Lives of the Stars Lecture 7: Supernovae

Presented by
Dr Helen Johnston
School of Physics

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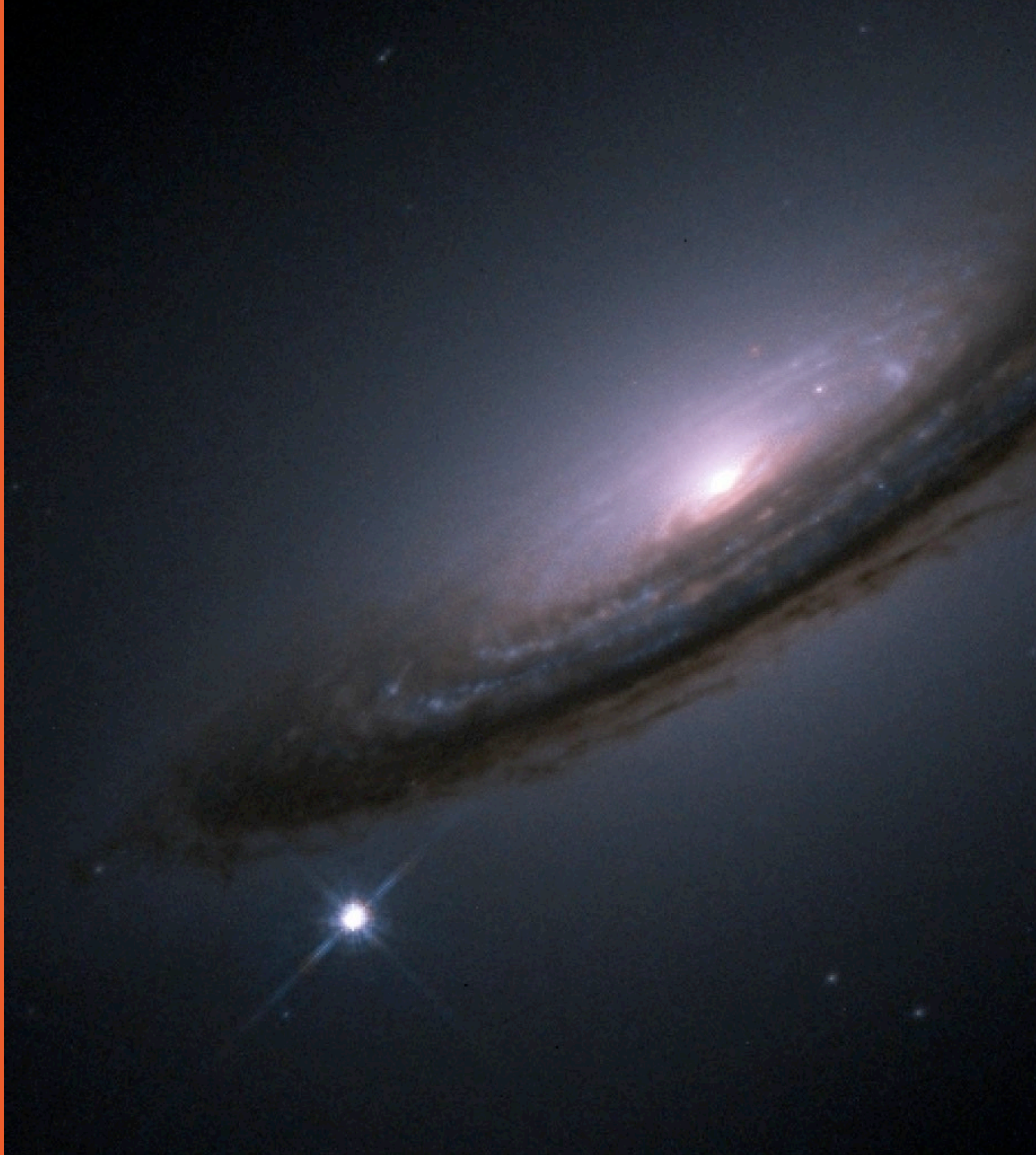
THE UNIVERSITY OF SYDNEY



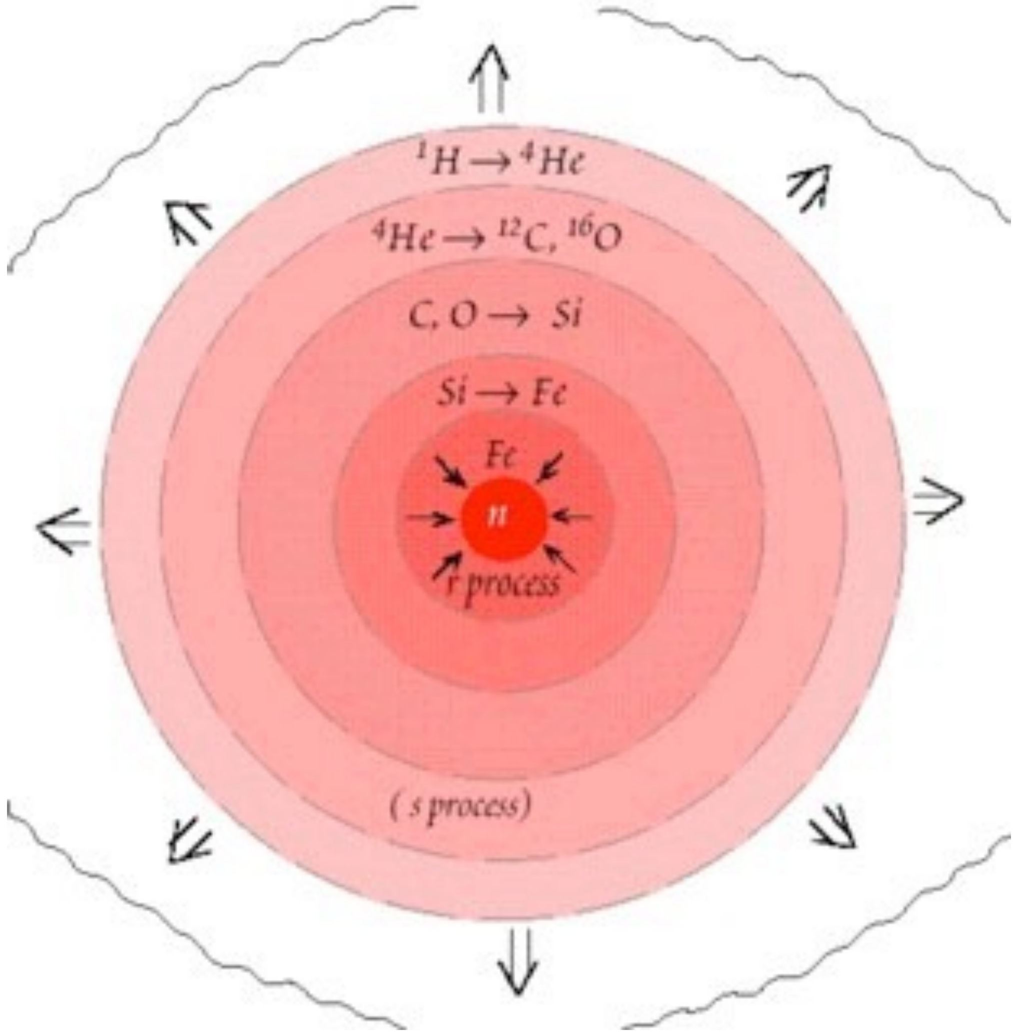
In tonight's lecture

- The ends of massive stars
  – *what happens when the star starts to collapse*
- Supernova!
  – *the explosion and what we see*
- Making the elements
  – *how much of the periodic table is manufactured in supernovae*
- Supernova 1987A
  – *a detailed look at the closest supernova*

The ends of massive stars

In previous weeks, we discussed what happened to stars after they left the main sequence, and how they ignite a series of nuclear fuels in their interiors, trying to stave off the collapse due to gravity.

When we stopped, the massive star had built up an onion-like structure in its core, with hydrogen on the outside, then helium, carbon, oxygen, and heavier and heavier elements towards the core, until the very centre of the core consists of iron, the residue from silicon burning. We discussed how there is no more energy to extract from fusing iron.



What happens next?

The mass of iron in the core is now about 1.2–1.4 solar masses, and it must still support the weight of the rest of the star. The pressure is huge, so the atoms are degenerate: the core is, in effect, a white dwarf, embedded in the still-sputtering remnants of the star. Silicon in the surrounding layer continues to burn, showering iron nuclei onto the core.

Eventually the mass of the core reaches 1.4 solar masses, and this is a significant number. It is the mass where degeneracy pressure can no longer support itself against gravity: the *Chandrasekhar limit*. Collapse begins within minutes.

As the collapse begins, two things happen to make it even more catastrophic. First, the temperature rises: but the iron can't start fusing to produce more energy to halt the collapse. Instead, the iron nuclei begin to break down because of *photodisintegration*: the gamma-ray photons in the core have enough energy to destroy heavy nuclei.

e.g.

$$Fe + \gamma \rightarrow 13\ {}^4He + 4n$$

$$^4He + \gamma \rightarrow 2\ {}^1H + 2n$$

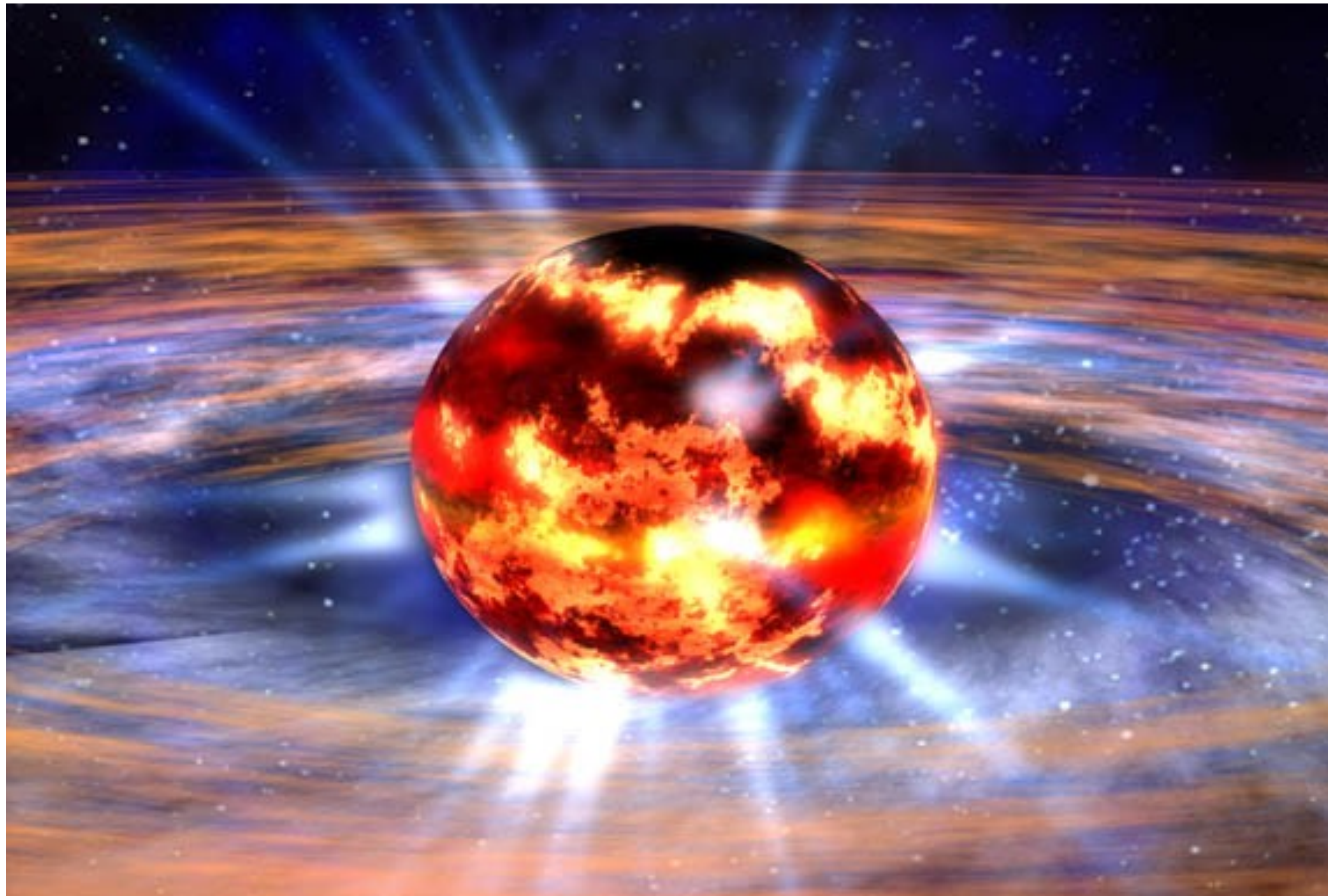
So much of what took millions of years to produce is undone in an instant. This break-up draws even more energy from the star, which reduces the pressure, which further hastens the collapse.

The degenerate electron soup can no longer hold up against the pressure, so the electrons are forced together with protons to form neutrons plus a neutrino:

$$p^+ + e^- \rightarrow n + \nu_e$$

The neutrinos escape directly from the core, and result in another large loss of energy and even faster collapse.

When the whole core has been converted to neutrons and they are squeezed tightly together, *neutron degeneracy* sets in, and this time this is stiff enough to resist the gravitational pressure. Now the force of gravity is being resisted by the strong nuclear force: in essence, the whole core is like one giant atomic nucleus! A neutron star has been born.



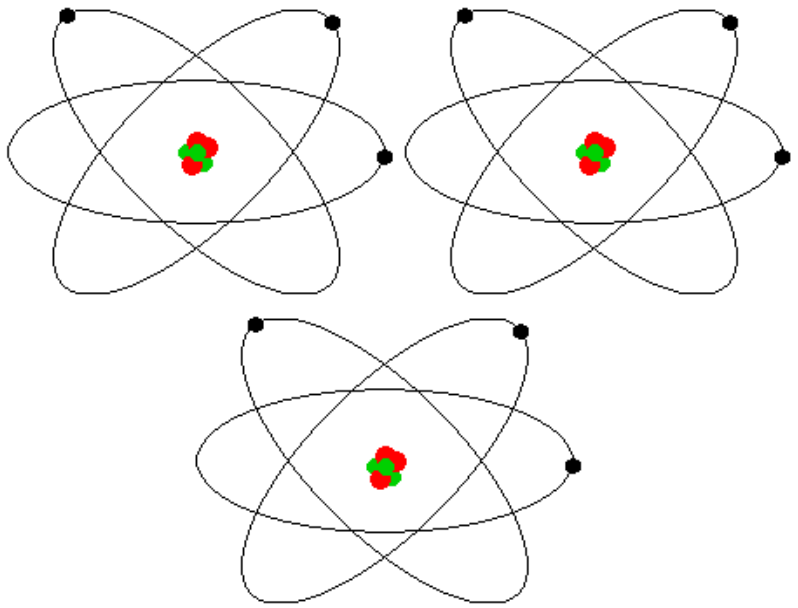
At the start of iron core collapse, the core properties are:

- Radius ~ 6000 km (~R_{earth})
- Density ~ 10^8 g/cc

A second later, the properties are:

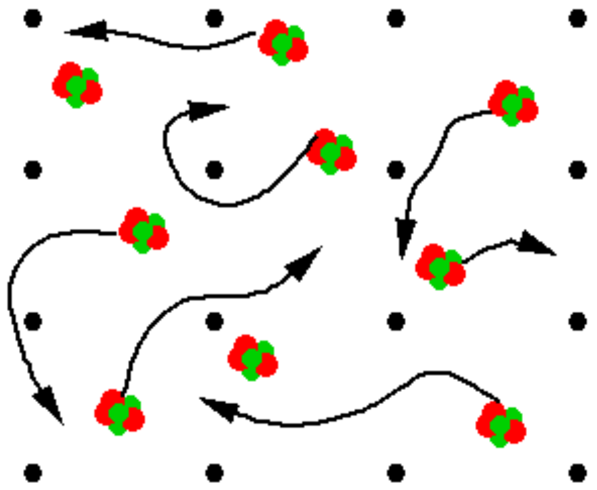
- Radius ~10 km
- Density ~10^{14} g/cc
- Collapse Speed ~0.25 c !

This is the third state of matter we've seen which can resist gravity:



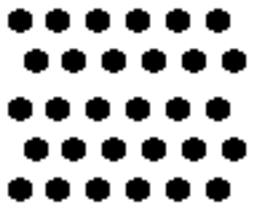
In *planets*, gravity is resisted by intact electron shells of ordinary atoms (normal matter).

Mean density: 10 g/cc



In *stars* and *white dwarfs*, electrons are forced so close together that they become rigid; their electromagnetic repulsion resists gravity (electron degeneracy).

Mean density: 10^8 g/cc

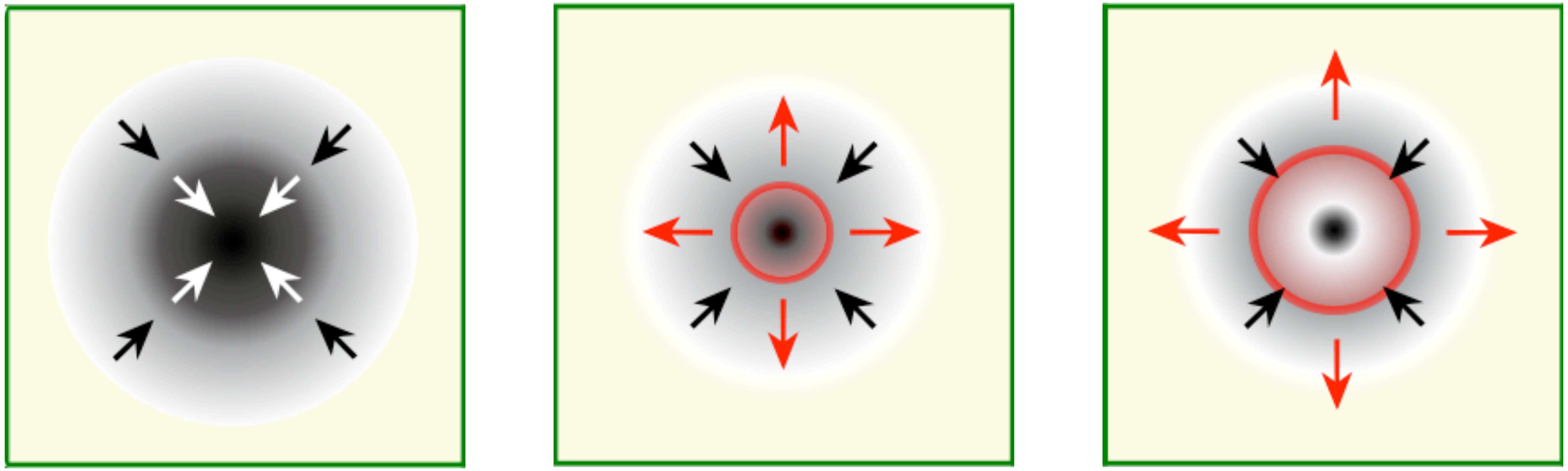


In *neutron stars*, neutrons are forced into virtual contact, and the strong nuclear force resists gravity (neutron degeneracy).

Mean density: 1014 g/cc

Envelope collapse

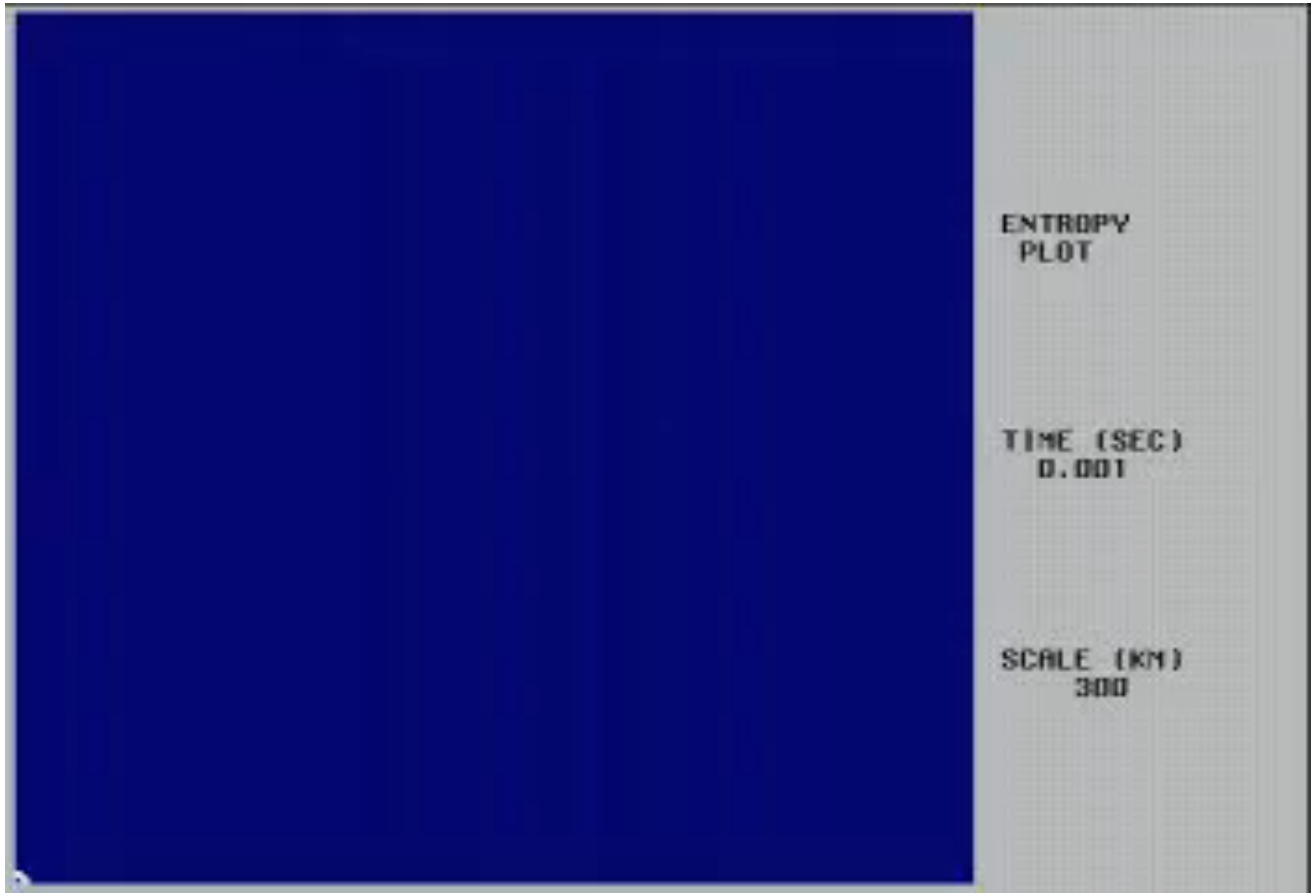
This all happens so fast that the core essentially collapses out from under the rest of the star. The outer layers are falling inwards, but when they meet the core they "bounce" off it so hard that they are ejected outwards again at a substantial fraction of the speed of light. This creates a blast wave which pushes the envelope back outwards at tremendous speed.



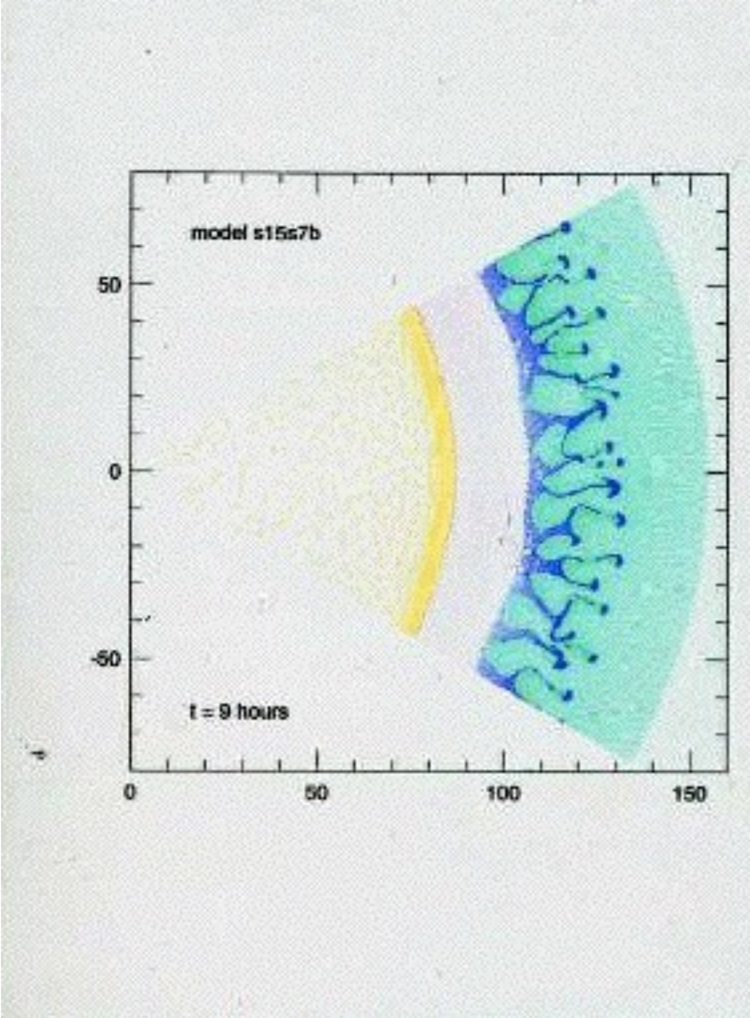
About 0.02 seconds after the bounce, there is a traffic jam between the infalling and the outflowing gas, and the shock wave *stalls*. Meanwhile neutrinos are flooding out from the core, and about 1% of them get absorbed by the enormously dense material at the shock front. This reheats the material, starts violent convection above the core, and *re-starts* the shock (about 300 ms after collapse).

