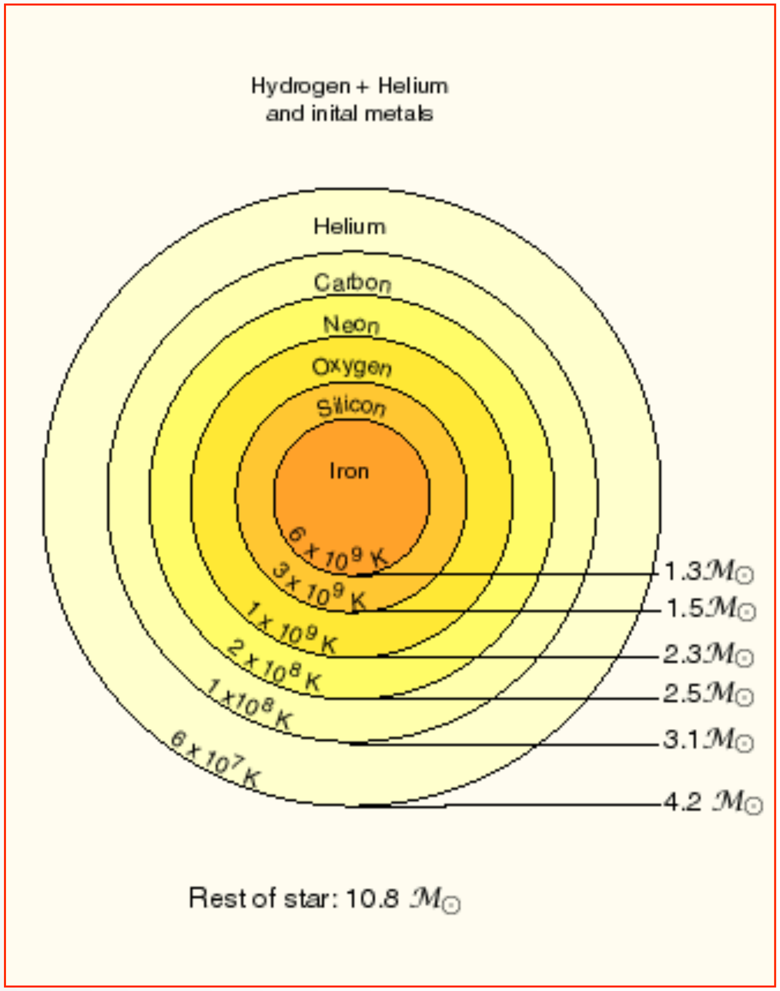
# AY5 Announcements

- One more chance on Lab this week! Friday, Nat Sci Annex 101, 10:40am
- Quiz 1 scores and histogram posted at class WWW site.
- Quiz 2: Tuesday April 30.
  - Stellar structure, energy sources, evolution and end points, formation of the elements

# AY5 Announcements

- Intro Astronomy text books are available for check out from ISB 211 (Maria)
- LSS (Learning Support Services) tutoring available for this class

# Massive-star Evolution

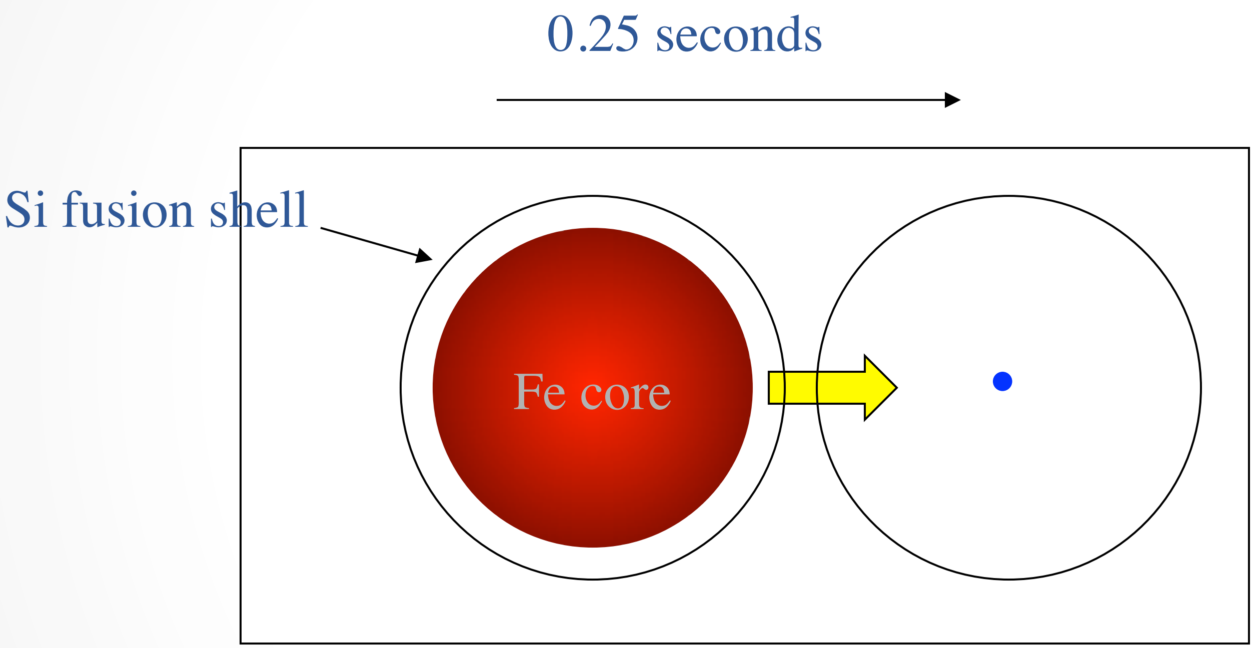



"ashes" from outer shells provide fuel for the next shell down

# Core Collapse

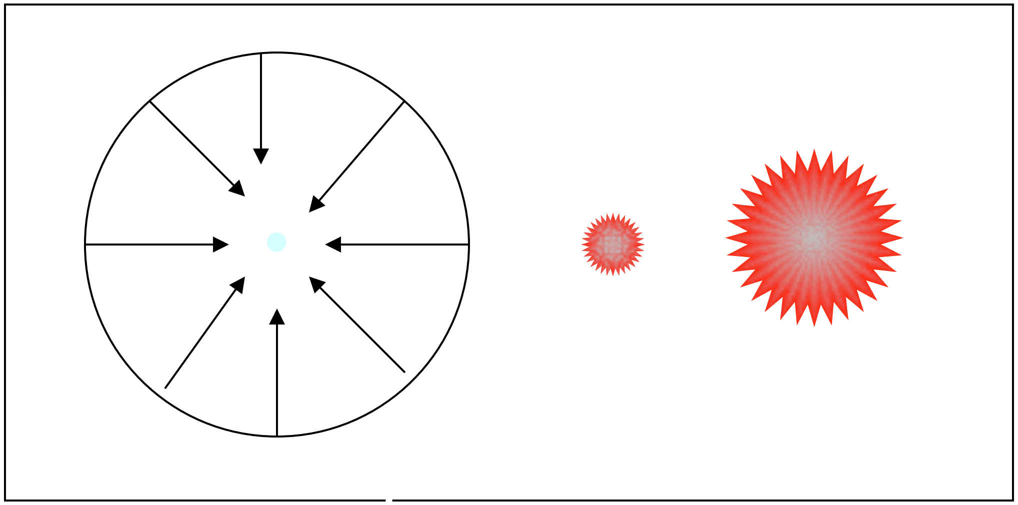
- The fusion chain stops at Fe and an Fe core very quickly builds.
- Within a day of starting to produce Fe, the core reaches the $1.4M_o$ Chandrasekar limit.
- On a timescale less than a second the core implodes and goes through a series of events leading to a tremendous explosion.

# Core-Collapse in Massive Stars




1) Fe core exceeds 1.4M and implodes
2) Temp reaches 5 billion K and photodisintegration begins to blast apart the Fe nuclei
3) Neutronization occurs: $e^- + p^+ \rightarrow n^0$ + neutrino

# Core-Collapse in Massive Stars

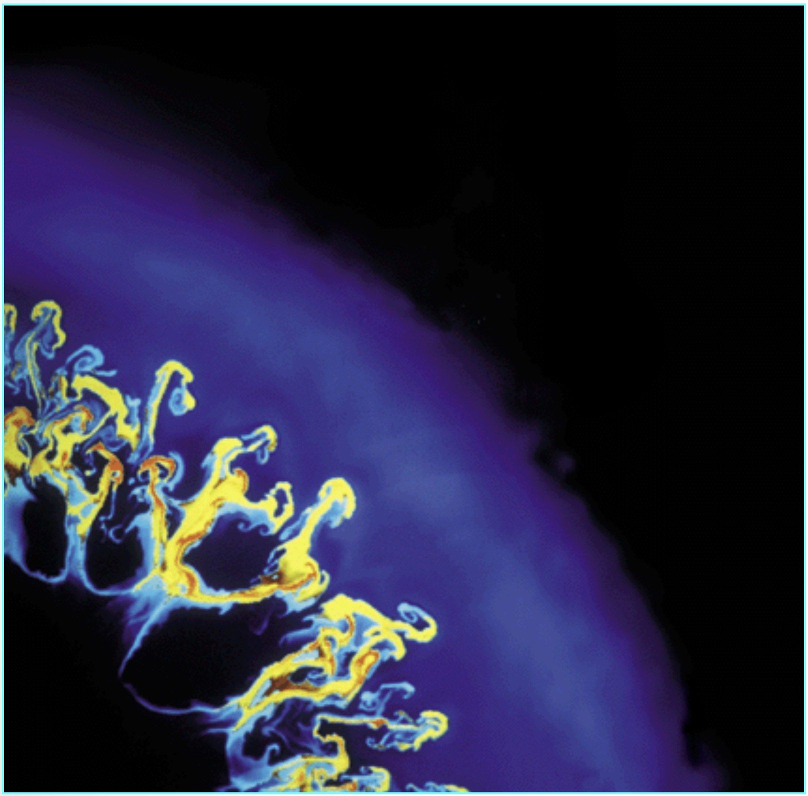


4) Neutron ball is at `nuclear density' (>$10^{17}$ kg/$m^3$) and is much harder than any brick wall.

5) Infalling layers crash into neutron ball, bounce off, create a shock wave and, with help from the neutrinos, blast off the outer layers of the star at 50 million miles/hour.

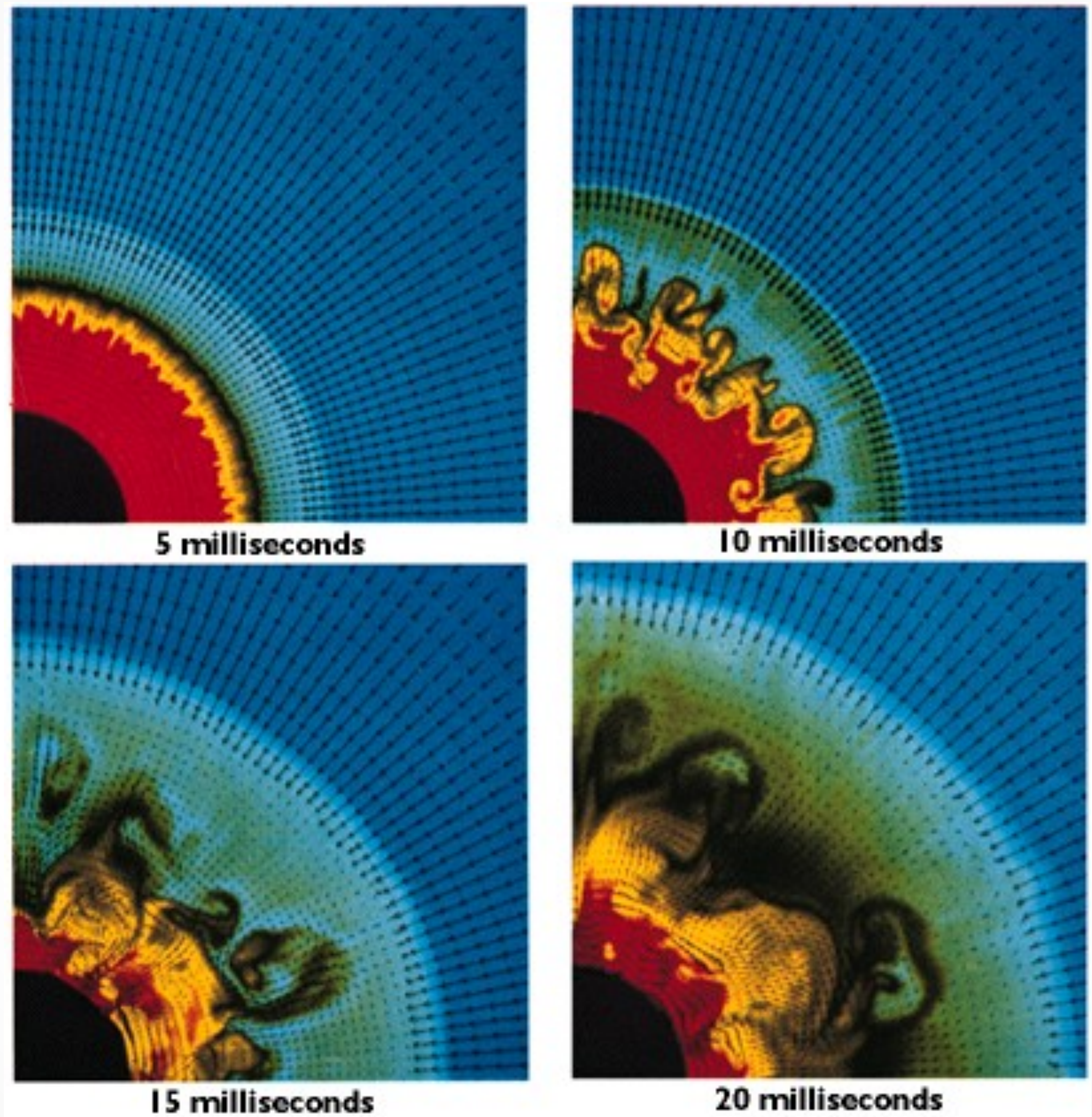
# SNII Bounce Shock wave

# Supernova Type II (SNII)



This is a wild event.

