Stellar Evolution

Reading assignment
TUESDAY 11/17: 16.1, 16.2, 16.4, and 16.5

Homework Assignment #4 due by:
TUESDAY 11/10 before 9AM.
Note that TUESDAY is a WED schedule —> NO CLASS

MIDTERM EXAM: THURSDAY Nov. 12

Jeans Criterion for Contraction

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What are the conditions that the gas must satisfy in order to contract to form stars?

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Kinetic energy

$$K = \frac{3}{2} N k T = \frac{3}{2} \frac{M_c}{\mu m_H} k T$$

Number of particles in the gas

$$\Rightarrow \quad 2K < |U| \iff \frac{3M_c}{\mu m_H} kT < \frac{3}{5}\frac{GM_c^2}{R_c}$$

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$$\Rightarrow \boxed{M_c > \left(\frac{5 k T}{\mu G m_H} \right)^{3/2} \left(\frac{3}{4\pi \rho_0} \right)^{1/2} =: M_J}$$

Jeans criterion to initiate spontaneous collapse of the cloud of gas

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Equivalently:

Jeans length

$$\boxed{R_c > R_J := \sqrt{\frac{15 kT}{4\pi G \mu m_H \rho_0}}}$$

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EXAMPLE: for a dense core of a giant molecular cloud

$$T \sim 10\ K \qquad n_{H_2} = 10\ cm^{-3}$$

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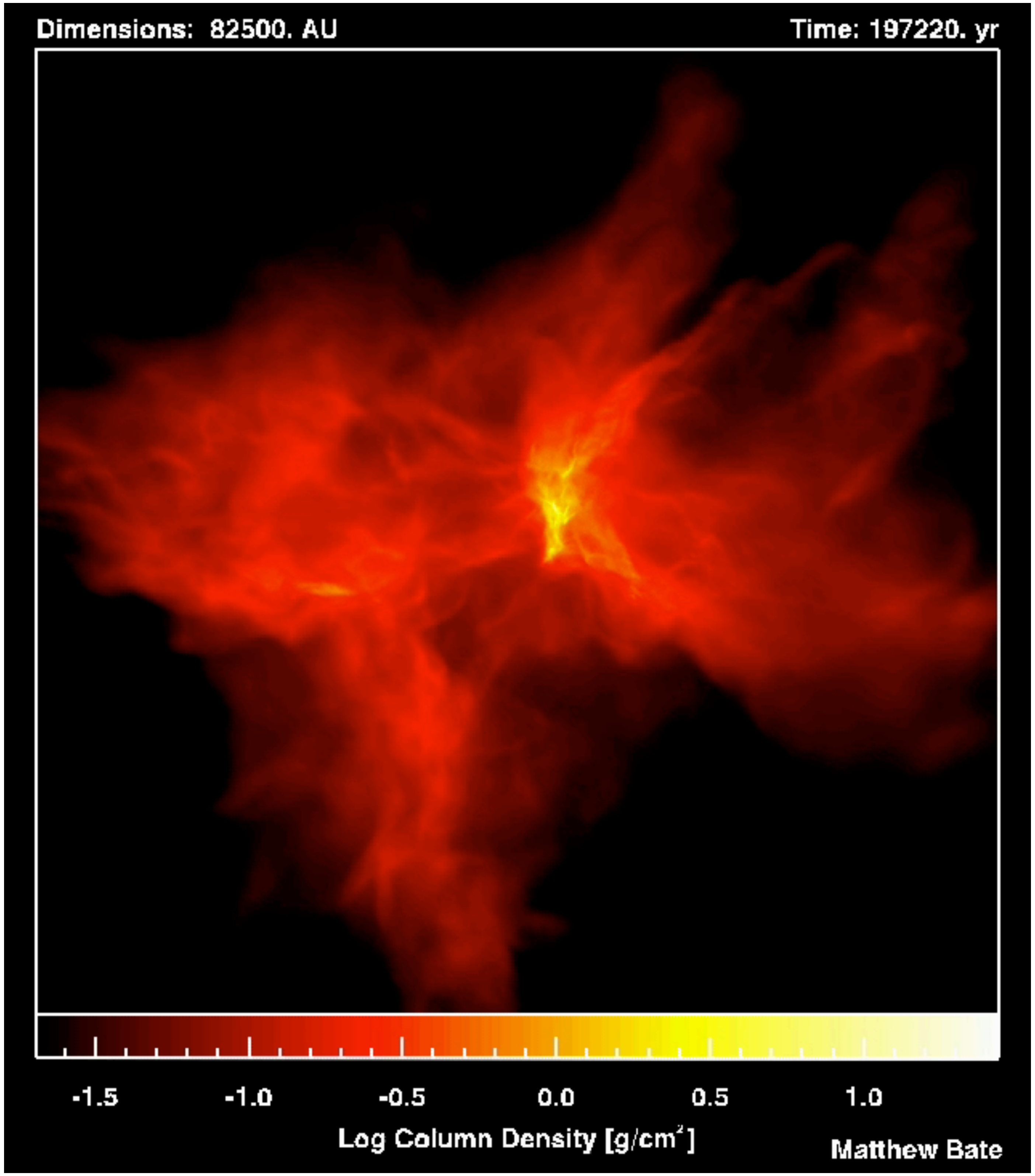
Since the characteristic masses of dense cores are ~10 M_{Sun}, the dense cores of giant molecular clouds (GMCs) are unstable to gravitational collapse, and are sites of star formation. In fact, M_{BE}~1.6 M_{Sun} —> definitely unstable.

Stars tend to form in groups, ranging from binary star systems to clusters containing many 10^5 stars —> fragmentation of the collapsing cloud: as the cloud collapses, the mass density increases while T remains constant —> initial inhomogeneities in density will cause the individual parts of the cloud to satisfy the Jeans criterion independently, collapsing locally, hence fragmentation



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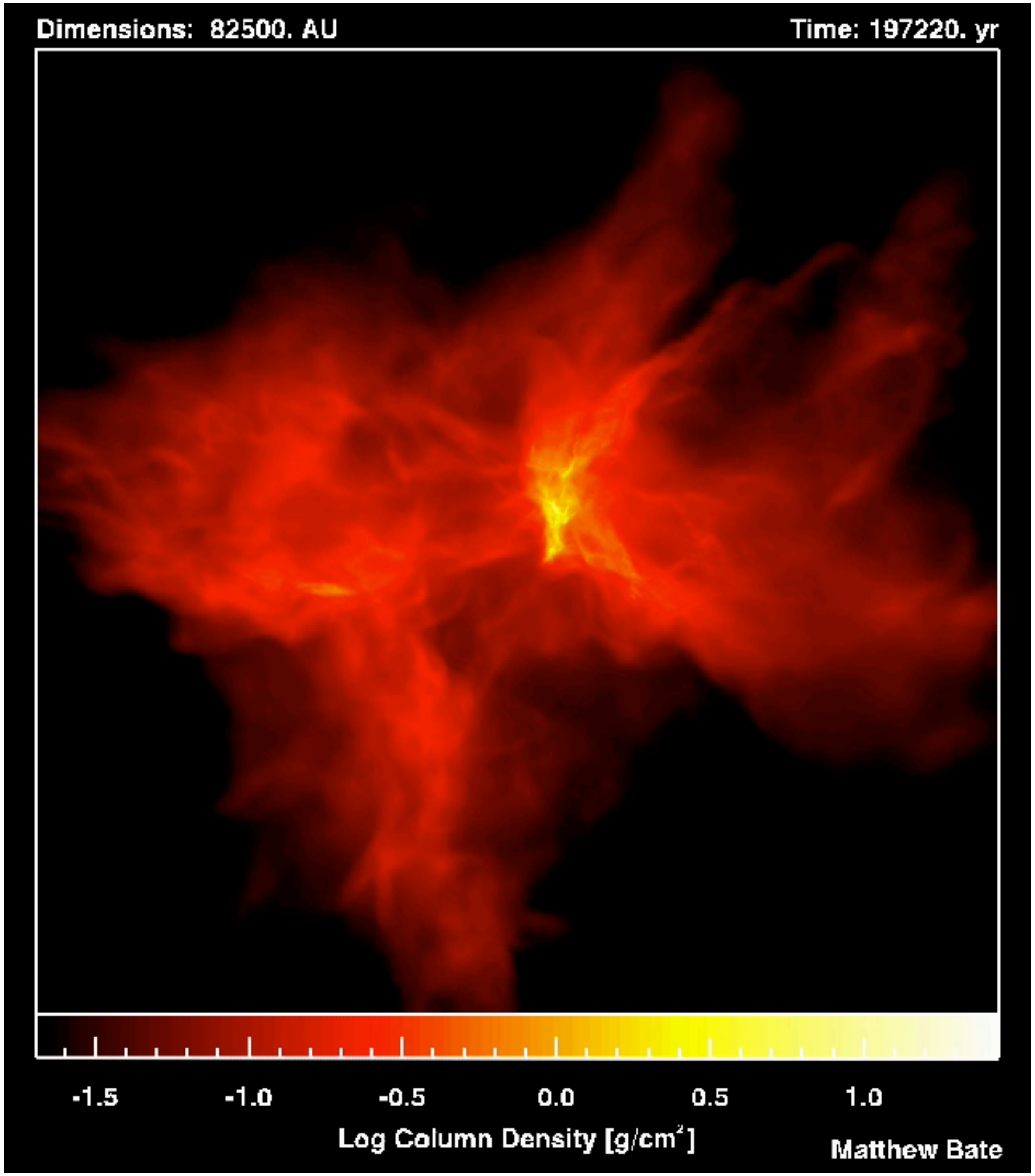

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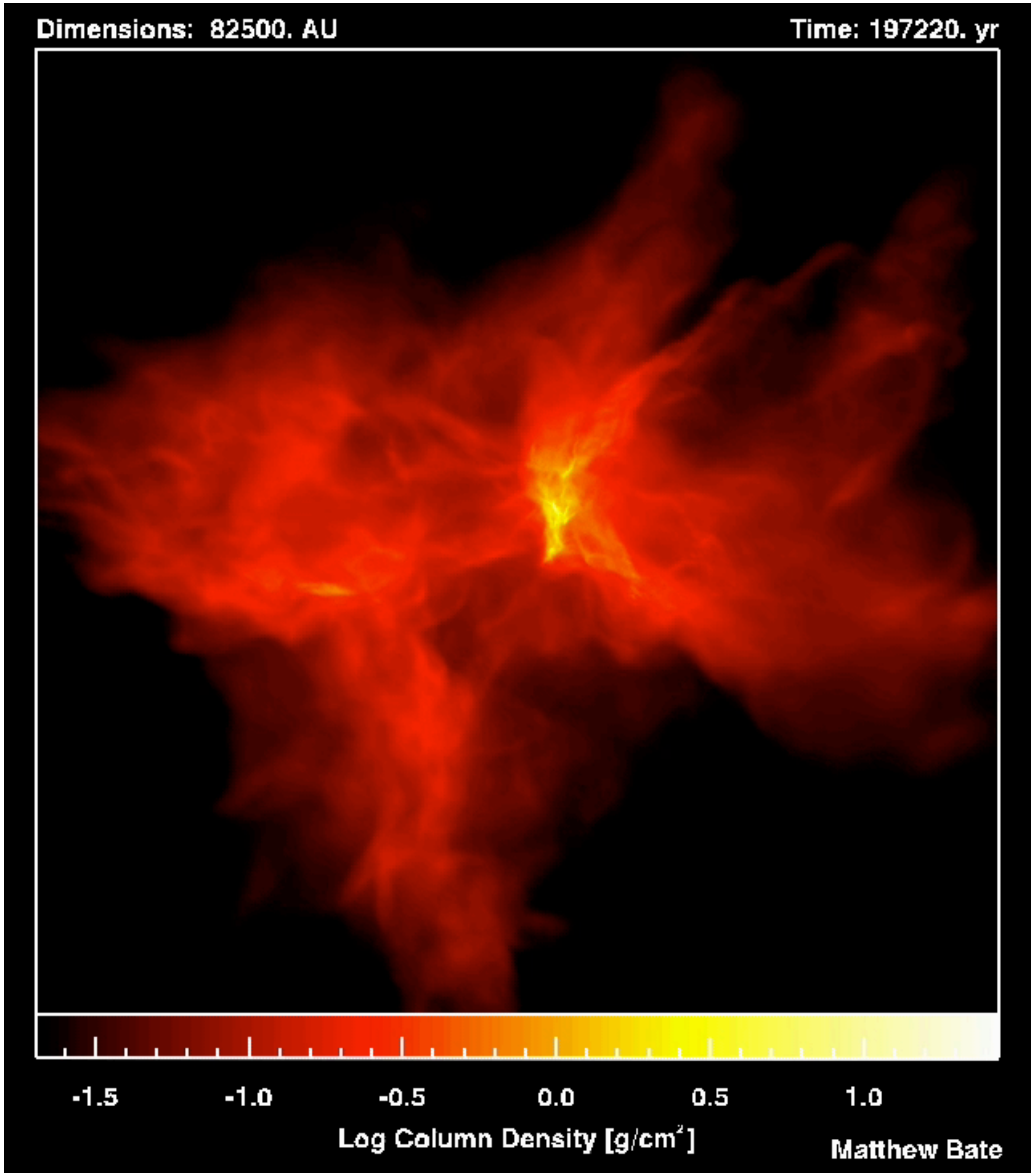
INITIAL MASS FUNCTION



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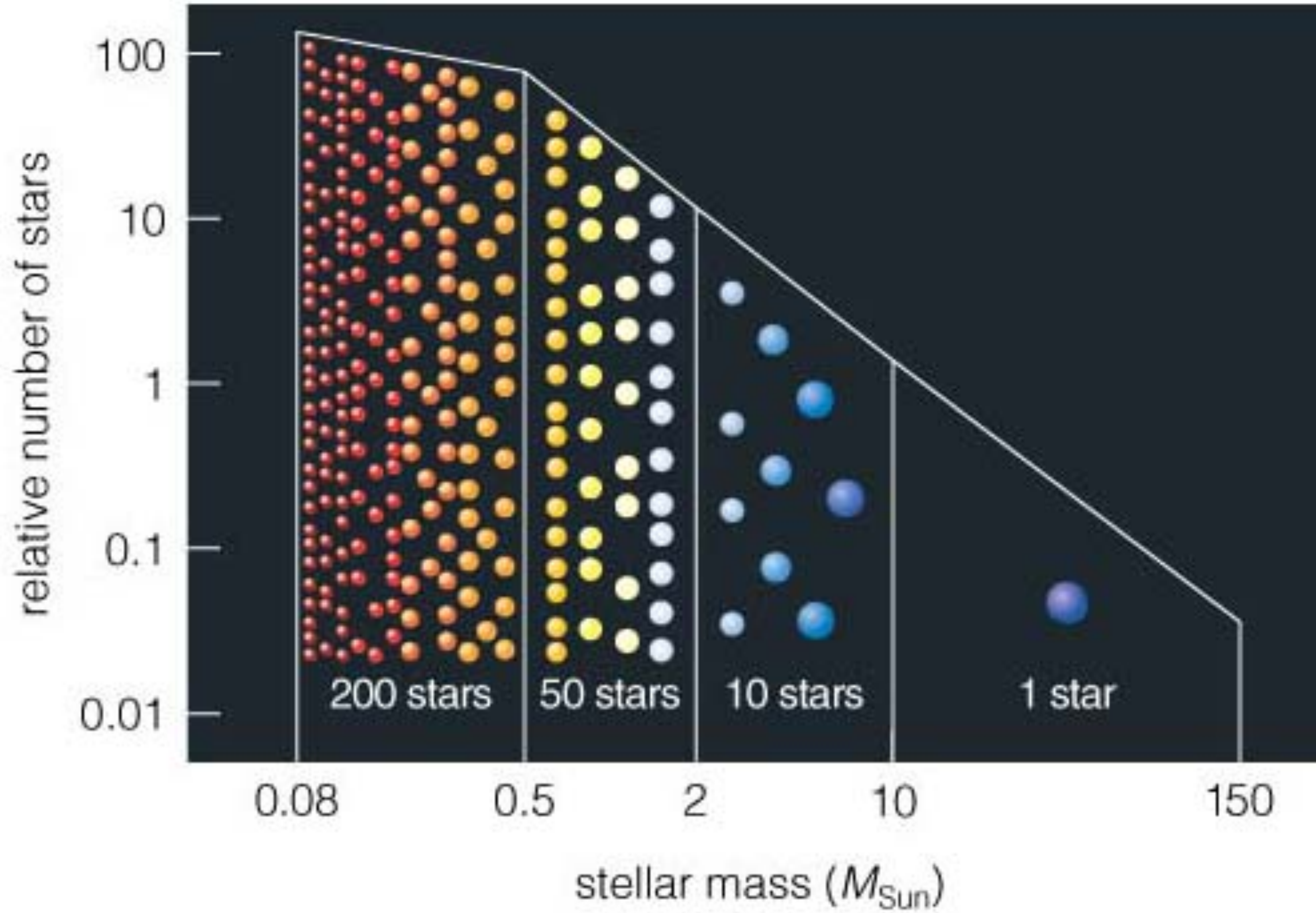

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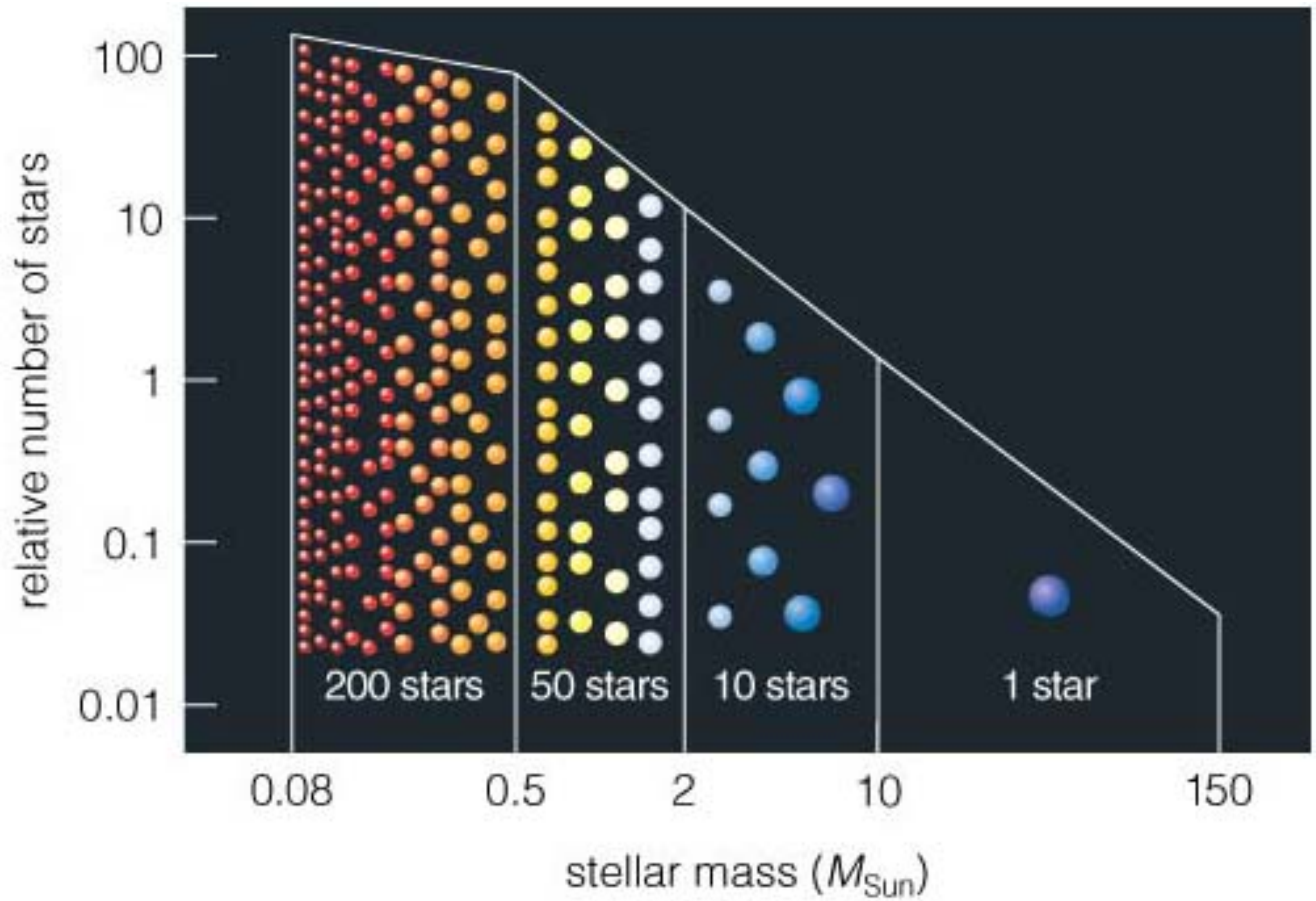
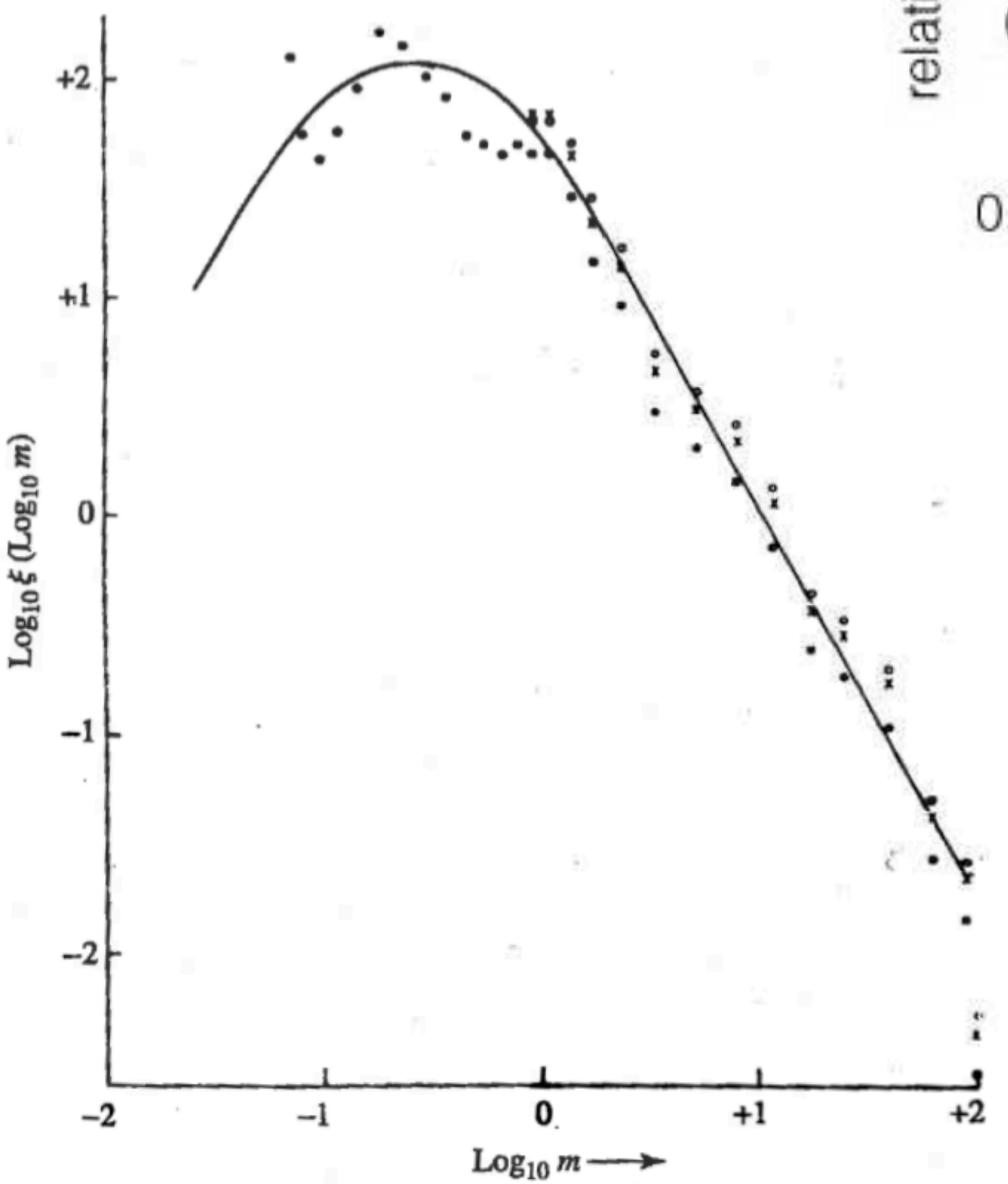
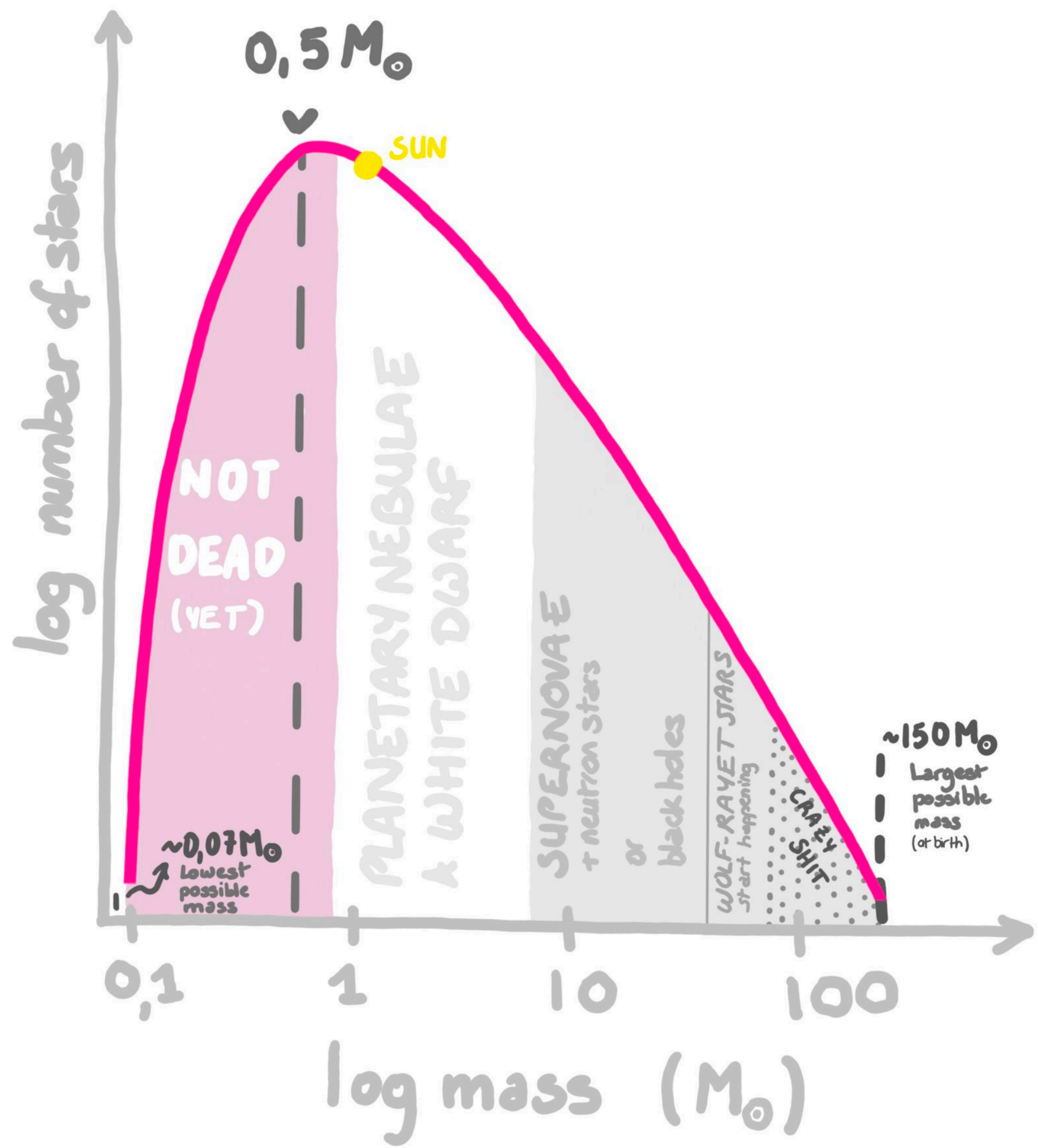




