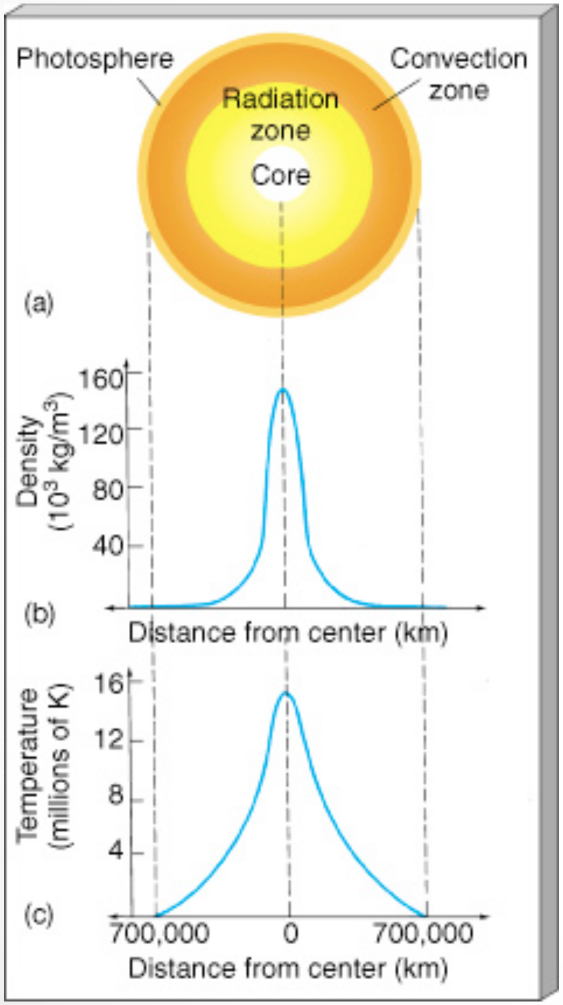
# Announcements

- Quiz 2 Thursday May 4
- Stellar properties, stellar structure, stellar evolution, stellar end points

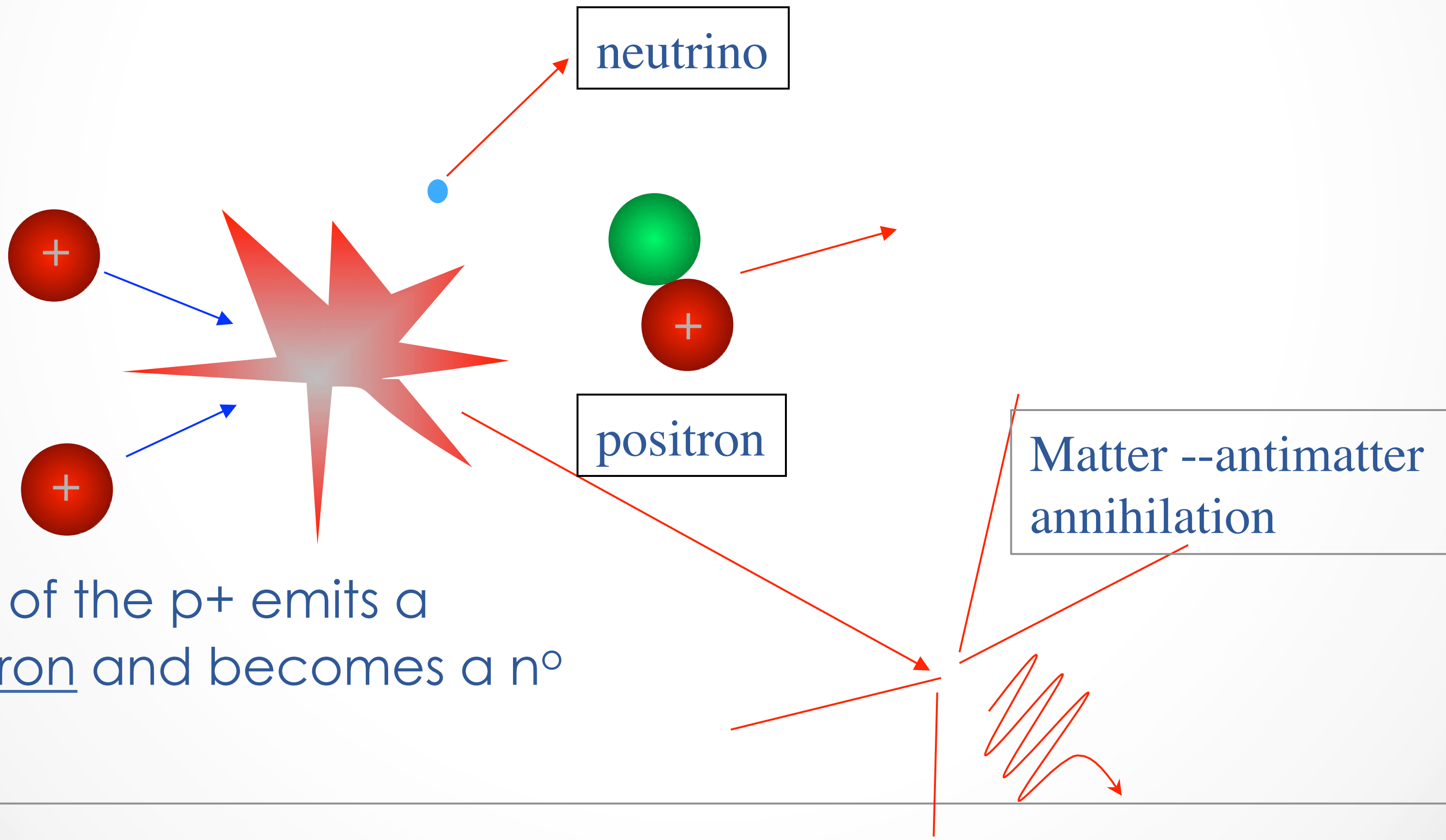
# Solar Model (from last class)




- Use "hydrostatic models" balancing thermal expansion vs gravitation contraction to determine the structure of the Sun and other stars
- These give the temperature and density at every radius and we use the physics of the last 100 years to determine what goes on under these physical conditions

# Hydrogen Fusion

- Key outcome of models is central temperatures high enough for $p^+$-$p^+$ fusion




One of the p+ emits a
Positron and becomes a n°

# 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.

# Stellar Lifetimes

- The Sun has a main-sequence lifetime of 10 billion years. What about the other stars?

  (1) The <u>fuel</u> for stars is mass

  (2) The <u>fuel consumption rate</u> is Luminosity

  So, it's easy!

$$\boxed{Life_{m-s} \propto \frac{Mass}{Luminosity}}$$

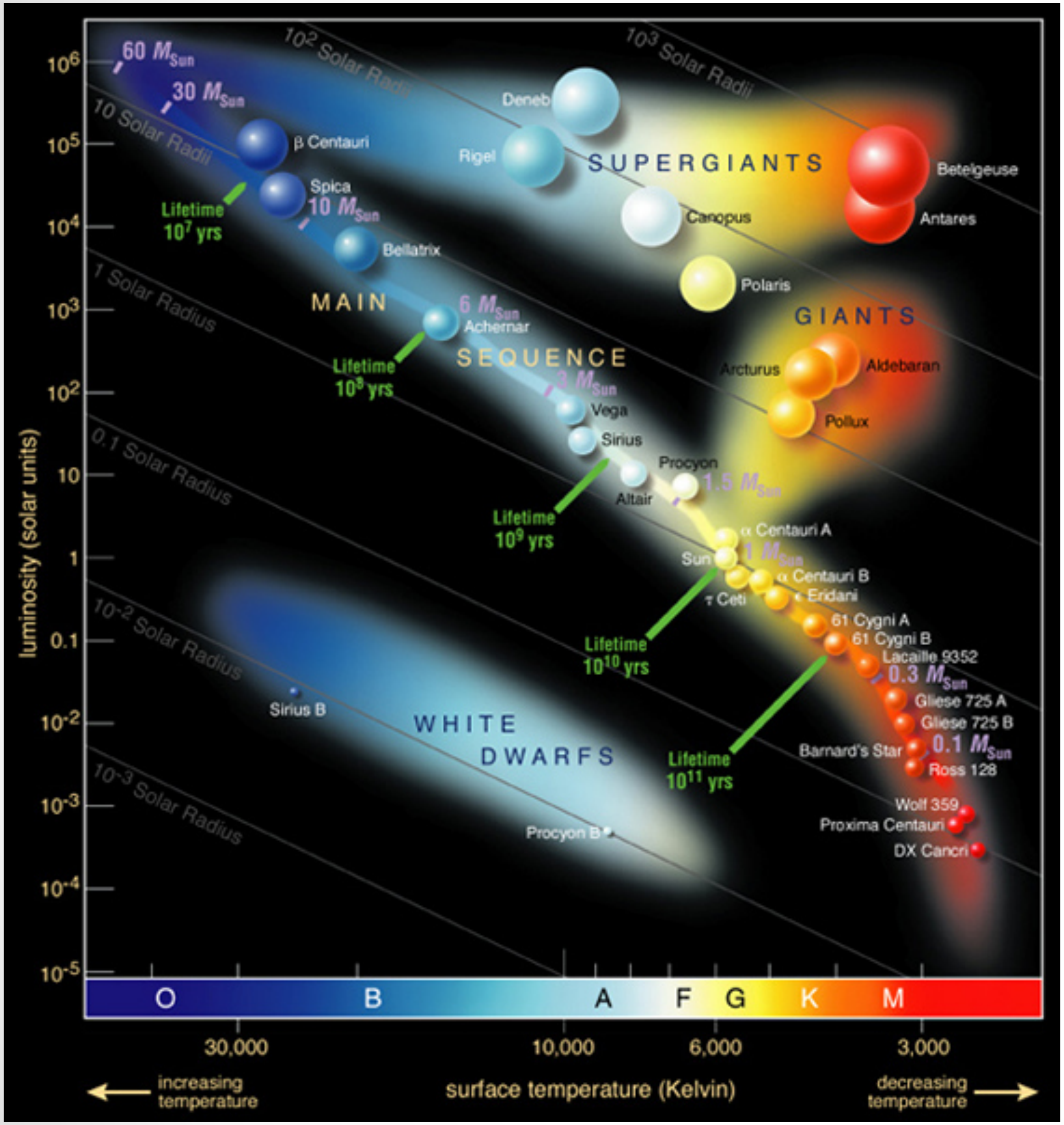
# Example Stellar Lifetime

Suppose you have a $15M_{SUN}$ star with a luminosity of $L=10{,}000L_{SUN}$. How long will this star spend on the main sequence?

$$\boxed{\text{Lifetime}(15M_{SUN}) = \frac{15}{10000} \times \text{Lifetime}(1M_{SUN})}$$

15 times as much fuel extends the life of the star

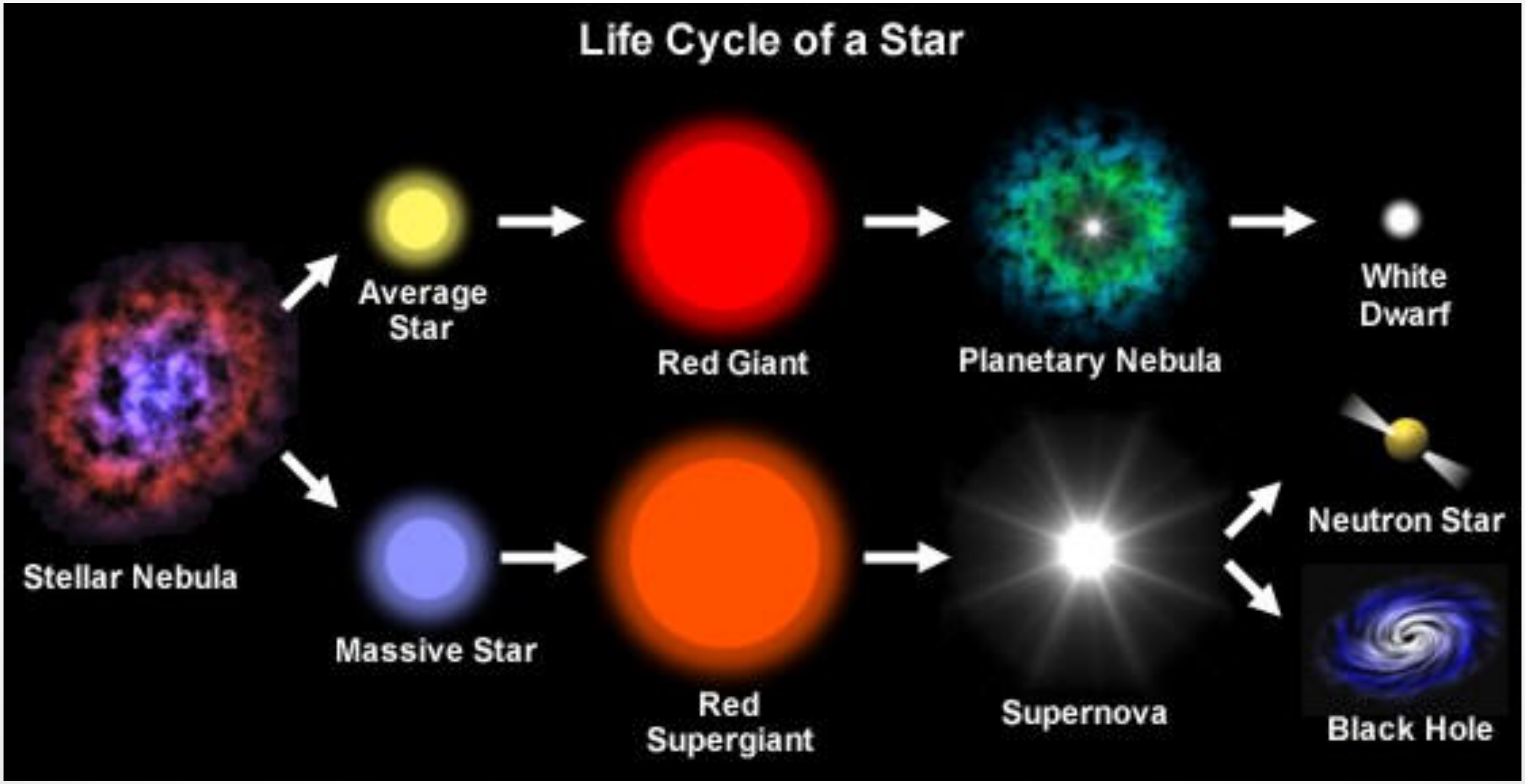
10,000 times L decreases the lifetime




# Now understand the main sequence in the H-R diagram

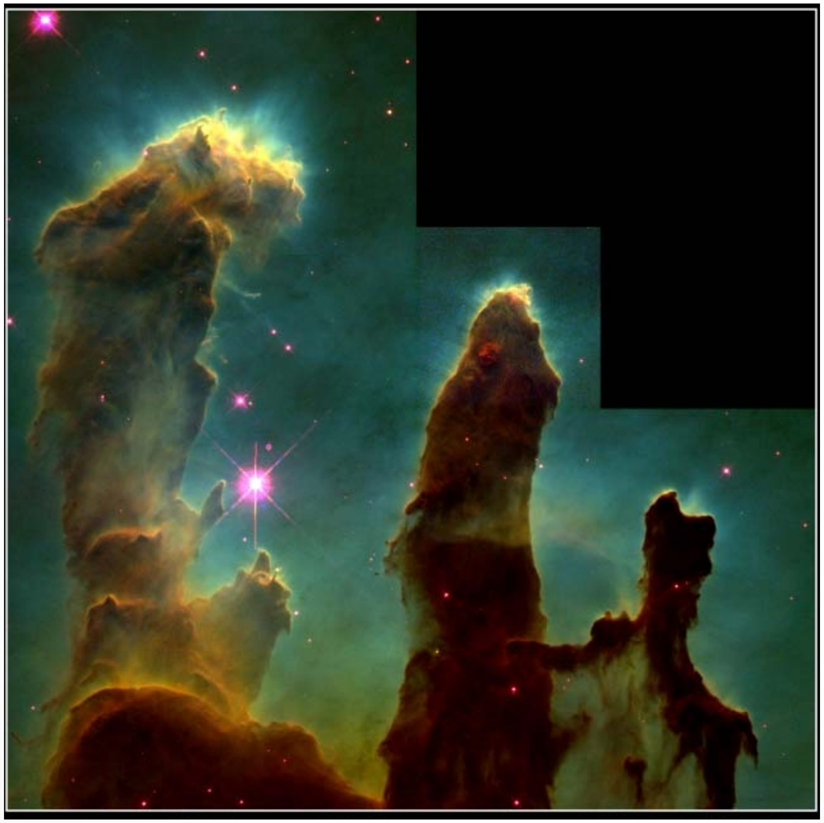
- Main sequence is a mass sequence. Higher mass leads to higher central temperature and higher luminosity
- It is also a sequence in stellar lifetime

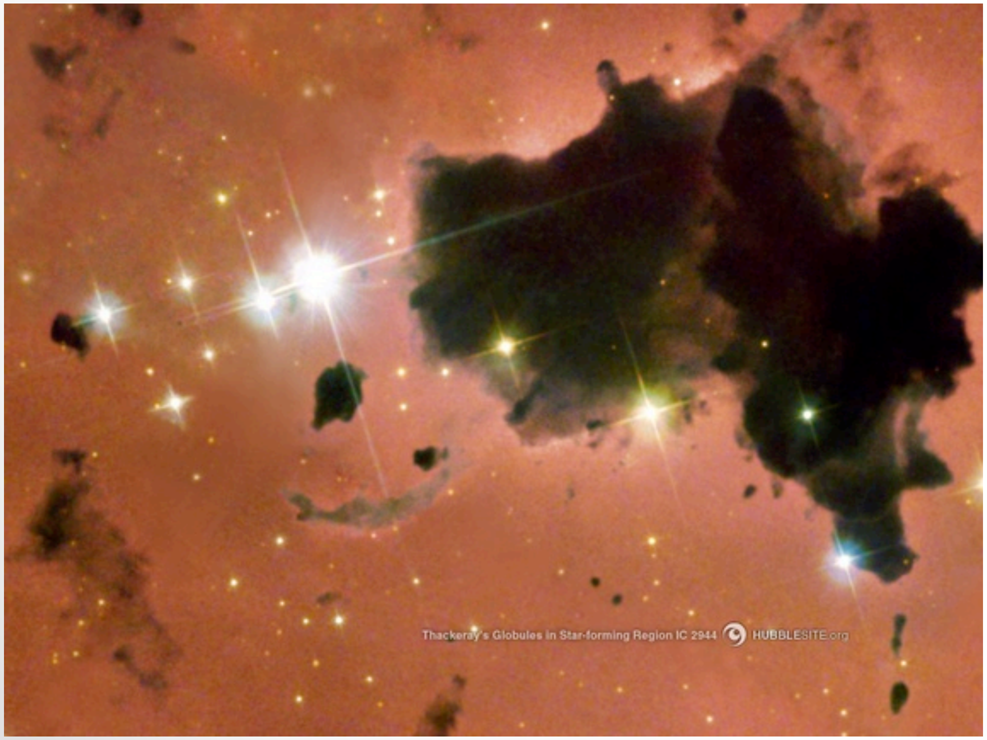
# Stellar Evolution



# 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.



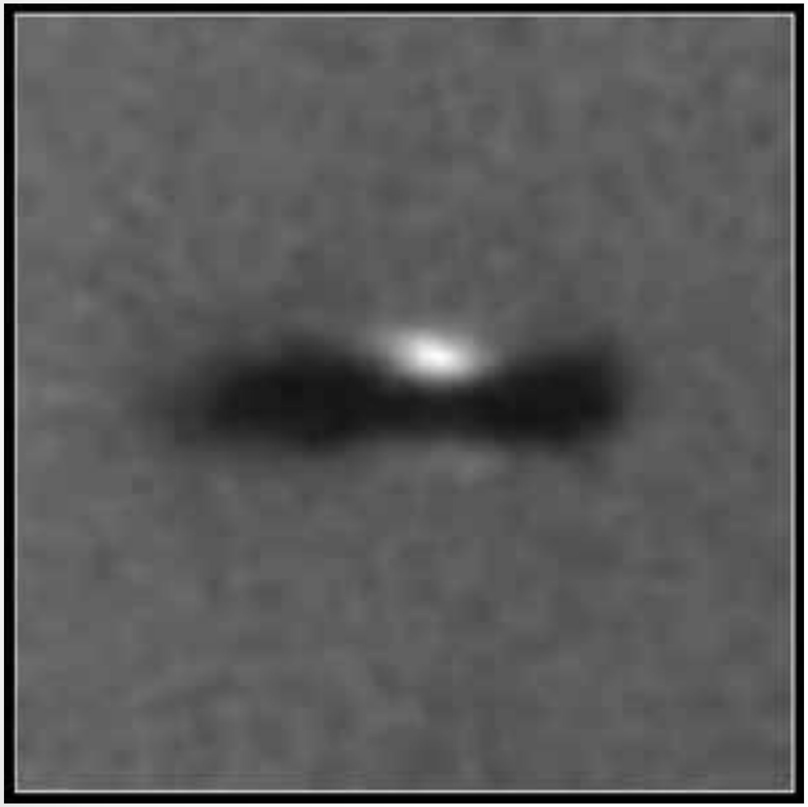



Gravitational collapse to a protostar requires very low temperatures and even the heating by the ambient light in the Galaxy can prevent star formation.

