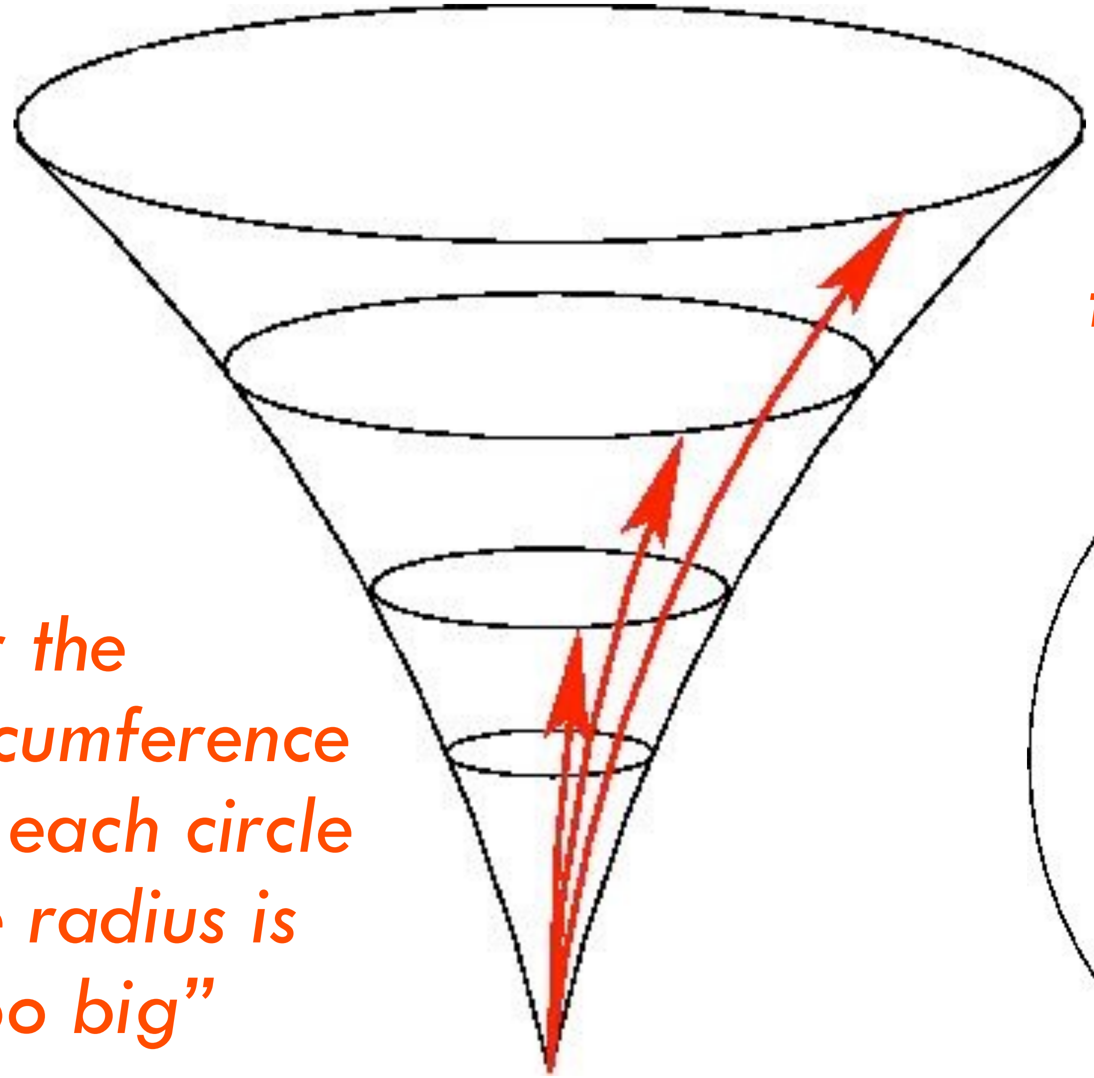
So for instance, in the absence of any mass and so any curvature, our 2D space-time would be flat. How do we check this? We draw straight lines (by laying rulers side by side and sliding them along), and they never intersect.





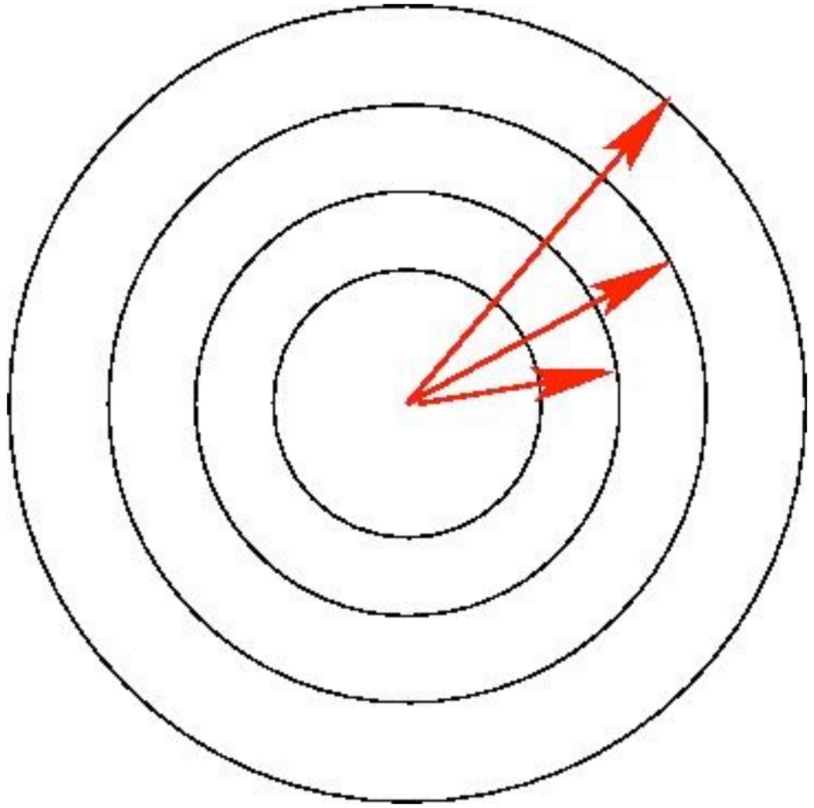
But if space is curved, then the lines can end up intersecting, or diverging. So by checking what straight lines do, we can *deduce* that space is curved, even if we can't see it

Similarly, in our 3D universe, we can't see the curvature of space, but we can deduce its existence. A 2D observer would deduce that space was curved because the circumference of a circle around a mass would not equal 2π times the radius.



