

AST5770

Solar and stellar physics

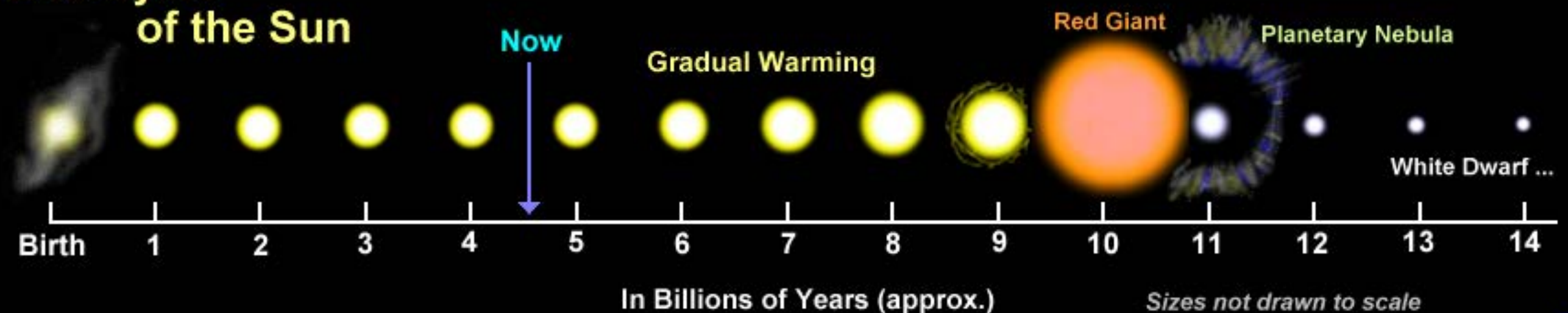
Sven Wedemeyer, University of Oslo, 2023

Stellar evolution

Recap

1. The pre-main sequence evolution follows a track in the Hertzsprung-Russell-Diagram specific for the stellar mass. What is that track called? What is a characteristic about the interior structure during this phase? How is effective temperature changing along the track?
2. What defines the Zero Age Main Sequence (ZAMS)?
3. Why is the main sequence phase with hydrogen fusion in the core so stable against temperature changes?
4. Why is Helium burning unstable for low mass stars?
5. Why do high mass stars reach higher burning stages in their cores?
6. What is the **mirror principle**?

Life Cycle of the Sun



Stellar Evolution

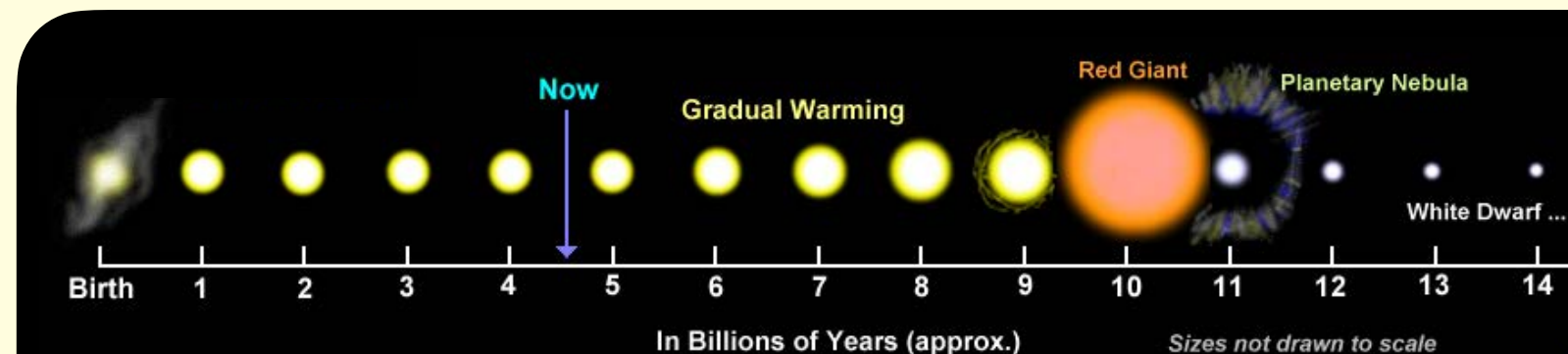
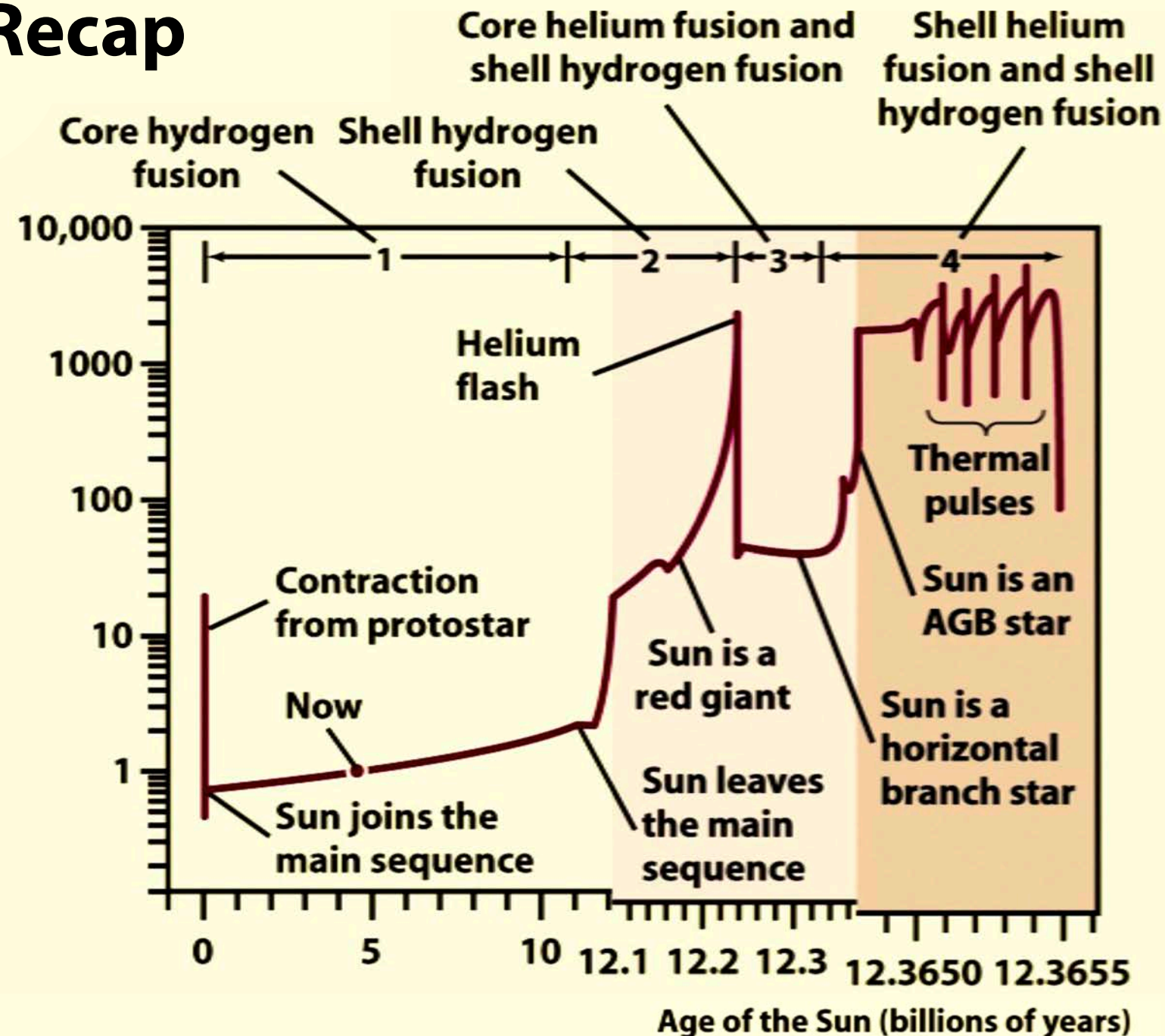
Evolution of the Sun — Recap