Deep in the black 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

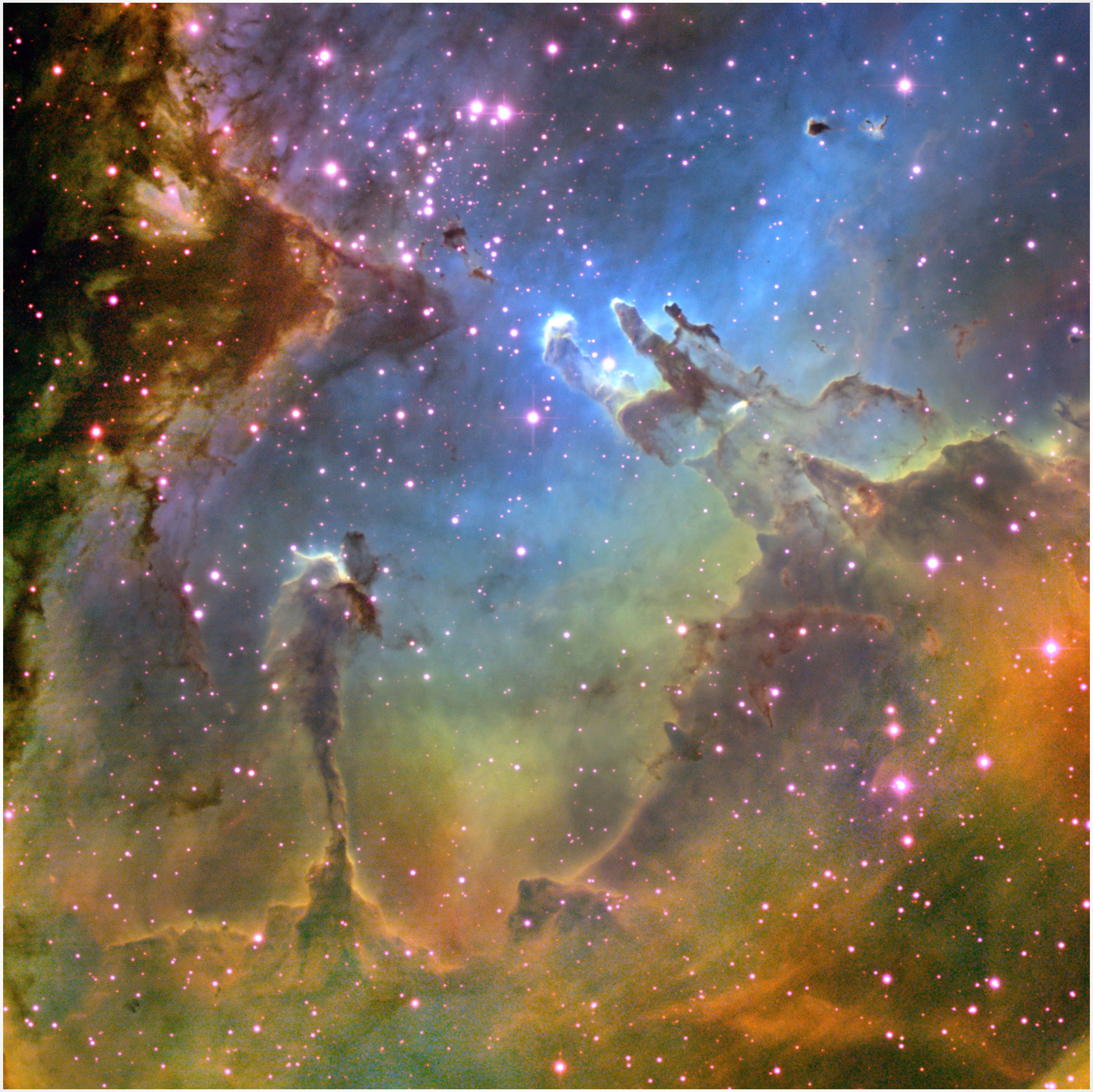
# Proto-planet

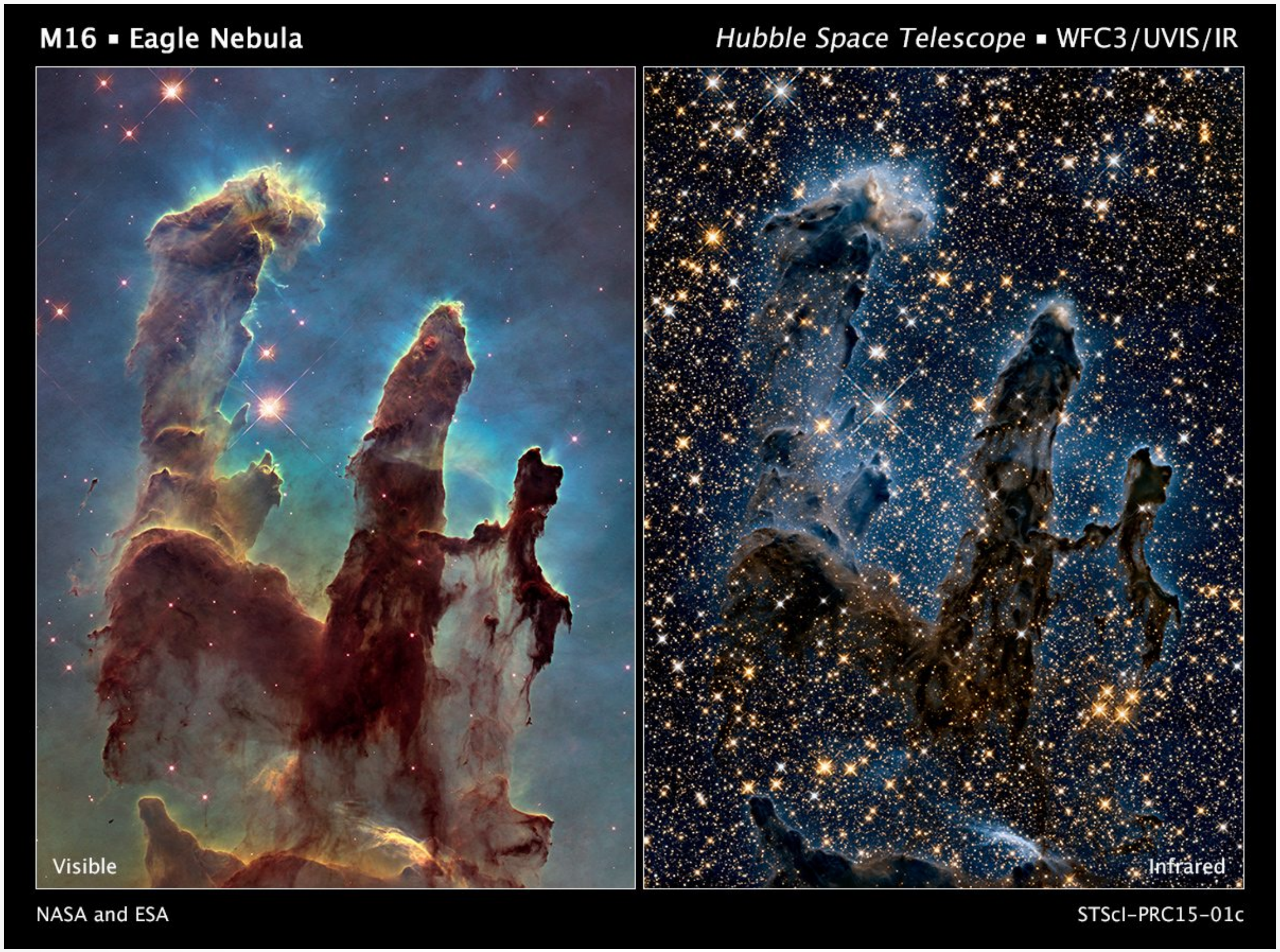


- The contracting mass heats up (conversion of gravitational potential energy)
- As it contracts it starts to spin faster (conservation of angular momentum) and some material forms a disk
- If there is enough initial mass that the central temperature reaches 10 million K, the fusion starts and a star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

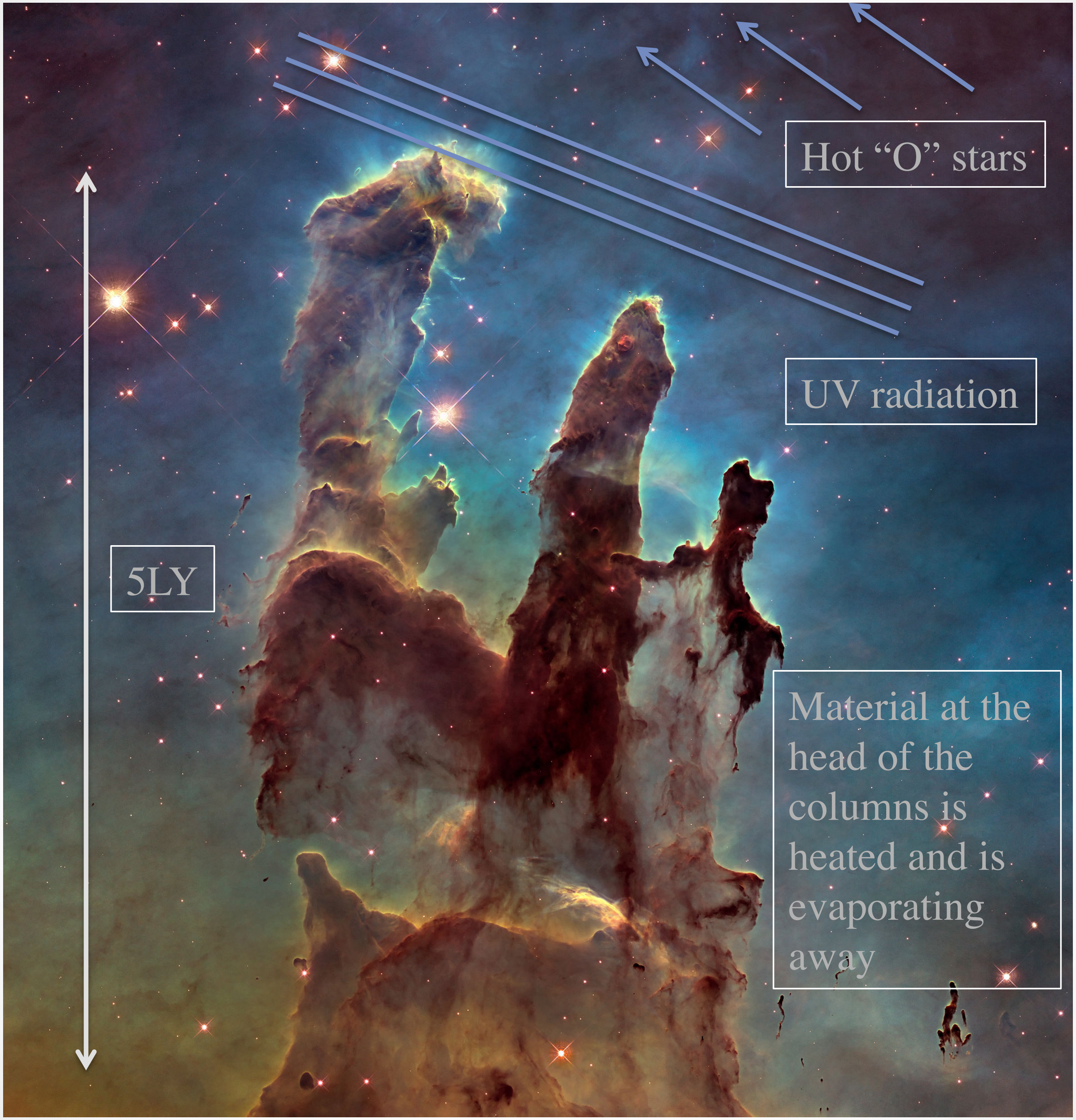
# Dust lanes in the plane of the Galaxy

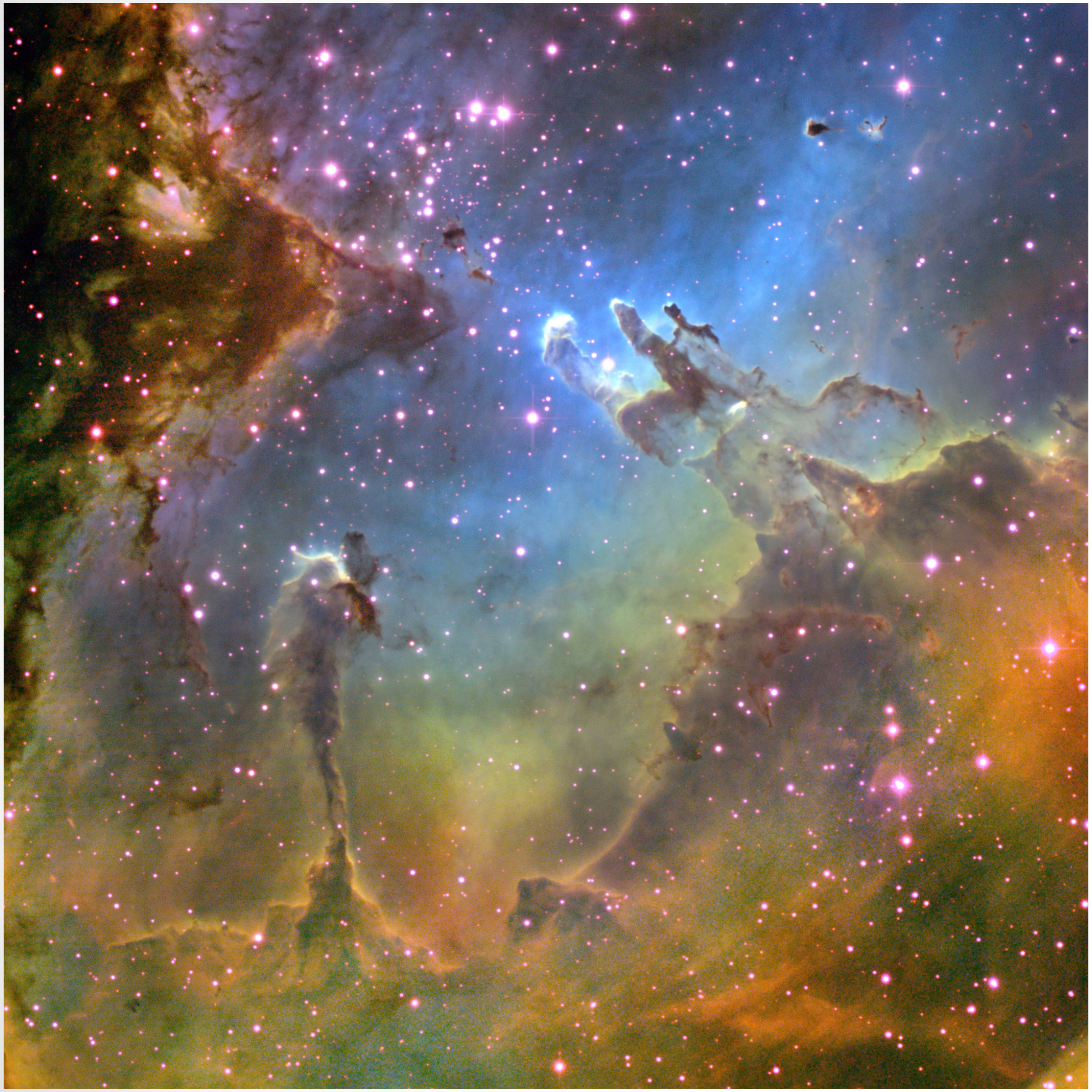
When stars are born they blast the nebula clear





M16 ▪ Eagle Nebula
Hubble Space Telescope ▪ WFC3/UVIS/IR
Visible
Infrared
NASA and ESA
STScI-PRC15-01c


