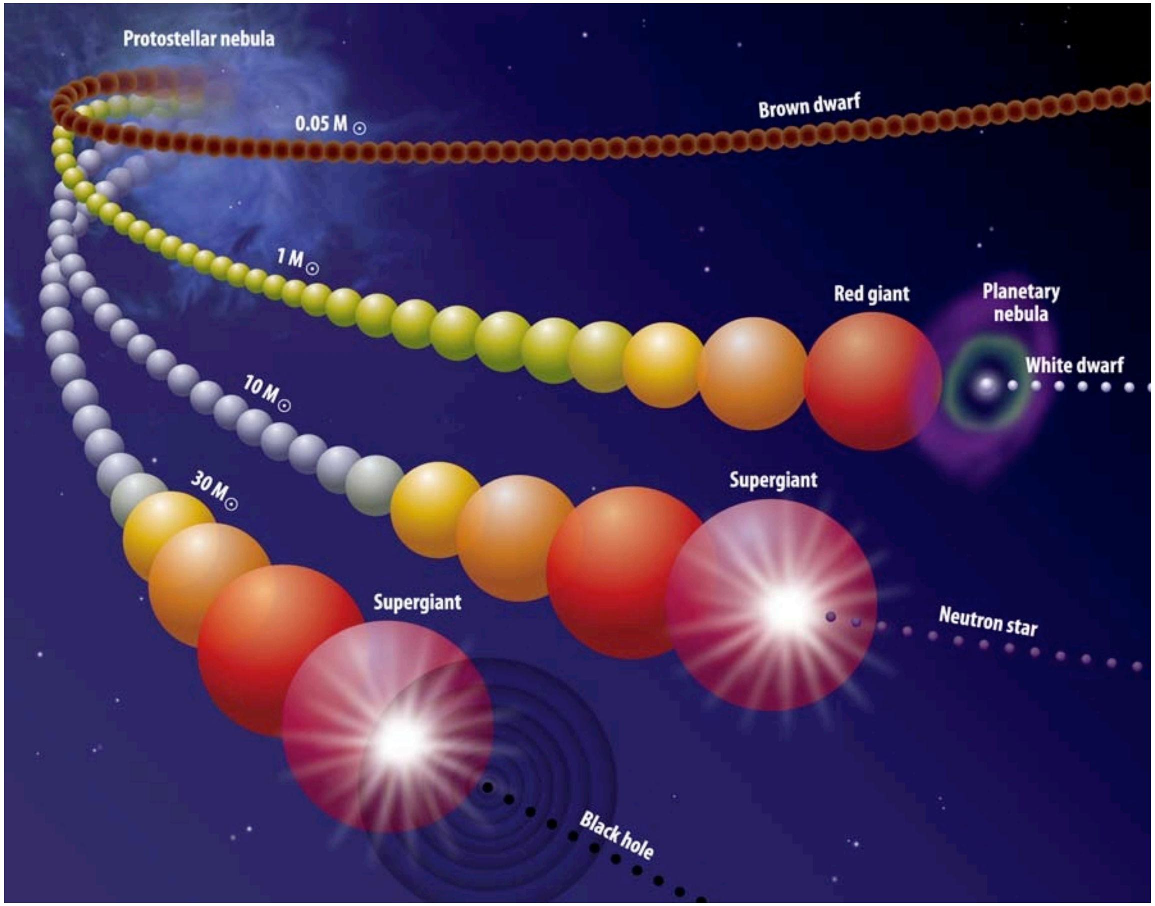
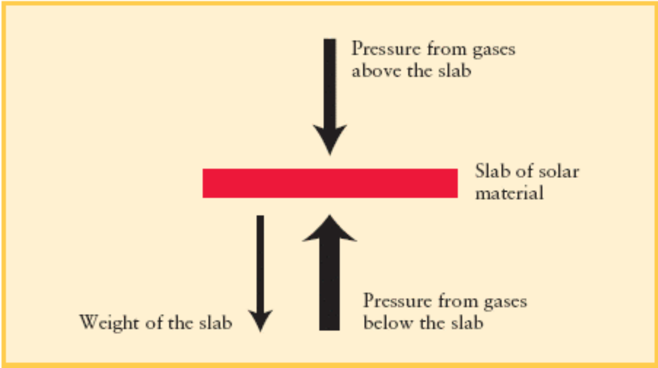
Stellar Evolution Towards Compact Objects



Stellar Evolution Towards Compact Objects

Stars are held in equilibrium by a **balance between gravity and radiation** pressure from photons produced in their hot interior.



(a) Material inside the sun is in hydrostatic equilibrium, so forces balance

The energy source of stars is **nuclear fusion** that mostly takes place in their hot and dense cores.

Fusion of hydrogen in stars with a core temperature close to that of our suns $T \approx T_{\odot} (T_{\odot} = 16$ million K) proceeds mostly through the following reaction:

$$4\ {}^{1}H \rightarrow {}^{4}He + \text{neutrinos} + \text{gamma-ray photons}$$

Stellar Evolution Towards Compact Objects

At some point a star's fuel will run out and the outward radiation pressure will not be available to support the star anymore.

Our Sun will eventually lose most of its outer layers forming a planetary nebula while the inner core will collapse into a compact object called a **white dwarf**.

The Eskimo nebula (NGC 2392). Hubble Space Telescope image of a planetary nebula, the glowing remains of a dying, Sun-like star.

Stellar Evolution Towards Compact Objects

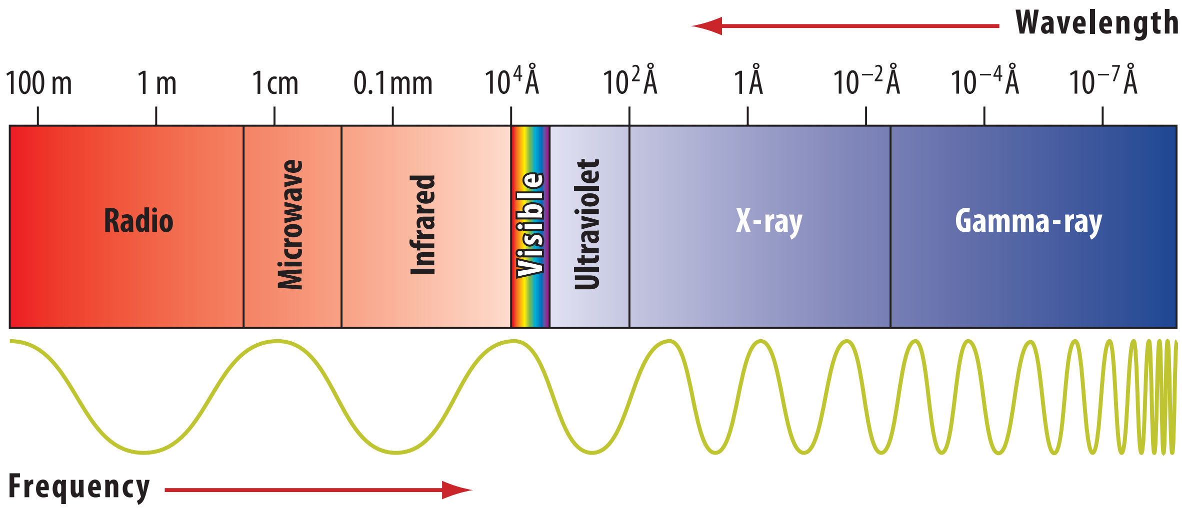
Stars are formed from the gravitational collapse of gas and dust. The collapse primarily occurs in regions of **low temperature** and relatively **high density** of gas and dust (Dark Nebulae).

As the protostar collapses **gravitational energy is converted to thermal energy**. The collapse stops when the temperature becomes high enough for hydrogen fusion to start in the core.

While a star is fusing hydrogen, it lies on the **main-sequence**.

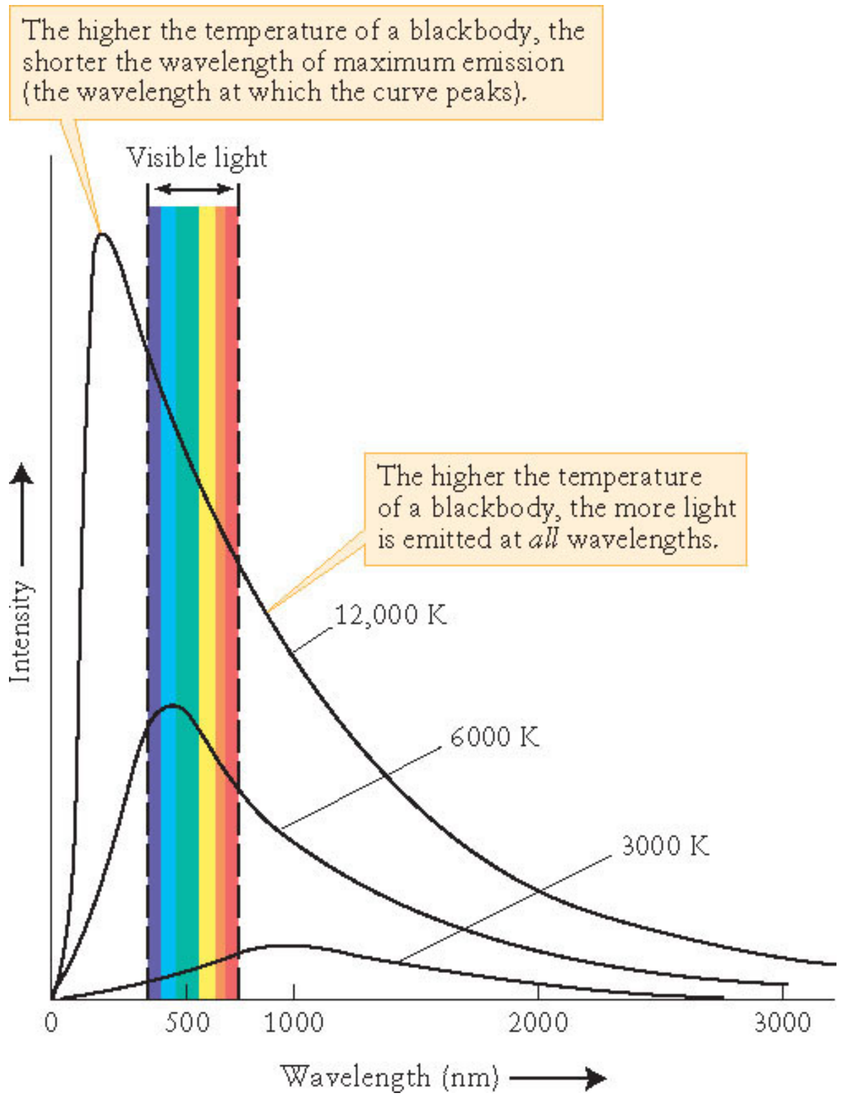
Stellar Evolution Towards Compact Objects

Thermal radiation is radiation emitted from an objects surface and is related to its **temperature**. The amount of energy and the dominant wavelength of the light emitted depends on the temperature of the object. *Higher temperatures result in shorter wavelengths and more energy emitted per unit time.*



The electromagnetic spectrum. The longest wavelengths and shorter frequencies correspond to photons with the lowest energies. Wavelengths are typically measured in m, cm, mm(1mm $=1 \times 10^{-3}$ m), nanometers (1nm$=1 \times 10^{-9}$ m) and angstroms (1Å$=1 \times 10^{-10}$ m).

Blackbody Radiation: Wien's Law



An ideal **blackbody absorbs** all the radiation that falls on it.

Wien's Law

$$\lambda_{max}(m) = \frac{0.0029\,K\,m}{T(K)}$$

λ_{max} = wavelength of maximum emission in meters

T = temperature of object in kelvins

Blue stars are hotter than red stars.

Temperatures of Stars

Example: The star Bellatrix in Orion that looks blue has a higher temperature than the red star Betelgeuse.

Stellar Evolution: On and After the Main Sequence

What happens when the Hydrogen runs out in a star with an initial mass of: $\mathbf{4\ M_{\odot} > M_{star} > 0.4 M_{\odot}}$? Our sun falls in this range.

WHAT HAPPENS IN THE **STARS CORE?**

In a star like our sun when H runs out in the core, **H fusion continues in a shell around the core**.

