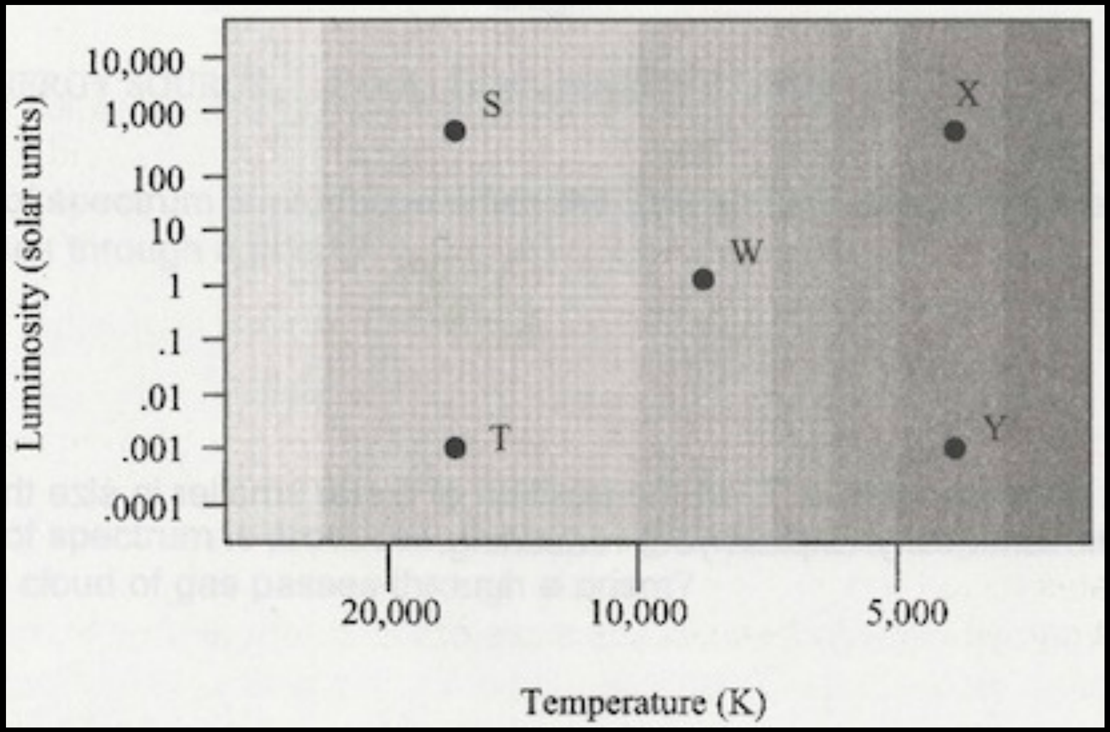
Memo’s for today:

- Expect an email containing an online survey designed to gather halfway point feedback
- MA Week 3 Assignment due Friday
- Sommers-Bausch Observatory Friday Night Open House -- 9:00 pm
  (I’ll be there)

Luminosity, Temperature, Size

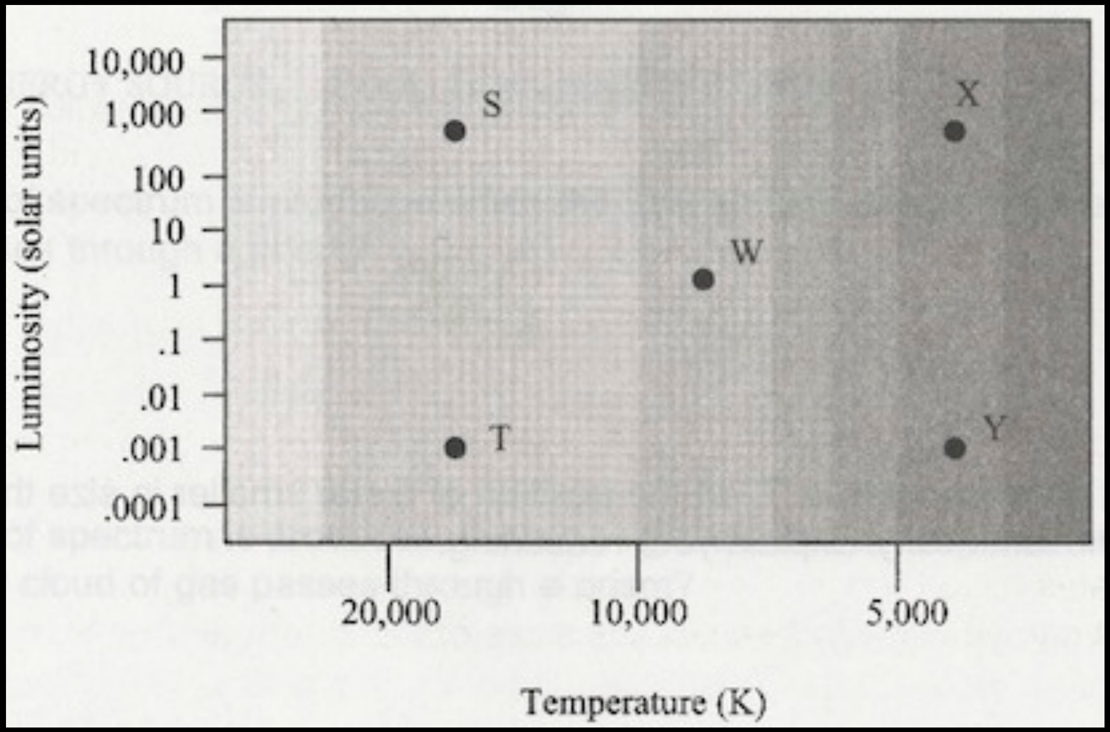


Where should you place a star that is bluer than Star T?

And if it has the same total energy output? (what does this correspond to?)

What else can you say about this star?

Luminosity, Temperature, Size



Where should you place a star that is the same color as Star W?

And if it has the same brightness but is further away? (brightness relates to what property?)

What else can you say about this star?

Reading Question:
What happens to brown dwarves over time?

A) Their contraction is halted by thermal pressure and they heat up

B) They turn into planets and form rings

C) They ignite fusion in their cores and remain as very cool stars

D) Their contraction is halted by degeneracy pressure and they cool

E) They fight with brown gnomes for dominance over the lawns of the universe

ASTR 1120
:: Star and Galaxies ::

Even stars can't cheat death

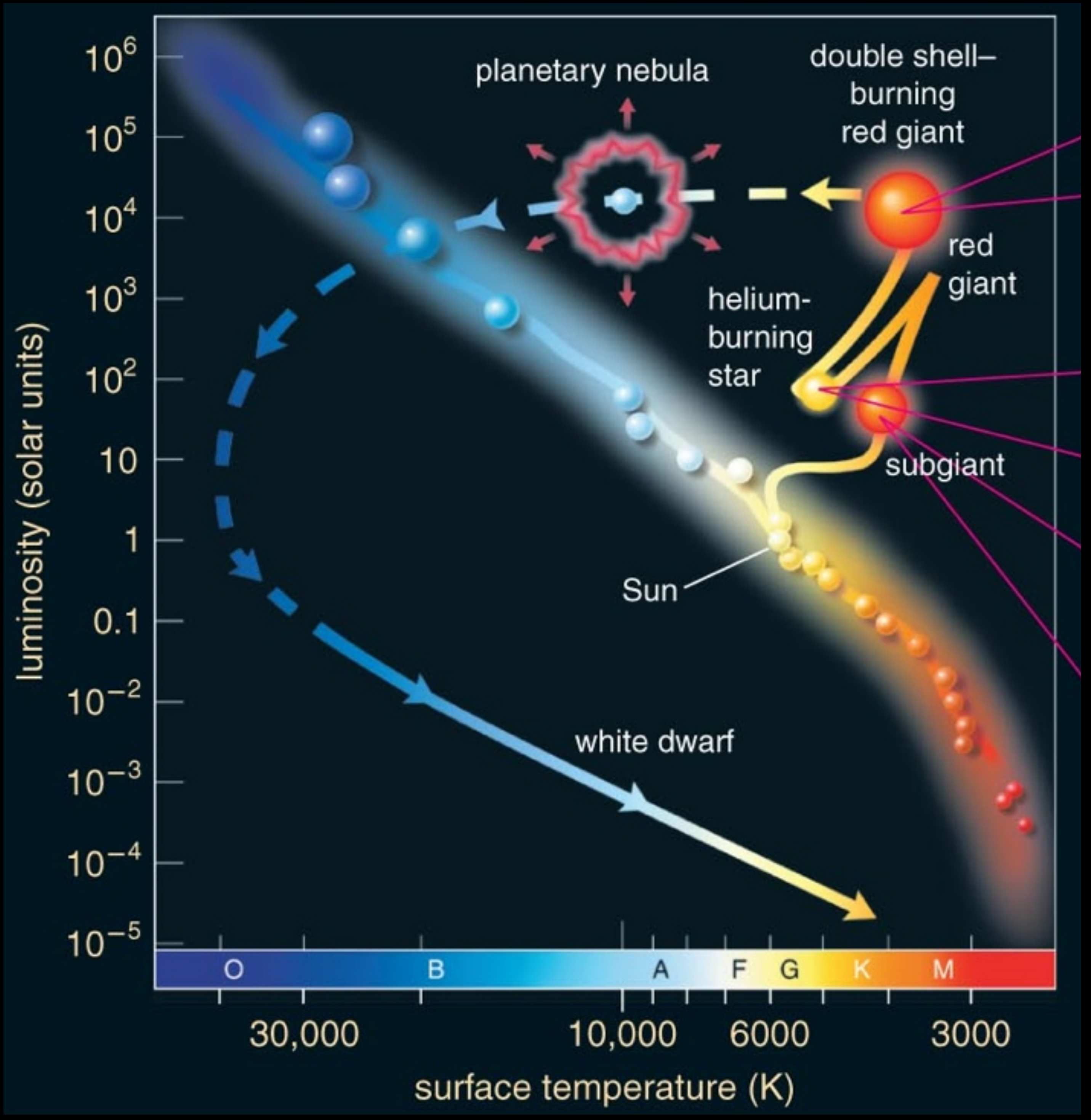
Adam Ginsburg & Devin Silvia
July 2010

Learning Goals

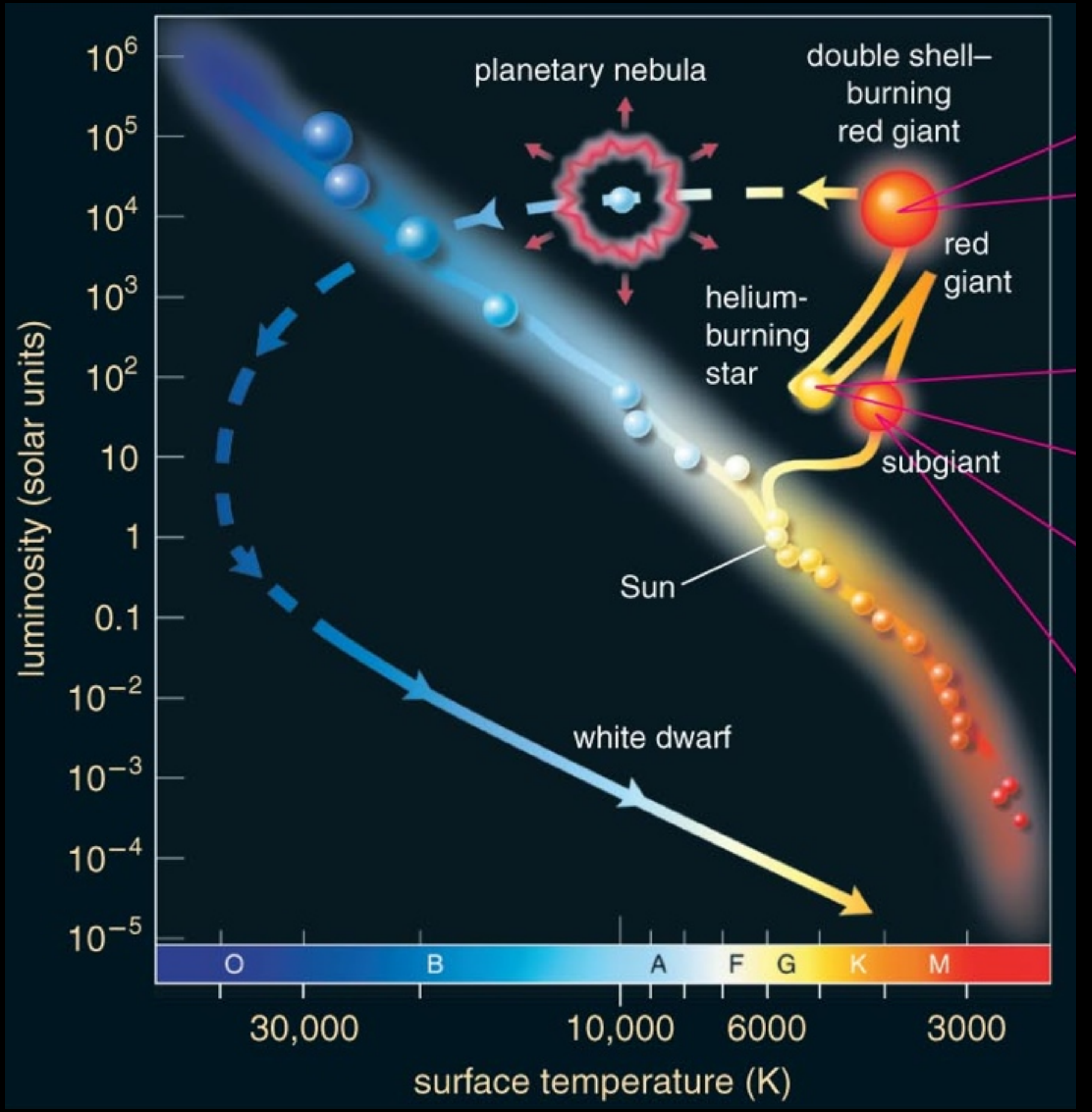
- How do stars die? What are their corpses like?
  - Terms: planetary nebula, white dwarf, neutron star, black hole, degeneracy pressure, supernova

Low-mass Death

- Fusion stops at carbon
  - Need T > 600 million K to fuse carbon
- No fusion = no energy source = Game Over.
- Core loses grip on outer layers that have been blown off during shell-burning, creates planetary nebula
- Inert carbon core is called a white dwarf



Given the temperature range of white dwarfs, at what wavelengths would you expect their black-body curves to peak?



