Week 9: Stellar Evolution / ISM

HW7 due Thursday at 10:45am

Read Ch. 15.3, 17.1-3, 16.1-2,
& Ch. 18 (either for Thursday or next week)

Syllabus updated

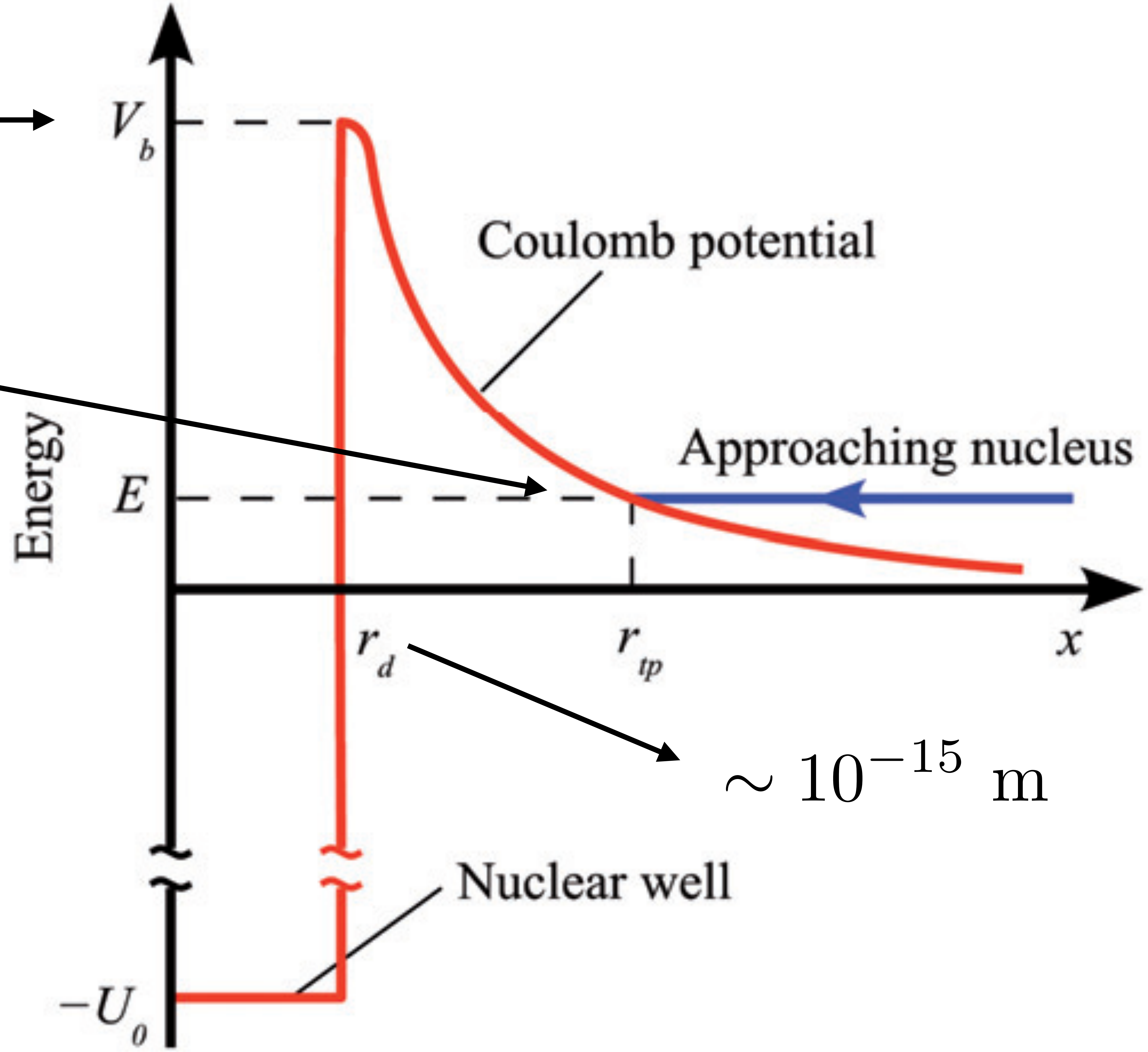
Fusion possible b/c of QM

$$U \approx \frac{e^2}{4\pi\epsilon_0 r} = 1.4 \text{ MeV}$$

$$\langle E \rangle = \frac{3}{2}kT_c \approx 2 \text{ keV}$$

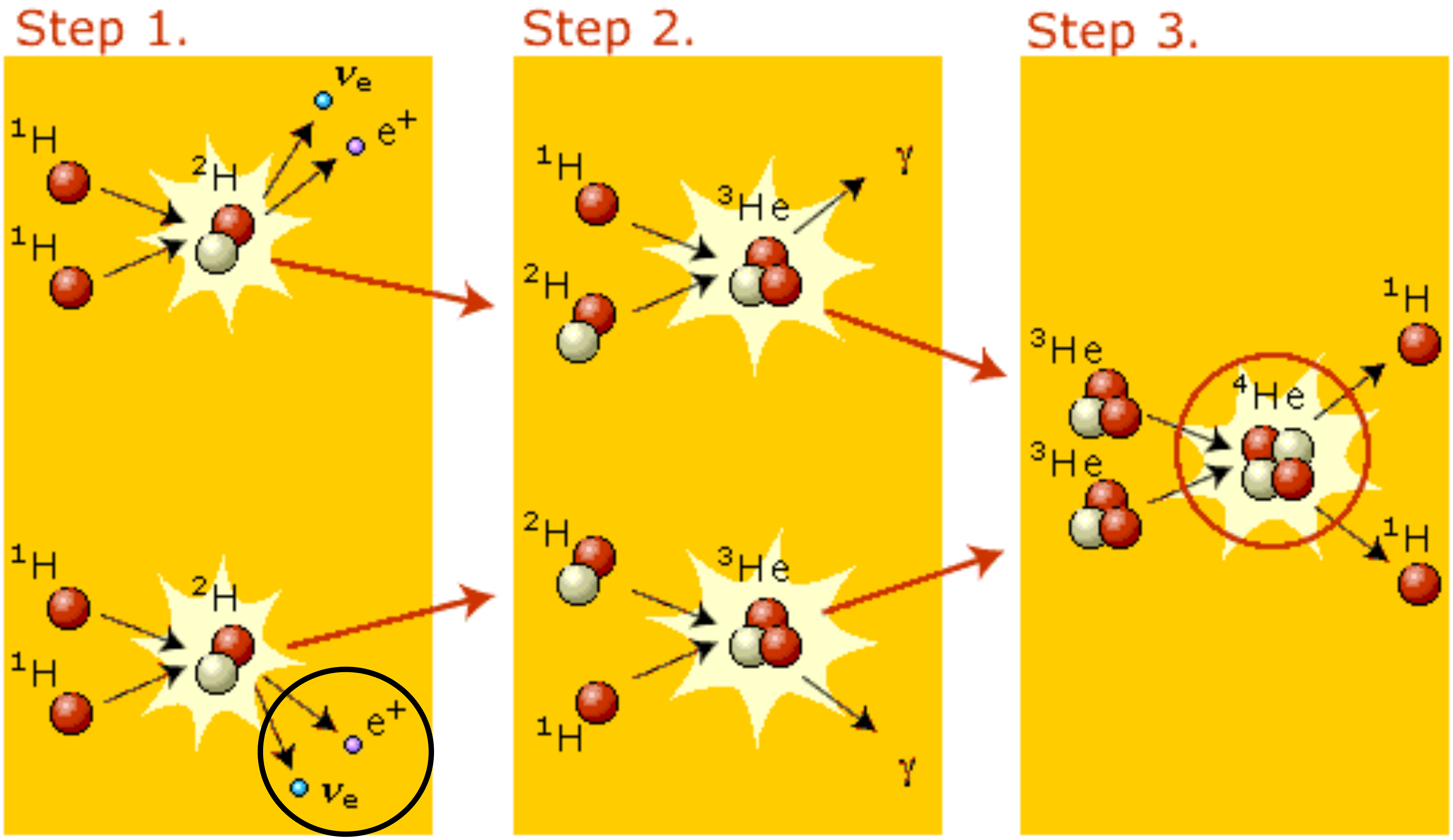
Particles are waves!

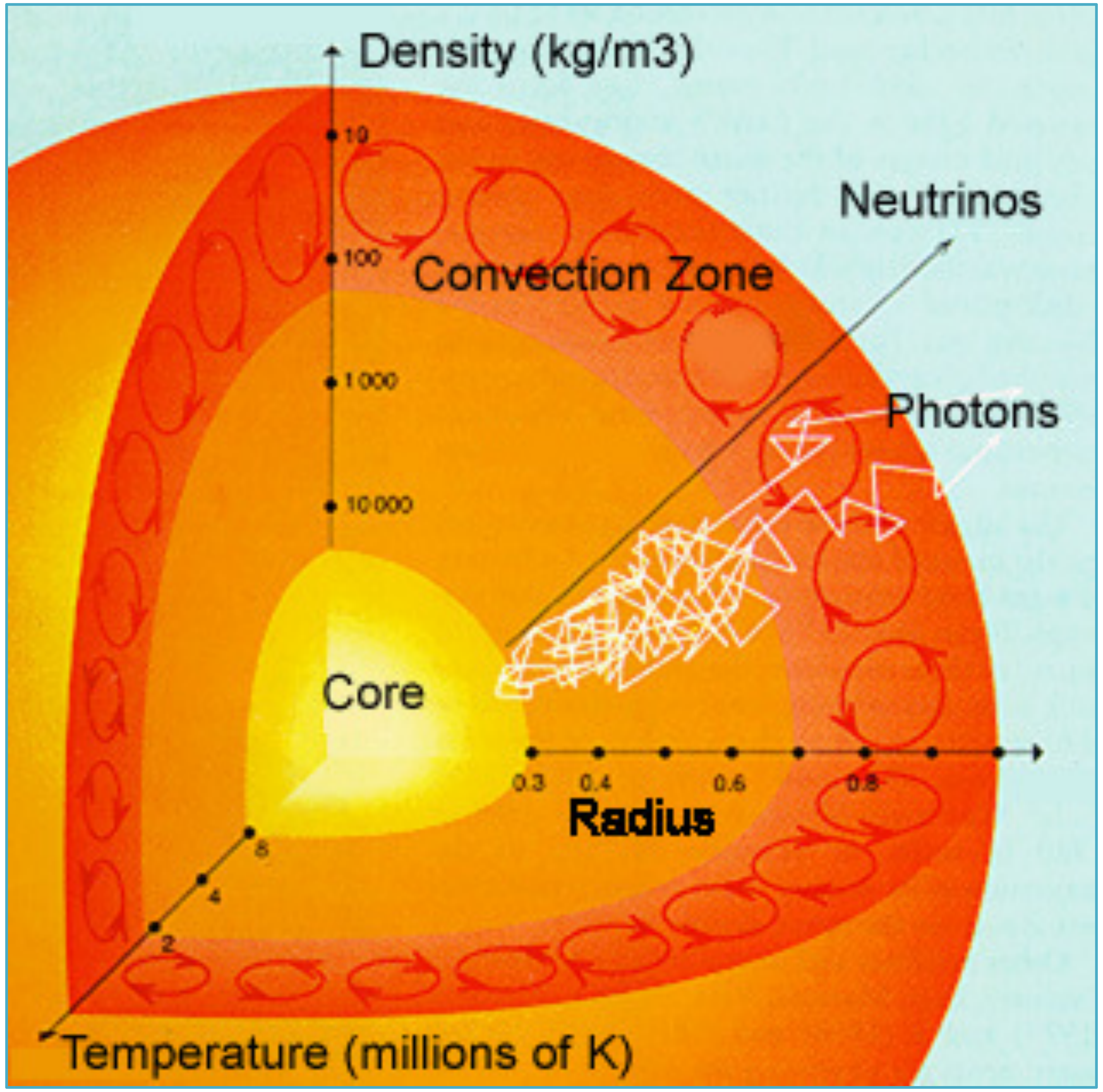
$$\lambda_{\text{prot}} = \frac{h}{p} = \frac{h}{m_p v} \approx 10^{-13} \text{ m}$$



$\sim 10^{-15}$ m

Proton-proton chain: $T_c < 1.8 \times 10^7$ K

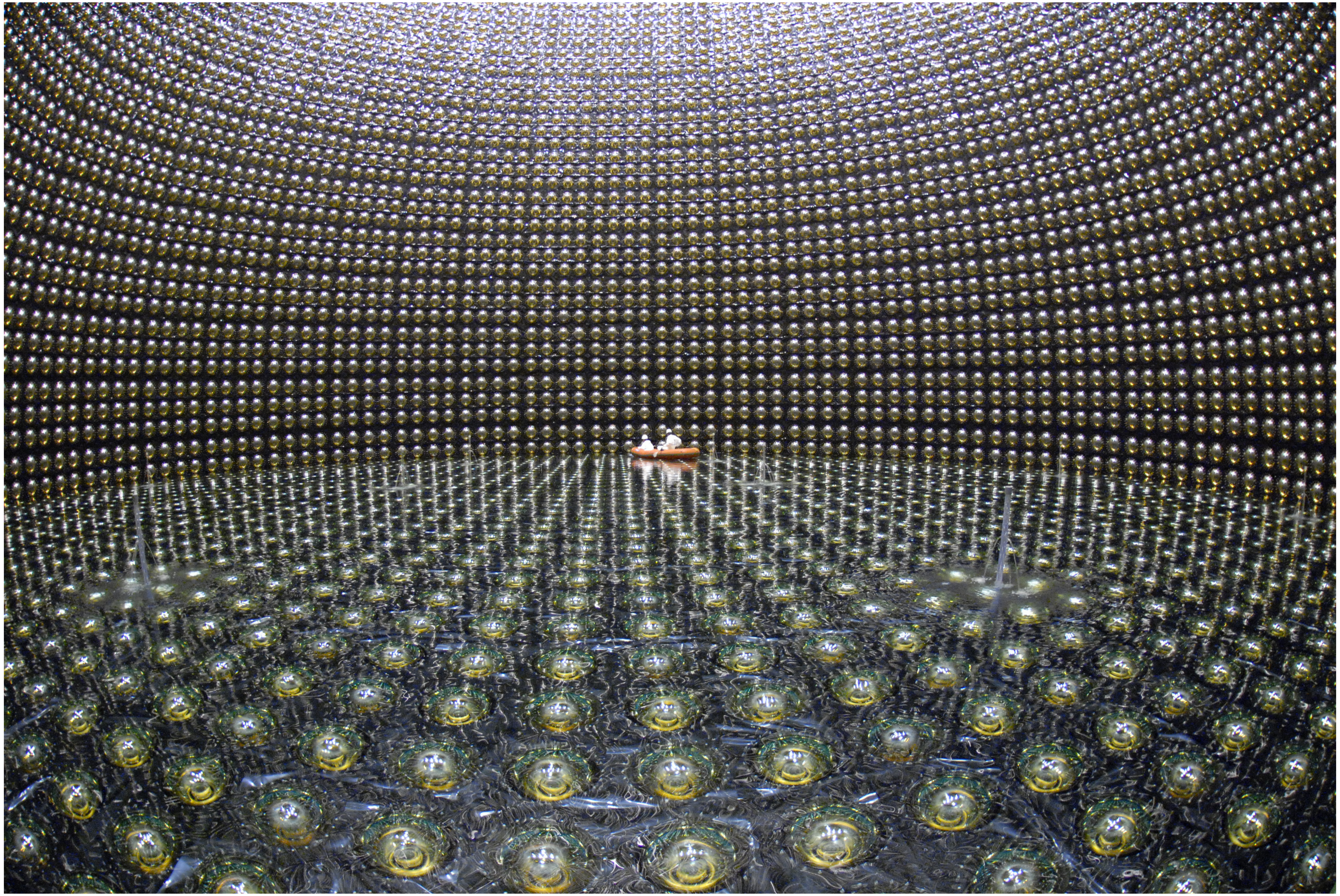




$$4\ \mathrm{p} \rightarrow {}^4\mathrm{He} + 2\gamma + 2\mathrm{e}^+ + 2\nu_\mathrm{e}$$

$$\mathrm{e}^+ + \mathrm{e}^- \rightarrow 2\gamma$$

Neutrino Detector



Super Kamiokande, Japan

CNO cycle: $T_c > 1.8 \times 10^7$ K

Carbon, Nitrogen, Oxygen used as catalysts

$$^{12}\mathrm{C} + 4\mathrm{p} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$$

