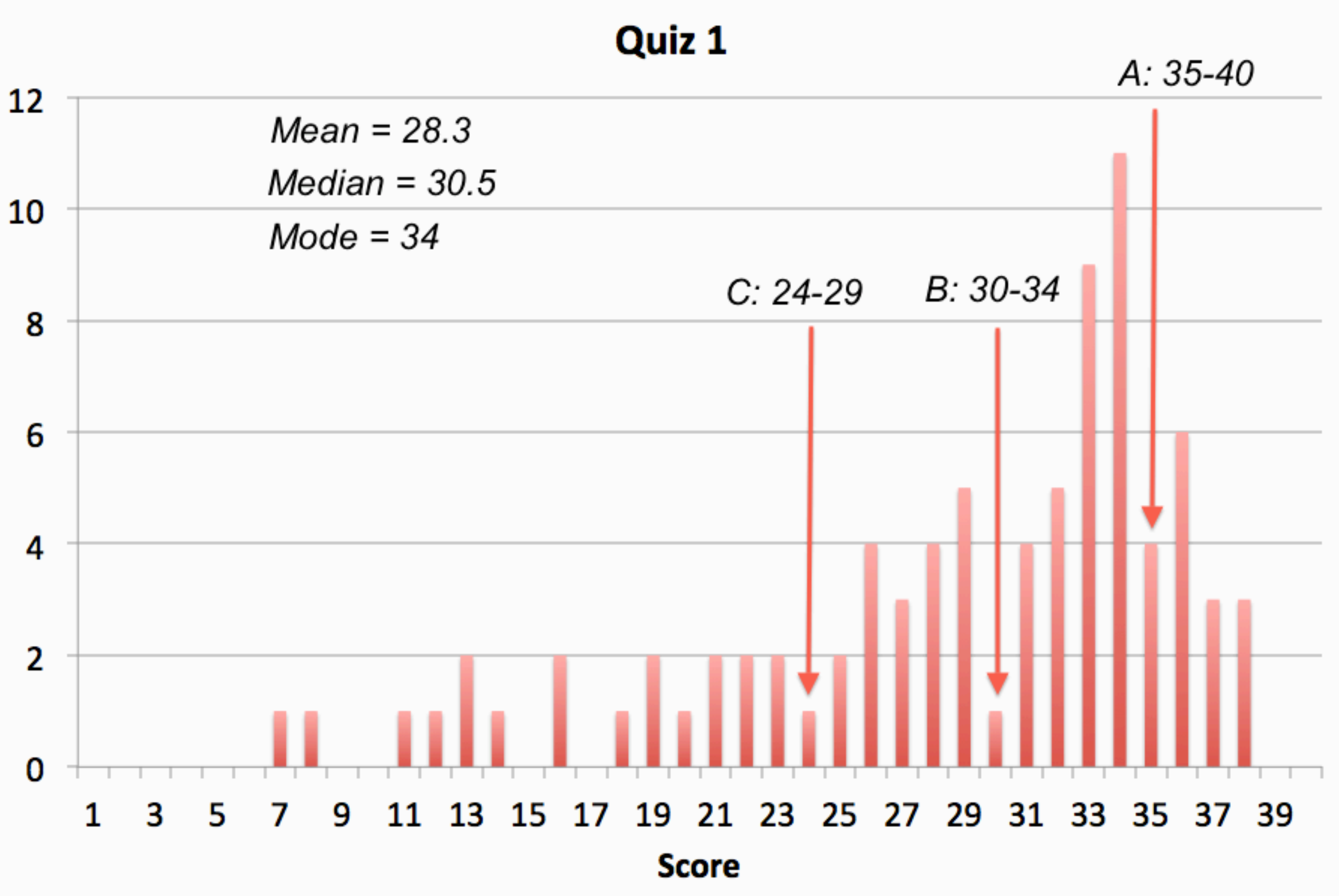
AY5 Announcements

- Lab this week in sections!
- Quiz 1 scores and histogram posted at class WWW site.
- Quiz 2: Thursday April 30.
  - Stellar structure, energy sources, evolution and end points, formation of the elements
- LSS (Learning Support Services) tutoring available for this class:
  - Theron Carmichael tcarmich@ucsc.edu
  - https://eop.sa.ucsc.edu/OTSS/tutorsignup/



Mean = 28.3

Median = 30.5

Mode = 34

C: 24-29

B: 30-34

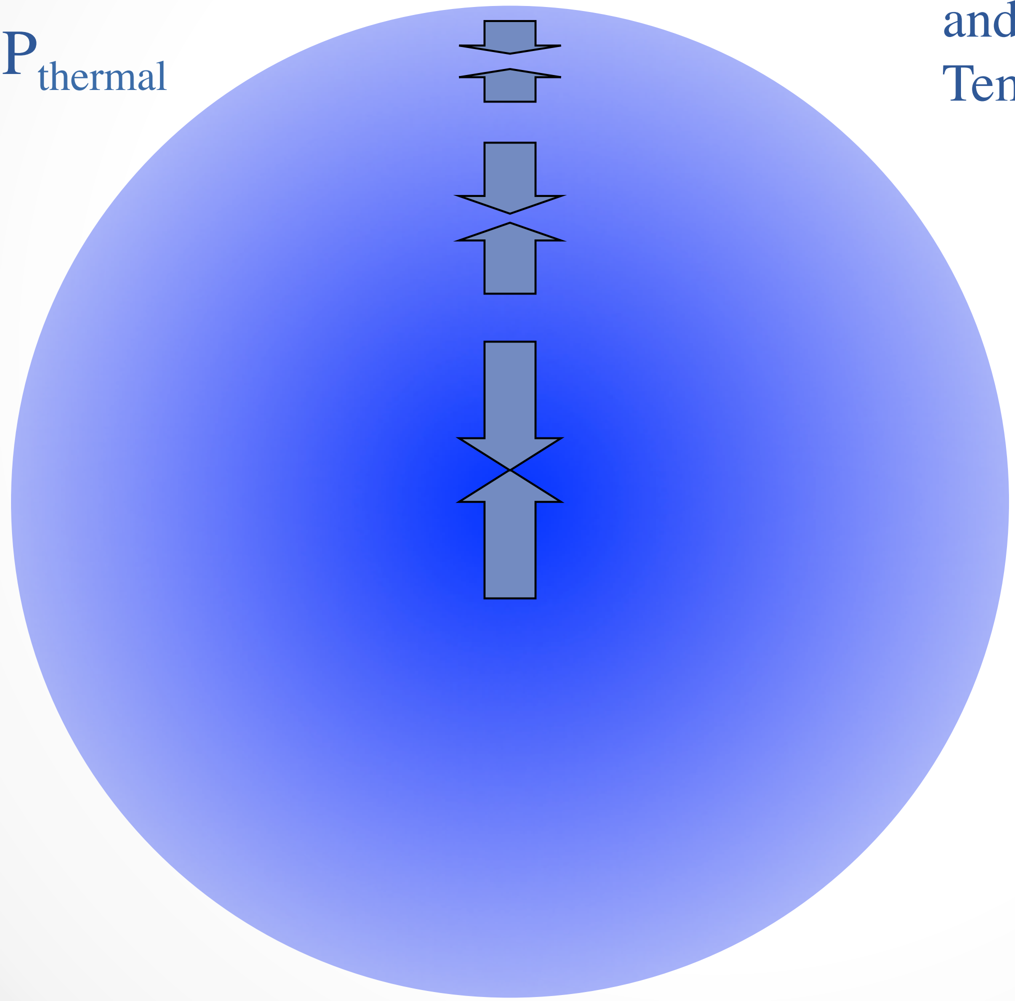
A: 35-40

From Last Lecture

Hydrostatic Equilibrium

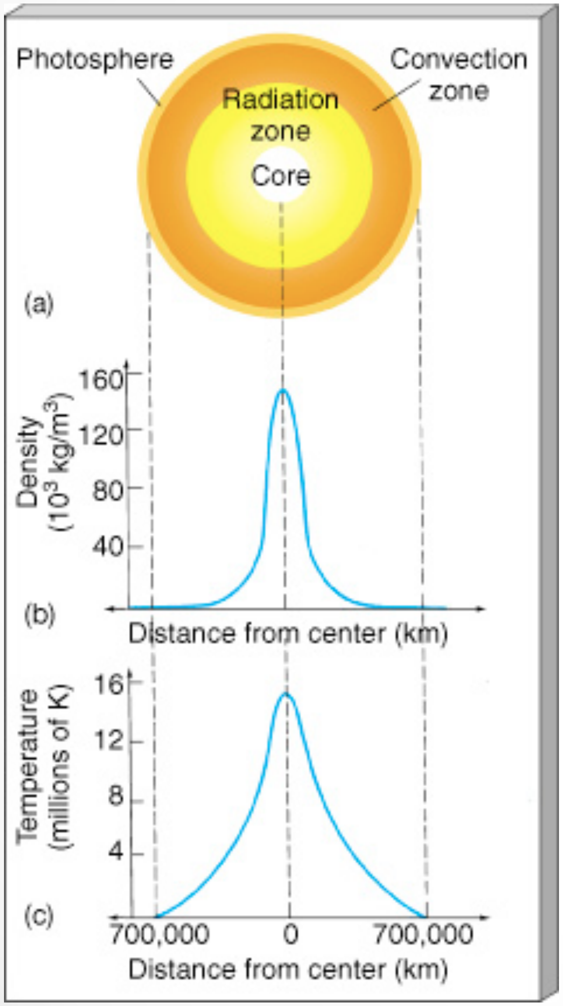
At each radius
$P_{grav}=P_{thermal}$

$P_{thermal}$ is due to gas pressure and is proportional to Temperature



As the weight of overlying material goes up, the temperature needs to go up to keep pressure balance

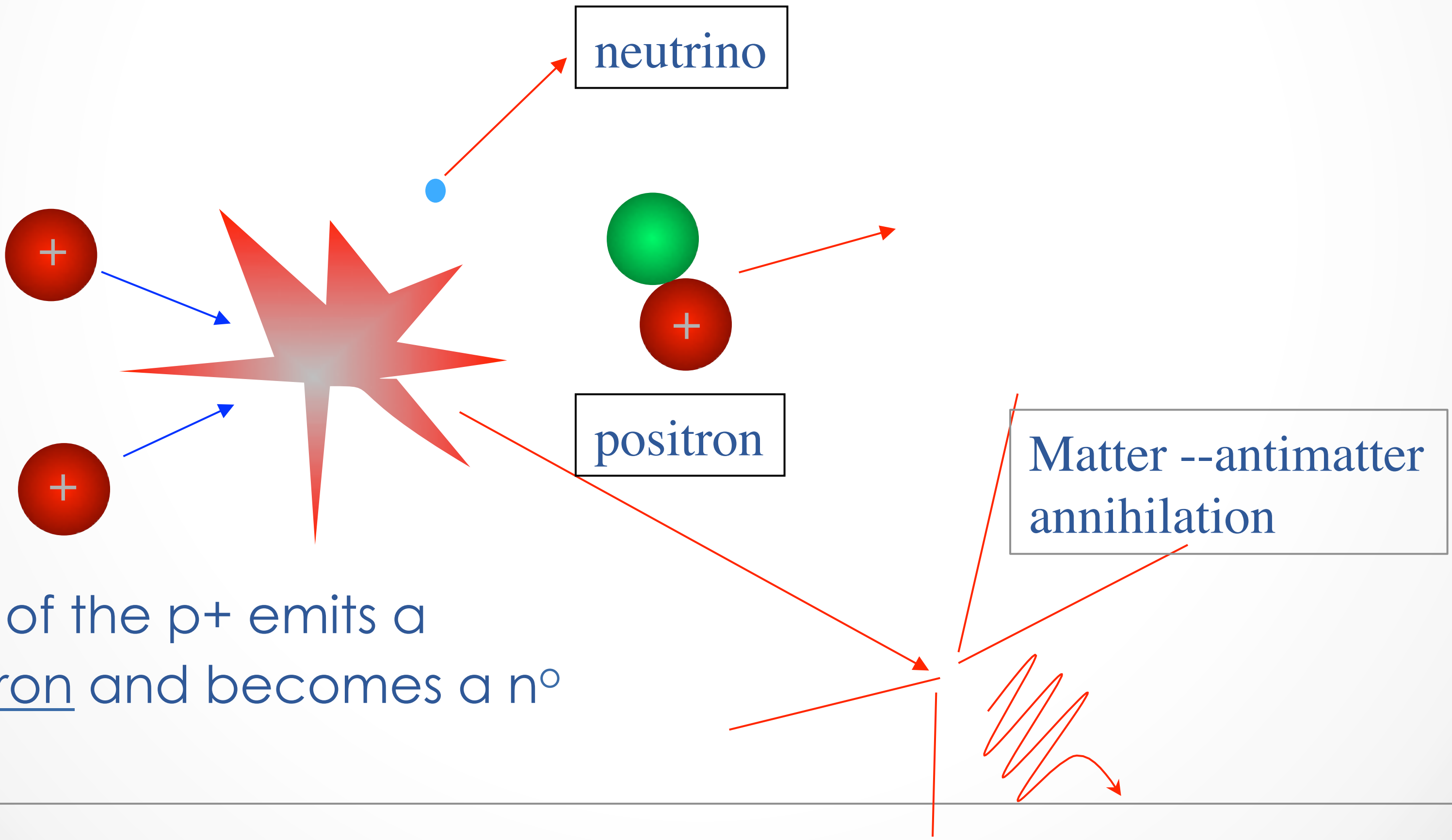
Solar Model



- Hydrostatic models for the Sun predict the central temperature to be about 16 x 10^6K.
- Some interesting things happen at this temperature! On Earth the only time this temperature has been reached is when H-bombs were exploded.

Hydrogen Fusion

- Proton fusion involves some interesting ideas.



neutrino

positron

Matter --antimatter annihilation

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

P-P Chain

- The amount of missing mass is:

$$\boxed{\Delta mass = 0.048 \times 10^{-24}\ grams}$$

- The energy generated is:

$$\boxed{E = \Delta mc^2 = 4.3 \times 10^{-5}\ ergs}$$

- This much energy is released by $4H^1$ with a total mass of 6.6943×10^{-24} grams. The efficiency of hydrogen fusion is therefore:

$$\boxed{6.4 \times 10^{18}\ \text{ergs/gram}}$$

Sun's Lifetime with H-fusion

- Total energy available:

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

- Lifetime of the fusion-powered Sun

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

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

Main-sequence lifetime

An $0.5M_{Sun}$ star generates a luminosity of $1/10\ L_{Sun}$. How long does this star spend on the main-sequence of the H-R Diagram? The main-sequence lifetime of the Sun is 10^9 years. (Iclicker quiz)

A. $0.5 \times 0.1 \times 10^9 = 0.5 \times 10^8$ years
B. $(0.5/0.1) \times 10^9 = 0.5 \times 10^{10}$ years
C. $0.5 \times 0.1 / 10^9 = 0.5 \times 10^{-11}$ years
D. Trick question: you need to have more information

The principal reason we have ruled out nuclear fission as the source of energy for the Sun is:

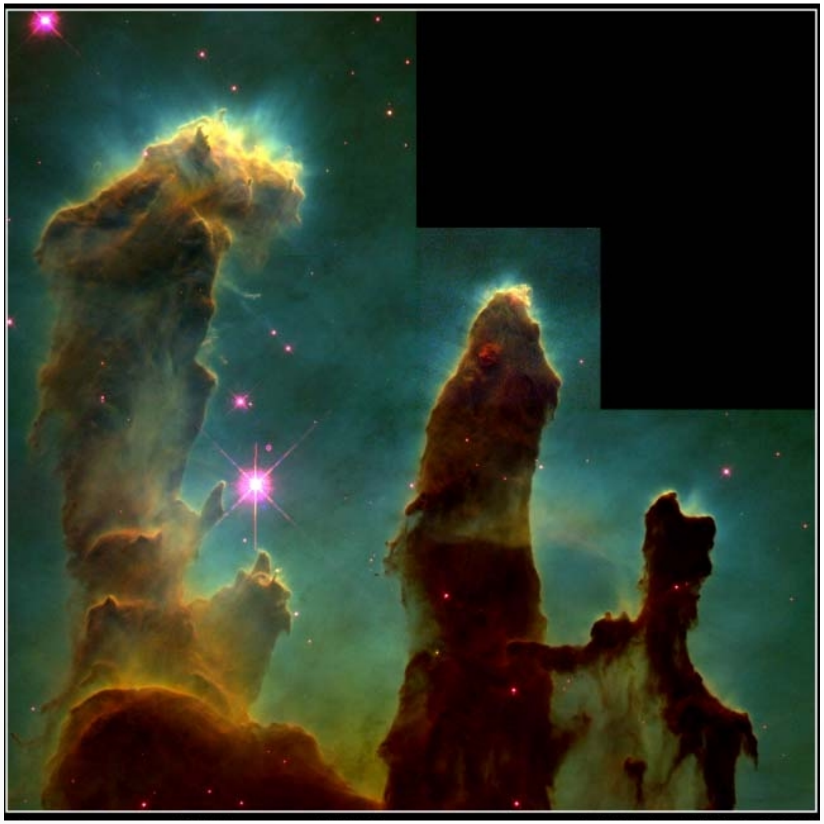
A. The spectrum of the Sun shows the surface is much too cool for a fission-powered Sun
B. The Sun has far too little fissionable material
C. The radioactivity of the Sun would have made life on Earth impossible
D. Even if the Sun were made completely of fissionable material (e.g. uranium) it would only last around 10 million years at its current luminosity

