REVIEW

Stellar energy sources

- Key test has been to
  - Determine the efficiency of a given energy source in **energy/mass** of the fuel
  - Calculate the **total energy** from that source given the mass of the Sun. For example: proton fusion

$$6.4\times10^{18}\,\frac{ergs}{gram}\times\left(2\times10^{33}\,grams\right)=12.8\times10^{51}\,ergs$$

  - Calculate the **lifetime** of the Sun given the total energy and the Sun's luminosity

$$\frac{12.8\times10^{51}\,ergs}{4\times10^{33}\,\frac{ergs}{\text{sec}}}=3.2\times10^{18}\,\text{sec}=10^{11}\,\text{years}$$

REVIEW

Energy Source for stars

- Coal/wood burning (conversion of molecular bonds to energy) too inefficient

4×10^{12} ergs/gram

- Contraction of the Sun over time: gravitational potential energy to heat too inefficient

1×10^{15} ergs/gram

REVIEW

Energy Source for stars

- Nuclear *fission* converting nuclear bonds into heat when "heavy" element (large number of protons and neutrons) nuclei break apart

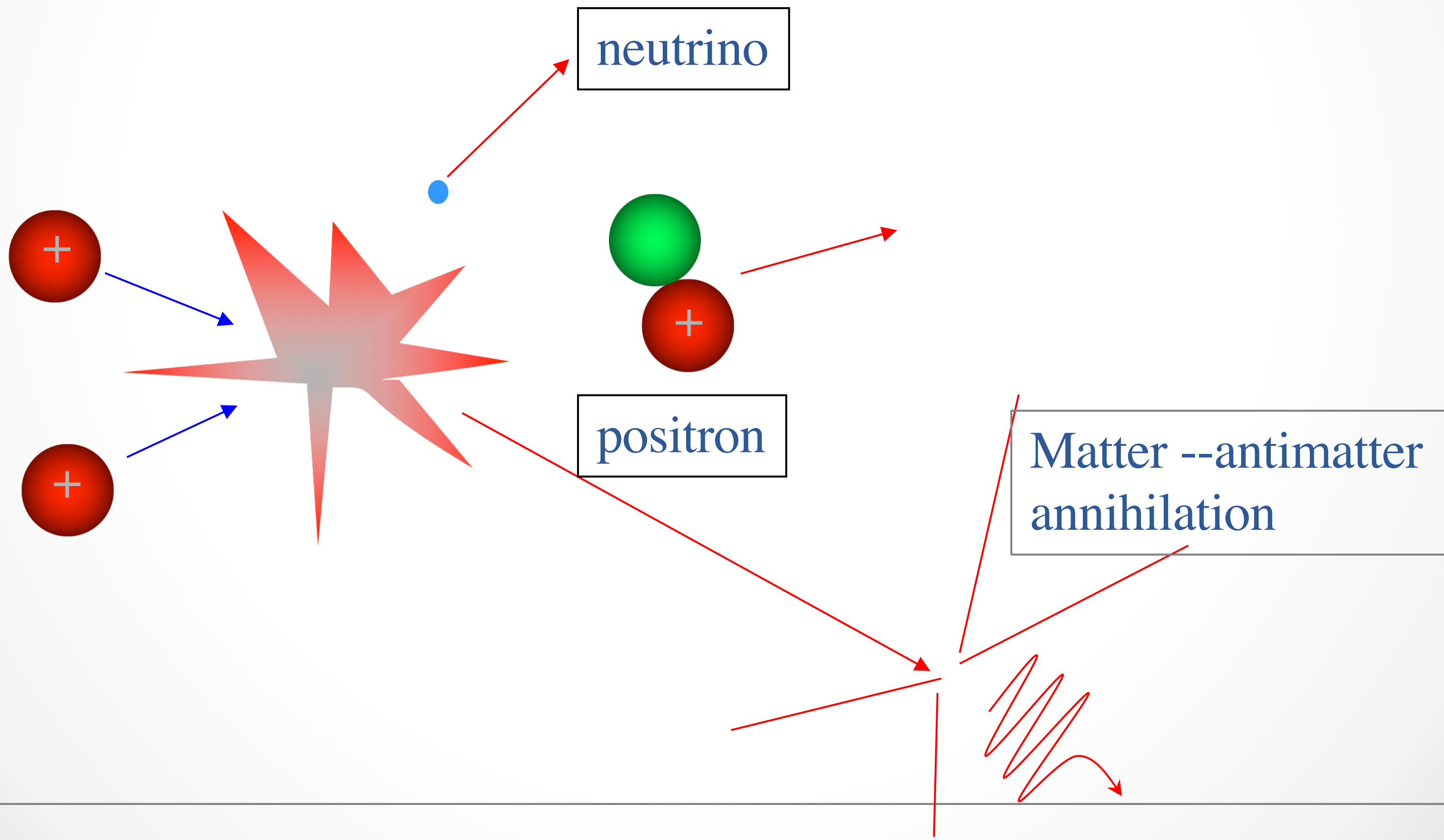
1×10^{18} ergs/gram

- This source is efficient enough to power the Sun for 6×10^{10} years = 60 billion years (age of the Sun is ~4.5 billion). Passes the lifetime test, but only a tiny fraction of the Sun is composed of fissionable material like Uranium

REVIEW

The answer: Hydrogen Fusion

- p^+-p^+ fusion



REVIEW

Fusion-powered Sun

1) Lots of fuel (hydrogen)

2) Conditions are right in the central 10% for the P-P cycle to run (temp > 10^7 K)

3) P-P fusion is efficient enough to power the Sun for billions of years.

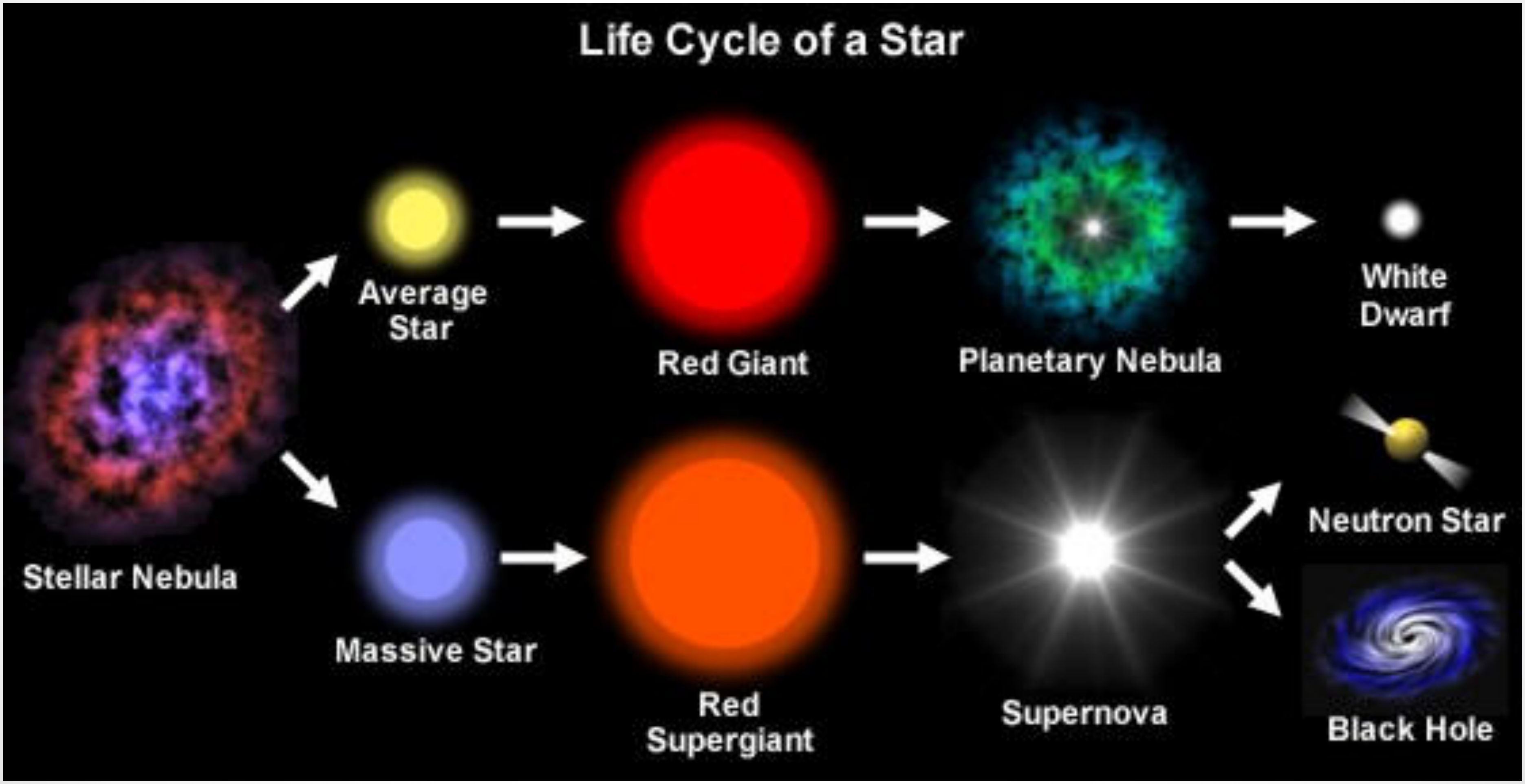
Clicker quiz

Which of the following best describes the basis for hydrostatic models of stars?

A. Gravity causes stars to be compressed to a liquid state
B. Explosions due to fusion are balanced against gravitational forces
C. The mass of a star is perfectly match by the volume of a star
D. The thermal expansion forces of a star are balanced by the gravitational contraction forces

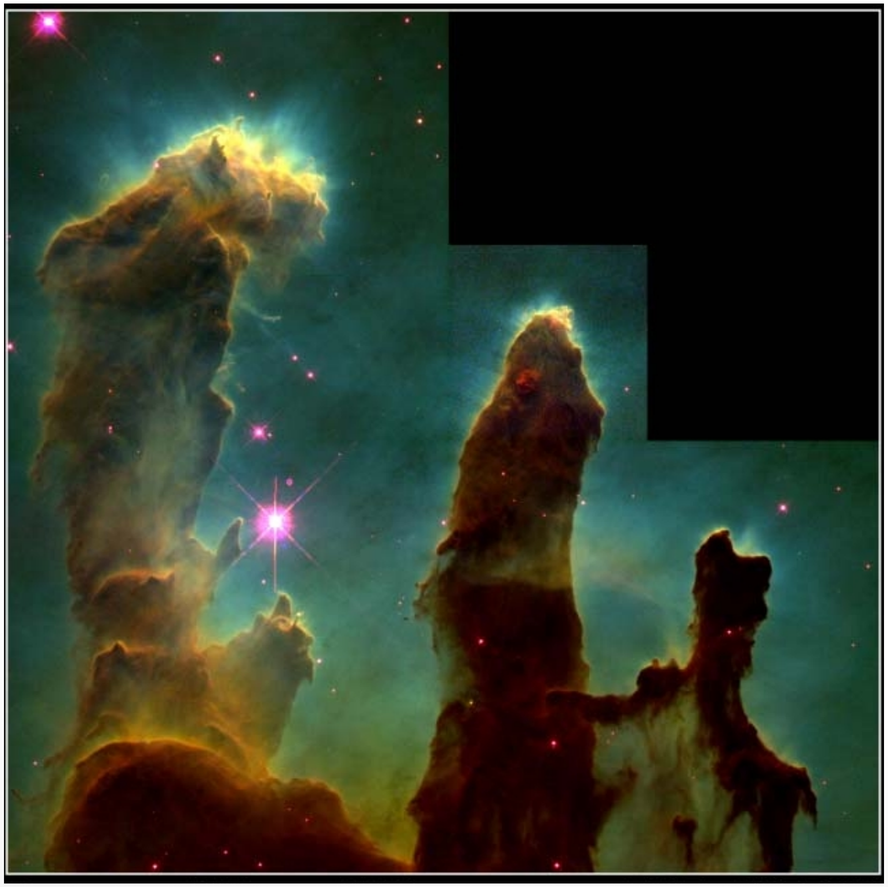
Stellar Evolution

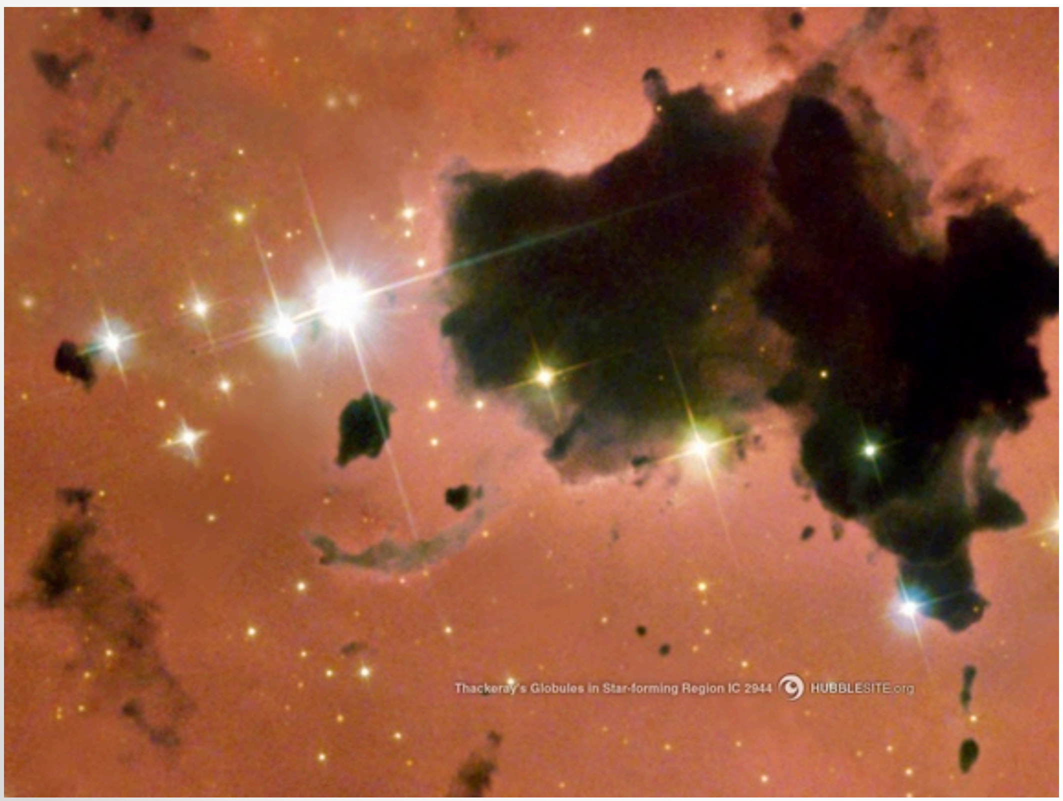
stars are born and stars die



Star Formation

Stars are born when gas in very cold regions collapses and converts gravitational potential energy into heat and reaches 15 million K to start hydrogen fusion.



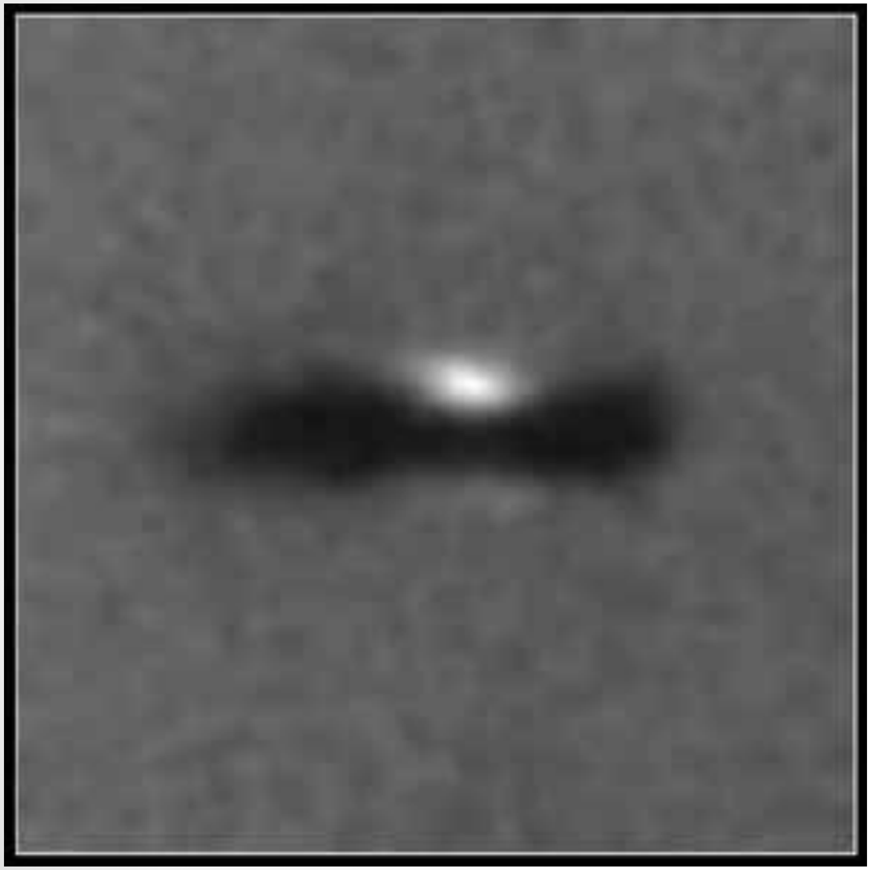


Gravitational collapse to a protostar requires very low temperatures and even the heating by the ambient light in the Galaxy can prevent star formation.

Deep in the hearts of dust clouds is where stars are born.