BAD INITIAL MASS FUNCTION

by @Sydonahi

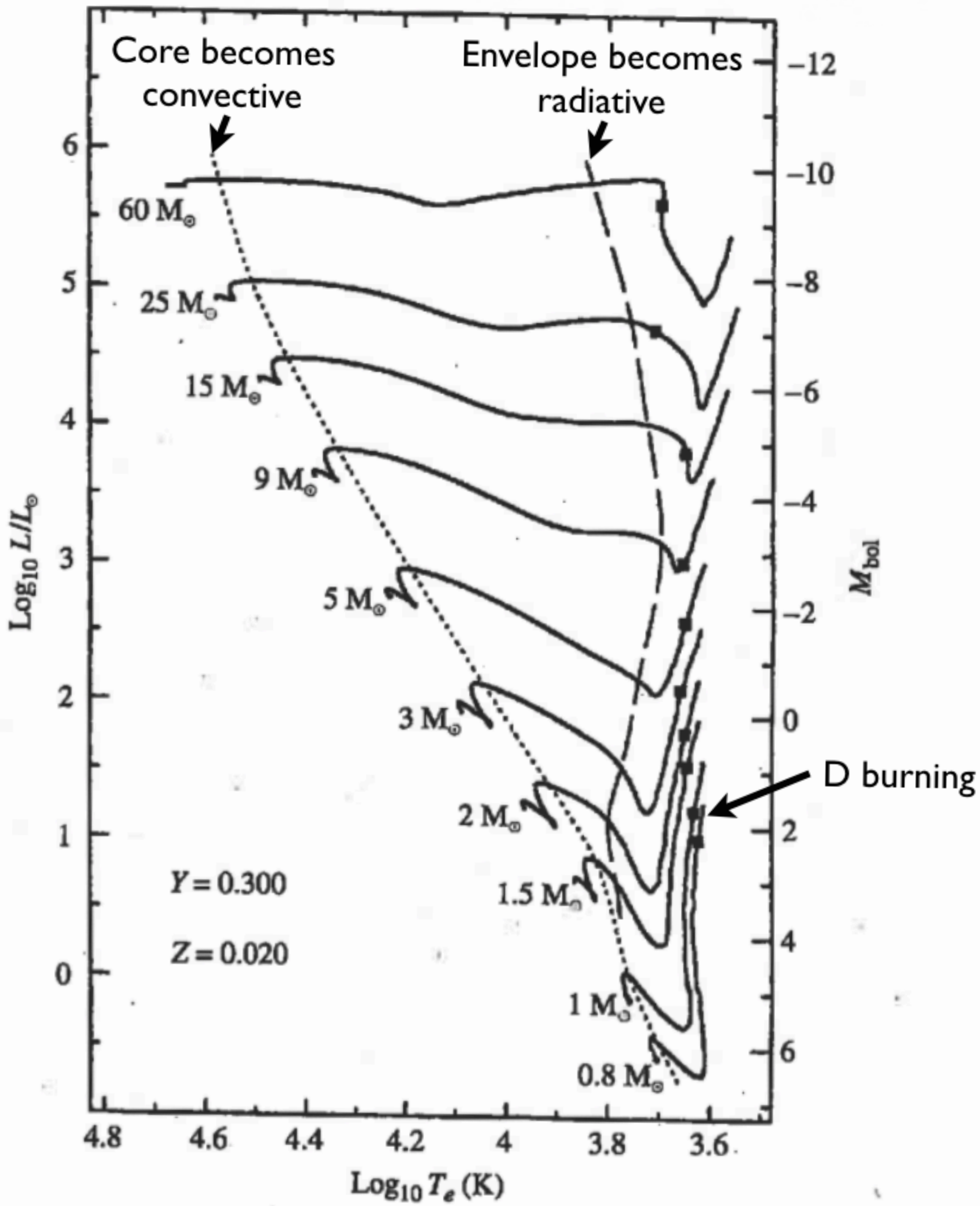
(and how stars die)



NOTE: More massive stars arrive on the main sequence much faster than low-mass stars:

$$t_{contraction} \approx 8\times10^{7}\,\frac{M}{M_\odot}\,\frac{L_\odot}{L}\ \mathrm{yr}$$

Zero-age main-sequence luminosity



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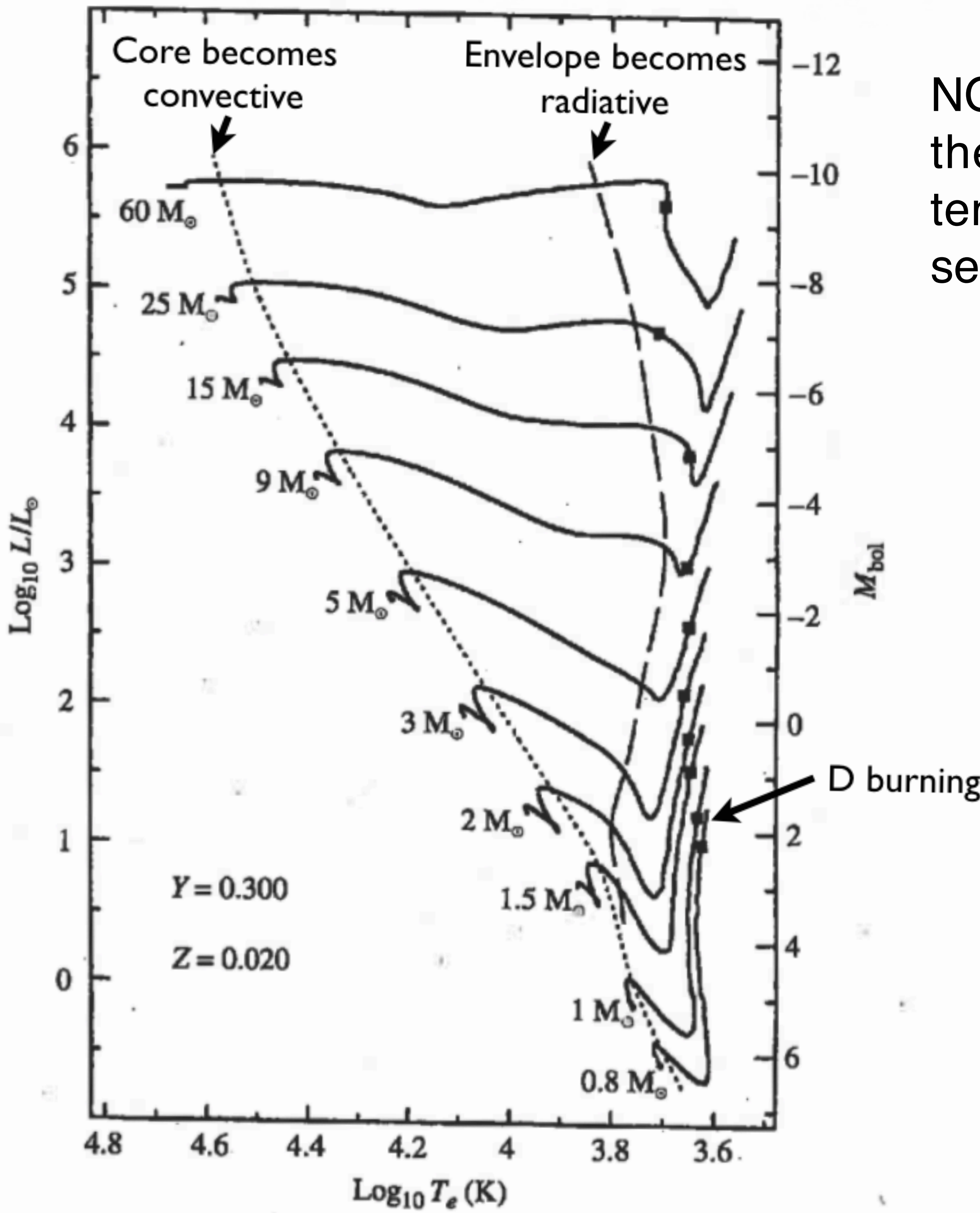

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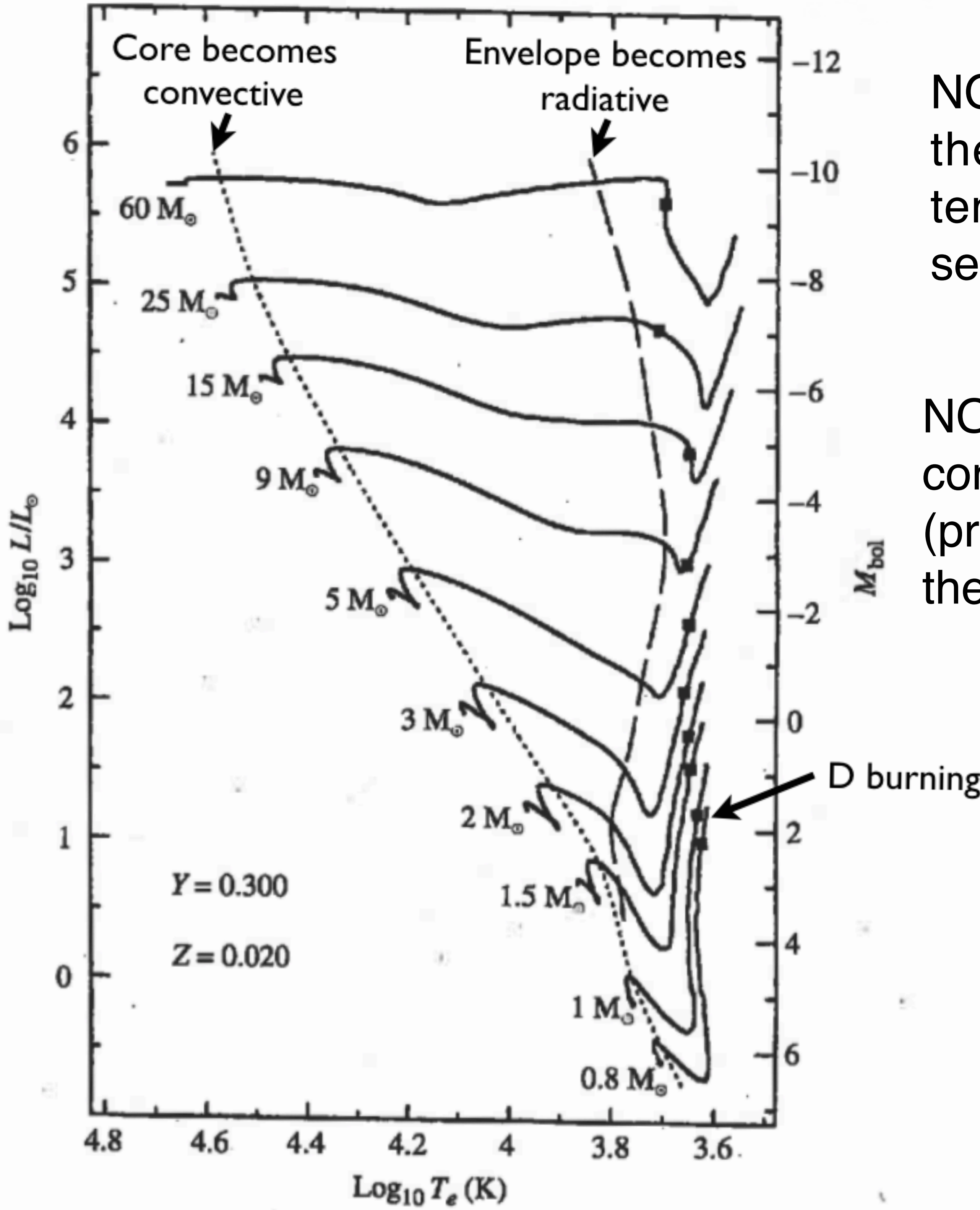

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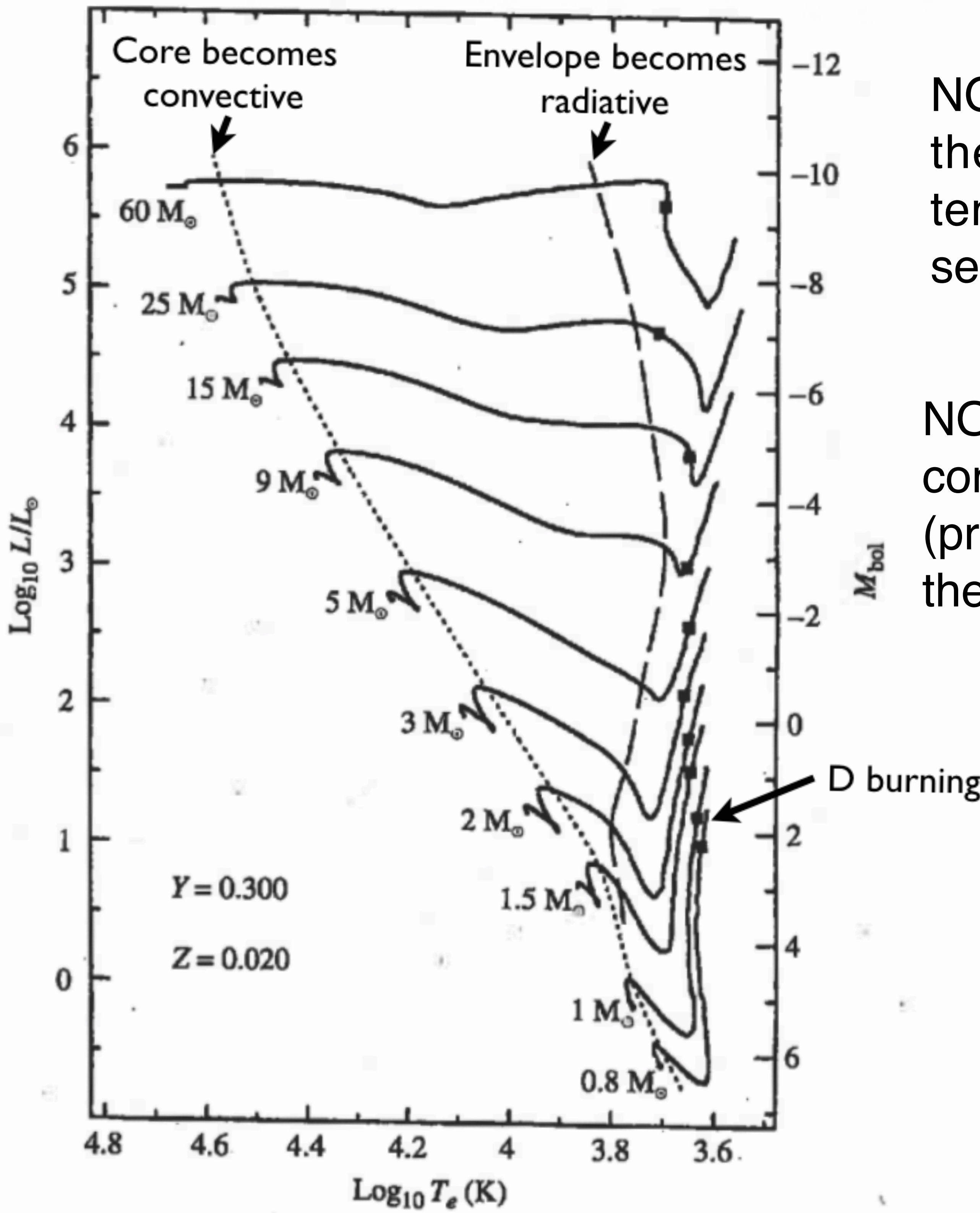