- Explosion energy in models predicted to be ~100 million times the luminosity of the Sun (as bright as a small galaxy)
- Many rare elements will be manufactured in non-equilibrium reactions*


5 milliseconds
10 milliseconds
15 milliseconds
20 milliseconds

# Supernovae II

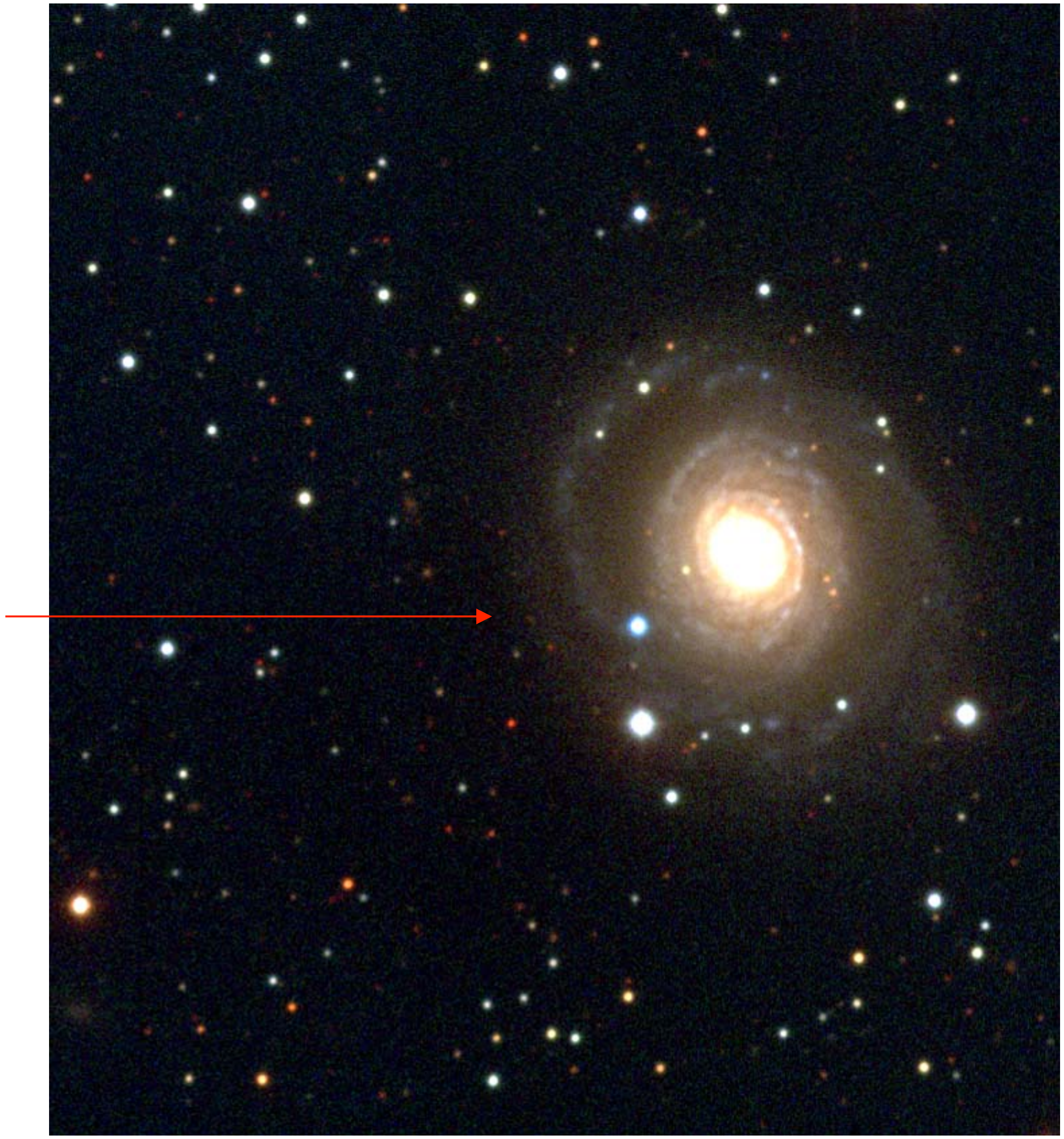
- Expect:
  - Rapidly expanding debris cloud
  - $10^8$ times the optical luminosity of the Sun
  - Chemically-enriched debris
  - Extremely dense 1.4 solar mass neutron ball left behind
  - Association with massive stars/star formation

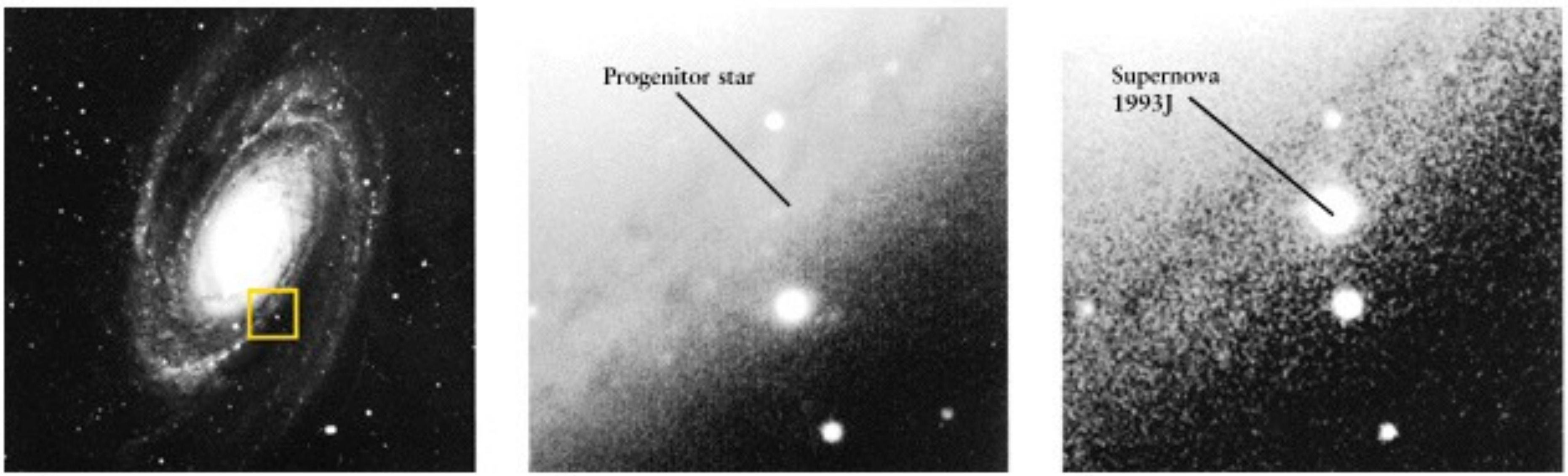
# Supernova II

- Any reasons to believe this story?

1) SN II have been seen in many galaxies in the last 100 years and always near star-formation regions:

Guilt by association!






a b c

# SNII

2) Predicted peak luminosity of $10^8 L_{\odot}$ is observed

3) Predicted expansion velocity of 10,000 to 20,000 km/sec is observed

4) In the Galaxy, when we point our telescopes at historical SN, we see chemically-enriched, rapidly expanding shells of gas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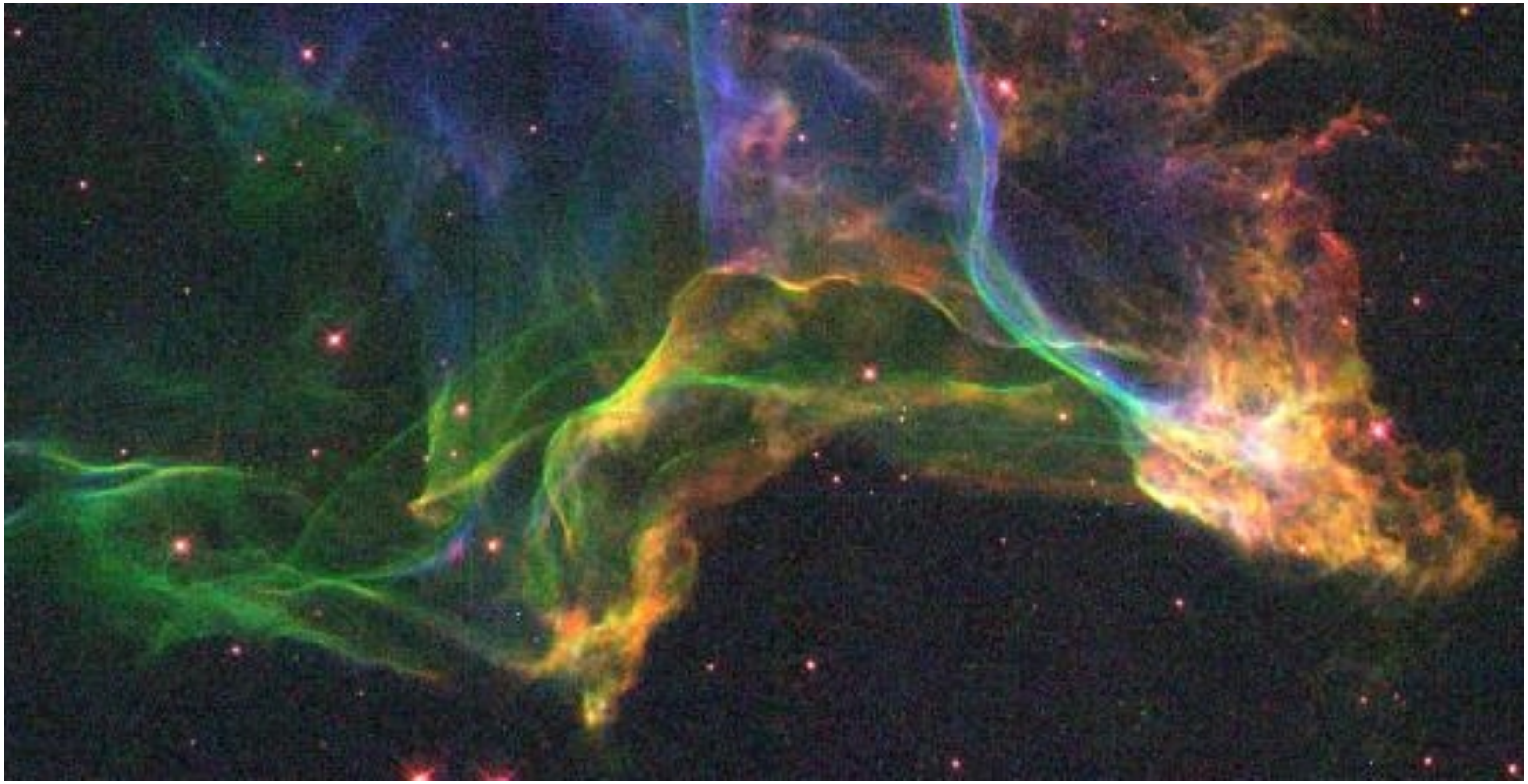


# NGC 1850 in LMC

# SN 1987a

- There was a major breakthrough in 1987.
- 165,000 years ago in a nearby galaxy called the Large Magellanic Cloud, a star blew up as a SNII.
- The first indication was a neutrino `burst' . About 10 billion neutrinos from SN1987a passed through every human on Earth. Neutrino detectors caught about 14 of them.
- 99% of a SNII energy is released as neutrinos.

# SN1987a

- The second indication, about 4 hours after the neutrinos arrived was a new naked-eye star in the LMC

# SN1987a

- For the first time, the progenitor star of a SNII was identified:

20$M_{\odot}$ Supergiant -- bingo!

- The final prediction of SNII theory is that there should be a very dense ball of neutrons left behind in the center of a SNII remnant. More later.

# Historical Galactic SN

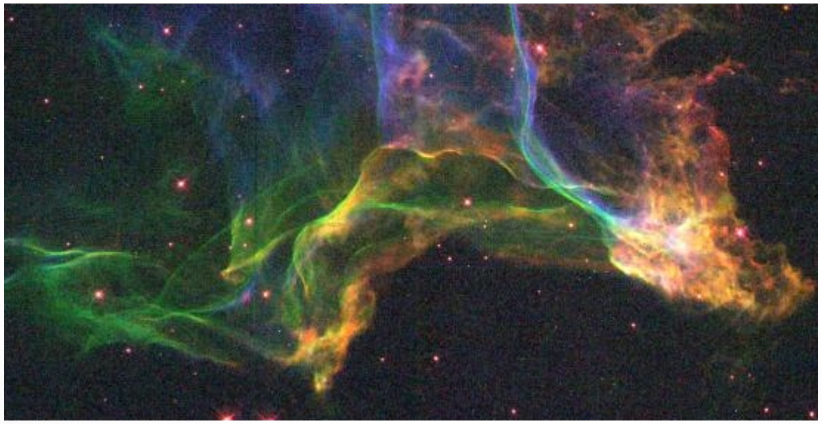
- We miss many in the Galaxy because of dust obscuration.
- From radio surveys for SN remnants, we have discovered 49 remnants for an inferred rate of 3.4 SN/century.
- There are several `historical supernovae' -- bright new stars that appeared in the sky and were recorded by various people.

# Historical SN

- 1006, 1054, 1181, 1572, 1604 and 1658 were years when bright `guest stars' were widely reported

# Historical SN

- For all the guest stars, point a modern telescope at the position and see a rapidly-expanding shell of material.
- In two cases, the remnant was discovered first

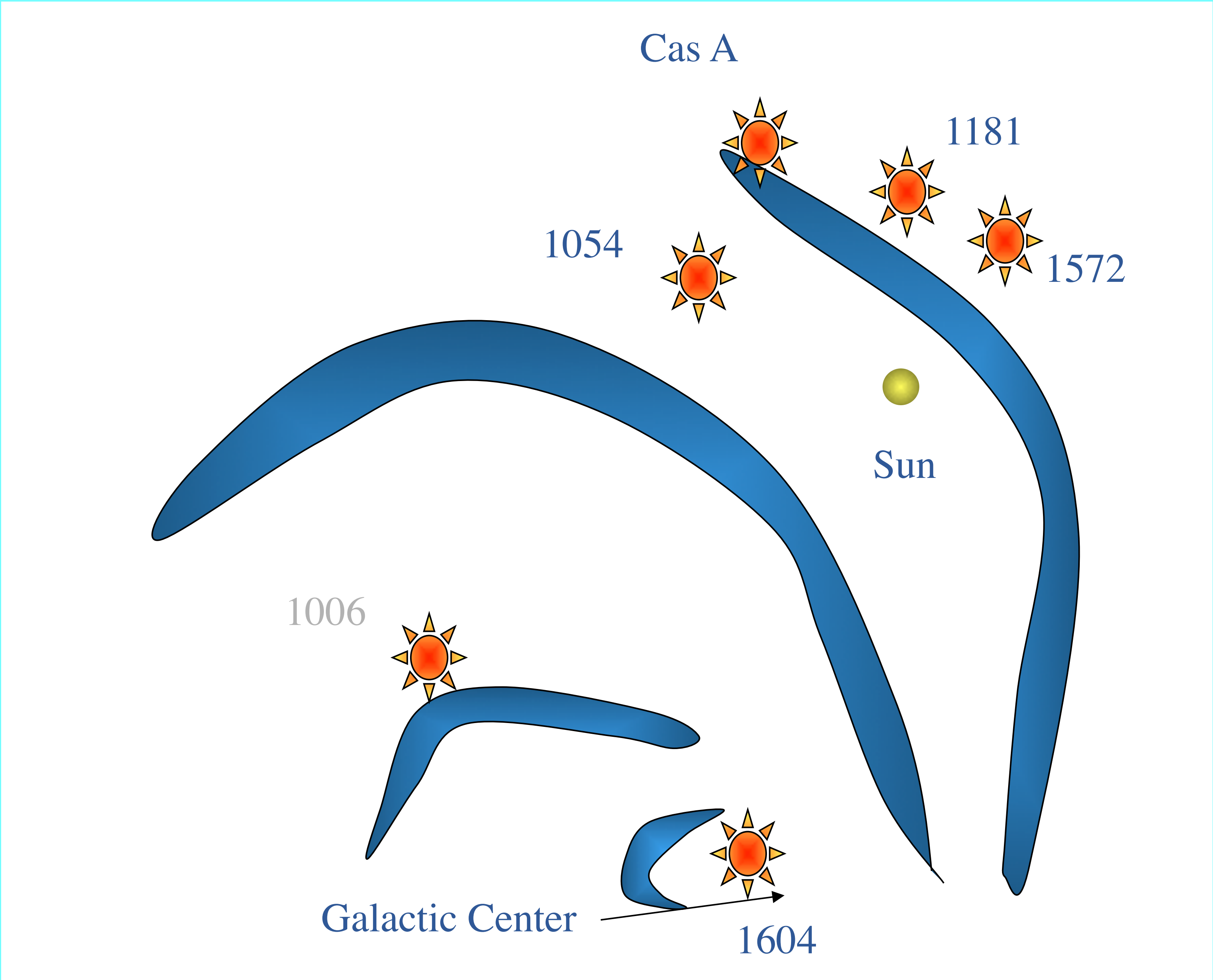


# Historical SN

- The 1054AD event was so bright it cast shadows during the day -- this is the position of the Crab Nebula

# Historical SN

- The nearest SN remnant is the `Gum'   nebula from around 9000BC. Four times closer than the Crab, it would have been as bright as the full moon.
- A mystery is `Cas A' -- this was a SN at about 1600AD, should have been very bright, but no records of it exist.