(Applies to stars with an initial mass of $1M_{\odot}$)

- **Main sequence (MS)**
 - H burning in core
 - Longest evolution stage
- **Red giant** stage
 - He burning in core, H burning in shell
 - ~10% of MS lifetime
- **Asymptotic Giant Branch (AGB)**
 - H and He burning in shell
 - Thermal pulses, **high mass loss**, circumstellar envelope
 - Lifetime derminded by mass loss rate (typically $\sim 10^6$ yr, $f(M_{\odot})$)
- **Post-AGB evolution**
 - Expulsion of envelope (planetary nebula due to UV radiation)
 - Exposed hot core (+small rest of previous envelope) → White Dwarf

Nuclear timescales!

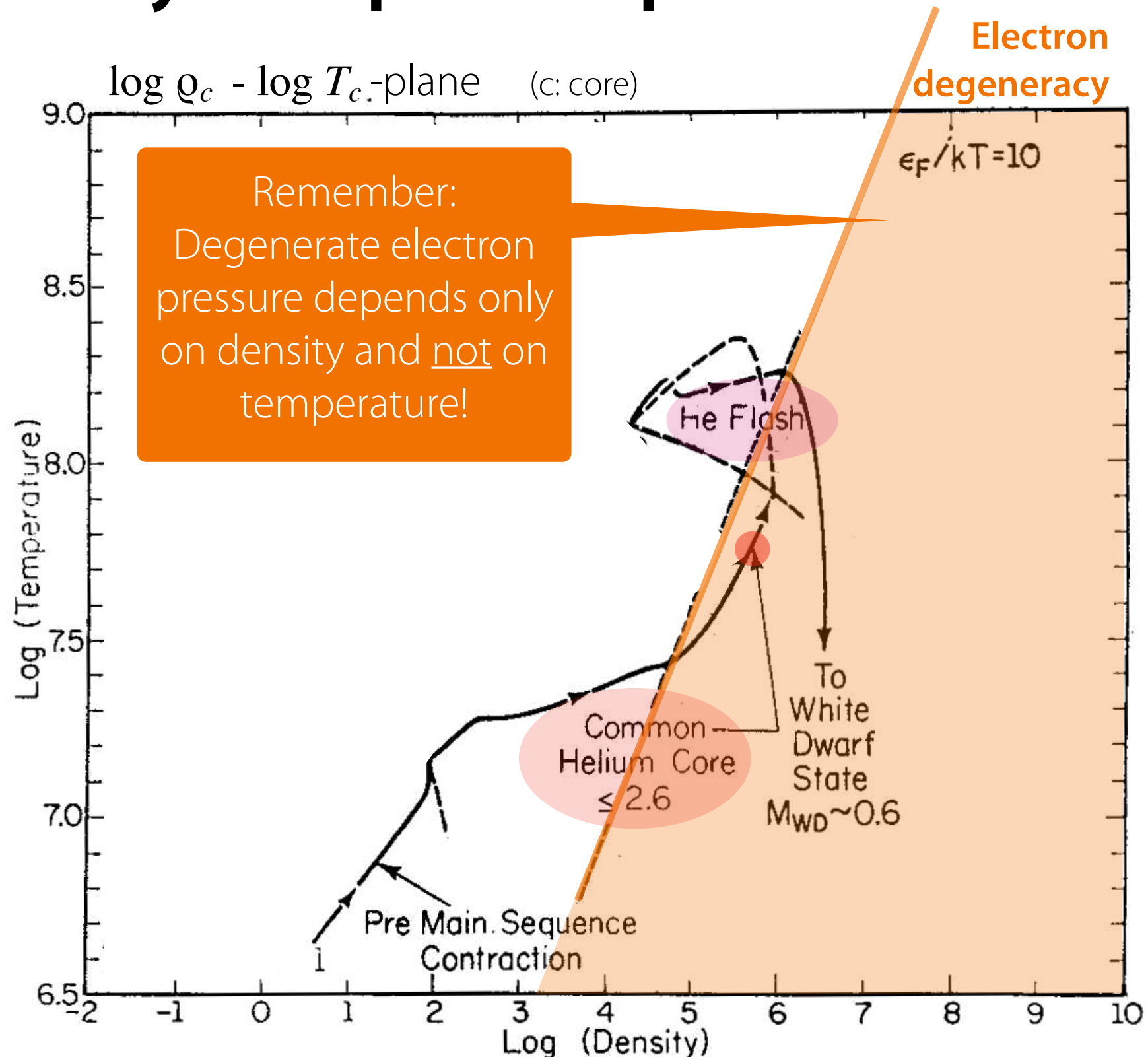
Luminosity of the Sun
(compared to the present-day value)