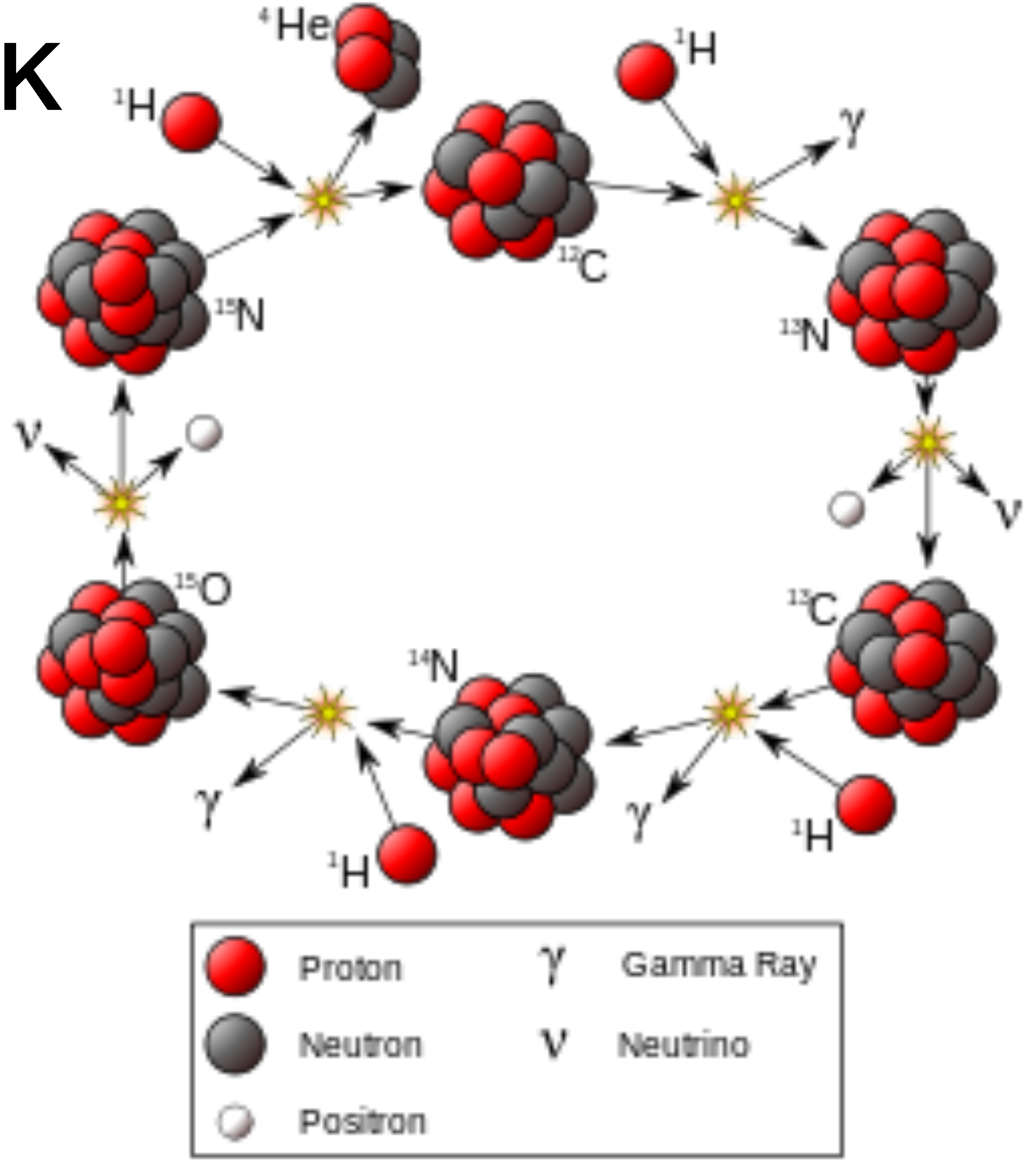
plus photons, neutrinos, and positrons

Triple Alpha Process

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be} + \gamma$$

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

Decays quickly, needs $T > 10^8$ K and high density so it encounters another helium nucleus (alpha particle) before it does



“Star” —> undergoing fusion

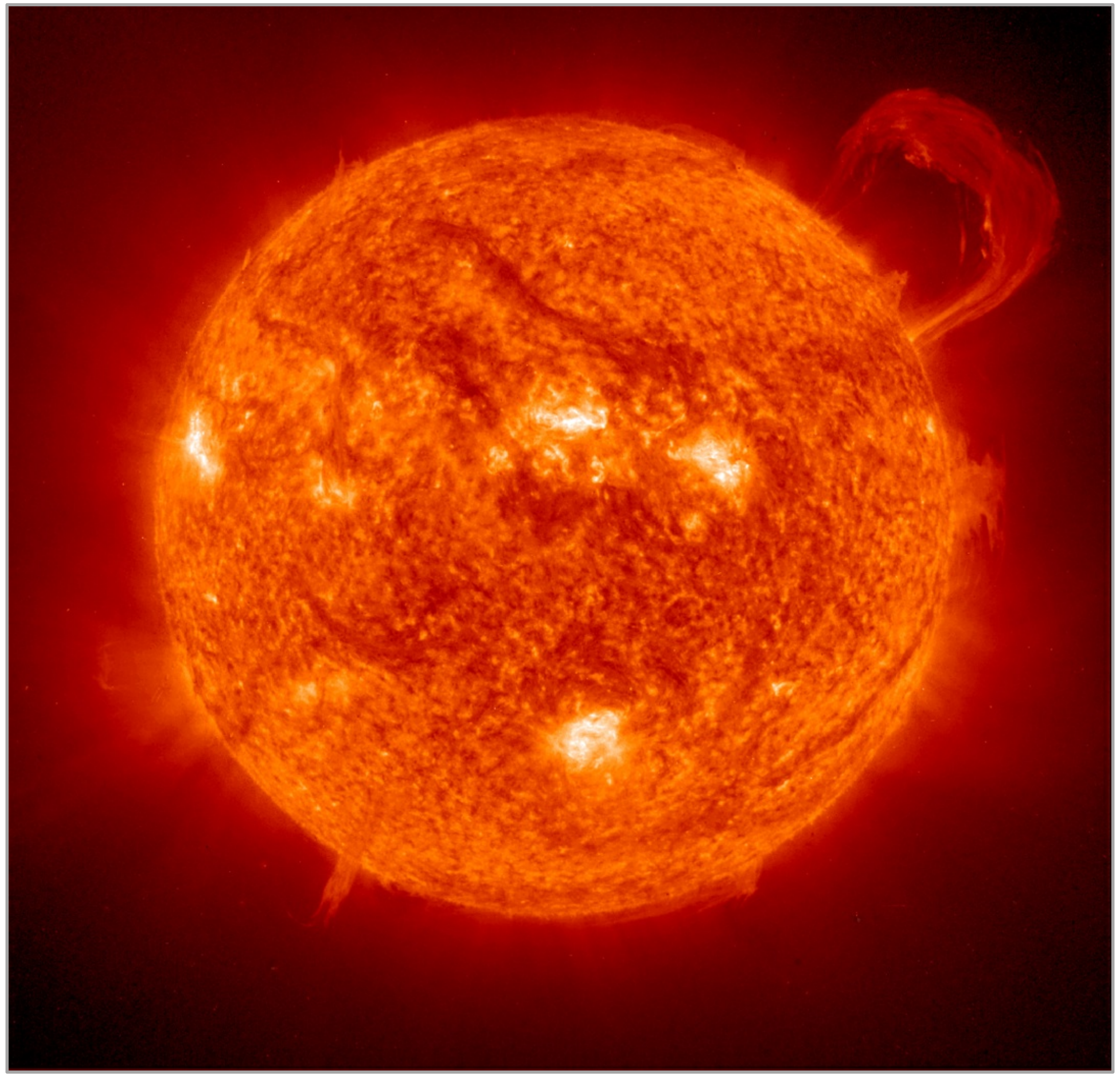
Formed from clouds of gas that collapse due to self-gravity

Density:

10^{-15} kg m^{-3}

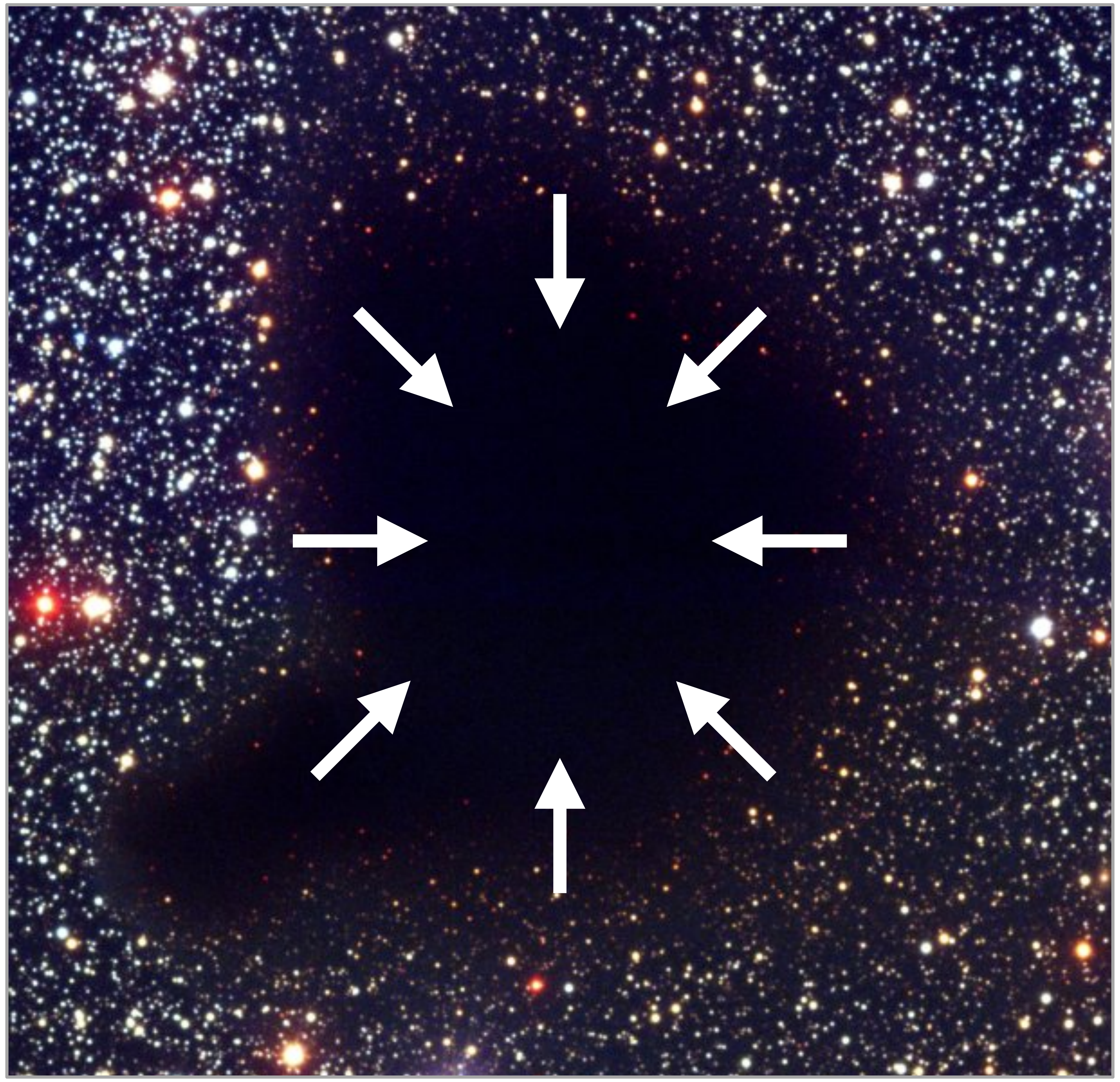
→

1400 kg m^{-3}



Forming a Star

Formed from clouds of gas that collapse due to self-gravity



Imagine a gas particle on an orbit with *e* = 1

$$P^2 = \frac{4\pi^2}{G}\frac{a^3}{M}$$

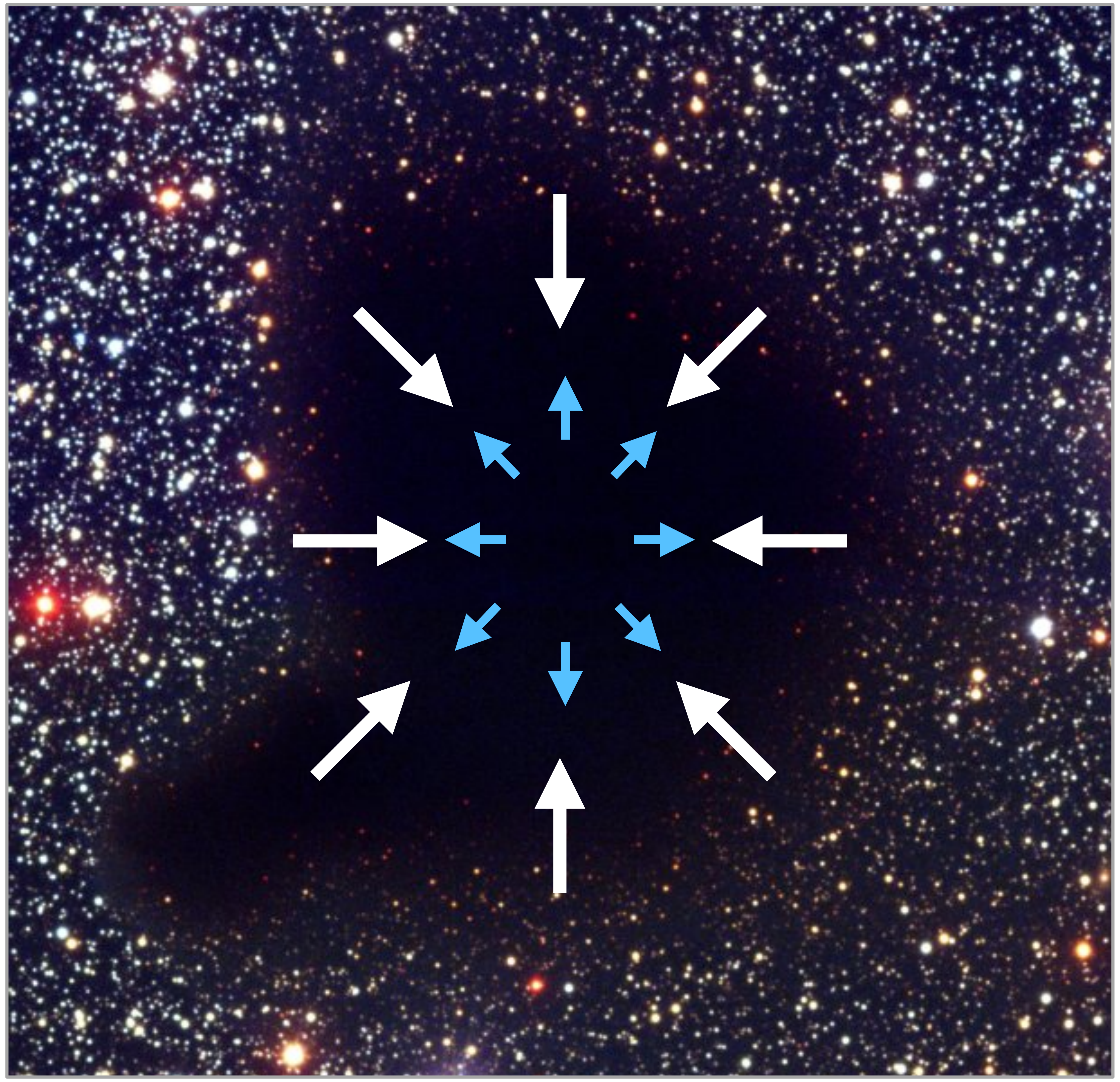
Halfway through the orbit, it reaches the center

$$t_{\rm ff} = \frac{P}{2} = \frac{2\pi}{2G^{1/2}}\frac{(r_0/2)^{3/2}}{M^{1/2}}$$
$$= \frac{\pi}{G^{1/2}}\frac{r_0^{3/2}}{(8\cdot 4\pi r_0^3\rho_0/3)^{1/2}}$$

$$t_{\rm ff} = \left(\frac{3\pi}{32G\rho_0}\right)^{1/2}$$

“Star” —> undergoing fusion

Formed from clouds of gas that collapse due to self-gravity



Pressure in the gas can keep the cloud from collapsing —> HSE

BUT, once a cloud of a given density and temperature reaches a critical size, it will collapse —> Jeans length