Stellar Evolution

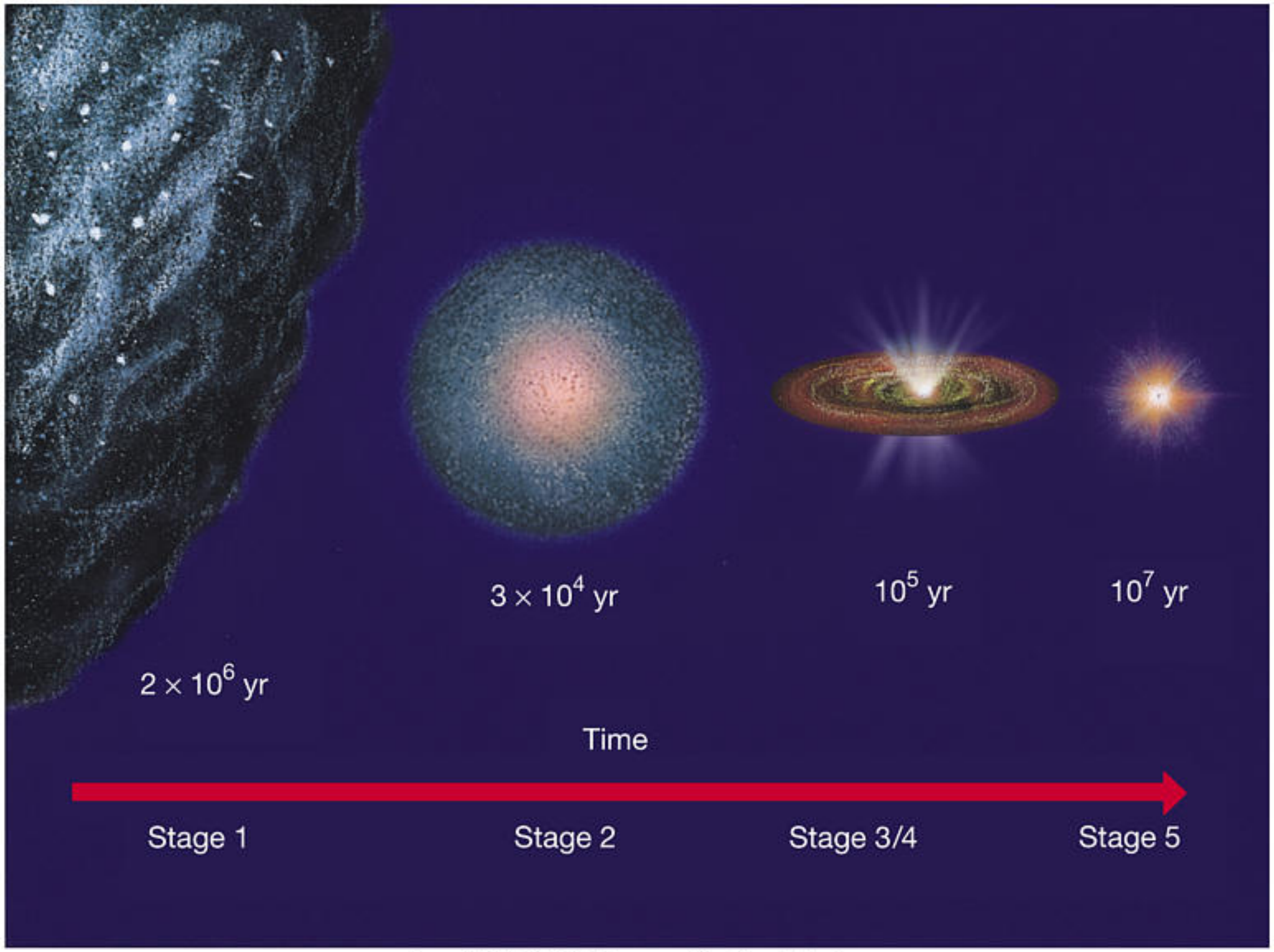
- We know a lot about stellar evolution. For this class we will gloss over most of the details and concentrate on three things:
  - Production and distribution of chemical elements by low-mass stars
  - Production and distribution of chemical elements in enormous explosions that end the lives of massive stars
  - Use of supernova explosions to map the Universe

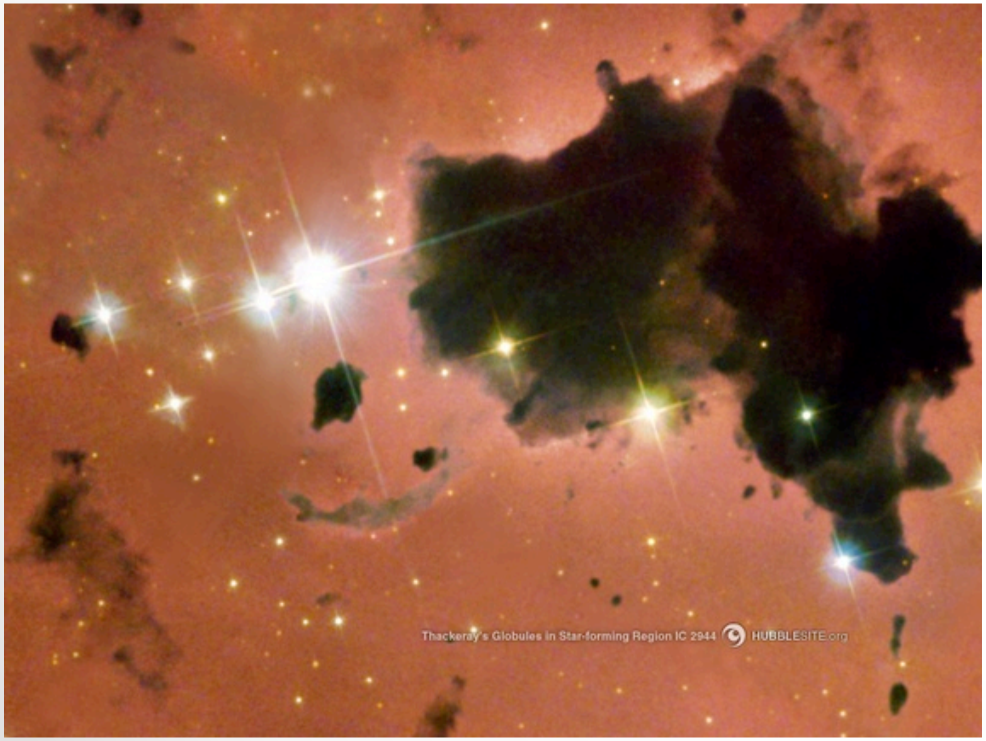
Stellar Evolution: Birth

Stars are born when gas in very cold regions collapses and converts gravitational potential energy into heat.



Cold gas cloud -> star



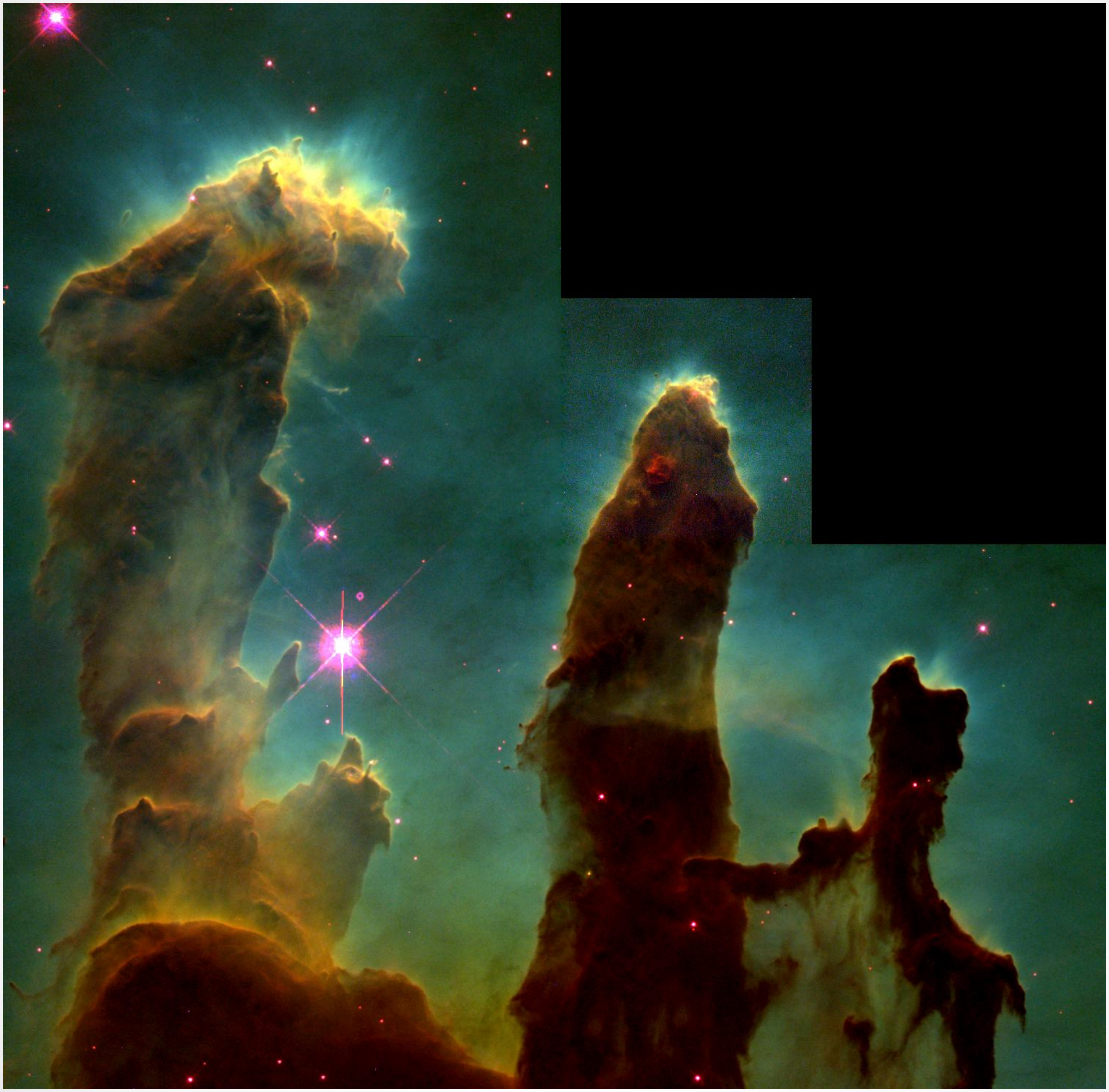


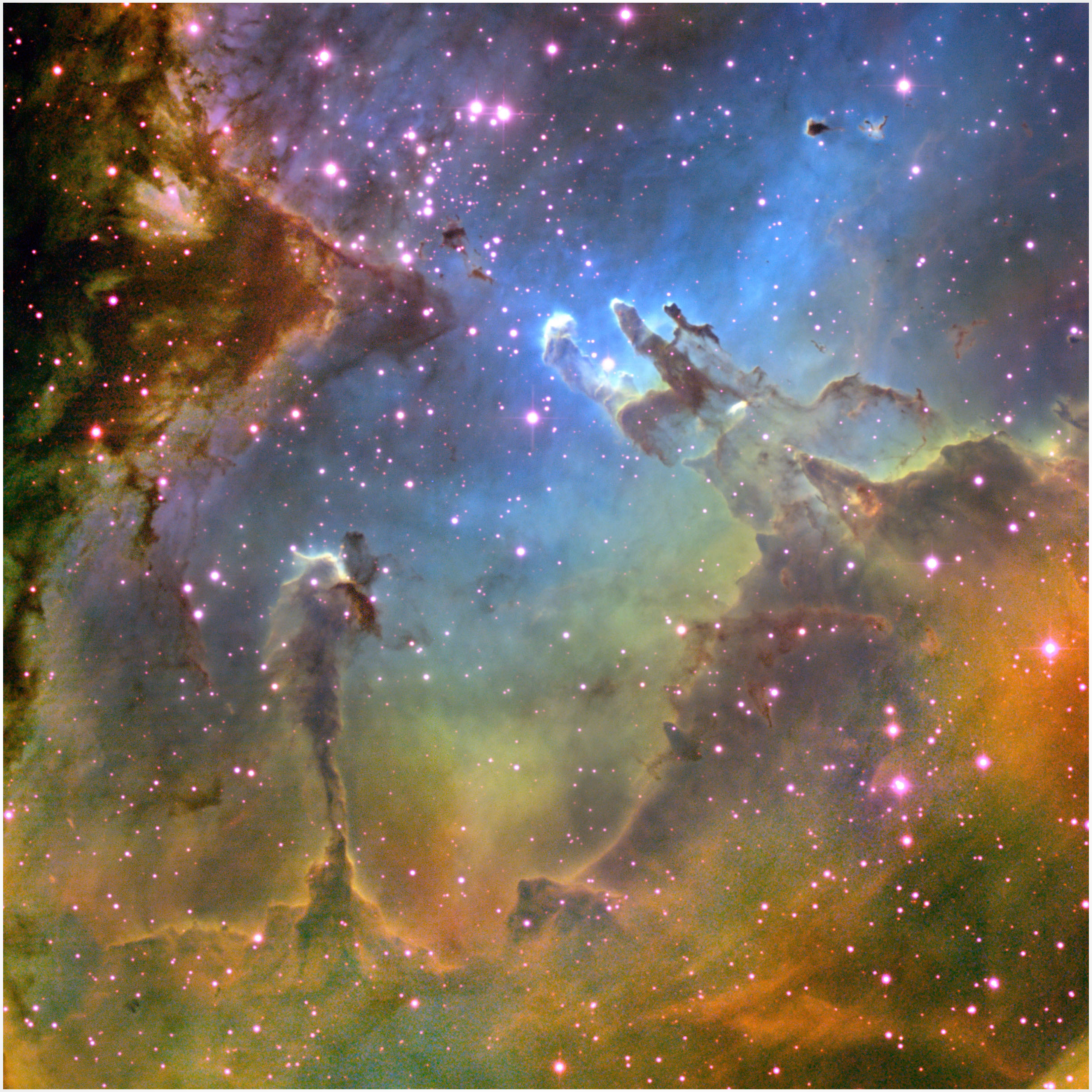
Gravitational collapse to a protostar requires very low temperatures and even the heating by the ambient light in the Galaxy can prevent star formation

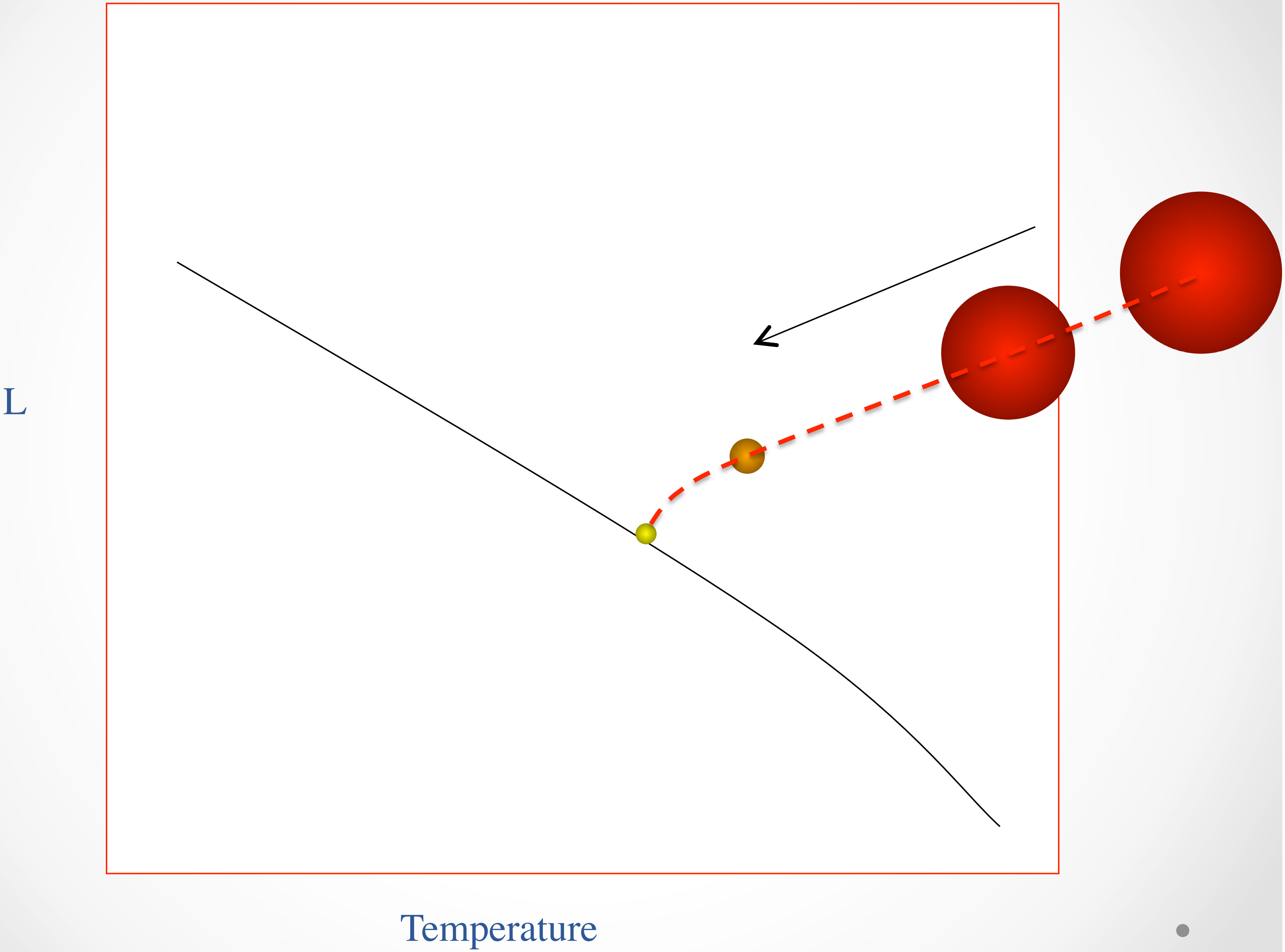
Deep in the black hearts of dust clouds is where stars are born