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

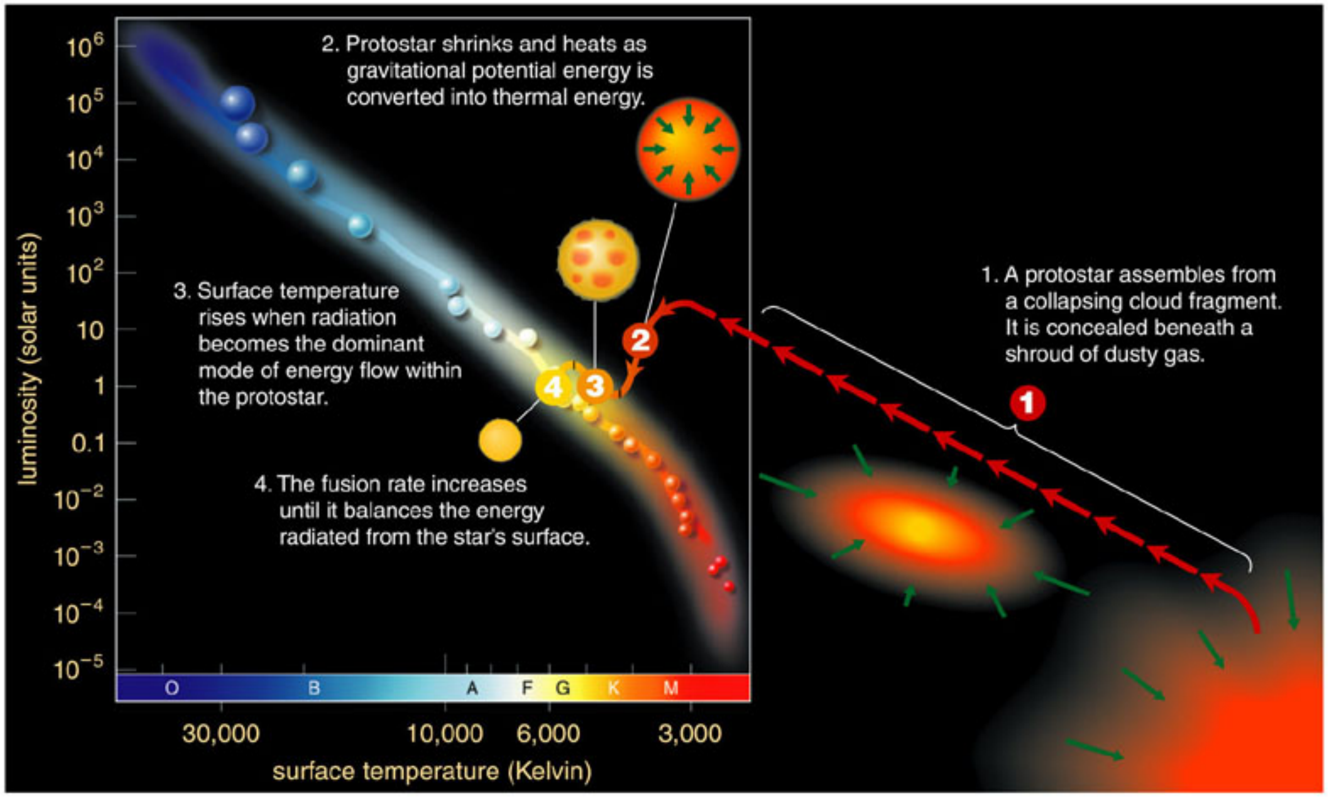


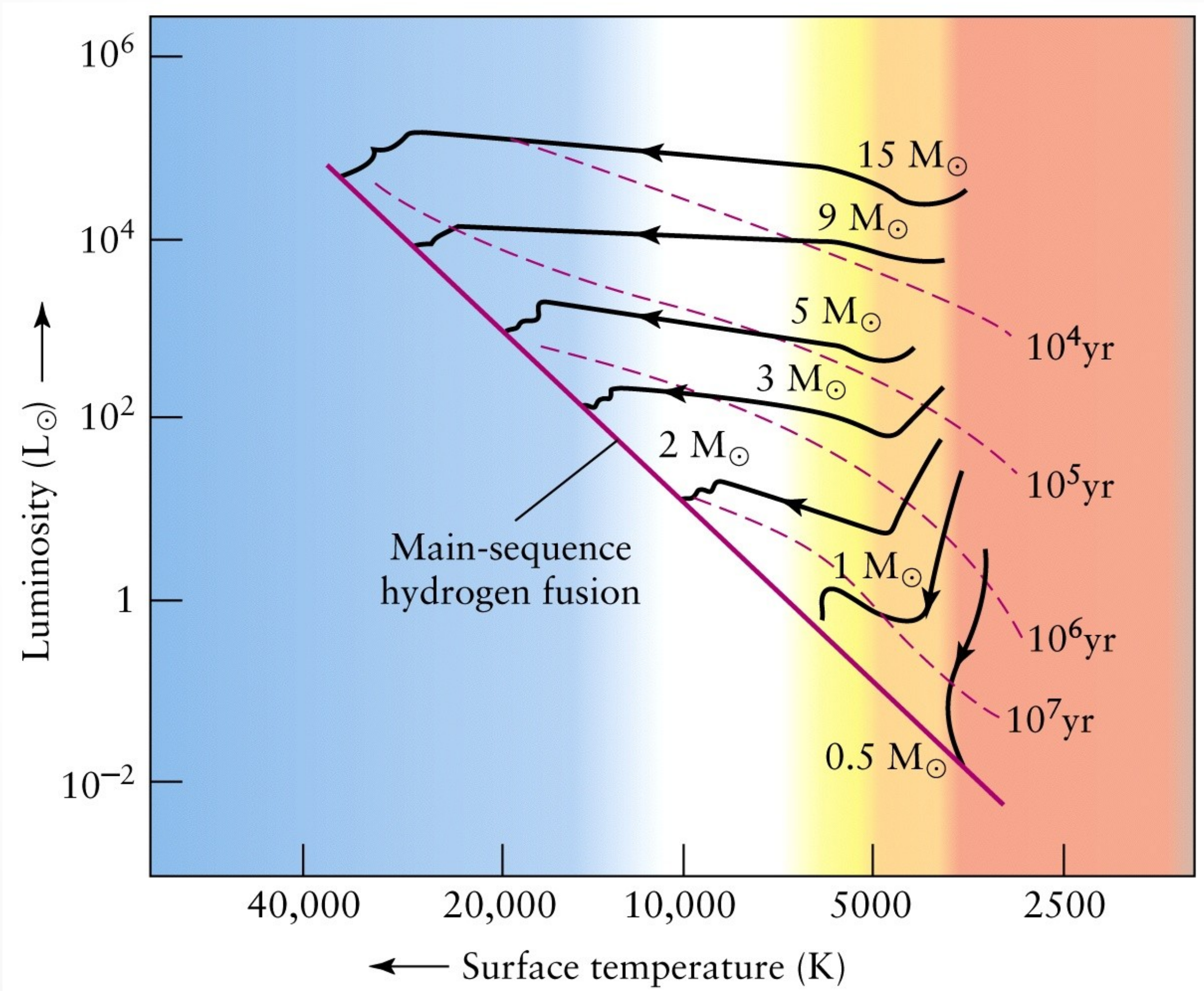
Star formation occurs in the coldest places in the Galaxy where dust shields gas clouds from stellar radiation

Gravity overcomes thermal pressure and the gas clouds collapse into protostars and disks

Once the stellar cores reach fusion temperatures, the stars are “born”, and the radiation fields shred the remaining gas clouds and dust

# Protostars and the HR diagram



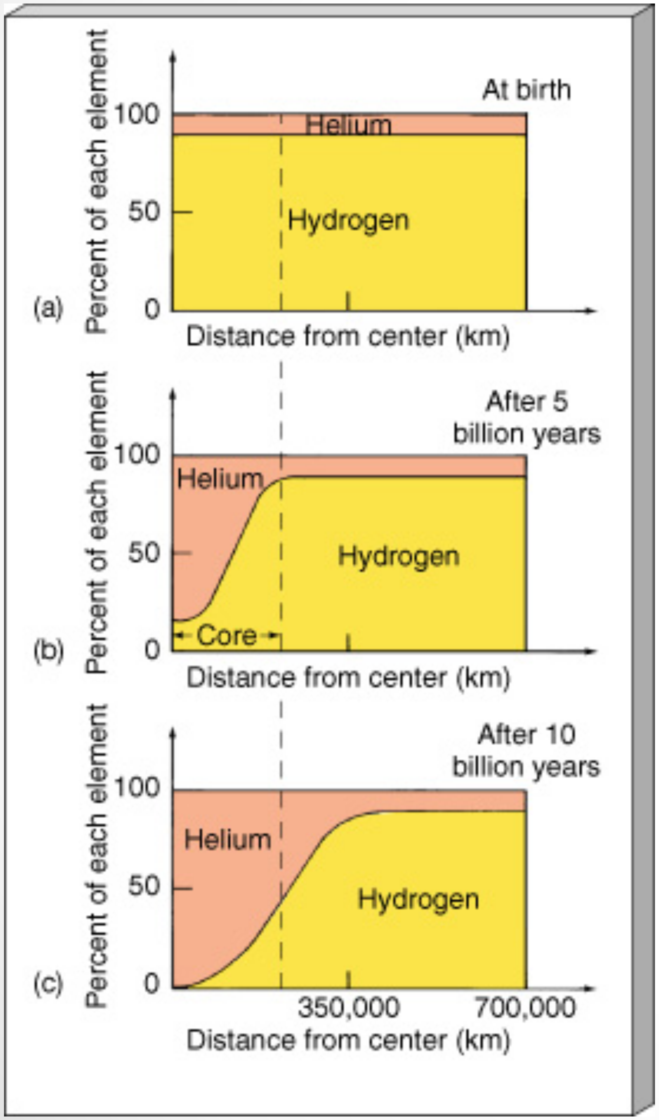


$10^6$
$10^4$
$10^2$
1
$10^{-2}$
Luminosity ($L_\odot$)
15 $M_\odot$
9 $M_\odot$
5 $M_\odot$
3 $M_\odot$
2 $M_\odot$
1 $M_\odot$
0.5 $M_\odot$
$10^4$yr
$10^5$yr
$10^6$yr
$10^7$yr
Main-sequence
hydrogen fusion
40,000
20,000
10,000
5000
2500
Surface temperature (K)

# Stellar Evolution

- We know a lot about stellar evolution. For this class we will gloss over most of the details and concentrate on three things:
  - The stellar evolution stages the Sun will undergo
  - The stellar evolution stages of massive stars
  - Production and distribution of chemical elements by low-mass stars
  - Production and distribution of chemical elements in enormous explosions that end the lives of massive stars
  - The end products of stellar evolution: White Dwarfs, Neutron Stars and Black Holes

# Stellar Evolution



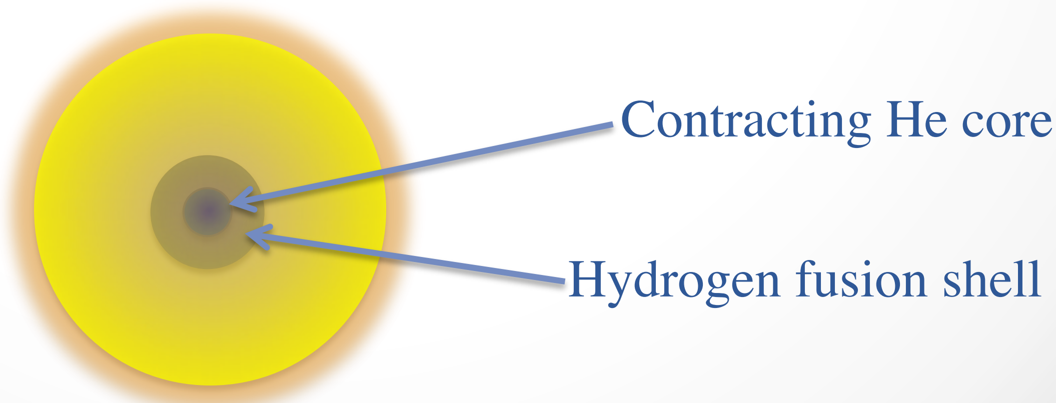

- As hydrogen is being converted into helium in the core of a star, its structure changes slowly and stellar evolution begins.
- The structure of the Sun has been changing continuously since it settled in on the main sequence.

# Stellar Evolution

- As the helium core grows, it compresses. Helium doesn't fuse to heavier elements for two reasons.
  - with 2 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.

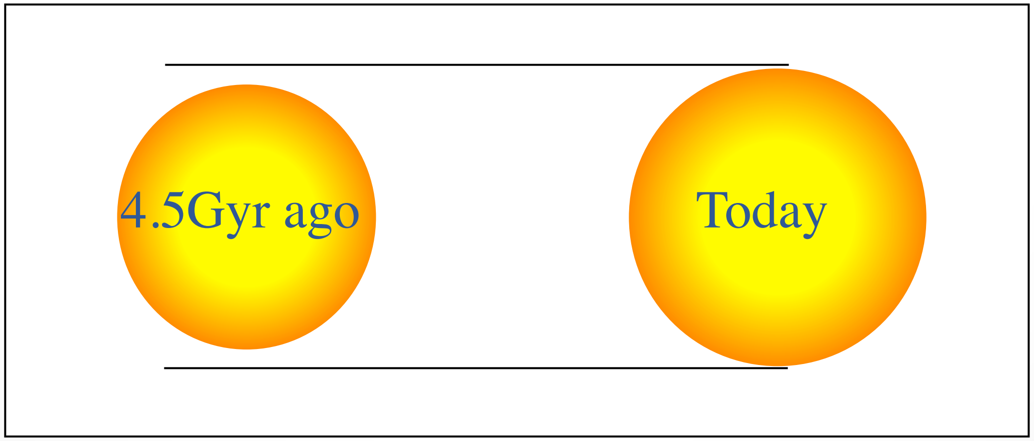
# Stellar Evolution

- 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

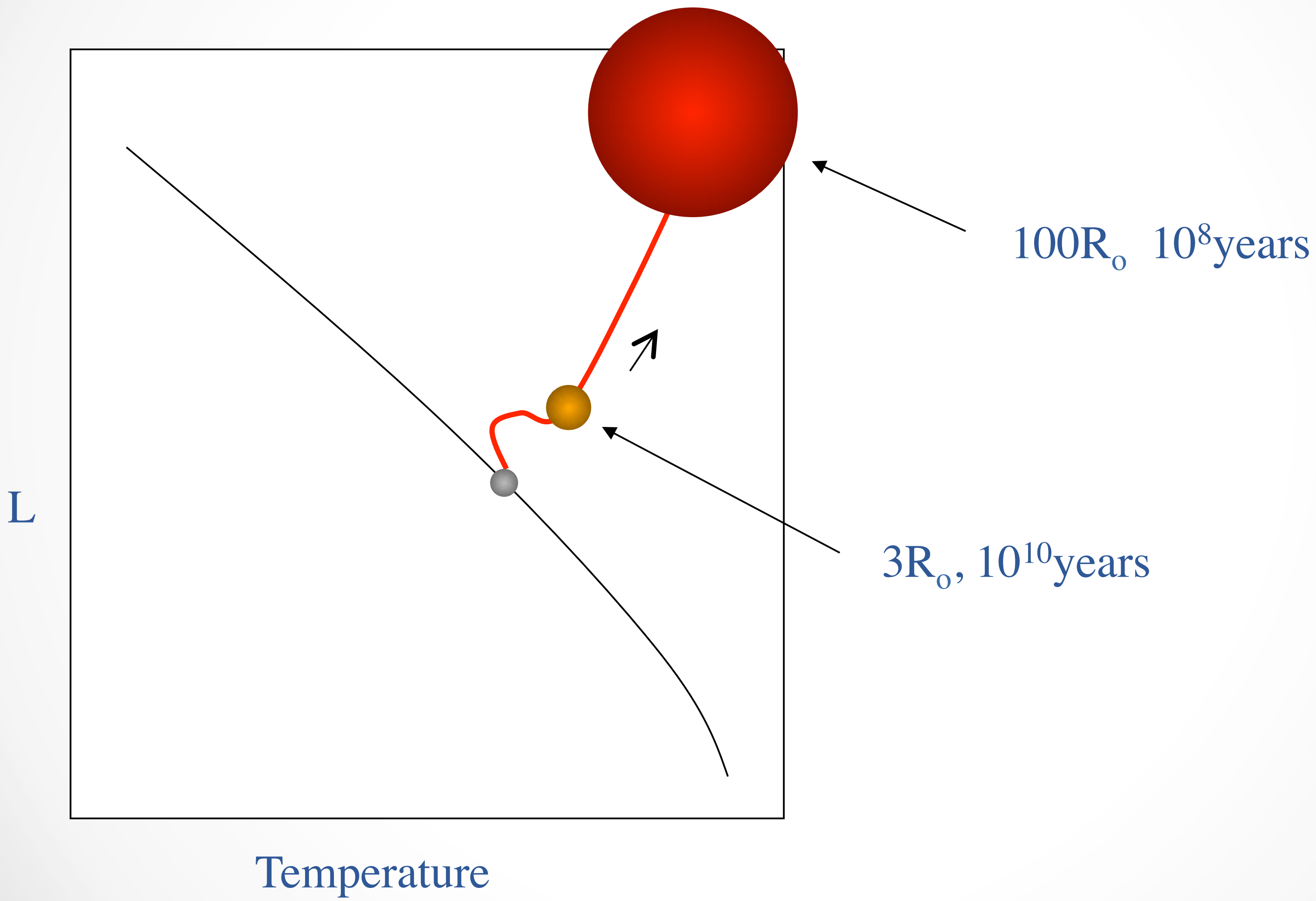
- Stars begin to evolve off the zero-age main sequence from day 1.
- Compared to 4.5 Gyr ago, the radius of the Sun has increased by 6% and the luminosity by 40%.

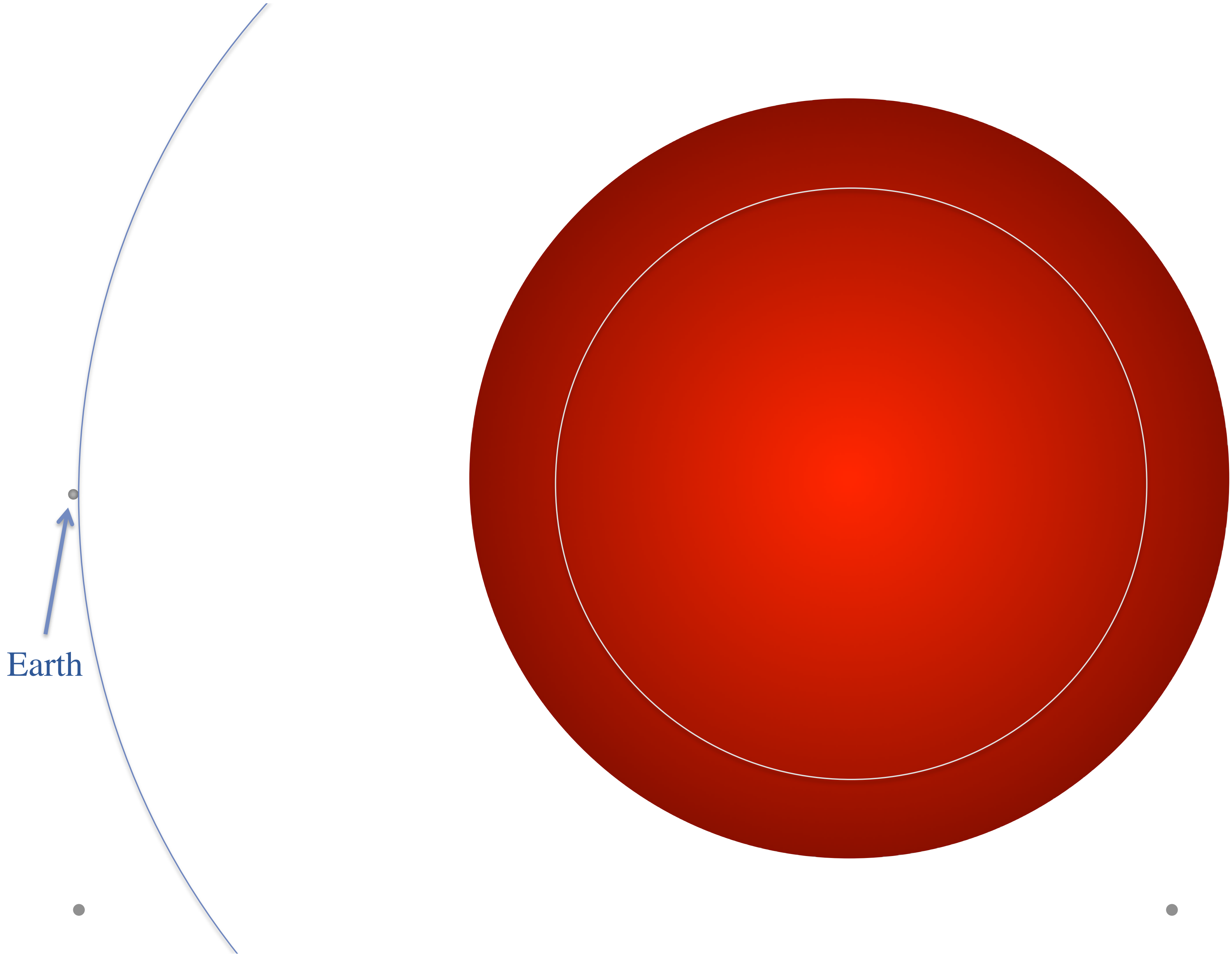


# Red Giants

- 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:
    - $L \sim 2000L_o$
    - $R \sim 0.5AU$ (half way to the Earth)
    - $T_{surface}$->3500k