A) Radio, Infrared

B) Infrared, Visible

C) Visible, Ultra-Violet

D) Ultra-Violet, X-ray

E) X-ray, Gamma-ray

What's up with planetary nebulae?

- White dwarf emits intense UV radiation
- Expanding gas is ionized and glows brightly (emission spectrum)
- Colors indicate composition
- Nothing to do with planets
- Will eventually fade out over time

Cat's Eye Nebula (Chandra Observatory + Hubble Space Telescope)

A Nebula Zoo

Eskimo Nebula
(Hubble Space Telescope)

A Nebula Zoo

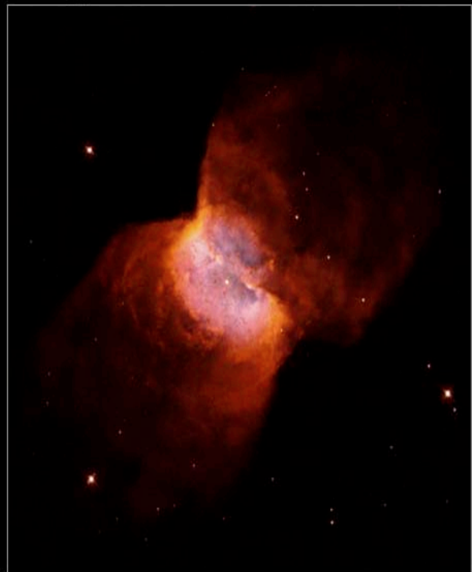
Spirograph Nebula
(Hubble Space Telescope)

A Nebula Zoo

Cat’s Eye Nebula in the visible
(Hubble Space Telescope)

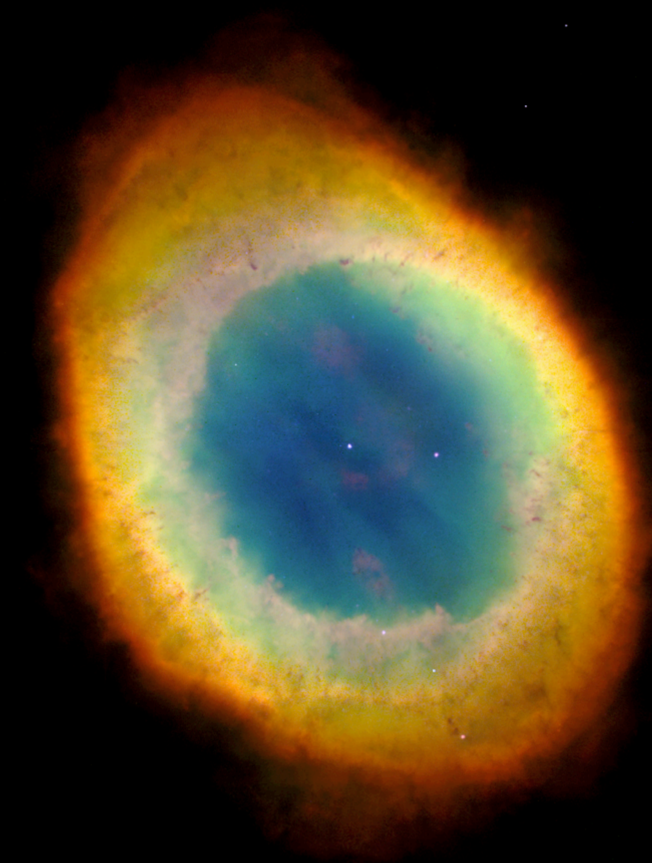
A Nebula Zoo

NGC 2346



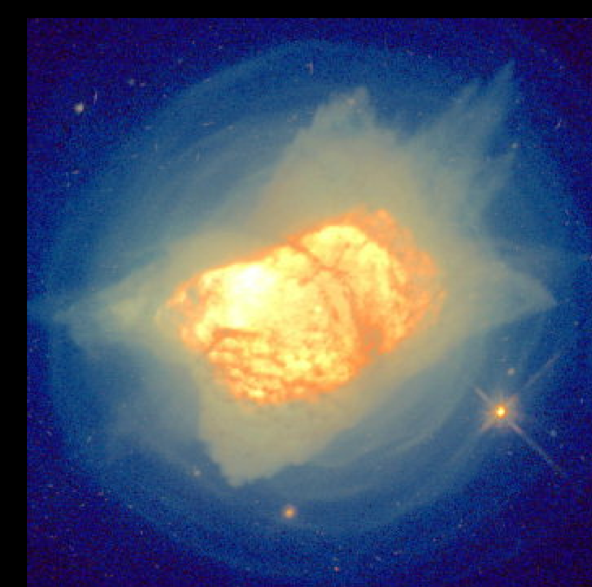
Planetary Nebula NGC 6751

Hubble Heritage



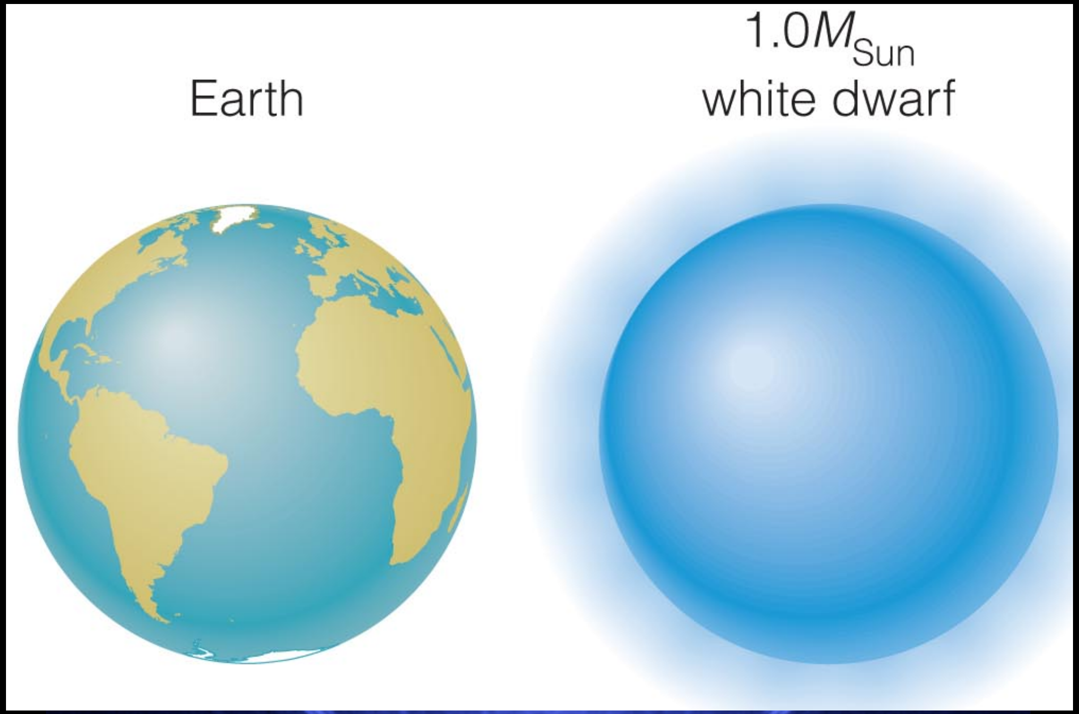
Planetary Nebula NGC 3132

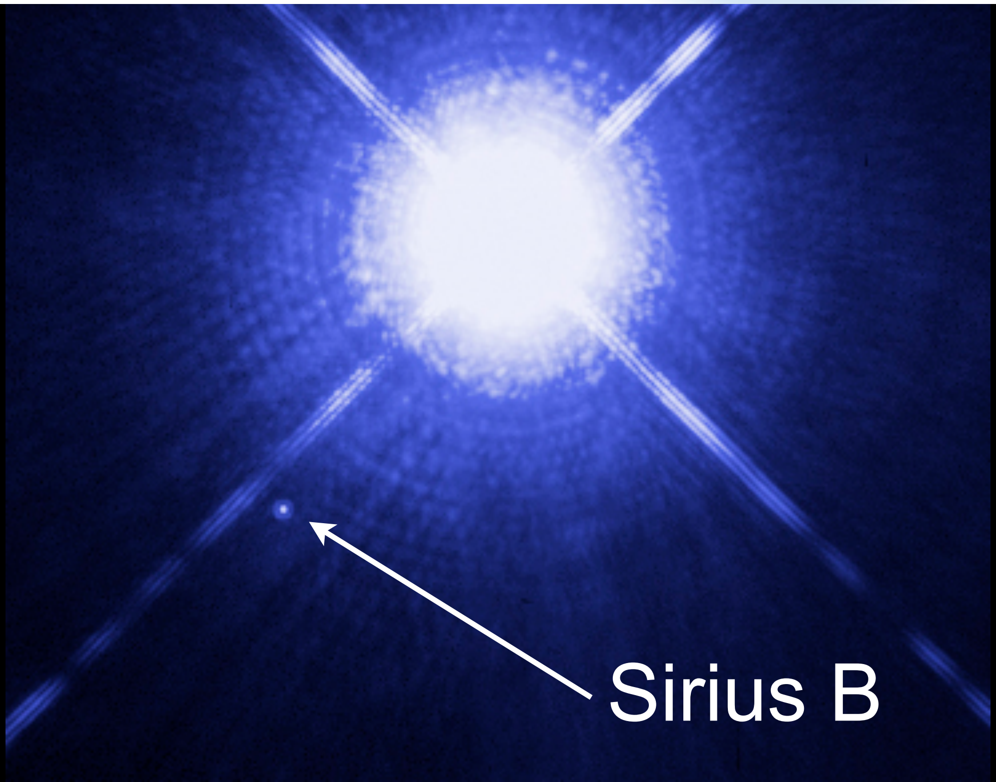
Hubble Heritage



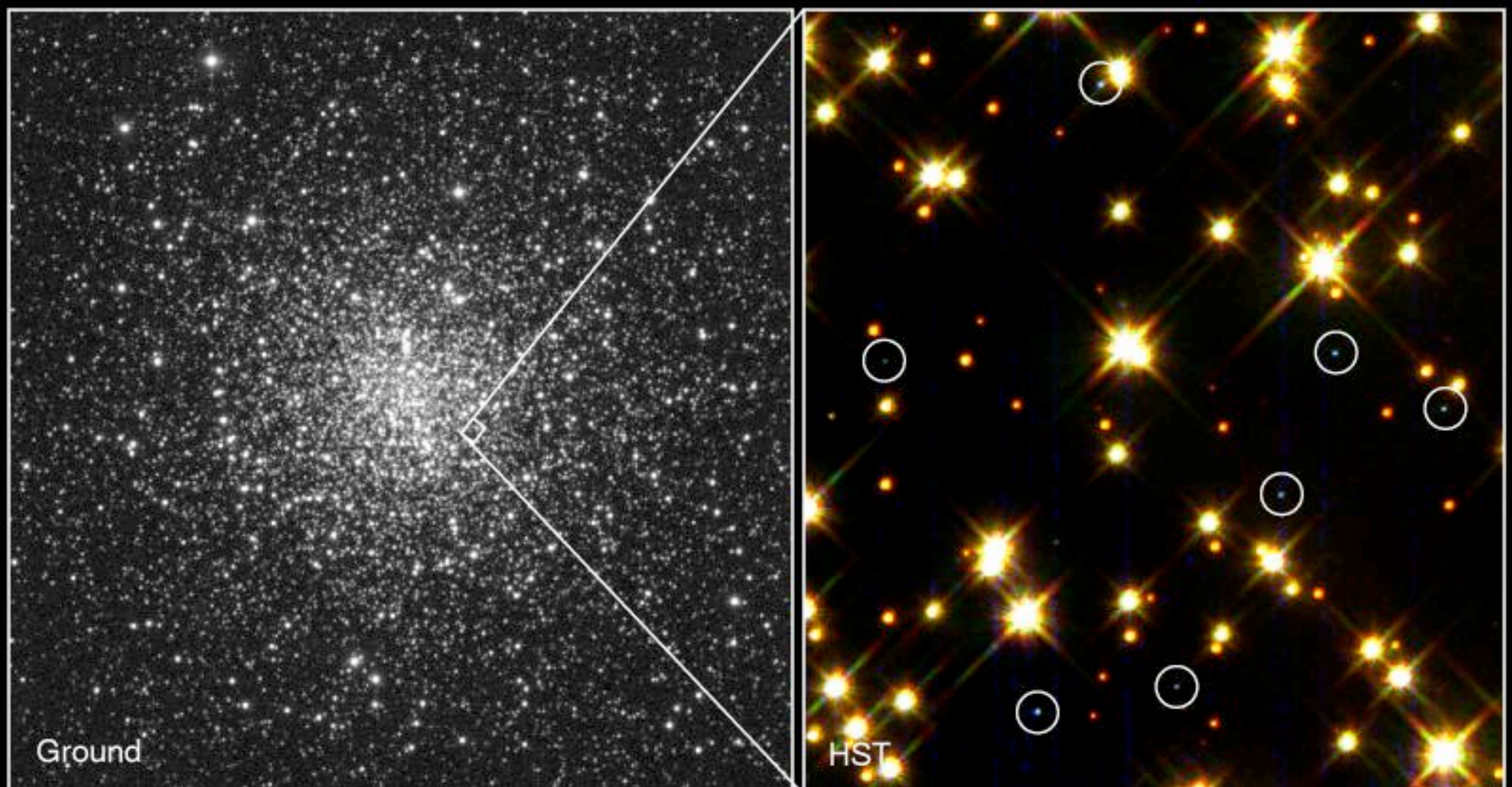
What about the white dwarf?

