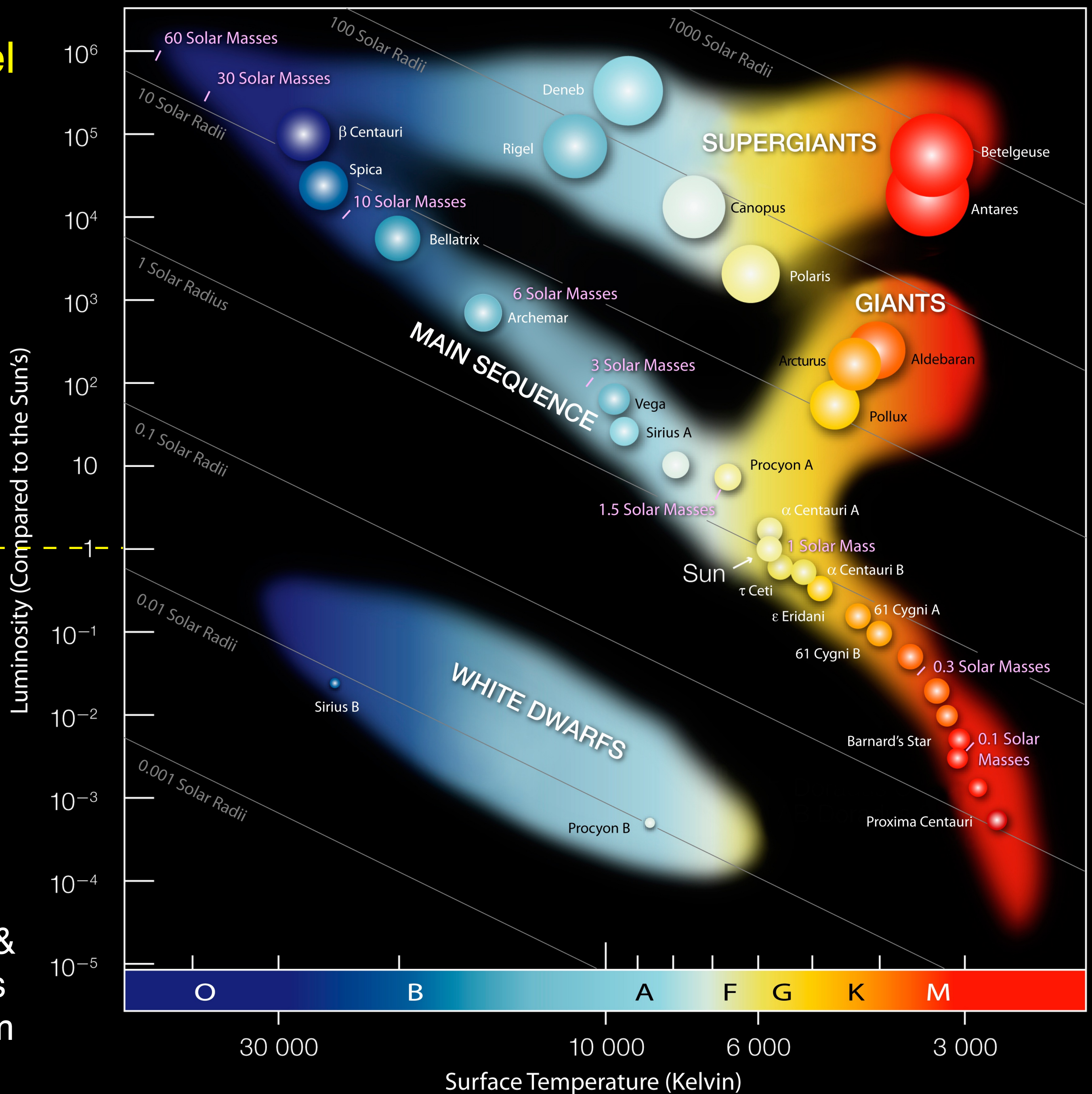
Stars in the Main Sequence of the Hertzsprung-Russel diagram

Hertzsprung-Russel diagram

Information on:

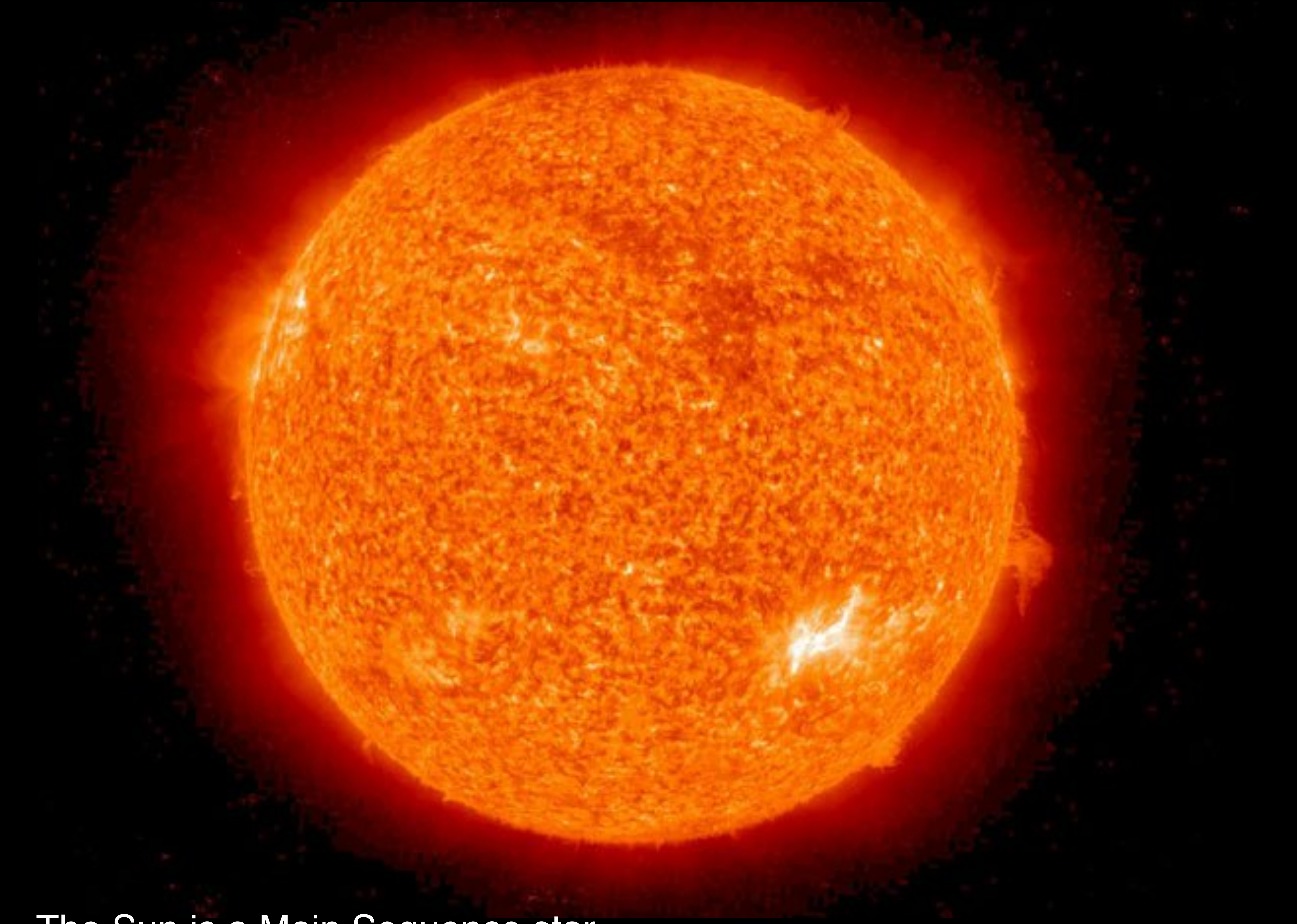
- Luminosity ***L***
- Temperature ***T***
- Radius ***R***

Solar luminosity:
$L_\odot$ = 3.846×10^{26} W =
= 3.846×10^{33} erg/s



Main Sequence (MS):
hydrogen fusion in core

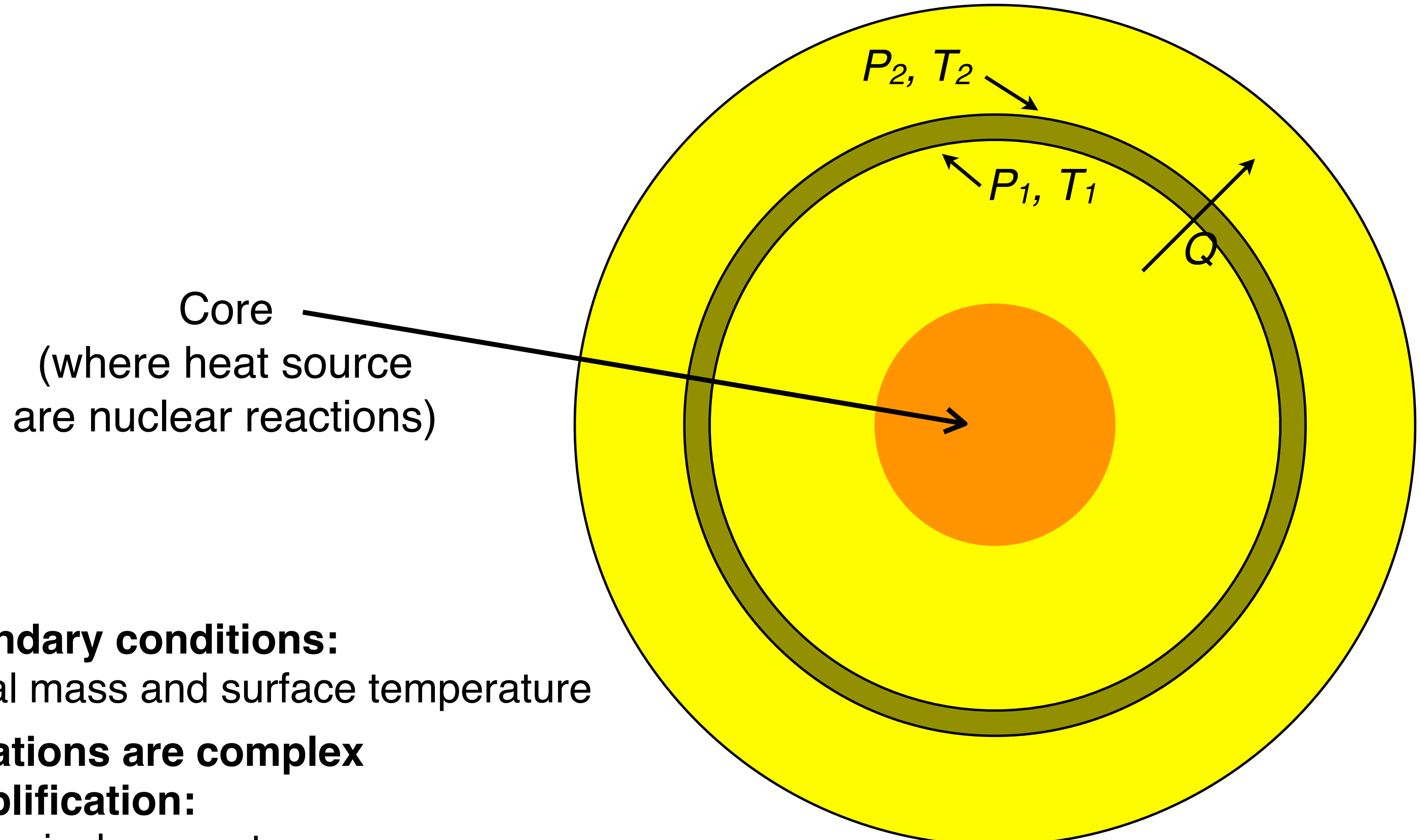
MS star of given mass & chemical composition is one point in HR diagram



The Sun is a Main Sequence star

Equation of stellar structure gives everywhere *P, T,* and *n*

Hydrostatic equilibrium: going to center, gravity balanced by pressure (gas + radiation)



Boundary conditions:

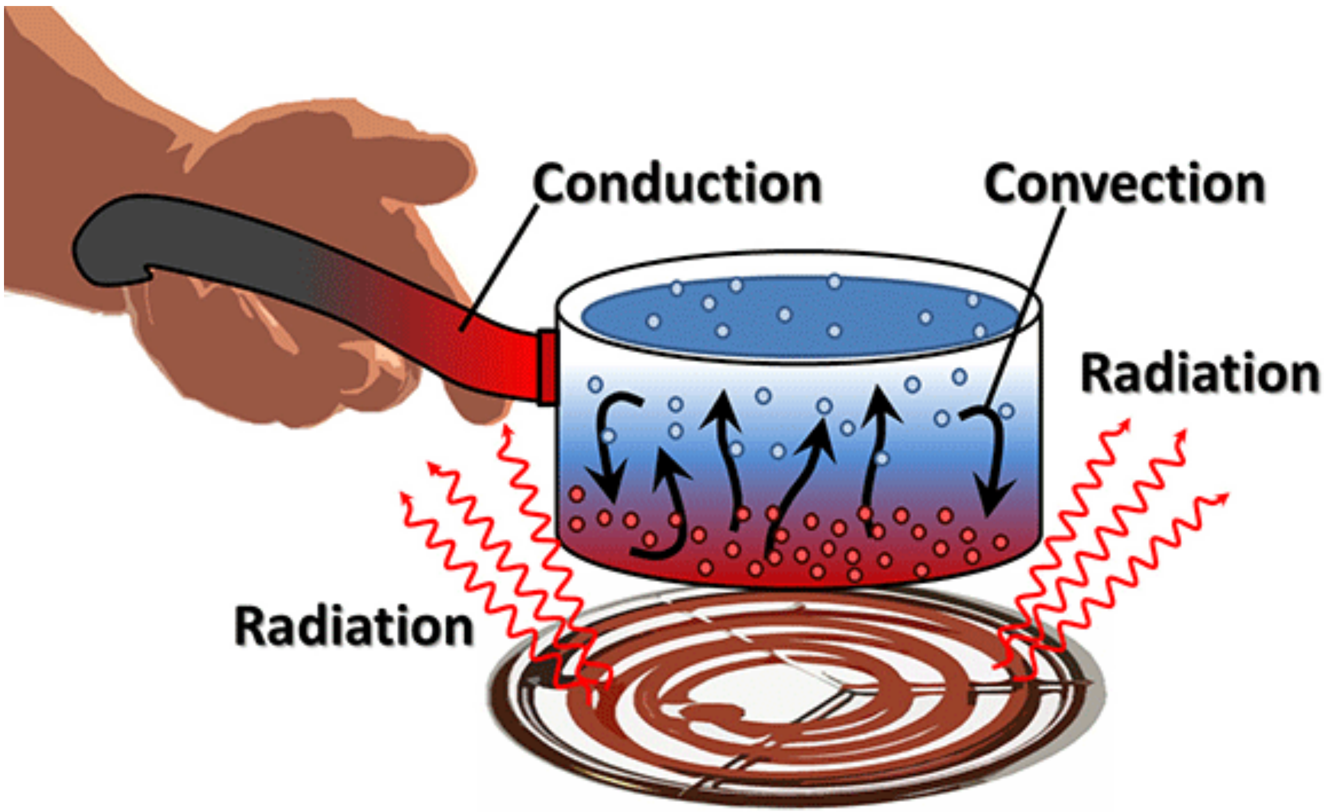
- total mass and surface temperature

Equations are complex
Simplification:

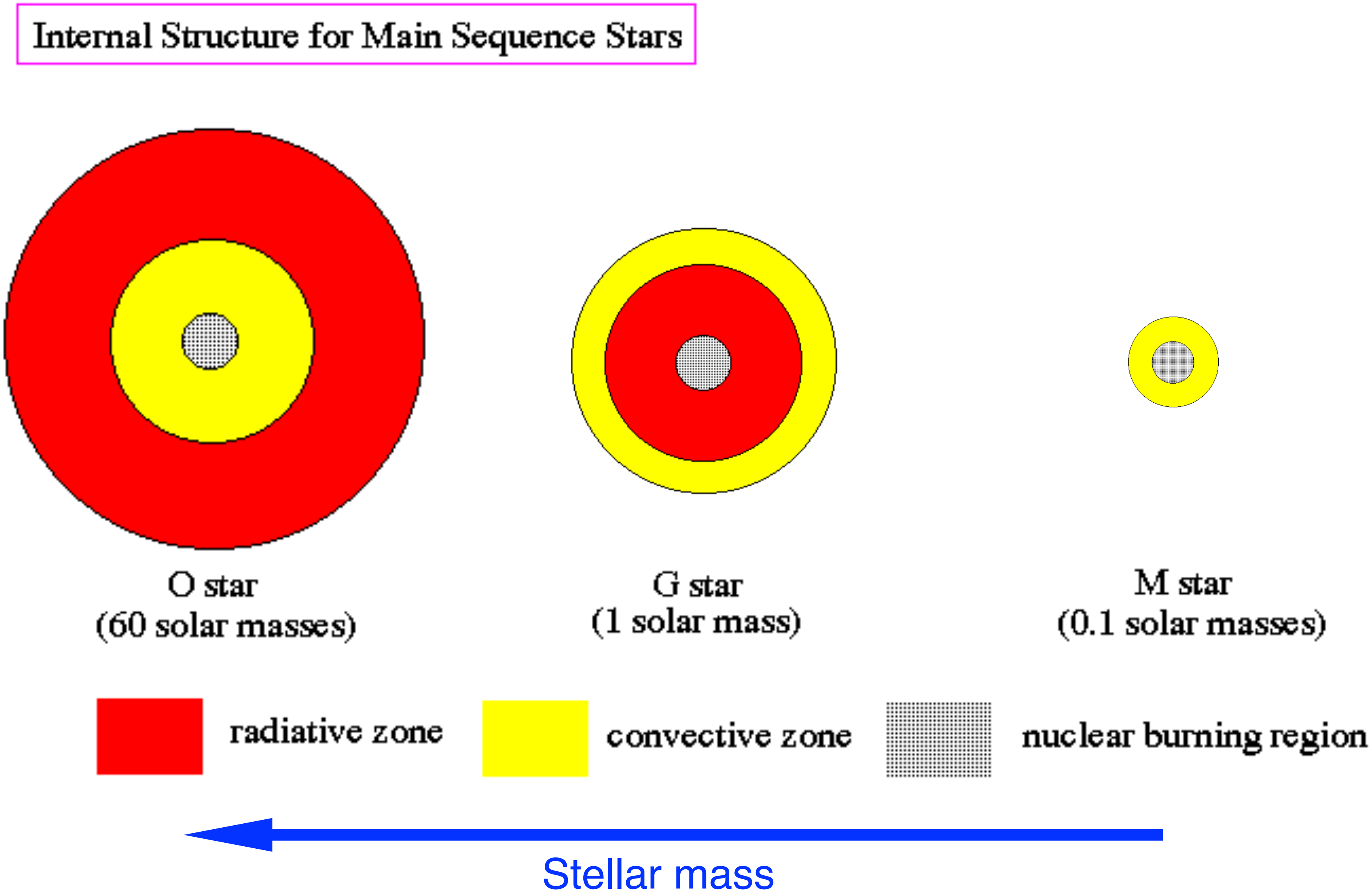
- spherical symmetry
- ideal gas
- thin spherical shell
- $P_1 > P_2 \rightarrow T_1 > T_2$
- energy flow is generated at interface (from center)

P : pressure
T : temperature
n : particle density
Q : energy flow (heat)

Three main ways for heat transfer

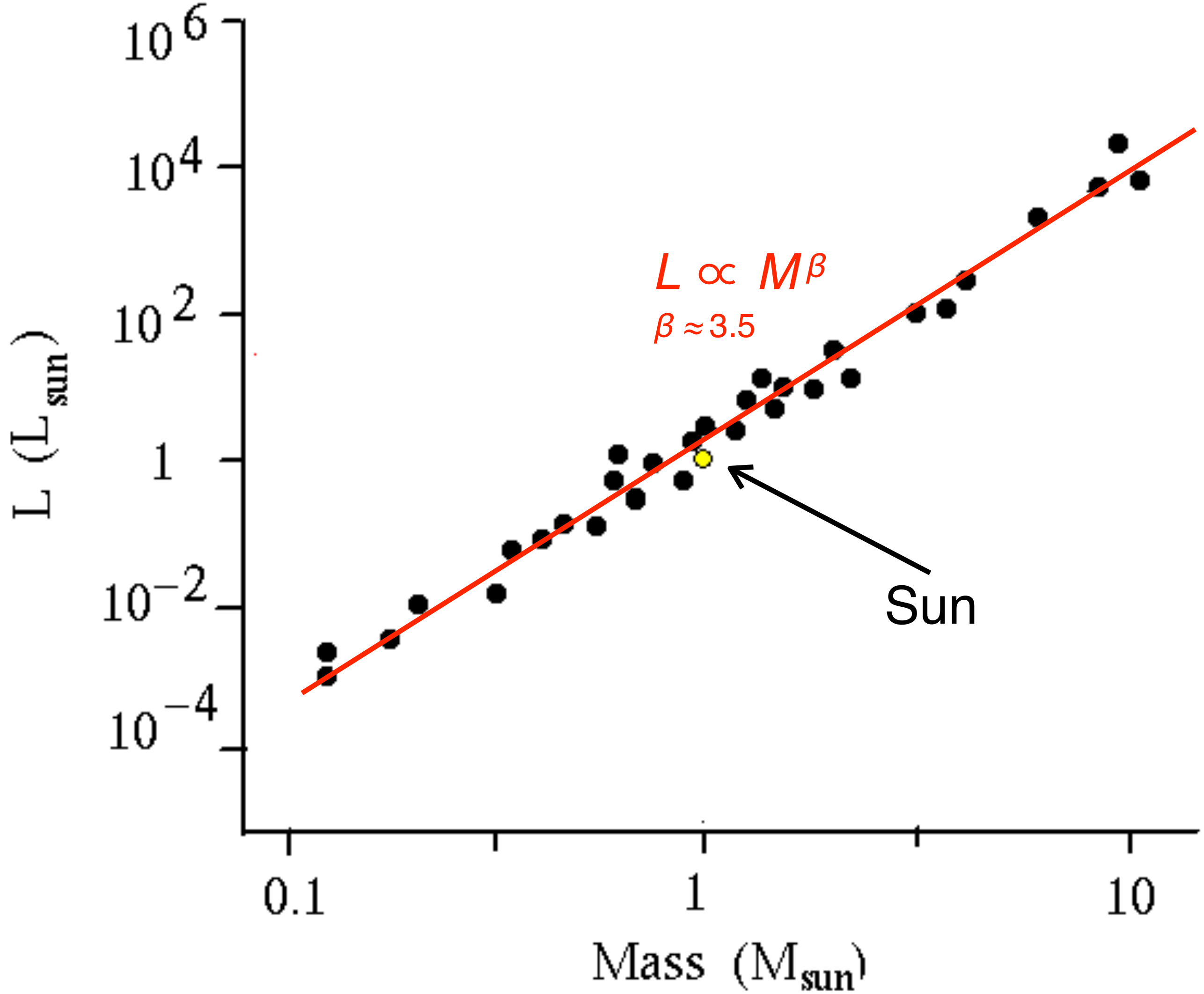


Different stellar structure for different star masses



Sun dominated by radiation, dwarf stars dominated by convection

Mass-luminosity relation for stars in Main Sequence



Most commonly slope used to estimate stellar lifetimes: $\beta = 3.5$

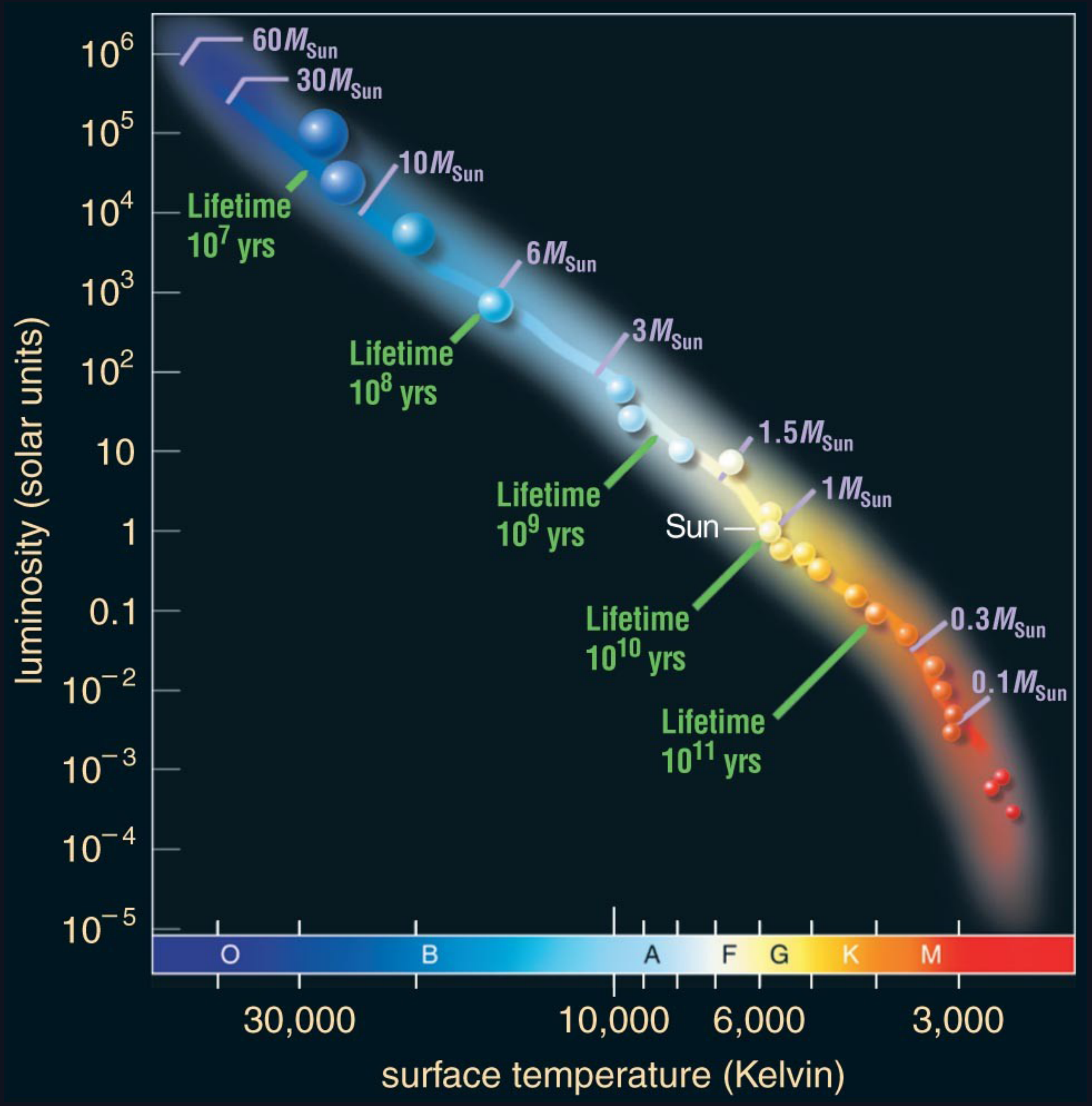
In more realistic approach: $3 < \beta < 4$

Key Properties of Main Sequence Stars

	Mass/$M_\odot$	Luminosity/$L_\odot$	Effective Temperature (K)	Radius/$R_\odot$	Main Sequence lifespan (yrs)
	0.10	3×10^{-3}	2900	0.16	2×10^{12}
	0.50	0.03	3800	0.6	2×10^{11}
	0.75	0.3	5000	0.8	3×10^{10}
The Sun	**1.0**	**1**	**6000**	**1**	**1×10^{10}**
	1.5	5	7000	1.4	2×10^{9}
	3	60	11000	2.5	2×10^{8}
	5	600	17000	3.8	7×10^{7}
	10	10,000	22000	5.6	2×10^{7}
	15	17,000	28000	6.8	1×10^{7}
	25	80,000	35000	8.7	7×10^{6}
	60	790,000	44500	15	3.4×10^{6}

Effective temperature: surface temperature of a star assuming black body emissivity

Lifetime of stars in Main Sequence with different mass



Nuclear reactions in stellar cores

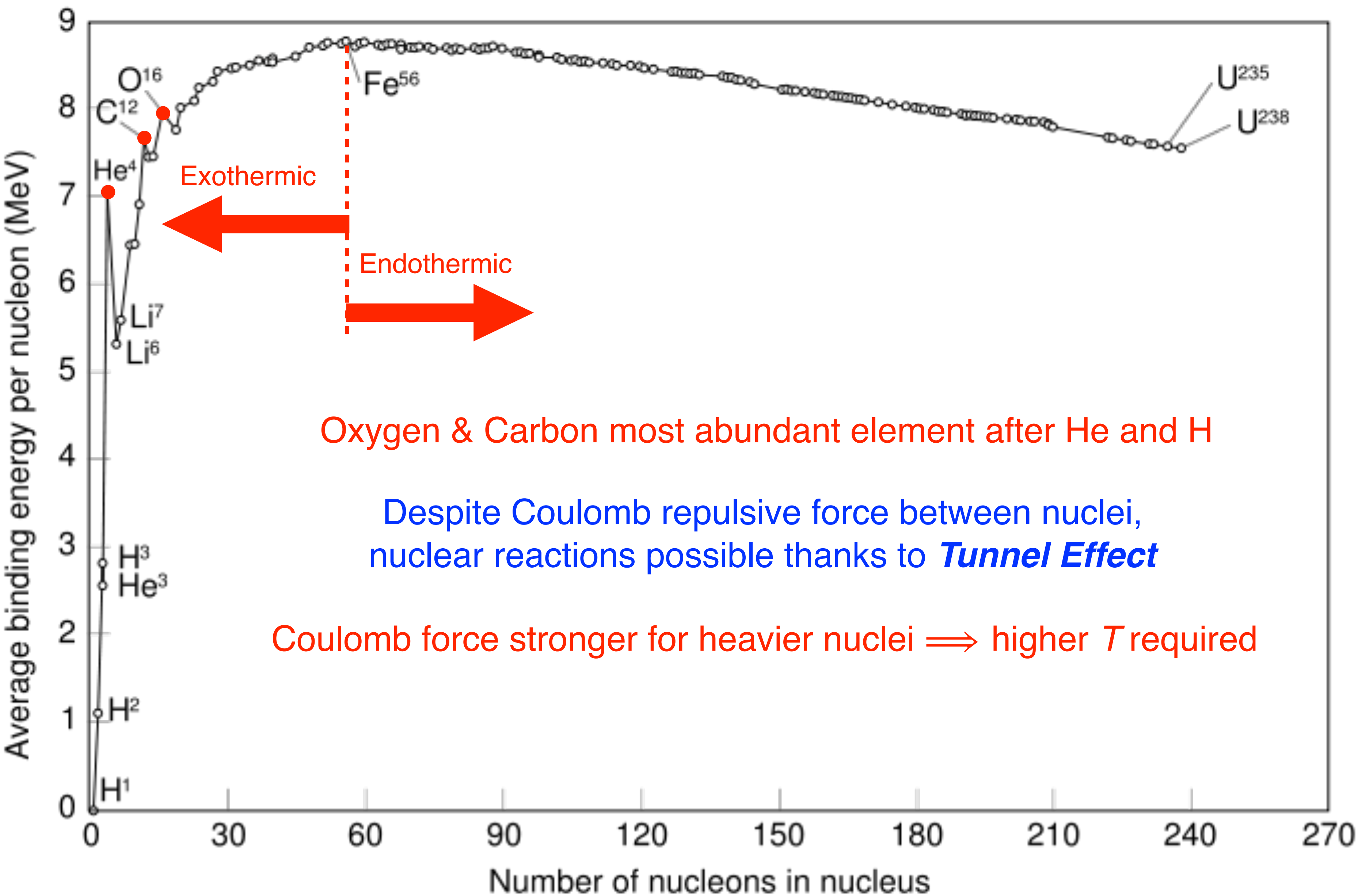
Chemical composition of stars very similar to Sun's