Cas A
1181
1054
1572
Sun
1006
Galactic Center
1604

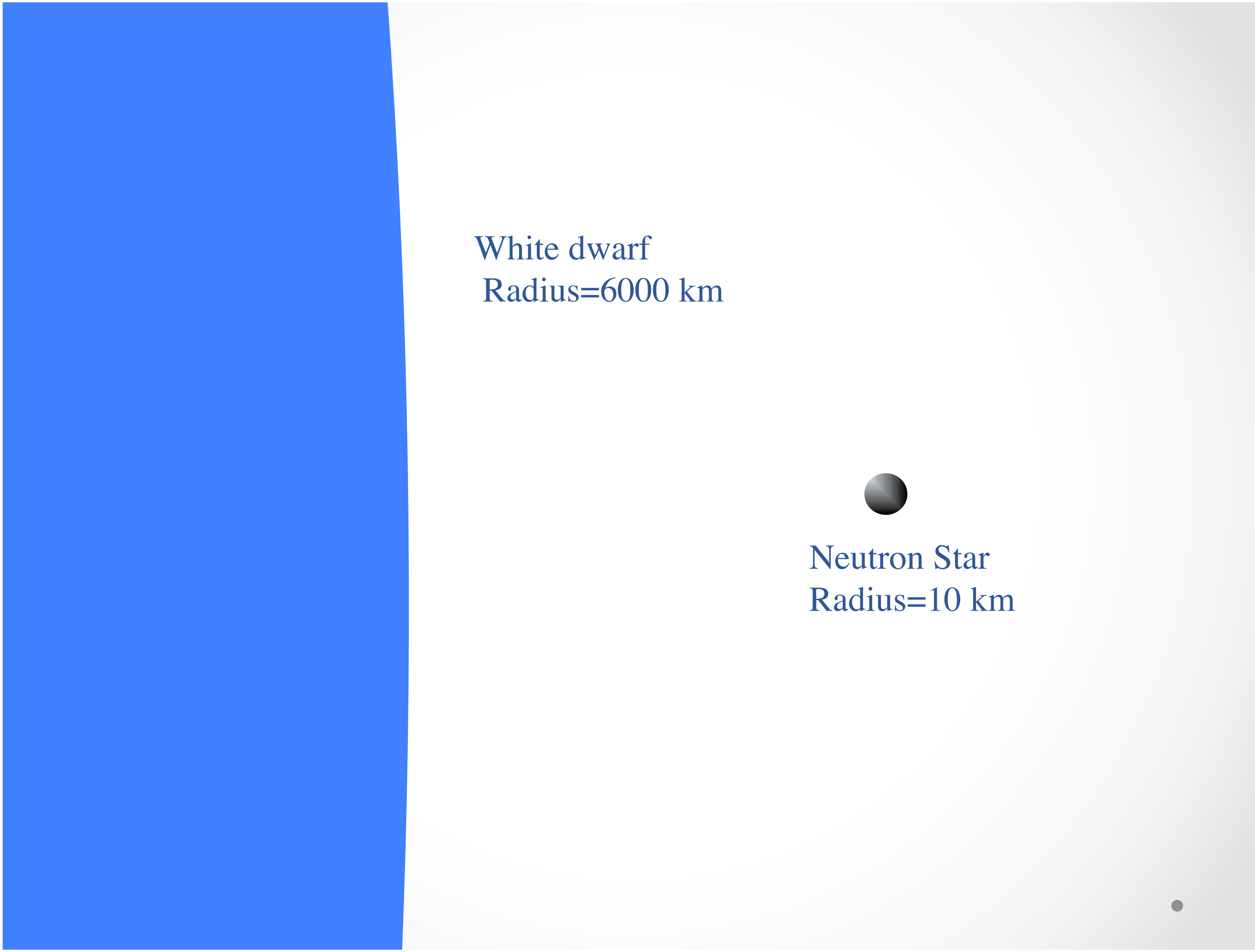
# Supernovae in the Galaxy

- We are long overdue for a bright Galactic Supernova.
- For a while, a nearby SN was a valid candidate for the source of the demise of the dinosaurs.
- There are the products of short-lived radioactive isotopes locked up in primitive meteorites which suggest a SN in the vicinity of the Solar System about 100,000 years before the Sun formed. A SN may have triggered the collapse of the proto-Sun.

# Next Galactic SN?

# Neutron Stars

- There is another test of SNII theory
- If the scenario is correct, there should be a VERY dense, VERY hot ball of neutrons left behind after the explosion.
- Object is supported by neutron degeneracy (although there is an "atmosphere" of normal matter)
- Call this a Neutron star (although like a White Dwarf it is not a star)


White dwarf
Radius=6000 km
Neutron Star
Radius=10 km

# Neutron Stars: Predictions

- Neutron star mass: > 1.4$M_{Sun}$ (collapse triggered)
- Neutron star radius: 10 - 80 km
- Neutron star density: $10^{14}$ grams/$cm^3$
  100 million tons/thimble (all of humanity)
- Initial Temperature: >2,000,000k
- Neutron star remnant will be spinning rapidly and have a huge magnetic field

# Conservation of Angular Momentum

- Any spinning object has `angular momentum' which depends on how fast it is spinning and how the object's mass is distributed.
- `how fast': $\underline{\omega}$ (greek letter omega)
- `mass distribution': Moment of inertia (<u>I</u>)

$$\vec{L} = I\vec{\omega}$$

# Conservation of Angular Momentum

- Conservation of angular momentum means:

$$L_{initial} = L_{final}$$

$$I_i \omega_i = I_f \omega_f$$

$$\frac{I_i}{I_f} = \frac{\omega_f}{\omega_i}$$

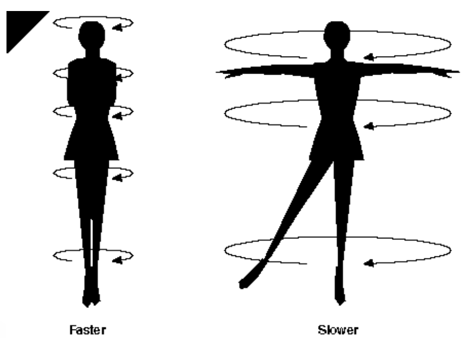
Moment of Inertia → $I$

Angular velocity → $\omega$

# Conservation of Angular Momentum

- Think about those ice skaters. With arms out, a skater has a large moment of inertia. Pulling his/her arms in reduces the moment of inertia.

Arms out: large I, low spin rate
Arms in: small I, high spin rate



# Conservation of Angular Momentum

- The moment of inertia for a solid sphere is:

$$I = \frac{2}{5}MR^2$$

- If a sphere collapses from a radius of $7\text{x}10^5$km to a radius of 10km, by what factor does it's spin rate increase?

$$L_{initial} = L_{final}$$

$$I_i \omega_i = I_f \omega_f$$

$$\frac{2}{5} M R_i^2 \omega_i = \frac{2}{5} M R_f^2 \omega_f$$

$$R_i^2 \omega_i = R_f^2 \omega_f$$

$$\omega_f = \frac{R_i^2}{R_f^2} \omega_i = \left( \frac{7 \times 10^5}{10} \right)^2 \omega_i = 4.9 \times 10^9 \omega_i$$

Sun rotates at 1 rev/month. Compress it to 10km and conserve L, it will spin up to 1890 revolutions/second (and fly apart)

# Magnetic Fields

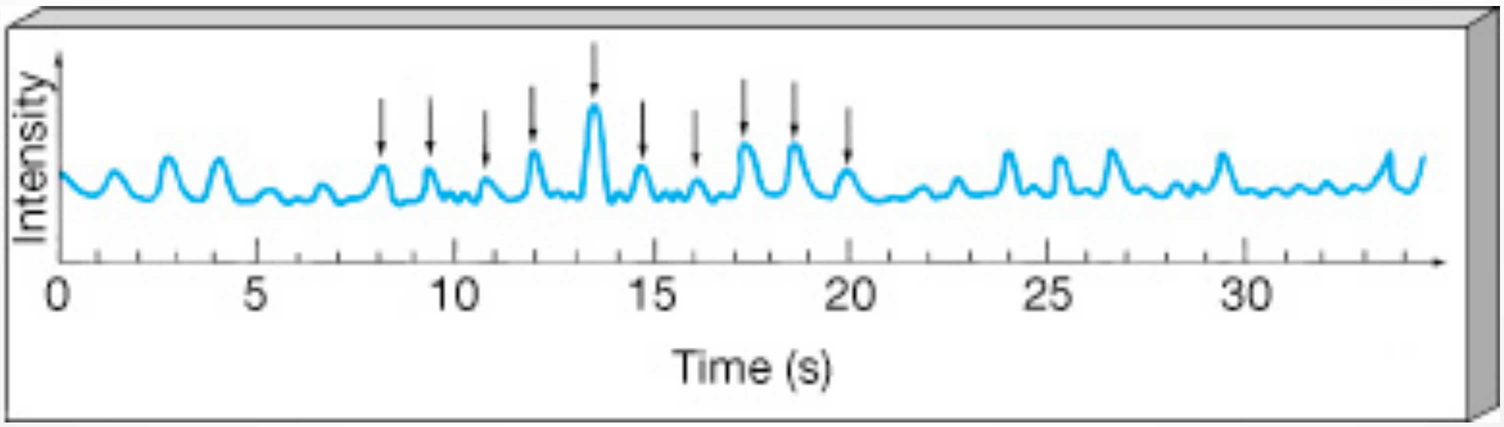
Magnetic field lines are also conserved. When the core collapses, the field lines are conserved, and the density of the field lines goes way up . This is the strength of the magnetic field.

# Neutron Stars

- The possibility of n-stars was discussed way back in the 1930's but for many decades it was assumed they would be impossible to detect (why?)
- But, in 1967, Jocelyn Bell and Tony Hewish set up a rickety barbed-wire fence in the farmland near Cambridge England to do some routine radio observations.

# LGMs

- Bell and Hewish discovered a source in Vela that let out a pulse every 1.3 seconds. Then they realized is was accurate to 1.337 seconds, then 1.3372866576 seconds. They soon realized that the best clocks of the time were not accurate enough to time the object. They called it ‘LGM’.



# First Pulsar

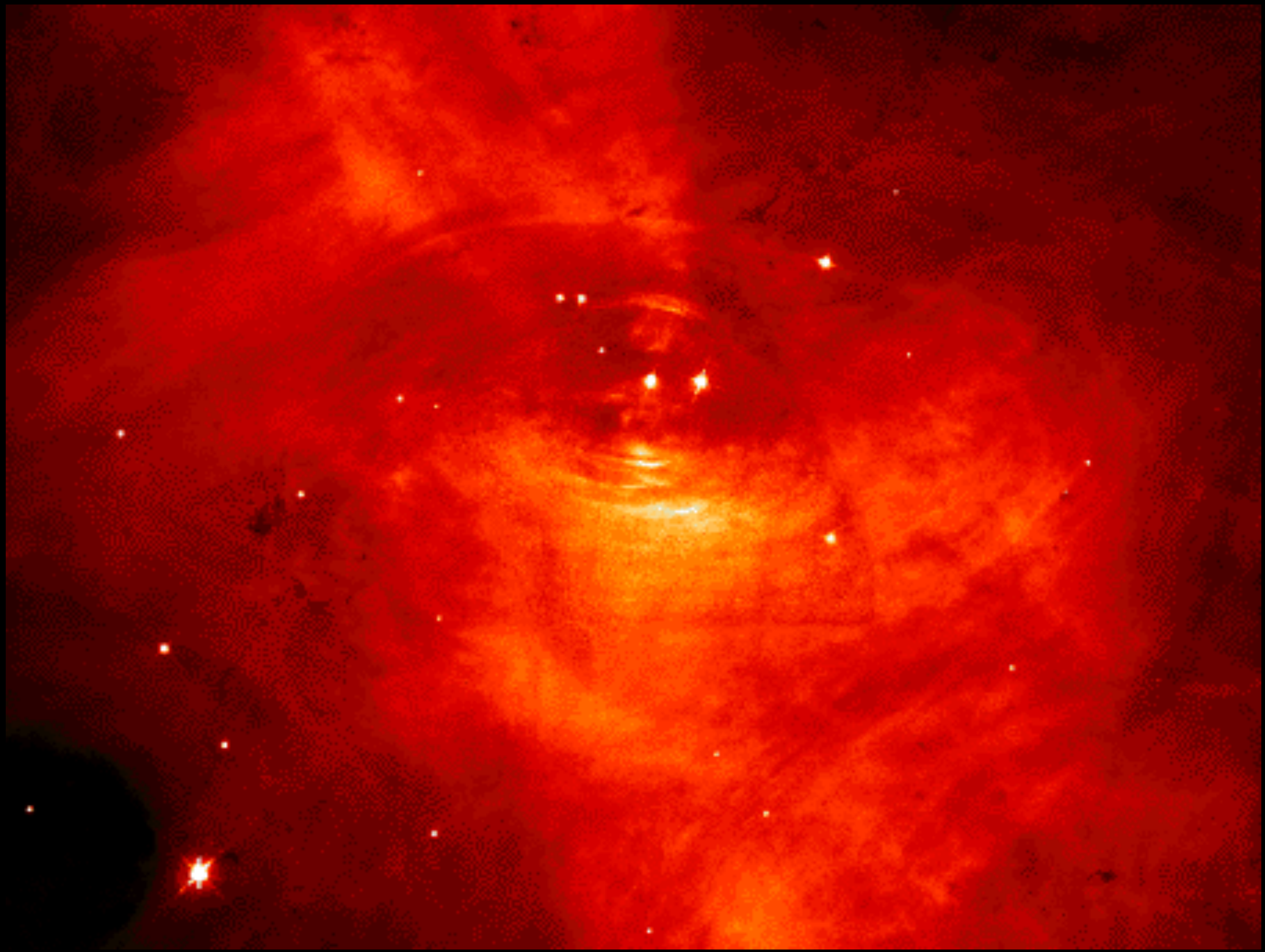
- Bell was a graduate student at the time. The source was assumed to be man made, but when no terrestrial source could be identified, they briefly considered an artificial extra-terrestrial source.
- When a second source was discovered (Cass A) they announced the discovery as a new phenomenon.