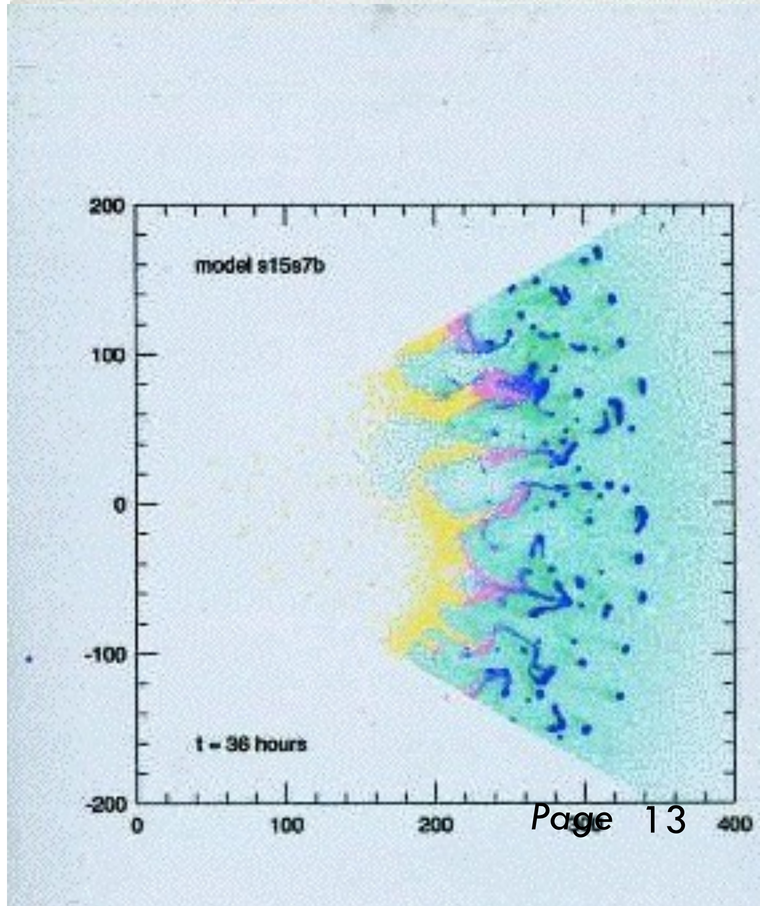
The blast wave smashes outward through the star, travelling at about 0.1c. Explosive nuclear fusion takes place behind the shock, and the shock violently heats and expands the layers of the star.

This is a supercomputer animation of the collapse of the core, the stalling of the shock, and the subsequent re-start by neutrino-induced convection.

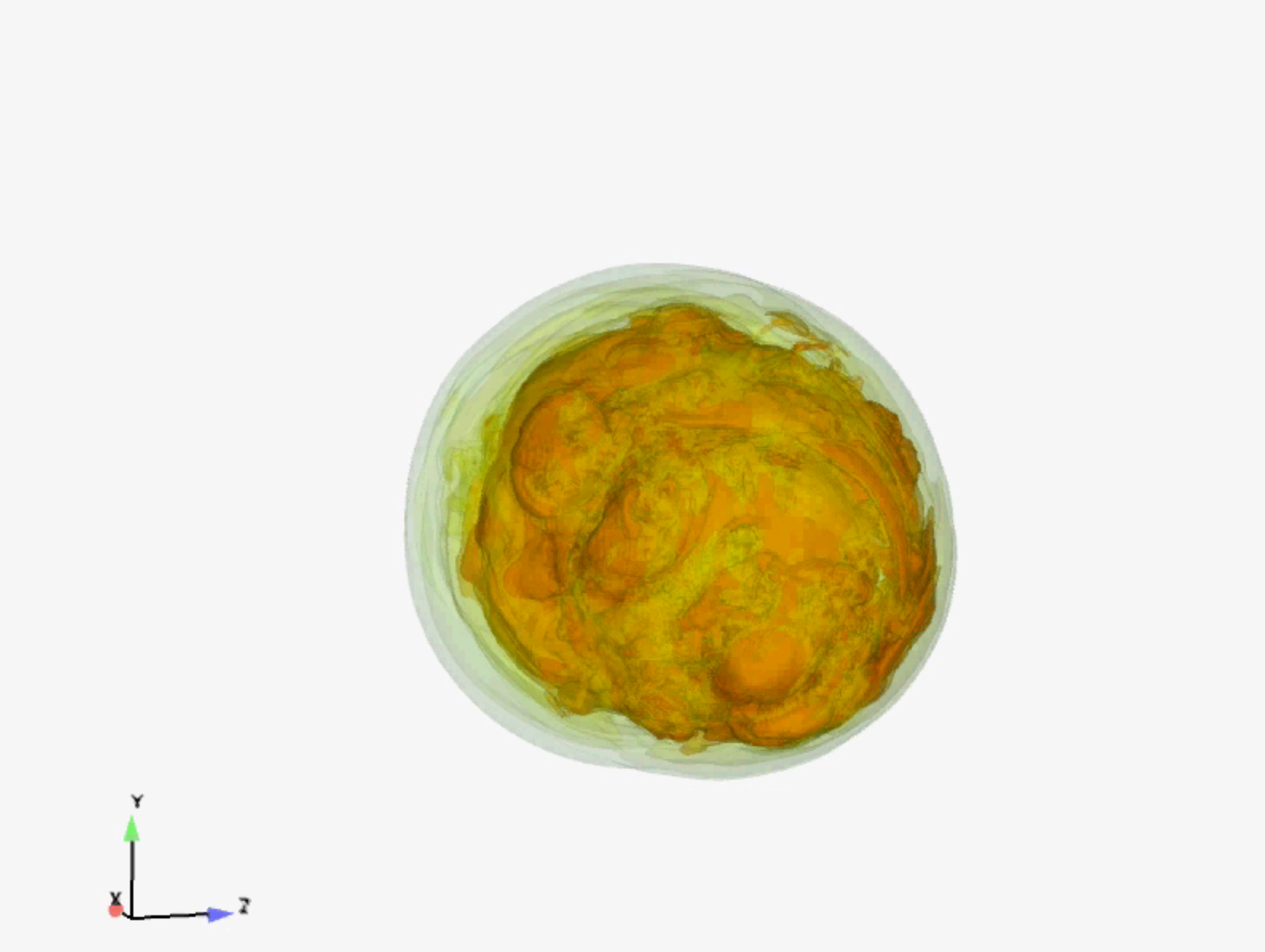


Models of the supernova explosion show how, as the shock runs into the envelope, instabilities develop and the layers of nuclear fuel get mixed.

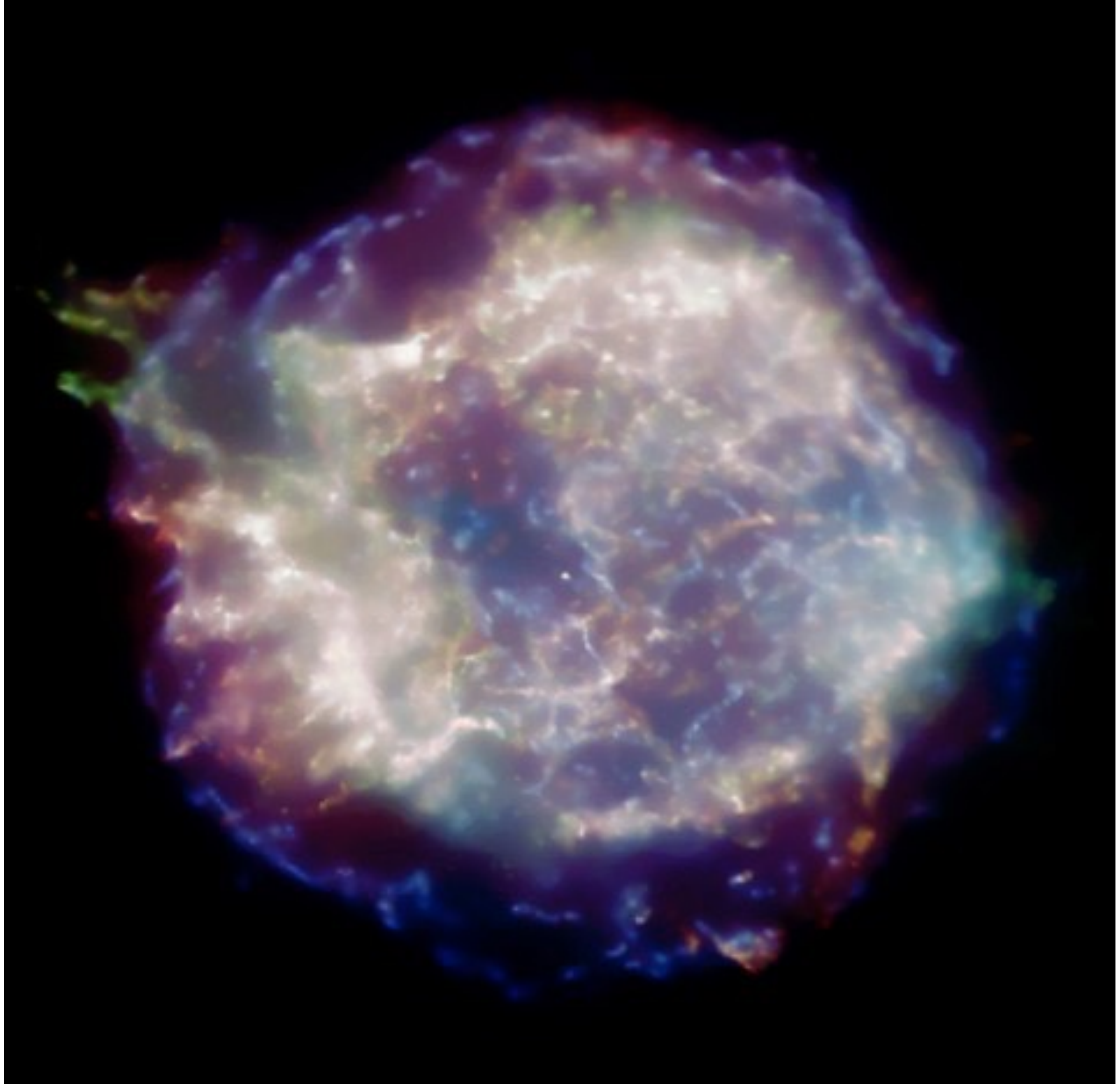




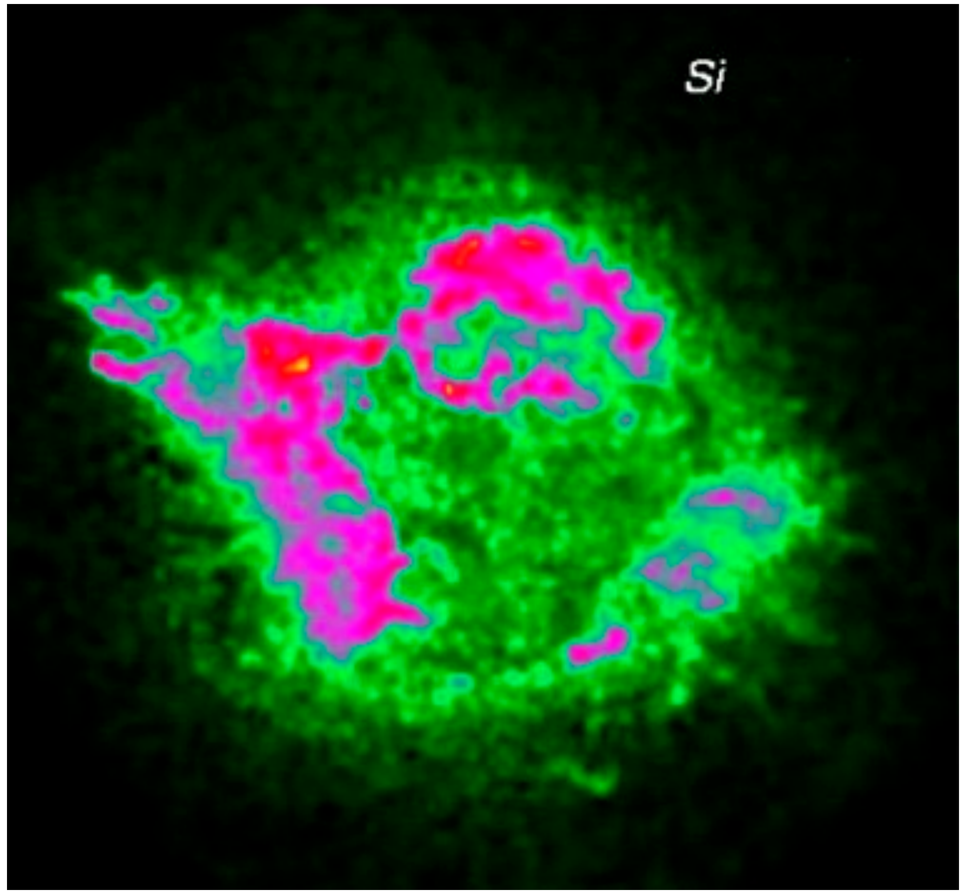
Doing these calculations even in 2D is extremely expensive. The few calculations that have been done in 3D show even stranger behaviour.

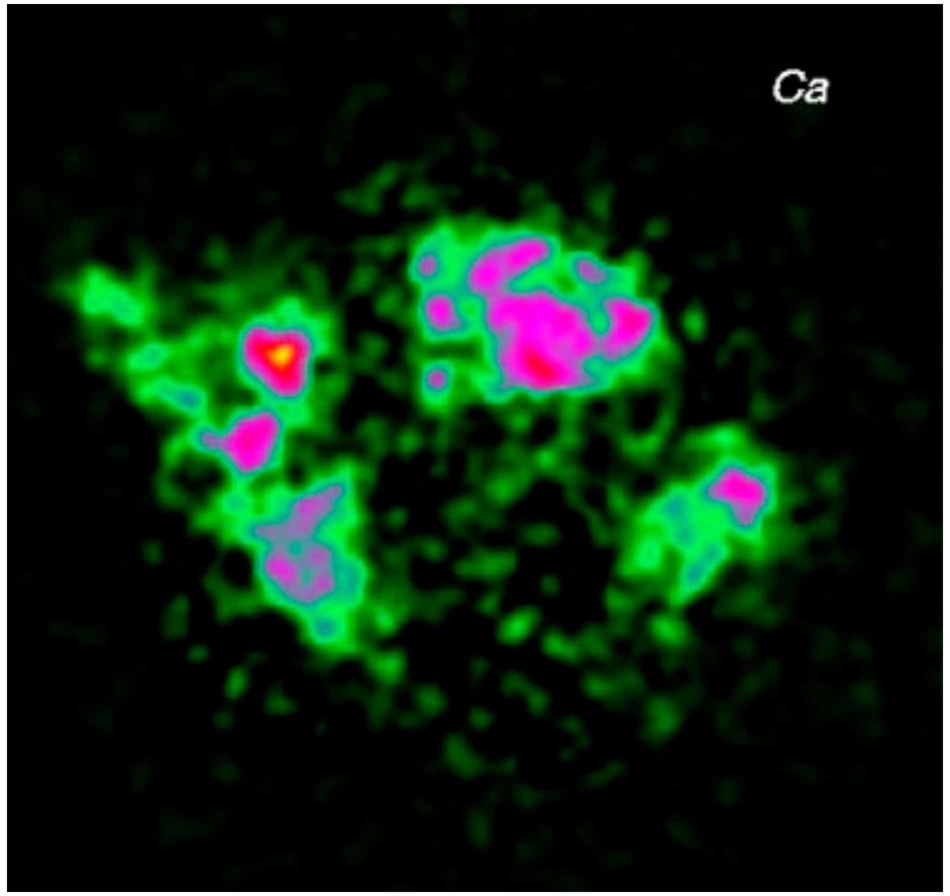


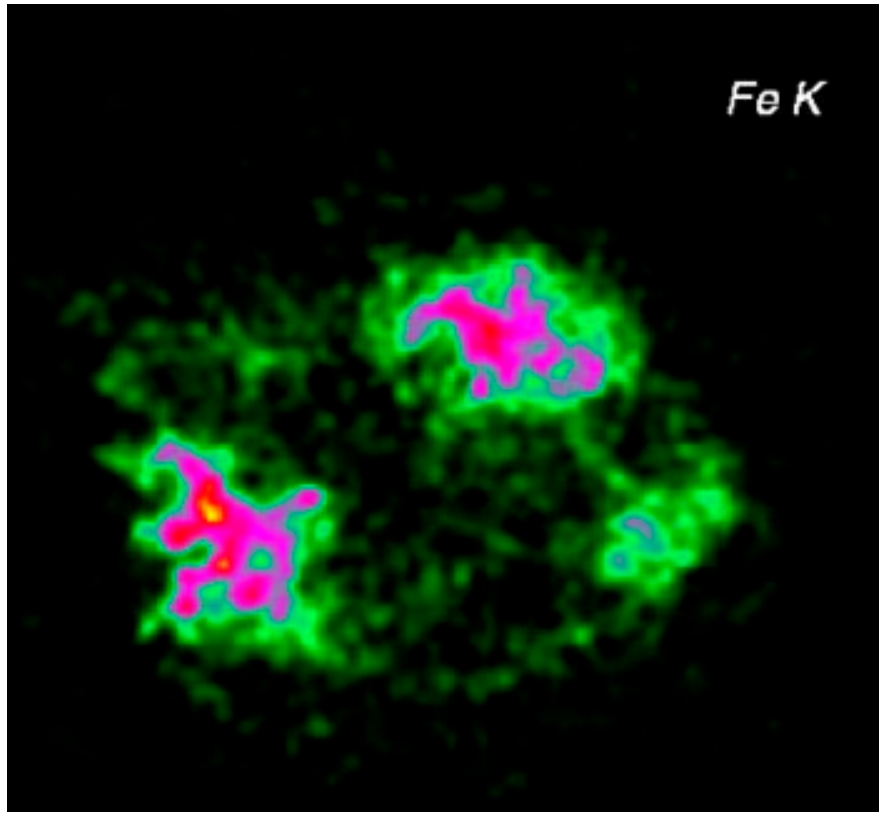
Chandra X-ray images of the Cassiopeia A supernova remnant show dramatic evidence of this mixing.



The Cassiopeia A remnant in X-rays.



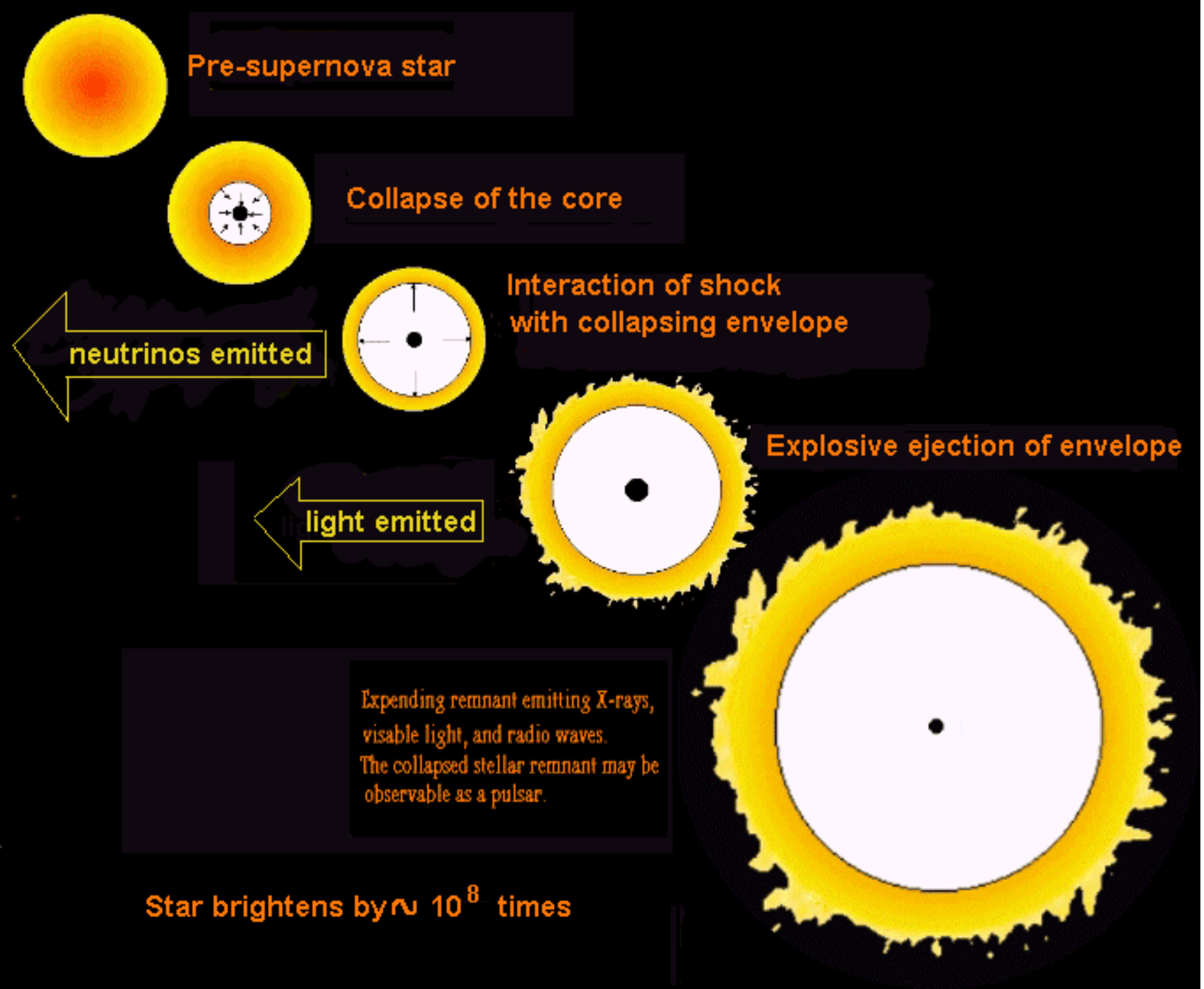




X-ray images in lines of silicon, calcium and iron. The silicon image shows a jet breaking out of the remnant. The presence of iron, made deep inside the star, at the outer edge of the remnant shows that there must have been substantial churning of the material, during or after the explosion.

Supernova!

Nothing is visible from the outside until the blast wave reaches the surface of the star. Then the star becomes an enormously expanding shell of gas. Within a day, the star is an incandescent ball a billion kilometres (10 AU) in diameter. The light increases as the surface area of the ball of gas increases. After several days or weeks, the gas cools, thins, and becomes more transparent: the light from the supernova begins to drop.



$t = 0$

0.1 s

0.5 s

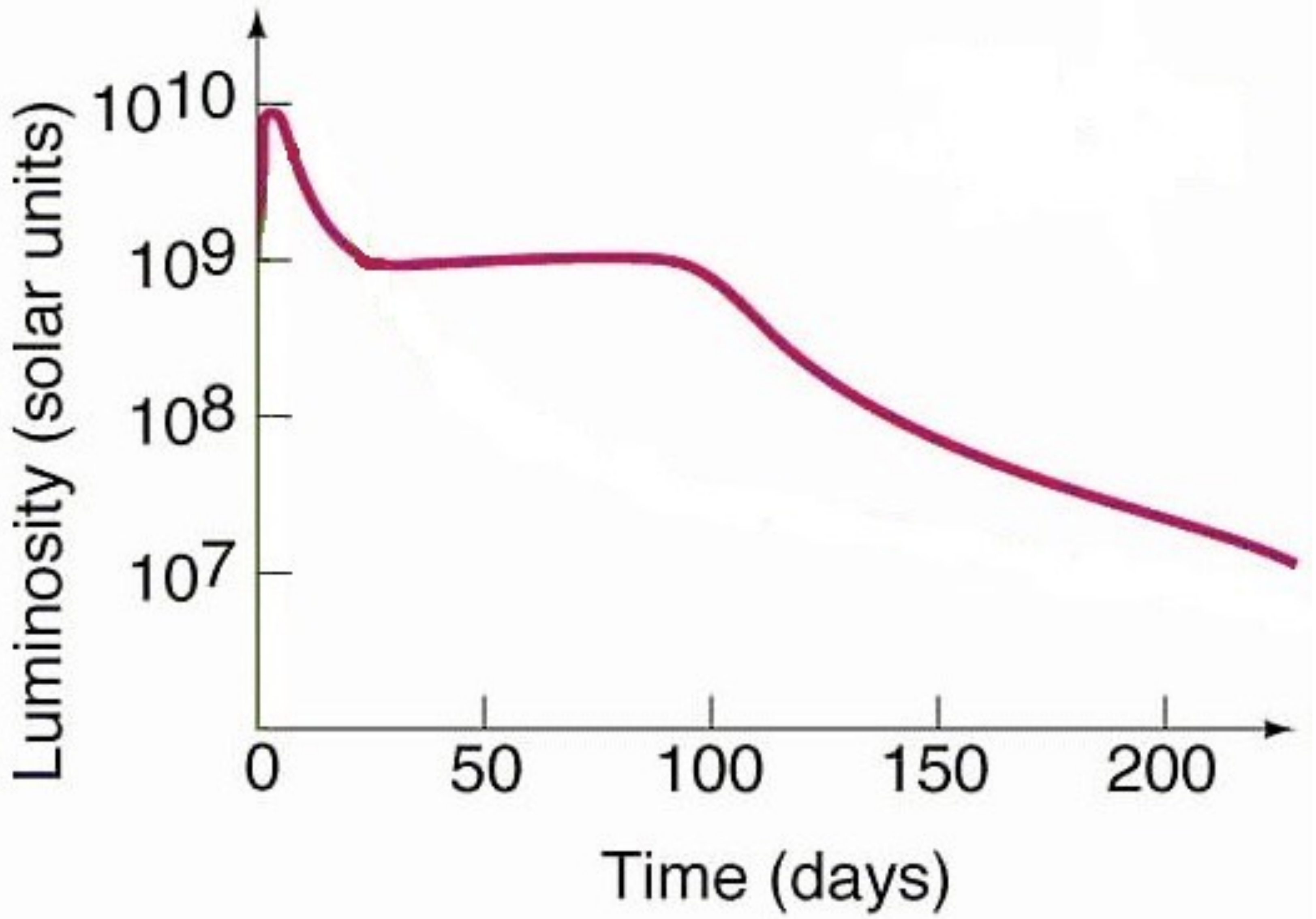
2 h

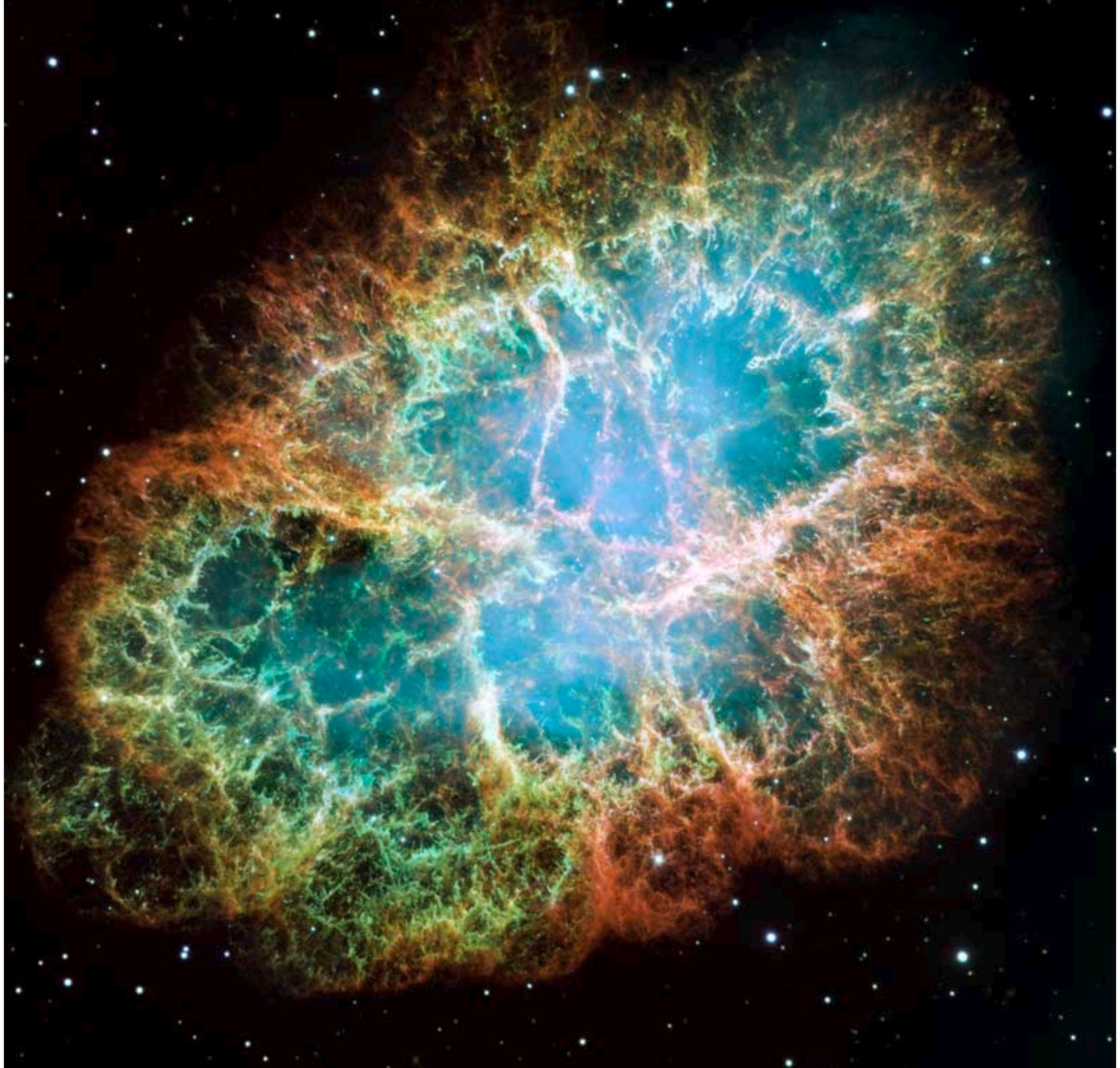
months

The luminosity of the star reaches 10 billion times solar luminosity in a matter of minutes: it can outshine a whole galaxy of stars.