The **core** cannot support the material above it so it **begins to shrink** and is compressed from the weight of the outer layers. When the gas in the core becomes compressed **its temperature** again **begins to rise**.

The increase in temperature increases the rate of H fusion reactions in the thin H shell that surrounds the core while there in no H fusion in the core.

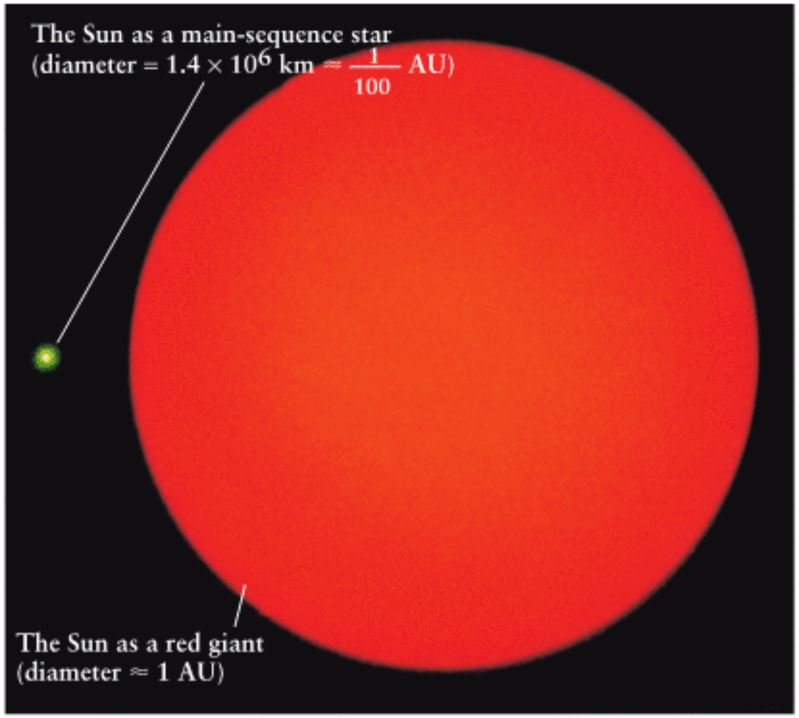
Stellar Evolution: On and After the Main Sequence

What happens when the Hydrogen runs out in a star with an initial mass of: $\mathbf{4M_{\odot} > M_{star} > 0.4M_{\odot}}$?

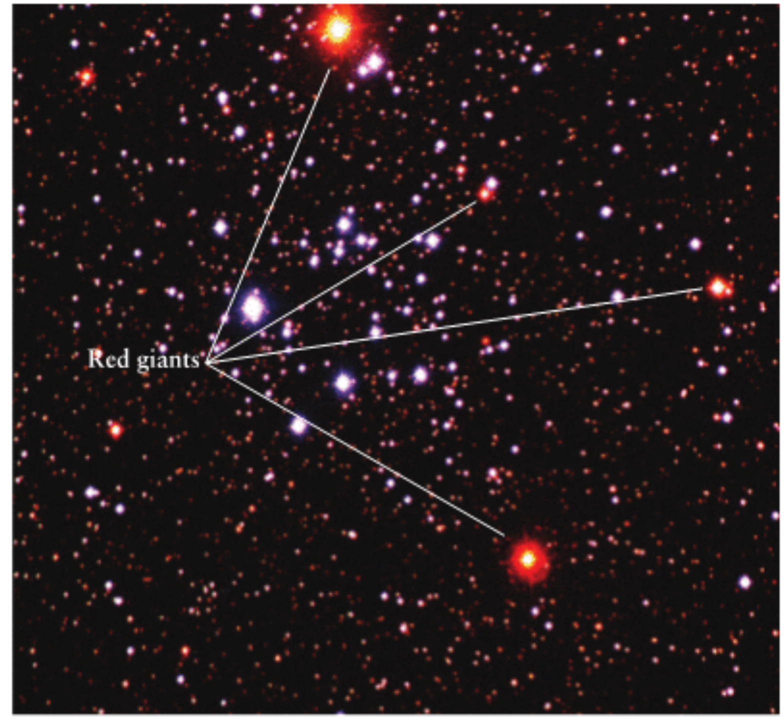
WHAT HAPPENS IN THE **STARS OUTER LAYERS?**
While the core is being compressed the **outer layers expand by the increased luminosity of the Hydrogen burning shell**. As the external layers of gas expand the temperature of this gas decreases.

When the temperature of the external layers drops to ~ 3,500 K the star appears reddish at which point is has become a **red giant**.

Stellar Evolution: On and After the Main Sequence



(a) The Sun today and as a red giant



(b) Red giant stars in the star cluster M50 R I V U X G

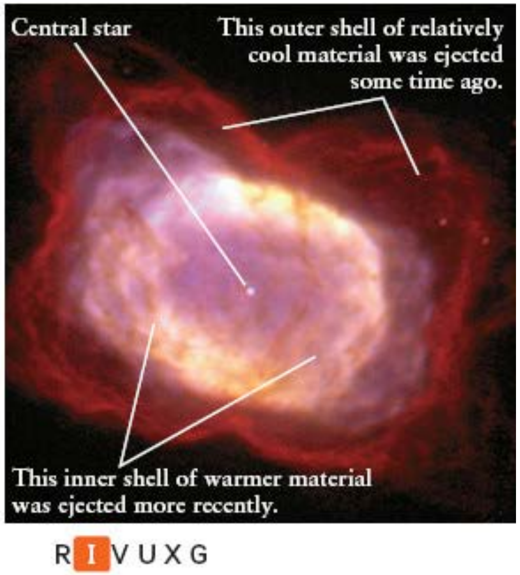
When the sun becomes a red giant its diameter will increase from ~ 0.01 AU to 1 AU.
1AU is the average distance between the Earth and Sun.

Stellar Evolution: On and After the Main Sequence

The heat generated in the core's collapse eventually starts **fusion of He** in the core (T_{core} ~ 100 million K).

When He runs out, the core will collapse again resulting in an increase in the core temperature (T). The outer layers of the star expand for a second time. The resulting giant star is called an **asymptotic giant branch (AGB)** star.

White Dwarfs



An AGB star can lose a significant fraction of its mass from **thermal pulses.** As the outer layers are ejected what remains is the C, O core that is quite hot (T_{core} ~ 100,000 K). This exposed core is called the **white dwarf**. Its strong UV radiation can ionize the surrounding shell and make the planetary nebula glow.

Planetary nebulae **enrich the interstellar medium** (ISM) with heavy elements produced in the AGB stars. About 15% of all matter ejected from stars into the ISM originates from planetary nebulae.

The Helix Nebula, is a large planetary nebula located in the constellation Aquarius. The estimated distance is about 700 light-years. Its age is estimated to be about 10,000 years.

This observation of the Helix Nebula was made with the **College of Charleston 24 inch CDK PlaneWave telescope**

Observers: CofC Students: Lucy Williamson and Dereck Morgado, CofC Faculty: Dr. Ashley Pagnotta and Dr. George Chartas.

When He fusion ends and $M_{star} < 1.4\ M_{\odot}$ => White Dwarf

What prevents a white dwarf from collapsing?

A white dwarf is held up by pressure generated by electrons being squeezed together too tightly. This pressure is called **degeneracy pressure.**

Wolfgang Pauli

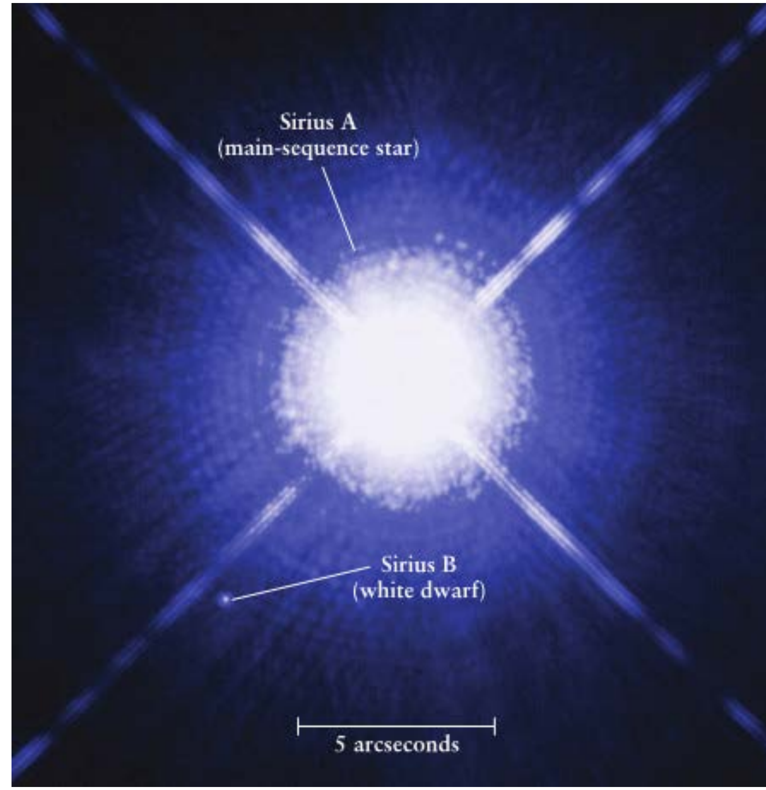
Degeneracy pressure also exists between protons and neutrons. Such particles with **half-integer spin are called fermions**. The spin can be envisioned as an angular momentum of the particle but it is intrinsic and nothing can change it!

White Dwarfs

A **white dwarf** gradually cools down as it radiates away its energy but **does not shrink**. It is supported by **electron degeneracy pressure** against gravitational collapse.

Electron degeneracy pressure does not depend on temperature.

Observations of white dwarfs in binary systems allow us to determine their mass, radius and density. The degenerate electron gas has a density of about 10^9 kg m^{-3} .
(ρ_{water}~1,000 kg m^{-3})



A teaspoon of degenerate electrons from Sirius B brought back to Earth would weigh as much as an elephant.

Massive Stars and Supernovae

The reason why high densities and temperatures are required to fuse elements heavier than He is that **heavy nuclei have large charges and therefore large electric forces** that tend to keep the nuclei apart.

When a star with initial mass **$M > 4M_\odot$ runs out of He** in its core the core begins to contract and the outer layers of the star expand.

Because the mass of the core of **a star with $M > 4M_\odot$** is more than the *Chandrasekhar limit* of 1.4 $M_\odot$, electron **degeneracy pressure cannot prevent the collapse of the star**. The temperature continues to rise and when it reaches 600 million kelvin carbon fusion begins.

Massive Stars and Supernovae

As each fuel is exhausted the inner part contracts becoming even hotter until a new set of nuclear reactions between heavier elements can take place.