- A stellar corpse: Carbon “rock” supported by electron degeneracy pressure
- Very dense, very small
- Gravity and degeneracy pressure balance indefinitely (assuming no additional mass is added)
- White dwarf will slowly cool off over time -- destined to become a “black dwarf”





I spy with my little eye...



White Dwarf Stars in M4 HST • WFPC2

PRC95-32 • ST ScI OPO • August 28, 1995 • H. Bond (ST ScI), NASA

Hubble spots 12-13 billion year old white dwarves

Which is correct order for some stages of life in a low-mass star?

A) protostar, main-sequence star, red giant, planetary nebula, white dwarf

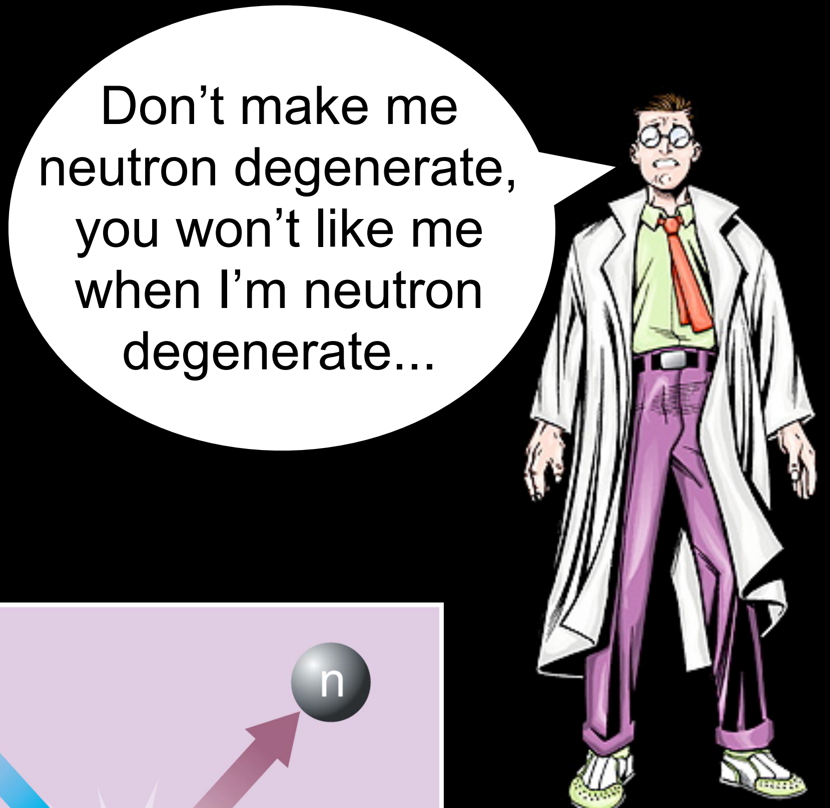
B) protostar, main-sequence star, red giant, supernova, neutron star

C) main-sequence star, white dwarf, red giant, planetary nebula, protostar

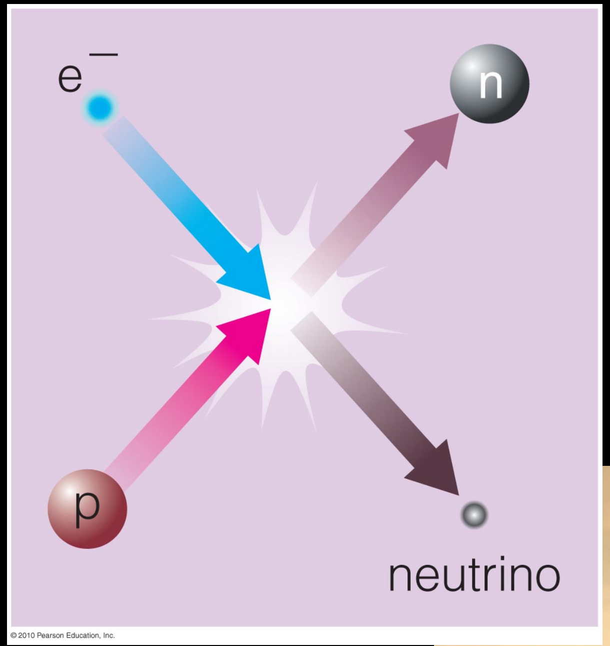
D) protostar, main-sequence star, planetary nebula, red giant

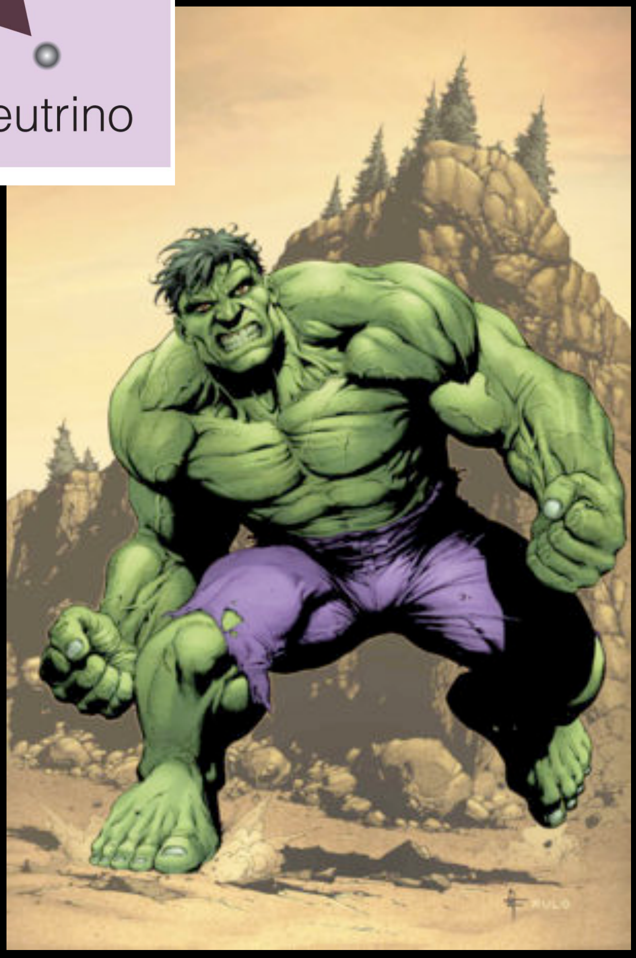
E) protostar, red giant, main-sequence star, planetary nebula, white dwarf

High-mass Death



- Successive layers of fused material build up on top of the core
- After fusion stops at iron, core is initially supported by electron degeneracy pressure, but its too weak and feeble
- The weight of the outer layers becomes too great and converts protons and electrons into neutrons and neutrinos
- Conversion takes less than 0.01 second for the ENTIRE CORE
- Nearly instantaneous core collapse
- Eventually, neutron degeneracy pressure pushes back, <u>hard</u>.





And then...

- Without support, the outer layers of the star start falling inward, very rapidly
- Then, very abruptly, they hit the neutron degenerate core
- What happens at this point?

"Bouncy balls" demo prediction:

A) All the balls will bounce back up together

B) The smallest ball will bounce higher than the largest ball, but no higher than when the little ball is dropped alone

C) The smallest ball will bounce to the height of the combined height of each ball dropped alone

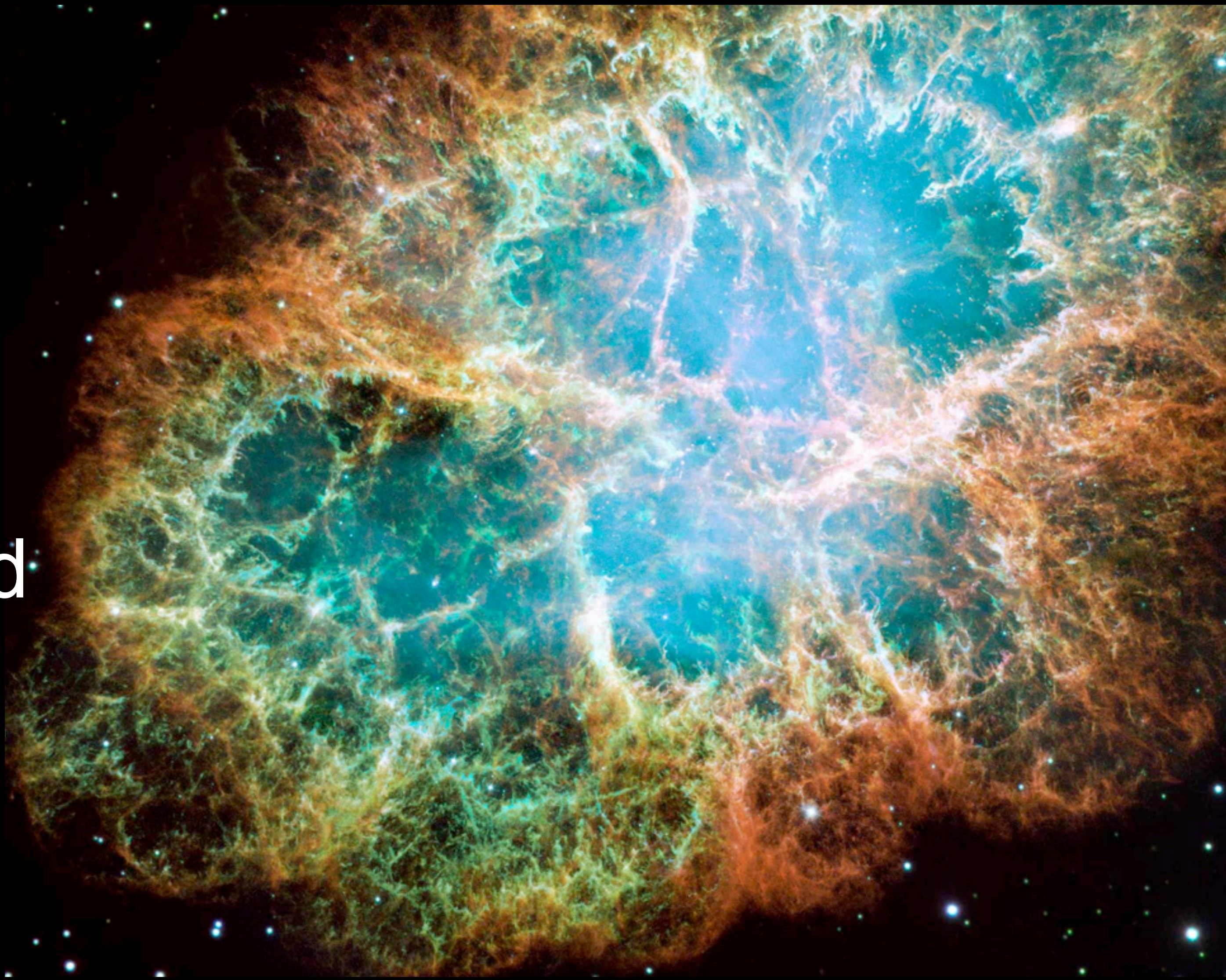
D) The smallest ball will bounce much higher than the largest ball

...things go KABLOOEY!

- The in-falling layers impact the extremely dense core and “bounce” off with a massive amount of energy
- We end up with a SUPERNOVA EXPLOSION
- Huge energy release from neutrinos

Supernovae

- For about a week, a supernova will shine as bright as ~10 billion Suns
- Heavy elements formed in the explosive death of massive stars are dispersed into the interstellar medium
- The leftover core may end up as a neutron star -- a compact object composed of almost exclusively neutrons



Crab Nebula (M1), first seen on July 4th 1054 from China -- visible in daytime!

Food for thought

- The only way to make elements heavier than hydrogen and helium is inside stars
- Without supernovae, there would be no way to make elements heavier than iron

WE ARE MADE OF STAR STUFF!

