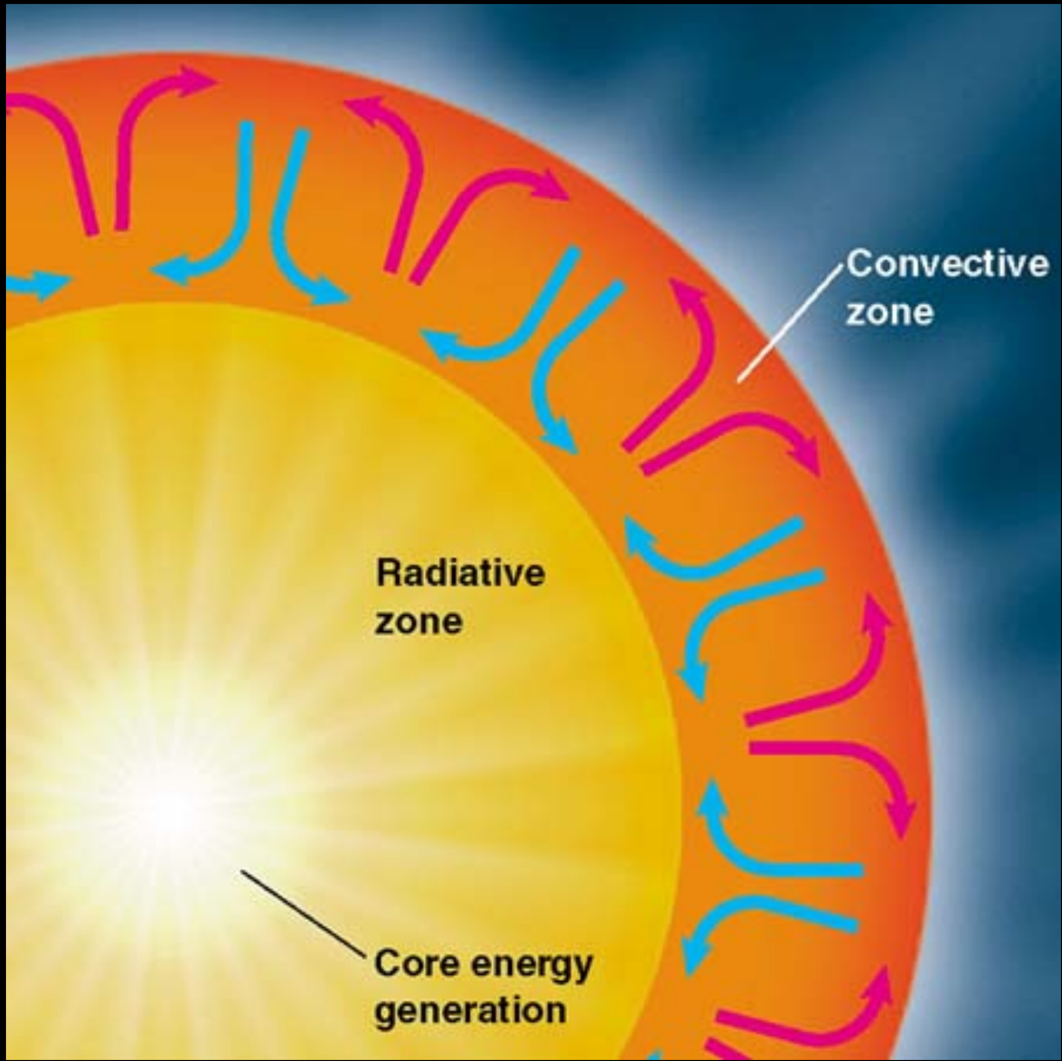
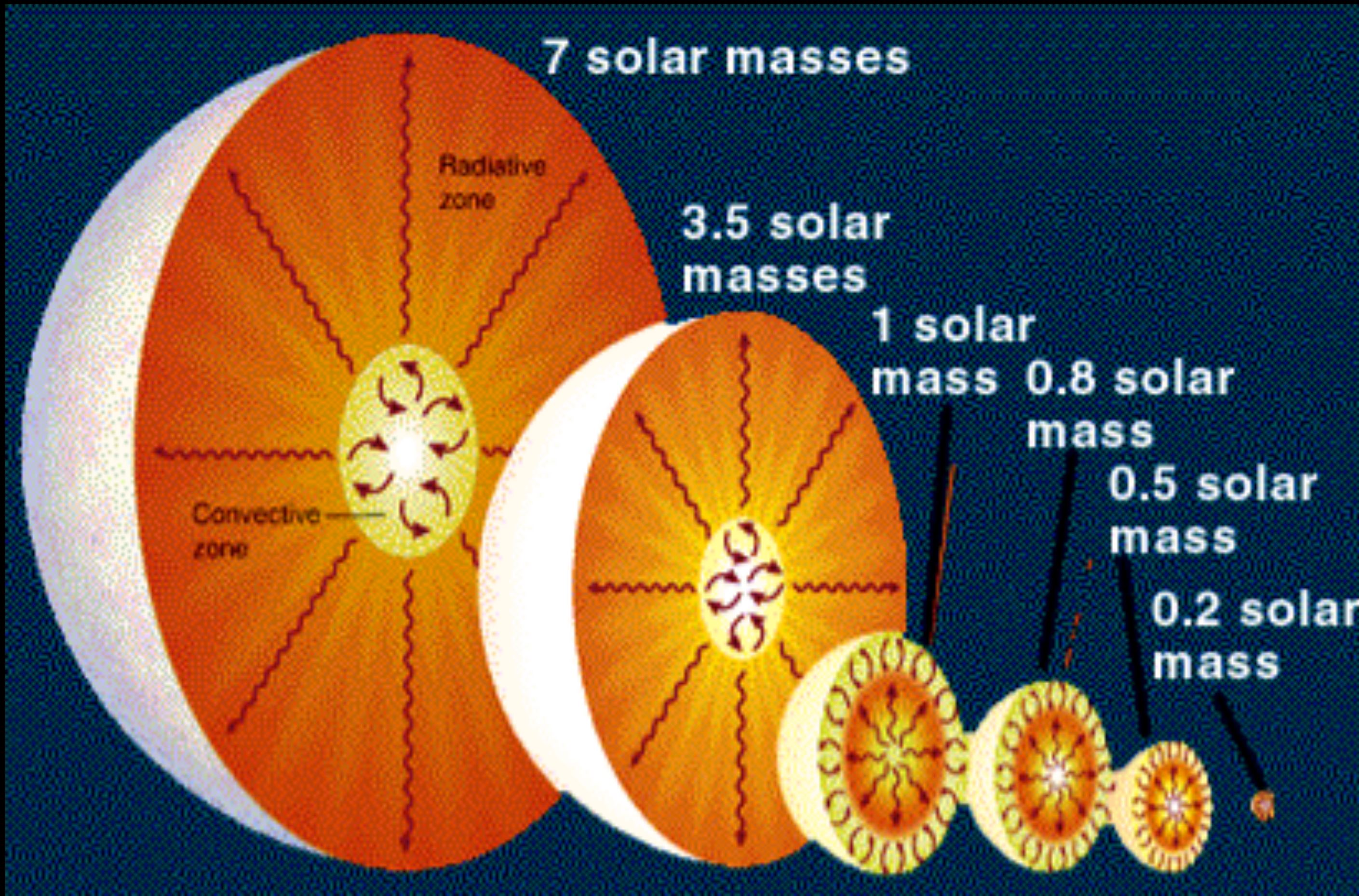
Energy Transport in the Sun



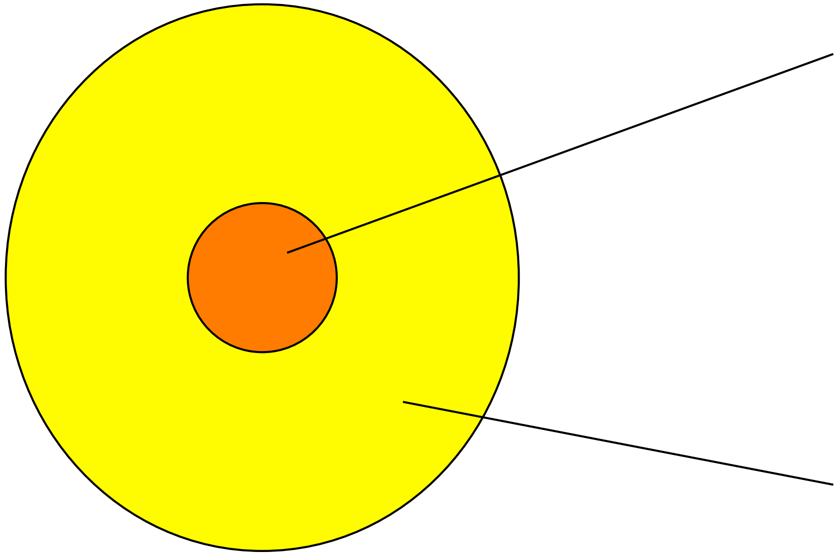
In the sun, energy is transported via radiation in the central regions, but by convection in the outer regions.

Energy Transport inside Stars



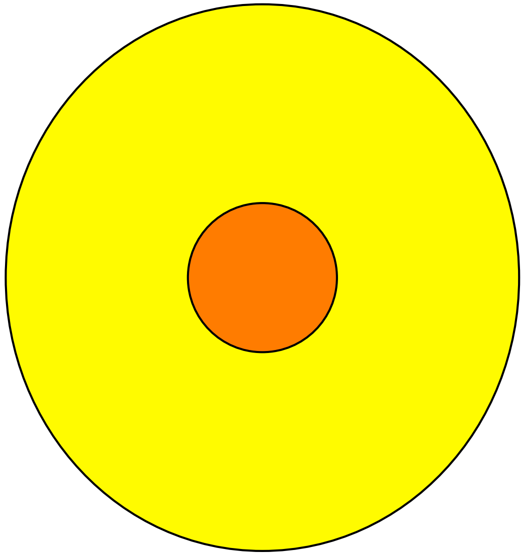
The structure and evolution of stars is accurately modeled with only a few well understood laws of physics ⇒ stellar models.

Sun’s Structure

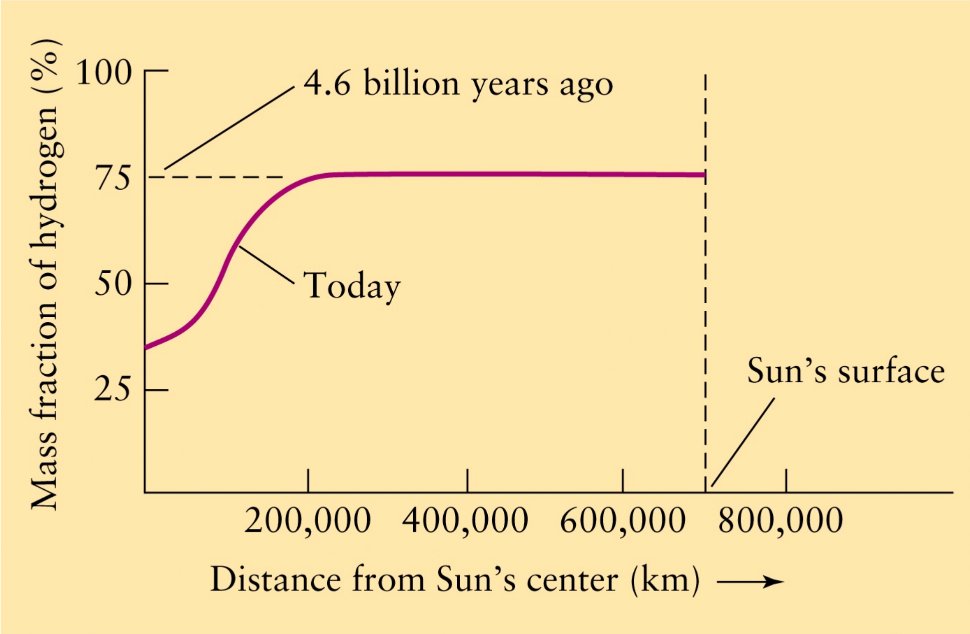


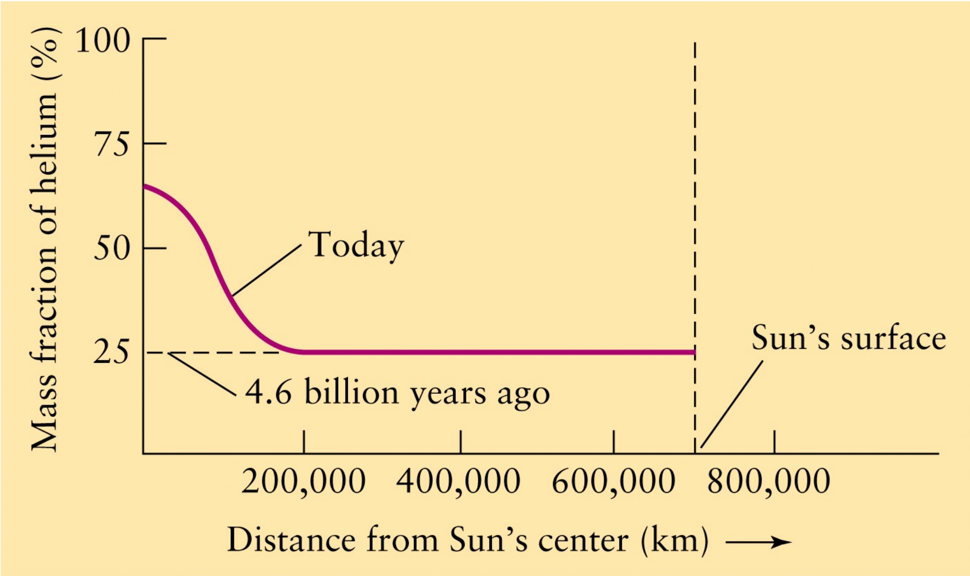
- Core
  - Where nuclear fusion occurs
- Envelope
  - Supplies gravity to keep core hot and dense

Main Sequence Evolution



- Core starts with same fraction of hydrogen as whole star
- Fusion changes H $\rightarrow$ He
- Core gradually shrinks and Sun gets hotter and more luminous

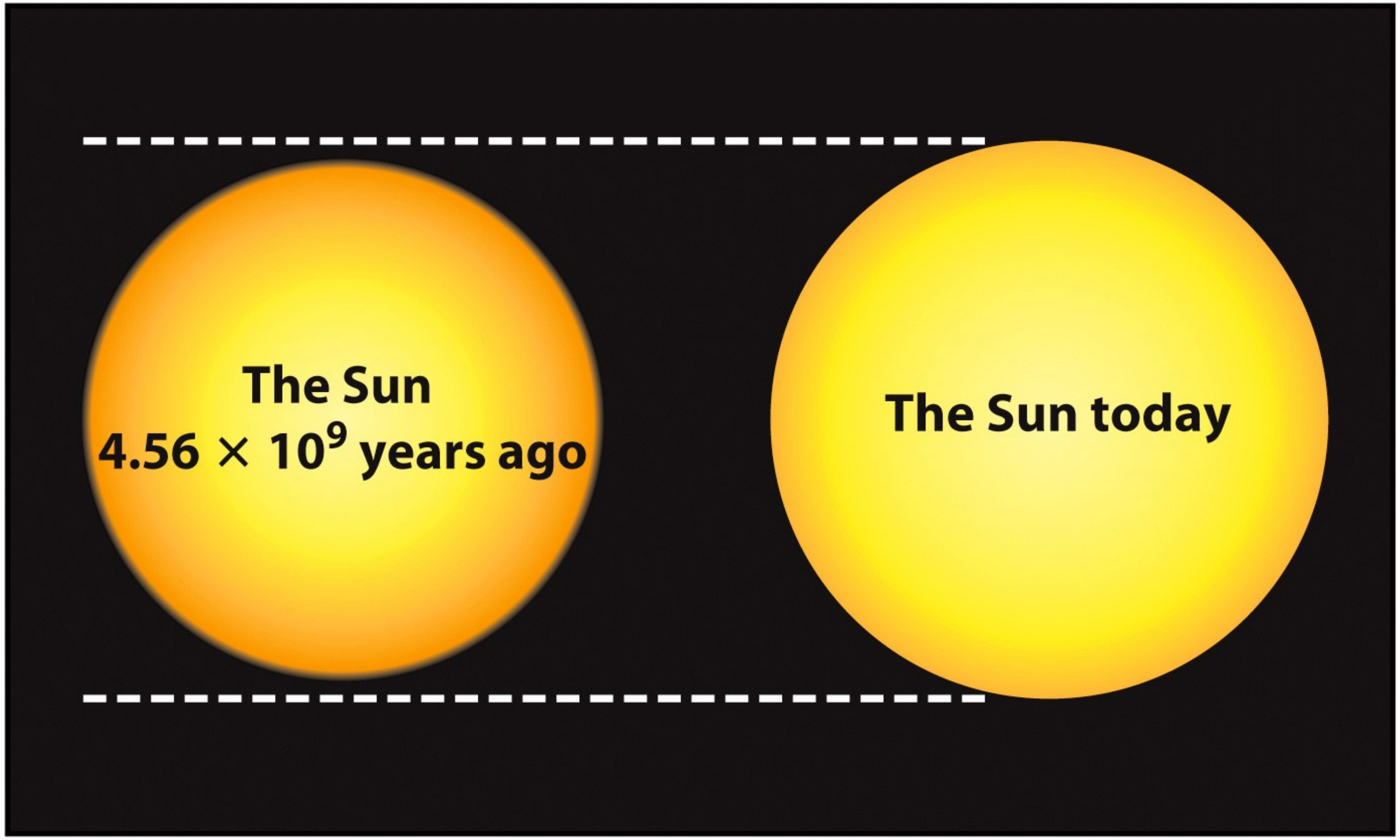




Since reaching the Main Sequence, H has been depleted in the core, while He has been built up there

We do not see this on the surface!