If density and size is determined, also have a critical mass —> Jeans mass

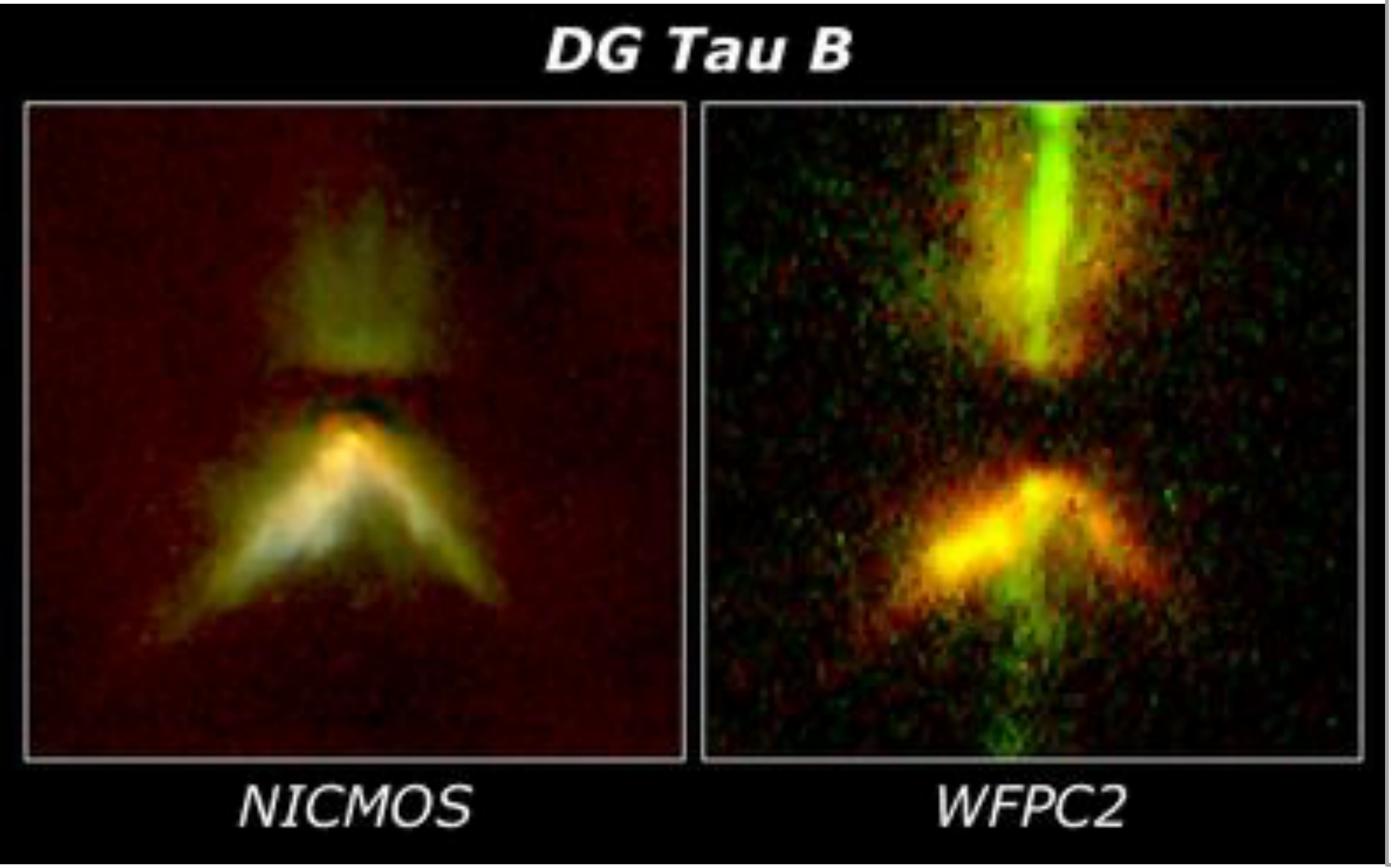
As a cloud collapses, density and temperature will change, causing the Jeans length and mass to shrink so the cloud fragments —> fragmentation

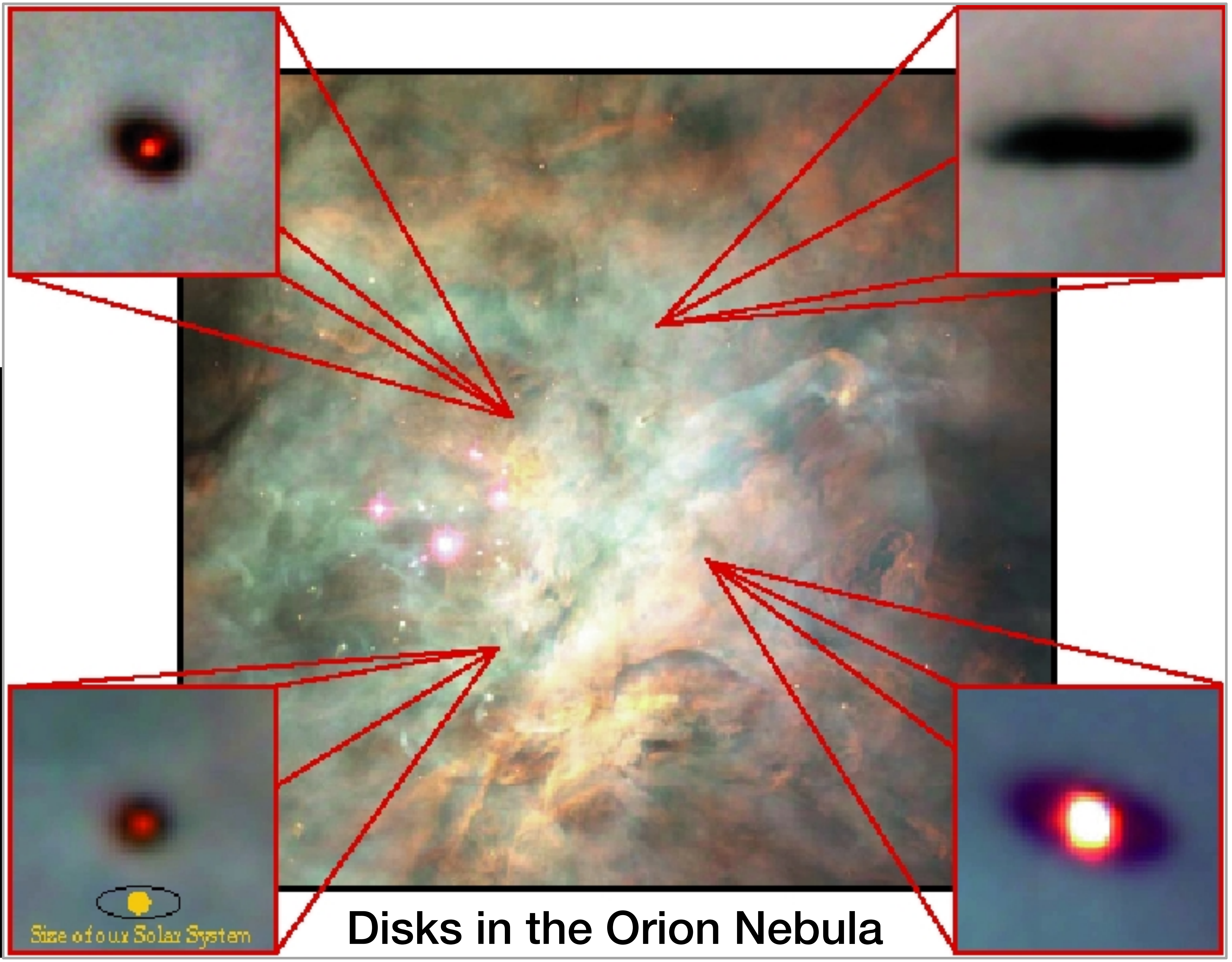
1 cloud produces many stars: a star cluster

Protostars form from an "accretion disk"

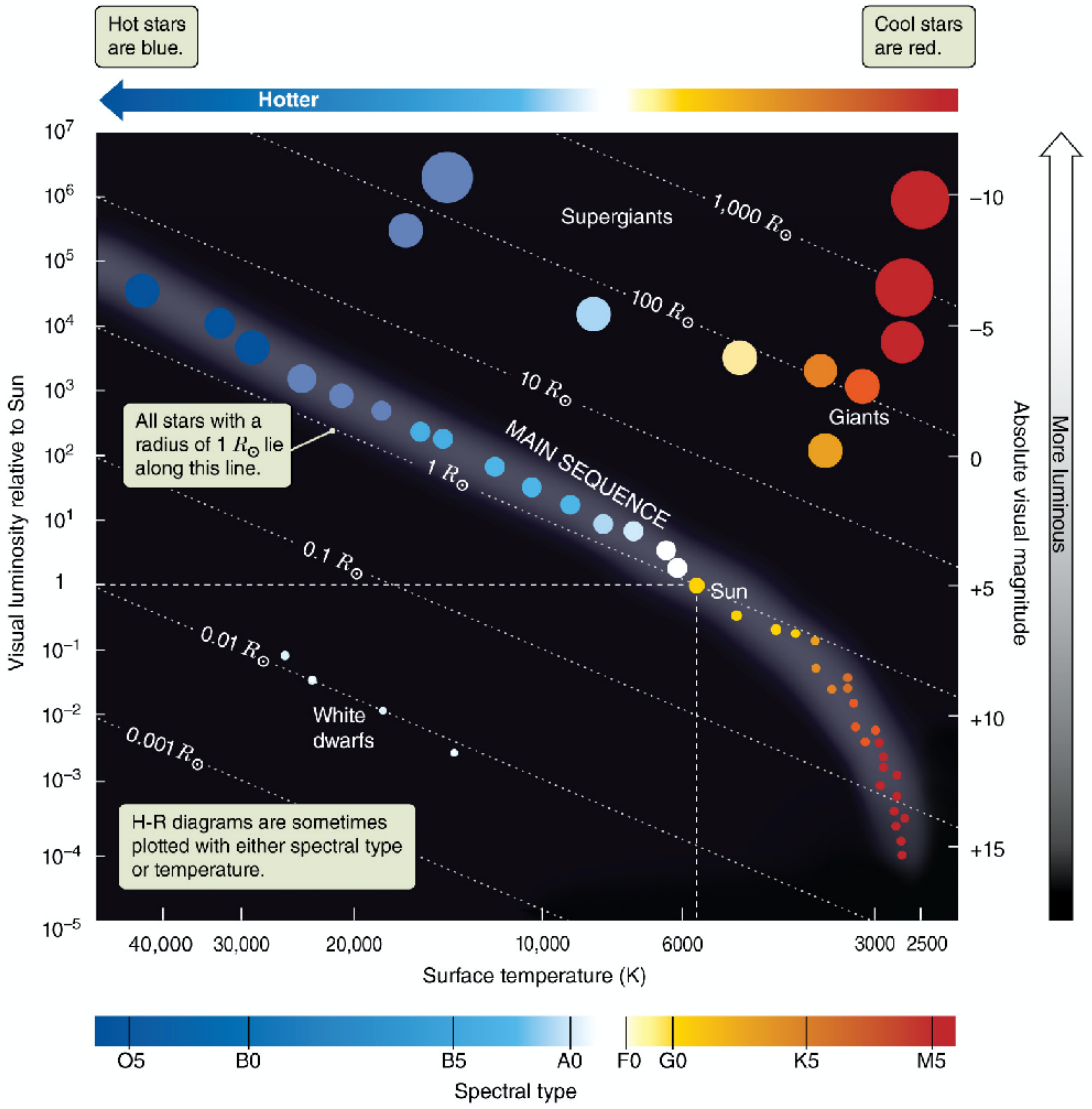
Angular momentum dissipated in the disk

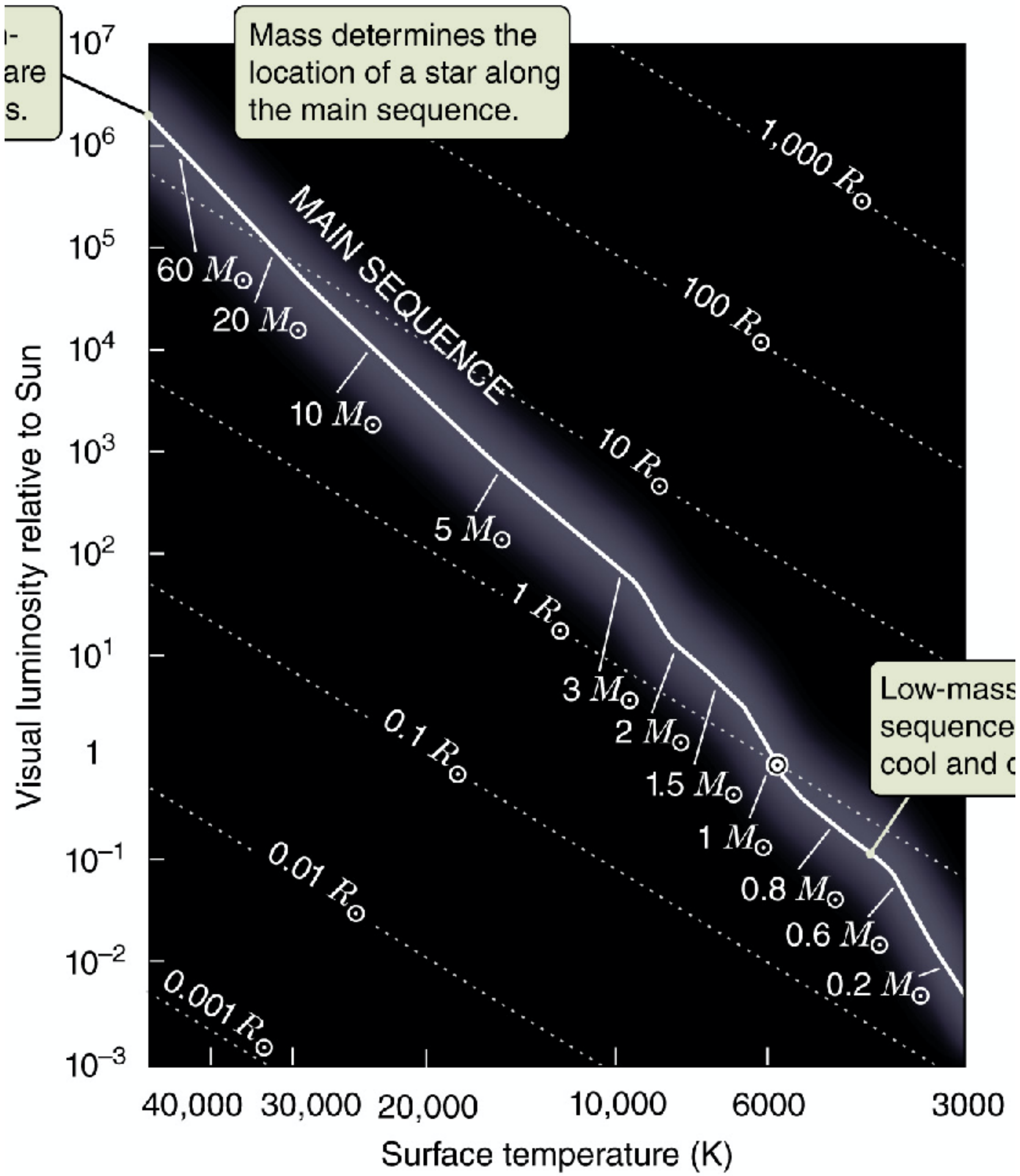
>99.9% of mass in the protostar, but planets with much less mass typically carry more angular momentum (which originates from the cloud)