- Our atoms are were once part of stars that blew up more than 4.6 billion years ago and ended up in the material that our Sun formed out of

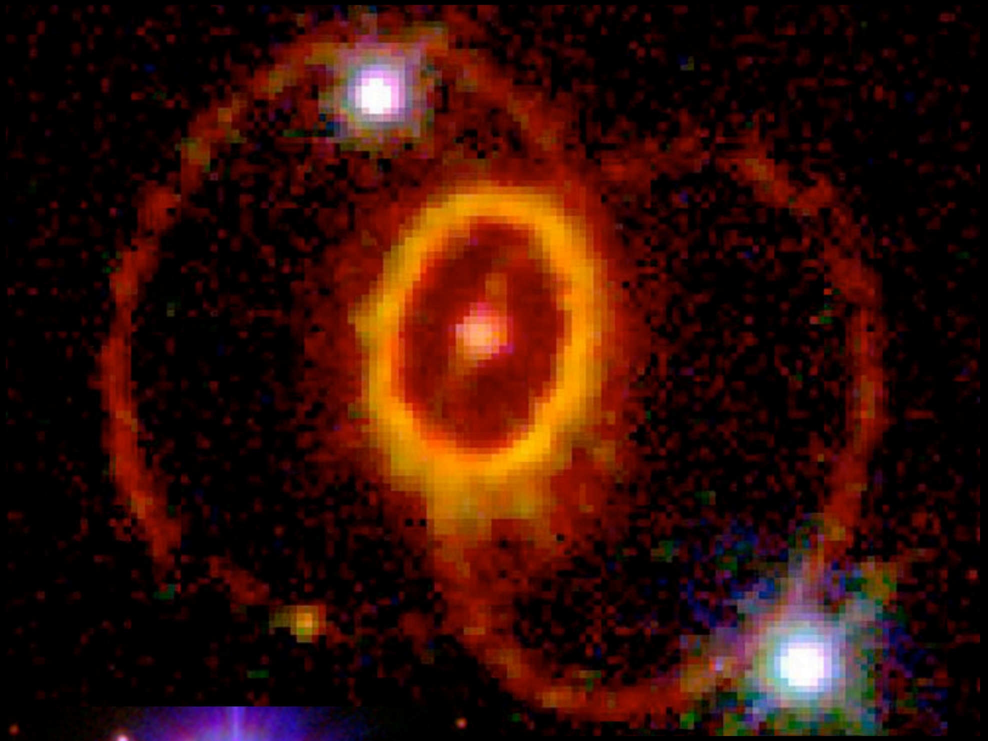
Whoa, you, like, totally just blew my mind, dude.

How do we know that all this is true?

- The Scientific Process
  - Observation
  - Conceptual Model (hypothesis)
  - Test the model with more observations
  - Can the model make any predictions?

Prediction:

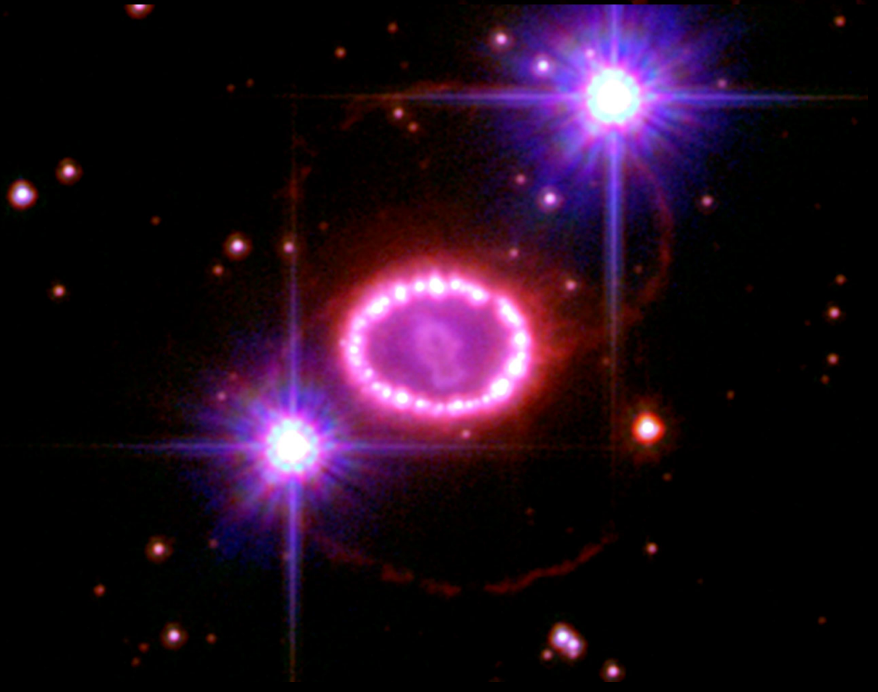
According to our model, if a supernova explosion is the result of core collapse into a neutron star, a ton of neutrinos should be generated



Observational Evidence:

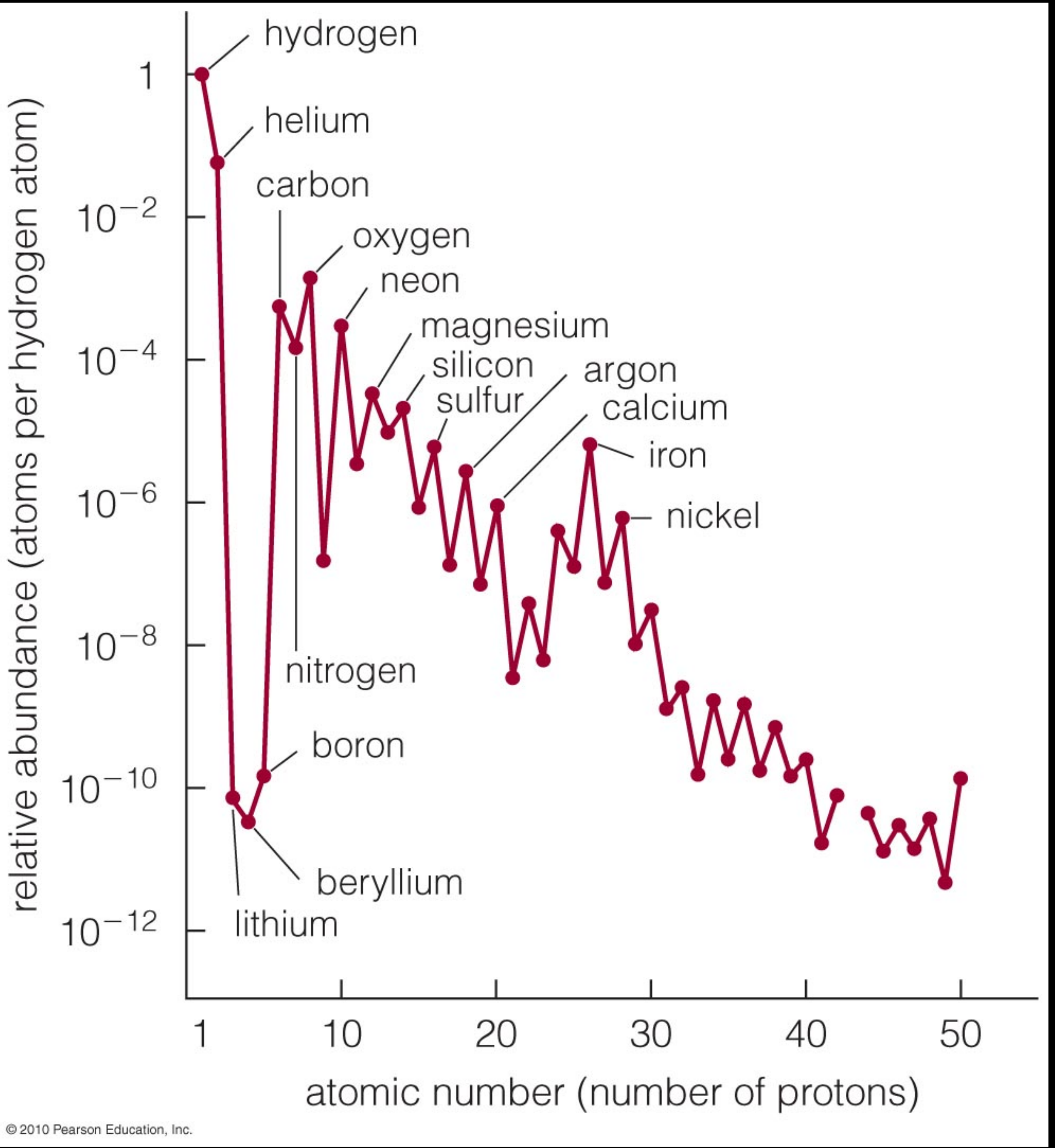
Supernova 1987A

A wave of neutrinos were detected that coincided with the outburst



Prediction:
If heavier elements really are the results of nuclear fusion via helium capture, then we there should be more elements with even numbers of atomic elements

Observational Evidence:
The interstellar medium contains higher proportions of even-numbered elements