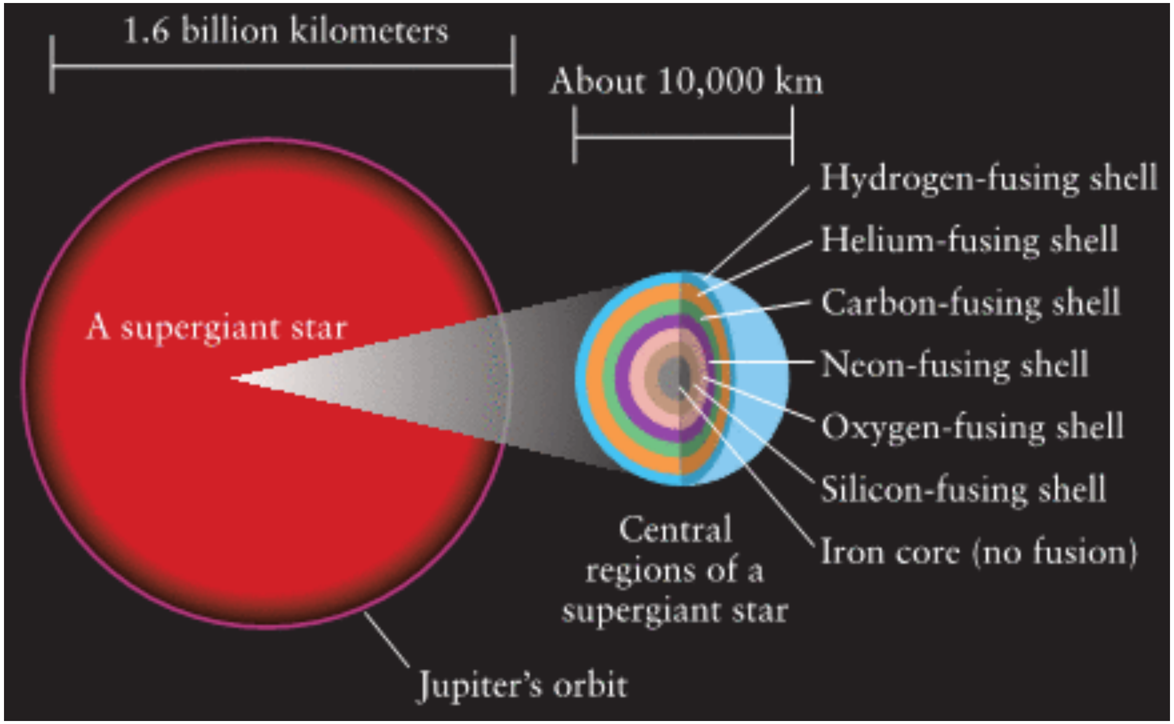
Carbon fusion: $T_{Fusion} = 600 \times 10^6$ K
Products = oxygen (O), neon (Ne), sodium (Na), magnesium (Mg)

If the star has $M > 8M_{\odot}$ additional reaction can occur:
Neon fusion: $T_{Fusion} = 10^9$ K
Products = oxygen (O), magnesium (Mg)

Oxygen fusion: $T_{Fusion} = 1.5 \times 10^9$ K
Product = silicon (Si), magnesium (Mg), phosphorus (P), sulfur(S)

Silicon fusion: $T_{Fusion} = 2.7 \times 10^9$ K
Products = Sulfur (S), Iron (Fe), Nickel (Ni)

Stellar Evolution



The structure of a supergiant star with an initial mass of > 8M$_\odot$. After several stages the core of the supergiant star will have multiple shells of material and its structure resembles that of an onion.

Stellar Evolution: Core Collapse

Core Collapse: A massive star with $M > 8M_{\odot}$ will eventually reach the point of fusing Si into Fe. Fusion of **Fe does not produce energy** so the core cannot generate heat from fusion but instead begins to collapse and heat up.

• Because of the high density, electrons combine with protons to form neutrons and neutrinos:

$$\mathbf{e^- + p^+ \rightarrow n + \nu}$$

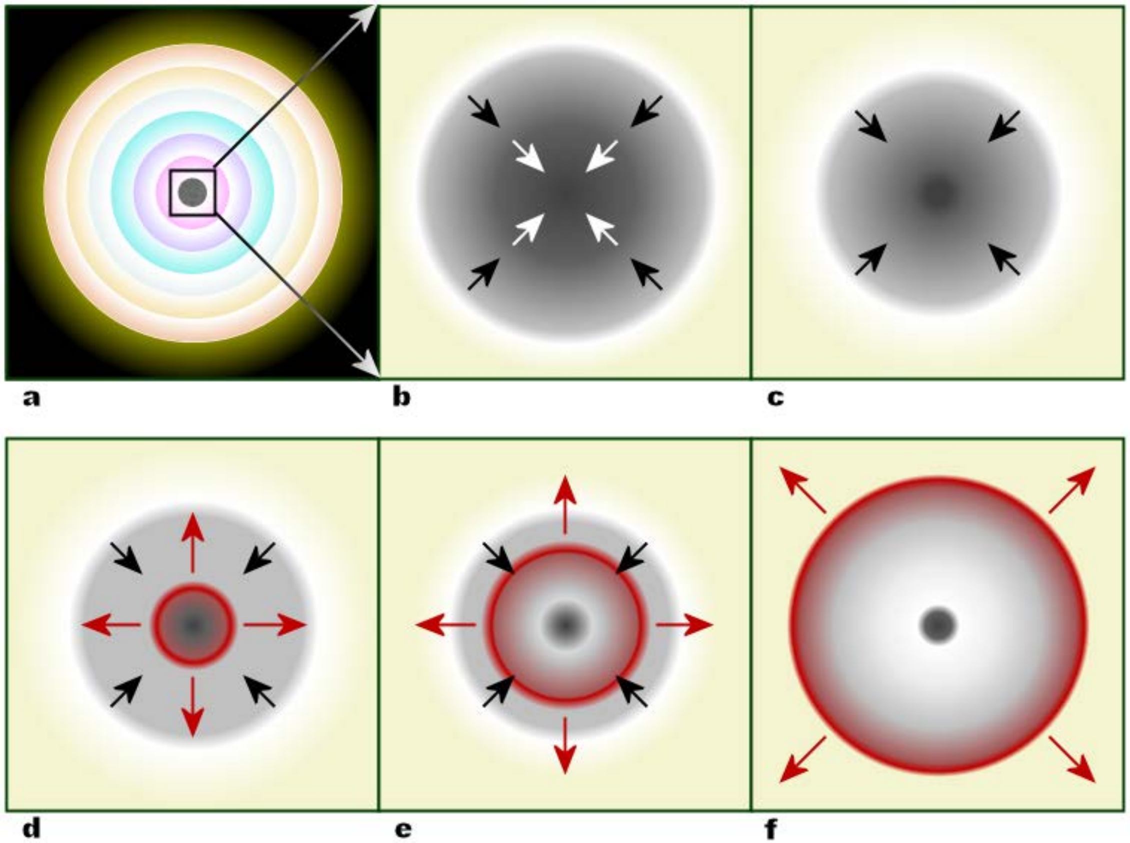
• The escape of the neutrinos **cools down the core and** leads to more compression. Seconds after the contraction began the density reaches the **nuclear density value** of $\sim 4 \times 10^{17}$ kg m^{-3}.

Stellar Evolution: Core Bounce

Core Bounce:

The strong nuclear force and neutron degeneracy pressure prevent the core from collapsing any more. Further compression results in the innermost part of the core **bouncing back and sending out a pressure wave**. It takes a few hours for the **shock wave** to reach the surface and **lift away the outer layers of the star**.

Stellar Evolution: Core Collapse and Bounce



Within a massive, evolved star (a) shells of elements undergo fusion, forming an iron core (b) that reaches Chandrasekhar-mass and starts to collapse. The inner part of the core is compressed into neutrons (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red). The shock starts to stall (e), but it is re-invigorated by a process that may include neutrino interaction. The surrounding material is blasted away (f), leaving only a degenerate remnant.

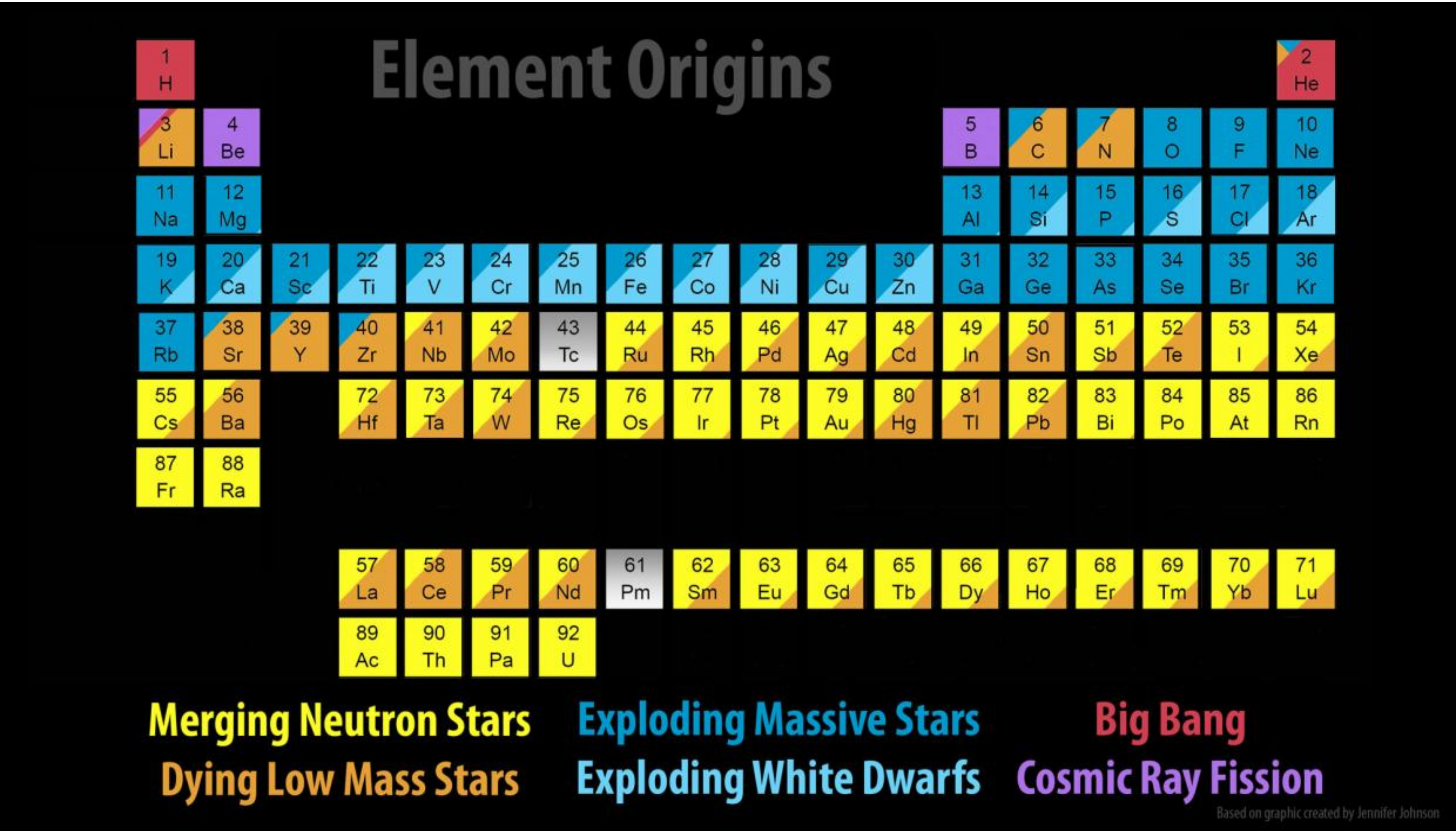
Stellar Evolution: Energetics of Supernova

ENERGETICS:

The **energy released as radiation** in a **core-collapse supernova** explosion is ~ 10^{44} Joules and **comes from gravitational energy** released by the collapse of the core and the infall of the outer layers of the star.

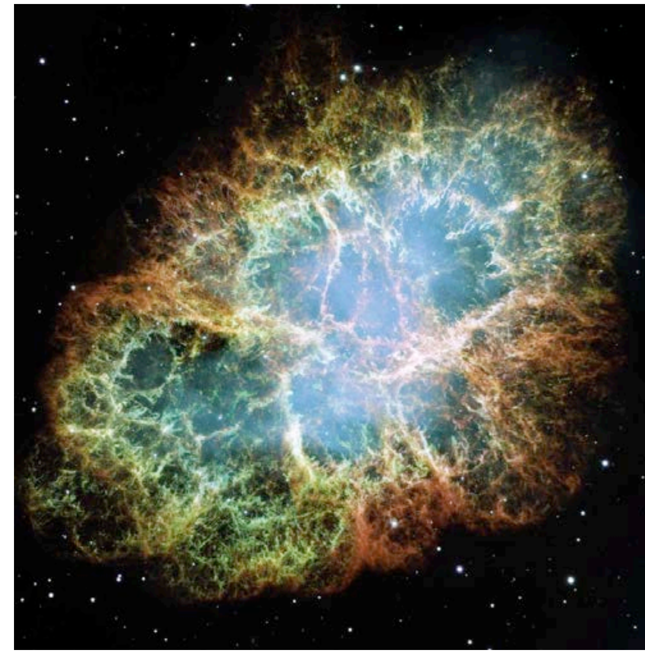
Our sun's power output is 3.8×10^{26} Joules per sec

The energy released in the form of neutrinos is about 100 times larger than the energy released in radiation.