The basic requirement is for gravity to overcome thermal pressure and have a volume of space begin to contract

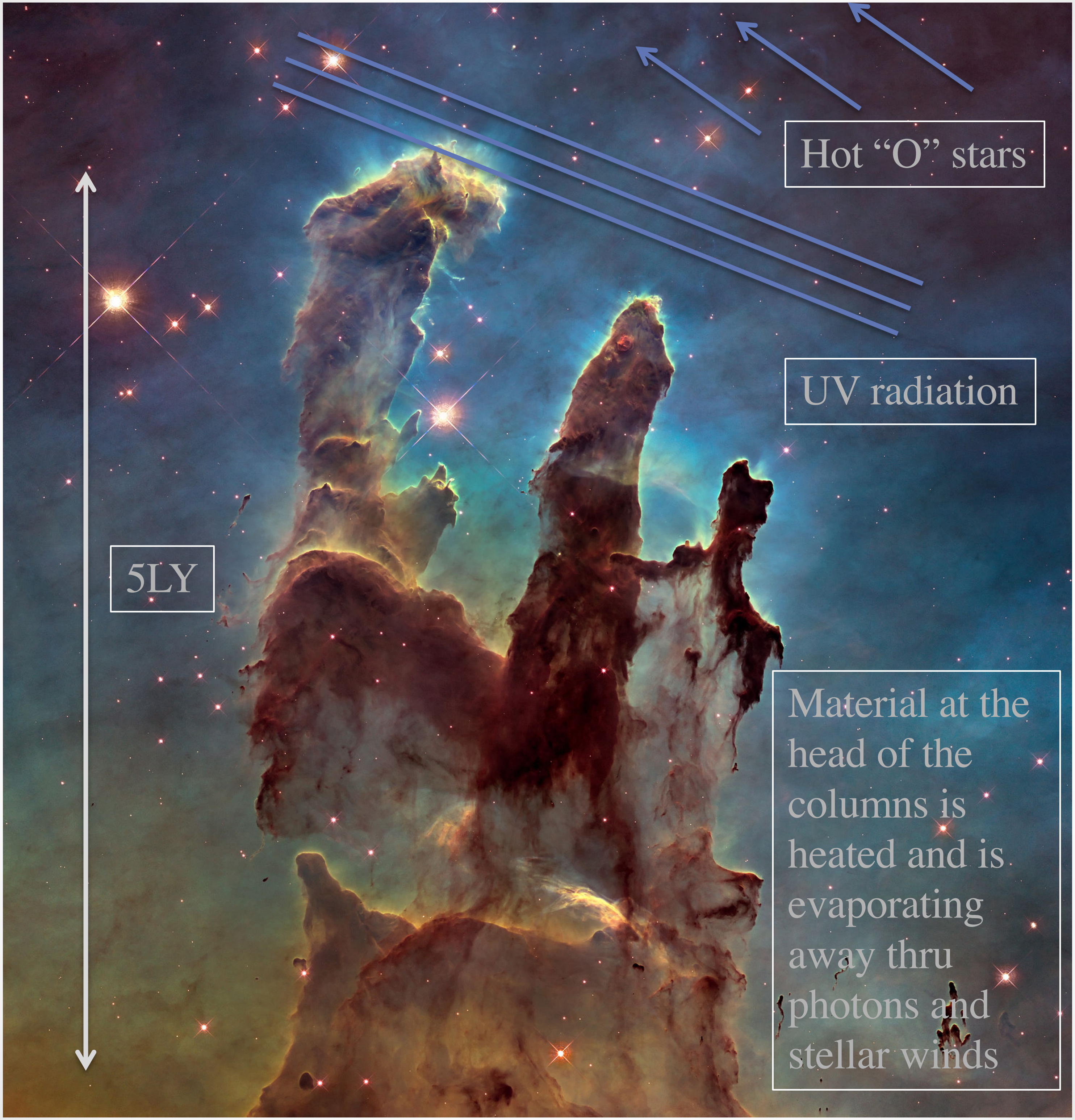
Protostar



- The contracting mass heats up (conversion of gravitational potential energy)
- As it contracts it starts to spin faster (conservation of angular momentum) and some material forms a disk
- If there is enough initial mass that the central temperature reaches 10 million K, the fusion starts and a star is born
- The radiation field heats and shreds the initial cloud from which it formed

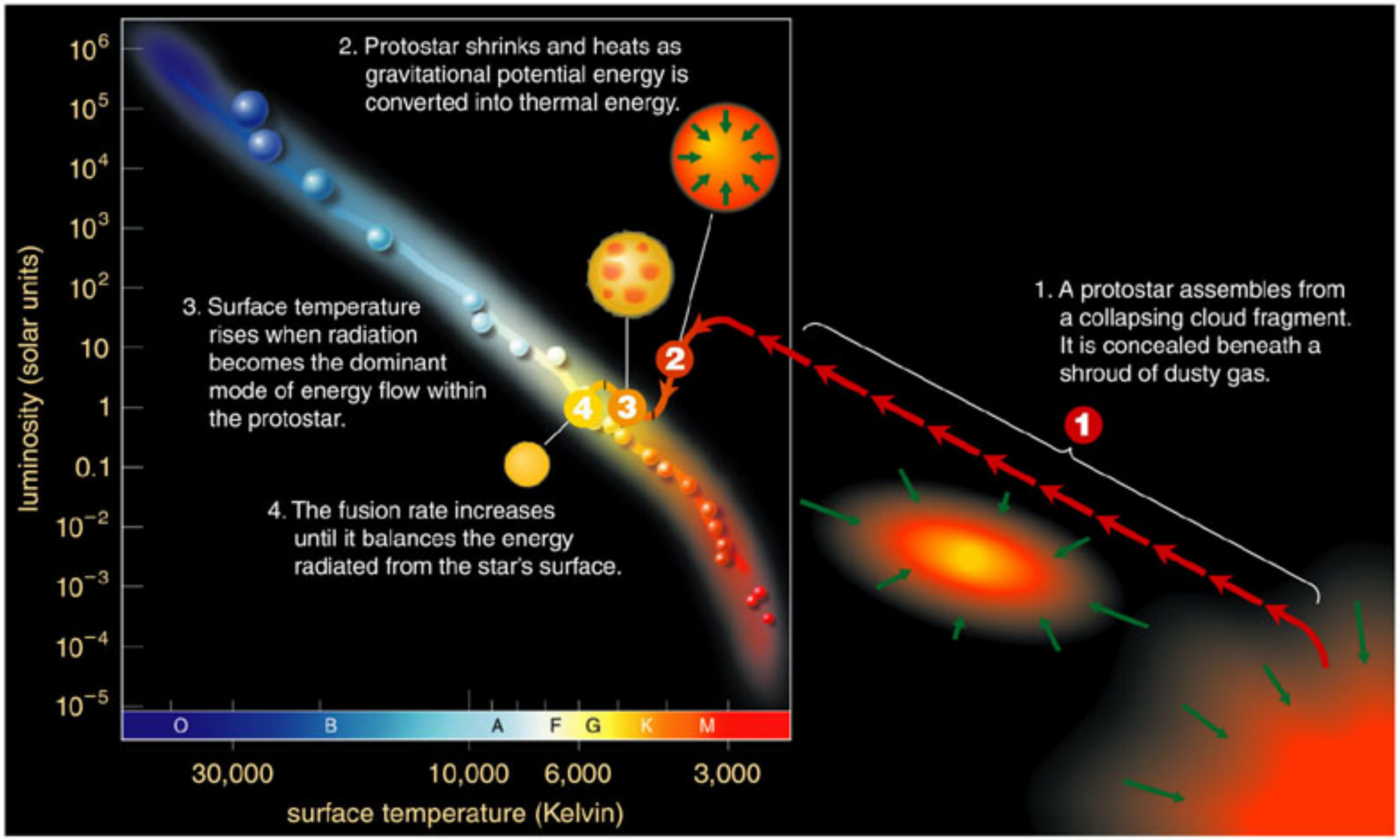
Dust lanes in the plane of the Galaxy

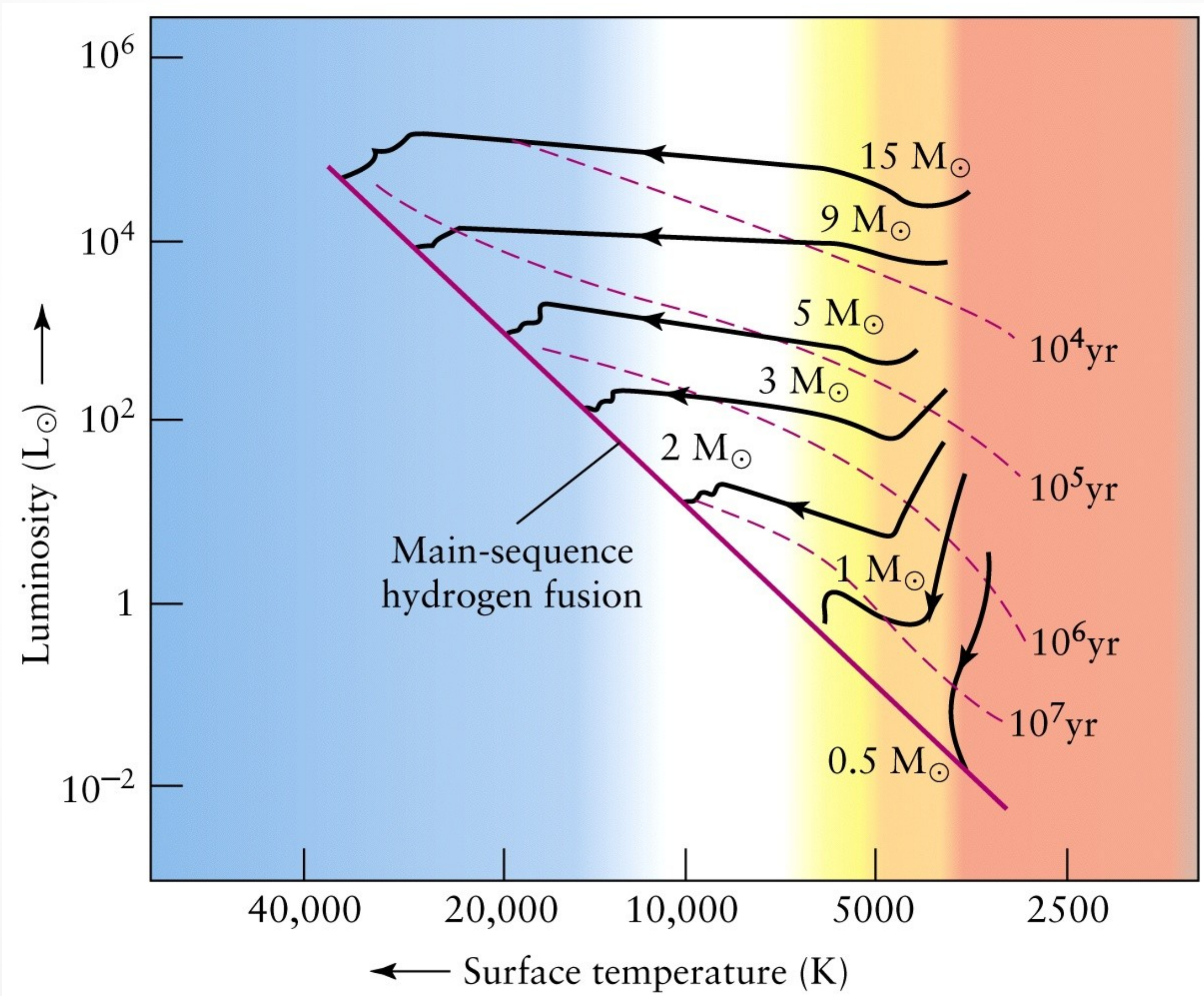
When stars are born they blast the nebula clear


Hot "O" stars
UV radiation
5LY
Material at the head of the columns is heated and is evaporating away thru photons and stellar winds


Hot stars
Eagle Nebula is ~7000 LY distant

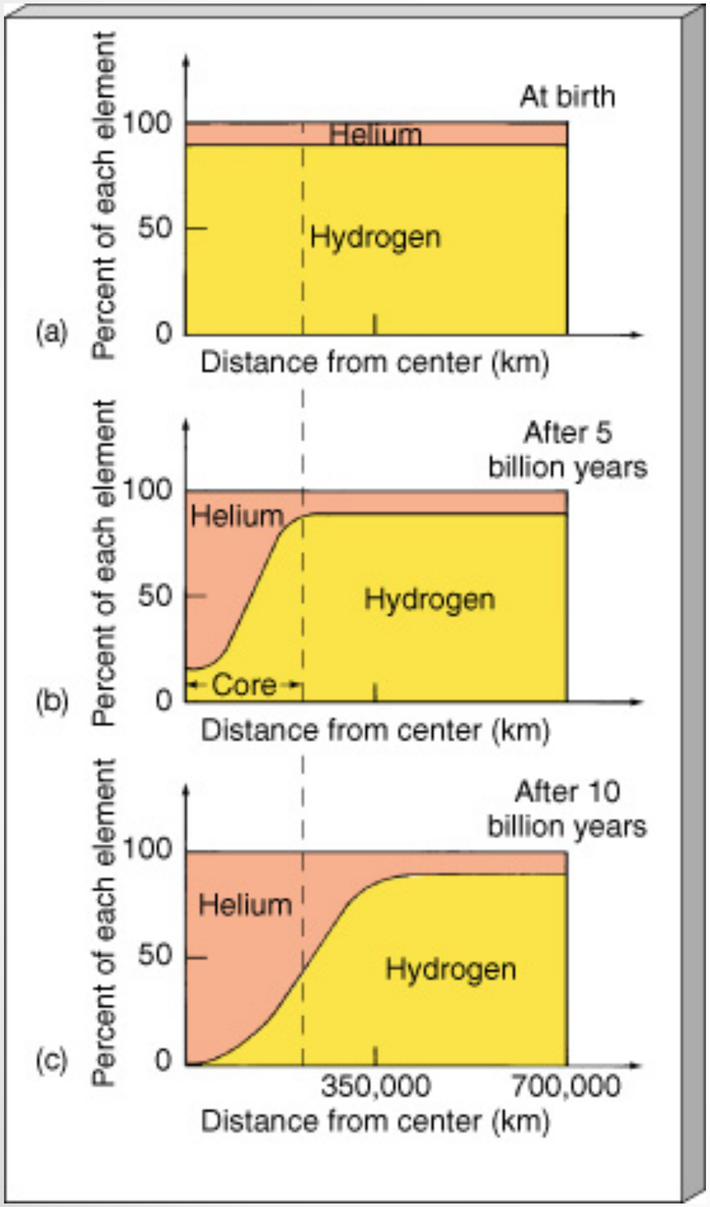
Protostars and the HR diagram





10^6
10^4
10^2
1
10^−2
Luminosity (L☉)
15 M☉
9 M☉
5 M☉
3 M☉
2 M☉
1 M☉
0.5 M☉
10^4yr
10^5yr
10^6yr
10^7yr
Main-sequence
hydrogen fusion
40,000
20,000
10,000
5000
2500
Surface temperature (K)

Stellar Evolution



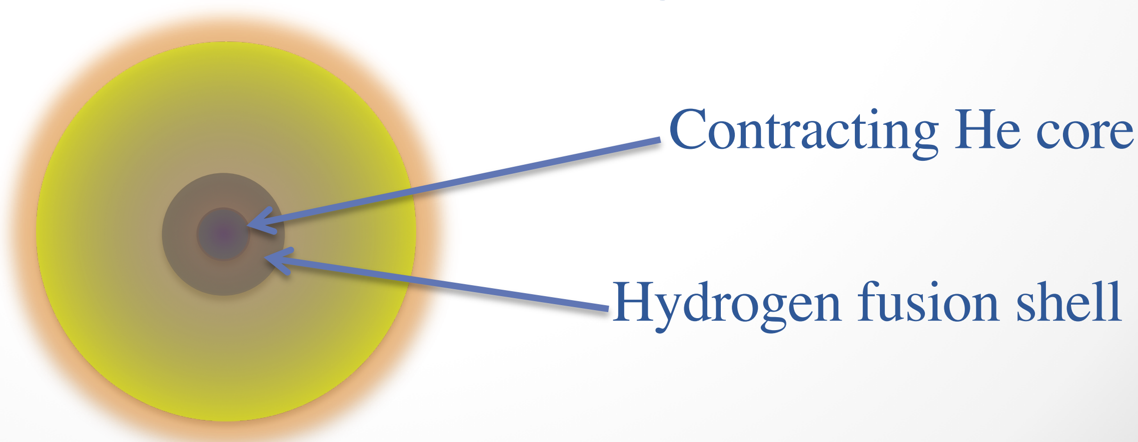
- Once on the Main Sequence, as hydrogen is being converted into helium in the core of a star, its structure changes slowly and stellar evolution begins.
- The structure of the Sun has been changing continuously since it settled in on the main sequence.

Stellar Evolution

- As the helium core grows, it compresses. Helium doesn't fuse to heavier elements for two reasons.
  - with two p+ per nucleus, the electric repulsion force is higher than was the case for H-fusion. This means that *helium fusion requires a higher temperature than hydrogen fusion* -- 100 million K
  - $He^4 + He^4 = Be^8$. This reaction doesn't release energy, it requires input energy. This particular Be isotope is very unstable.

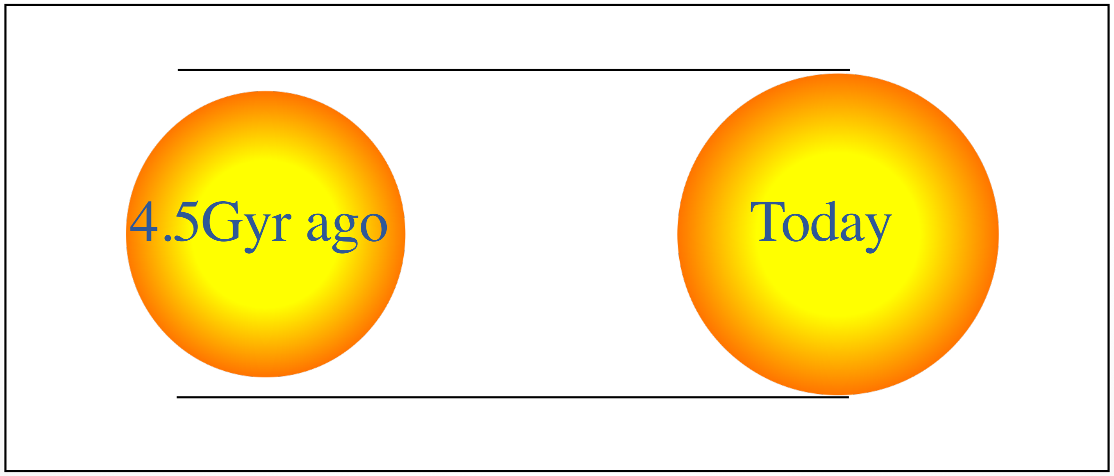
Stellar Evolution

- As the Helium core contracts, it releases gravitational potential energy and heats up.
- Hydrogen fusion continues in a shell around the helium core.
- *Once a significant helium core is built, the star has two energy sources.*
- Curiously, as the fuel is being used up in the core of a star, its luminosity is increasing



Stellar Evolution

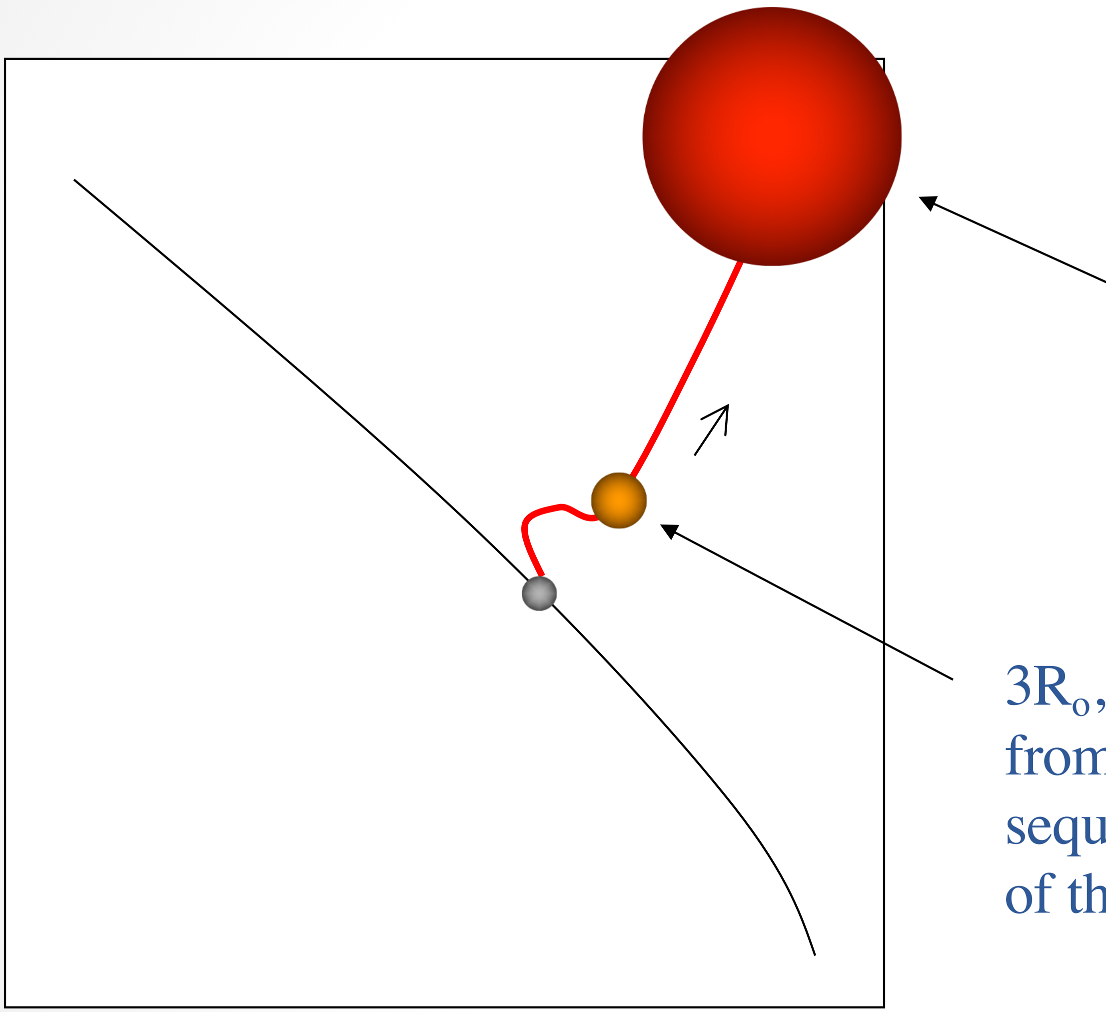
- Stars begin to evolve off the zero-age main sequence from day 1.
- Compared to 4.5 Gyr ago, the radius of the Sun has increased by 6% and the luminosity by 40%.