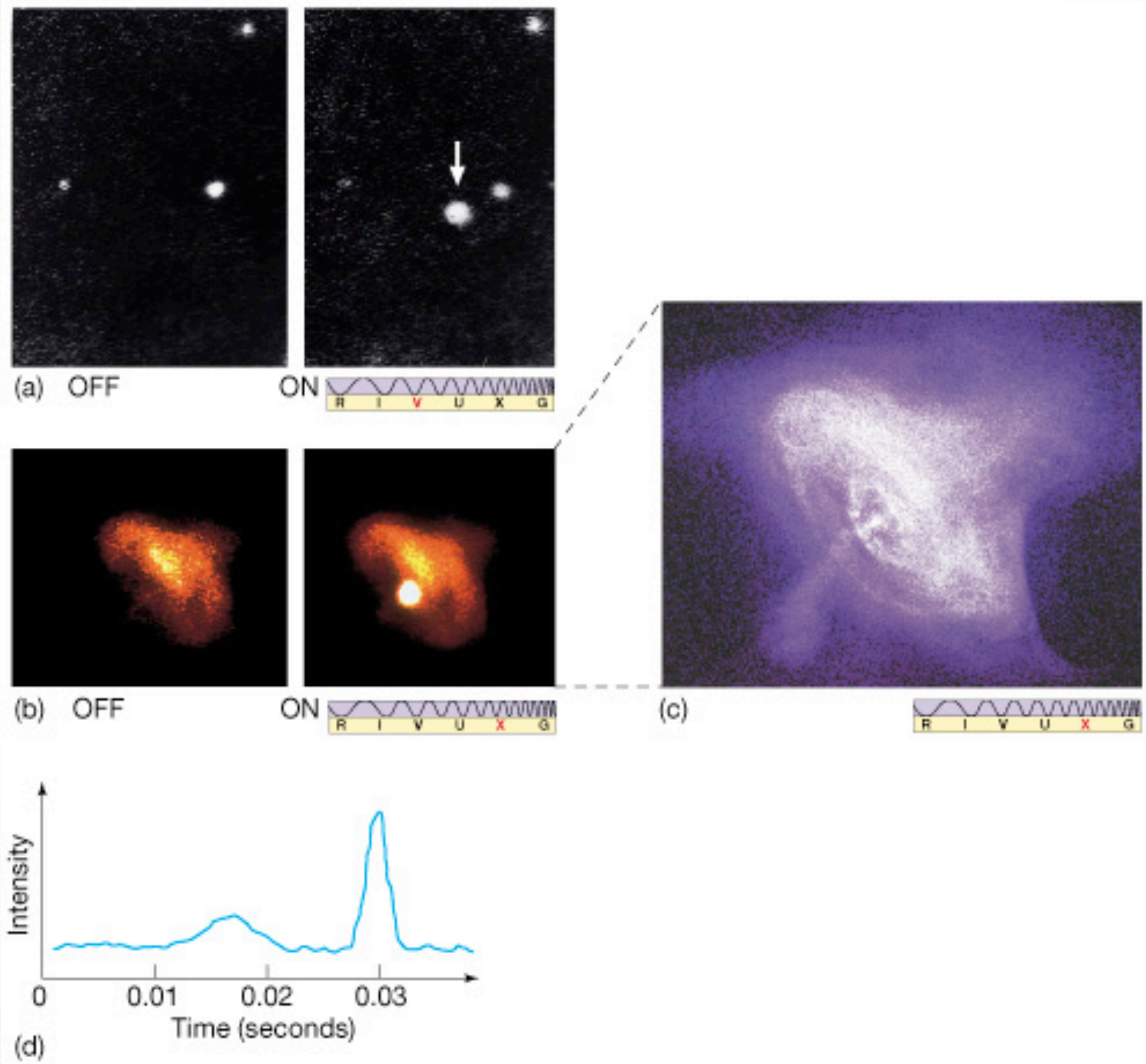
- The discovery led to a year of wild speculation, but explanations involving neutron stars quickly rose to the top.
- A pulsing source with period of 0.033 seconds was discovered in the Crab nebula.
- Big clue! Spin the Sun or Earth or a WD 30 times per second and they will be *torn apart*.
- *Need a small object with very large material strength.*

# Pulsars

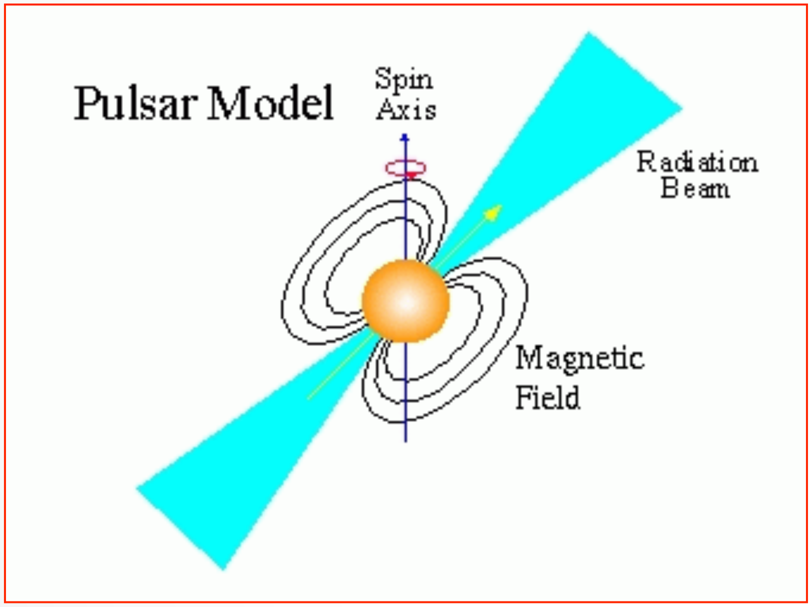
- The new objects were named ‘pulsars’ and is was soon discovered that they were slowly slowing down -- this provided the answer to the mystery of why the Crab Nebula was still glowing.
- There are now more than 2000 known pulsars in the Galaxy.


HST
Palomar




(a) OFF
ON
R I V U X G
(b) OFF
ON
R I V U X G
(c)
R I V U X G
Intensity
0
0.01
0.02
0.03
Time (seconds)
(d)

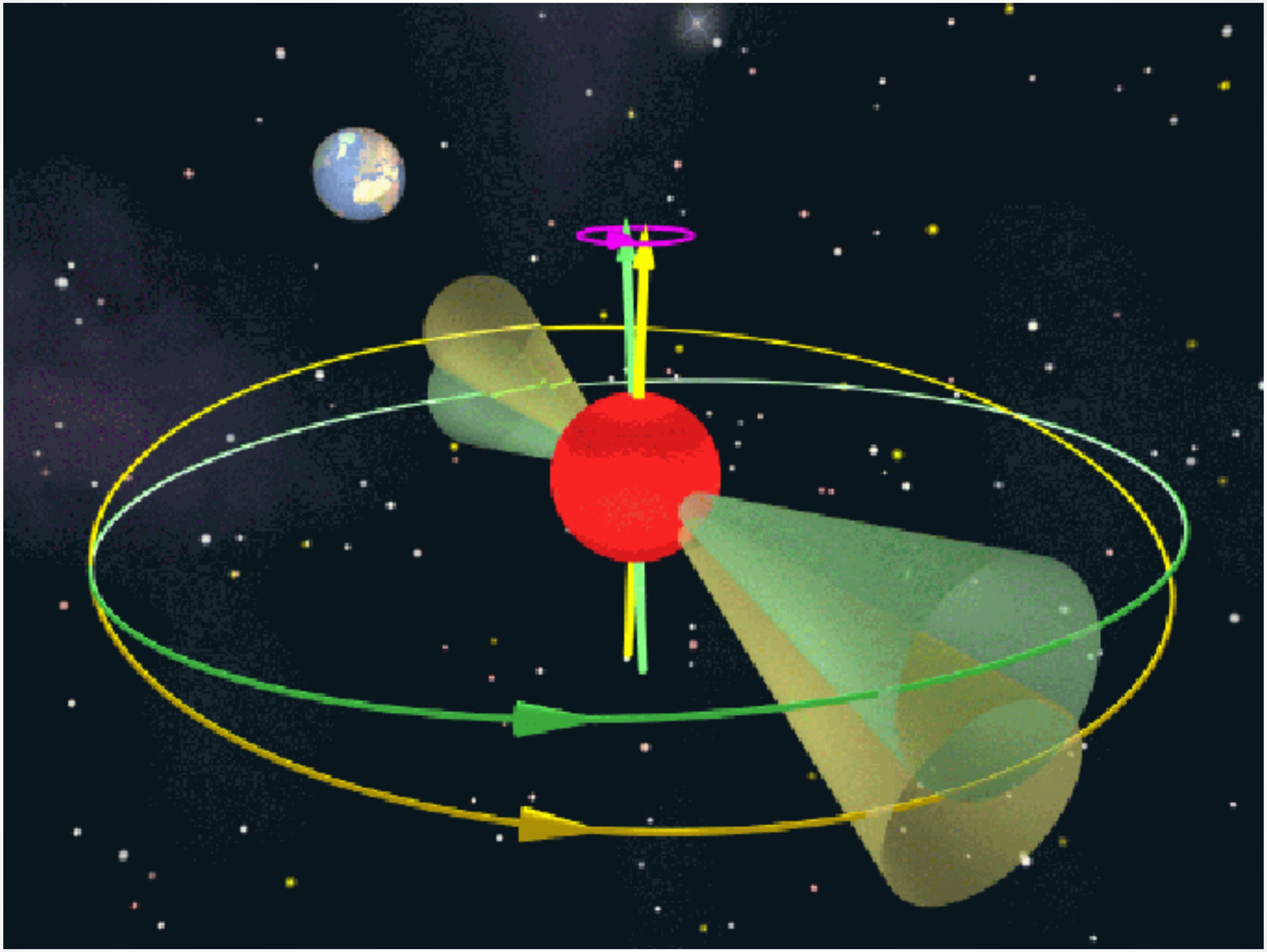
# Pulsars: The Lighthouse Model




- So, what is the pulsing all about?
- The key is to have a misalignment of the nstar magnetic and spin axes?
- What do you call a rotating powerful magnetic field?

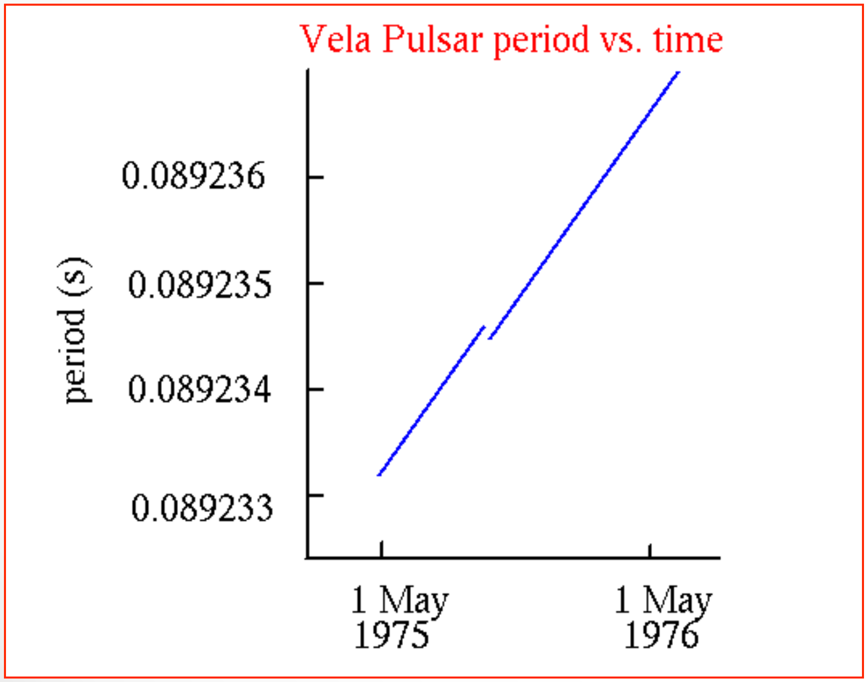
# Lighthouse model

- A rotating magnetic field is called a generator. The pulsar is a dynamo which is typically about $10^{29}$ times more powerful than all the powerplants on Earth. The huge electric field rips particles off the surface and accelerates them out along the magnetic field axis.
- The misalignment of the magnetic and spin axes results in a lighthouse-like effect as the beam sweeps past the Earth once per rotation period.



