AY1 Announcements

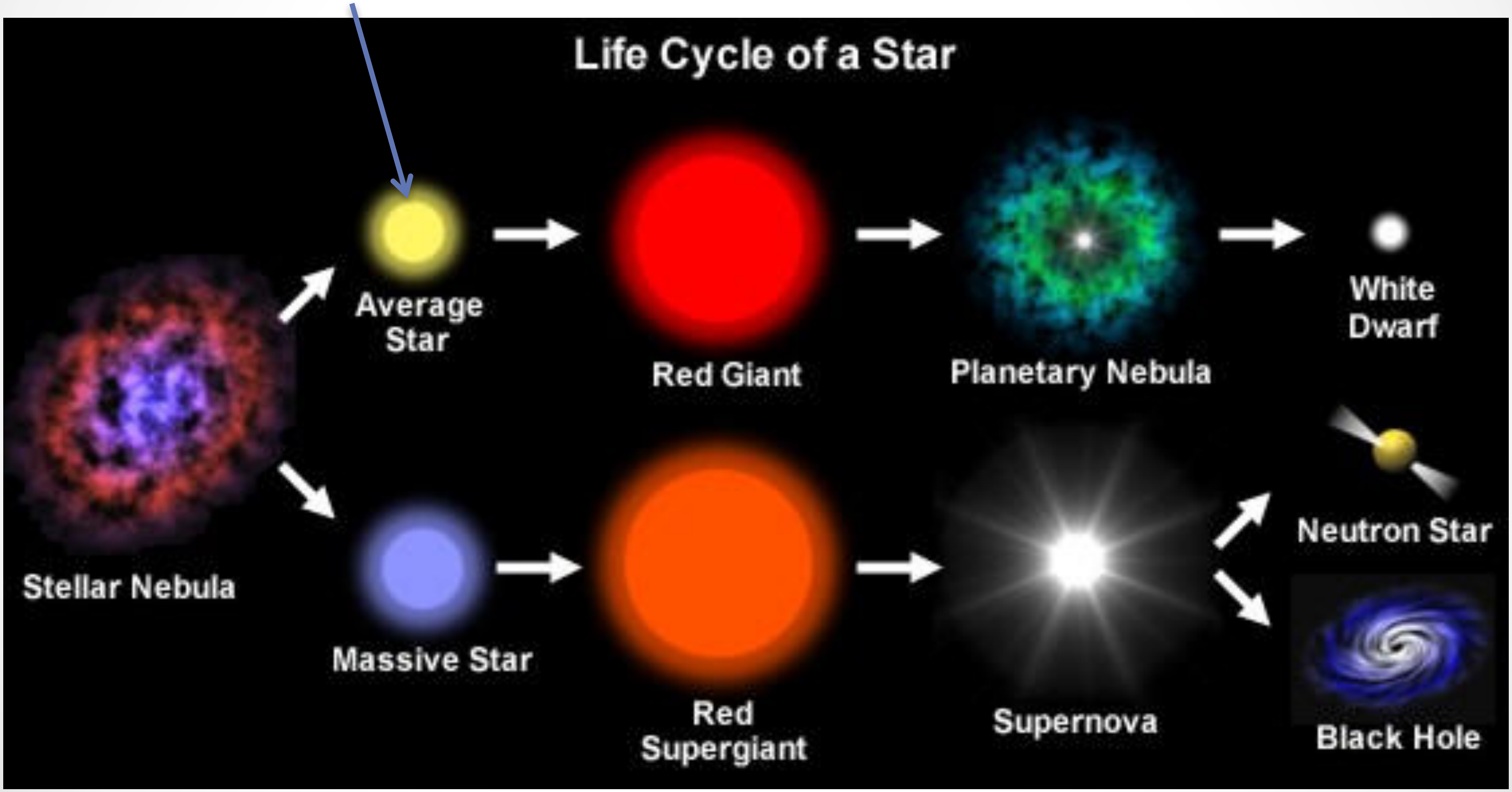
- Quiz 2: Thursday May 4
  - Stellar properties, stellar structure, energy sources, evolution and end points,

Where are we?

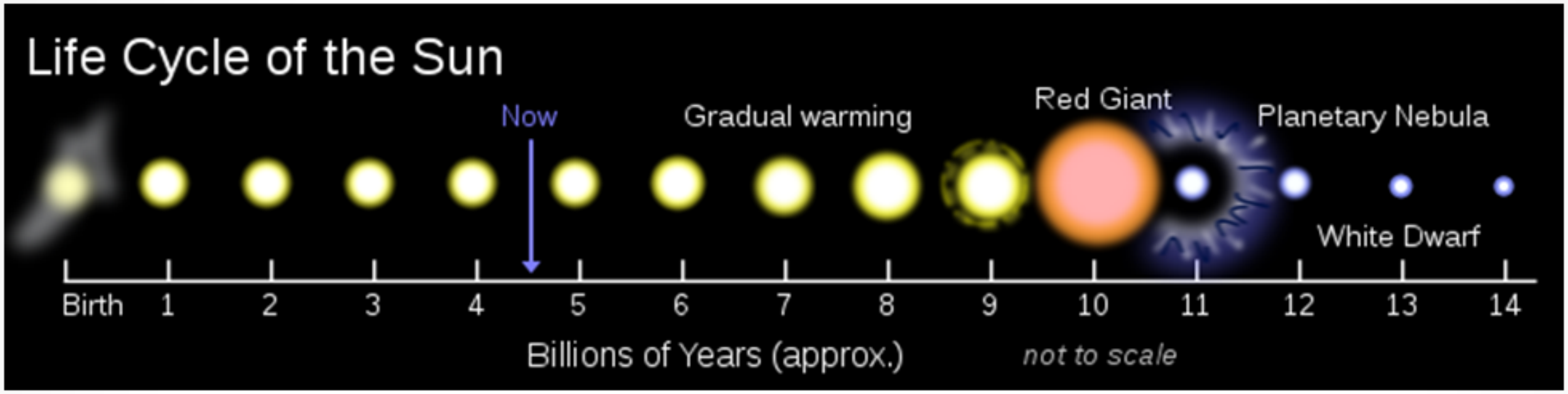
- Stellar evolution of <8$M_{\odot}$ stars (Red giants, planetary nebulae, white dwarfs)
- Stellar evolution of >8$M_{\odot}$ stars (core-collapse supernovae)
- Finish off SNII predictions: Neutron stars and pulsars

Stellar Evolution

$0.1M_{SUN} - 8M_{SUN}$



Stars with initial mass <8M_{Sun}

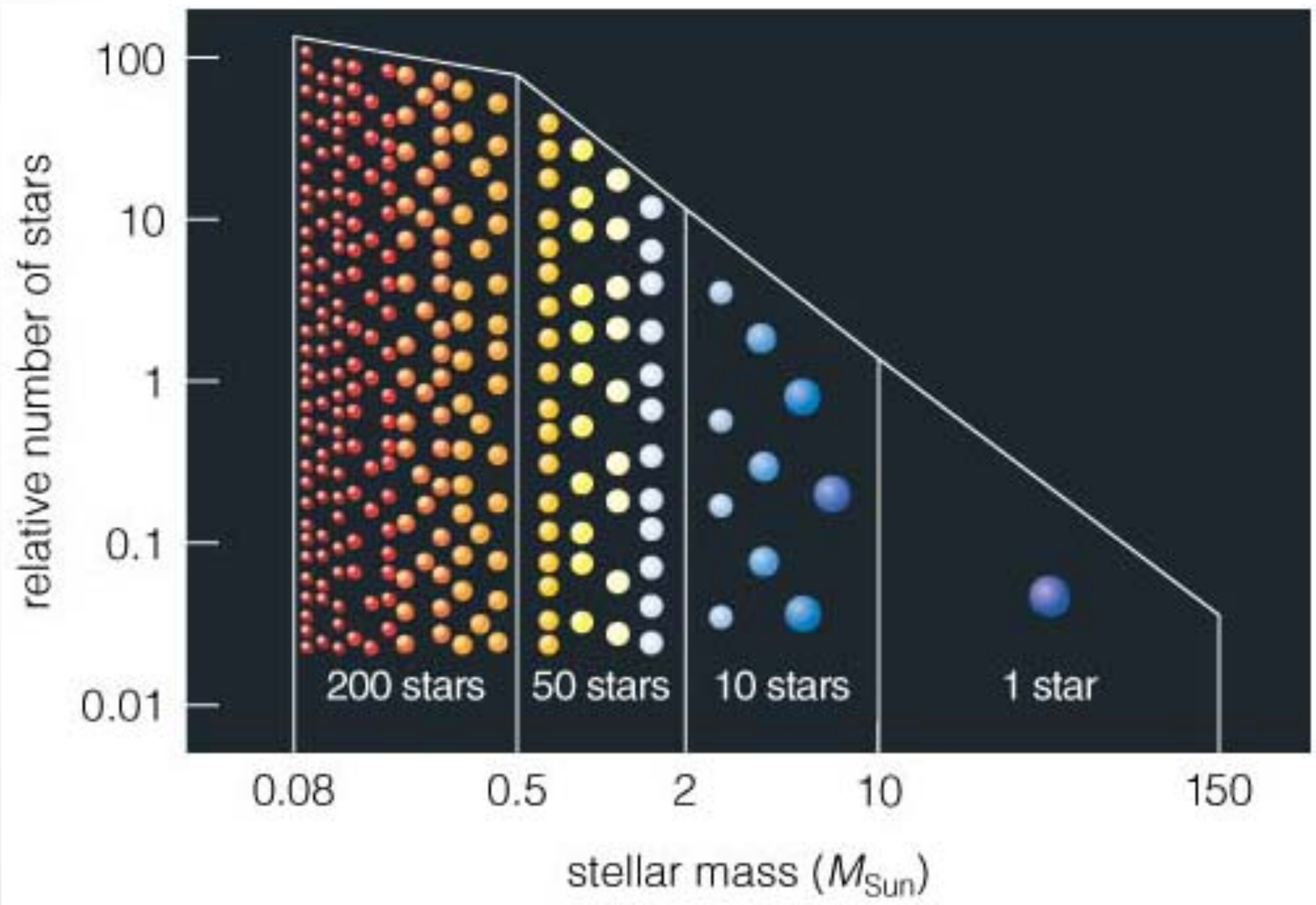


Approximately ½ of the initial main-sequence mass is sent back to the interstellar medium in stellar winds and (mostly) in the ejected planetary nebula

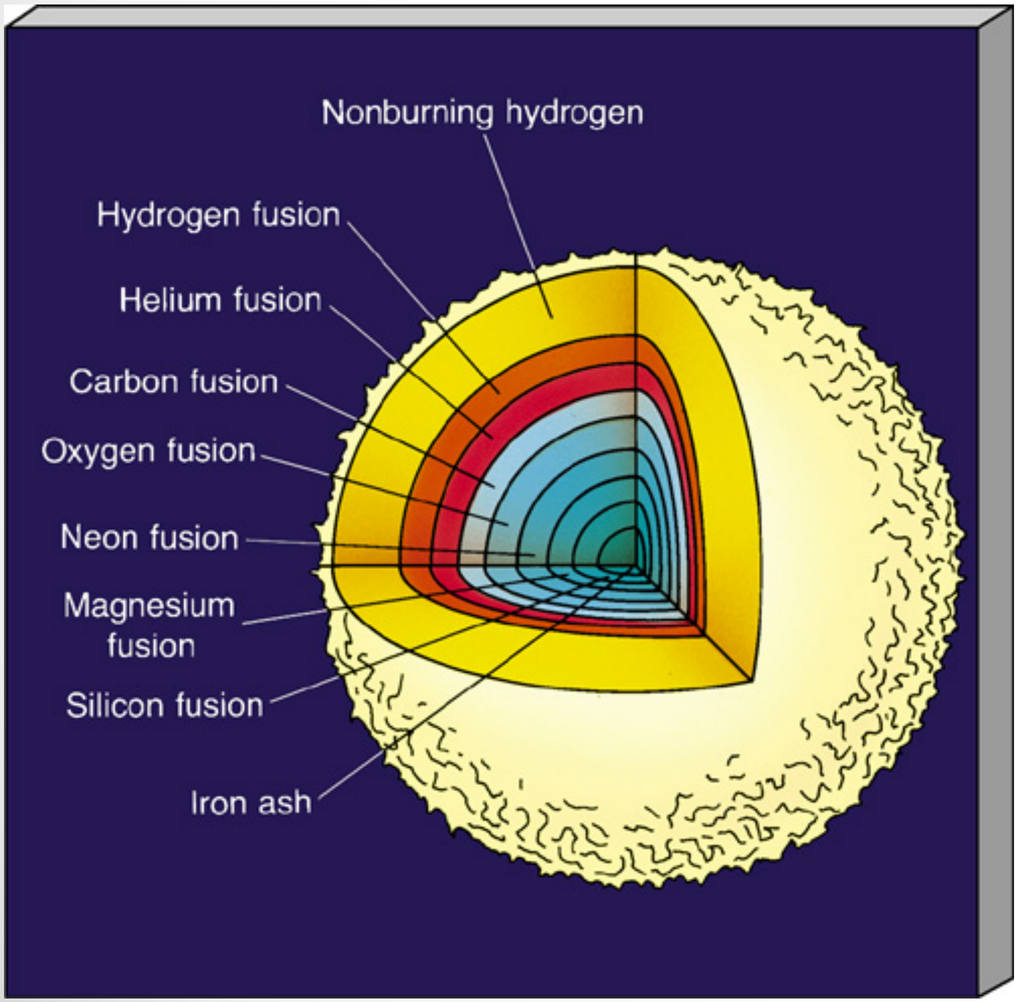
The material returned to the inter-stellar medium is enriched in He, Ca, O, Mg, and Ne (the exact mix depends on the initial main-sequence mass