Disks in the Orion Nebula


Hot stars are blue.
Cool stars are red.
Hotter
Supergiants
Giants
MAIN SEQUENCE
Sun
White dwarfs
All stars with a radius of 1 $R_\odot$ lie along this line.
H-R diagrams are sometimes plotted with either spectral type or temperature.
1,000 $R_\odot$
100 $R_\odot$
10 $R_\odot$
1 $R_\odot$
0.1 $R_\odot$
0.01 $R_\odot$
0.001 $R_\odot$
Visual luminosity relative to Sun
Absolute visual magnitude
More luminous
Surface temperature (K)
40,000 30,000 20,000 10,000 6000 3000 2500
Spectral type
O5 B0 B5 A0 F0 G0 K5 M5


Mass determines the location of a star along the main sequence.
MAIN SEQUENCE
60 $M_\odot$
20 $M_\odot$
10 $M_\odot$
5 $M_\odot$
3 $M_\odot$
2 $M_\odot$
1.5 $M_\odot$
1 $M_\odot$
0.8 $M_\odot$
0.6 $M_\odot$
0.2 $M_\odot$
1,000 $R_\odot$
100 $R_\odot$
10 $R_\odot$
1 $R_\odot$
0.1 $R_\odot$
0.01 $R_\odot$
0.001 $R_\odot$
Visual luminosity relative to Sun
Surface temperature (K)
40,000 30,000 20,000 10,000 6000 3000

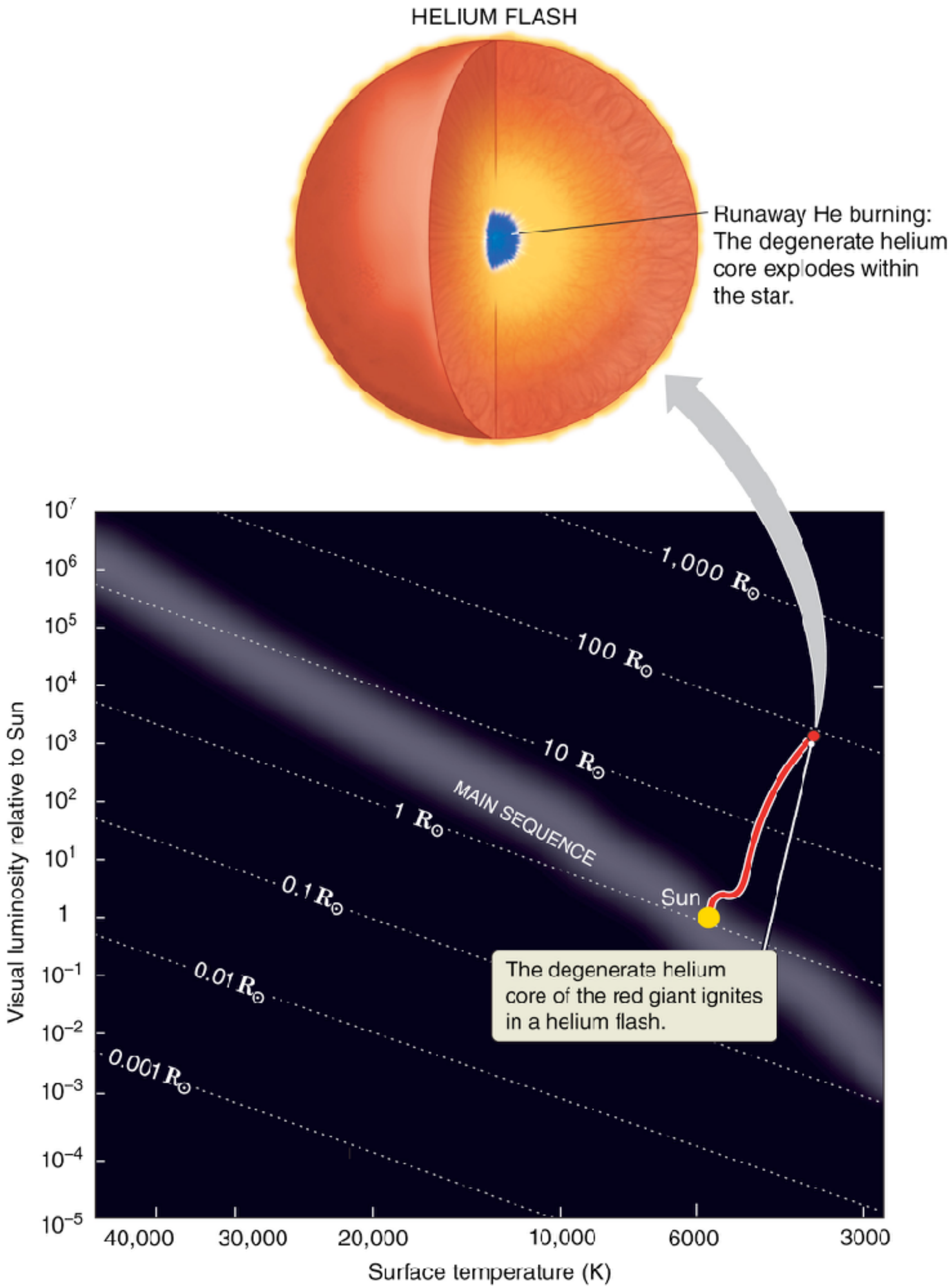
Lifetime as a function of mass

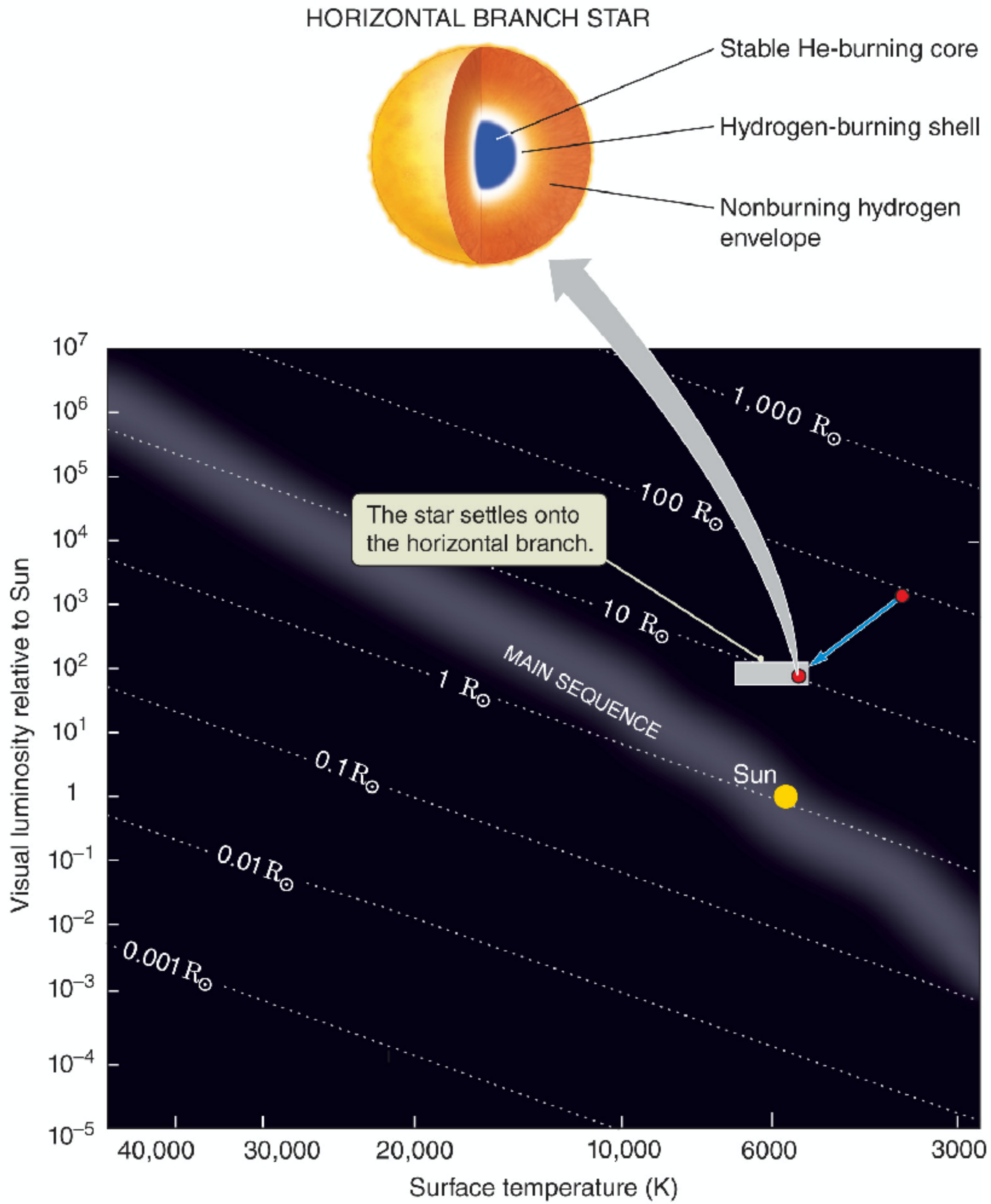
$$\text{Main Sequence Lifetime} = 1 \times 10^{10} \, \frac{\text{Mass}\,[\mathrm{M}_\odot]}{\text{Luminosity}\,[\mathrm{L}_\odot]} \text{ years}$$

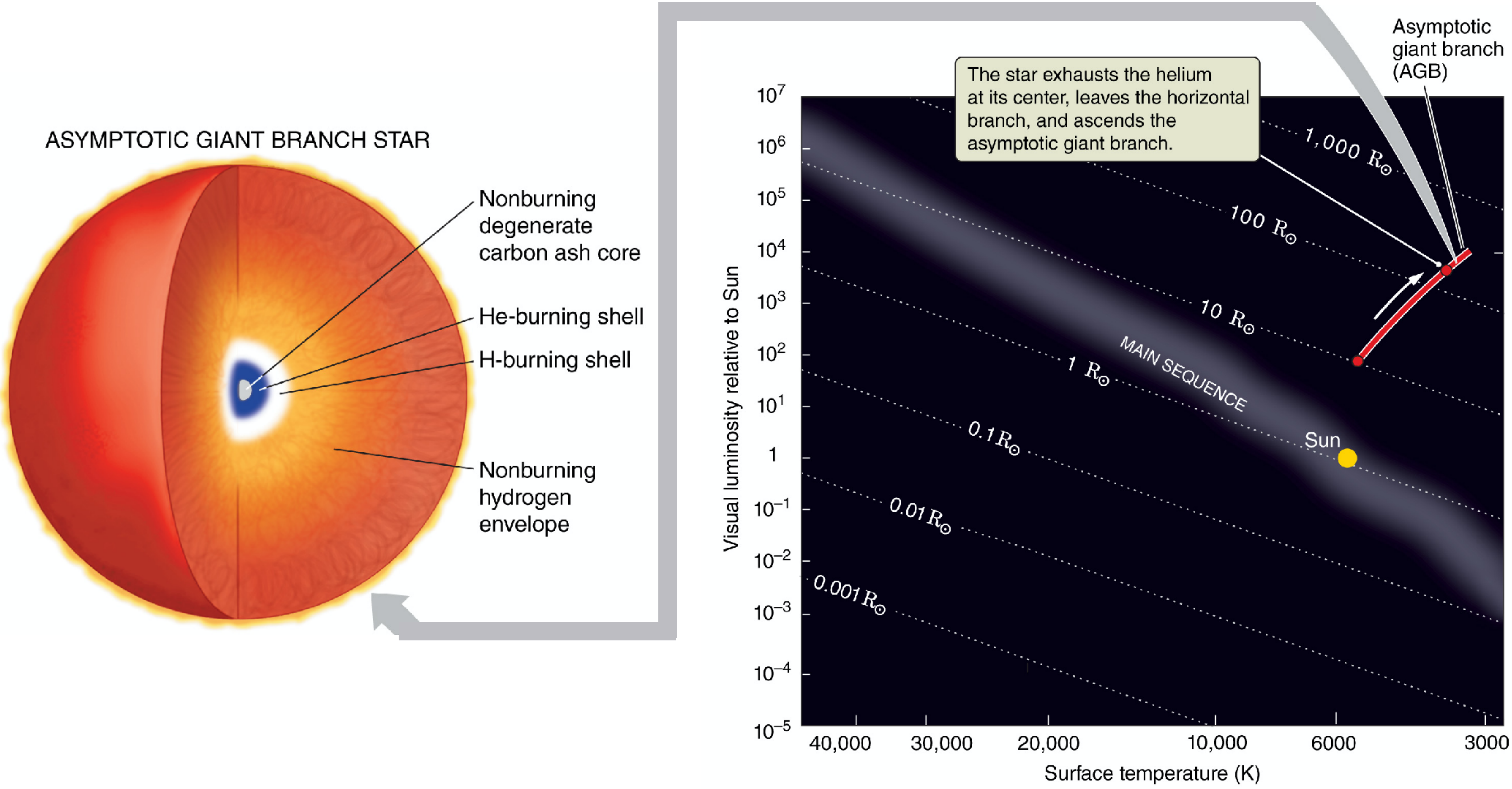
$$\frac{L_{\rm MS}}{L_\odot} = \left(\frac{M_{\rm MS}}{M_\odot}\right)^{3.5}$$

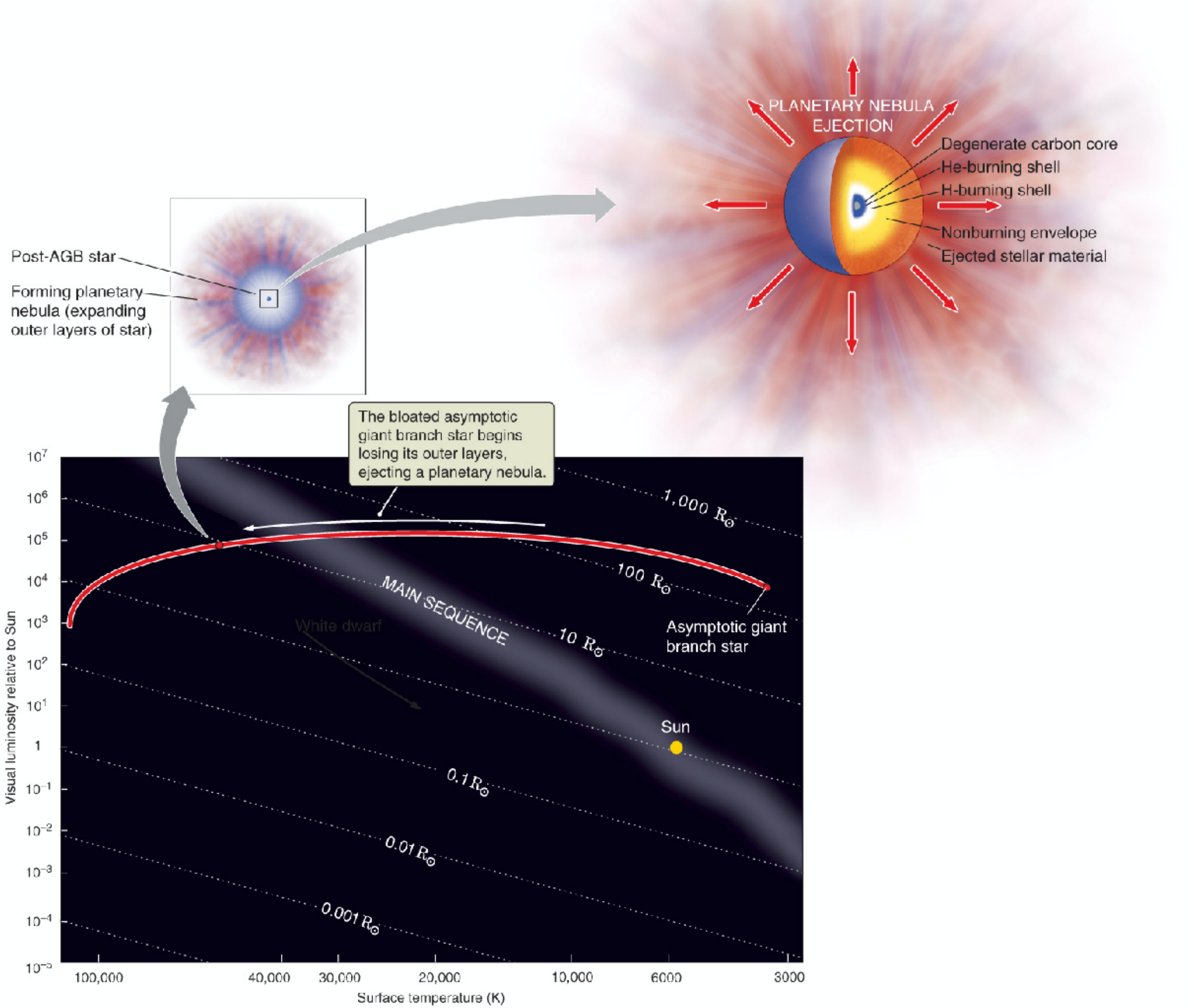
$$\text{Main Sequence Lifetime} = 10^{10} \, \frac{M_{\rm MS}/M_\odot}{(M_{\rm MS}/M_\odot)^{3.5}} \text{ years}$$