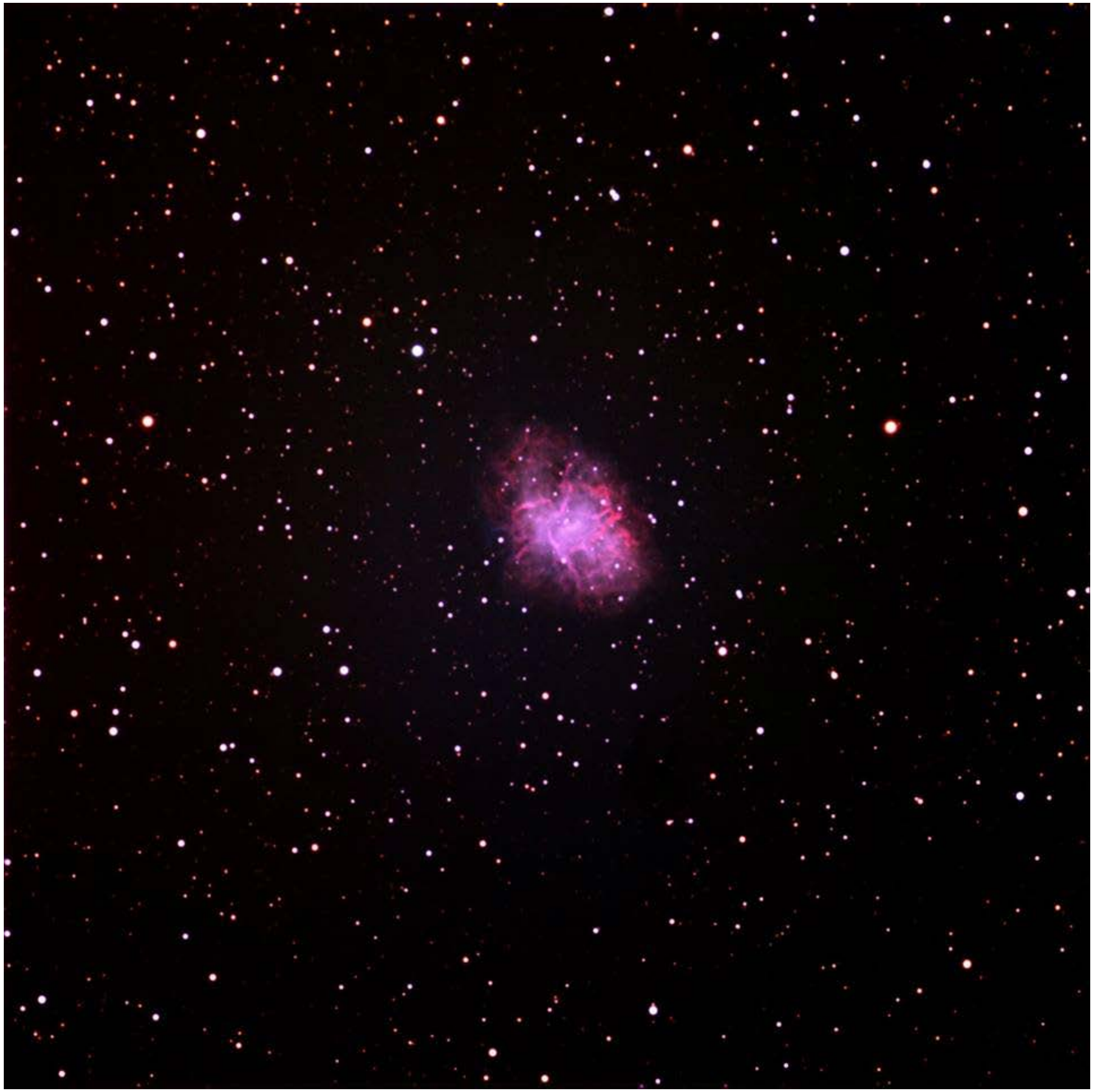

Element Origins
1 H
2 He
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
57 La
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
89 Ac
90 Th
91 Pa
92 U
Merging Neutron Stars
Exploding Massive Stars
Big Bang
Dying Low Mass Stars
Exploding White Dwarfs
Cosmic Ray Fission
Based on graphic created by Jennifer Johnson

Observed Supernovae: SN 1054 A

In 1054 AD a supernova was observed in the constellation Taurus by Chinese, Japanese, Native Americans, and Persian/Arab astronomers. It was bright enough to be visible in the night sky for almost 2 years.



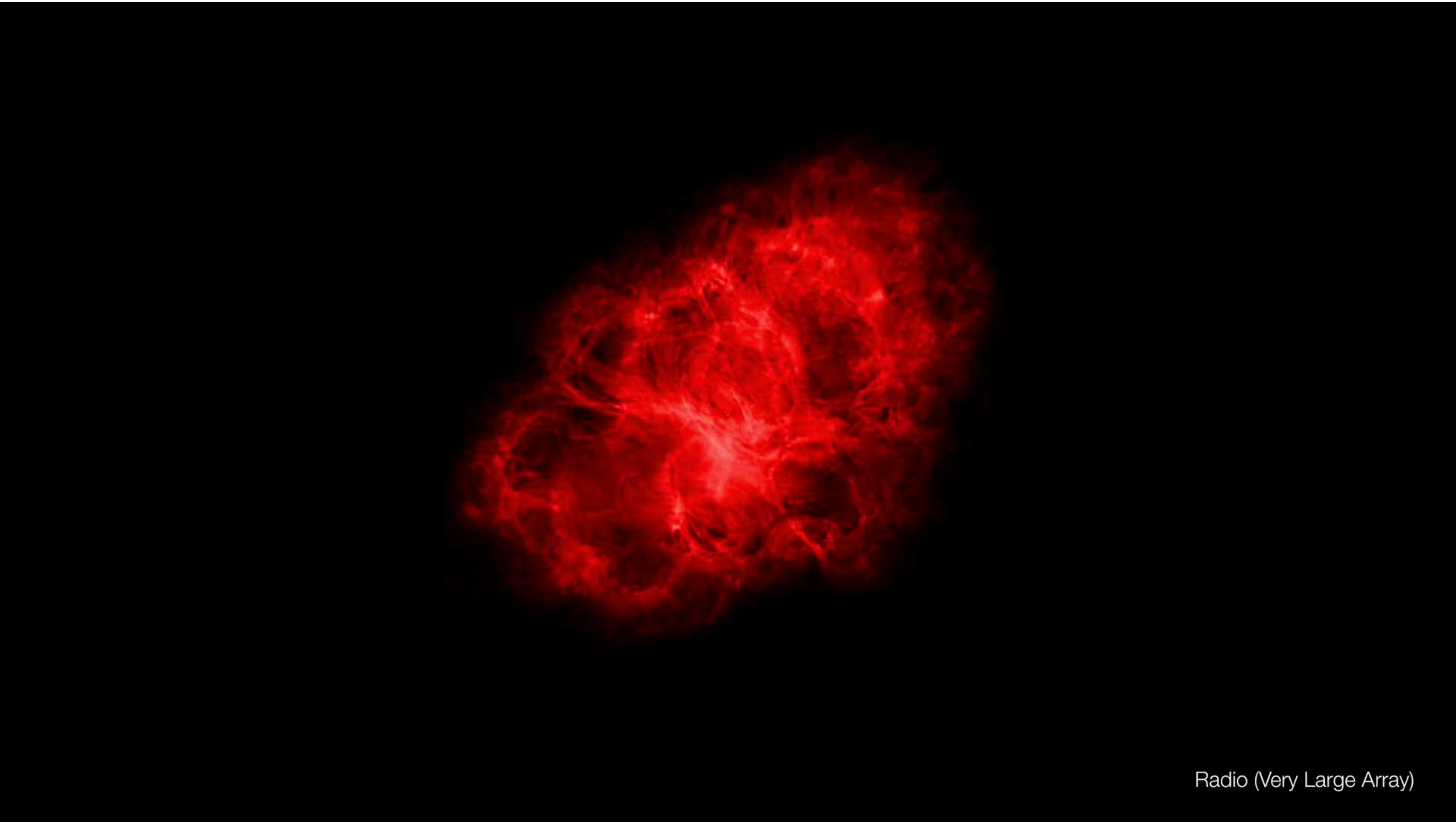
The Crab Nebula is the remnant from the supernova in 1054. It is ~6,500 ly away.

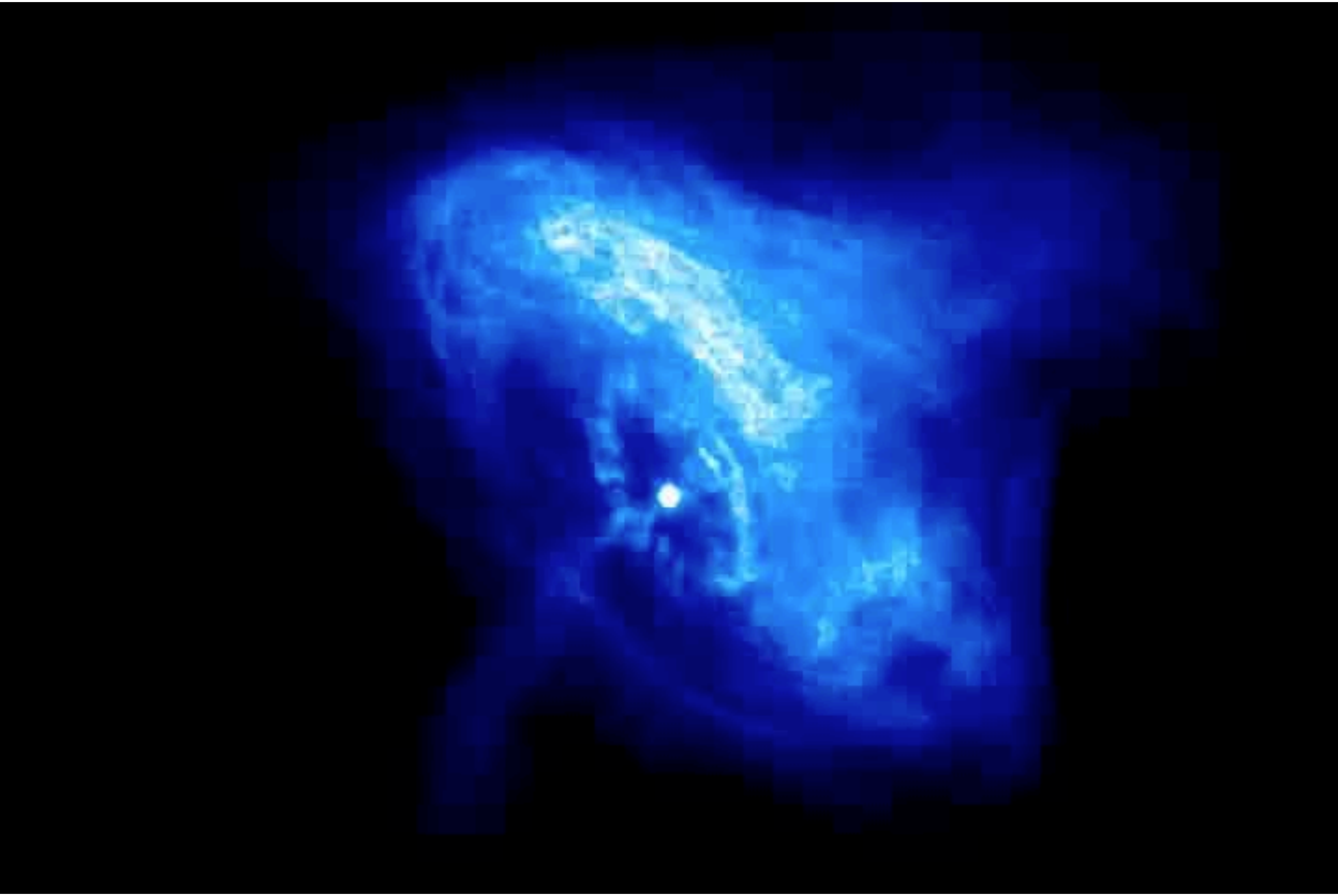


The Crab nebula is the remnant of a bright supernova. Light from this supernova first reached Earth in 1054.

The Crab nebula lies at a distance of about 6,500 light-years from Earth.

The observation was made with the College of Charleston 24 inch CDK PlaneWave telescope.