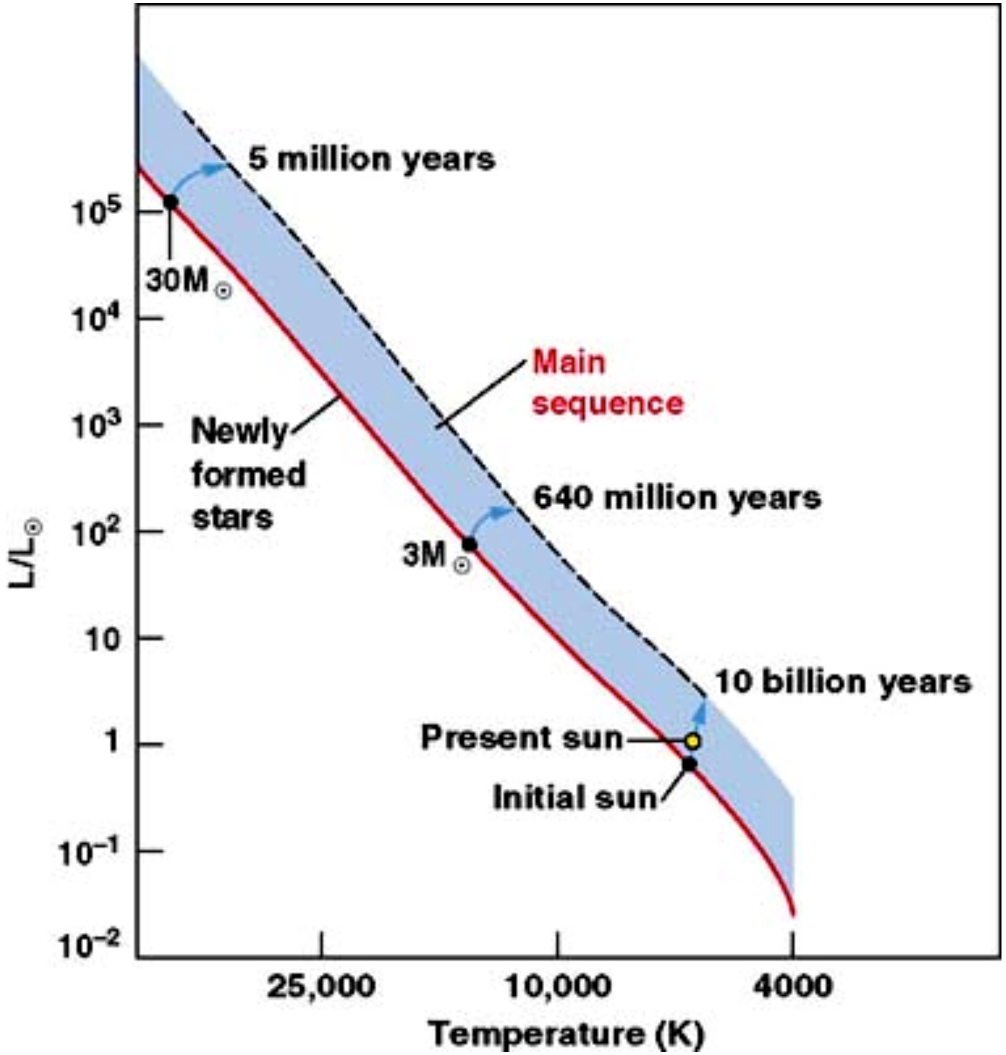
Gradual change in size of Sun



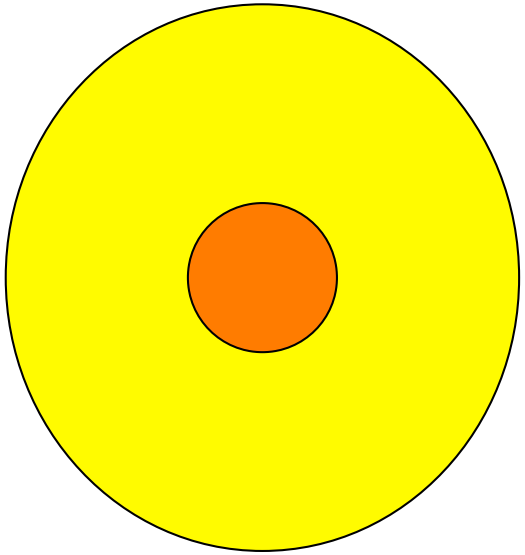
Now 6% larger, 5% hotter ⇒ 40% brighter

Main Sequence Evolution

- When stars initiate H burning in their cores, they are located on the ***zero-age main sequence*** (ZAMS).
- As they age, they evolve slowly away from the ZAMS.
- Most stars, regardless of their mass, spend roughly 90% of their total lifetimes as main sequence stars.

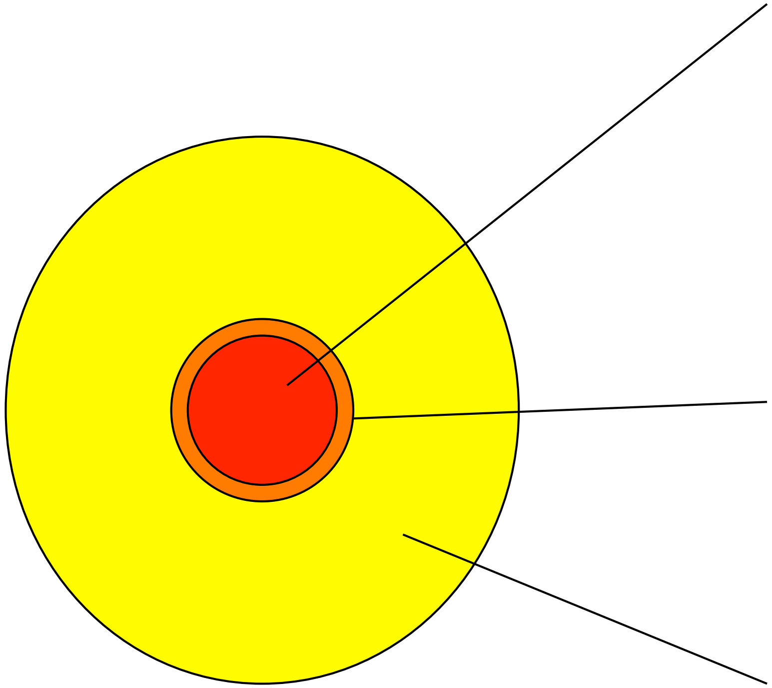


Main Sequence Evolution



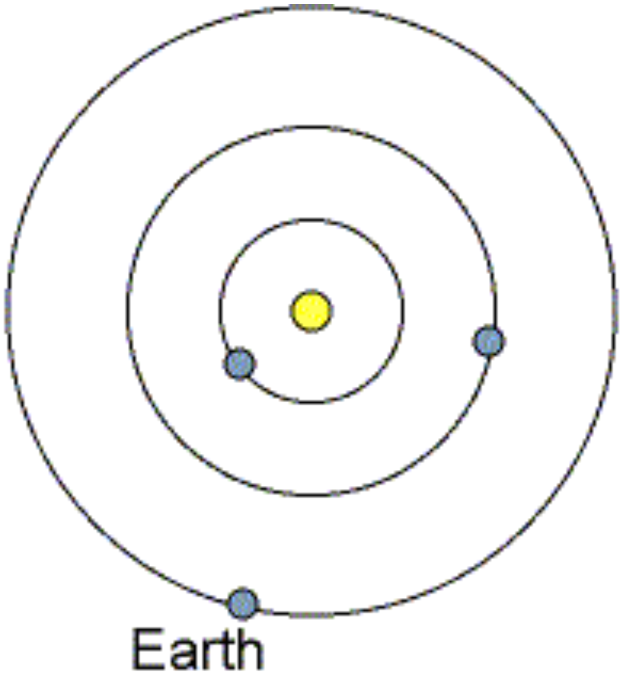
- Fusion changes H → He
- Core depletes of H
- Eventually there is not enough H to maintain energy generation in the core
- Core starts to collapse

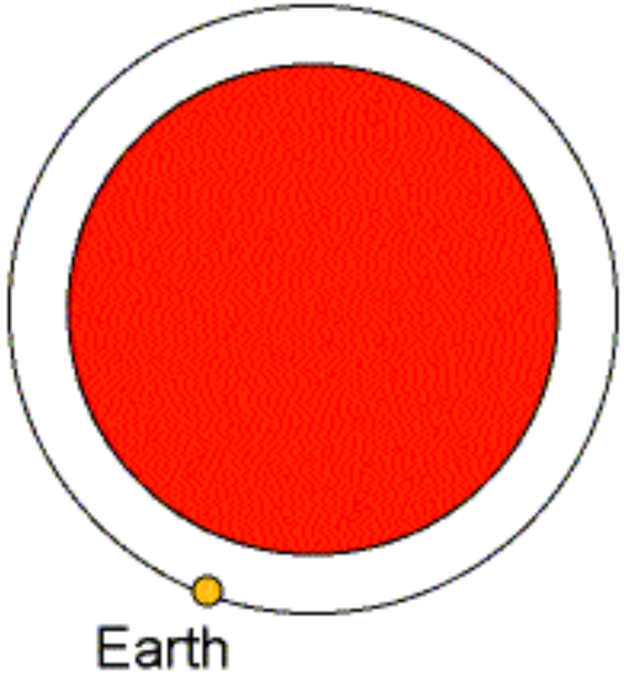
Red Giant Phase



- He core
  - No nuclear fusion
  - Gravitational contraction produces energy
- H layer
  - Nuclear fusion
- Envelope
  - Expands because of increased energy production
  - Cools because of increased surface area

Sun's Red Giant Phase

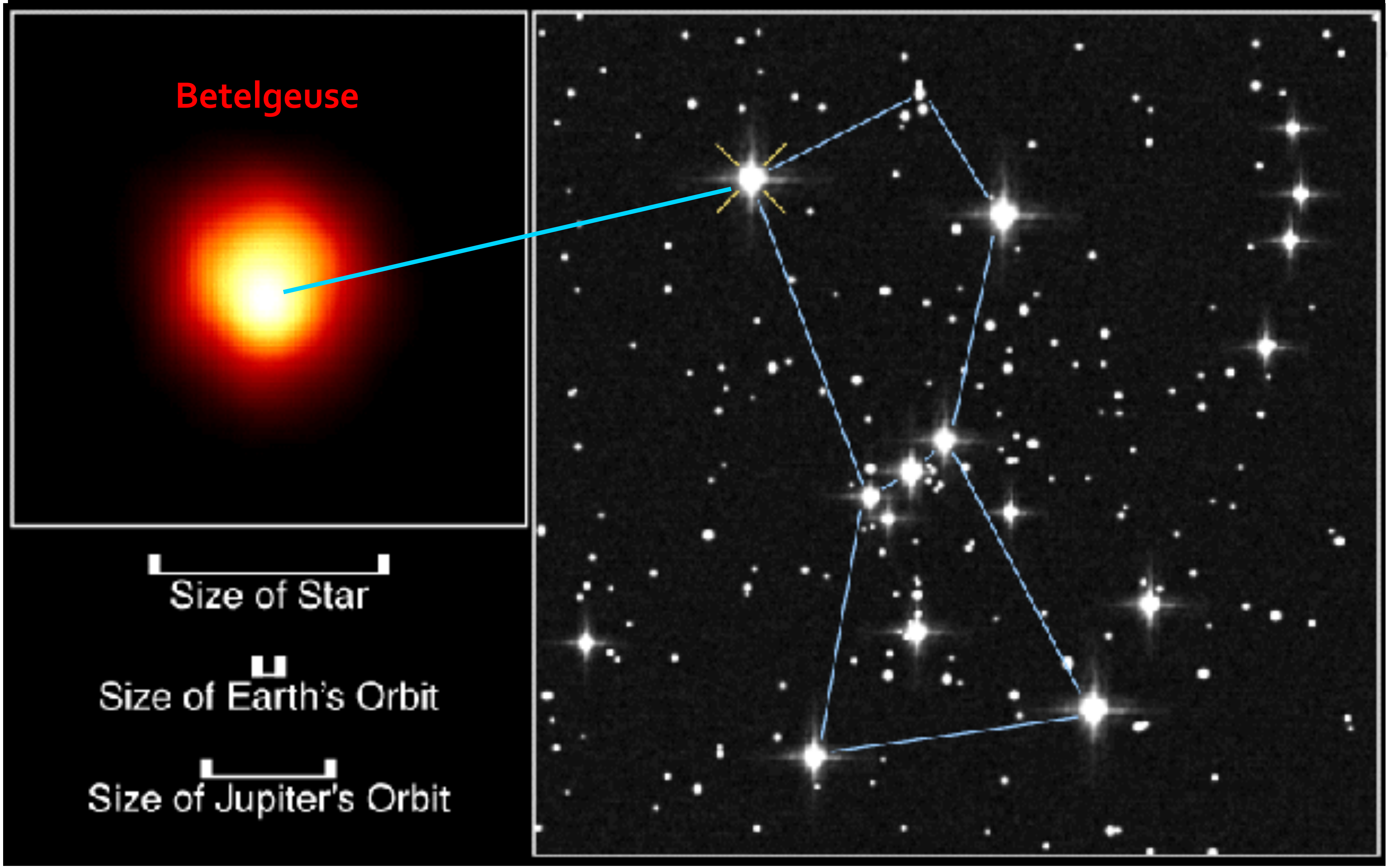


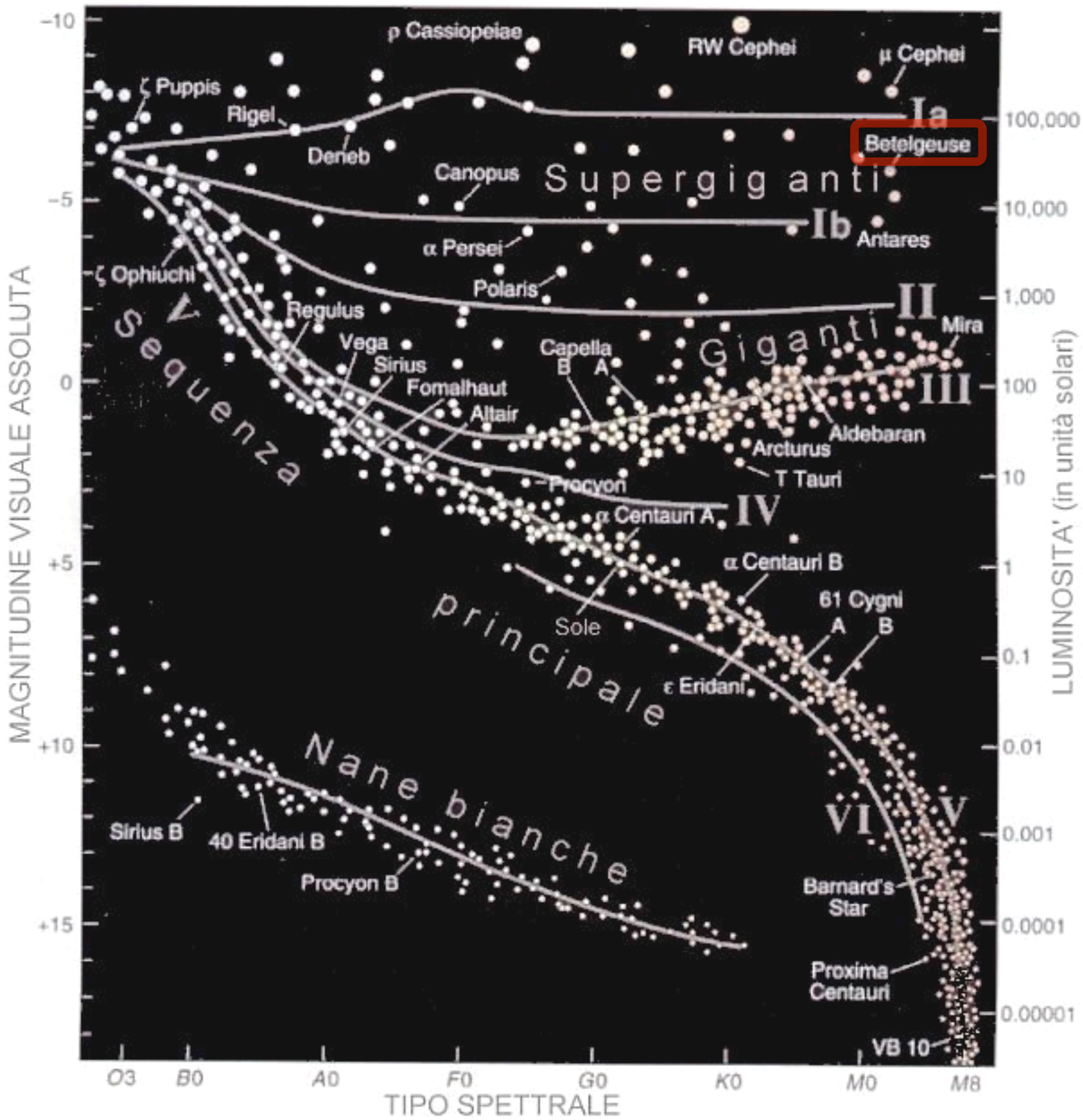


Now: hot core + warm surface; small size.