Element abundances in the Sun

Element	**#particles**	**Mass(X) / Mass(total)**
H	92.1%	0.74
He	7.8%	0.25
Z	0.1%	0.014

Z: all chemical elements heavier than helium

Binding energy (or rest frame energy) per nucleon, as a function of mass number



Oxygen & Carbon most abundant element after He and H

Despite Coulomb repulsive force between nuclei, nuclear reactions possible thanks to ***Tunnel Effect***

Coulomb force stronger for heavier nuclei $\Longrightarrow$ higher T required

Hydrogen fusion in core of Main Sequence stars

Two main ways: **proton-proton (pp) chains & CNO Cycle**

pp I: $4p \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu_e + 2\gamma$

pp II: $4p + e^{-} \rightarrow {}^{4}_{2}He + e^{+} + 2\nu_e + 2\gamma$

pp III: $4p \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu_e + 3\gamma$

CNO: $4p \rightarrow {}^{4}_{2}He + 2e^{+} + 2\nu_e + 2\gamma$

Higher core *T* ↓

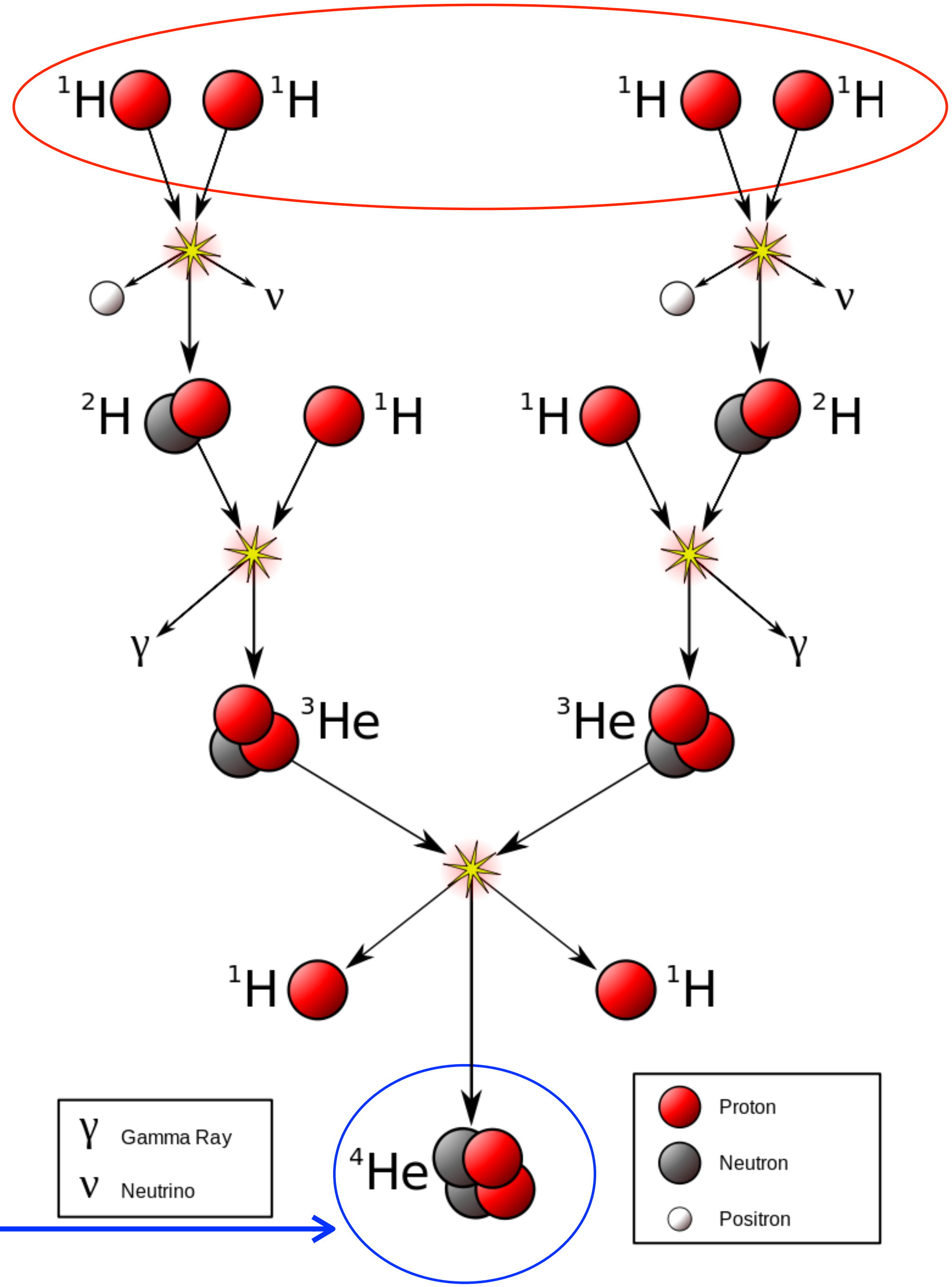
1 He atom formed from 4 protons

ν_e: electron neutrino
γ: gamma-ray photon
p: proton
CNO: carbon nitrogen oxygen

Total energy released for one pp chain: $E = 26.73$ MeV $= 4.28 \times 10^{-12}$ J

4 protons

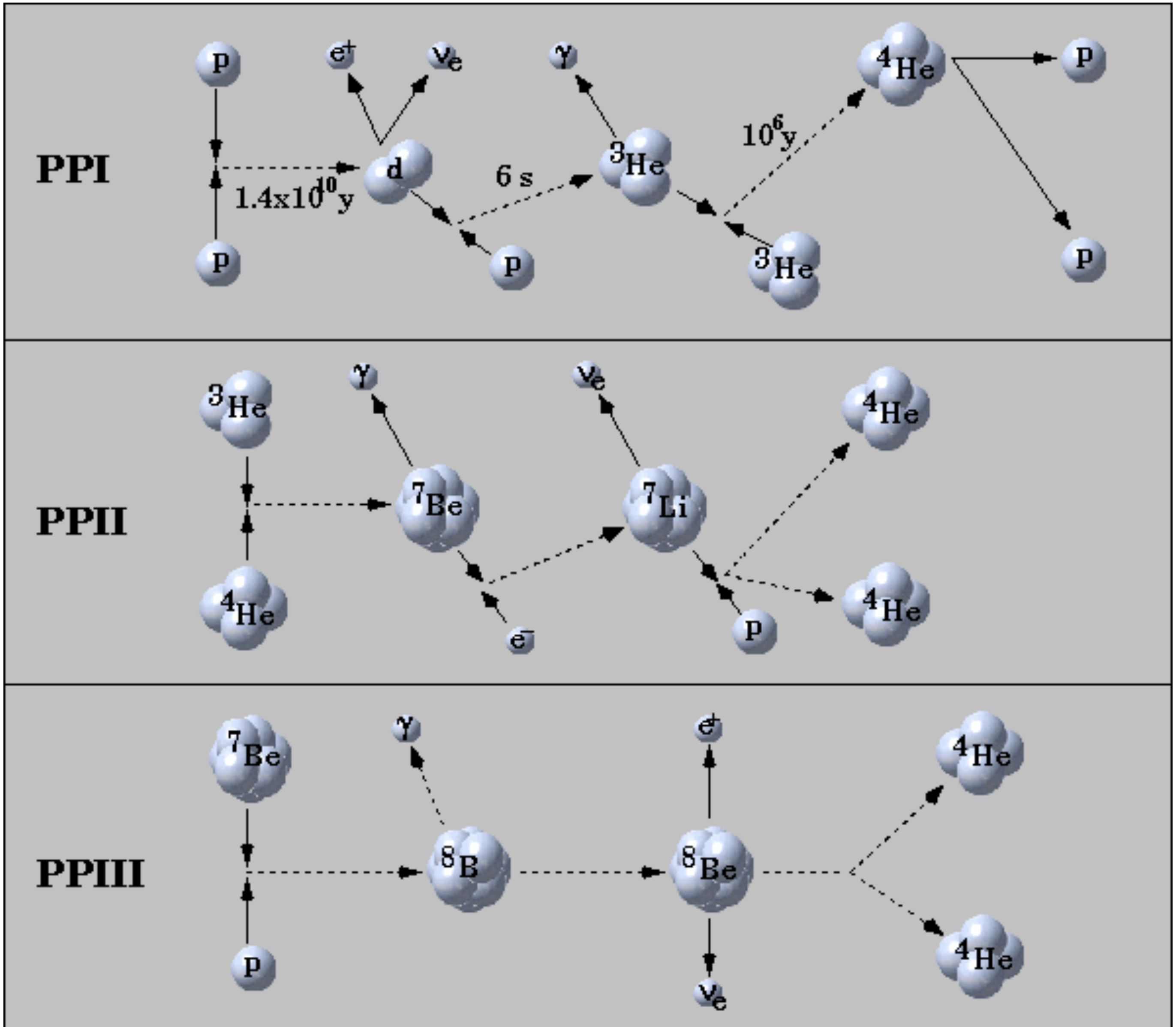
pp I chain



1 He atom

The 3 pp chains

For the Sun:



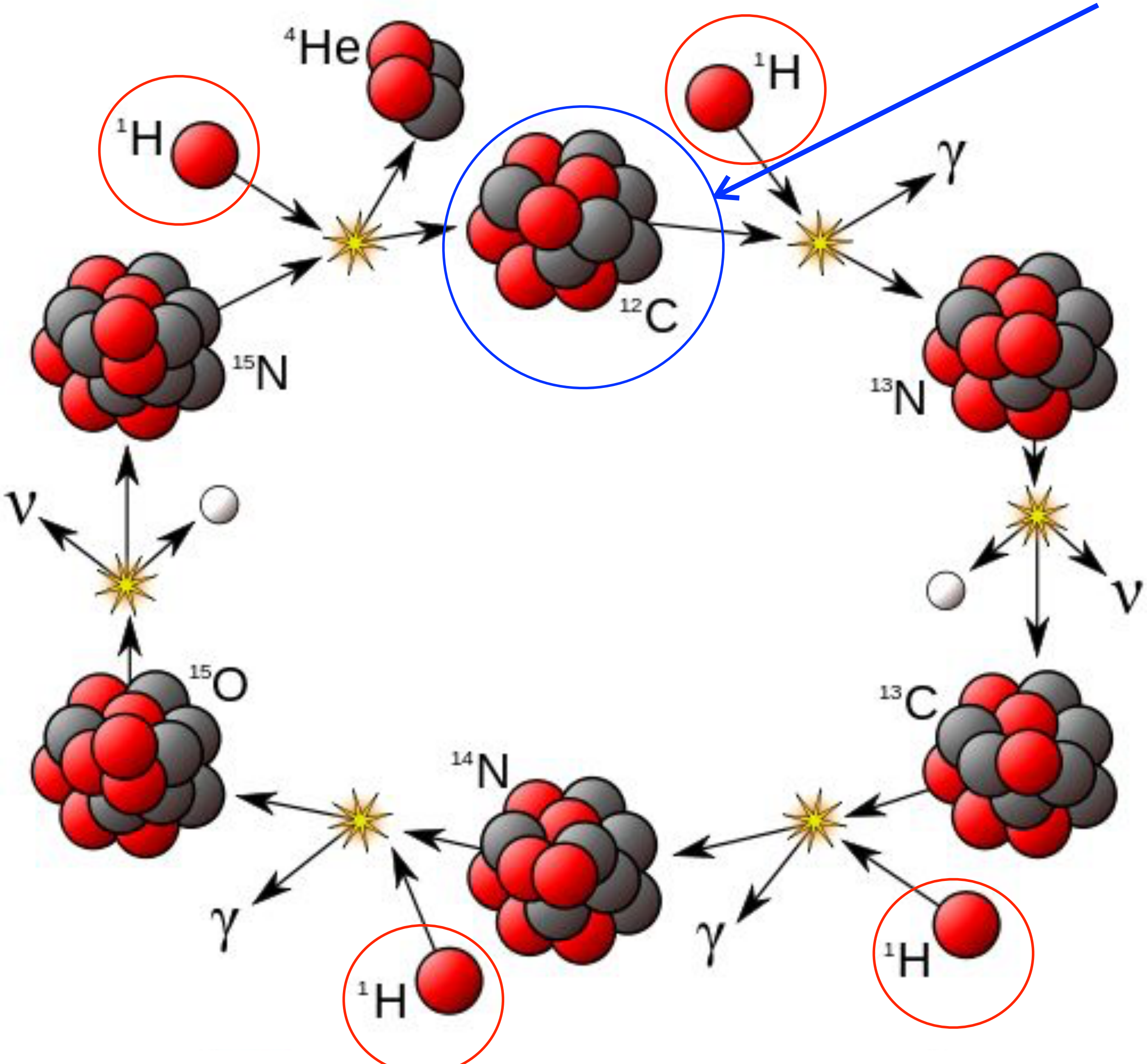
85%

15%

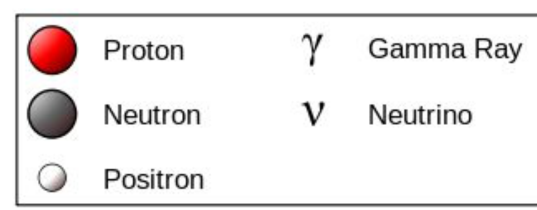
0.02%

CNO cycle

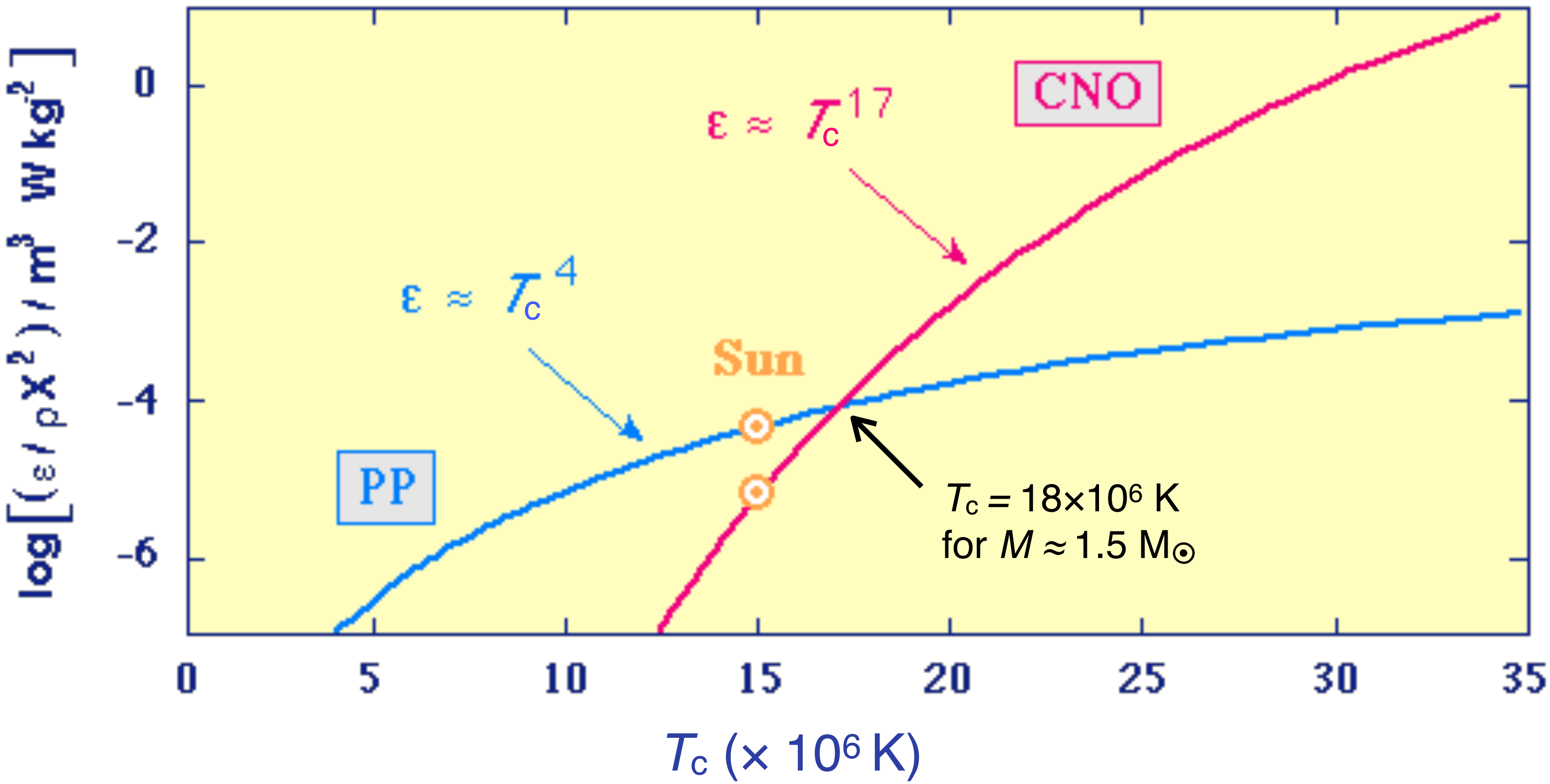
Start: ^{12}C acts as nuclear catalyst



Atoms used as catalysts:
carbon, nitrogen, oxygen



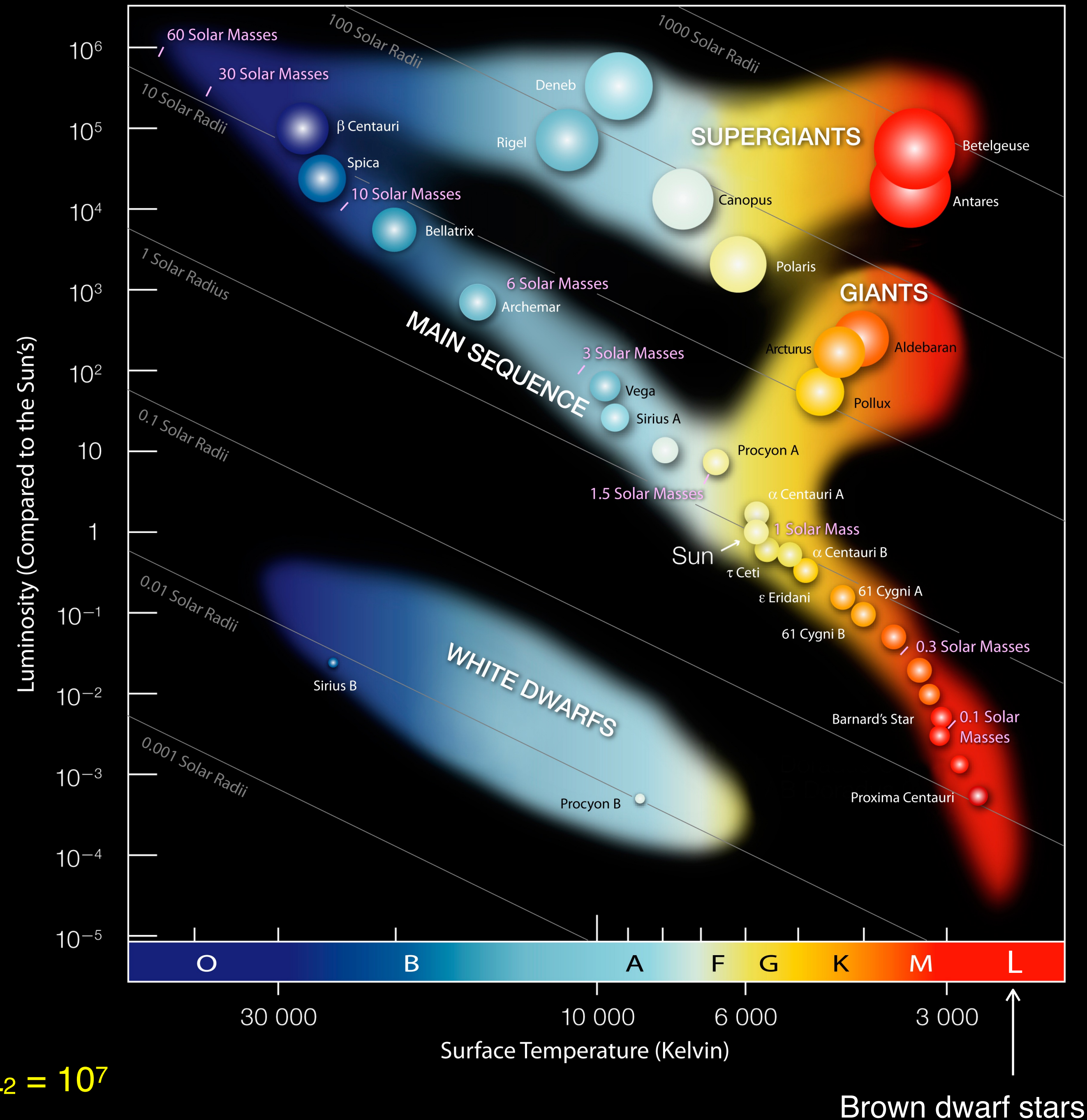
Rate of **energy release** as a function of core temperature T_c for **pp chains** and **CNO cycle**



Every second, Sun converts 4×10^9 kg of H to energy (radiated to space)

Hydrogen in Sun's core will be **exhausted** in another **5 billion years**

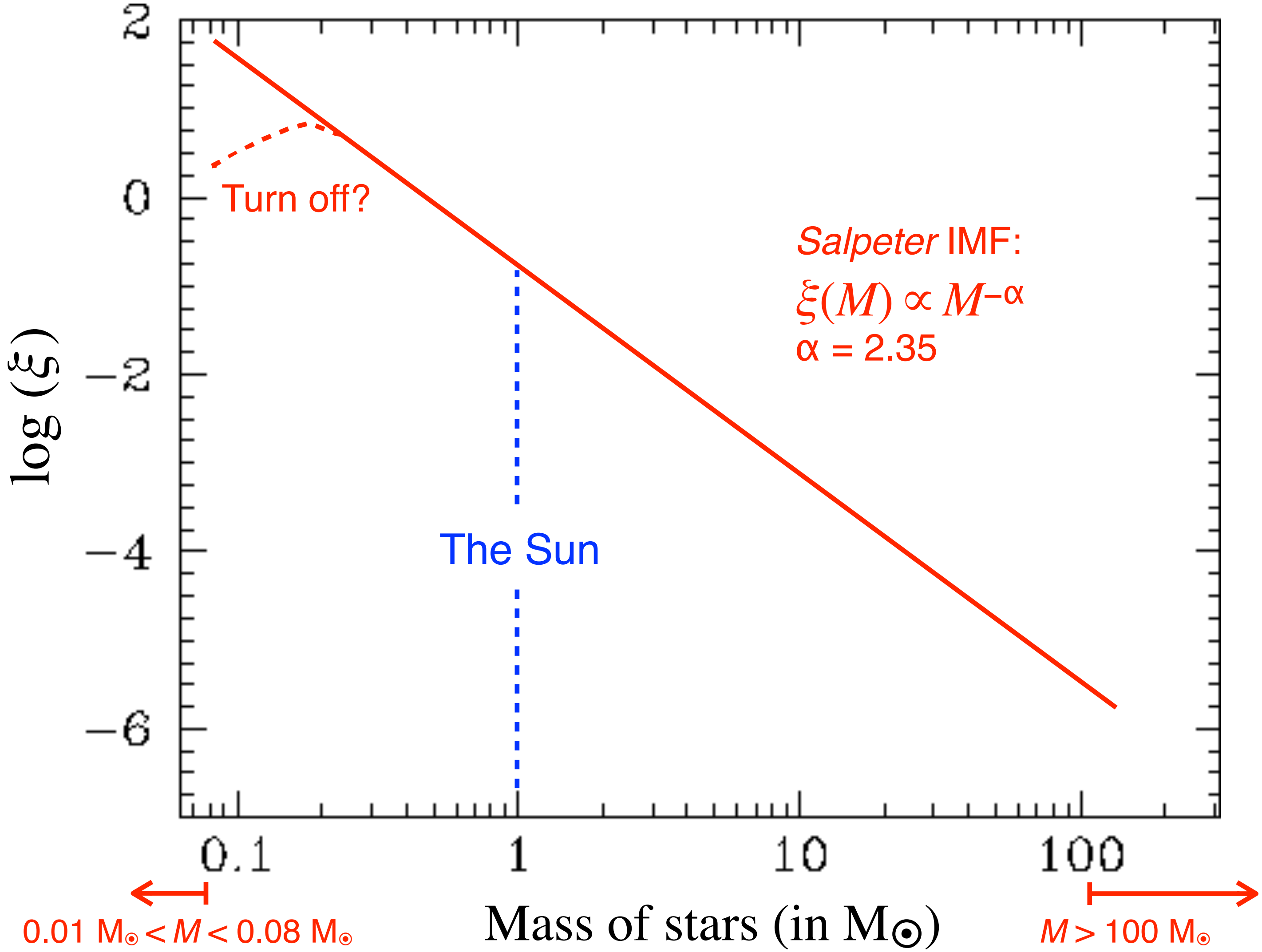
Hertzsprung-Russel diagram



Nuclear reactions strong function of T_c (then mass)

Thus: $M_1/M_2 = 100 \Longrightarrow L_1/L_2 = 10^7$

Stellar initial mass function (IMF): number of stars per mass interval



$0.01\ M_\odot < M < 0.08\ M_\odot$
no significant nuclear reactions
L-type brown dwarf stars

$M > 100\ M_\odot$
Strong radiation pressure
Stars do not form easily

L-type stars are 2× more numerous than all other stars
but count for 15% of stellar mass in MW

Smallest stars (L–type, $M < 0.08\ M_\odot = 80\ M_J$) nuclear reactions are not very significant $\Longrightarrow$ brown dwarf stars visible in IR ($T < 2600$ K)

HST image of *Trapezium Cluster* in Orion nebula

Optical

Cool stars are bright in the IR

Infrared

Mass lower limit 0.013 $M_\odot$ (14× Jupiter mass) minimum required to start nuclear fusion of deuterium

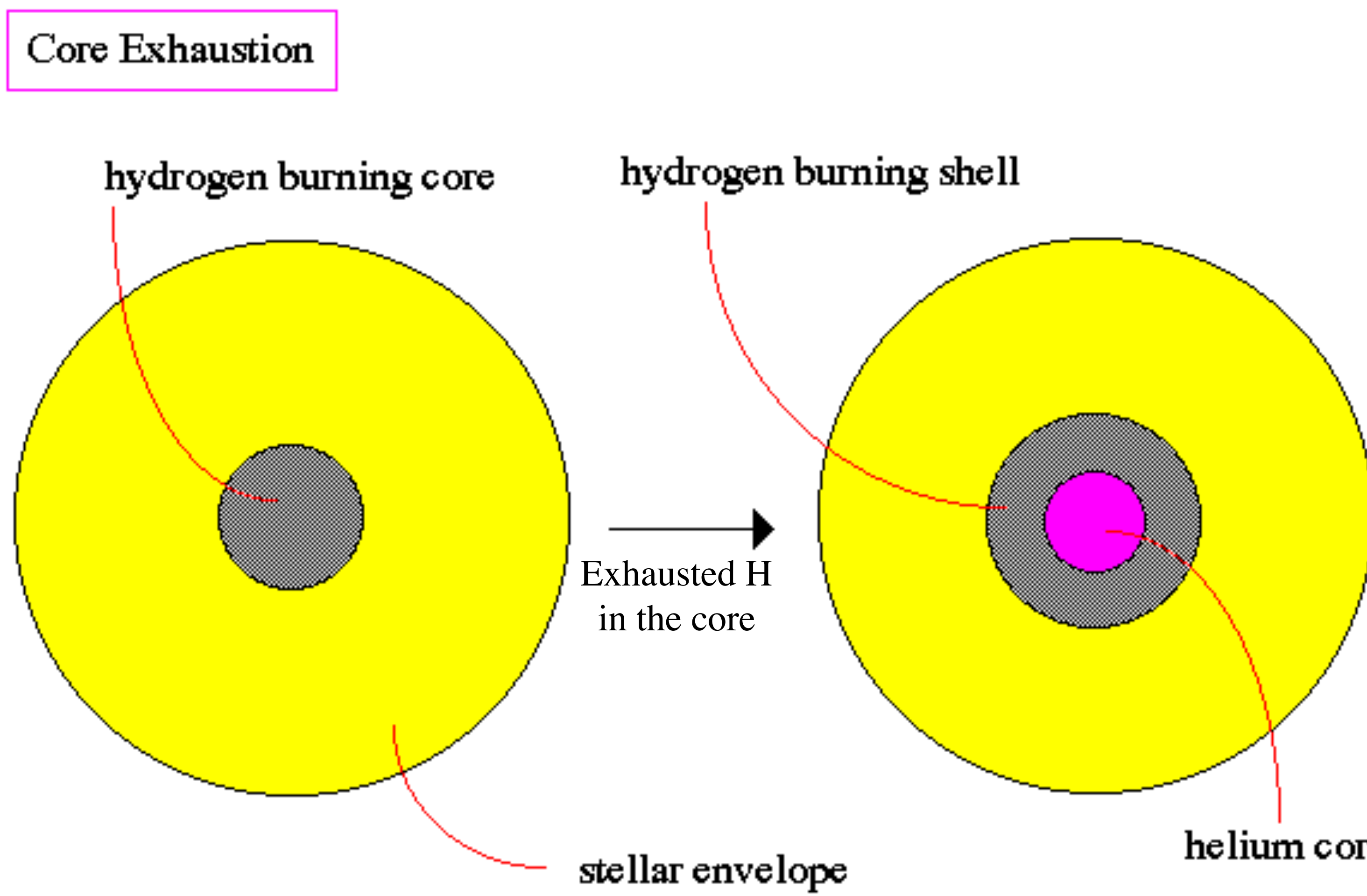
Star life beyond the Main Sequence

(hydrogen exhaustion in core)

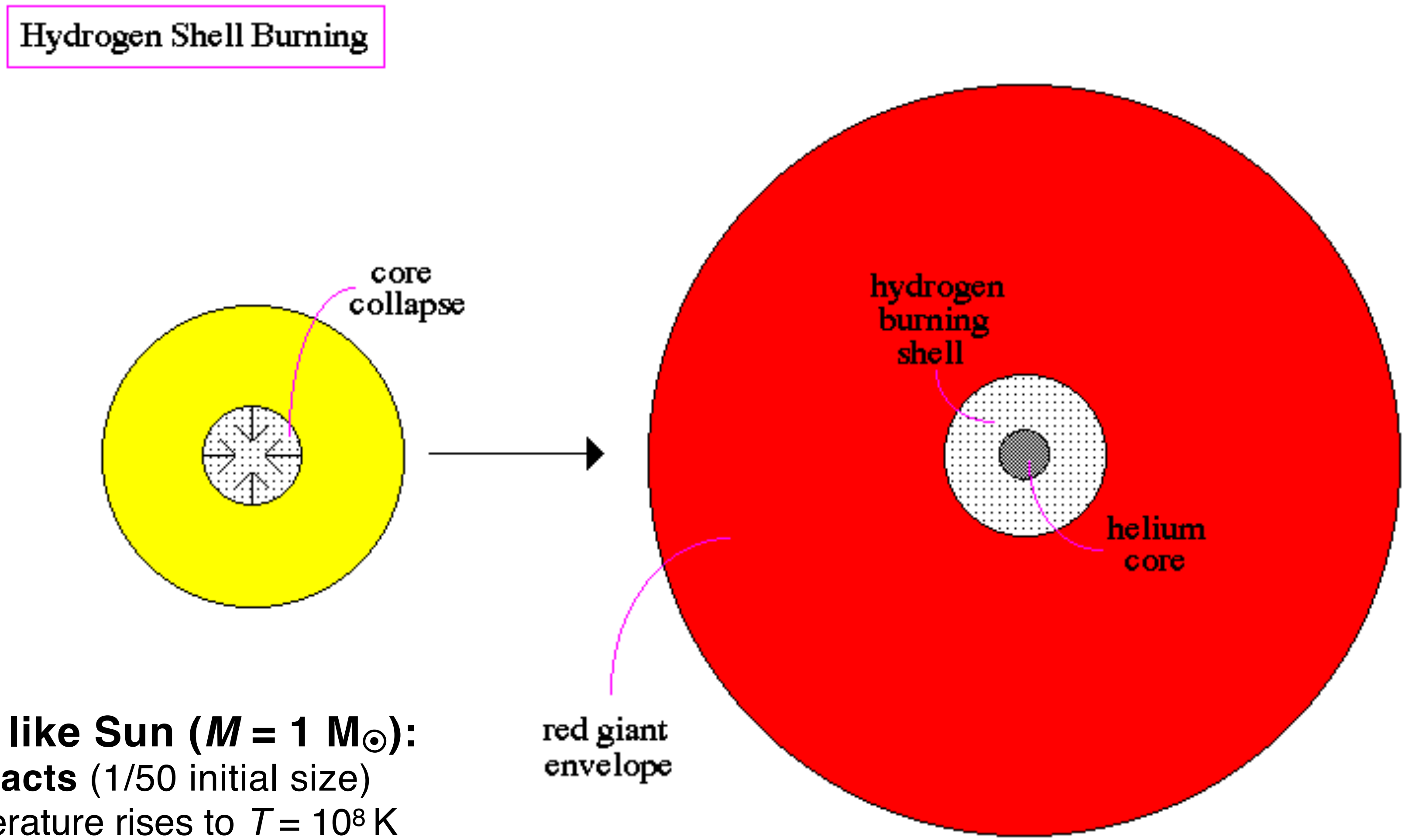
Star leaves MS when hydrogen fusion ends in core