Radio (Very Large Array)

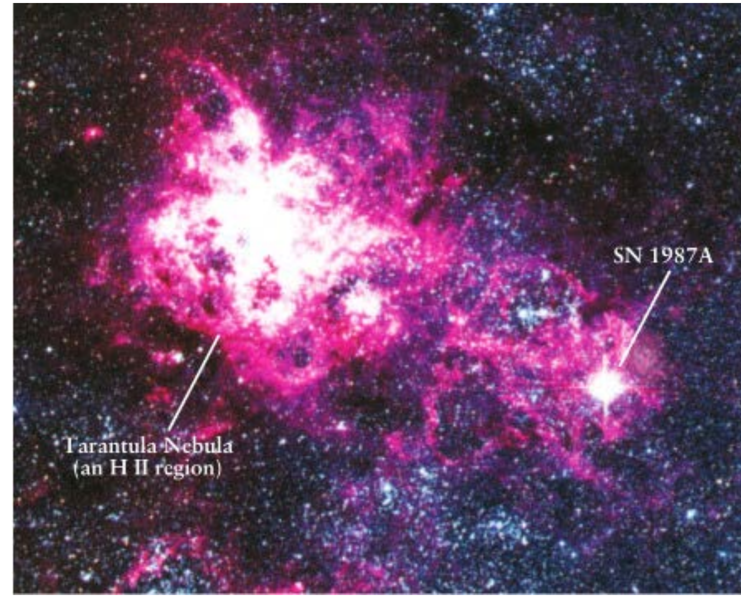


Observed Supernovae: SN 1987 A

On Feb 1987 supernova 1987 A was discovered in the Large Magellanic Cloud (~ 170,000 ly away). It was so bright it could be seen without a telescope in the southern hemisphere.

For the first 20 days after the supernova the ejected **outer layers were glowing** from the heat deposited by the shock wave.

SN 1987 A is also emitting **gamma rays from the decay of radioactive isotopes** created during the supernova explosion.



The remnant of SN 1987 A. Light from SN 1987 A continues to arrive.

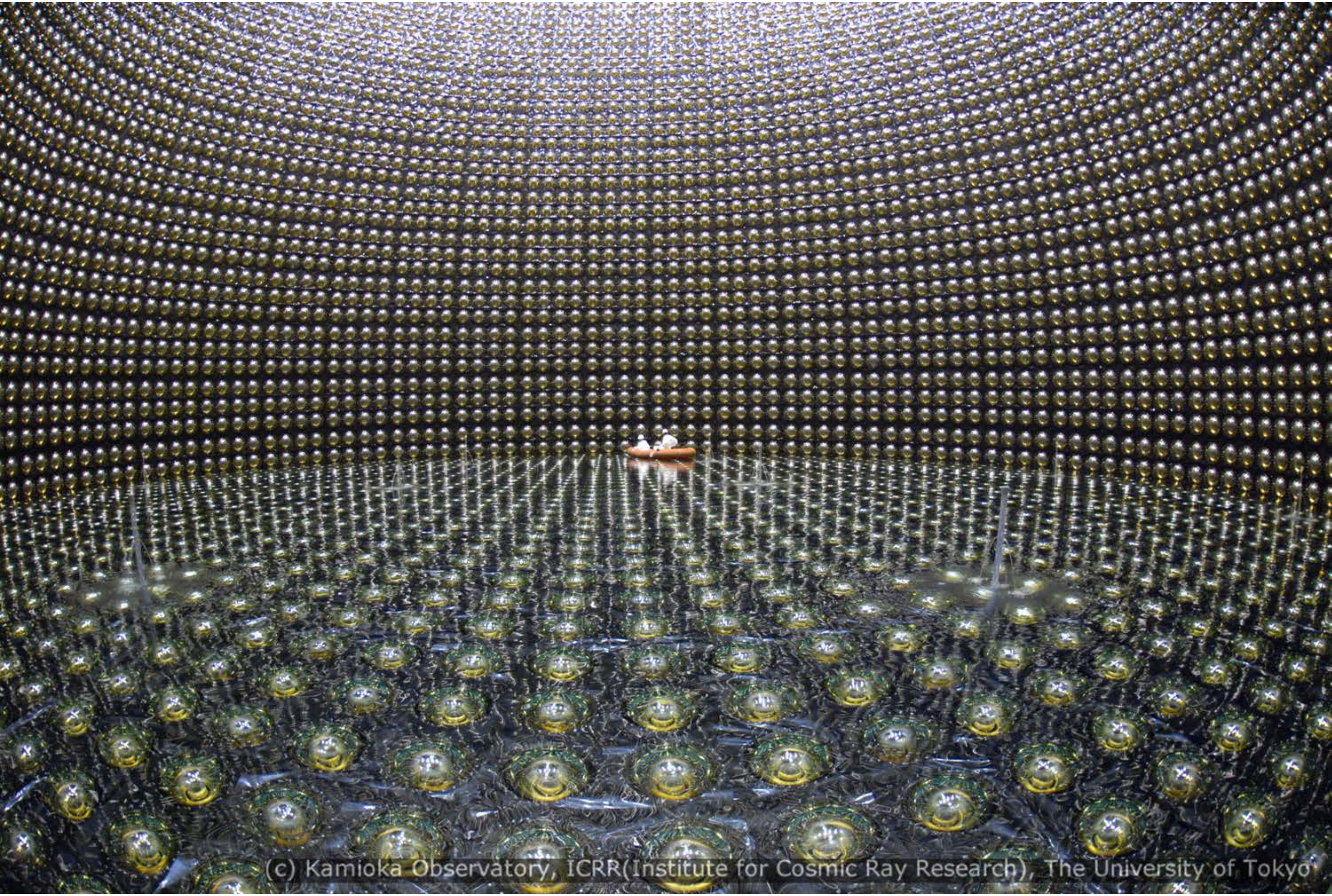
Five very bright supernovae have been observed without a telescope in the last 1000 years.

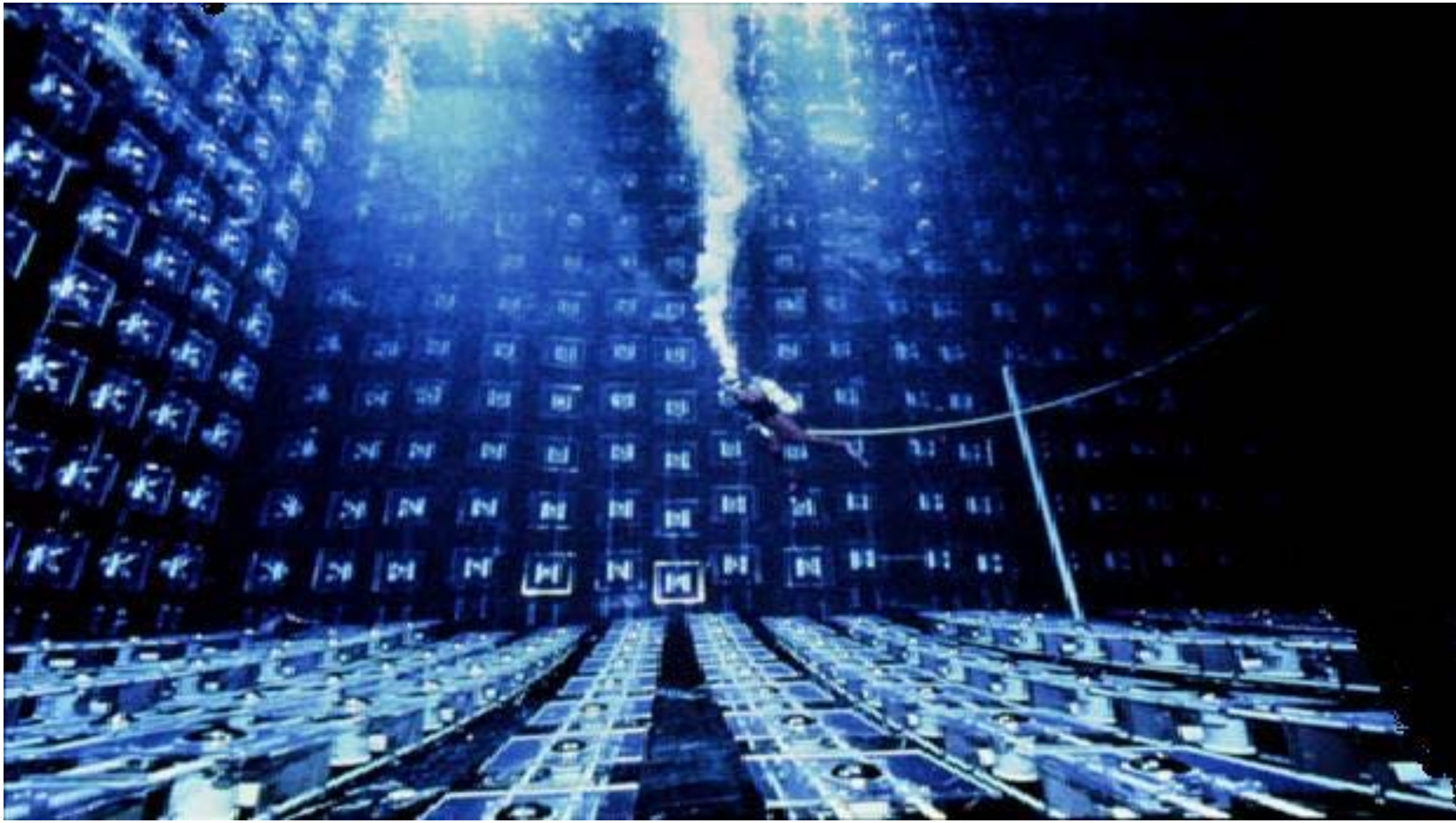
Confirmation of Supernova Model

During the core collapse of a star $M > 8M_{\odot}$ the density and temperature in the core are so high that a flood of neutrinos are produced. **A detection of these neutrinos would provide support to the core collapse model**.

The core collapse and bounce model predict that the neutrino outburst lasts for a few seconds and that the shock wave takes a few hours to reach the surface.

At the time of SN 1987 A two major neutrino detectors were operating: **Kamiokande II and IMB**


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



The Irvine-Michigan-Brookhaven (IMB) detector was a 60-foot cube of ultra-pure water constructed in a salt mine underneath Lake Erie. The water was surrounded by 2000 light-sensitive phototubes, designed to detect proton decay. The experiment became famous for the observation of the neutrino burst emitted by Supernova 1987 A.

Confirmation of Supernova Model

12 neutrinos were detected by **Kamiokande** and 8 neutrinos by **IMB** from SN 1987 A on Feb 23, 1987 !

The neutrino events were detected 3 hours before the UV flash from SN 1987 was detected.

Astronomers found that over a 10-second period, SN 1987A emitted 10^{58} neutrinos with a total energy of 10^{46} Joules! This is more than 100 times the amount of electromagnetic radiation emitted by the supernova and 100 times more than what the sun has emitted over its 4.56 billion years!