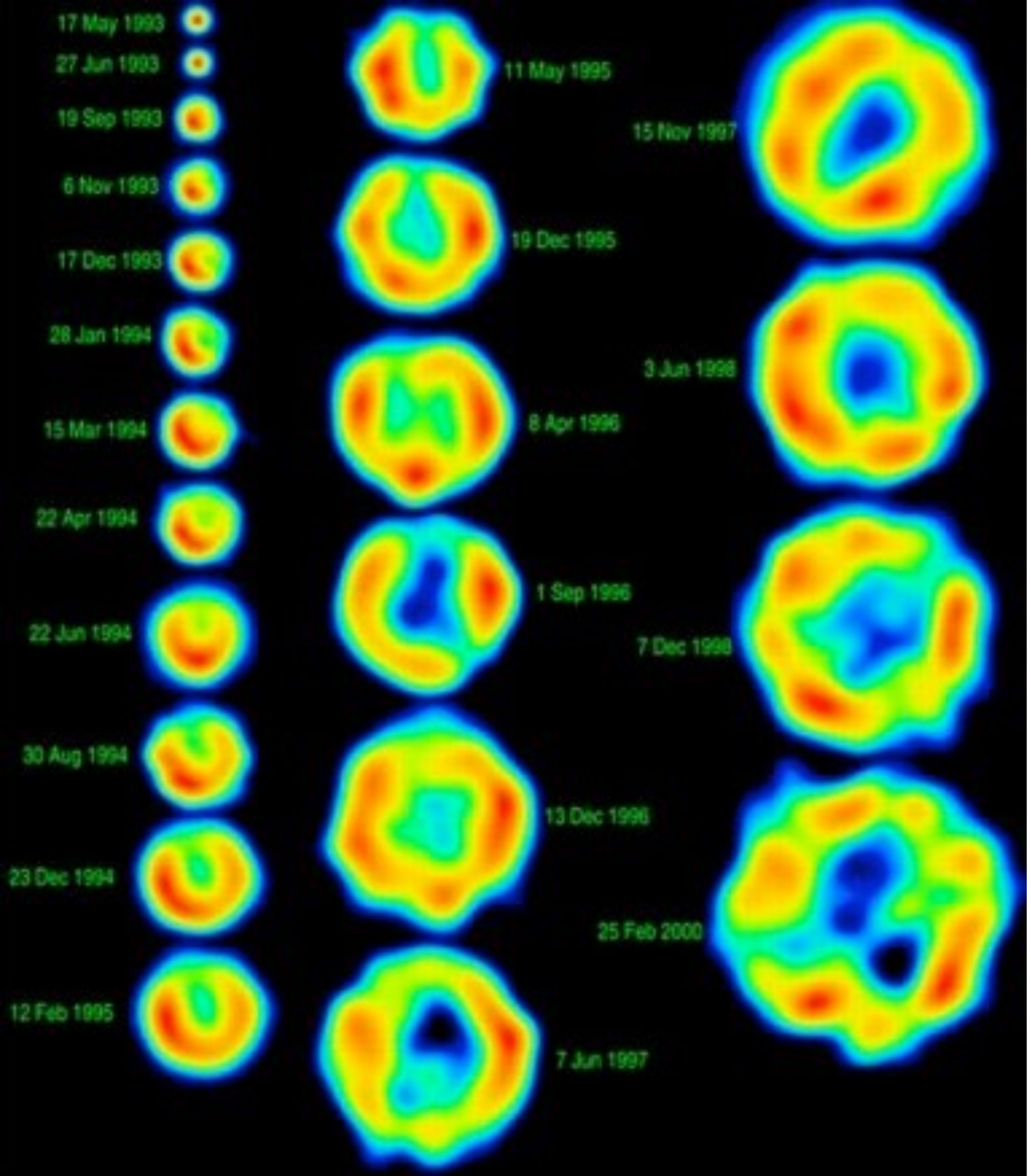
SN1994D in NGC 4526

The decline tapers off, however, to a slow exponential decrease. Radioactive elements formed in the blast (principally Ni and Co) begin to decay, and the energy release heats the surrounding debris. This produces a “bump” in the light-curve, where the decay in brightness slows down or halts for some weeks.





The Crab Nebula, remnant from a supernova explosion in 1054.

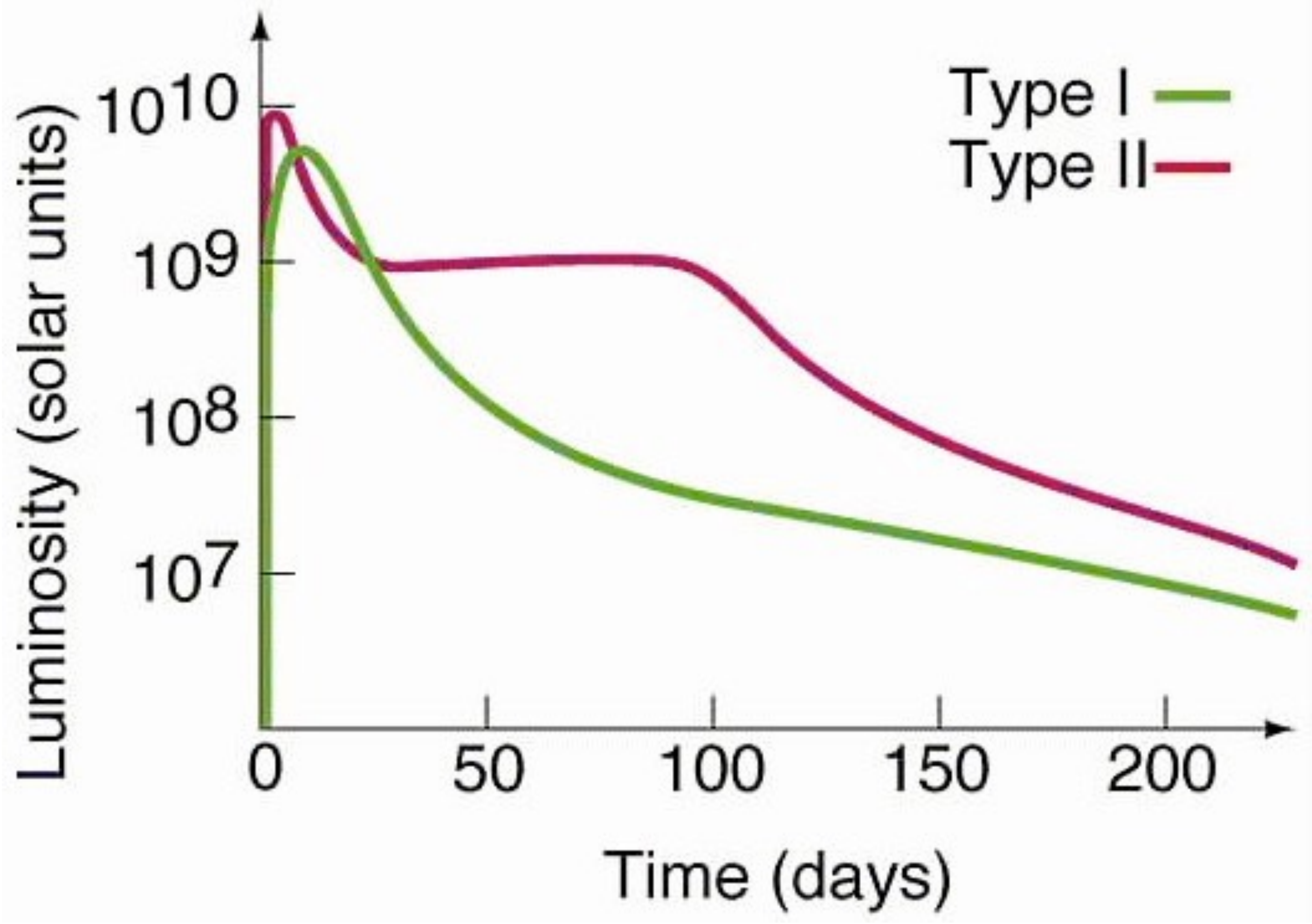


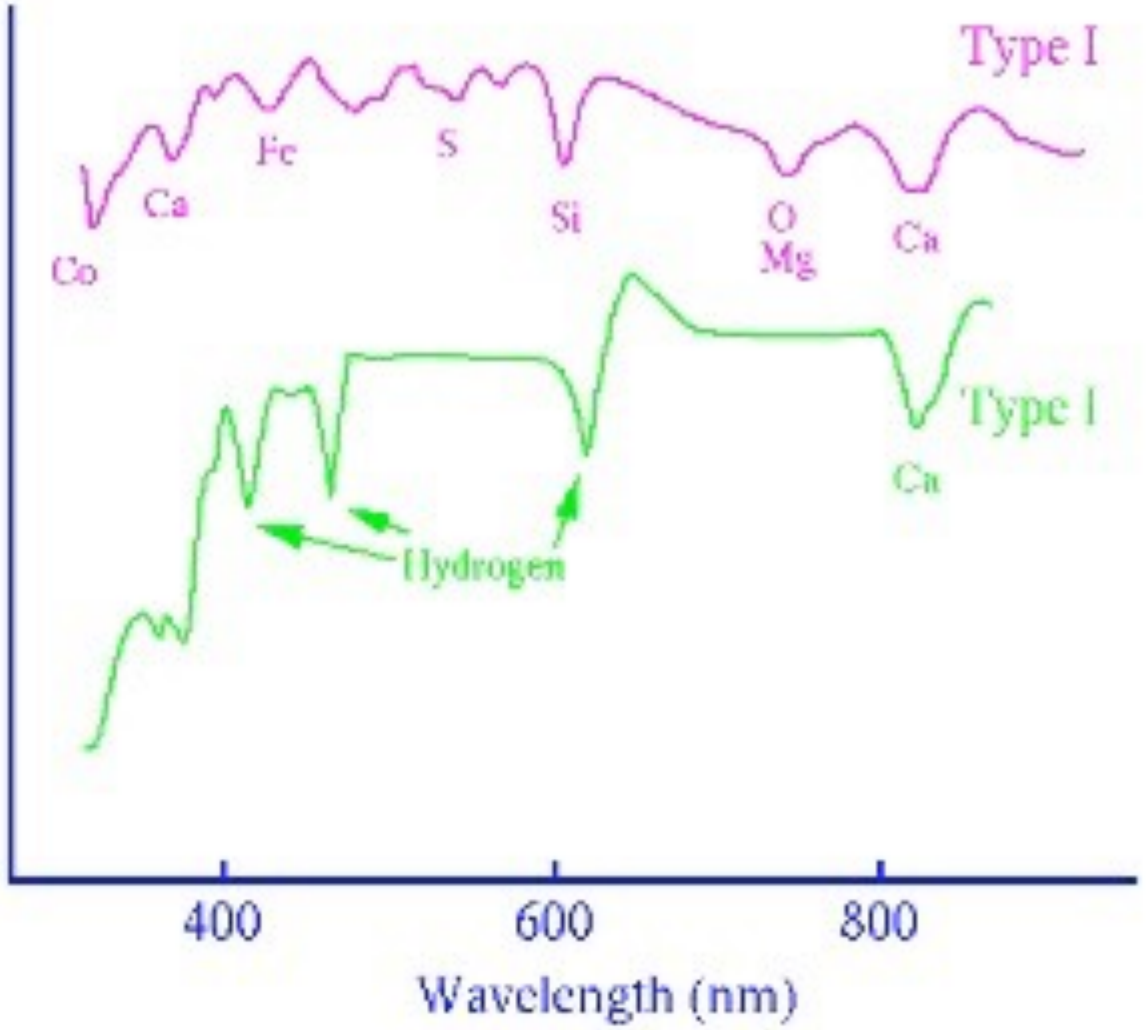
The shell of ejected gas continues to expand into interstellar space. By watching the shell over many years, we can actually measure this expansion.

Radio images show the remnant from SN1993J in M81 expanding over 4 years.

Thermonuclear supernovae

It happens that there is a whole class of supernovae which do not show this "bump" in the light curve. We believe these are a completely different type of explosion. A white dwarf, accreting matter in a binary system, accretes enough to push it over the Chandrasekhar limit, so it starts to collapse. However, unlike the iron core of a massive star, the collapsing white dwarf is made up of carbon and oxygen, which ignites during the collapse. The fury of the resulting explosion tears the star completely apart in a second.

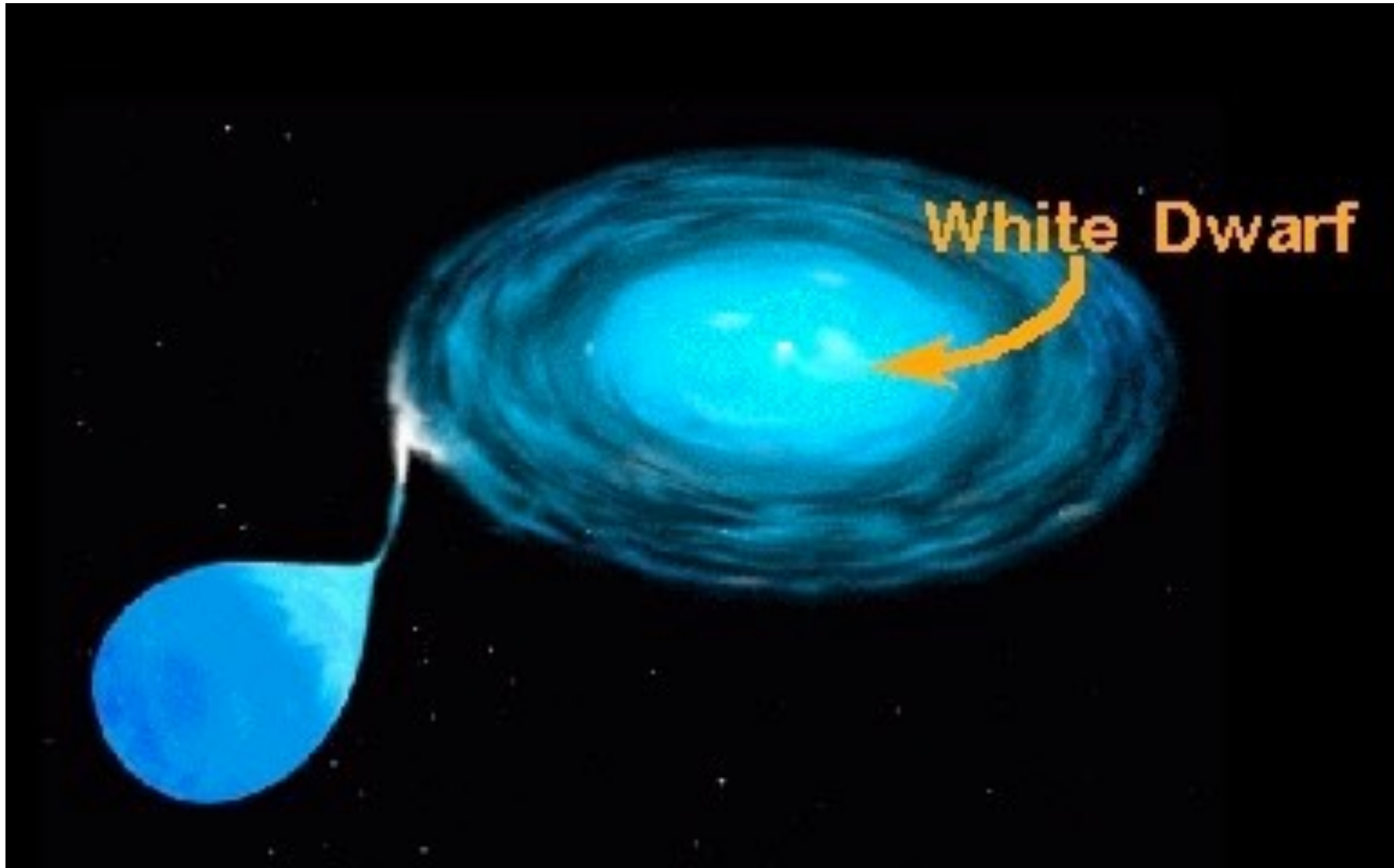




Type Ia (thermonuclear) supernovae do not show the bump corresponding to the decay of radioactive elements. Their spectra also do not show any hydrogen, since the exploding white dwarf contains none.

SN Ia supernovae have leapt into prominence recently with the awarding of the 2011 Nobel Prize to two teams for their discovery of the accelerating universe, based on observations of SNe Ia.

We will see in the last lecture that we still don't understand how a SN 1a works.



Making the heavy elements

Let's revisit the question of where the heavy (post-iron) elements are formed. You recall that reactions on the main sequence produce a limited number of low-atomic number elements.

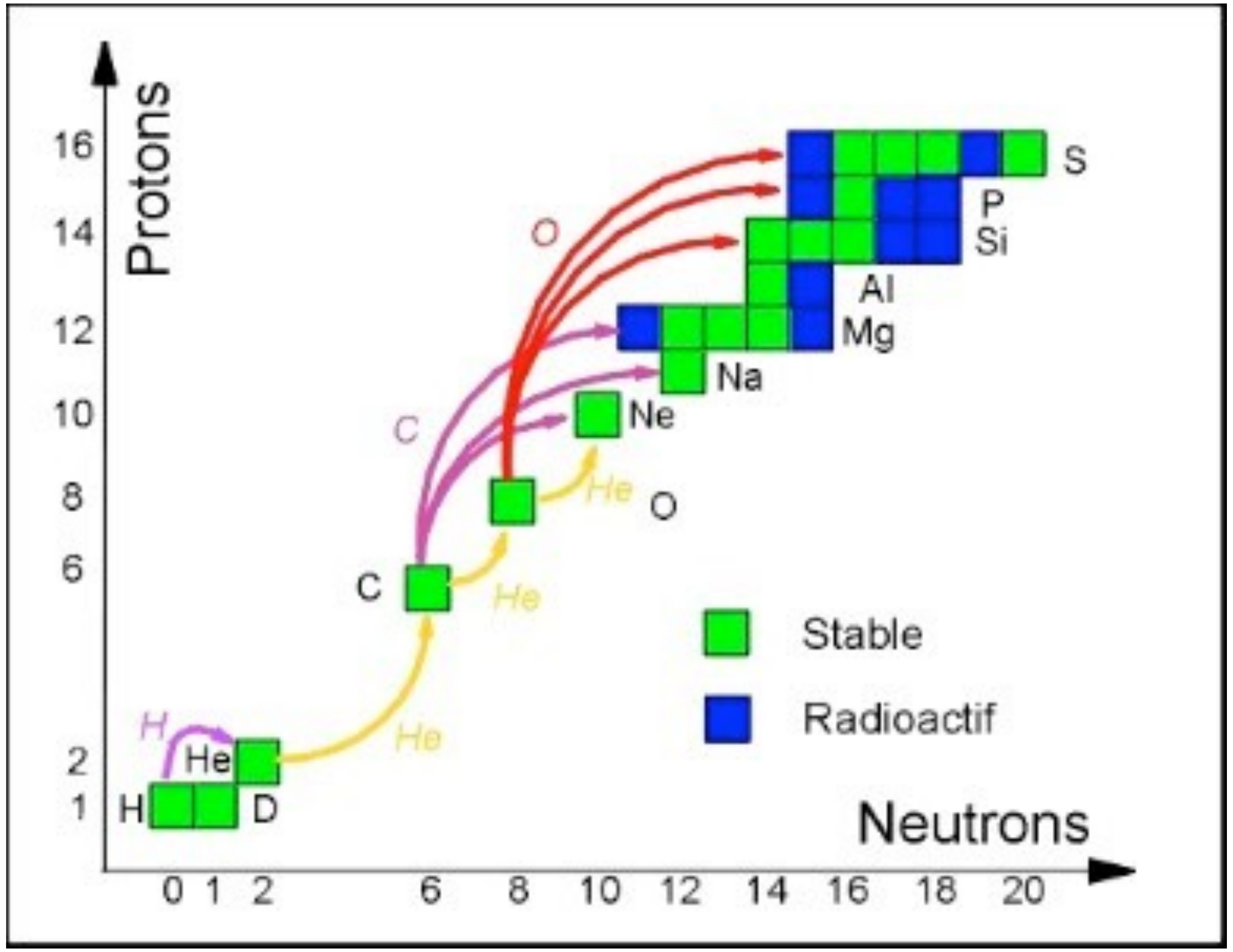


TABLE I,1. Table of elements and isotopes [compiled from *Chart of the Nuclides* (Knolls Atomic Power Laboratory, April, 1956)].

Elements		Isotopes	
Stable	81	Stable	272
Radioactive:		Radioactive:	
Natural ($Z \leq 83$)	1[a]	Natural ($A < 206$)	11[d]
($Z > 83$)	9[b]	($A \geq 206$)	44
Natural:		Natural:	
Stable and Radioactive	91	Stable and Radioactive	327
Radioactive:		Radioactive:	
Artificial ($Z \leq 83$)	1[c]	Artificial ($A < 206$)	702
($Z > 83$)	10	($A \geq 206$)	169
Total	102	Total	1198
Neutron	1	Neutron	1
	103		1199

[a] Tc, observed in *S*-type stars.
[b] Including At and Fr produced in weak side links of natural radioactivity
[c] Pm, not observed in nature.
[d] Including H^3, C^{14}, and Tc^{99}.

nuclear material into any other even at low energies of interaction.

With this relatively simple picture of the structure and interactions of the nuclei of the elements in mind, it is natural to attempt to explain their origin by a synthesis or buildup starting with one or the other or both of the fundamental building blocks. The following question can be asked: What has been the history of the matter, on which we can make observations, which produced the elements and isotopes of that matter in the abundance distribution which observation yields? This history is hidden in the abundance distribution of the elements. To attempt to understand the sequence of events leading to the formation of the elements it is necessary to study the so-called universal or cosmic abundance curve.