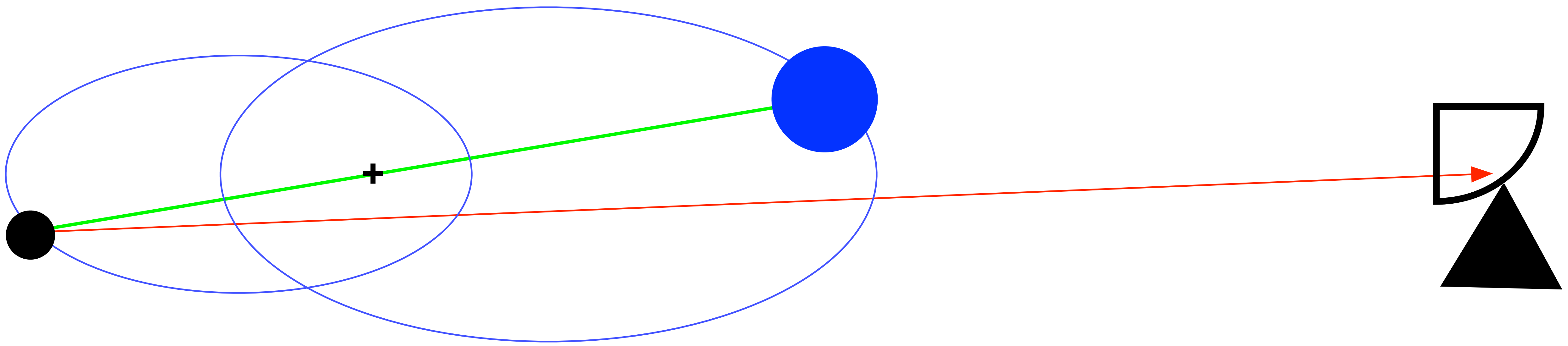
for the circumference of each circle the radius is "too big"

top view:



Analogously, careful measurement of the shape of spheres around a mass in 3D space would show that each sphere had a circumference less than 2π times the radius.

This is where the binary pulsars are so important: we can actually measure th
extra distance the light must travel when it goes near the companion, becaus
the companion's mass is distorting space-time.



The signal from the pulsar arrives earlier or later depending on where the pulsar is in its orbit.

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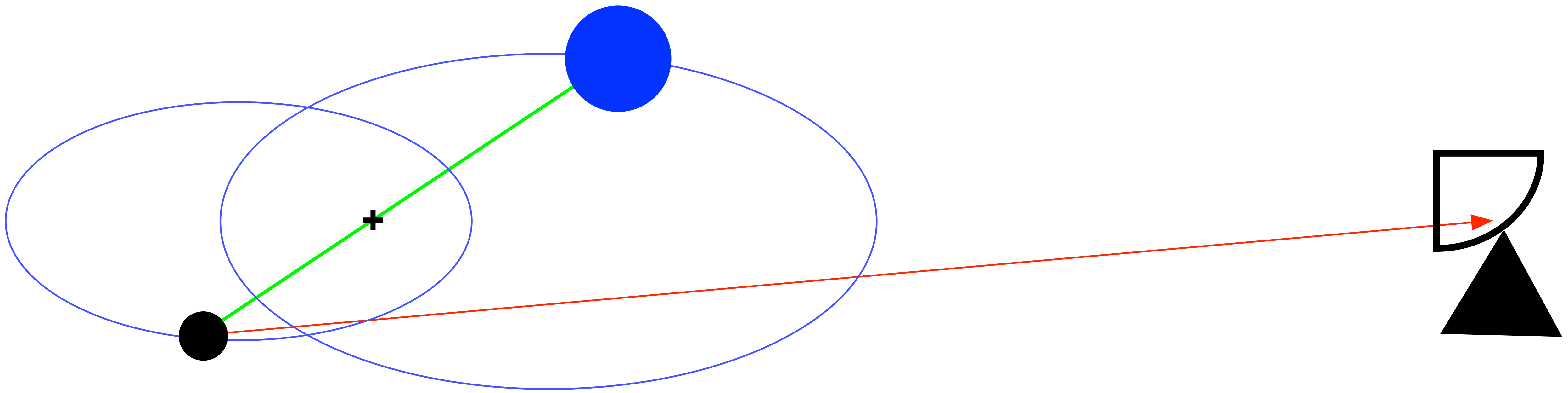

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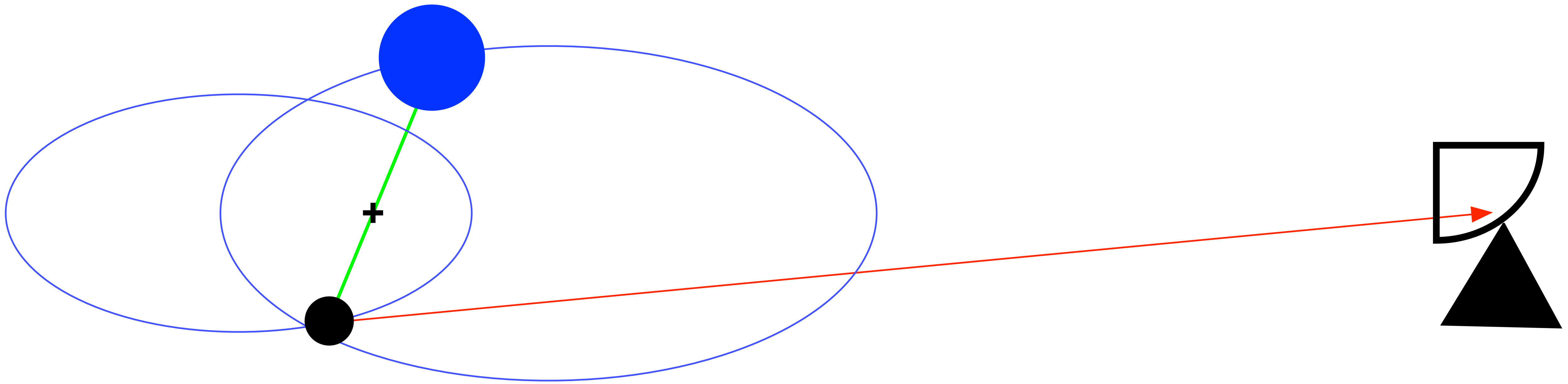