# Red Giant

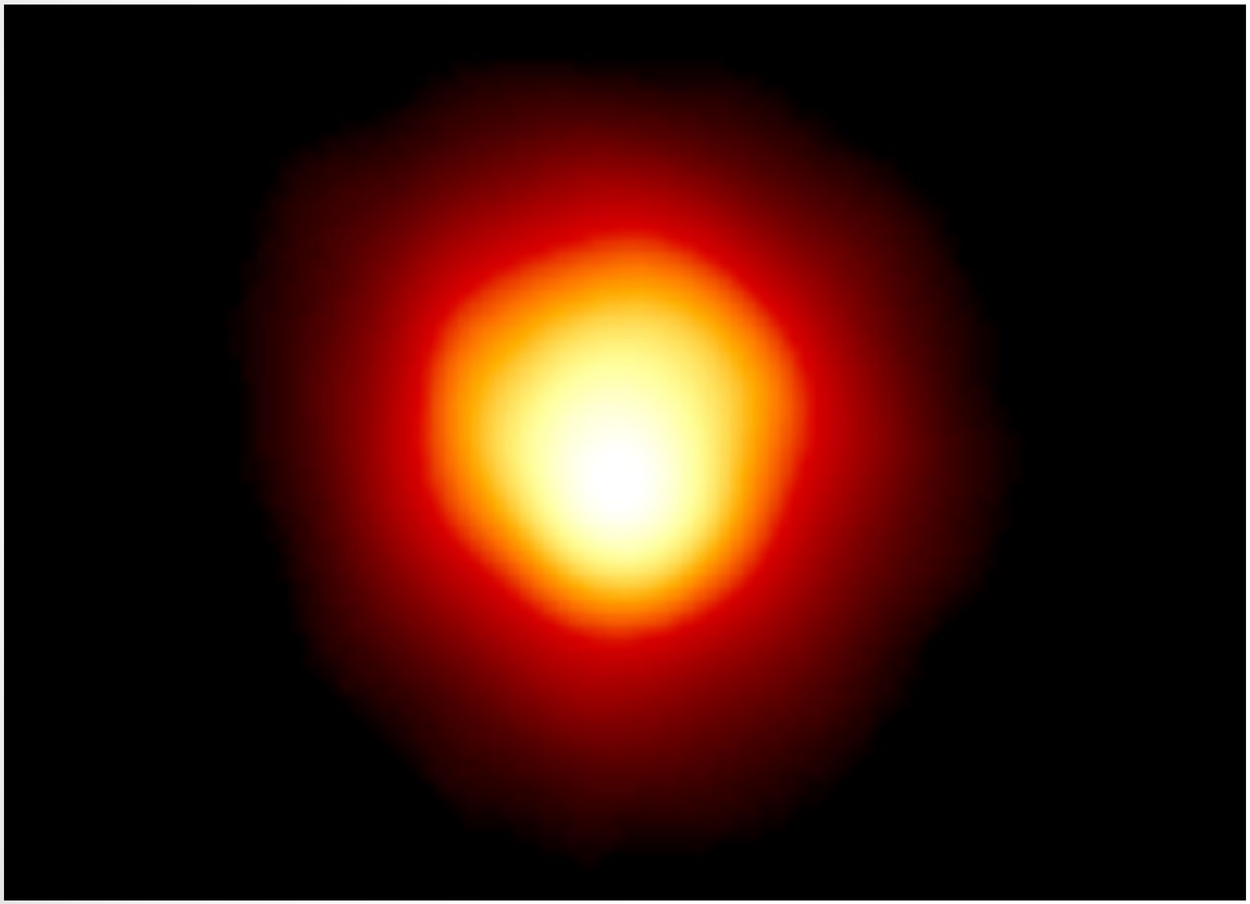



Earth

# 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.

# 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

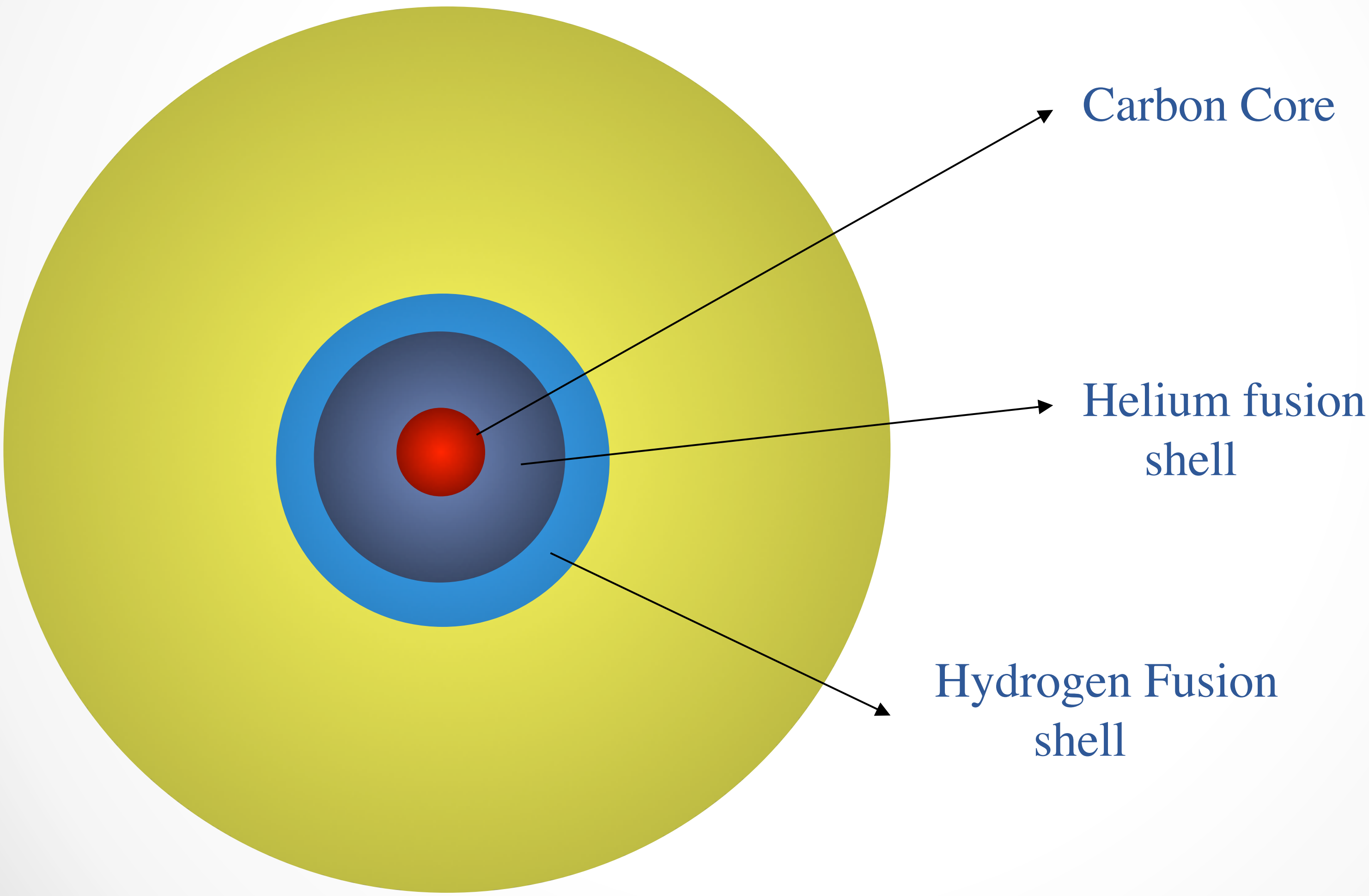
Be natural for Helium fusion to be the next energy source for an evolving star

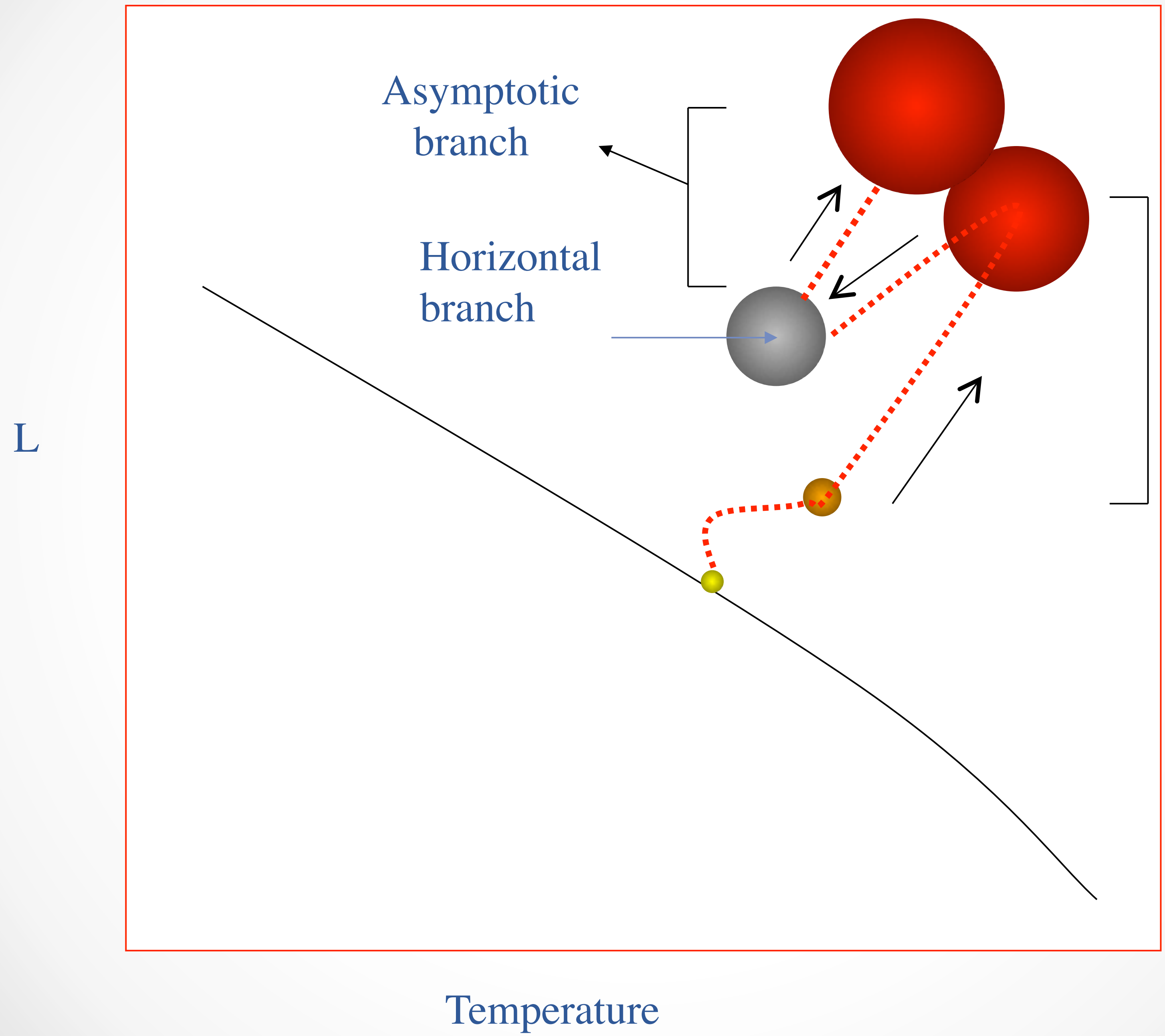
Helium fusion requires two steps:

$$\boxed{\begin{array}{c} He^4 + He^4 \rightarrow Be^8 \\ Be^8 + He^4 \rightarrow C^{12} \end{array}}$$

The Berylium 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.