Future: very hot core + cool surface. Large size

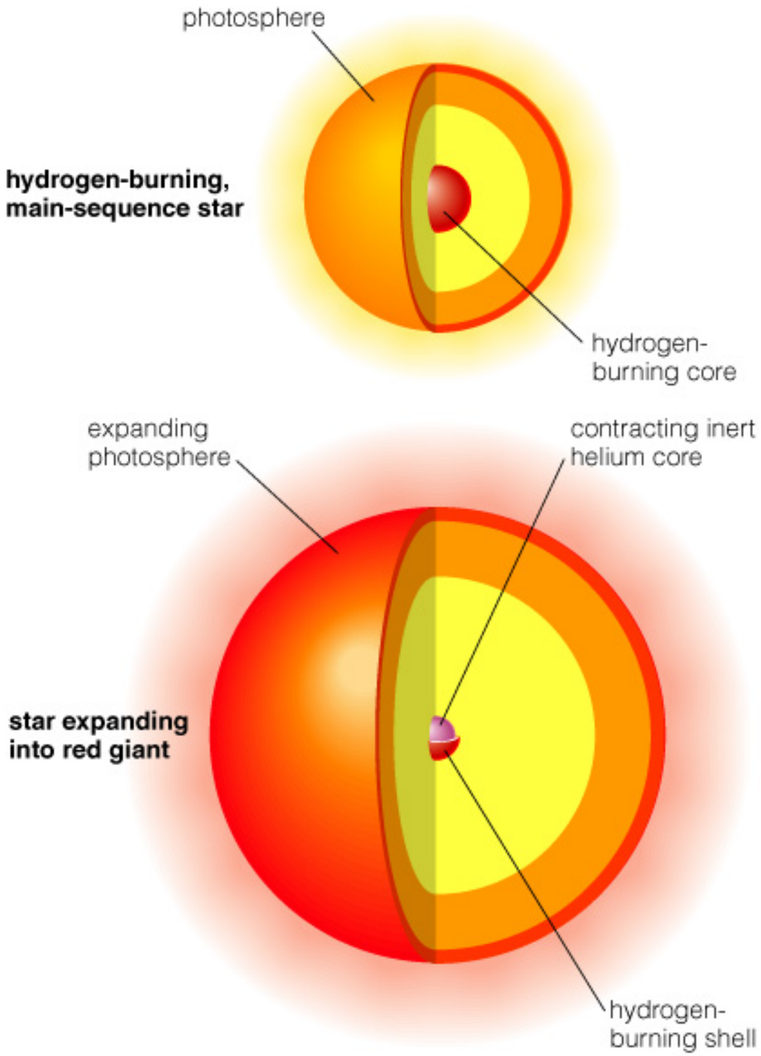
Red Giant Phase





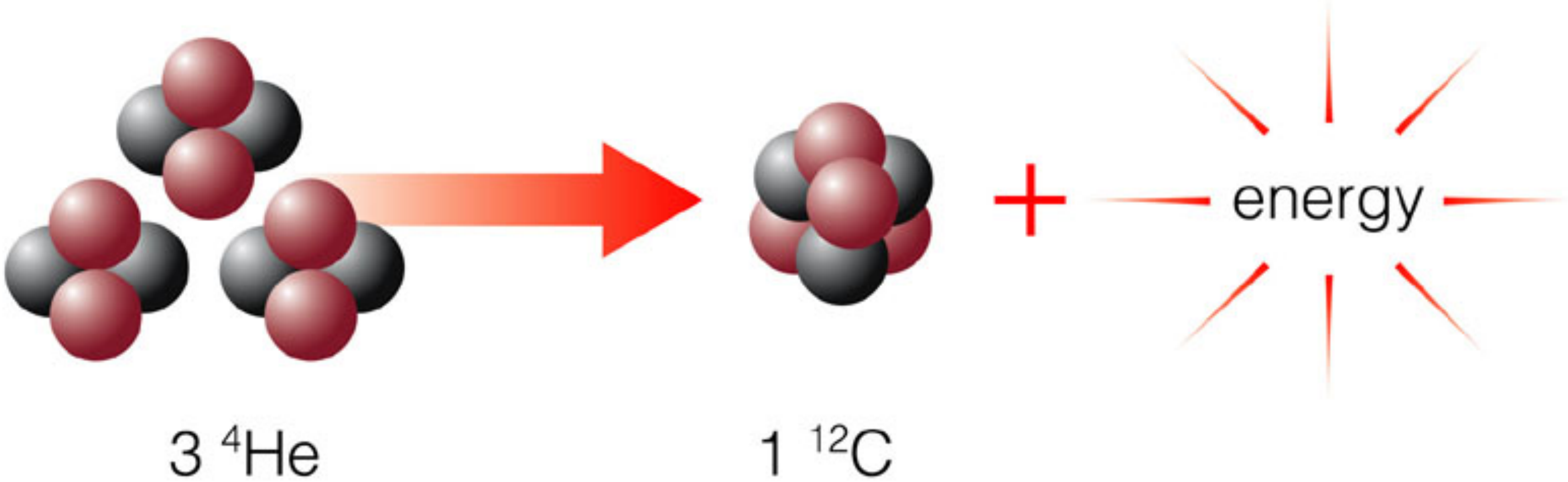
MAGNITUDINE VISUALE ASSOLUTA
-10
-5
0
+5
+10
+15
LUMINOSITA' (in unità solari)
100,000
10,000
1,000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
ρ Cassiopeiae
RW Cephei
μ Cephei
ζ Puppis
Rigel
Deneb
Canopus
Betelgeuse
Antares
Supergiganti
Ia
Ib
II
III
IV
V
VI
α Persei
Polaris
ζ Ophiuchi
Regulus
Vega
Sirius
Fomalhaut
Altair
Capella
B
A
Giganti
Mira
Aldebaran
Arcturus
T Tauri
Procyon
α Centauri A
α Centauri B
61 Cygni
Sole
ε Eridani
Sequenza
principale
Nane bianche
Sirius B
40 Eridani B
Procyon B
Barnard's Star
Proxima Centauri
VB 10
O3
B0
A0
F0
G0
K0
M0
M8
TIPO SPETTRALE

Broken Thermostat



- As the core contracts, H begins fusing to He in a shell around the **degenerate** core
- Luminosity increases because the core thermostat is broken (no nuclear reactions) ⇒ the increasing fusion rate in the shell does not stop the core from contracting

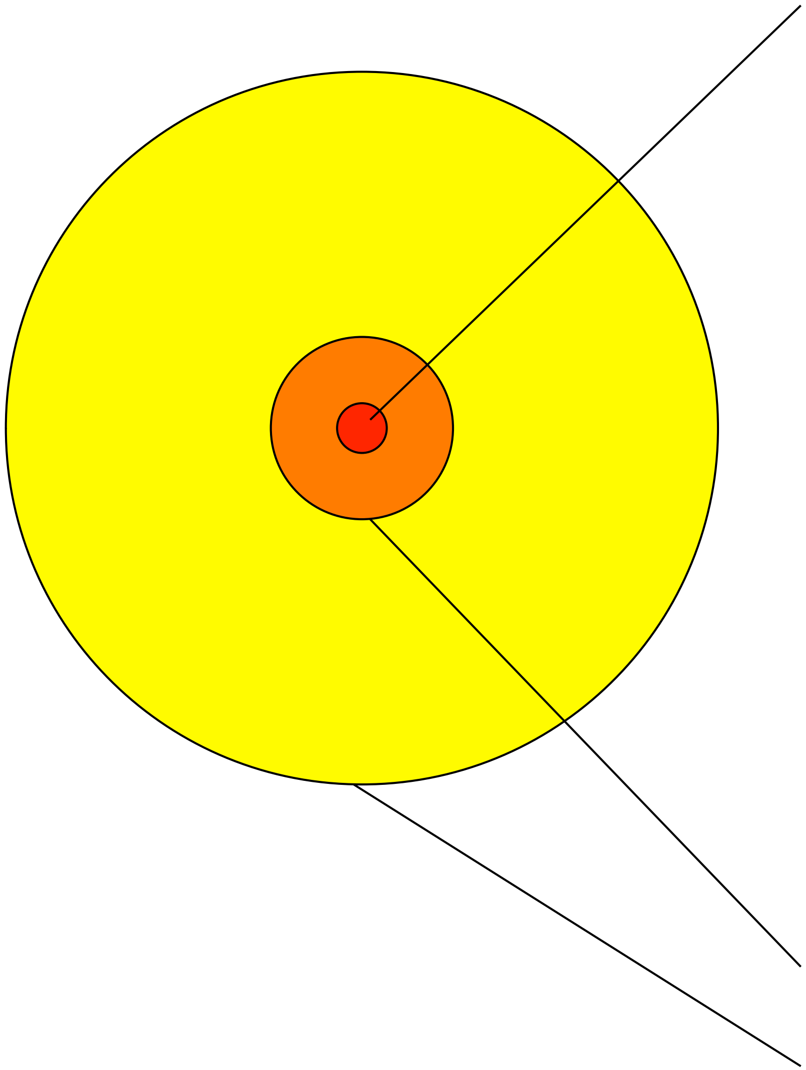
Helium fusion



Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion

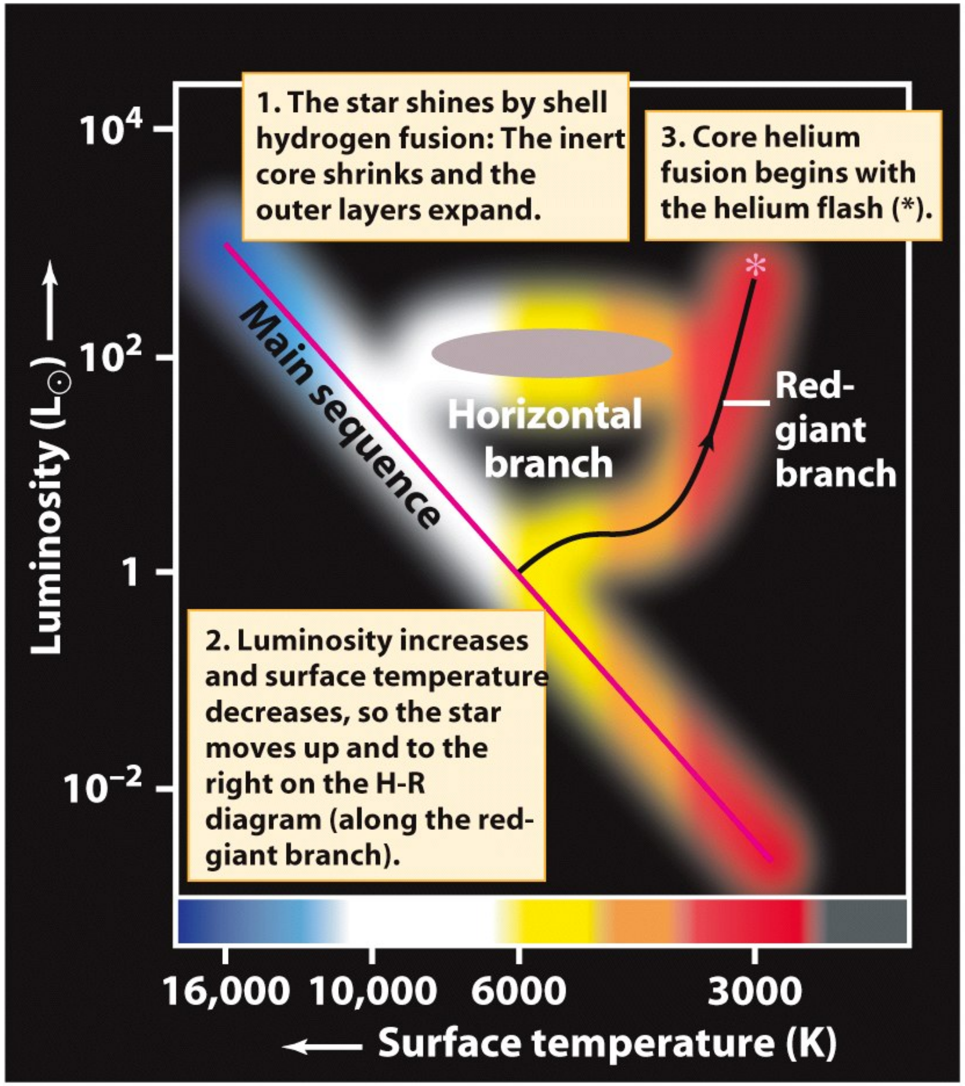
Fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon

Helium Flash



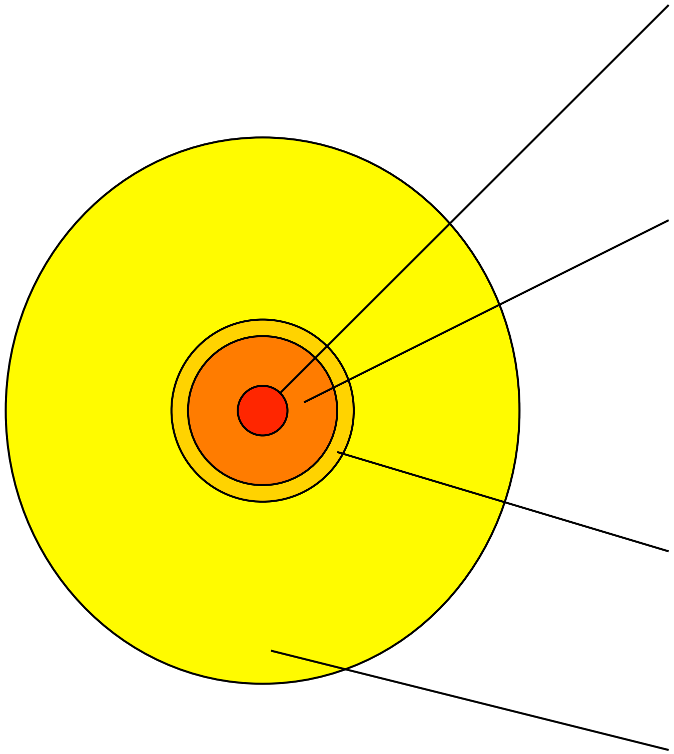
- He core
  - Eventually the core gets hot enough to fuse Helium into Carbon.
  - This causes the temperature to increase rapidly to 300 million K and there's a sudden flash when a large part of the Helium gets burned all at once.
  - We don't see this flash because it's buried inside the star.
- H layer
- Envelope