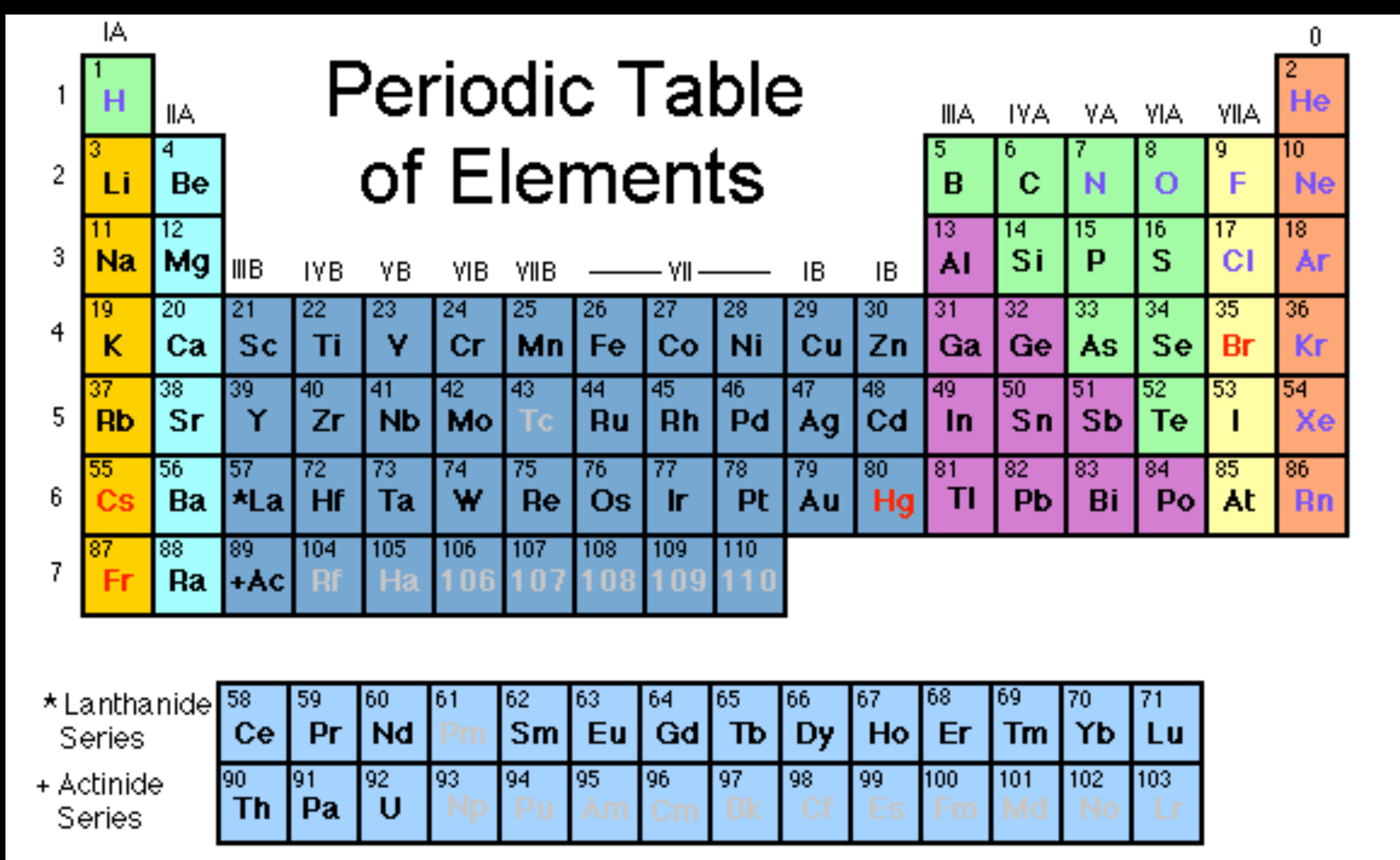


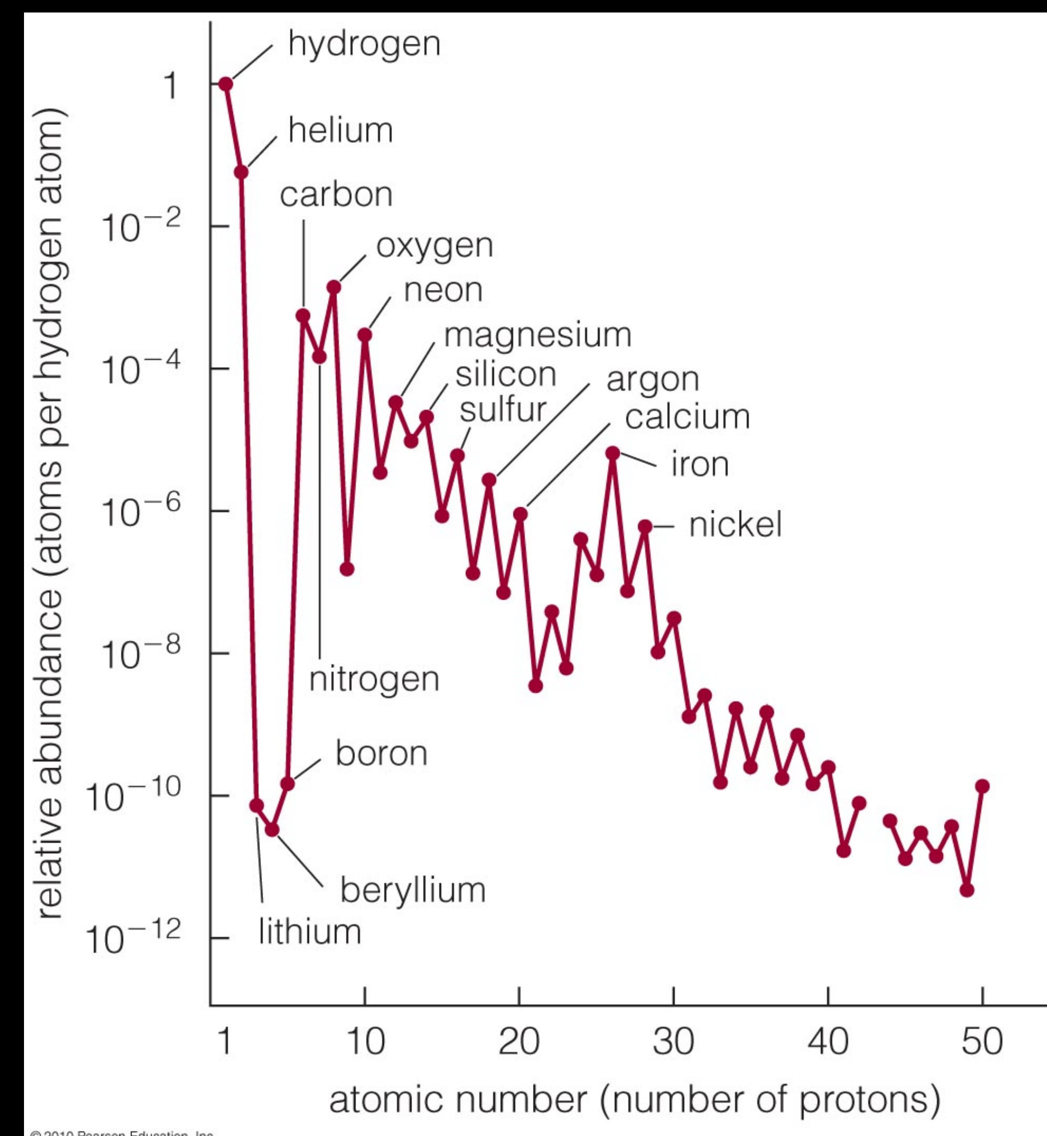
Prediction:

If elements heavier than iron (Fe) are made primarily by rare fusion reactions before and during a supernova, then these elements should be very rare

Observational Evidence:

These elements are indeed rare, both in the interstellar medium, and here on Earth





Prediction:

If all heavy elements are created inside high-mass stars, older stars should have fewer heavy elements in them

Observational Evidence:

Heavy elements are indeed more abundant in younger stars than in older stars.

Sun (young star):

70% H 28% He 2% Other

HE 0107-5240 (oldest known star):

~74% H ~26% He .00001% Other

Algol is a binary system consisting of a 3.7 M_{Sun} main sequence star and a 0.8 M_{Sun} red giant. Why is this strange?

A) A 3.7 M_{Sun} star should have become a red giant before a 0.8 M_{Sun} star

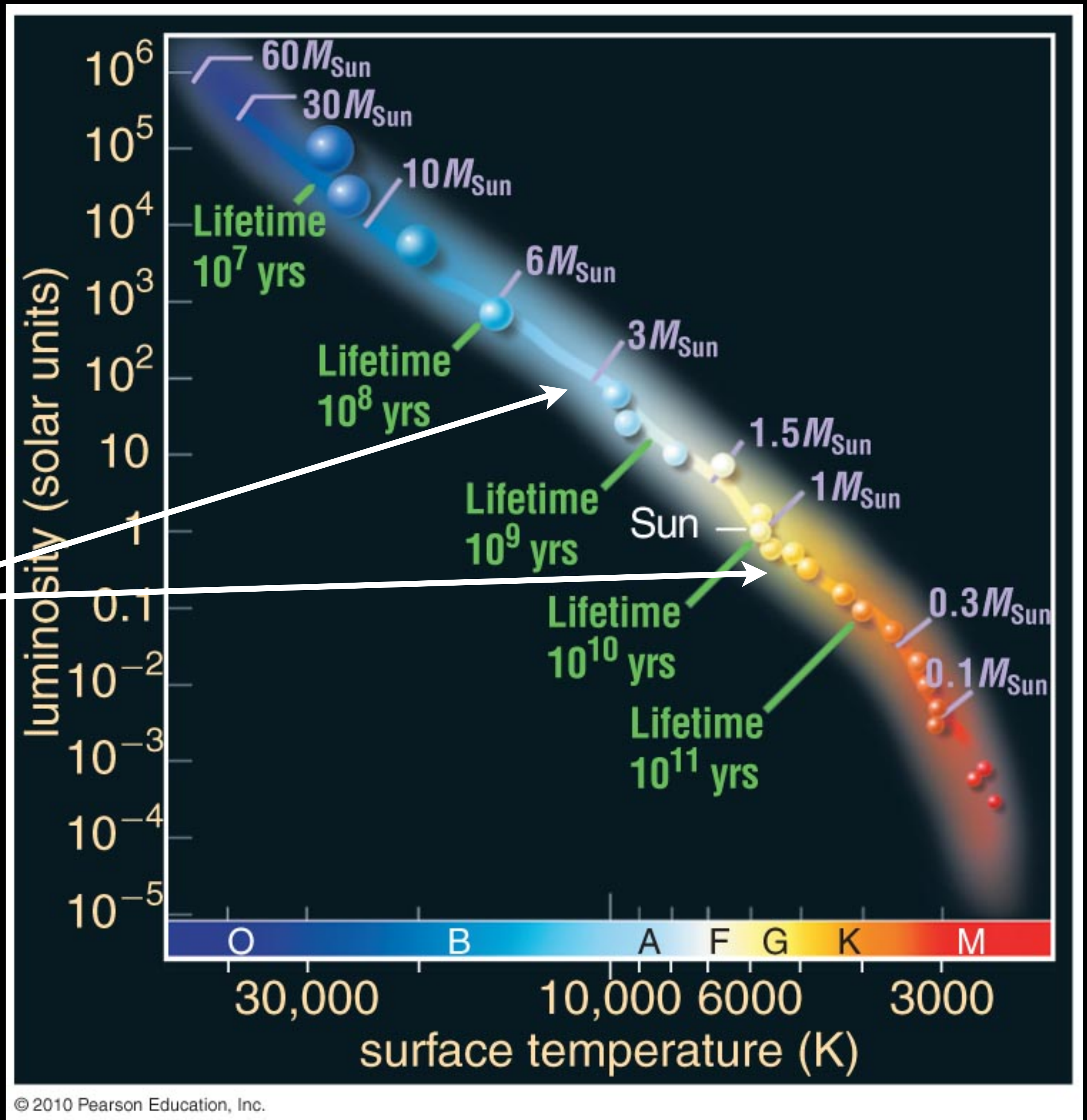
B) Binary stars usually have the same mass

C) 0.8 M_{Sun} stars usually never become red giants

D) The two stars in a binary system should both be at the same stage in their evolution

So, what's your deal Algol?

- Binary systems can have different masses but are usually formed at the same time
- According to everything we know, the more massive star should have had a shorter main sequence lifetime

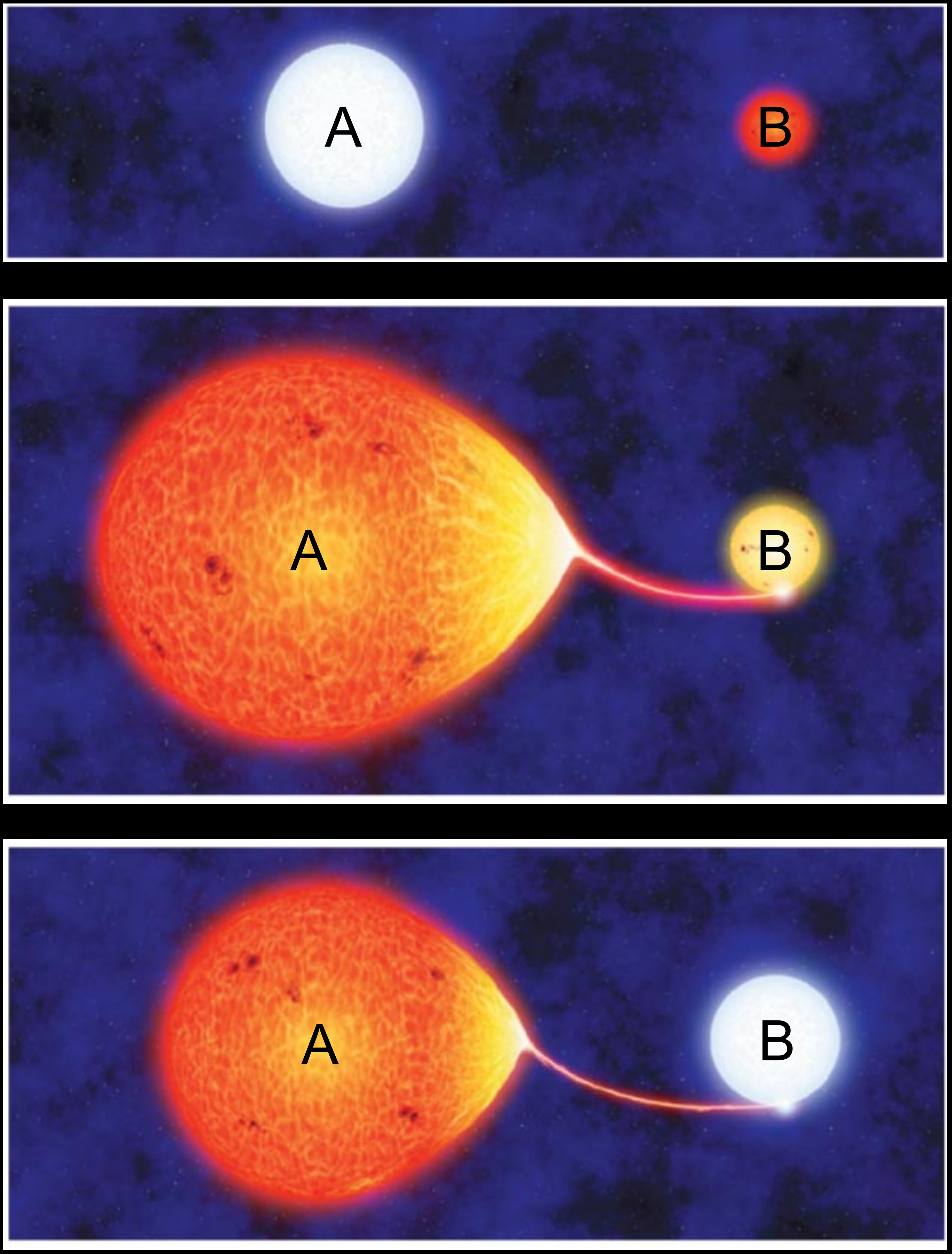


The key to the mystery?