Required development of infrared detectors to pinpoint stars forming

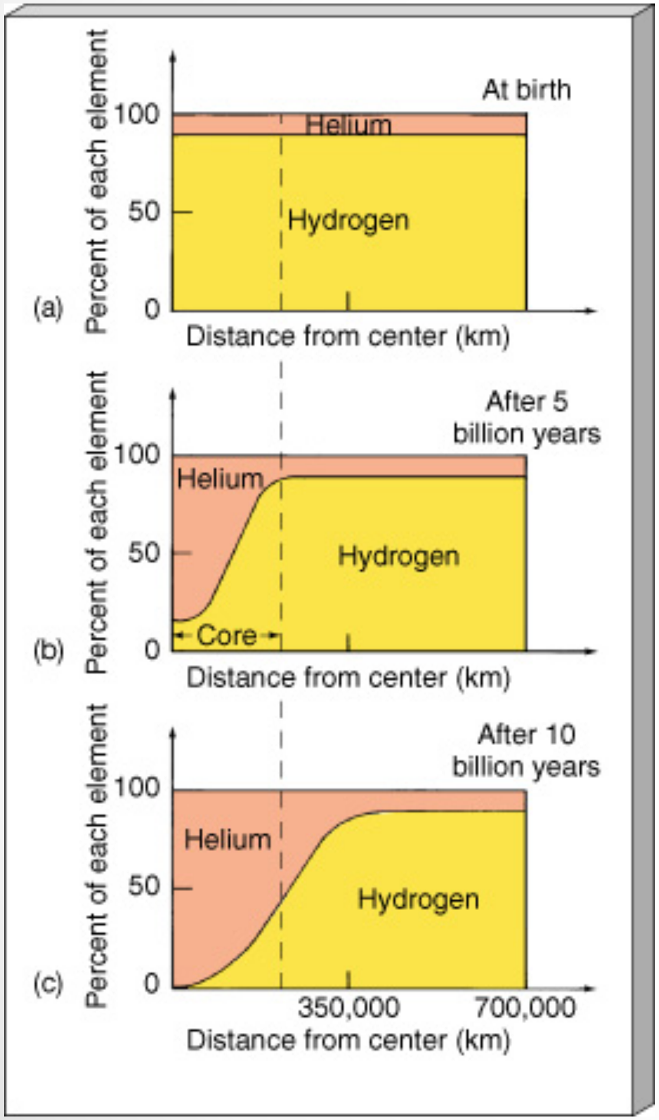
When stars are born they blast the nebula clear






L
Temperature

Stellar Evolution



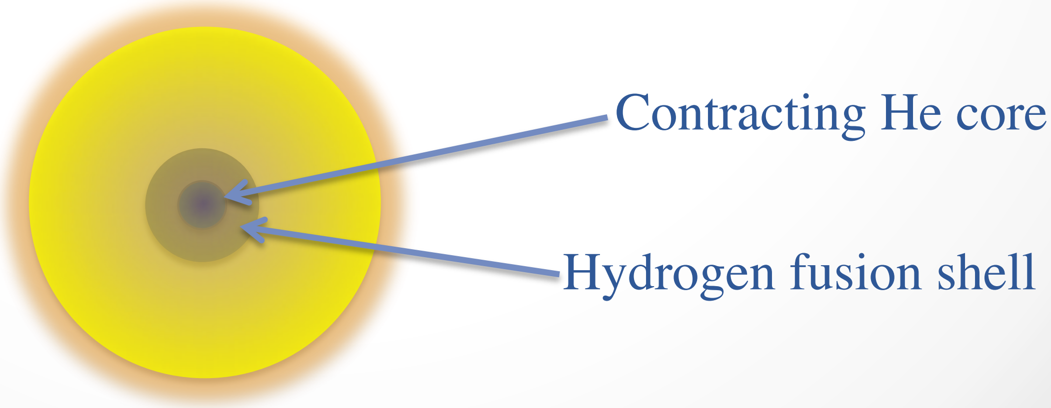
- As hydrogen is being converted into helium in the core of a star, its structure changes slowly and stellar evolution begins.
- The structure of the Sun has been changing continuously since it settled in on the main sequence.

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 -- <u>100 million K</u>
  - $He^4 + He^4 = Be^8$. This reaction doesn't release energy, it requires input energy. This particular Be isotope is very unstable.

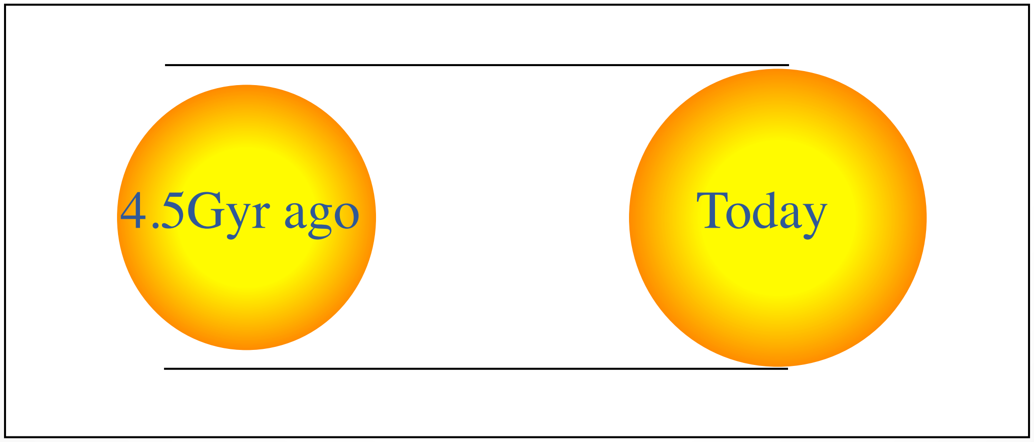
Stellar Evolution

- 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

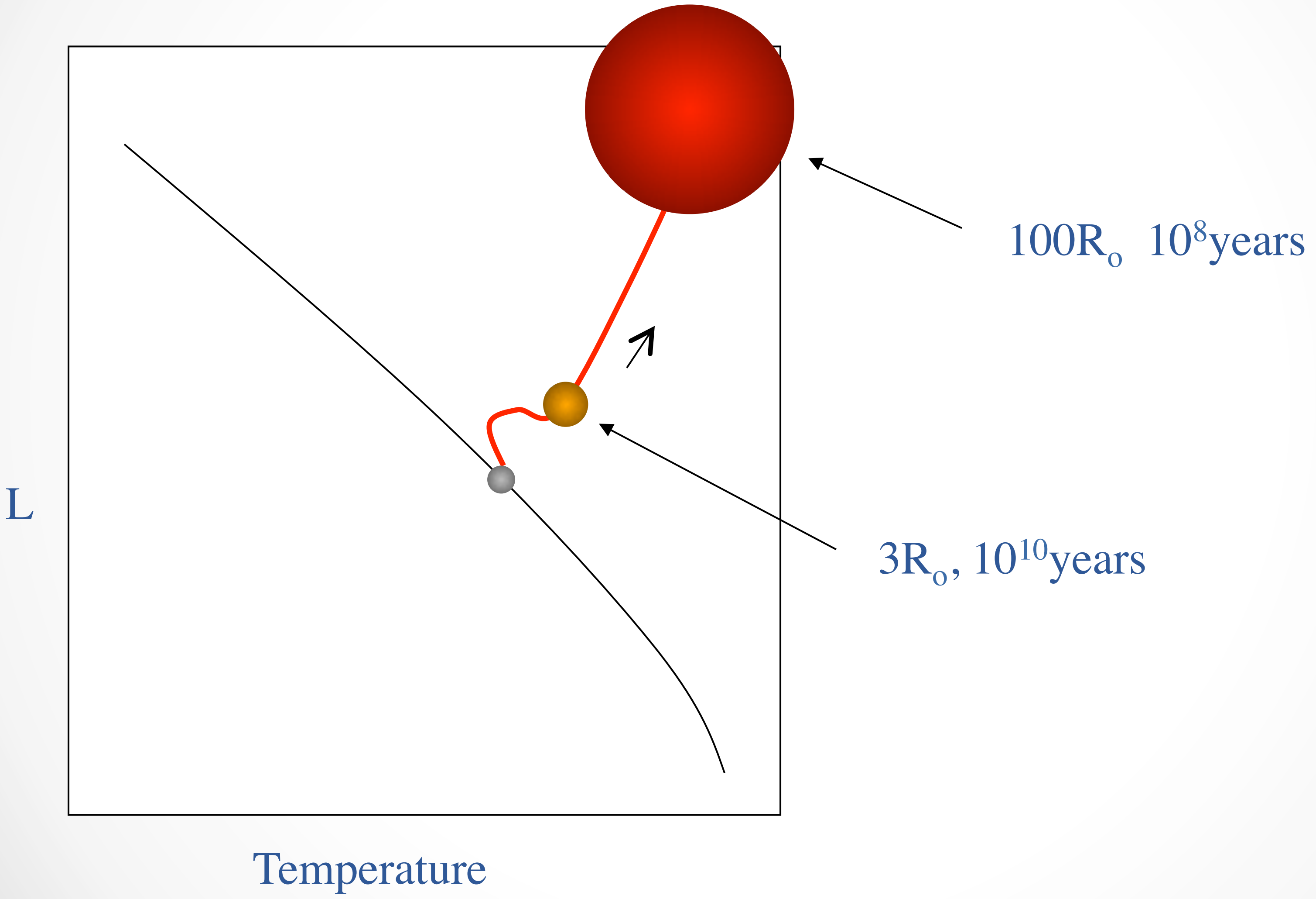
- Stars begin to evolve off the zero-age main sequence from day 1.
- Compared to 4.5 Gyr ago, the radius of the Sun has increased by 6% and the luminosity by 40%.



Stellar Evolution:Red Giants

- Hydrostatic equilibrium is gently 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

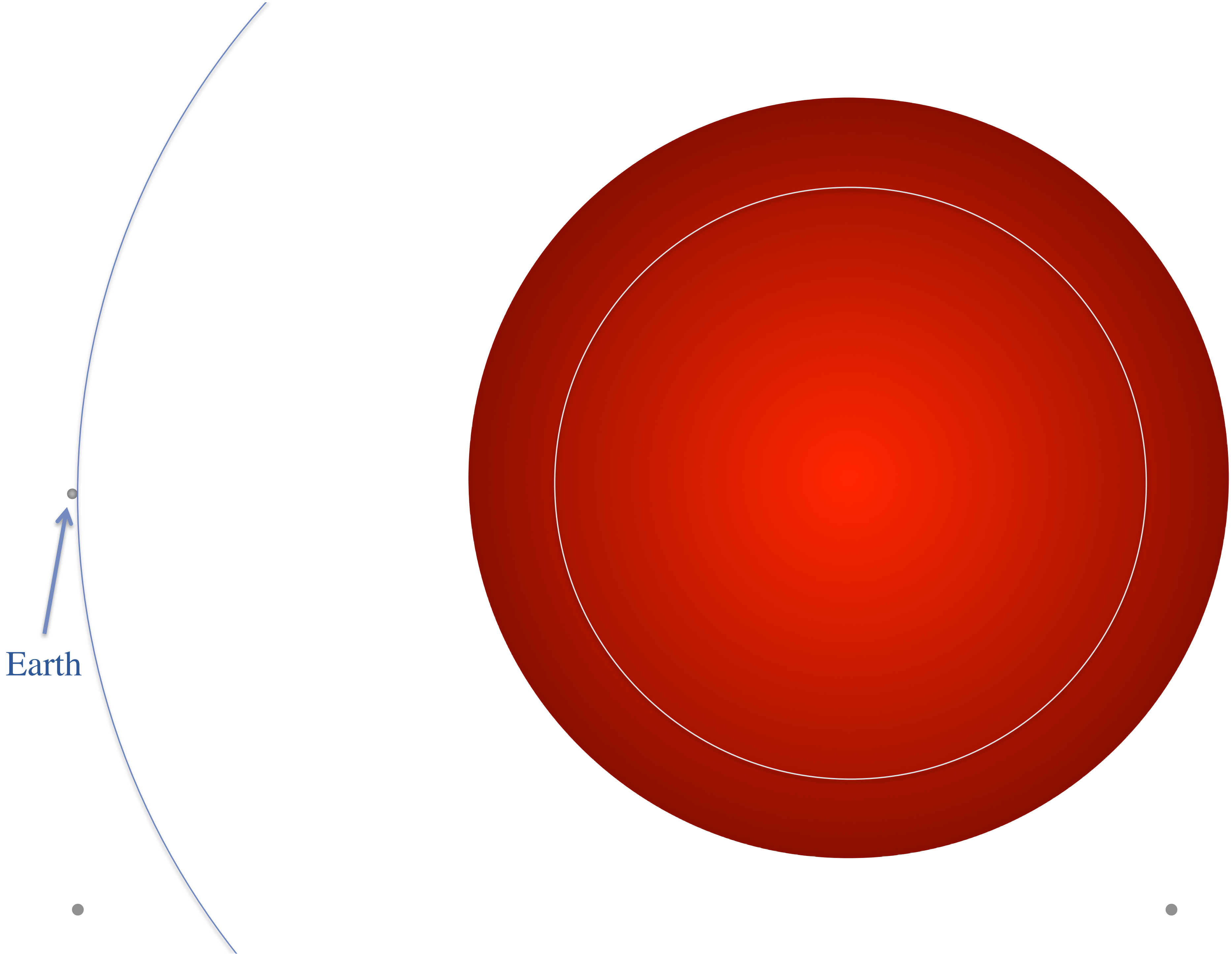


$100R_o$ 10^8years

$3R_o$, 10^{10}years

L

Temperature


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.

Helium Fusion

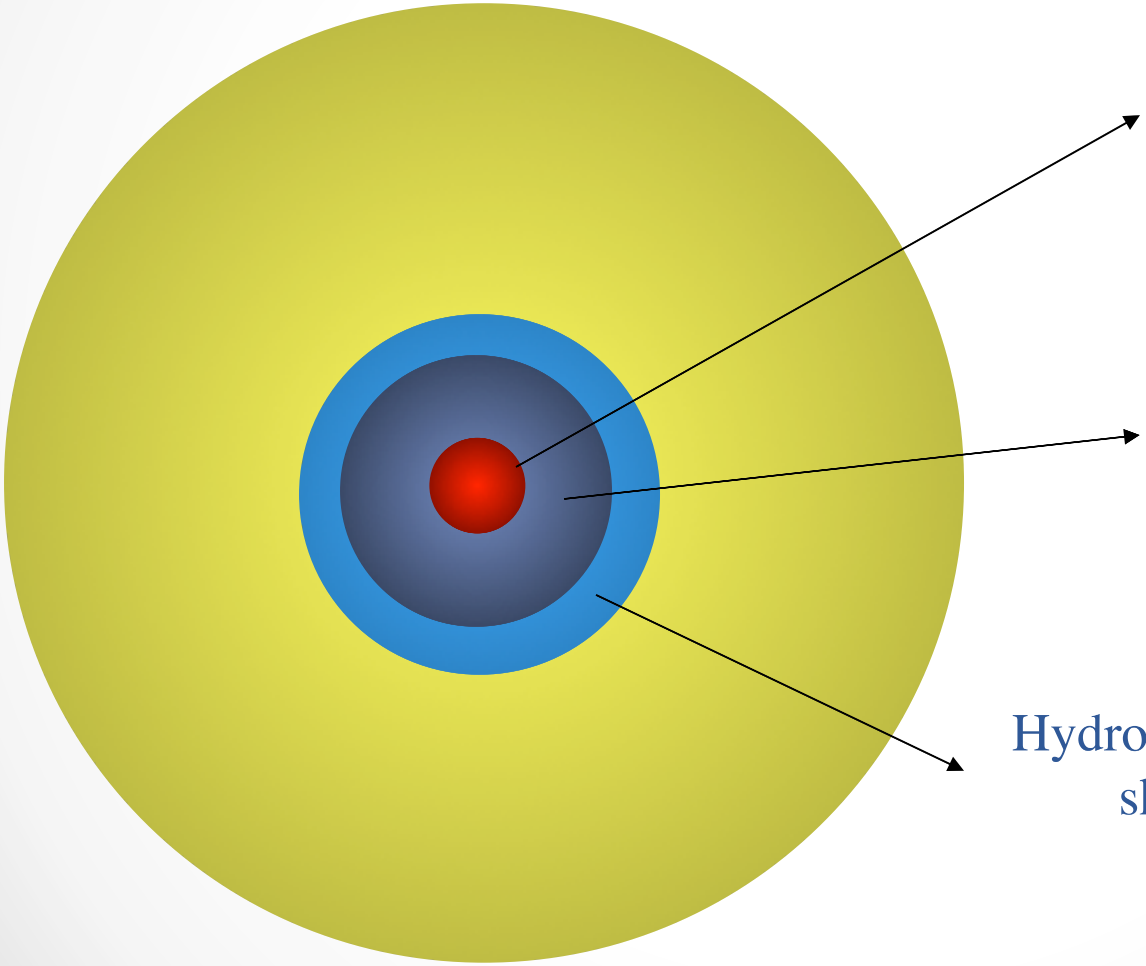
Be natural for Helium fusion to be the next energy source for an evolving star

Helium fusion requires two steps:

$He^4 + He^4 \text{ -> } Be^8$
$Be^8 + He^4 \text{ -> } C^{12}$

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.