The "initial mass function"

- The vast majority of stars are formed with an initial main-sequence mass that is $<8M_{Sun}$

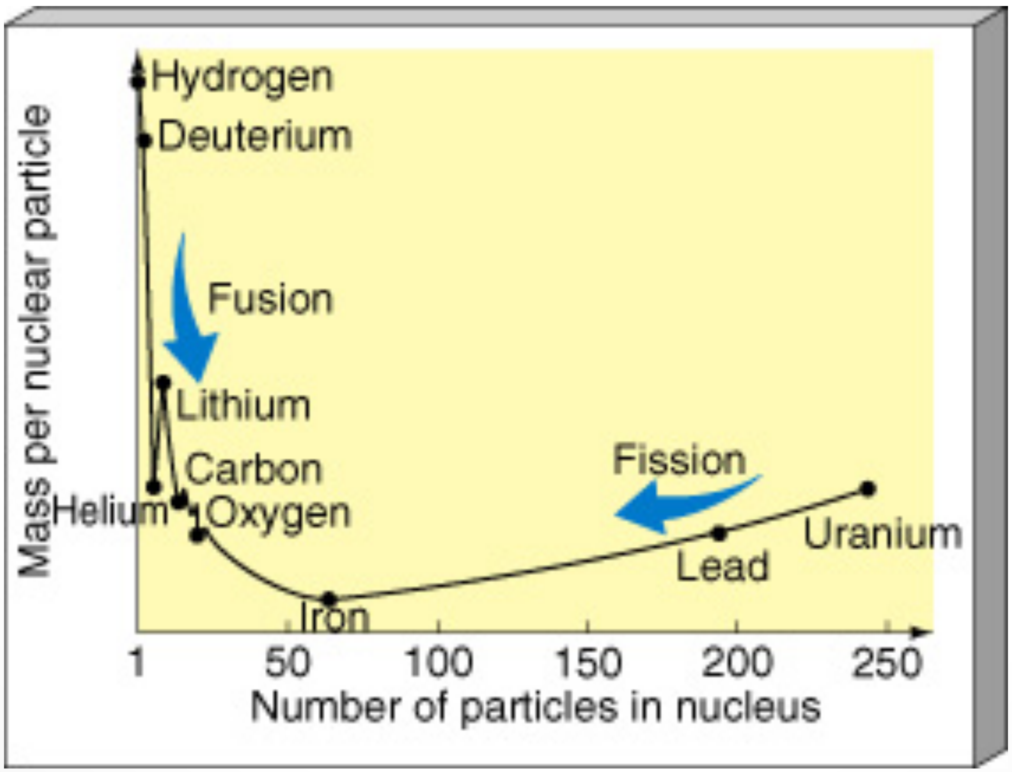


Massive Star Evolution



- The critical difference between low and high-mass star evolution is the core temperature.
- In stars with $M>8M_{SUN}$ the central temperature is high enough to fuse elements all the way to Iron (Fe)

An easier way to think about this is in the mass/nucleon for a given nucleus. If a nuclear reaction produces a nucleus with less mass/nucleon, energy was released via $E=mc^2$.



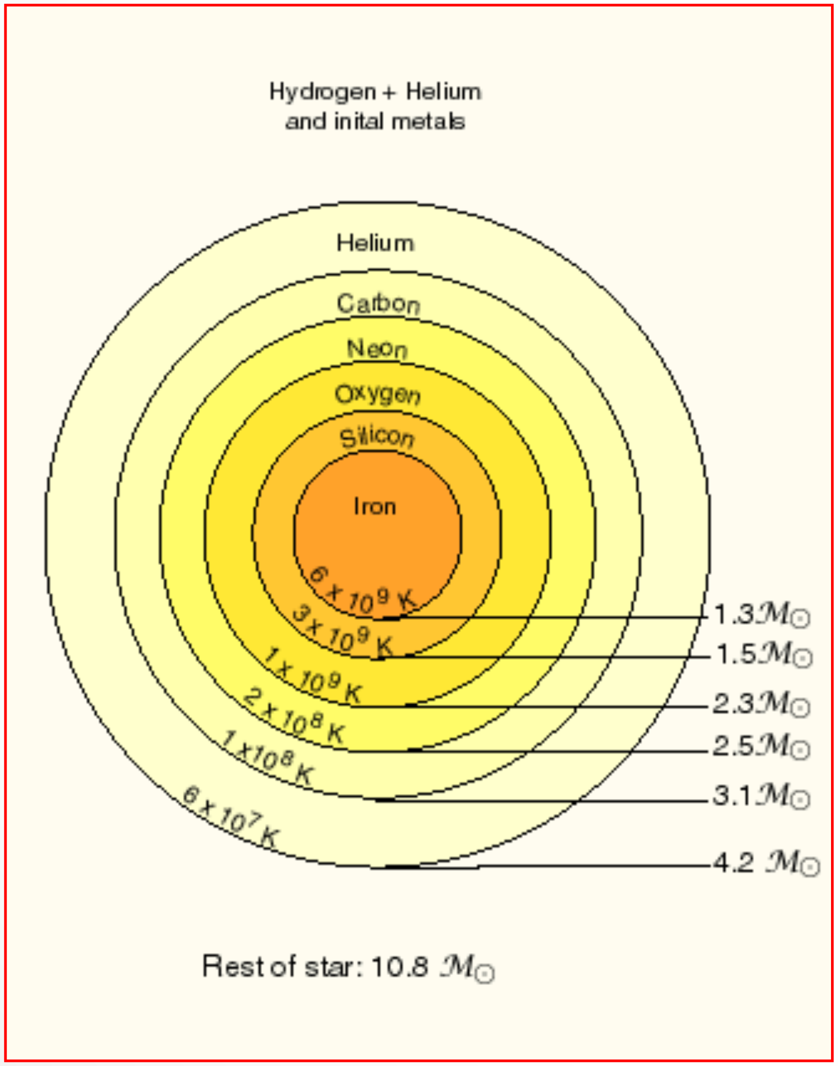
Nucleosynthesis

- Fusing light elements together results in more nuclear binding energy and less mass per nucleon. When the mass disappears, it is converted to energy: *light-element fusion produces energy*.
- But, when fusing any element to Fe, you now need to PROVIDE some energy to be converted into mass and Nature doesn't like to do this.
- On the other hand, elements heavier than Fe can break apart and go to less mass/nucleon and release energy.

Back to Massive Stars Nucleosynthesis

Stage	Central T	Duration (yr)
H fusion	40 million K	7 million
He fusion	200 million K	500 thousand
C fusion	600 million K	600
O fusion	1.2 billion K	1
Ne fusion	1.5 billion K	6 months
Si fusion	2.7 billion K	1 day

Massive-star Evolution

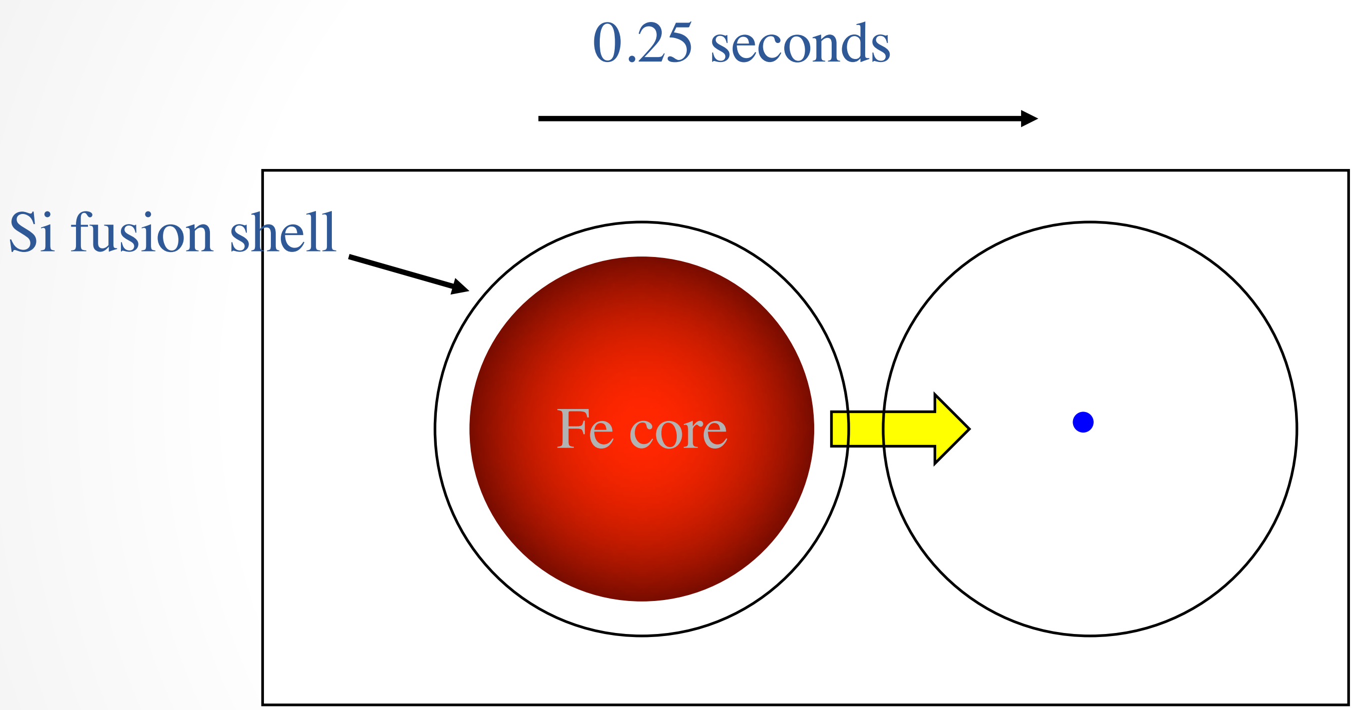


"ashes" from outer shells provide fuel for the next shell down

Core Collapse

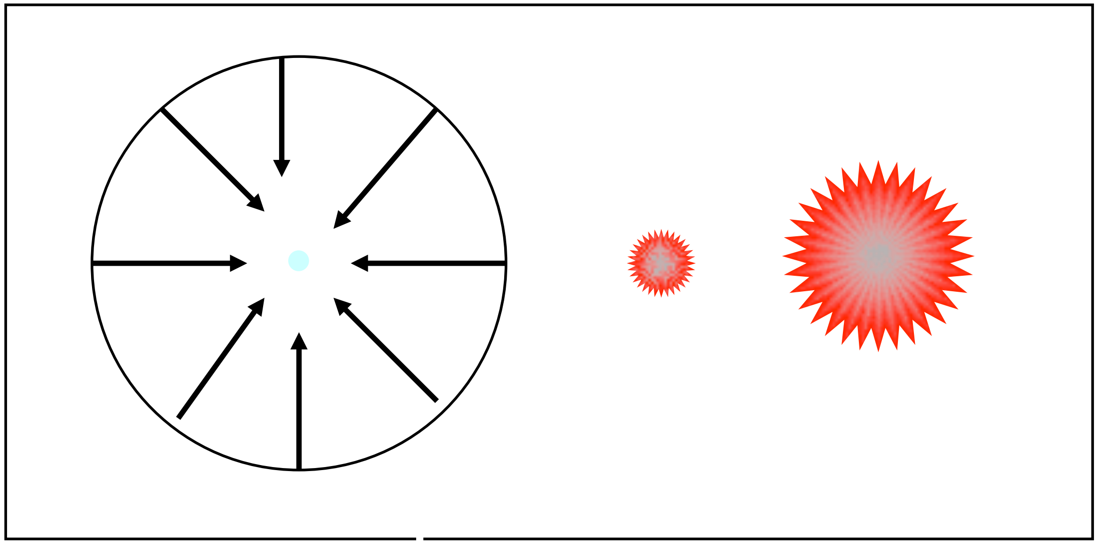
- The fusion chain stops at Fe and an Fe core very quickly builds.
- Within a day of starting to produce Fe, the core reaches the $1.4M_{\odot}$ Chandrasekar limit and can no longer be supported by thermal pressure or the more powerful electron degeneracy pressure
- On a timescale less than a second 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