Red Giants

- Hydrostatic equilibrium is lost and the tendency of the Sun to expand wins a little bit at a time with its dual energy source. The Sun is becoming a Red Giant. Will eventually reach:
    - $L \sim 2000 L_{o}$
    - $R \sim 0.5$AU (half way to the Earth)
    - $T_{surface}$->3500k

Red Giant

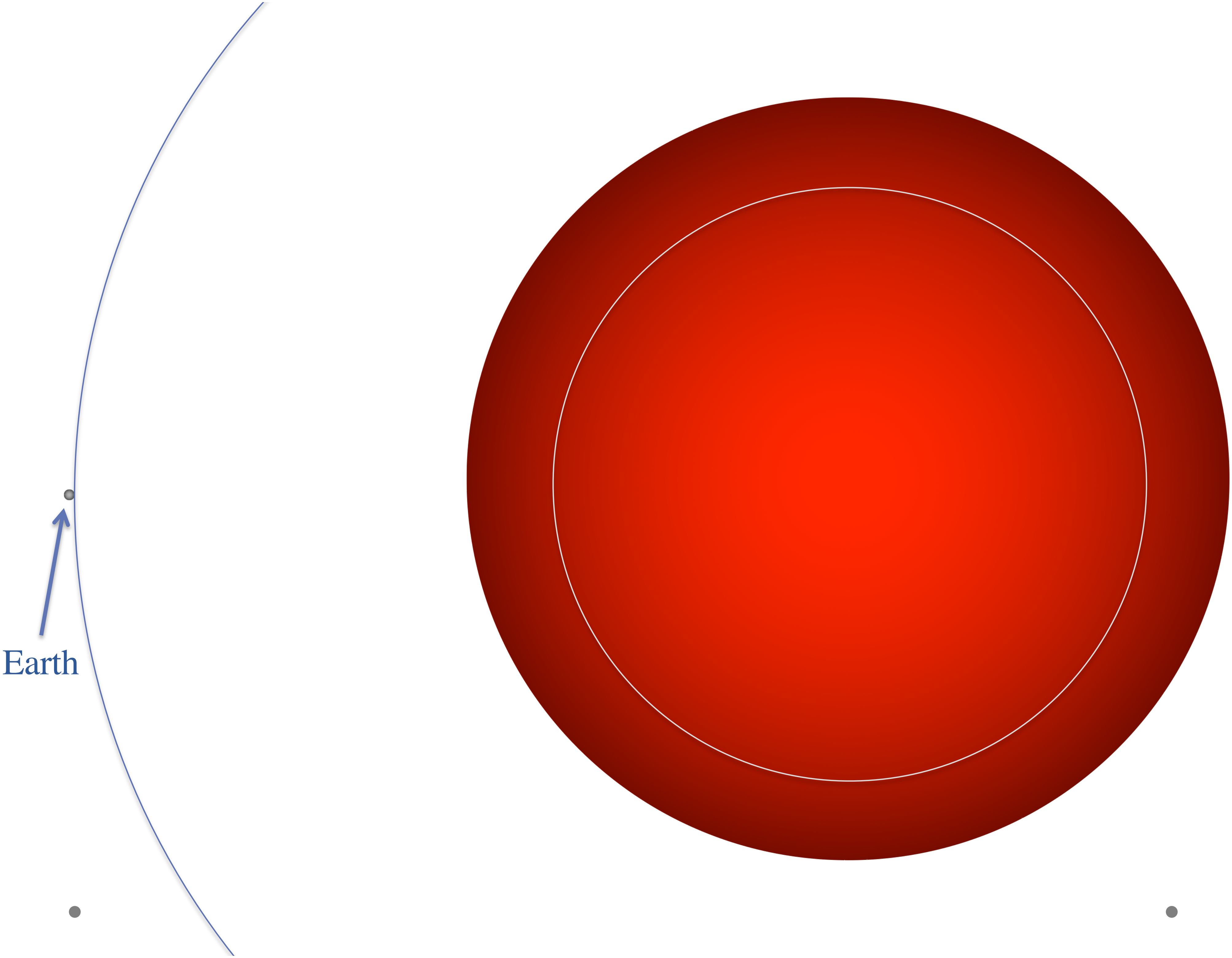


L

Temperature

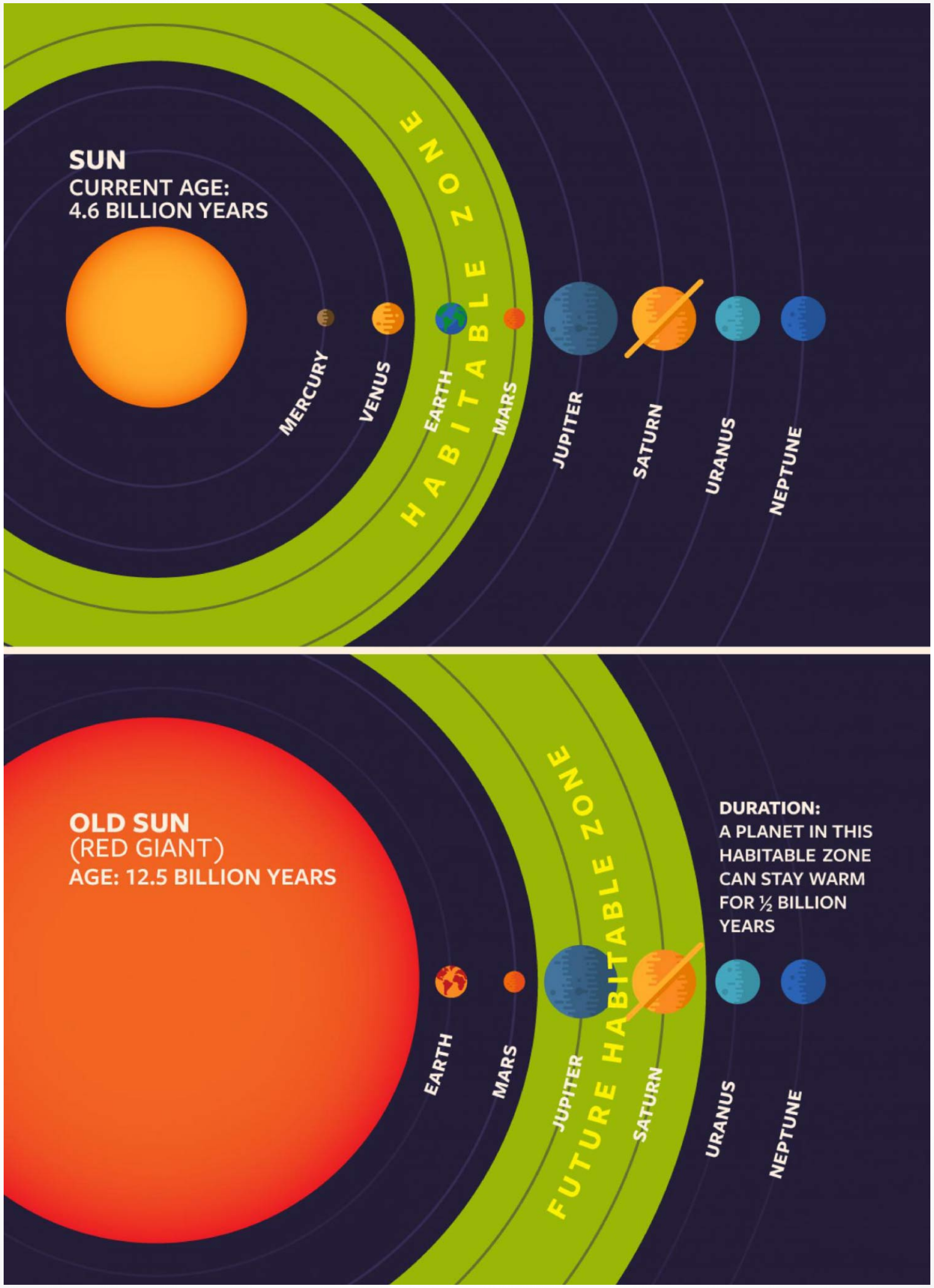
$100R_o$ 10^8years

$3R_o$, 10^{10}years:10 billion years from settling on the main sequence to evolving to the base of the red giant branch

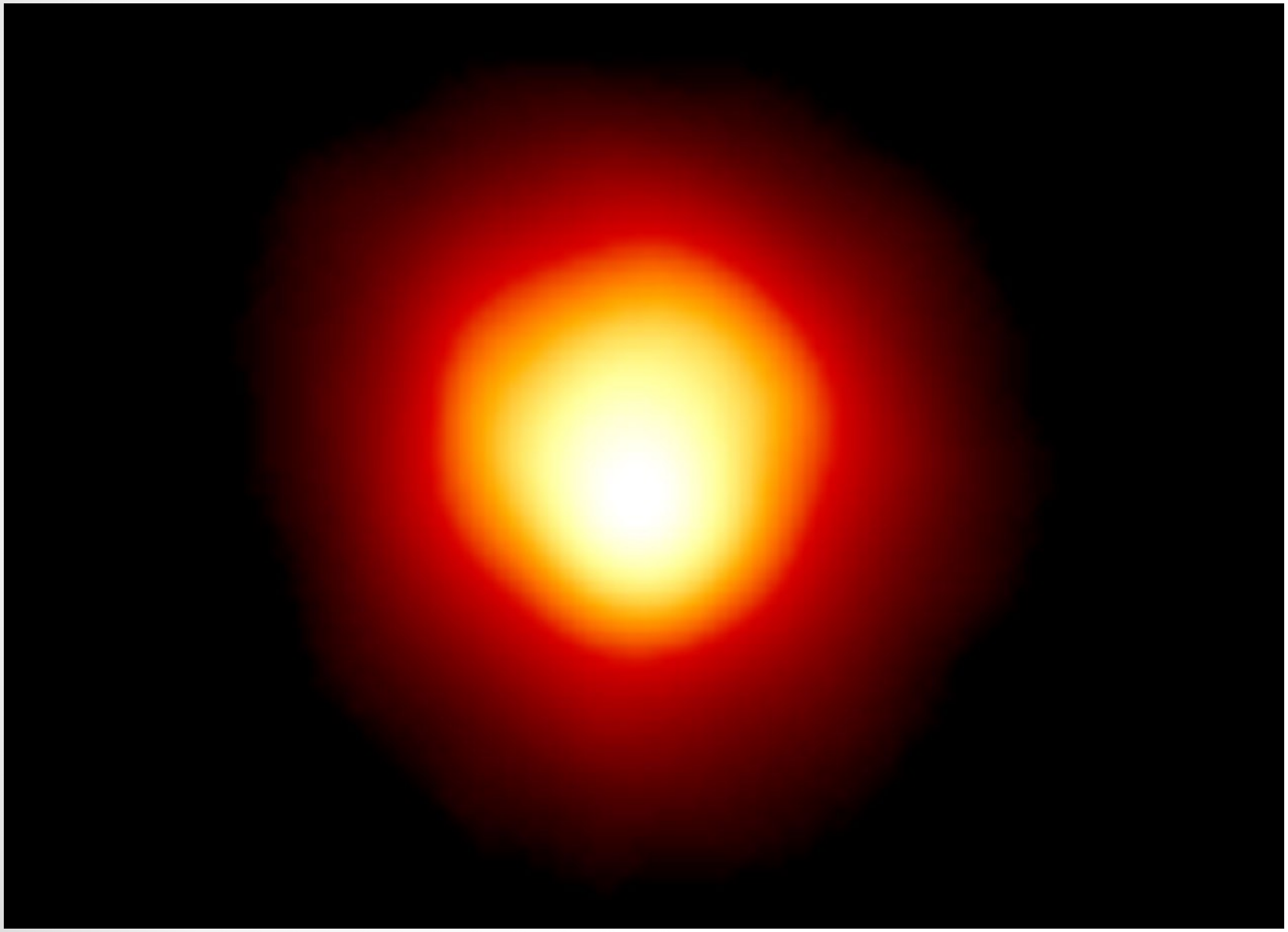

Earth

Sun as a Red Giant

- When the Sun becomes a Red Giant, Mercury and Venus will be vaporized, the Earth burned to a crisp.
- Long before the Sun reaches the tip of the RGB (red giant branch) the oceans will be boiled away and most life will be gone.
- The most `Earthlike' environment at this point will be Titan, a moon of Saturn.


SUN
CURRENT AGE:
4.6 BILLION YEARS
HABITABLE ZONE
MERCURY
VENUS
EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE
OLD SUN
(RED GIANT)
AGE: 12.5 BILLION YEARS
FUTURE HABITABLE ZONE
DURATION:
A PLANET IN THIS HABITABLE ZONE CAN STAY WARM FOR ½ BILLION YEARS
EARTH
MARS
JUPITER
SATURN
URANUS
NEPTUNE

Red Giants



We have inferred large radii and low surface temperatures for many stars and with special techniques have resolved the nearest red giants and verified the models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Red giants in an old open cluster

Note there are many more main-sequence stars than red giants consistent with the theory-based relative lifetimes in the two stellar phases

Helium Fusion

Be natural for Helium fusion in the core to be the next energy source for an evolving star

Helium fusion requires two steps:

$He^4 + He^4 \rightarrow Be^8$

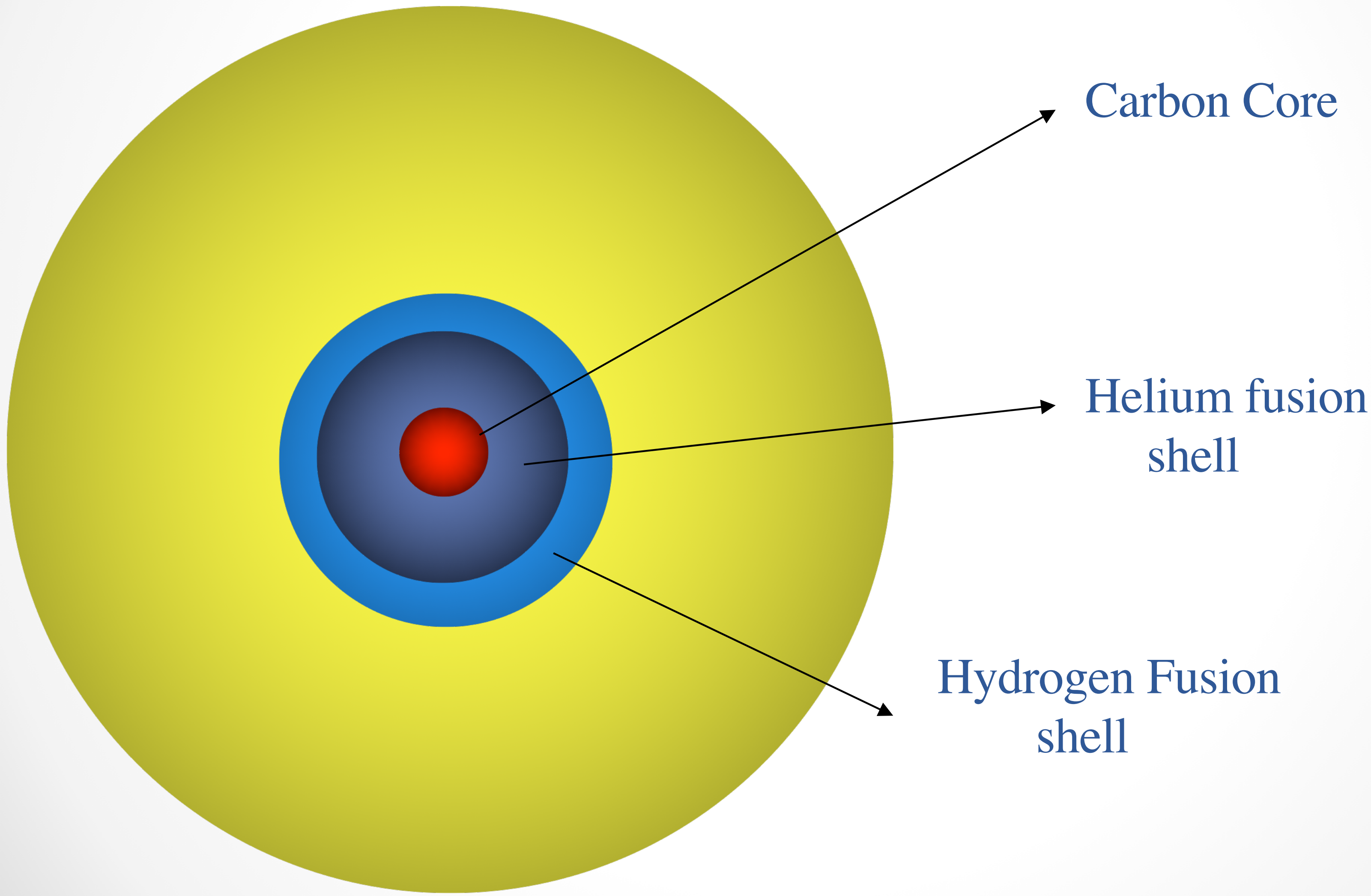
$Be^8 + He^4 \rightarrow C^{12}$

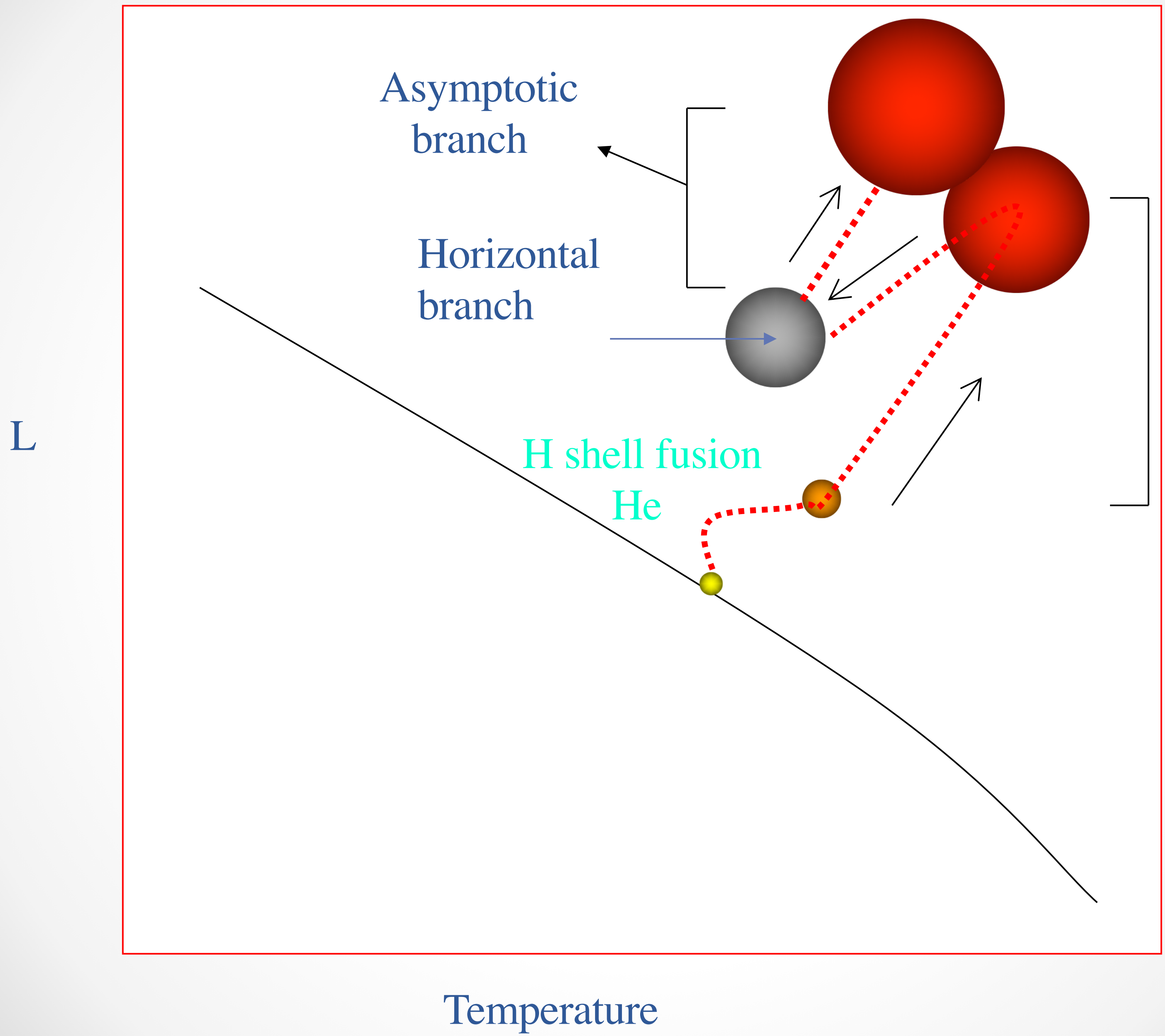
The Beryllium falls apart in 10^{-6} seconds so you need not only high enough T to overcome the electric forces, you also need very high density so there are some Be^8 nuclei around.