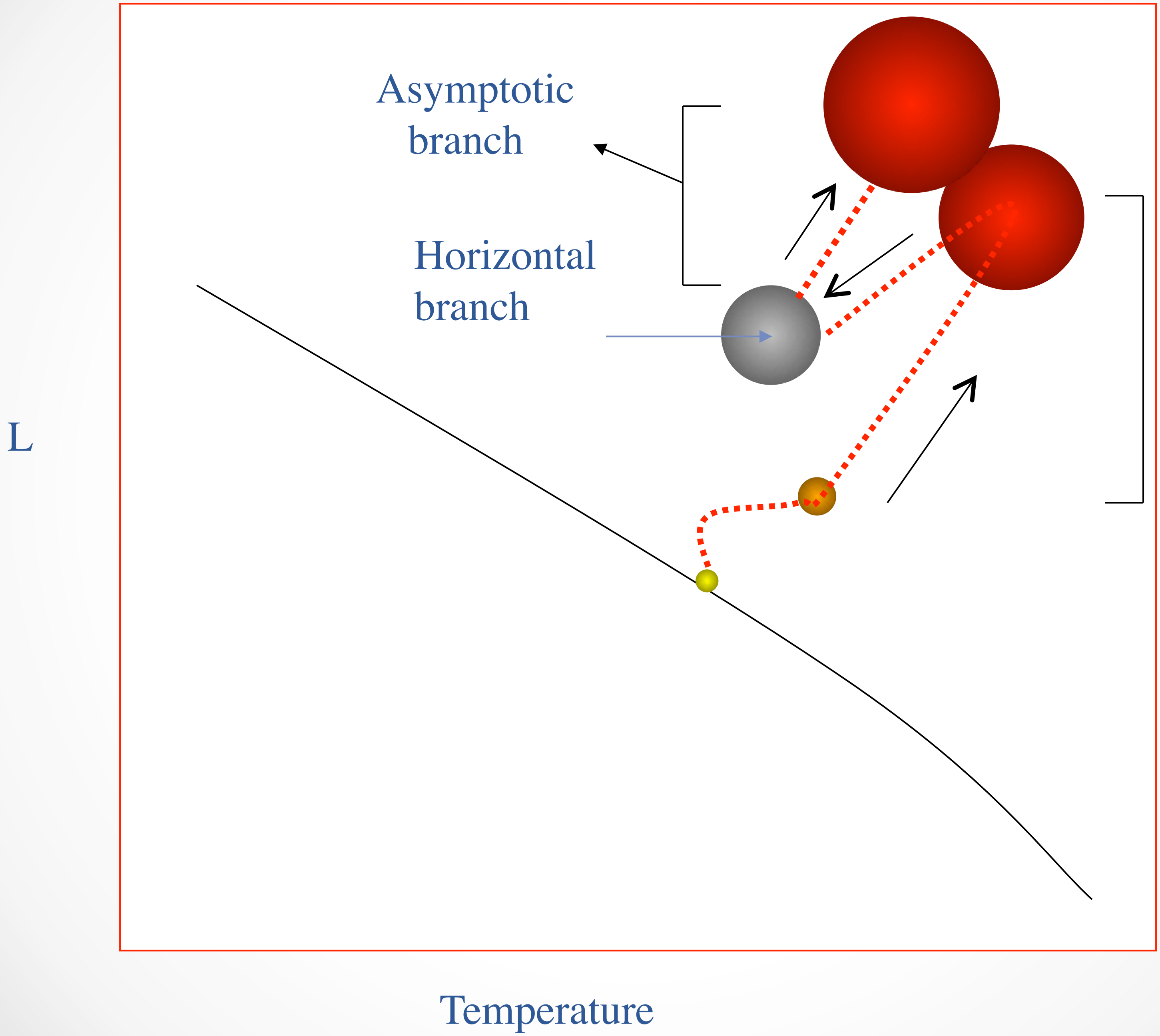
Giant Star Structure



Carbon Core

Helium fusion
shell

Hydrogen Fusion
shell



Asymptotic branch

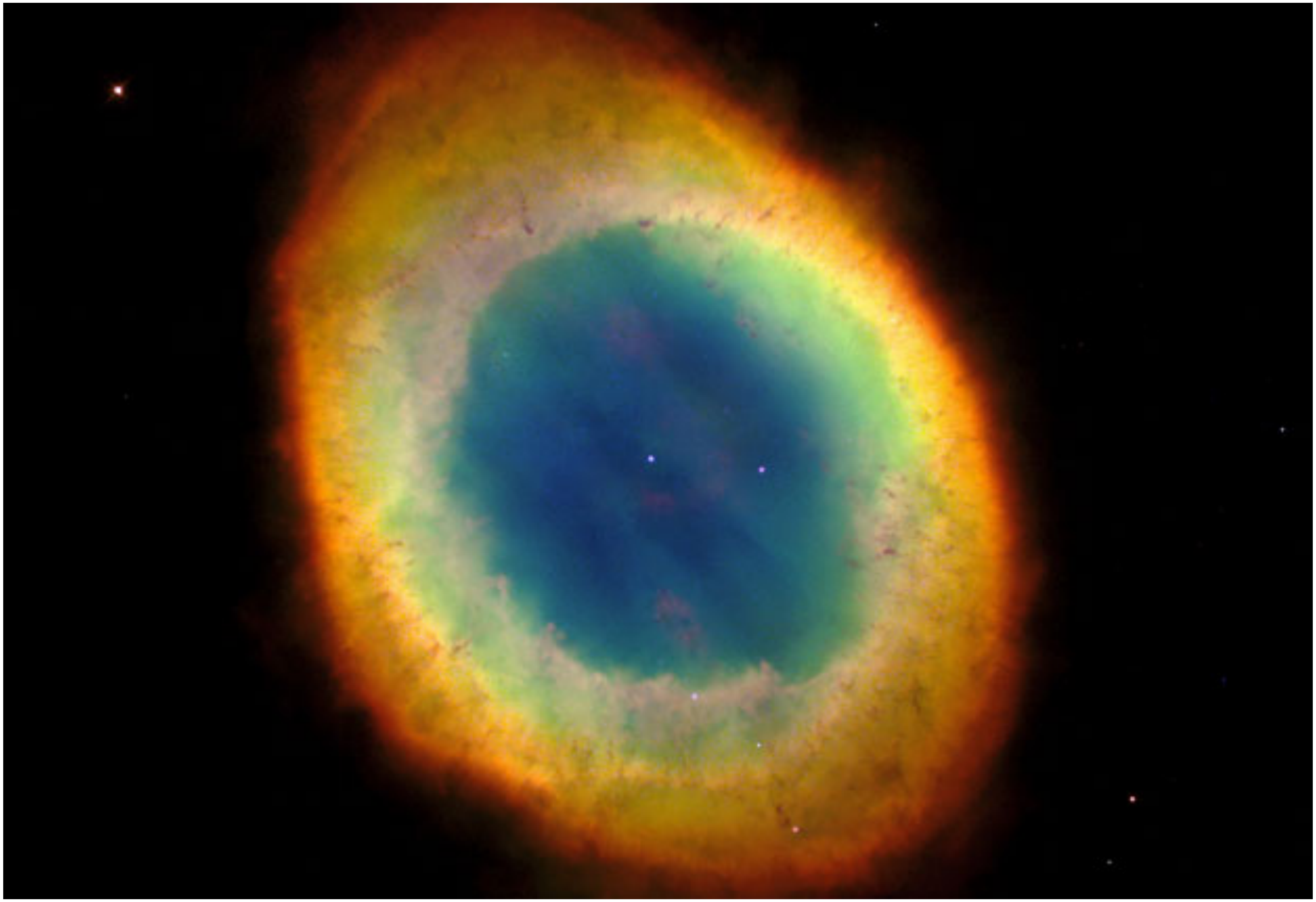
Horizontal branch

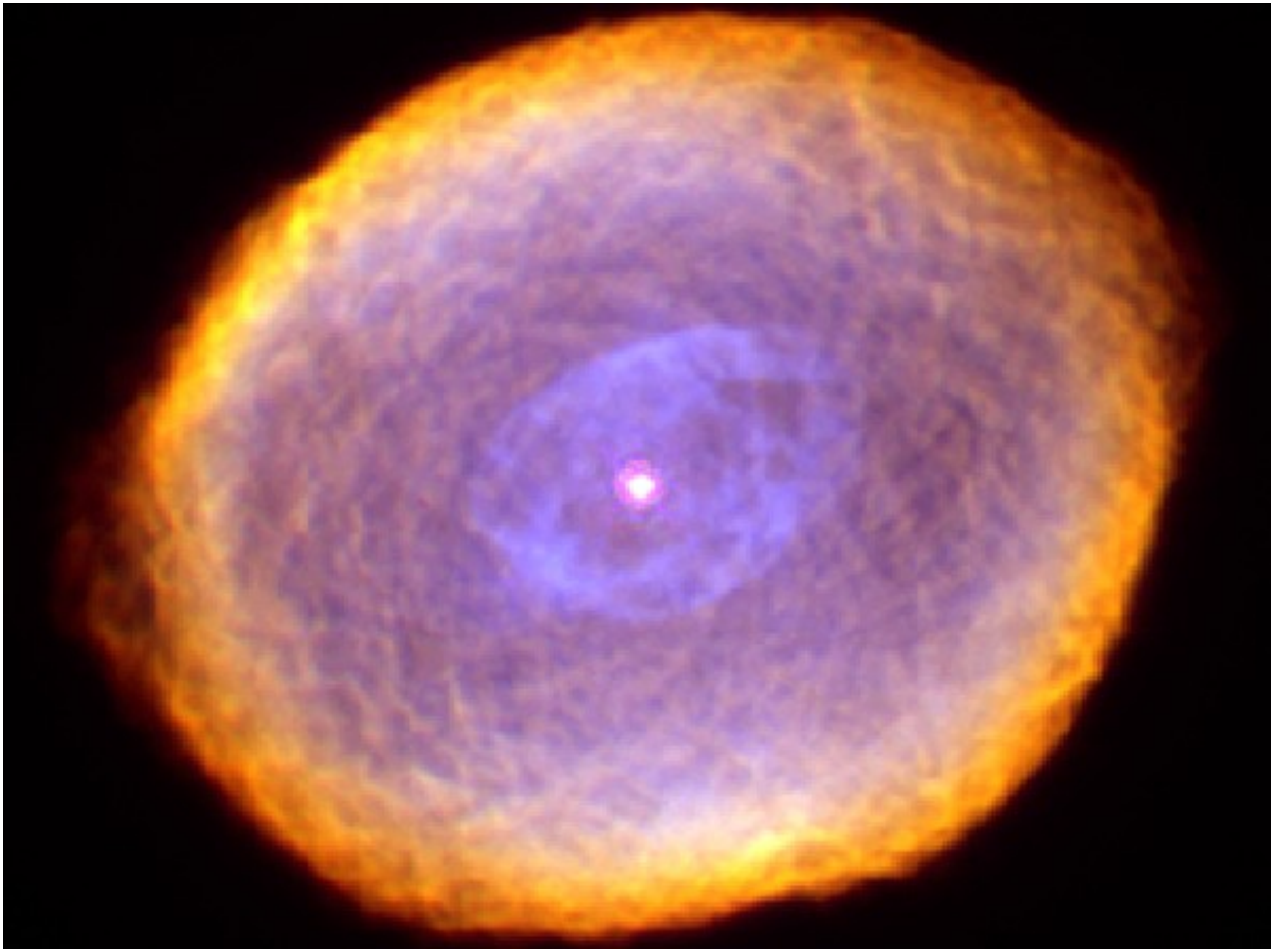
L

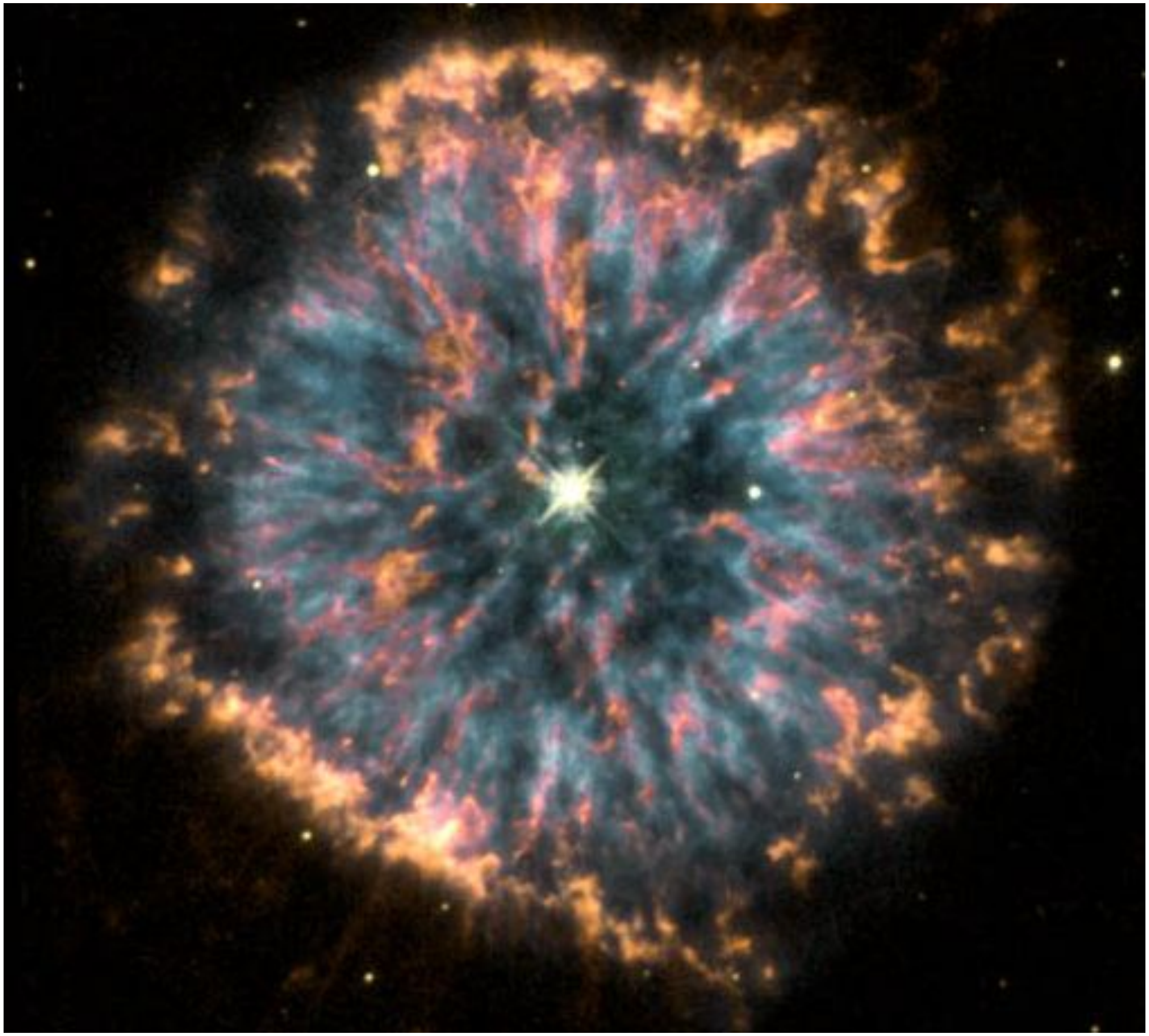
Temperature

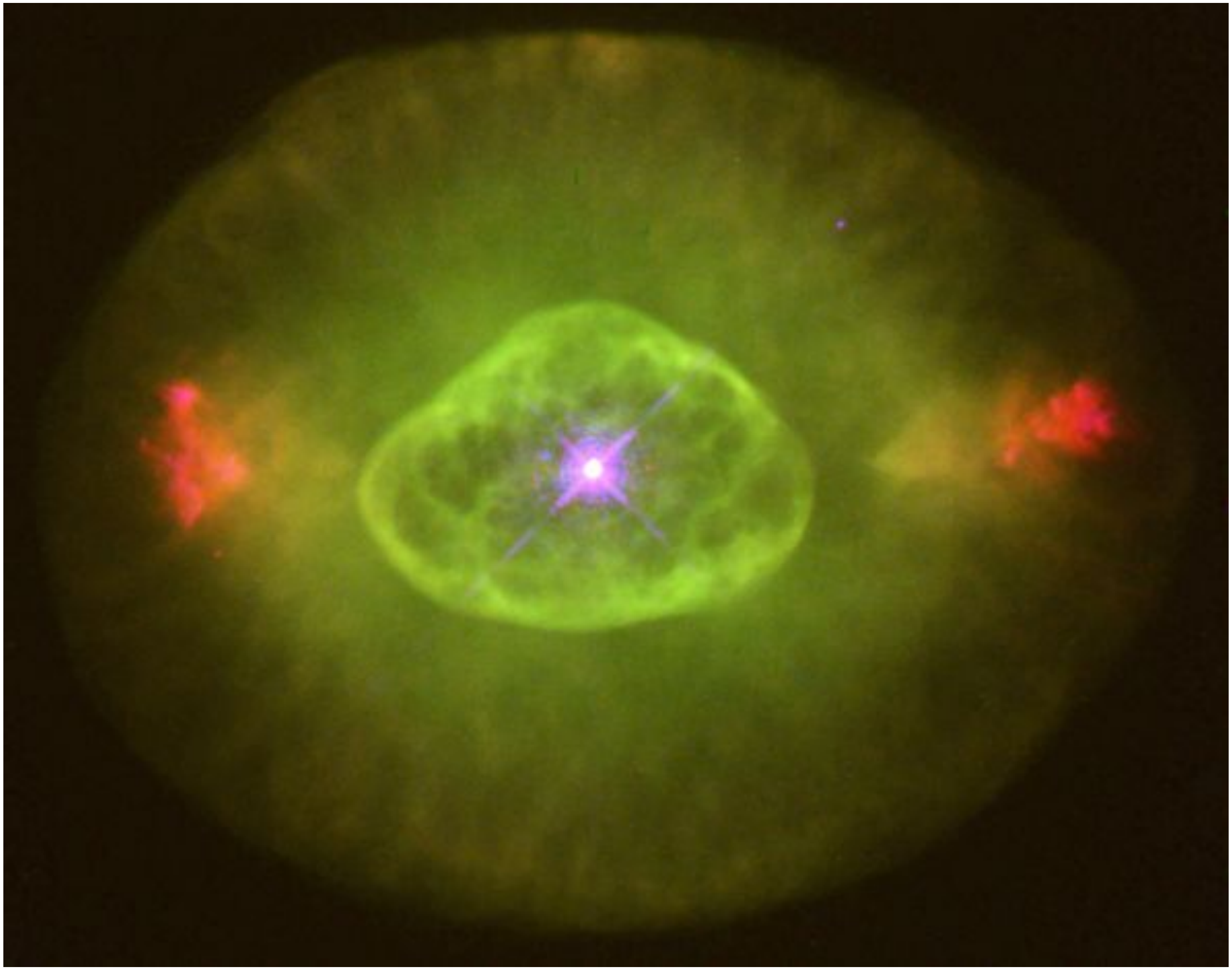
Planetary Nebula Stage

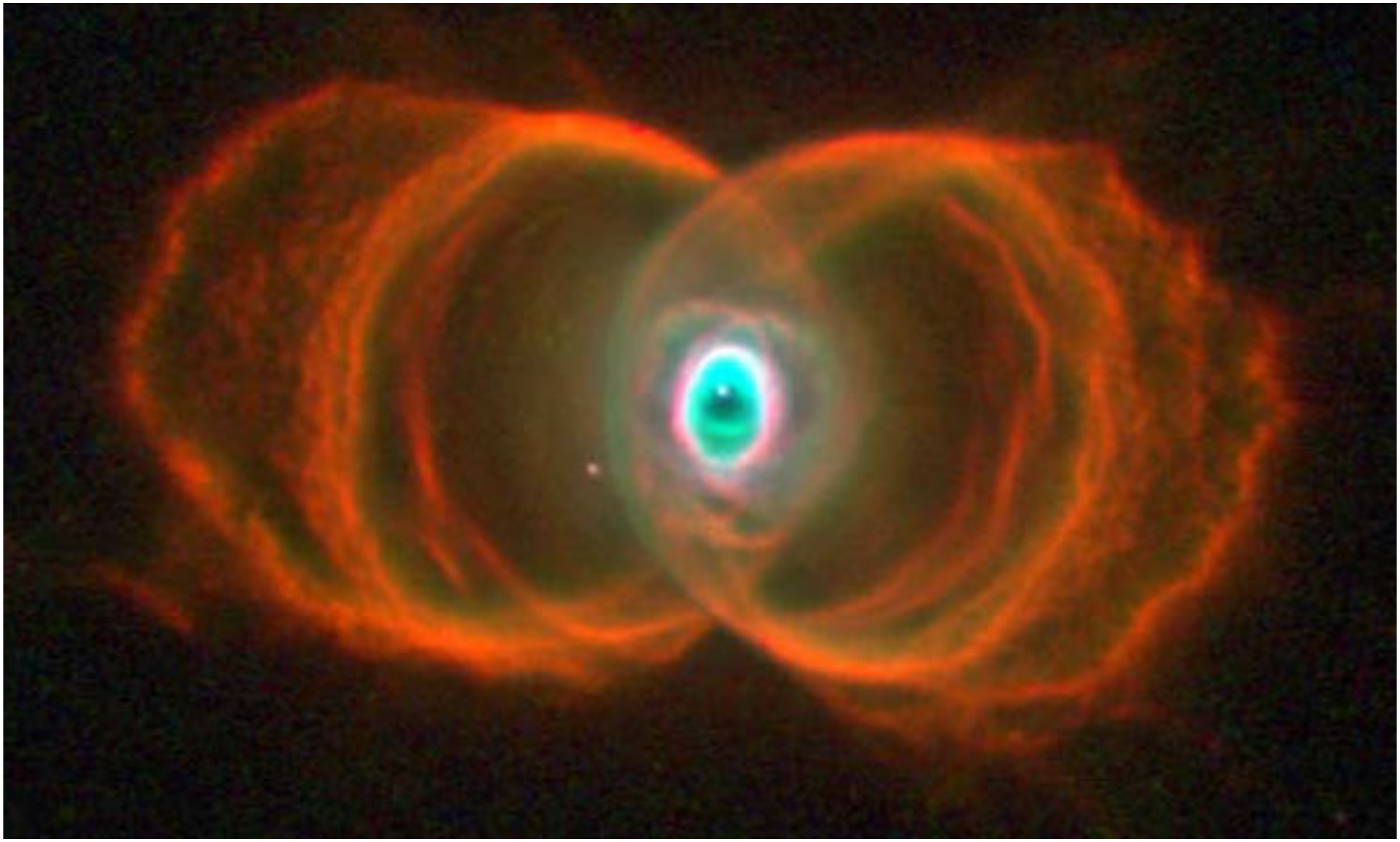
- The trips up the Giant Branch get terminated when the star's outer envelope becomes detached and begins to *drift off into space*. (!!)
- The former envelope shines in the light of emission lines.
- As the envelope expands and becomes transparent the very hot core of the giant star can be seen at its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

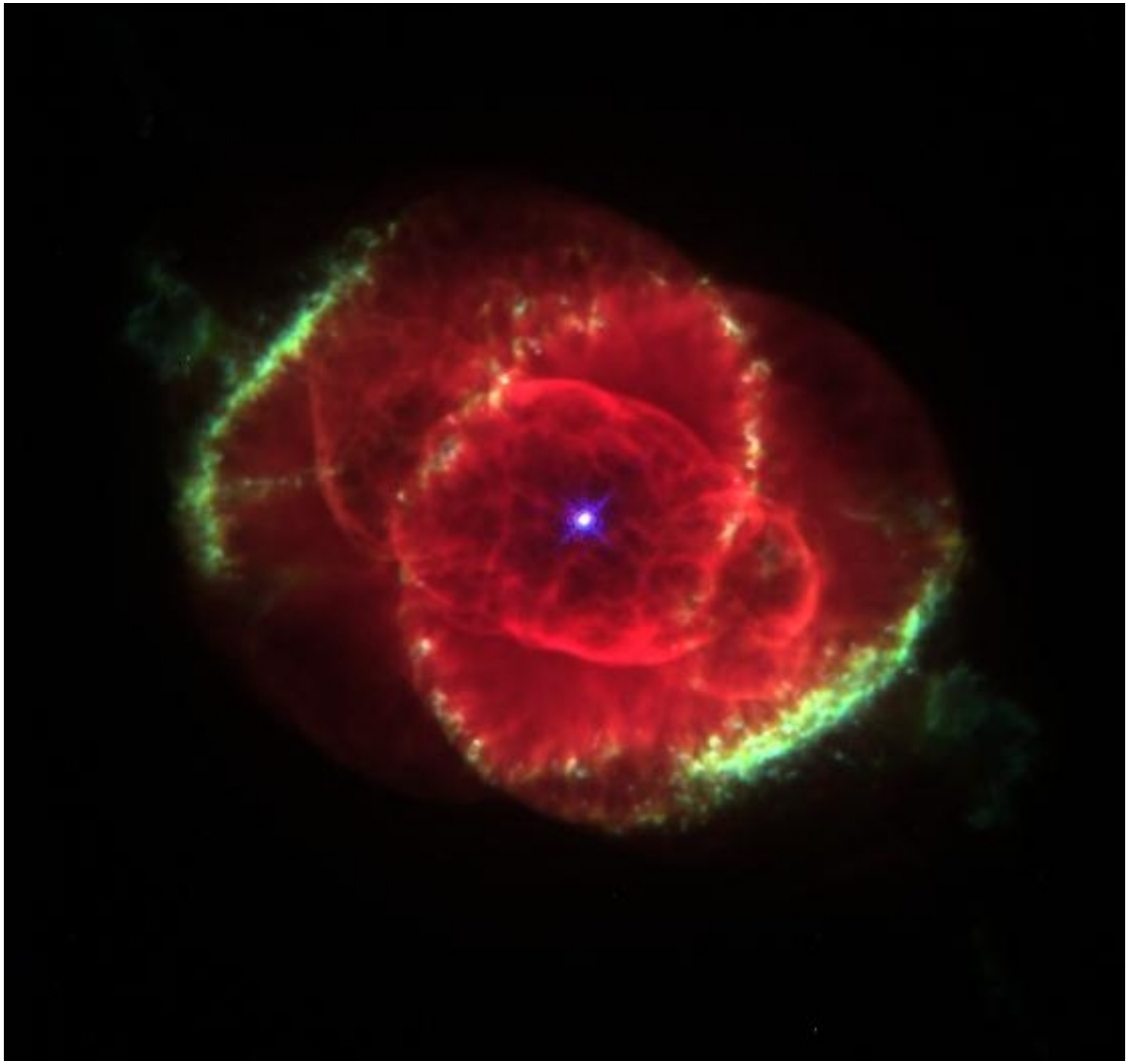






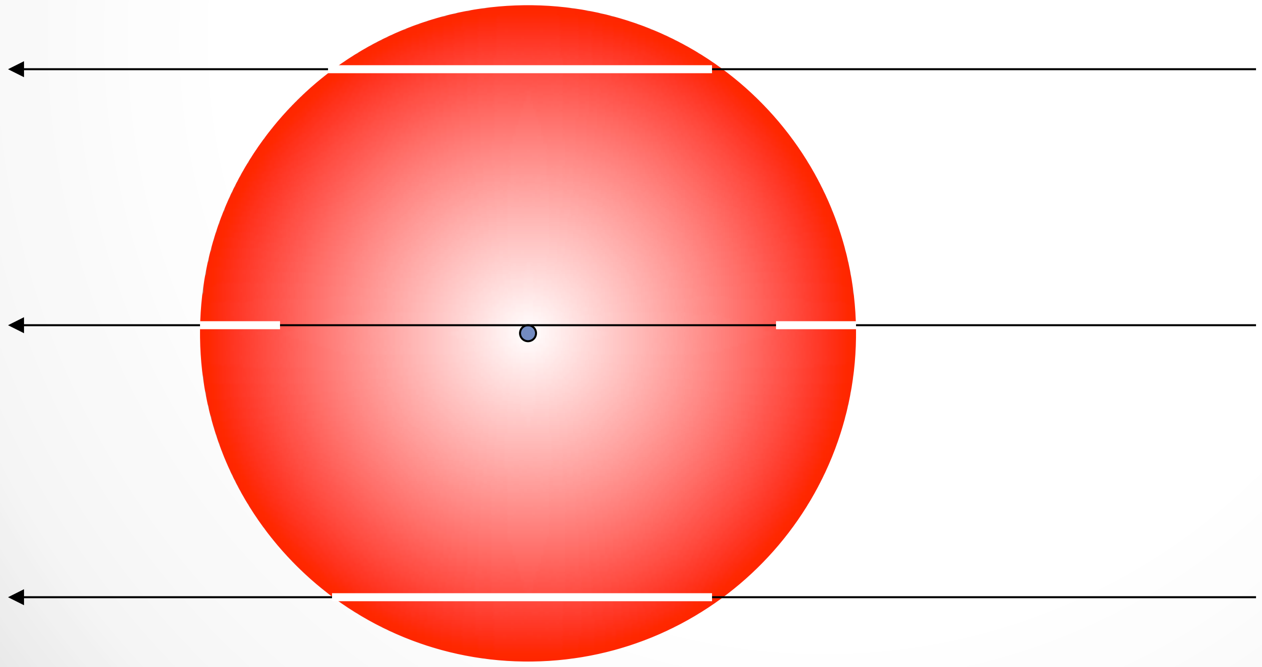