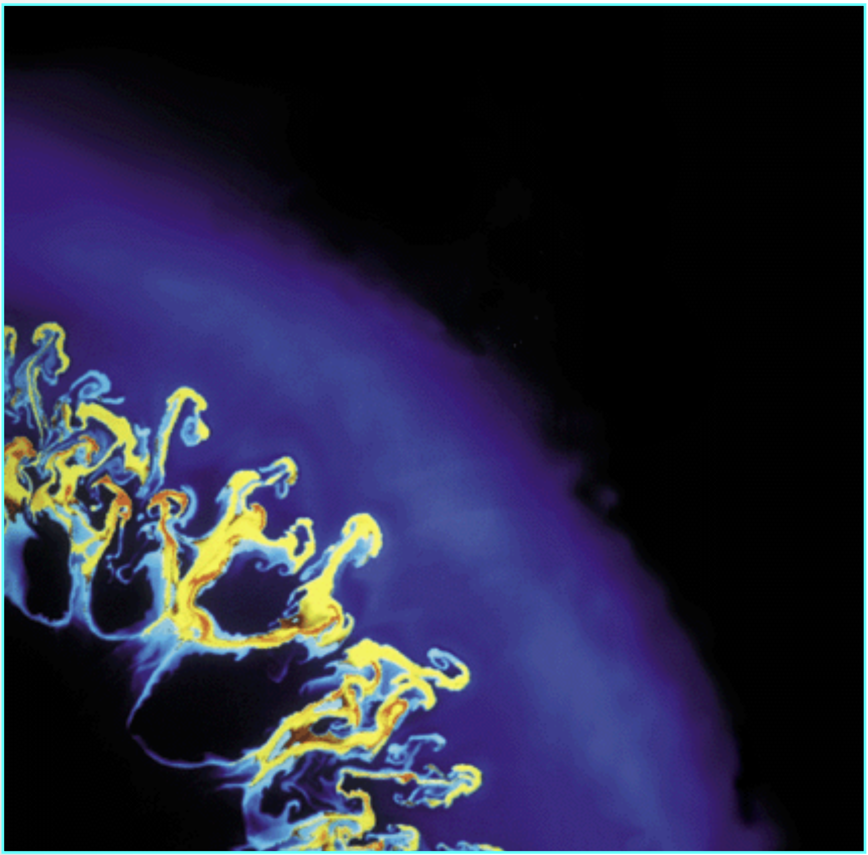


4) Neutron ball is at `nuclear density' ($>10^{17}$ kg/m^3) and is much harder than any brick wall.

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.

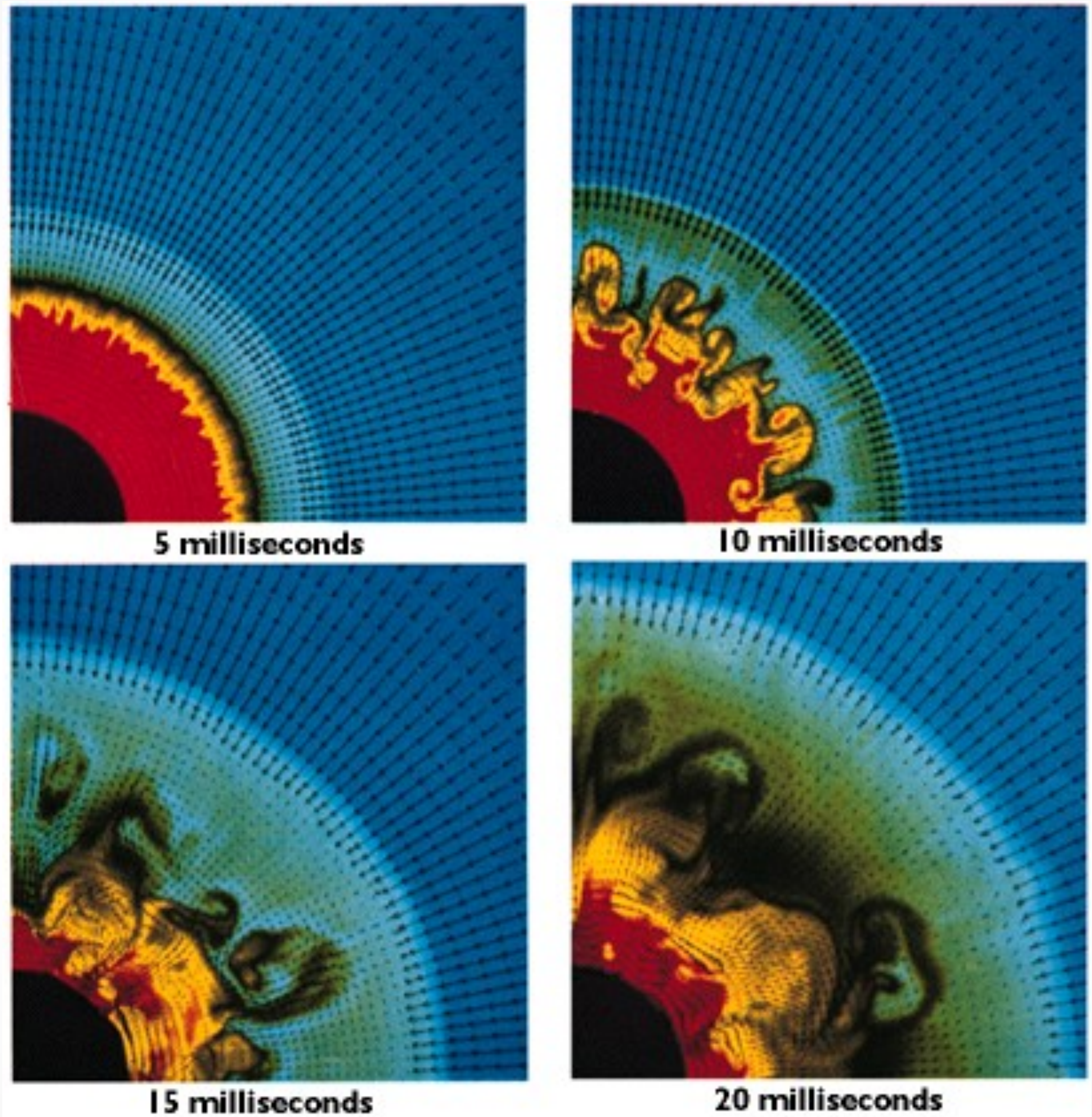
SNII Bounce Shock wave

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, heavy elements will be manufactured in non-equilibrium reactions*


5 milliseconds
10 milliseconds
15 milliseconds
20 milliseconds

Supernovae II

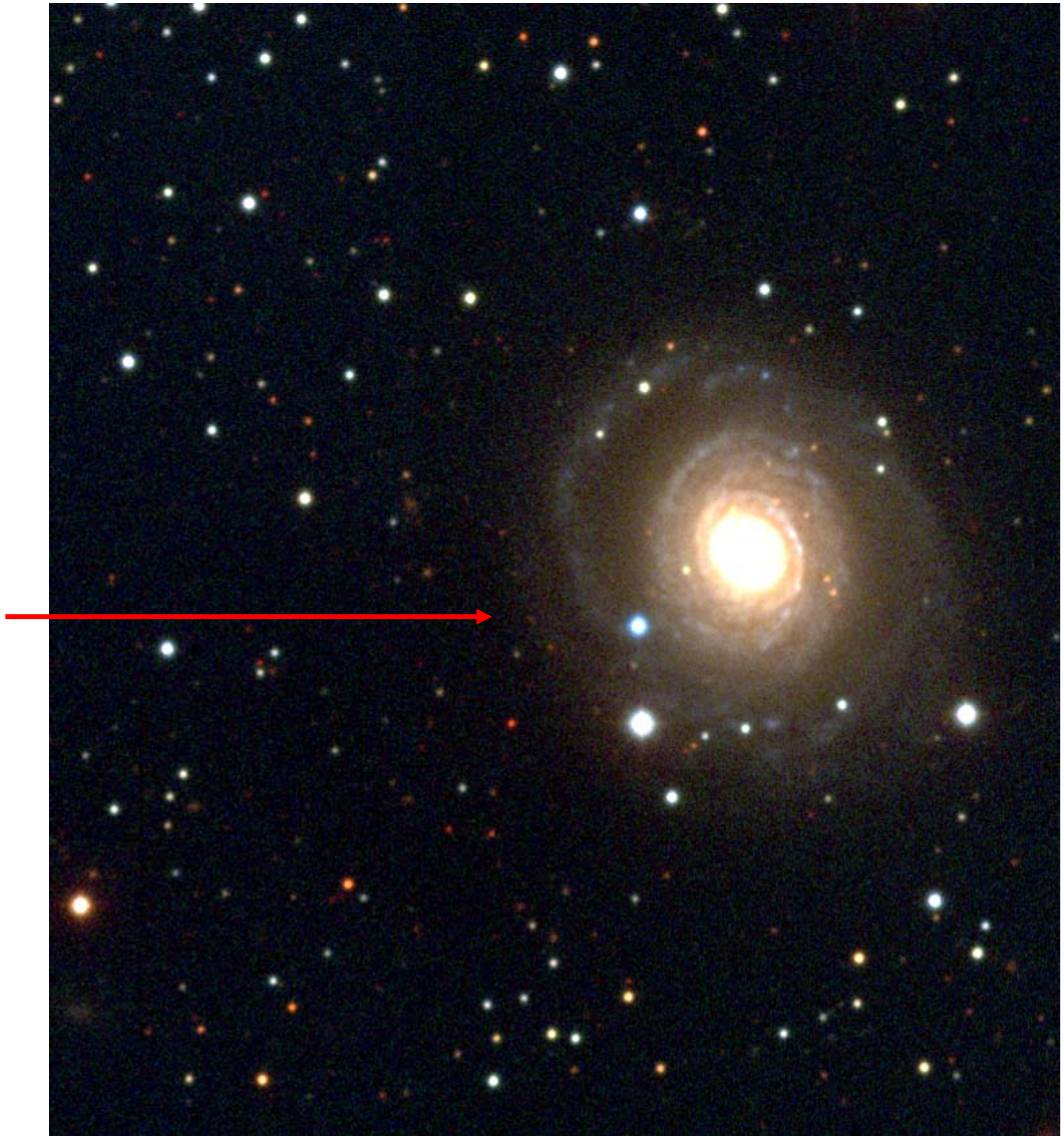
- Expect:
  - Association with massive stars/star formation
  - Rapidly expanding debris cloud
  - 10^8 times the optical luminosity of the Sun
  - Chemically-enriched debris
  - Extremely dense 1.4 solar mass neutron ball left behind

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!