Movement on HR diagram



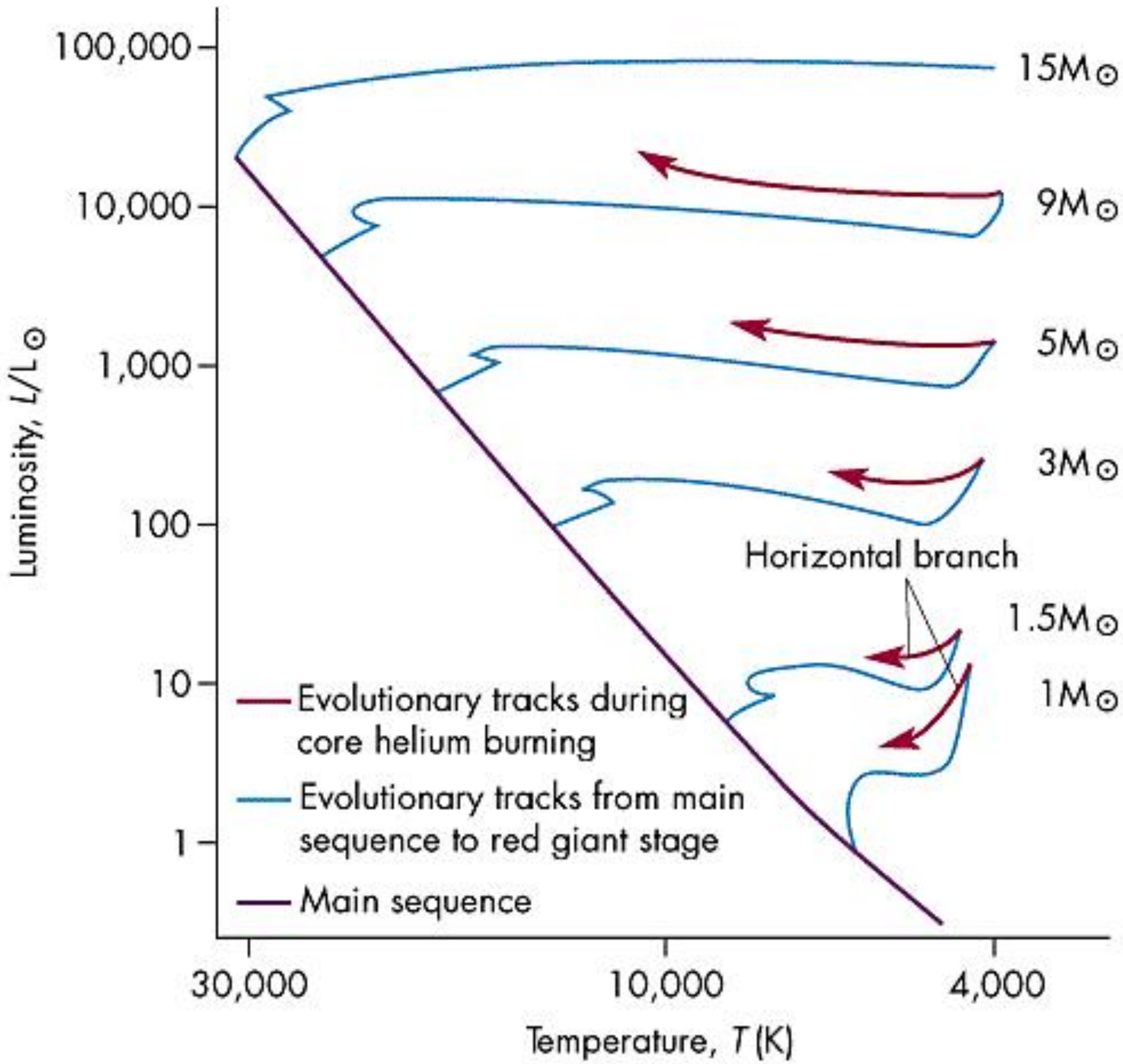
Before the helium flash: A red-giant star

Red Giant after Helium Ignition



- He burning core
  - Fusion burns He into C, O
- He rich core
  - No fusion
- H burning shell
  - Fusion burns H into He
- Envelope

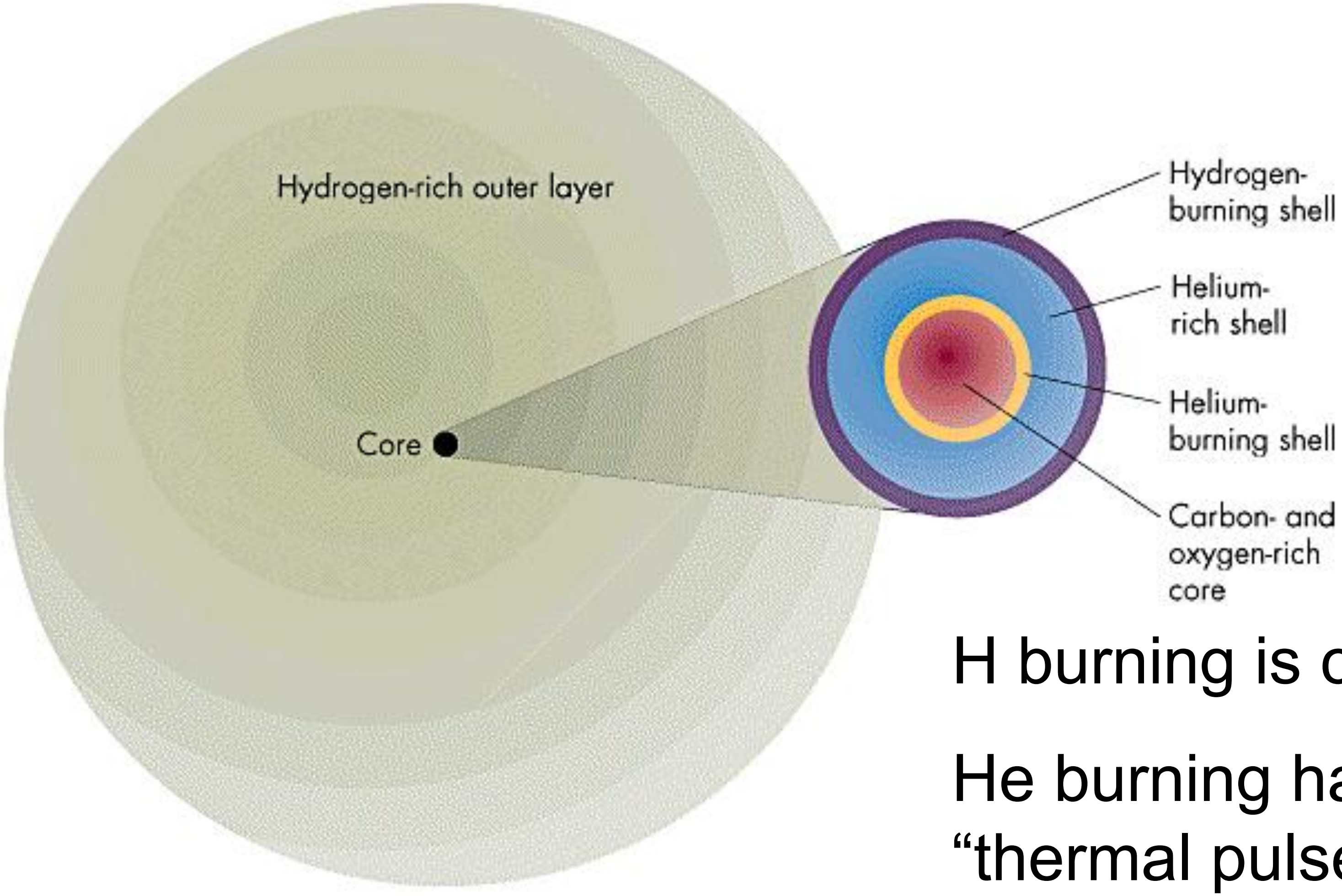
Sun moves onto Horizontal Branch



Sun burns He into Carbon and Oxygen in the core

Sun becomes hotter and smaller (L~constant): **Horizontal Branch**

Helium burning in the core stops

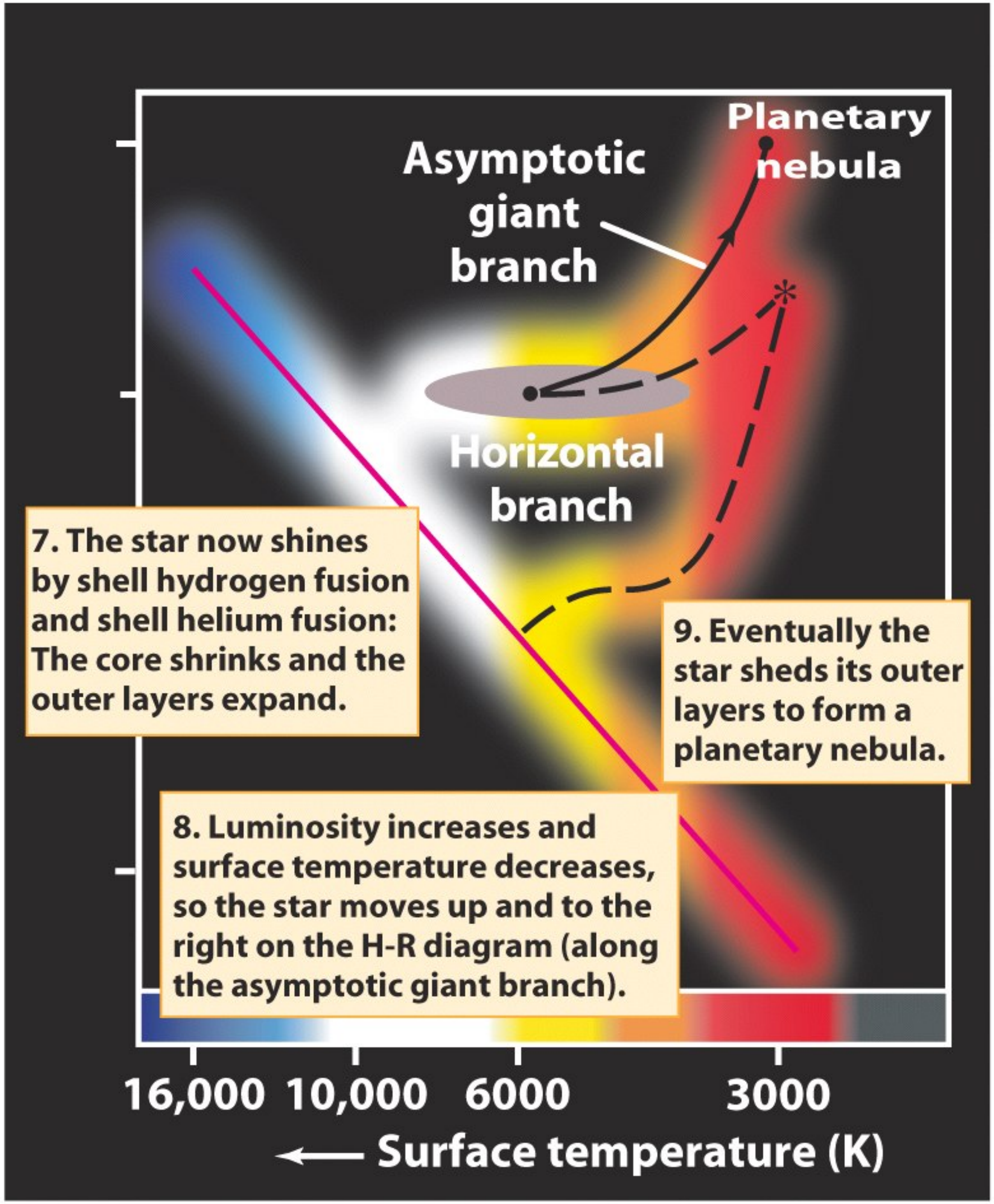


H burning is continuous

He burning happens in "thermal pulses"

Core is degenerate

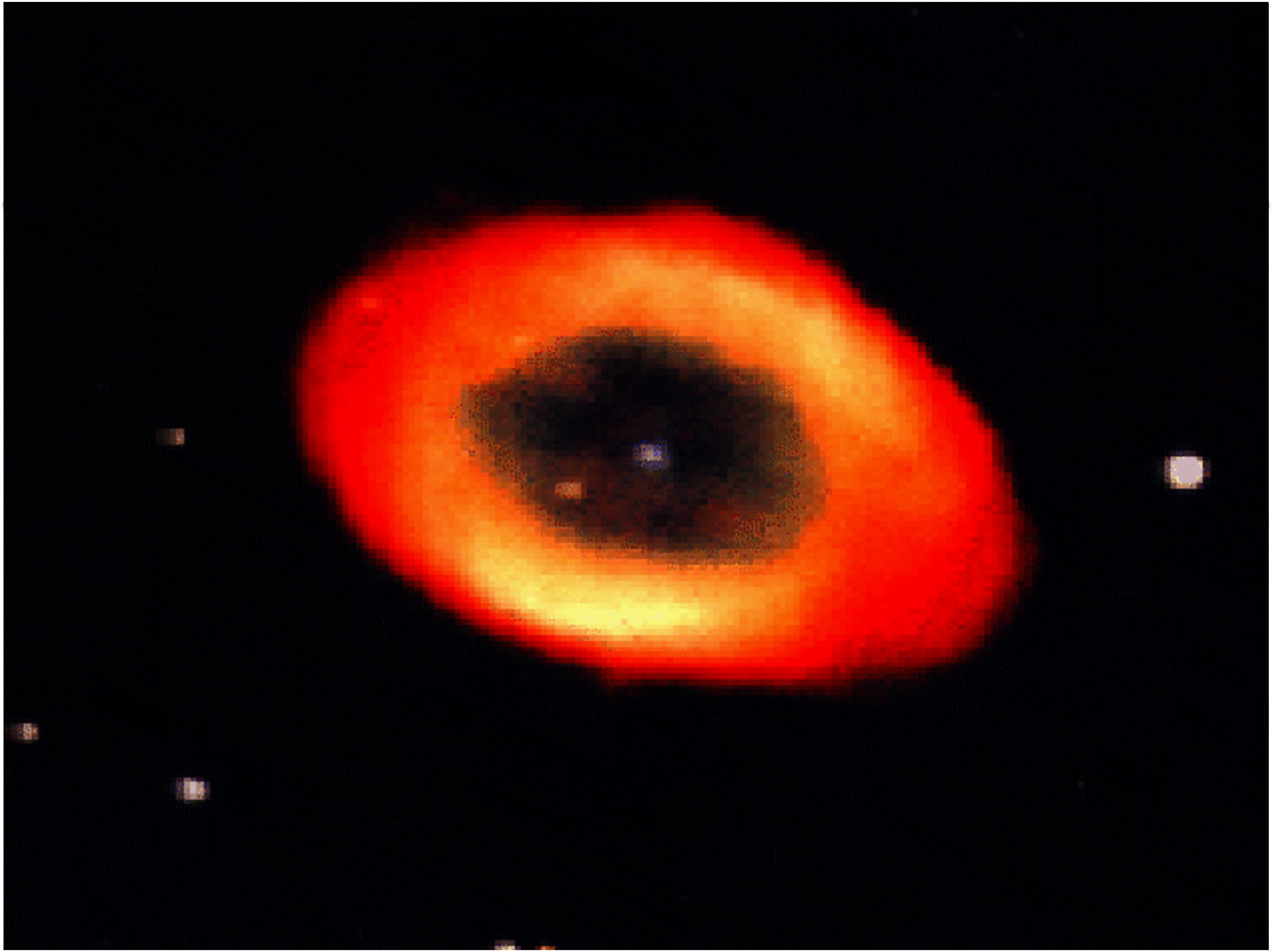
Sun moves onto Asymptotic Giant Branch (AGB)



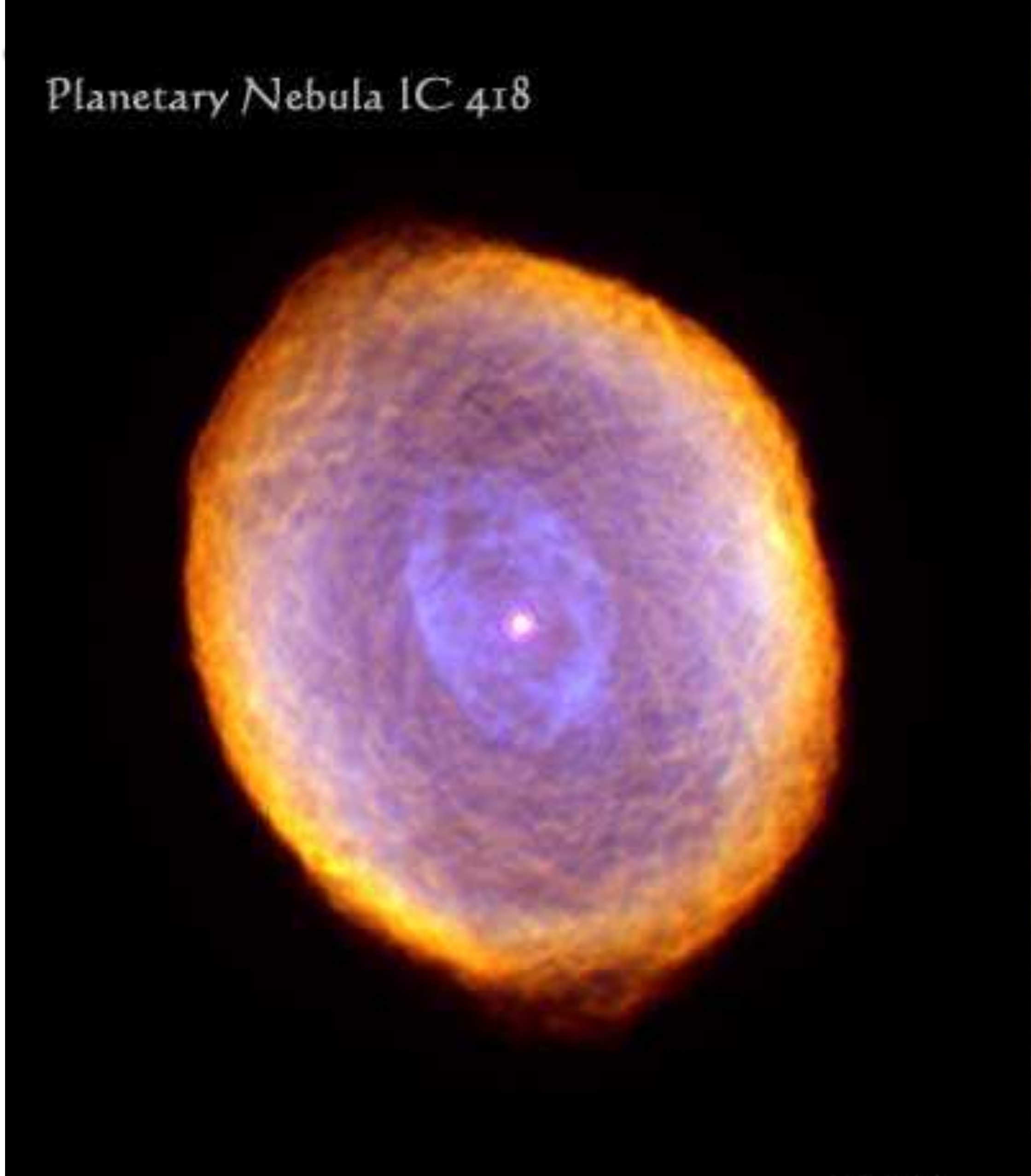
After core helium fusion ends: An AGB star