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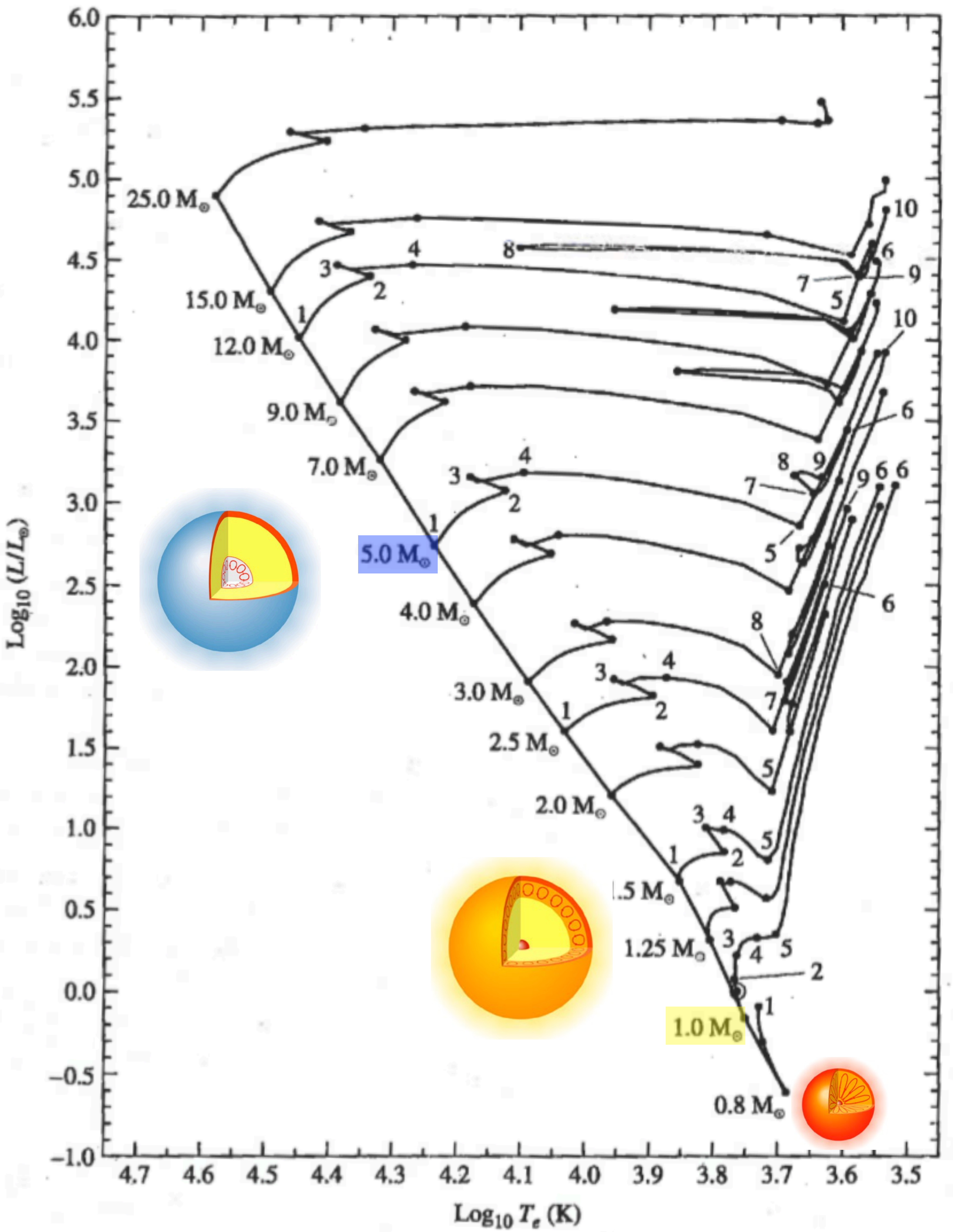
Stars with $0.013<M/M_{Sun}<0.072$ are **brown dwarfs** (L and T spectral type):

$0.072<M/M_{Sun}<0.06$ —> Li burning

$0.072<M/M_{Sun}<0.013$ —> D burning

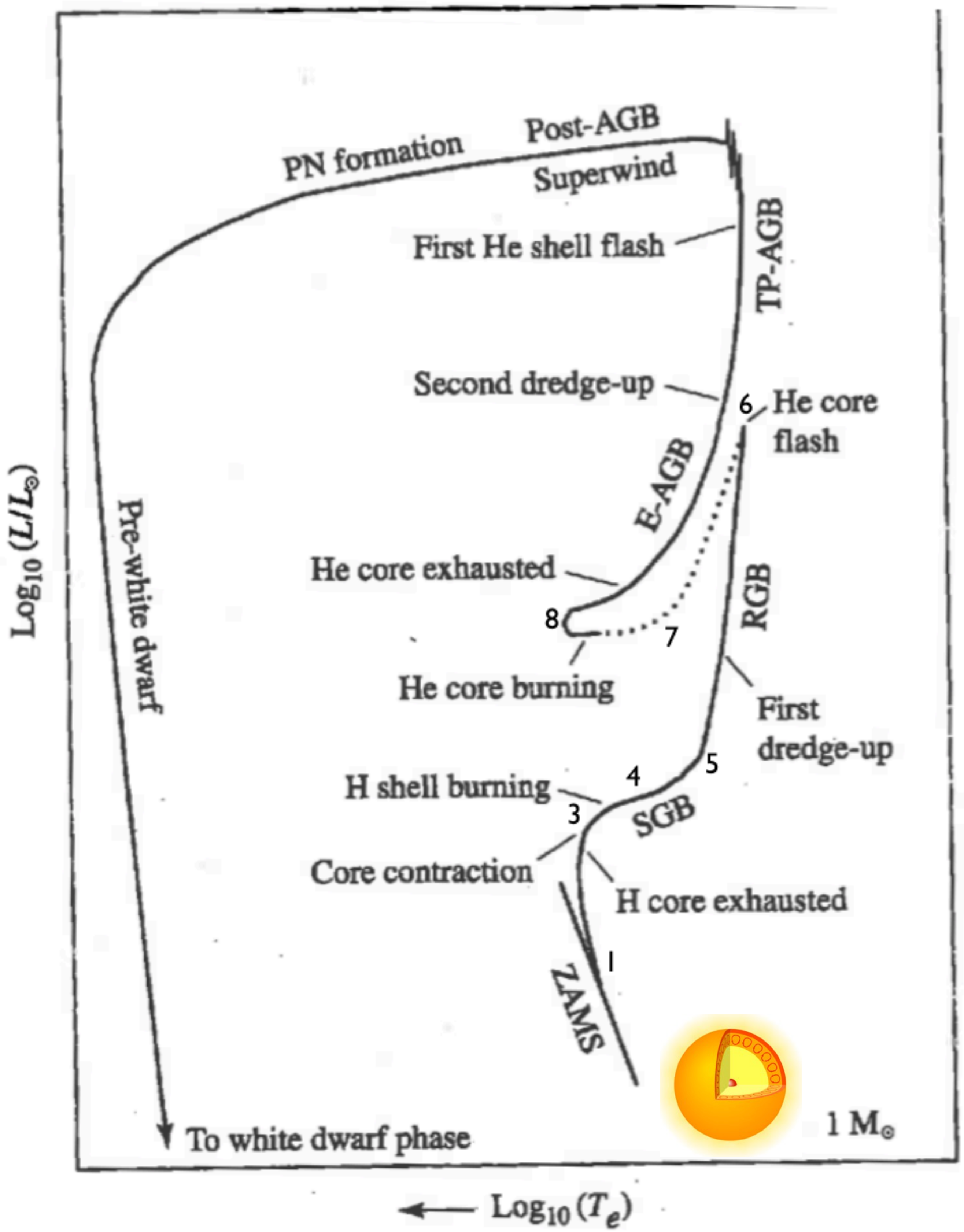


MAIN SEQUENCE

For a given chemical composition, ZAMS = locus of points in HR diagram characterizing static stars of homogeneous composition fusing H—>He in the core

For very massive stars, the lifetime of the star becomes constant, i.e., $M>100\ M_{Sun}$, $t\sim 3\times10^{6}$ yr, with lifetime not set by E/L, but by M/(dM/dt) because of large mass loss ($10^{-3}\ M_{Sun}$/yr —> $\sim10^{5}$ yr

Evolution of low-mass star:



$$P = \frac{\rho\, kT}{\mu\, m_H}$$

[1-to-3]: as H—>He, mean molecular weight increases in core, P decreases, core contracts increasing T and density, and rate of reaction increases, with L slowly increasing (as well as R and T_{eff}). The envelope is convective, and it does not expand much, hence same T_{eff}.

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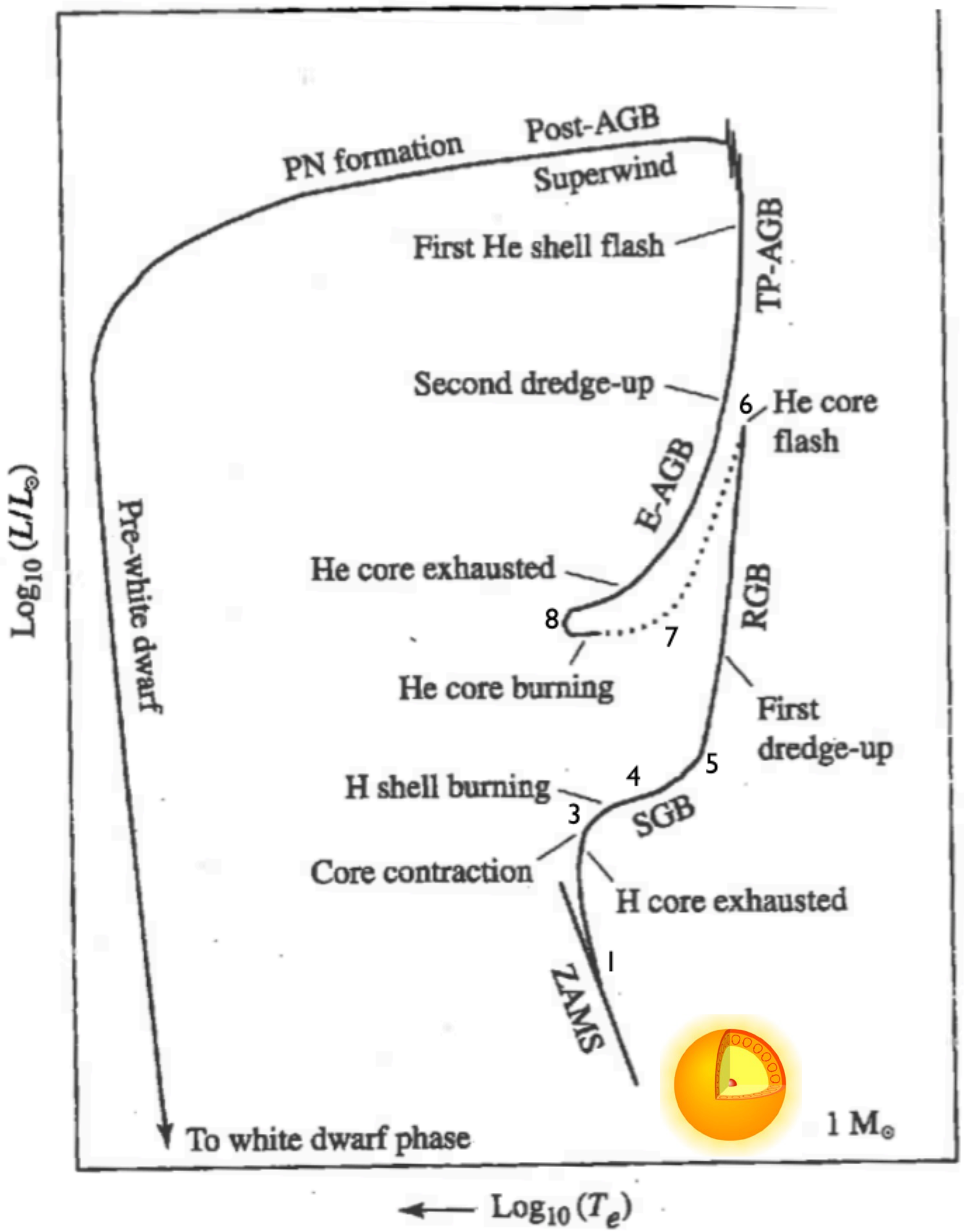

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[3]: When H in core is depleted, H—>He proceeds in a shell around a small, predominantly ^{4}He isothermal core and L=0 from nuclear fusion. The L produced in shell exceeds that produced by the core because of larger T —> L raises, and some of this energy goes into a slow expansion of the envelope —> T_{eff} decreases and track bends right. The ^{4}He produced in the shell is added to the core, which increases its mass.

The $_4$He core is able to support the material above as long as $\mathbf{M_{iso,core} < f_{SC} M}$, with f_{SC} Schönberg-Chandrasekhar limit.

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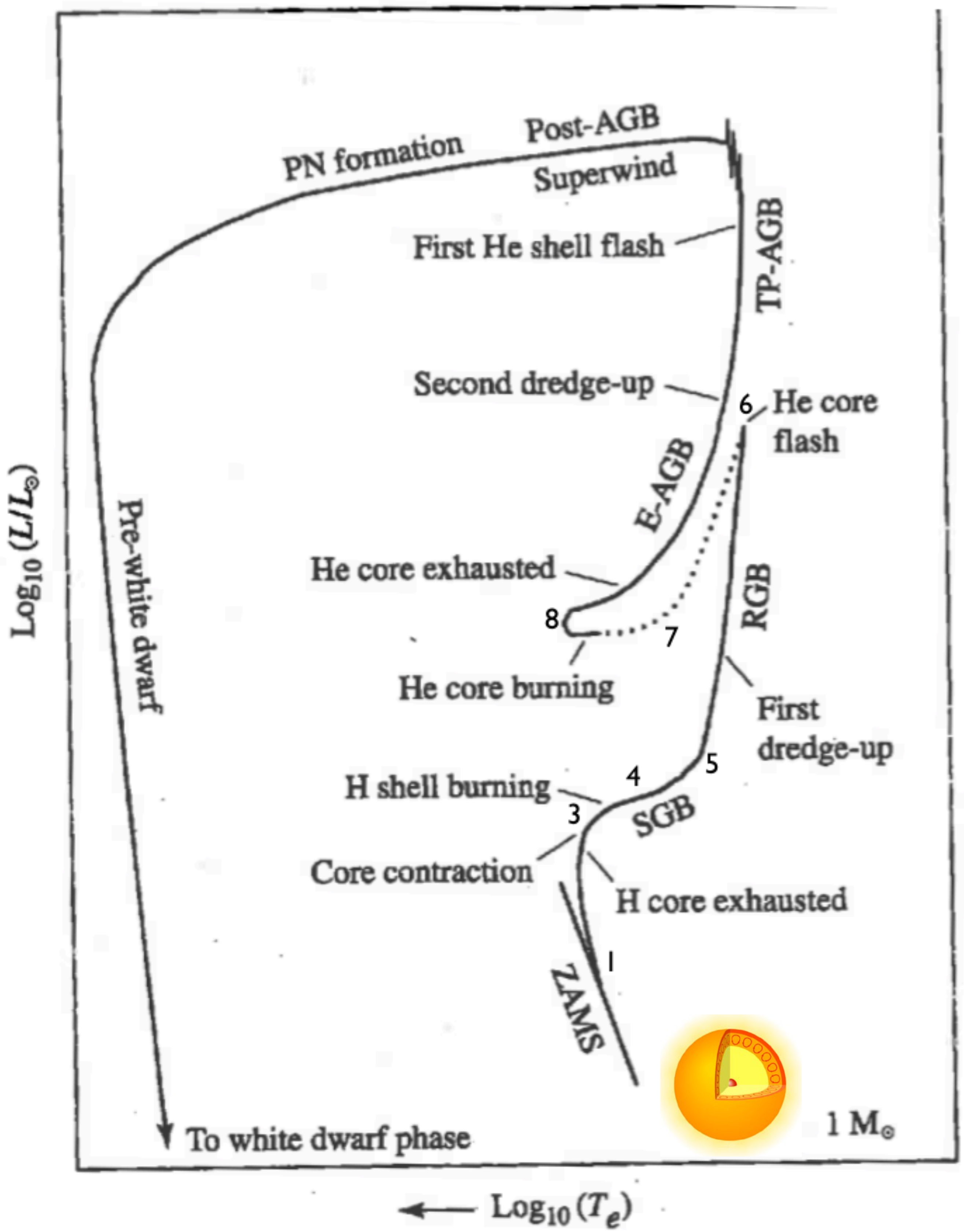

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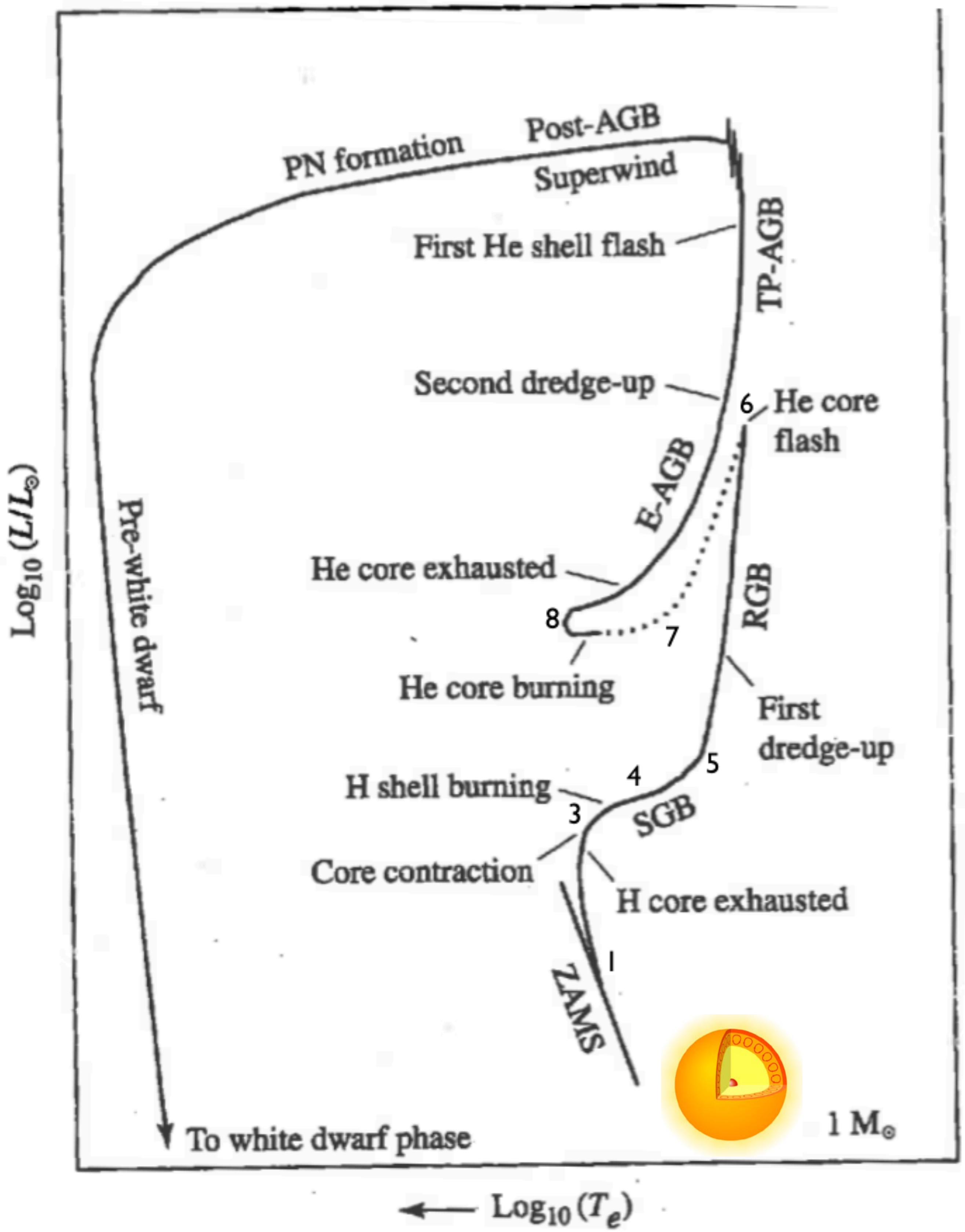

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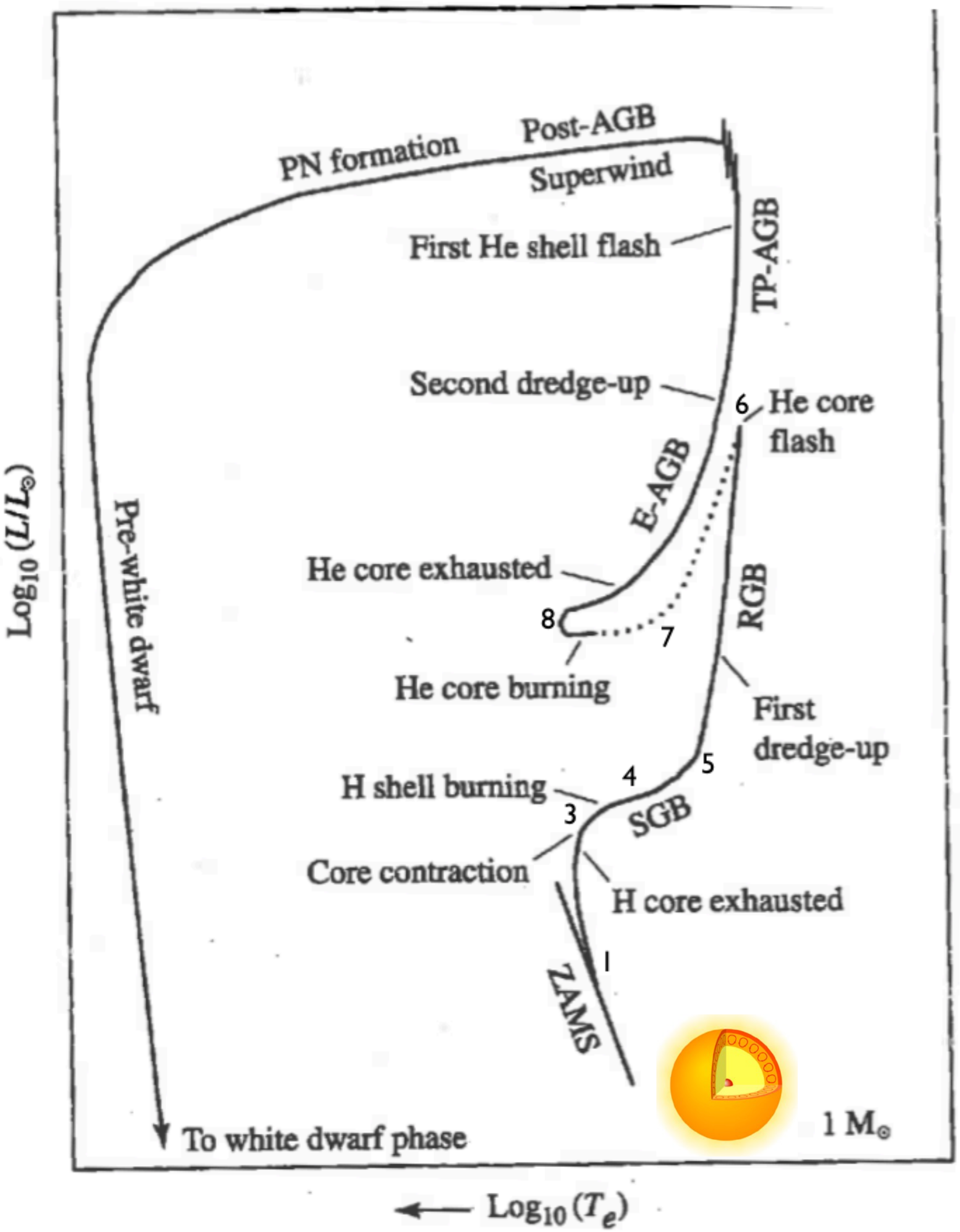