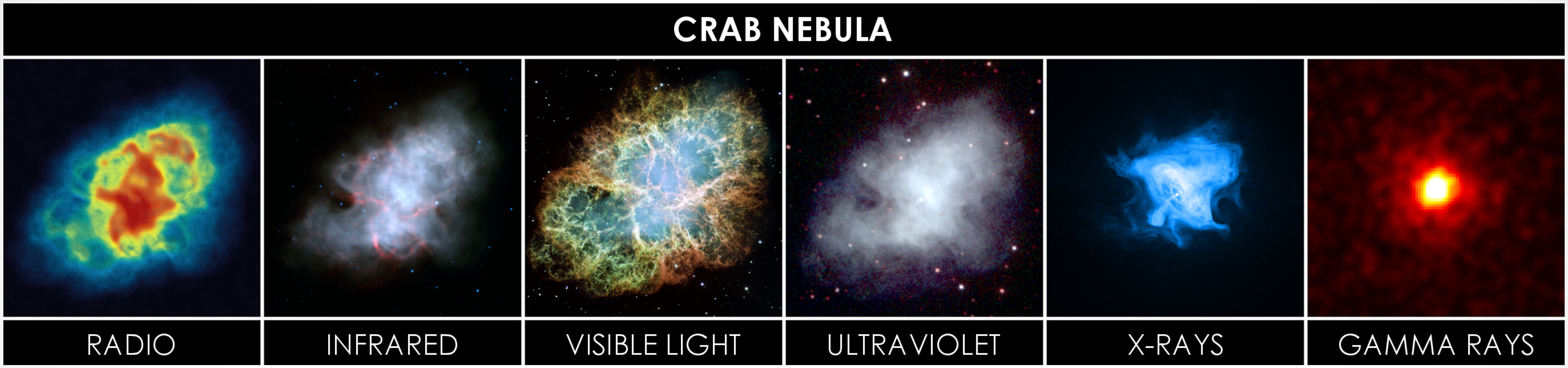
SNII

2) Predicted peak luminosity of 10^8 L_o 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

Crab Nebula



In 1054AD there was a “guest” star in the sky that was bright enough to be seen during the day

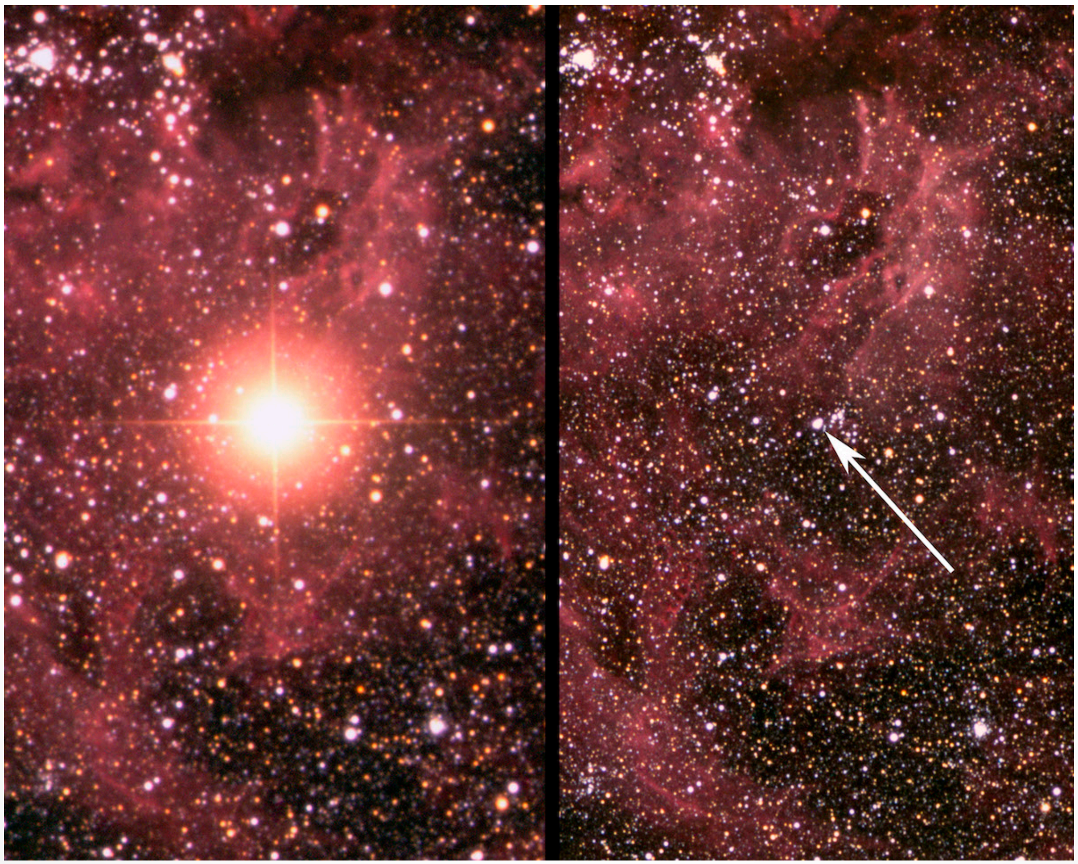
Point our telescopes there now and see a rapidly-expanding nebula with enhanced abundances of many elements and a rapidly rotating neutron star in the center

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



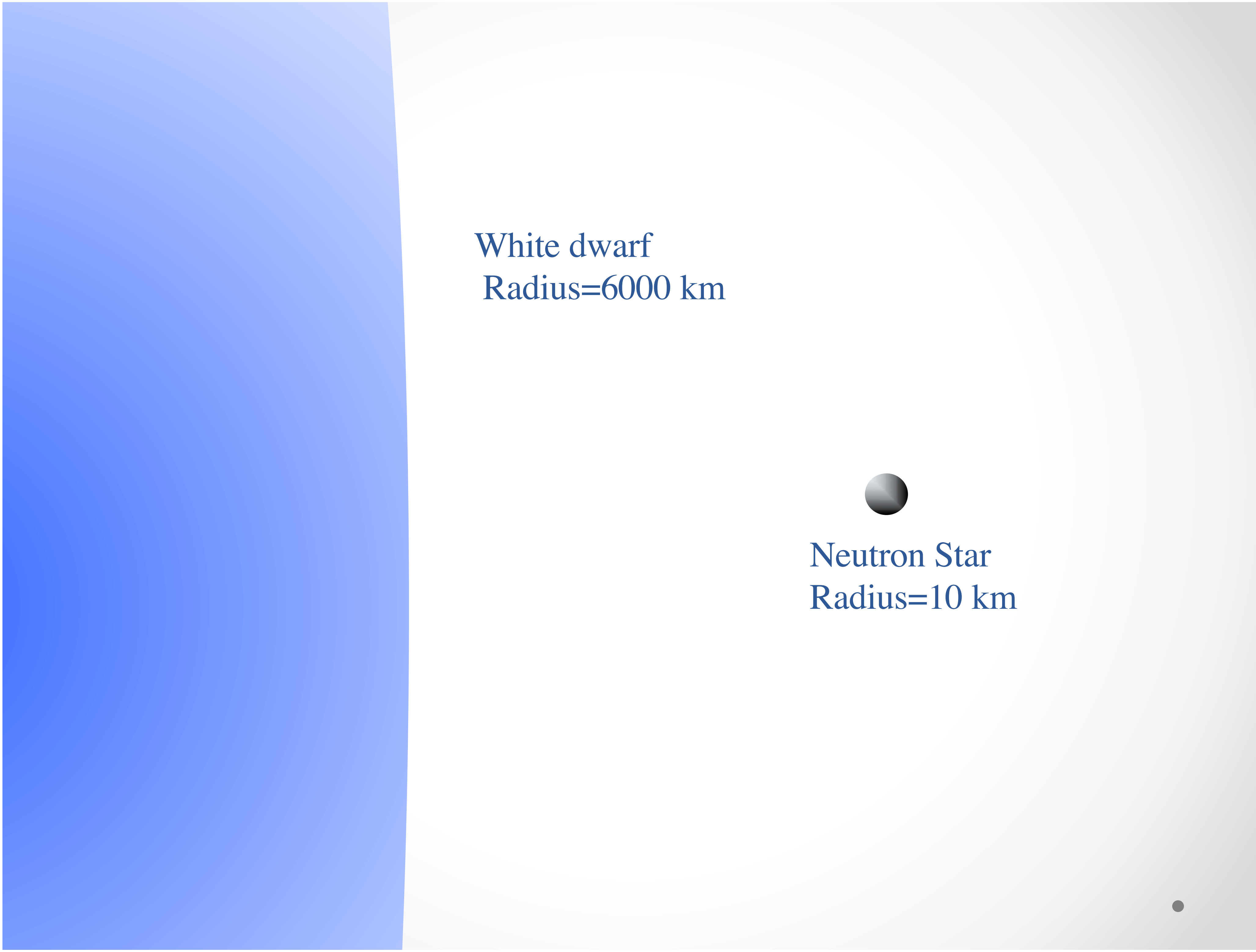
SN1987a

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

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

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: > $1.4M_{Sun}$ (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 (I)

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

Conservation of Angular Momentum

- Conservation of angular momentum means:

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

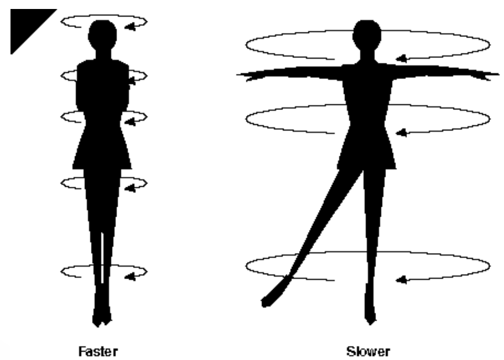
Moment of Inertia → $$I_i \omega_i = I_f \omega_f$$ ← Angular velocity

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

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 $7x10^5$km to a radius of 10km, by what factor does it's spin rate increase?

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

$$I_i\omega_i = I_f\omega_f$$

$$\frac{2}{5}MR_i^2\omega_i = \frac{2}{5}MR_f^2\omega_f$$

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

$$\omega_f = \frac{R_i^2}{R_f^2}\omega_i = \left(\frac{7\times10^5}{10}\right)^2\omega_i = 4.9\times10^9\omega_i$$

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

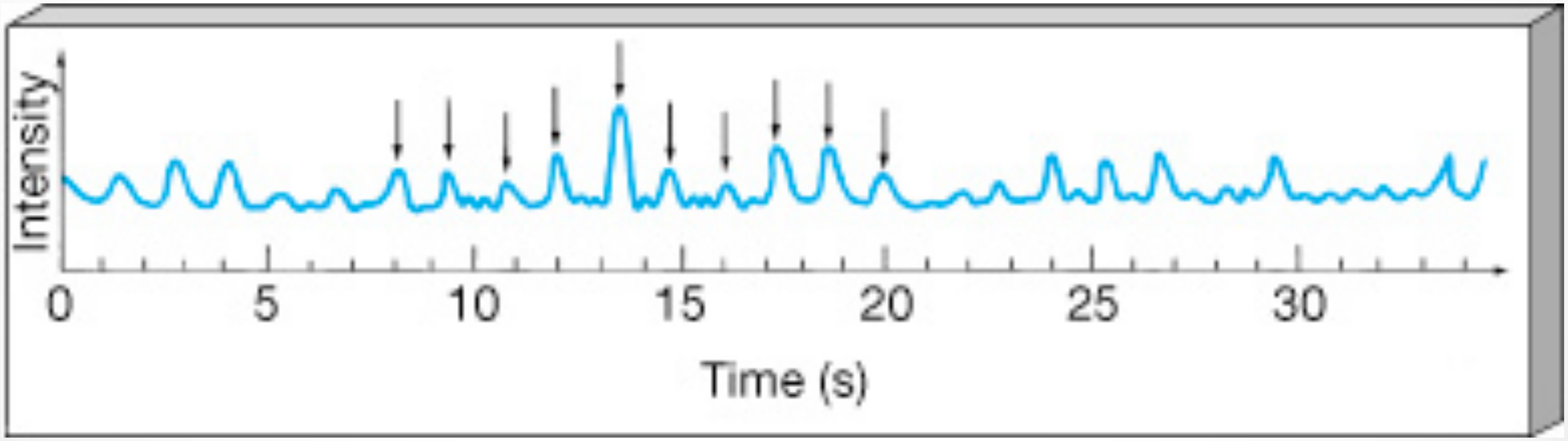
Magnetic field lines are also conserved. When the core collapses, the field lines are conserved, and the density of the field lines goes way up . This is the strength of the magnetic field.