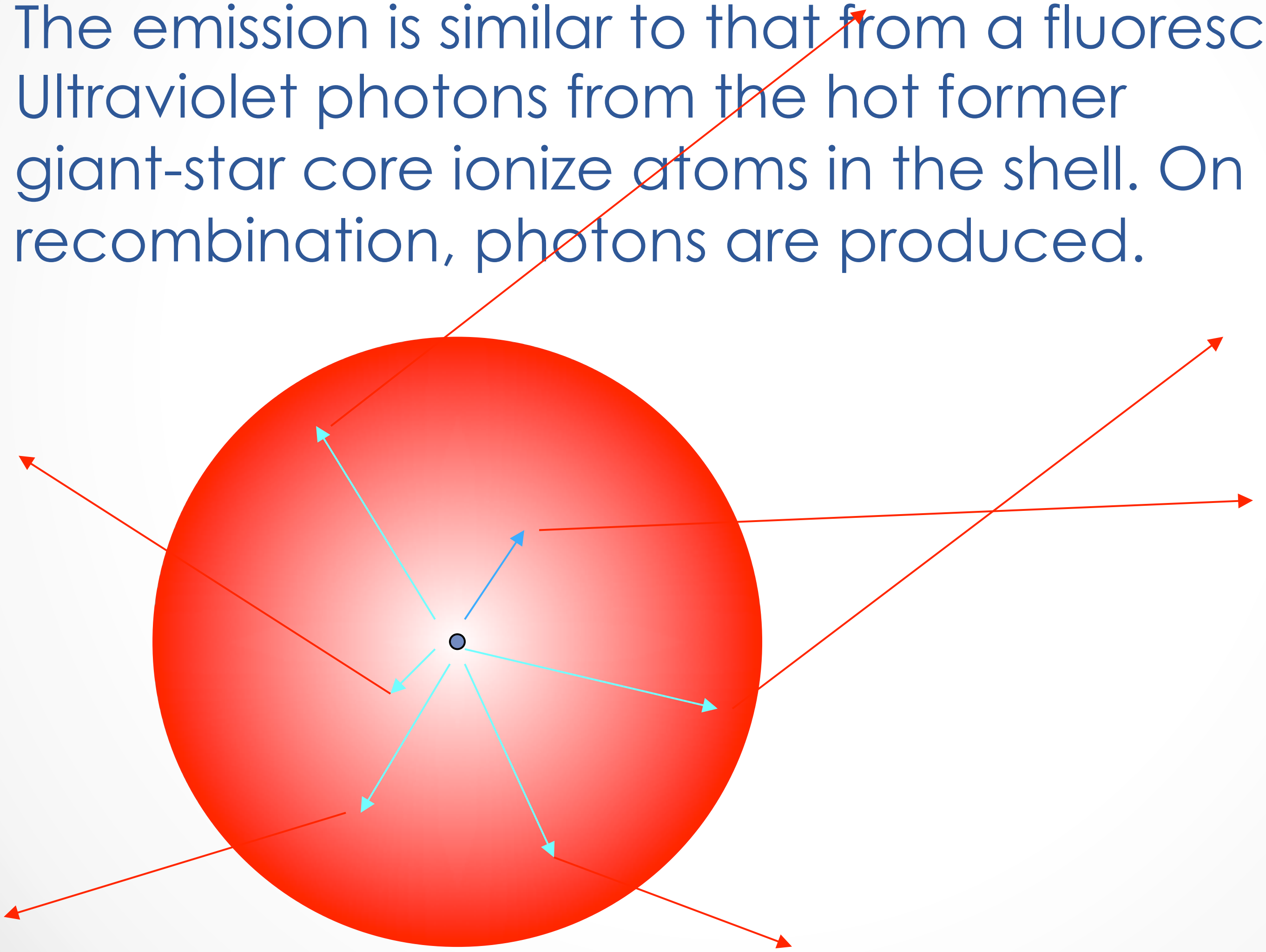
Planetary Nebulae

- 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 (eh?)

(3) Mass ~ $0.6M_{o}$

(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

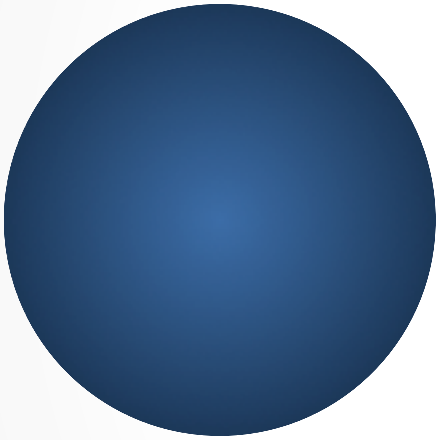
- Electrons are particles called `fermions' (rather than `bosons') that obey a law of nature called the Pauli Exclusion Principle.
- This law says that you can only have two electrons per unit 6-D phase-space volume in a gas.

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

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



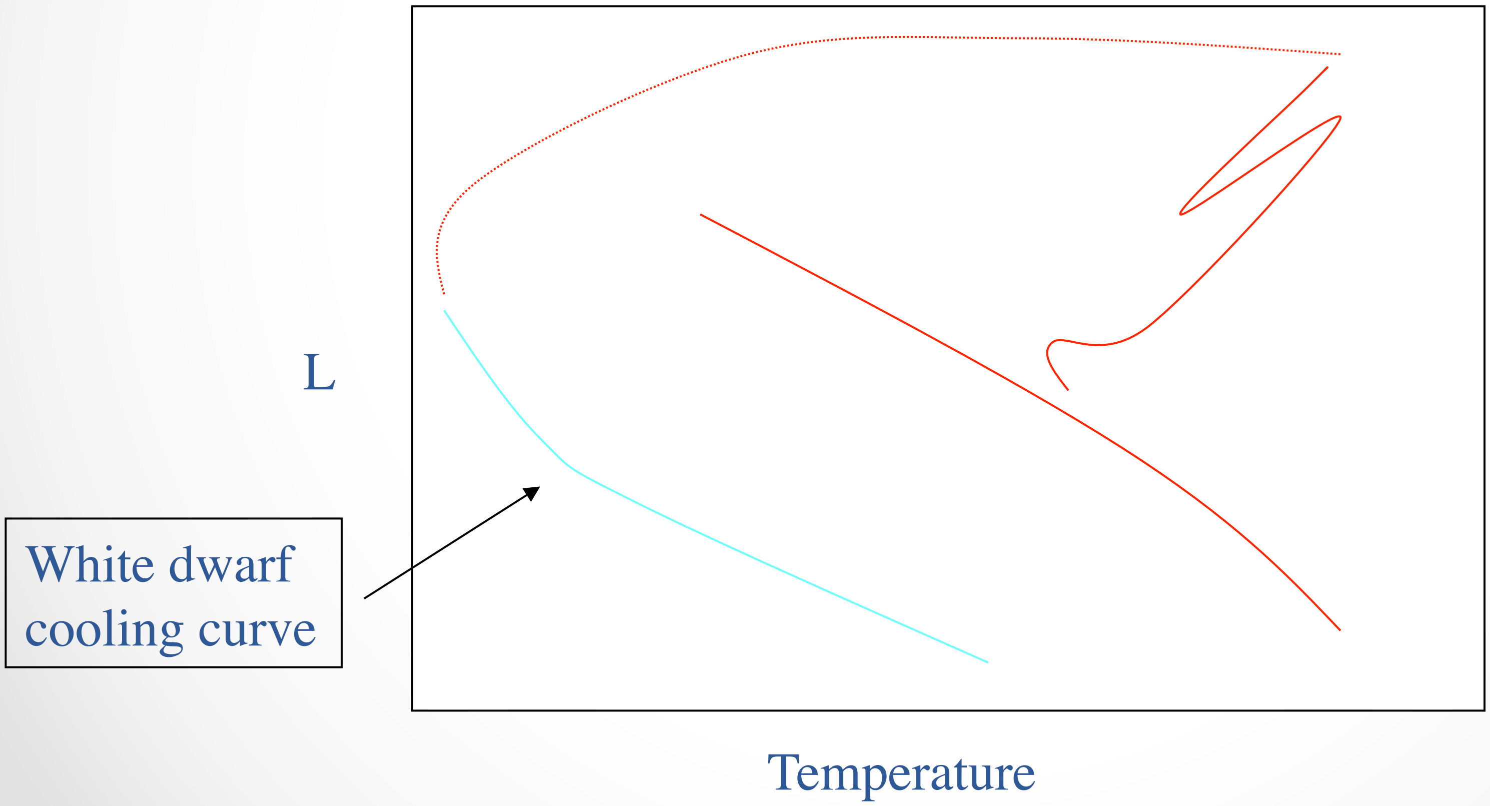
- Energy source: none
- Equilibrium:

  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

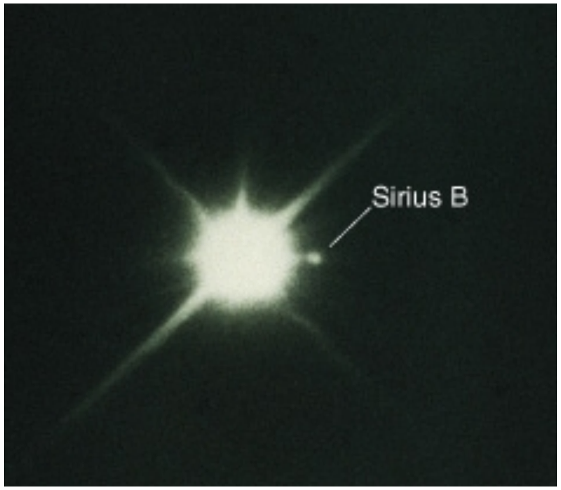
- WDs appear in the HR-Diagram in the upper left and VERY rapidly evolve downward and to the right.