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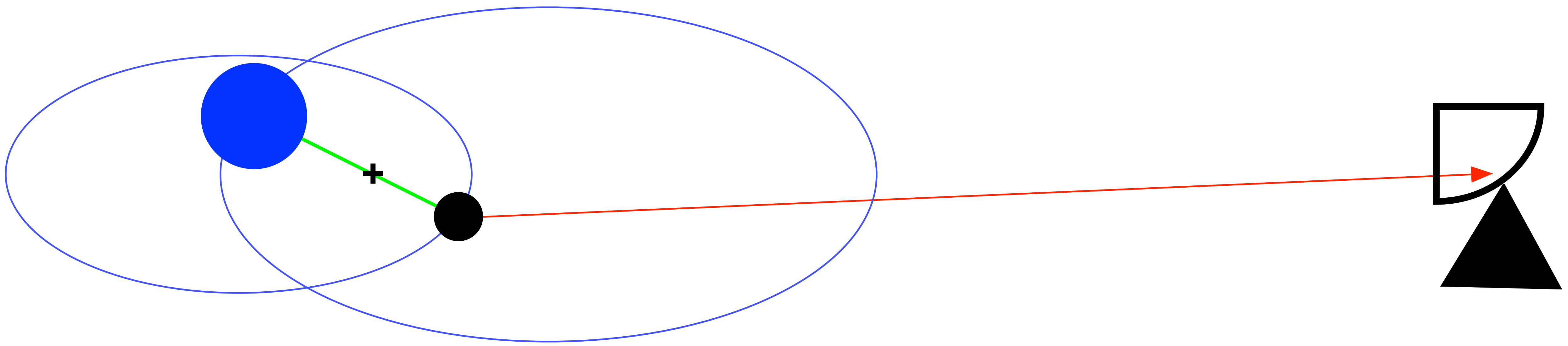

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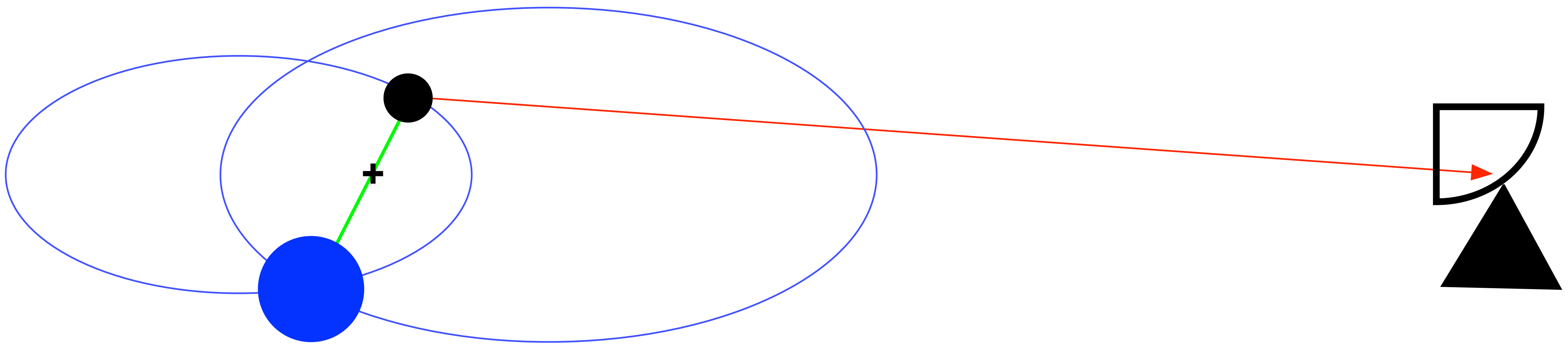

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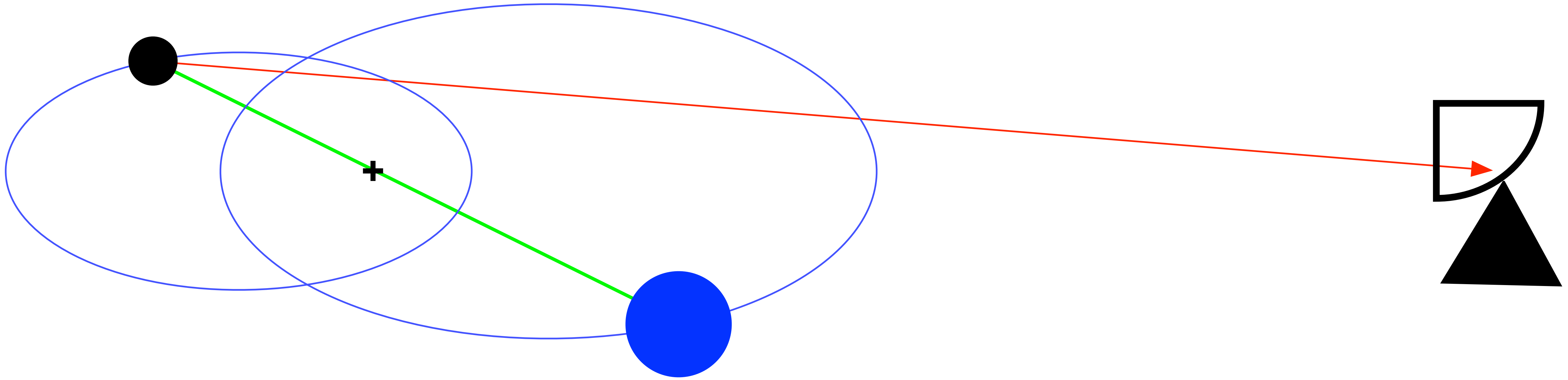