For star mass $M < 0.5\ M_\odot$, no helium burning in the core
Degeneracy pressure of electrons (Pauli exclusion principle for fermions) stops contraction
Degeneracy pressure does not depend on temperature but on **density only**

For masses $1\ M_\odot < M < 2\ M_\odot$ $\rightarrow$ hydrogen burning in the shell



After MS phase: T drops → core collapse → gravitation energy converted into heat → H burning in shell around core → expanding envelope → **Red Giant**



For stars like Sun (M = 1 $M_{\odot}$):

Core **contracts** (1/50 initial size)

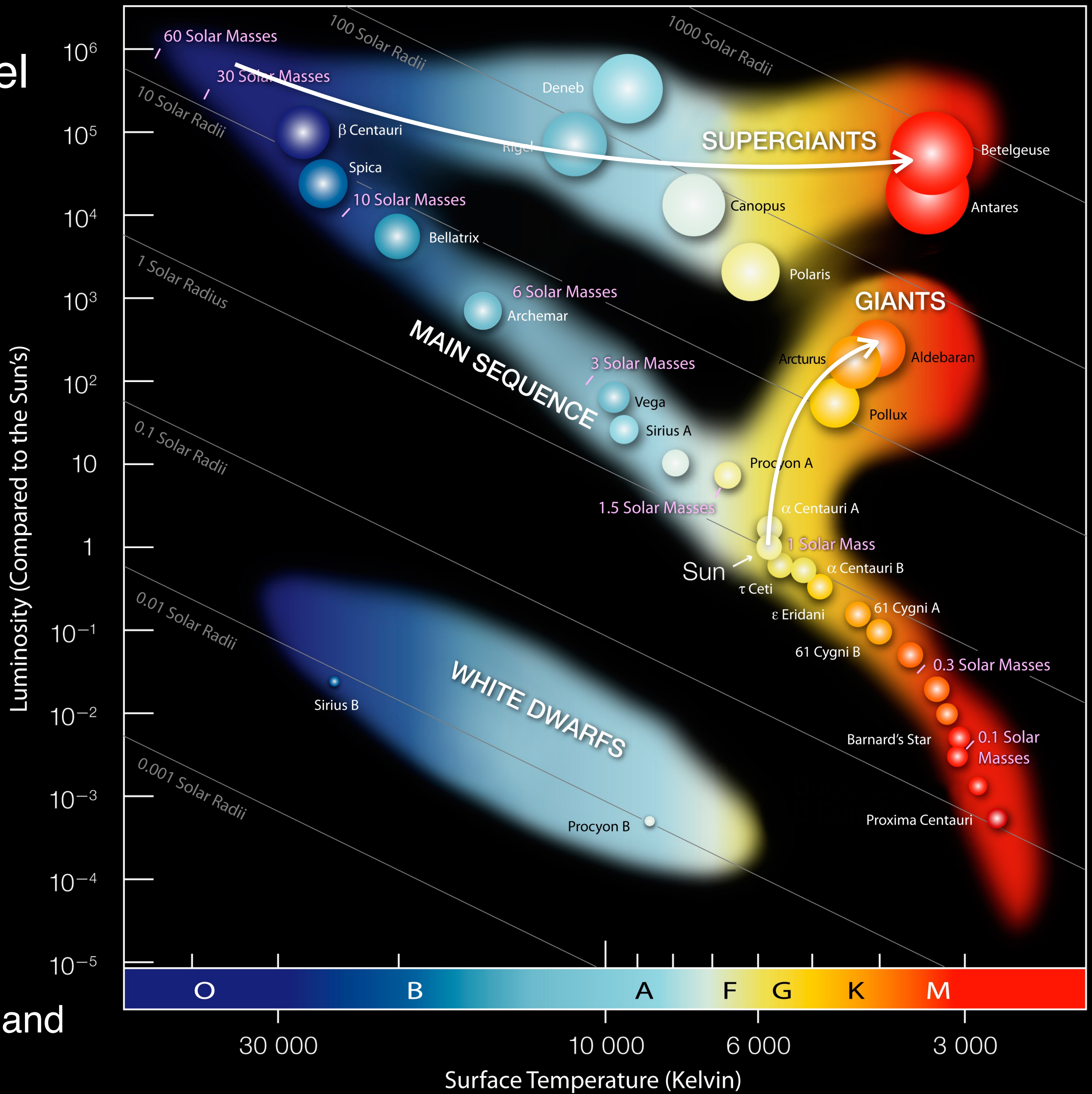
Core temperature rises to $T = 10^8$ K

Hydrogen fusion in the shell starts

Star **expands** ten times initial radius (energy conservation)

Surface temperature drops: $T = 3500$ K (*red giant star*)

Hertzsprung-Russel diagram



Transition to red giant and red supergiant phase

After red giant, for $M > 0.5\ M_\odot \rightarrow T = 10^8$ K in core → **He fusion**

He fusion (triple-alpha process) to produce carbon

3α process in He core:

$$^4He + {}^4He \rightleftharpoons {}^8Be$$

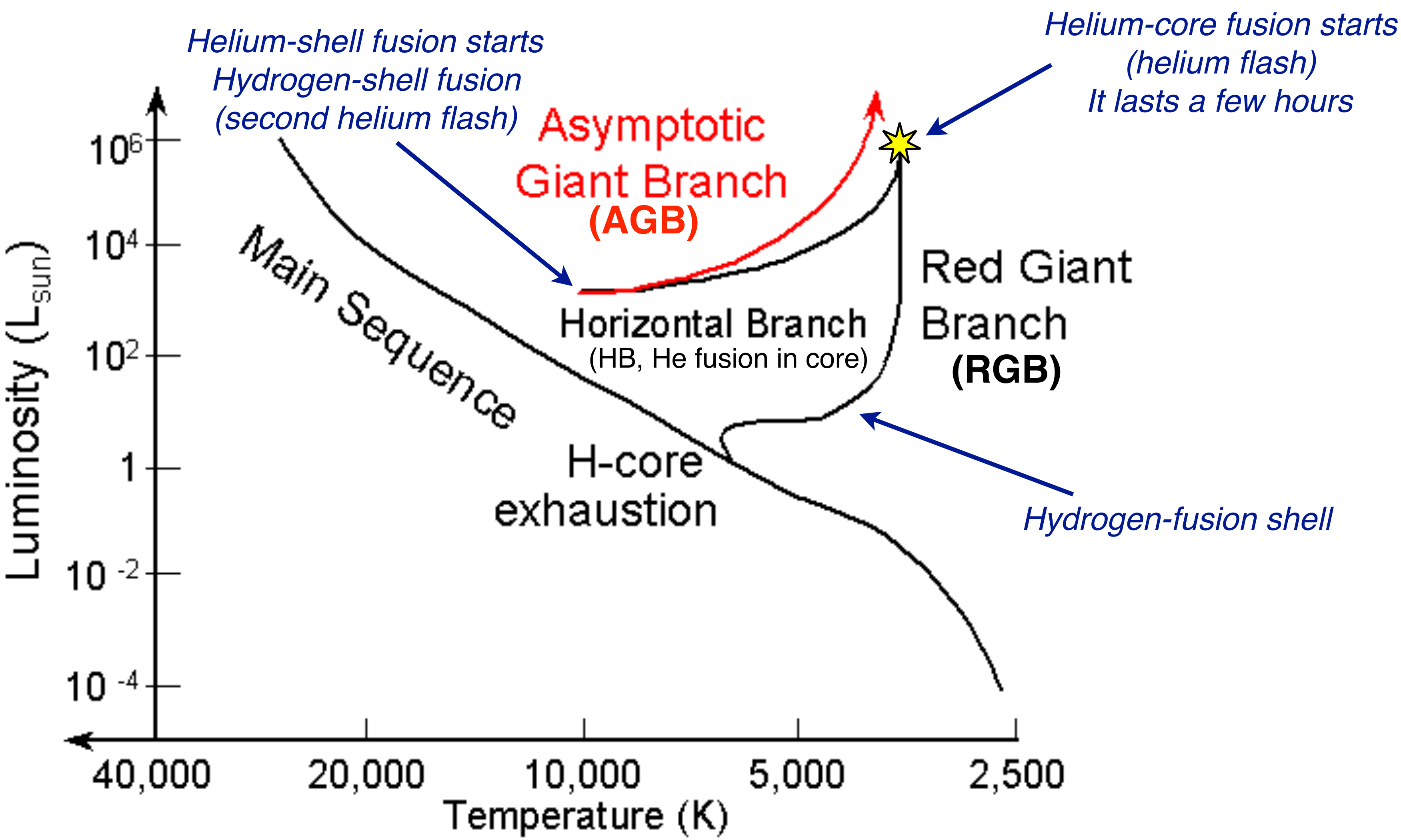
$$^4He + {}^8Be \rightleftharpoons {}^{12}C^* \rightarrow {}^{12}C + 2\gamma$$

- *E* released 1.17×10^{-12} J per C nucleus (or 3.9×10^{-13} J per He nucleus)
- This is 10% of energy with H fusion (**10 times faster**)
- Energy released very temperature sensitive, $E \propto T^{40}$, necessary to have Be + He before Be goes back to He

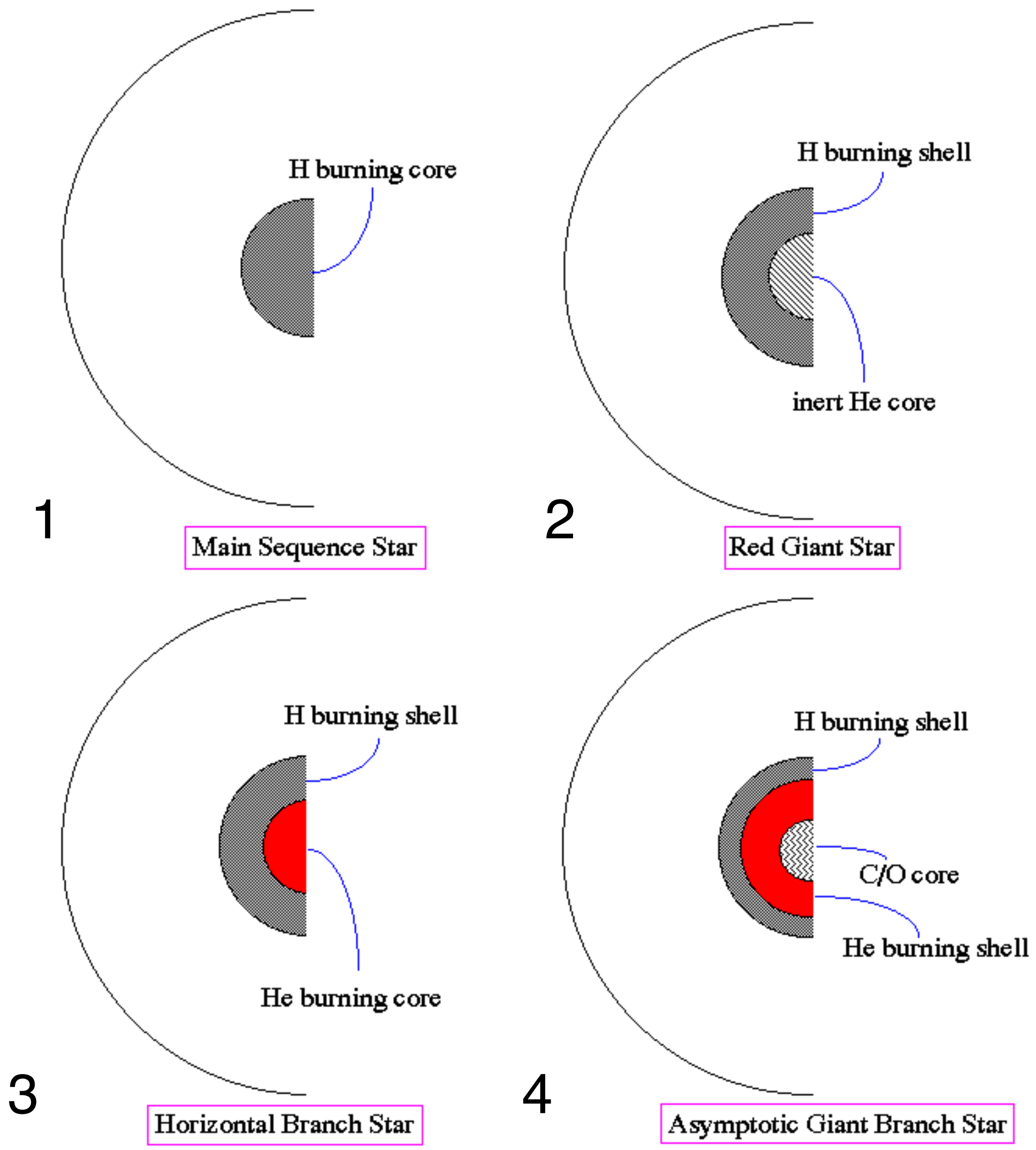
α particle: nucleus of helium atom

Evolution of stars in Hertzsprung-Russel diagram for medium-size star ($M < 2\ M_\odot$ → **He flash in core**)

- Then He fusion in core (**Horizontal Branch**)
- At end of HB, **core of inert carbon and oxygen**
- Electrons and nuclei in core again become degenerate, star expands and cools → **Asymptotic Giant Branch** (AGB)