Whether or not this abundance curve is universal is not the point here under discussion. It is the distribu-

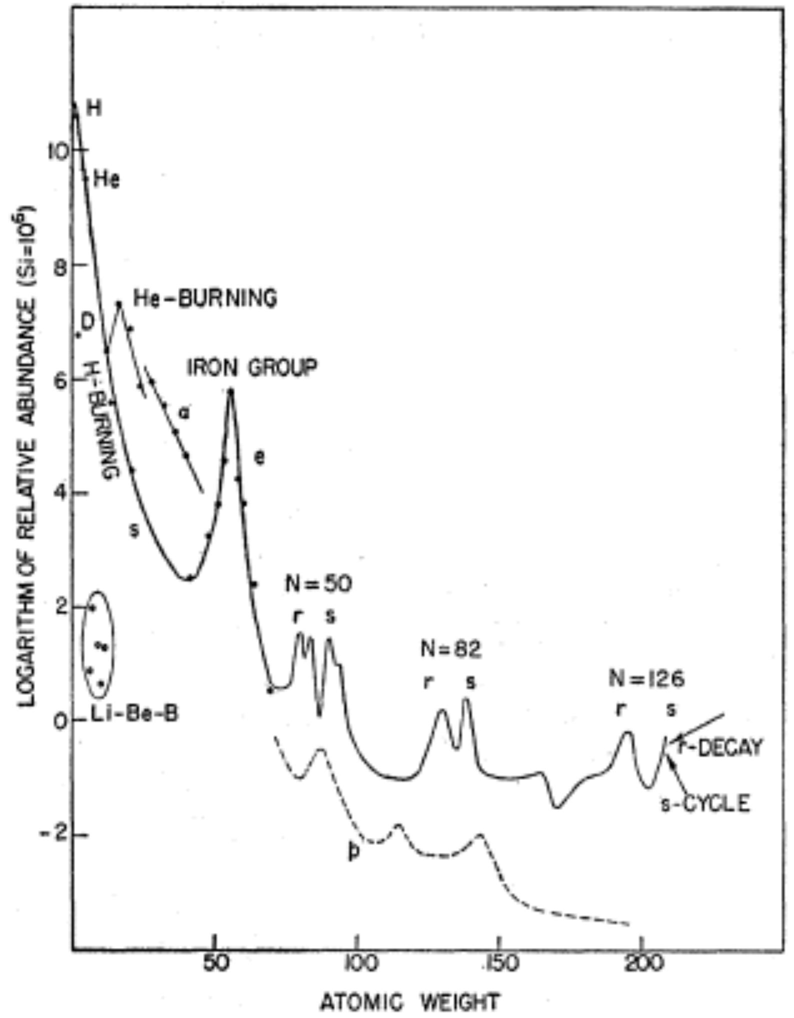
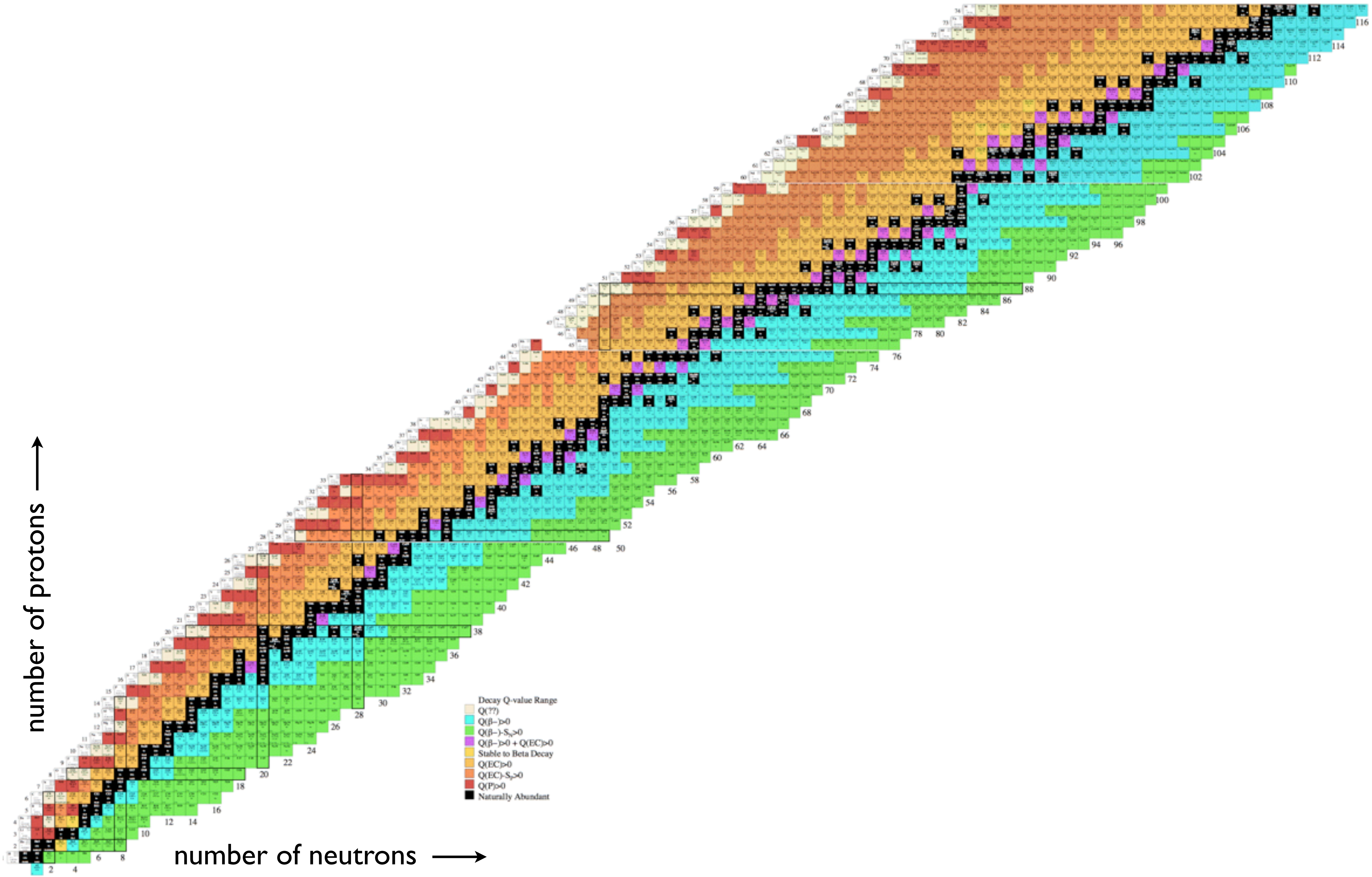


FIG. I,1. Schematic curve of atomic abundances as a function of atomic weight based on the data of Suess and Urey (Su56). Suess and Urey have employed relative isotopic abundances to determine the slope and general trend of the curve. There is still considerable spread of the individual abundances about the curve illustrated, but the general features shown are now fairly well established. These features are outlined in Table I,2. Note the overabundances relative to their neighbors of the alpha-particle nuclei $A = 16, 20, \cdots 40$, the peak at the iron group nuclei, and the twin peaks at $A = 80$ and 90, at 130 and 138, and at 194 and 208.

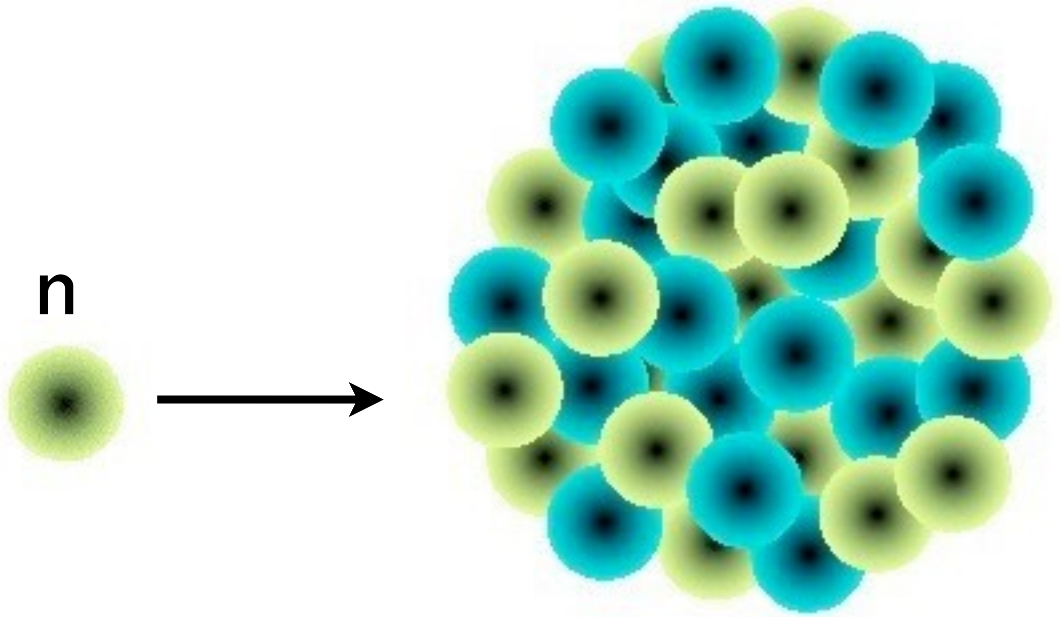
the sun were first derived by Russell (Ru29) and the most recent work is due to Goldberg, Aller, and Müller (Go57). Accurate relative isotopic abundances are available from mass spectroscopic data, and powerful use was made of these by Suess and Urey in compiling


number of protons
number of neutrons
Decay Q-value Range
Q(??)
Q(β−)>0
Q(β−)-Sn>0
Q(β−)>0 + Q(EC)>0
Stable to Beta Decay
Q(EC)>0
Q(EC)-Sp>0
Q(P)>0
Naturally Abundant

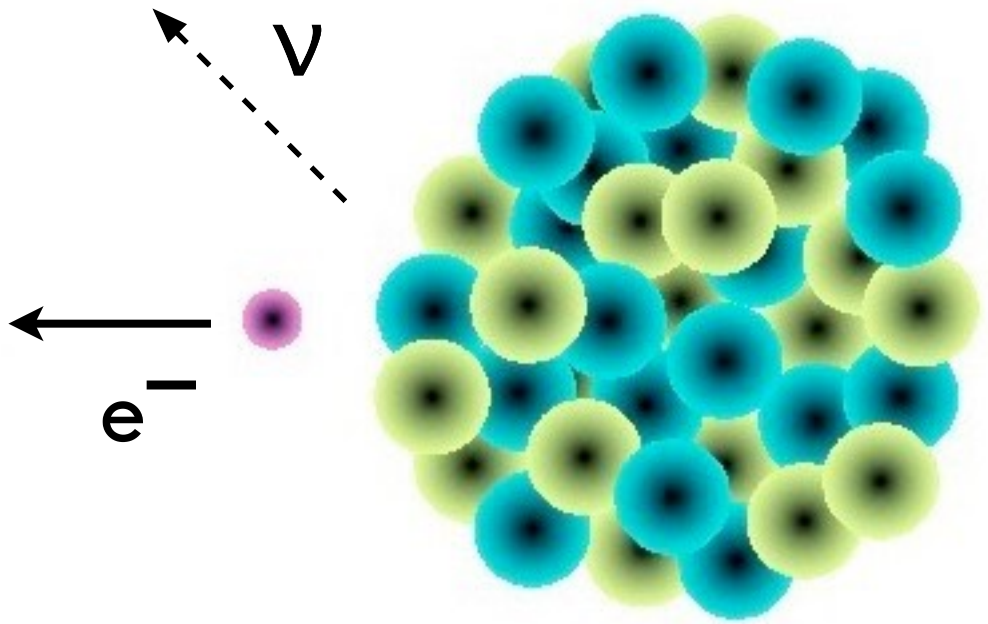
A few of the heavier elements are in fact by-products of ordinary stellar reactions in massive stars at the end of their lives: in red giant stars. “Spare” neutrons can collide with nuclei, building up heavier nuclei over thousands of years. This process is slow, allowing some of the captured neutrons to decay to protons by emitting an electron. This is called the *s-process* (for slow).

Elements formed in this way include technetium, strontium, zirconium and barium.

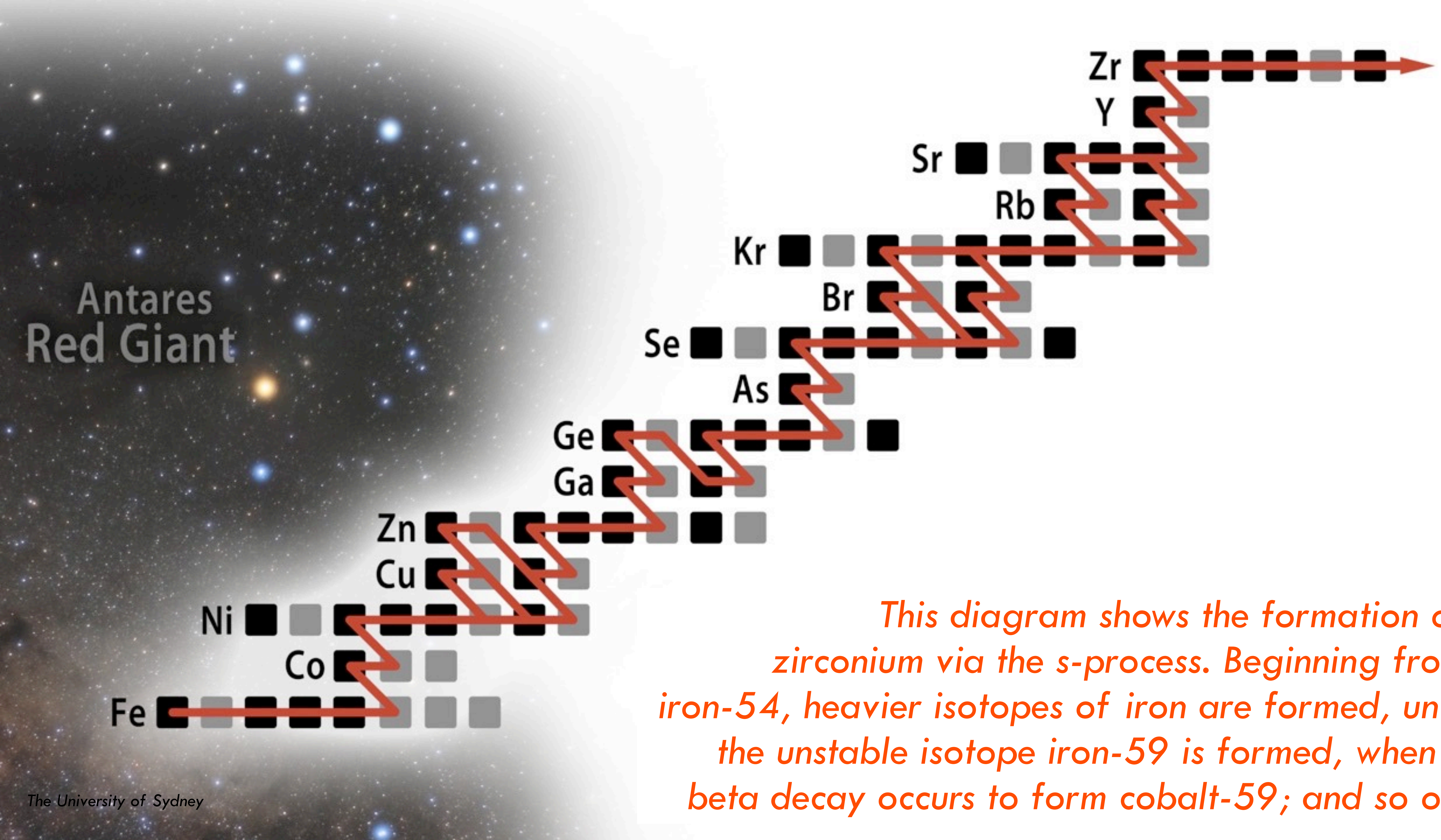
A neutron is captured by a nucleus to form another isotope of the same element.



When the resulting isotope is unstable, one neutron changes by *beta decay* (emission of an electron plus a neutrino) to a proton.



The resulting nucleus is now a different element, since it has a different number of protons.



This diagram shows the formation of zirconium via the s-process. Beginning from iron-54, heavier isotopes of iron are formed, until the unstable isotope iron-59 is formed, when a beta decay occurs to form cobalt-59; and so on.

Explosive burning

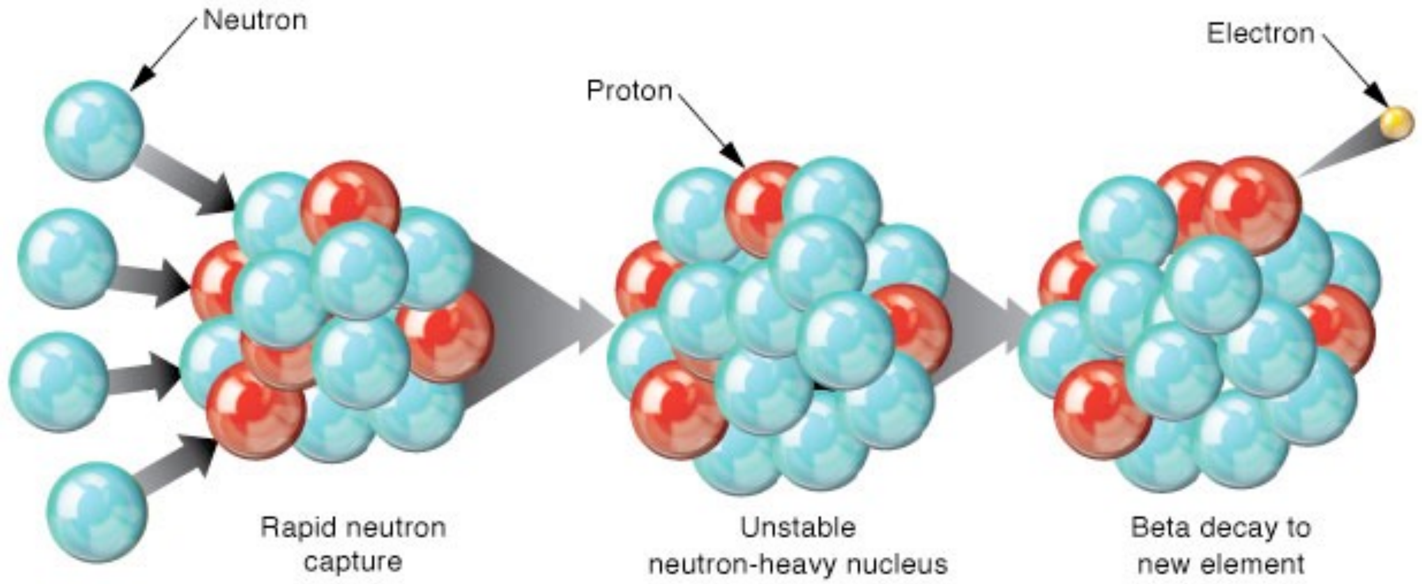
But most of the heavier elements are formed in the supernova explosion itself.

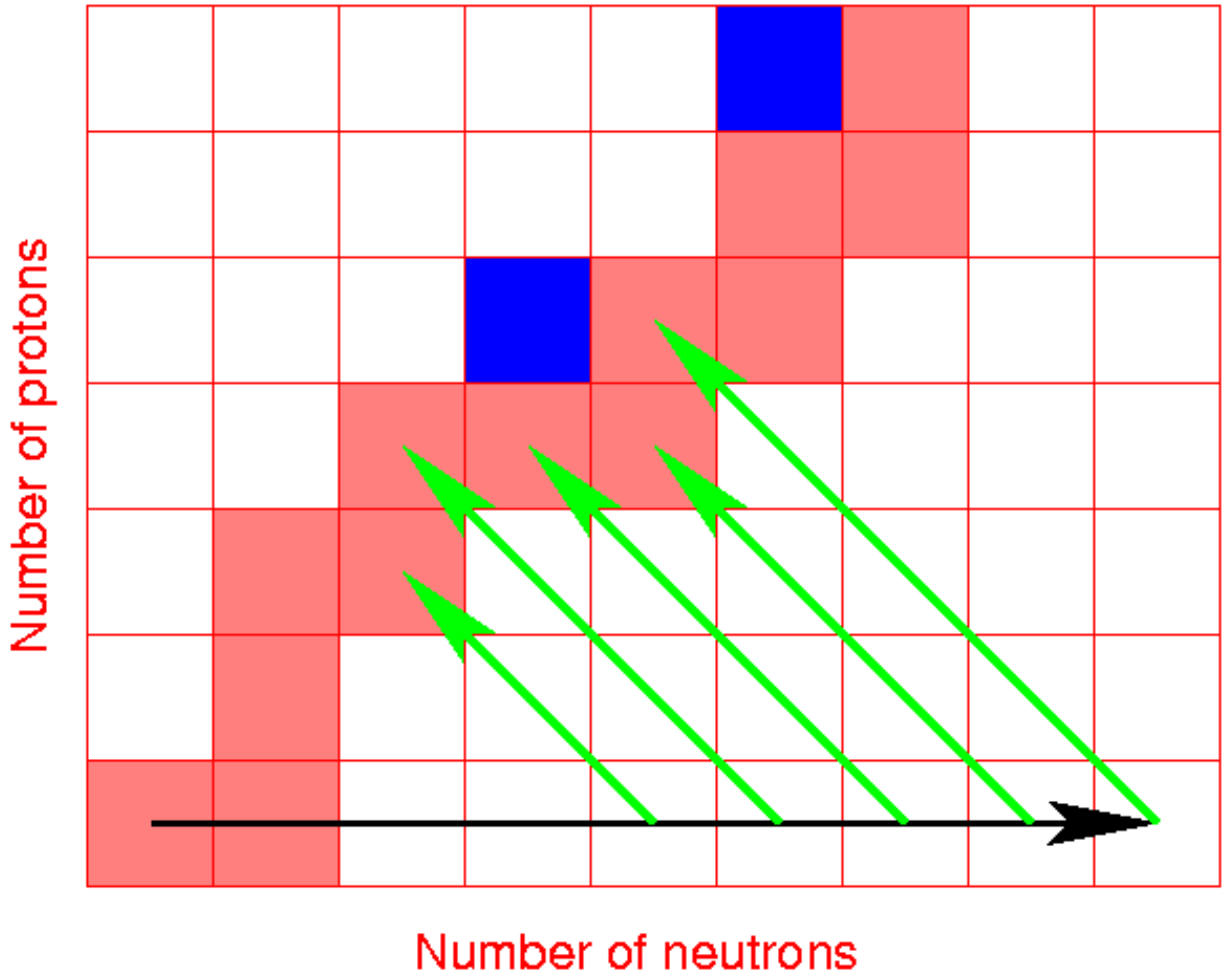
As the shock-wave explodes out through the onion-like layers of the star, it heats them to enormously high temperatures (sort of like standing next to a hydrogen bomb!). Since nuclear reactions are very temperature sensitive, nucleosynthesis that might otherwise have taken days or years can occur within a few seconds.

Nuclei quickly fuse with oxygen and silicon in the wake of the blast front, to build up elements as heavy as nickel: this process is called *explosive silicon and oxygen burning*. Elements formed in this way include sulphur, argon, and the radioactive nickel and cobalt which are a major source of energy for the early months of the supernova light curve.

The heaviest elements

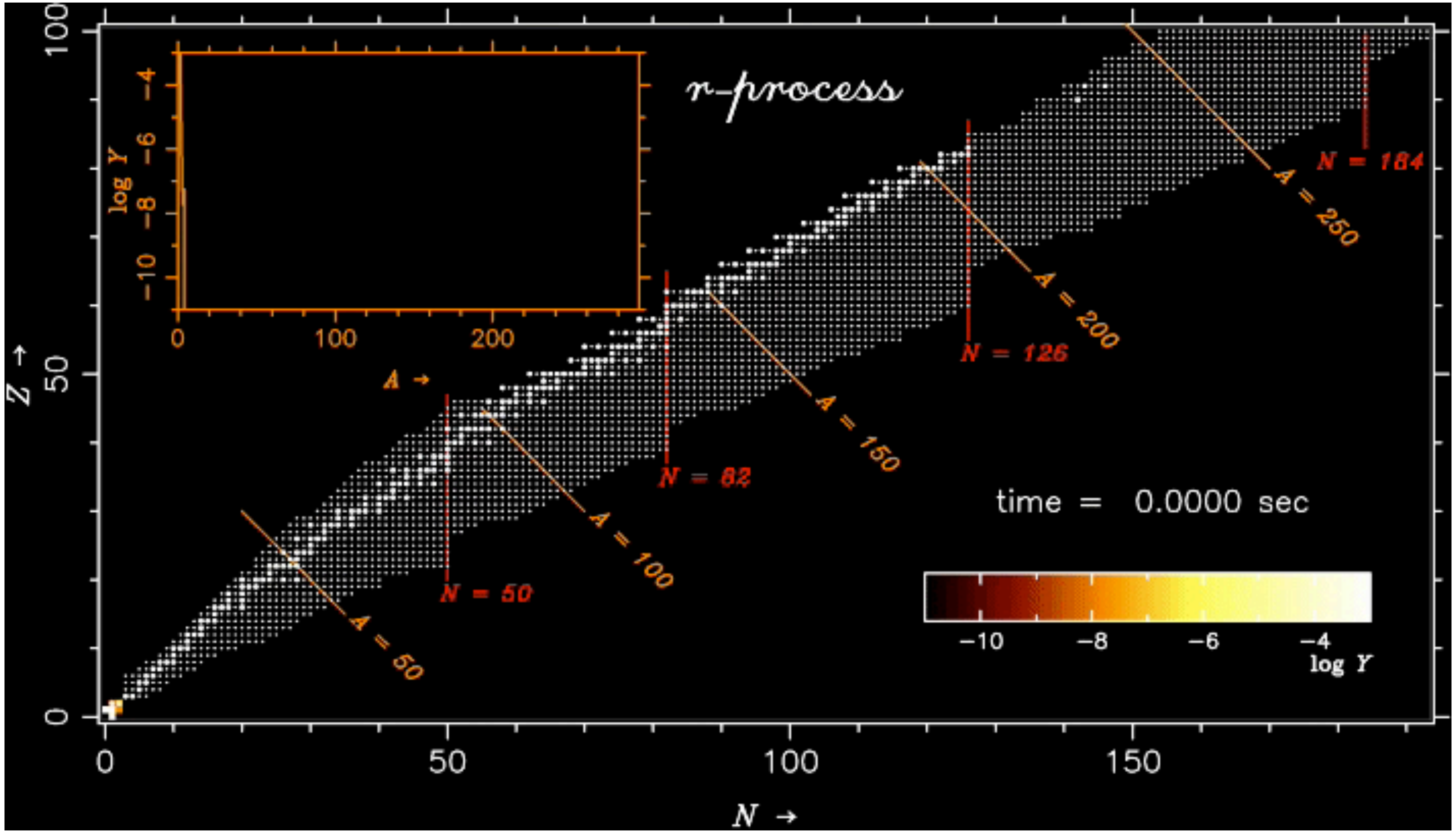
The elements heavier than iron are produced almost exclusively in Type II supernovae. The outgoing shock wave generates a flood of neutrons as it hits atoms in its path. Nuclei in the gas above are bombarded by these neutrons, and grow fatter and fatter, until within seconds all the elements up to uranium are formed. When the flood of neutrons stops, neutrons beta-decay back to a stable isotope. Because this process is so rapid compared to the s-process, we call this the *r-process*. Elements formed by the r-process include iodine, gold and platinum, as well as all the long-lived radioactive elements like radium and uranium.





The r-process for forming heavy elements. Multiple neutrons are captured by a nucleus, then when the flood of neutrons stops, neutrons decay to protons until a stable nucleus is reached. Note that the r-process cannot produce some isotopes (blue shading).