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 because the surface area was so tiny the total radiation will be small
- 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’.



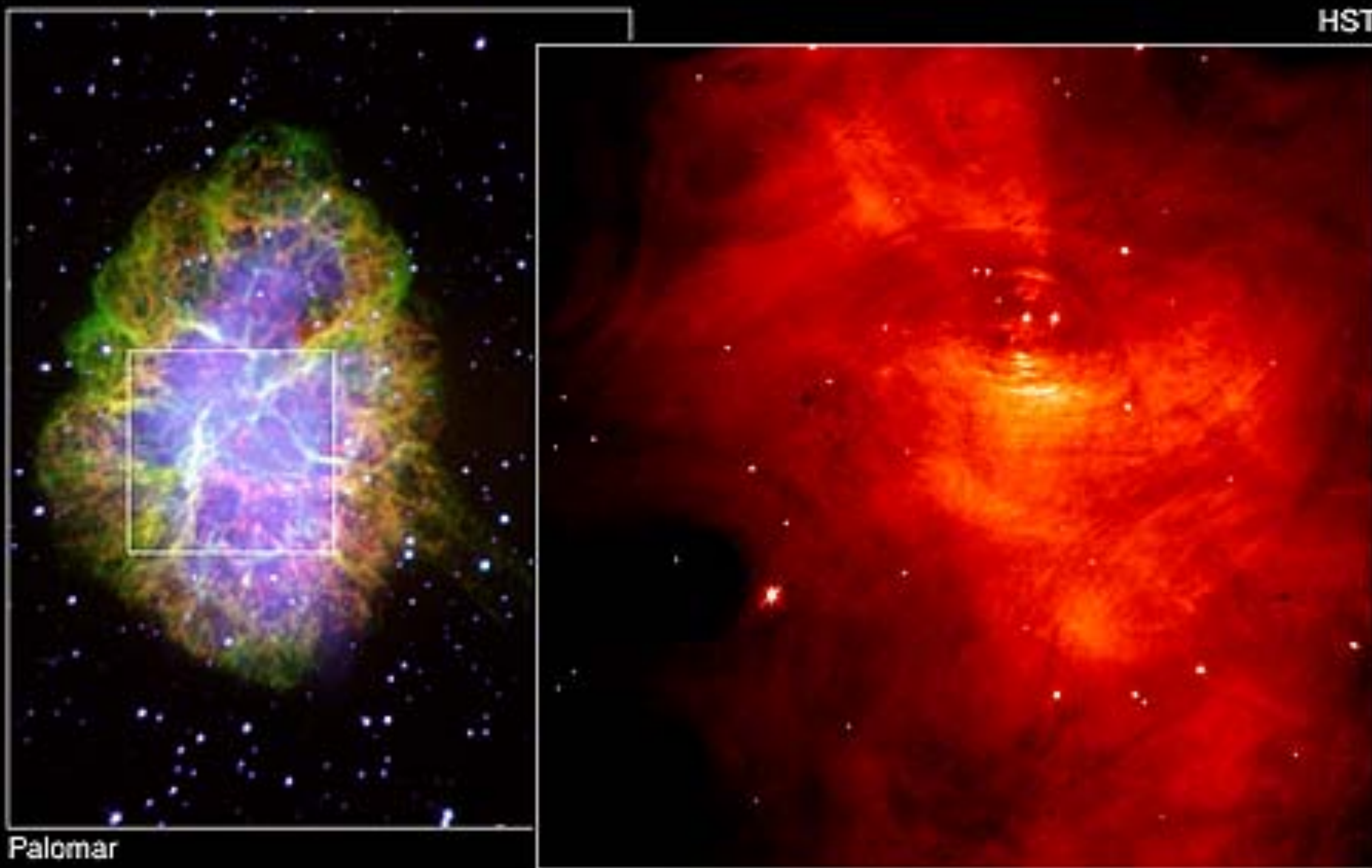
First Pulsar

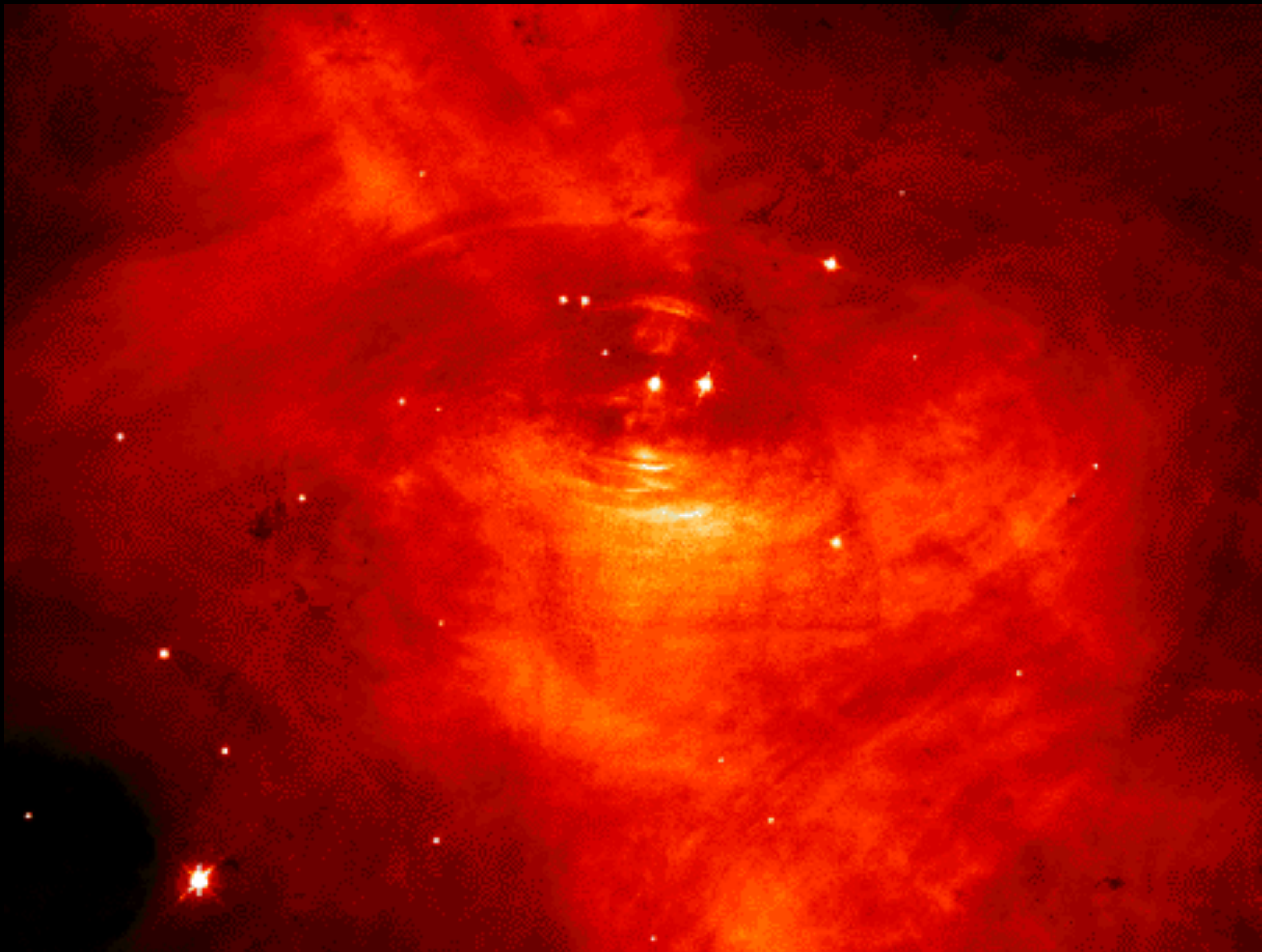
- Bell was a graduate student at the time. The source was assumed to be man made, but when no terrestrial source could be identified, they briefly considered an artificial extra-terrestrial source.
- When a second source was discovered (Cass A) they announced the discovery as a new phenomenon.

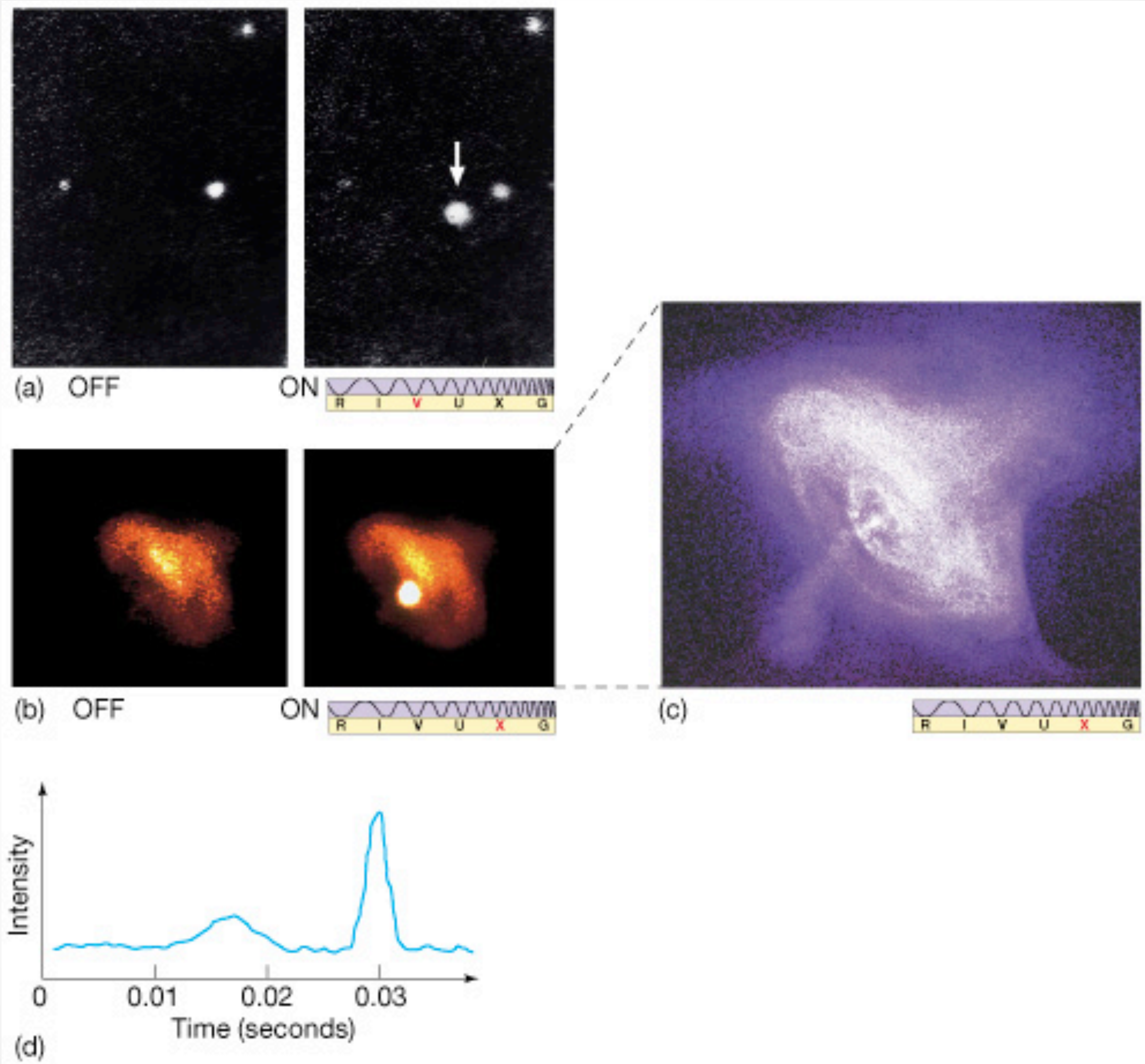
- The discovery led to a year of wild speculation, but explanations involving neutron stars quickly rose to the top.
- A pulsing source with period of 0.033 seconds was discovered in the Crab nebula.
- Big clue! Spin the Sun or Earth or a WD 30 times per second and they will be *torn apart*.
- *Need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