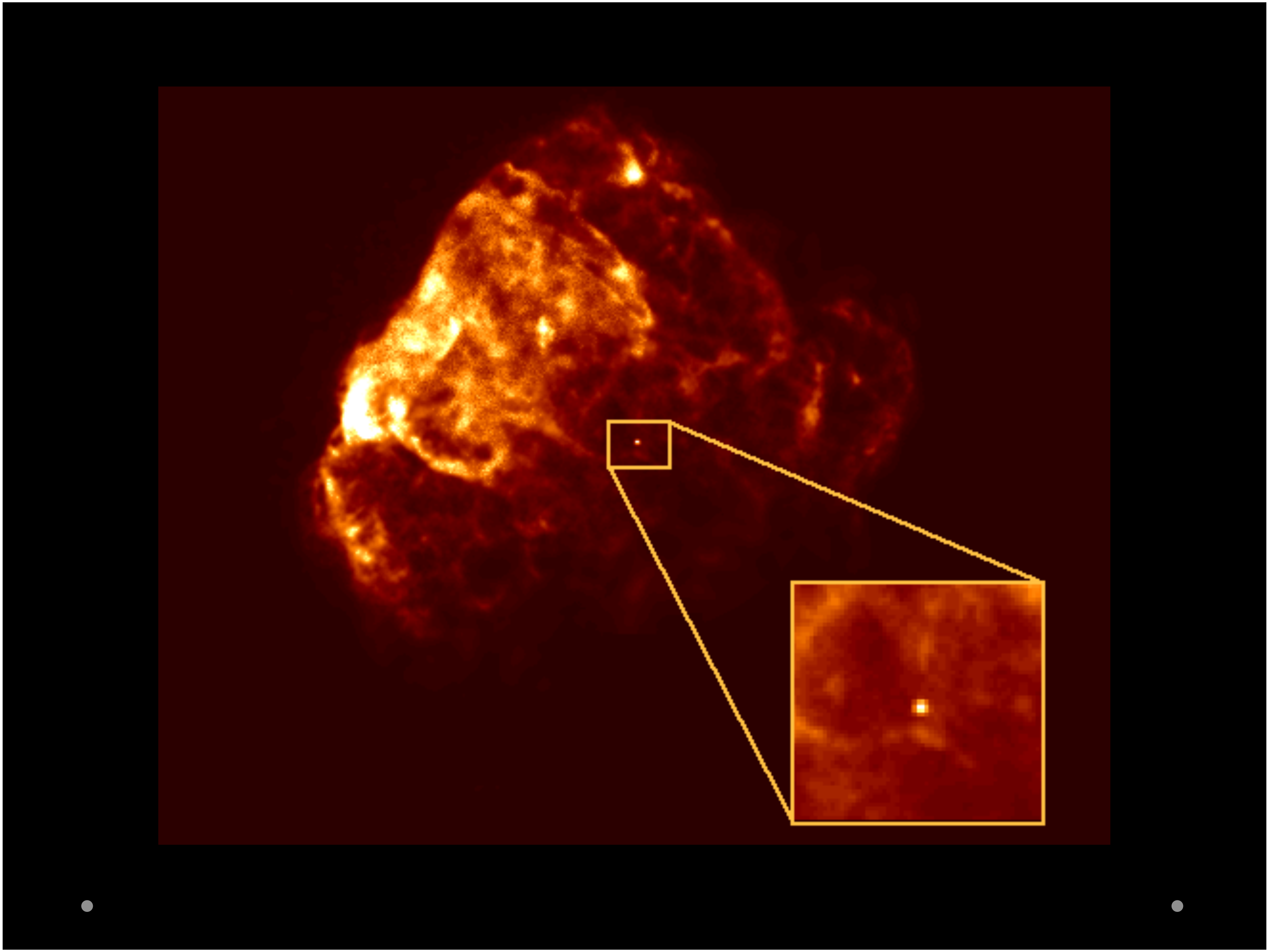
# Pulsars

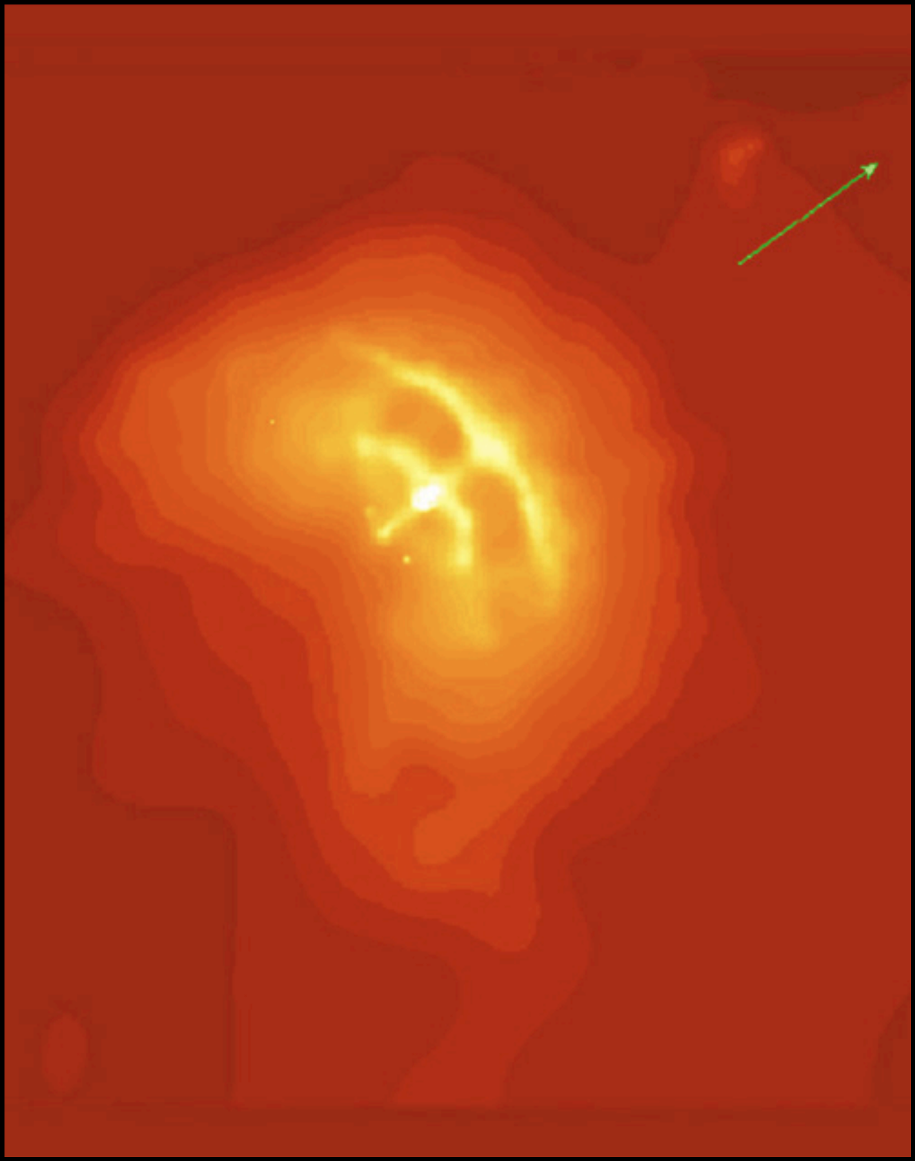
- The period of the Crab pulsar is decreasing by 3 x $10^{-8}$ seconds each day. The rotational energy is therefore decreasing and the amount of the

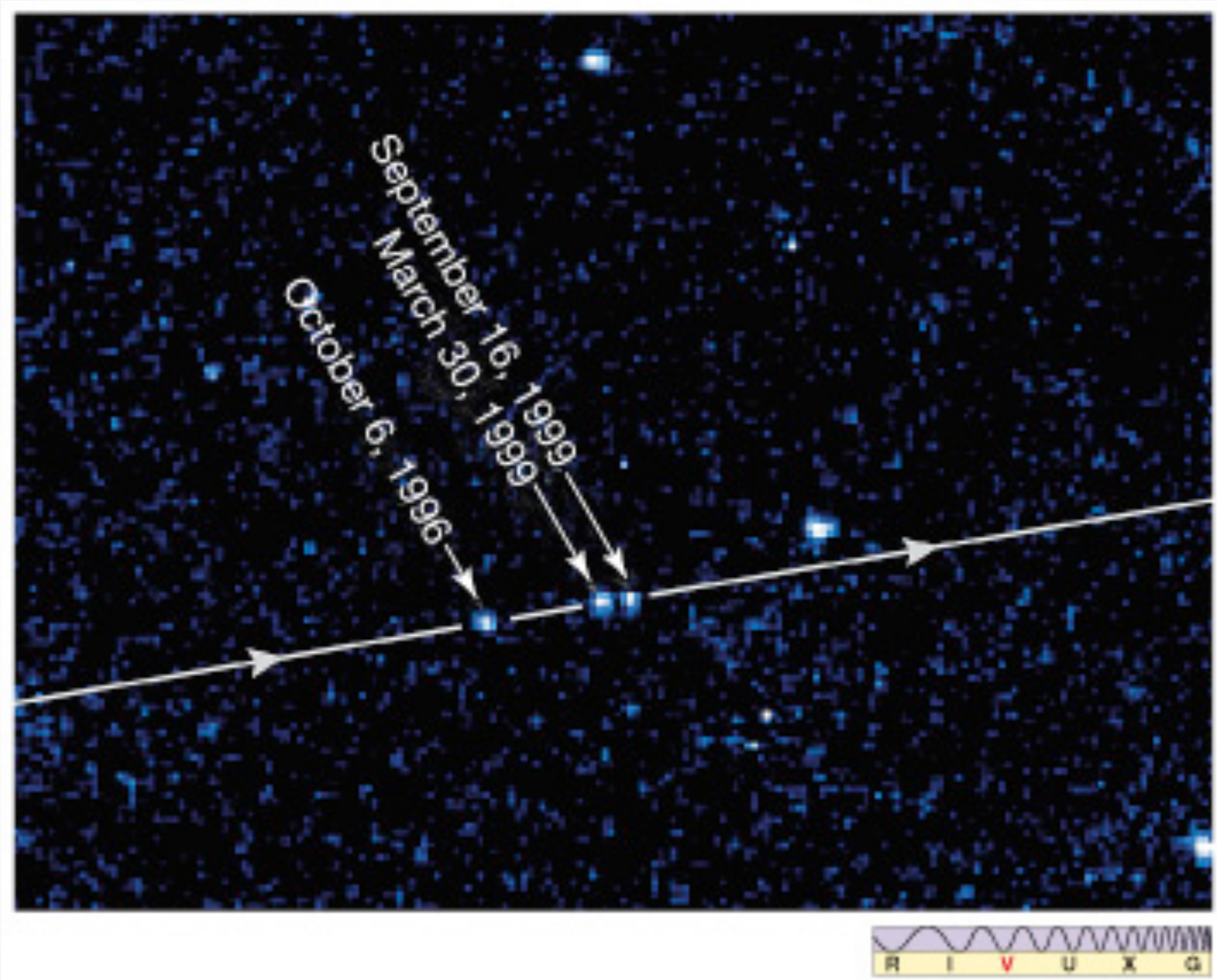



decrease in rotation energy is equal to the luminosity of nebula. Old pulsars spin more slowly.

- There is a mysterious cutoff in pulsar periods at 4 seconds. The Crab will slow to this in about 10 million years. The pulsar will turn off. Although the n-star will still be there, it will be essentially invisible.
- Most pulsars have large space velocities. This is thought to be due to asymetric SNII explosions.






September 16, 1999
March 30, 1999
October 6, 1996
R I V U X G

# Neutron stars in binary systems

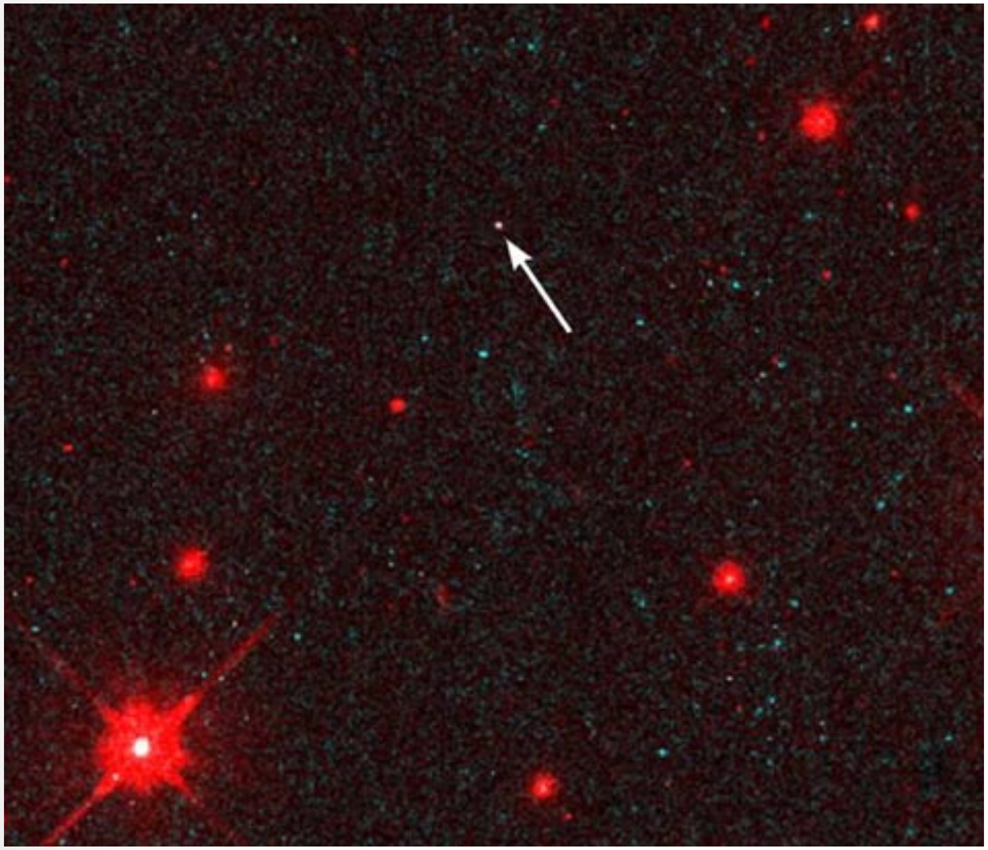
- Some neutron stars were discovered in binary systems that allowed measurement of the n-star mass:

In 10 of 11 cases, $M=1.44M_{Sun}$

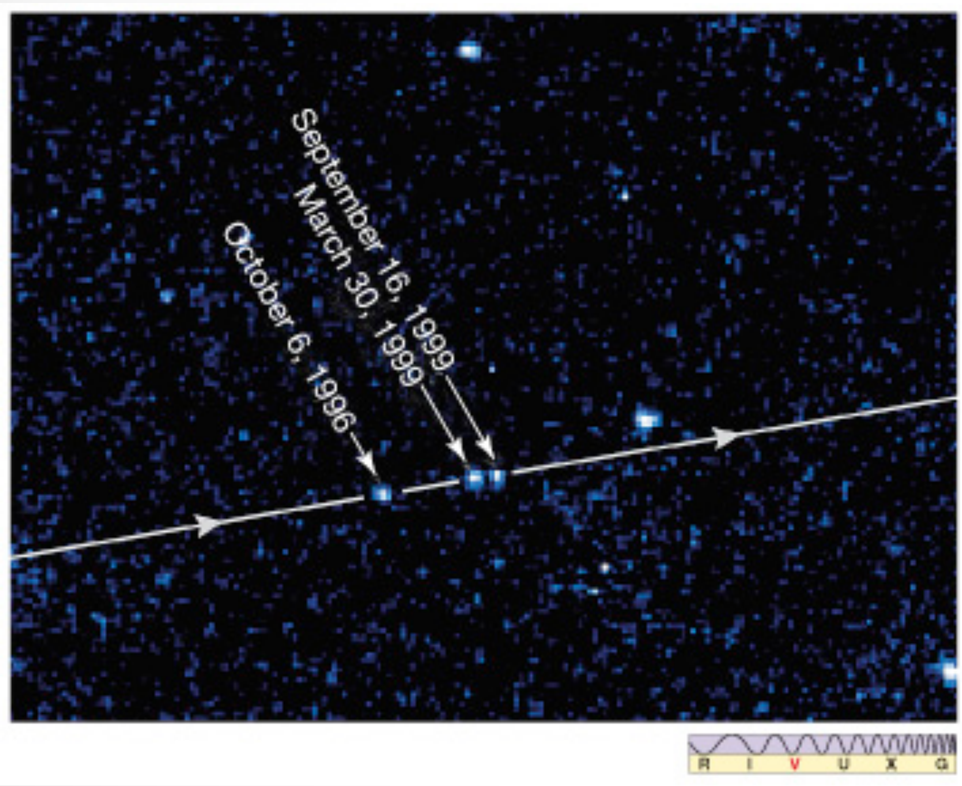
- This is good! Neutron stars are all supposed to be more massive than the Chandrasekar limit and there is even reason to expect them to be close to this limit as that is what initiated the core collapse in a SNII

# Detecting Neutron Stars

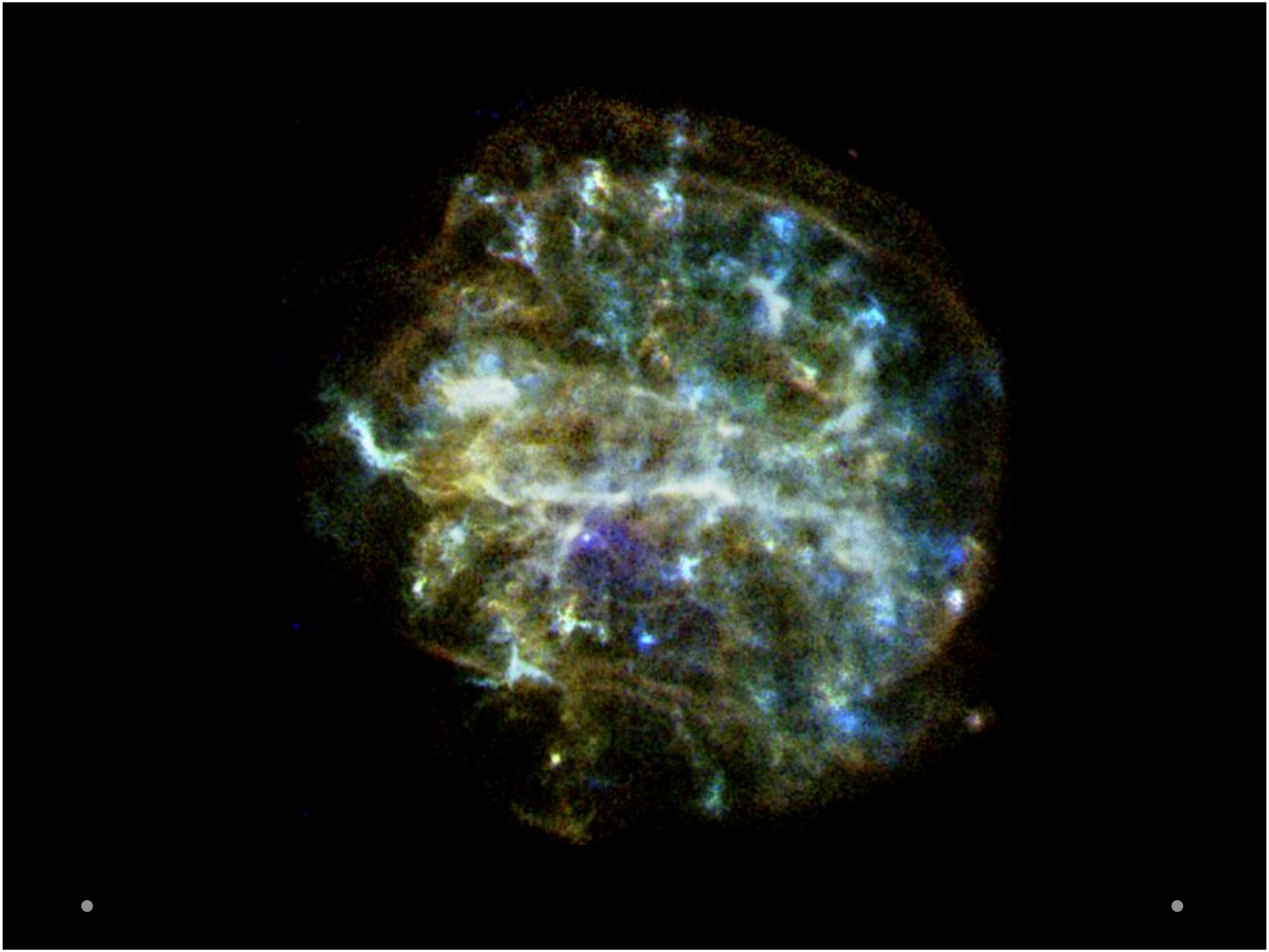
- Detecting n-stars via their photospheric emission is difficult.
- N-stars are VERY hot, but have a tiny surface area so have low luminosity.
- Initial temperature may be greater than 3,000,000k so a very young n-star will emit most of its Planck radiation in X-rays.