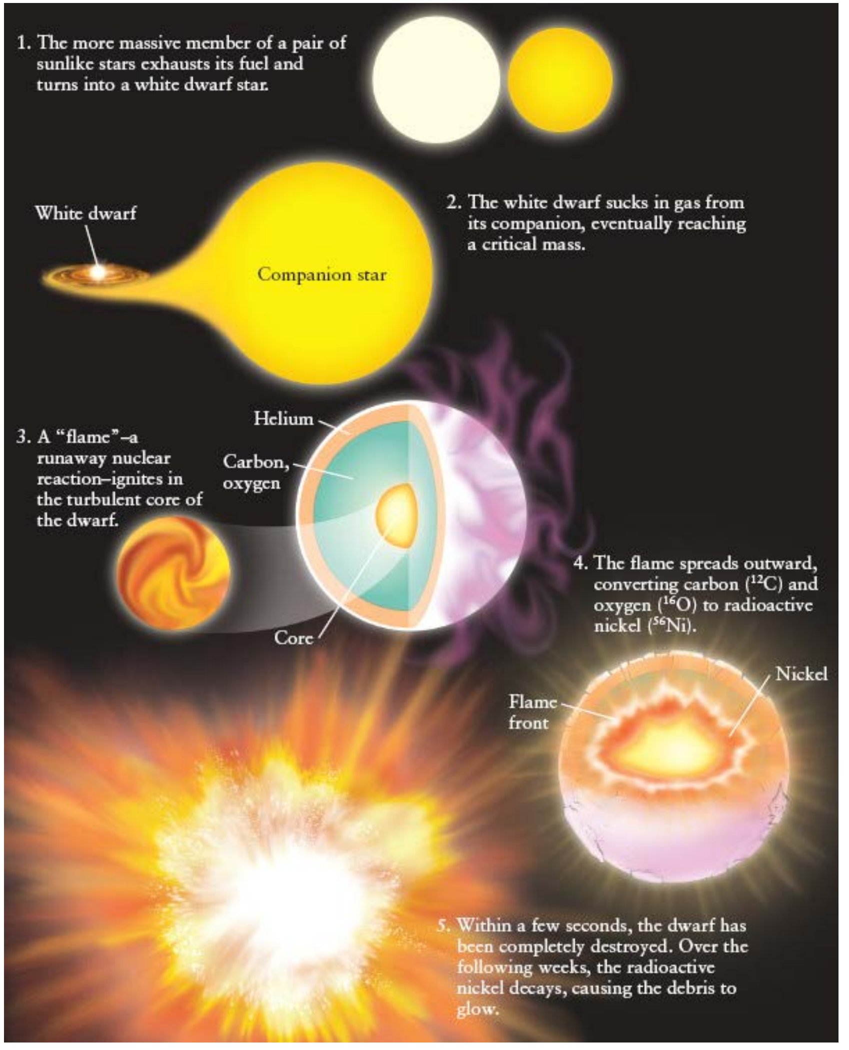
Supernovae from Accretion onto a White Dwarf

Not all supernovae are the result of the core collapse of a massive star.

A different type of supernova occurs when **accretion onto a white dwarf** from a companion star leads to the explosion of the white dwarf.

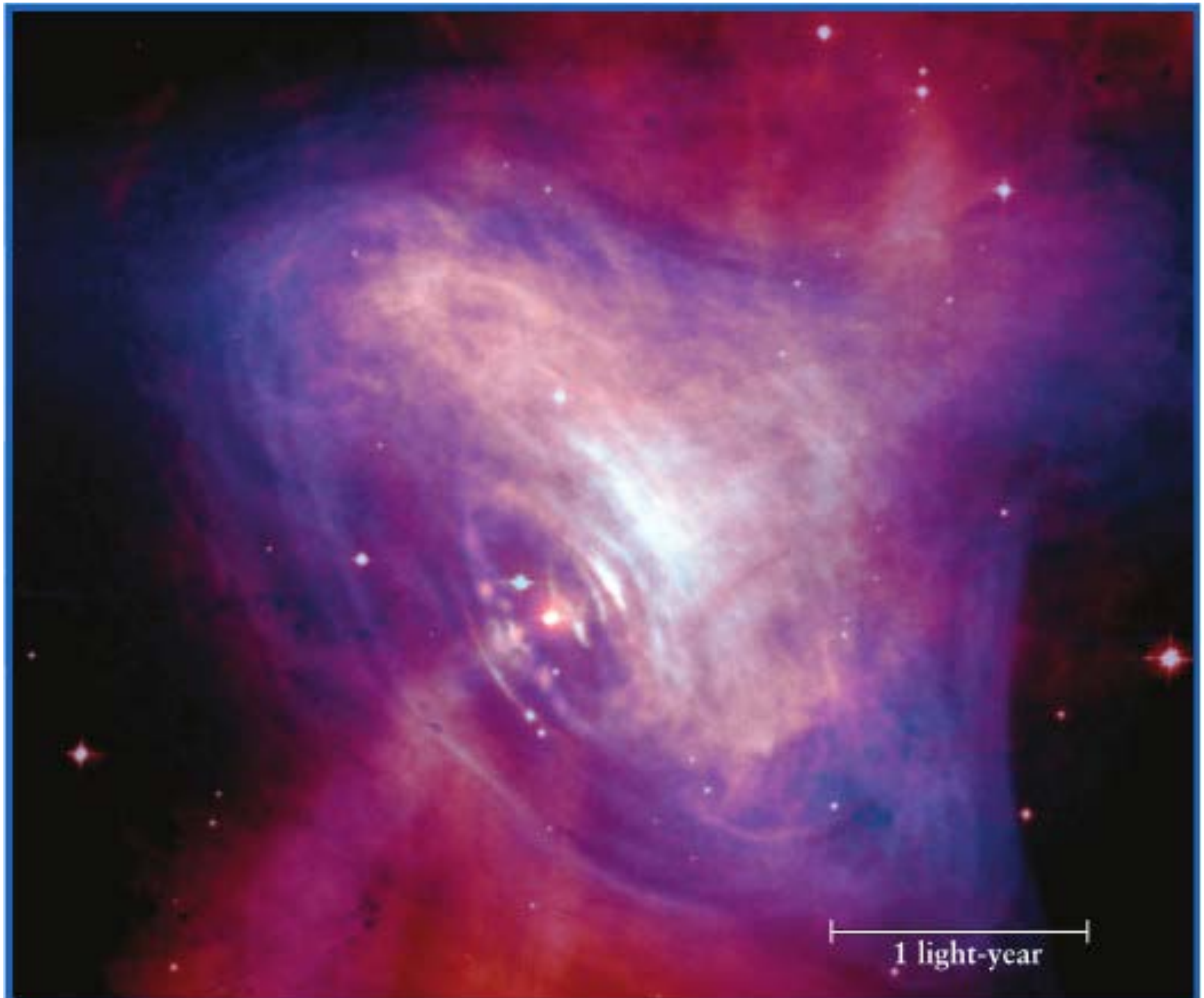
The **white dwarf sucks in mass from its companion** and eventually the total mass of the white dwarf approaches the *Chandrasekhar limit* of 1.4 $M_{\odot}$.

The increased pressure applied to the white dwarf's interior causes **carbon to fuse to silicon in the core** resulting in an increase of the core temperature.




CAASTRO
ALL-SKY ASTROPHYSICS

Neutron Stars



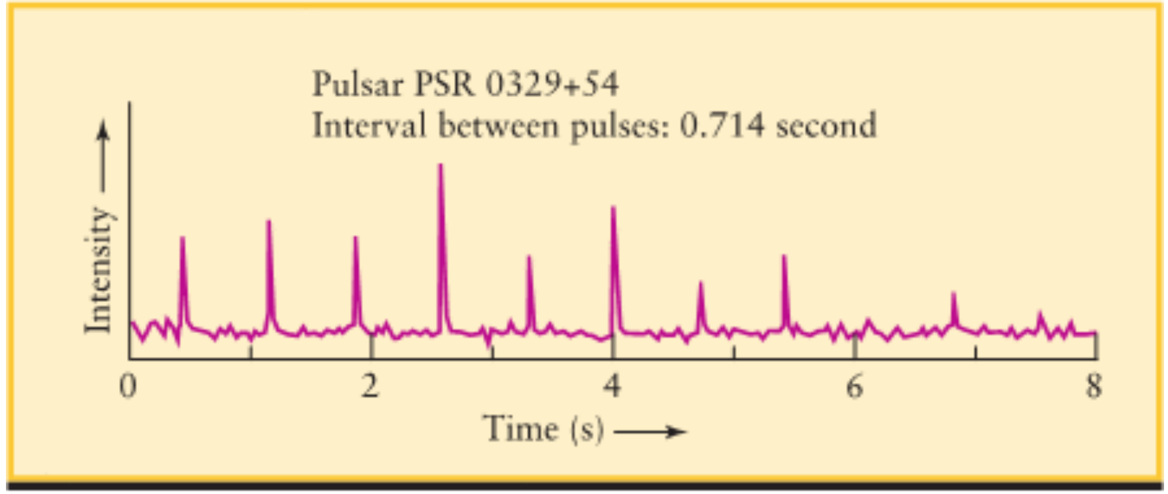
Neutron Stars

We now know that **SN 1054 was a Type II supernova** that ended the life of a massive star and left behind a **neutron star and a remnant nebula (Crab Nebula).**

English physicist **James Chadwick** discovered the neutron in 1932. The neutron is a subatomic particle with a mass similar to that of a proton and with no electric charge.

Astronomers **Zwicky** and **Baade** first suggested that the collapse of a massive star could lead to an object made up primarily of neutrons (neutron star).

Neutron Stars



In 1967 graduate student Jocelyn Bell from Cambridge University was working on a project to detect fluctuations of radio signals caused by motion of gas between the source and observer.

While searching for these fluctuations she detected radio periodic pulses from a particular location in the sky. Many similar sources with periodic pulses were soon discovered and such objects were called **pulsars**.

Neutron Stars

We now know that **pulsars are just rotating neutron stars**.

The **neutron star spins up** when it forms **during the collapse** of a spinning star. (a figure skater on ice can increase spin by bringing in their arms).

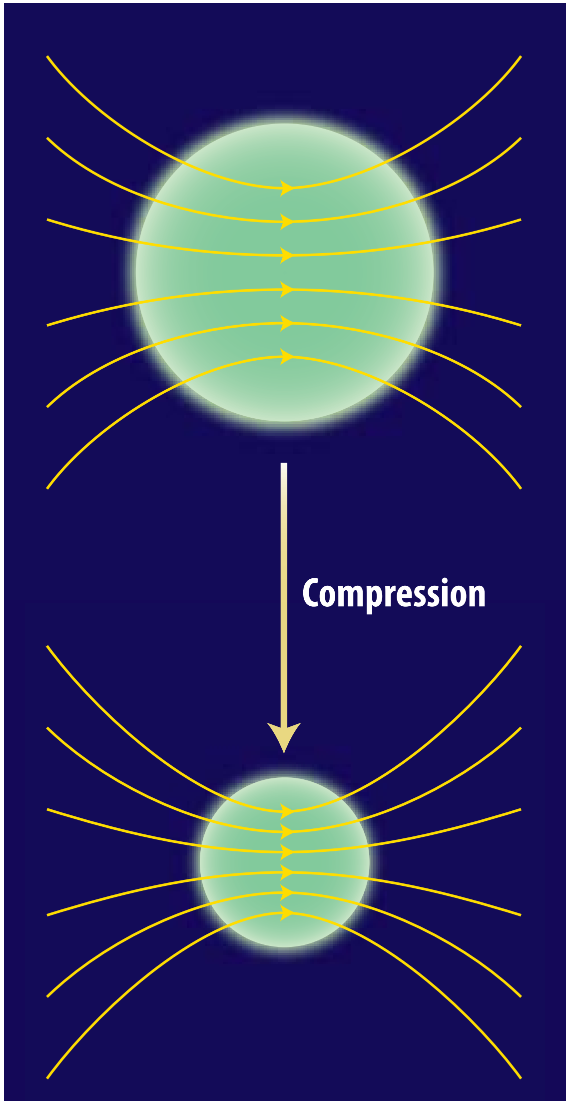
One year after the discovery of the first pulsar the **central object in the crab nebula** was found to be pulsating at ~30 times a second.

The spinning neutron star is the middle of the Crab nebula explained the origin of its glow. **The energy source of its glow is the rotational energy of the neutron star**.