Red Giants and He fusion

- It was realized in the 1960s that the contracting helium core of a star moving up the giant branch was one of the places where it was **hot** enough and **dense** enough for Helium to Berylium to Carbon fusion to occur:
  - 100 million K
  - 100,000 gm/cm^2

Giant Star Structure

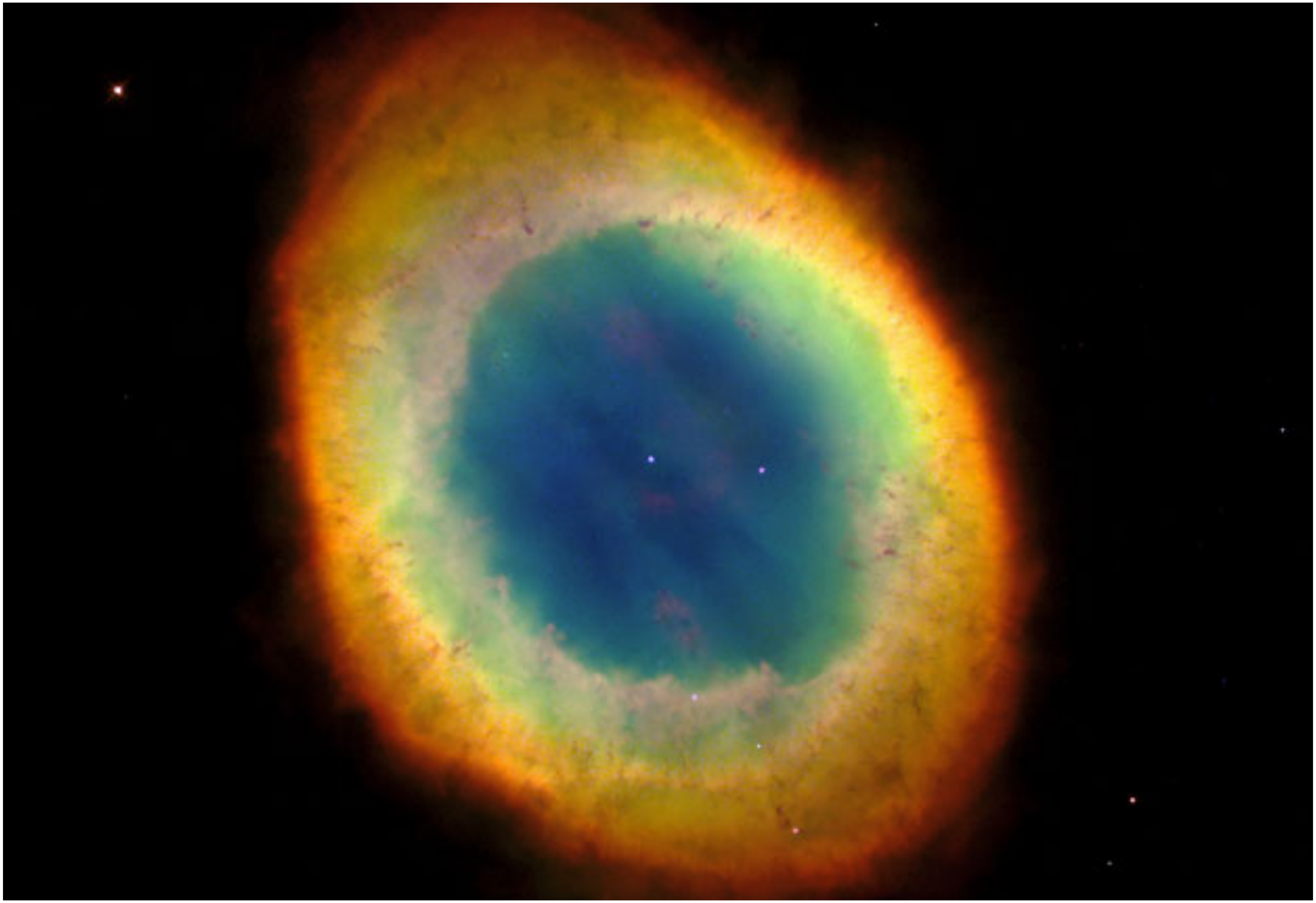


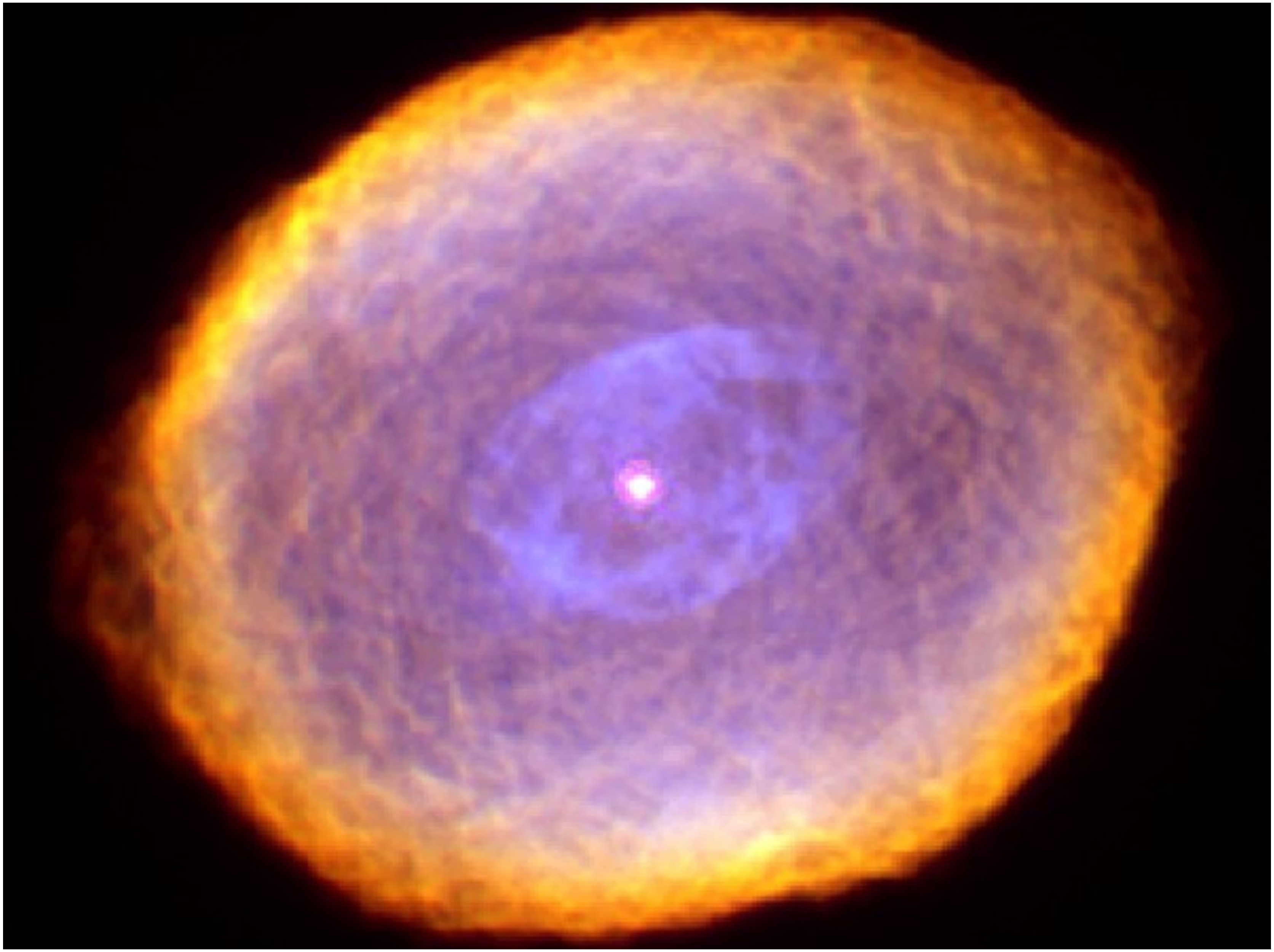


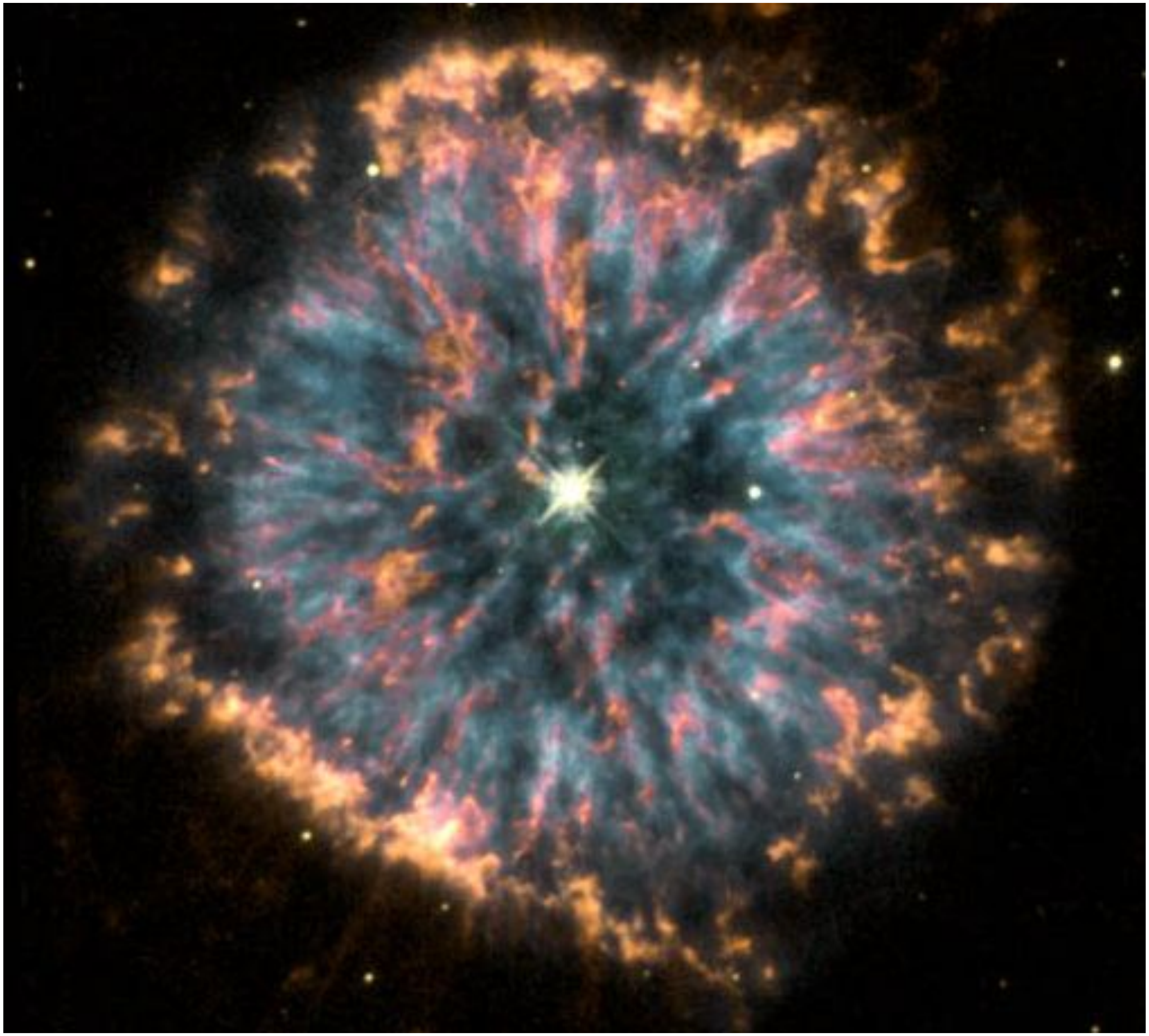
Asymptotic branch
Horizontal branch
H shell fusion
He
L
Temperature

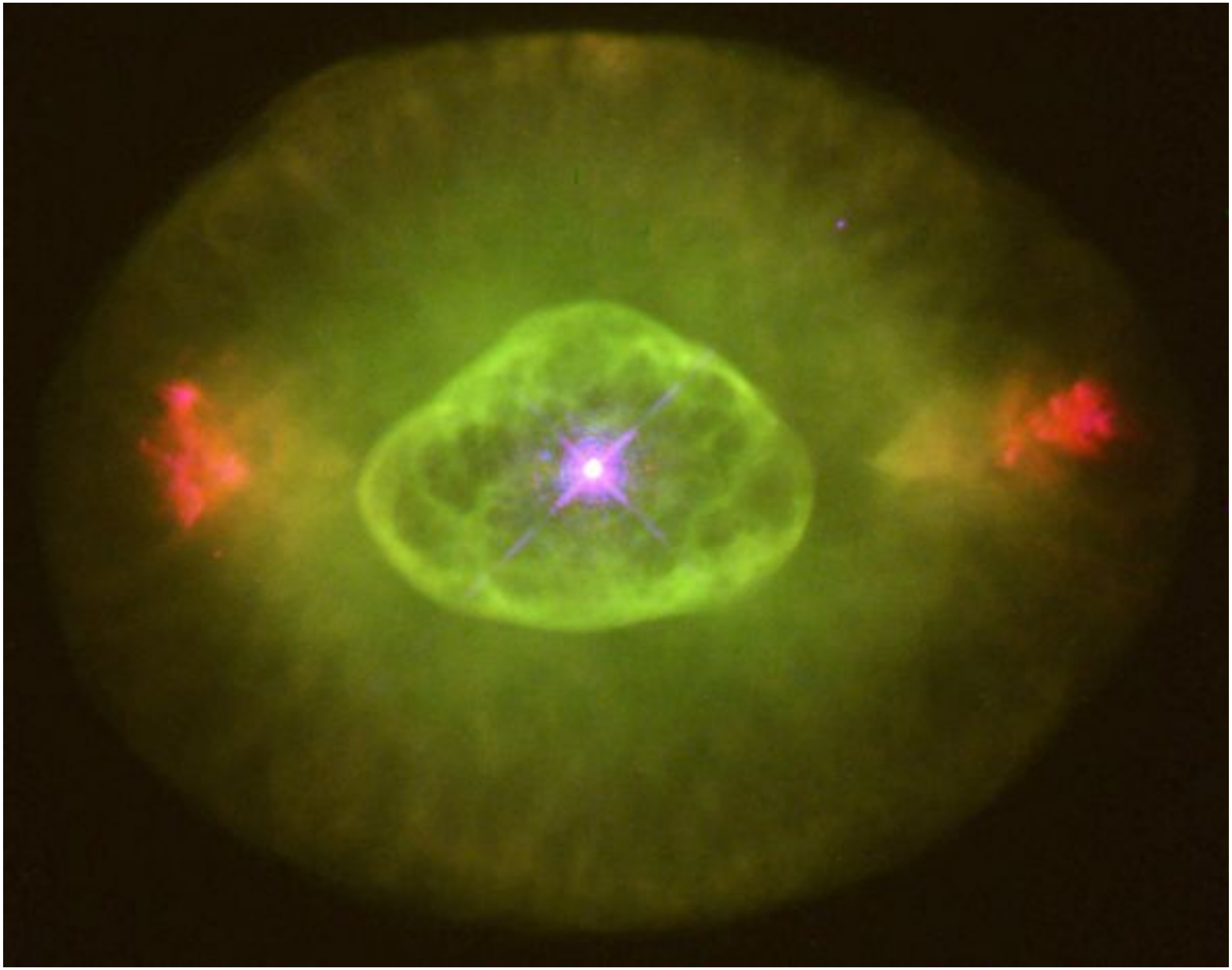
Planetary Nebula Stage

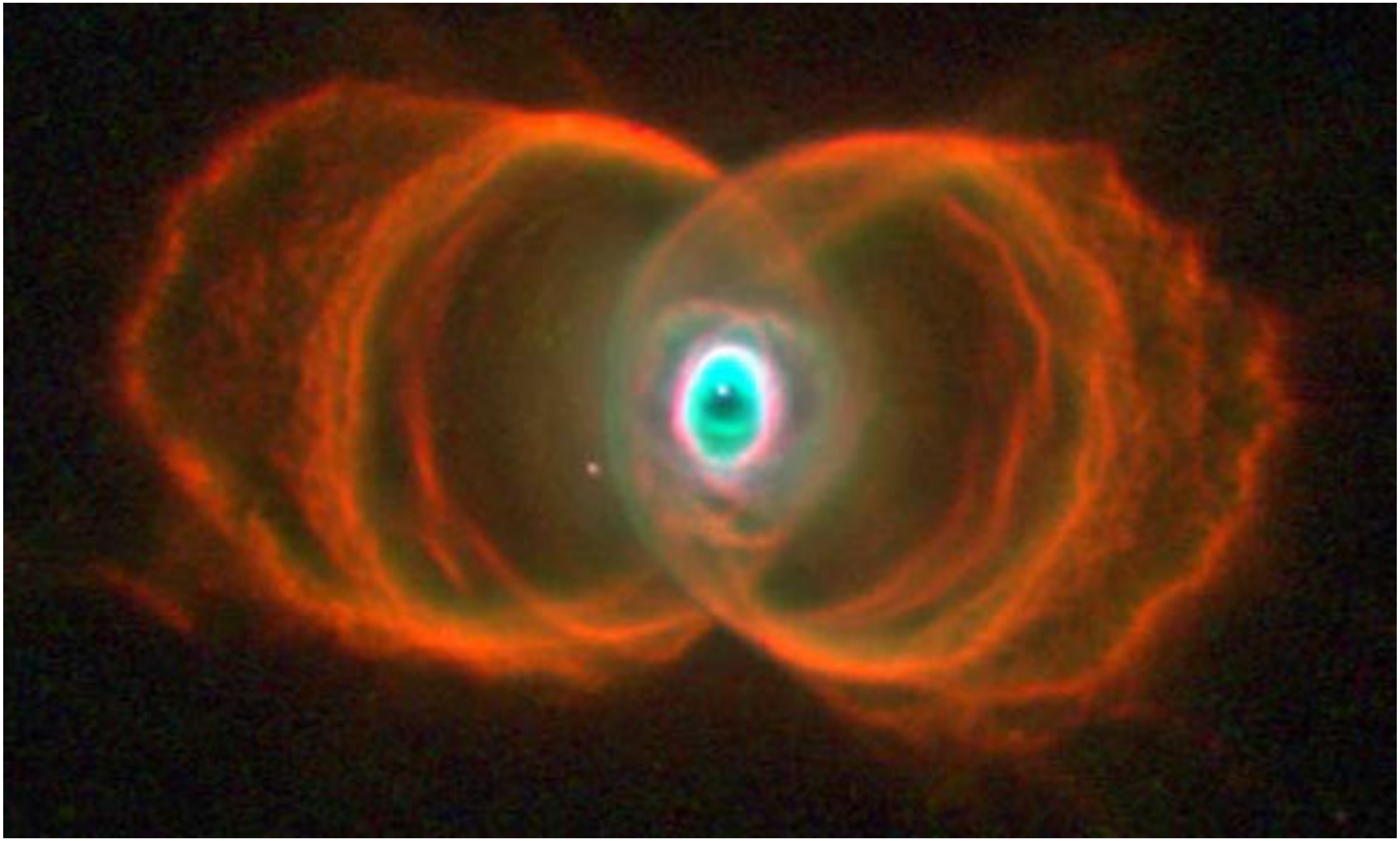
- The trips up the Giant Branch get terminated when the star's outer envelope becomes detached and begins to *drift off into space*. (!!)
- The former envelope shines in the light of emission lines.
- As the envelope expands and becomes transparent the very hot core of the giant star can be seen at its center.