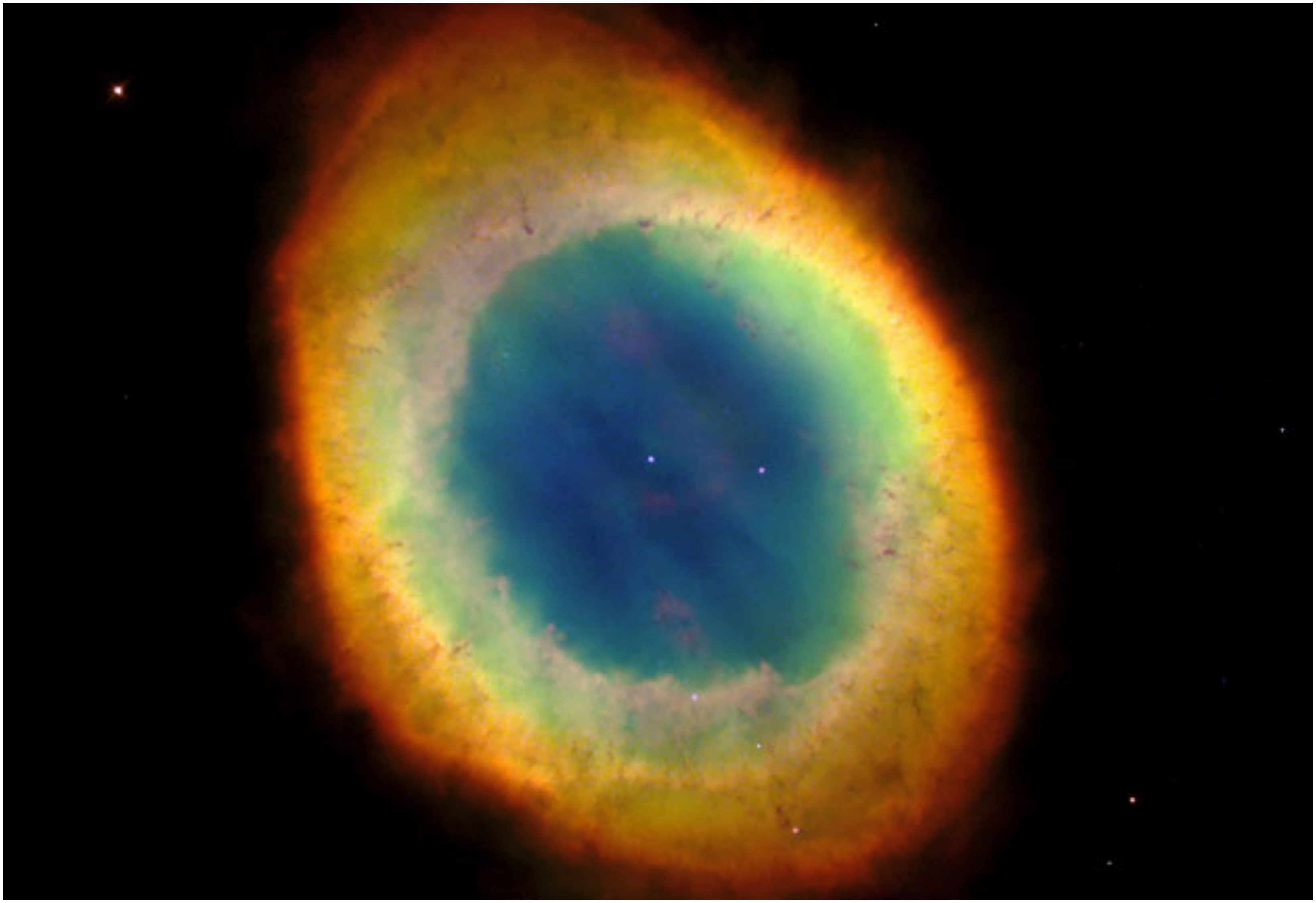
# Giant Star Structure

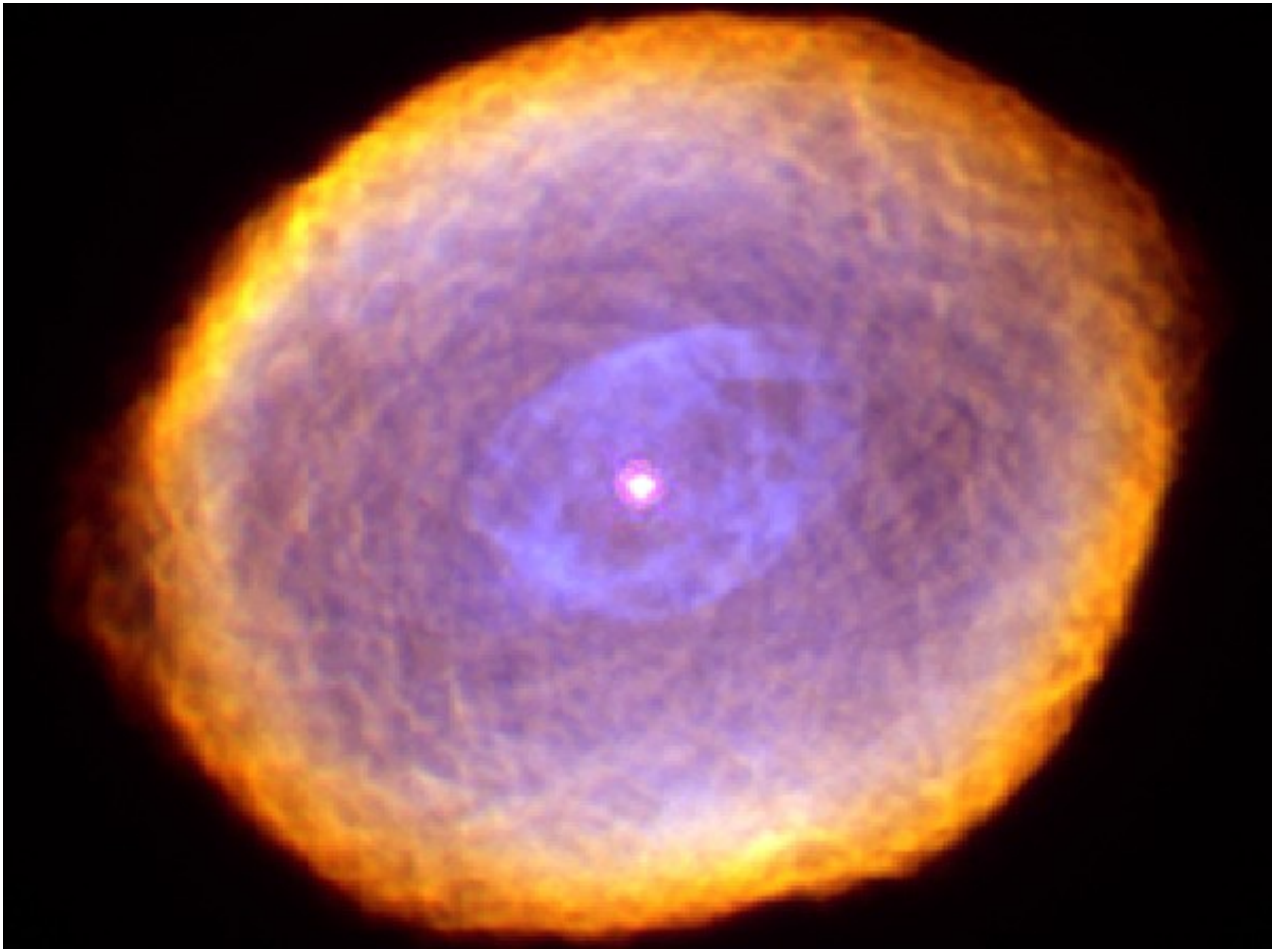


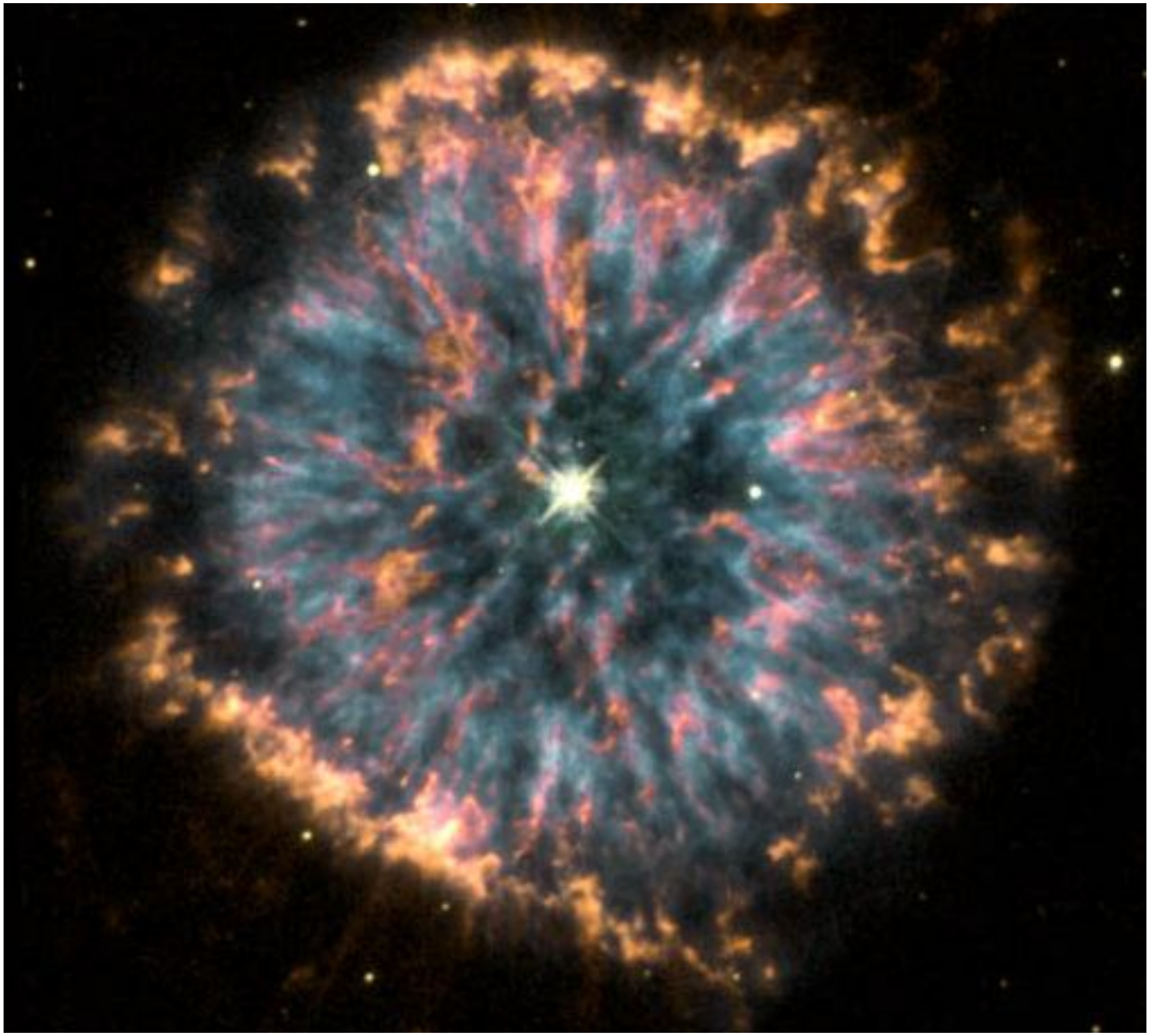

Asymptotic
branch
Horizontal
branch
L
Temperature

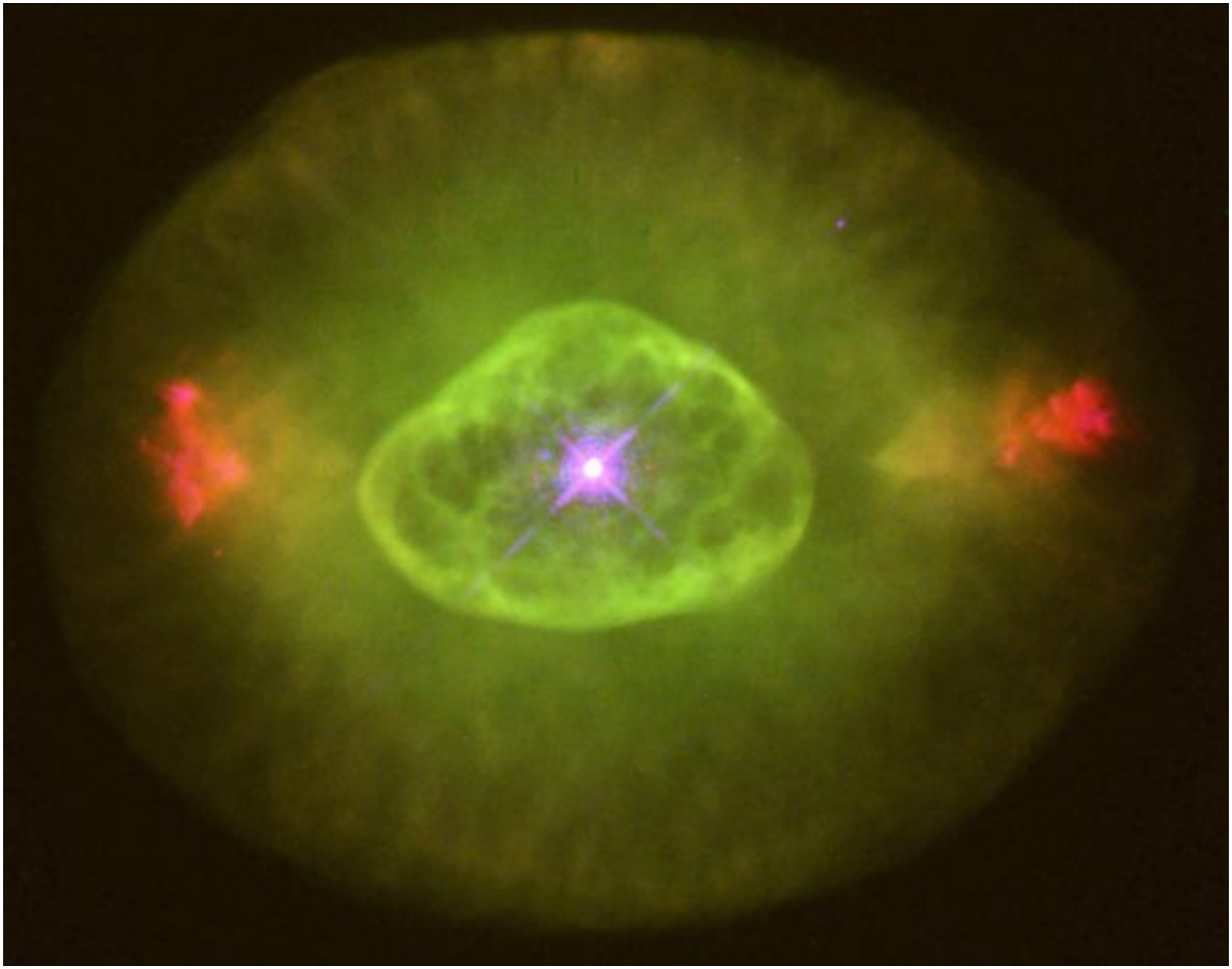
# Planetary Nebula Stage

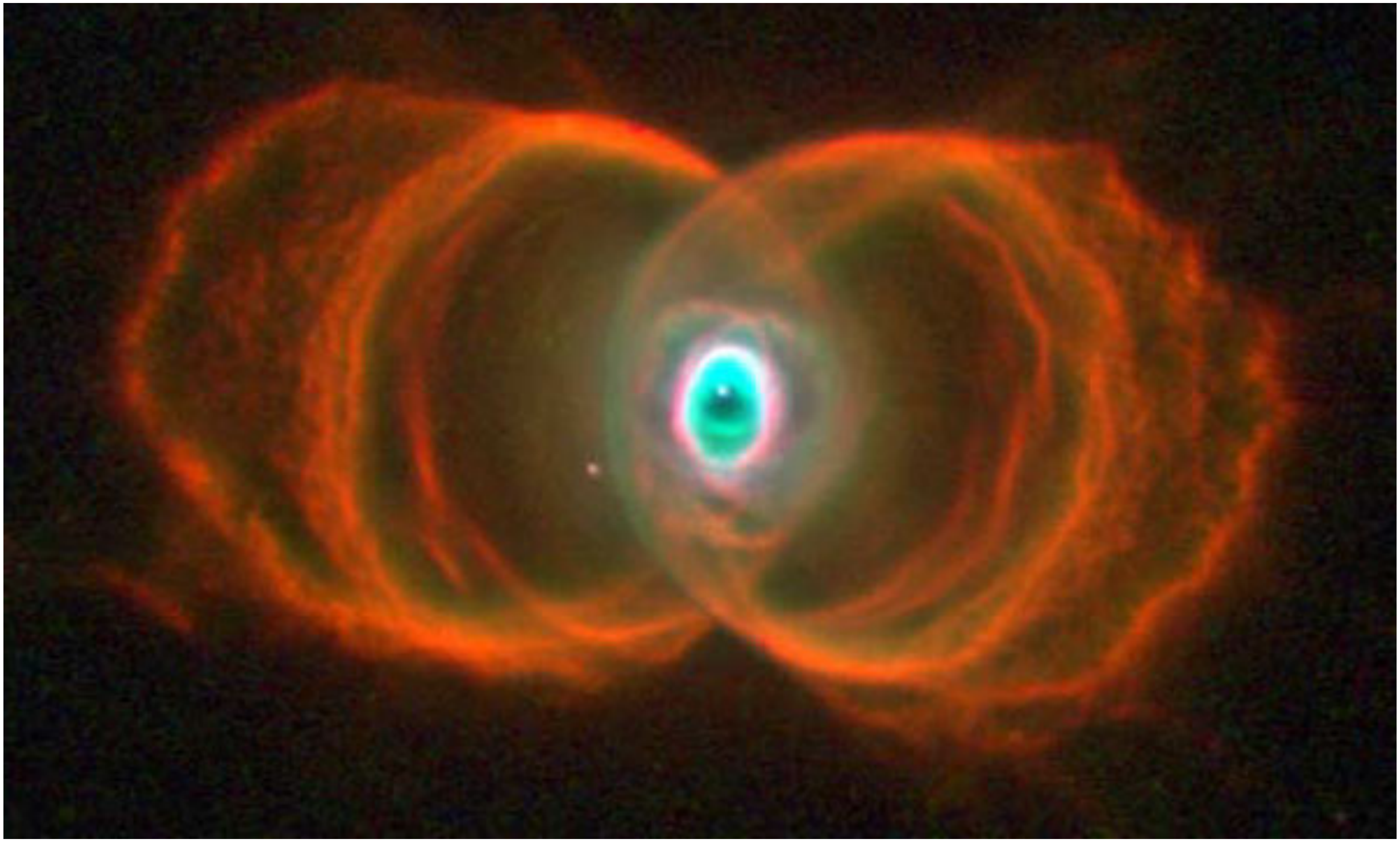
- The trips up the Giant Branch get terminated when the star's outer envelope becomes detached and begins to *drift off into space*. (!!)
- The former envelope shines in the light of emission lines.
- As the envelope expands and becomes transparent the very hot core of the giant star can be seen at its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

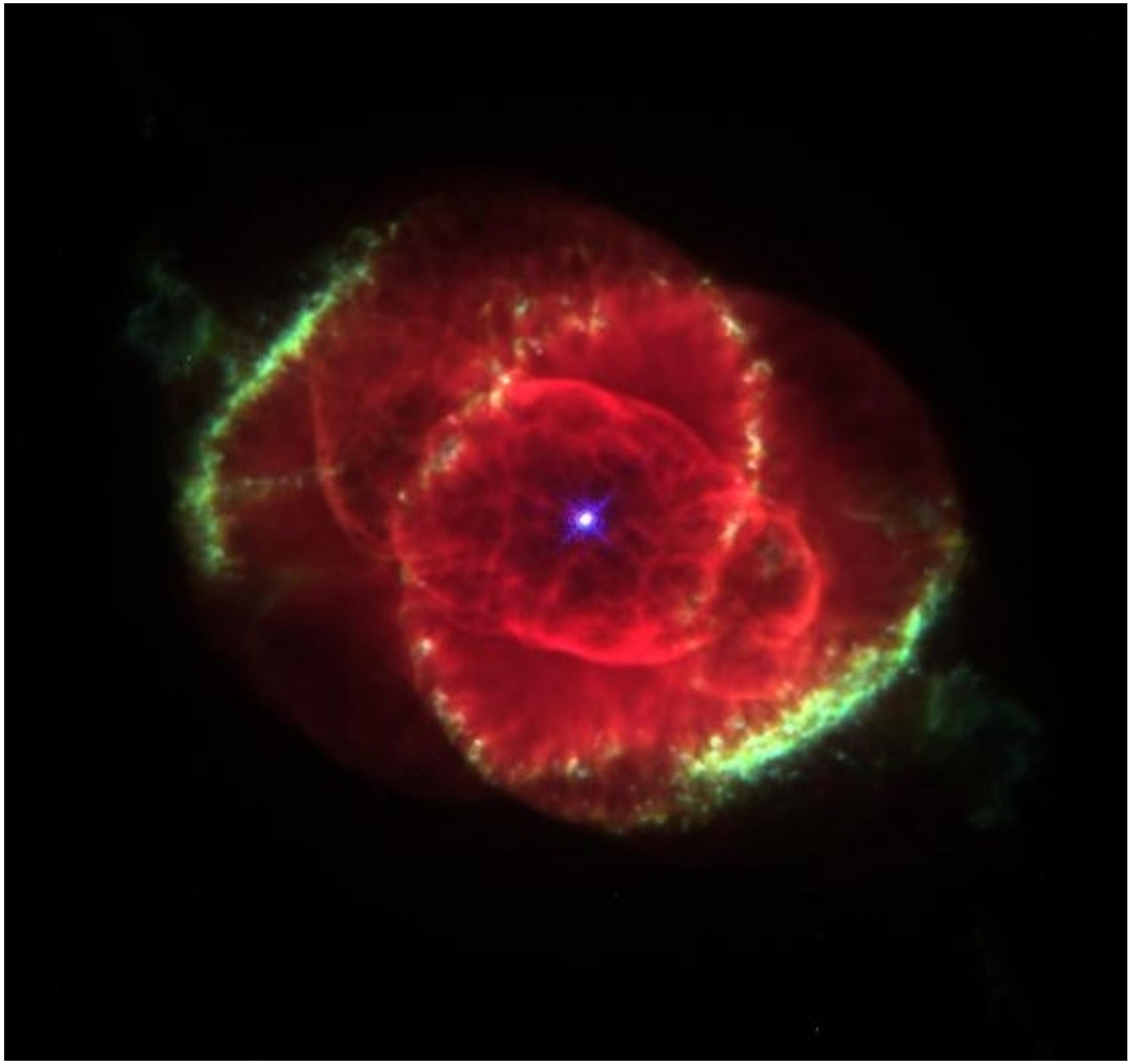






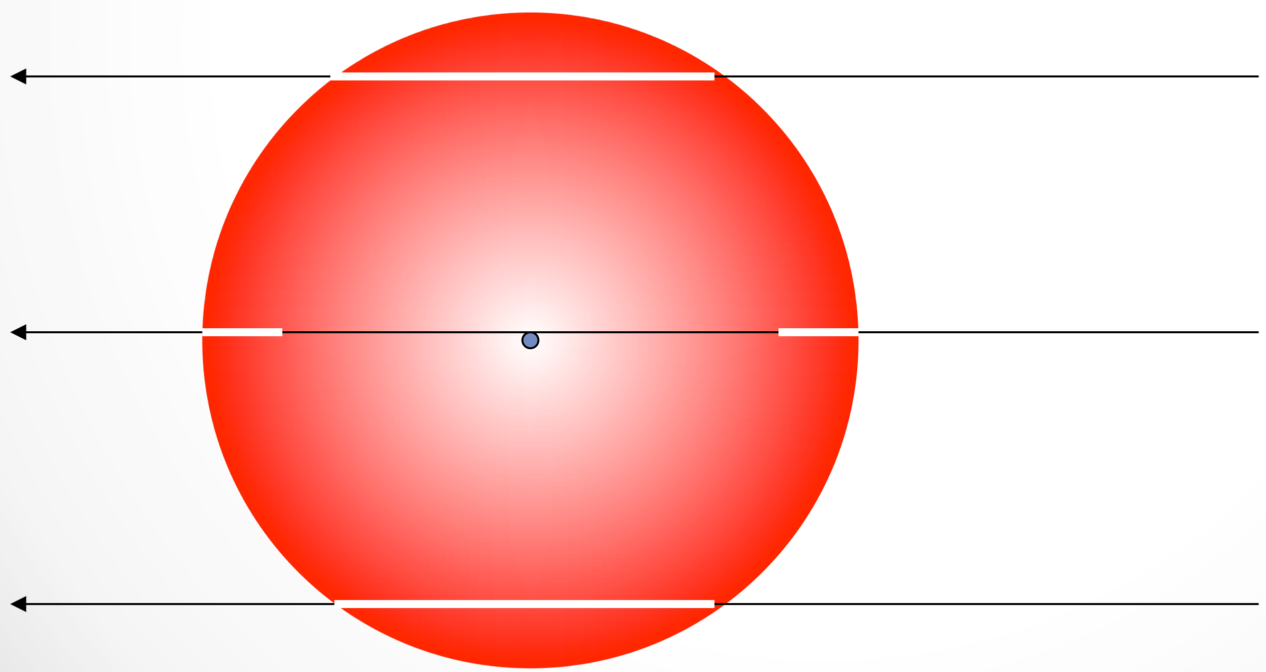






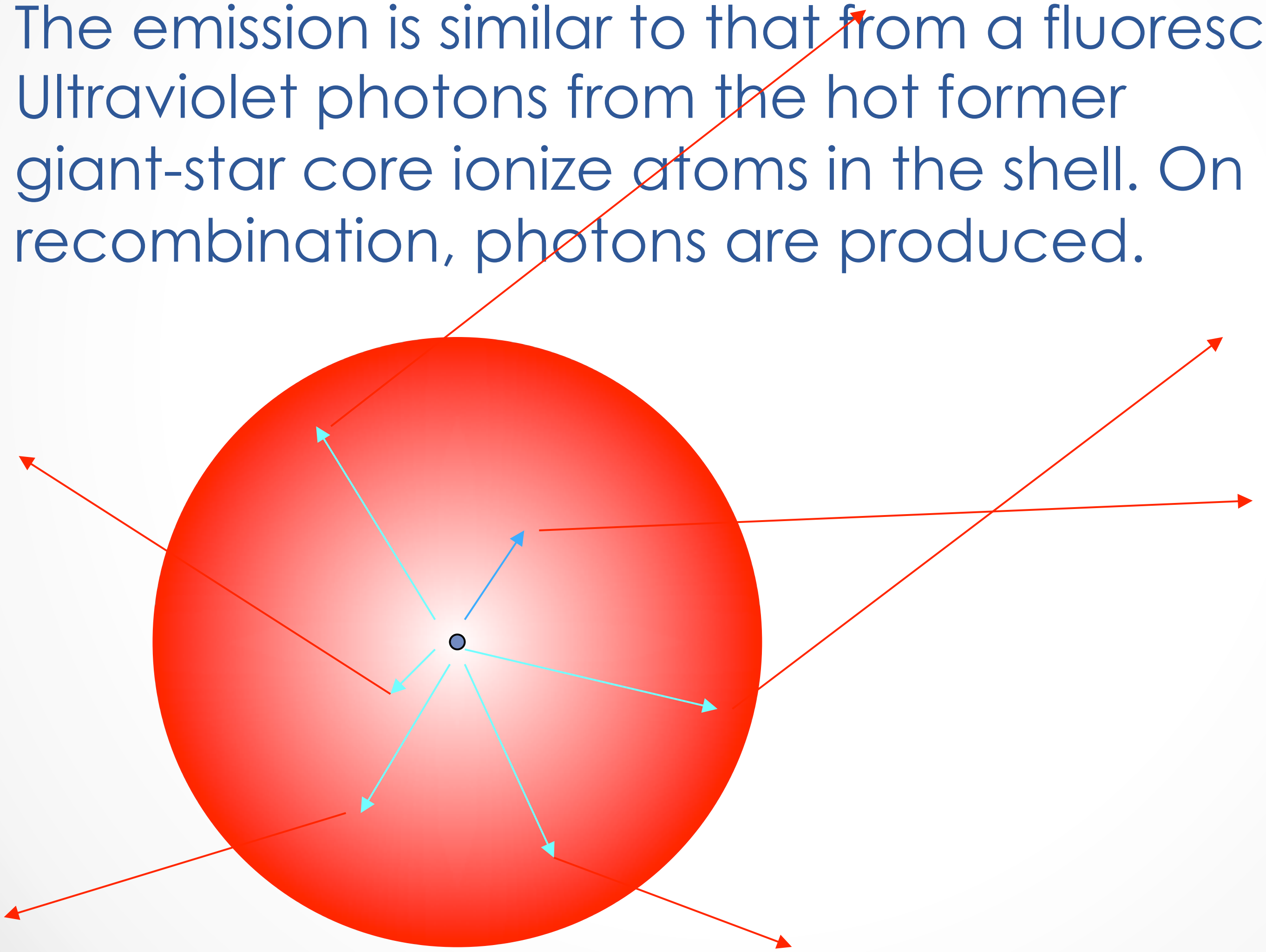
# Planetary Nebulae

- 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 AGB 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.