White dwarf cooling curve

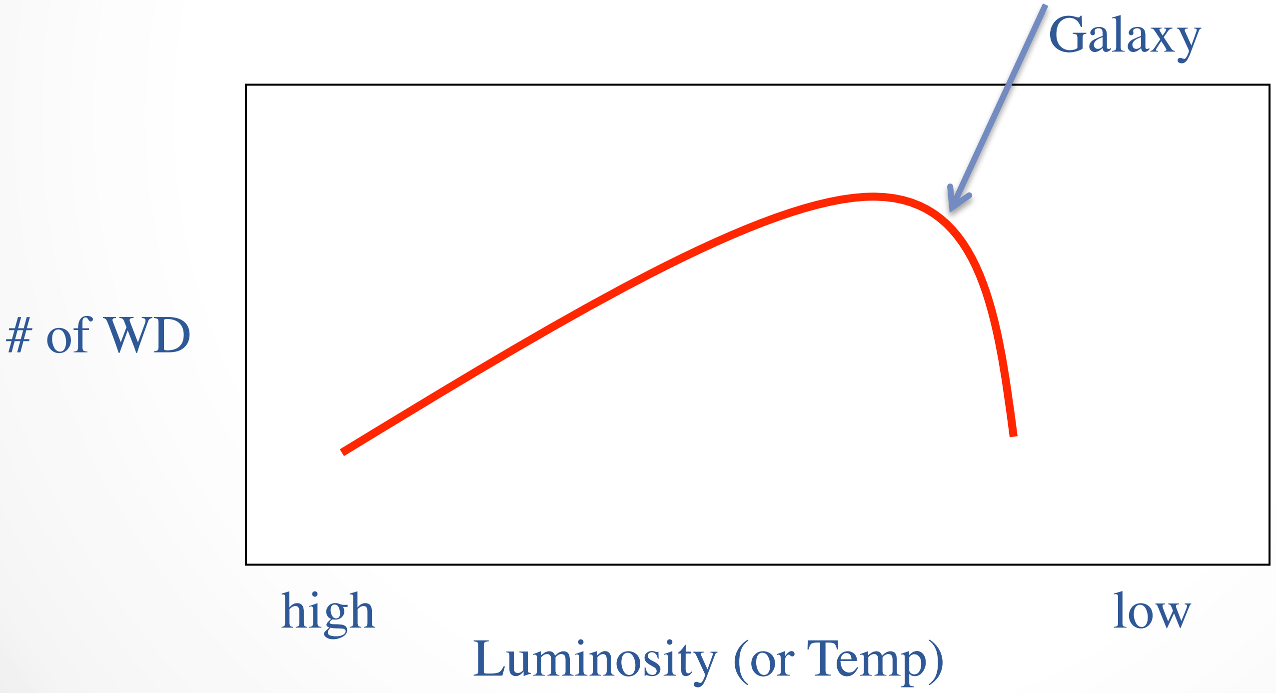
White Dwarfs

- ~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:



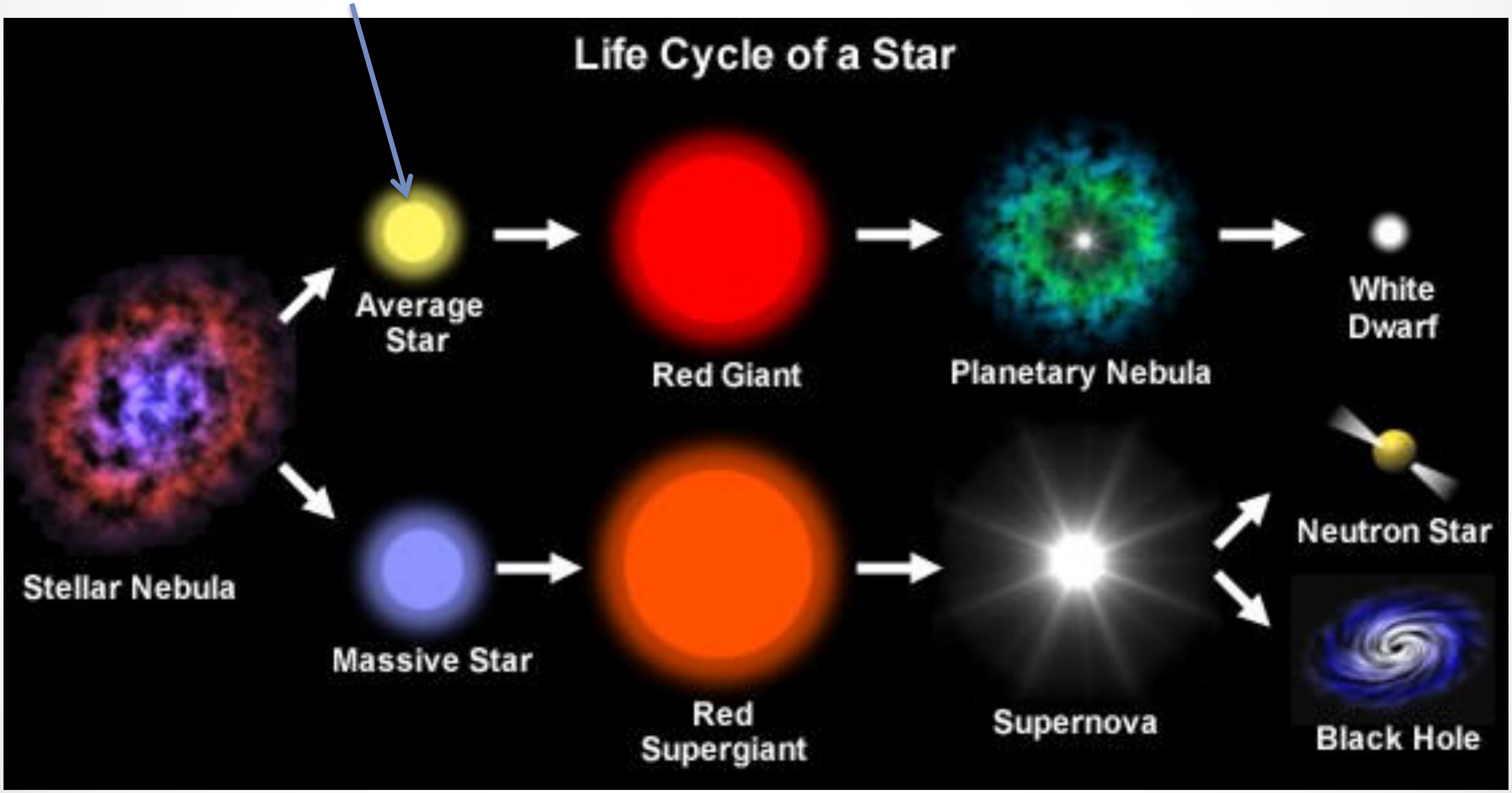
This drop off in WDs at low L and T is because of the finite age of the Galaxy

Evolution of <8M_{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.*

Stellar Evolution

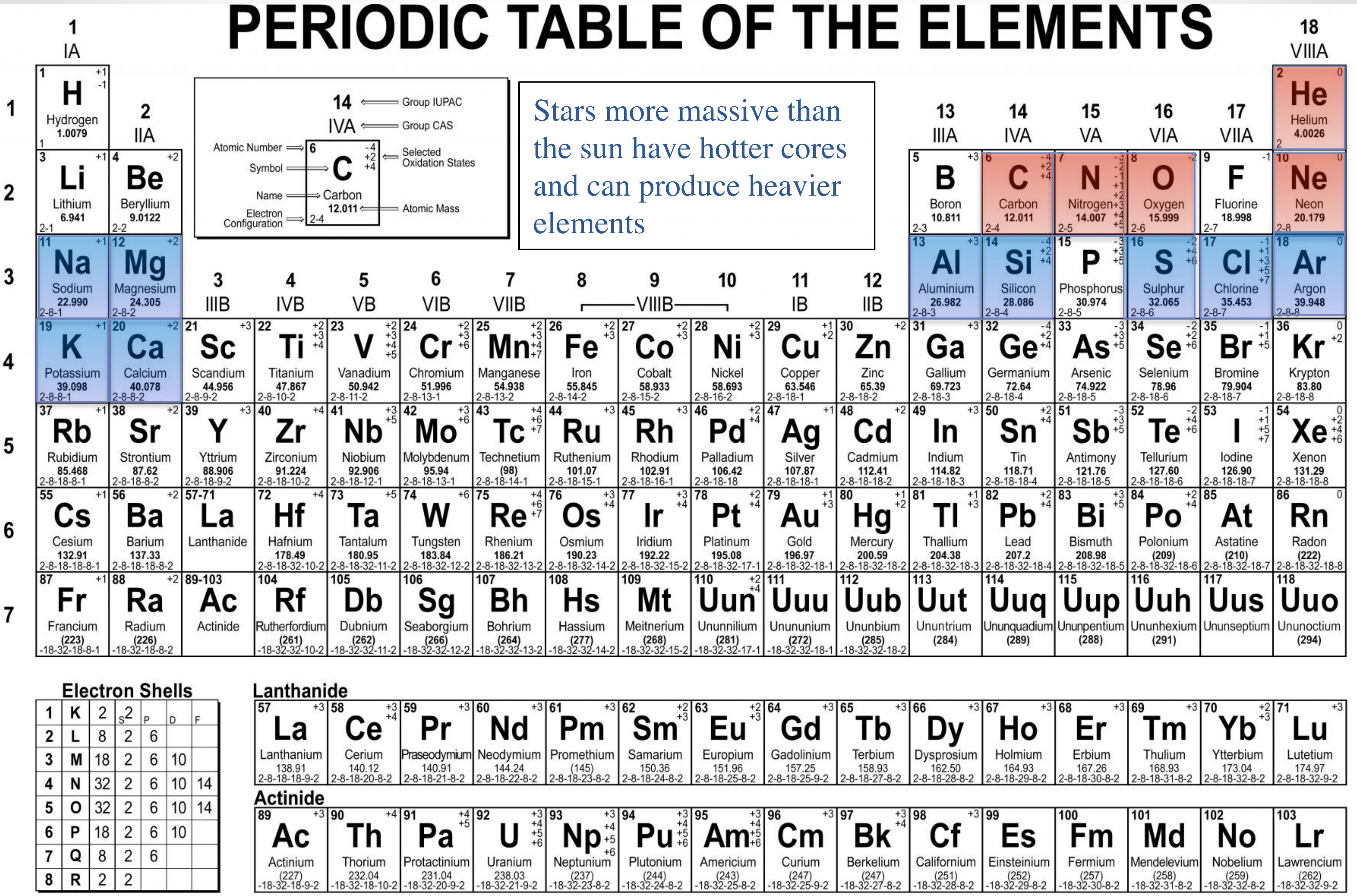
$0.1M_{SUN} – 8M_{SUN}$



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)

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



PERIODIC TABLE OF THE ELEMENTS

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

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

1	K	2	S 2	P	D	F
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			

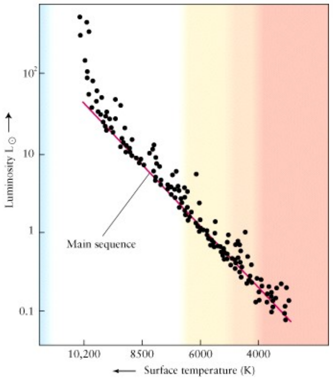
Lanthanide

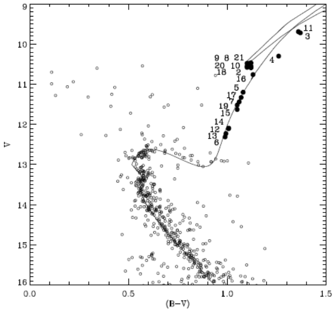
57 **La** Lanthanium 138.91 2-8-18-18-9-2 +3	58 **Ce** Cerium 140.12 2-8-18-20-8-2 +3 +4	59 **Pr** Praseodymium 140.91 2-8-18-21-8-2 +3	60 **Nd** Neodymium 144.24 2-8-18-22-8-2 +3	61 **Pm** Promethium (145) 2-8-18-23-8-2 +3	62 **Sm** Samarium 150.36 2-8-18-24-8-2 +2 +3	63 **Eu** Europium 151.96 2-8-18-25-8-2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

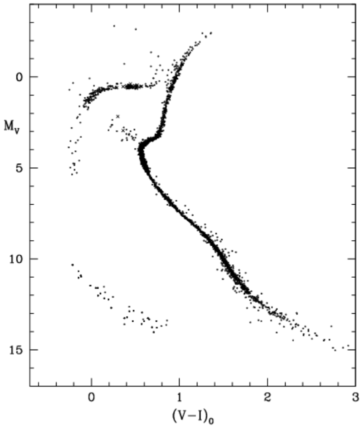
Actinide

89 **Ac** Actinium (227) -18-32-18-9-2 +3	90 **Th** Thorium 232.04 -18-32-18-10-2 +4	91 **Pa** Protactinium 231.04 -18-32-20-9-2 +4 +5	92 **U** Uranium 238.03 -18-32-21-9-2 +3 +4 +5 +6	93 **Np** Neptunium (237) -18-32-23-8-2 +3 +4 +5 +6	94 **Pu** Plutonium (244) -18-32-24-8-2 +3 +4 +5 +6	95 **Am** Americium (243) -18-32-25-8-2 +3 +4 +5 +6	96 **Cm** Curium (247) -18-32-25-9-2 +3	97 **Bk** Berkelium (247) -18-32-27-8-2 +3 +4	98 **Cf** Californium (251) -18-32-28-8-2 +3	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

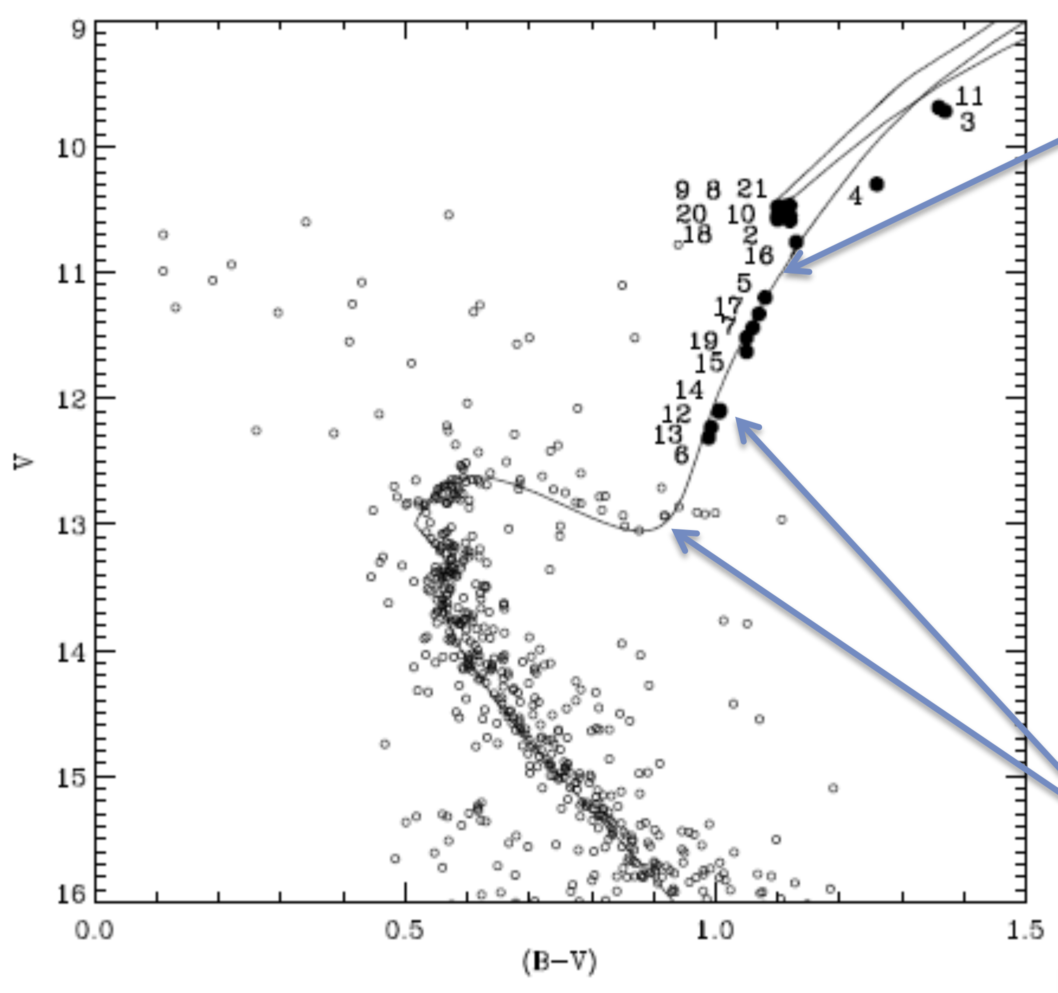
Why do we think this is right?







Why do we think this is right?