Pulsars

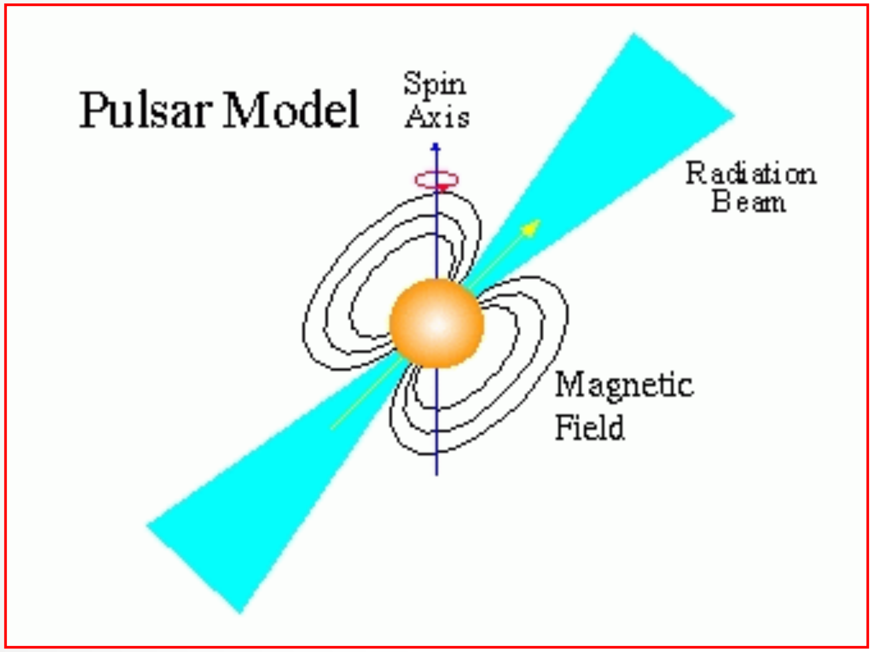
- The new objects were named ‘pulsars’ and is was soon discovered that they were slowly slowing down -- this provided the answer to the mystery of why the Crab Nebula was still glowing.
- There are now more than 2000 known pulsars in the Galaxy.
- Pulsar map


Palomar
HST




(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)

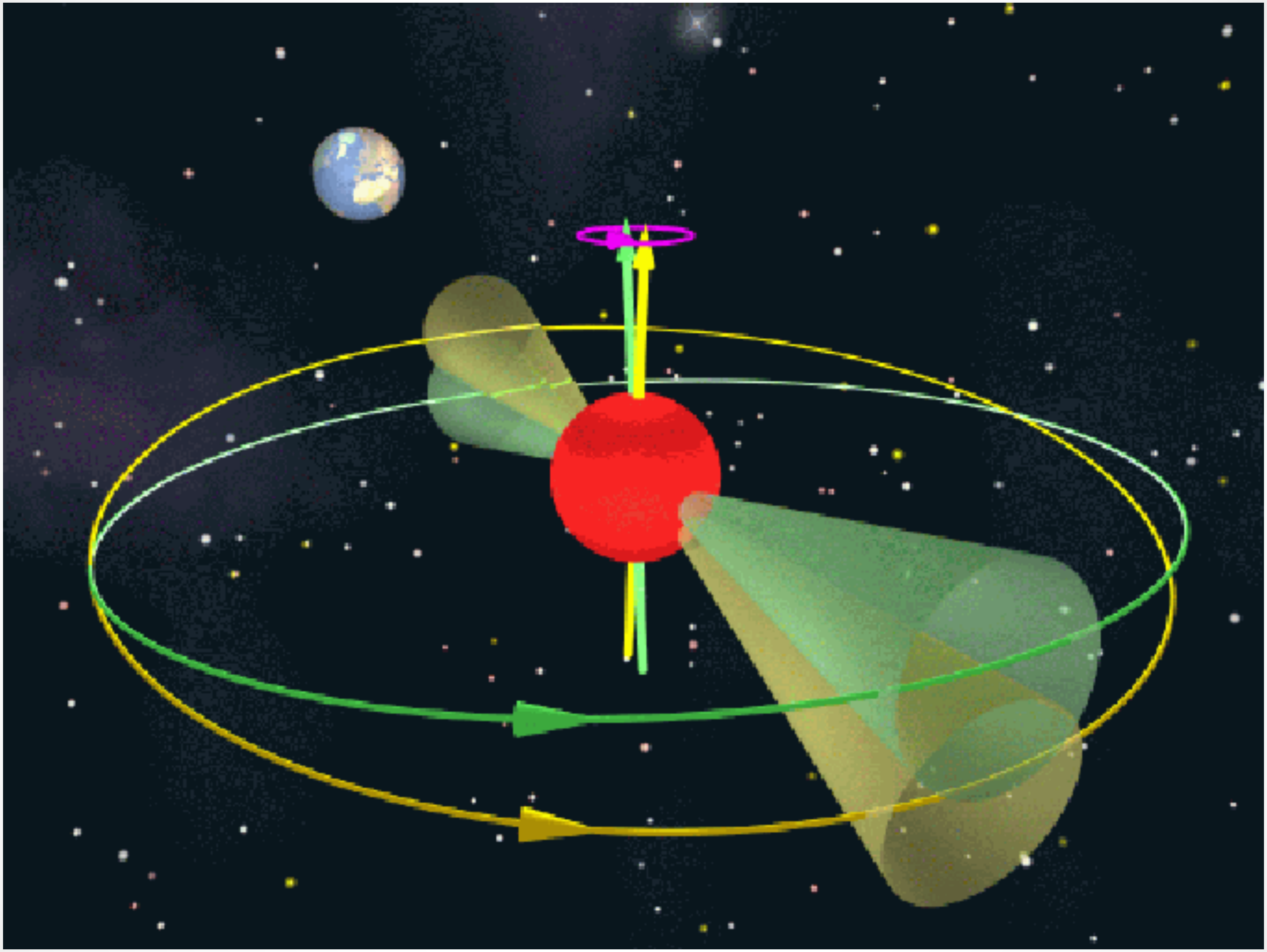
Pulsars: The Lighthouse Model



- 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?

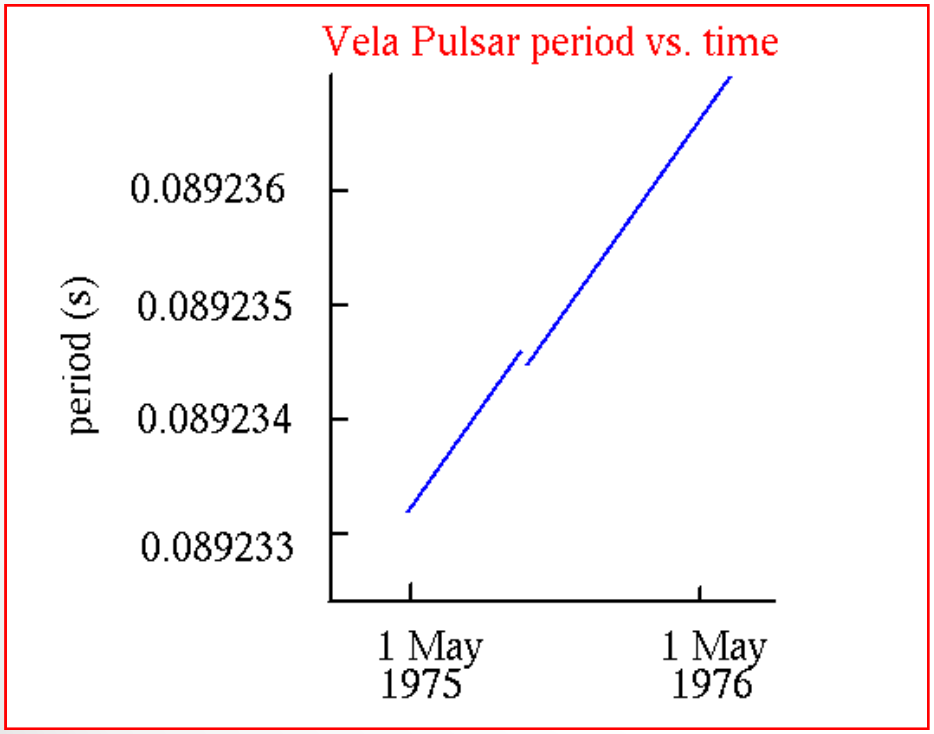
Lighthouse model

- 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.