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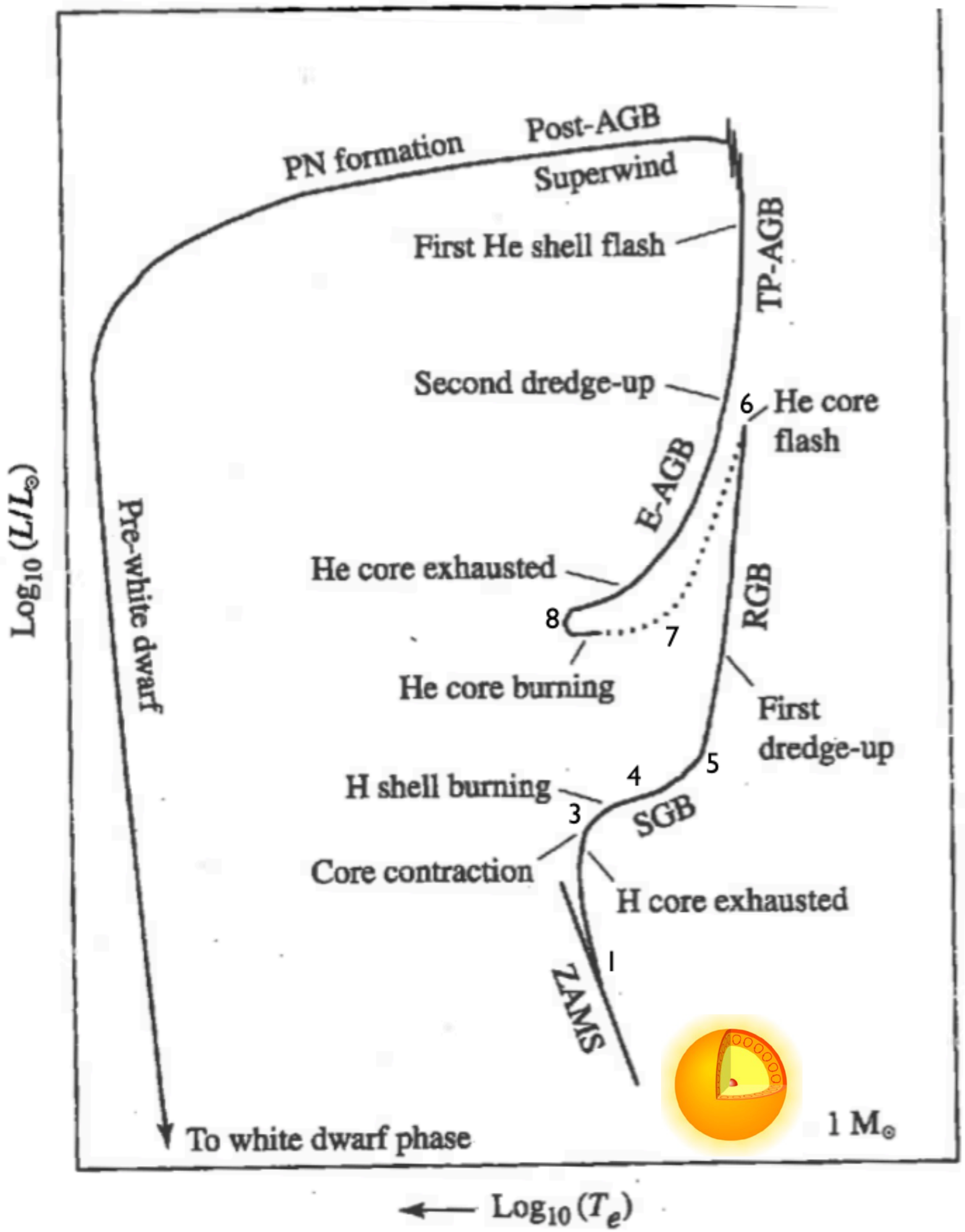

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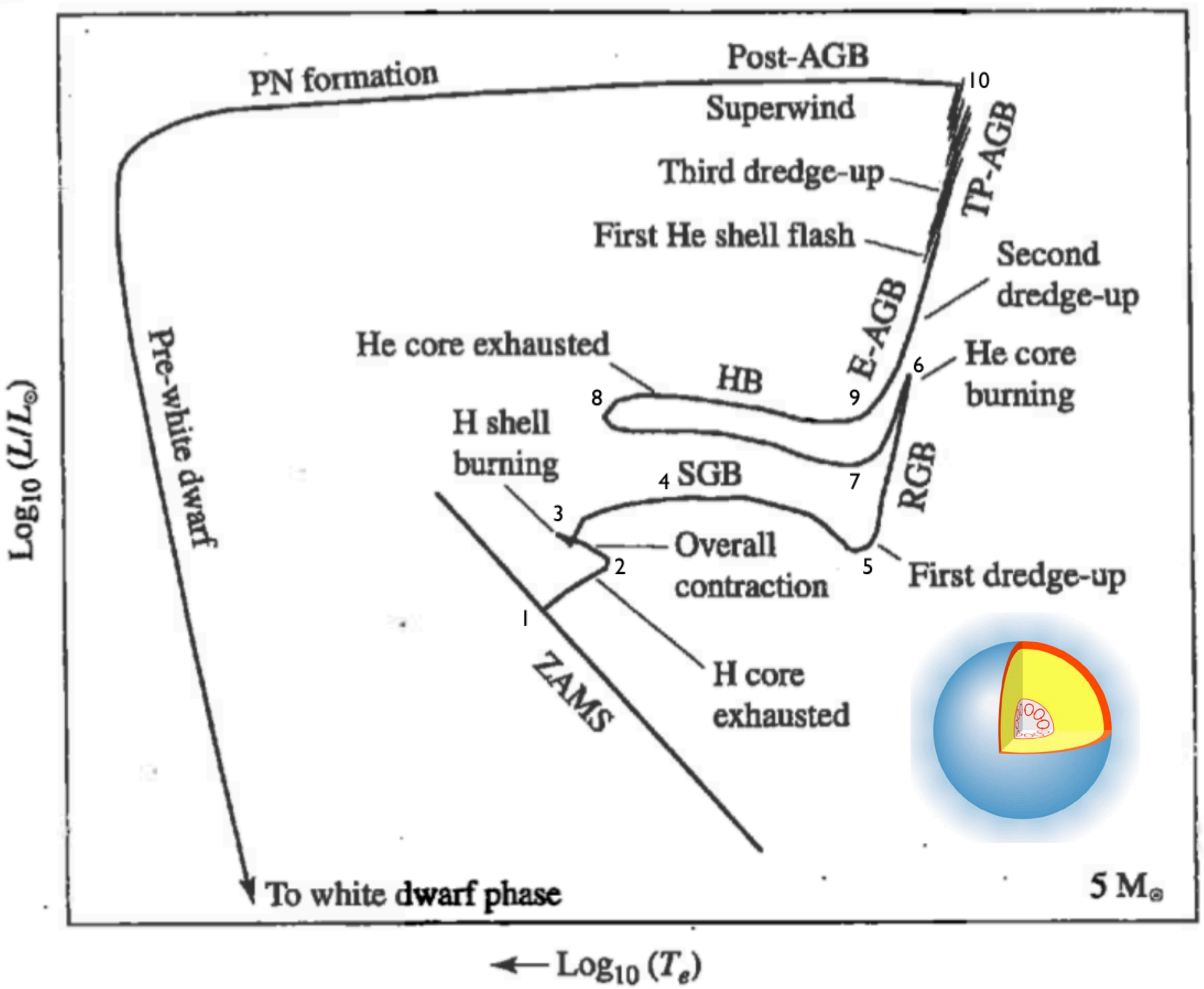
NOTE: As the density increases, e^- degenerate pressure kicks in, and $M_{iso,core}$ can reach 13% of the entire mass before collapsing.

Evolution of high-mass star:



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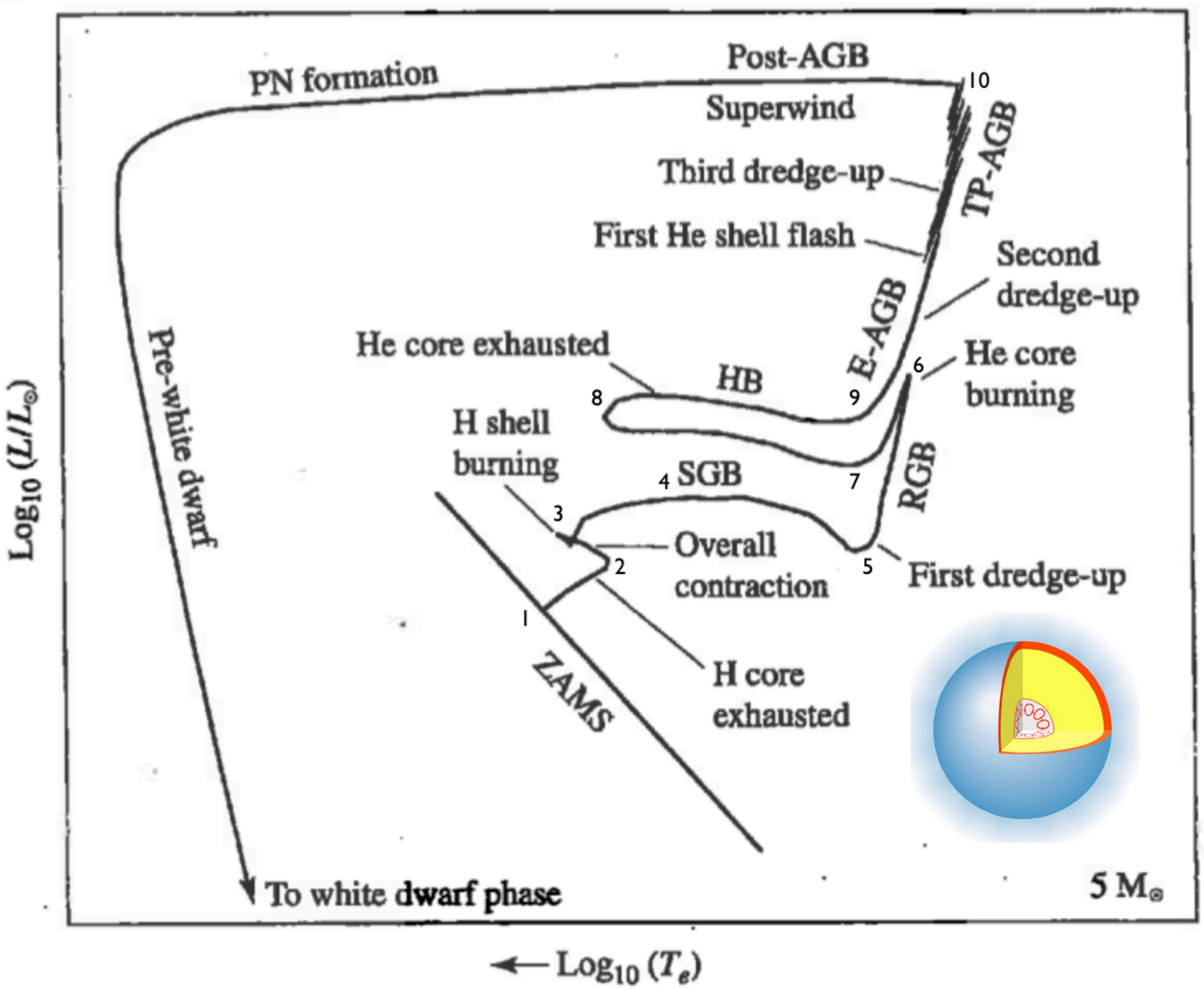

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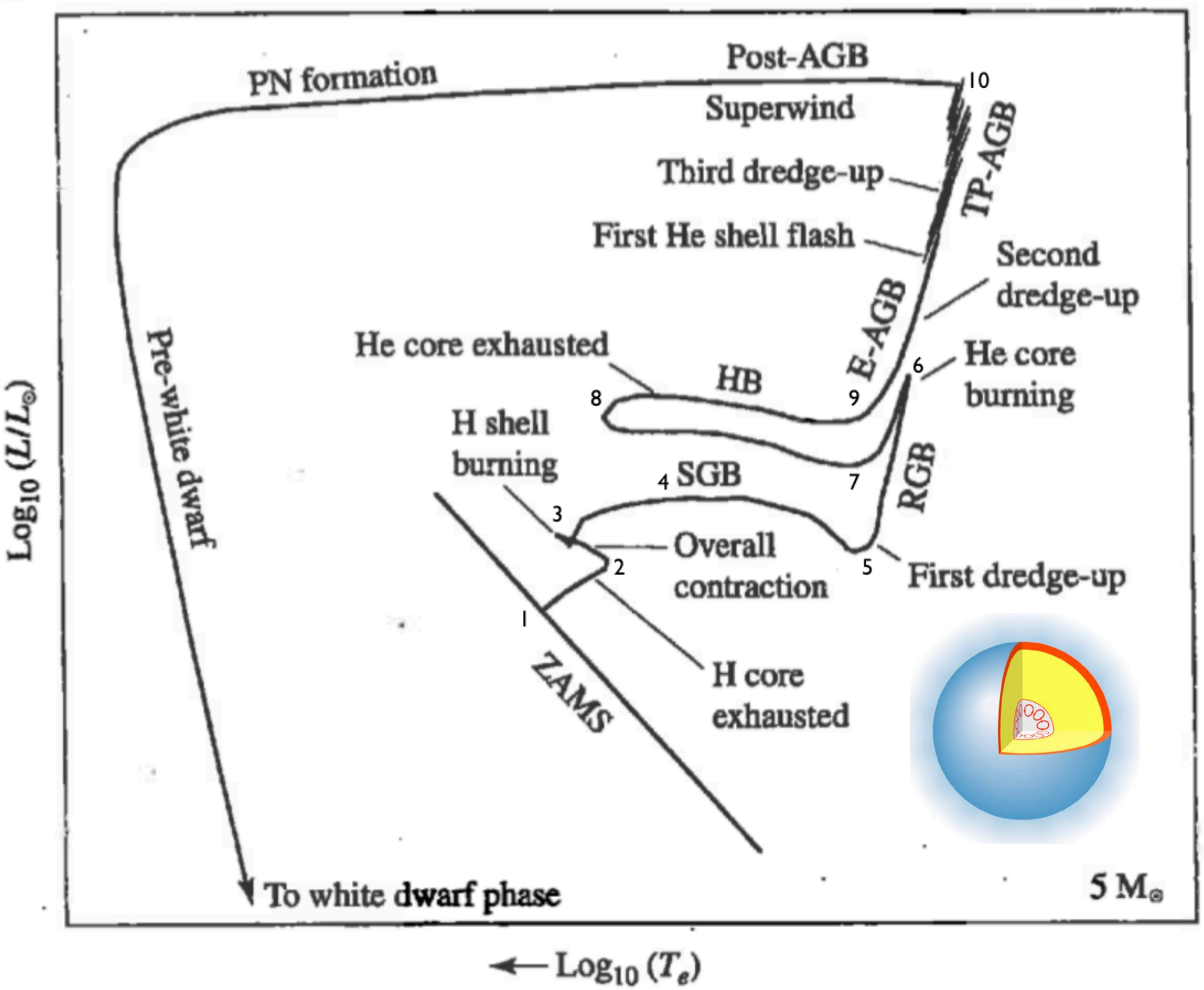

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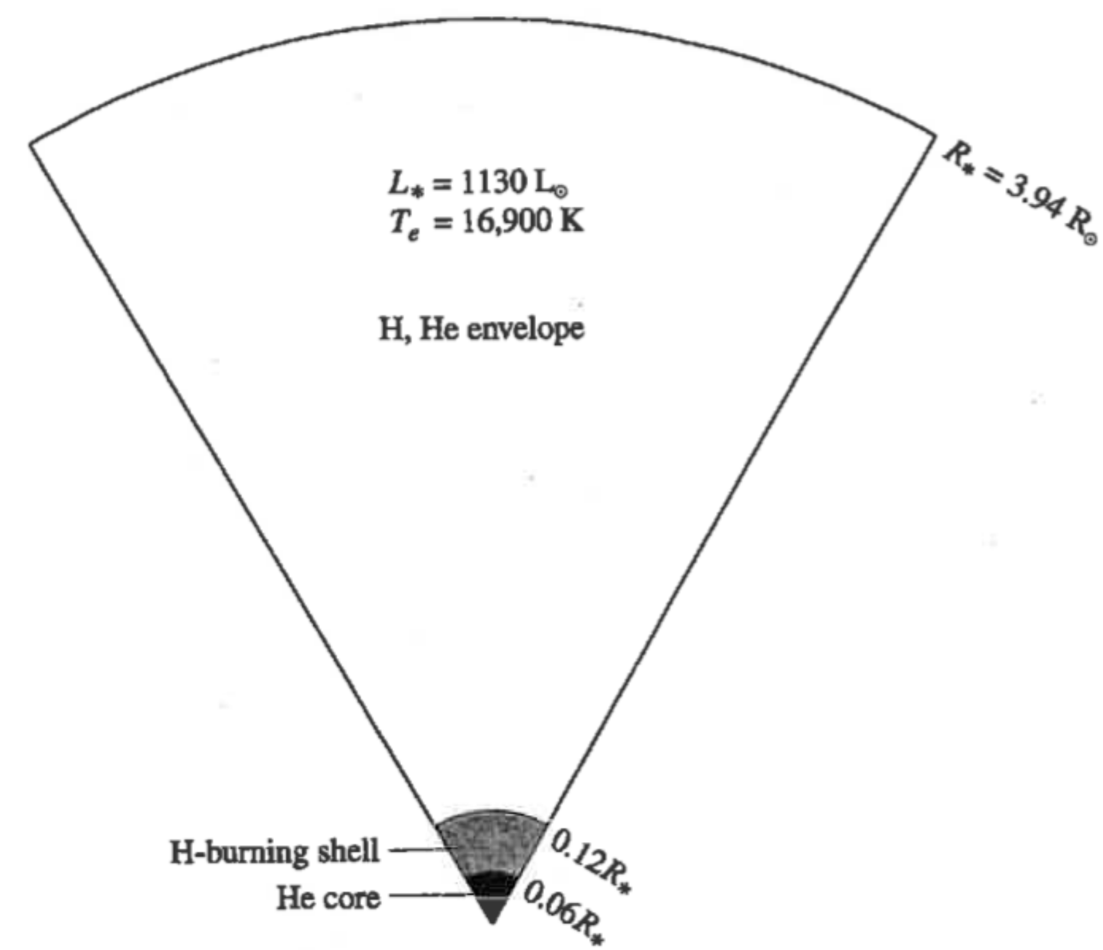
[3]: T outside the core is large enough to ignite H fusion in a shell.



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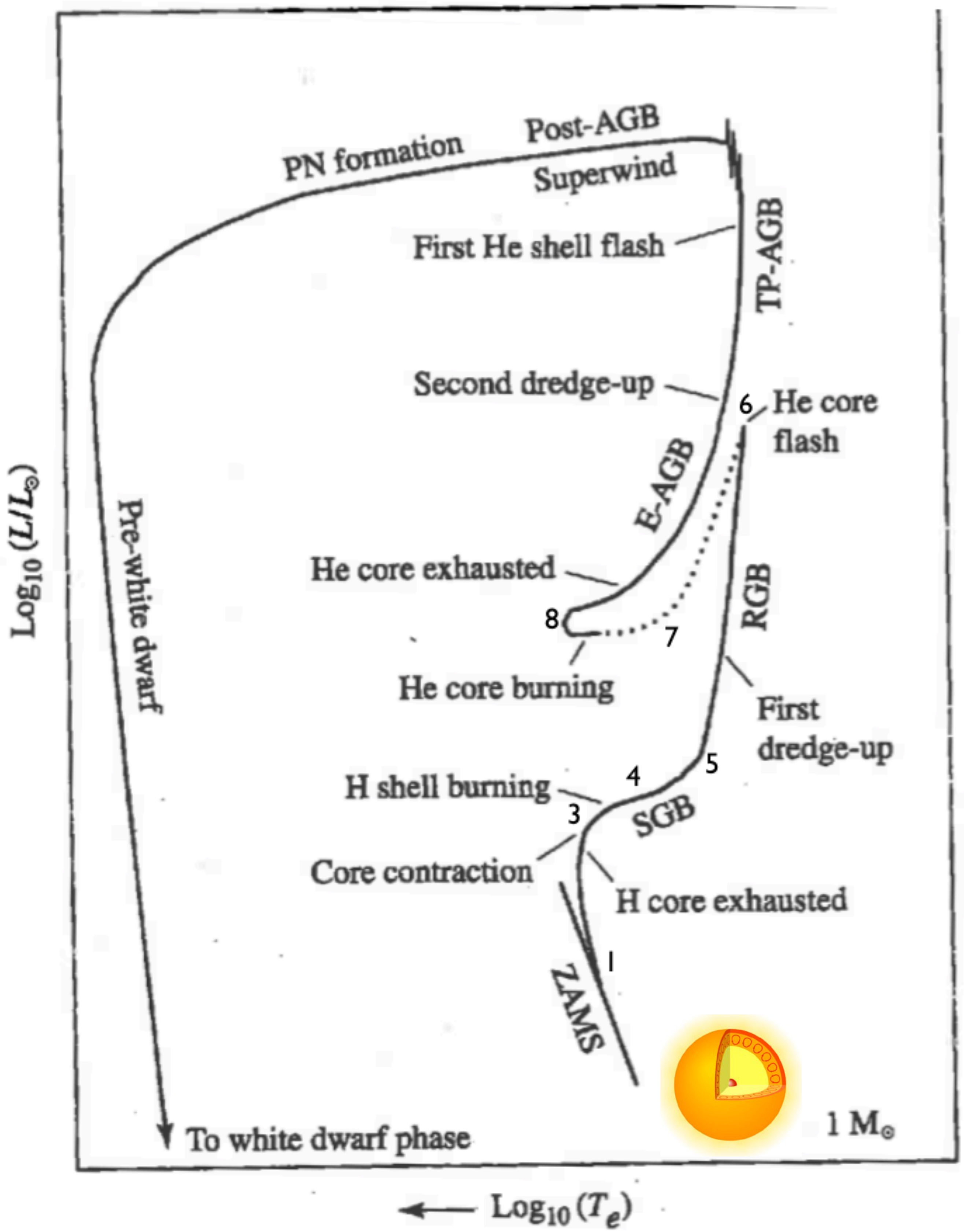
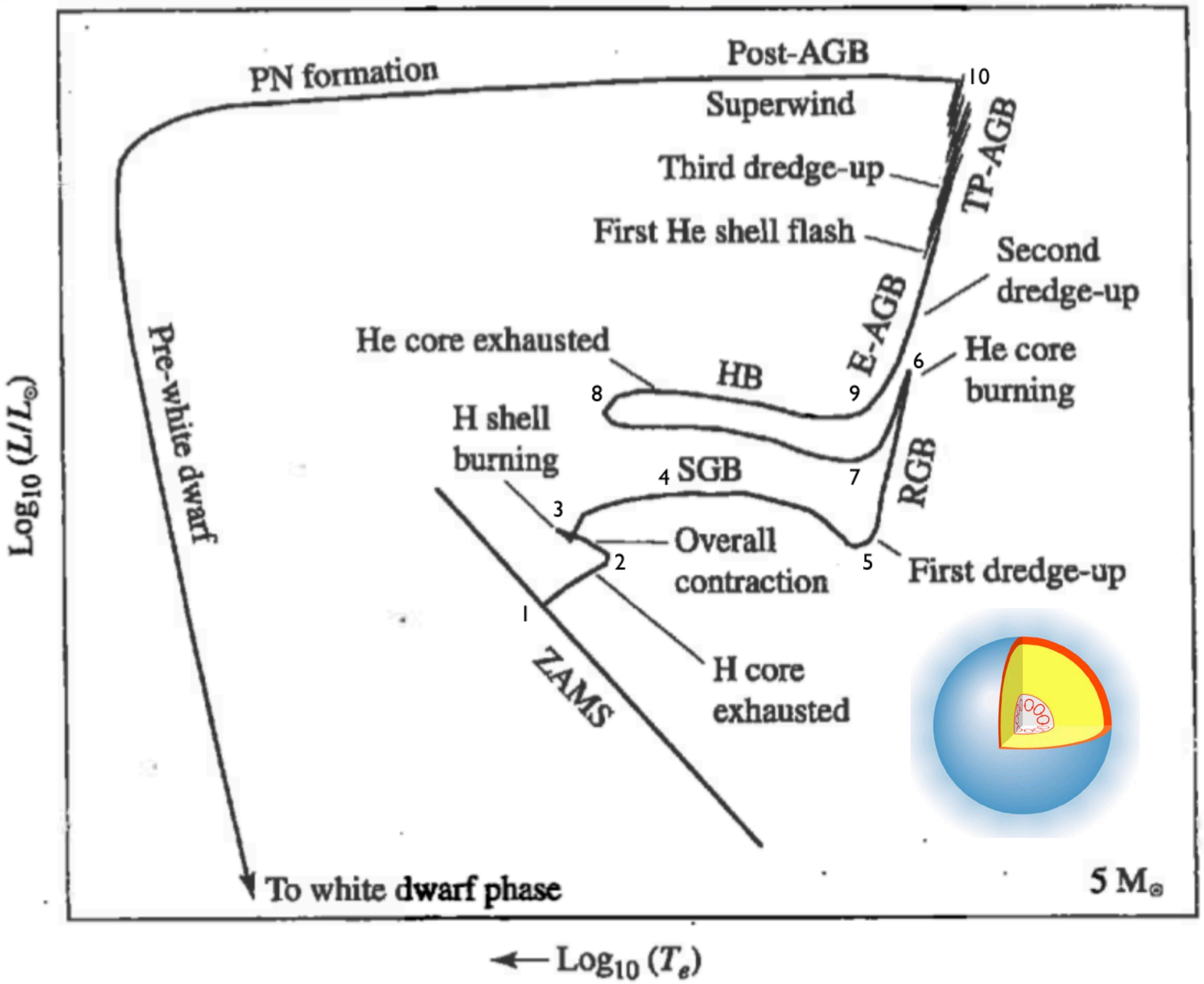


At **[4]** the core contracts rapidly as SC limit is reached.