# Electron Degeneracy

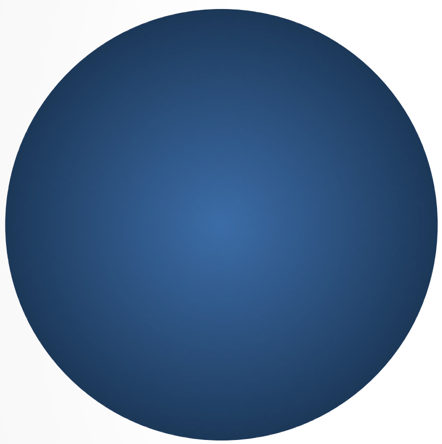
- Electrons are particles called `fermions' (rather than `bosons') that obey a law of nature called the Pauli Exclusion Principle.
- This law says that you can only have two electrons per unit 6-D phase-space volume in a gas.

$$\boxed{\Delta x \Delta y \Delta z \Delta p_x \Delta p_y \Delta p_z}$$

# 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



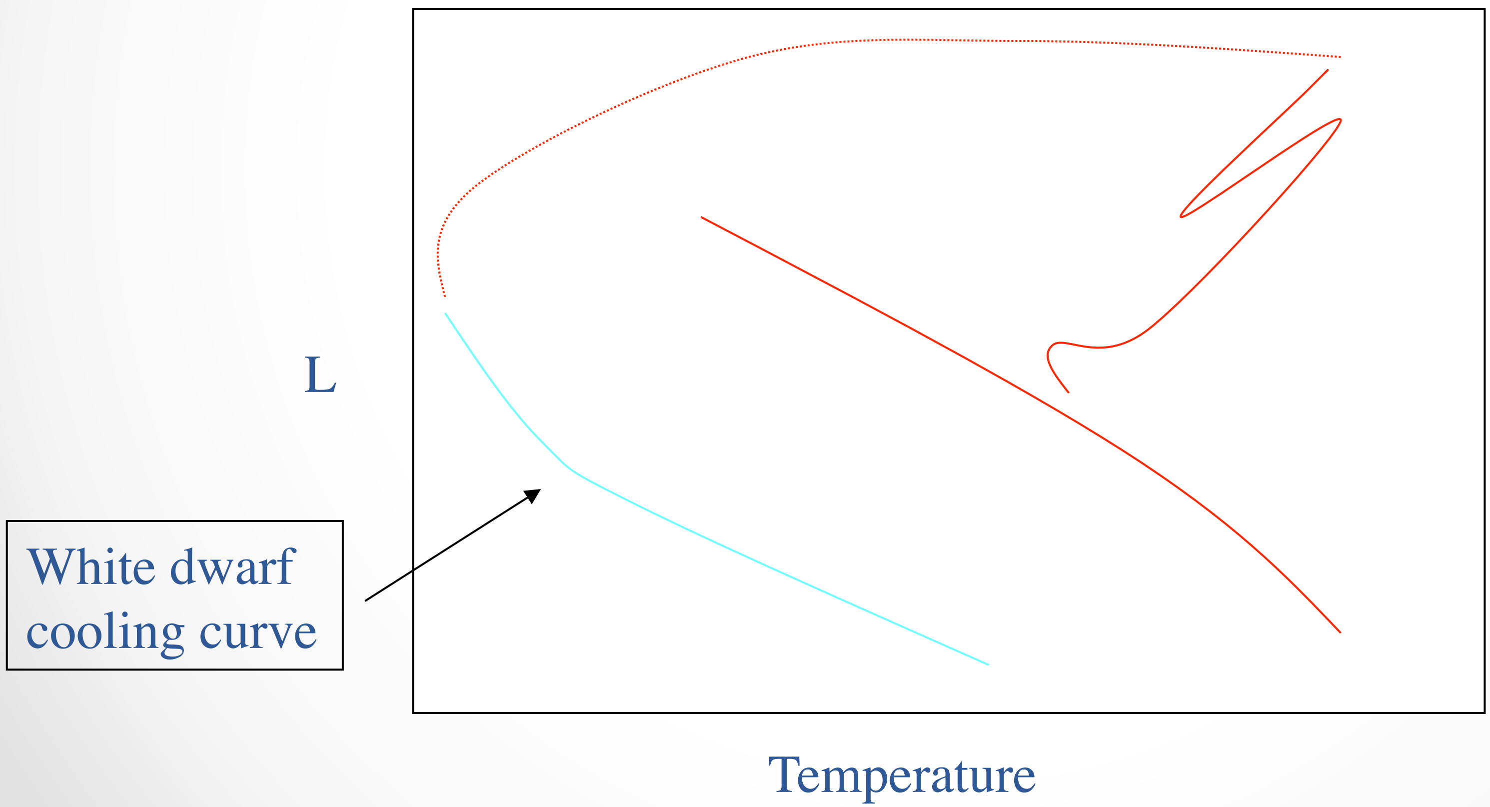
- Energy source: none
- Equilibrium:

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

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

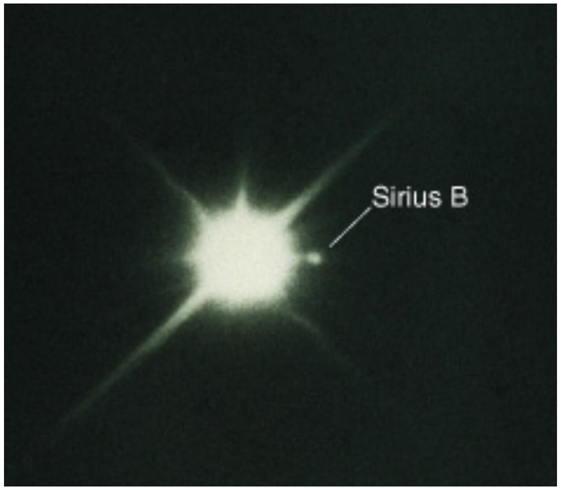
# White Dwarfs

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



# White Dwarfs

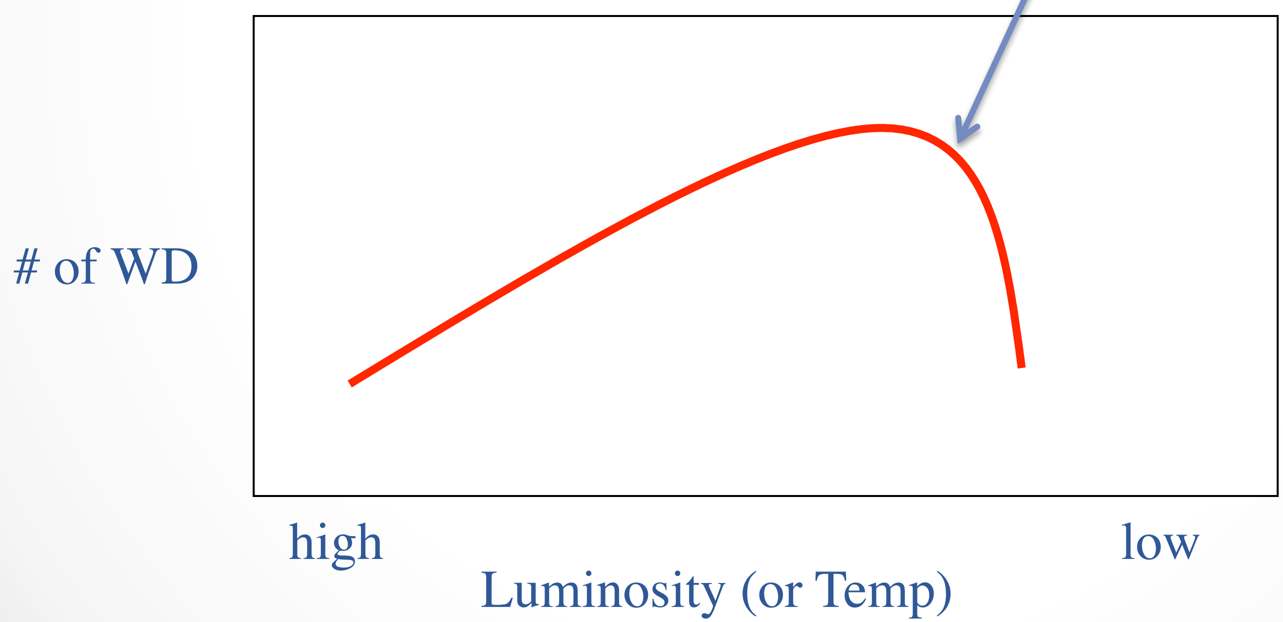
- ~97% of stars end their lives as WDs. They are very common, though hard to see.
- Because it is in a binary orbit, the mass and extreme density of Sirius B was determined in 1910. Seemed completely impossible at the time.



# White Dwarf Cosmochronology

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

This drop off in WDs at low L and T is because of the finite age of the Galaxy



# Evolution of <8$M_{Sun}$ Stars

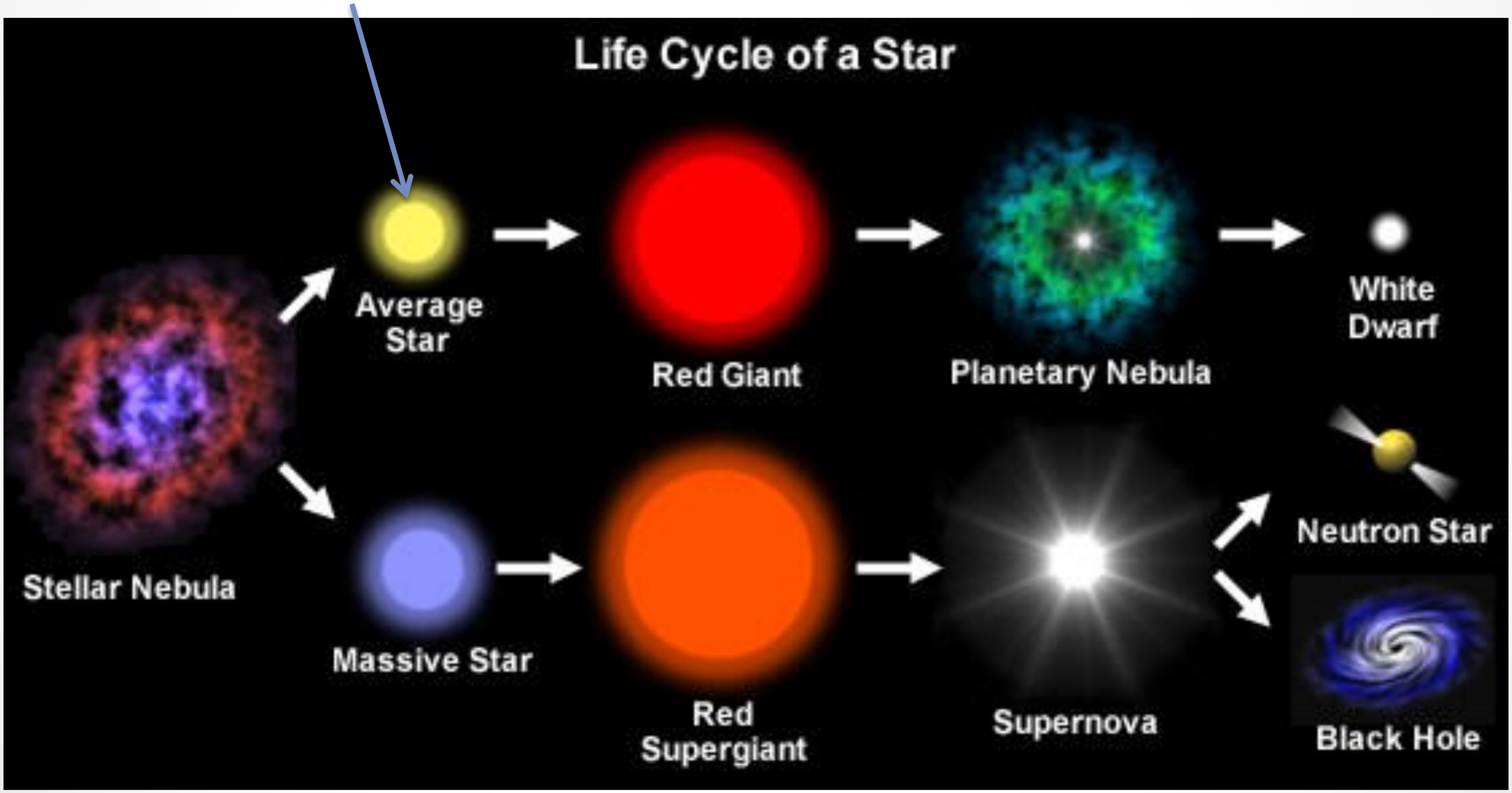
- For stars less than 8$M_{\odot}$ these last slides describe the evolution pretty well. There are some differences in the details that depend on the initial main-sequence mass.
- For stars that start with 4$M_{\odot}$, it gets hot enough in the cores to ignite start carbon fusion on the main sequence.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

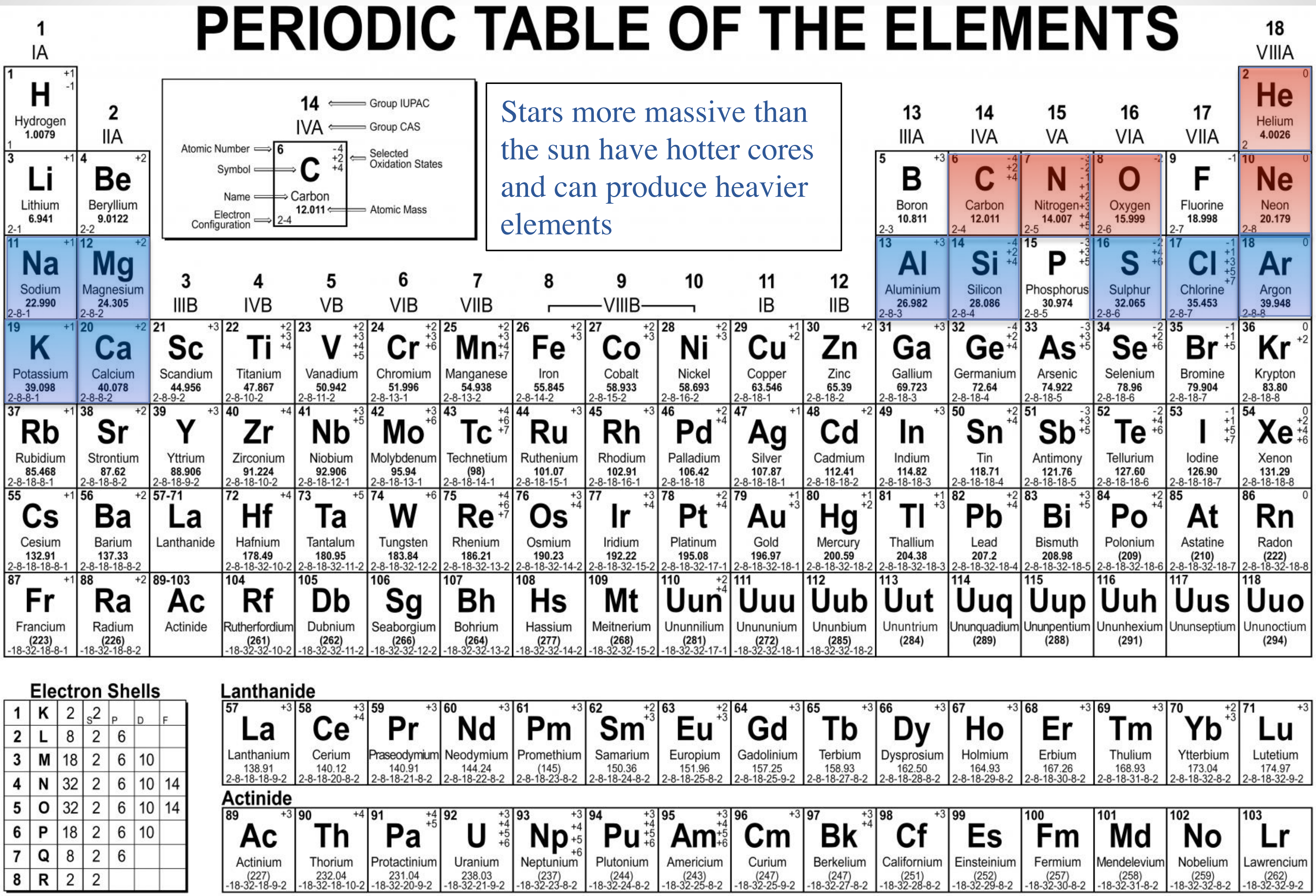
Which of the following is true of the White Dwarf the Sun will eventually become?

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

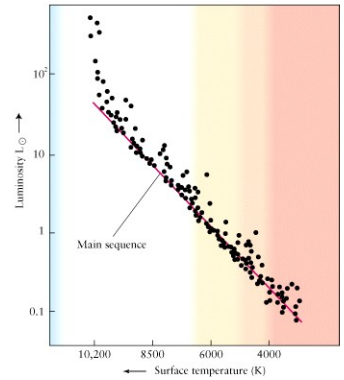
$0.1M_{SUN} - 8M_{SUN}$

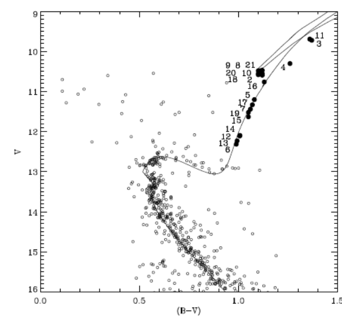


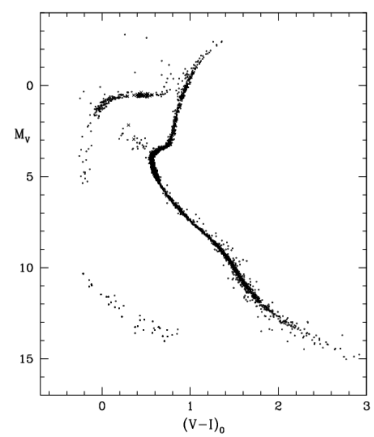



Stars more massive than the sun have hotter cores and can produce heavier elements

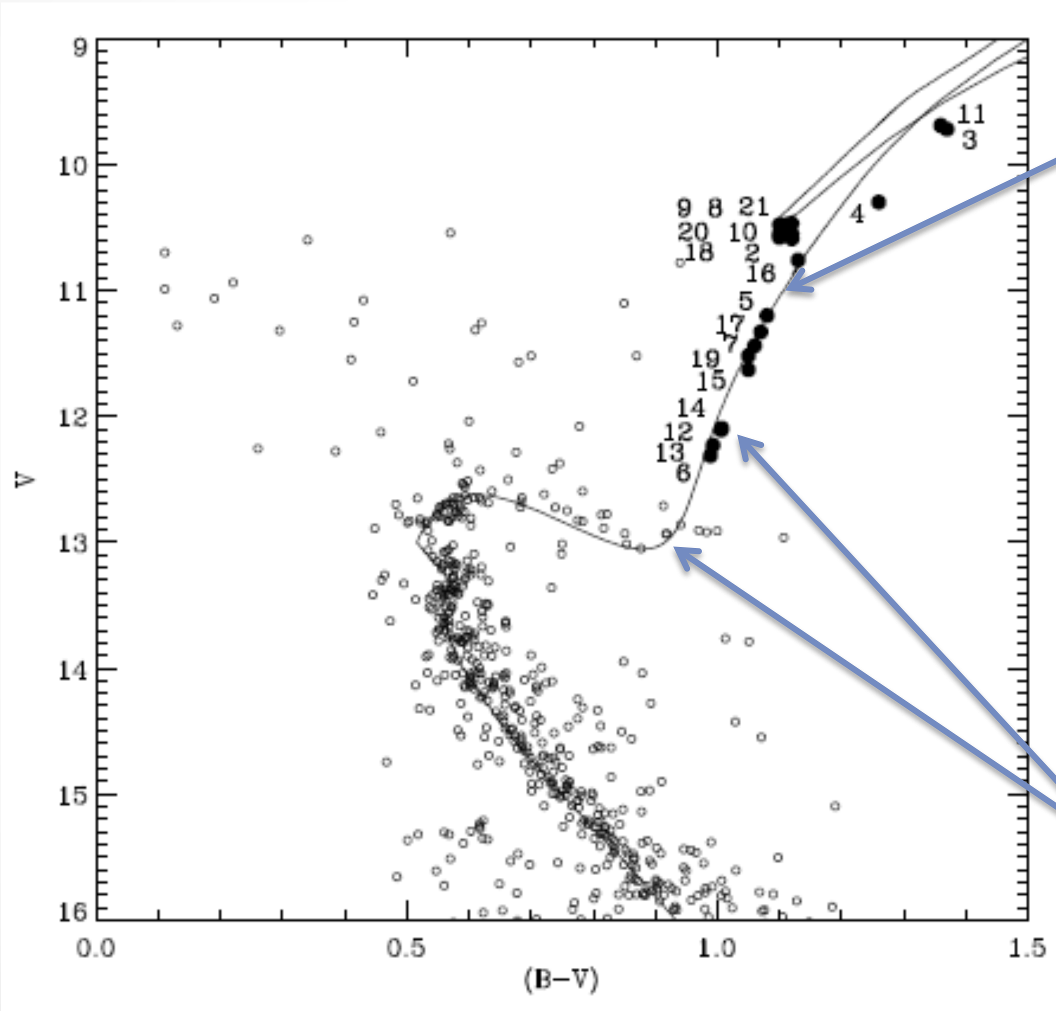
# Why do we think this is right?