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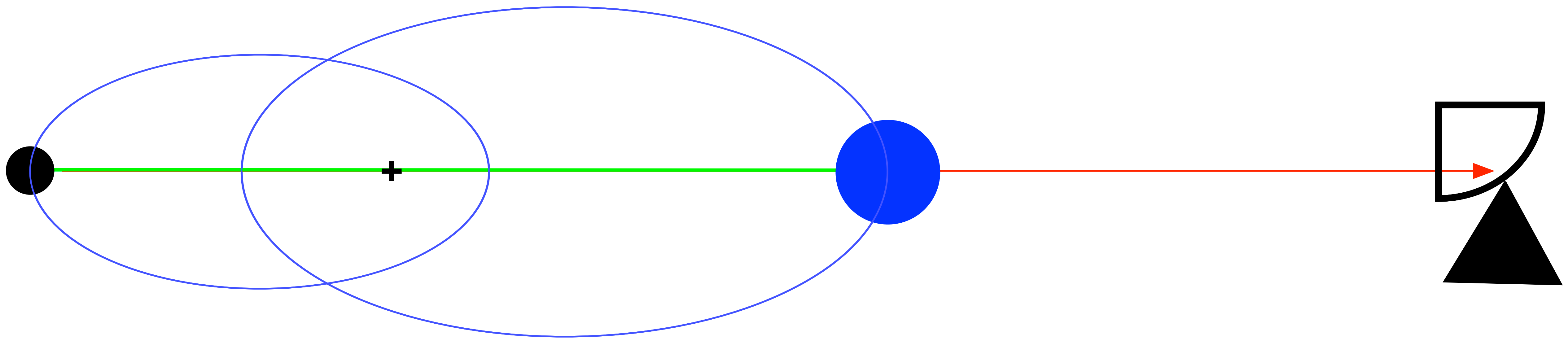
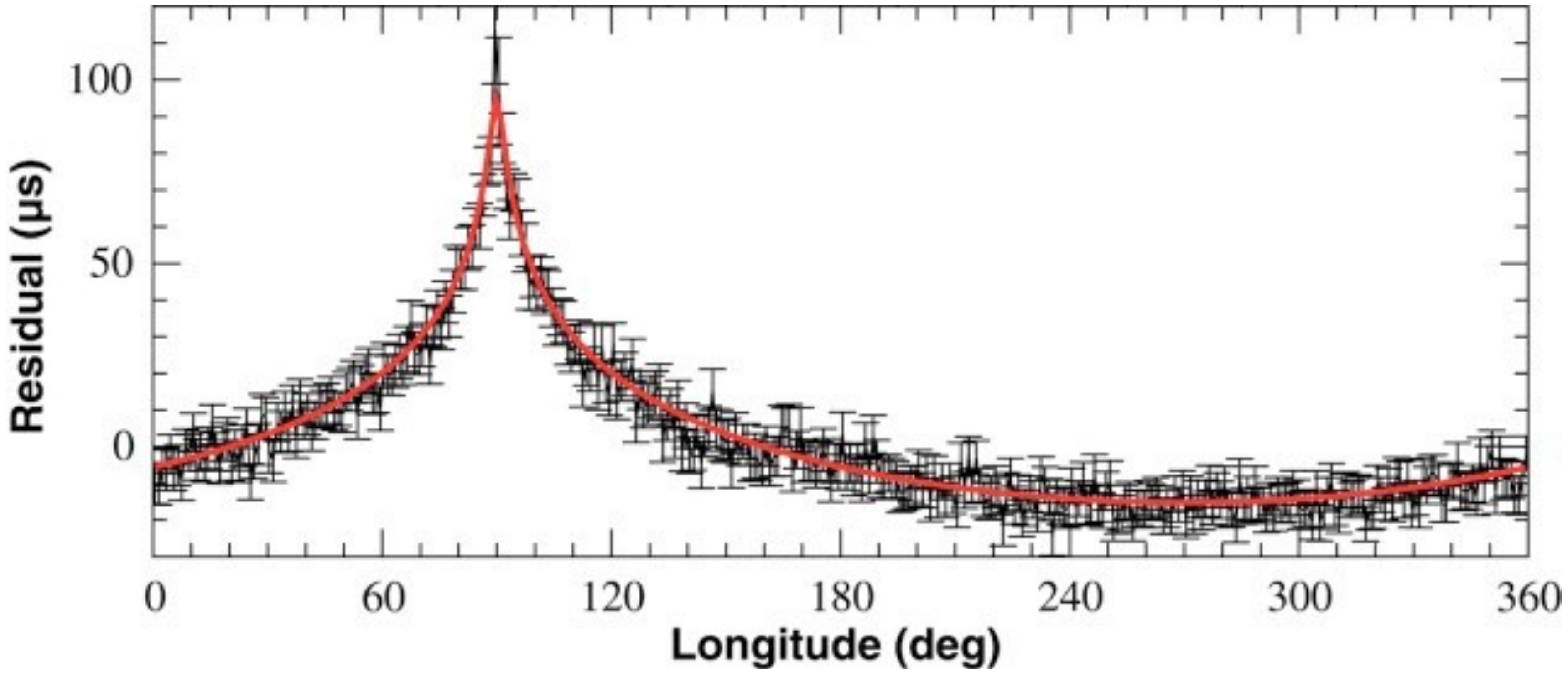


The signal from the pulsar arrives earlier or later depending on where the pulsar is in its orbit. But when the light travels near the companion, there is an *extra* delay because the mass of the companion is bending space.

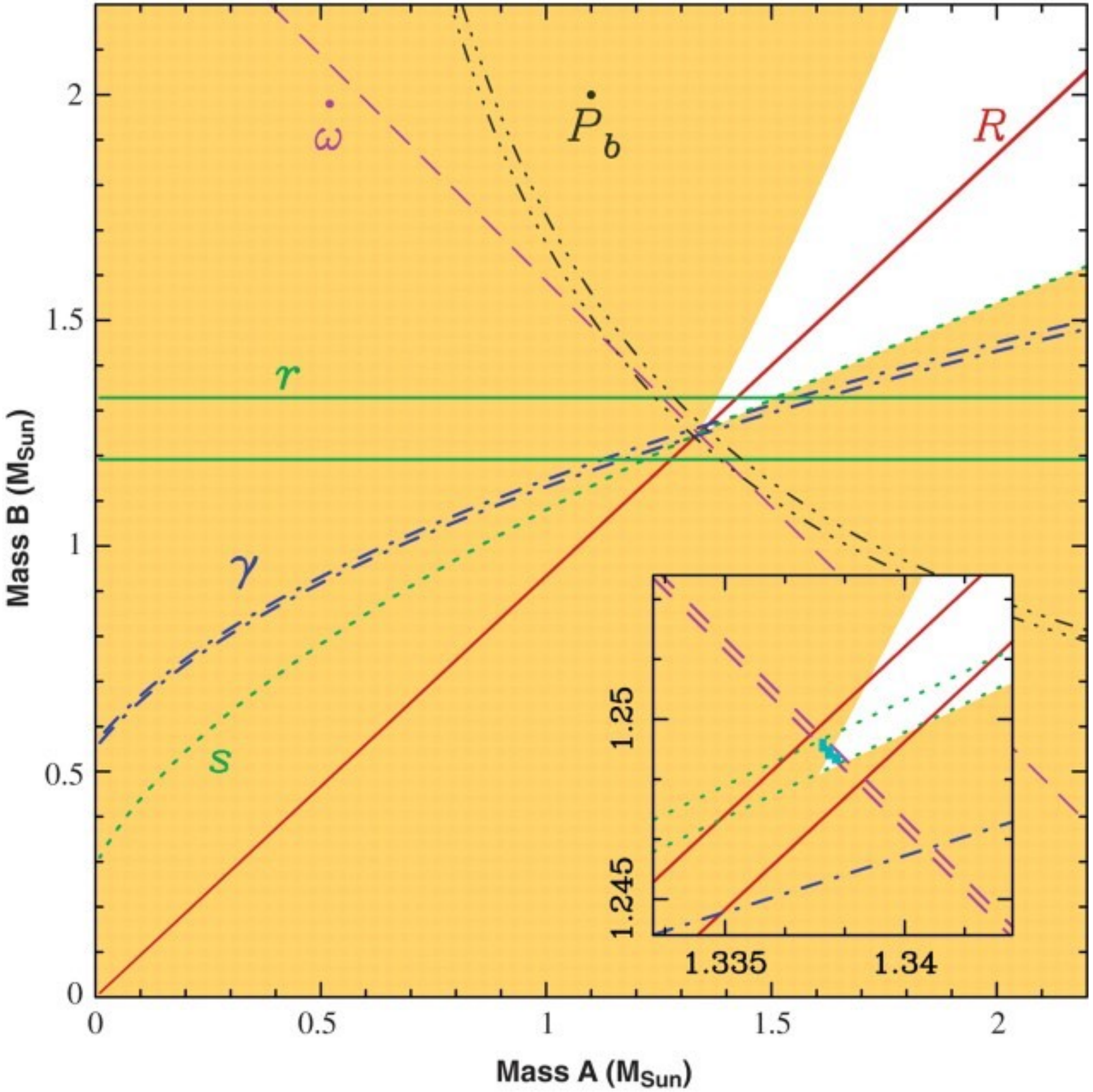
This delay is called the *Shapiro delay*, and can be measured in pulsars in binaries which are nearly edge-on, so that the pulsar's signal travels near to companion.