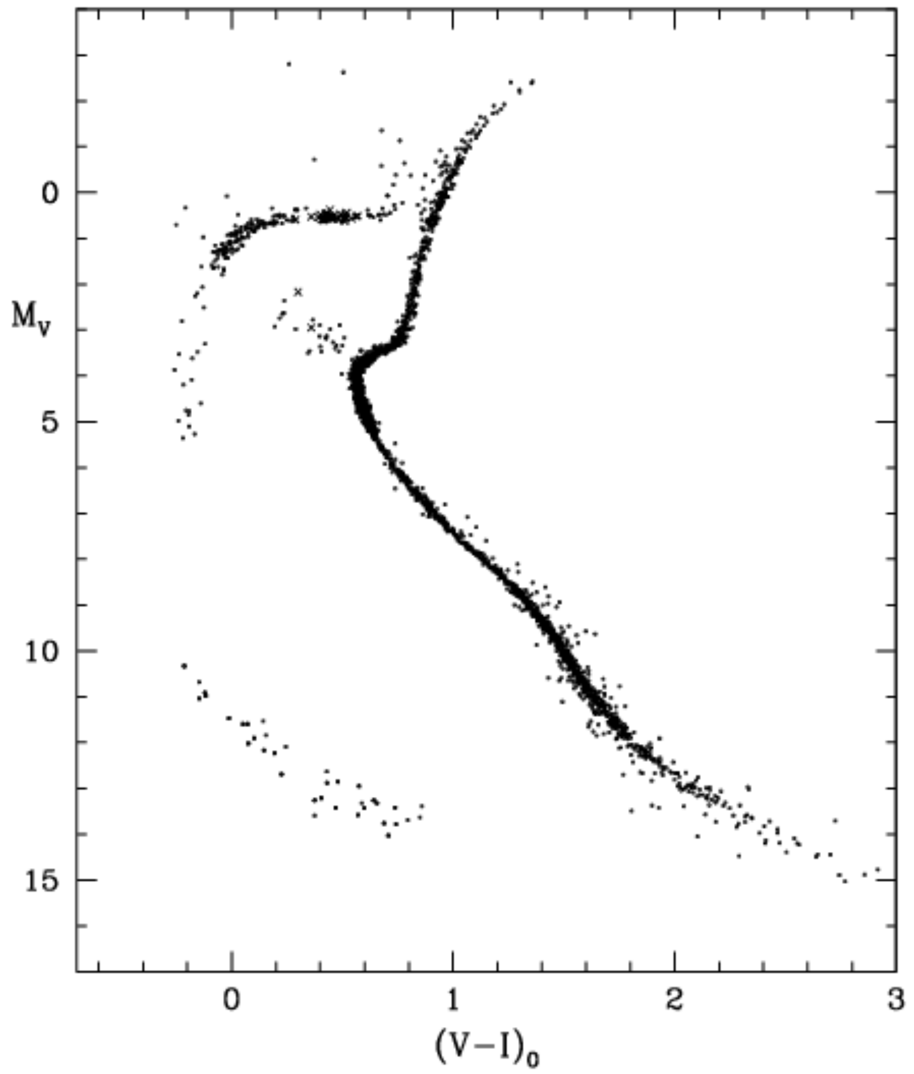


Line is model evolution track

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

Open and solid points are observations of stars

Why do we think this is right?



The number of stars in each phase of evolution is a deeper test as it depends directly on the fuel consumption in that phase

Have to understand the detailed structure and physics of energy generation to get this right and we do!

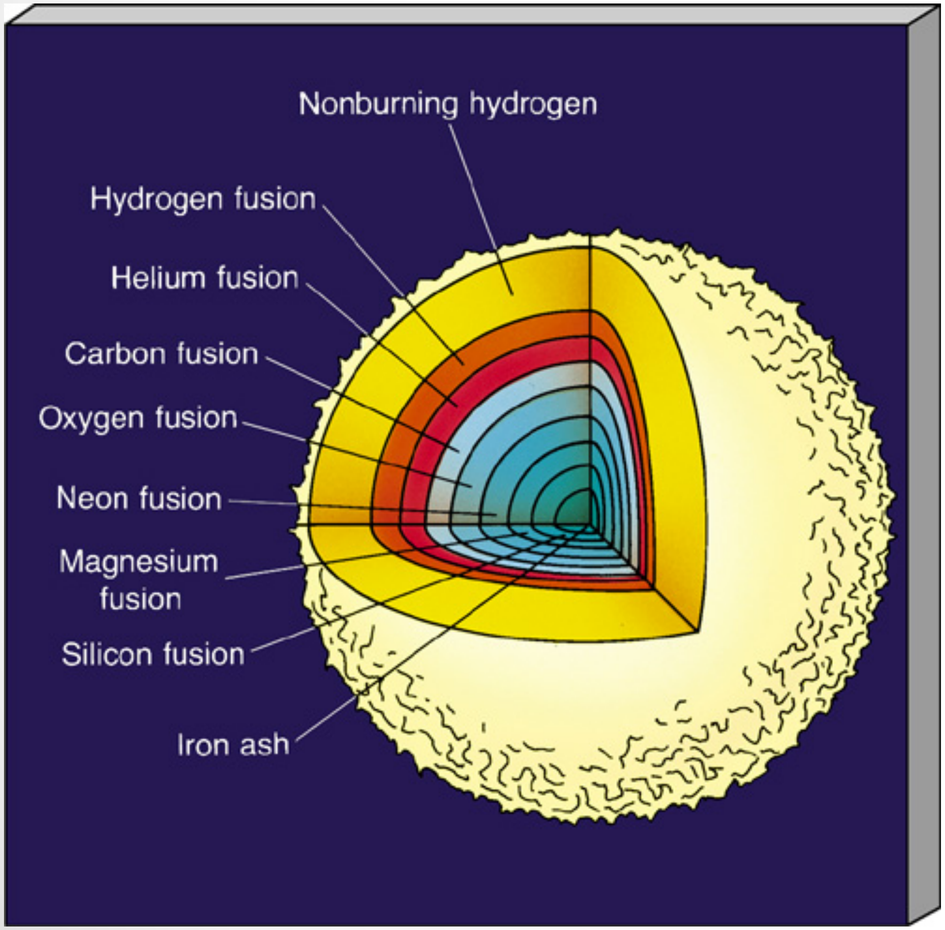
The Evolution of High-mass Stars

- 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)

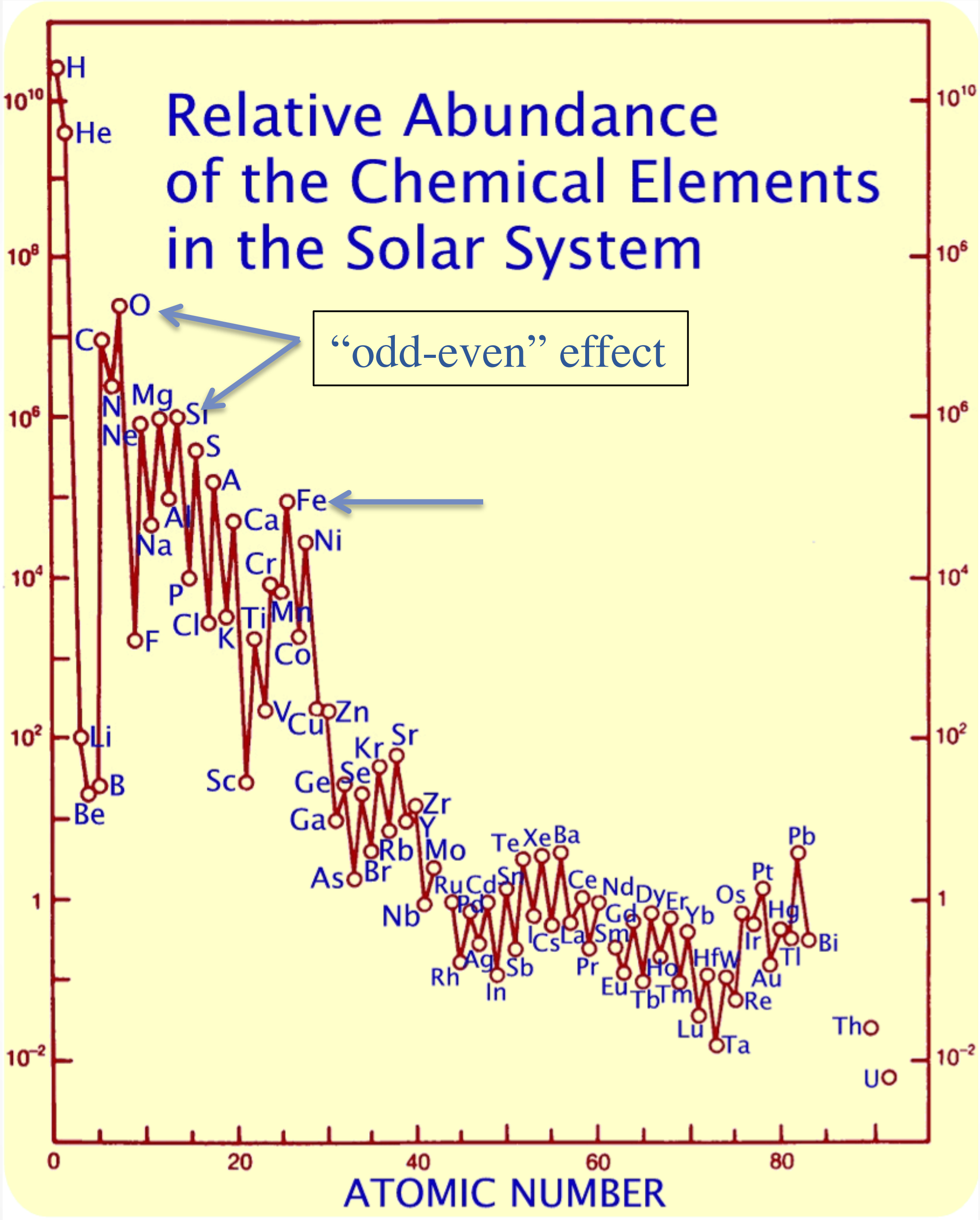
Nucleosynthesis in Massive Stars

- Fusing nuclei to make new elements is called nucleosynthesis.

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

Massive Star Nucleosynthesis

- In a $25M_o$ 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.

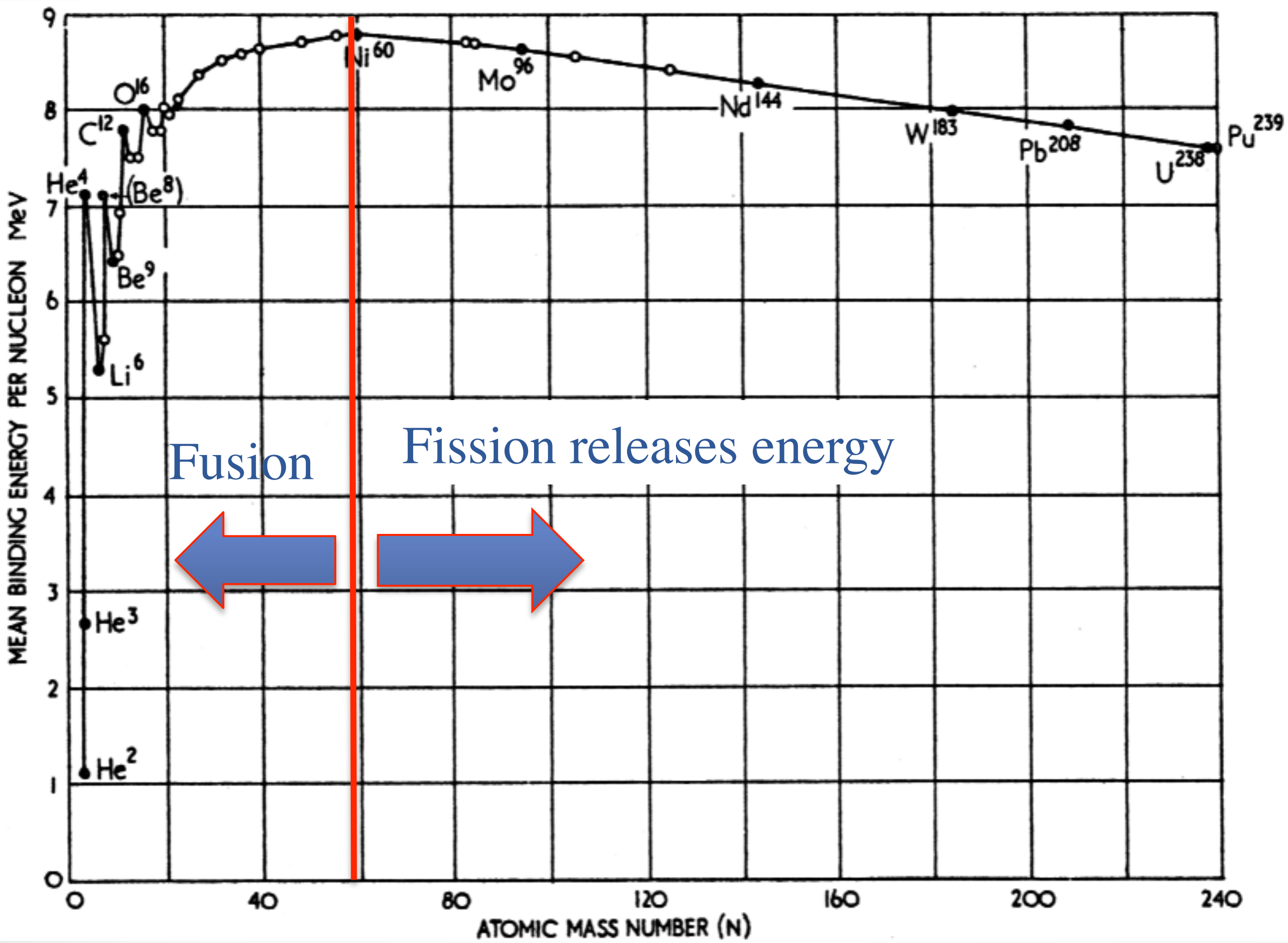


"odd-even" effect

Note log scale

What is special about Fe?

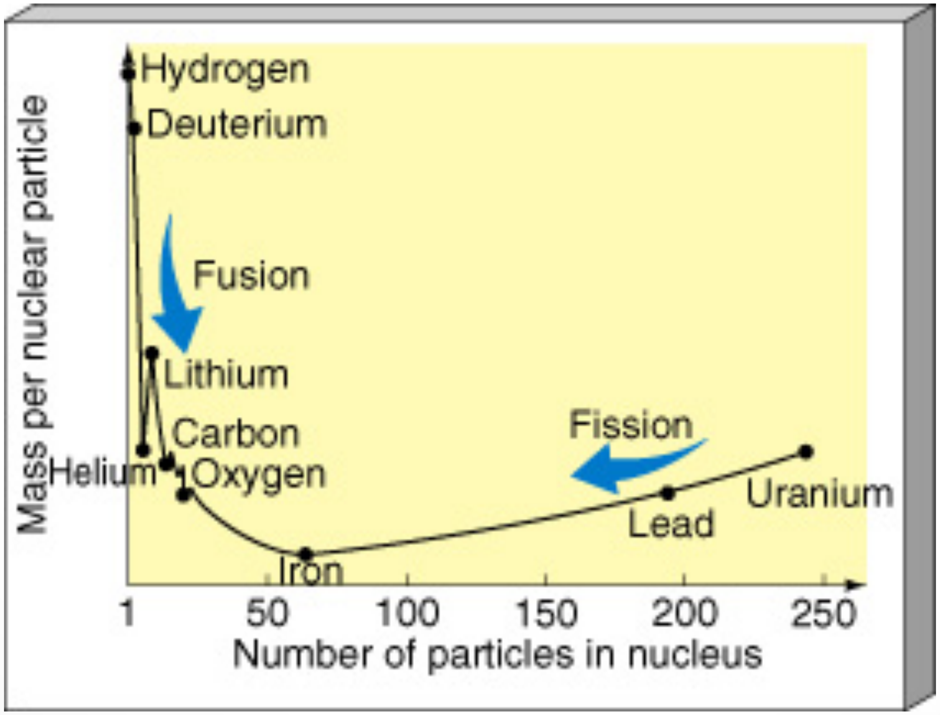
- Fe is at the peak of the `curve of binding energy'



Fusion

Fission releases 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 $E=mc^2$.