# 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

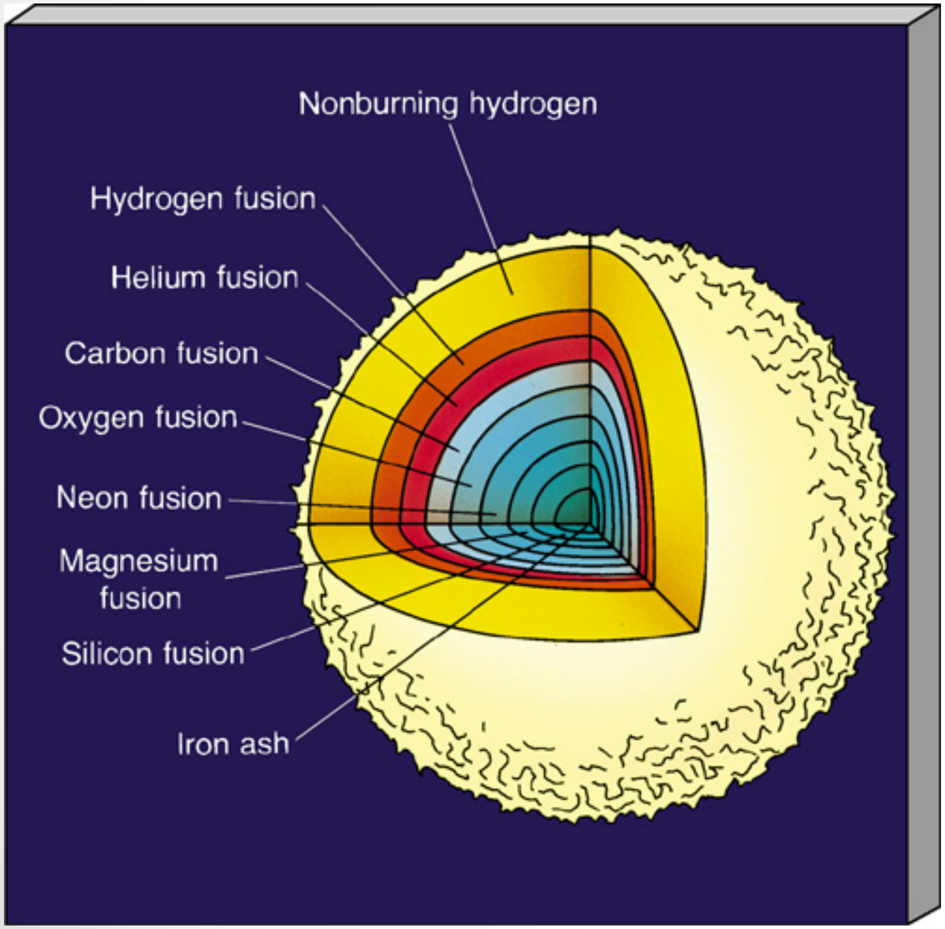
# The Evolution of High-mass Stars

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

Main-sequence Lifetimes

| | |
|---|---|
| $1M_{Sun}$ | $10 \times 10^9$ years |
| $3M_{Sun}$ | $500 \times 10^6$ years |
| $15M_{Sun}$ | $15 \times 10^6$ years |
| $25M_{Sun}$ | $3 \times 10^6$ 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

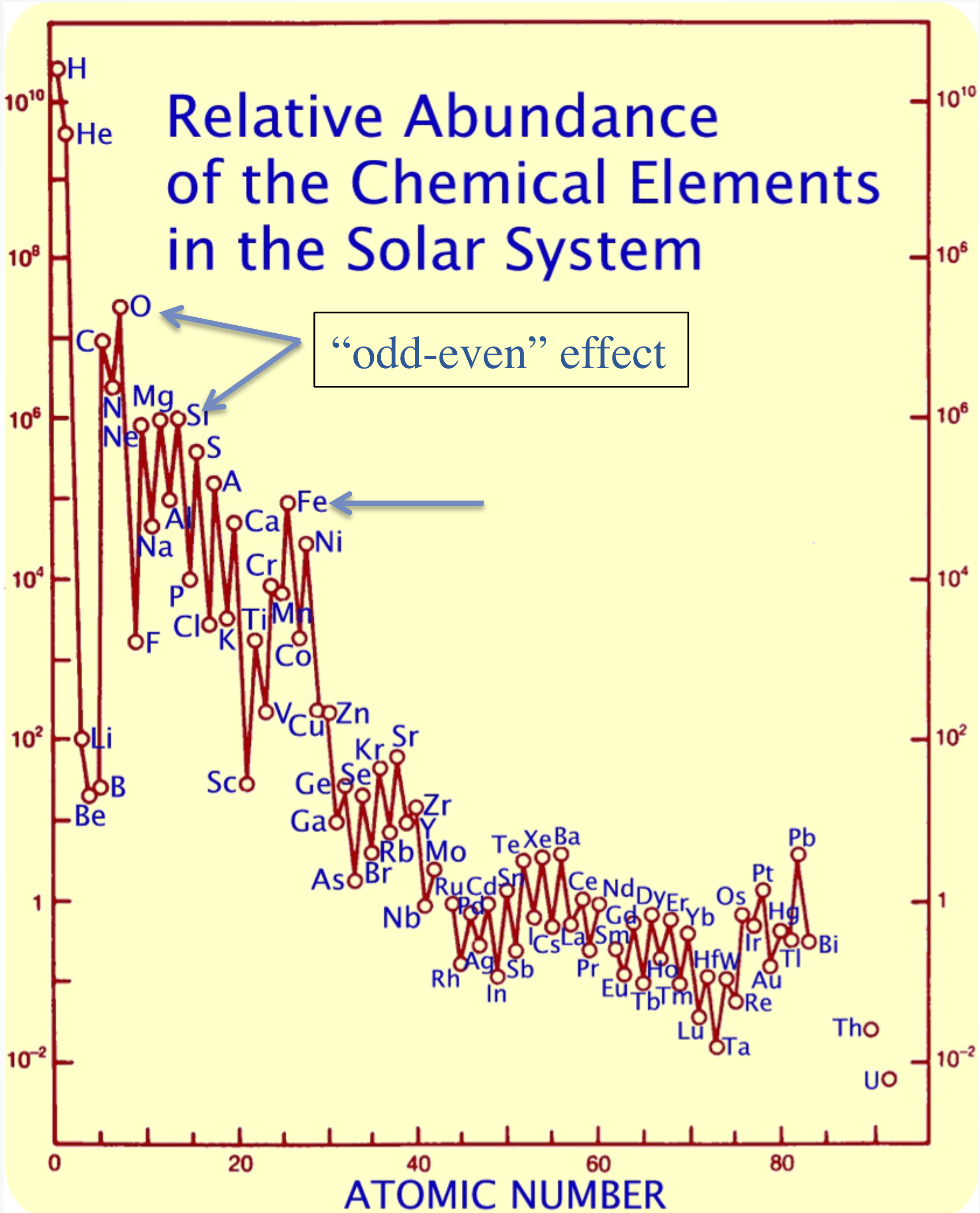
- Fusing nuclei to make new elements is called nucleosynthesis.

| 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

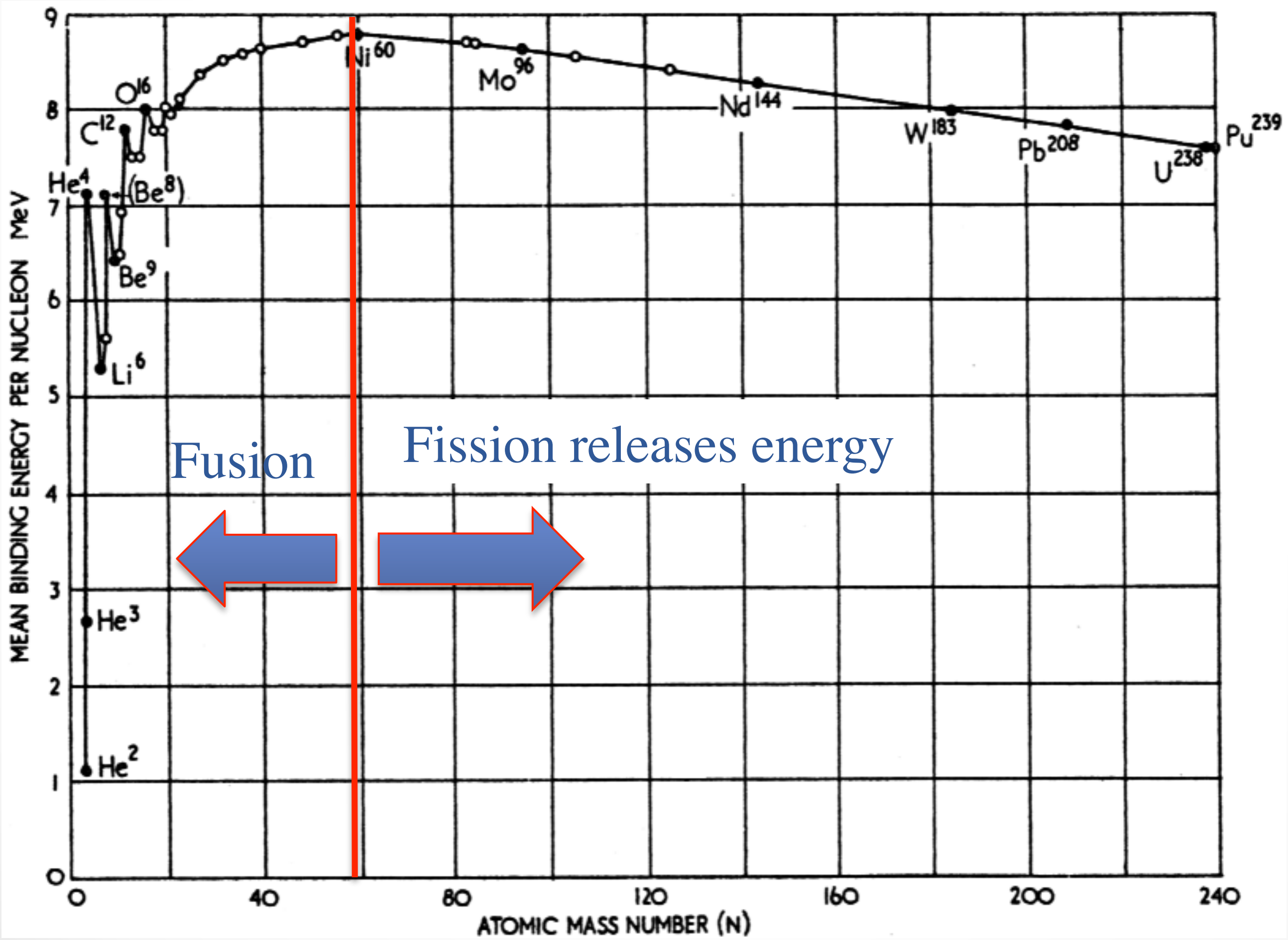
- In a $25M_{\odot}$ star nucleosynthesis proceeds quickly to Fe (why it stops there we will get to in a minute).
- The most common reaction is called the `alpha process' and it is fusing $He^4$ to existing nuclei. This process is reflected in to abundance of various elements in the Universe today.

Note log scale

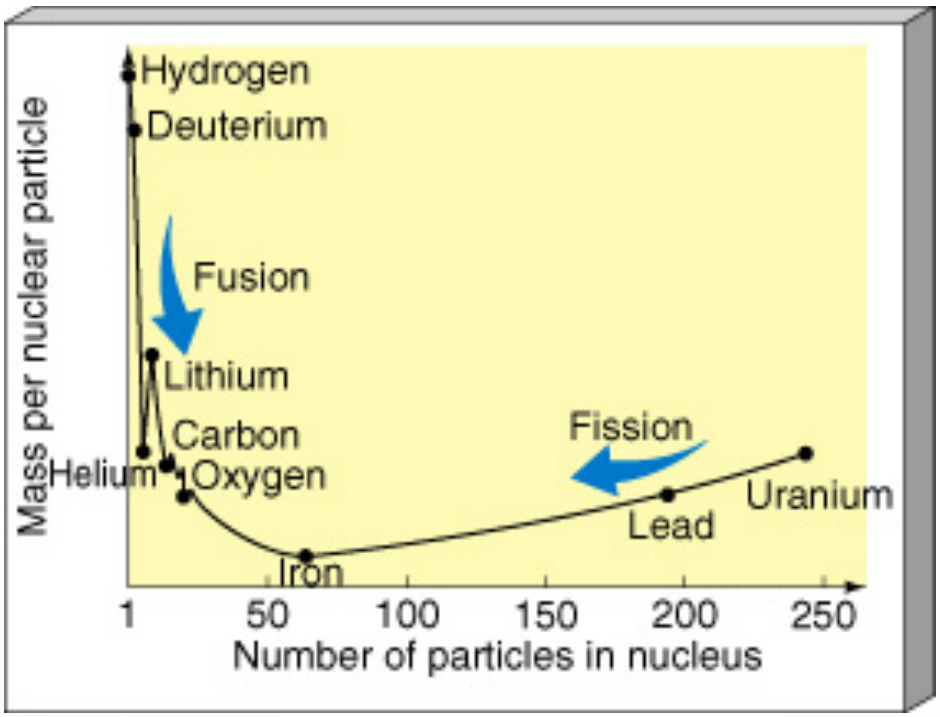


# What is special about Fe?

- 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 $E=mc^2$.



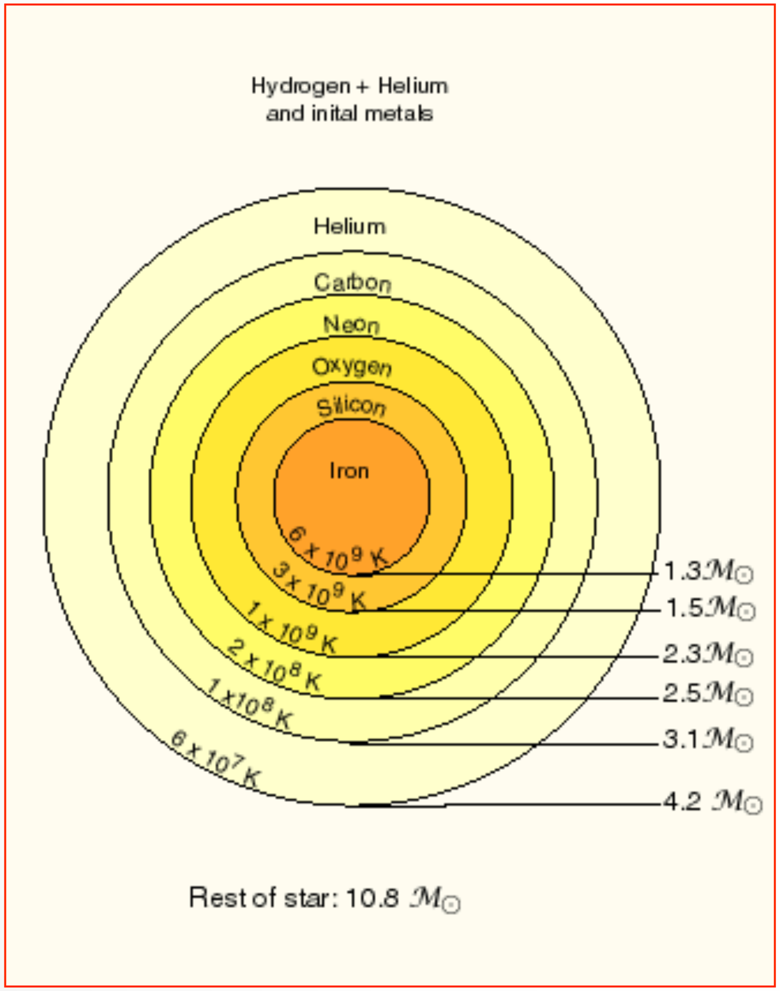
# Nucleosynthesis

- 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

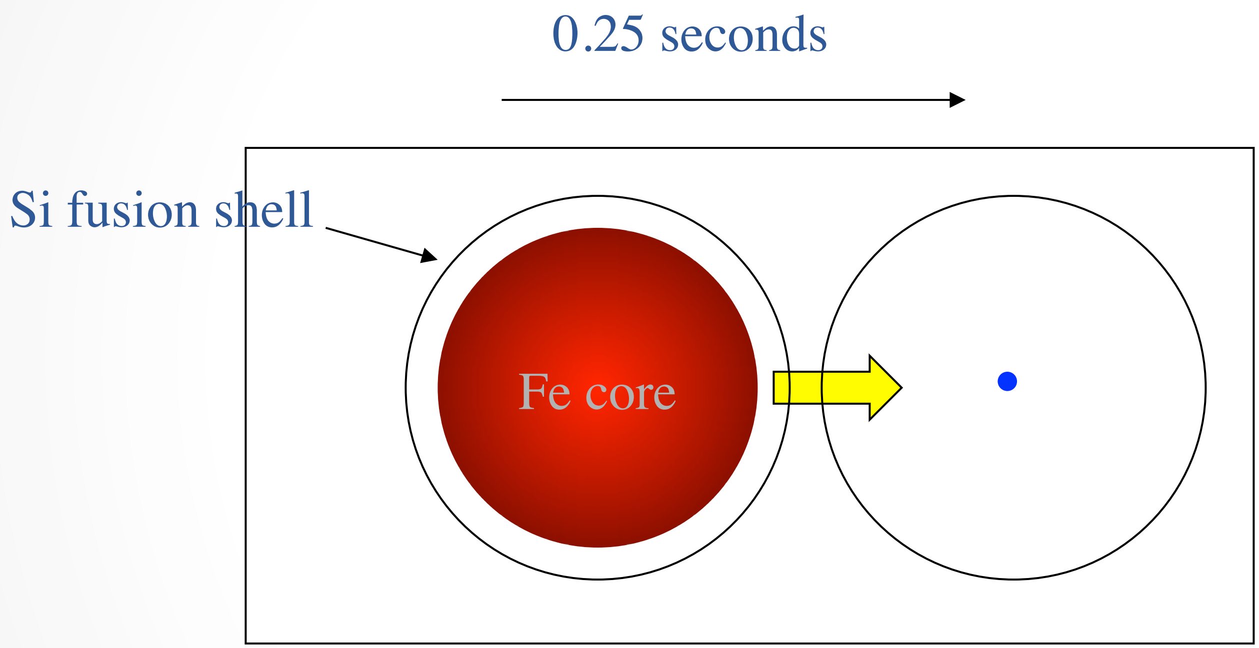



"ashes" from outer shells provide fuel for the next shell down

# Core Collapse

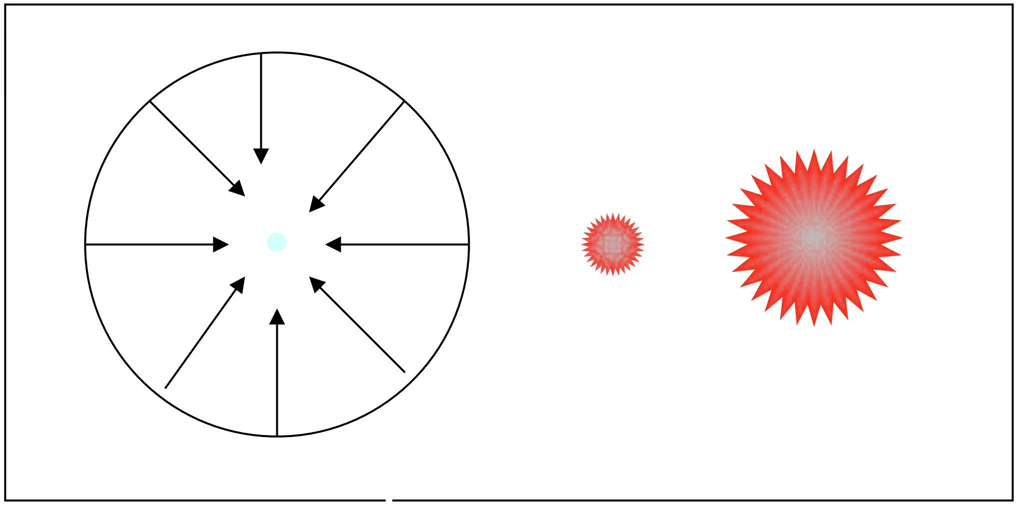
- The fusion chain stops at Fe and an Fe core very quickly builds.
- Within a day of starting to produce Fe, the core reaches the $1.4M_{o}$ Chandrasekar limit (e-degeneracy)
- On a timescale less than a second the core implodes and goes through a series of events leading to a tremendous explosion.