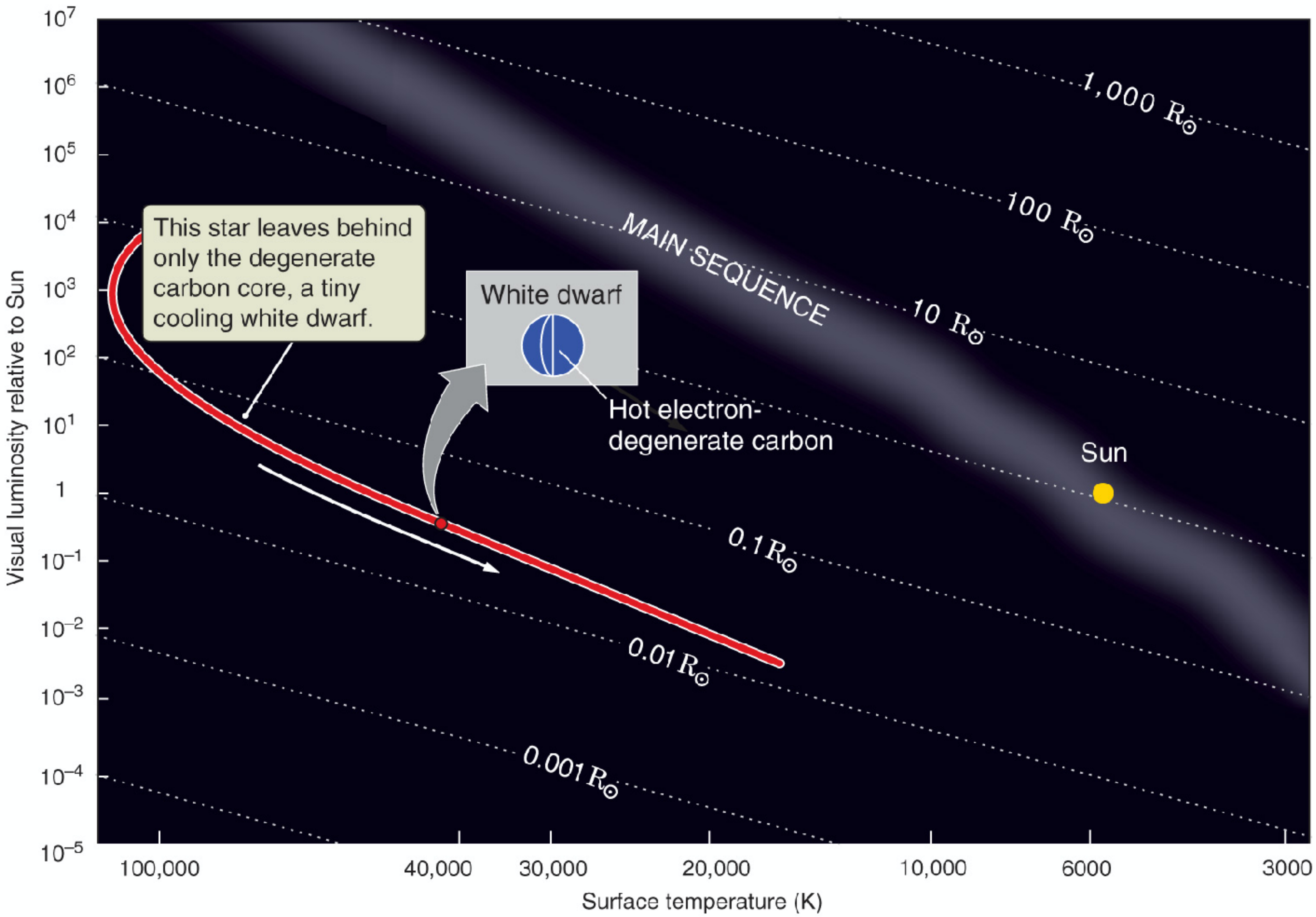
$$\text{Main Sequence Lifetime} = 10^{10} \left(\frac{M_{\rm MS}}{M_\odot}\right)^{-2.5} \text{ years}$$


HELIUM FLASH
Runaway He burning: The degenerate helium core explodes within the star.
1,000 R⊙
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
MAIN SEQUENCE
Sun
The degenerate helium core of the red giant ignites in a helium flash.
Visual luminosity relative to Sun
Surface temperature (K)
40,000
30,000
20,000
10,000
6000
3000


HORIZONTAL BRANCH STAR
Stable He-burning core
Hydrogen-burning shell
Nonburning hydrogen envelope
1,000 R⊙
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
The star settles onto the horizontal branch.
MAIN SEQUENCE
Sun
Visual luminosity relative to Sun
Surface temperature (K)
40,000
30,000
20,000
10,000
6000
3000


ASYMPTOTIC GIANT BRANCH STAR
Nonburning degenerate carbon ash core
He-burning shell
H-burning shell
Nonburning hydrogen envelope
The star exhausts the helium at its center, leaves the horizontal branch, and ascends the asymptotic giant branch.
Asymptotic giant branch (AGB)
1,000 R⊙
100 R⊙
10 R⊙
1 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
MAIN SEQUENCE
Sun
Visual luminosity relative to Sun
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^−1
10^−2
10^−3
10^−4
10^−5
40,000
30,000
20,000
10,000
6000
3000
Surface temperature (K)

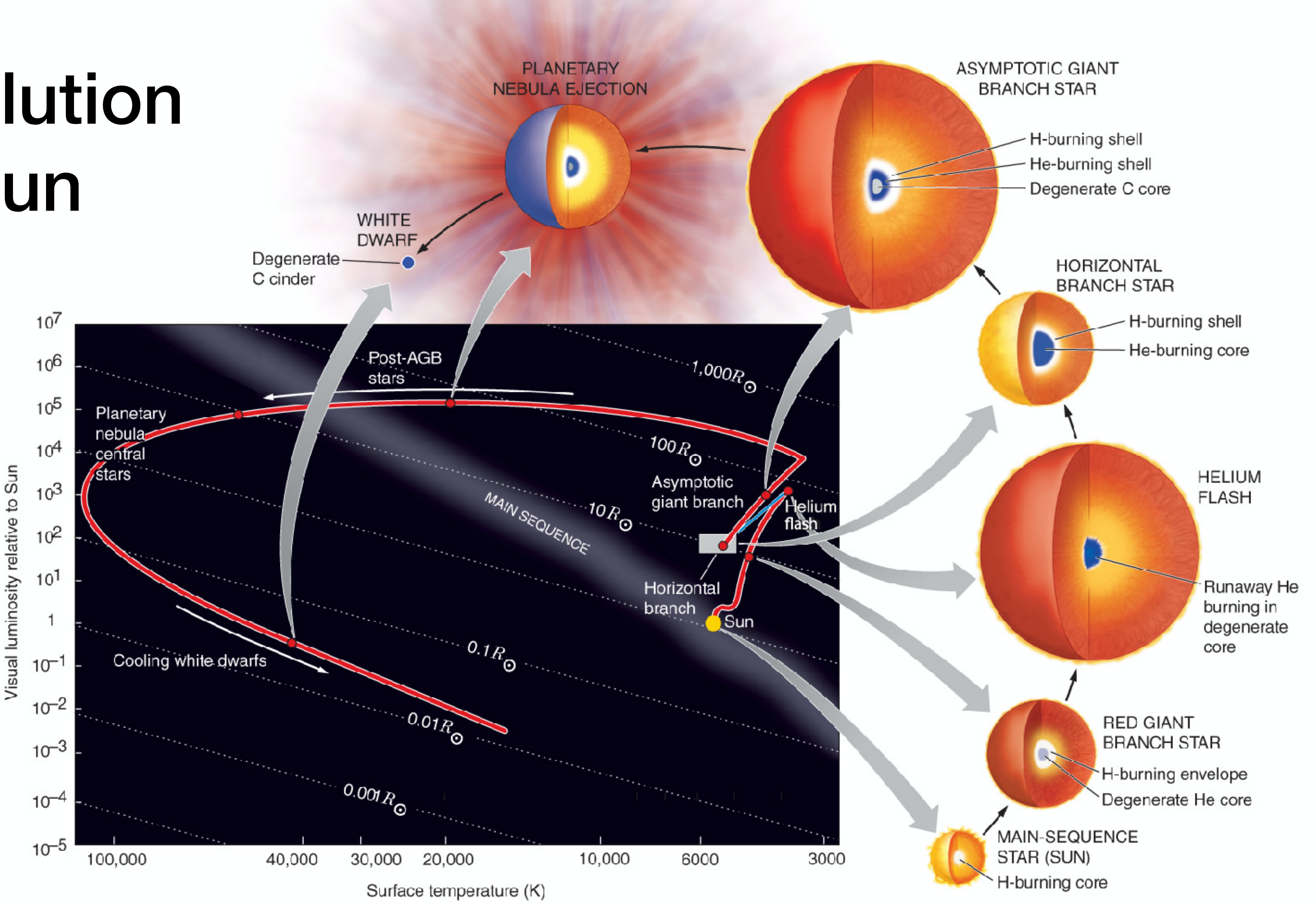

PLANETARY NEBULA EJECTION
Degenerate carbon core
He-burning shell
H-burning shell
Nonburning envelope
Ejected stellar material
Post-AGB star
Forming planetary nebula (expanding outer layers of star)
The bloated asymptotic giant branch star begins losing its outer layers, ejecting a planetary nebula.
1,000 R⊙
100 R⊙
10 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
MAIN SEQUENCE
White dwarf
Asymptotic giant branch star
Sun
Visual luminosity relative to Sun
Surface temperature (K)
100,000
40,000
30,000
20,000
10,000
6000
3000



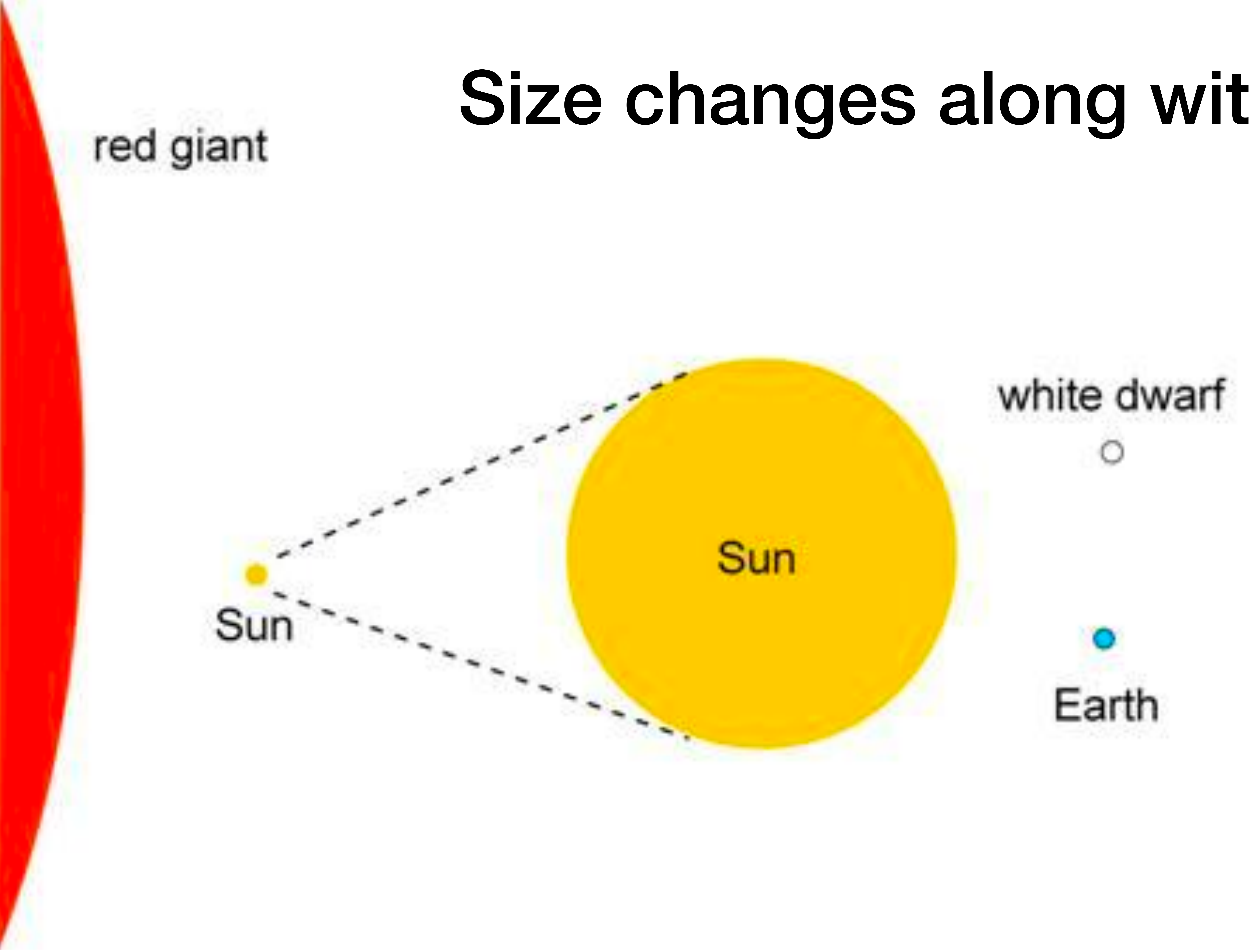
This star leaves behind only the degenerate carbon core, a tiny cooling white dwarf.
White dwarf
Hot electron-degenerate carbon
MAIN SEQUENCE
1,000 R⊙
100 R⊙
10 R⊙
0.1 R⊙
0.01 R⊙
0.001 R⊙
Sun
Visual luminosity relative to Sun
Surface temperature (K)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
100,000
40,000
30,000
20,000
10,000
6000
3000