Stellar Evolution

Tracks in the core density—temperature plane

- **At end of H-burning:**
core contracts while outer layers expand
(**mirror principle!**)
➡ Higher core density
 - Occurs for each nuclear burning stage.
- **Low-mass stars**
 - Core becomes **degenerate** before igniting He-burning
 - Degenerate He cores keep getting more massive and hotter due to H-shell burning
 - Ignite helium in an unstable manner (**He flash**)



Stellar Evolution

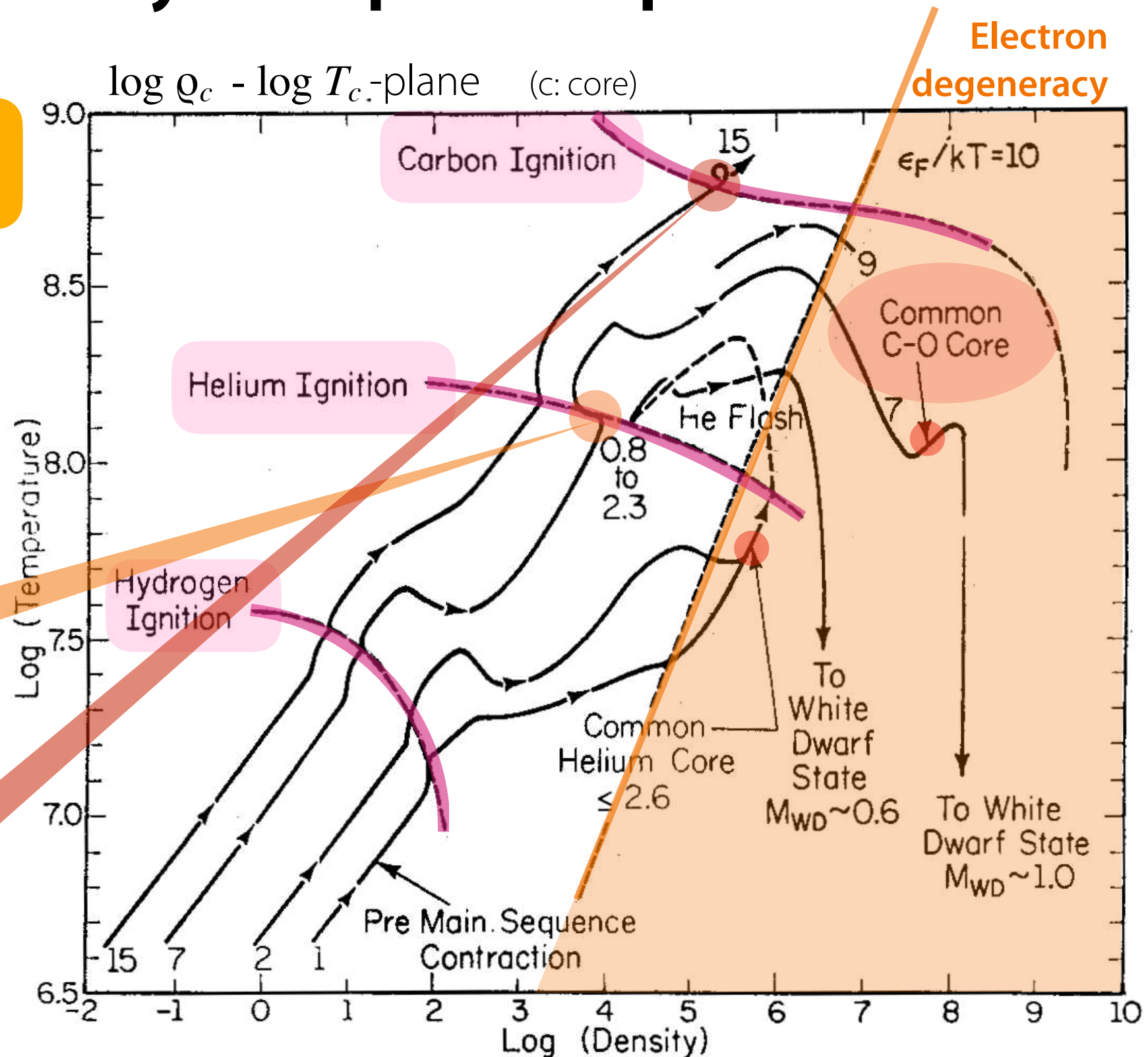
Tracks in the core density—temperature plane

- Evolution strongly depends on initial mass!**

- Due to changes of conditions in the core, becoming degenerate later, after igniting higher burning stages