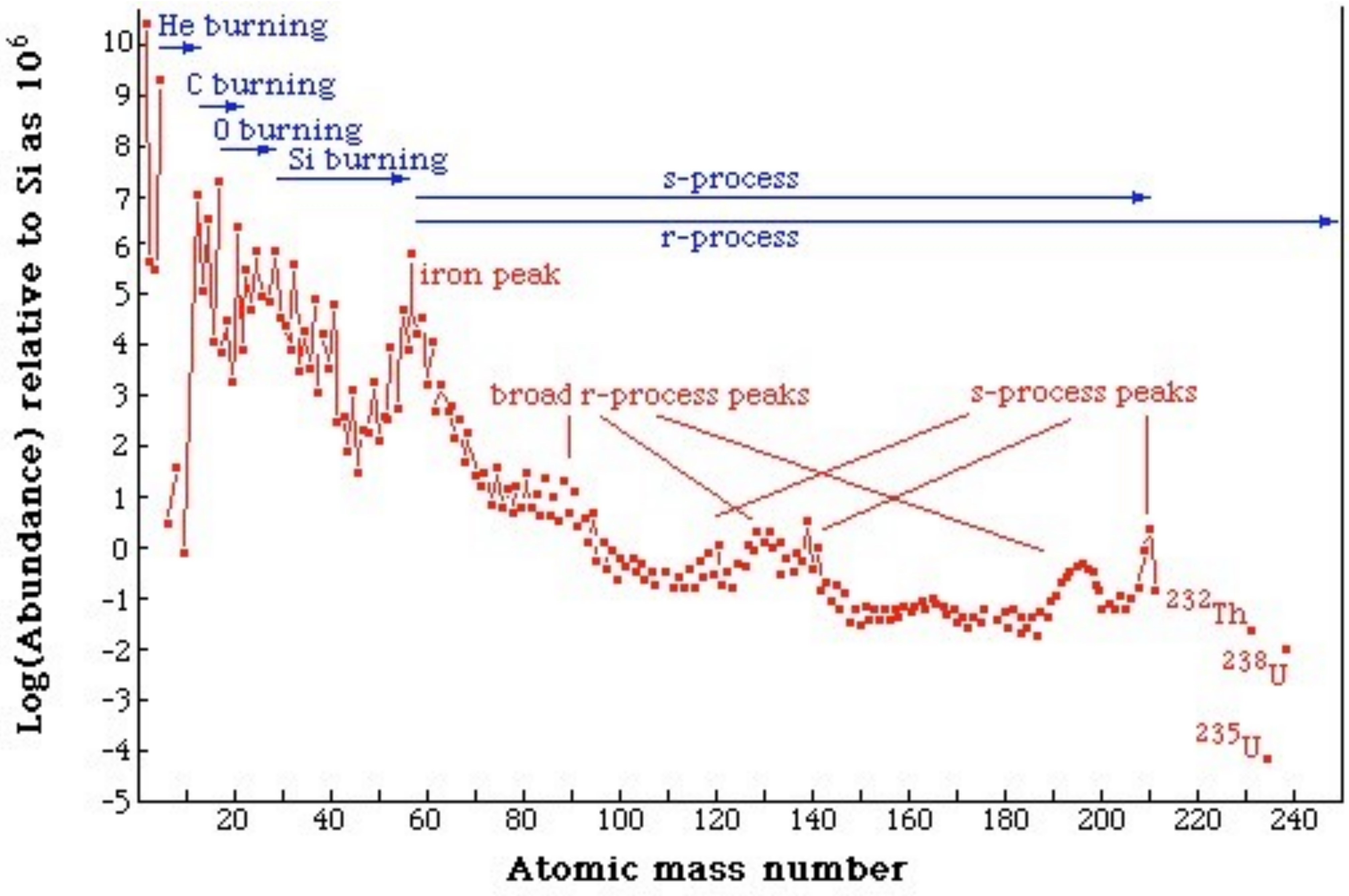
Here's a simulation of the r-process, showing the initial flood of neutrons producing heavy isotopes, which then decay into stable nuclei.



A very few elements are formed in other ways.

- Some are not formed in stars at all, but in the ISM, where atoms are struck by cosmic rays and split apart to form lighter atoms, like beryllium and boron.
- There are a couple of other processes which must occur in order to make certain elements: the *e-process* (equilibrium) and the *p-process* (proton capture) to make elements such as molybdenum and chromium respectively. However, it is not clear where these exotic processes take place.

So the elements are formed in a range of places, from the cores of ordinary stars, to supernova explosions, to the depths of interstellar space.



Thus the heavy elements on Earth were formed in a supernova; in particular, nuclear power plants are releasing energy which was stored by some ancient supernova.

We can even work out how long ago “our” supernova happened. A supernova will produce almost equal numbers of ^{235}U and ^{238}U, but these isotopes decay at different rates, with half-lives of 700 million years and 4.5 billion years respectively. The current ratio of ^{235}U:^{238}U in moon rocks is 0.007, so the nuclei must have formed about 6.6 billion years ago.

So the gas from which the Solar System formed was enriched by a supernova explosion which took place about 2 billion years before the Sun and planets formed.

SN 1987A

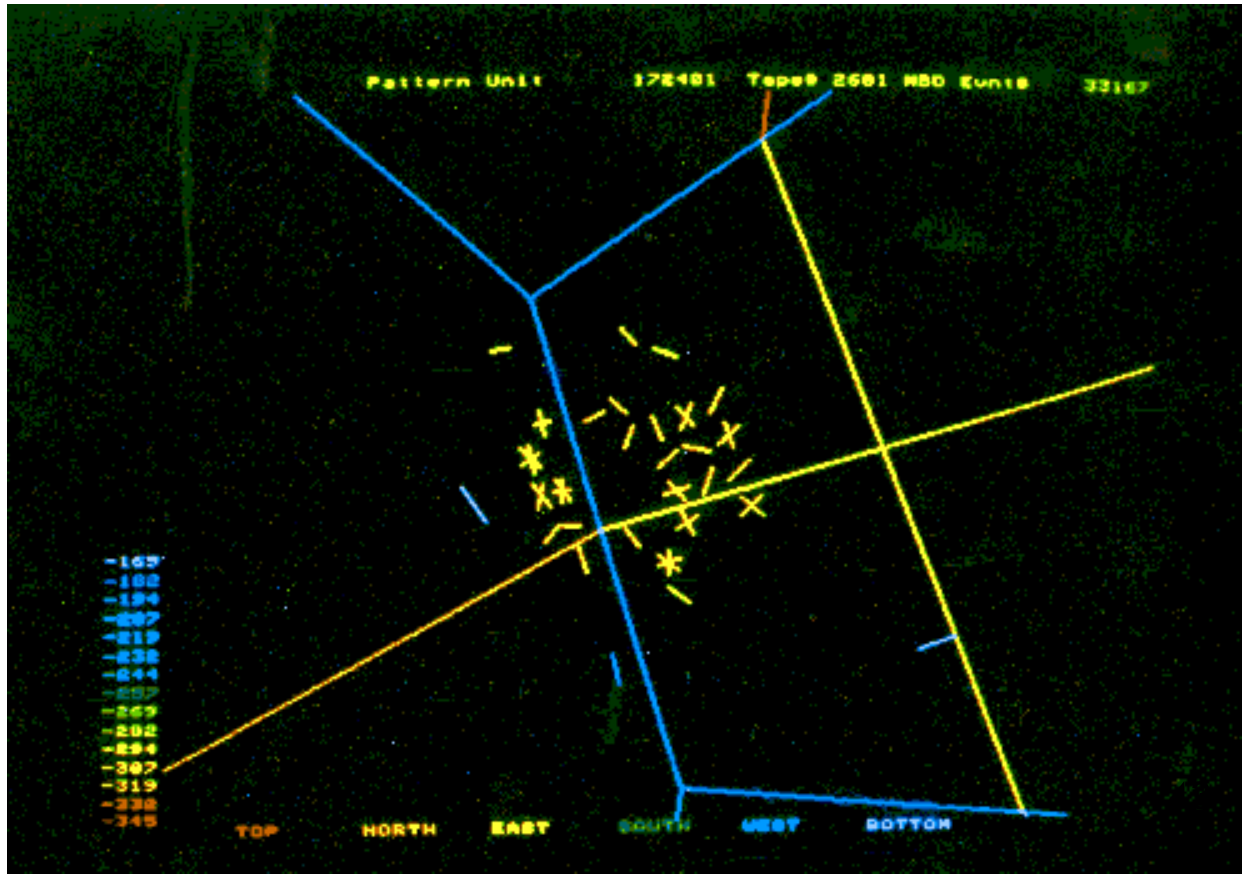
On 23 February 1987, the nearest supernova to earth since Kepler's supernova of 1604 exploded in the Large Magellanic Cloud. We were extraordinarily lucky to have so many new astronomical instruments available to study it with.

The supernova took place in the Tarantula Nebula, also known as 30 Doradus, a vast star-forming region about 600 pc across.

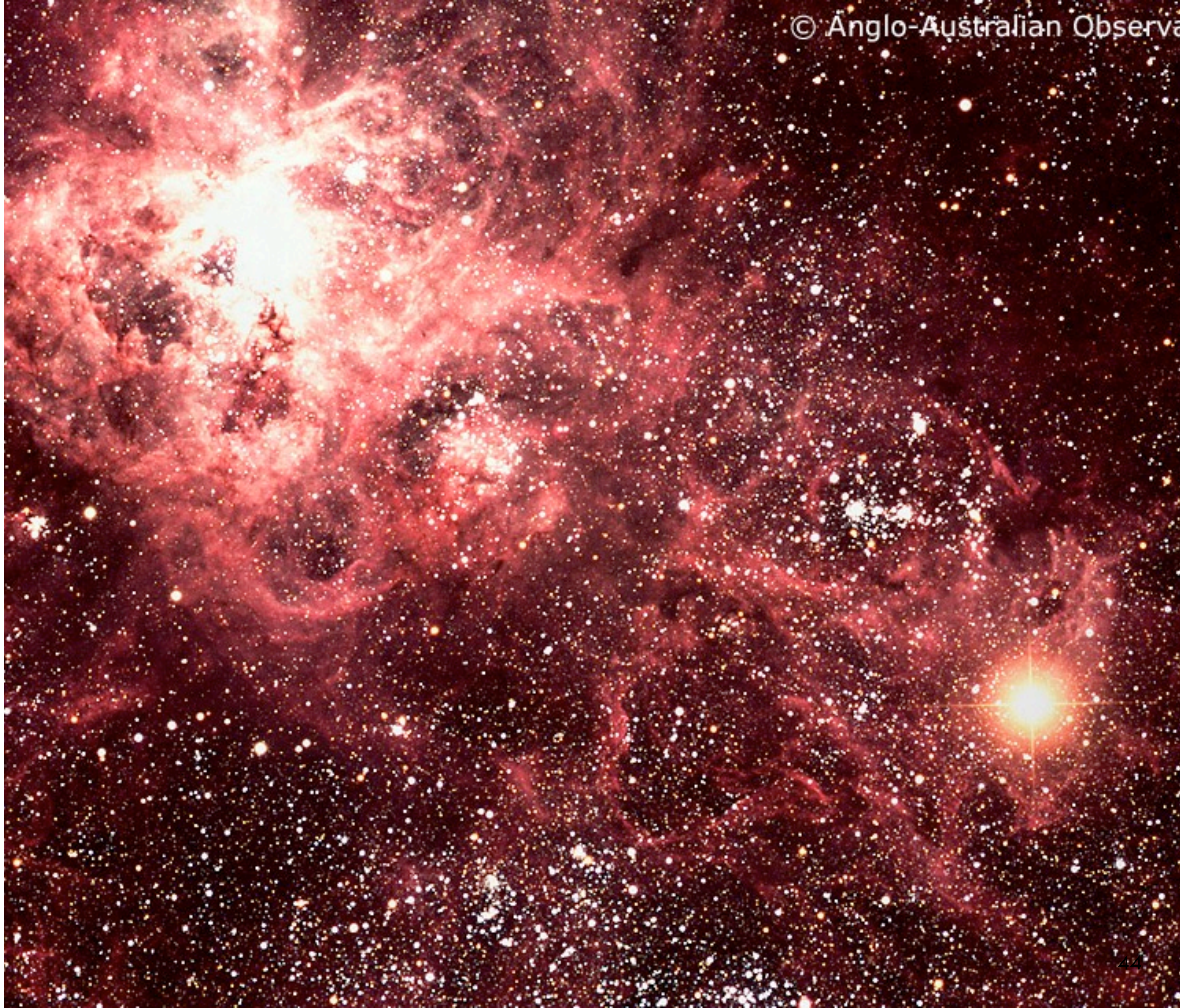
The Large Magellanic Cloud, with the Tarantula Nebula visible as the bright red region towards the top of the picture.

The first detection of the new supernova was actually made by two *northern* hemisphere observatories. The Kamiokande experiment in Japan and the IMB experiment in Ohio both detected a burst of neutrinos associated with the supernova: 12 and 8 events respectively, observed some hours before the optical supernova was spotted. Of course, the connection with the supernova was not realised until after the optical discovery.

One of the neutrino events from the IMB detector. The neutrino produced a flash of light, which was detected by several photo-multiplier tubes: by noting which PMTs responded, the direction and energy of the original neutrino can be deduced.

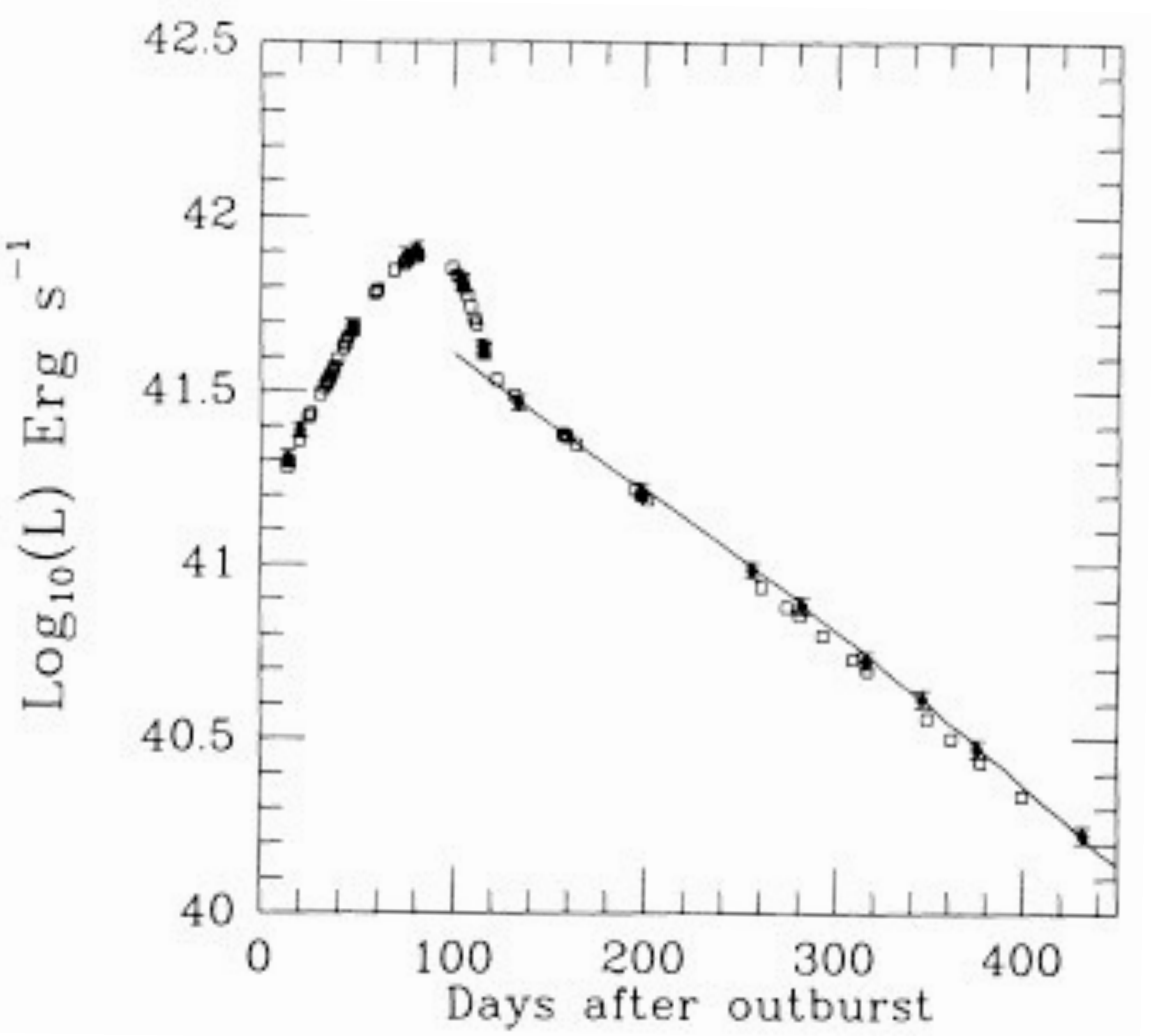


Three hours after the neutrino detection, the first visible light reached Earth. It was seen independently by at least four observers, in Chile, New Zealand and South Africa on the evening of 24 February 1987.

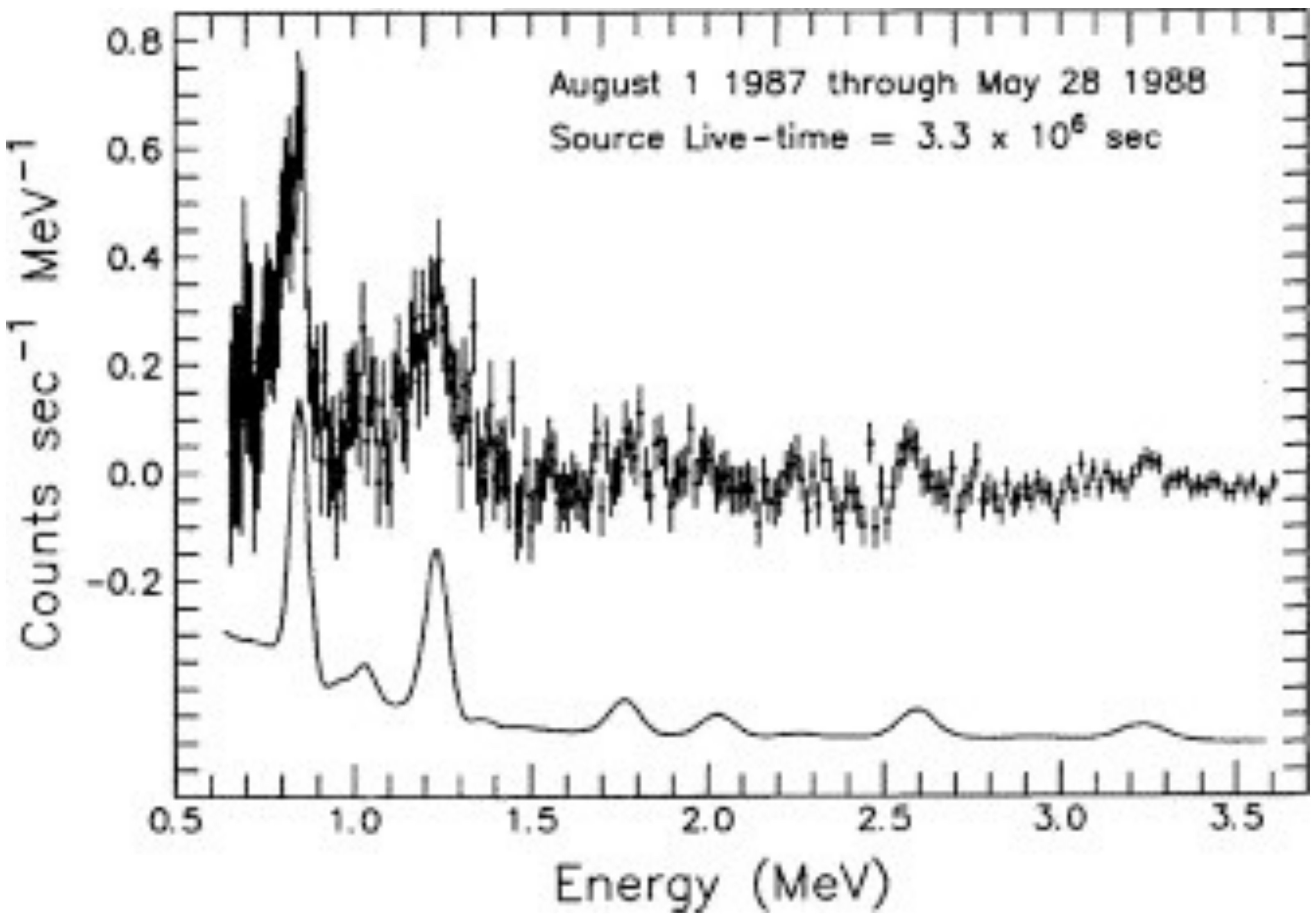


AAT image of the supernova, about two weeks after discovery.

The light-curve was measured to behave exactly as expected: it faded quickly until June 1987, when it settled into a much slower fade, of about 1% a day. This behaviour continued exactly for two years, and corresponded exactly to the laboratory-measured half-life of cobalt-56 (77 days), which is the result of the (rapid) decay of ^{56}Ni which is produced in the blast. We could even determine the mass of nickel produced: about 0.08 solar masses, or about 1% of the mass of the core just prior to the explosion.



What's more, several satellites detected gamma-ray emission lines from ^{56}Co, which was clinching proof that the radioactive cobalt was made in the supernova itself.



The gamma-ray spectrum of SN 1987A, compared with models for the ^{56}Co lines.

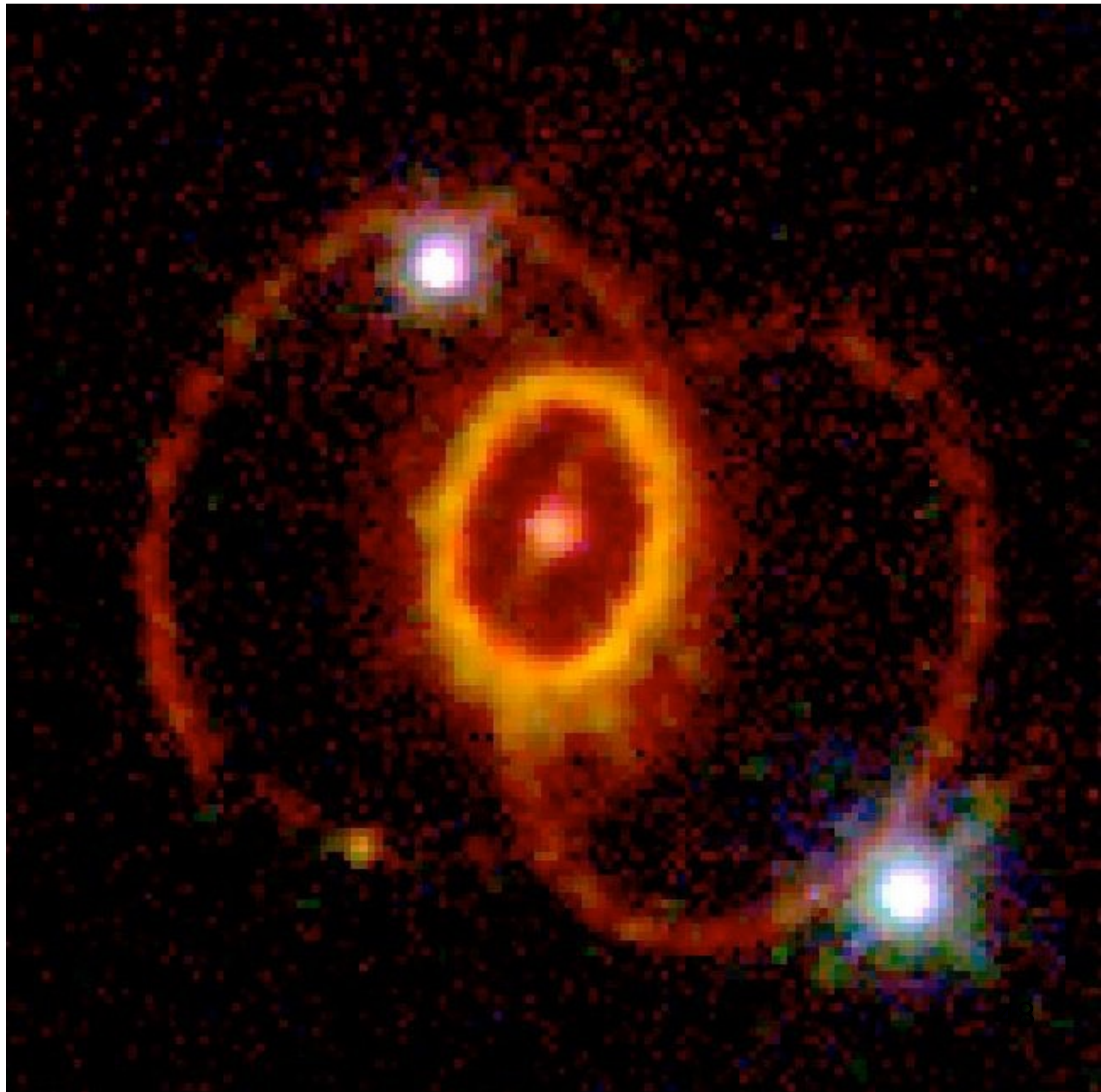
However, several other aspects of the explosion came as an enormous surprise.

First, and most importantly, astronomers were able to definitively identify the progenitor star from pre-supernova images.

Disconcertingly, the star, Sk –69° 202, was a *blue* supergiant instead of a red one. The fact that the star had disappeared after the explosion was clinching proof.

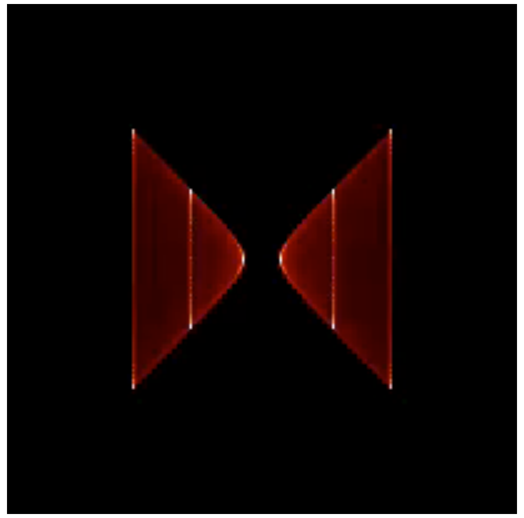
Several years later, HST obtained images of SN1987A, showing an amazing system of three rings of glowing gas. There is an inner equatorial ring, and two outer rings which are almost co-axial with the inner ring but on either side of the equatorial plane, and about 2.5 times larger than the inner ring.