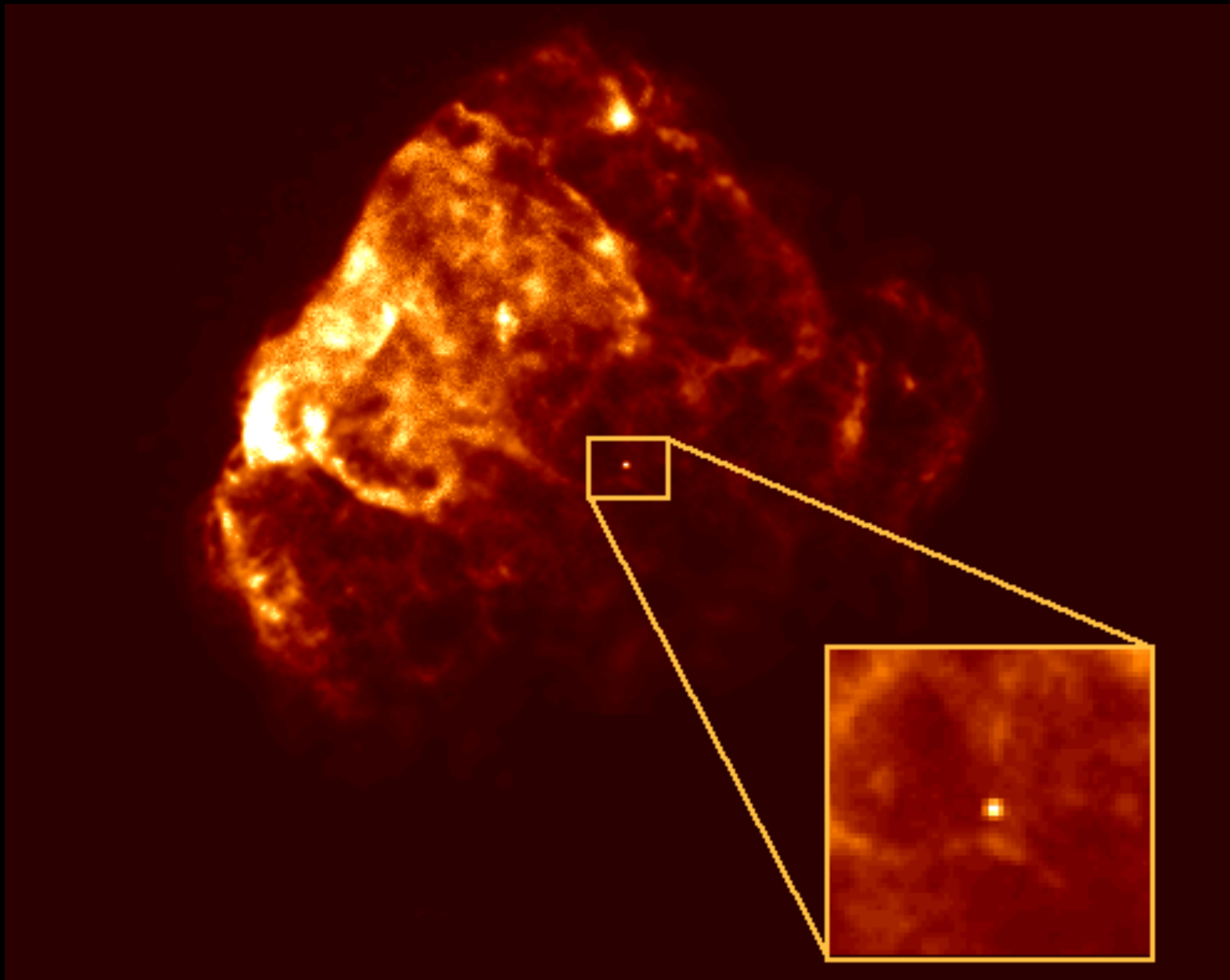
Pulsars

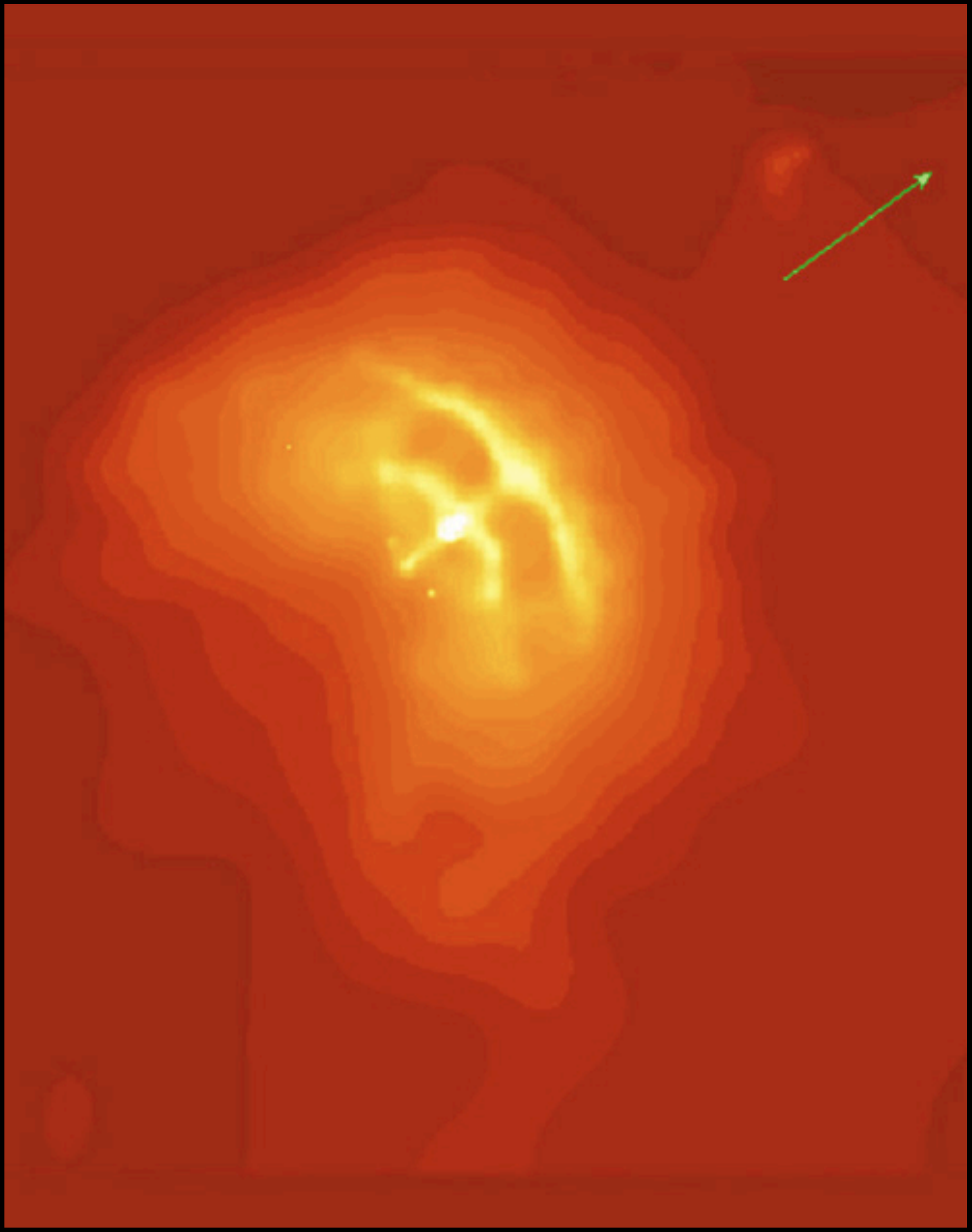
- The period of the Crab pulsar is decreasing by 3 x 10^{-8} seconds each day. The rotational energy is therefore decreasing and the amount of the



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.





Neutron stars in binary systems

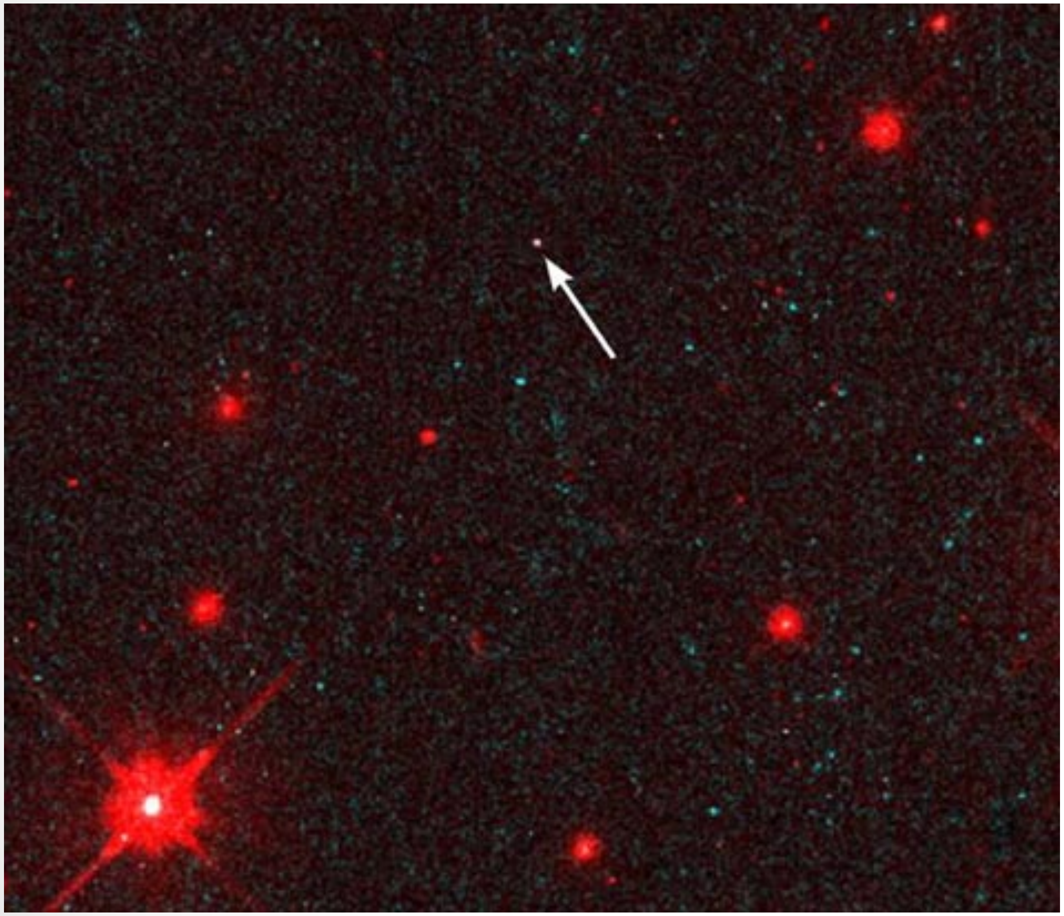
- Some neutron stars were discovered in binary systems that allowed measurement of the n-star mass:

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

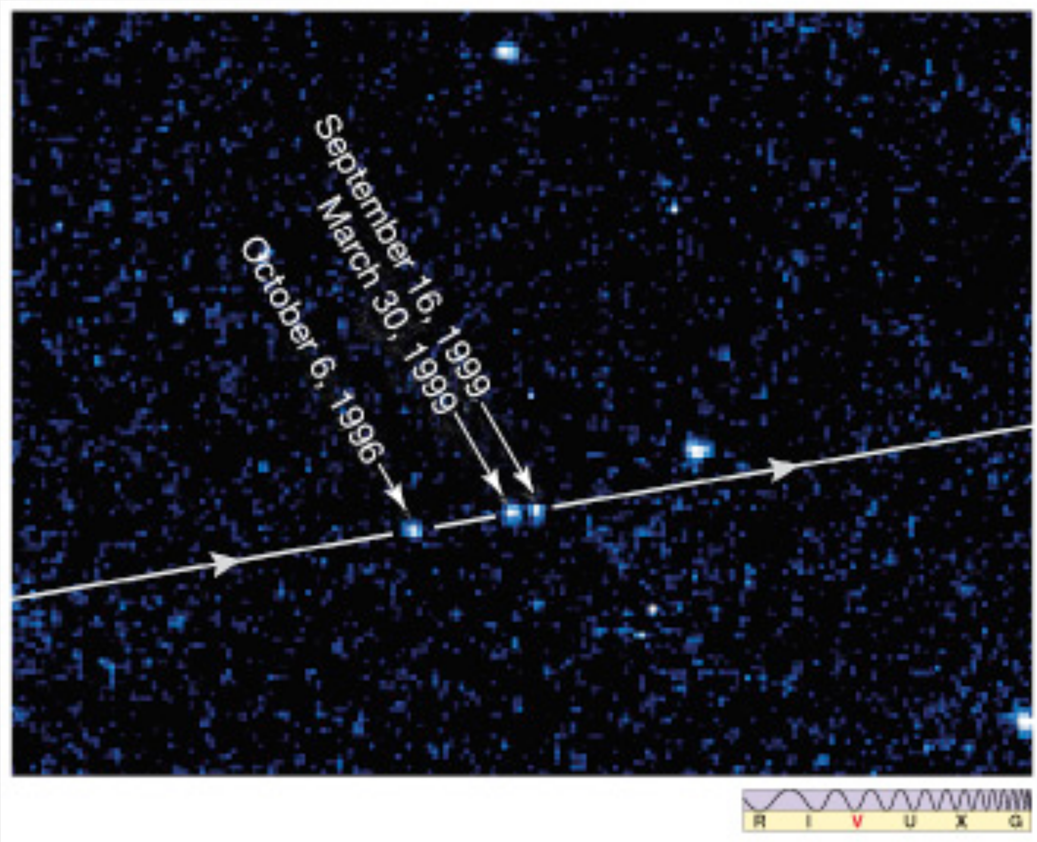
- This is good! Neutron stars are all supposed to be more massive than the Chandrasekar limit and there is even reason to expect them to be close to this limit as that is what initiated the core collapse in a SNII