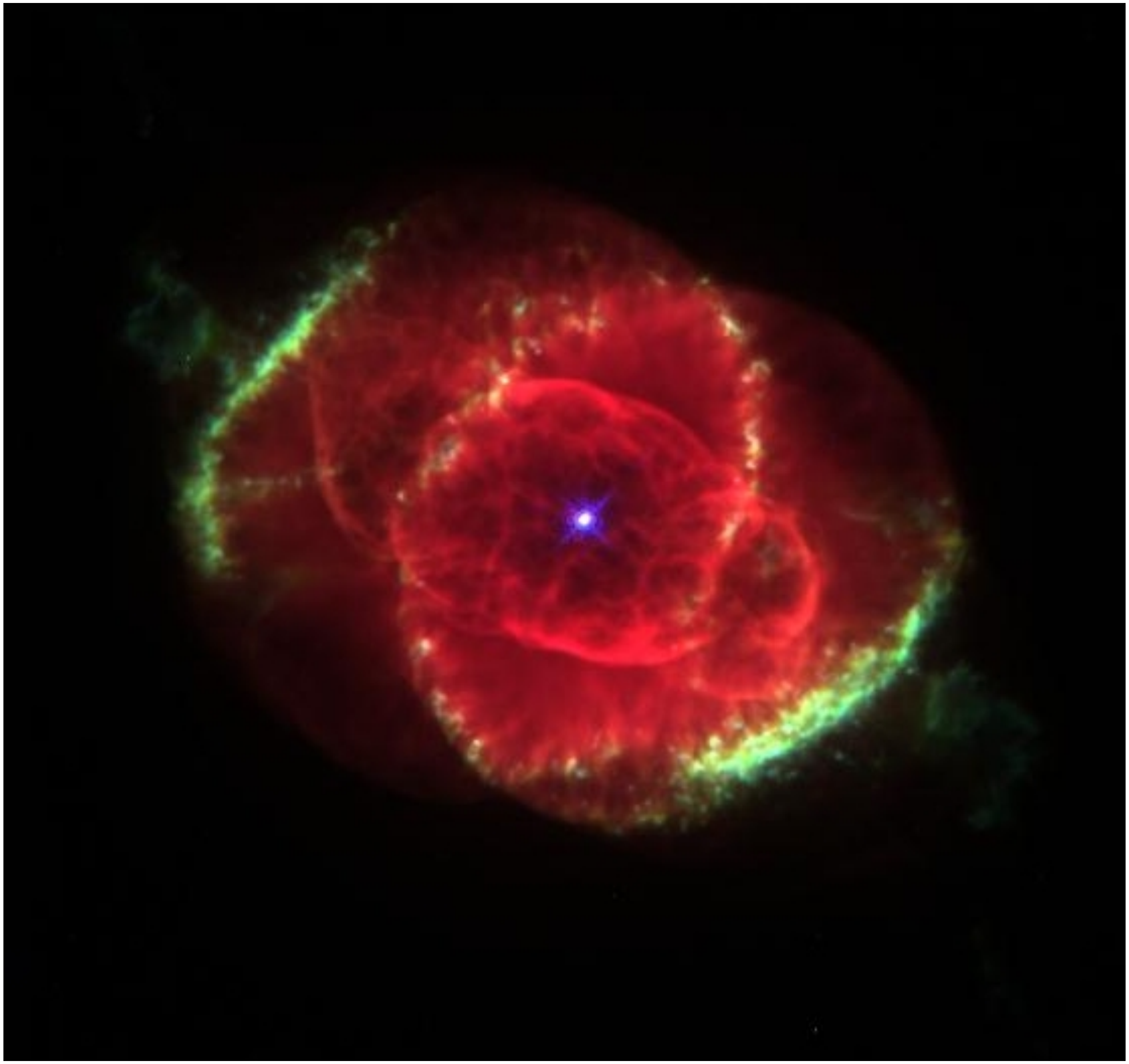






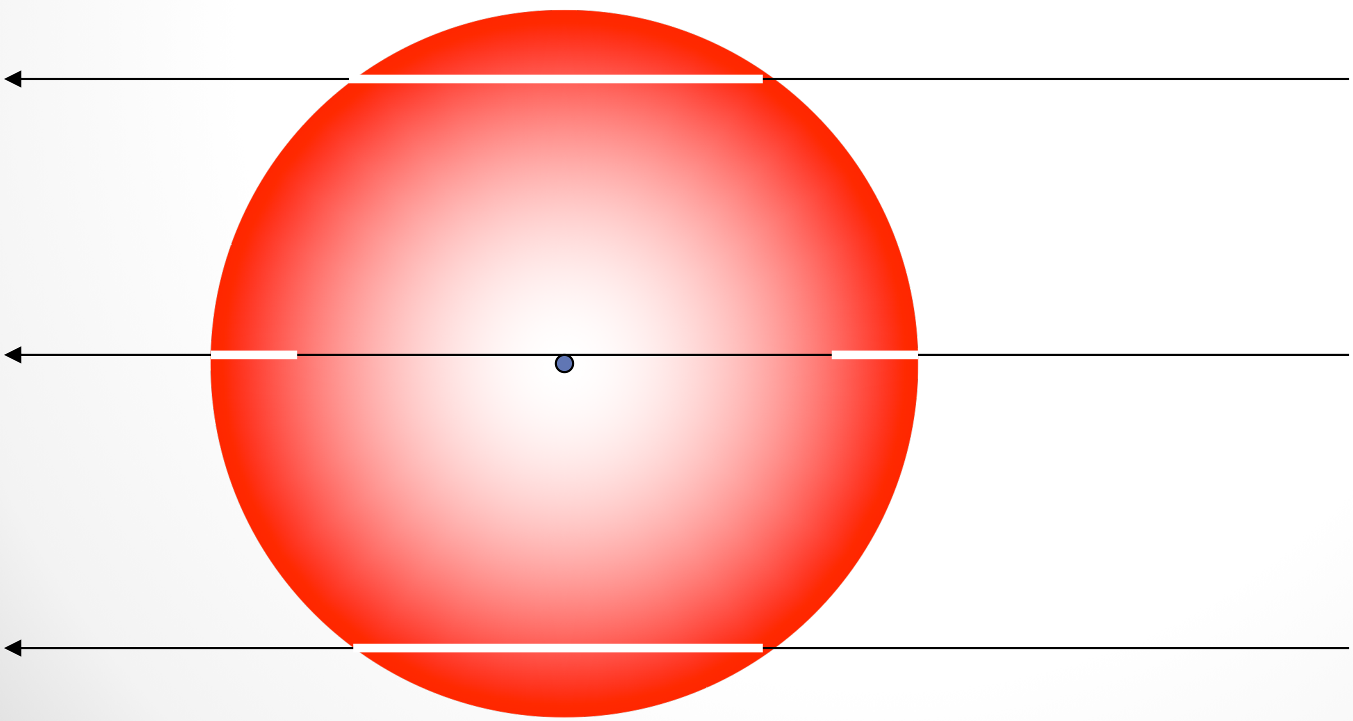






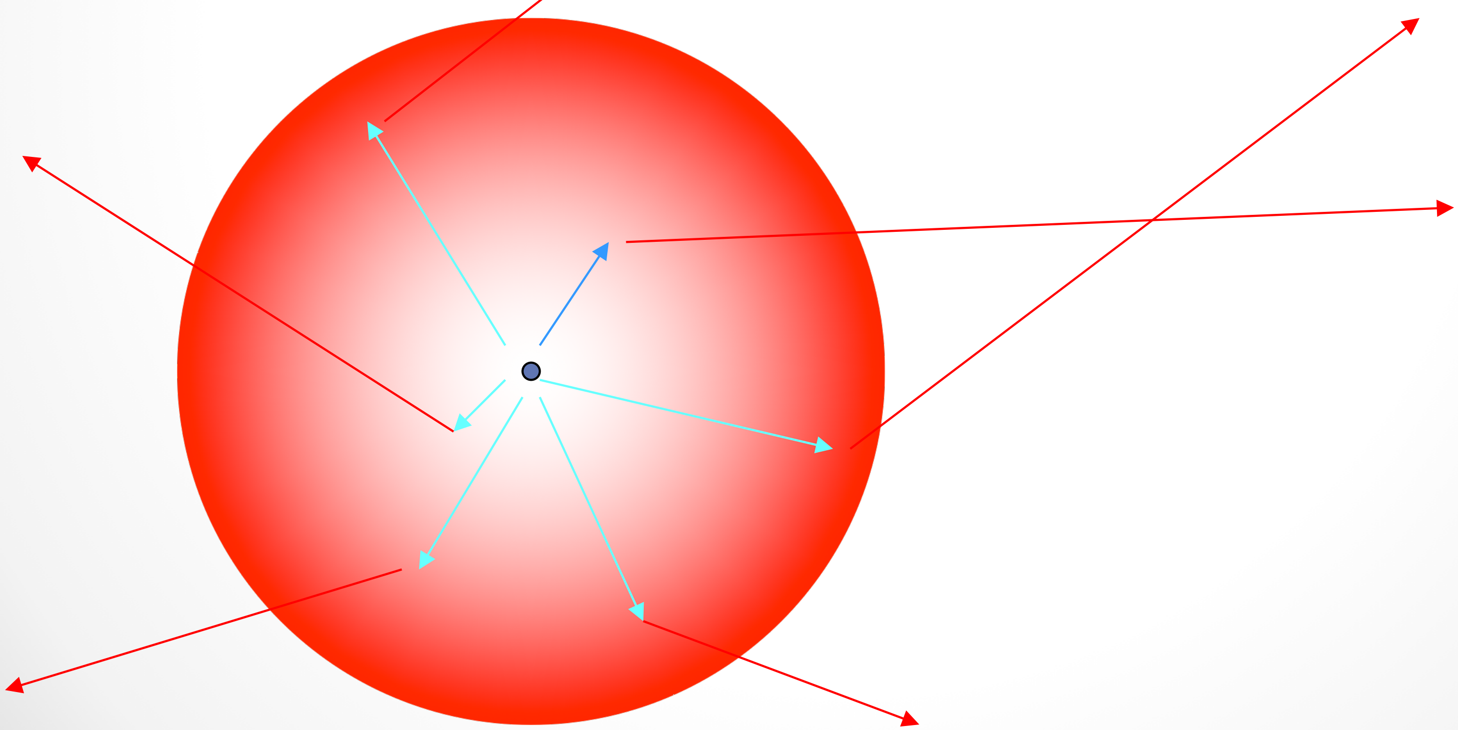
Planetary Nebulae

- The outer envelope expanding out as a shell appears as a ring in the sky.



Planetary Nebulae

- The emission is similar to that from a fluorescent light. Ultraviolet photons from the hot former giant-star core ionize atoms in the shell. On recombination, photons are produced.



Planetary Nebulae Shells

- The ejection mechanism for the shell is a combination of winds from the core, photon pressure, perhaps the shell flashes and the large radius of the star.
- The shell expands into space at relatively low speed (20 km/sec).
- Approximately 50% of the giant star mass is ejected.

Planetary Nebulae Shell

- The shell expands and is visible for about 30,000 years growing to a size of more than a light year.
- The shell is enhanced in the abundance of He, Carbon, Oxygen (because of convection during the giant phase). This is one of the means by which `Galactic Chemical Evolution' proceeds.
- There are about 30,000 PN in the Galaxy at any time.

Planetary Nebulae Central `Star'

The object in the center of the nebula is the former core of the giant-branch star.

(1) It is hot! T>150,000k initially

(2) Supported by e- degeneracy*

(3) Mass ~ $0.6M_{\odot}$

(4) Radius ~ 6000km (Earth)

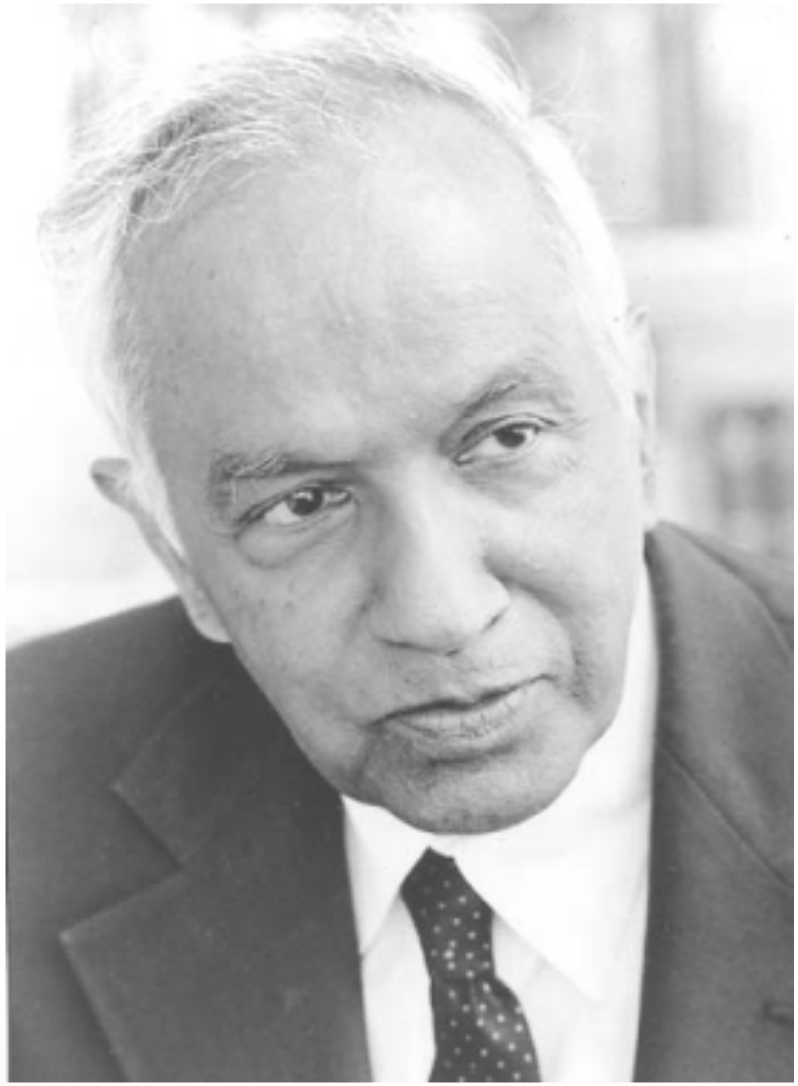
(5) Density ~ 10^9 kg/m^3

A thimble of material at this density would weight about 5 tons on Earth.

Planetary Nebulae Central `Star’

- The central `star’ isn’t a star because it has no energy source. This is a white dwarf.
- Supported against gravity by e-*degeneracy*.
- Lots of residual heat, no energy source, a white dwarf is like a hot ember. As it radiates energy into space, the white dwarf cools off.
- There is an upper limit to the mass of a WD set by e-degeneracy. $1.4M_{\odot}$ is the “Chandrasekar Limit”.

Chandrasekar



Electron Degeneracy

- Electrons are particles called `fermions' (rather than `bosons') that obey a law of nature called the Pauli Exclusion Principle.
- This law says that you can only have two electrons per unit 6-D phase-space volume in a gas.

$$\Delta x \Delta y \Delta z \Delta p_x \Delta p_y \Delta p_z$$

Electron Degeneracy

- When you have two e- per phase-space cell in a gas the gas is said to be *degenerate* and it has reached a density maximum -- you can't pack it any tighter.
- Such a gas is supported against gravitational collapse by electron degeneracy pressure.
- This is what supports the helium core of a red giant star as it approaches the tip of the RGB and what supports a White Dwarf

White Dwarf

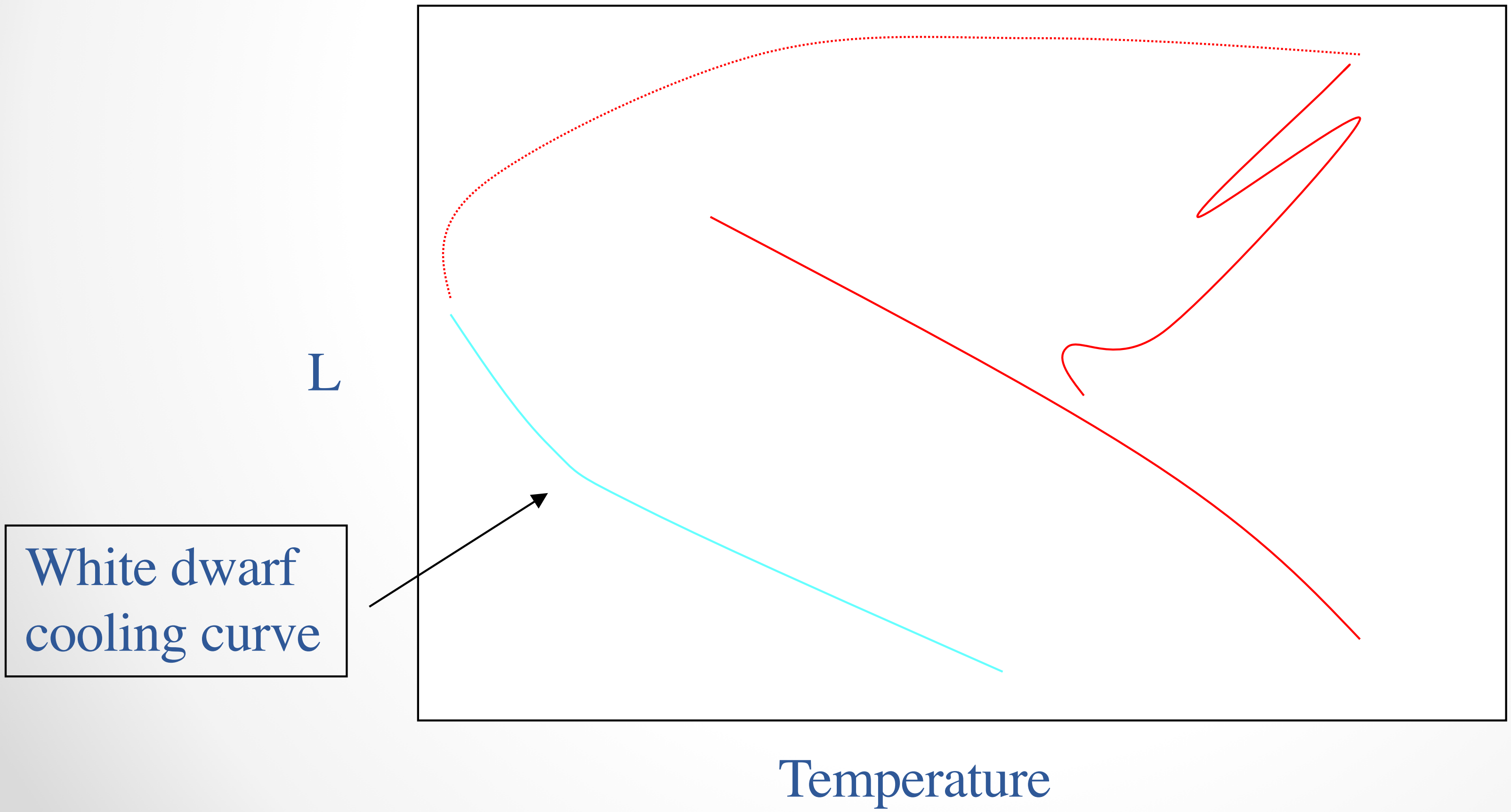
- Energy source: none
- Equilibrium:

  e- degeneracy vs gravity
- Size: 6000km (Earth)
- Density: 10^6 gr/cm^3 (ton per teaspoon)

http://en.wikipedia.org/wiki/White_dwarf

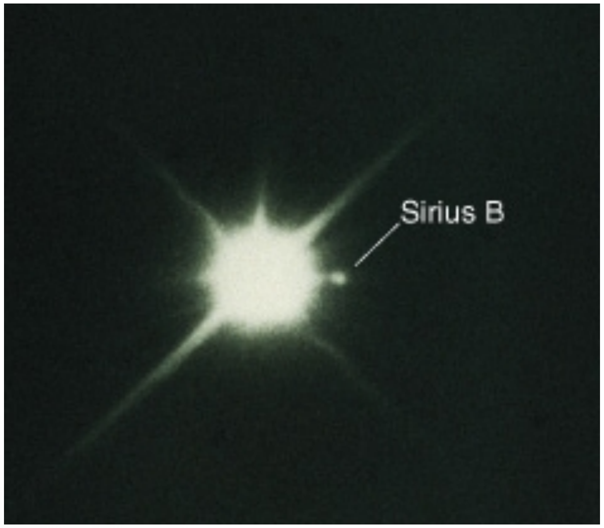
White Dwarfs

- WDs appear in the HR-Diagram in the upper left and VERY rapidly evolve downward and to the right.