It appears that the rings must have been ejected in two episodes of violent mass loss, one about 20,000 years (the outer rings) and one about 10,000 years (the inner ring) before the supernova explosion.



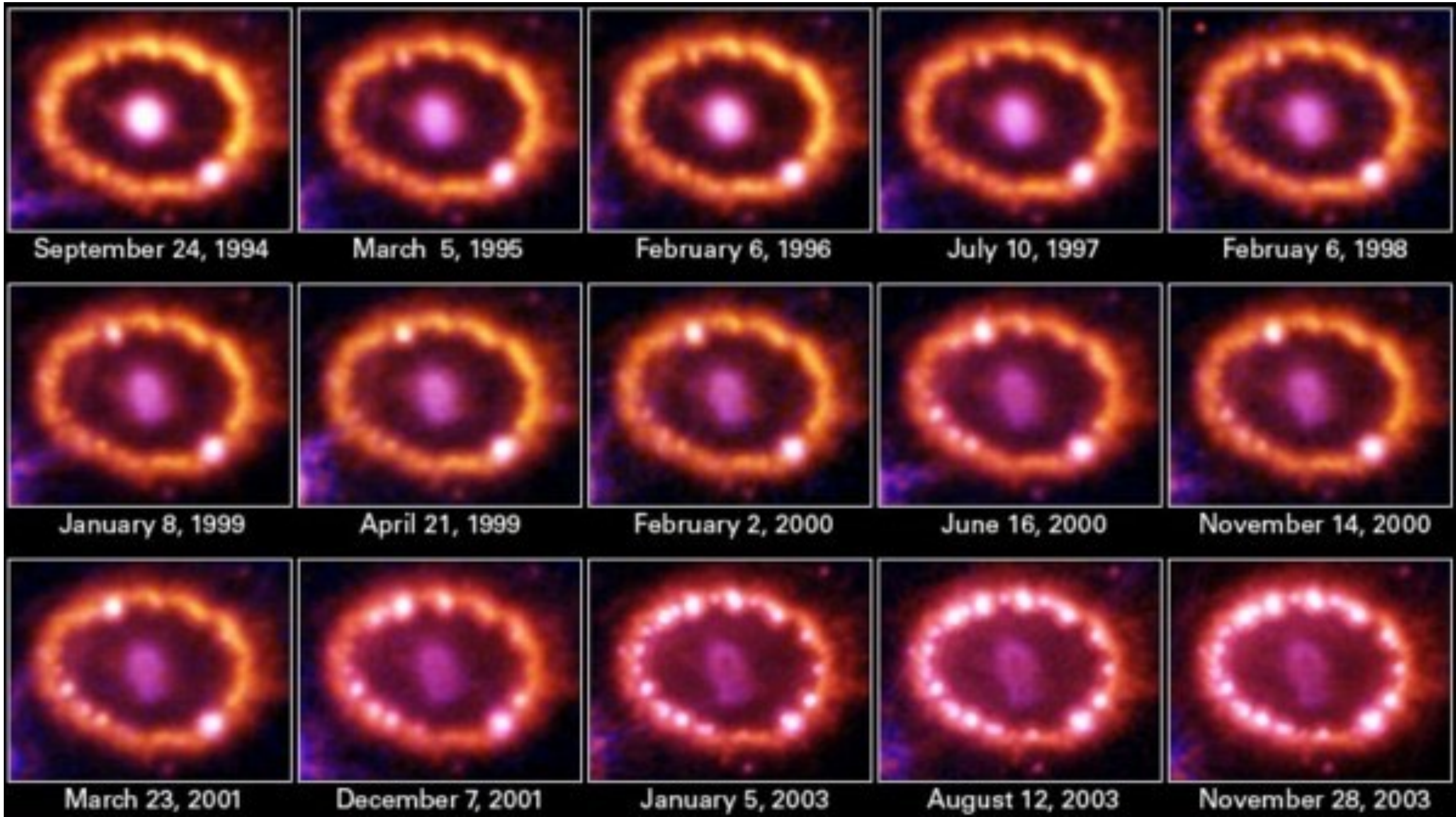
This animation shows the 3-D geometry of the rings.

A nebula discovered a few years ago around another star, dubbed the "Red Square", may be a very similar structure seen from side on.



Infrared image of the Red Square, and animation showing a possible geometry.

We can see the central ring light up as the shock wave from the supernova reaches it. Note the change in the central fireball.



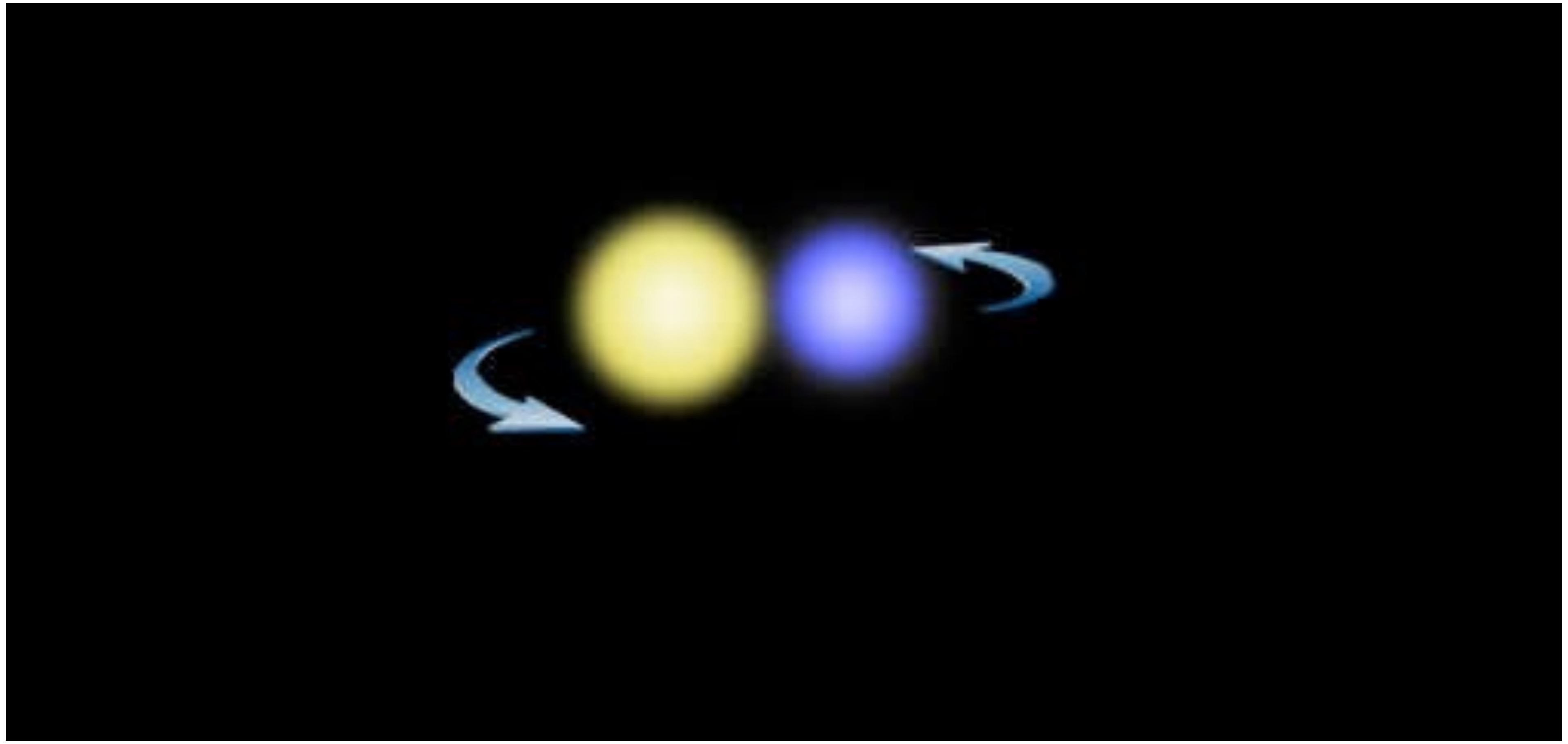
The ejected material contains chemical anomalies, which suggest that the envelope of the pre-supernova star had been thoroughly mixed.

These anomalies are not yet understood. The axial symmetry of the rings suggests that rotation played a crucial role; so either the pre-supernova star was rotating very rapidly, or was in a binary system.

The most likely scenario is that the progenitor was in a binary system, and either accreted large amounts of material from its companion, or (more likely?) merged with the companion completely. The companion star dissolves completely in the primary's envelope. Because of the added mass and dredge-up of material, the progenitor turns into a blue supergiant.

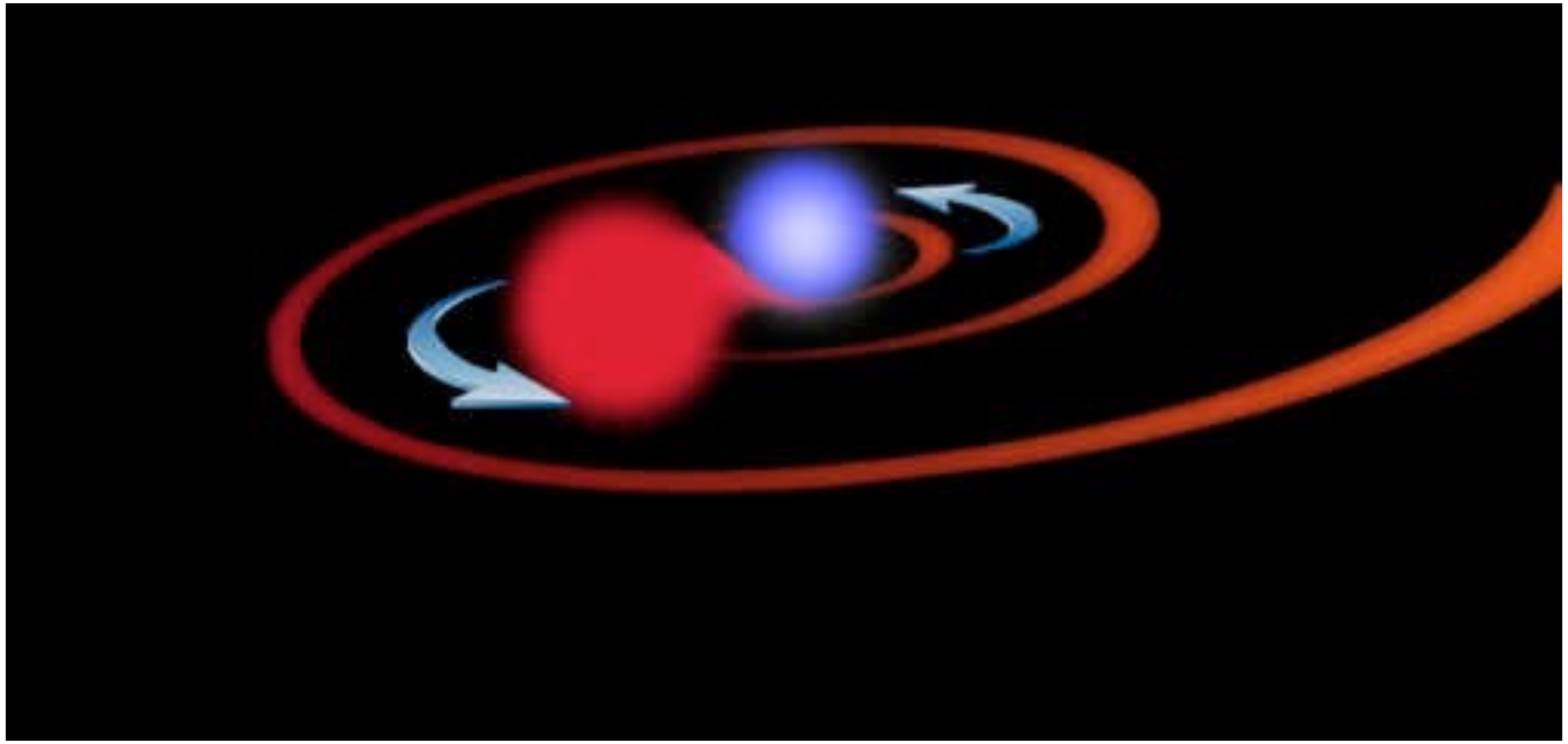
This sequence shows one possible scenario for the creation of the ring around SN 1987A.

20,000 yrs ago



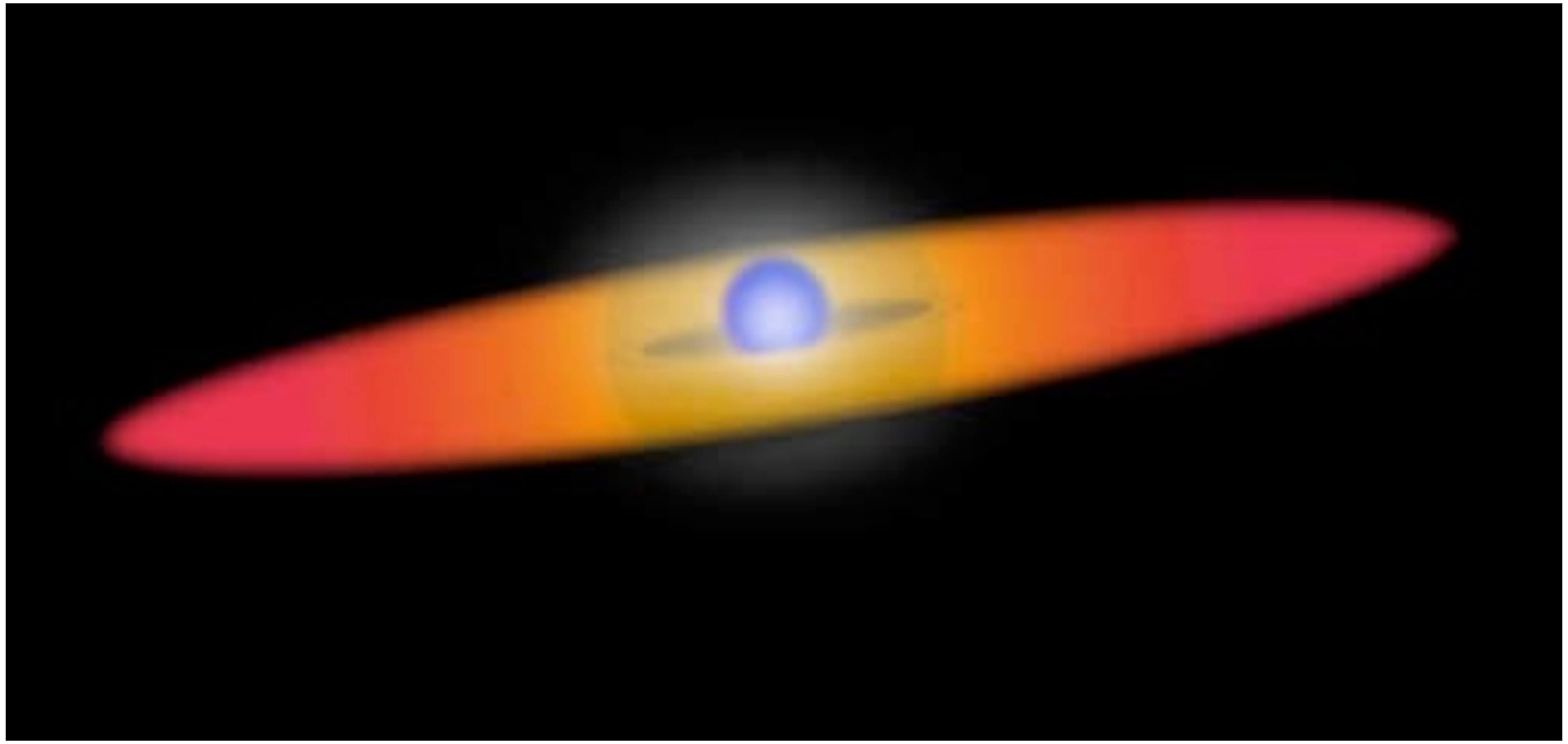
The larger star in a binary system swells up to become a red giant.

This sequence shows one possible scenario for the creation of the ring around SN 1987A.



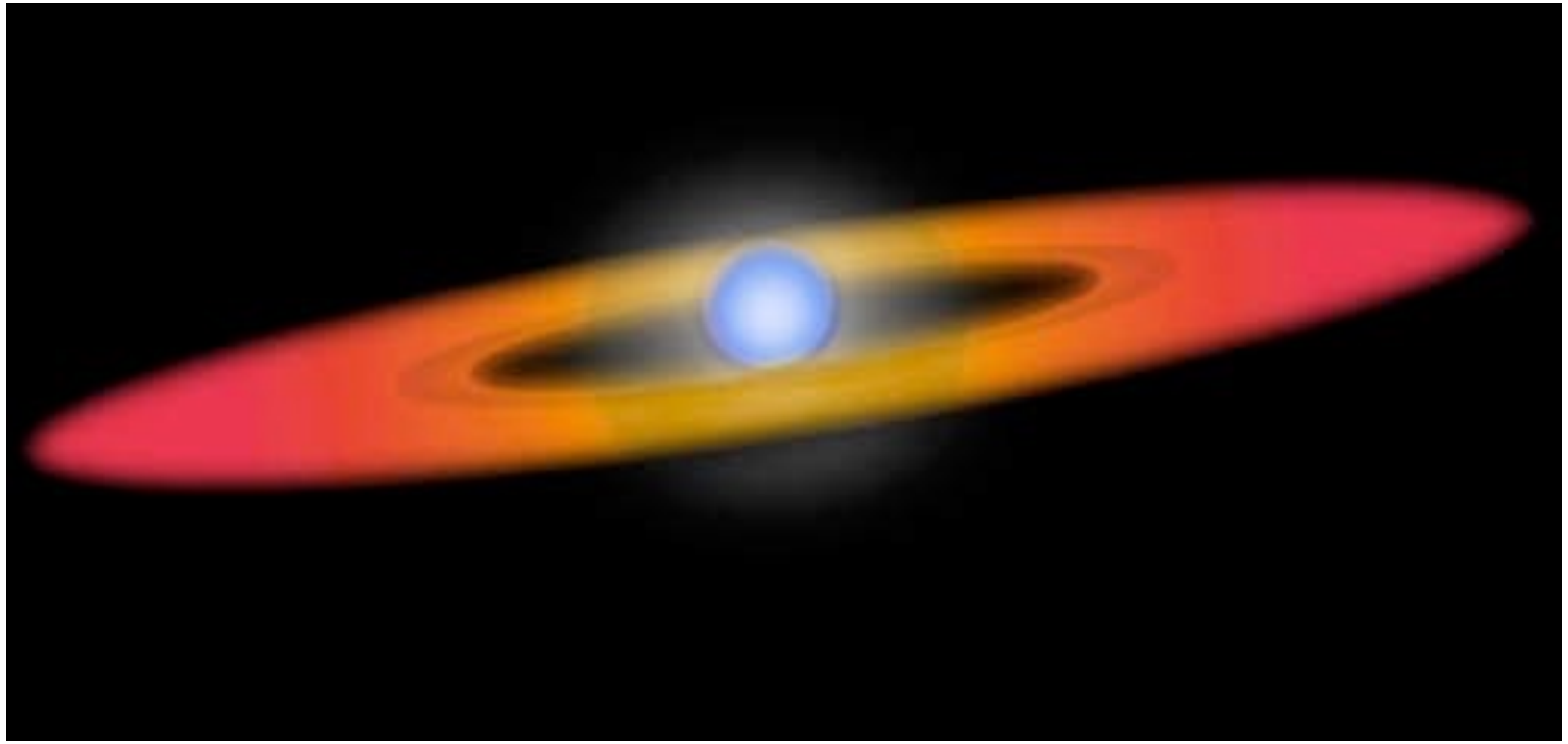
The red star passes matter to the blue star: some overflows to create a disk.

This sequence shows one possible scenario for the creation of the ring around SN 1987A.



Stars merge into one blue star surrounded by a disk of gas.

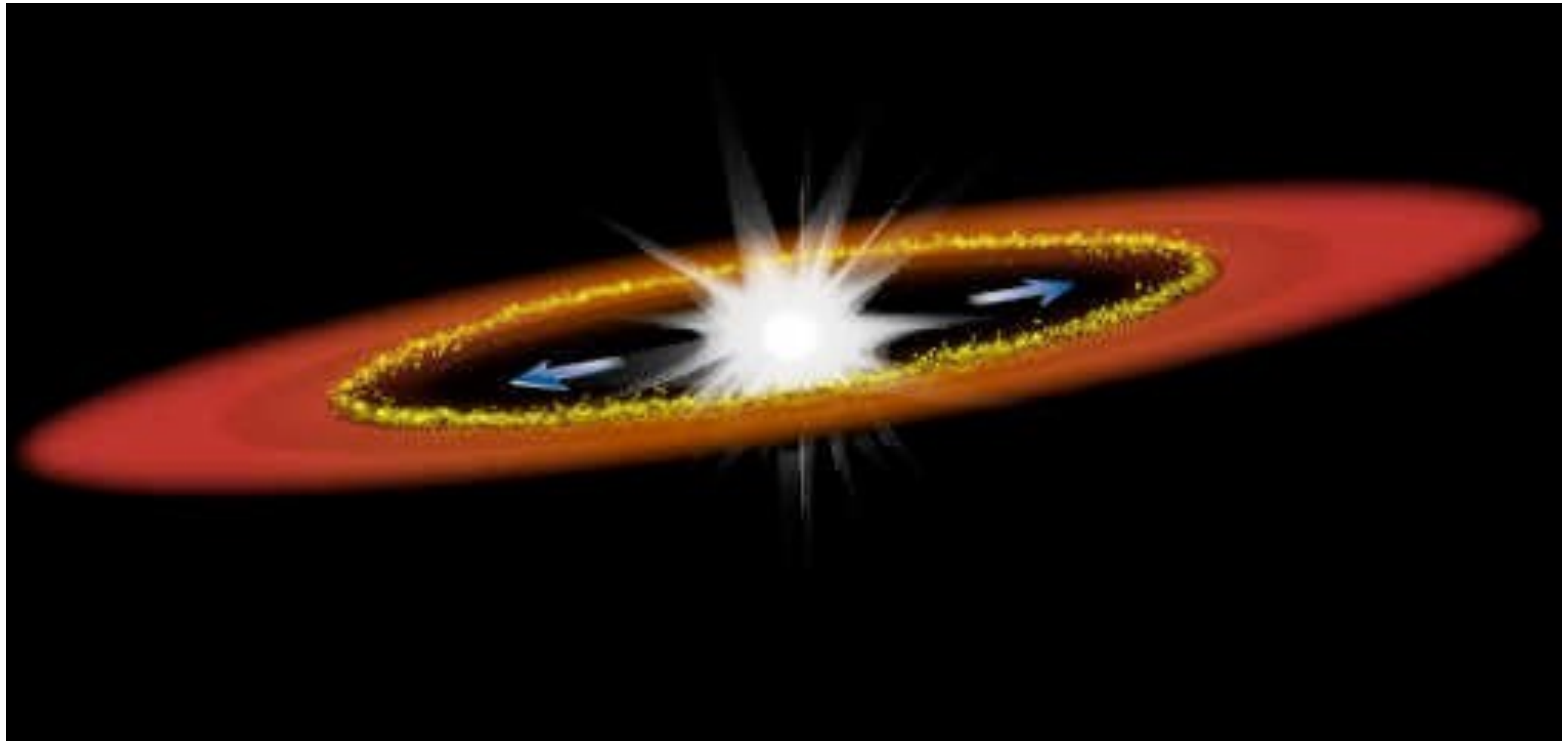
This sequence shows one possible scenario for the creation of the ring around SN 1987A.



Wind from blue star carves a hole in the disk.

This sequence shows one possible scenario for the creation of the ring around SN 1987A.

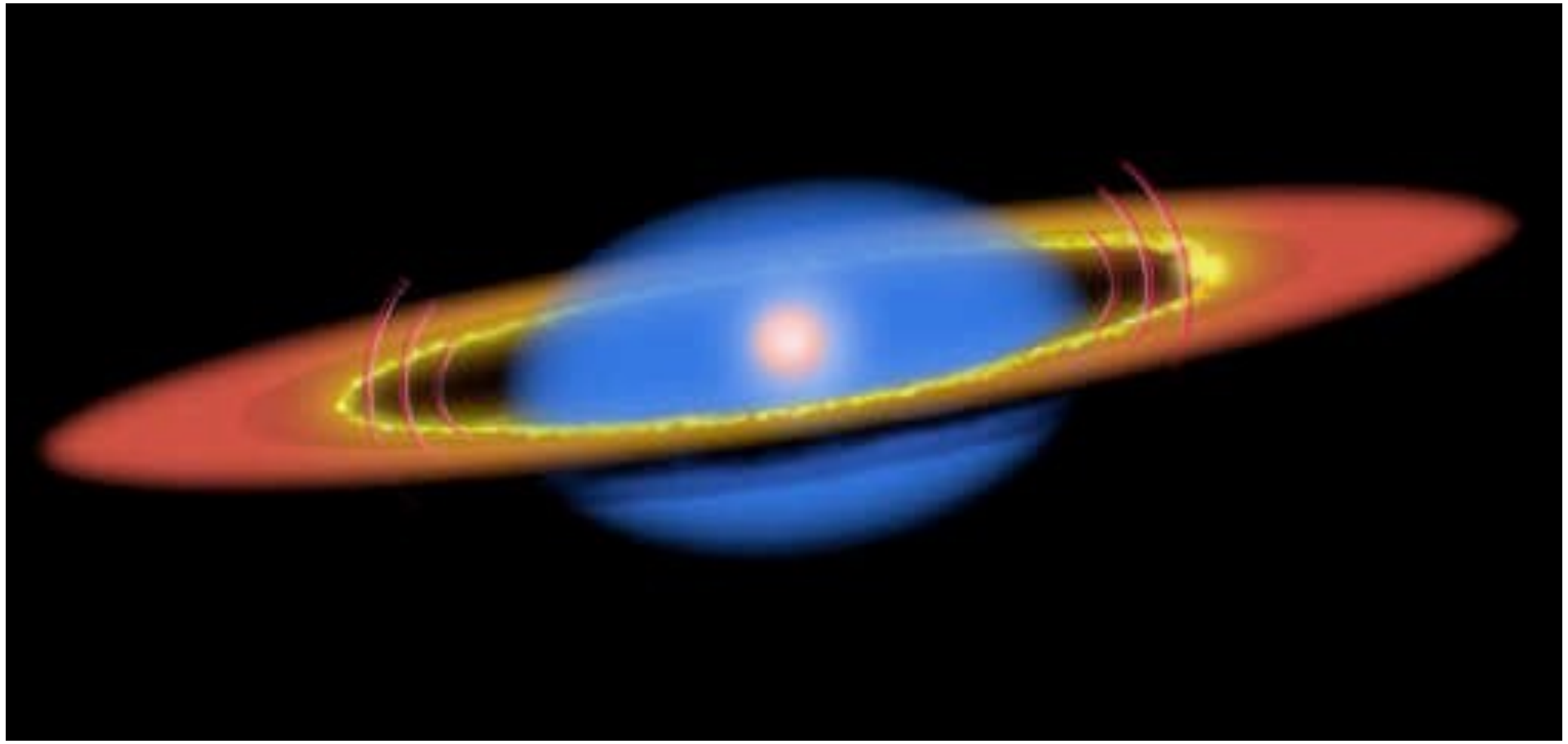
February 1987: Supernova explodes



Rapidly moving debris and shockwave move out from explosion.