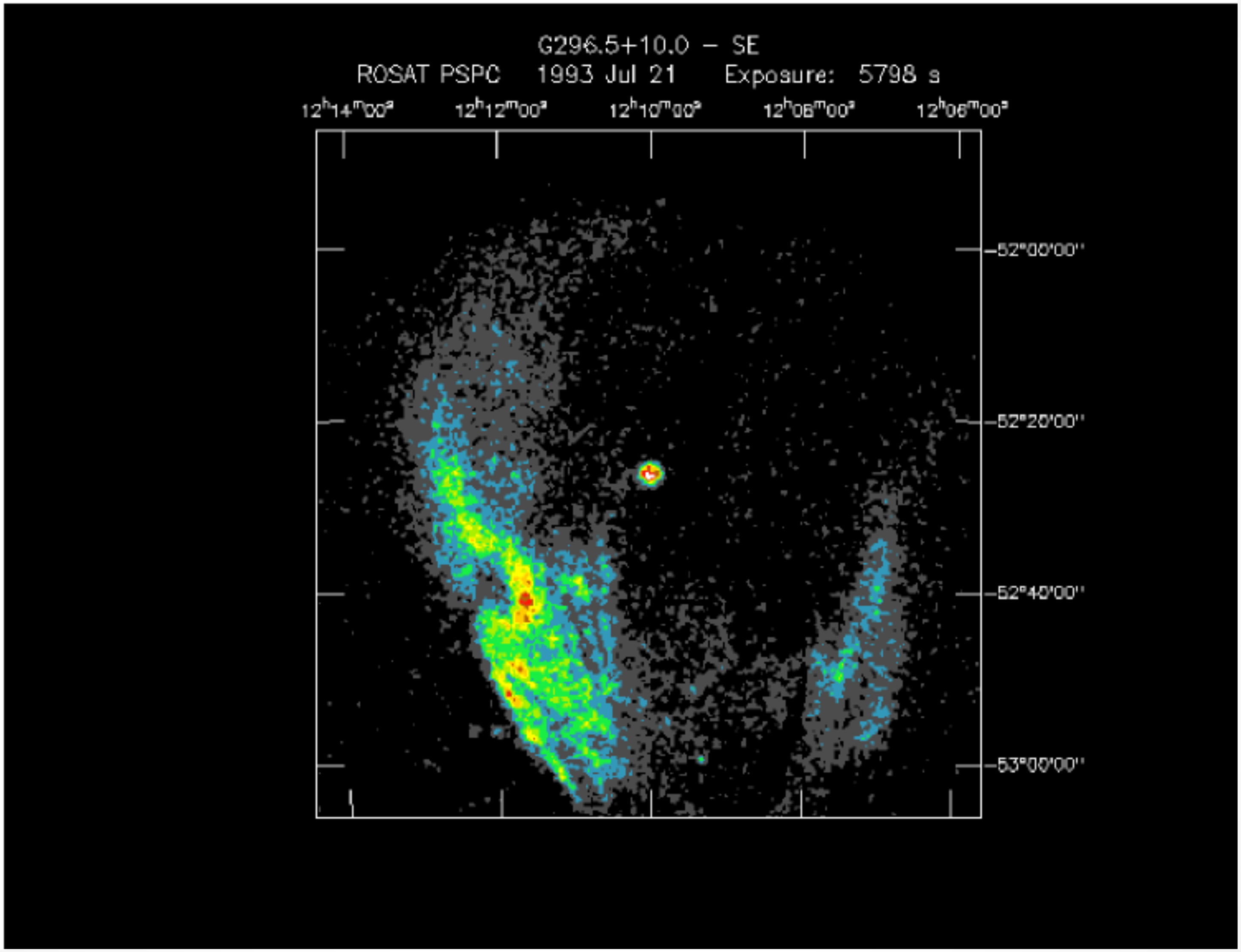


- First isolated n-star observed in photospheric light was discovered in 1997.
- $T_{surface}$=700,000
- Estimated age is $10^6$ years.
- This is combined x-ray through visible light image




- In 2002 there are about 6 isolated n-stars known that are seen in the light of their Plank radiation.
- Most are very nearby (<300 pc) and traveling VERY fast.




G296.5+10.0 – SE
ROSAT PSPC 1993 Jul 21 Exposure: 5798 s
12h14m00s
12h12m00s
12h10m00s
12h08m00s
12h06m00s
-52°00'00''
-52°20'00''
-52°40'00''
-53°00'00''

Sun: R=$10^5$km

density=6 gram/$cm^3$

Neutron `star' : R=20km

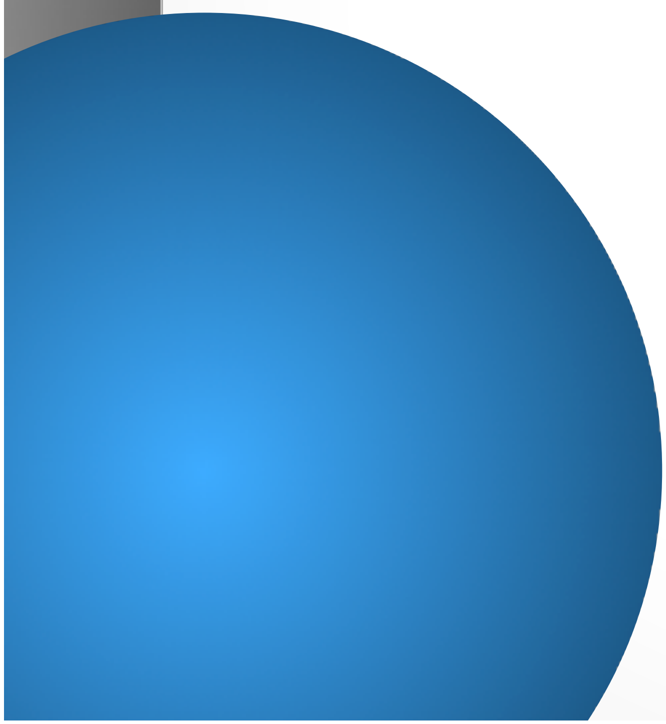
density=$10^{14}$

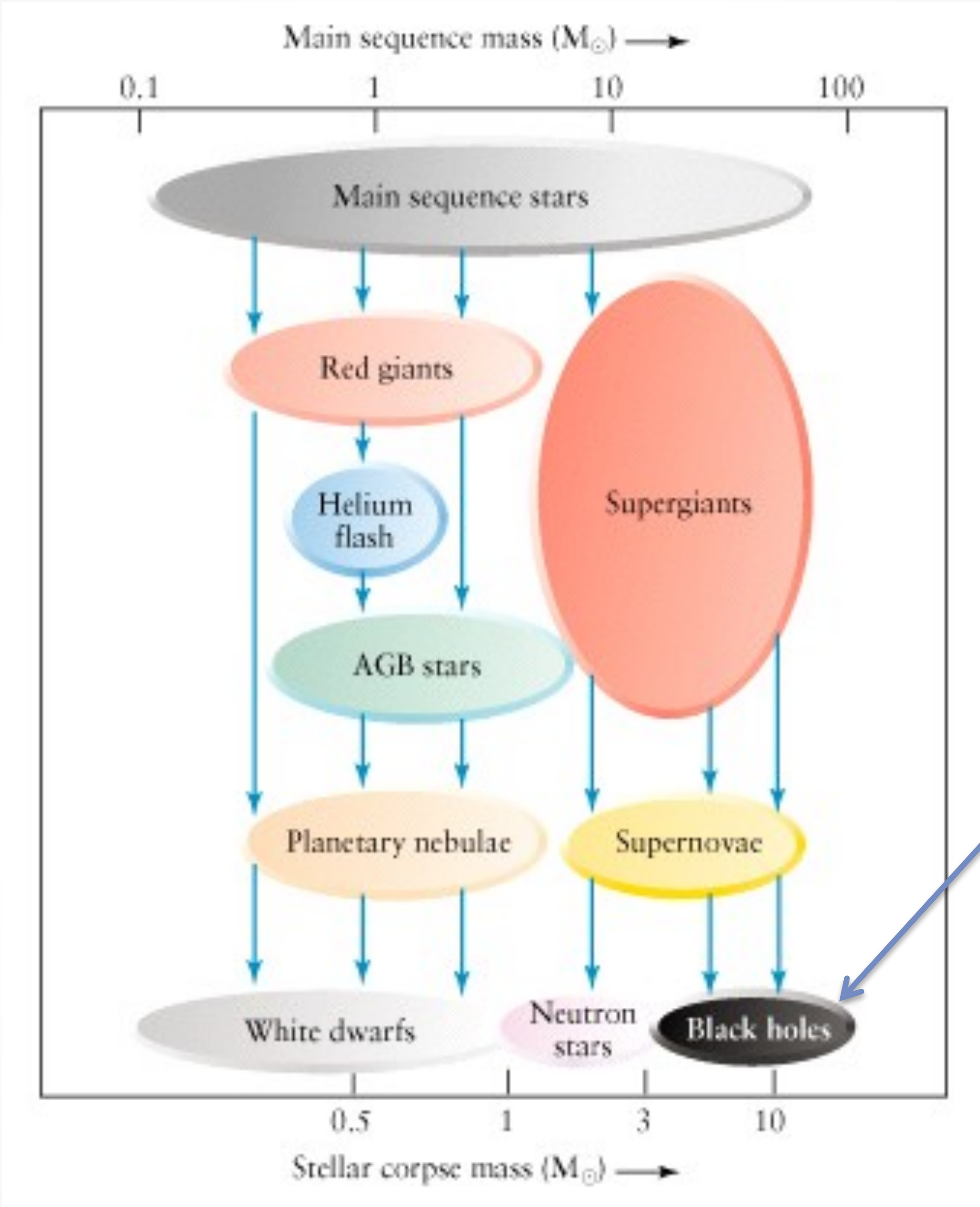
Mass > 1.4$M_\odot$

White Dwarf: R=6000km

density=$10^6$

Mass < 1.4$M_\odot$





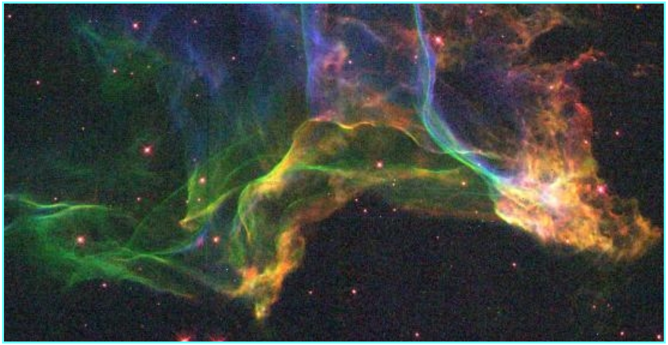

Next section

# Chemical Evolution Of the Universe

- Low-mass stars synthesize "new" He, C, O, Ne, Ar, Mg during the main-sequence and giant-branch phases.
- These freshly-minted elements are brought to the surface via convection and re-distributed via stellar winds and planetary nebulae into the interstellar medium to be incorporated into later generations of stars.

# Chemical Evolution II

- For more massive stars, `equilibrium’ fusion reactions produce elements all the way up to Fe.
- Freshly made elements are delivered via stellar winds or, sometimes more spectacularly via supernova explosions



# PERIODIC TABLE OF THE ELEMENTS

Key: 14 ⟸ Group IUPAC; IVA ⟸ Group CAS; Atomic Number ⟹ 6; Symbol ⟹ C; Name ⟹ Carbon; Electron Configuration ⟹ 2-4; Atomic Mass ⟸ 12.011; Selected Oxidation States ⟸ -4 +2 +4