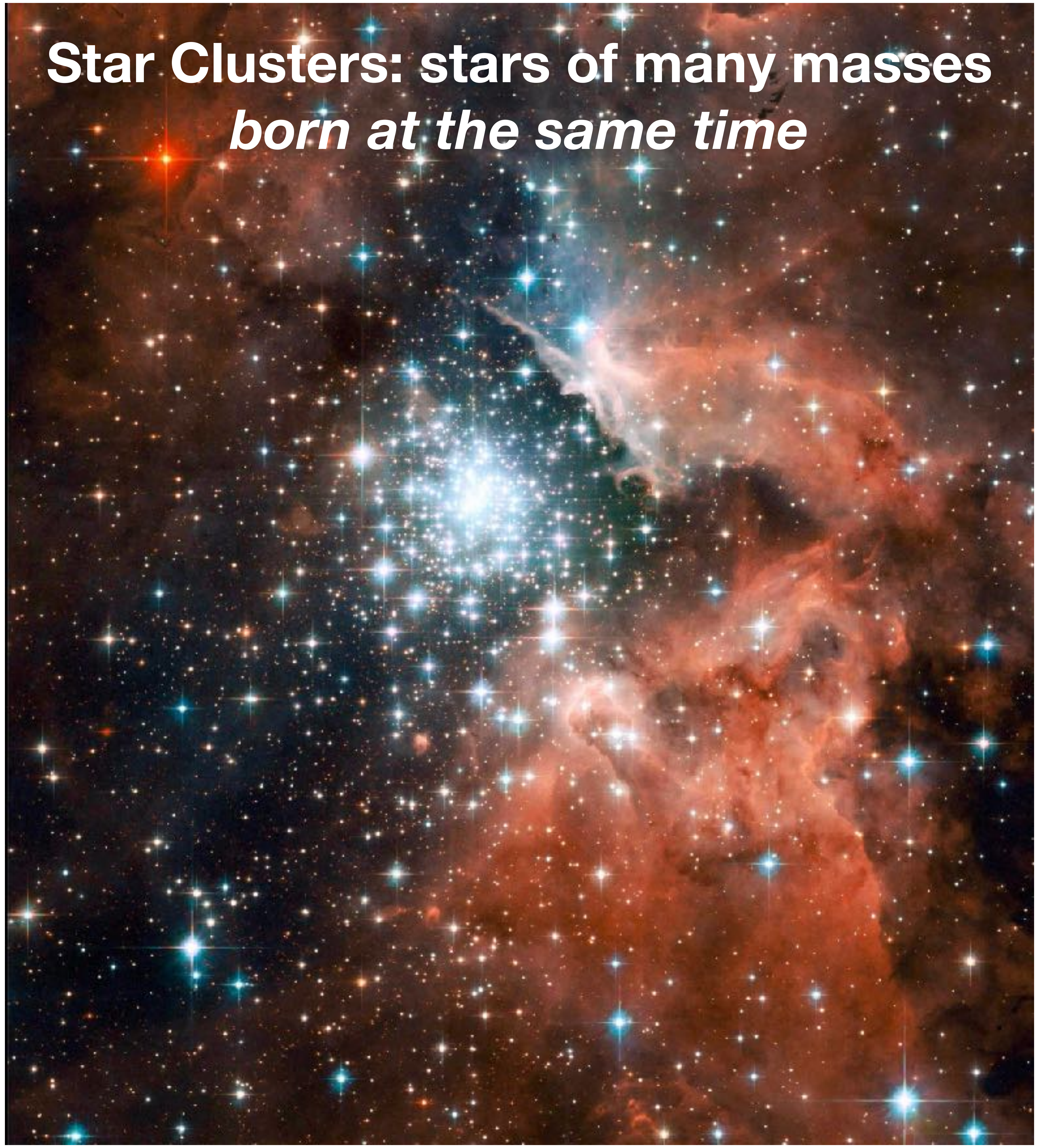
Future Evolution of the Sun

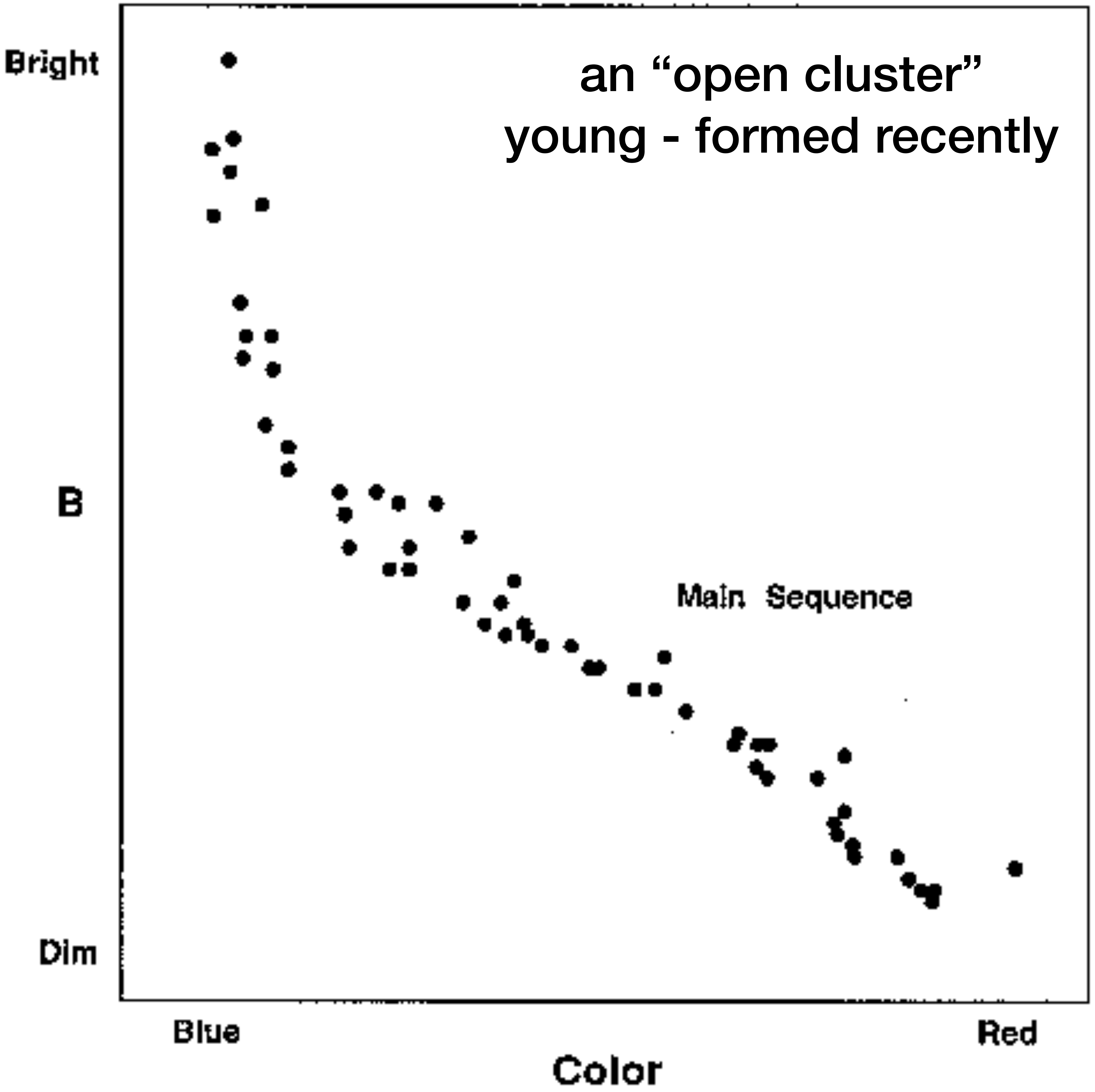
Again, this time with feeling!



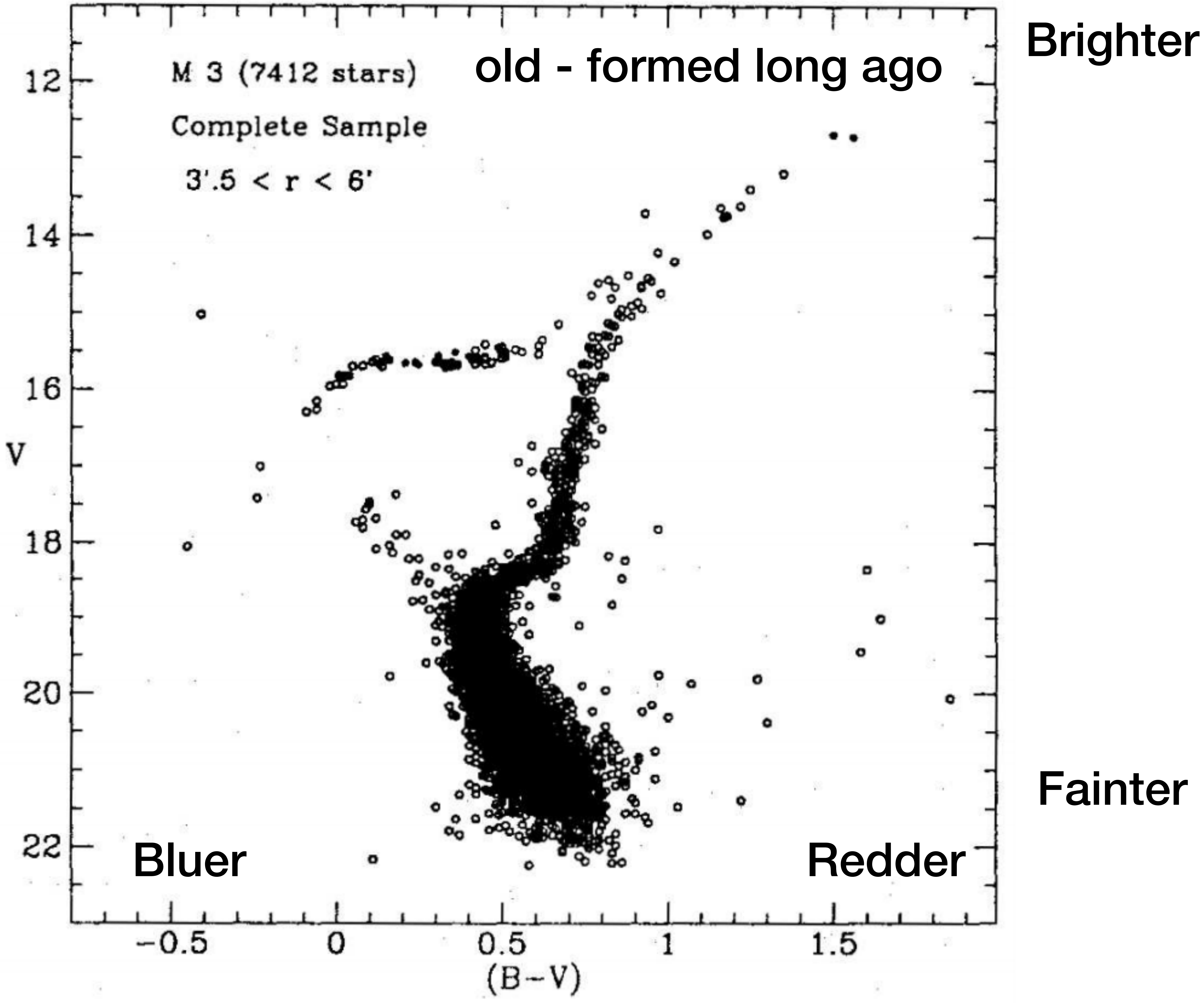
Size changes along with temperature



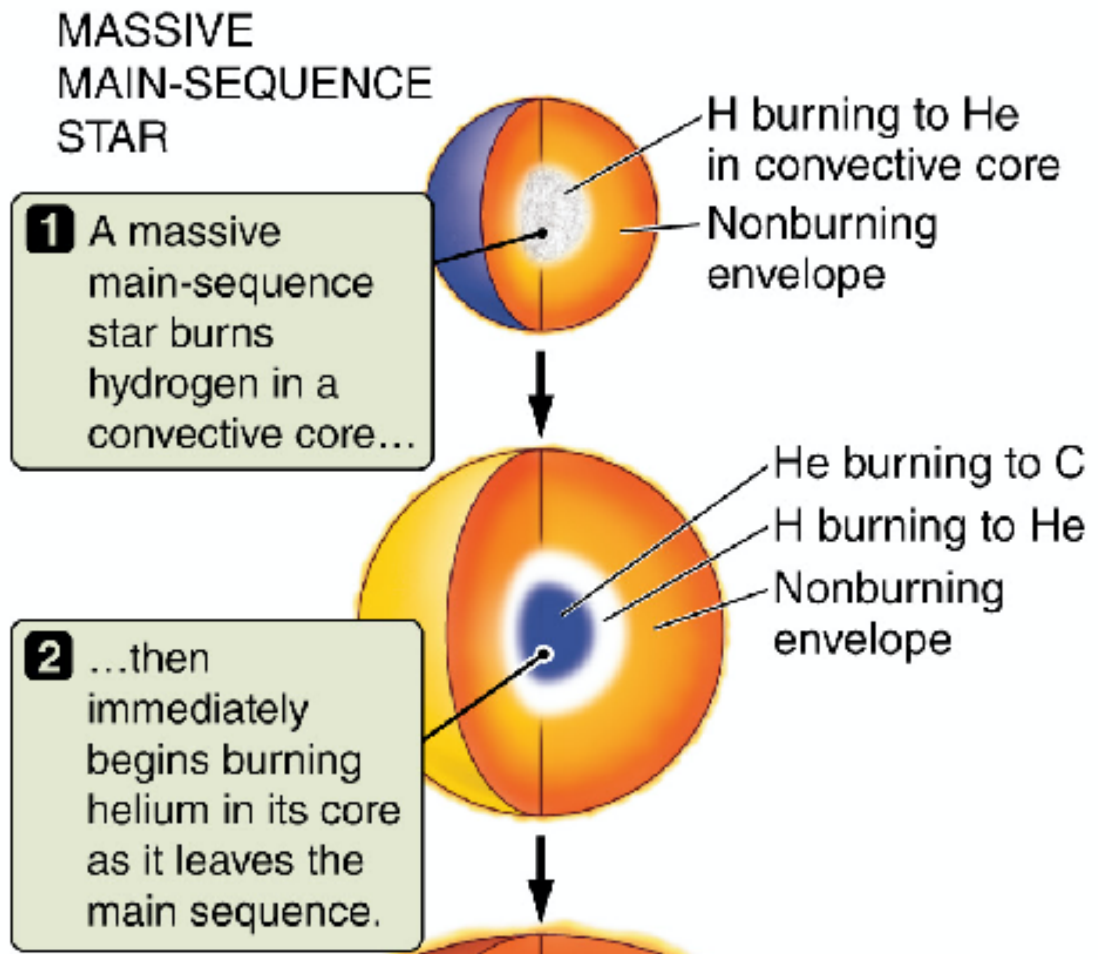

Star Clusters: stars of many masses
born at the same time


an "open cluster"
young - formed recently
Bright
B
Dim
Main Sequence
Blue
Red
Color

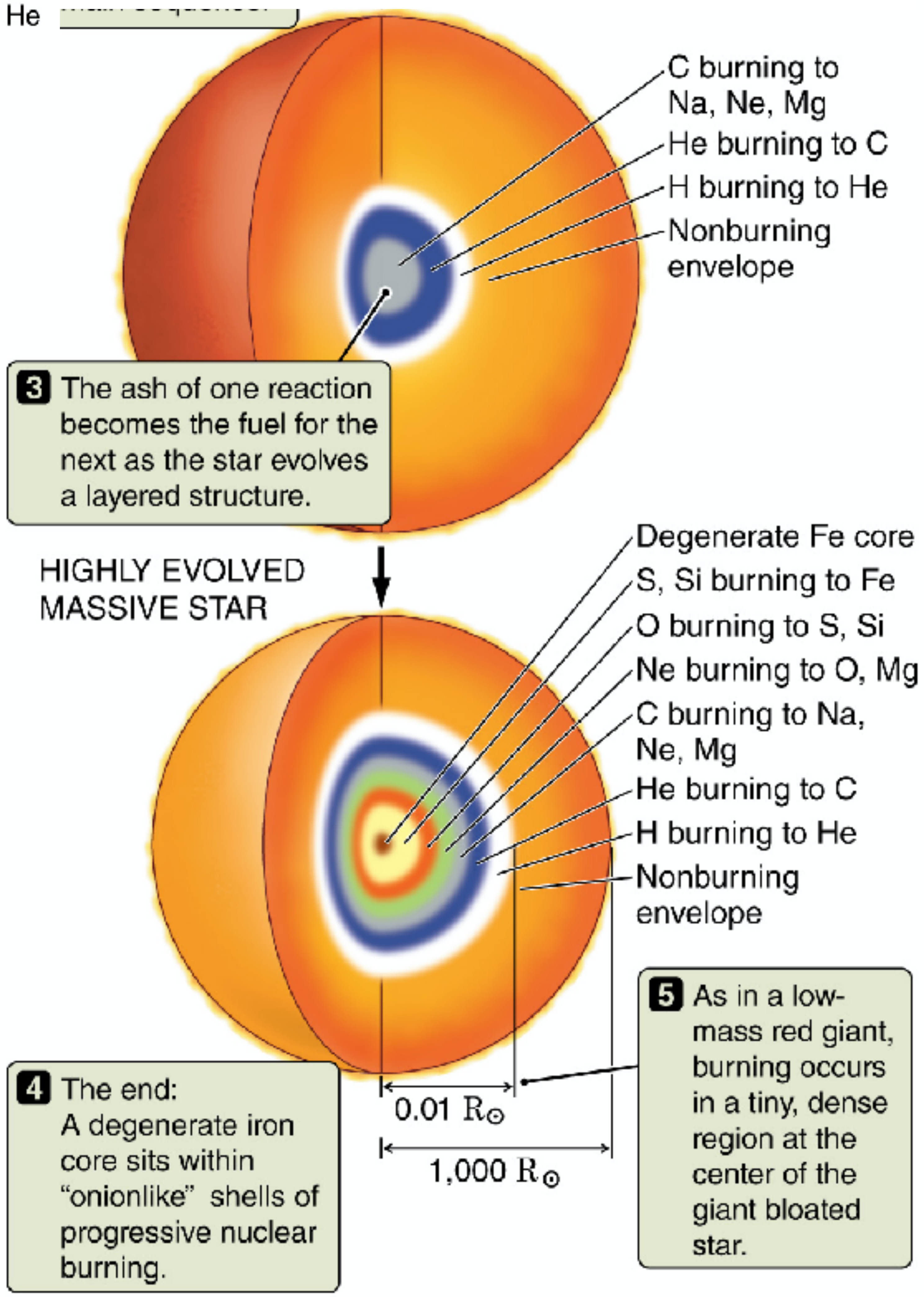
Globular Cluster Color-Magnitude Diagram