- Higher masses: He burning ignites in a stable manner

- Very high masses ($>7 M_{\odot}$) reach C burning

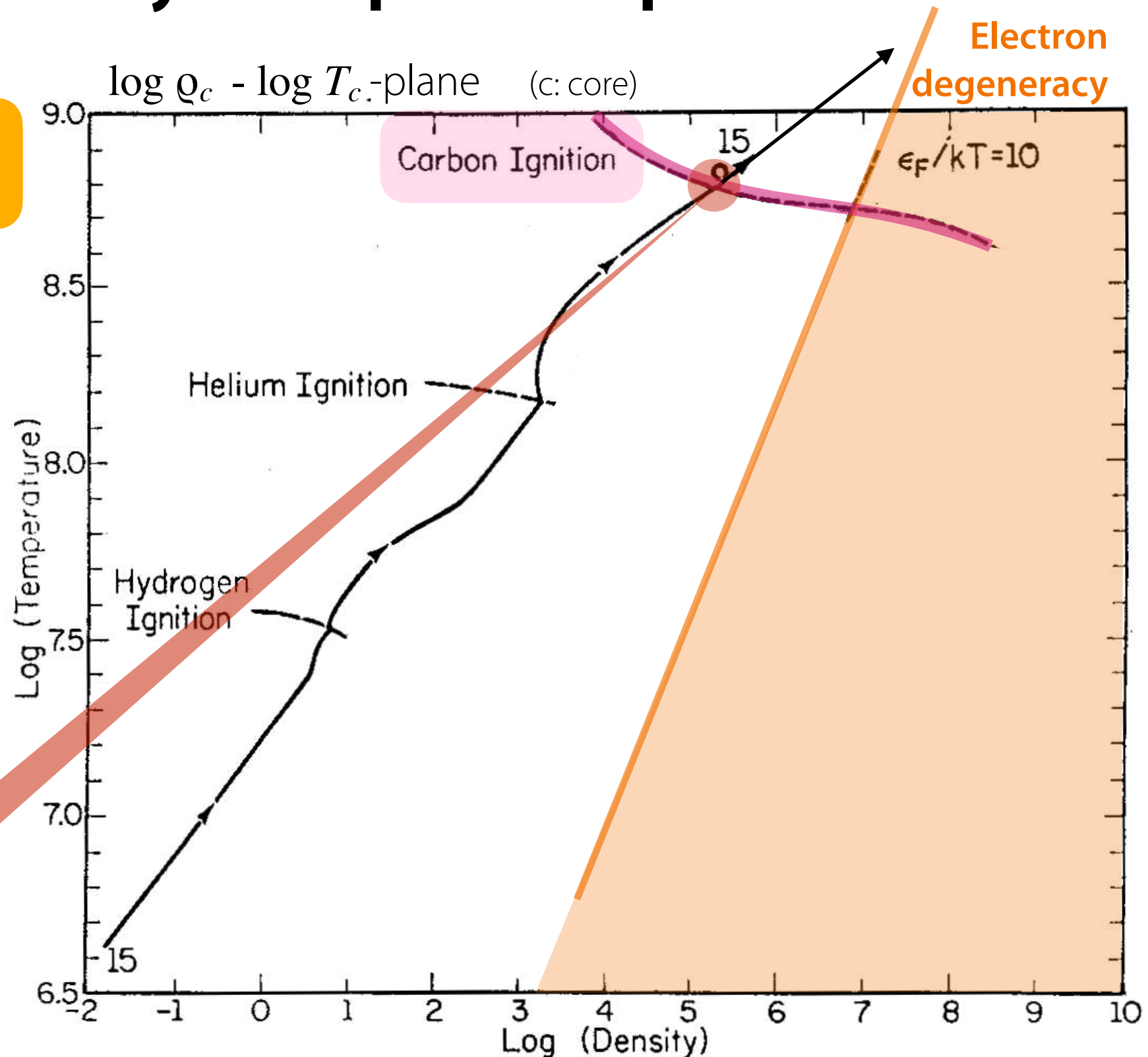


Stellar Evolution

Tracks in the core density—temperature plane

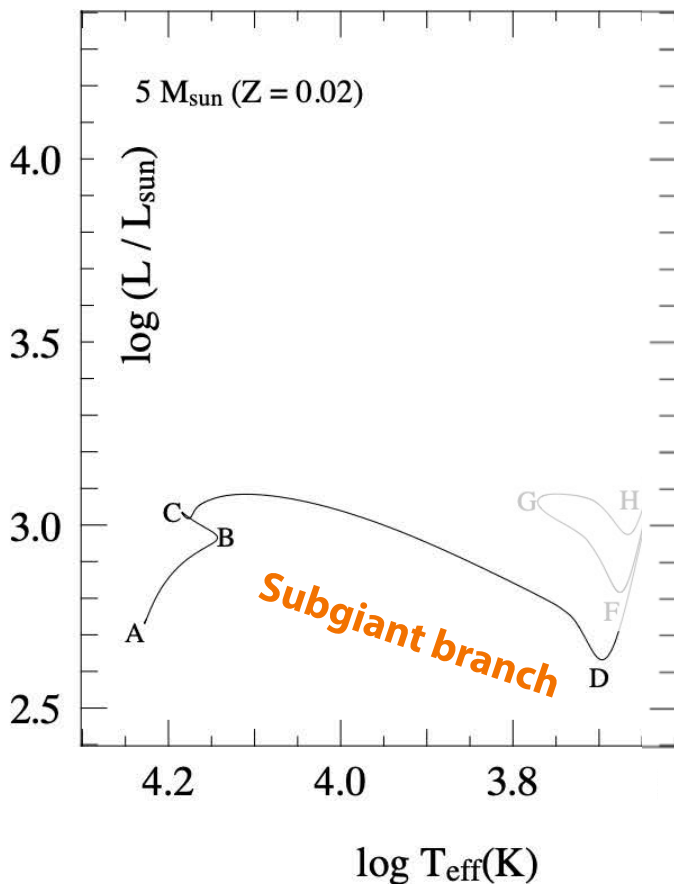
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Post-main sequence evolution

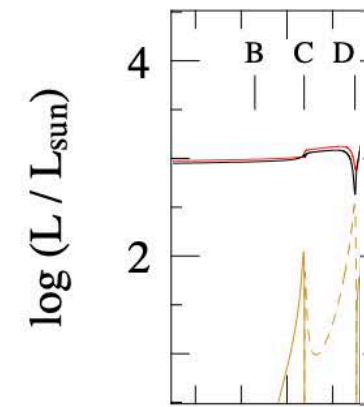
Hydrogen-shell burning in intermediate-mass stars



- **A:** Start at ZAMS
- **B:** start of overall contraction phase, near end of MS phase
- **C:** exhaustion of H in centre,
 - convective core disappears
 - core mass remains below Schönberg-Chandrasekhar (S-C) limit, in thermodyn. equilibrium at beginning of H-shell burning