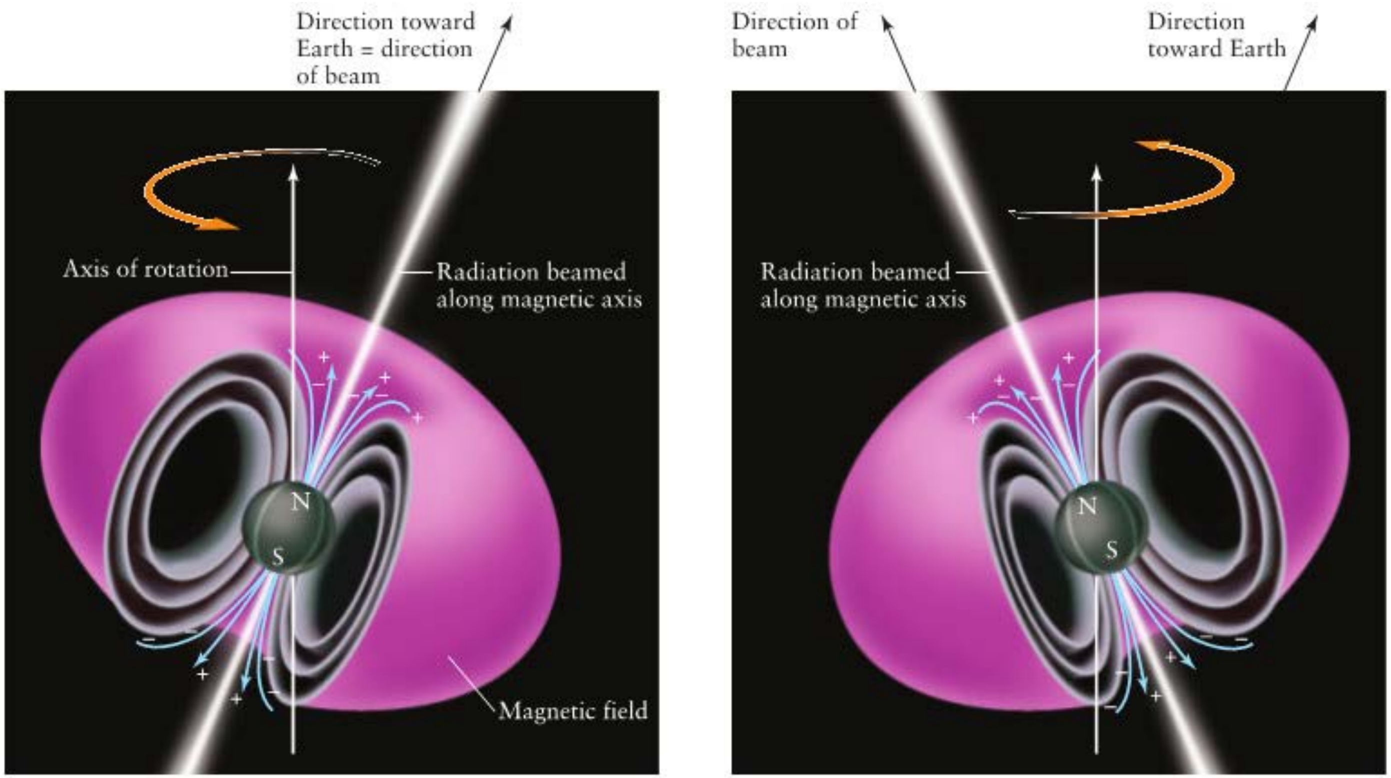
Neutron Stars

As the star collapses, the plasma drags the magnetic field lines with it (surface area shrinks by a factor of 10^{10}). This implies that the magnetic field of a neutron star would be at least 10^{10} times larger than that of the ordinary star from which it collapsed from.

Earth's magnetic field ~ 0.5 Gauss
MRI ~ 30,000 Gauss
WD magnetic field ~ 10^6 Gauss
NS magnetic field ~$10^{12\text{-}15}$ Gauss



Neutron Stars



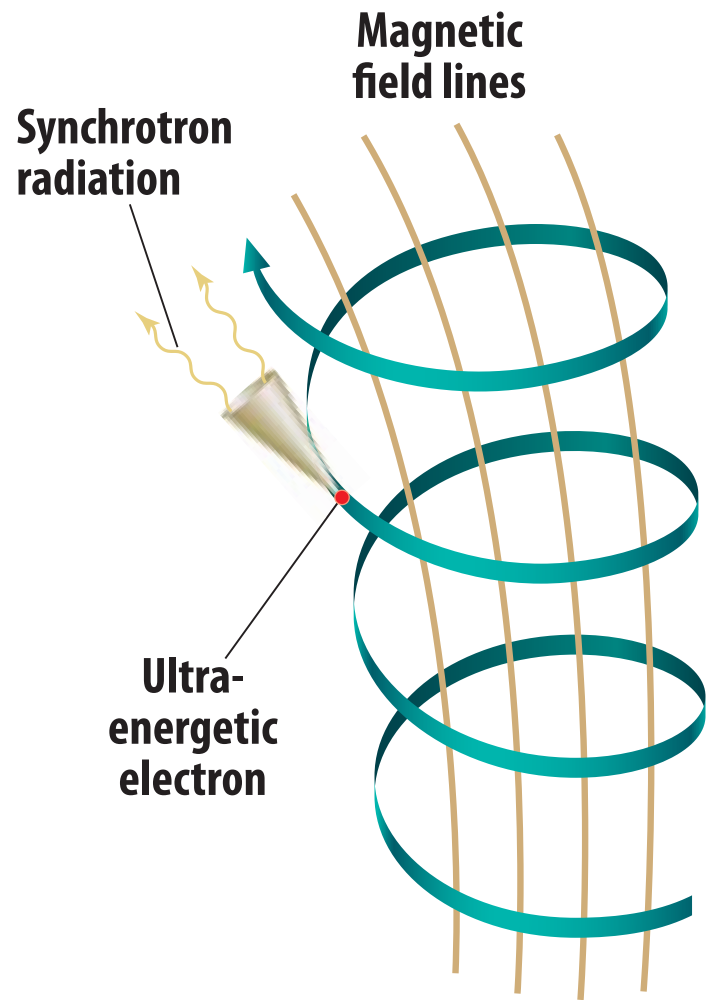
(a) One of the beams from the rotating neutron star is aimed toward Earth: we detect a pulse of radiation.

(b) Half a rotation later, neither beam is aimed toward Earth: we detect that the radiation is "off."

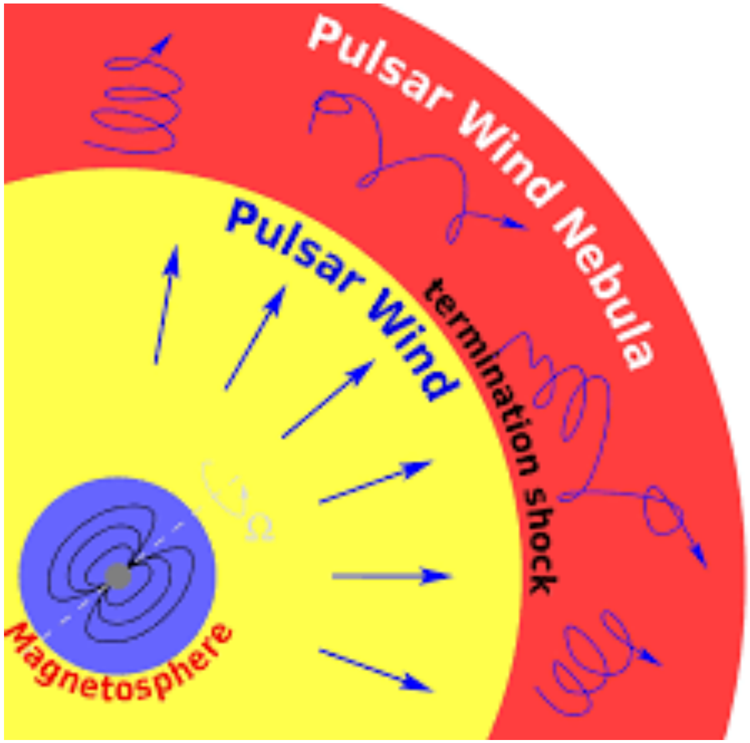
A spinning magnetic field creates an electric field (similar to a car alternator). Electrons and positrons are accelerated by the neutron star's strong electric field to very large velocities. These charged particles emit synchrotron radiation that is collimated in a narrow beam.

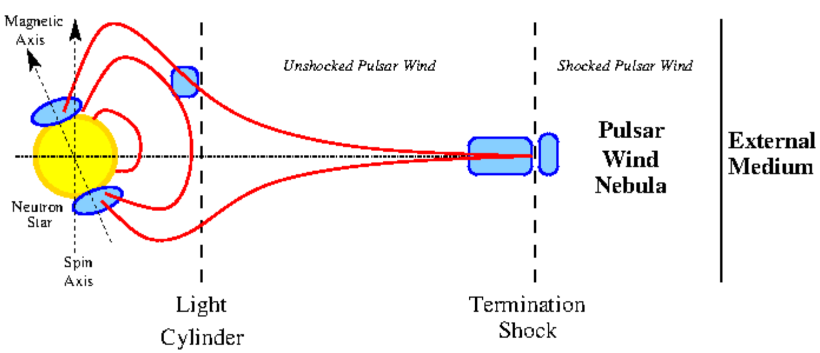
Neutron Stars

The neutron star uses some of its rotational energy to accelerate the electrons. This transfer gradually slows down the neutron star.



Neutron Stars: Pulsar Winds





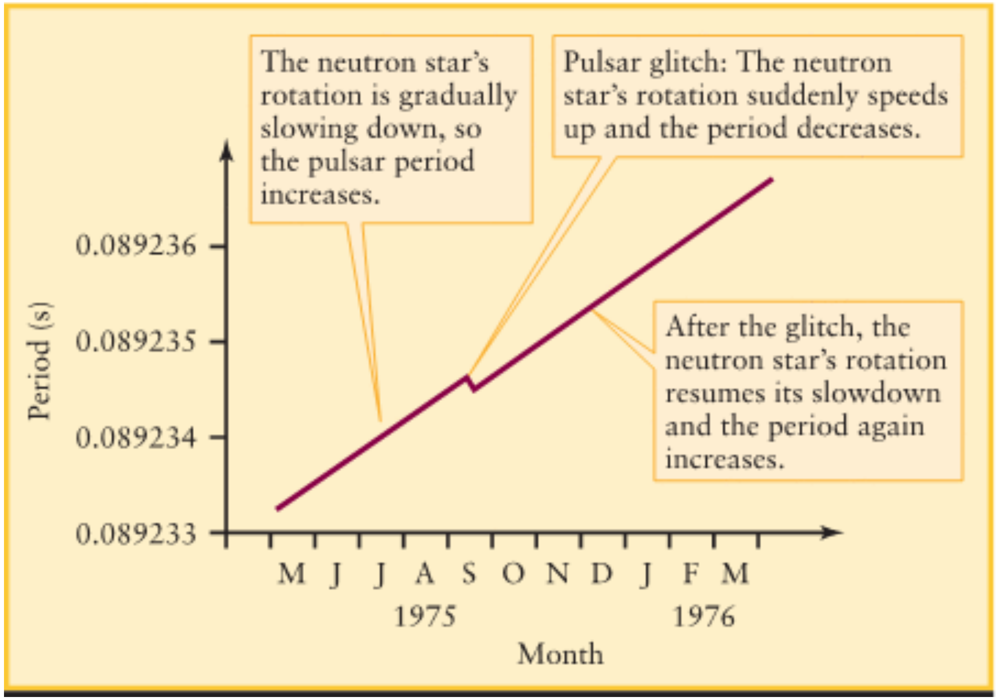
Production of a pulsar wind from accelerated electrons that reach the light cylinder.

Pulsar Wind Analogy

Interior of Neutron Stars

Neutron stars are supported by **neutron degeneracy pressure**. Theory predicts that neutron degeneracy pressure can hold up a star of mass of up to 3 $M_\odot$.

To figure out the interior of neutron stars, scientists study sudden increases in their rotational speed (glitches) of the rotational speed.



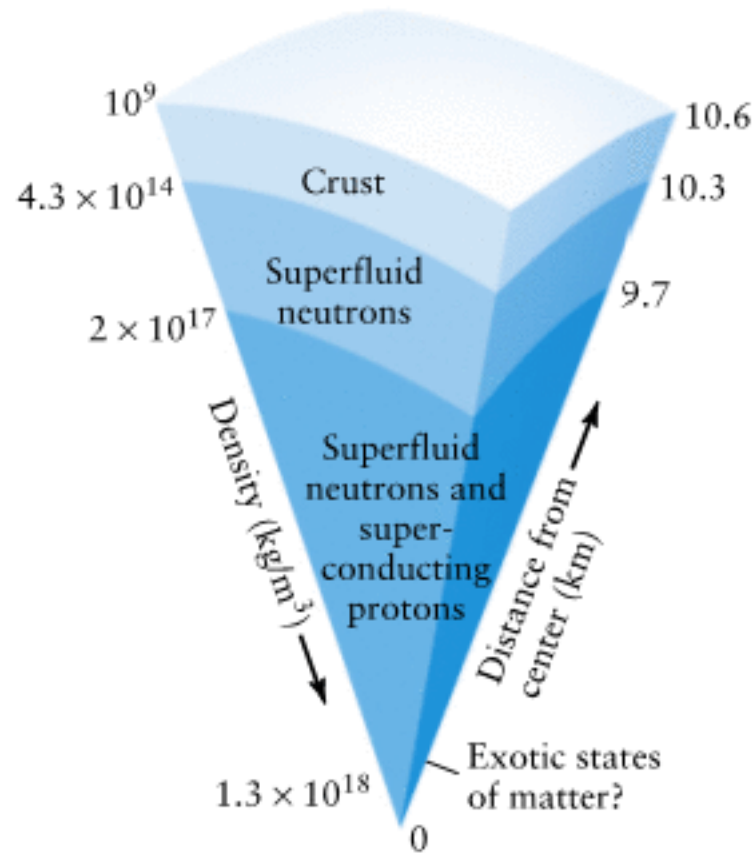
Interior of Neutron Stars

A neutron star has a solid crust on its surface and an interior sea of **degenerate neutrons**. The crust is made mostly of iron, with some nickel, germanium and krypton.