# 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

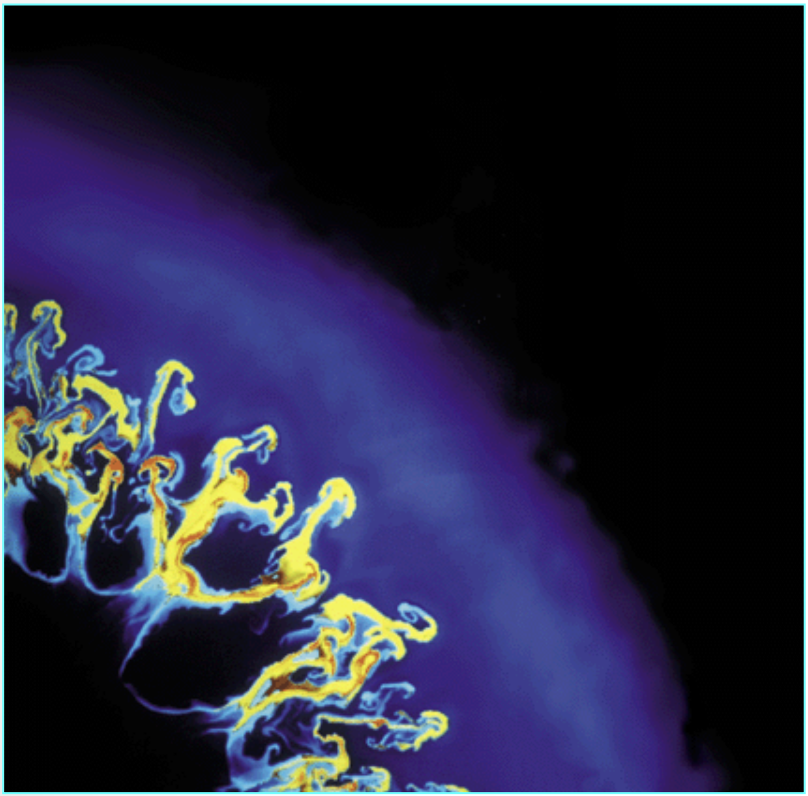
# Core-Collapse in Massive Stars



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.

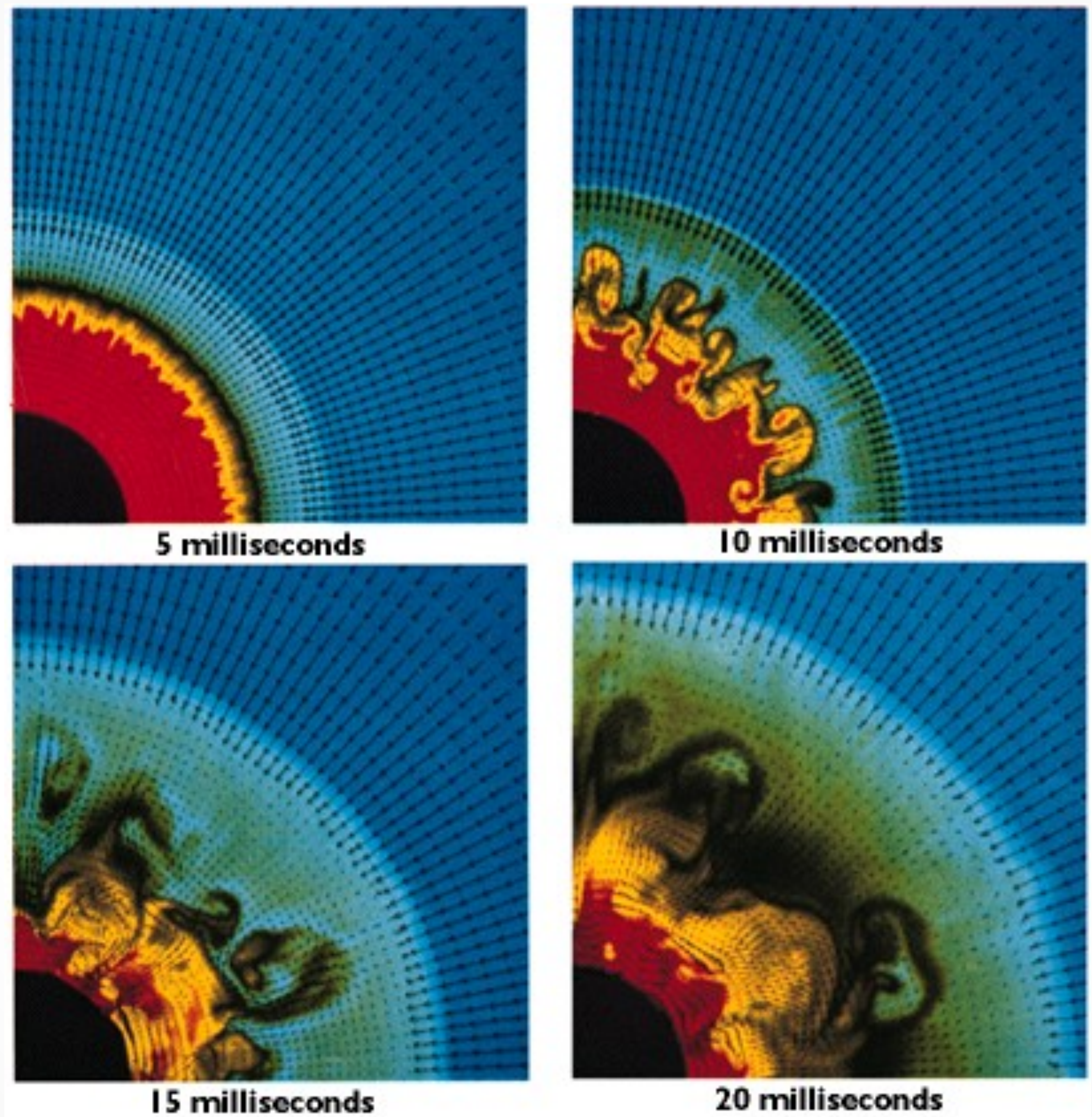
# SNII Bounce Shock wave

# 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

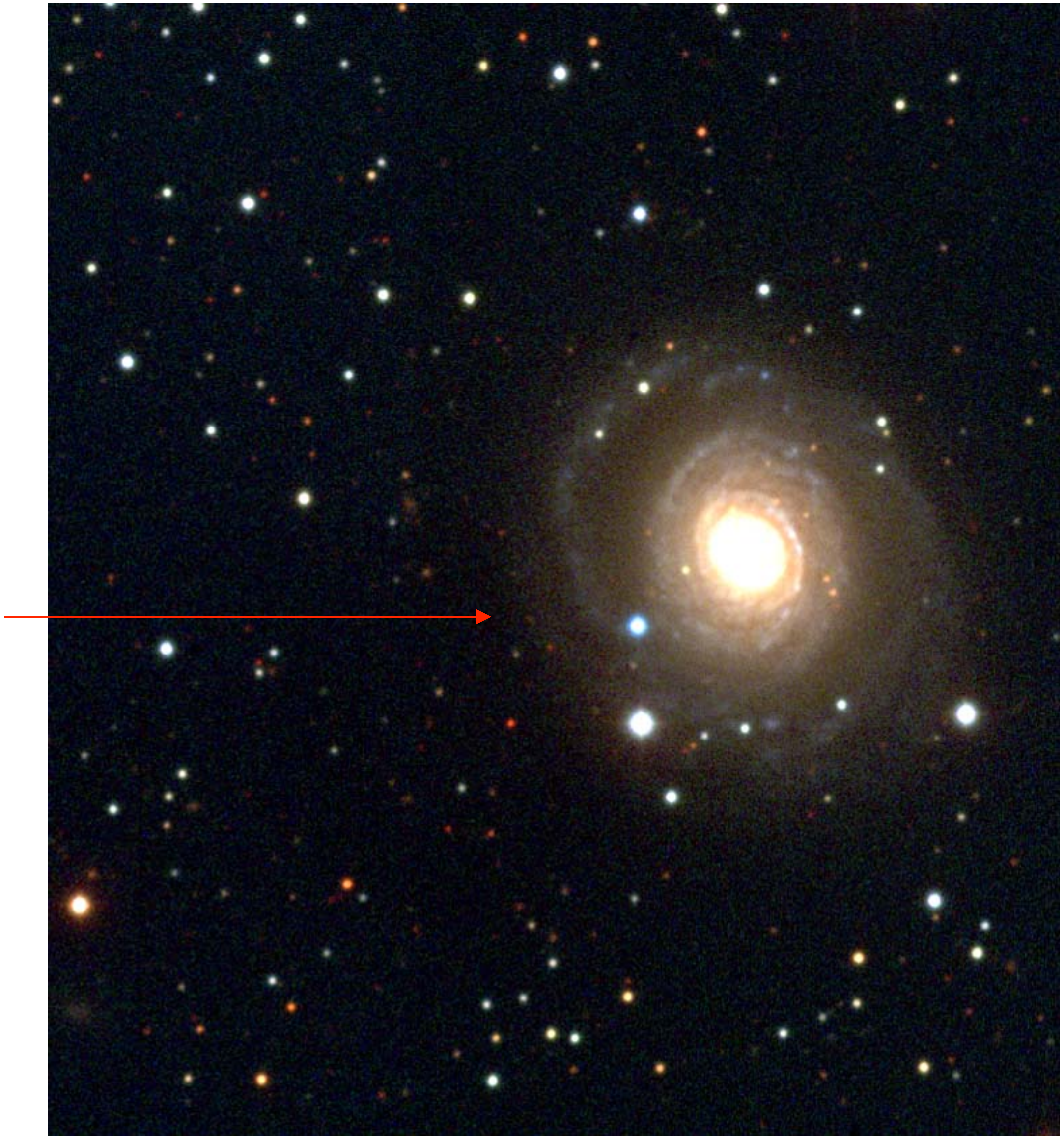
- Expect:
  - Association with massive stars/star formation
  - Rapidly expanding debris cloud
  - $10^8$ times the optical luminosity of the Sun
  - Chemically-enriched debris
  - Extremely dense 1.4 solar mass neutron ball left behind

# 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!



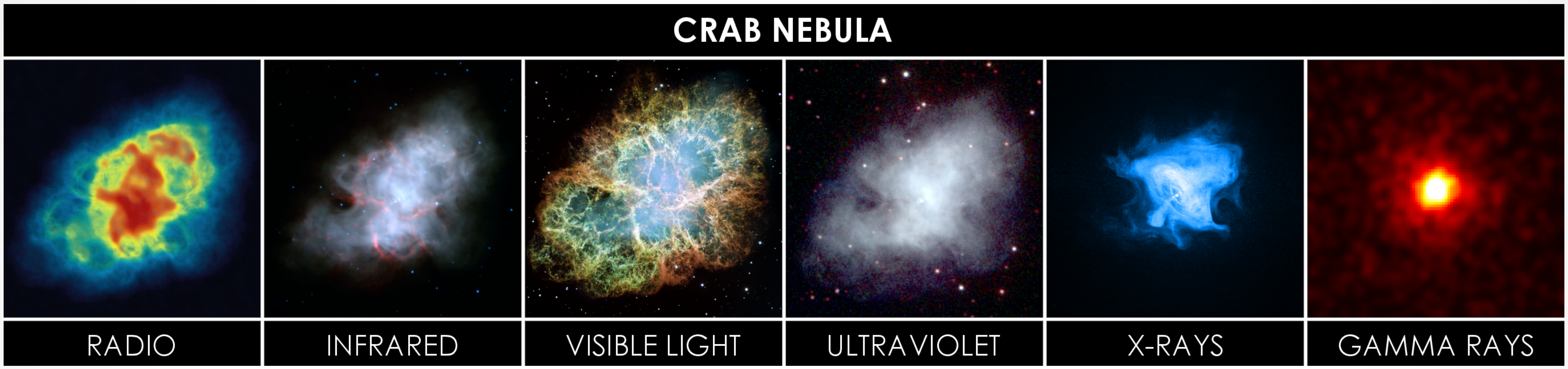
# SNII

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

# Crab Nebula




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

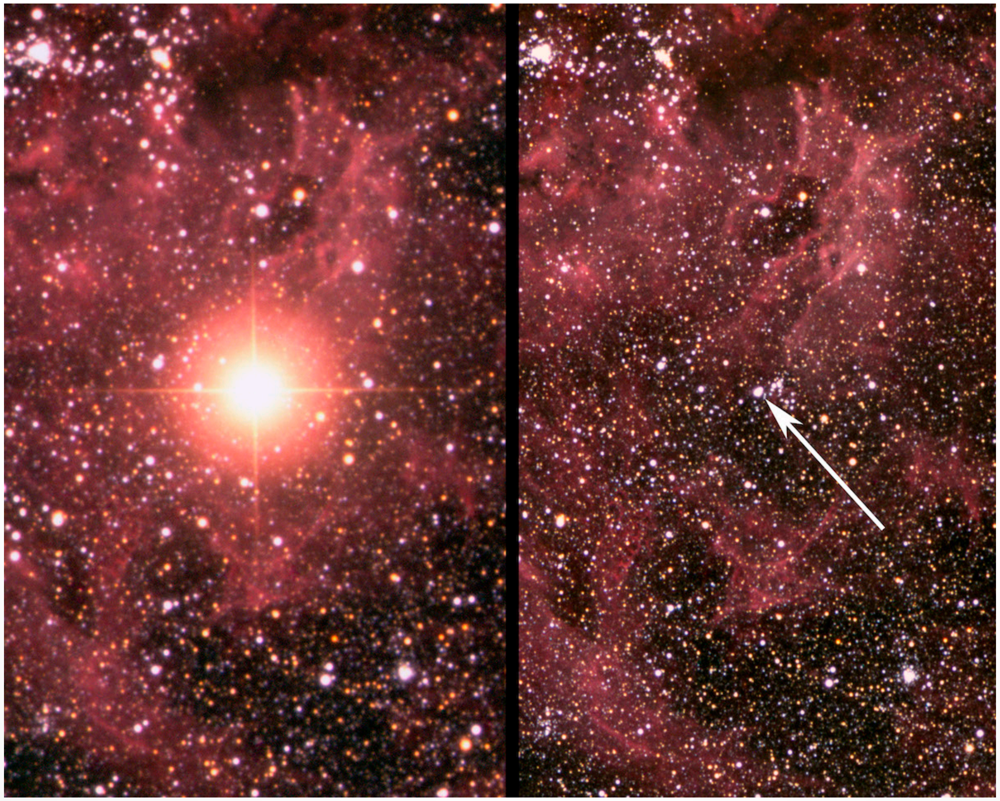
Point our telescopes there now and see a rapidly-expanding nebula with enhanced abundances of many elements and a rapidly rotating neutron star in the center

# 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

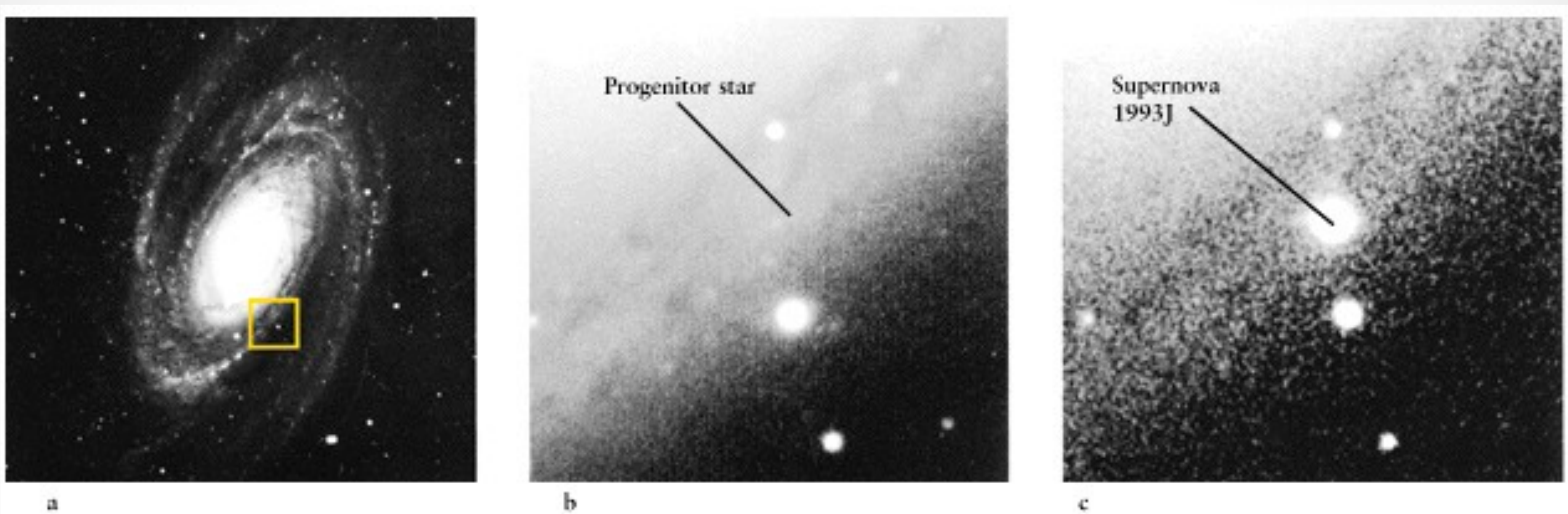
- The second indication, about 4 hours after the neutrinos arrived was a new naked-eye star in the LMC



# SN1987a

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

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


Progenitor star
Supernova
1993J
a
b
c