The double pulsar, J0737–3039A and B, is nearly edge-on, so this delay is easily measurable.

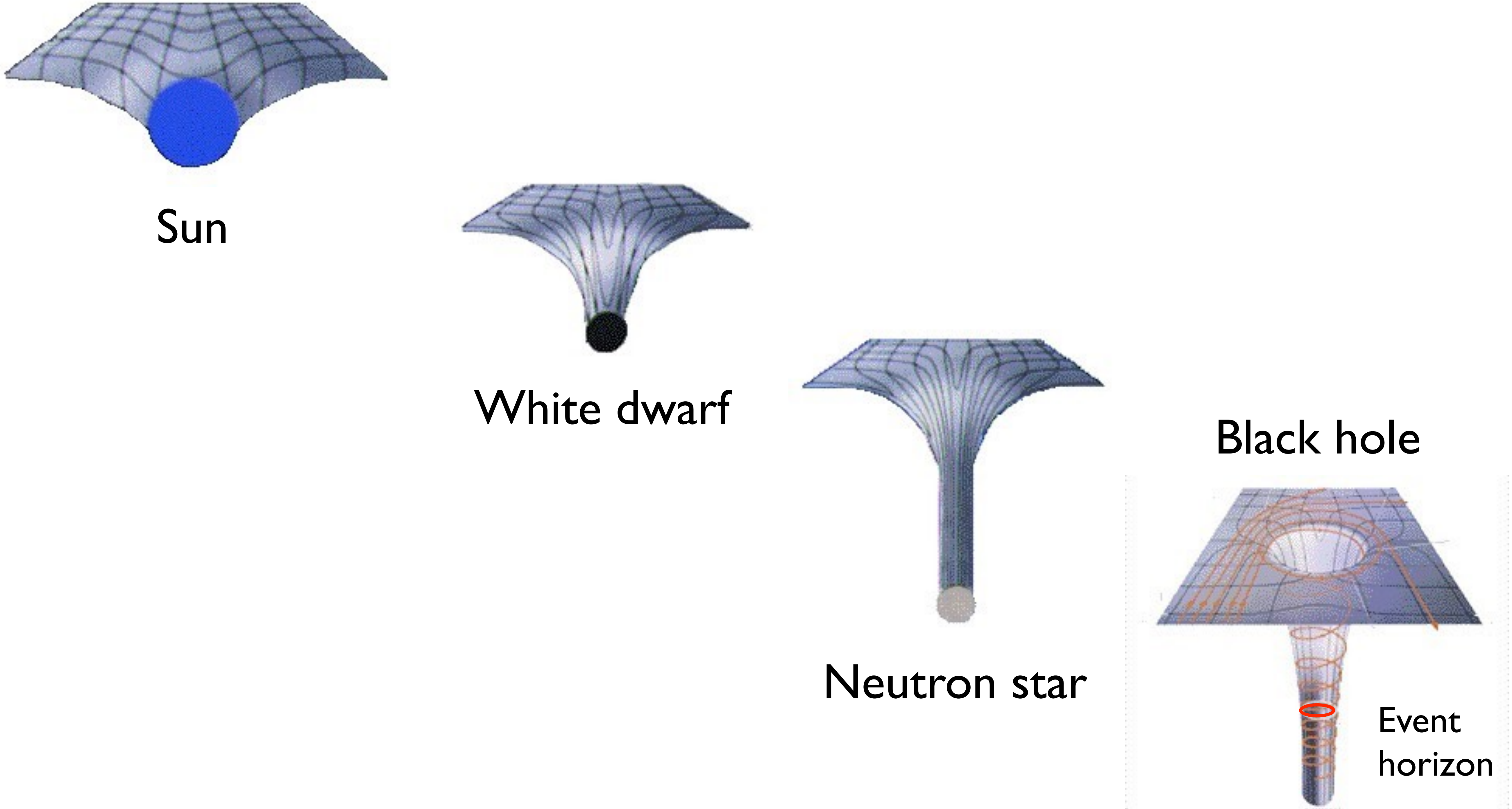
Measurement of the Shapiro delay for the double pulsar PSR J0737–3039A.



In fact, the double pulsar provides the most stringent test yet of the theory of General Relativity; the pulsar parameters agree with GR predictions to 0.05%.



Now let's consider what happens when we take a star of a given mass and make it smaller. The surface gravity increases; space-time gets more curved.