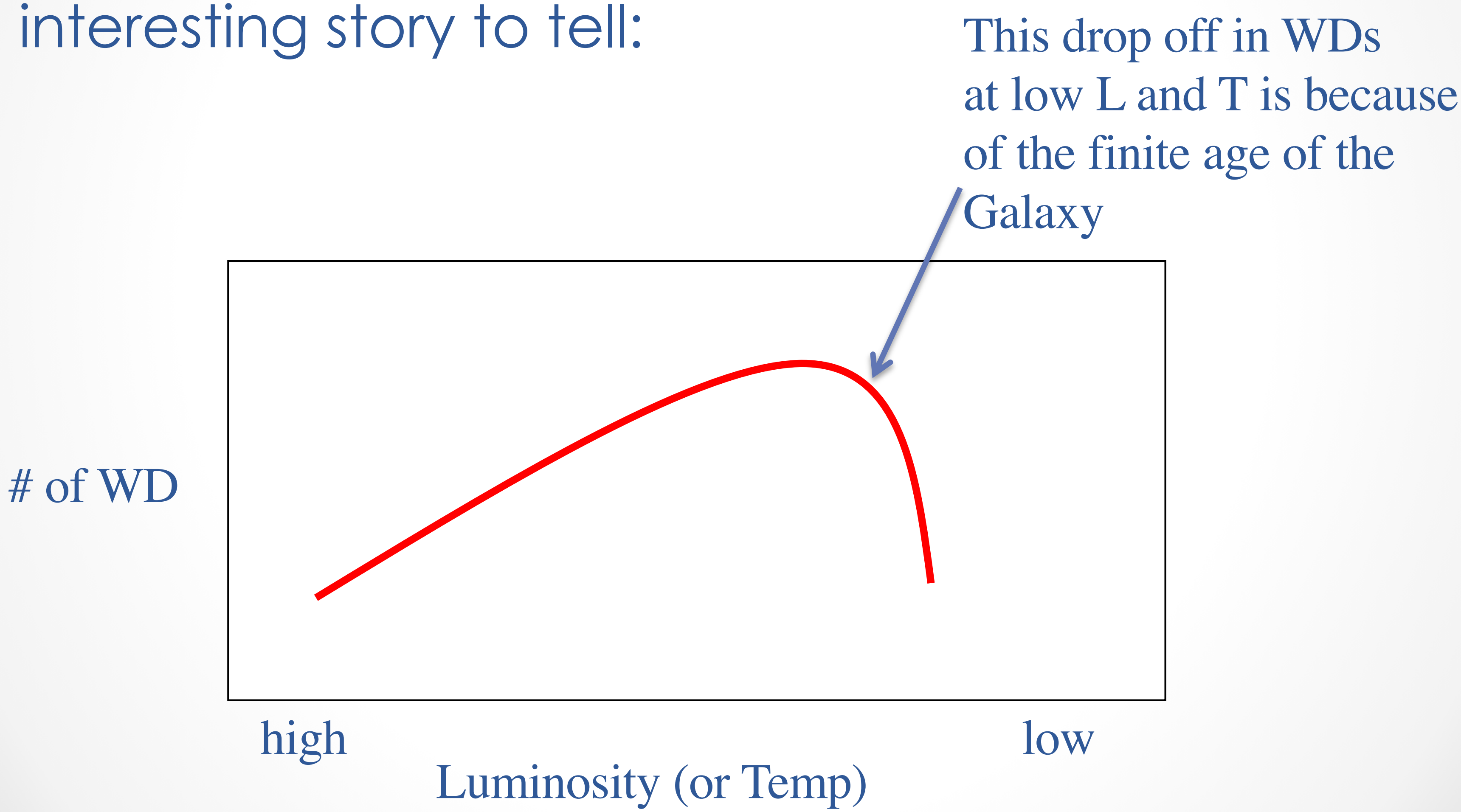
White Dwarfs

- ~97% of stars end their lives as WDs. They are very common, though hard to see.
- Because it is in a binary orbit, the mass and extreme density of Sirius B was determined in 1910. Seemed completely impossible at the time.



White Dwarf Cosmochronology

- The WDs in the solar neighborhood have an interesting story to tell:



Evolution of <8M$_{Sun}$ Stars

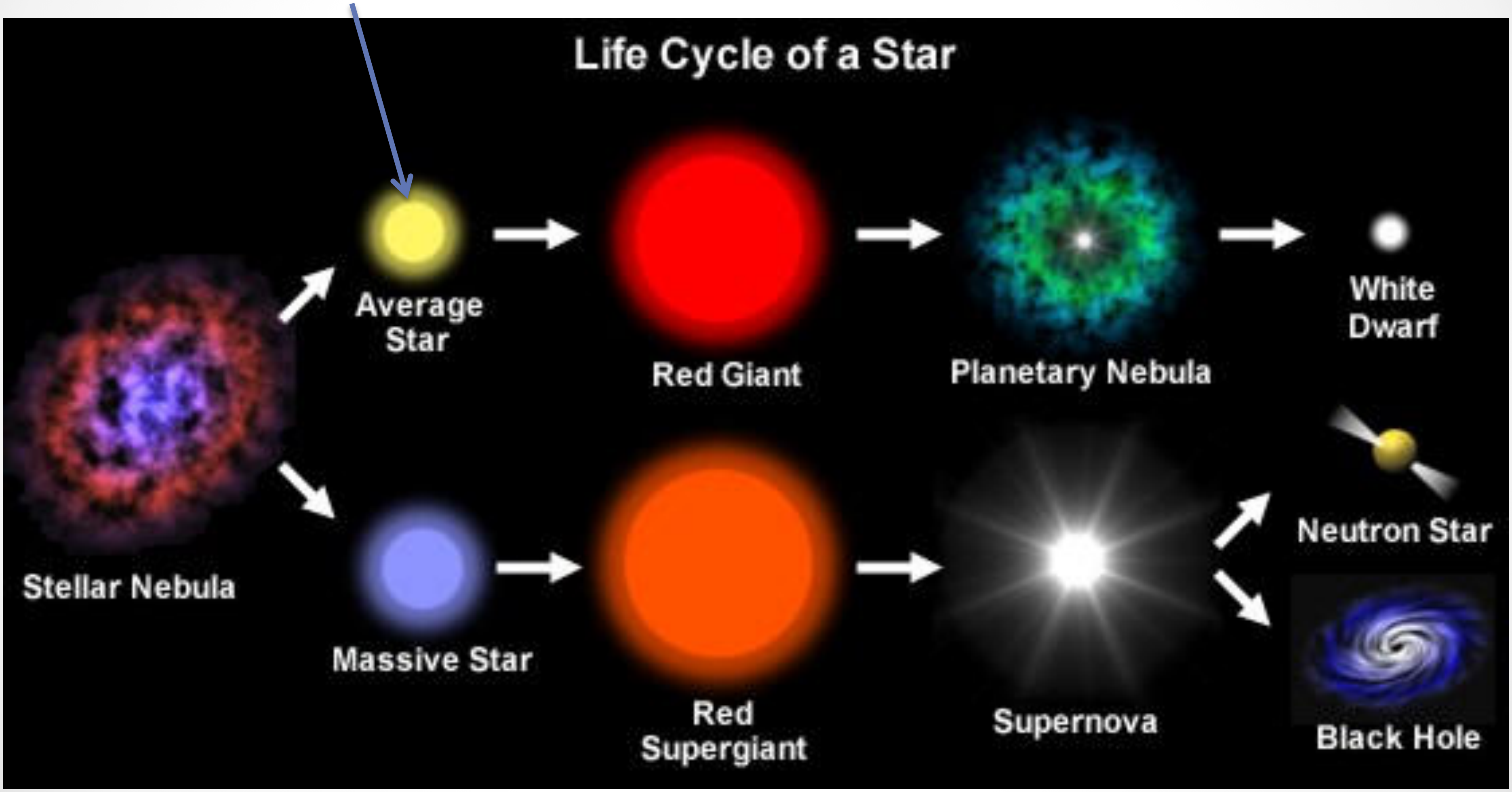
- For stars less than 8M$_{\odot}$ these last slides describe the evolution pretty well. There are some differences in the details that depend on the initial main-sequence mass.
- For stars that start with 4M$_{\odot}$, it gets hot enough in the cores to ignite start carbon fusion on the main sequence.
- *The WD remnant contains Ne, Mg and Si and the amount of enriched material returned to the ISM is larger.*

Which of the following is true of the White Dwarf the Sun will eventually become?

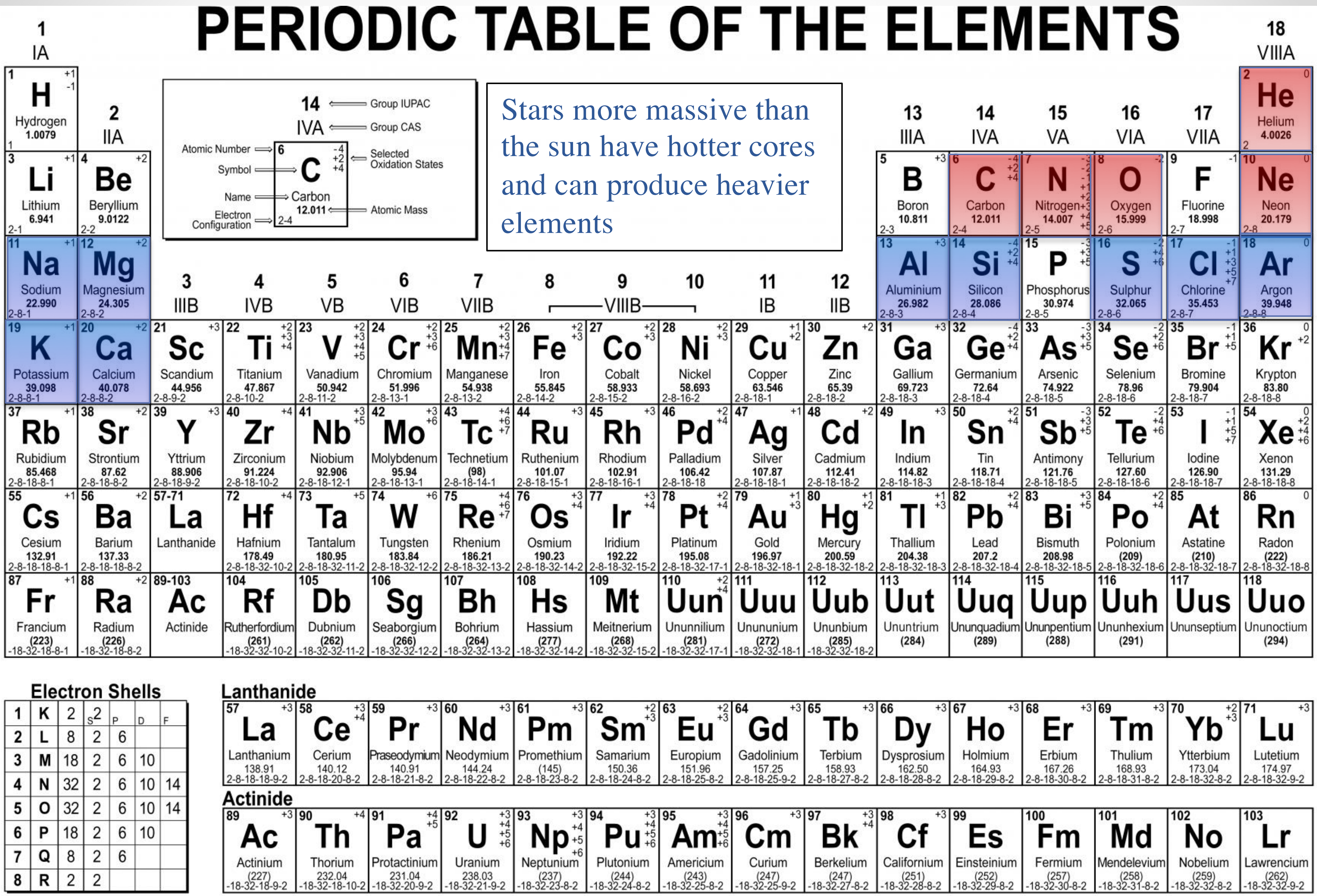
A. It will be slightly more massive than the Sun as it will have converted the light-weight hydrogen into heavier helium
B. It will have a slightly larger radius than the Sun because of its high temperature
C. It will be enriched in He compared to the Sun
D. It will be much more luminous than the Sun because of its high fusion rate (Rate is proportional to T^4)

Stellar Evolution

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

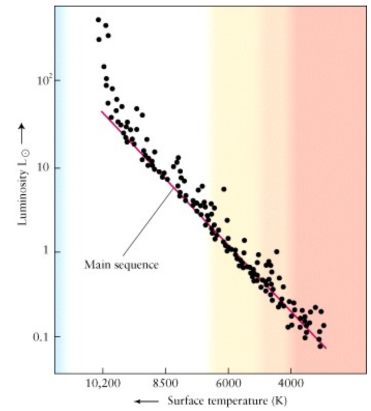


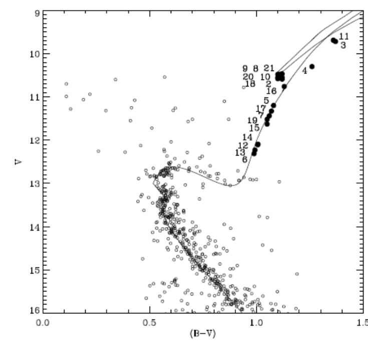
PERIODIC TABLE OF THE ELEMENTS

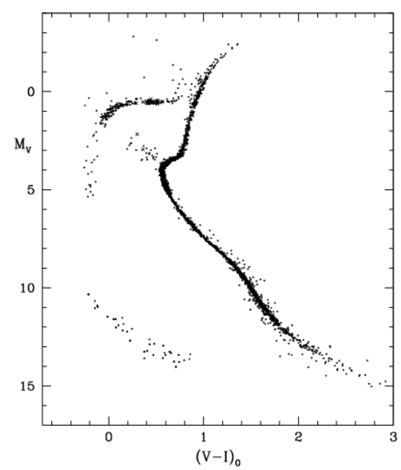


Stars more massive than the sun have hotter cores and can produce heavier elements

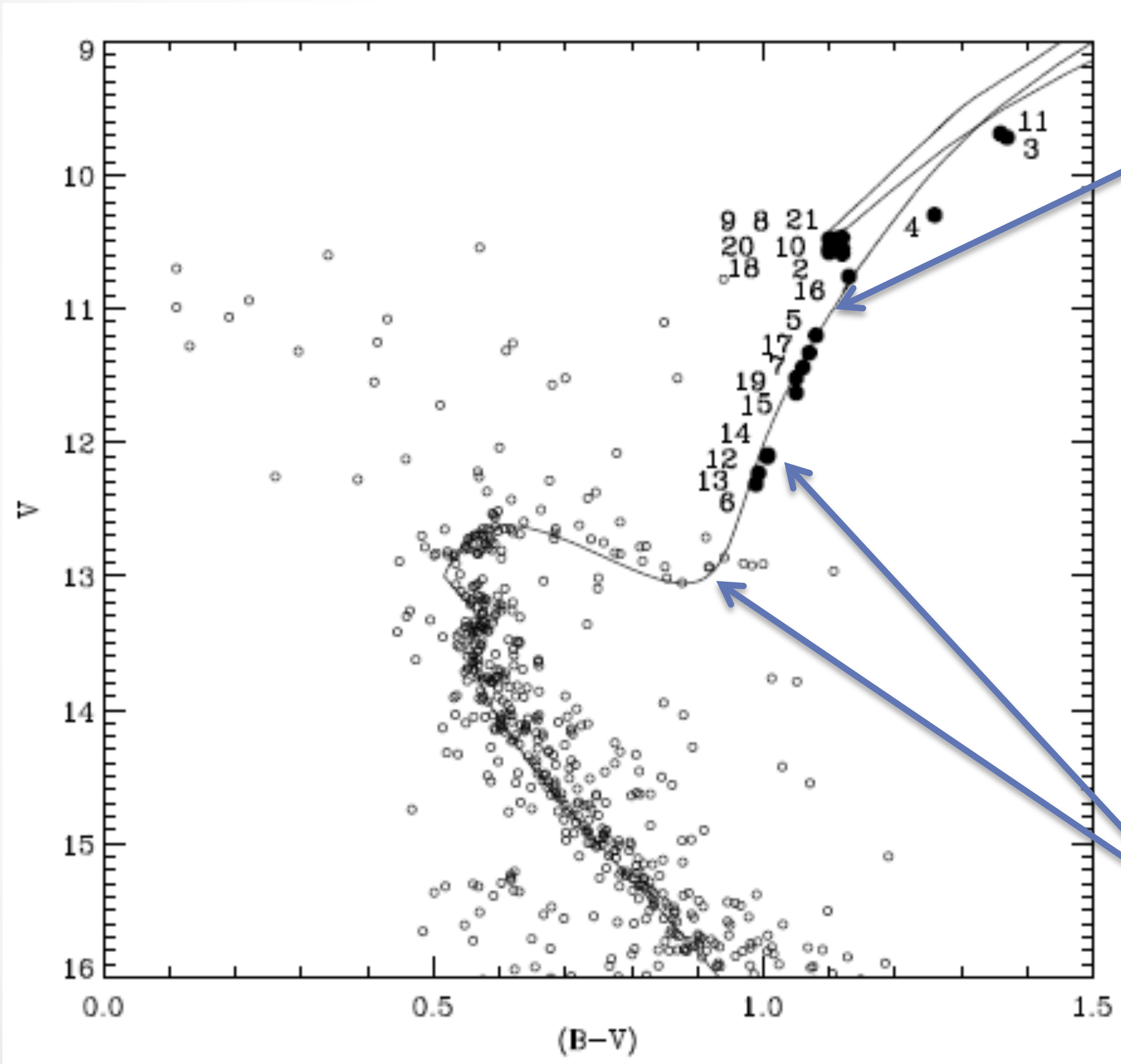
Why do we think this is right?







Why do we think this is right?