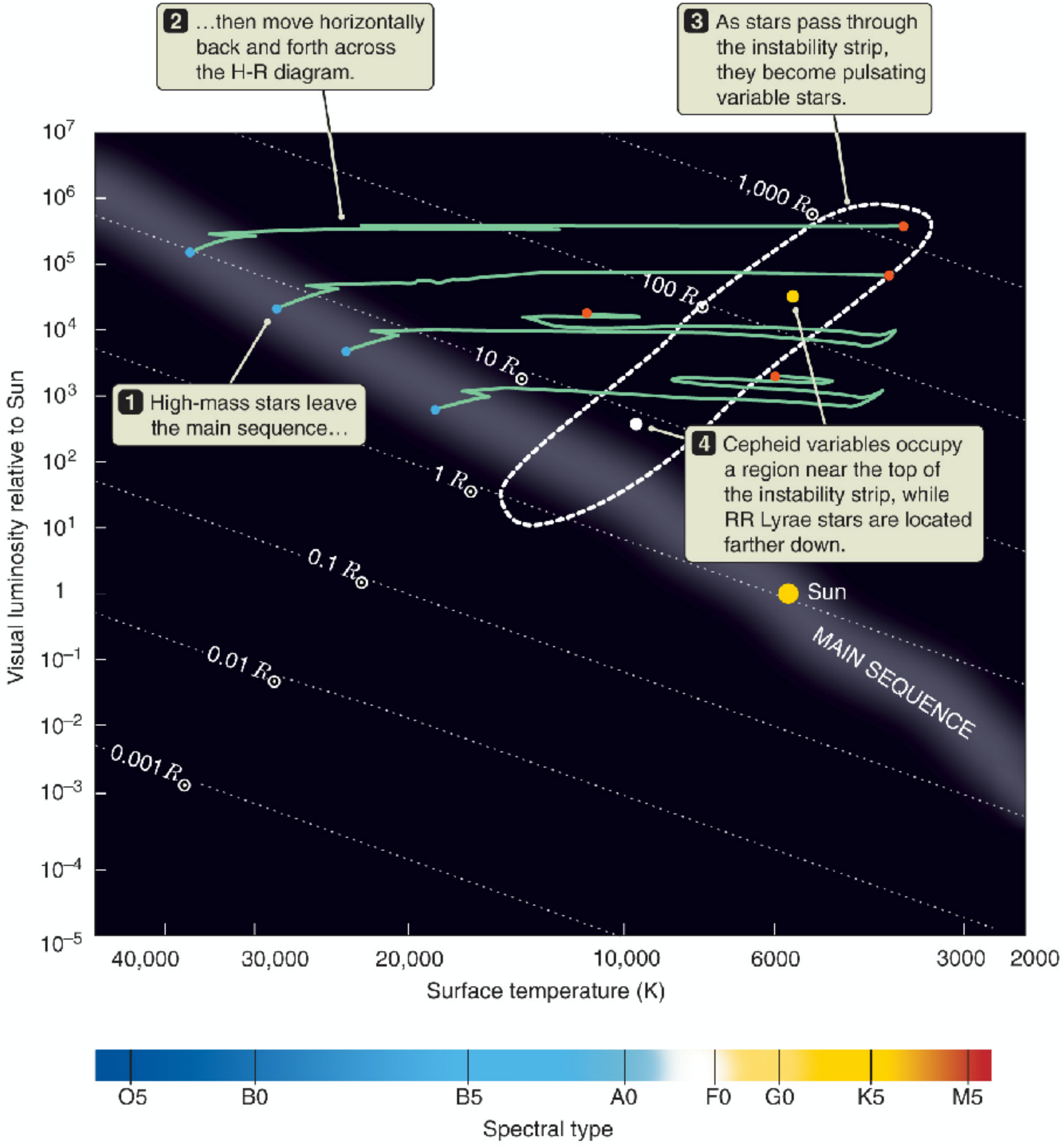


High Mass Stars = High Core Temps = CNO

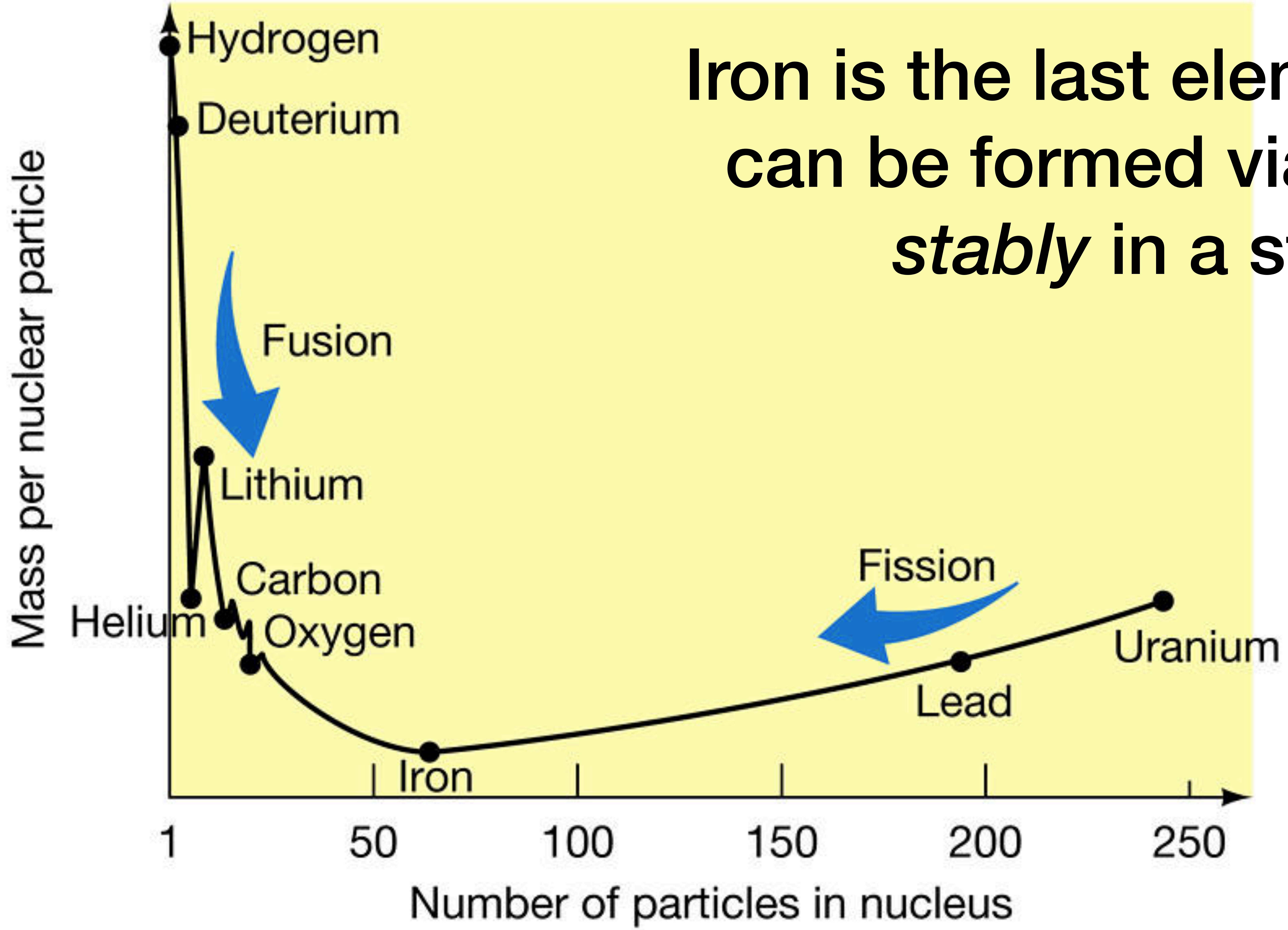


Evolution of High Mass Stars

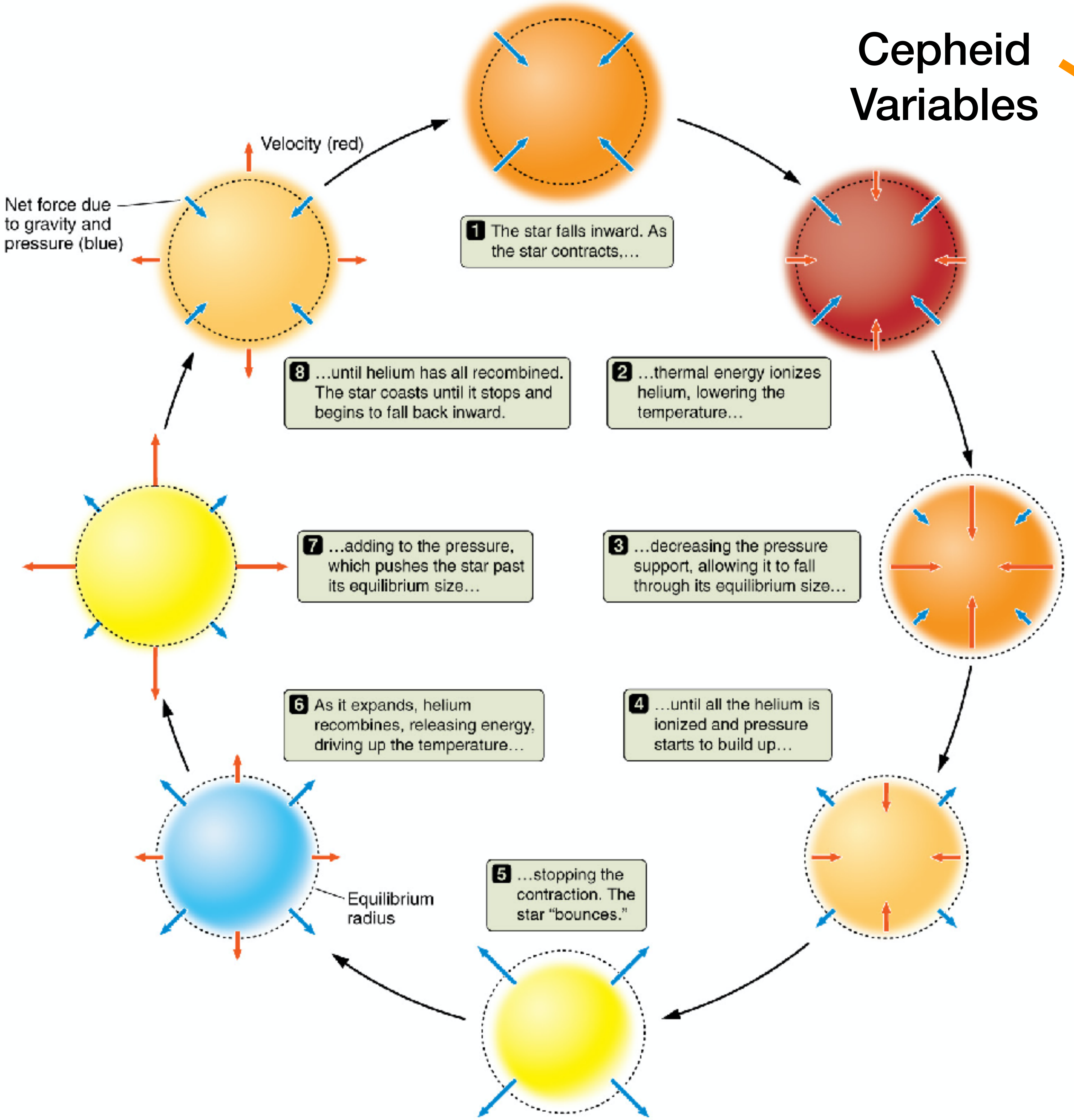


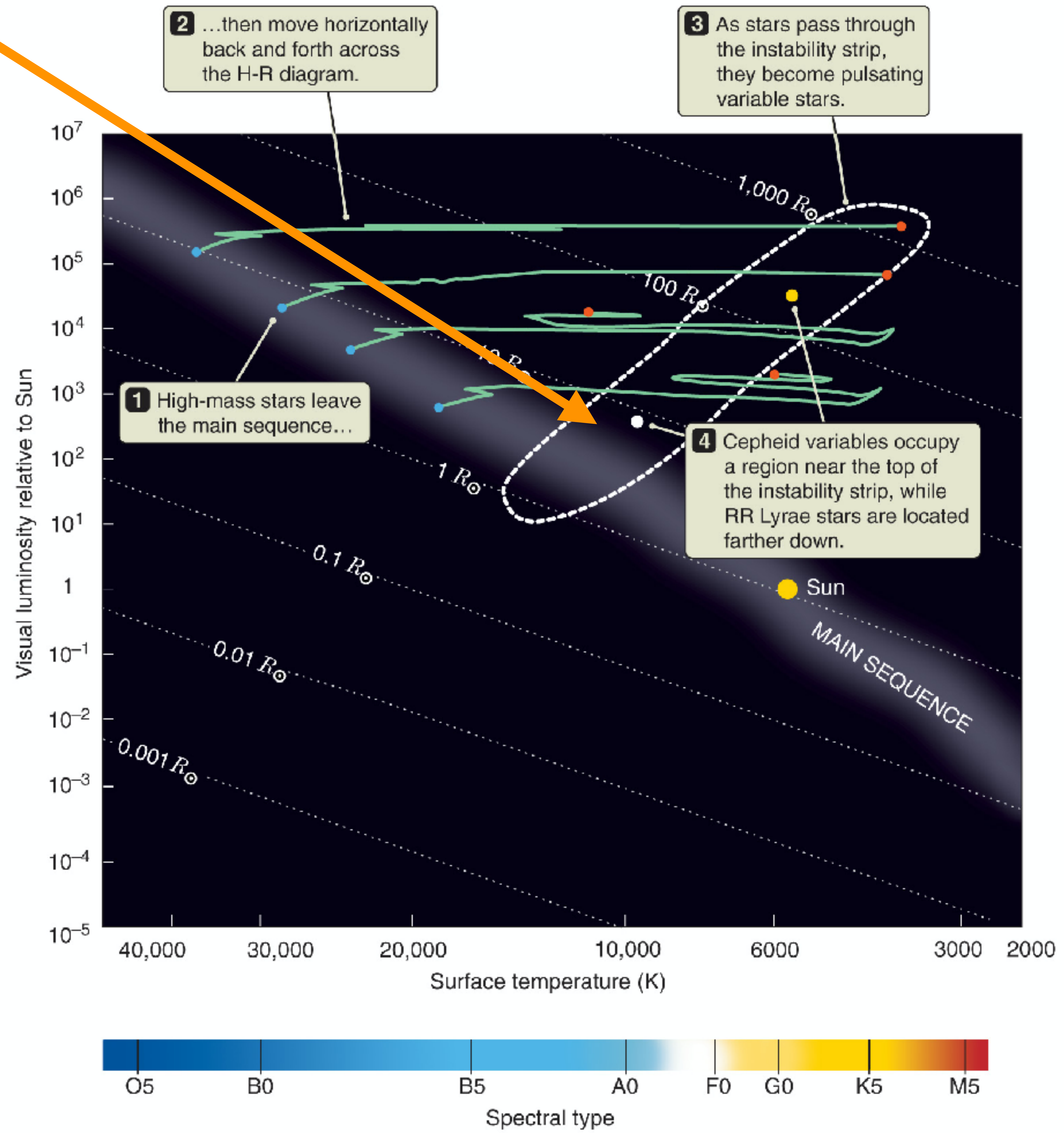


Iron is the last element that can be formed via fusion *stably* in a star

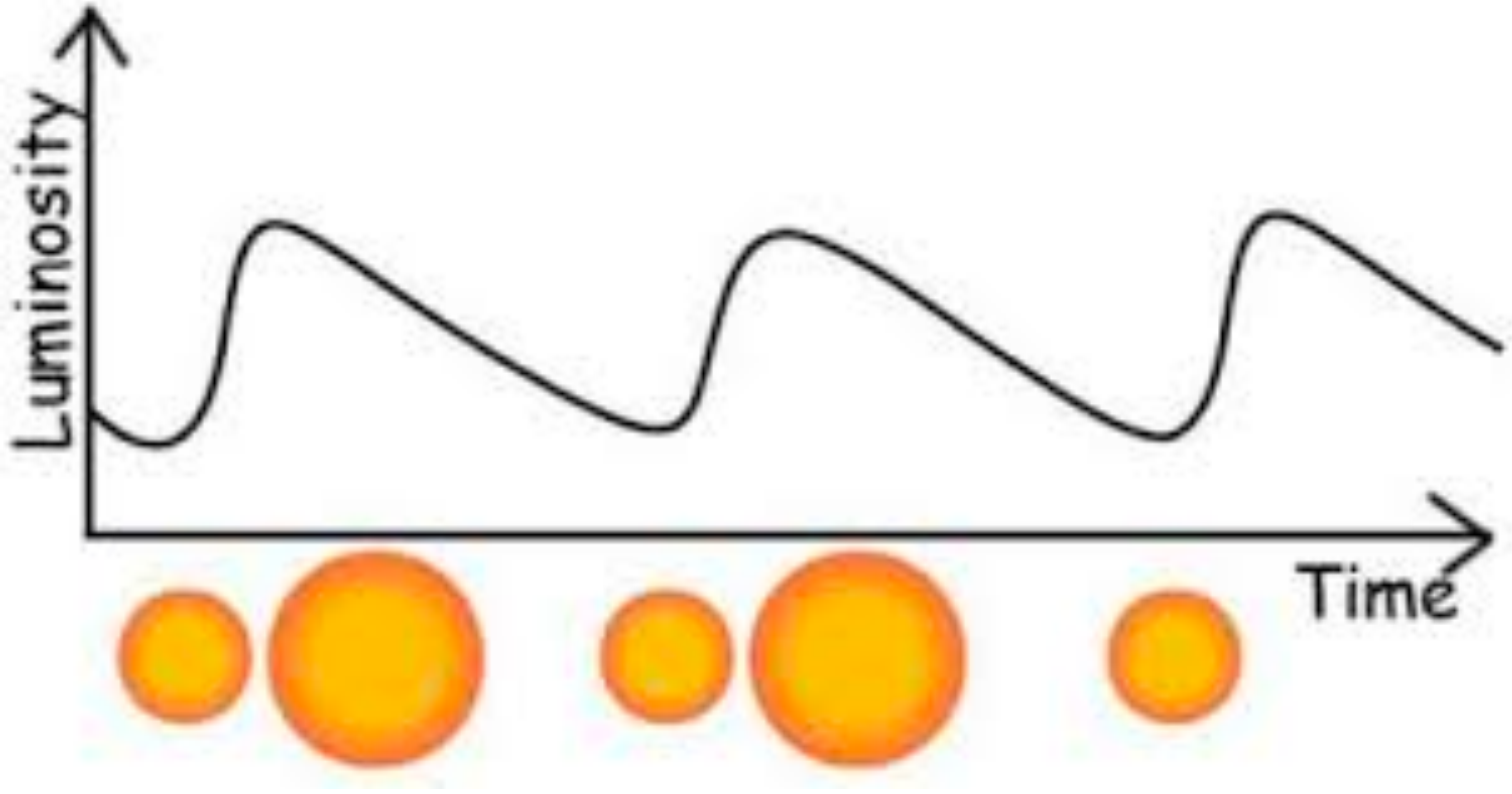


Cepheid Variables





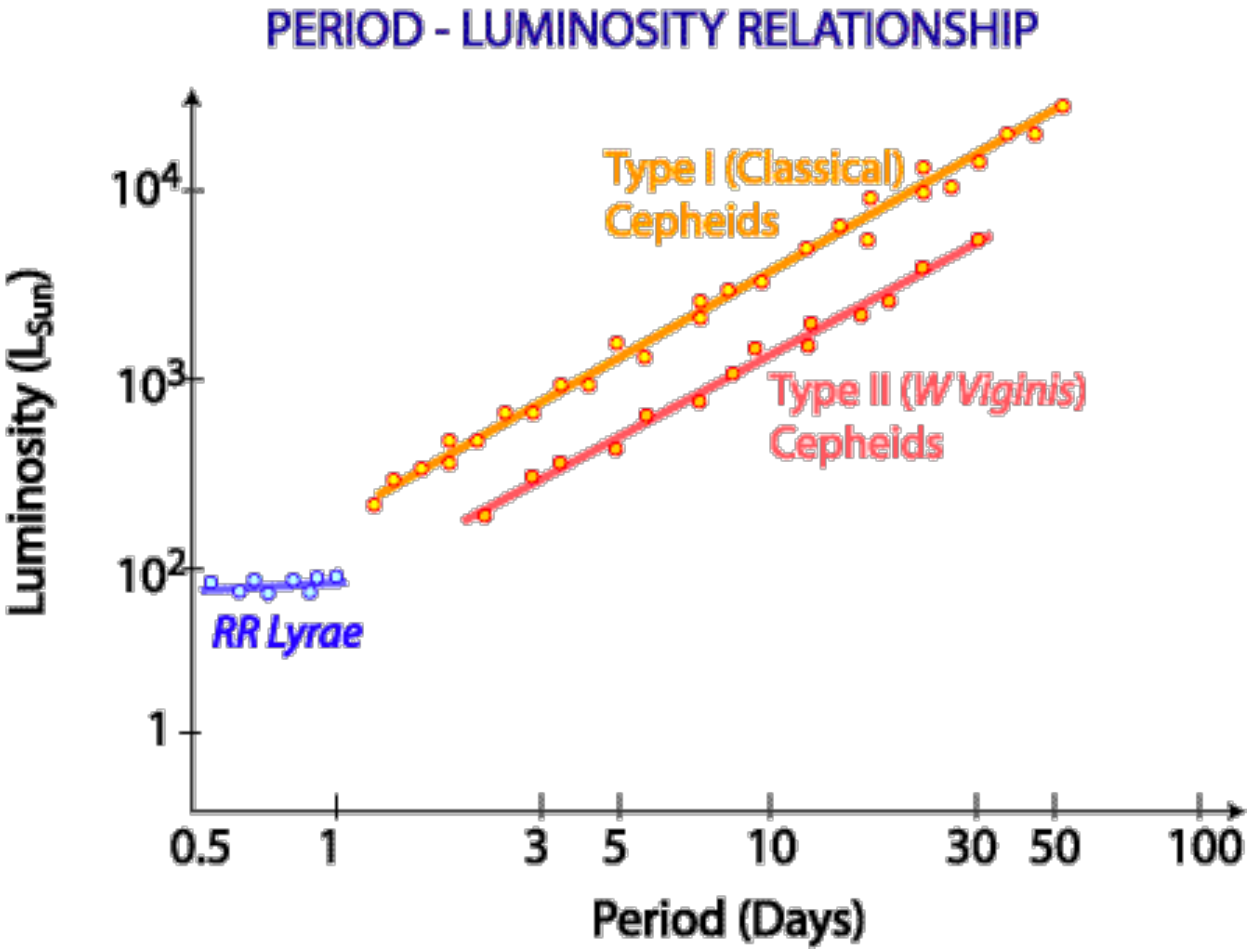
A Cepheid's luminosity can be inferred



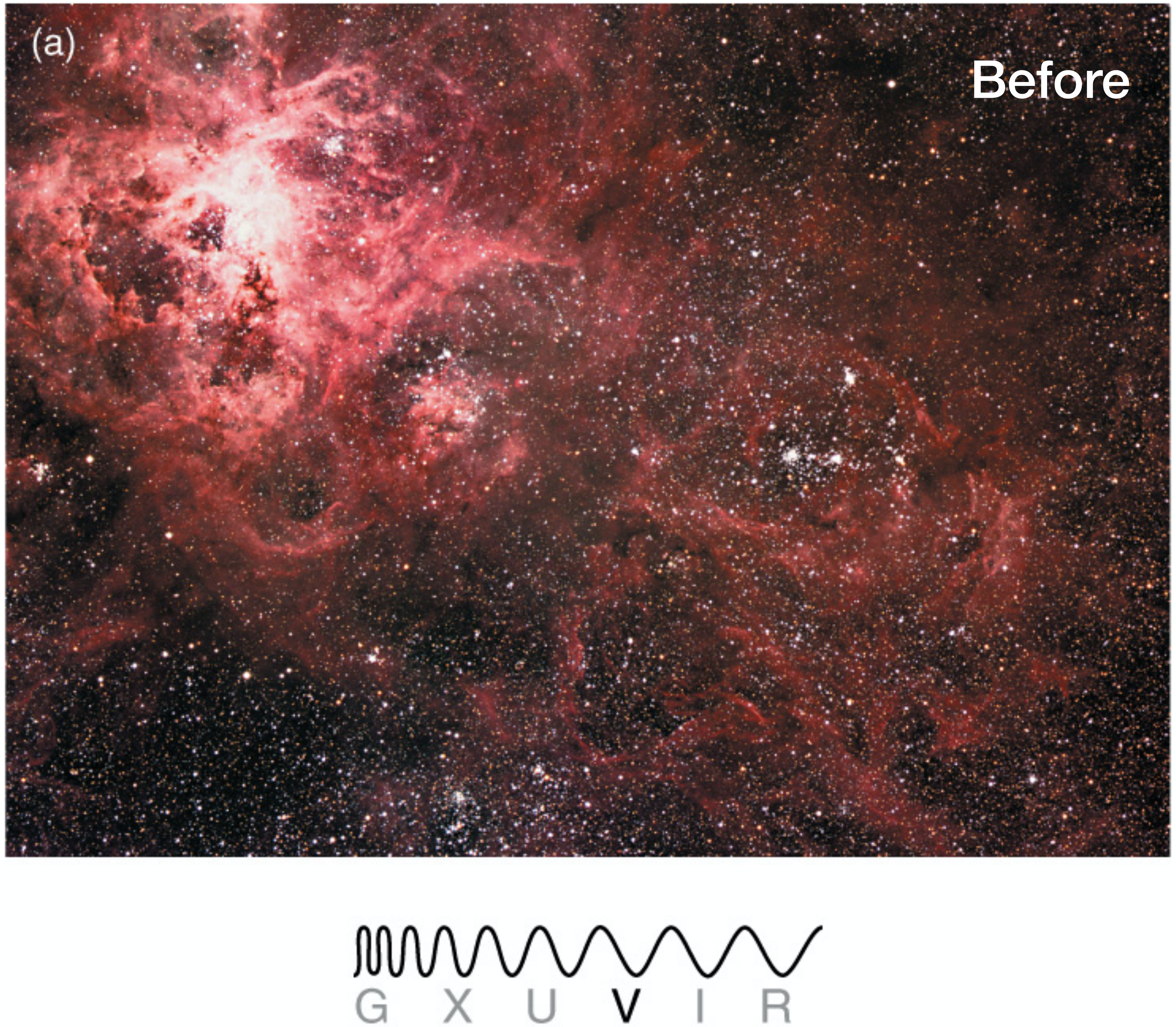
Empirically discovered by Henrietta Leavitt in 1912

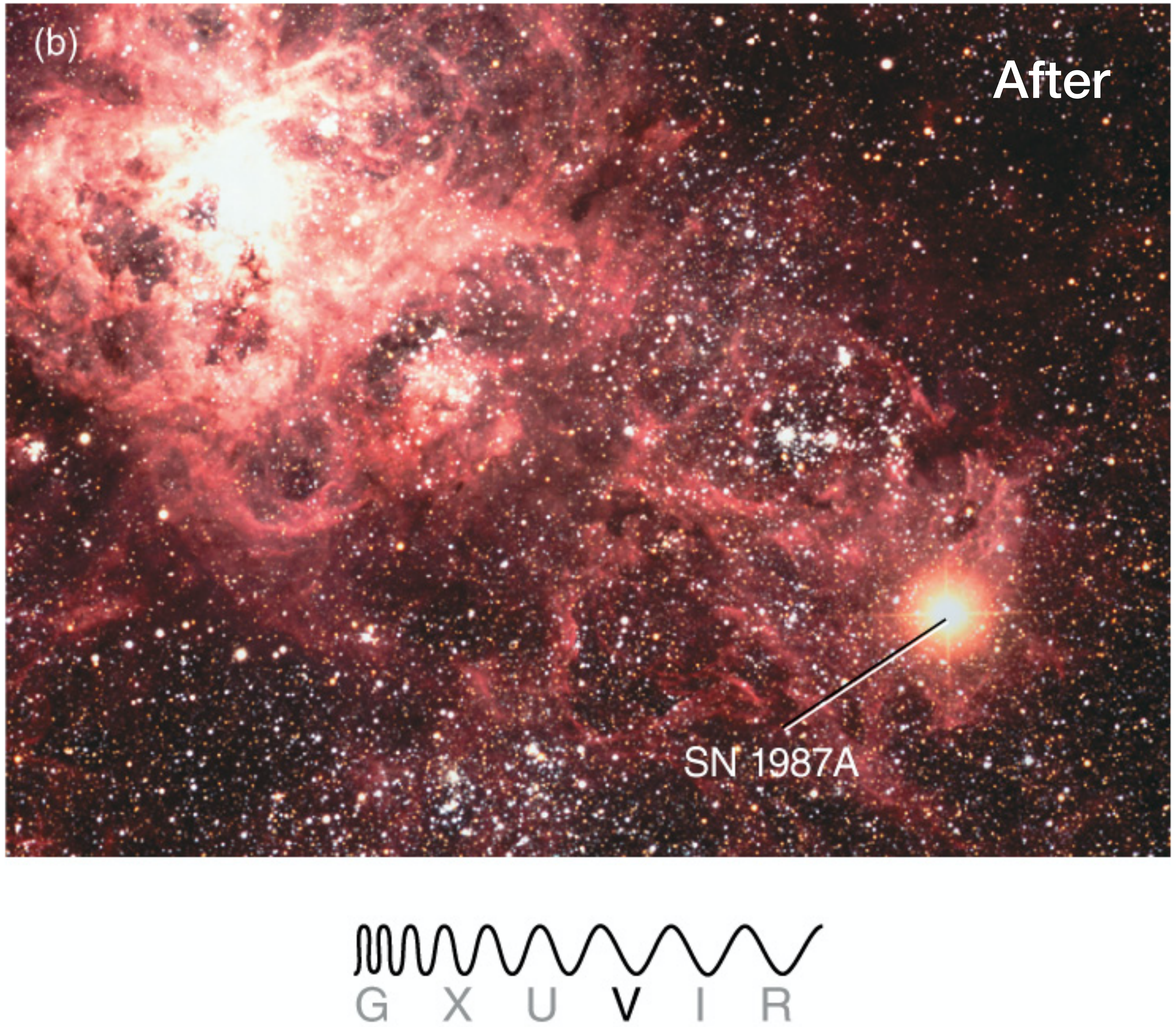
$$\overline{M}_V = -2.76 \log(P/10 \text{ days}) - 4.16$$

$$\log(d/10 \text{ pc}) = 0.2(\overline{m}_V - \overline{M}_V)$$



Type II Supernovae





Betelgeuse: Future Supernova

… were a supernova to go off within about 30 light-years of us, that would lead to major effects on the Earth, possibly mass extinctions. X-rays and more energetic gamma-rays from the supernova could destroy the ozone layer that protects us from solar ultraviolet rays. It also could ionize nitrogen and oxygen in the atmosphere, leading to the formation of large amounts of smog-like nitrous oxide in the atmosphere.

- Mark Reid, Harvard-Smithsonian CfA

430 light-years away (safe distance, unless it explodes as a gamma ray burst pointed at us)

May appear as bright as the full moon, visible during the day!