This sequence shows one possible scenario for the creation of the ring around SN 1987A.

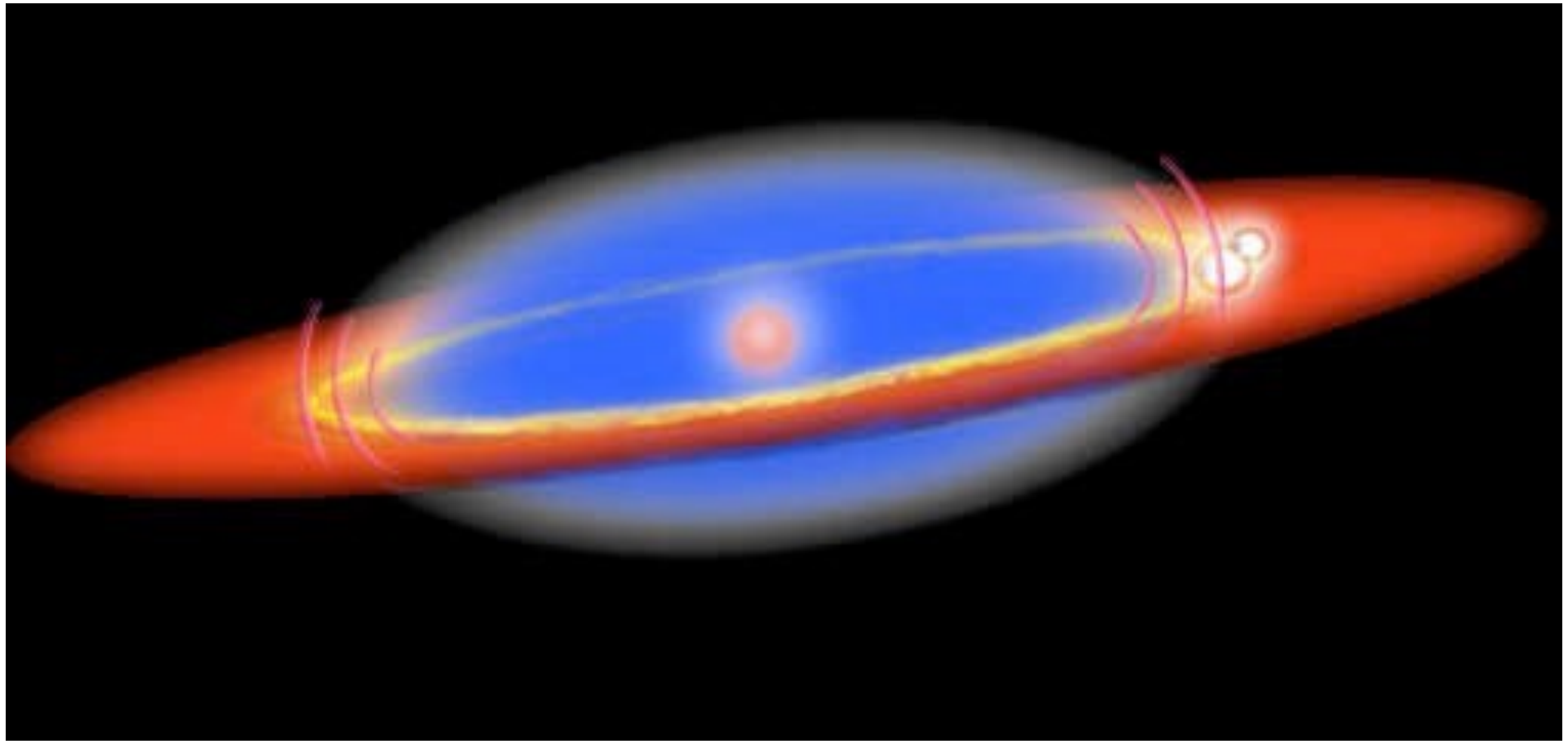
1991–1996



Boost of light illuminates inner edge of ring.

This sequence shows one possible scenario for the creation of the ring around SN 1987A.

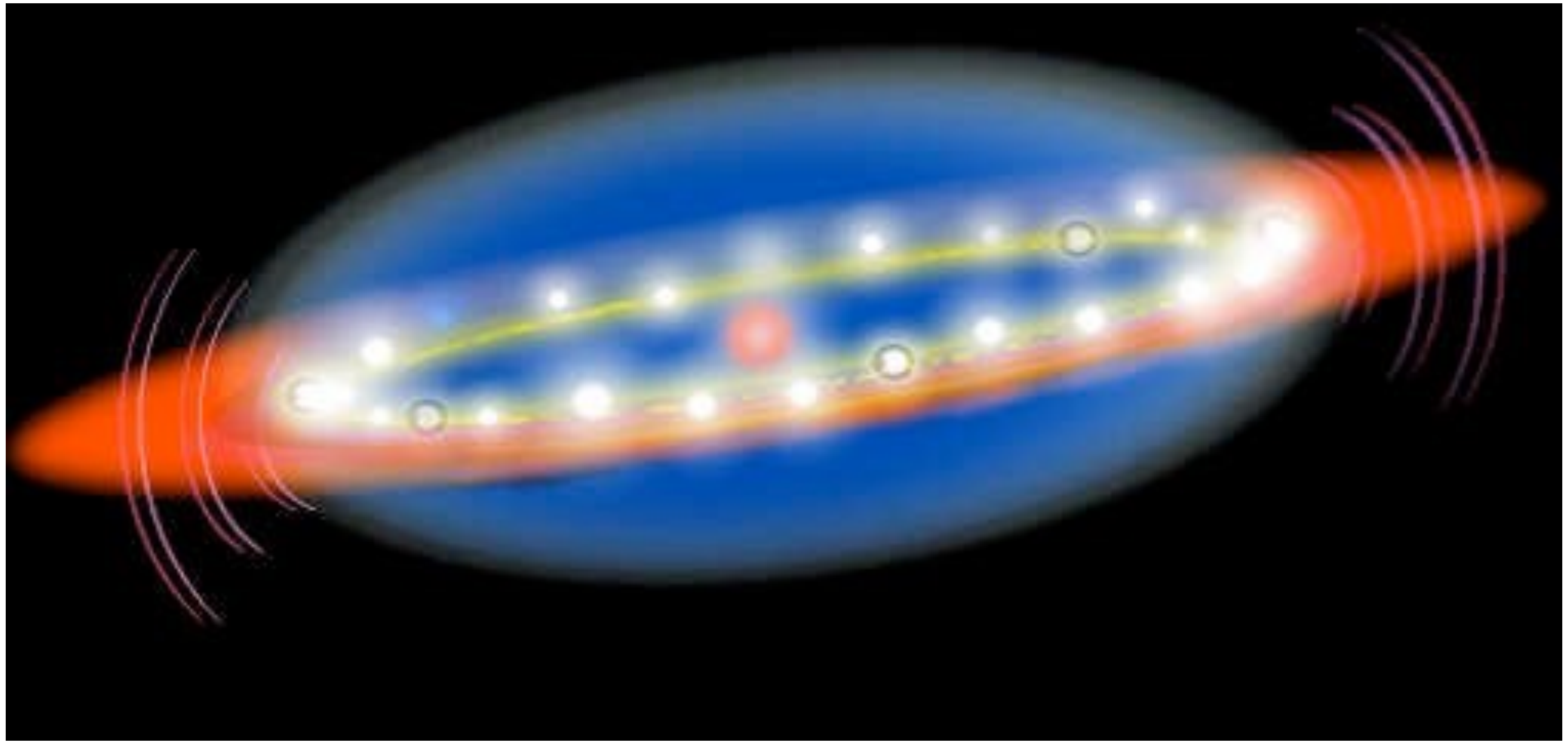
1997



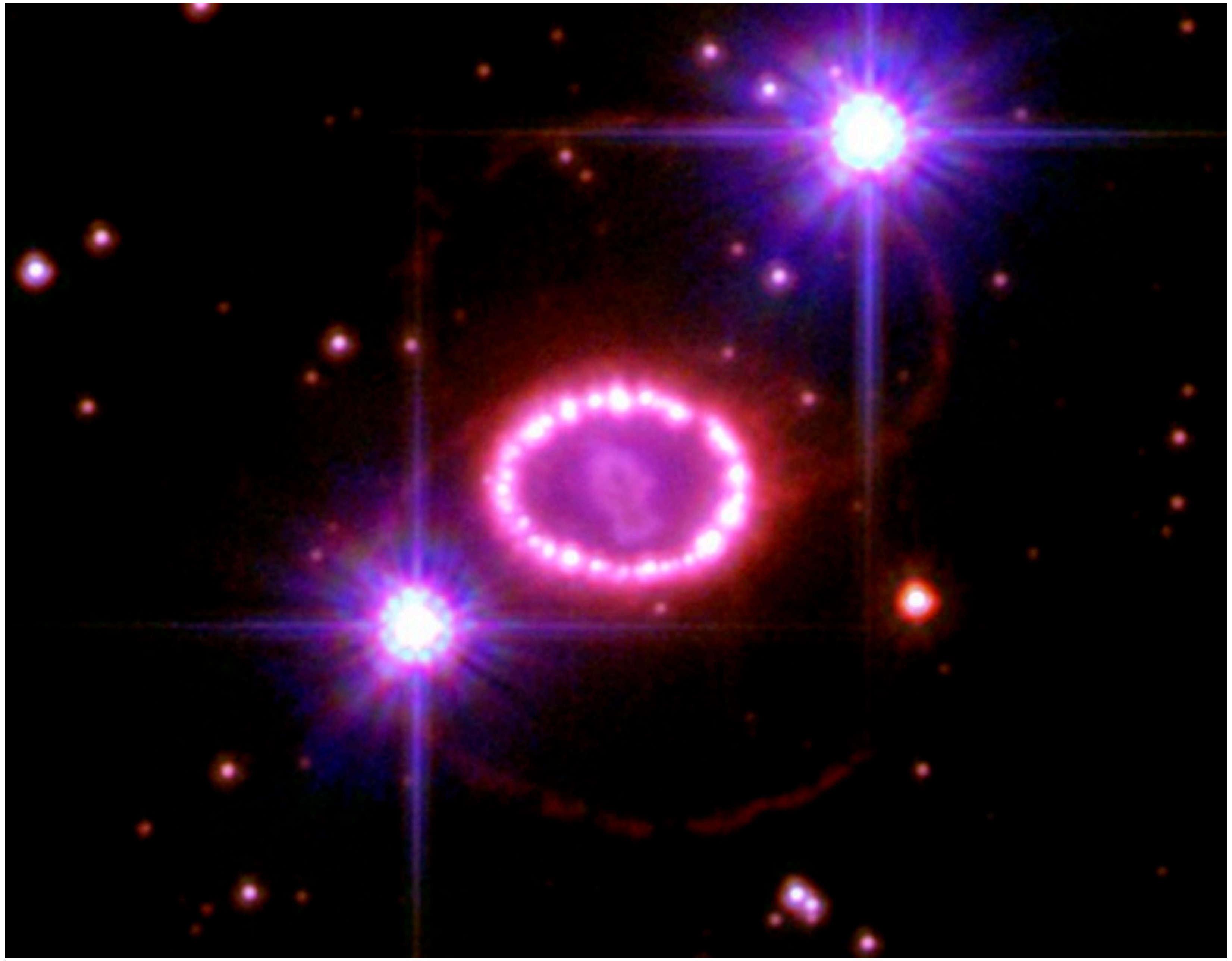
Shockwave hits piece on inner edge of ring

This sequence shows one possible scenario for the creation of the ring around SN 1987A.

2007

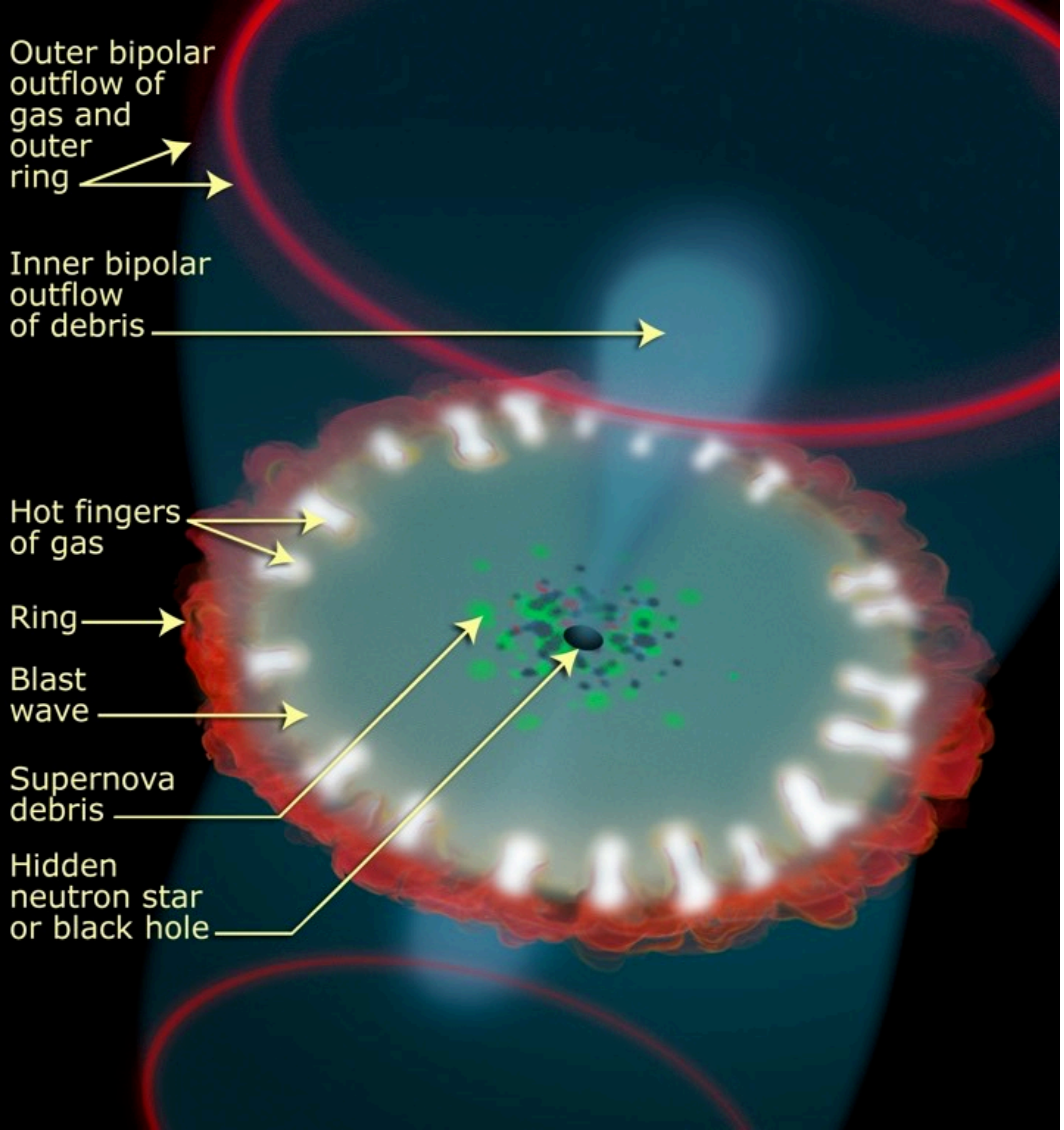


Ring lights up from full impact.

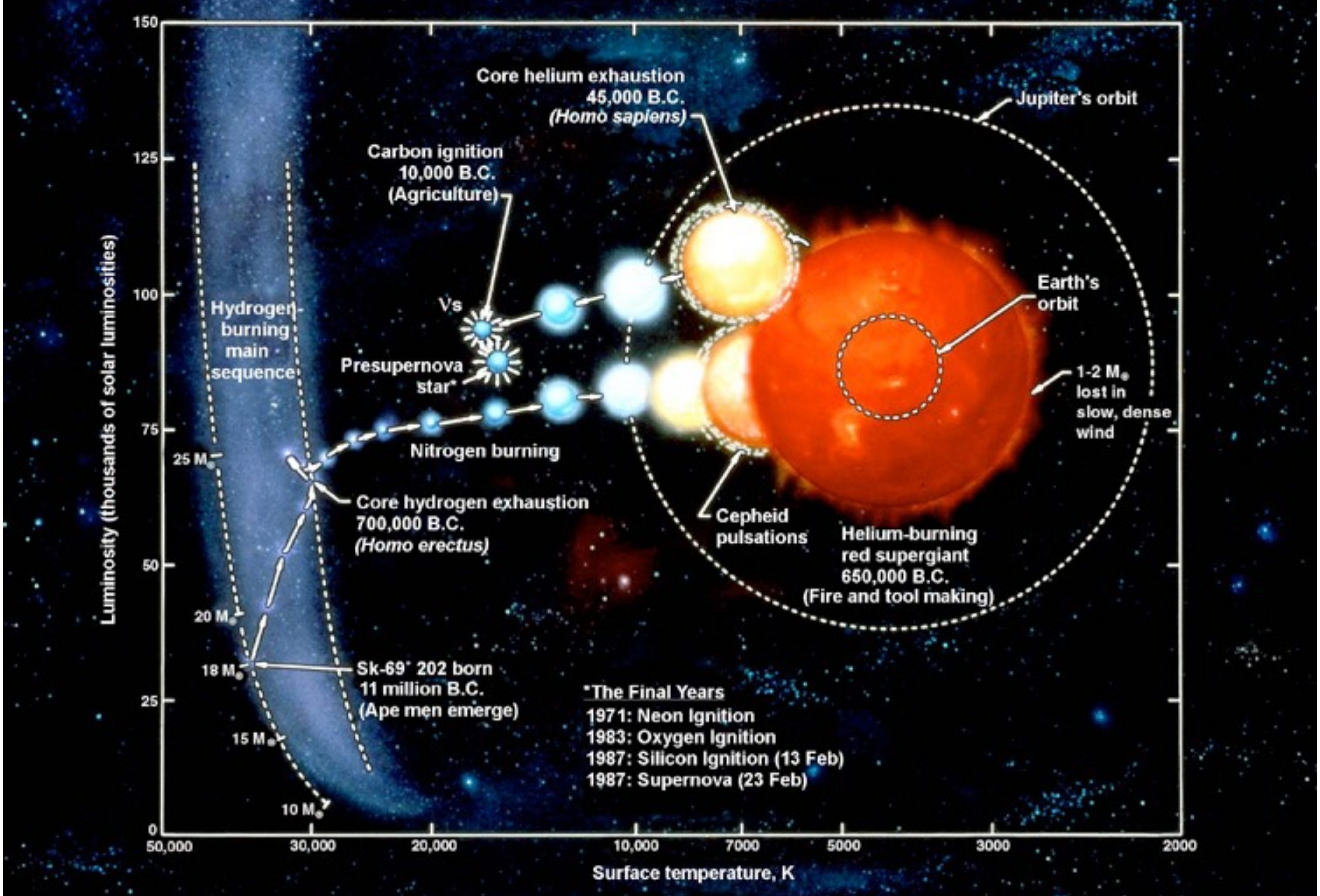


Hubble picture of SN1987A's rings taken 20 years after the explosion.

Inner debris of the Supernova 1987A (SN 1987A) ring



Despite intensive searching, the stellar remnant left behind has still not been found. It is presumably either a neutron star or a black hole, but for whatever reason, it is not yet visible.



Core helium exhaustion
45,000 B.C.
(Homo sapiens)
Jupiter's orbit
Carbon ignition
10,000 B.C.
(Agriculture)
Vs
Presupernova
star*
Hydrogen-burning main sequence
Earth's orbit
1-2 M⊙ lost in slow, dense wind
Nitrogen burning
25 M⊙
20 M⊙
18 M⊙
15 M⊙
10 M⊙
Core hydrogen exhaustion
700,000 B.C.
(Homo erectus)
Cepheid pulsations
Helium-burning
red supergiant
650,000 B.C.
(Fire and tool making)
Sk-69° 202 born
11 million B.C.
(Ape men emerge)
*The Final Years
1971: Neon Ignition
1983: Oxygen Ignition
1987: Silicon Ignition (13 Feb)
1987: Supernova (23 Feb)
Luminosity (thousands of solar luminosities)
150
125
100
75
50
25
0
50,000
30,000
20,000
10,000
7000
5000
3000
2000
Surface temperature, K

Recorded supernovae visible to the naked eye.

Year	Where observed	Brightness
185	China	Brighter than Venus
369	China	Brighter than Mars or Jupiter
1006	China, Japan, Korea, Europe, Arabia	Brighter than Venus
1054	China, SW India, Arabia ➔ Crab Nebula	Brighter than Venus
1572	Tycho	Nearly as bright as Venus
1604	Kepler	Brighter than Jupiter
1987	Ian Shelton (Chile)	-

Next April 30th is the 1011th anniversary of the brightest supernova in history, SN 1006.

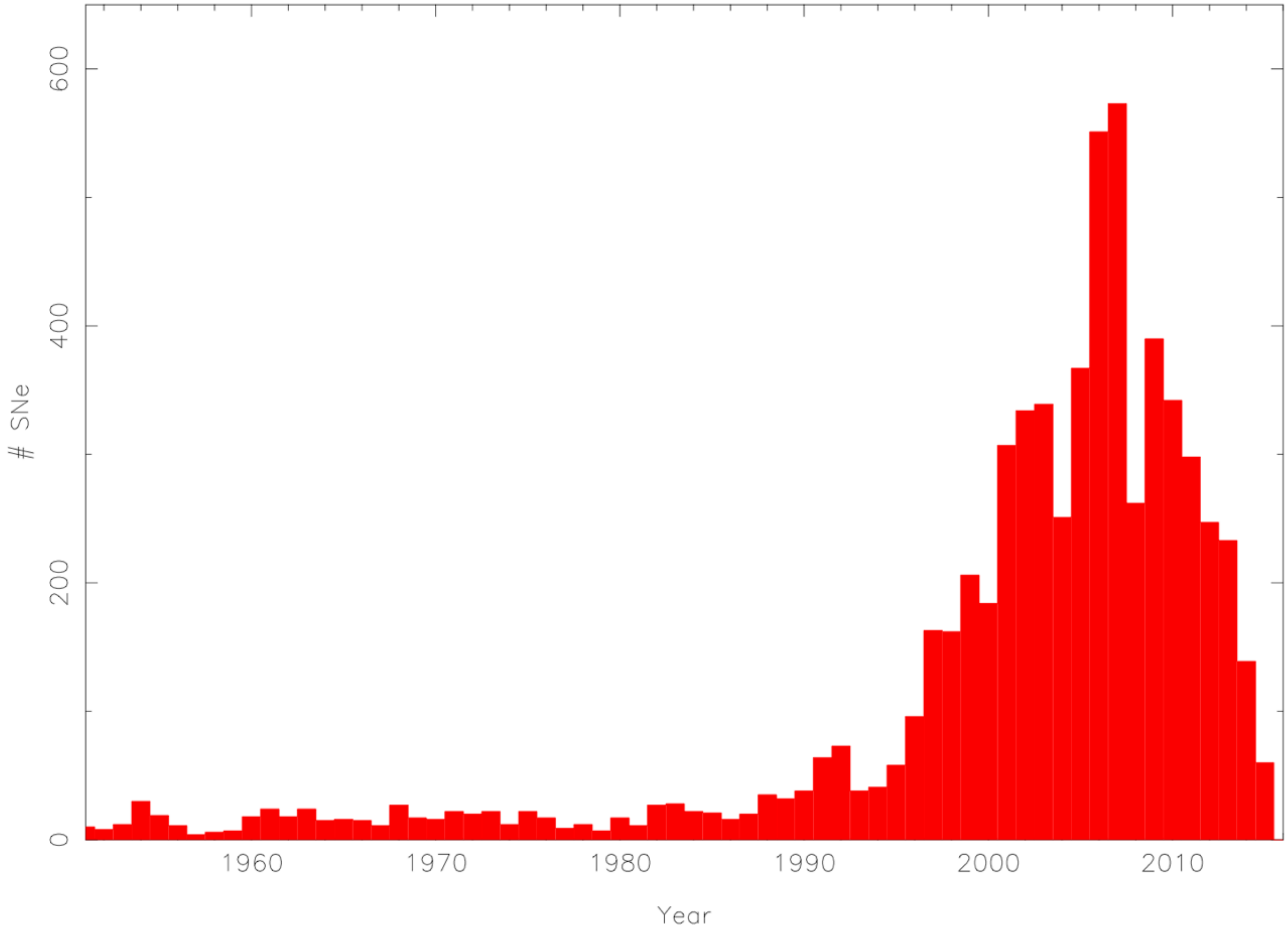
The Egyptian astrologer Ali bin Ridwan wrote

> *"I will now describe for you a spectacle that I saw at the beginning of my education. This spectacle appeared in the zodiacal sign Scorpio… It was a large nayzak [spectacle], round in shape, and its size 2½ or 3 times the magnitude of Venus. Its light illuminated the horizon and it twinkled very much. The magnitude of its brightness was a little more than a quarter of the brightness of the moon."*

The star reached magnitude about –7.5, and was visible during daylight for some time. The star remained visible for more than a year.