Line is model evolution track

Stellar evolution models match observed stellar temperatures and luminosities in star clusters very well

Open and solid points are observations of stars

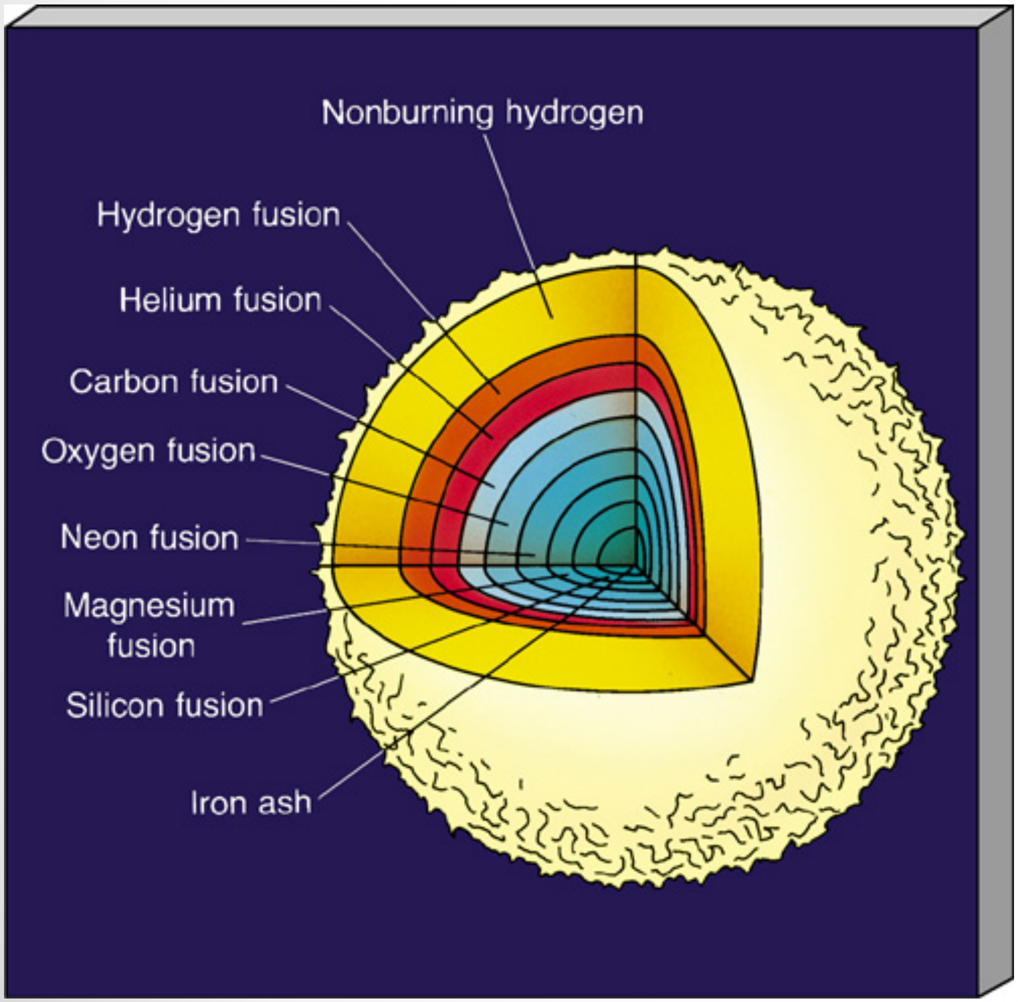
The Evolution of High-mass Stars

- For stars with initial main-sequence mass greater than around $8M_o$ the evolution is much faster and fundamentally different.

Main-sequence Lifetimes

$1M_{Sun}$	10×10^9 years
$3M_{Sun}$	500×10^6 years
$15M_{Sun}$	15×10^6 years
$25M_{Sun}$	3×10^6 years

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)

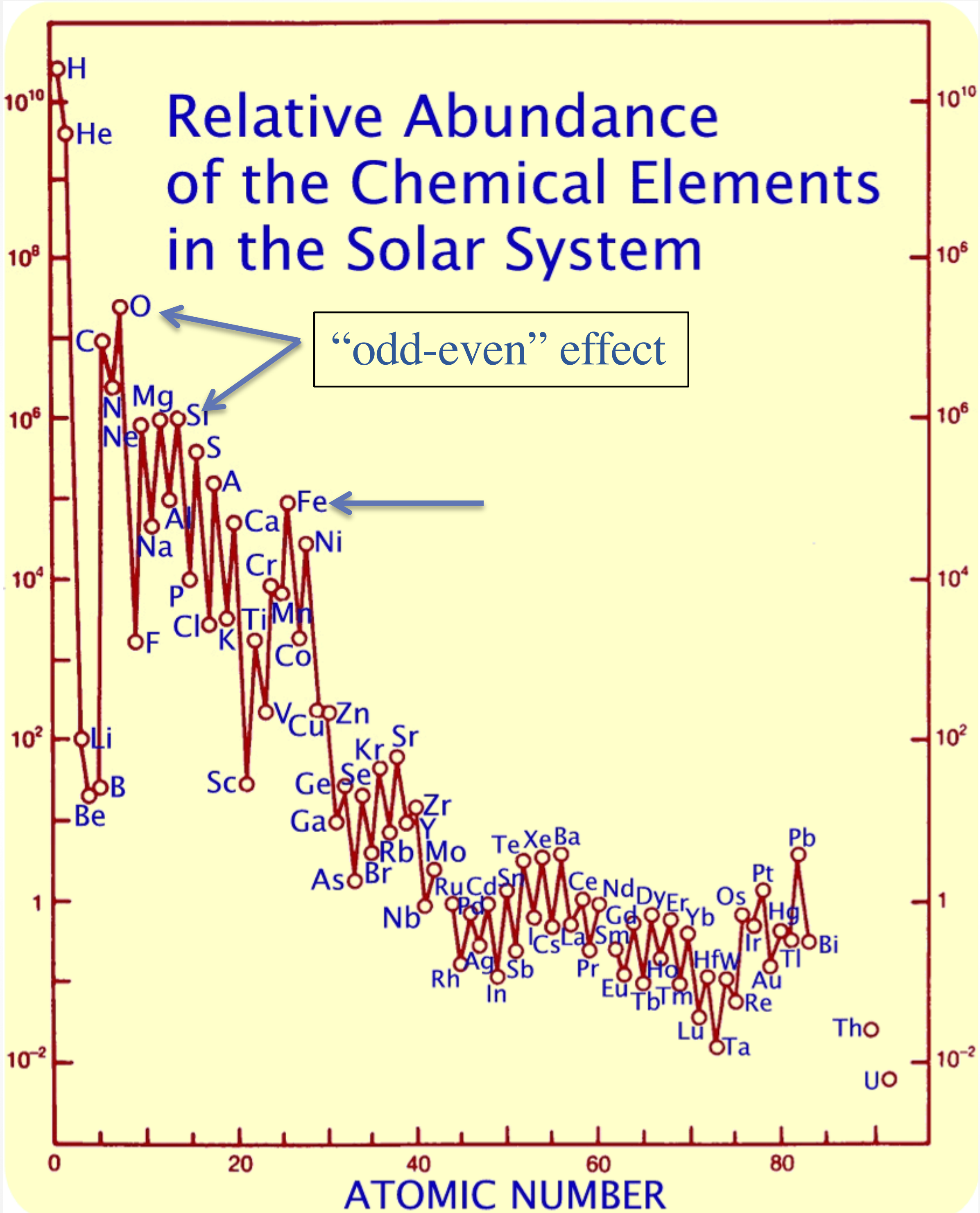
Nucleosynthesis in Massive Stars

- Fusing nuclei to make new elements is called nucleosynthesis.

Temperature	Fusion reaction
15 million K	H -> He^{4}
100 million K	He^{4}-> C^{12}
600 million K	C^{12}-> O^{16} (Mg^{24})
15000 million K	O^{16}-> Ne^{20} (S^{32})
etc	etc

Massive Star Nucleosynthesis

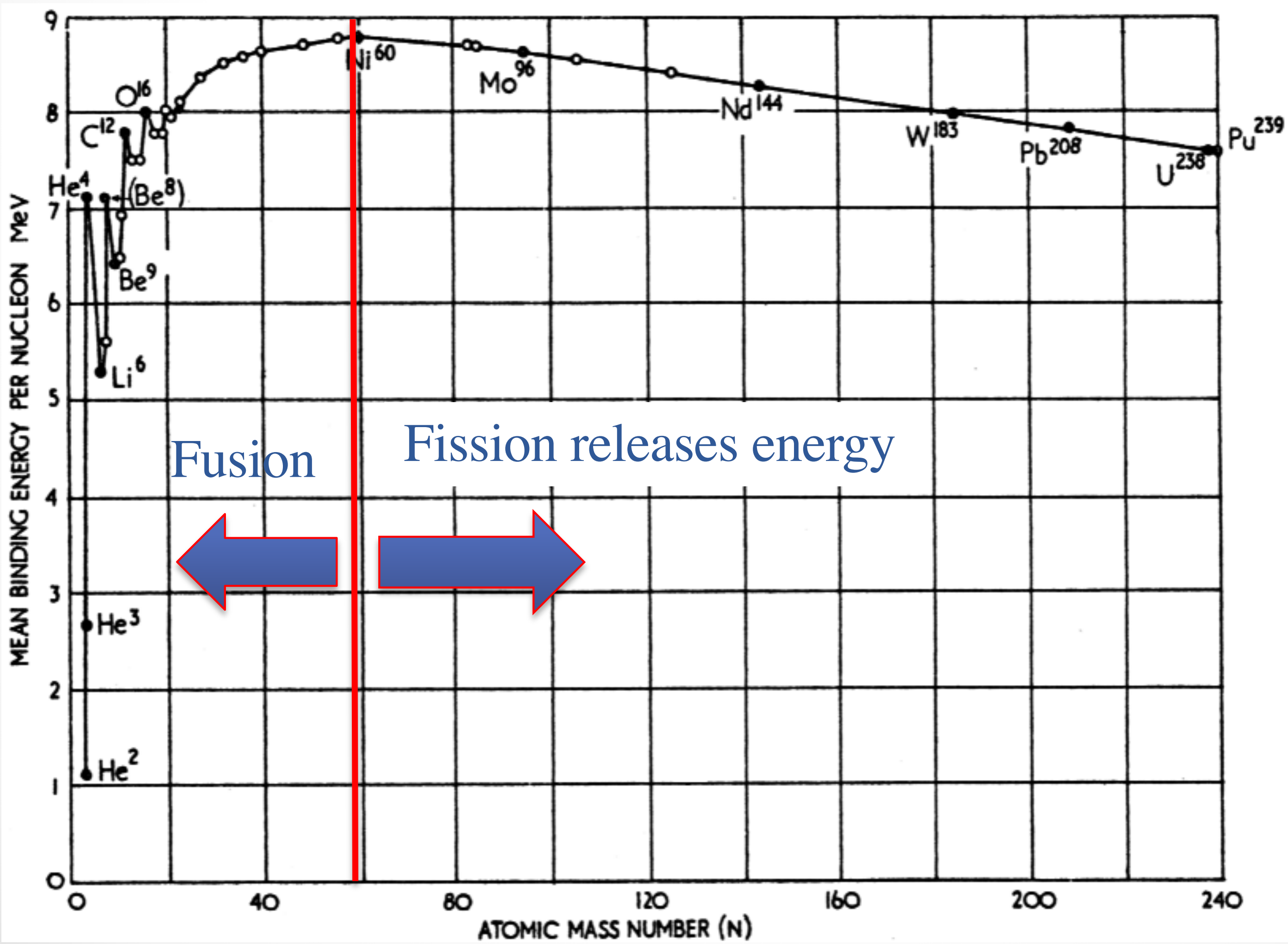
- In a $25M_{\odot}$ star nucleosynthesis proceeds quickly to Fe (why it stops there we will get to in a minute).
- The most common reaction is called the `alpha process' and it is fusing He^4 to existing nuclei. This process is reflected in to abundance of various elements in the Universe today.



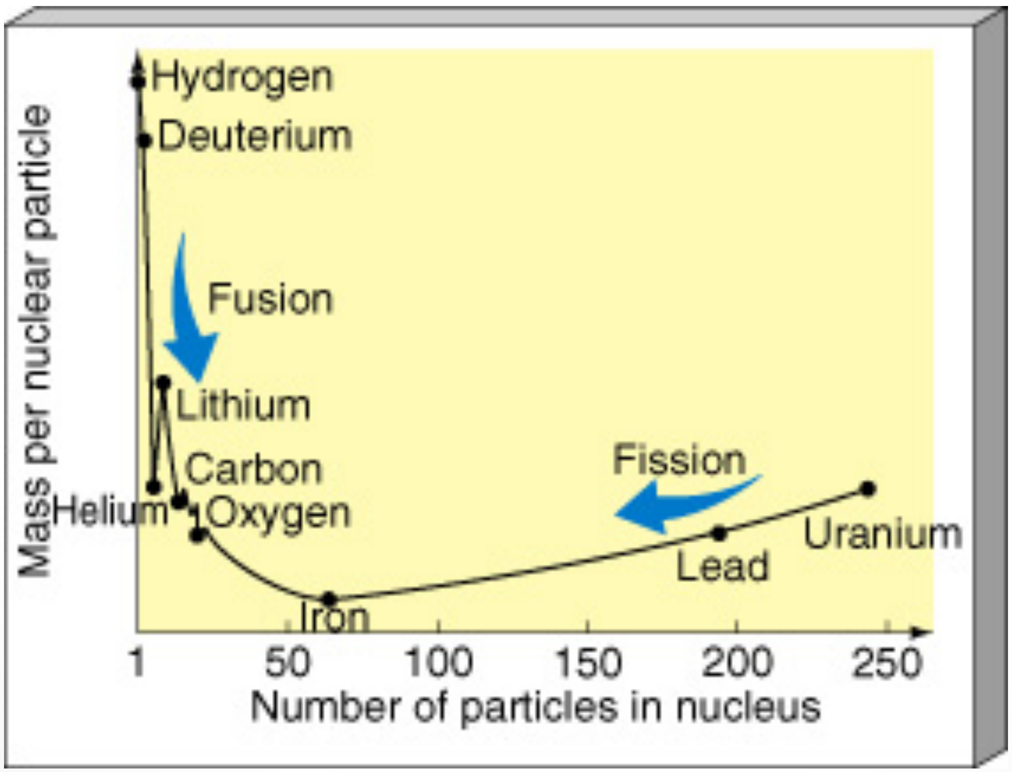
Note log scale

What is special about Fe?

- Fe is at the peak of the `curve of binding energy'



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 $E=mc^2$.



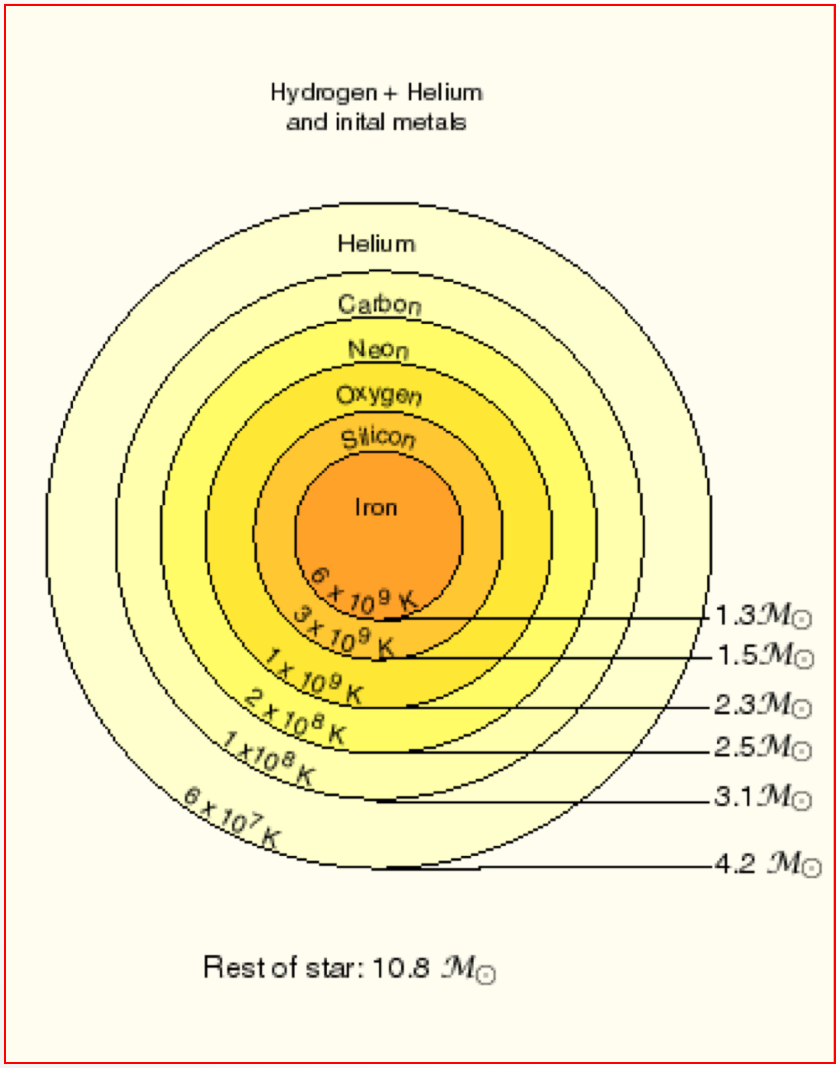
Nucleosynthesis

- 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

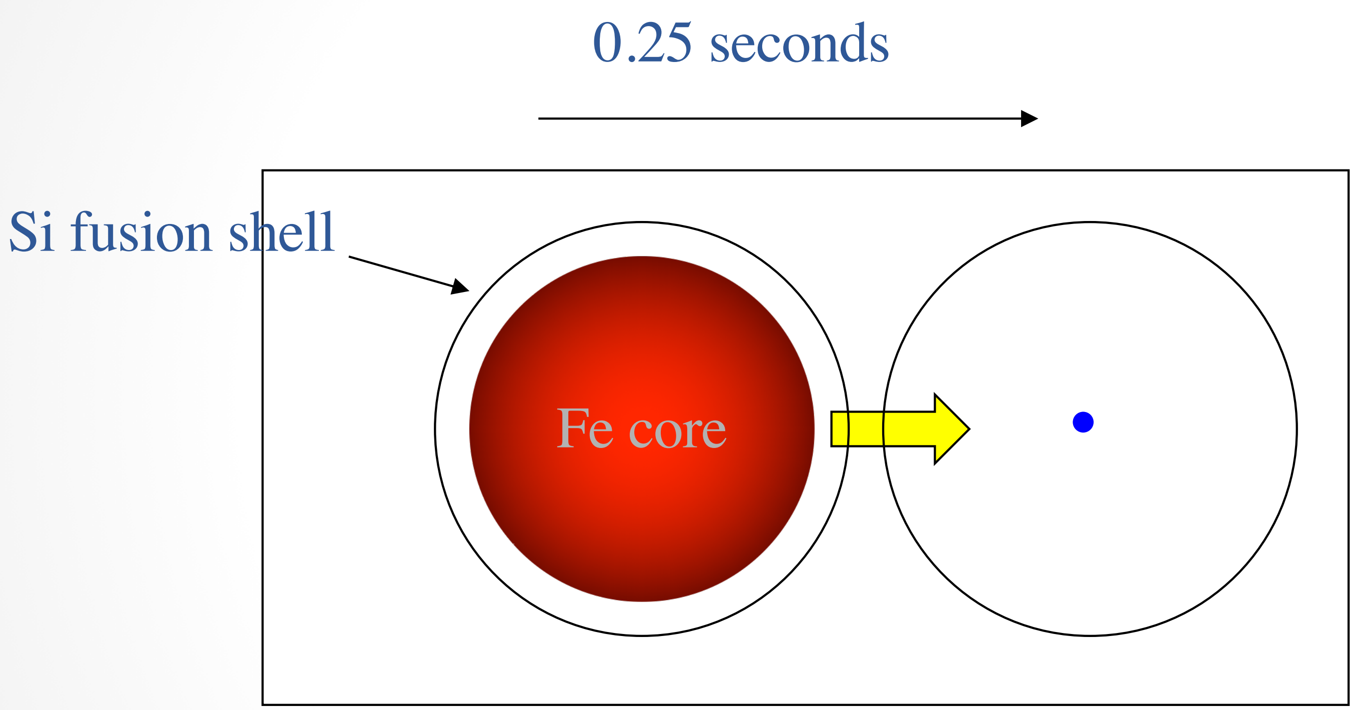


"ashes" from outer shells provide fuel for the next shell down

Core Collapse

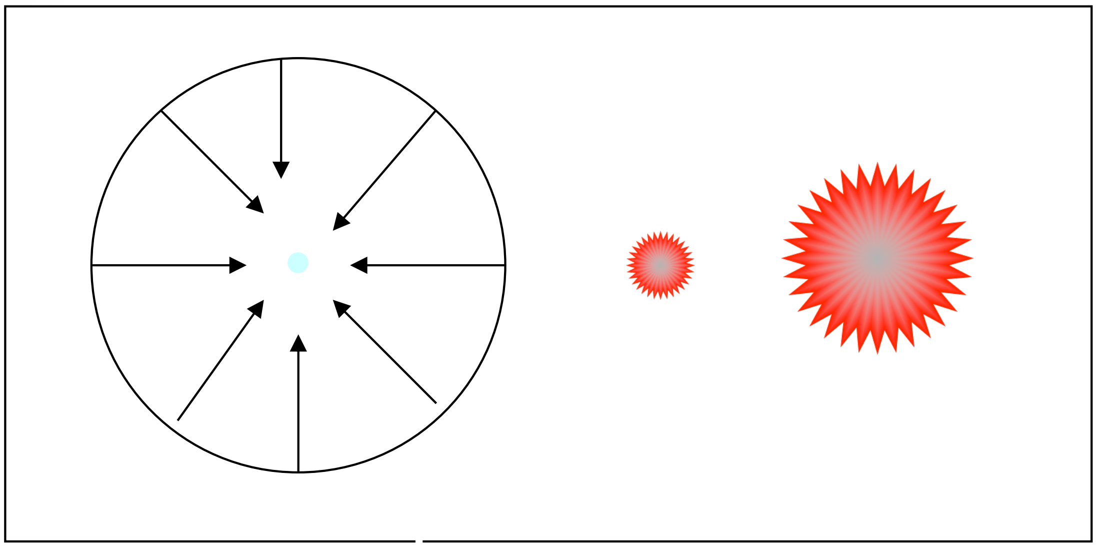
- The fusion chain stops at Fe and an Fe core very quickly builds.
- Within a day of starting to produce Fe, the core reaches the 1.4M_o Chandrasekar limit (e-degeneracy)
- On a timescale less than a second the core implodes and goes through a series of events leading to a tremendous explosion.