Detecting Neutron Stars

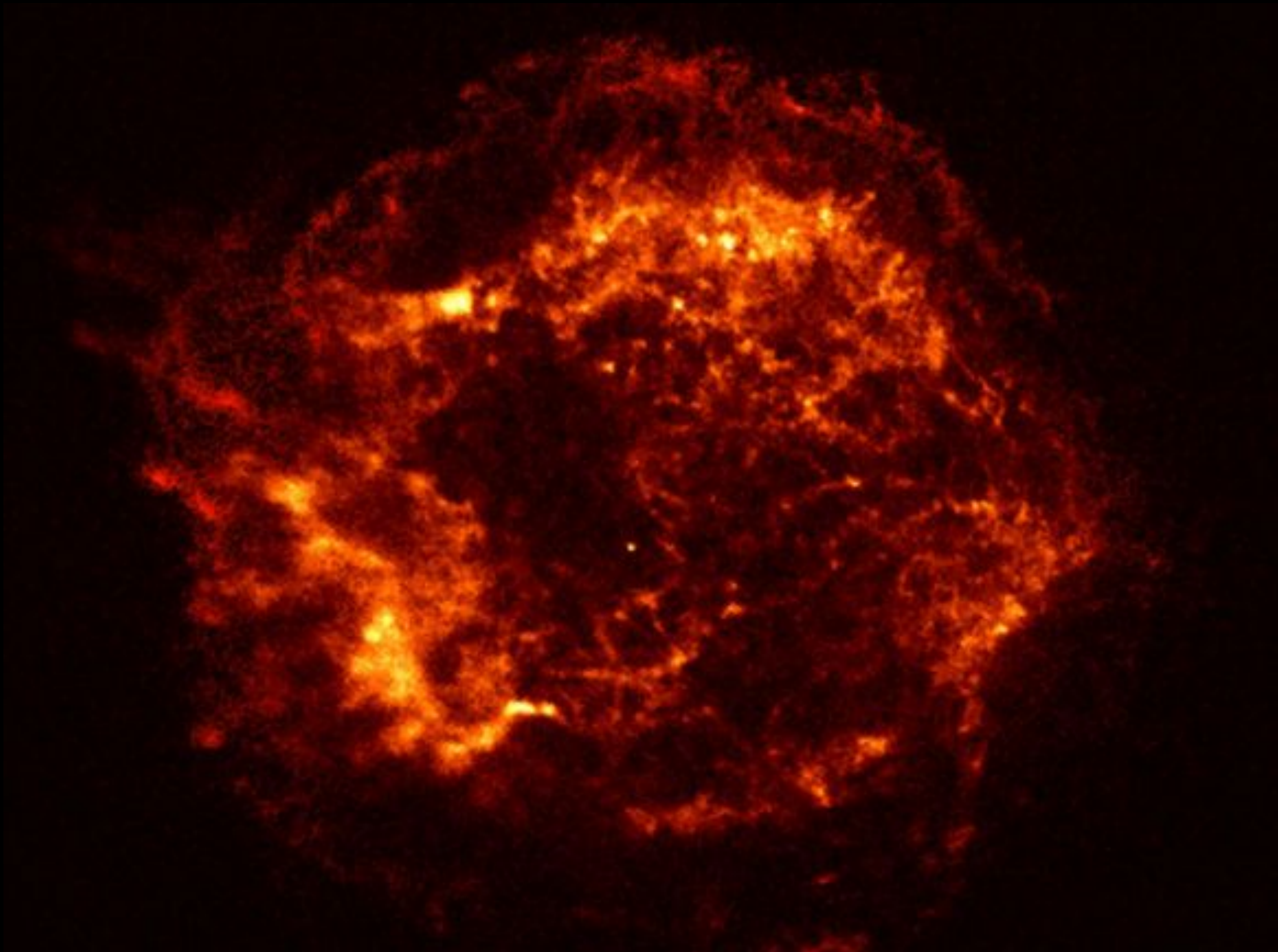
- Detecting n-stars via their photospheric emission is difficult.
- N-stars are VERY hot, but have a tiny surface area so have low luminosity.
- Initial temperature may be greater than 2,000,000k so a very young n-star will emit most of its Planck radiation in X-rays.

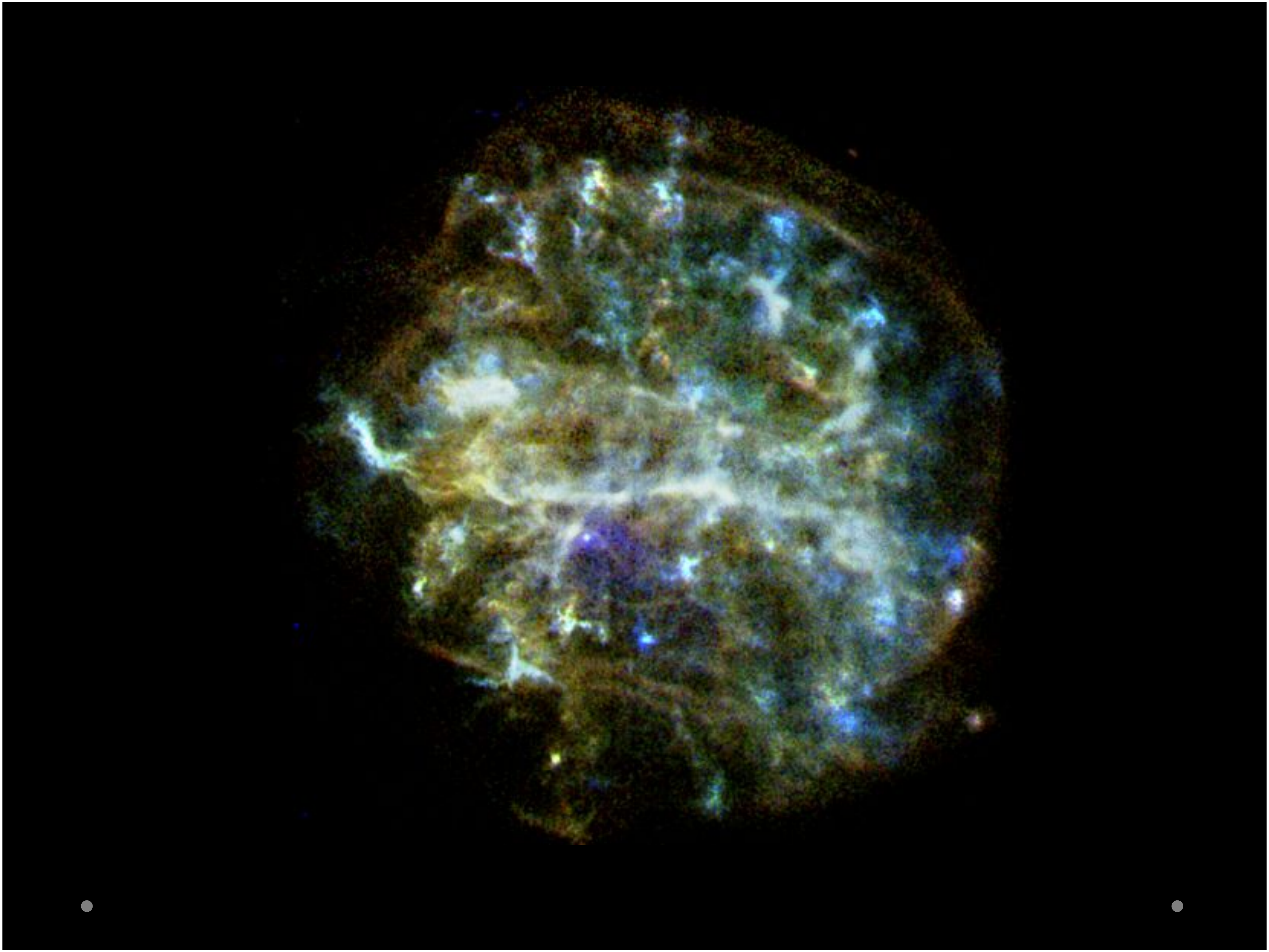


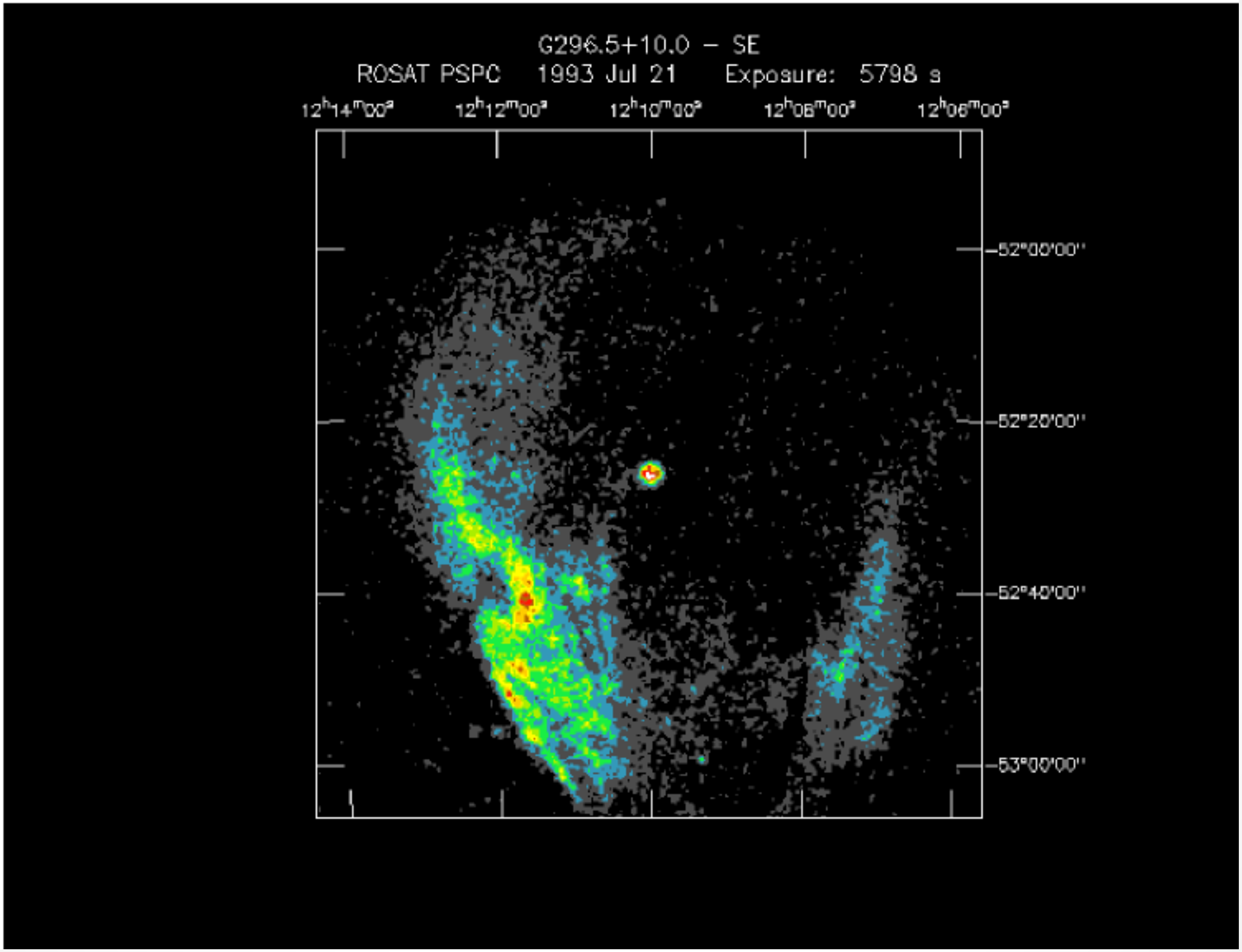
- First isolated n-star observed in photospheric light was discovered in 1997.
- $T_{surface}$=700,000
- Estimated age is 10^6 years.
- This is combined x-ray through visible light image



- In 2017 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

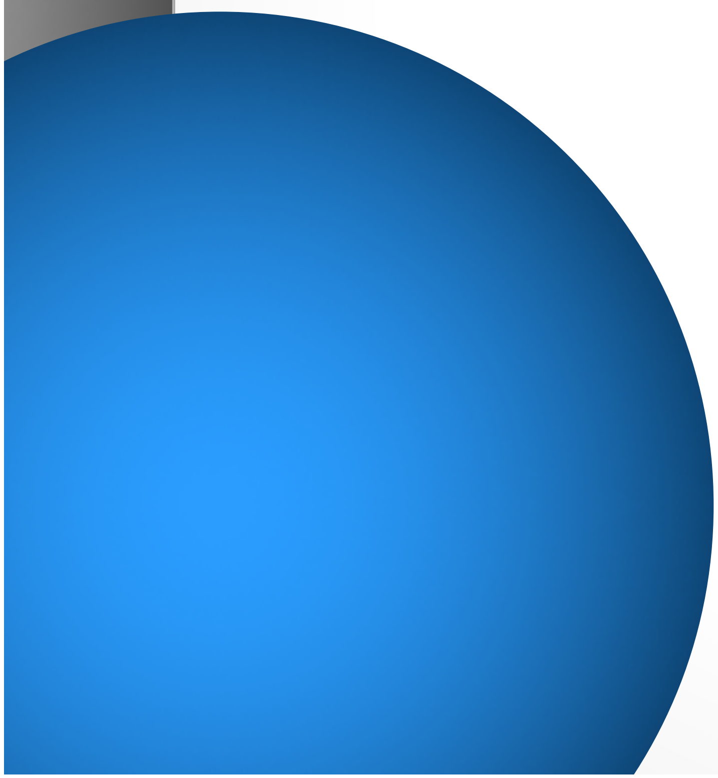
density=10^{14}

Mass > $1.4M_\odot$

White Dwarf: R=6000km

density=10^6

Mass < $1.4M_\odot$



- End of material for Quiz 2