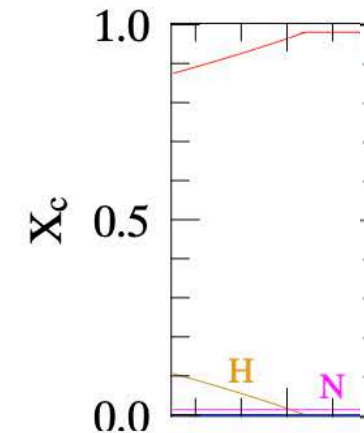
- **C–D:** H-shell burning, relatively slow, lasting about 2×10^6 yr
 - (thick) burning shell initially occupies large region in mass
 - He-core gradually grows until exceeding the S-C limit,
- **After C:**
 - Core contraction speeds up (all layers below burning shell contract)
 - At the same time: all layers above shell (=envelope) expand ('mirror principle')
 - Changes at accelerating rate towards end of C-D phase.
 - Density + temperature gradients grow — shell gets thinner

Model of internal evolution of a $5 M_{\odot}$ star, initial composition $X = 0.7$, $Z = 0.02$.



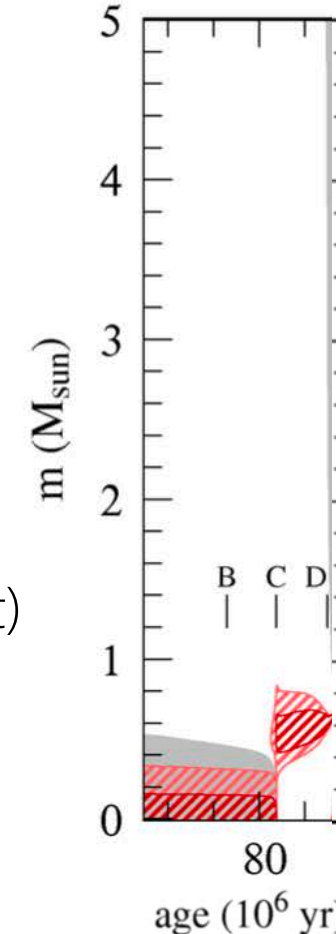
Luminosity contributions

- H burning (red line),
- He burning
- gravitational energy release
- surface luminosity.



Central mass fractions

^1H , ^4He , ^{12}C , ^{14}N and ^{16}O



Kippenhahn diagram:

Internal structure as function of mass coordinate m

Gray areas: convective

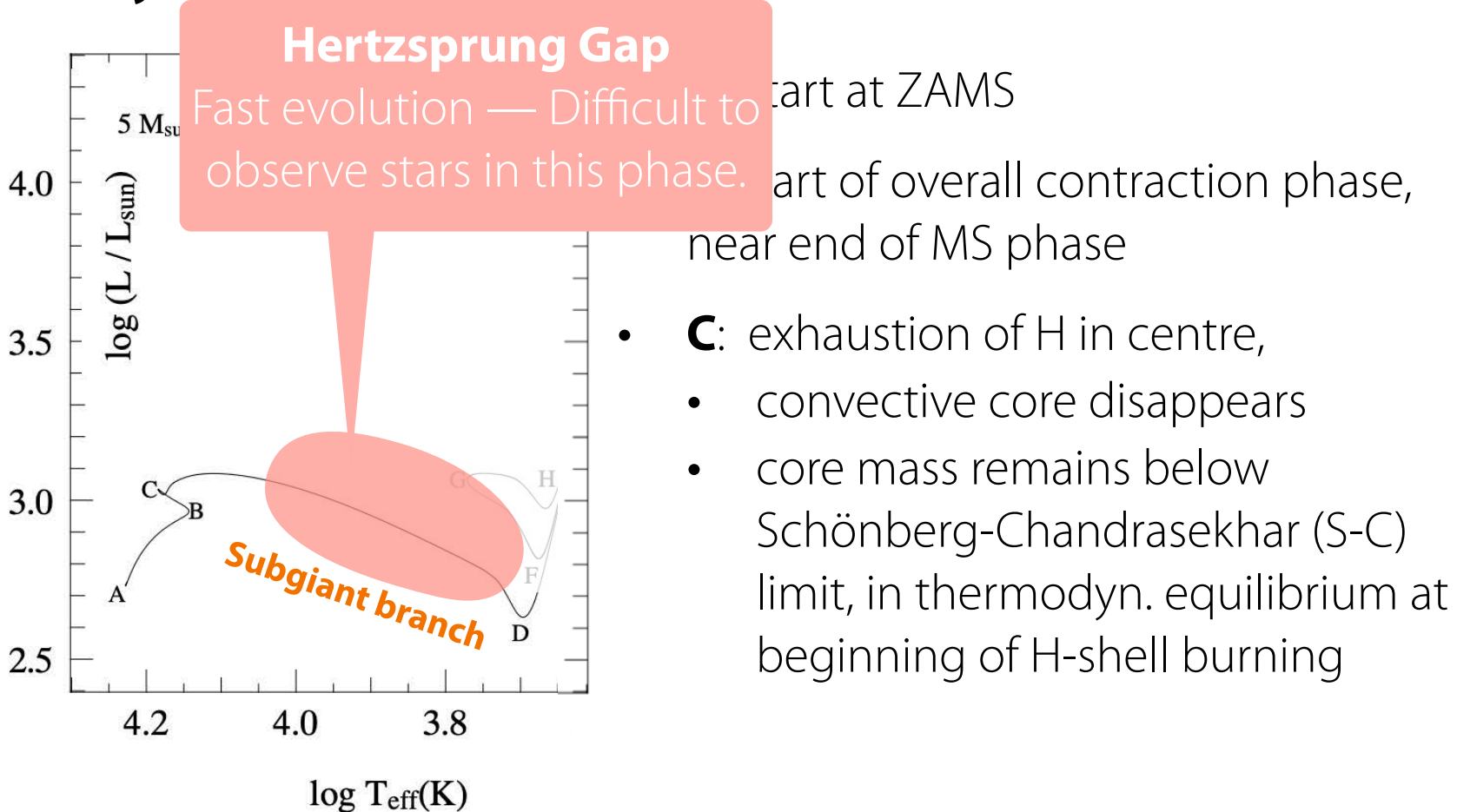
Red hatched: nuclear energy generation

Dark red $\epsilon_{\text{nuc}} > 10 \text{ L/M}$

Light red $\epsilon_{\text{nuc}} > 2 \text{ L/M}$

Post-main sequence evolution

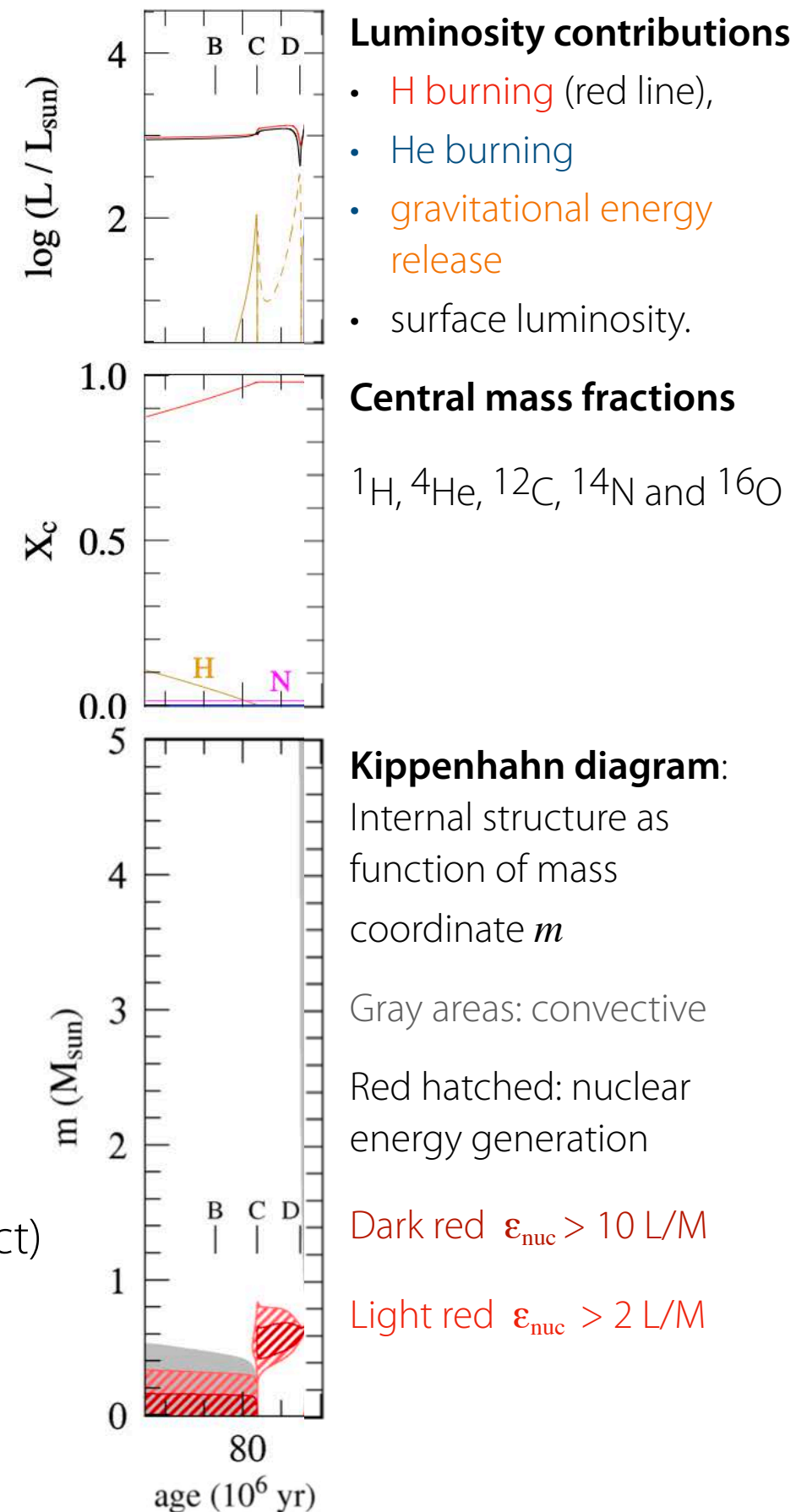
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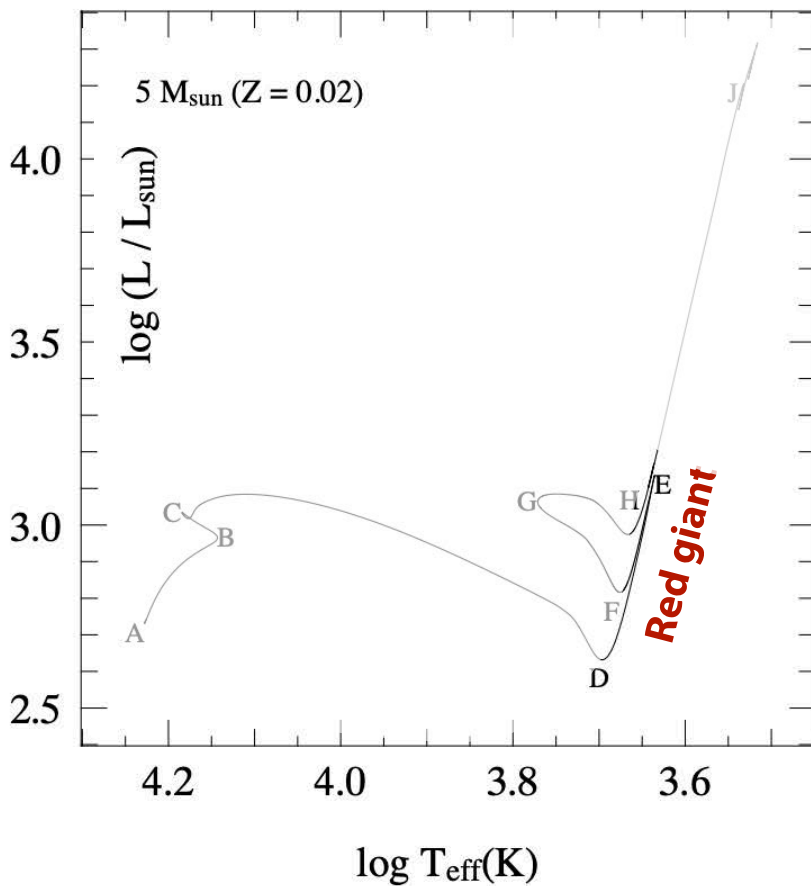
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Post-main sequence evolution