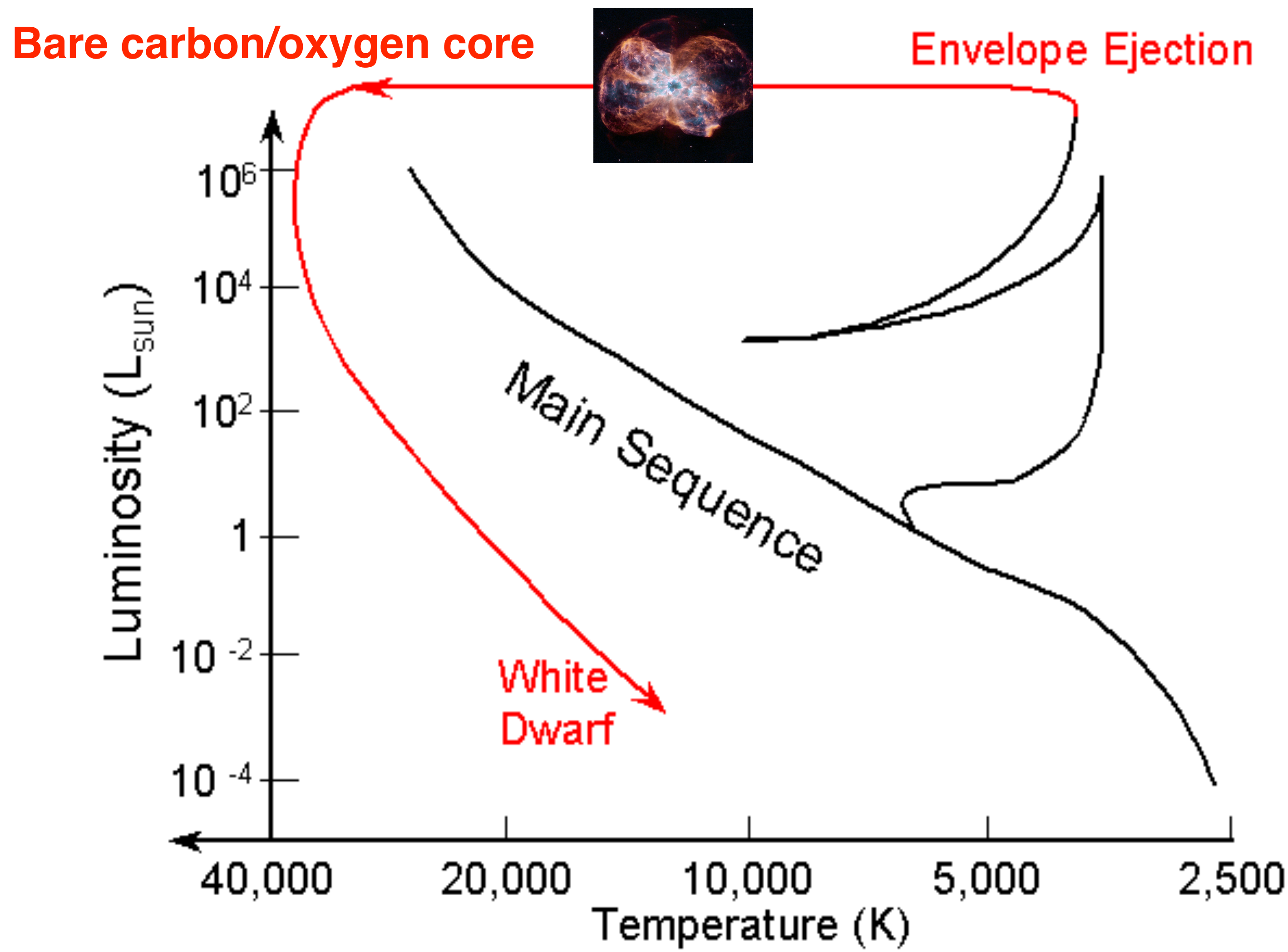
Evolution of a stellar core for medium-size star: **summary**



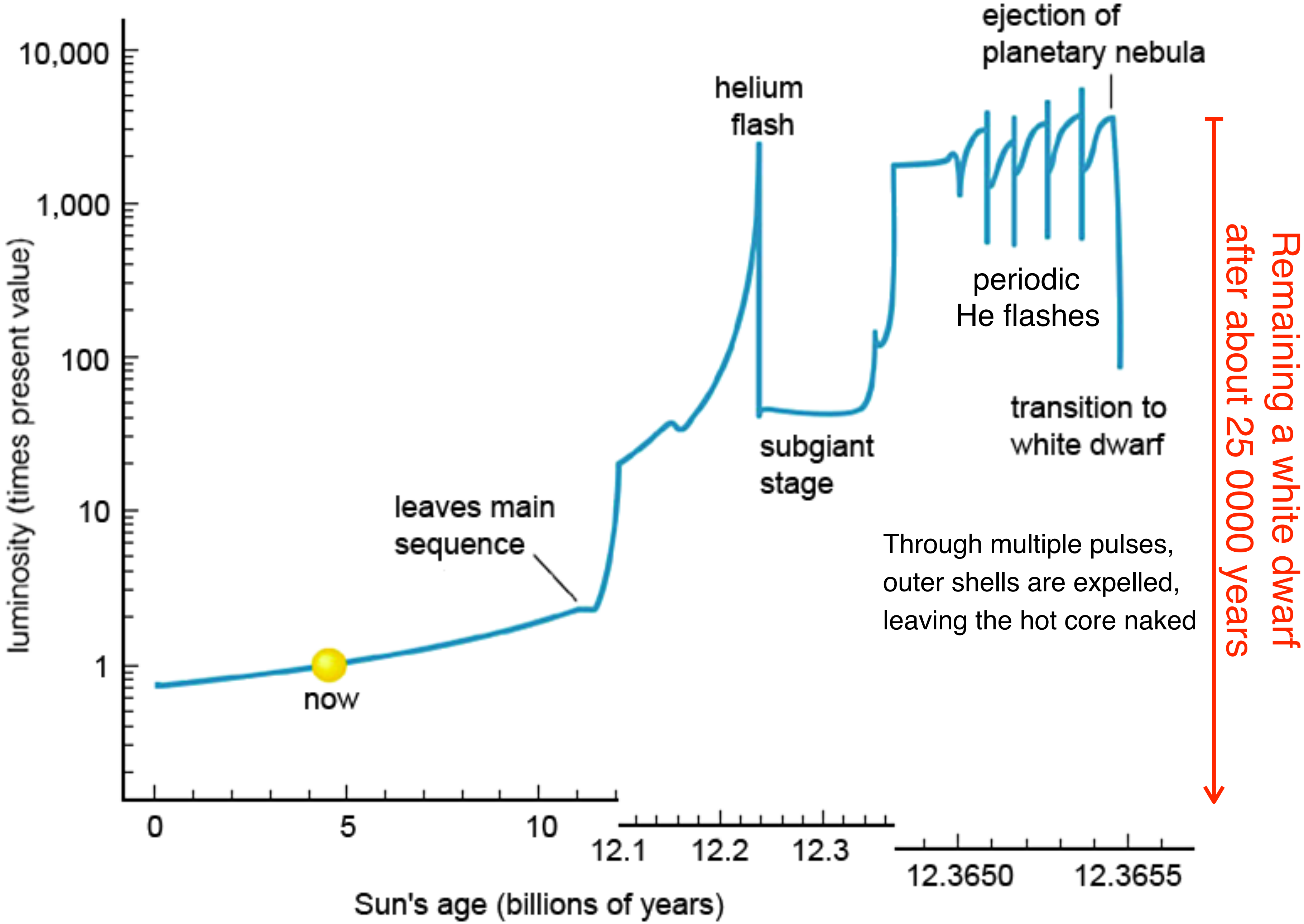
During He fusion, small changes in $T \rightarrow$ large changes in energy release ($E \propto T^{40}$)

Huge **thermal pulses** destabilize outer envelope: ***Planetary Nebula*** phase

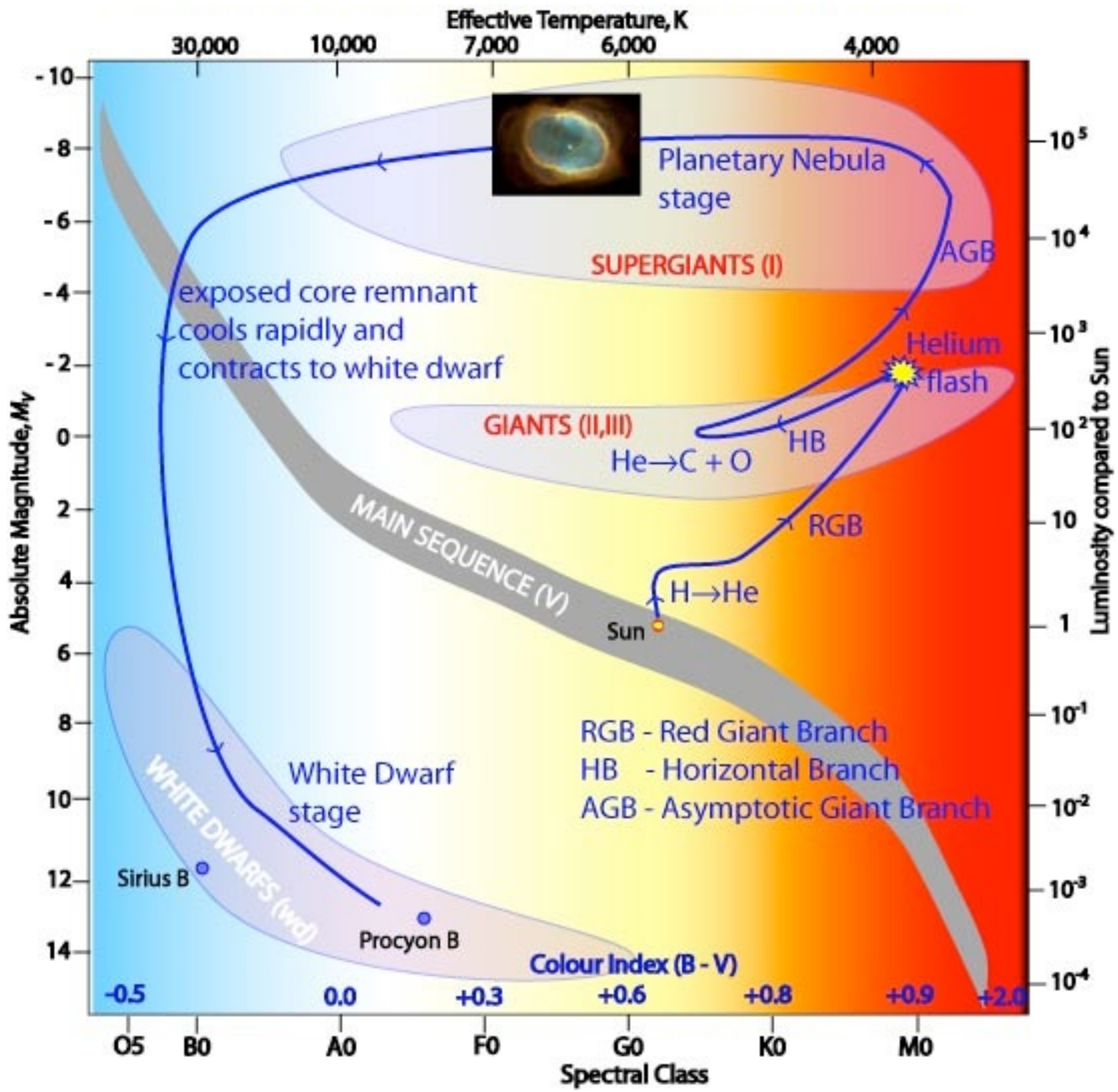
Planetary nebula: large tenuous gas shells expanding at $v \sim$ a few km/s
enough against gravity, gas dissipates in outer space in ~ 20,000 yr



Sun’s luminosity through time



Sun's post-MS time evolution



Planetary nebula gallery

Eskimo Nebula

Ring Nebula

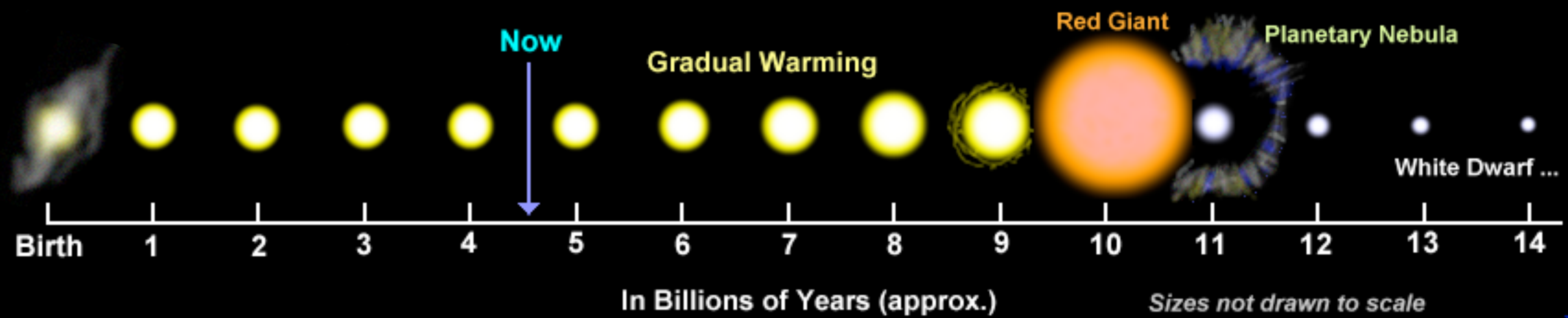
Necklace Nebula

Spirograph Nebula (IC 418)