| Period | 1 IA | 2 IIA | 3 IIIB | 4 IVB | 5 VB | 6 VIB | 7 VIIB | 8 VIIIB | 9 VIIIB | 10 VIIIB | 11 IB | 12 IIB | 13 IIIA | 14 IVA | 15 VA | 16 VIA | 17 VIIA | 18 VIIIA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 +1 -1 H Hydrogen 1.0079 1 | | | | | | | | | | | | | | | | | 2 0 He Helium 4.0026 2 |
| 2 | 3 +1 Li Lithium 6.941 2-1 | 4 +2 Be Beryllium 9.0122 2-2 | | | | | | | | | | | 5 +3 B Boron 10.811 2-3 | 6 -4 +2 +4 C Carbon 12.011 2-4 | 7 -3 -2 -1 +1 +2 +3 +4 +5 N Nitrogen 14.007 2-5 | 8 -2 O Oxygen 15.999 2-6 | 9 -1 F Fluorine 18.998 2-7 | 10 0 Ne Neon 20.179 2-8 |
| 3 | 11 +1 Na Sodium 22.990 2-8-1 | 12 +2 Mg Magnesium 24.305 2-8-2 | | | | | | | | | | | 13 +3 Al Aluminium 26.982 2-8-3 | 14 -4 +2 +4 Si Silicon 28.086 2-8-4 | 15 -3 +3 +5 P Phosphorus 30.974 2-8-5 | 16 -2 +4 +6 S Sulphur 32.065 2-8-6 | 17 -1 +1 +3 +5 +7 Cl Chlorine 35.453 2-8-7 | 18 0 Ar Argon 39.948 2-8-8 |
| 4 | 19 +1 K Potassium 39.098 2-8-8-1 | 20 +2 Ca Calcium 40.078 2-8-8-2 | 21 +3 Sc Scandium 44.956 2-8-9-2 | 22 +2 +3 +4 Ti Titanium 47.867 2-8-10-2 | 23 +2 +3 +4 +5 V Vanadium 50.942 2-8-11-2 | 24 +2 +3 +6 Cr Chromium 51.996 2-8-13-1 | 25 +2 +3 +4 +7 Mn Manganese 54.938 2-8-13-2 | 26 +2 +3 Fe Iron 55.845 2-8-14-2 | 27 +2 +3 Co Cobalt 58.933 2-8-15-2 | 28 +2 +3 Ni Nickel 58.693 2-8-16-2 | 29 +1 +2 Cu Copper 63.546 2-8-18-1 | 30 +2 Zn Zinc 65.39 2-8-18-2 | 31 +3 Ga Gallium 69.723 2-8-18-3 | 32 -4 +2 +4 Ge Germanium 72.64 2-8-18-4 | 33 -3 +3 +5 As Arsenic 74.922 2-8-18-5 | 34 -2 +4 +6 Se Selenium 78.96 2-8-18-6 | 35 -1 +1 +5 Br Bromine 79.904 2-8-18-7 | 36 0 +2 Kr Krypton 83.80 2-8-18-8 |
| 5 | 37 +1 Rb Rubidium 85.468 2-8-18-8-1 | 38 +2 Sr Strontium 87.62 2-8-18-8-2 | 39 +3 Y Yttrium 88.906 2-8-18-9-2 | 40 +4 Zr Zirconium 91.224 2-8-18-10-2 | 41 +3 +5 Nb Niobium 92.906 2-8-18-12-1 | 42 +3 +6 Mo Molybdenum 95.94 2-8-18-13-1 | 43 +4 +6 +7 Tc Technetium (98) 2-8-18-14-1 | 44 +3 Ru Ruthenium 101.07 2-8-18-15-1 | 45 +3 Rh Rhodium 102.91 2-8-18-16-1 | 46 +2 +4 Pd Palladium 106.42 2-8-18-18 | 47 +1 Ag Silver 107.87 2-8-18-18-1 | 48 +2 Cd Cadmium 112.41 2-8-18-18-2 | 49 +3 In Indium 114.82 2-8-18-18-3 | 50 +2 +4 Sn Tin 118.71 2-8-18-18-4 | 51 -3 +3 +5 Sb Antimony 121.76 2-8-18-18-5 | 52 -2 +4 +6 Te Tellurium 127.60 2-8-18-18-6 | 53 -1 +1 +5 +7 I Iodine 126.90 2-8-18-18-7 | 54 0 +2 +4 +6 Xe Xenon 131.29 2-8-18-18-8 |
| 6 | 55 +1 Cs Cesium 132.91 2-8-18-18-8-1 | 56 +2 Ba Barium 137.33 2-8-18-18-8-2 | 57-71 La Lanthanide | 72 +4 Hf Hafnium 178.49 2-8-18-32-10-2 | 73 +5 Ta Tantalum 180.95 2-8-18-32-11-2 | 74 +6 W Tungsten 183.84 2-8-18-32-12-2 | 75 +4 +6 +7 Re Rhenium 186.21 2-8-18-32-13-2 | 76 +3 +4 Os Osmium 190.23 2-8-18-32-14-2 | 77 +3 +4 Ir Iridium 192.22 2-8-18-32-15-2 | 78 +2 +4 Pt Platinum 195.08 2-8-18-32-17-1 | 79 +1 +3 Au Gold 196.97 2-8-18-32-18-1 | 80 +1 +2 Hg Mercury 200.59 2-8-18-32-18-2 | 81 +1 +3 Tl Thallium 204.38 2-8-18-32-18-3 | 82 +2 +4 Pb Lead 207.2 2-8-18-32-18-4 | 83 +3 +5 Bi Bismuth 208.98 2-8-18-32-18-5 | 84 +2 +4 Po Polonium (209) 2-8-18-32-18-6 | 85 At Astatine (210) 2-8-18-32-18-7 | 86 0 Rn Radon (222) 2-8-18-32-18-8 |
| 7 | 87 +1 Fr Francium (223) -18-32-18-8-1 | 88 +2 Ra Radium (226) -18-32-18-8-2 | 89-103 Ac Actinide | 104 Rf Rutherfordium (261) -18-32-32-10-2 | 105 Db Dubnium (262) -18-32-32-11-2 | 106 Sg Seaborgium (266) -18-32-32-12-2 | 107 Bh Bohrium (264) -18-32-32-13-2 | 108 Hs Hassium (277) -18-32-32-14-2 | 109 Mt Meitnerium (268) -18-32-32-15-2 | 110 +2 +4 Uun Ununnilium (281) -18-32-32-17-1 | 111 Uuu Unununium (272) -18-32-32-18-1 | 112 Uub Ununbium (285) -18-32-32-18-2 | 113 Uut Ununtrium (284) | 114 Uuq Ununquadium (289) | 115 Uup Ununpentium (288) | 116 Uuh Ununhexium (291) | 117 Uus Ununseptium | 118 Uuo Ununoctium (294) |

## Electron Shells

| | | | S | P | D | F |
|---|---|---|---|---|---|---|
| 1 | K | 2 | 2 | | | |
| 2 | L | 8 | 2 | 6 | | |
| 3 | M | 18 | 2 | 6 | 10 | |
| 4 | N | 32 | 2 | 6 | 10 | 14 |
| 5 | O | 32 | 2 | 6 | 10 | 14 |
| 6 | P | 18 | 2 | 6 | 10 | |
| 7 | Q | 8 | 2 | 6 | | |
| 8 | R | 2 | 2 | | | |

## Lanthanide

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 57 +3 La Lanthanium 138.91 2-8-18-18-9-2 | 58 +3 +4 Ce Cerium 140.12 2-8-18-20-8-2 | 59 +3 Pr Praseodymium 140.91 2-8-18-21-8-2 | 60 +3 Nd Neodymium 144.24 2-8-18-22-8-2 | 61 +3 Pm Promethium (145) 2-8-18-23-8-2 | 62 +2 +3 Sm Samarium 150.36 2-8-18-24-8-2 | 63 +2 +3 Eu Europium 151.96 2-8-18-25-8-2 | 64 +3 Gd Gadolinium 157.25 2-8-18-25-9-2 | 65 +3 Tb Terbium 158.93 2-8-18-27-8-2 | 66 +3 Dy Dysprosium 162.50 2-8-18-28-8-2 | 67 +3 Ho Holmium 164.93 2-8-18-29-8-2 | 68 +3 Er Erbium 167.26 2-8-18-30-8-2 | 69 +3 Tm Thulium 168.93 2-8-18-31-8-2 | 70 +2 +3 Yb Ytterbium 173.04 2-8-18-32-8-2 | 71 +3 Lu Lutetium 174.97 2-8-18-32-9-2 |

## Actinide

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 89 +3 Ac Actinium (227) -18-32-18-9-2 | 90 +4 Th Thorium 232.04 -18-32-18-10-2 | 91 +4 +5 Pa Protactinium 231.04 -18-32-20-9-2 | 92 +3 +4 +5 +6 U Uranium 238.03 -18-32-21-9-2 | 93 +3 +4 +5 +6 Np Neptunium (237) -18-32-23-8-2 | 94 +3 +4 +5 +6 Pu Plutonium (244) -18-32-24-8-2 | 95 +3 +4 +5 +6 Am Americium (243) -18-32-25-8-2 | 96 +3 Cm Curium (247) -18-32-25-9-2 | 97 +3 +4 Bk Berkelium (247) -18-32-27-8-2 | 98 +3 Cf Californium (251) -18-32-28-8-2 | 99 Es Einsteinium (252) -18-32-29-8-2 | 100 Fm Fermium (257) -18-32-30-8-2 | 101 Md Mendelevium (258) -18-32-31-8-2 | 102 No Nobelium (259) -18-32-32-8-2 | 103 Lr Lawrencium (262) -18-32-32-9-2 |

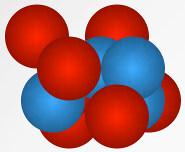
# Chemical Evolution III

- What about the trans-Fe elements?
- *Equilibrium* fusion reactions of light elements don't proceed past Fe because of Fe's location at the peak of the curve of binding energy.
- However, in certain circumstances, supernovae for example, non-equilibrium reactions can build elements beyond Fe in the Periodic Table. Many of these are radioactive, but some are stable.

# Neutron Capture Elements

There are two principle paths to building the elements heavier than Fe. Both use the addition of neutrons to existing `seed' nuclei (neutrons have no charge so are much easier to add to positively-charged nuclei).

- S-process (slow addition of neutrons)
- R-process (rapid addition of neutrons)



# The S-process

- The S-process stands for the Slow addition of neutrons to nuclei. The addition of a $n^o$ produces heavier isotope of a particular element. However, if an electron is emitted (this is called beta-decay), the nucleus moves one step up the periodic table.

# S-Process

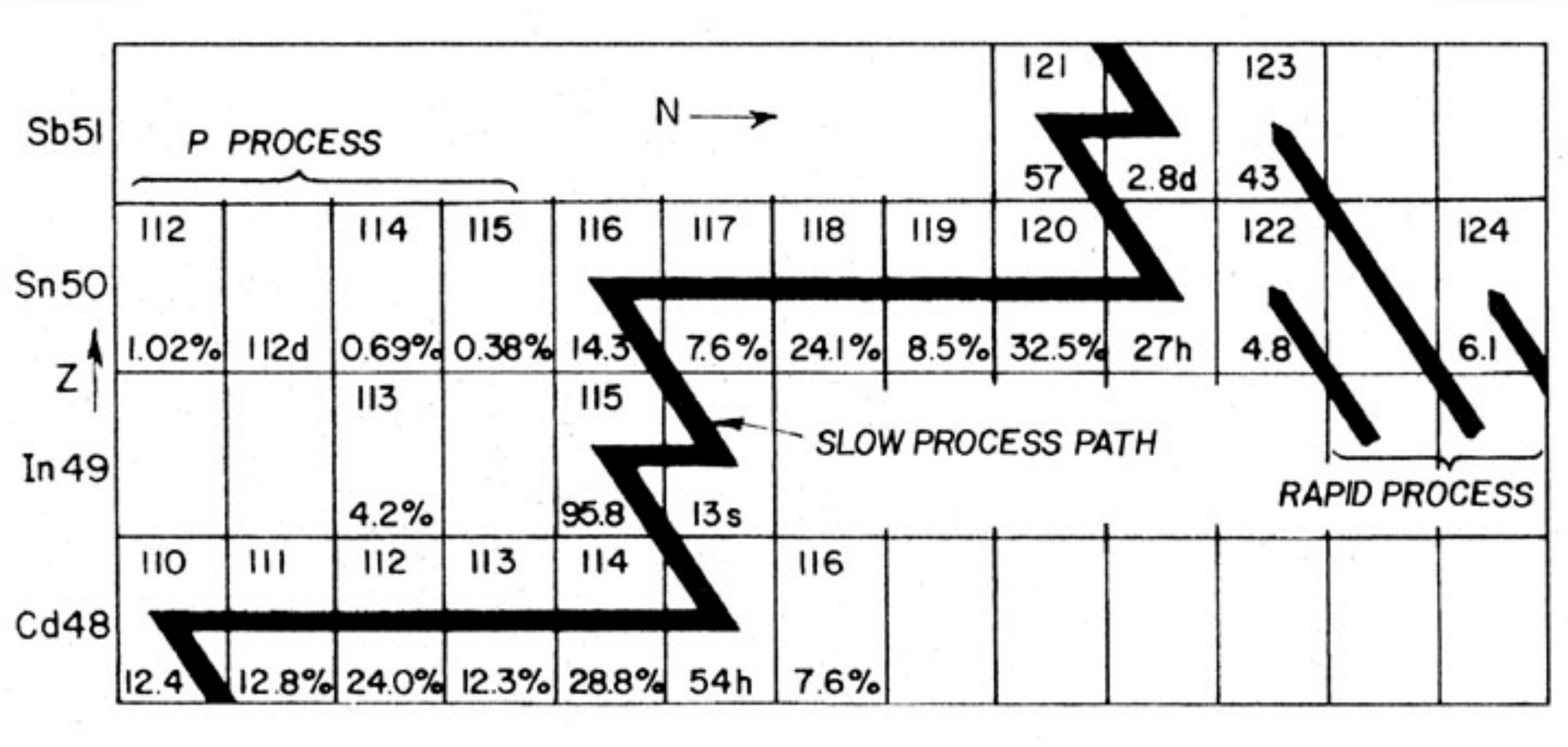
- `Slow' here means that rate of $n^{o}$ captures is low compared to the beta-decay rate.
- It really is slow, sometimes 100's of years go by between neutron captures.

$$_{26}Fe^{56} + n^{o} \text{ --> } _{26}Fe^{57}$$
$$_{26}Fe^{57} \text{ --> } _{27}Co^{57} + e^{-}$$

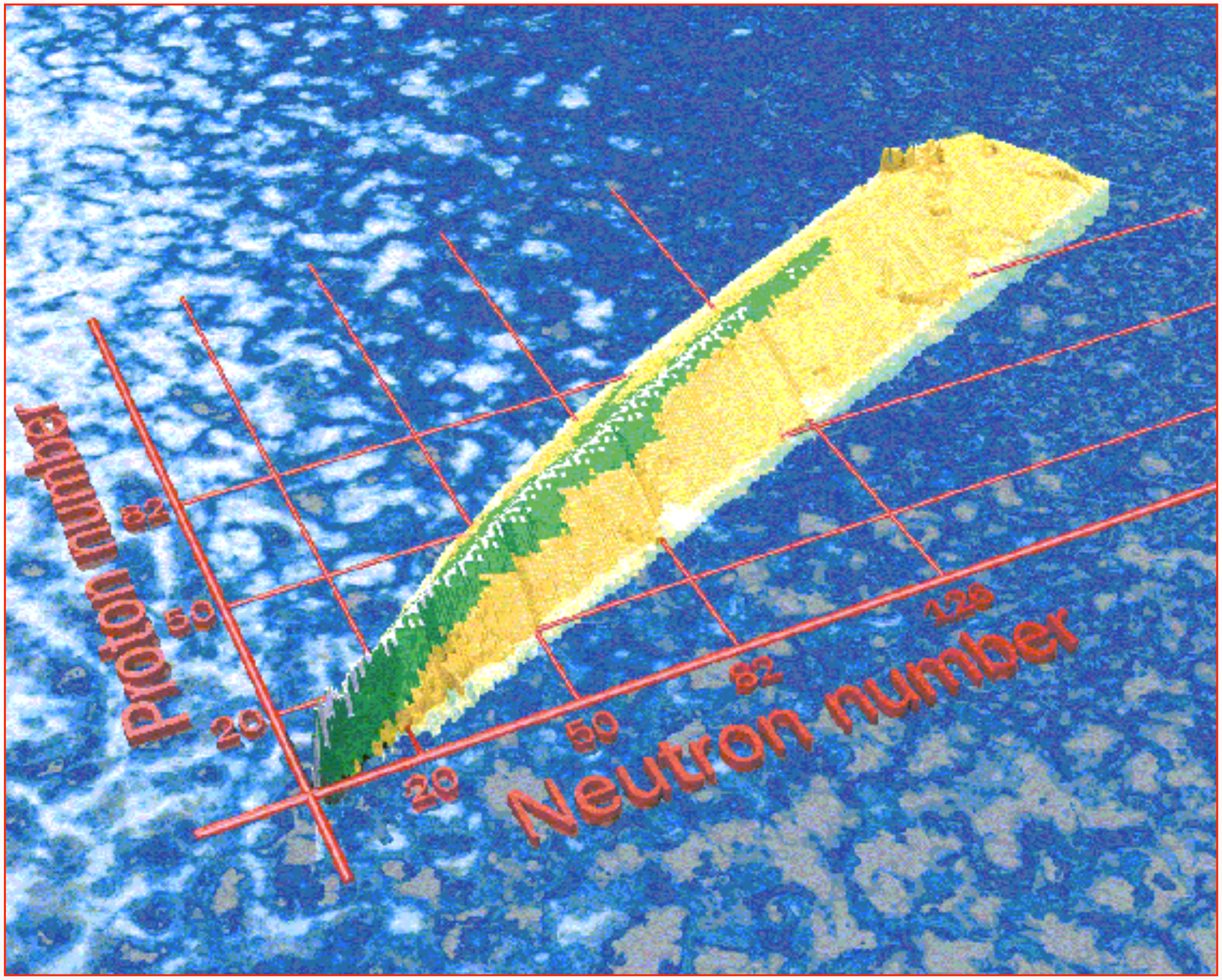
Here a neutron changed into a proton by emitting an electron

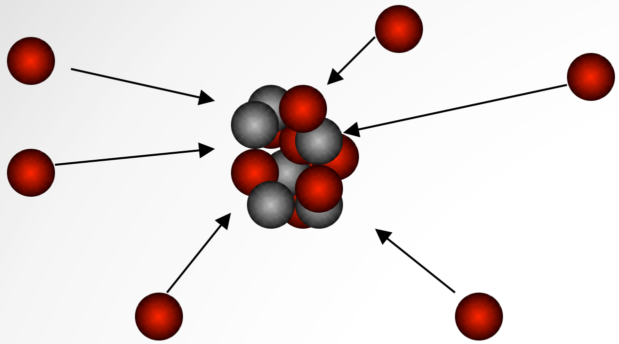
- The S-process can produce elements up to #83 - Bismuth. There are peaks in the Solar System abundance of heavy elements at $^{38}$Sr, $^{56}$Ba and $^{82}$Pb. These are easily understood in the context of the S-process and `magic' numbers of neutrons.
- The site of the S-process is AGB stars during and between shell flashes. The n° source is a by-product of $C^{13}+He^{4} \rightarrow O^{16}$
- $^{43}$Tc is an s-process nucleus and proof that it is in operation in AGB stars.