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

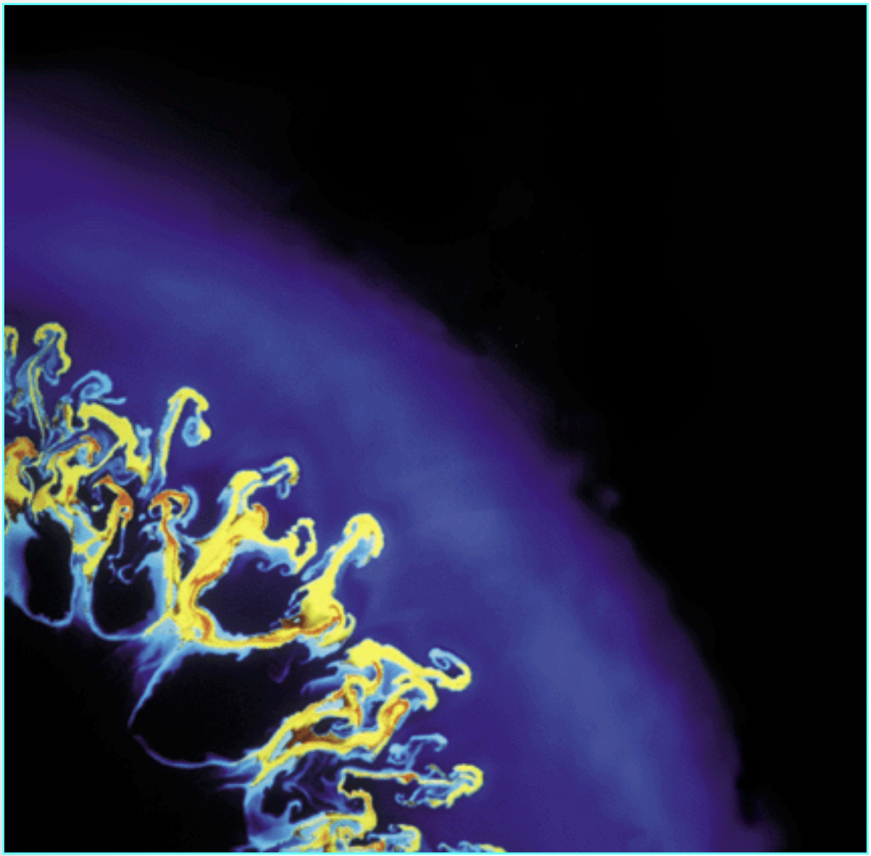
Core-Collapse in Massive Stars



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.

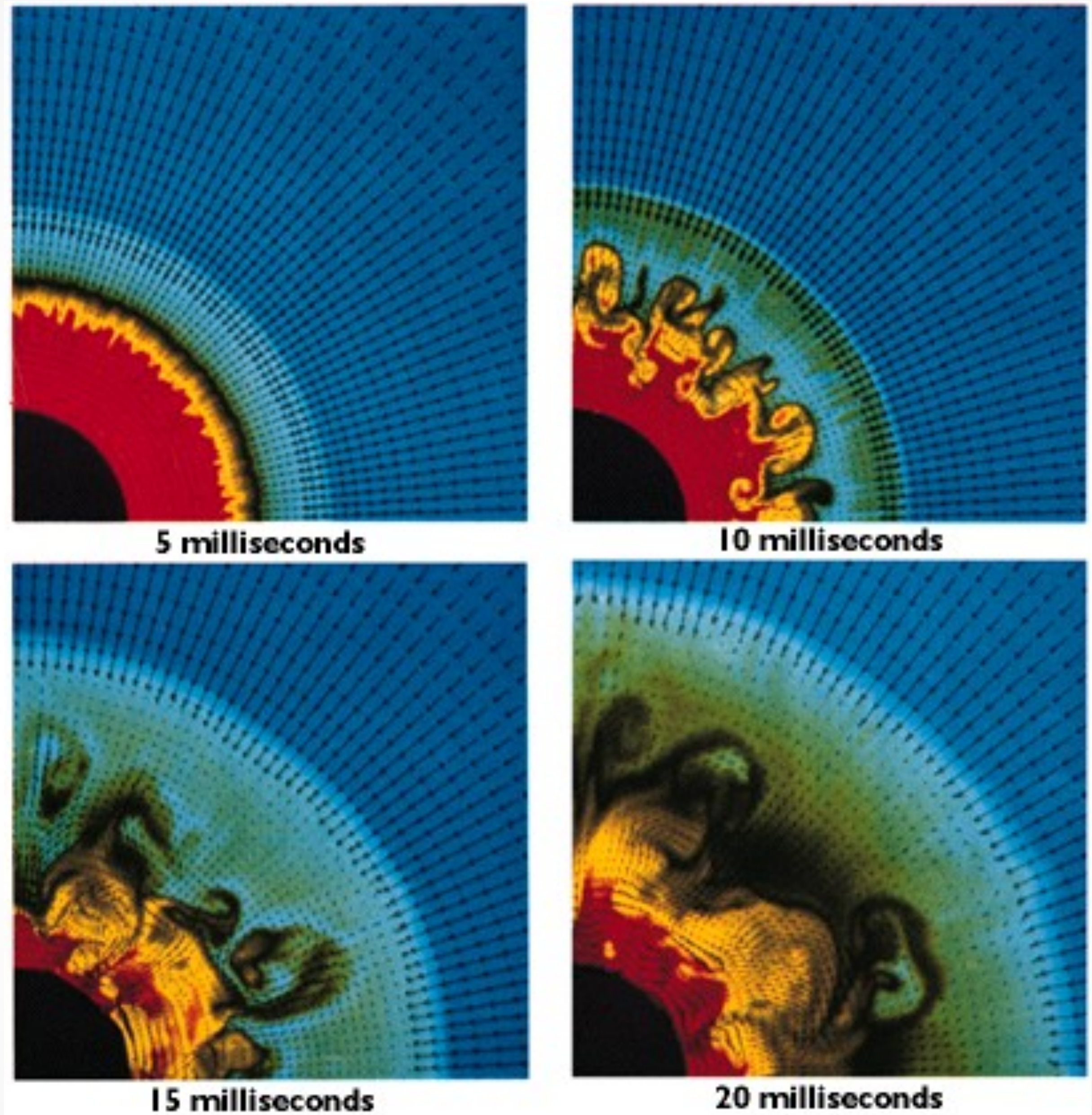
SNII Bounce Shock wave

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

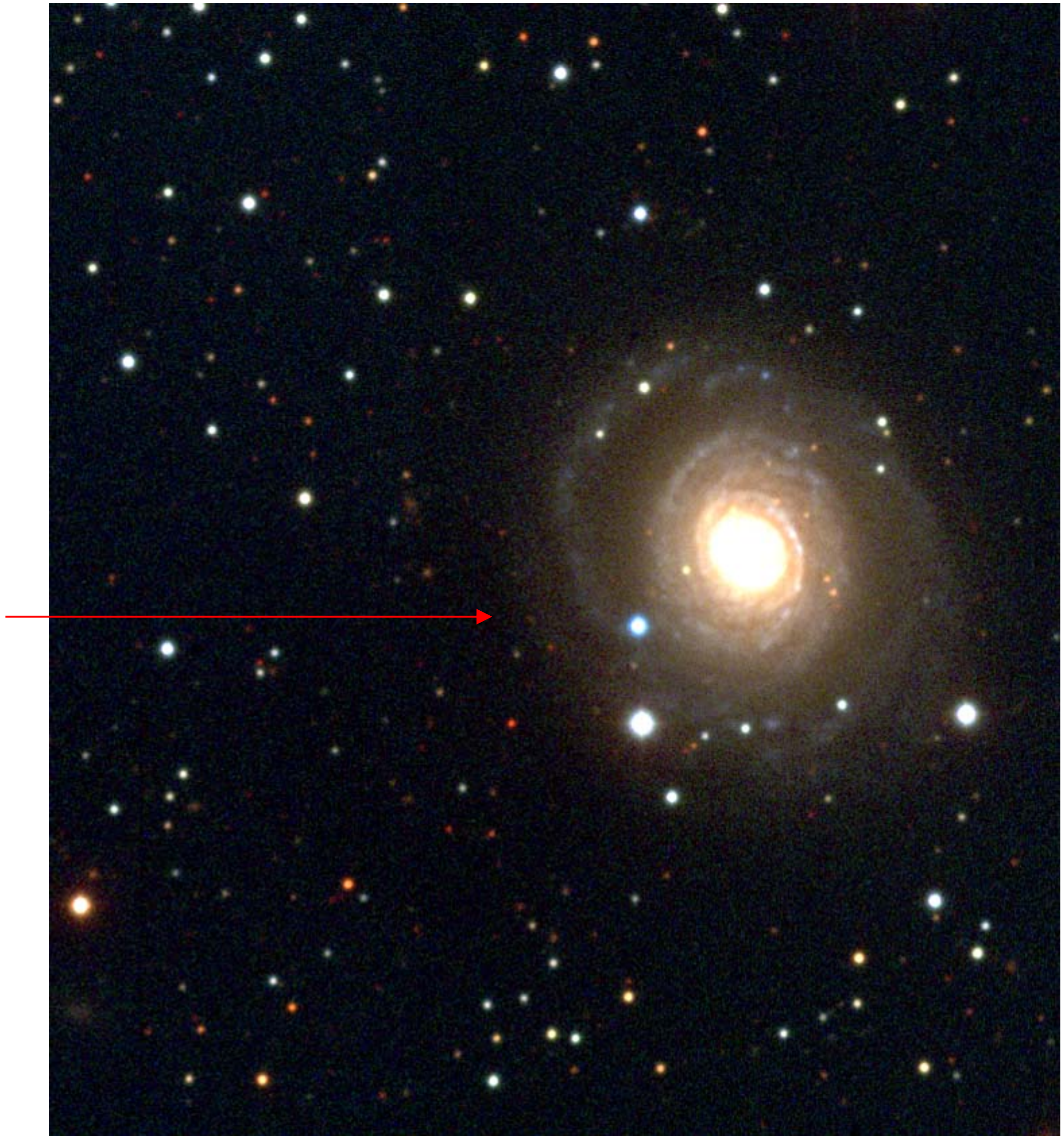
- Expect:
  - Association with massive stars/star formation
  - Rapidly expanding debris cloud
  - 10^8 times the optical luminosity of the Sun
  - Chemically-enriched debris
  - Extremely dense 1.4 solar mass neutron ball left behind

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!



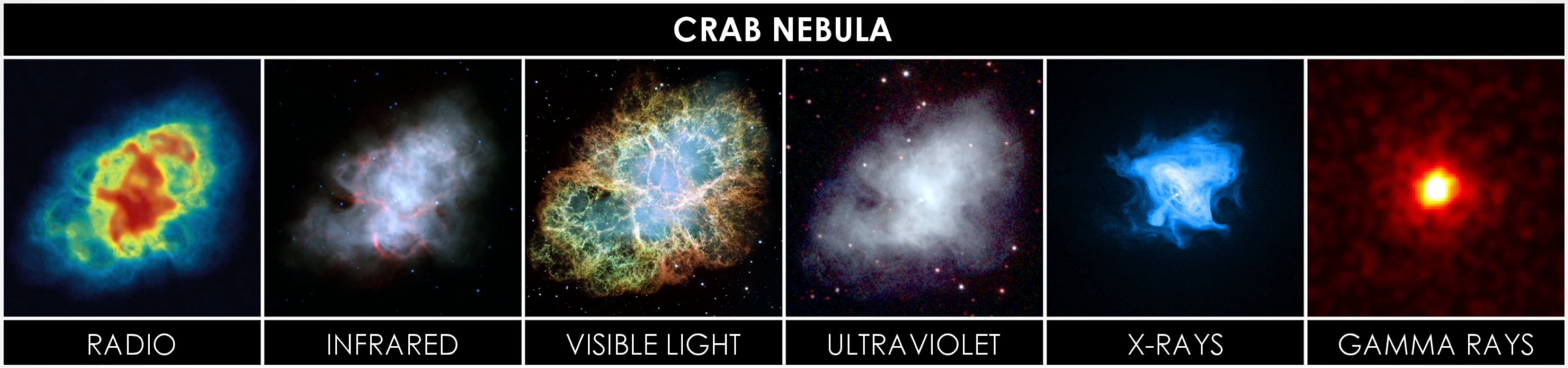
SNII

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

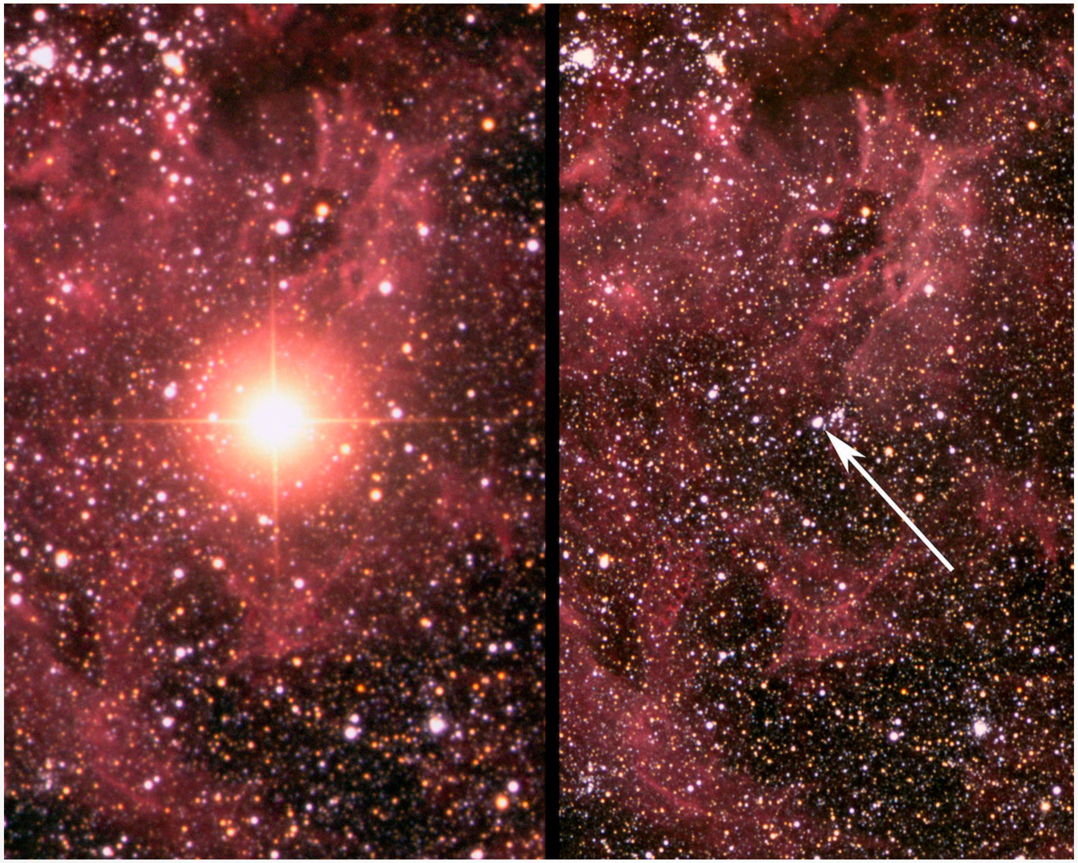
Point our telescopes there now and see a rapidly-expanding nebula with enhanced abundances of many elements and a rapidly rotating neutron star in the center

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

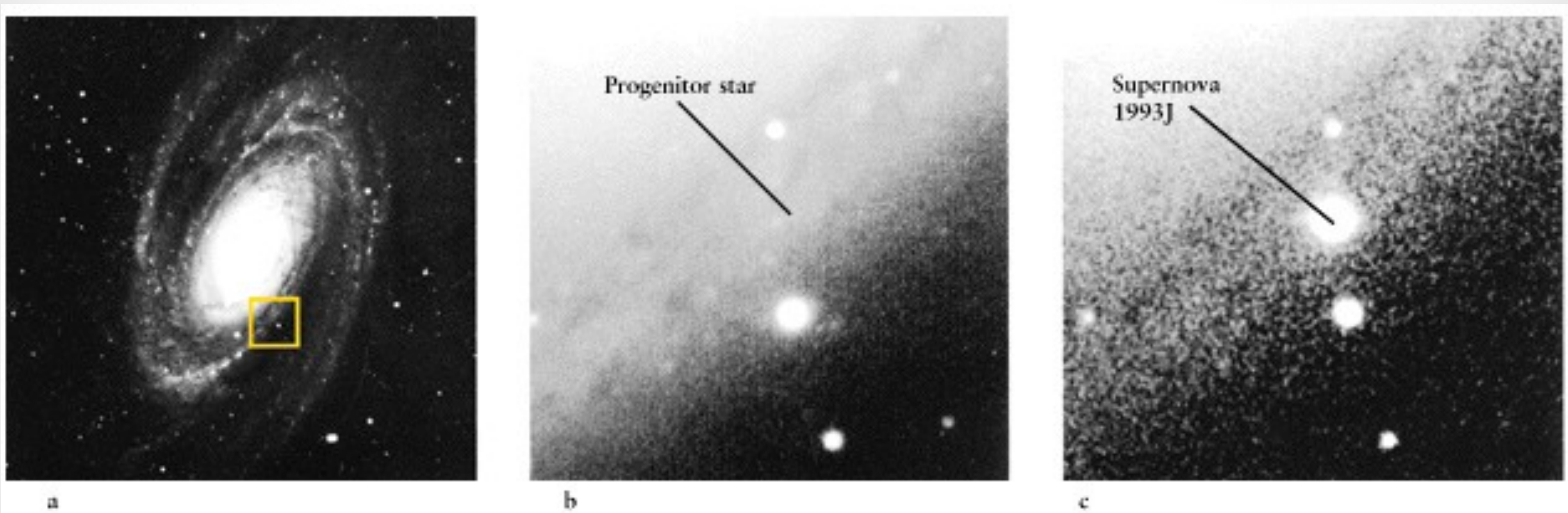
- The second indication, about 4 hours after the neutrinos arrived was a new naked-eye star in the LMC



SN1987a

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

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


Progenitor star
Supernova
1993J
a
b
c