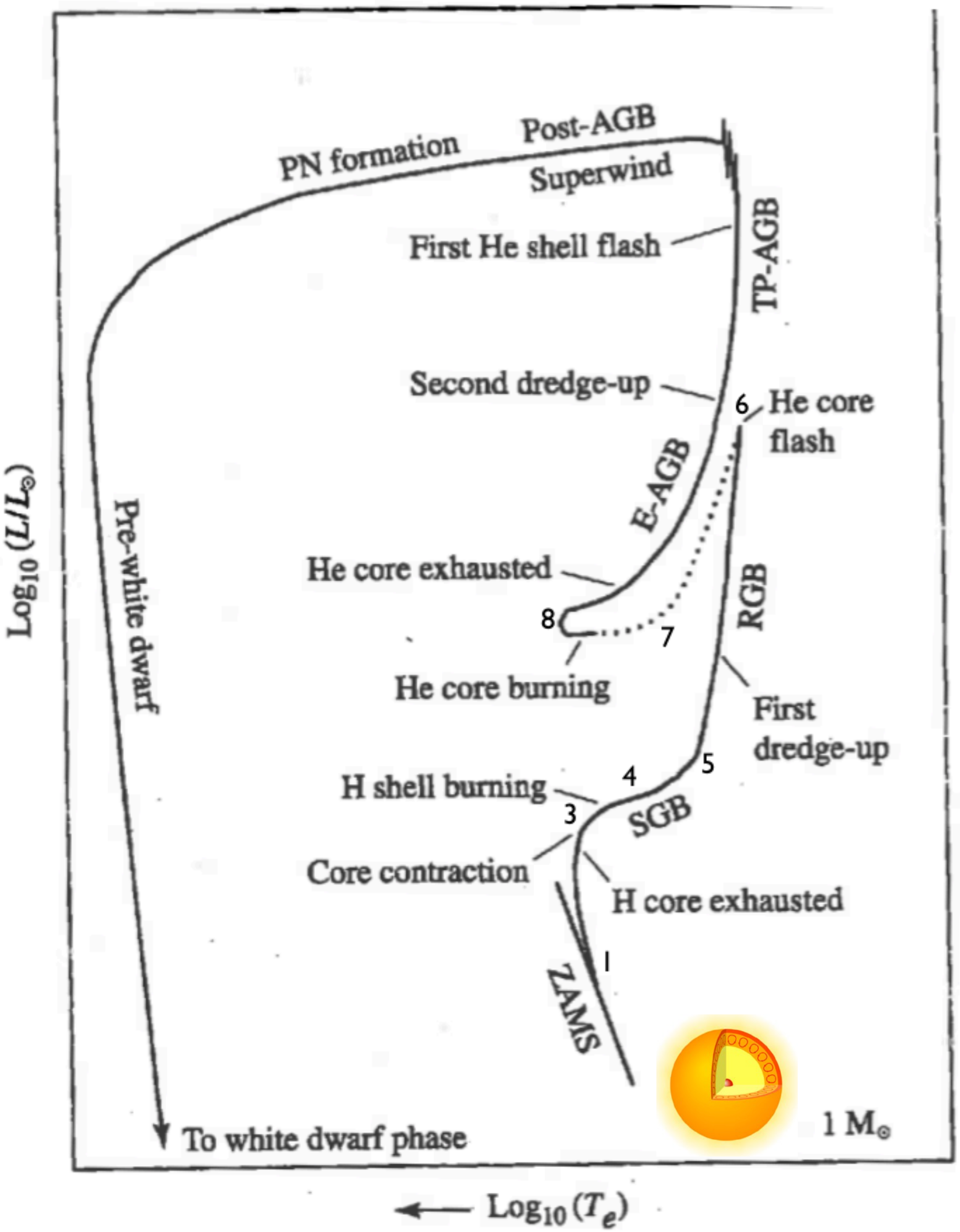
[4-to-5]: as the core contracts, the gravitational energy released causes the envelope to expand. Moreover, T and density in H-fusing shell increase (as it is dragged inward as the core contracts), making energy production rate to increase rapidly —> the envelope expands, absorbing the energy produced by the shell —> lower T_{eff}, with redward evolution on the HR (the Sub-Giant Branch).

Evolution of high-mass star:



[4-to-5]: For a high-mass star, the energy absorbed is large enough for the L to decrease slightly.

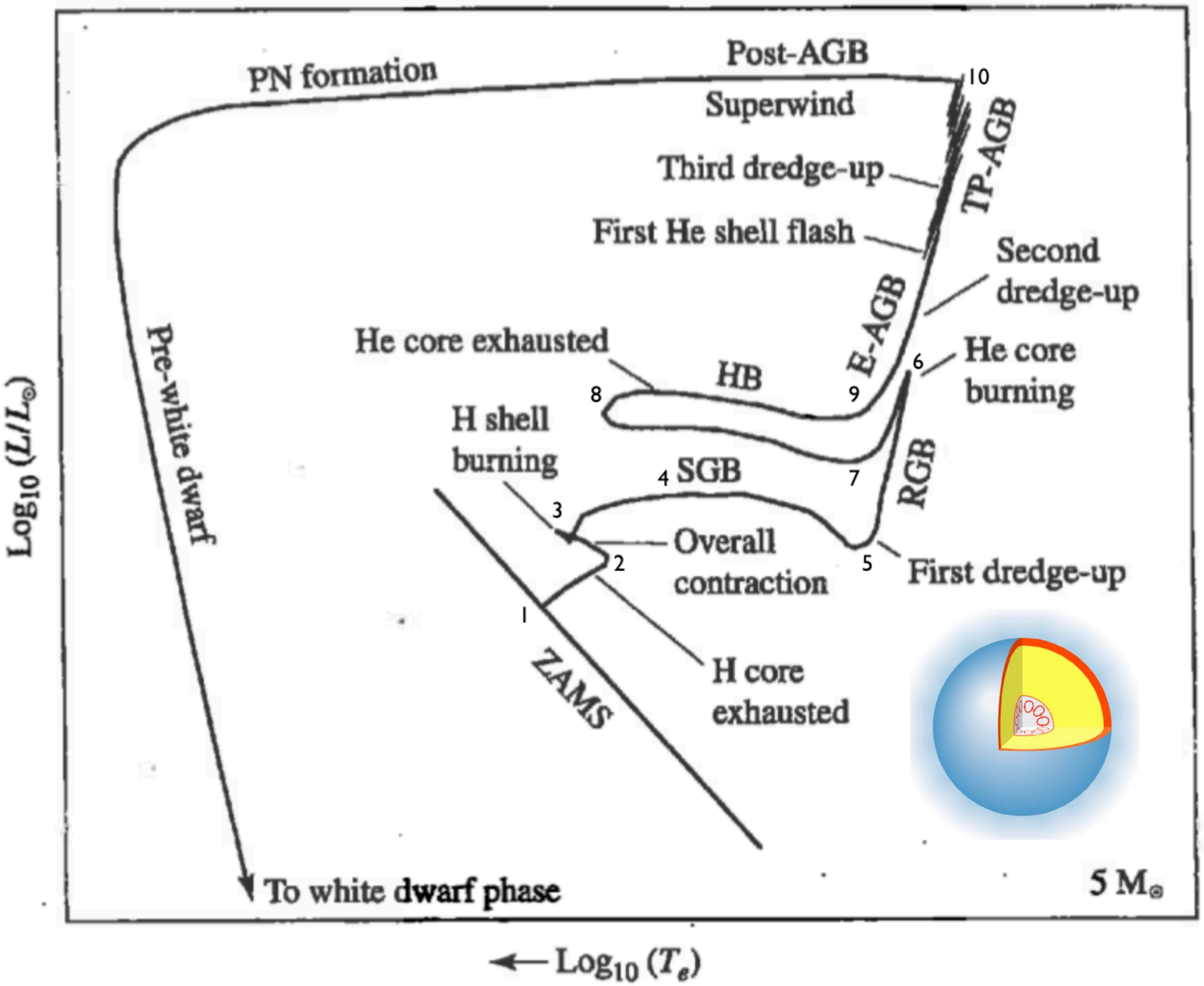
Evolution of low-mass star:



[5-to-6]: As the star evolves to [5], the convection zone near the surface extends deep into the interior of the star, i.e., the star is dominated by convection, and the energy is transported very efficiently to the surface ==> the star moves rapidly upward along the Red Giant Branch (RGB).

The convection zone deepens into the regions where nuclear fusion modified the chemical composition; ^{12}C is transported inward, ^{3}He and ^{14}N outward. The surface $^{12}C/^{14}N$ decreases. This is the **1st dredge up phase**, i.e., transport of material from deep interior to the surface.

Evolution of high-mass star:

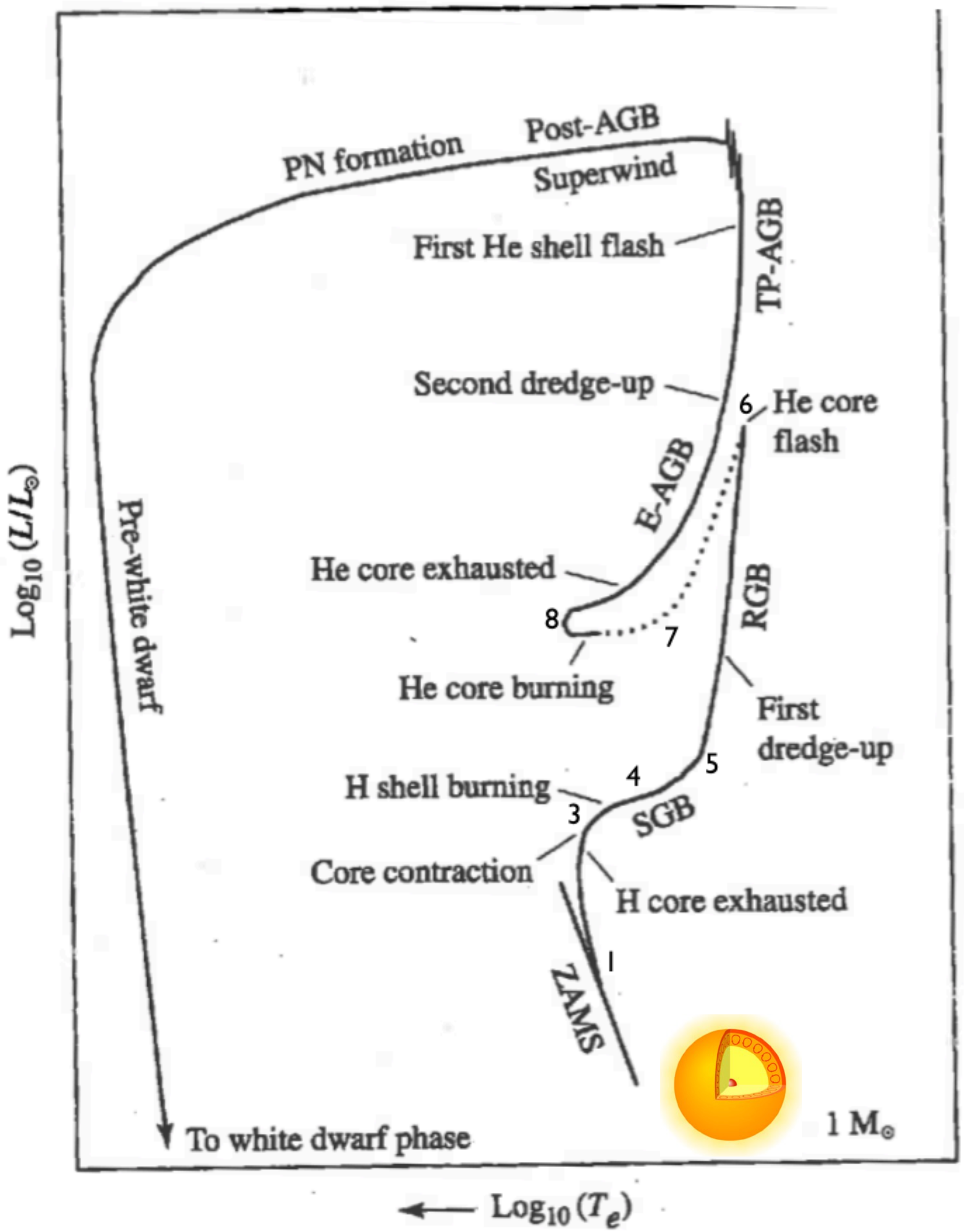


[5-to-6]: Same as above

[6]: Red Giant Tip (RGT)

[6-to-7]: At the tip of the RGB, T=1.3x10^8 K, and density is 7.7x10^3 g/cm^3, high enough for He fusion to ignite, producing ^{12}C, some of which is further processed into ^{16}O. As the nuclear reaction rate is strongly dependent on T, the core is convective. The core expands (ideal gas law), and this pushes the H-fusing shell outward, cooling it and the rate of energy output decreases —> abrupt decrease in L. At the same time, the envelope contracts, and T_{eff} increases, and the star moves to a bluer color.

Evolution of low-mass star:

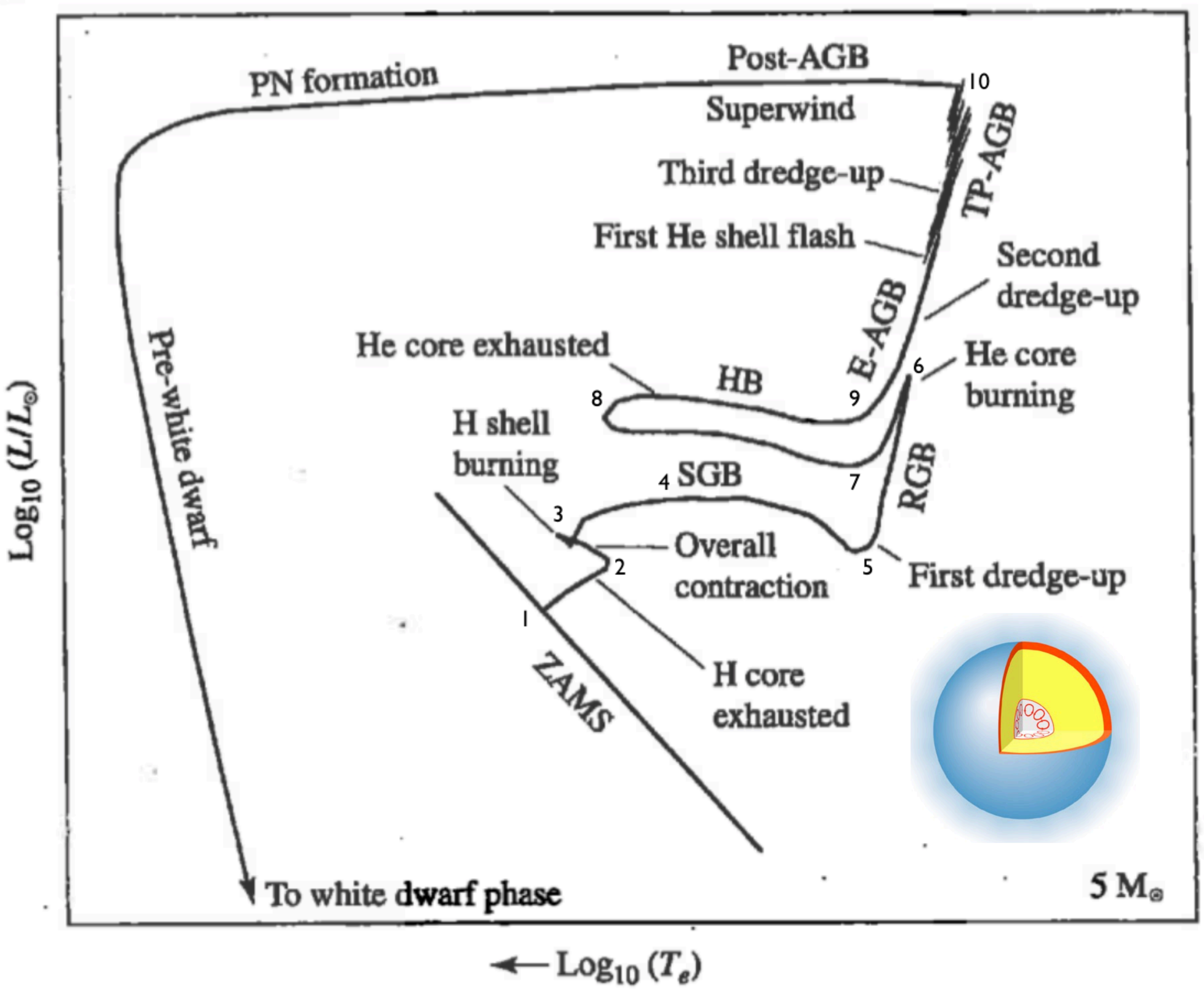


[6]: For $M<1.8\ M_{Sun}$, as the core collapses from 5 to 6, it becomes strongly e^-degenerate. When T and density are large enough to start the He fusion ($T\sim10^8$K, density$\sim10^4$ g/cm^3), the energy is released explosively (**He flash**).

The energy released during the He flash is $\sim10^{11}\ L_{Sun}$!!! But lasts for only a few seconds, with most of this energy not reaching the surface, as absorbed by the overlying layers and causing some mass loss from surface. The energy generated removes the degeneracy, and then it goes into kinetic (thermal) energy needed to expand the core —> T and density decrease, slowing reaction rate —> core convective, quiescent He fusion in core and H-fusing shell (**HORIZONTAL BRANCH**).

1/4 of the life of a star is spent on the HB (2/3 on the MS)

Evolution of high-mass star:

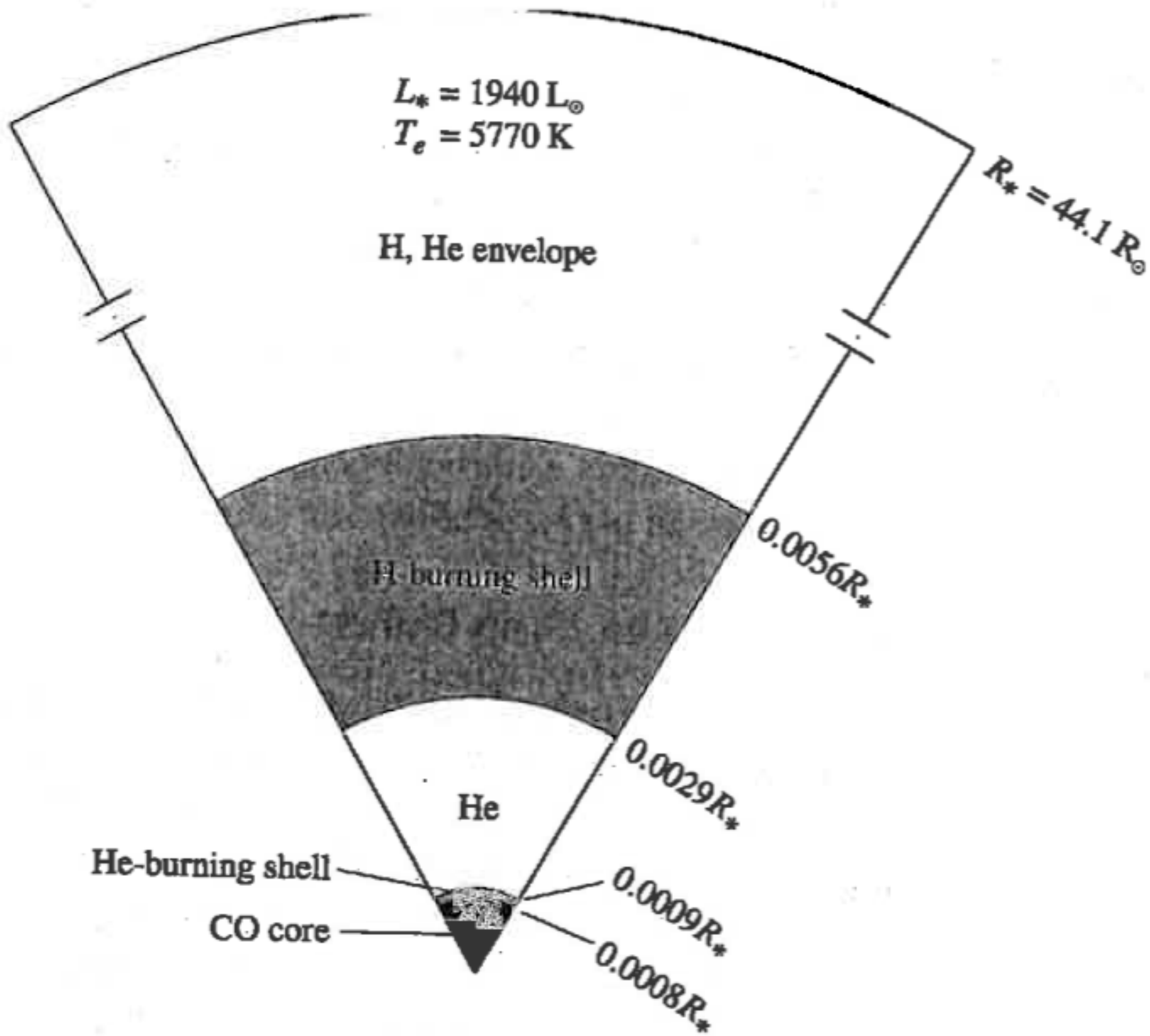


[7-to-8]: As the envelop contracts following the RGT, the H-fusing shell compresses, the energy output from the shell increases, the L increases and T_{eff} increases
—> deep convection zone in envelope shrinks with convective core
—> blue evolution on the HB.