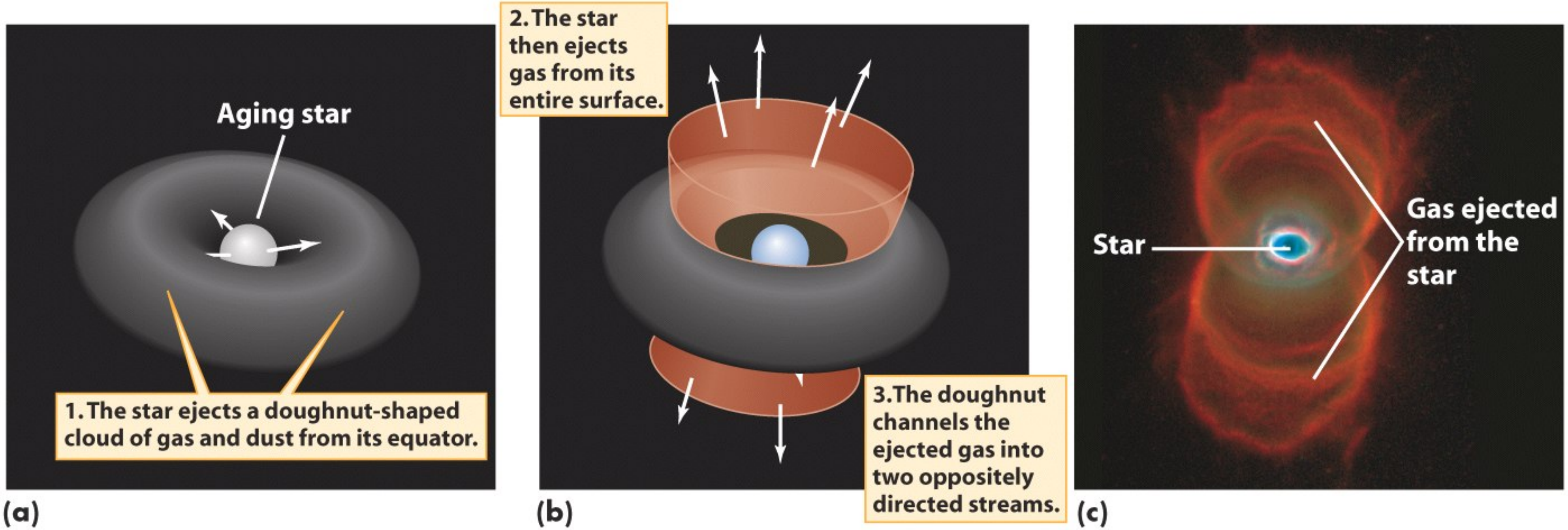
Sun loses mass via winds

- Creates a “planetary nebula”
- Leaves behind core of carbon and oxygen surrounded by thin shell of hydrogen
- Hydrogen continues to burn



Planetary nebula



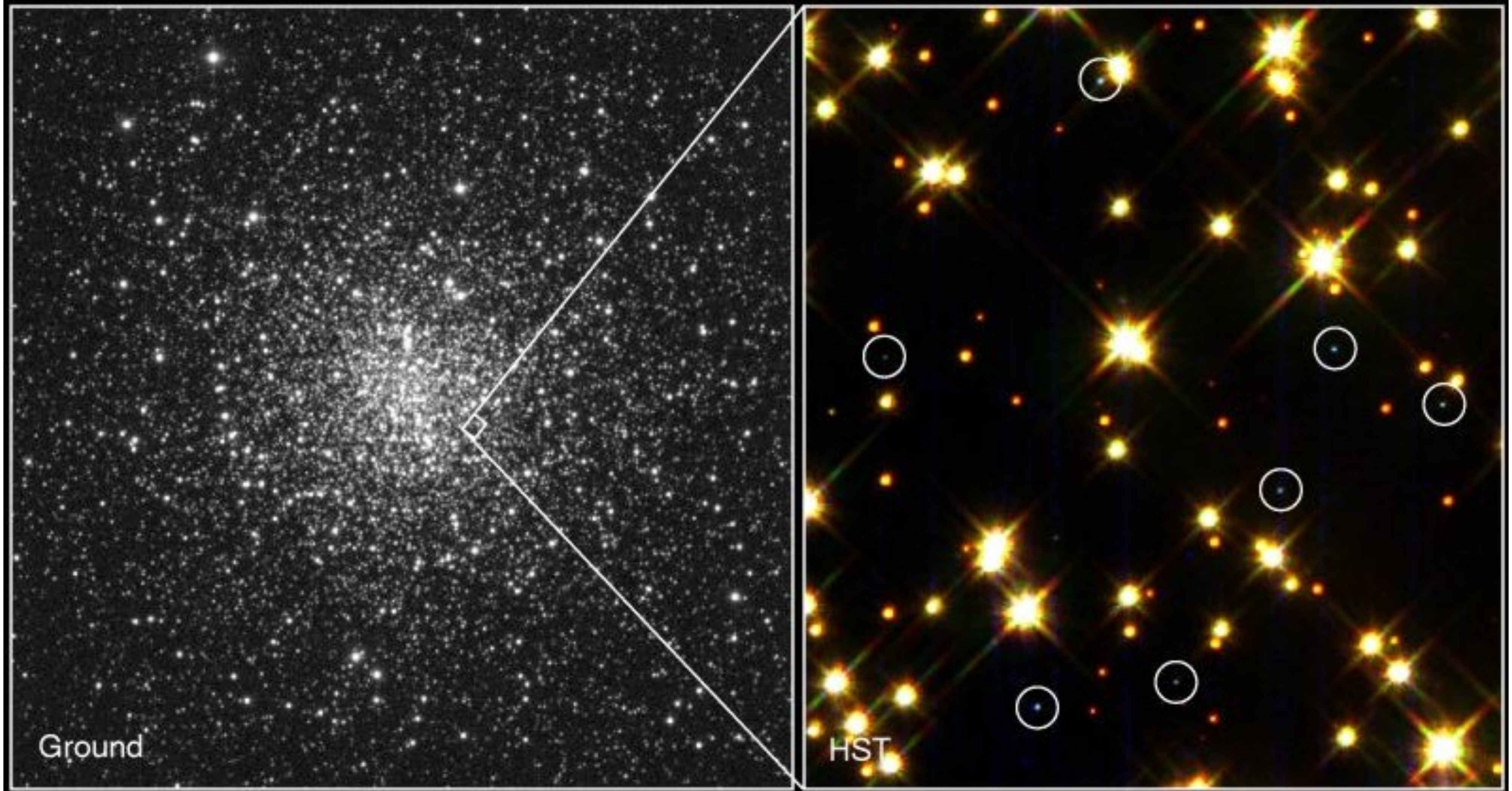


Aging star
1. The star ejects a doughnut-shaped cloud of gas and dust from its equator.
(a)
2. The star then ejects gas from its entire surface.
3. The doughnut channels the ejected gas into two oppositely directed streams.
(b)
Star
Gas ejected from the star
(c)

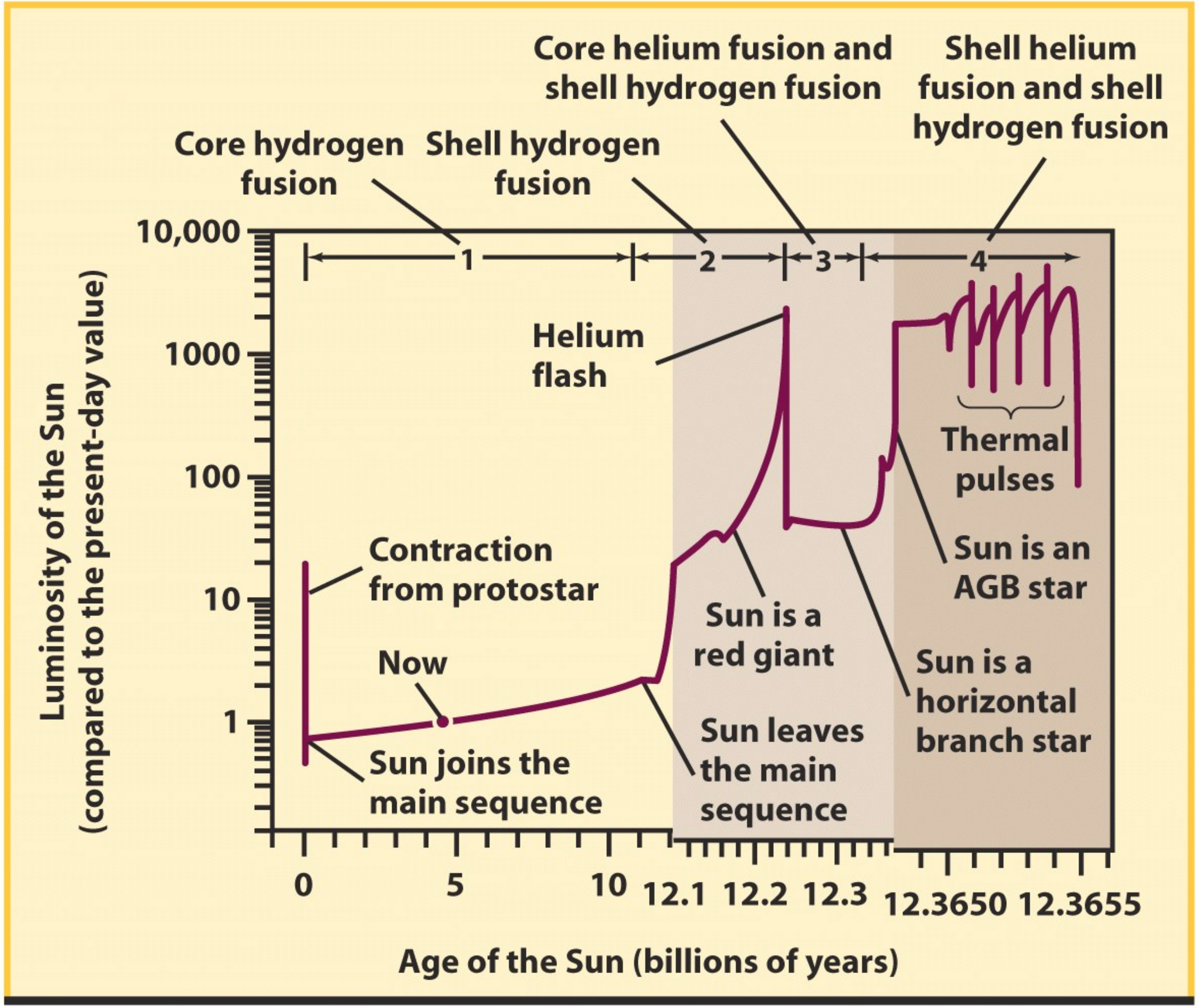
White dwarf

- Star burns up rest of hydrogen
- Nothing remains but degenerate core of Oxygen and Carbon
- "White dwarf" cools but does not contract because core is degenerate
- No energy from fusion, no energy from gravitational contraction
- White dwarf slowly fades away…