The supernova remnant from SN 1006 seen by Chandra; the remnant is now 70 light years across.

With the advent of automated telescopes, supernovae are now being discovered faster than ever before. But we still haven't had one in the Milky Way since Kepler's supernova of 1604.

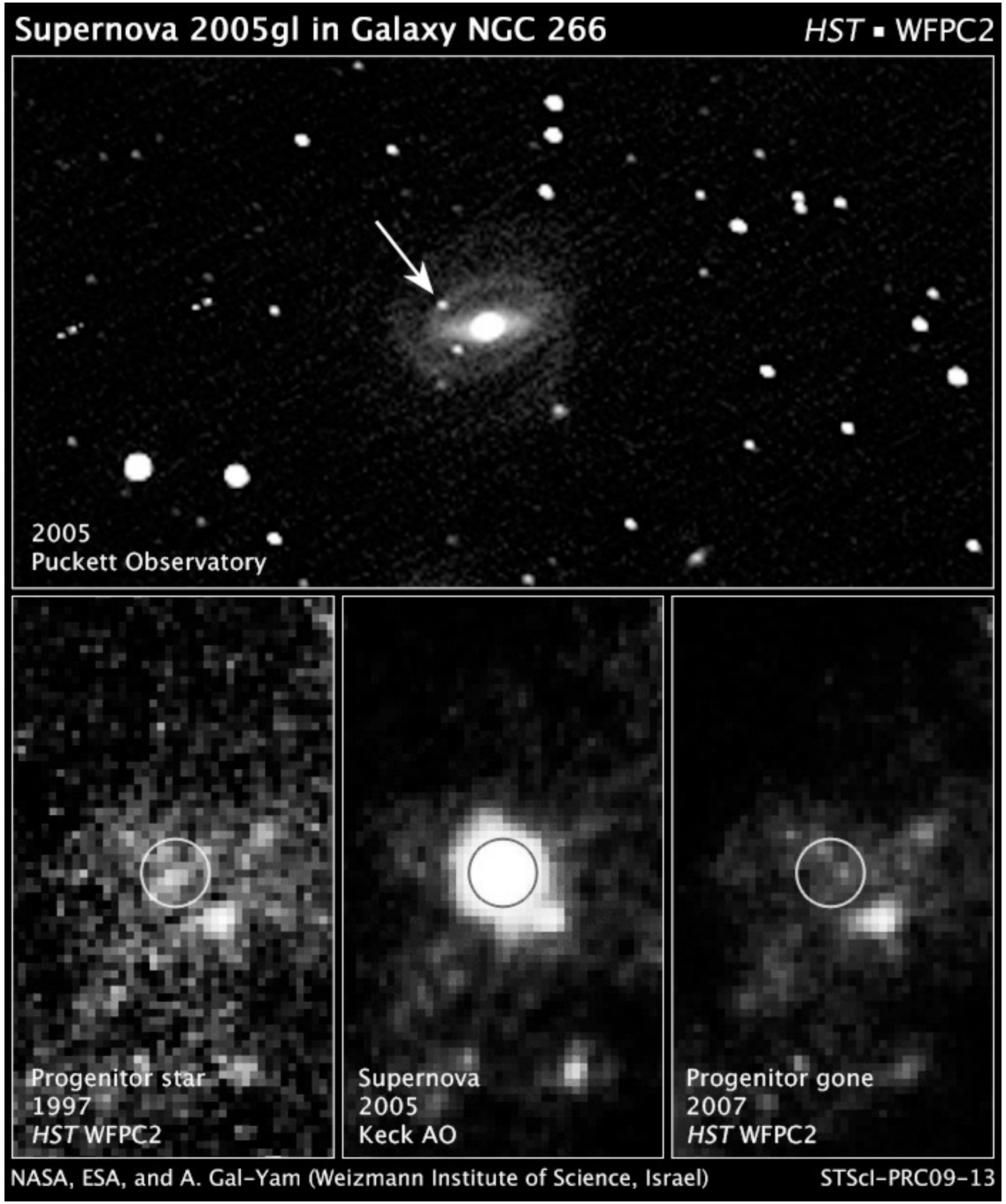


What's next

The next big task is to identify supernova progenitors. This requires detecting a star at the location of a supernova before the explosion, and showing that it has vanished after the explosion subsides.

This requires having images of a lot of stars.

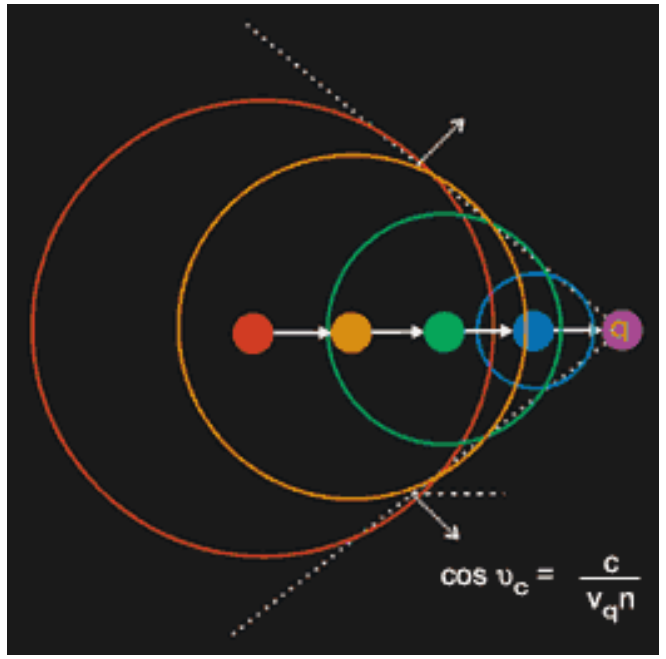
In a couple of cases, Hubble images have shown such objects.

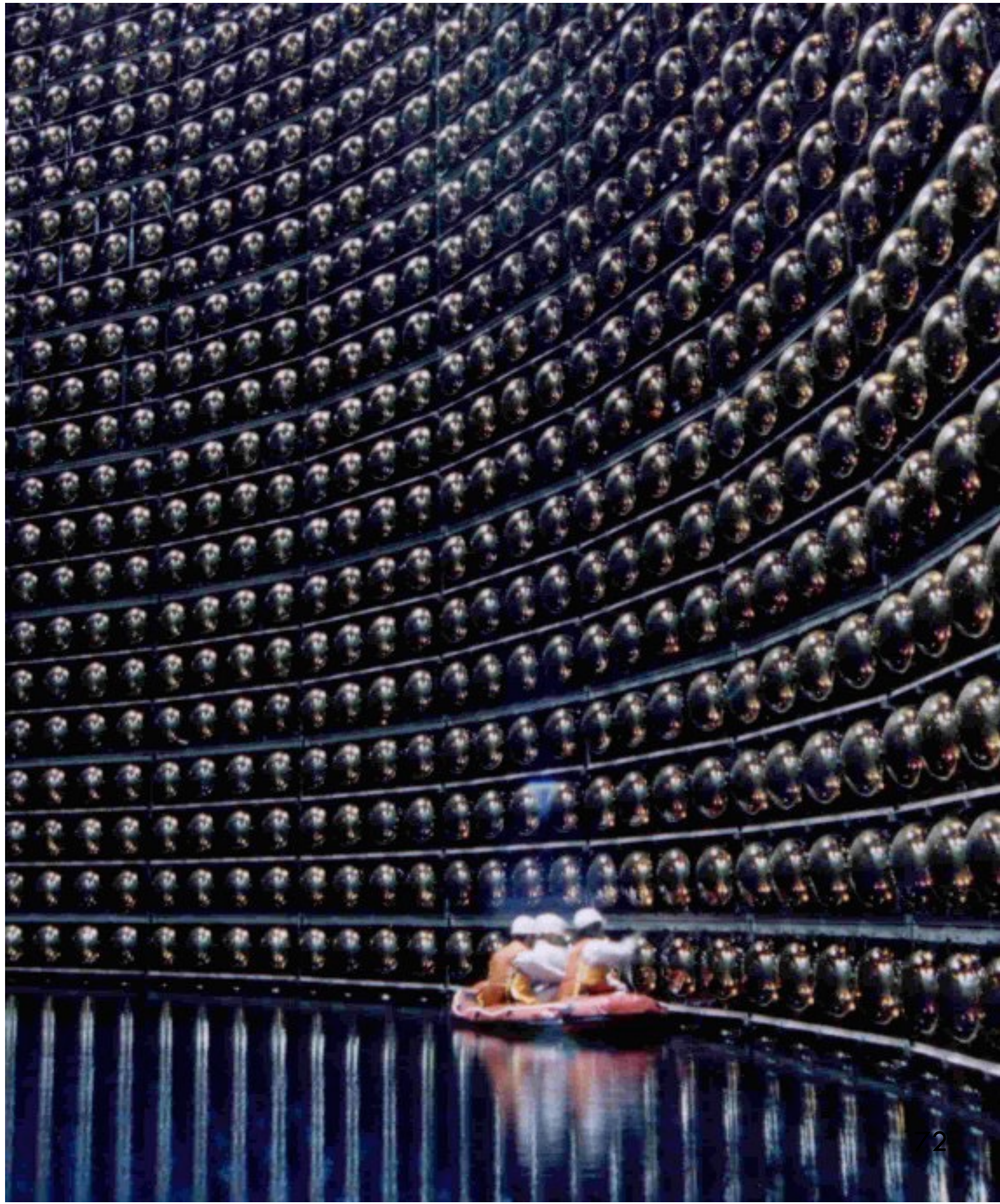


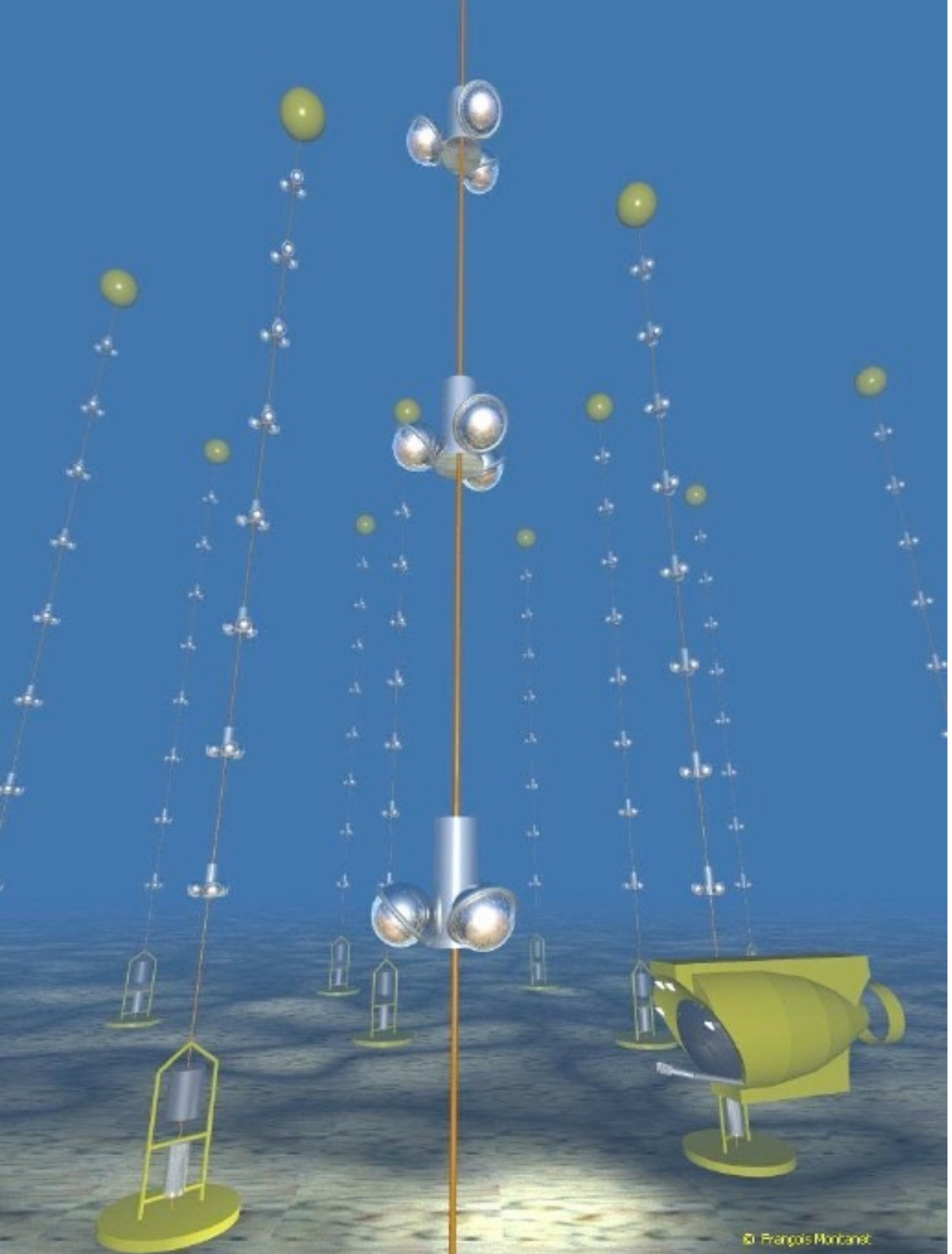
Hubble & Keck images of SN 2005gl, showing that the star at the location of the SN has vanished 2 years later

The detection of neutrinos from another supernova is also awaited with enormous interest.

Super-Kamiokande in Japan, uses 50,000 tonnes of pure water and 11,200 photomultiplier tubes in a 40m high x 40m diameter cylinder, to detect brief flashes of light from particles moving faster than local light speed: *Cherenkov radiation*.



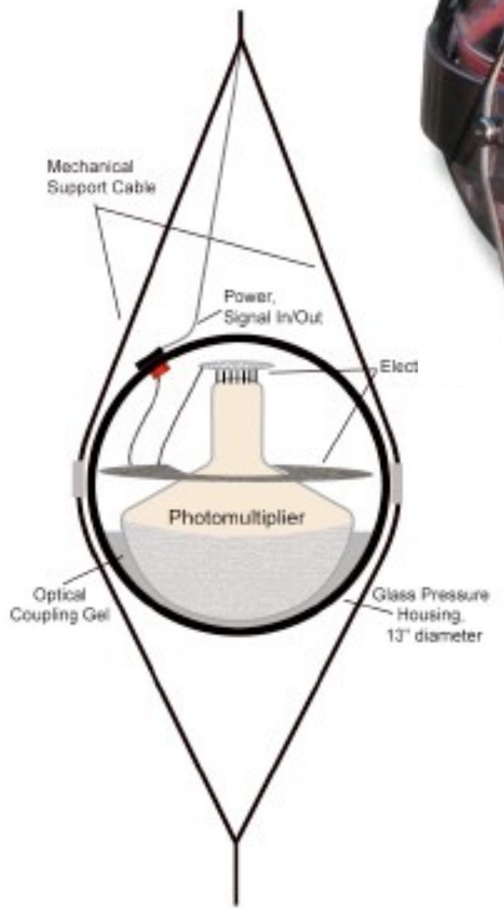




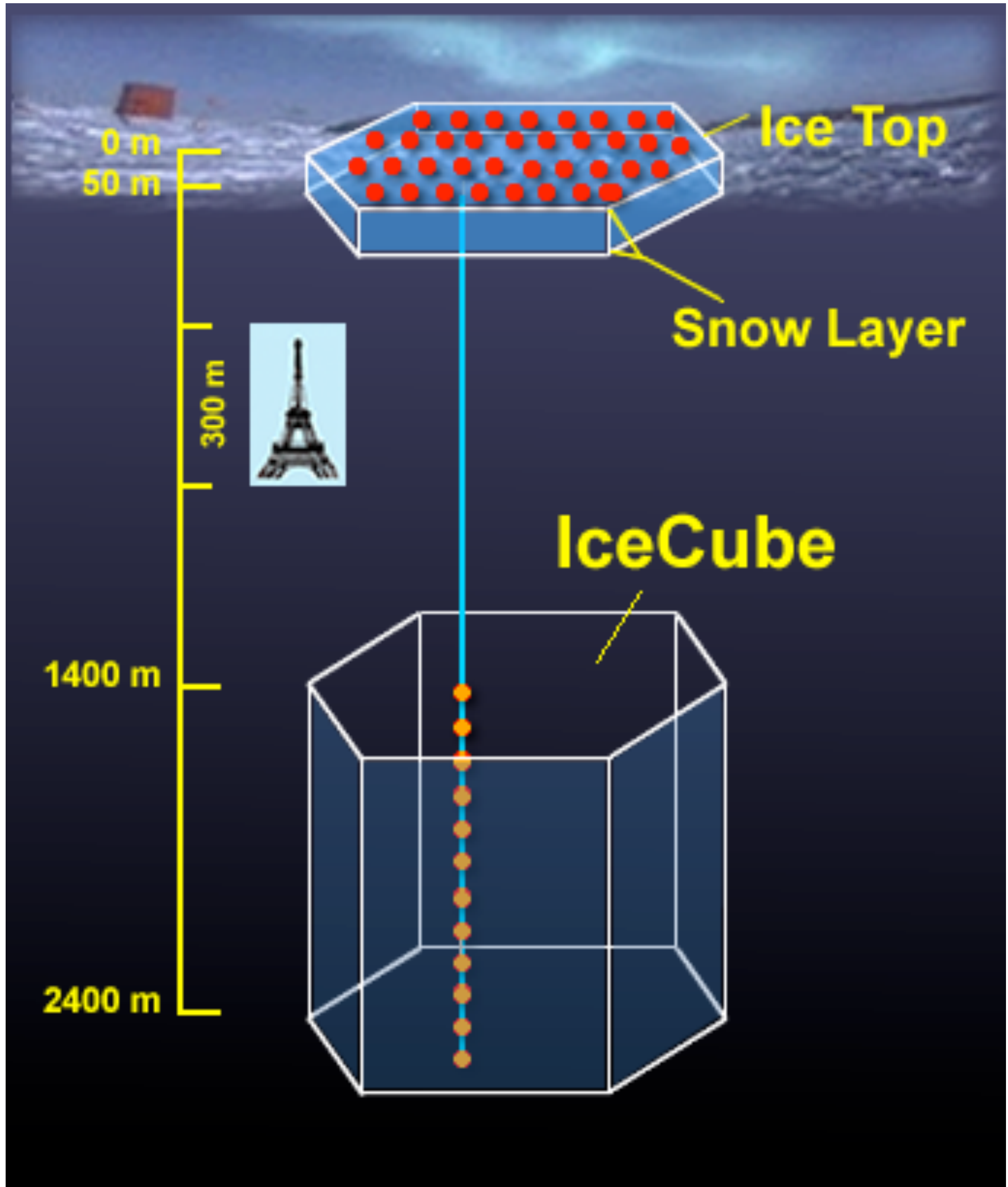
The next generation of neutrino detectors is now coming online, with much larger detector volumes (~1 km^3), all detecting Cherenkov radiation from neutrino interactions:

- *NESTOR* and *ANTARES*: towers of photo-multiplier tubes anchored to floor of Mediterranean Sea

IceCube: strings of PMTs lowered into Antarctic ice. Holes are drilled 2 km to where ice is clear. 86 cables, each with 60 sensor modules, have been deployed 2450 m under the ice.



Neutrinos have been detected from outside the solar system, though their exact origin remains a mystery.



Next week

we'll look at stellar graveyards, the end products of stellar evolution and the only truly stable stages in a star's life: white dwarfs, neutron stars, and black holes

Further reading

- "**Cosmic Catastrophes: Exploding Stars, Black Holes, and Mapping the Universe**" by J. Craig Wheeler (Cambridge UP, 2007) – the first edition from 2007 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.

- "**The Supernova Story**" by Laurence Marschall (Plenum Press, 1988) is a very nice book, including an excellent description of the excitement in the astronomical community generated by the explosion of SN 1987A, from someone who was right in the middle of it all.

- A more technical, but still quite general, article about SN 1987A is by Fransson et al.: "**Twenty years of Supernova 1987A**", ESO Messenger 127, p. 44 (2007), available at http://www.eso.org/sci/publications/messenger/archive/no.127-mar07/m127-Fransson.html

- David Bishop has an archive showing the timeline of the discovery of SN 1987A at http://www.rochesterastronomy.org/snimages/sn1987a.html; this is part of his "Bright Supernovae" pages http://www.rochesterastronomy.org/SNIMAGES/

- Peter Tuthill has a page about his discovery of the Red Square nebula at http://www.physics.usyd.edu.au/~gekko/redsquare.html

- NASA's "Observatorium" has a nice article called "**Stellar Evolution and Death**" at http://observe.arc.nasa.gov/nasa/space/stellardeath/stellardeath_intro.html

- There's a complete list of every supernova ever discovered at the IAU: Central Bureau for Astronomical Telegrams http://www.cfa.harvard.edu/iau/lists/Supernovae.html

Sources for images used:

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- Structure of the core just prior to the supernova explosion: from "Geochemistry" by William White, http://www.geo.cornell.edu/geology/classes/geo455/Chapters.HTML
- Artist's impression of neutron star: from http://www.nasa.gov/mission_pages/GLAST/science/neutron_stars.html
- Core bounce: from Wikipedia https://en.wikipedia.org/wiki/Type_II_supernova
- Animations of core collapse: from Adam Burrow's Movies, http://www.astro.princeton.edu/~burrows/
- Rayleigh-Taylor instabilities in the shock front: fron Stan Woosley, Astronomy 12: Stars and Stellar Evolution, Lecture 17 http://www.ucolick.org/~woosley/classnotes_winter2006.html
- 3D supernova model: from Blondin & Mezzacappa 2007, "Pulsars from an instability in the accretion shock of supernovae", Nature 445 58 http://adsabs.harvard.edu/abs/2007Natur.445...58B
- X-ray images of Cas A: from Chandra Photo Album, http://chandra.harvard.edu/photo/2002/0237/0237_xray.jpg and http://chandra.harvard.edu/photo/2000/cas_a062700/index.html
- Sequence of events in a supernova: from Astronomy 201: Our Home in the Universe, http://astrosun2.astro.cornell.edu/academics/courses//astro201/sn.htm
- Supernova 1994D: by the High-z Supernova Search Team, from APOD 2000 March 12, http://apod.nasa.gov/apod/ap000312.html
- Supernova Types I and II light-curves: from AAVSO Variable Star of the Month, March 2001: Supernova 1987A, http://www.aavso.org/vstar/vsots/0301.shtml
- HST images of supernova remnants: from Hubblesite http://hubblesite.org/gallery/album/nebula_collection/pr2005037a/
- Expanding shell from SN1993J in M81: image courtesy of NRAO/AUI, from NRAO Image Gallery, http://www.nrao.edu/imagegallery/php/level3.php?id=392
- Cataclysmic binary picture: from Hubble Site News Center, May 22 1995, http://hubblesite.org/newscenter/newsdesk/archive/releases/1995/23/
- Nucleosynthesis on the main sequence: from "Principes de Geochimie" by Michael Higgins, http://wwwdsa.uqac.uquebec.ca/~mhiggins/cours/6sct265/chapitre2.htm
- S-process nucleosynthesis: from Nautilus: Research http://exp-astro.physik.uni-frankfurt.de/nautilus/index.php?id=research&lang=en
- r-process sketch: from LLNL Research Highlight, July 2014, "Evidence of a turbulent beginning", https://str.llnl.gov/july-2014/borg
- Element abundances and nucleosynthesis sites:
- Nuclear power plant: from Wikipedia, http://en.wikipedia.org/wiki/Image:Nuclear_Power_Plant.jpg
- The deduction of the age of the SN which formed Earth's heavy elements is from "Gravity from the ground up" by Bernard Schutz (Cambridge UP, 2003), p. 126 (Investigation 11.3).
- Supernova image from March 1987: image by Marcelo Bass, CTIO/NOAO/AURA/NSF, http://www.noao.edu/image_gallery/html/im0644.html
- LMC/Tarantula Nebula: NOAO image, from Astronomy Picture of the Day 2000 Feb 22, http://apod.nasa.gov/apod/ap000222.html
- IMB event from SN 1987A: from "The IMB Experiment" by Jack Vander Velde, http://www-personal.umich.edu/~jcv/imb/imbp5.html
- The Tarantula Nebula and SN1987A: image by David Malin, from http://www.aao.gov.au/images/
- Light curve of SN1987A: from original paper by Bouchet et al. 1991, A&A 245 490; available online at http://adsabs.harvard.edu/abs/1991A&A...245..490B
- Before and after images of SN 1987A: images by David Malin, http://www.aao.gov.au/images/
- Rings from SN 1987A: Hubble Site News Center, May 19 1994, http://hubblesite.org/newscenter/newsdesk/archive/releases/1994/22/. Animation of the rings' orientation: from Hubble Site News Center, May 12 1997, http://hubblesite.org/newscenter/newsdesk/archive/releases/1997/14/. Scenario for ring formation: from Hubble Site News Center, Feb 10, 1998, http://hubblesite.org/newscenter/newsdesk/archive/releases/1998/08/. Lighting up of the ring: from Hubble Site News Center, Feb 19, 2004, http://hubblesite.org/newscenter/newsdesk/archive/releases/2004/09/. December 2006 image, from Hubble Site News Center, Feb 22 2007 http://hubblesite.org/newscenter/archive/releases/2007/10/

- Red Square nebula: from Peter Tuthill http://www.physics.usyd.edu.au/~gekko/redsquare.html
- Life cycle of SN 1987A: from http://www.astro.princeton.edu/~burrows/papers/rob/Stellar_Evolution.jpg
- SN 1006: imagined image by Tunc Tezel from APOD 2006 April 30 http://apod.nasa.gov/apod/ap060430.html; Chandra image from APOD 2005 December 26 http://apod.nasa.gov/apod/ap051226.html
- Number of supernova per year: plot by HMJ, using data from the IAU: Central Bureau for Astronomical Telegrams http://www.cfa.harvard.edu/iau/lists/Supernovae.html
- SN2005gl: from Hubble news release STScl-2009-13, “Hubble Uncovers an Unusual Stellar Progenitor to a Supernova”, http://hubblesite.org/newscenter/archive/releases/star/2009/13/
- SuperKamiokande: Super Kamiokande Photo Gallery http://www-sk.icrr.u-tokyo.ac.jp/sk/gallery/index-e.html
- ANTARES: from ANTARES site http://antares.in2p3.fr/
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