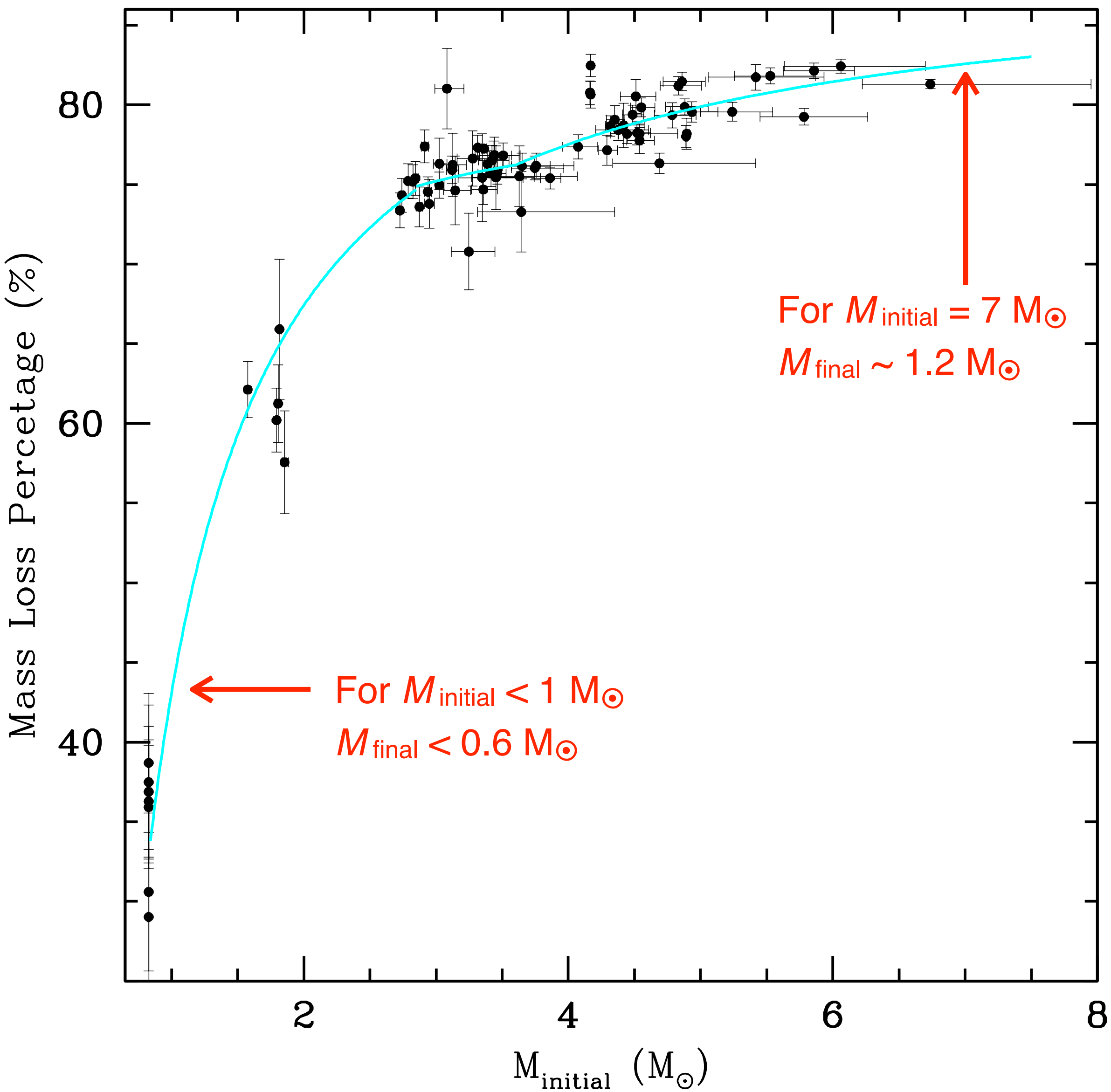
Cat’s Eye Nebula

Hour Glass Nebula

Life cycle of the Sun

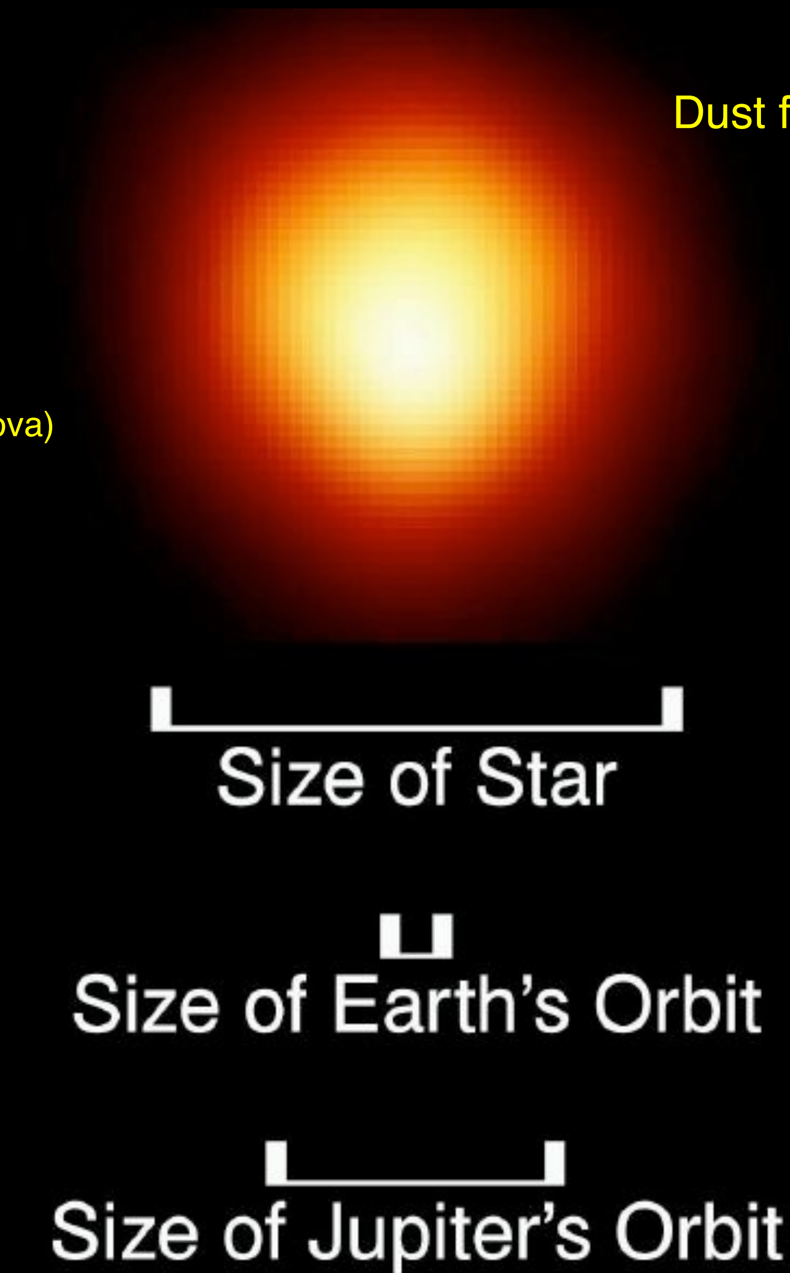


Total mass loss before white dwarf remnant as a percentage of initial mass



Stellar wind & mass loss in massive stars

Betelgeuse
Mass: $M = 15 - 20\ M_{\odot}$
Surface temperature: $T \sim 3600$ K
Radius: $R \sim 1000\ R_{\odot}$
Stage before massive explosion (supernova)



Dust forms in atmosphere of red giant stars
Thanks to: low gravity
high gas density
low temperature

Mass loss in massive stars due to radiation pressure

<u>Mass loss rate:</u>

$M = 100\ M_\odot$ star: up to 1/2 mass before end of MS

O stars: $10^{-6}\ M_\odot$ / yr

The Sun: $10^{-14}\ M_\odot$ / yr

Wolf-Rayet star *WR124*

Distance: 3.35 kpc

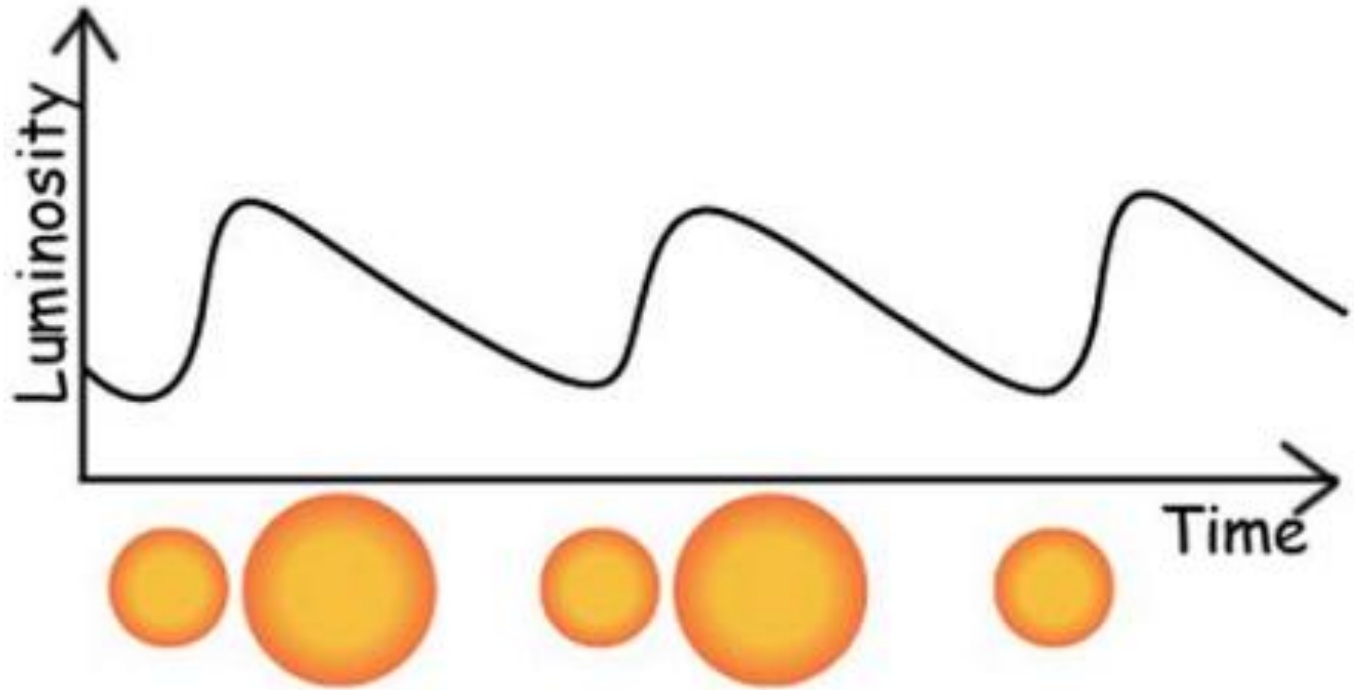
Mass: $M = 9\ M_\odot$

Temperature: $T = 35{,}900$ K

Age: 8.6 Myr

Variable stars: *Cepheids*

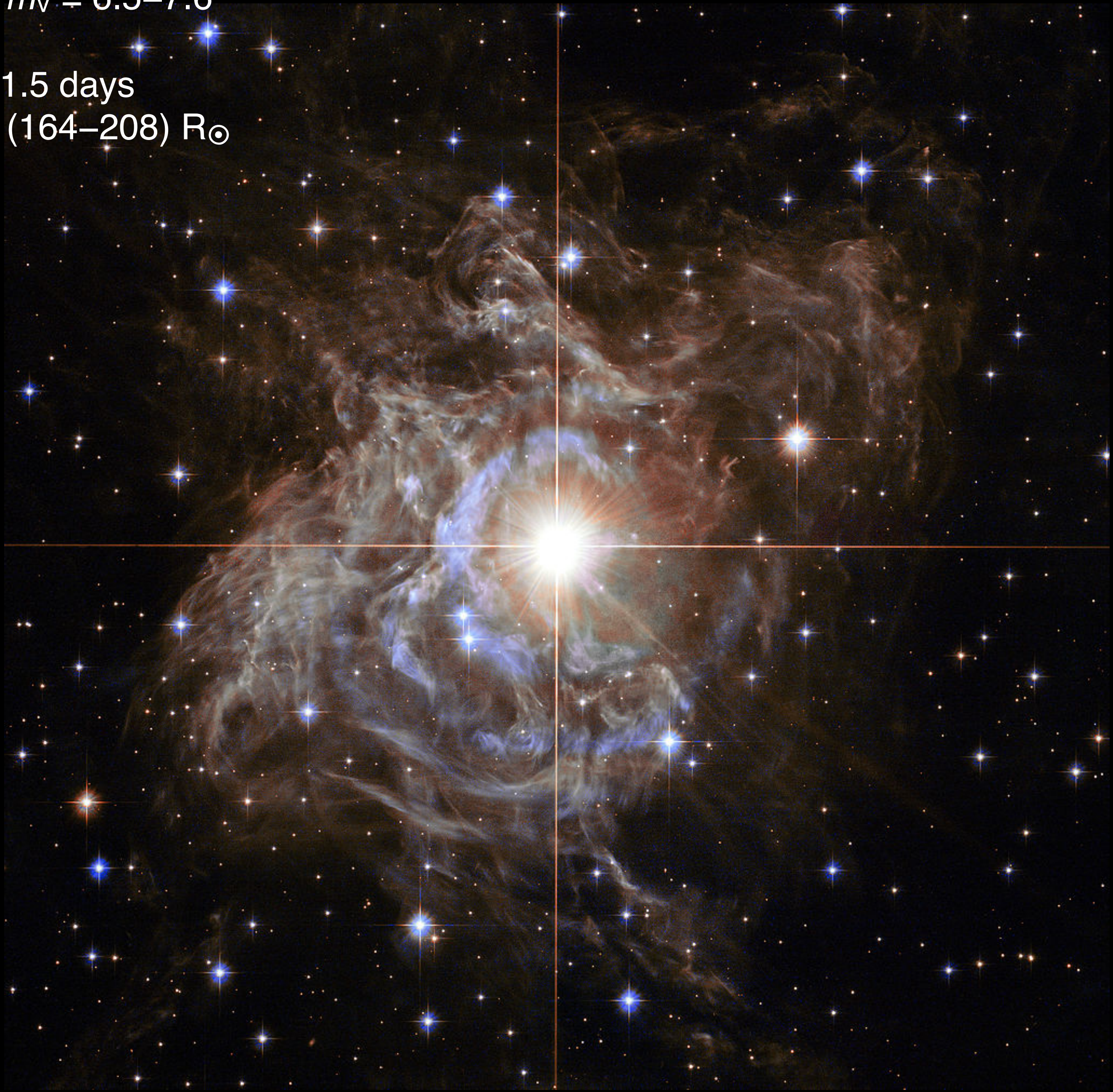
(masses are 4–20 times higher than the Sun)



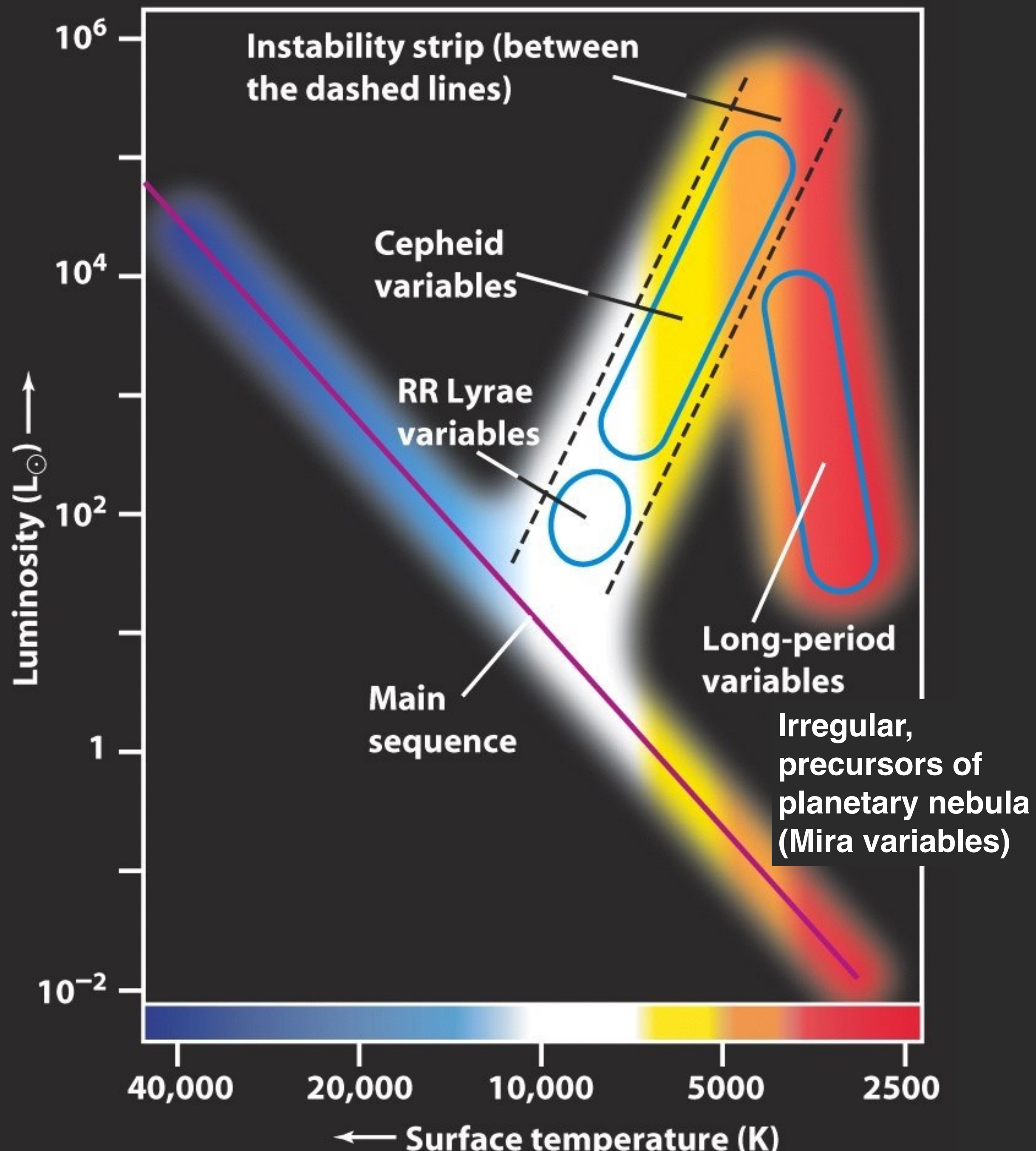
- Stars in AGB (He-shell burning) developing **thermal pulses** (*R* varies by more than 10%)
- At distance from center where $T = 40{,}000$ K → He^{+} → He^{2+} → free electrons interacting with radiation (gas less transparent) → radiation trapped inside → *P* goes up, layers inside expands, density drops → → layer gets transparent again
- Regular cycle repeats (pulsation)
- During pulsation, large mass loss ($10^{-6}\ M_{\odot}$ / yr), dust grains and molecules formation (relatively high density and low temperature in outflow) → circumstellar shell formation
- Pulsation is short in star's lifetime