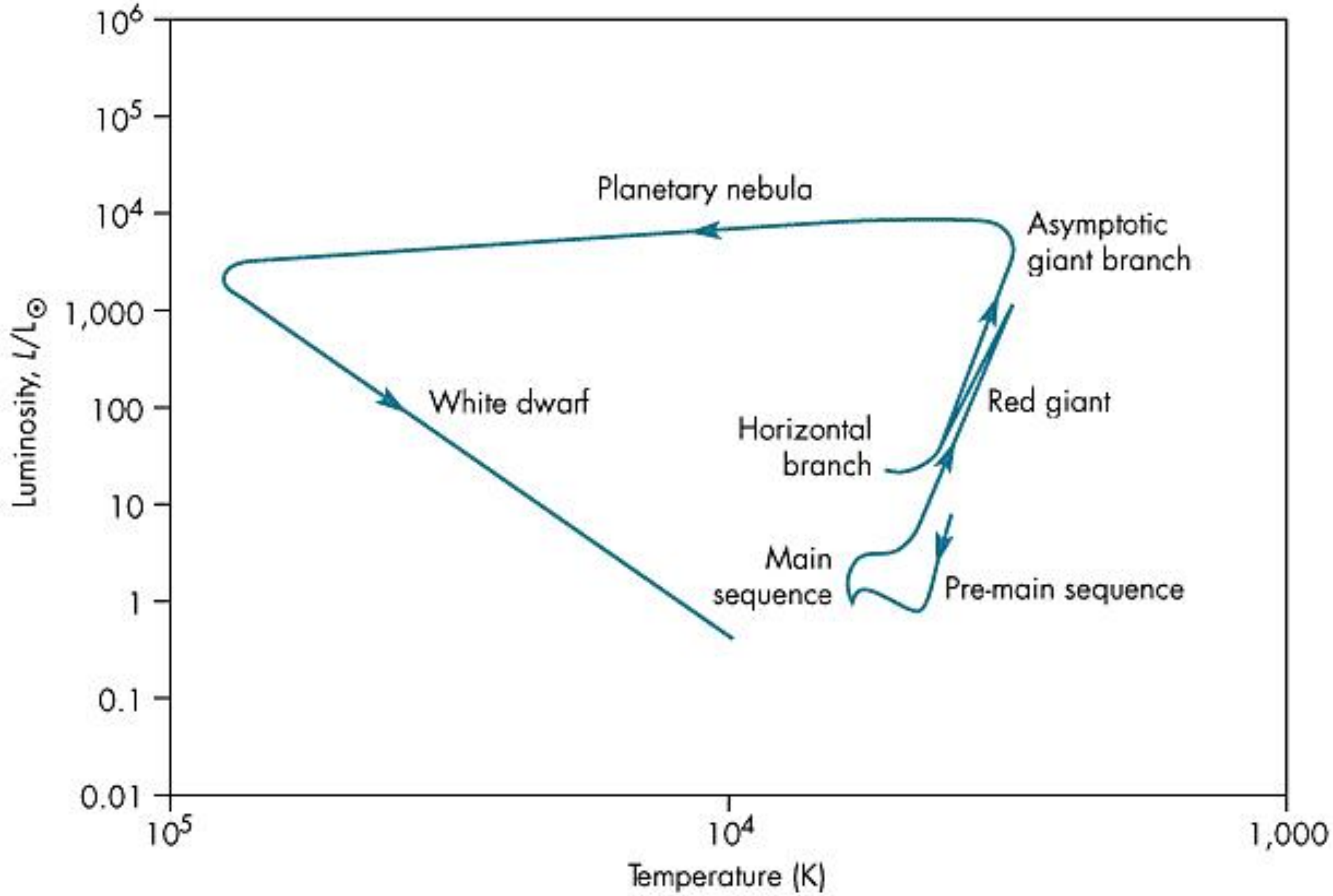
White dwarf



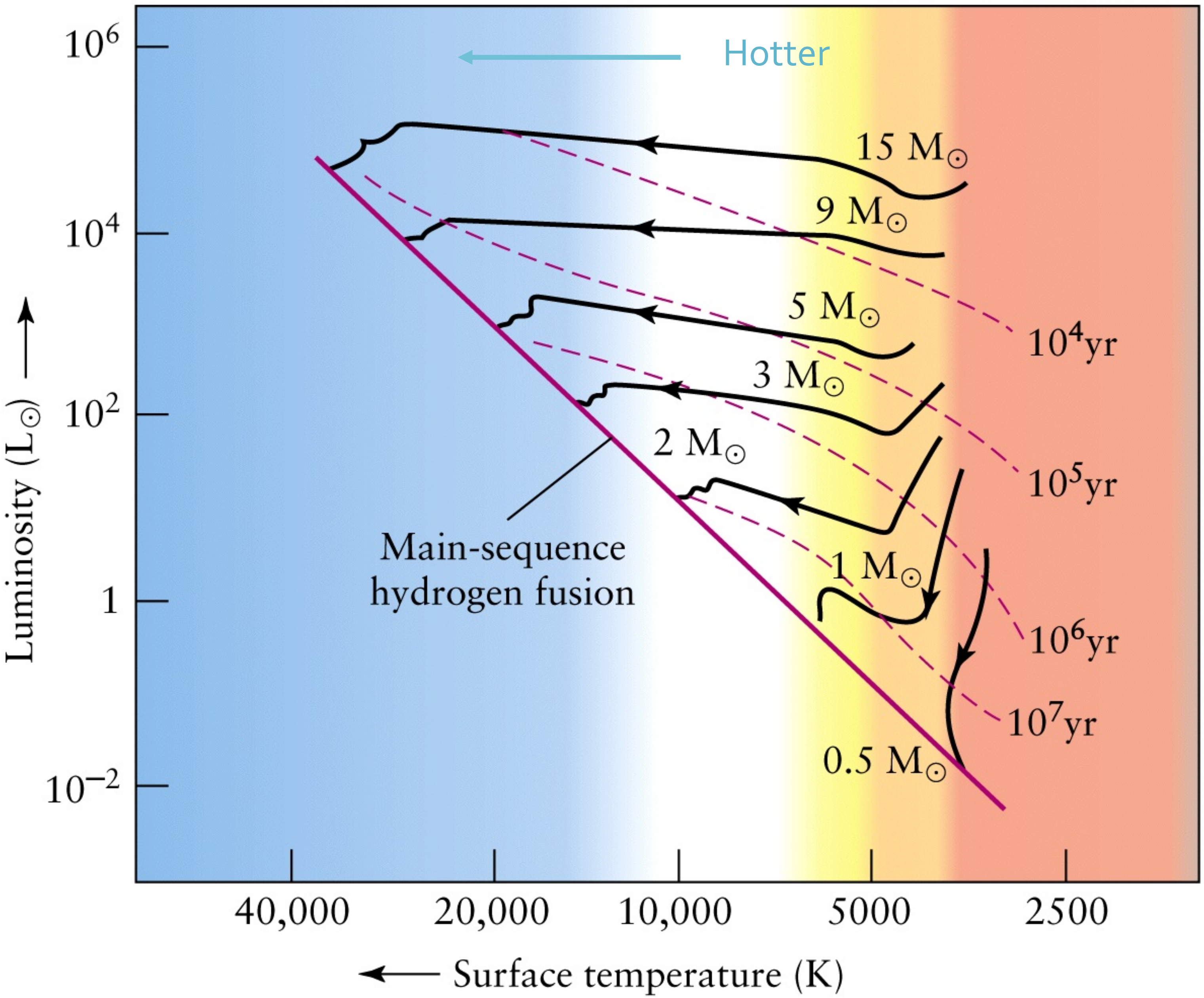
Time line for Sun's evolution



Evolution on HR diagram



Higher mass protostars contract faster



Higher mass stars spend less time on the main sequence

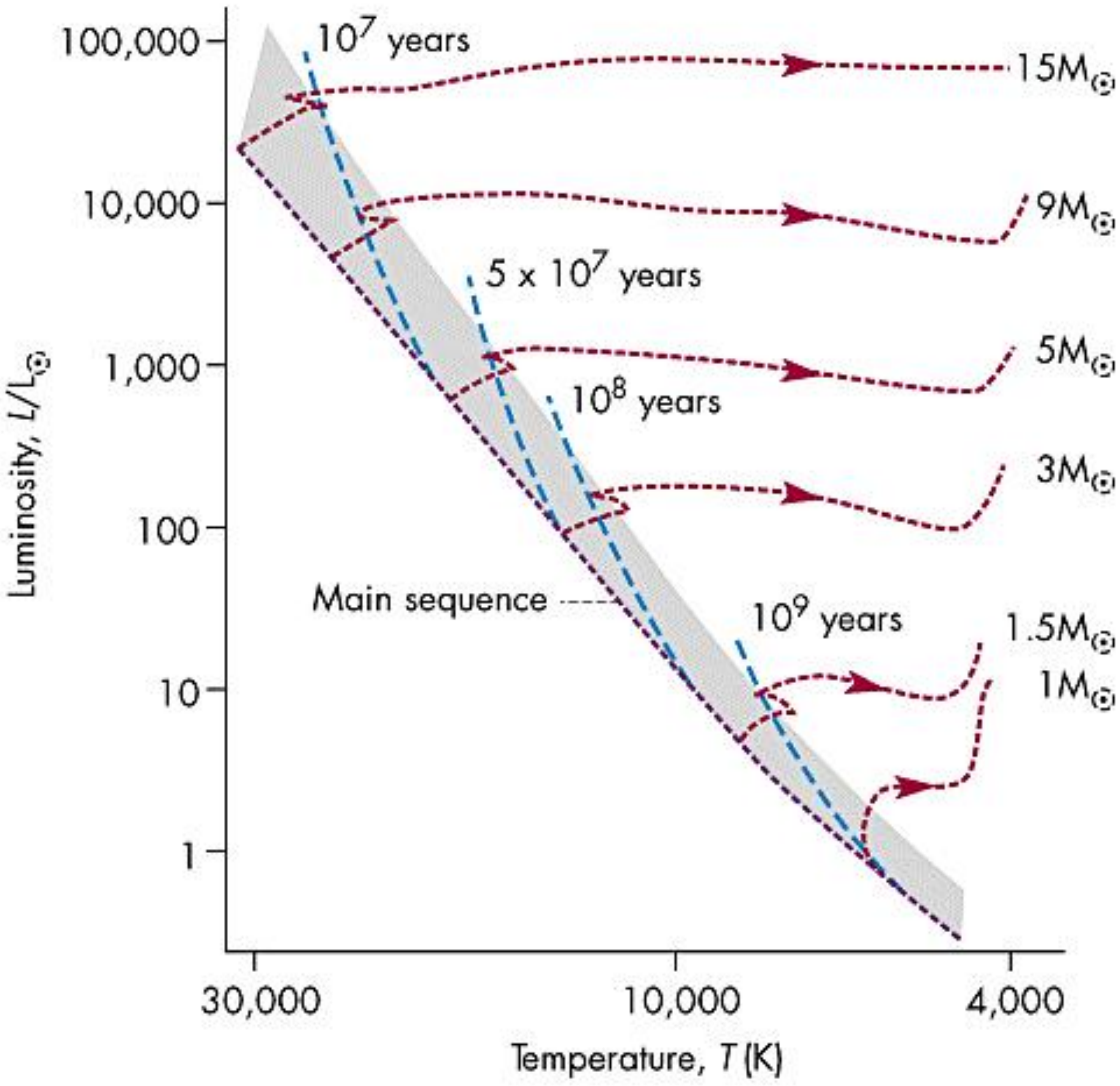


Table 21-1 Main-Sequence Lifetimes

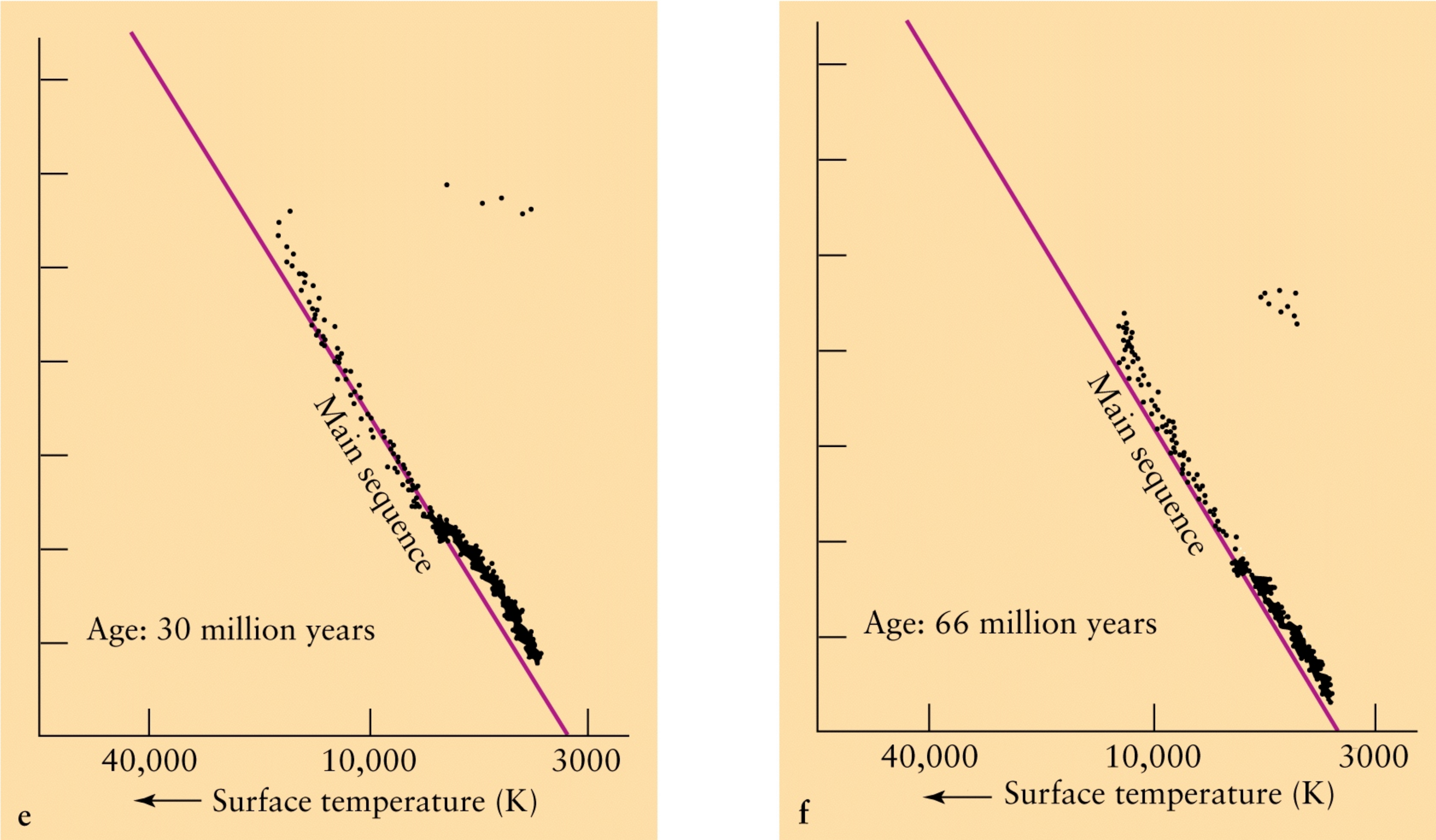
Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	3
15	30,000	B	10,000	15
3	11,000	A	60	500
1.5	7000	F	5	3000
1.0	6000	G	1	10,000
0.75	5000	K	0.5	15,000
0.50	4000	M	0.03	200,000

Determining the age of a star cluster

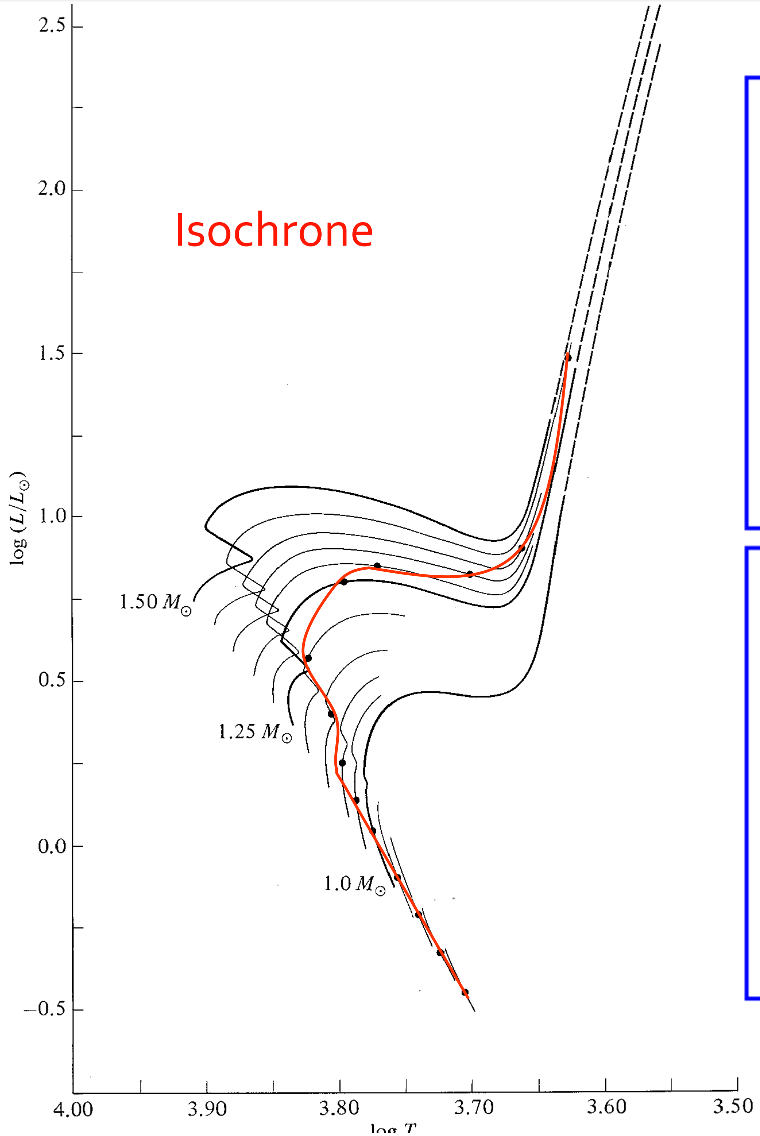
- Imagine we have a cluster of stars that were all formed at the same time, but have a variety of different masses

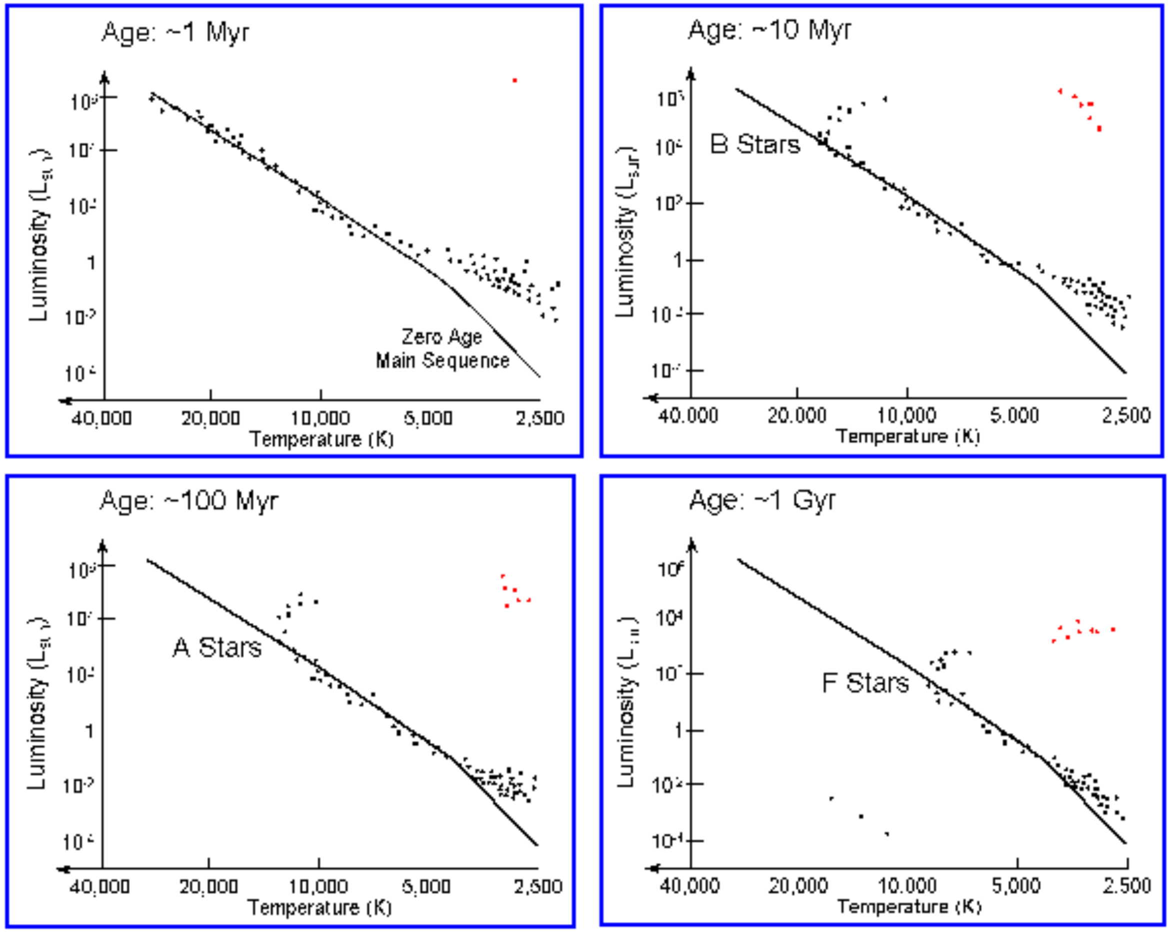
- Using what we know about stellar evolution is there a way to determine the age of the star cluster?

For a group of stars formed at the same approximate time, the more luminous ones evolve faster.