[8]: at some point, the mean molecular weight in the core has increased, and the core begins to contract along with the expansion and cooling of the envelope —> begin redward evolution of the HB.

[8-to-9]: shortly after, the He in the core is exhausted, converted to C and O, and now there is an inert CO core which begins contraction —> fast evolution on the redward HB. As the core contracts, and the shell above it too, T increases, and He-fusing ignites in shell.

Evolution of high-mass star:



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As the core contracts, and the shell above it too, T increases —> He fusion ignites in shell. The energy released expands the outer envelope, including the H-fusing shell, which cools, halting temporarily H fusion.

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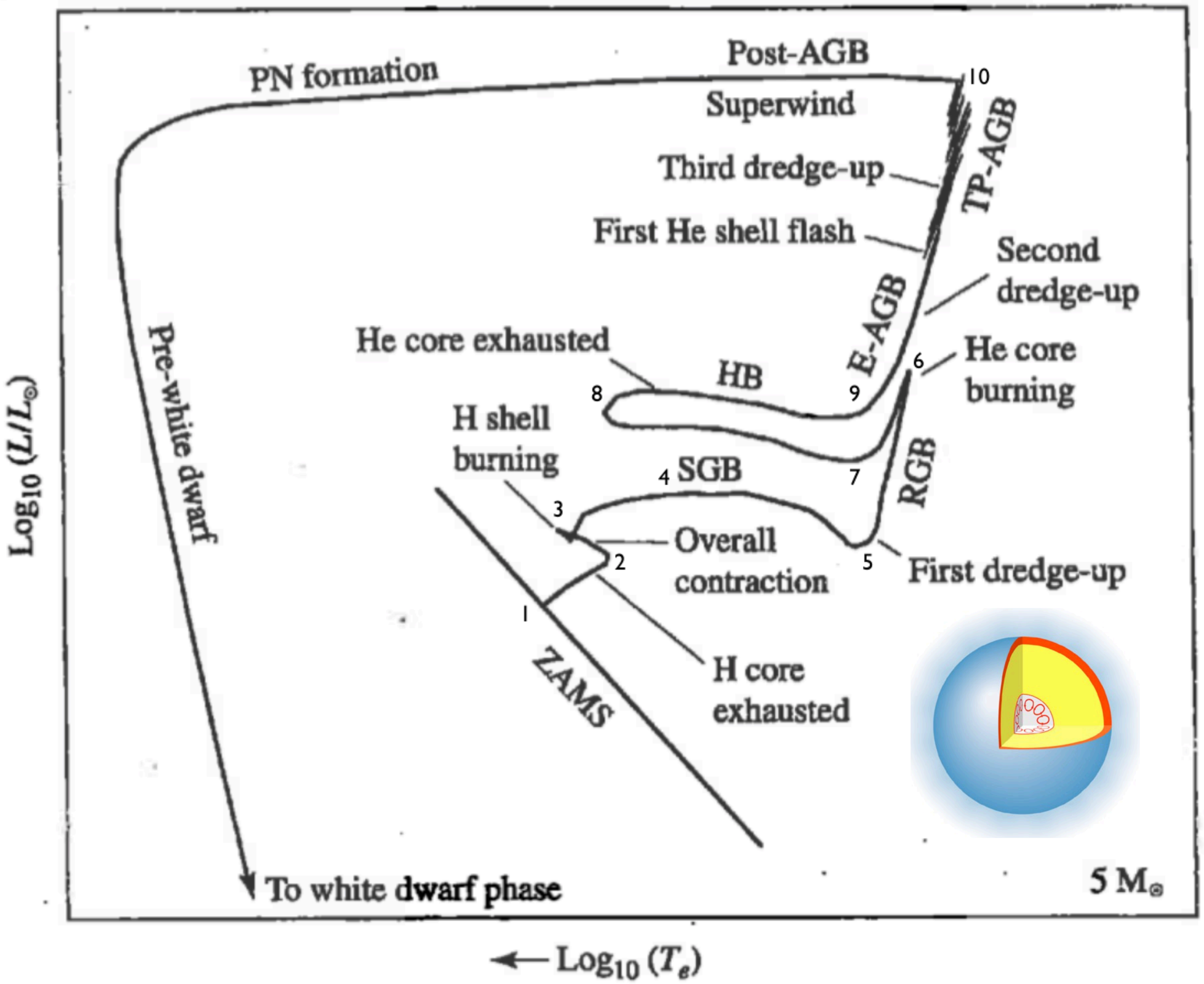
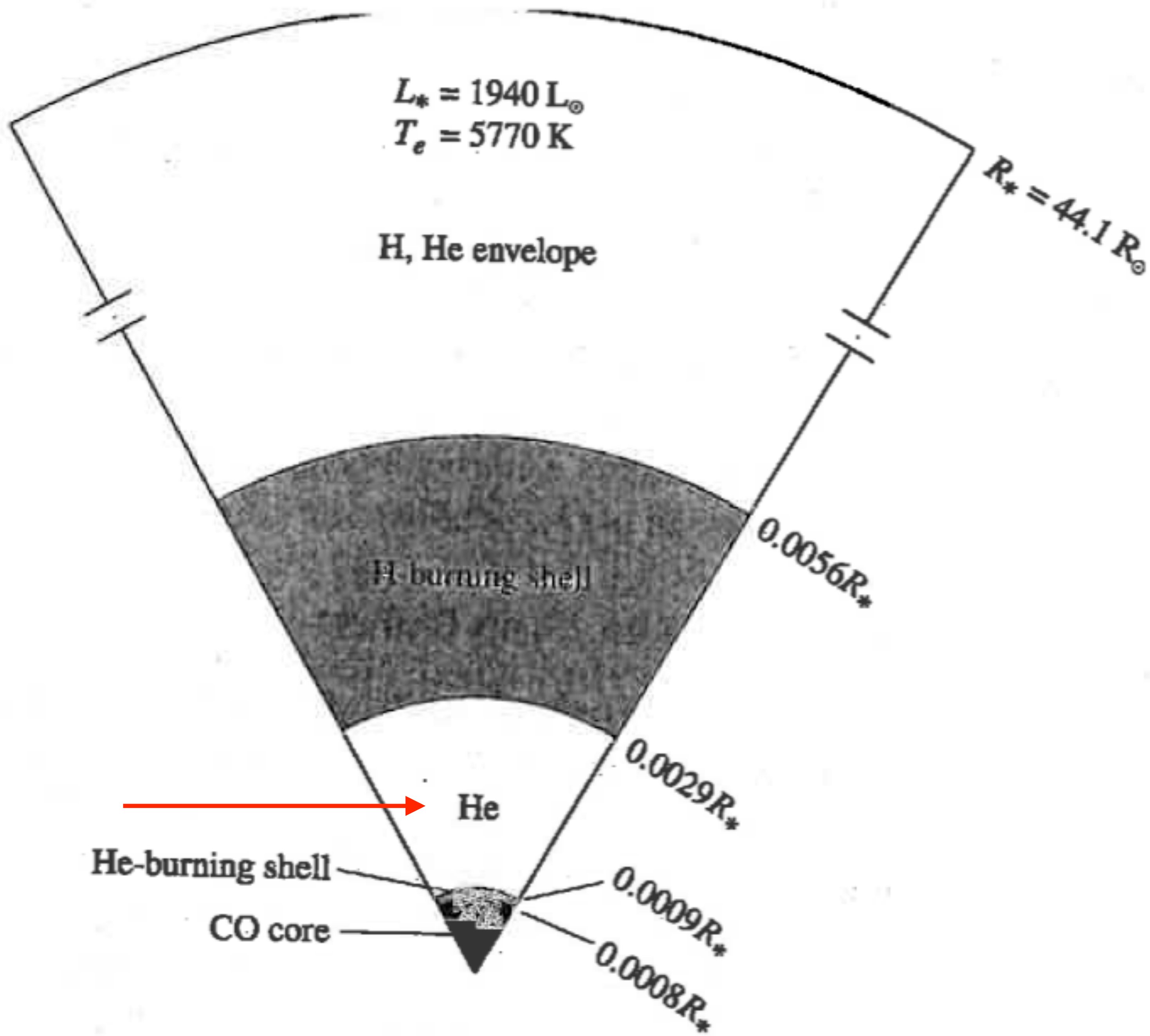


[9-to-10]: When the redward evolution of the HB reaches the Hayashi track (no solution of stellar structure transporting energy exists at lower T_{eff}), the evolutionary track bends upward, along the Early Asymptotic Giant Branch (**E-AGB**). This is analogous to the H-fusing shell, but with the He-fusing shell.

$T_C \sim 2 \times 10^8$K, density$\sim 10^6$ g/cm^3. In the E-AGB, the star has He- and H-fusing shells, with the former dominating the energy output, and the latter nearly inactive.

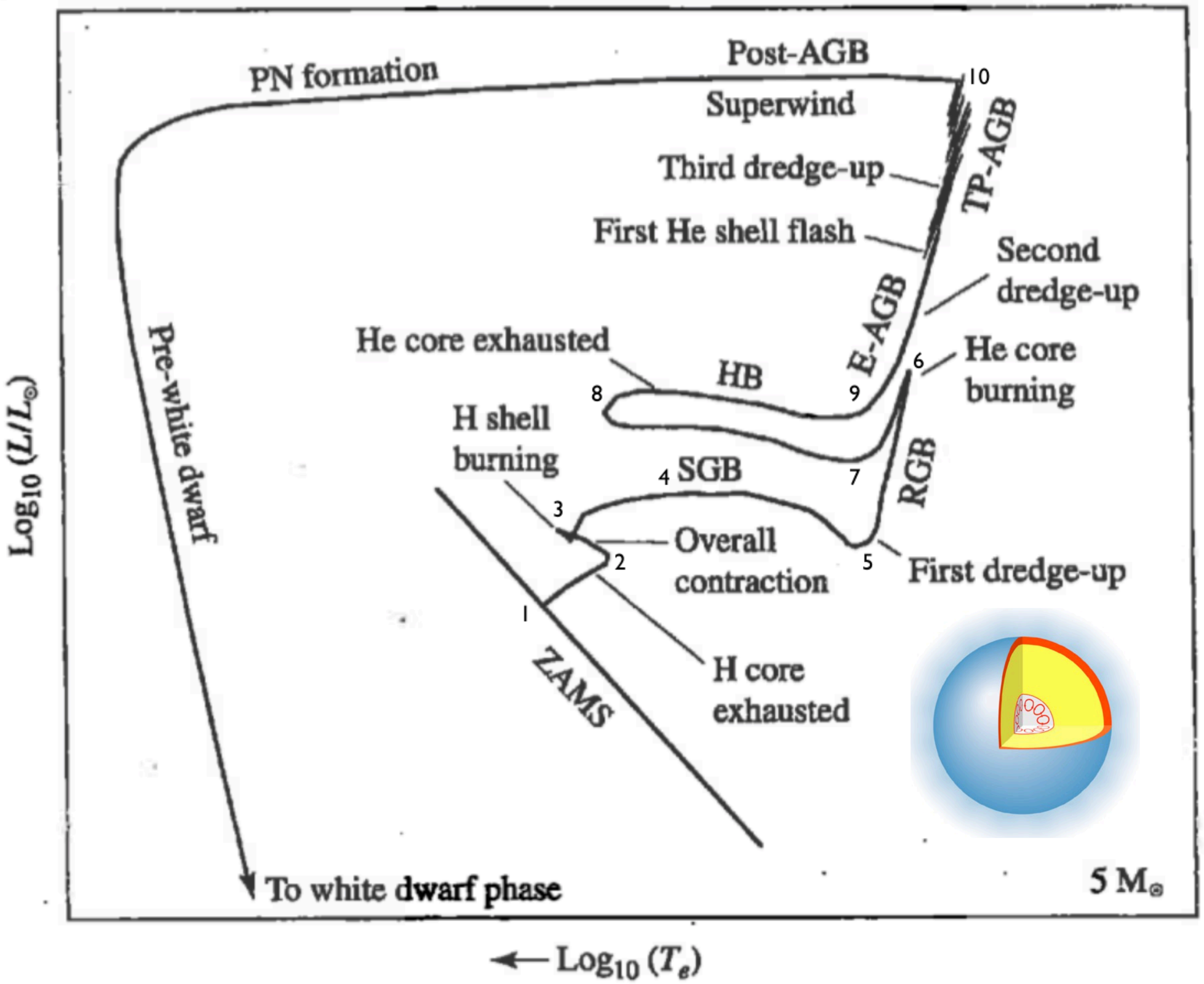
Evolution of high-mass star:



[9-to-10]: The outer envelope expands as it absorbs much of the energy produced by the He-fusing shell —> T_{eff} decreases and the convective envelope deepens into the chemical discontinuity between the H-rich outer layer and the He-rich region above the He-fusing shell

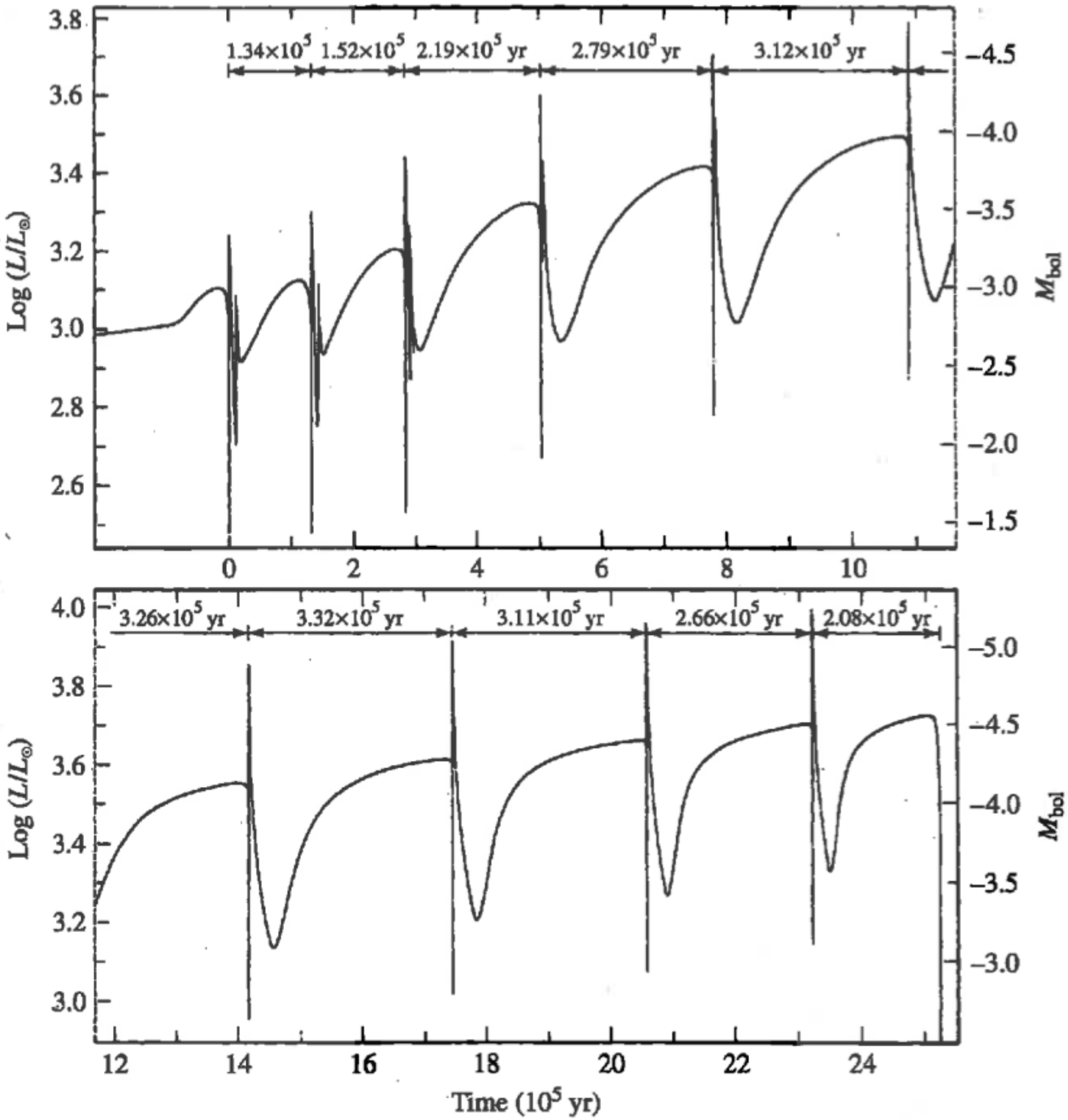
—> 2nd dredge-up phase, increasing He and N content of the envelope.

Evolution of high-mass star:



[9-to-10]: Near the upper portion of the AGN (Thermal Pulsating AGB), the dormant H-fusing shell reignites, dominating the energy output of the star.

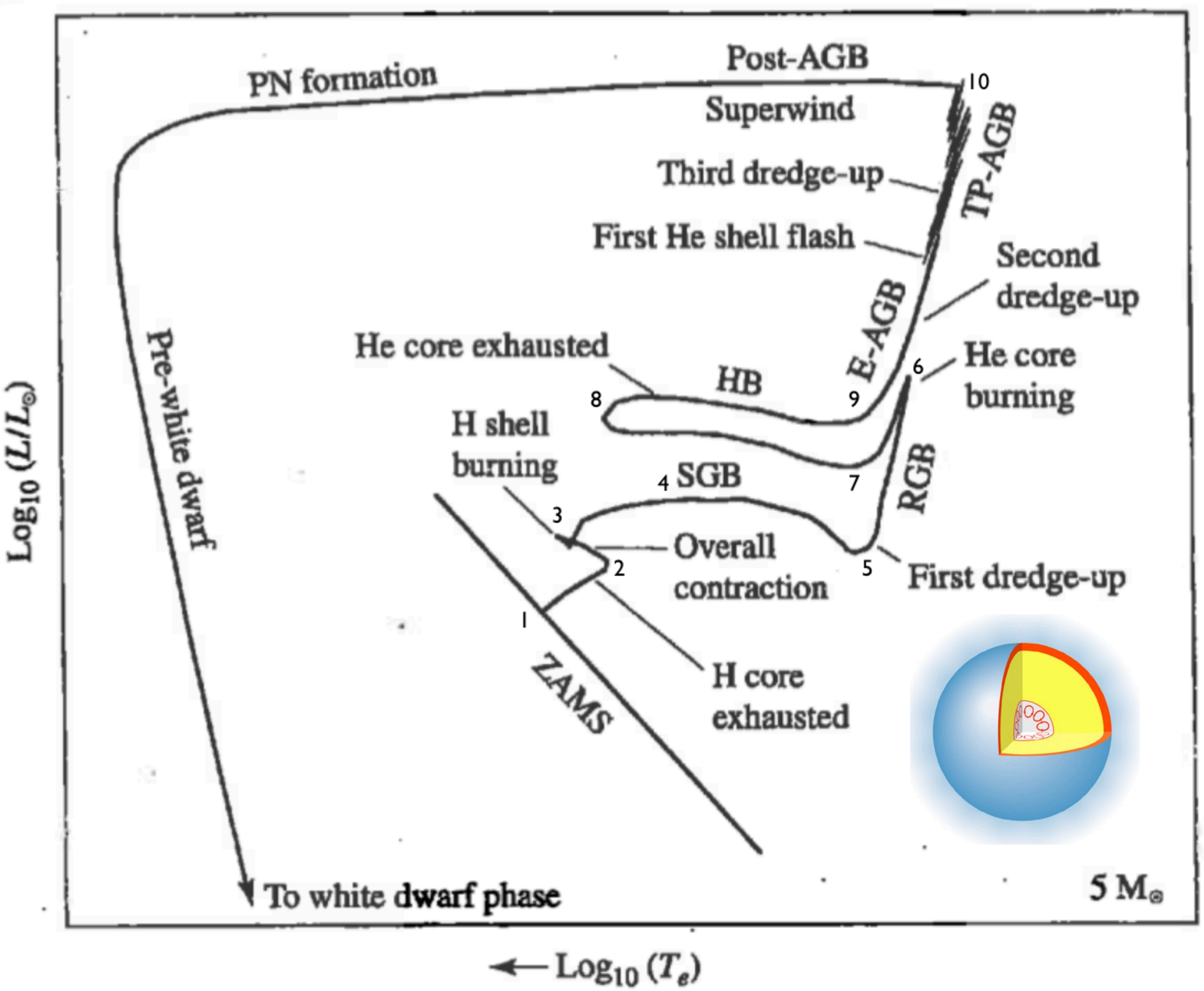
This begins intermittent He- and H-shell flashes, i.e., thermal pulsations.



The period between pulses, function of the mass of the star, ranges from thousands of years for M~5 M_{Sun}, to hundreds of thousands of years for M~0.6 M_{Sun}, with pulse amplitude growing with each event

—> abrupt changes of luminosity at the surface

Evolution of high-mass star:



[9-to-10]: The depth of the convecting envelope increases with the pulse strength of the flashes.

For M>2 M_{Sun}, the convection zone extends all the way down to regions where C has been produced: **3rd dredge-up phase**.

C-rich material is brought to the surface, decreasing the O/C ratio. The O-rich spectrum of a star transforms over time to a C-rich spectrum.