Red giant phase



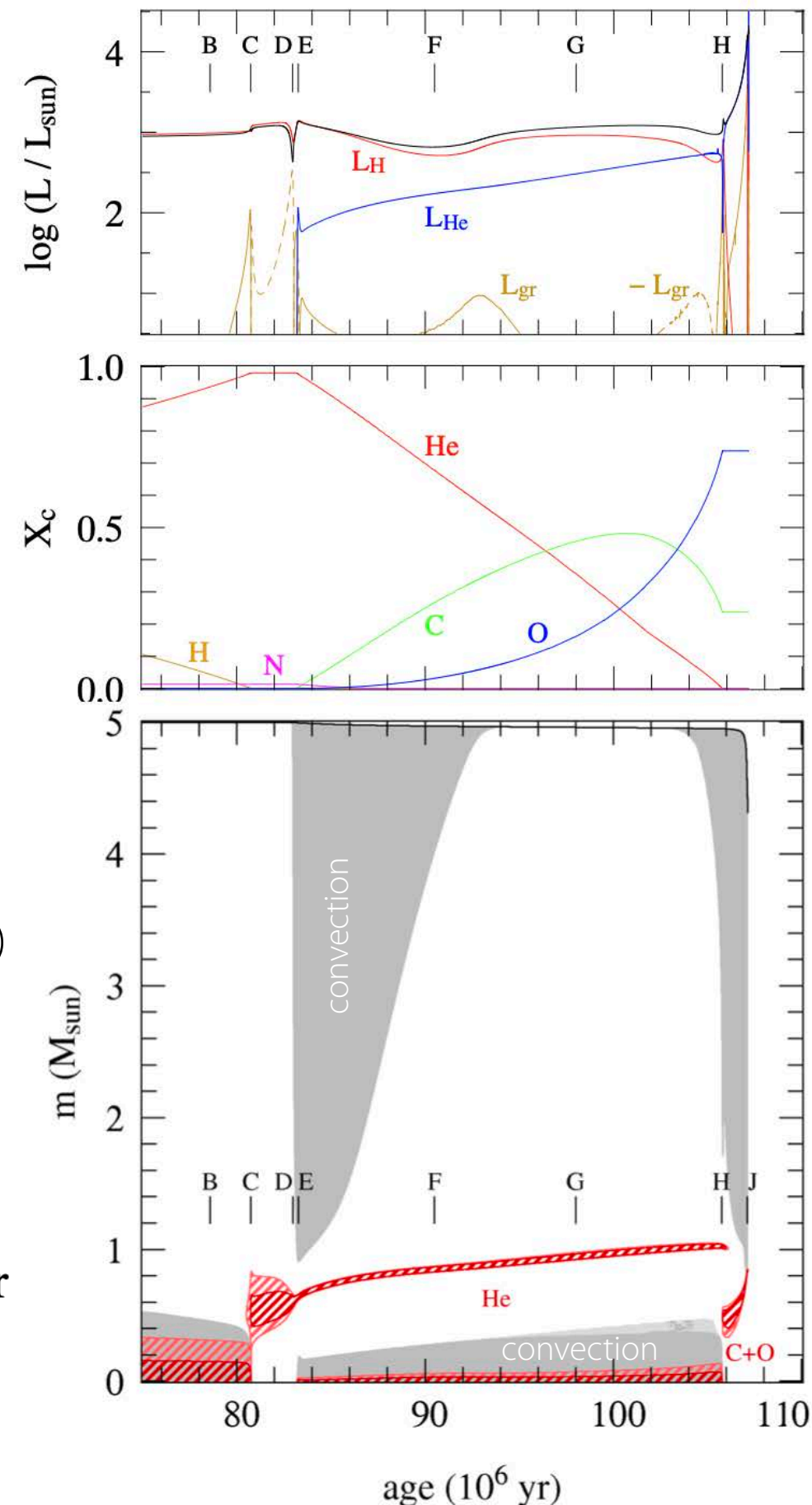
- **D**: Opacity in thin shell increases
 - Radiative energy transport inefficient, convection sets in
- **D-E**: Red giant phase
 - Convection in core + deep convection zone (up to surface)
 - Relatively short lived phase ($\sim 10\%$ of main sequence) lifetime
- **E**: Outer convection zone reaches into former (thick) H-burning shell
 - Fusion product (CNO cycle) brought to surface ("dredge-up")

- **E**: envelope becomes loosely bound, relatively easy to remove mass from surface driven by large radiation (still open questions...)

➡ Strong **mass loss** on the red giant branch (stellar wind)