Cepheid variable star *RS Puppis*

Apparent magnitude: $m_V = 6.5–7.6$
Mass: $M = 9.2\ M_\odot$
Period of pulsation: 41.5 days
Radius variation: $R = (164–208)\ R_\odot$
Distance: 1.7 kpc



Pulsating stars



Evolution of massive stars after MS

When $T = 3\times10^8$ K in core in red giant stars (***M* < 8 M$_\odot$**), carbon fusion starts

3α (**triple alpha**) process in He core for **carbon production**:

$$^{4}He + {}^{4}He \rightleftharpoons {}^{8}Be$$

$$^{4}He + {}^{8}Be \rightleftharpoons {}^{12}C^{*} \rightarrow {}^{12}C + 2\gamma$$

Then carbon fusion for **oxygen production**:

$$^{4}He + {}^{12}C \rightarrow {}^{16}O + \gamma$$

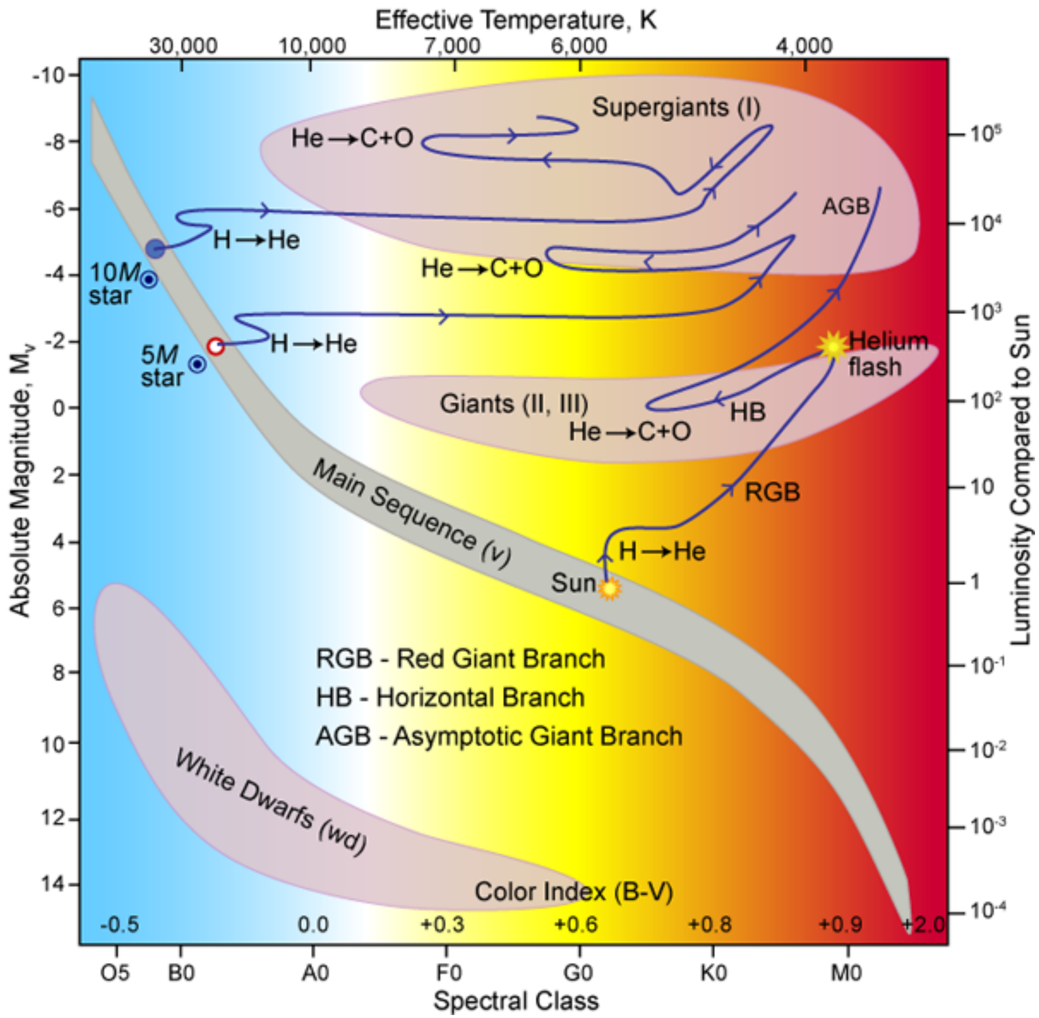
These two processes **main source of C and O in the universe**
For *M* < 8 M$_\odot$, other reactions not triggered (core left with O & C)

Evolution of **massive stars** ($M > 5\ M_\odot$) after MS

Color changes → T drops to 4000 K (red)

Luminosity doesn't change much → R gets very large (*Betelgeuse*: $R = 1000\ R_\odot$ for $M = 20\ M_\odot$)

Due to mass loss (winds or in binary systems), color can change from blue to red and back



For $M > 5\ M_\odot$, **radiation pressure** main support to star

Element production in massive stars (mass limits not precisely known!)

Core contracts $\Longrightarrow$ T in the core increases

- **For $M > 5\ M_\odot$:**

When He exhausted in the core, T goes up to 3×10^8 K, then oxygen production:

$^{12}{}_{6}C + {}^{4}{}_{2}He \rightarrow {}^{16}{}_{8}O + \gamma$

This, 3α and H shell burning main sources of energy

- **For $M > 8\ M_\odot$, carbon fusion** in core (**elements** with mass number $A \sim 20$ formed):

$^{12}{}_{6}C + {}^{12}{}_{6}C \rightarrow {}^{24}{}_{12}Mg + \gamma$
$^{12}{}_{6}C + {}^{12}{}_{6}C \rightarrow {}^{23}{}_{11}Na + {}^{1}{}_{1}H$
$^{12}{}_{6}C + {}^{12}{}_{6}C \rightarrow {}^{20}{}_{10}Ne + {}^{4}{}_{2}He$

New reactions with heavier elements (from C to Mg)

$T = 10^9$ K, **photo-disintegration** of nuclei, reverse reaction. Moreover, **neon burning** to give Mg:

$^{20}{}_{10}Ne + \gamma \rightarrow {}^{16}{}_{8}O + {}^{4}{}_{2}He$

$^{20}{}_{10}Ne + {}^{4}{}_{2}He \rightarrow {}^{24}{}_{12}Mg + \gamma$

$T = 2 \times 10^9$ K, **oxygen burning** in core to give Si:

$^{16}{}_{8}O + {}^{16}{}_{8}O \rightarrow {}^{28}{}_{14}Si + {}^{4}{}_{2}He$

α particle reacts immediately & disappears

After O exhausted, $T \rightarrow 3 \times 10^9$ K, **photo-disintegration** of Si:

$^{28}{}_{14}Si + \gamma \rightarrow {}^{24}{}_{12}Mg + {}^{4}{}_{2}He$

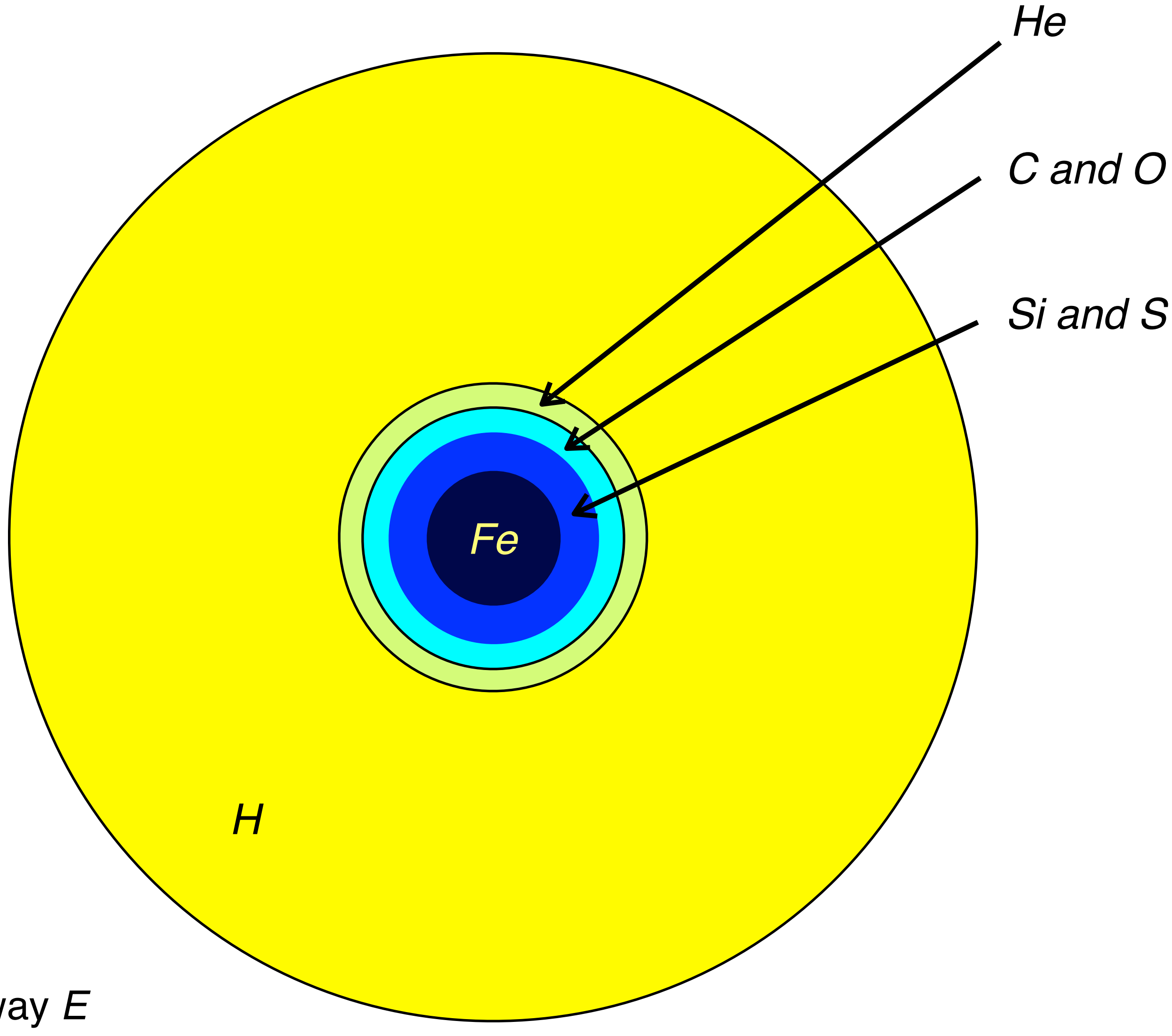
α particle reacts with Si and subsequent elements (**silicon burning**):

$^{28}{}_{14}Si + {}^{4}{}_{2}He \rightarrow {}^{32}{}_{16}S + \gamma$
$^{32}{}_{16}S + {}^{4}{}_{2}He \rightarrow {}^{36}{}_{18}Ar + \gamma$
$^{36}{}_{18}Ar + {}^{4}{}_{2}He \rightarrow {}^{40}{}_{20}Ca + \gamma$
....

Fast sequence of fusion before **final explosion**

Until $A \sim 56$ reached. **Iron group** elements: Fe, Cr, Mn, Co, Ni (when completed, $T = 7 \times 10^9$ K)

Highly evolved **supergiant** with different shells of heavier elements going to center (like onion) with iron core



Each reaction faster
Less *E* produced
More neutrinos carrying away *E*
P cannot stop gravitational collapse

This condition will soon take to massive explosion & star destruction (**supernova**)

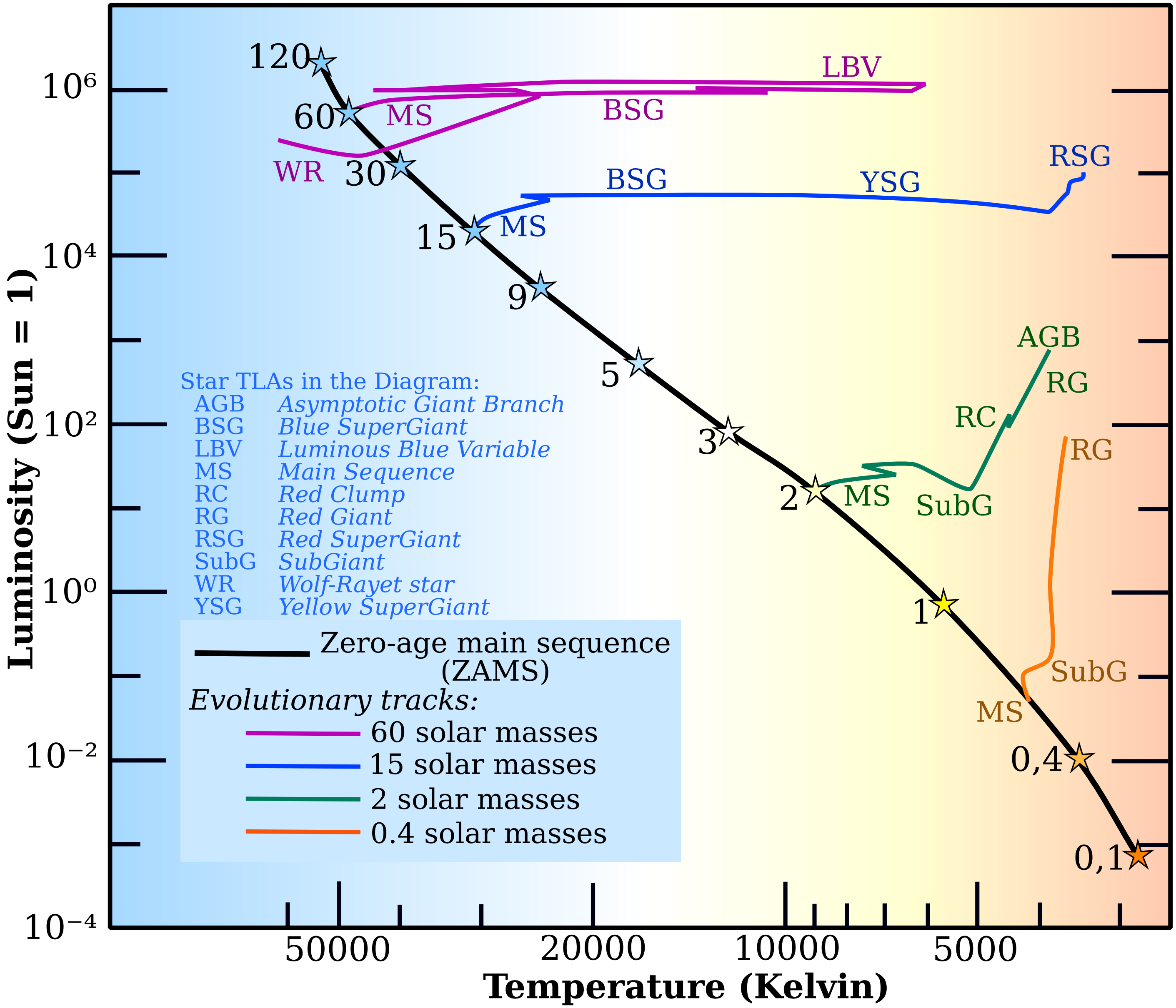
Life time of a star with mass $\boldsymbol{M = 25\ M_\odot}$

(before explosion as a supernova)

<u>Chemical elements consumption time in the core</u>

Hydrogen (main sequence) .... 6 million years
Helium .... 500,000 years
Carbon ………………………………………… 600 years
Neon ……………………………………………... 1 year
Oxygen ………………………………………… 6 months
Silicon ………………………………………….. ~ 1 day

Summary: evolution of stars in Hertzsprung-Russel diagram



Summary of element production in stars (before mass loss)

$M < 0.5\ M_\odot$	up to He
$0.5\ M_\odot < M < 8\ M_\odot$	up to about O
$8\ M_\odot < M < 10\ M_\odot$	up to about Mg + small amount of heavier elements
$M > 10\ M_\odot$	wide range of elements, including Fe peak & heavier

Heaviest elements produced by different process: merger of stellar remnants after supernova (neutron stars) & nuclear reactions in new explosive event (*kilonova*)