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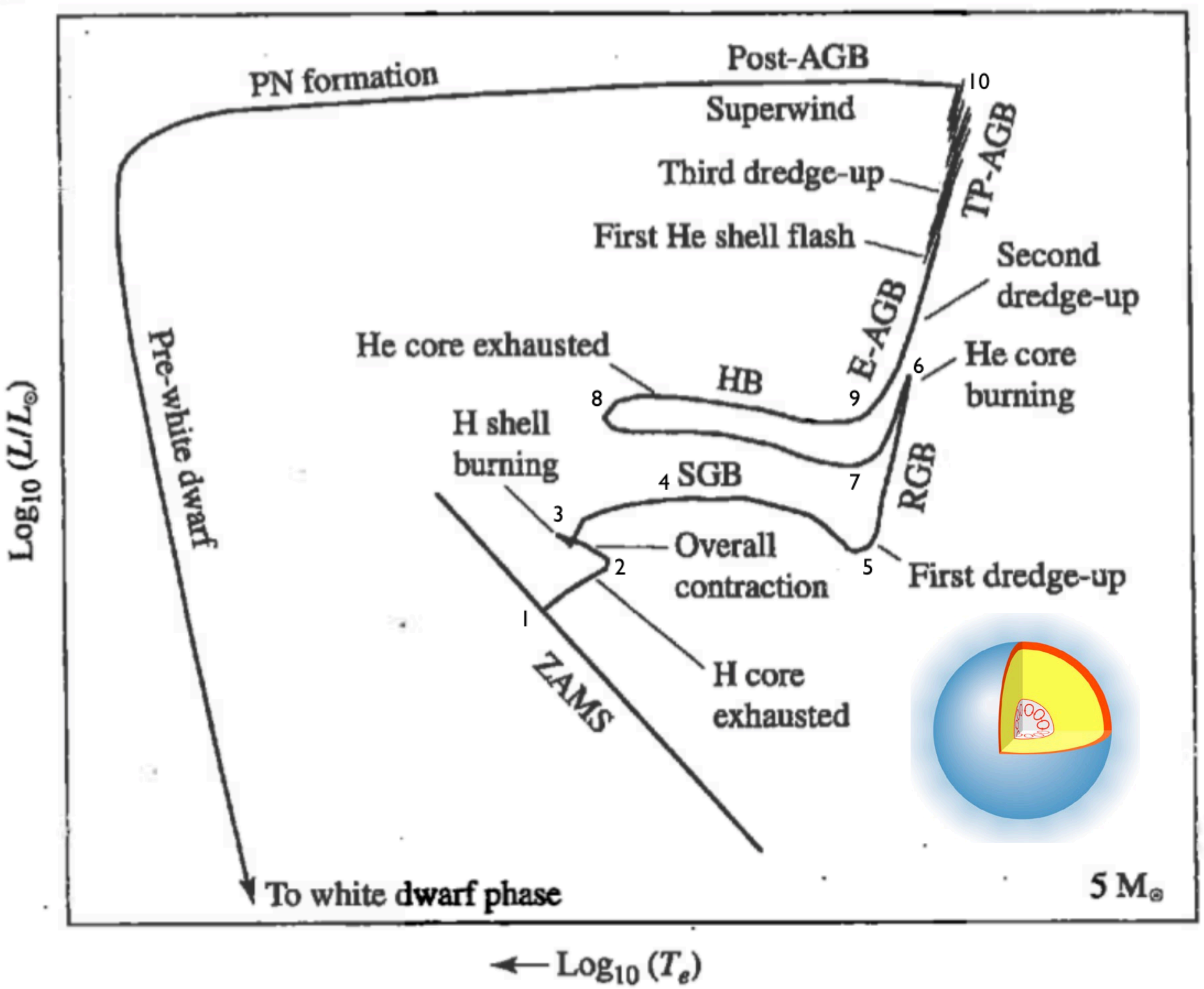

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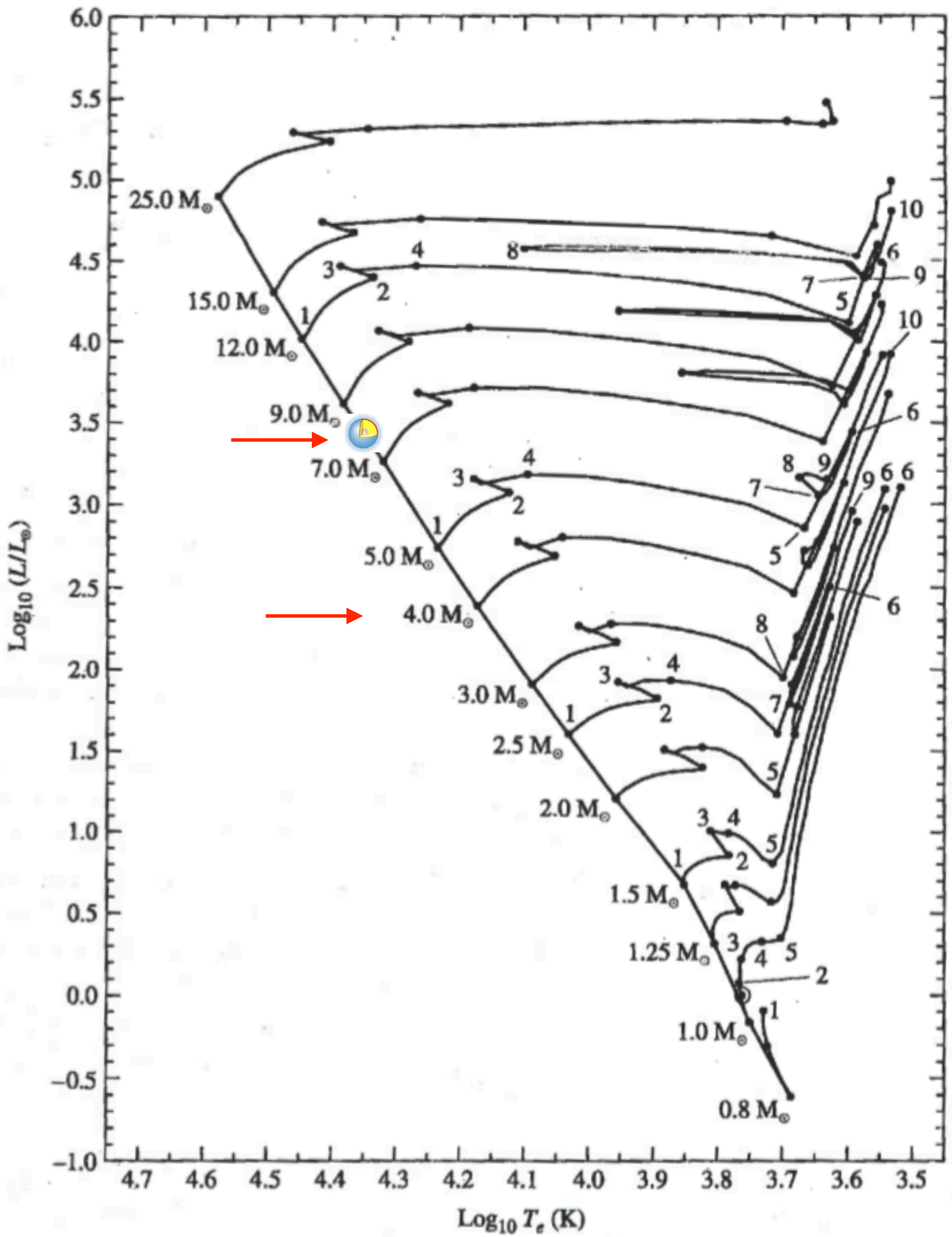
AGB stars lose mass at a rapid rate, as high as $dM/dt{\sim}10^{-4}\ M_{Sun}/yr$. $T_{eff}{\sim}3000K$ (cool) —> dust grains form in the expelled matter.



For M>8 M_{Sun}, the core will undergo significant further nuclear burning.

For M<8 M_{Sun}, the He-fusing shell converts more and more He into C, and then O, increasing the mass of the C-O core as the star evolves up the AGB. The density of the core gets large enough that e- degeneracy pressure dominates.

For M<4 M_{Sun}, the C-O core will never get hot enough to ignite C/O fusion —> white dwarf of C-O

For 4<M/M_{Sun}<8, mass loss prevents catastrophic core collapse, experiencing additional nucleosynthesis in the core, leading to the core composition of O, Ne, Mg, with M_{core}<1.4 M_{Sun} (Chandrasekhar limit) —> white dwarf of O-Ne-Mg.

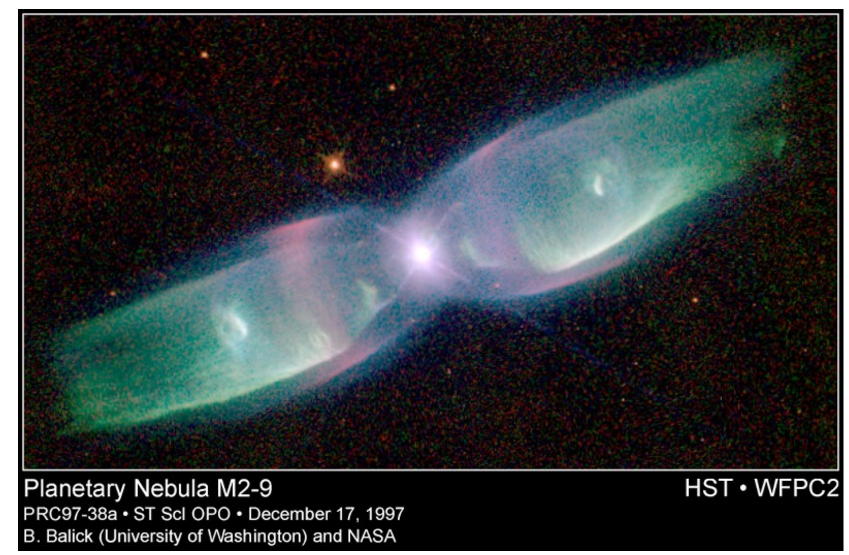
Post-Asymptotic Giant Branch (P-AGB):

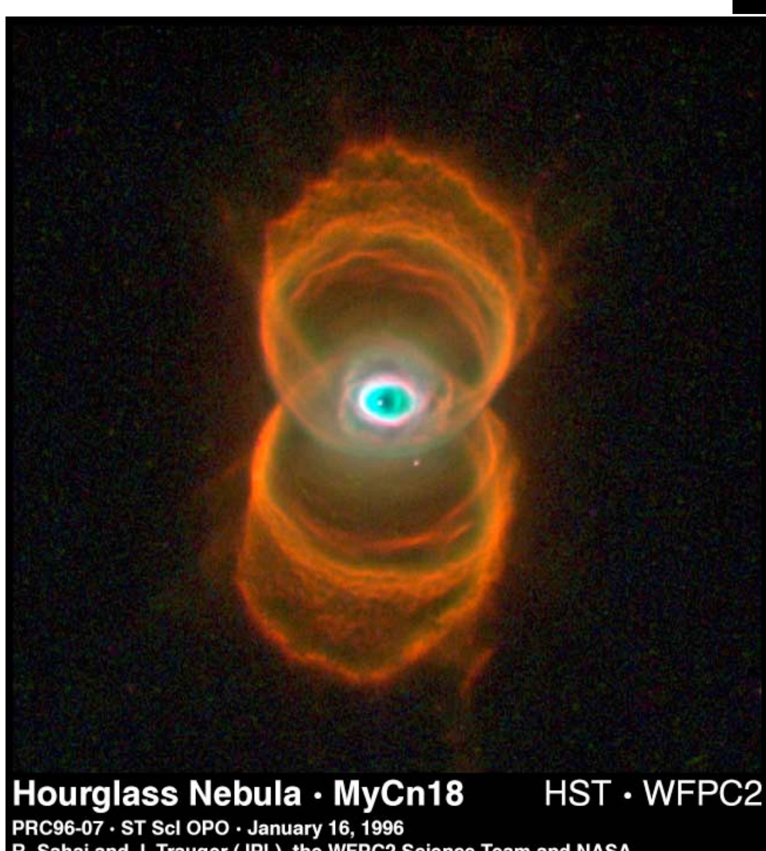
As the cloud of dust and expelled material around the star continues to expand, it becomes optically thin, exposing the central star, which exhibits a spectrum of an F or G supergiant. The star moves horizontally to larger T_{eff} —> P-AGB.

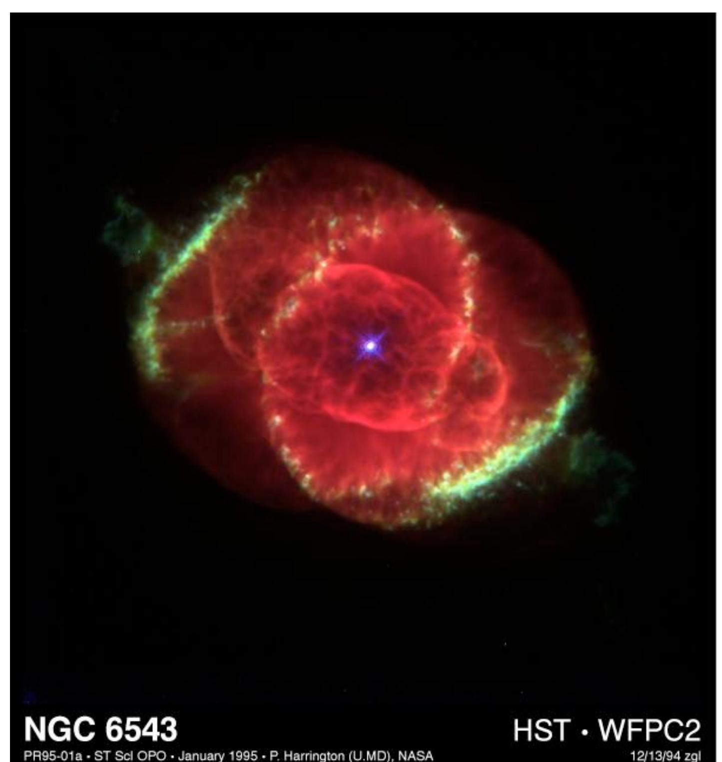
The star's envelope is expelled, the H- and He-fusing shells are extinguished, and the luminosity drops rapidly. The hot central object, revealed, cools to become a **white dwarf, the degenerate C-O (or O-Ne-Mg) core**, surrounded by a thin layer of H and He.

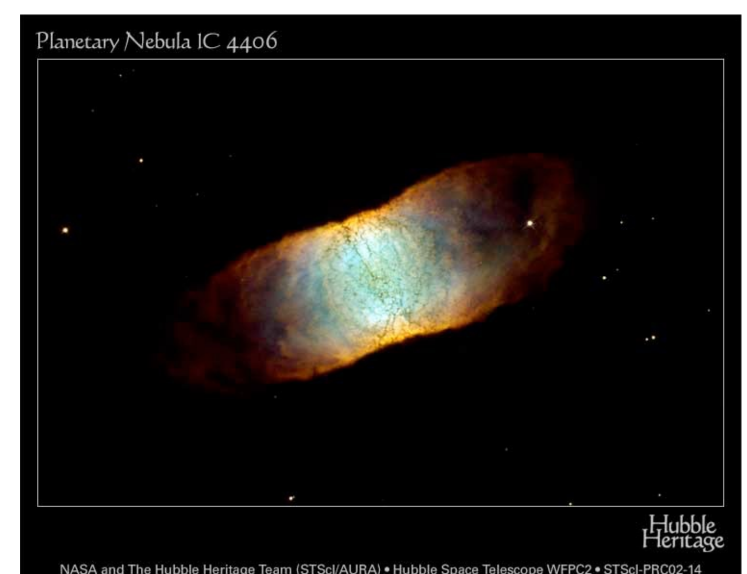
Planetary Nebulae:

The expanding shell of gas around a WD progenitor is called a **planetary nebula**. The UV light emitted by the hot, central WD is absorbed by the gas, exciting and ionizing it. Atoms de-excite emitting optical photons. Typical temperature are 10^4K, with emission from OIII]5007A, OII]3727A, NeIII], and H Balmer and NII] lines. Typical velocity of the expanding gas is 10-30 km/s. After ~50,000 years, the planetary nebula dissipates into the ISM.

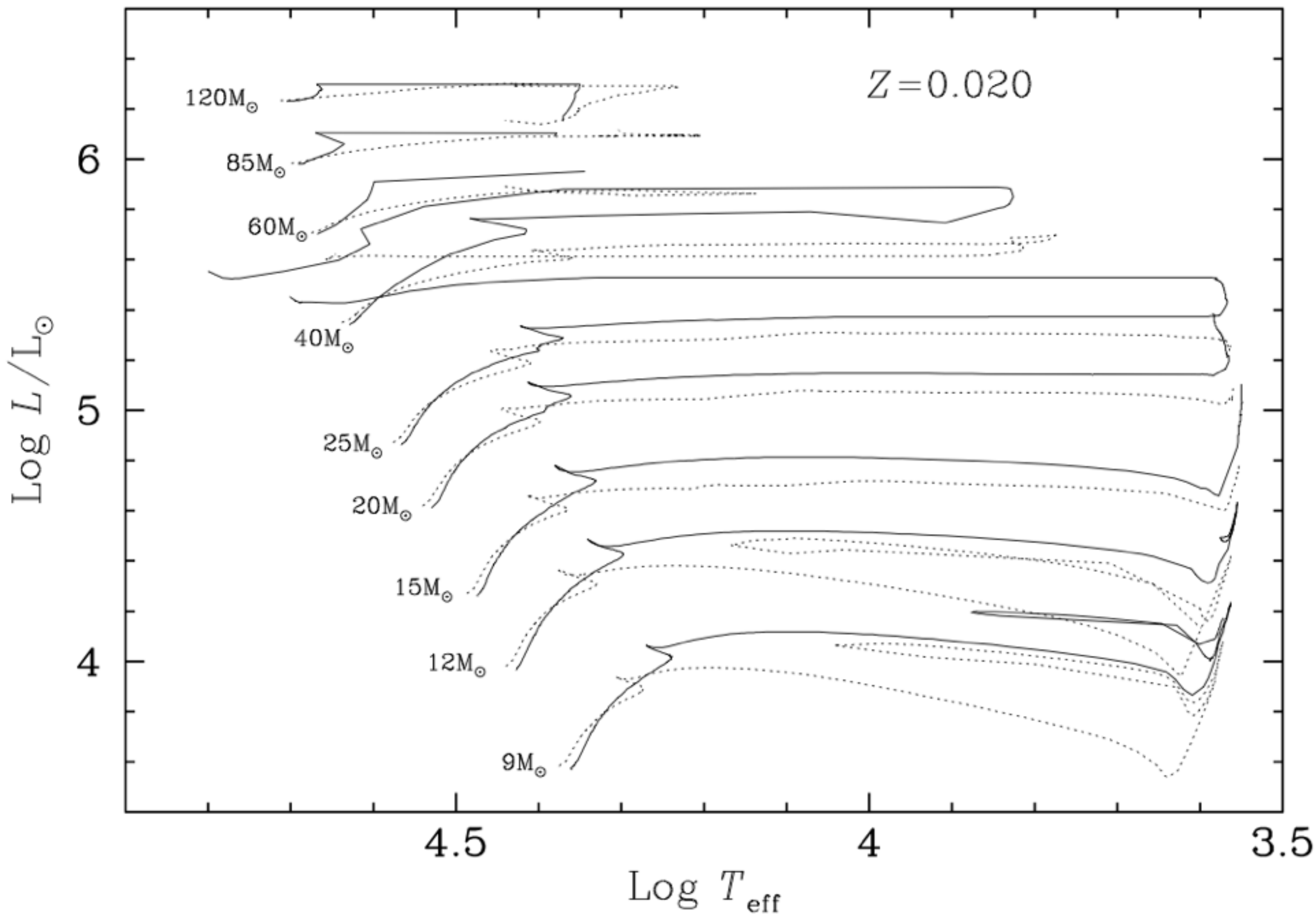








Massive stars: M>8 M_{Sun}



Massive stars: $M > 8\ M_{Sun}$

For a star with $M > 8\ M_{Sun}$, the temperature in the core can get high enough for C and O fusion, ending its life as a CORE-COLLAPSE SUPERNOVA (type Ib, Ic, II).

The He-fusing shell adds ash to the C/O core, the core continues to contract, T rises until C fusion ignites, generating ^{16}O, ^{20}Ne, ^{23}Na, ^{23}Mg, ^{24}Mg (very dependent on mass of the star) ==> onion-like shell structure.