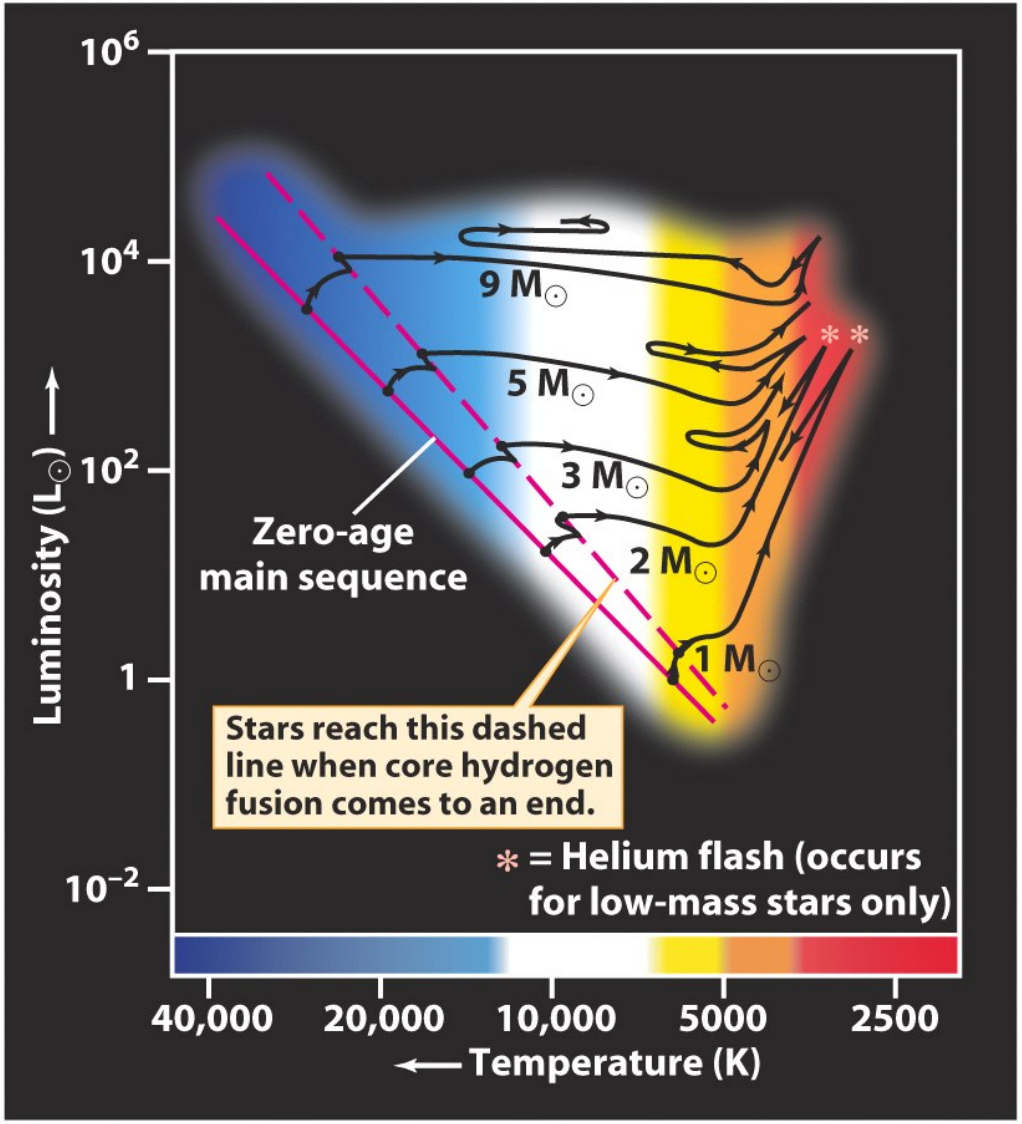


Cluster age and turn-off point

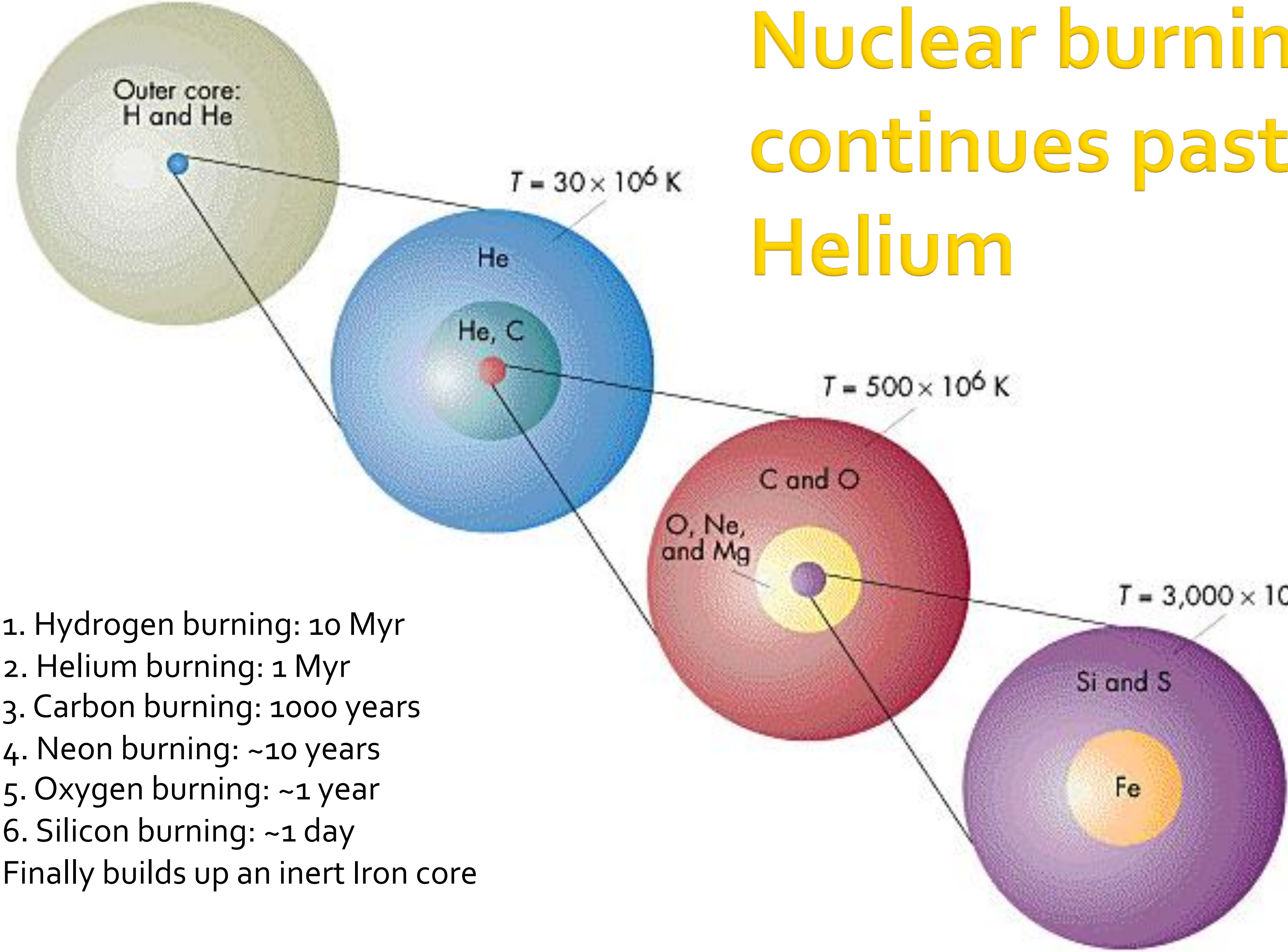




Higher mass stars do not have helium flash



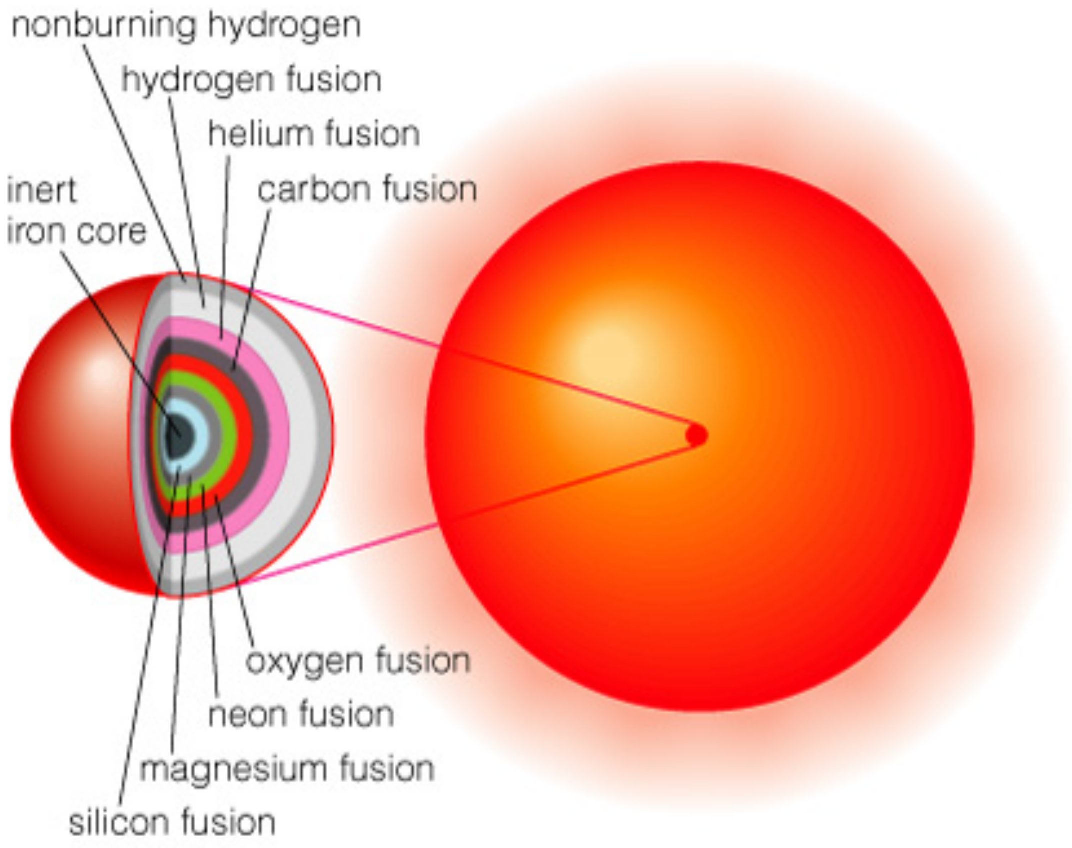
Nuclear burning continues past Helium



1. Hydrogen burning: 10 Myr
2. Helium burning: 1 Myr
3. Carbon burning: 1000 years
4. Neon burning: ~10 years
5. Oxygen burning: ~1 year
6. Silicon burning: ~1 day