Binary Mass Exchange

- The 0.8 M_{Sun} star was initially more massive than its companion
- As it grew into a red giant, it began to dump mass onto the smaller star
  - This is technically called “Roche lobe overflow”
- As it transferred mass, it shrunk until eventually the transfer stopped, resulting in its current state

Initially, Star A is more massive



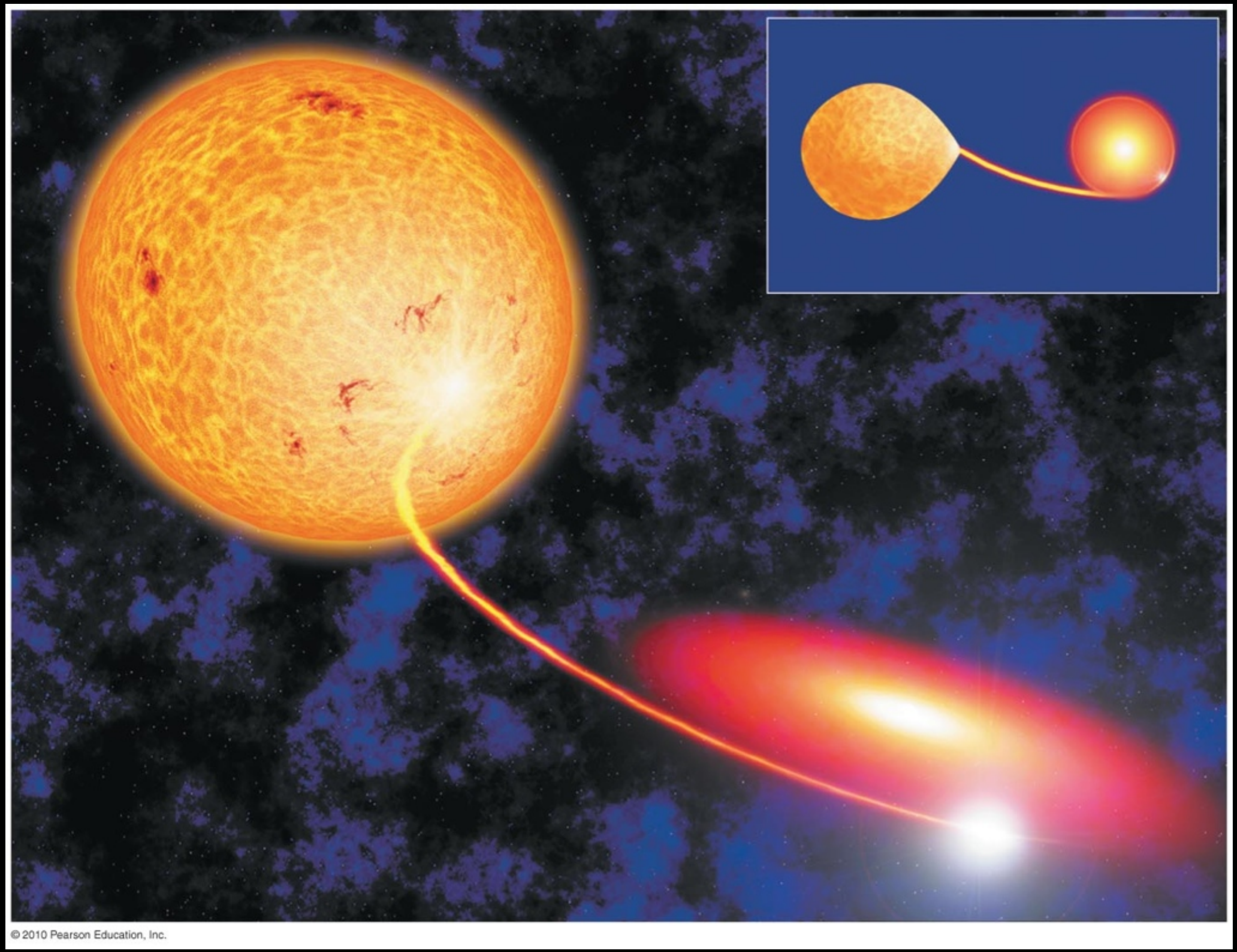
Now, Star B is more massive

What if the binary included a White Dwarf?

- No white dwarf can have a mass greater than 1.4 M_{Sun} (Chandrasekhar limit)
- But, if you end up with binary mass exchange, this limit could be reached

How one goes about approaching the white dwarf mass limit:

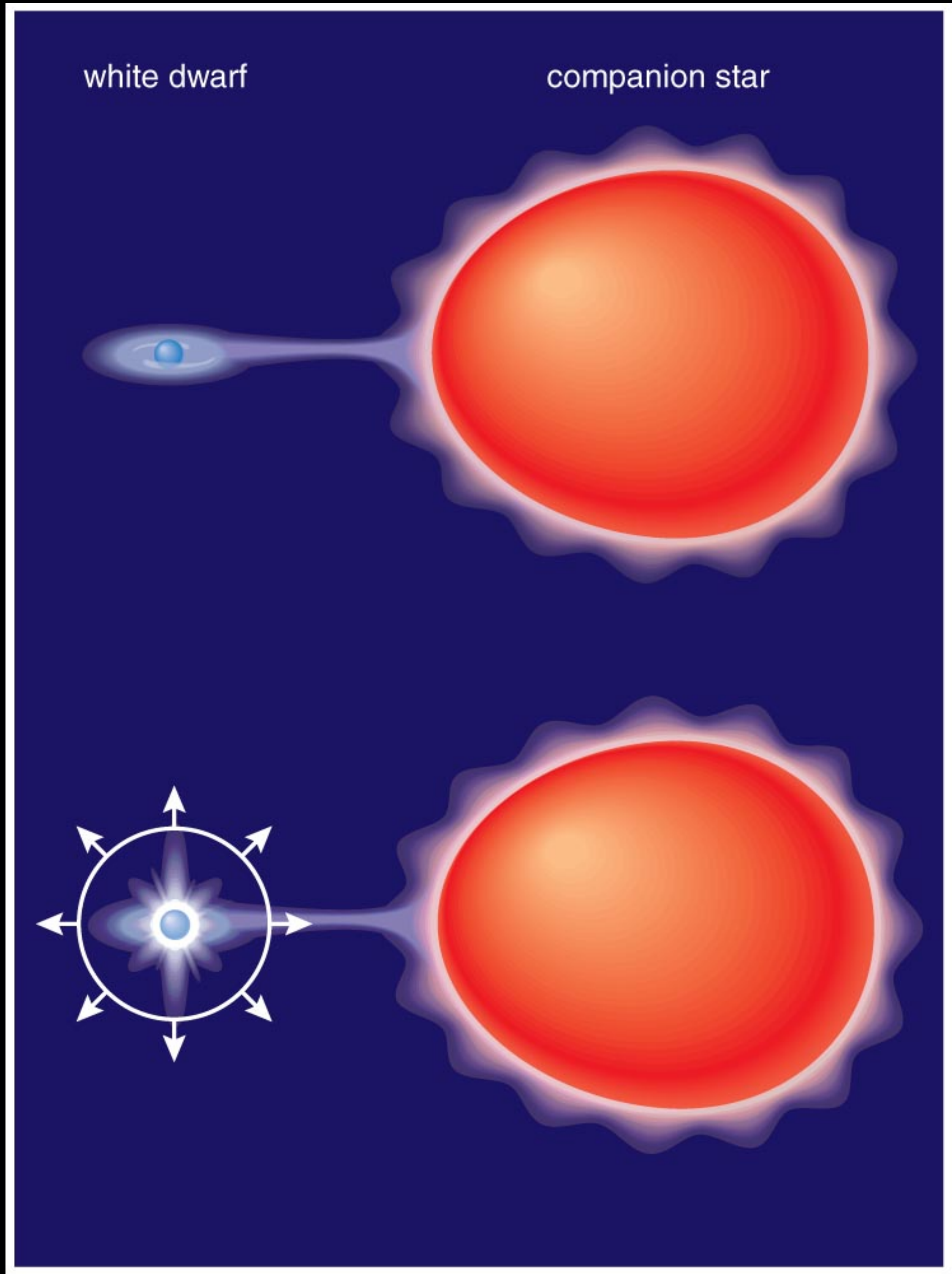
- Need to have stars in a close binary
- If the companion to the white dwarf is large enough it could fill its Roche lobe and begin transferring mass
- The transferred mass will form an accretion disk (why?)



Accretion can lead to Novae

(Different than "supernovae")

- Small amount of hydrogen gas falls onto the white dwarf and forms a thin shell the surface
- As the layer builds up the temperature and pressure increases
- If the temperature reaches 10 million K, hydrogen fusion ignites!
- A nova can be as bright as 100,000 Suns
- Can repeat numerous times



Prediction: If a lot of material from the accretion disk makes it onto the white dwarf, what will happen?

A) The winds from the white dwarf will blow all the material off.

B) The white dwarf will have enough mass to collapse more and start carbon fusion at the core.

C) The white dwarf will turn into a red giant.

D) The companion star will explode in a supernova.

When accretion crosses over the 1.4 M_{Sun} limit

- Temperature rises over the threshold needed to fuse carbon
- Carbon fusion ignites almost instantly through the entire white dwarf -- carbon bomb! (similar to the helium flash in red giants)
- This is called a white dwarf supernova (Type 1a)
- No compact remnant left behind

Why do white dwarf supernovae only occur in older star populations?

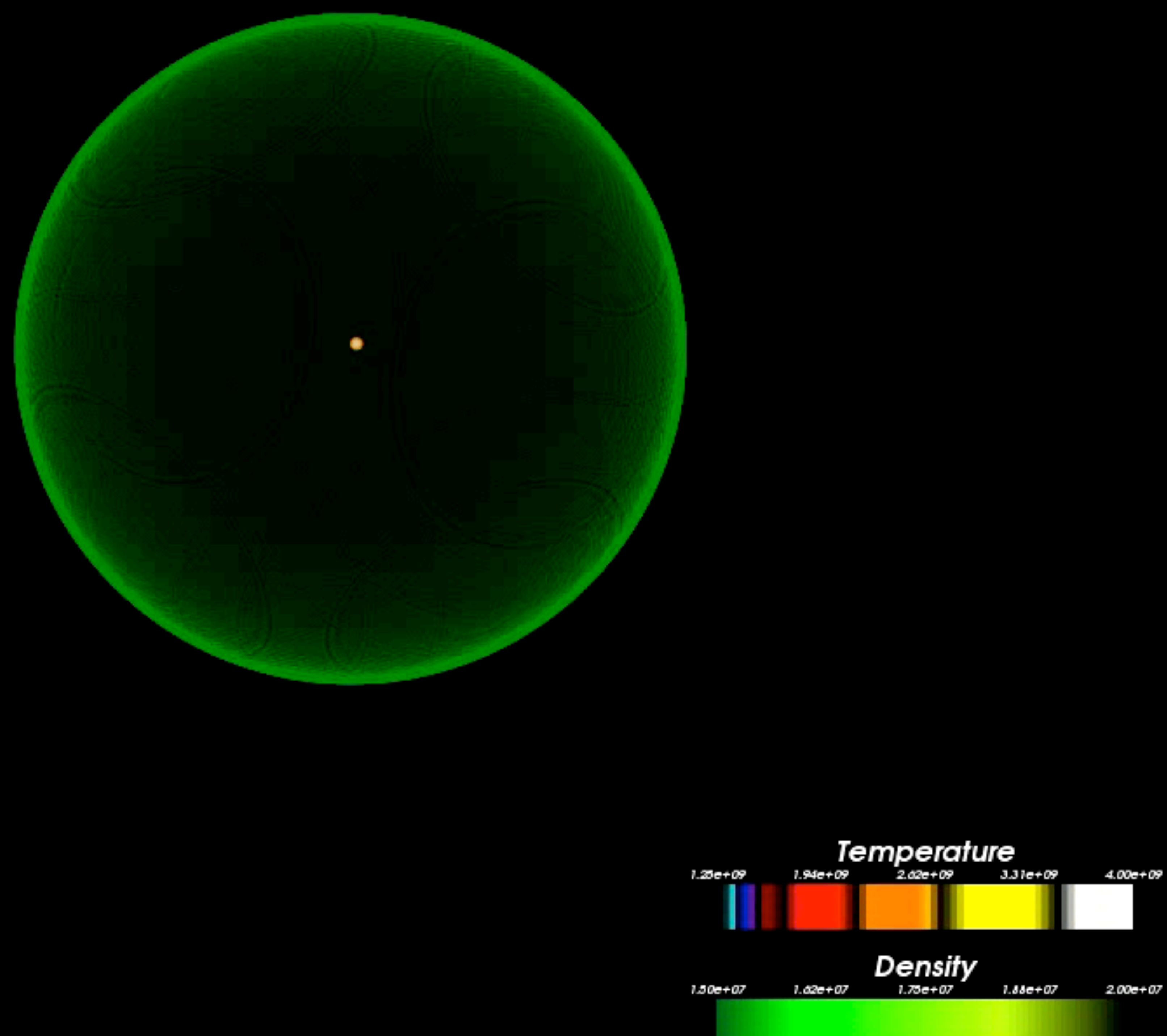
A) Supernovae can not occur in any star that is less than 5 billion years old

B) The supernovae actually occurred when the star was much younger, but it takes light a long time to reach our telescopes on Earth

C) White dwarfs are only produced by long-lived low-mass stars in their last stages of life

D) Snow white slept for 5 billion years, and the white dwarfs needed to keep her company during this time

White Dwarf Deflagration



Where is the primary source of fusion happening during a nova?

A) In the core, iron is being fused into heavier elements.

B) In the core, carbon is being fused into heavier elements.

C) In shells surrounding the core.

D) On the surface, hydrogen is being fused into helium.

E) No fusion occurs in a nova.

Where is the primary source of fusion happening during a white dwarf supernova?

A) In the core, iron is being fused into heavier elements.

B) In the core, carbon is being fused into heavier elements.

C) In shells surrounding the core.

D) On the surface, hydrogen is being fused into helium.

E) No fusion occurs in a white dwarf supernova.

Where is the primary source of fusion happening during a <u>massive star supernova</u>?

A) In the core, iron is being fused into heavier elements.

B) In the core, carbon is being fused into heavier elements.

C) In shells surrounding the core.

D) On the surface, hydrogen is being fused into helium.