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Following C fusion, the O in the resulting Ne/O core will fuse, producing new core dominated by ^{28}Si. At $T \sim 3 \times 10^9$ K, Si fusion begins:

$$Si^{28} + He^4 \rightleftharpoons S^{32} + \gamma$$
$$S^{32} + He^4 \rightleftharpoons Ar^{36} + \gamma$$
$$\vdots$$
$$Cr^{52} + He^4 \rightleftharpoons Ni^{56} + \gamma$$

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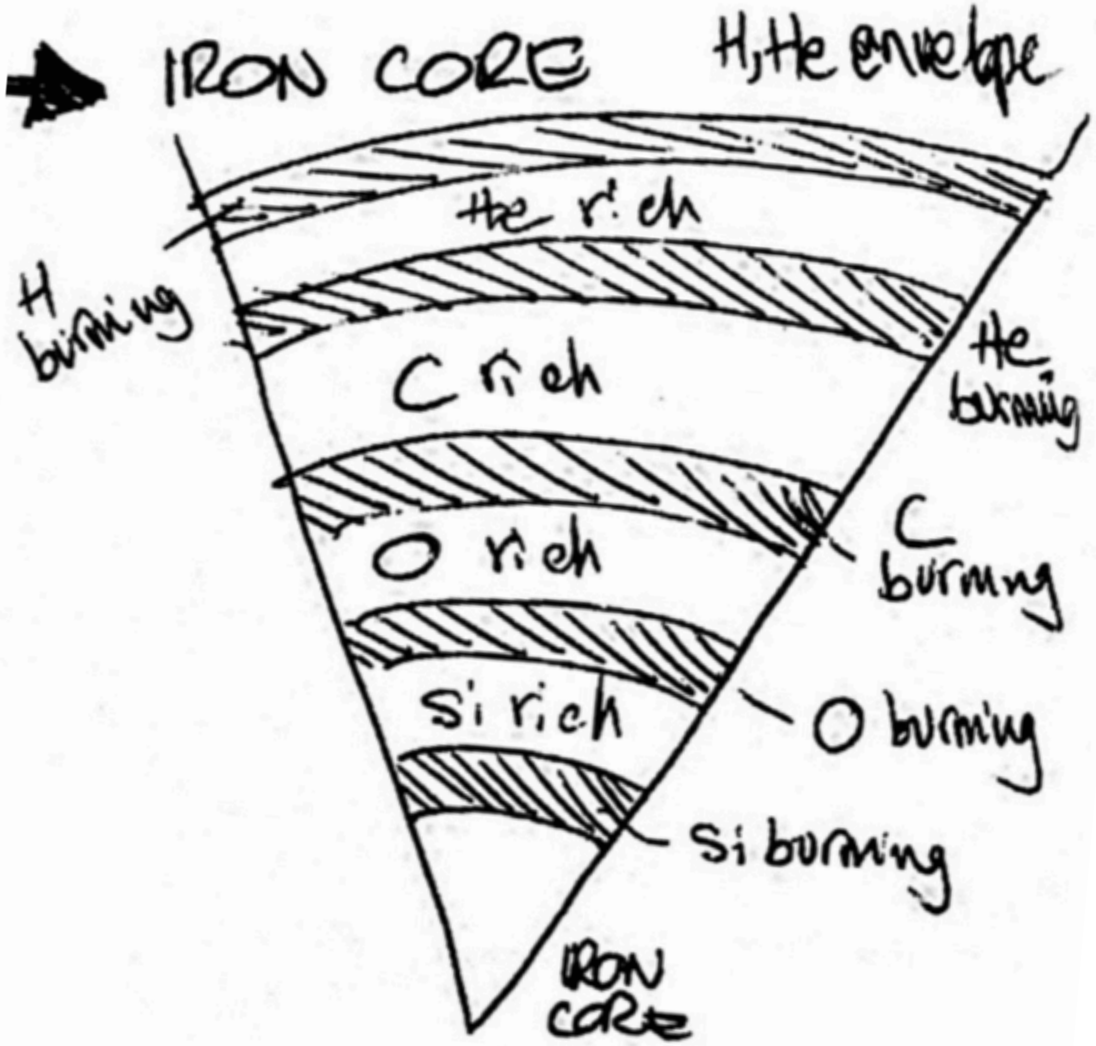
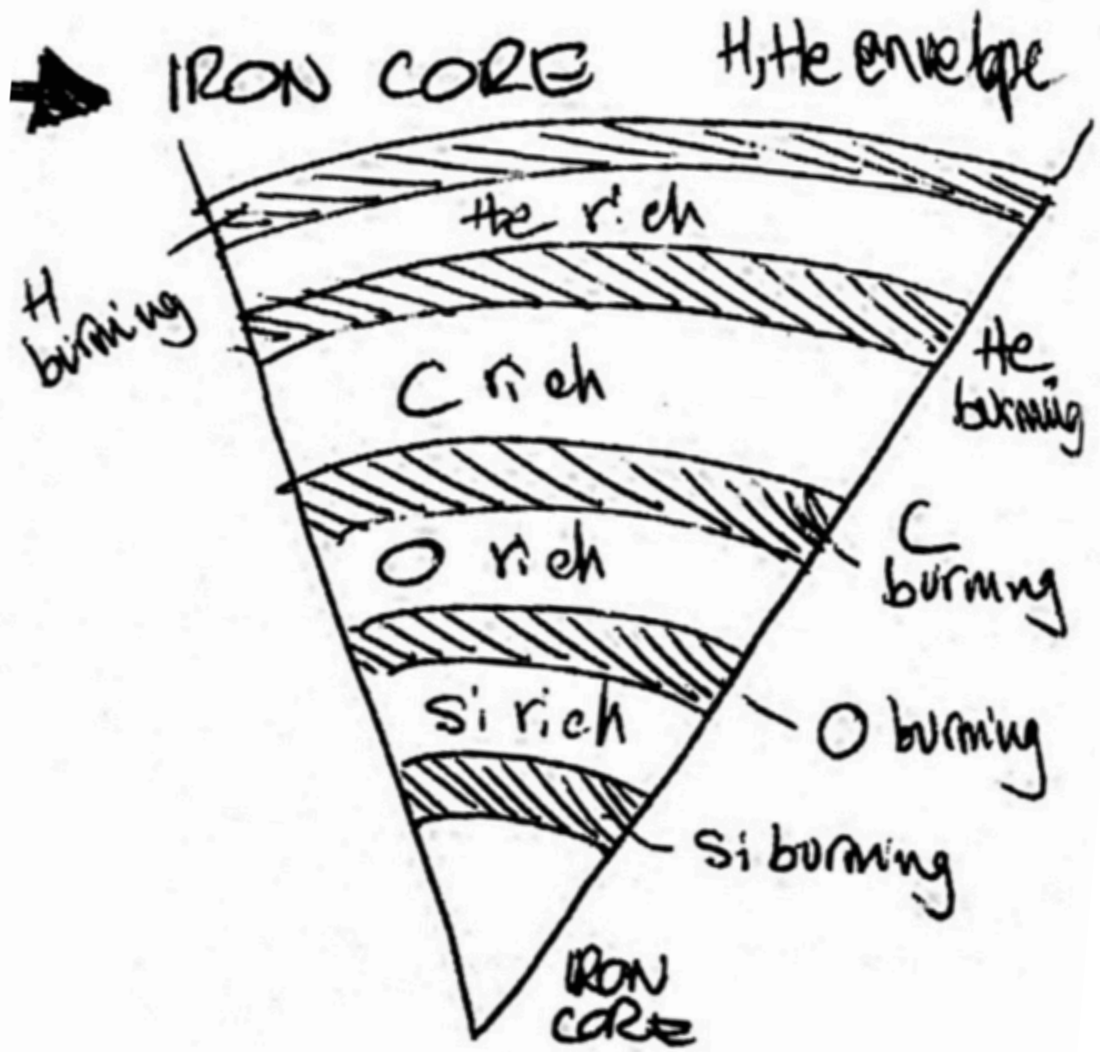
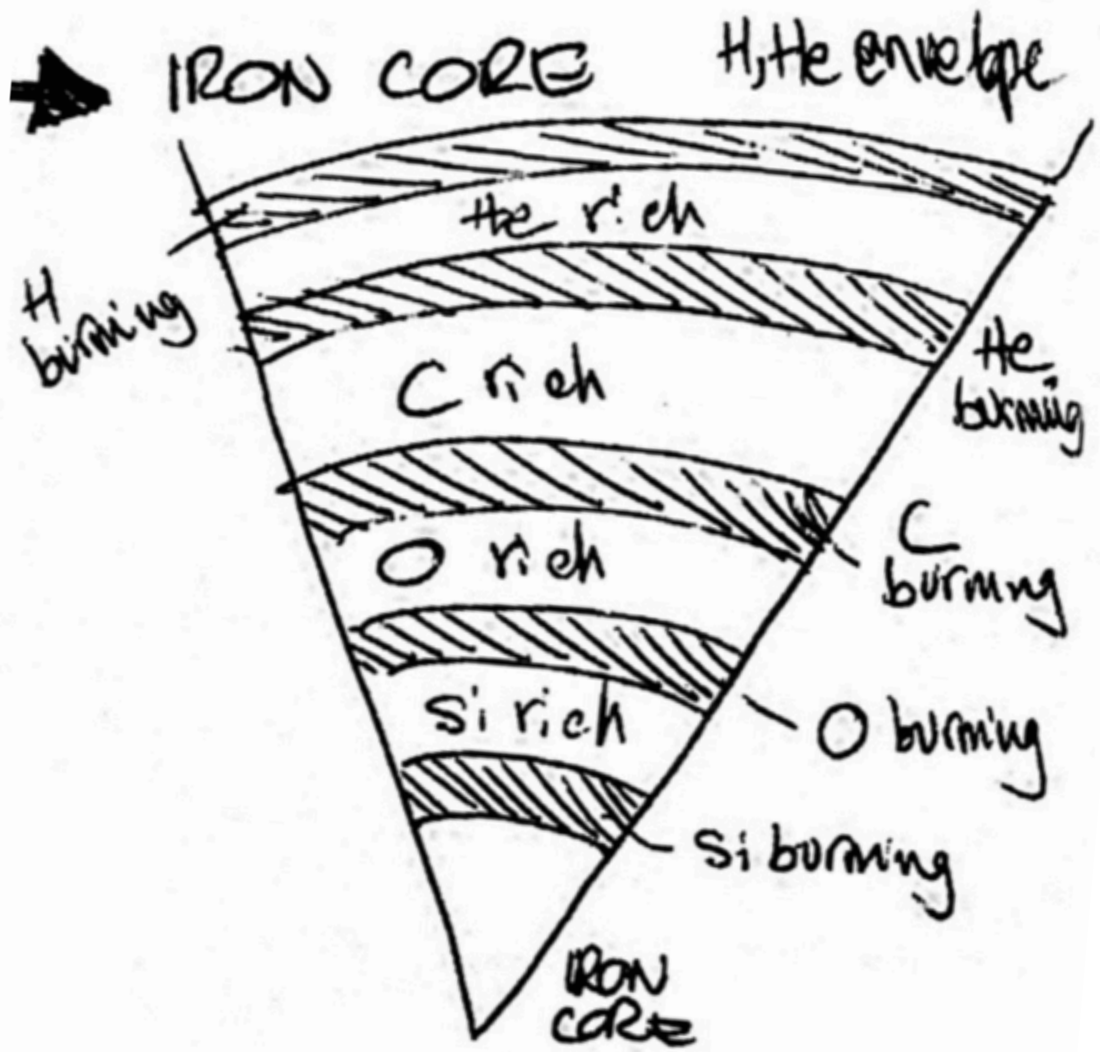
Si fusion produces nuclei centered near ^{56}Fe, most abundant being ^{54}Fe, ^{56}Fe, ^{56}Ni.

IRON CORE


H,He envelope
He rich
H burning
C rich
He burning
O rich
C burning
Si rich
O burning
Si burning
IRON CORE



At each succeeding reaction, less and less energy is generated per unit of mass of fuel —> the timescale of each sequence becomes shorter:



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O core fusion ~ 200 days
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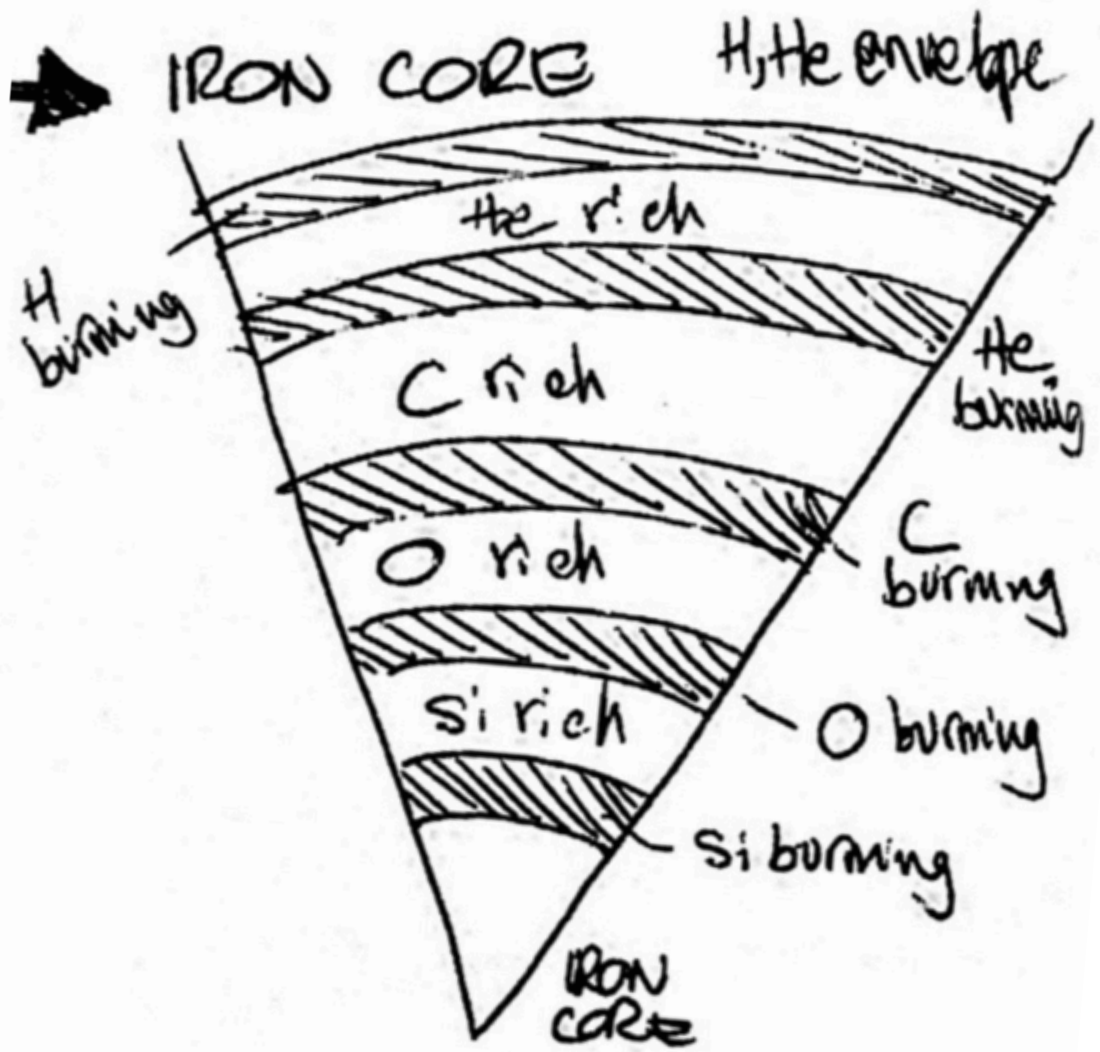

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$$Fe^{56} + \gamma \rightarrow 13\,He^4 + 4n$$
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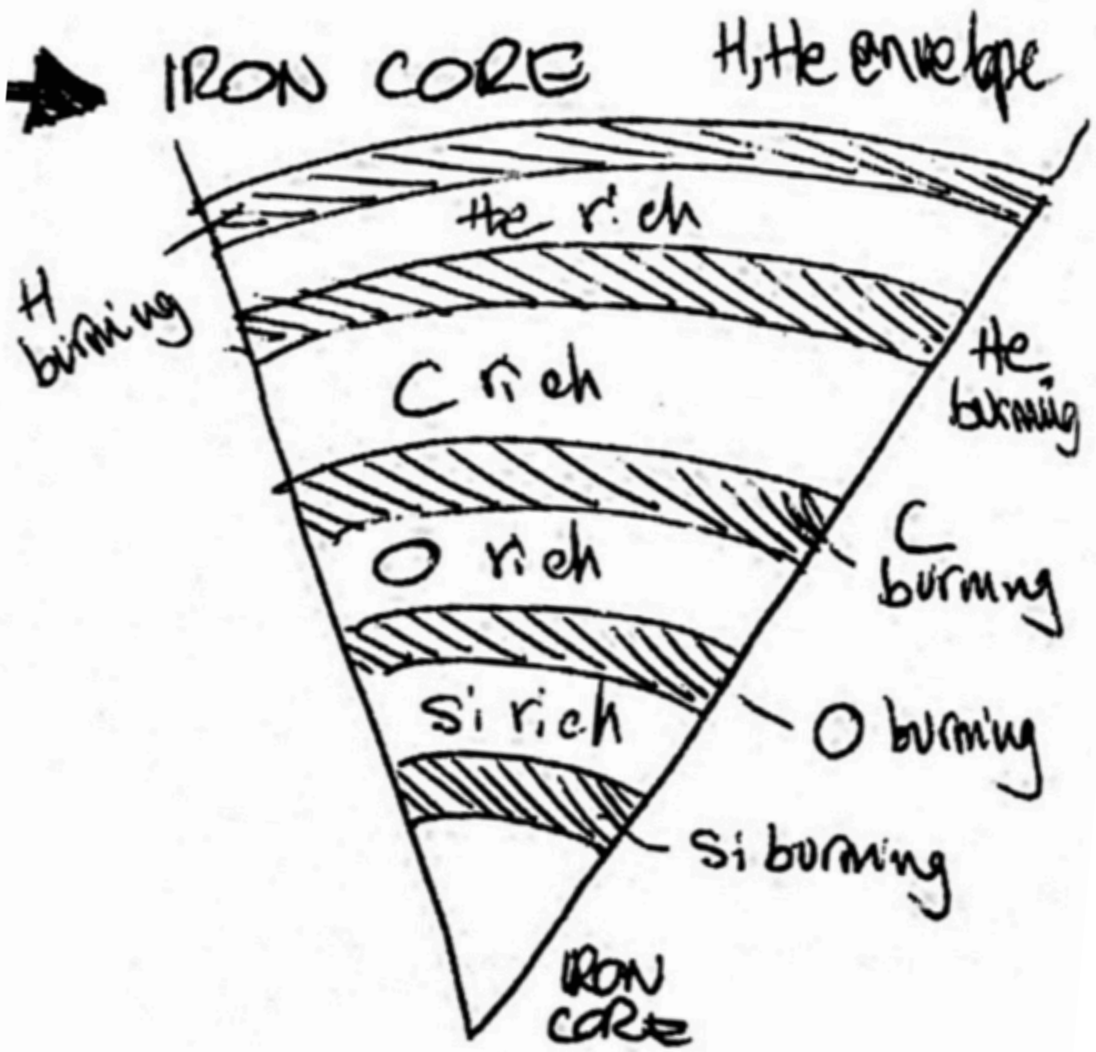

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This is a highly endothermic process (energy is needed), hence thermal energy is removed from the gas that would have otherwise provided the pressure to support the core. Moreover, at density~10^{10} g/cm^3 and T~8x10^9 K for a M=15 M_{Sun}, electrons (which were providing support via electron degeneracy pressure) are captures by nuclei:

$$p^+ + e^- \rightarrow n + \nu_e$$

NOTE: During Si fusion, the photon luminosity of a star with $M=20\ M_{Sun}$ is 10^7 times smaller than the energy leaving with neutrinos!

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At this point, neutron degeneracy pressure dominates, halting the collapse; the core rebounds, sending pressure waves outward into the falling material from the outer core —> shock wave moving outward. The shock will drive the envelope and the remainder of the nuclear-processed matter in front of it. The total kinetic energy in the expanding material is ~10^{51} erg, roughly 1% of the energy released in neutrinos. At r~100 AU, the material becomes optically thin, with ~10^{49} erg of energy released as photons with peak luminosity nearly ~10^{43} erg/s, or $3\times10^9\ L_{Sun}$ ==> **CORE-COLLAPSE SUPERNOVA**

NOTE:

If $M < 25\ M_{Sun}$ —> neutron star, supported by degenerate neutron pressure

If $M \gg 25\ M_{Sun}$ —> black hole

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s- and r- process nucleosynthesis:

$${}^{A}_{Z}X + n \longrightarrow {}^{A+1}_{Z}X + \gamma$$

$$\xrightarrow{\text{beta decay}} {}^{A+1}_{Z+1}X + e^{-} + \bar{\nu}_e + \gamma$$

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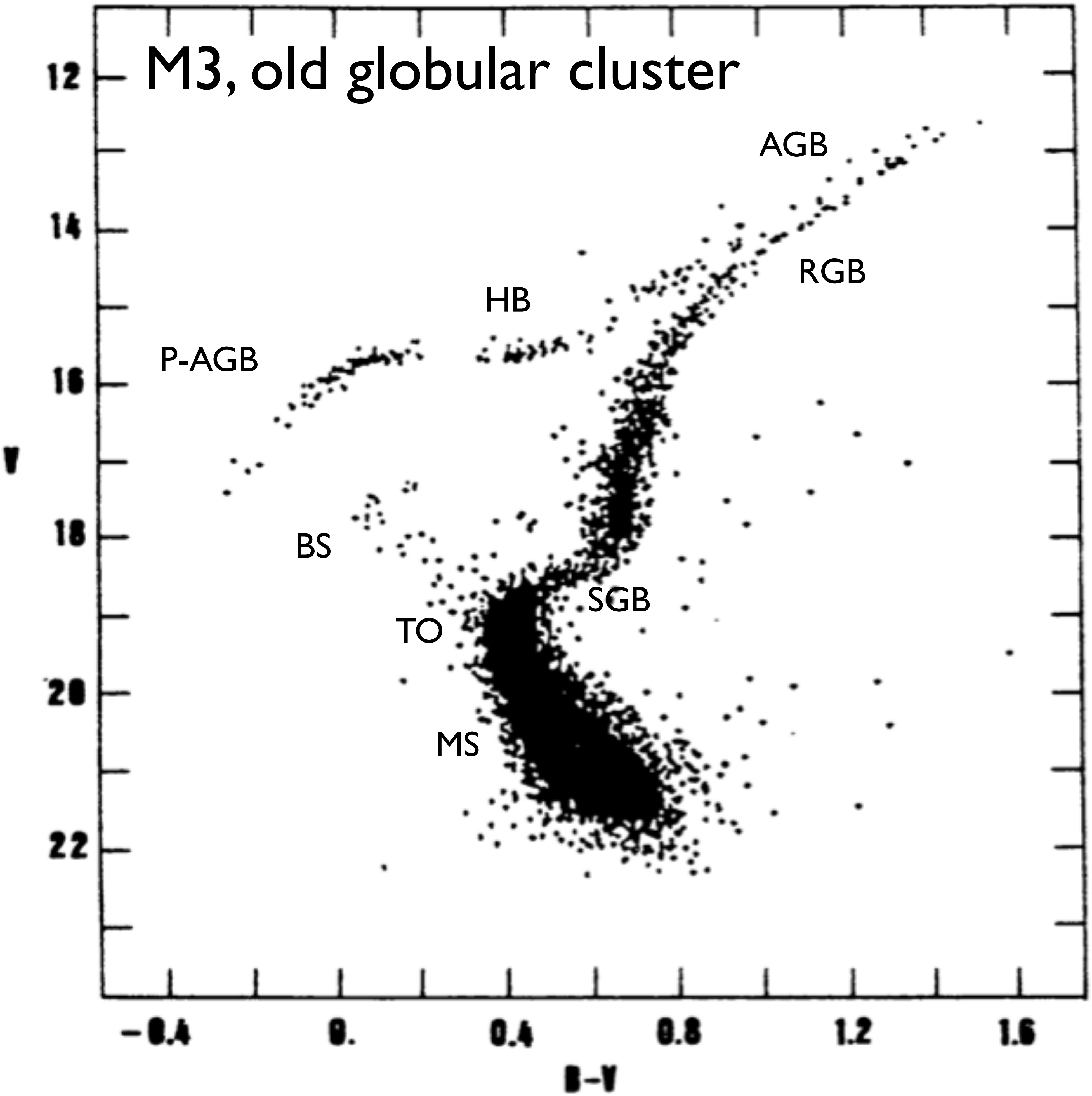
If the beta-decay half-life is short compared to the timescale for neutron capture, then SLOW PROCESS (“s”). s-process reactions tend to yield stable nuclei.

If the beta-decay half-life is long compared to the timescale for neutron capture, then RAPID PROCESS (“r”). r-process reactions result in n-rich nuclei.

“s” processes tend to happen in normal phases of stellar evolution, whereas “r” processes occur during supernova explosions when large flux of neutrons exists. These processes account for the abundance ratios of nuclei with A>60.



M3, old globular cluster
AGB
RGB
HB
P-AGB
BS
SGB
TO
MS
12
14
16
18
20
22
V
−0.4
0.
0.4
0.8
1.2
1.6
B−V