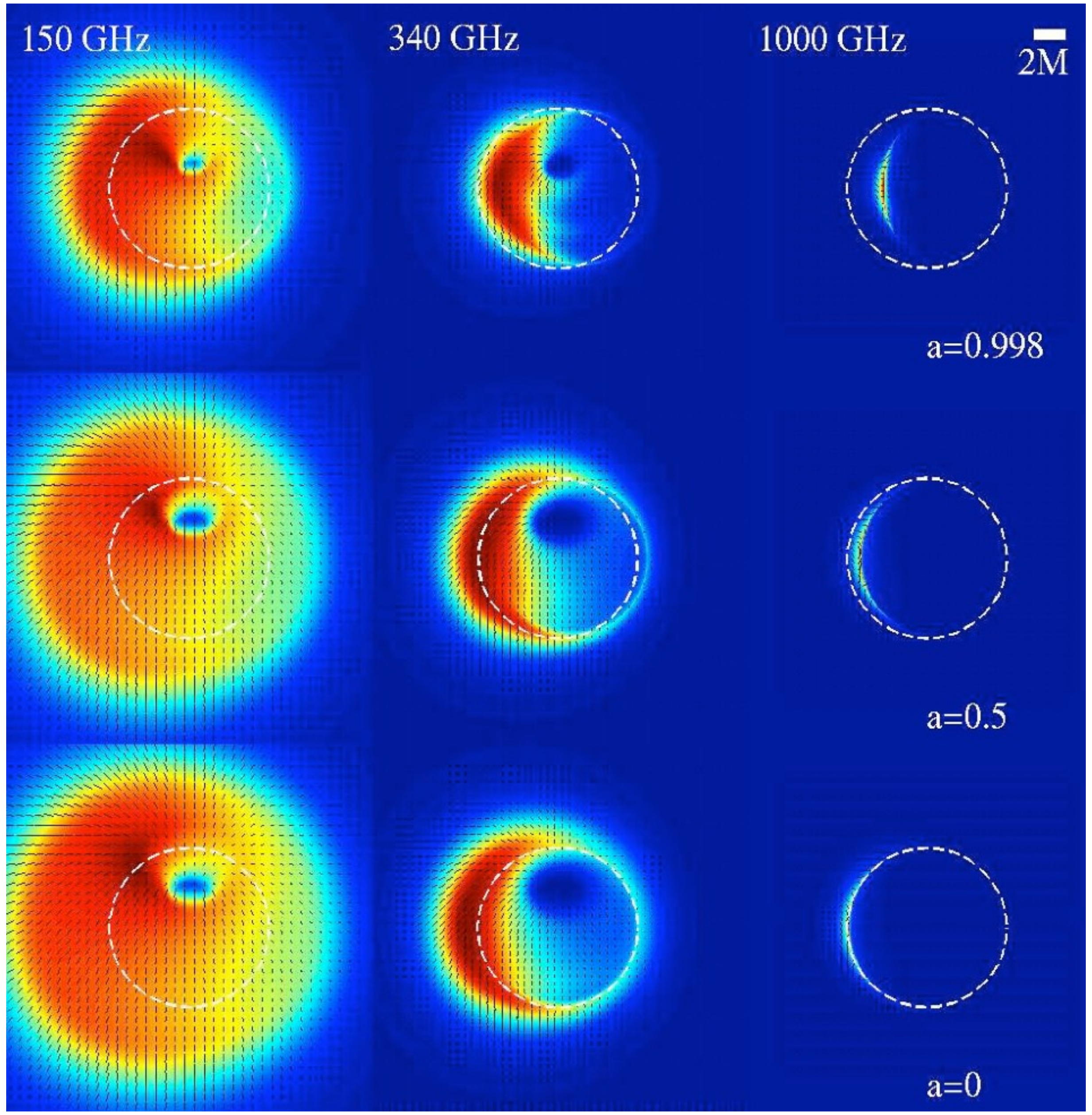
Since no information can come out of the black hole, we can only see the effects it has on particles moving near it.

Unfortunately, there aren't many astronomical measurements which can tell the difference between motion near a neutron star and a black hole.

Finding a pulsar in a binary with a black hole would be the best way to investigate a black hole at close range… but we have to find one first.

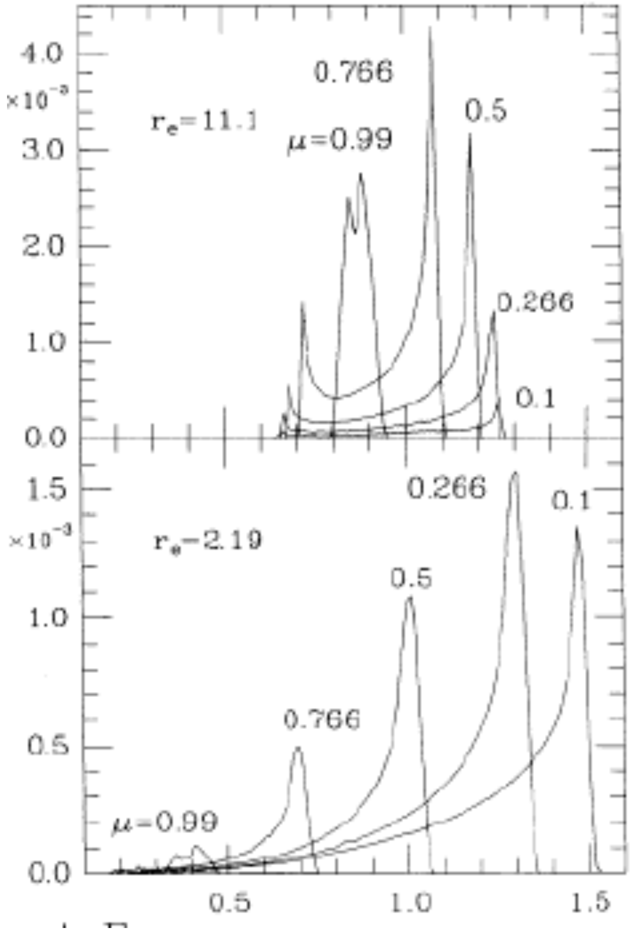
There are a few potential measurements we could make, but at the moment they're still just beyond our capacity.