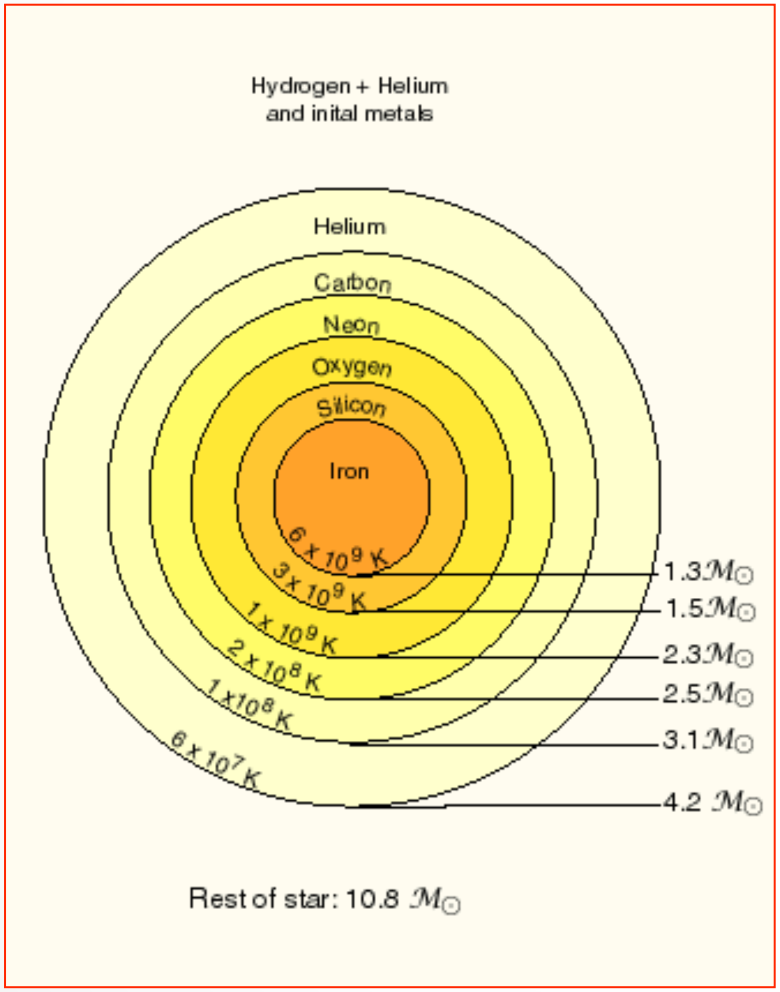
Nucleosynthesis

- 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

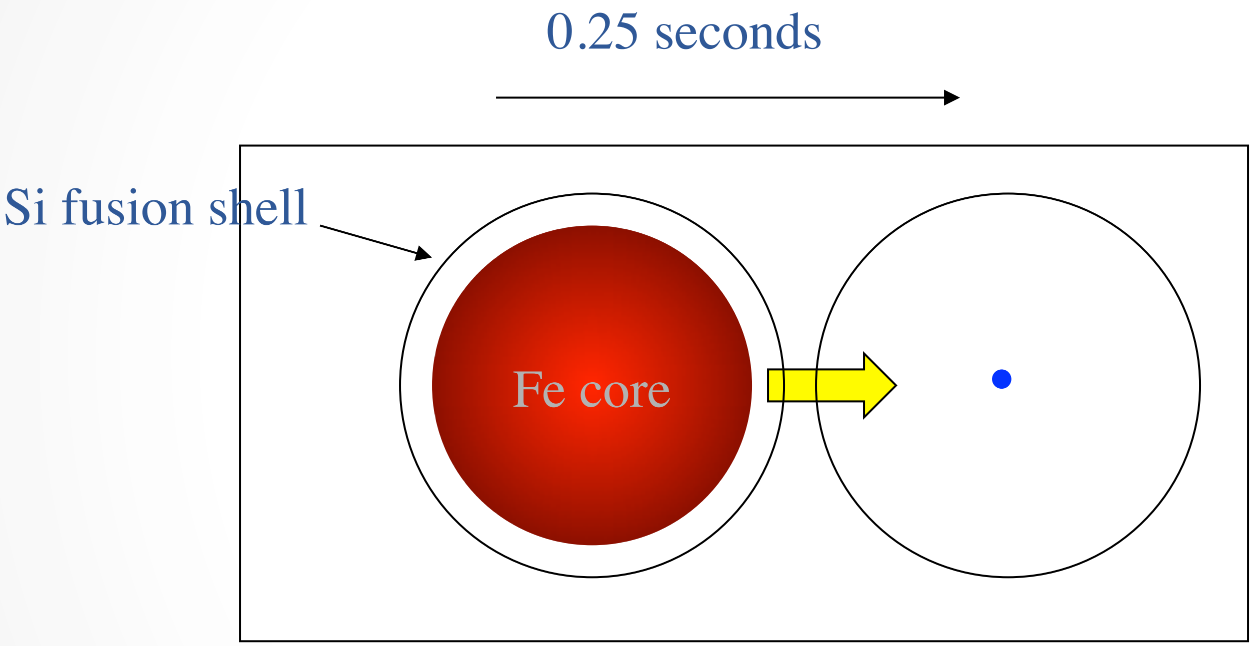


“ashes” from outer shells provide fuel for the next shell down

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.
- 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

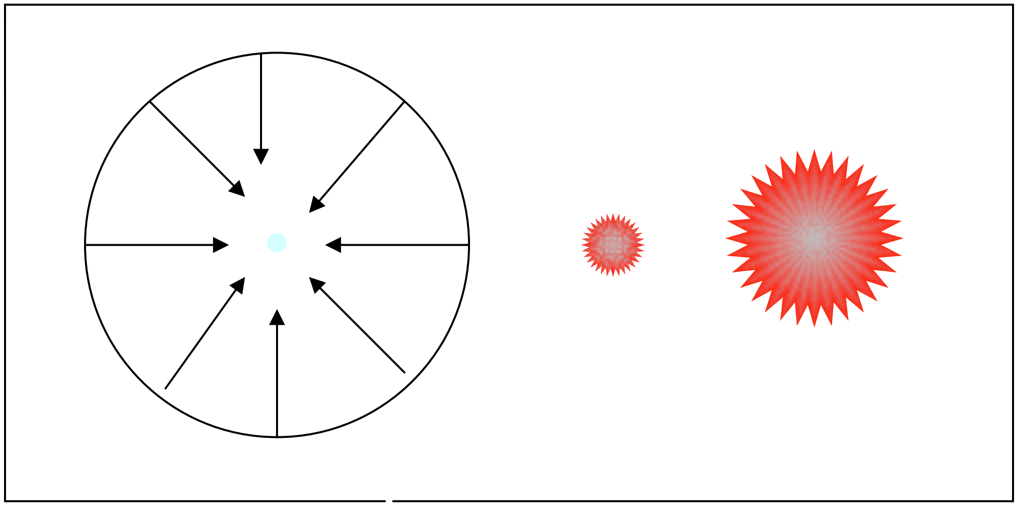

0.25 seconds

Si fusion shell

Fe core

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

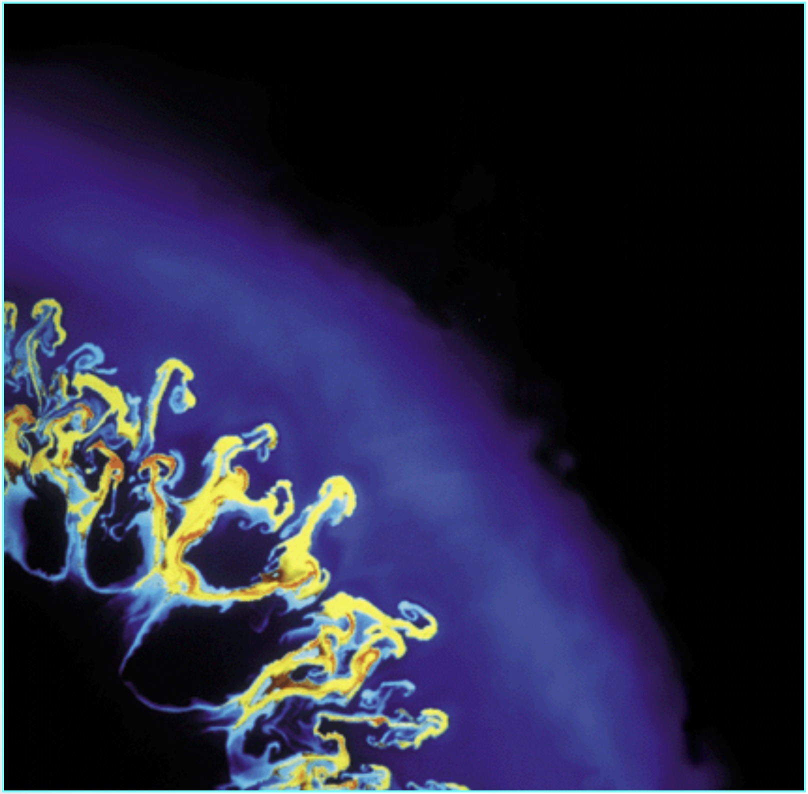
Core-Collapse in Massive Stars



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.

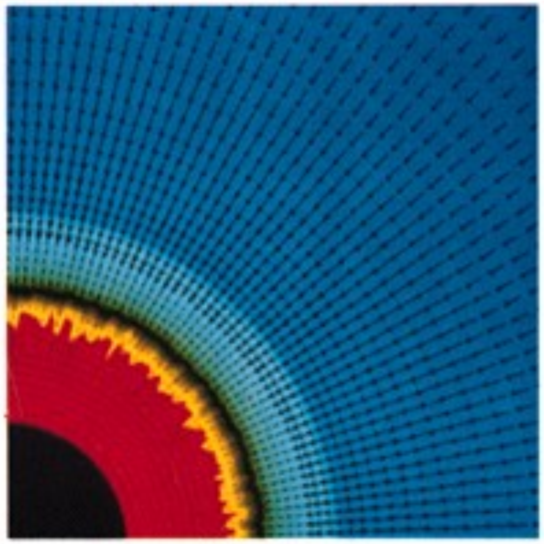
SNII Bounce Shock wave

Supernova Type II (SNII)

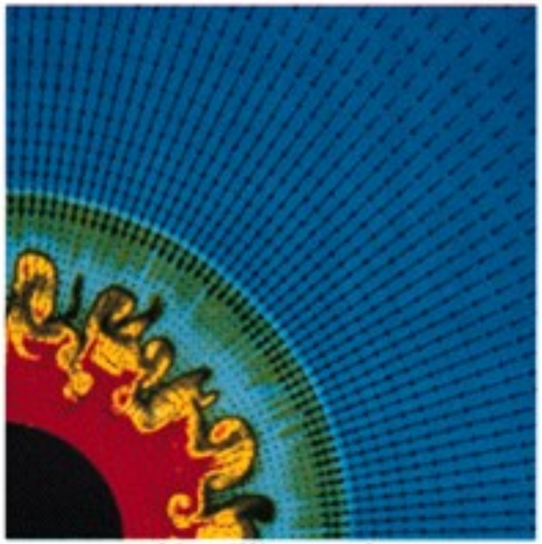


This is a wild event.

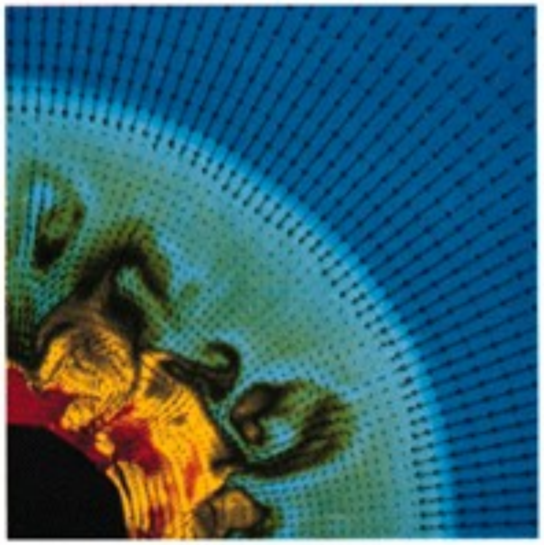
- Explosion energy in models predicted to be ~100 million times the luminosity of the Sun (as bright as a small galaxy)
- Many rare elements will be manufactured in non-equilibrium reactions*



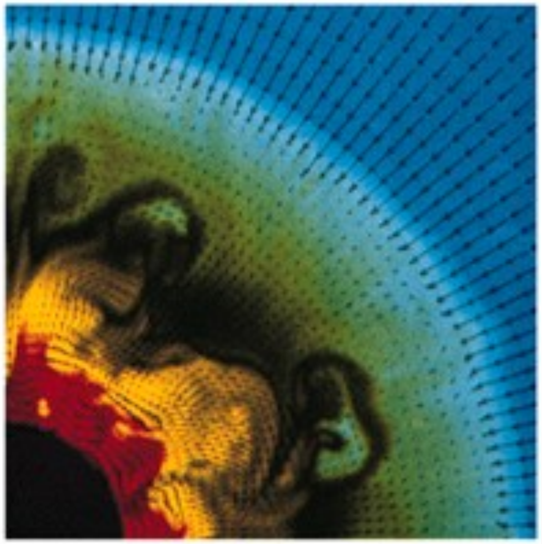
5 milliseconds



10 milliseconds



15 milliseconds



20 milliseconds

Supernovae II

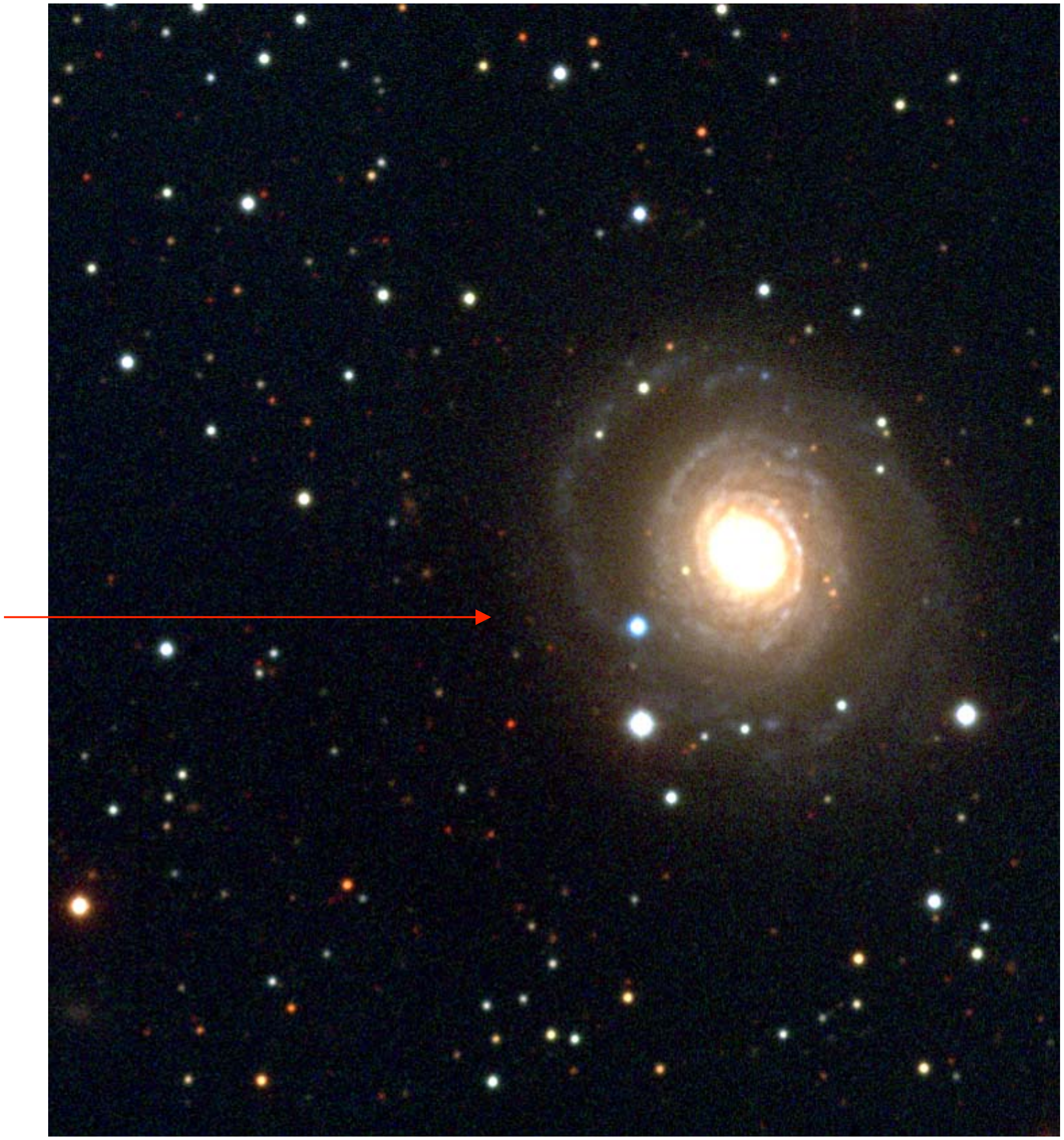
- Expect:
  - Rapidly expanding debris cloud
  - 10^8 times the optical luminosity of the Sun
  - Chemically-enriched debris
  - Extremely dense 1.4 solar mass neutron ball left behind
  - Association with massive stars/star formation

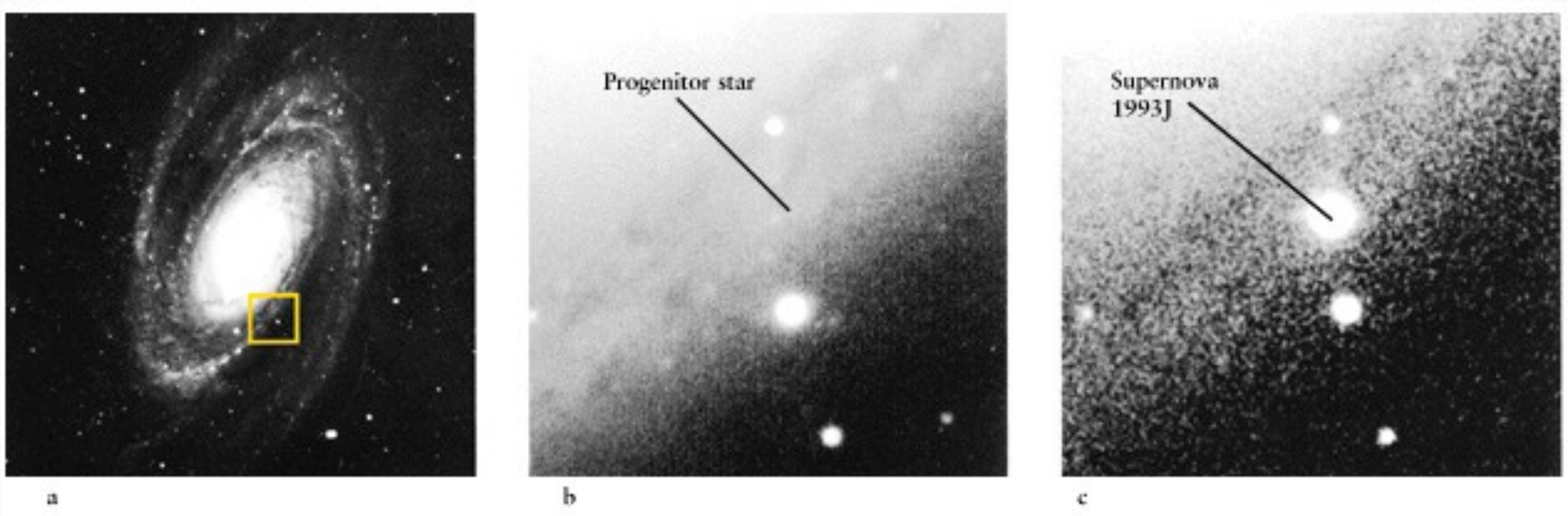
Supernova II

- 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!




Progenitor star
Supernova
1993J
a
b
c

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