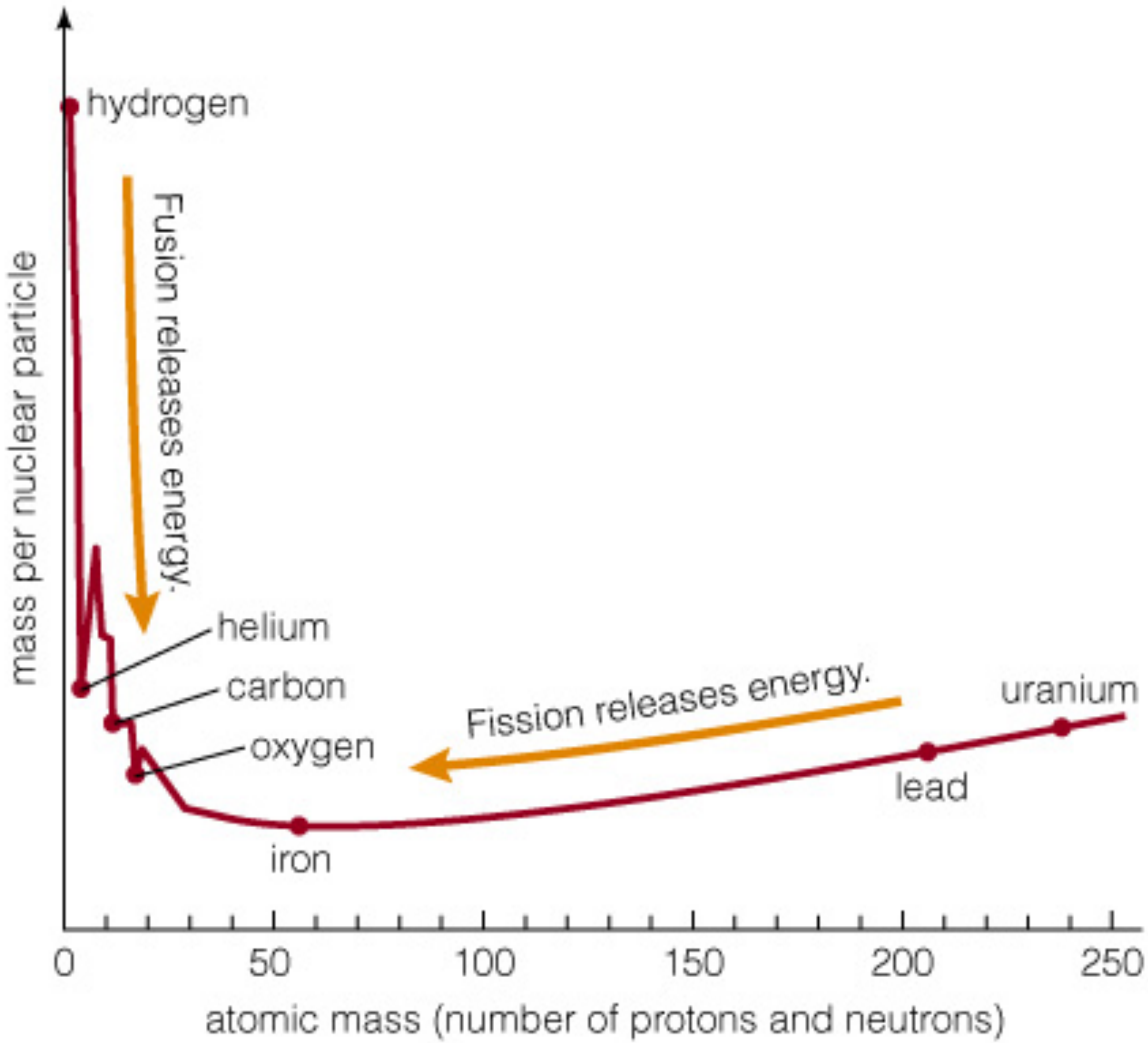
Finally builds up an inert Iron core

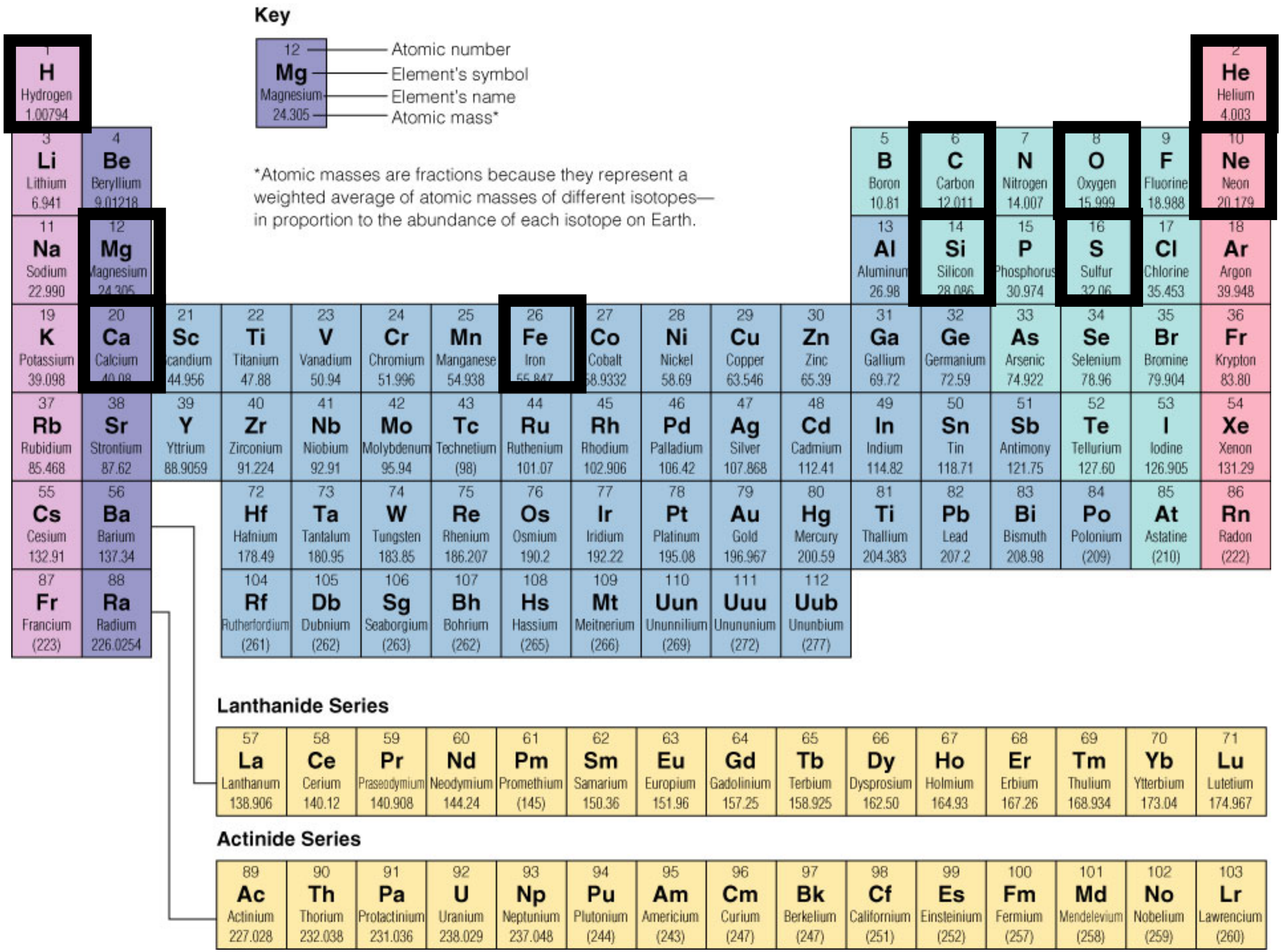
Multiple Shell Burning



- Advanced nuclear burning proceeds in a series of nested shells

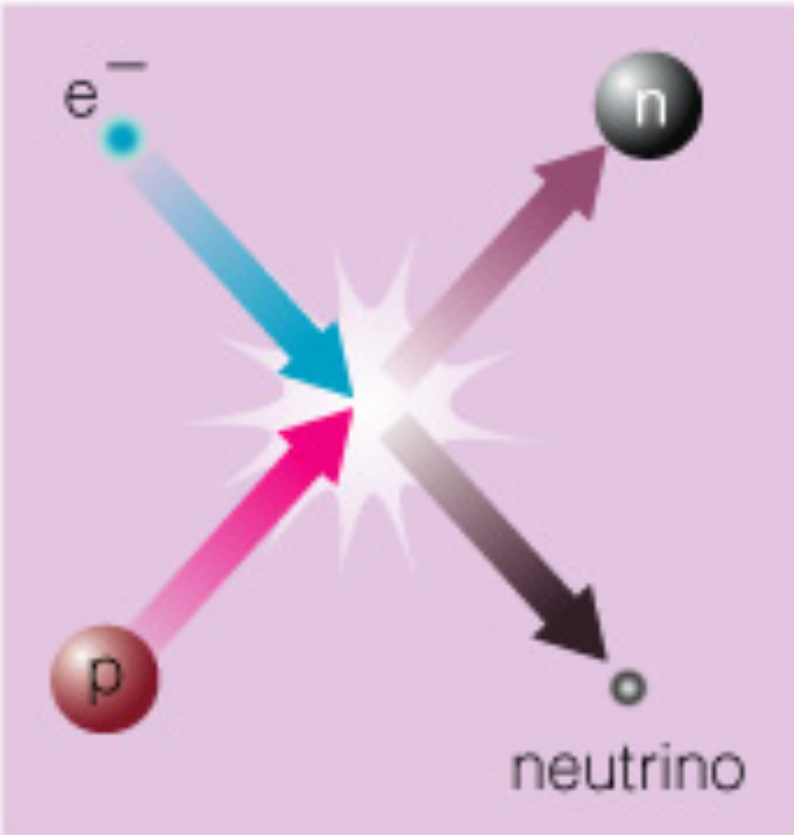
Why does fusion stop at Iron?





Advanced reactions in stars make elements like Si, S, Ca, Fe

Supernova Explosion



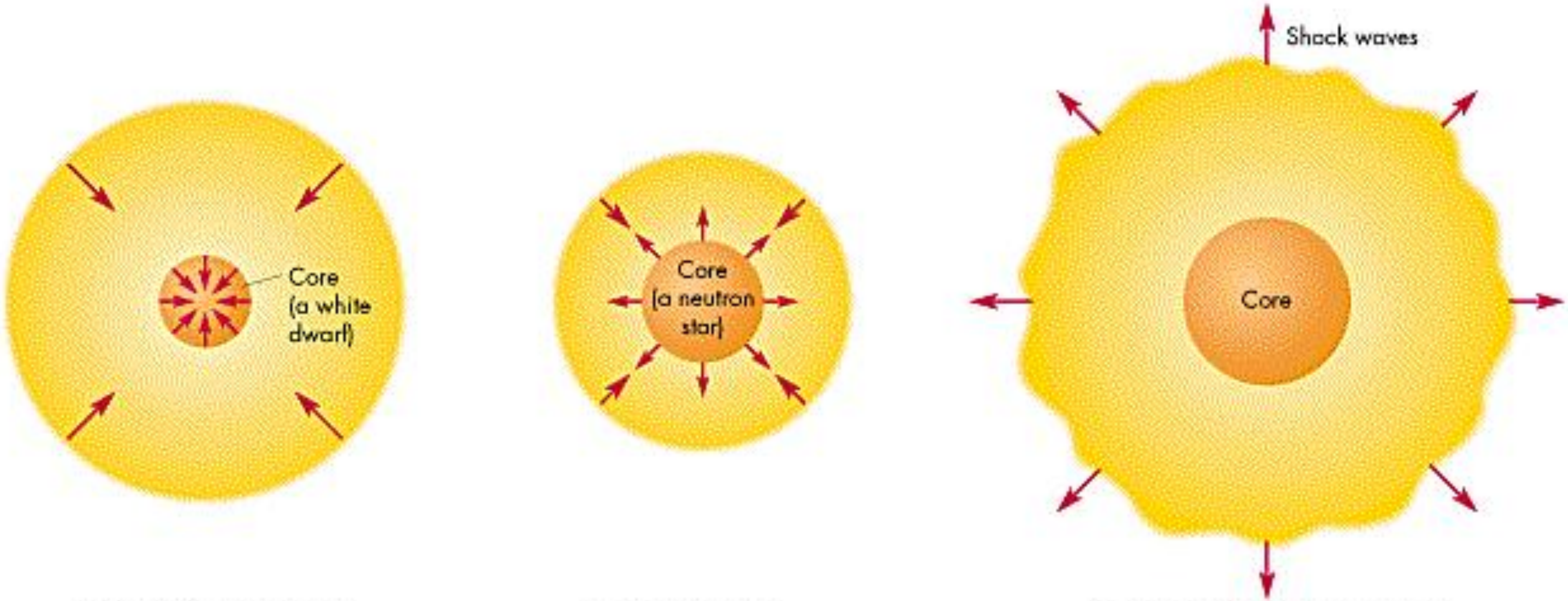
- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos

- Neutrons collapse to the center, forming a **neutron star**

Core collapse

- Iron core is degenerate
- Core grows until it is too heavy to support itself
- Core collapses, density increases, normal iron nuclei are converted into neutrons with the emission of neutrinos
- Core collapse stops, neutron star is formed
- Rest of the star collapses in on the core, but bounces off the new neutron star (also pushed outwards by the neutrinos)

Supernova explosion



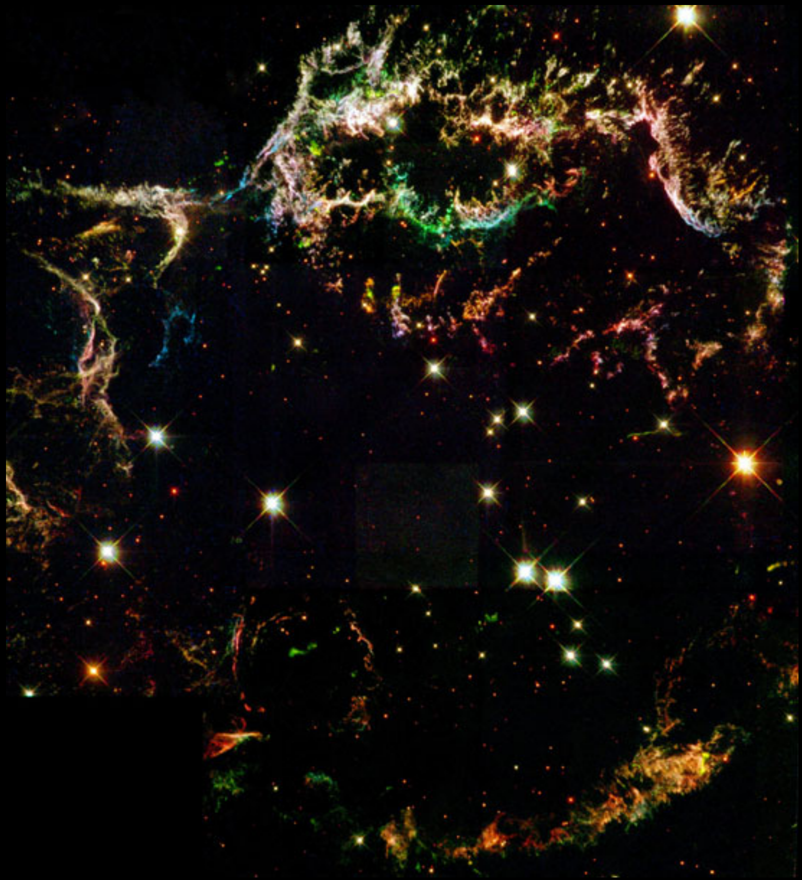
A Step 1: The iron core of the red giant collapses

B Step 2: Neutron-rich core rebounds

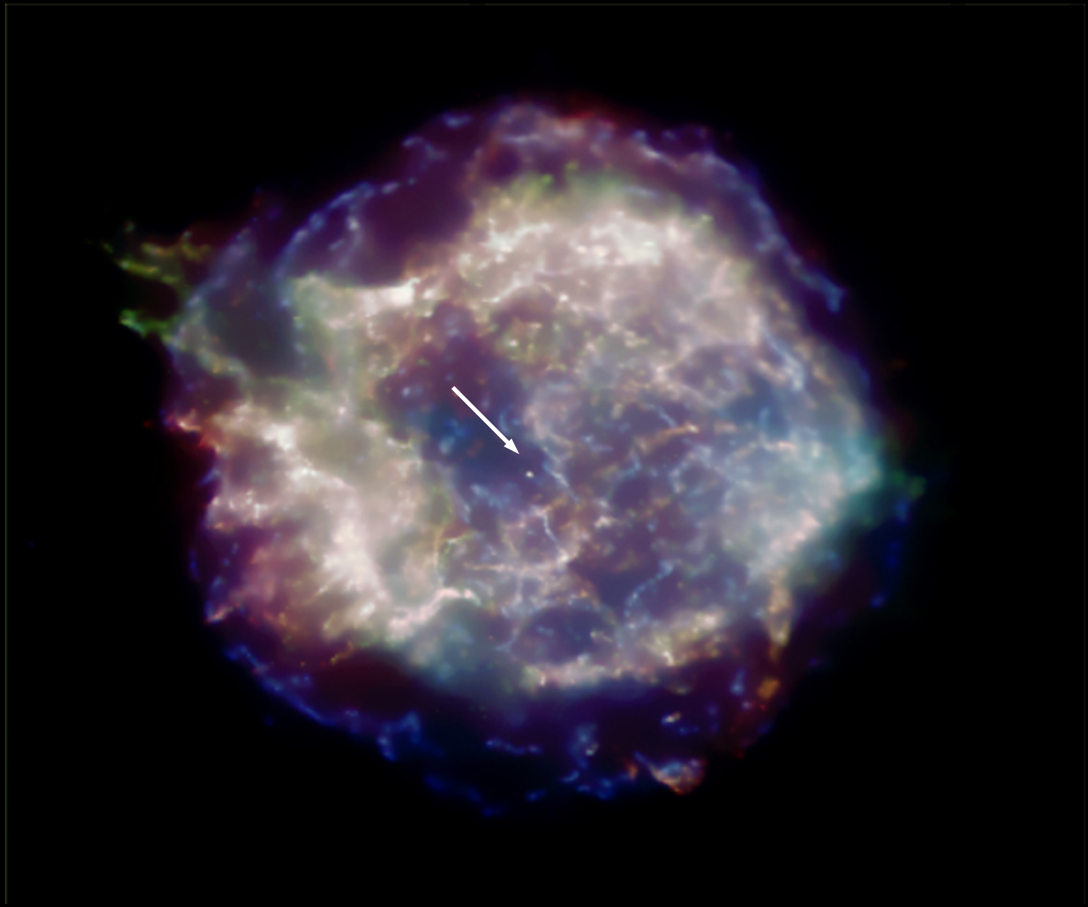
C Step 3: The shock wave moves outward through the star

Supernova Remnant: Cas A (320 yrs)

Optical



X-rays



Neutron star

Electron degeneracy cannot stop collapse

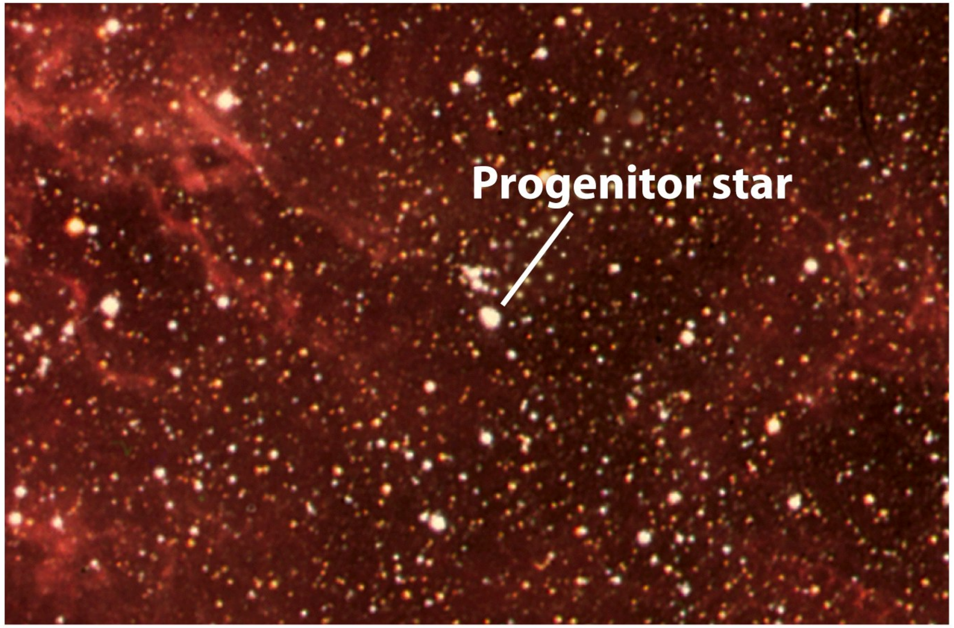
⇨ **neutronization**

$$p + e^- \longrightarrow n + \nu$$

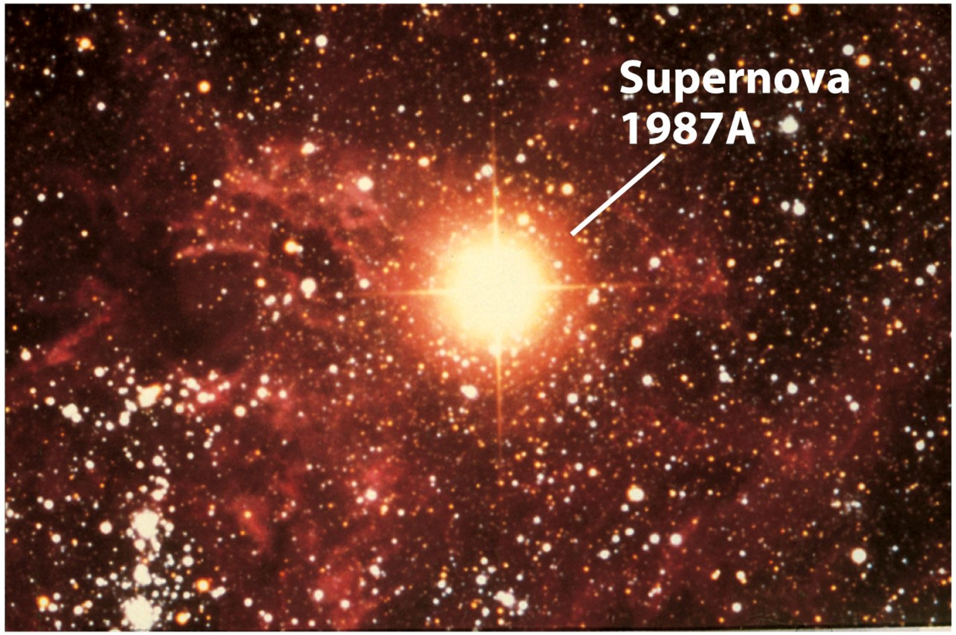
⇨ **collapse is stopped by neutron degeneracy**

SN1987A

In 1987 a nearby supernova gave us a close-up look at the death of a massive star



Before the star exploded



After the star exploded

Neutrinos from SN1987A