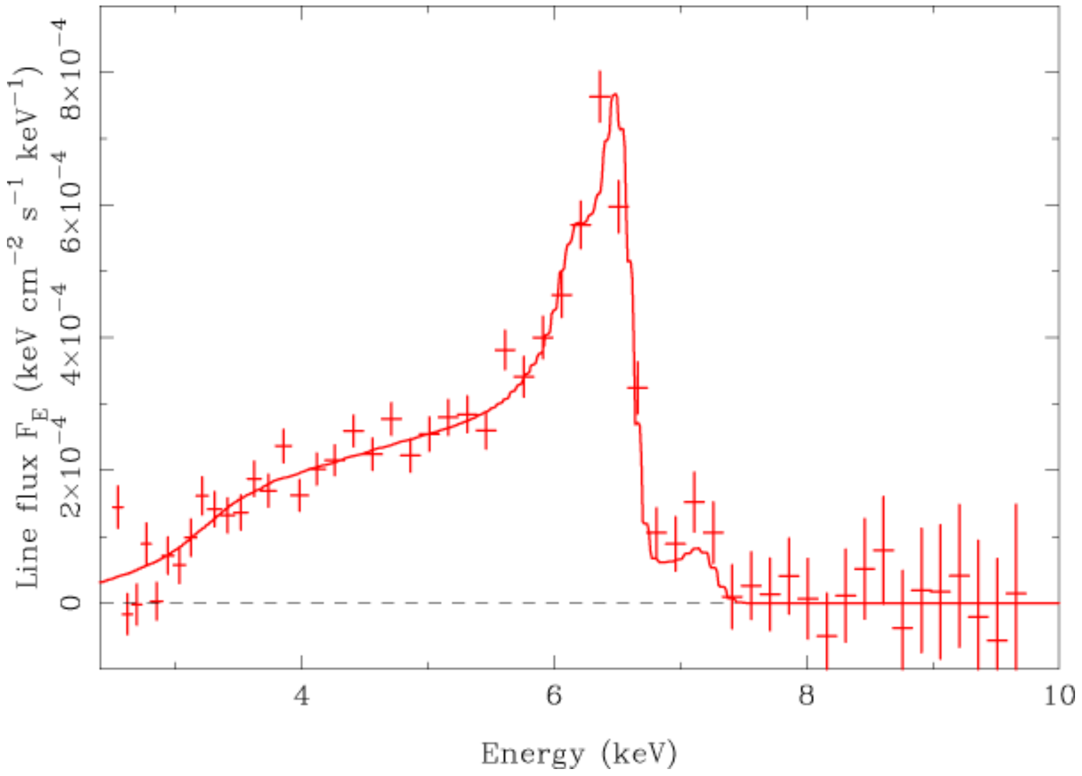
A spinning black hole will warp spacetime so that the centre of the image shifts depending on what frequency it is observed at; this effect could potentially be seen for the black hole at the Galactic centre, which is the black hole with the largest angular size.



Calculated images for black holes rotating at different speeds (fastest at top).

A spinning black hole will produce a strongly asymmetric emission line. Some asymmetric lines are being found near supermassive black holes, but the results are not totally convincing yet.

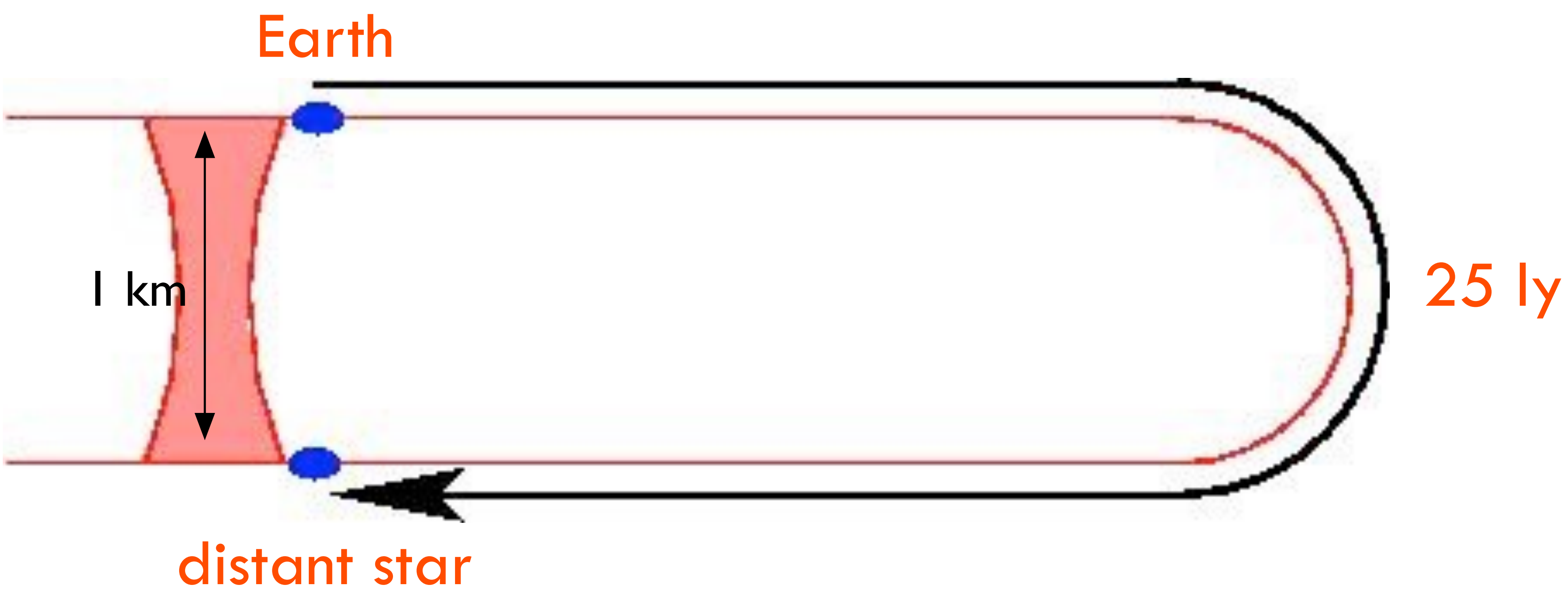




(left) Predicted line profiles from a disk around a rotating black hole. (right) X-ray iron line observed from the supermassive black hole in the galaxy MCG–6-30-15.

Even weirder...

Einstein's equations actually allow for a bridge between a black hole and its inverse, a *white hole*, with a passage between them. Such a passage has become a staple of SF writers. Unfortunately, for the standard black hole solution, this worm hole exists for only a single moment in time: at any other time, the wormhole has vanished, and there is only the trap of the singularity.



In his novel “Contact”, Carl Sagan wanted to send his heroine into a black hole, and sent a draft to Kip Thorne, a world expert on relativity. This started Thorne thinking about other possibilities for wormholes.

He found a solution allowed by physics: it involved *exotic matter*, a strange substance which has negative energy, and so has the property one would call “antigravity”. He showed that if you could thread a wormhole with this exotic matter, it could be stable. Sagan re-wrote the last chapter of his book to take this into account.

What’s more, these solutions also allow the construction of time machines... but that’s another story.