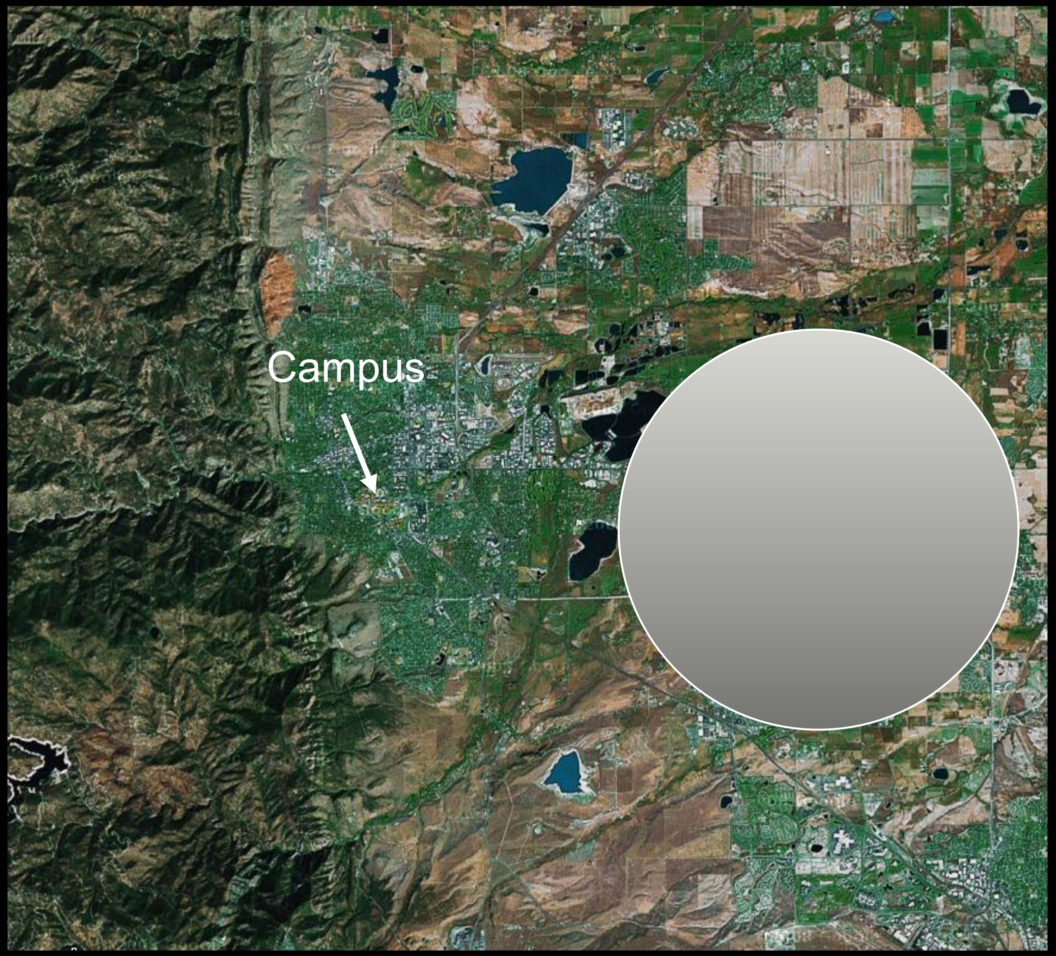
E) No fusion occurs in a massive star supernova.

Stellar Explosion Recap

- White Dwarf Nova
  - Binary systems only
  - Occurs in older star populations
  - White dwarf still survives
- White Dwarf Supernova
  - Binary systems only
  - Occurs in older star populations
  - Nothing left
- Massive Star Supernova
  - Found in young star formation regions
  - Make neutron stars or black holes

Neutron Stars

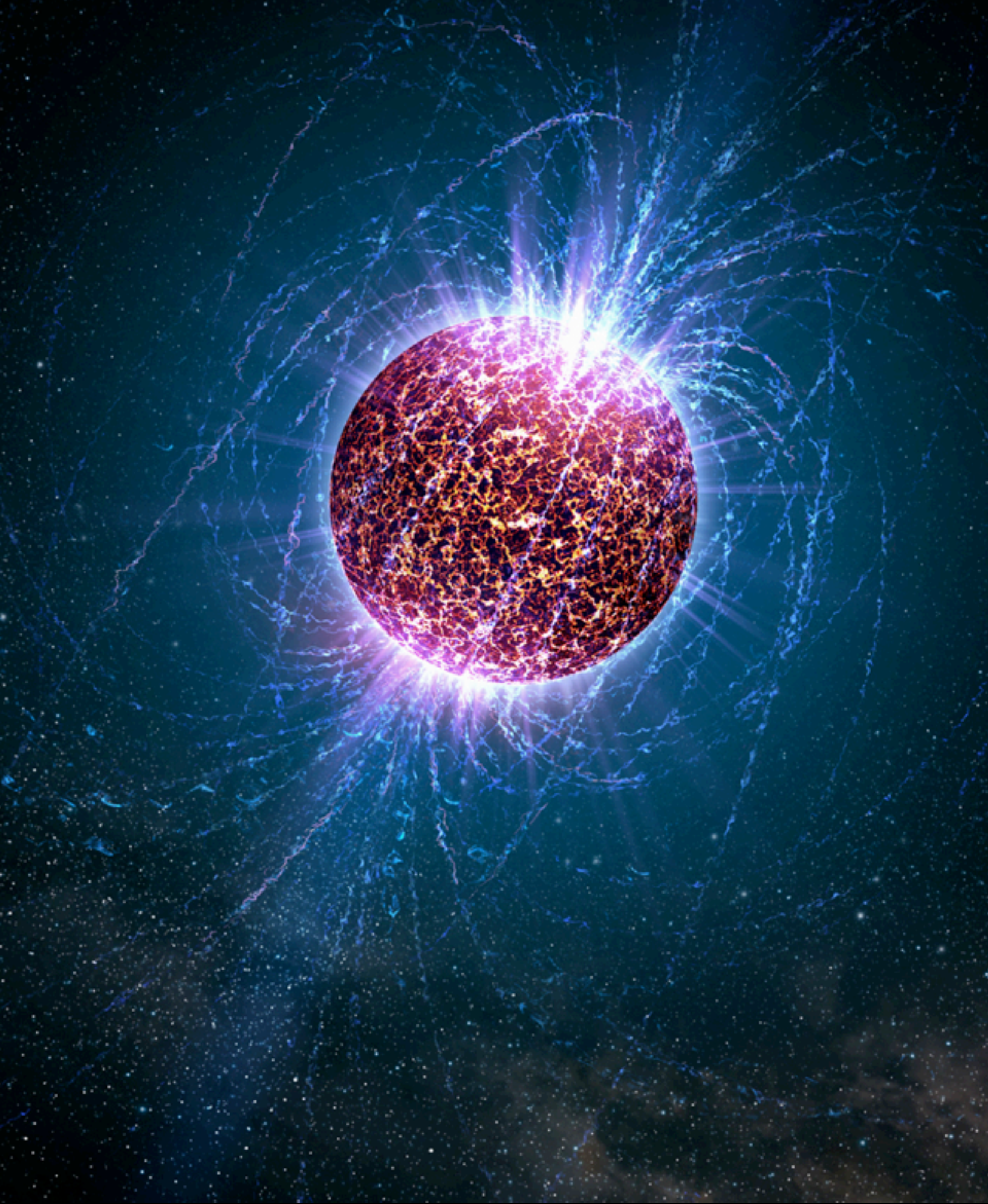
- Structure determined by gravity vs. neutron degeneracy pressure
- Size ~ 10 km
- Mass ~ 1 - 3 M_{Sun}
- More massive = smaller!!
- Extremely strong gravity at surface (v_{escape} ~ 0.5c)
- Sun's worth of mass compressed into a city size (1 teaspoon = 10 million tons)
- Spinning very rapidly (why?)



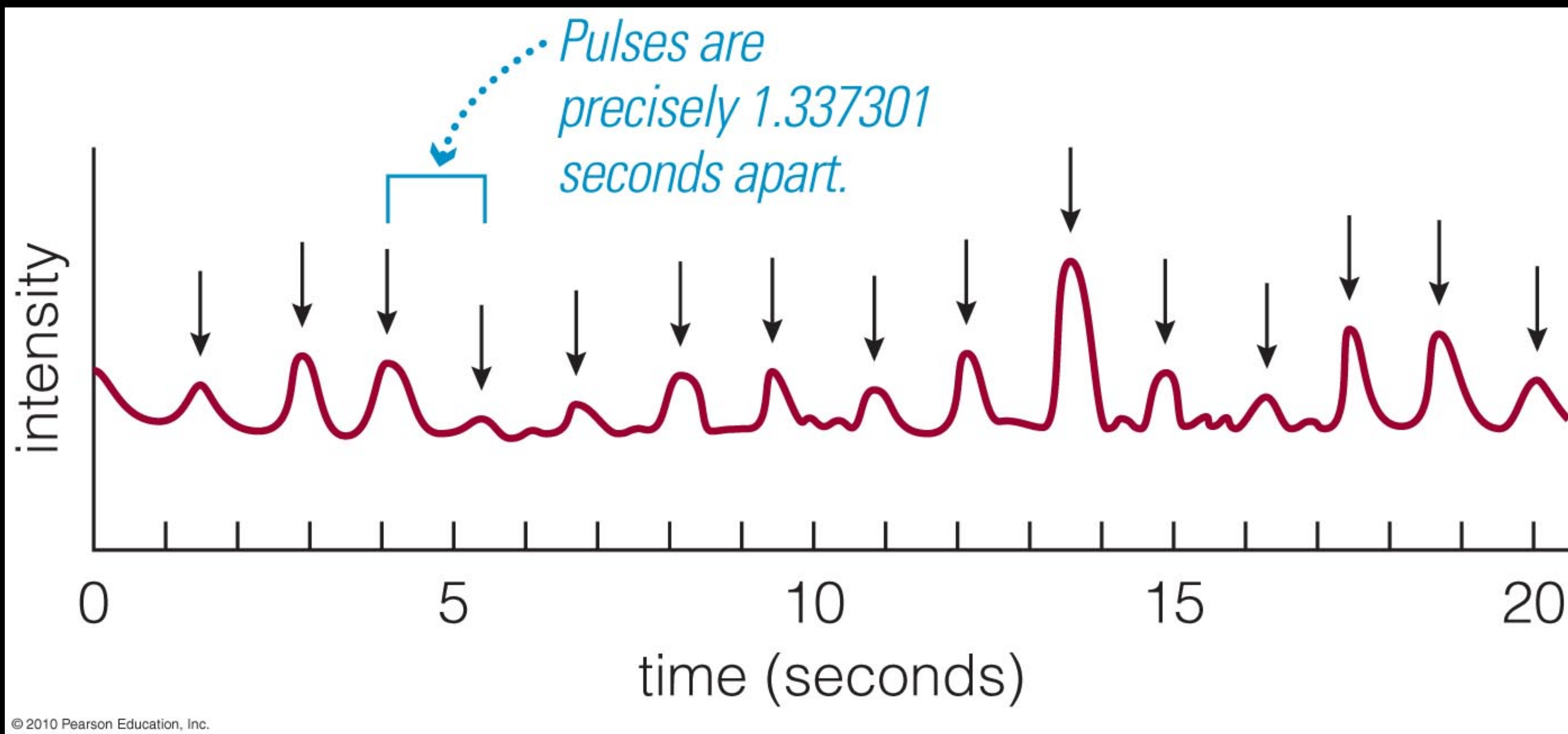
Neutron star over Boulder

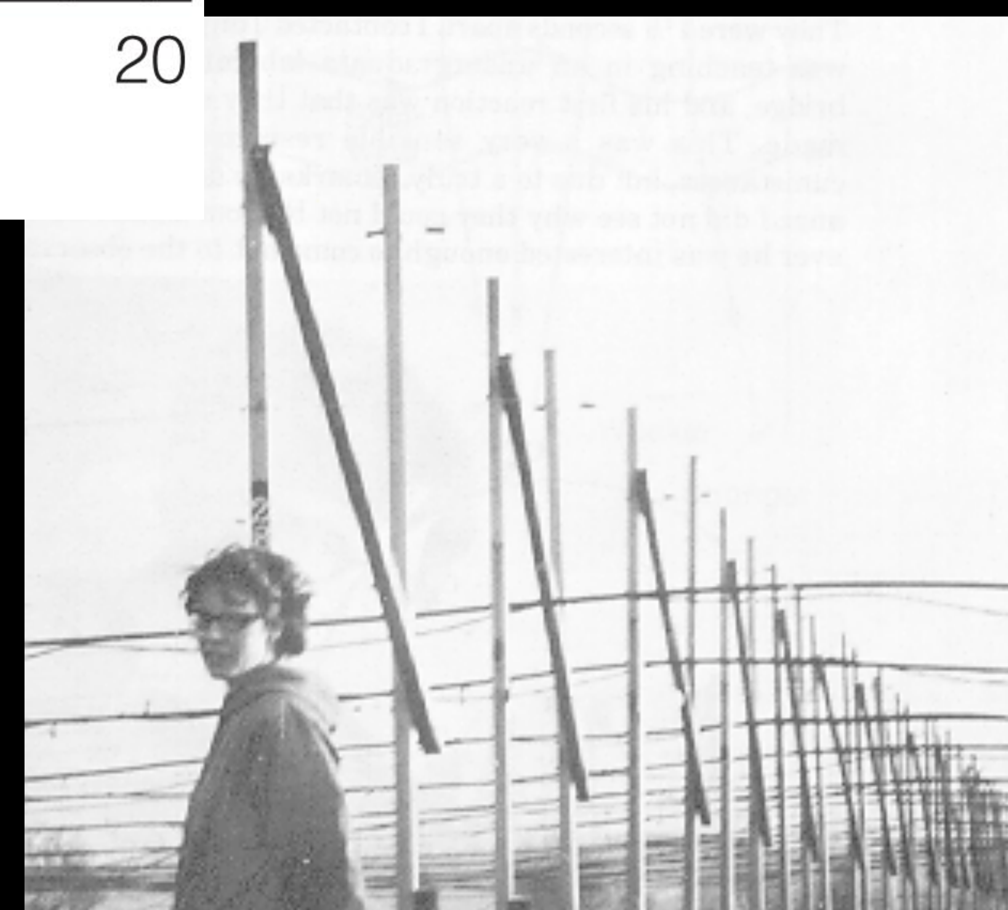
Results of Conservation

- Conservation of Angular Momentum
  - Extremely fast rotation rate (100s to 1000s of times per second!)
- Conservation of Magnetic Flux
  - Intense magnetic fields (10^{12} Gauss -- 1 trillion times that of the Earth’s magnetic field!)