As one goes into the neutron star more **free neutrons** are present. These free neutrons move around with **no friction (superfluid)**.

Friction-free **whirlpools of superfluid neutrons** may form in the interior.

The **protons** in the core experience **no electrical resistance** moving around. This phenomenon, is **called superconductivity.**



Near the core the pressure is so large that protons and neutrons may dissolve into quarks.

Black Hole Stellar Remnants

During the course of a star's evolution, it will shed a significant fraction of its mass. The mass that it's left with ($M_{remnant}$) will determine its fate.

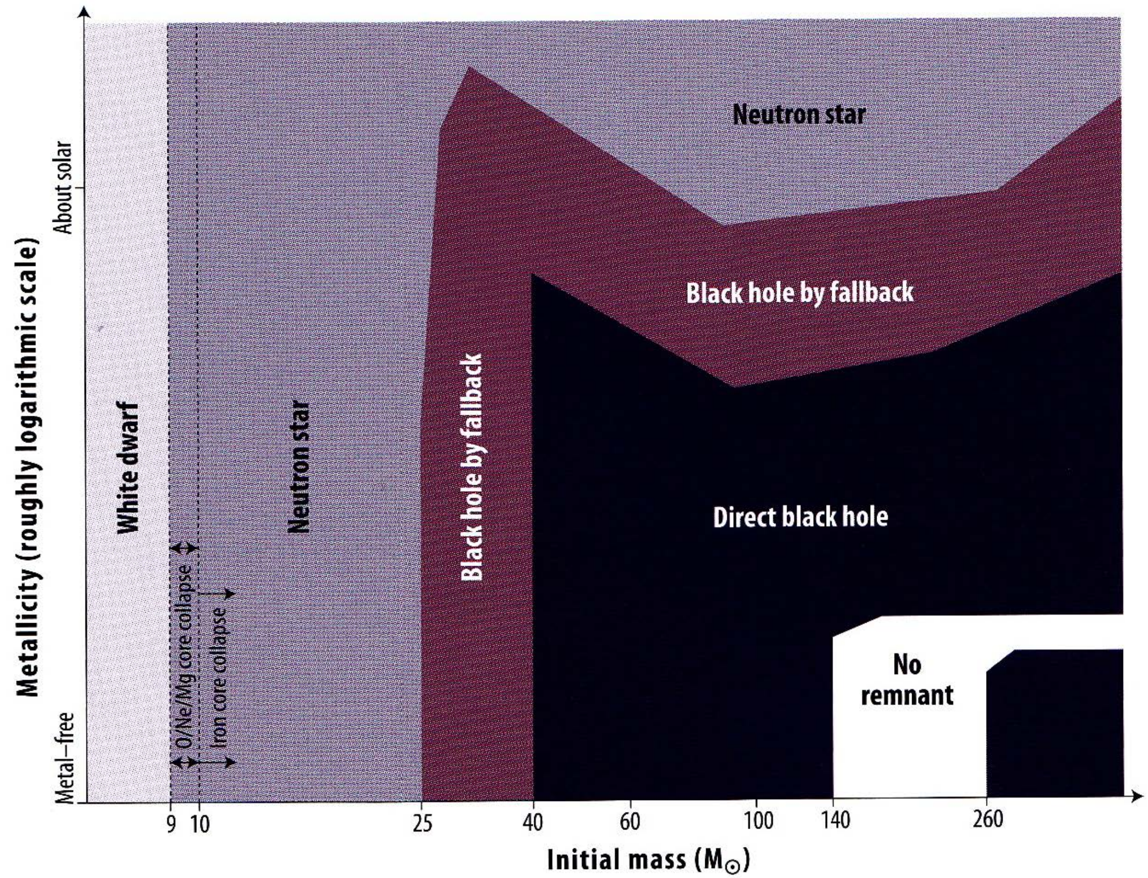
Typically, stars with an initial mass of less than $8M_\odot$ will end up as white dwarfs.

Fate depending on the mass of the **stellar remnant**:

$M_{remnant} < 1.4M_\odot$ => White dwarf
$1.4_\odot < M_{remnant} < 3M_\odot$ => Neutron star
$M_{remnant} > 3M_\odot$ => Black hole

It is estimated that there are ~ 100 million neutron stars and ~100 million black holes in our galaxy.

Black Hole Stellar Remnants



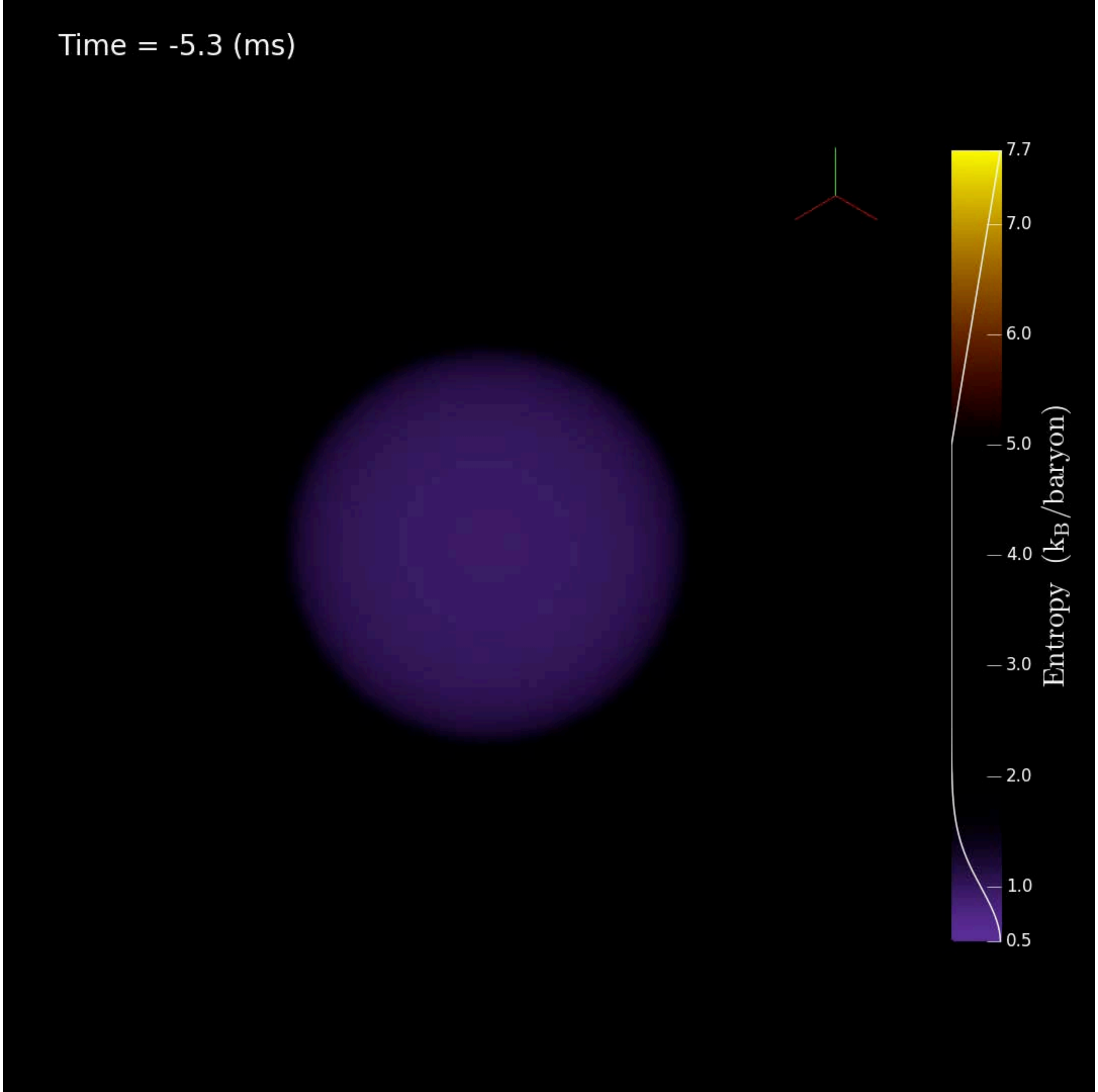
The diagram illustrates the probable fates of stars with different initial masses and chemical compositions. Stars with high metallicity are thought to lose much of their mass by stellar winds. Fallback refers to effect that initially the remnants after the supernova is a neutron star but material from the explosion falls back onto the neutron star causing it to collapse.

Stellar Evolution

We infer the evolution of stars even though their lifetime may range from millions to billions of years by studying many stars of different ages.

One can study the effects of mass on the evolution of stars by observing stellar populations in **globular clusters**. A globular cluster may be made up of millions of stars tightly bound by gravity and containing stars of different mass that **formed almost at the same time**.

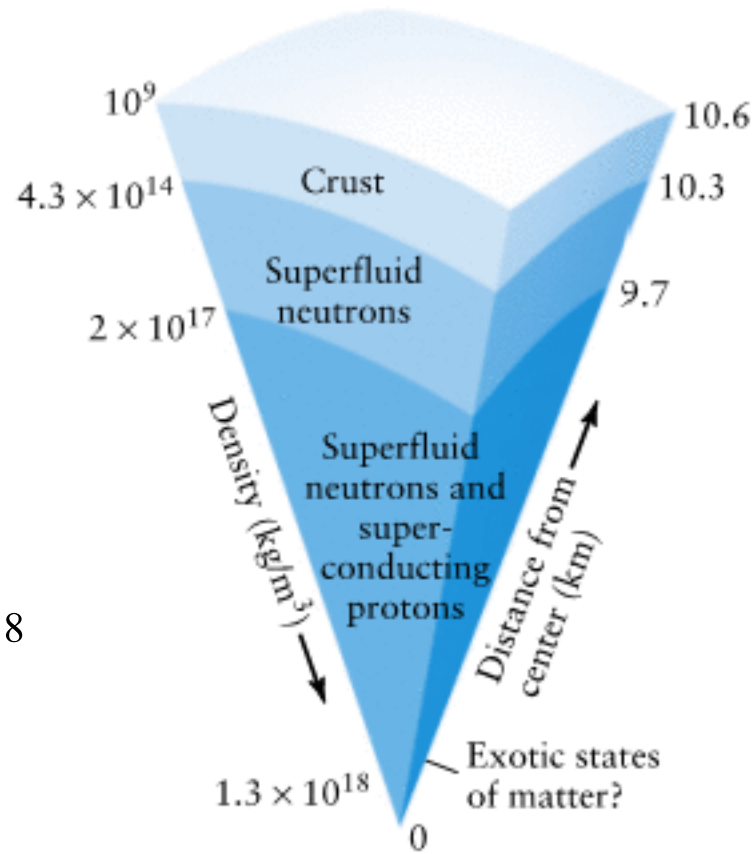
A great location to study many stars is in a giant molecular cloud with ongoing star formation. The Orion Nebula is a great example of a stellar nursery.


Time = -5.3 (ms)
7.7
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.5
Entropy (k_B/baryon)

Interior of Neutron Stars

Models of the internal structure of a neutron star strongly suggest that the **protons in the core experience no electrical resistance** moving around. This phenomenon, is called **superconductivity**.

It has been speculated that near the core the pressure reaches a few $\times 10^{18}$ kg/m^3 at which levels the neutrons and protons dissolve into more fundamental particles called **quarks**.



A model of a neutron star.