Next week

…is our last lecture. I propose to tell you about interacting binary stars, and their link to the discovery of gravitational waves.

Further reading

- “**Cosmic Catastrophes: Exploding Stars, Black Holes, and Mapping the Universe**” by J. Craig Wheeler (Cambridge UP, 2007) – the first edition from 2000 was subtitled “Supernovae, Gamma-ray Bursts and Adventures in Hyperspace” – is a wonderful description of the violent end of stars. He has a very good overview of stellar evolution first, and one of the best explanations (and use) of the “rubber sheet” diagrams which we’ve introduced here as potential well diagrams for looking at binaries. I’ll be recommending this book for black holes next week as well. Be warned: some people have reported finding it rather hard going.

- “**Gravity’s Fatal Attraction: black holes in the universe**” by Mitchell Begelman and Martin Rees (Scientific American Library, 1998) is a nice book about black holes. It’s geared more towards the supermassive black holes in the centres of galaxies, but it has a nice description of SS 433, for instance.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.

- There are a couple of articles and press releases about the discovery of the double pulsar, at the Australia Telescope site, http://www.atnf.csiro.au/news/newsletter/feb04/page1.html, and Jodrell Bank http://www.jb.man.ac.uk/news/doublepulsar/

- If you'd really like to get your mind around higher dimensions, you should start off with reading "**Flatland**" by Edwin Abbott. Written in 1884, it's about a two-dimensional being who gets to experience life in three-dimensional space. Not one, but two movies were recently made about the book: I have "Flatland the Movie" (to distinguish it from "Flatland the Film (!)), and it's very enjoyable. Short, too: only 35 min long.

- Robert Duncan has a very good page about magnetars at " `Magnetars', Soft gamma repeaters and Very Strong Magnetic Fields" , http://solomon.as.utexas.edu/~duncan/magnetar.html

- Cole Miller has a more technical, but still readable, page called "Introduction to Neutron Stars" http://www.astro.umd.edu/~miller/nstar.html

- 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 excellent discussion of topics like 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/docs/teachers/blackholes/imagine/contents.html

- The UCLA Galactic Centre Group page at http://www.galacticcenter.astro.ucla.edu/about.html has lots of interesting images and animations about their work measuring the mass of the black hole at the centre of our Galaxy.

- http://www.bigear.org/vol1no1/burnell.htm reproduces an article originally presented as an after-dinner speech at one of the Texas Symposia by Jocelyn Bell Burnell – it's a very personal and entertaining account of the discovery of pulsars. She gave a paper about serendipitous discoveries, available at http://pos.sissa.it/cgi- bin/reader/conf.cgi?confid=99, including a description of several people who almost discovered pulsars before she did. She appeared on an episode of the BBC series "Beautiful Minds" http://www.bbc.co.uk/programmes/b00ry9jq – the episode is not currently available, but watch it if you get the chance.

- The ATNF pulsar catalogue keeps an up-to-date list of every known pulsar at http://www.atnf.csiro.au/people/pulsar/psrcat/

Sources for images used:

- Black hole image: from NBC http://www.nbcnews.com/science/space/science-interstellar-look-beyond-wormhole-n241441
- Stellar fates: from Chandra Resources: Stellar evolution, http://chandra.harvard.edu/resources/illustrations/stellar_evolution.html
- NGC 2440 and its white dwarf: from Astronomy Picture of the Day, 2004 January 11, http://apod.nasa.gov/apod/ap040111.html
- Sizes of white dwarfs: from Wikipedia http://en.wikipedia.org/wiki/White_dwarf
- 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
- 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
- White dwarf masses: from “A spectroscopic determination of the mass distribution of DA white dwarfs” by Bergeron, Saffer and Liebert, ApJ 394, 228-247 (1992)
- Animation of lighthouse model: from “Stars and Galaxies: A Hypertext Course” by Richard McCray, Lecture 7 http://cosmos.colorado.edu/cw2/courses/astr1120/text/chapter7/lesson7.html
- Crab pulsar: from "Optical images of the Crab Pulsar" from the SEDS M1 page: http://www.seds.org./messier/more/m001_pulsar.html
- Neutron star interior: from Science@NASA: Crusty young star makes its presence felt, http://science.msfc.nasa.gov/newhome/headlines/ast29sep98_1.html; second image from Cole Miller’s “Introduction to Neutron Stars” http://www.astro.umd.edu/~miller/nstar.html
- Neutron star masses: from Neutron Star Masses by Max Camenzind, http://www.lsw.uni-heidelberg.de/users/mcamenzi/NS_Mass.html
- Binary pulsar: from 1993 Nobel Poster for Physics, http://www.nobel.se/physics/laureates/1993/illpres/discovery.html
- X-ray binary: University of Palermo High-Energy Astrophysics Group, http://www.fisica.unipa.it/astrofisica/sistemiX.shtml
- 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/
- Making a magnetar: from “`Magentars', soft gamma repeaters & very strong magnetic fields” by Robert Duncan, http://solomon.as.utexas.edu/~duncan/magnetar.html
- Image of magnetar 1E 1048.15937: from “A wind bubble around a magnetar”, http://www.atnf.csiro.au/research/highlights/2004/gaensler/gaensler.html
- Fates of stars: from Woosley, Heger and Weaver 2002, Rev Mod. Phys. 74, 1015, Figs 12 and 16 http://link.aps.org/abstract/RMP/v74/p1015
- Braking pulsar: slow-down rate, from Kramer et al., “A Periodically Active Pulsar Giving Insight into Magnetospheric Physics”, Science 312, 549 (2006); animation of pulsar from Jodrell Bank Press Release 2006/06, “Part-time pulsar yields new insight into inner workings of cosmic clocks”, http://www.jb.man.ac.uk/news/brakingpulsar/
- Quark stars: from Chandra resources http://chandra.harvard.edu/resources/illustrations/neutronstars_4.html
- Velocity of companion to A0620–00: from “Doppler tomography of the black hole binary A0620-00 and the origin of chromospheric emission in quiescent X-ray binaries” by Gonzalez Hernandez & Casares 2010 http://xxx.adelaide.edu.au/abs/1004.0435
- Spectra of SS433: from “Gravity’s Fatal Attraction” by Begelman and Rees (Scientific American Library 1998), p. 137
- Artist’s impression of SS433: from ESO press release eso9107, https://www.eso.org/public/news/eso9107/
- X-ray and radio images of the Galactic centre: from UMass/Columbia Chandra X-ray Survey of the Galactic Center Images, http://www.astro.umass.edu/~wqd/gcs/images.htm
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