# S-process path



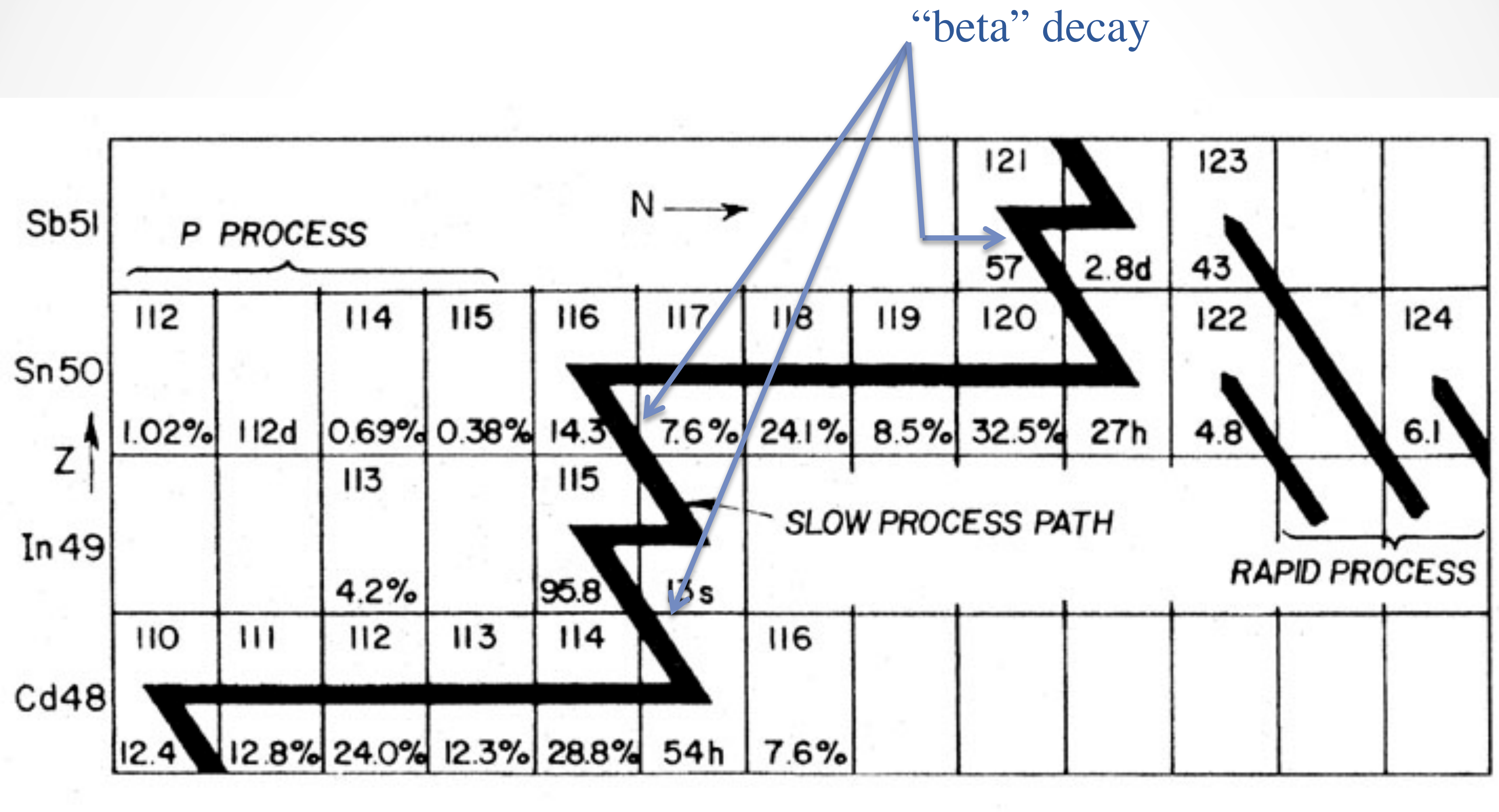

Nuclear mass - neutrons+protons


Proton number
20
50
82
Neutron number
20
50
82
126

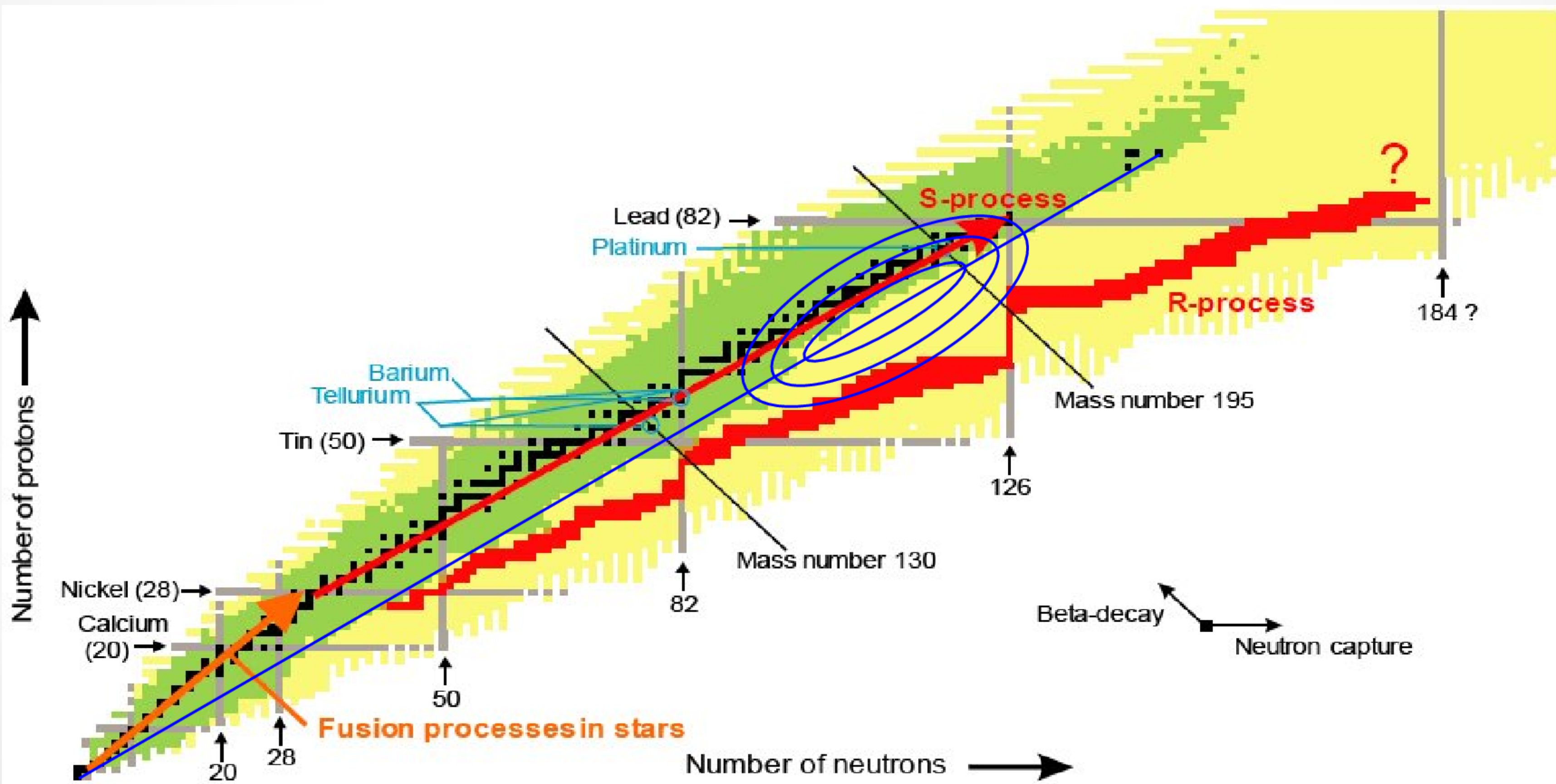


# The R-process

- The R-process is the Rapid addition of neutrons to existing nuclei. Rapid here means that many neutrons are added before a beta-decay occurs.
- First build up a VERY heavy isotope, then as beta-decays occur you march up in atomic number and produce the REALLY HEAVY STUFF.




Number of neutrons



Lead (82)
Platinum
S-process
?
R-process
184 ?
Barium
Tellurium
Tin (50)
Mass number 195
126
Mass number 130
82
Nickel (28)
Calcium
(20)
Beta-decay
Neutron capture
50
Fusion processes in stars
20
28
Number of protons
Number of neutrons

# The R-process

- For this to happen need a big burst of neutrons. The most promising place with the right conditions is in a SNII explosion right above the collapsed core.
- We see an overabundance of R-process elements in the oldest stars. As the early chemical enrichment of the Galaxy was through SNII, this is evidence of SNII as the source of r-process elements

# R-process

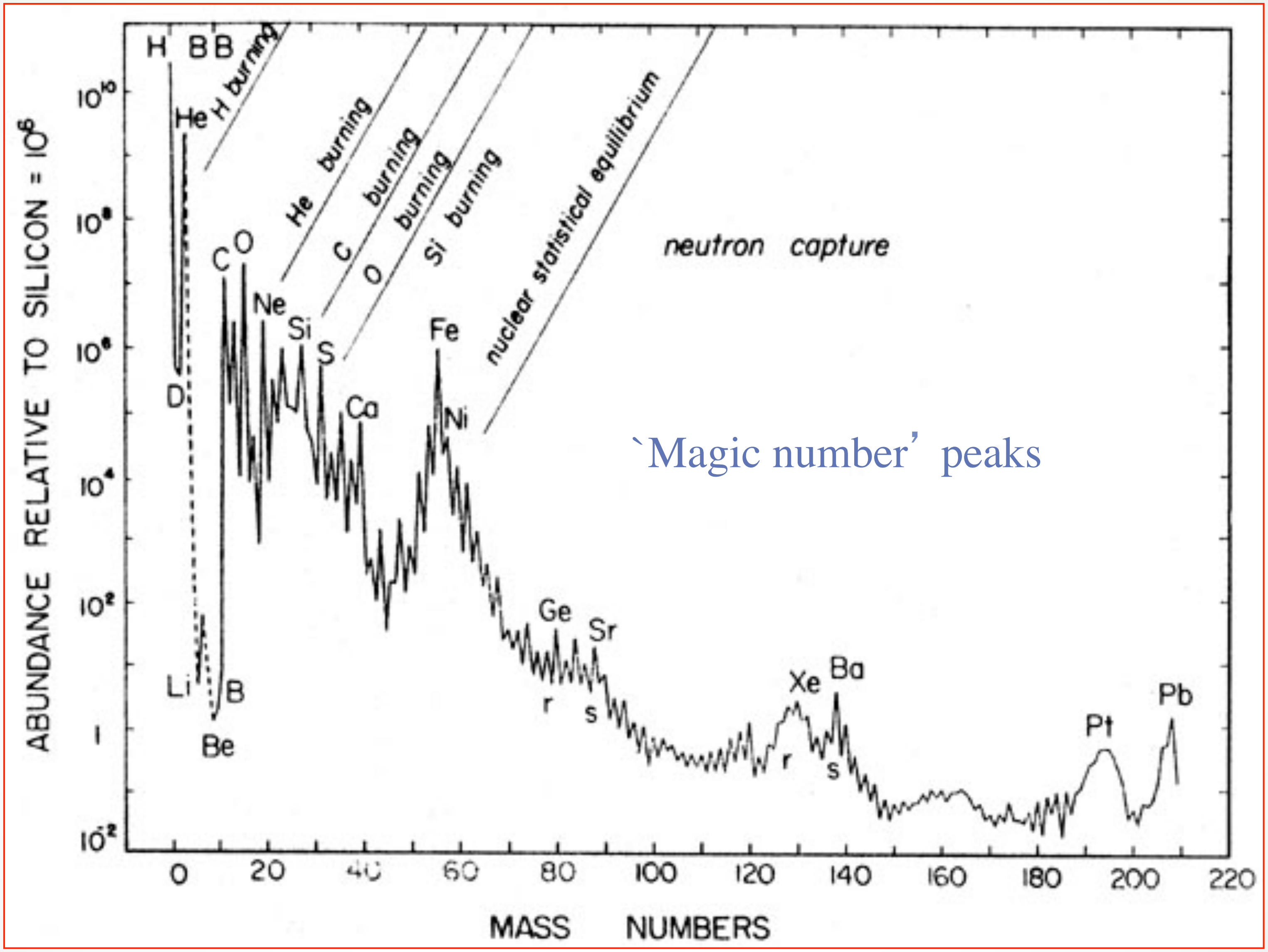
- If we look at the Crab Nebula or other SNII remnants we don't see r-process elements.
- We DO see regions of enhanced O, Si, Ne and He which appear to reflect the `onion skin' structure of the massive star progenitor.

# Solar Composition by Mass

H ..........78.4%
He.........19.8%
O .......... 0.8%
C ........... 0.3%
N ........... 0.2%
Ne ......... 0.2%
Si .......... 0.04%
Fe .......... 0.04%

Gold.........0.000000009%
($2.1 x $10^{24}$ at $300/ounce)

Big Bang (H, He)
Low-mass stars (O, C)
High-mass stars (O through Fe)


H
BB
H burning
He
He burning
C burning
O burning
Si burning
nuclear statistical equilibrium
neutron capture
C
O
Ne
Si
S
Fe
Ca
Ni
D
Li
B
Be
Ge
Sr
r
s
Xe
Ba
Pt
Pb
ABUNDANCE RELATIVE TO SILICON = $10^6$
MASS NUMBERS
`Magic number' peaks