Evidence for Rapid Rotation: The Pulsar

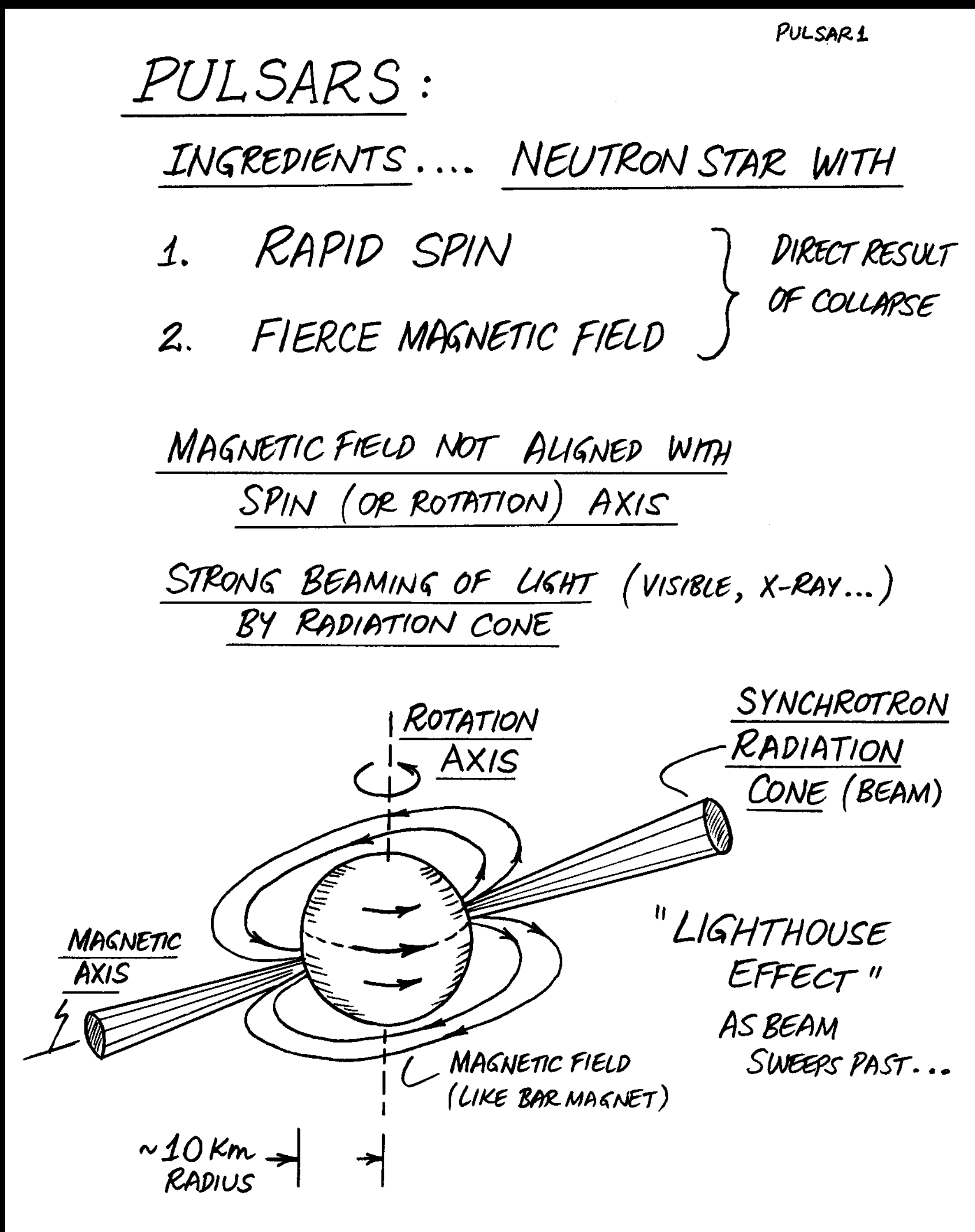




Jocelyn Bell: Cambridge (UK) graduate student in 1967 (+Anthony Hewish) discovered pulsars by accident!

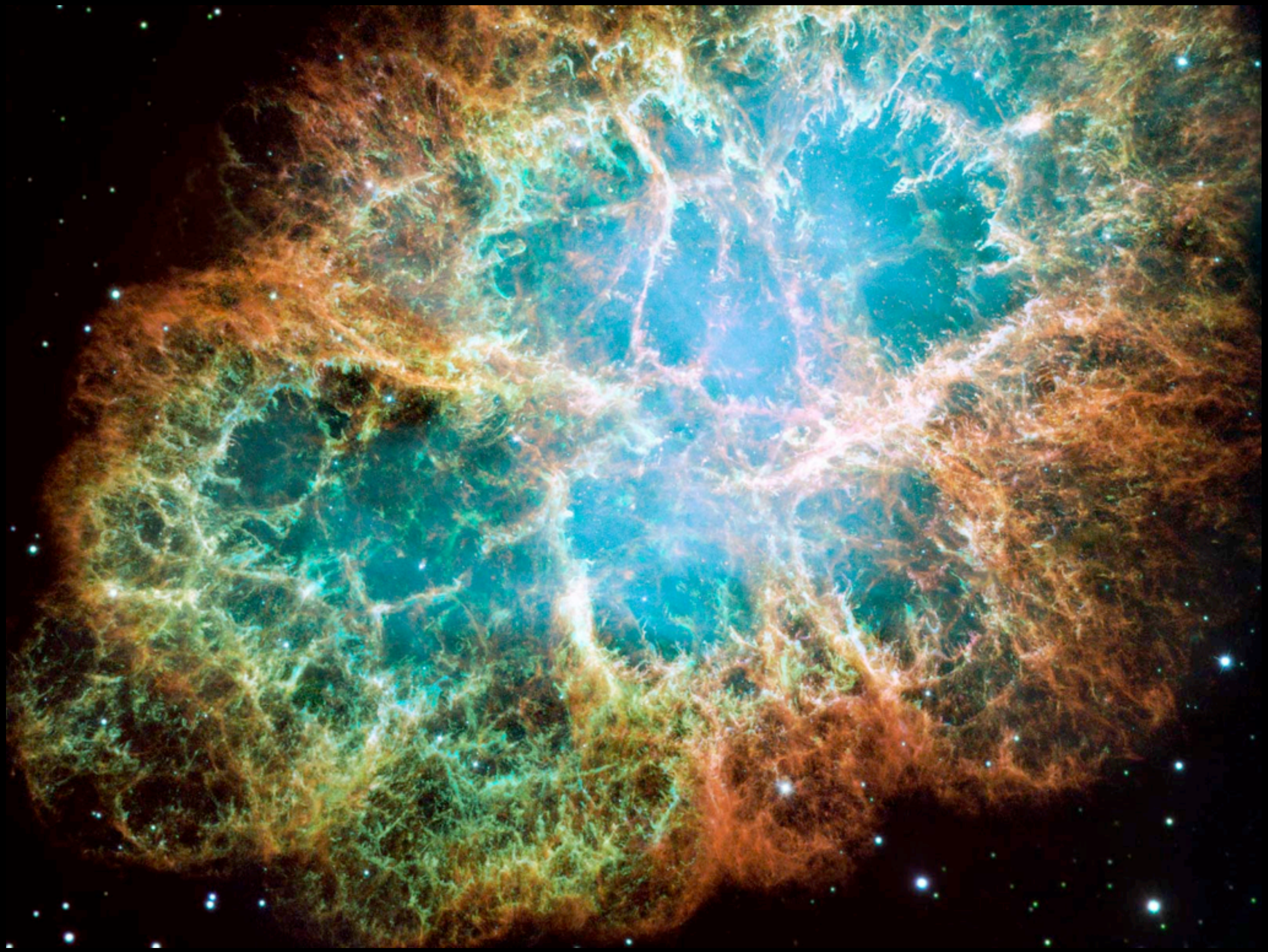
Named it LGM-1 (Little Green Men)
Just WHAT could cause the signal?

Theory of Pulsars

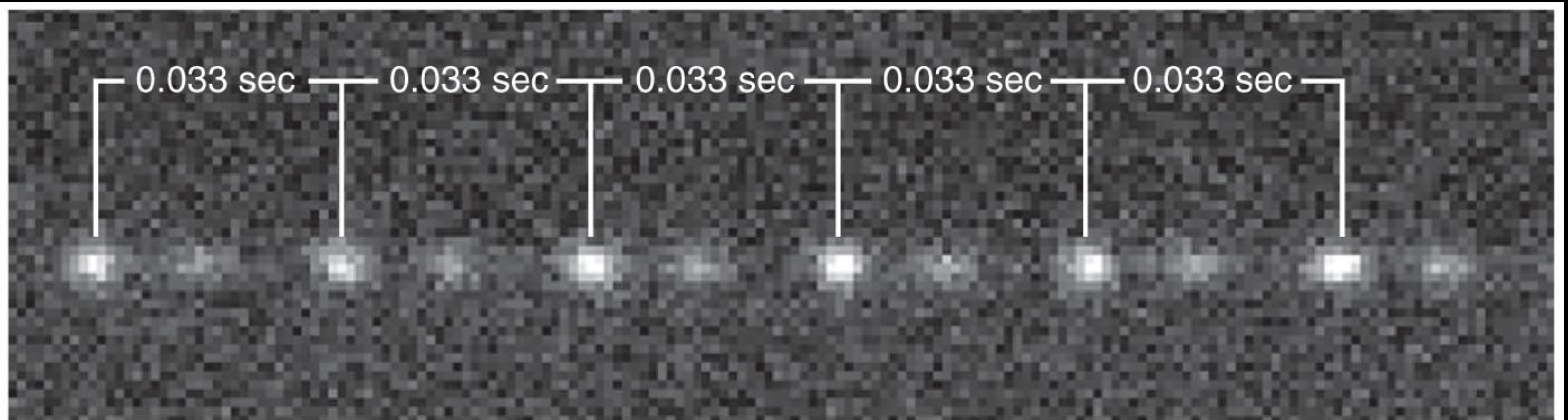


- Charged particles travel along fierce magnetic fields toward magnetic poles
- Results in beams of radiation
- Acts as a cosmic "lighthouse"

Mystery Solved



Pulsar discovered in a known supernova remnant, the Crab Nebula



When a neutron star is formed, will we (on Earth) always see a pulsar?

A) Yes, because due to conservation of angular momentum the neutron star will always be spinning.

B) Yes, neutron stars always give off pulses of light which we can detect with sensitive enough telescopes.

C) No, some neutron stars don't spin.

D) No, it depends on the orientation of the neutron star's magnetic field.

It’s….. DEMO TIME!

What if you put a neutron star in a close binary?

- Matter from companion can fall onto the neutron star --> accretion disk
- In-falling matter releases lots of energy, heats up the disk, glows in X-rays
  - Called an X-ray binary
- Hydrogen that falls onto the neutron star surface is steadily fused into helium
- Helium “ash” builds up over time, once temperature reaches 100 million K, the helium ignites!
  - Called an X-ray burst (similar to white dwarf novae)

But what if the mass is too great?

- When neutron degeneracy pressure can’t cut the mustard...

...our supernova core becomes a **BLACK HOLE**!

All of the mass collapses to a single point

No solid surface for mass to build up on

Our Stellar Graveyard

- Source: Lower mass stars (<8 M_{Sun})
  - Result: White Dwarfs
    - Balance: Gravity vs. electron degeneracy pressure
- Source: High mass stars (8~20 M_{Sun})
  - Result: Neutron Stars
    - Balance: Gravity vs. neutron degeneracy pressure
- Source: Most massive stars (>20M_{Sun})
  - Result: Black Holes
    - No balance, Gravity wins

Stop: Tutorial Time

Types of Spectra, pg. 61