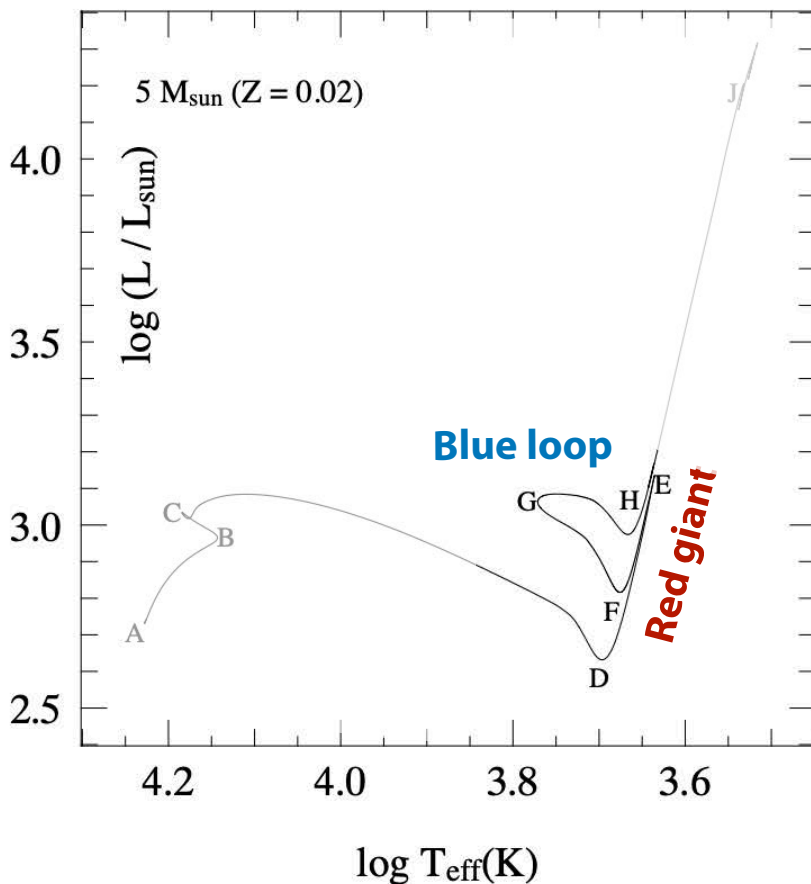
- Mass loss rate (Reimers): $\dot{M} = -4 \times 10^{-13} \eta \frac{L}{L_{\odot}} \frac{R}{R_{\odot}} \frac{M_{\odot}}{M} M_{\odot}/\text{yr}$
- Typically used: $\eta \sim 0.25 - 0.5$
- 1 $M_{\odot}$ star lost about 0.3 $M_{\odot}$ when reaching tip of giant branch (E).

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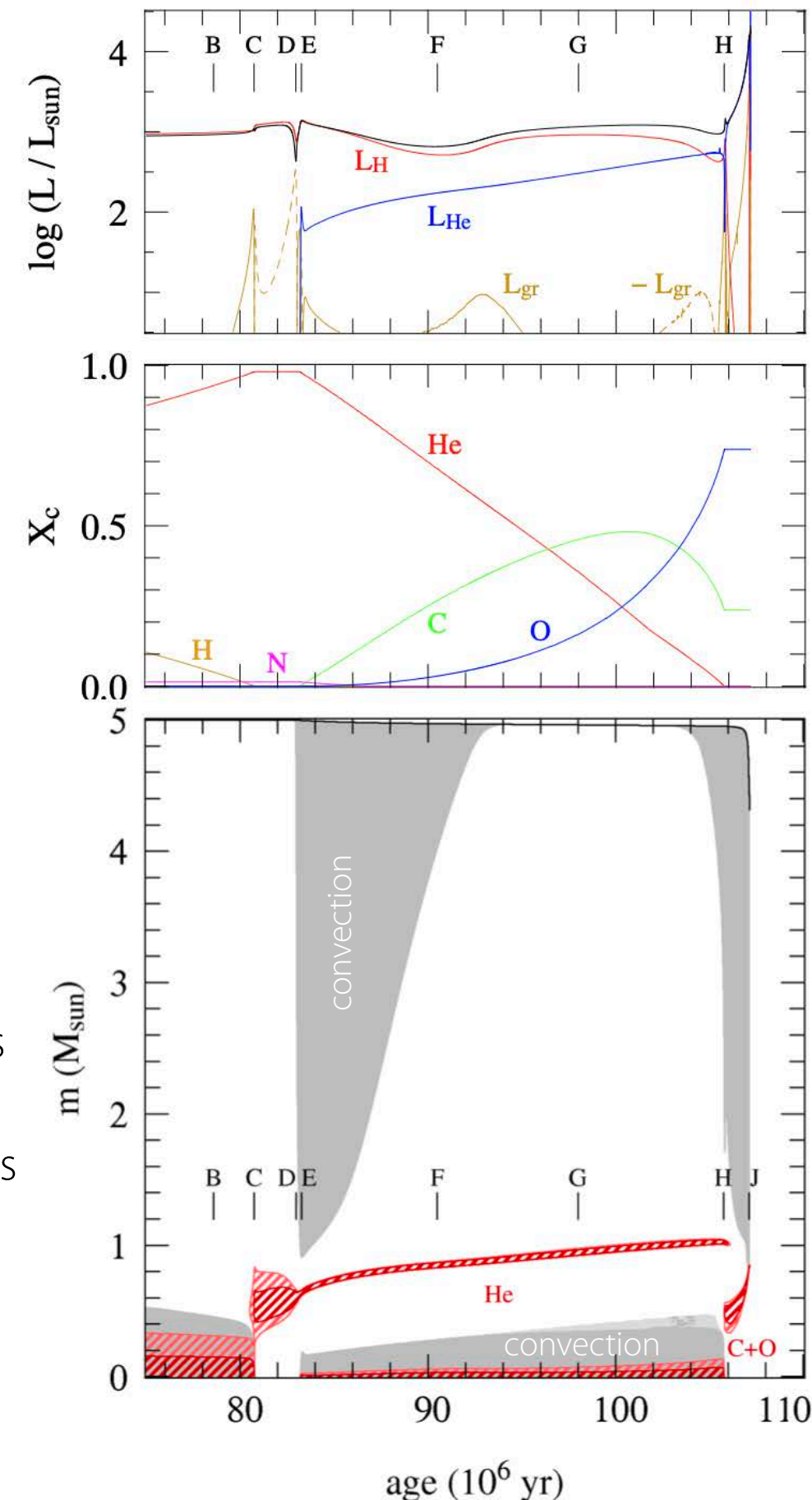
Post-main sequence evolution

Red giant phase and blue loop



- **E**: He core mass reaches $0.6 M_{\odot}$, central temperature 10^8 K
 - C, O-burning ignites in core (H-burning continues in thin shell)
 - For low-mass stars: degenerate core — H-shell burning and mass growth at increasing until He-burning suddenly ignites (He flash)
- **E-F**: envelope contracts, stellar radius decrease, luminosity decreases
 - Star forced to evolve along its Hayashi line.
 - Outer convection zone becomes shallower, envelope becomes radiative
- **F-G-H**: Blue loop — min. radius reached at G
- **H**: end of core He burning

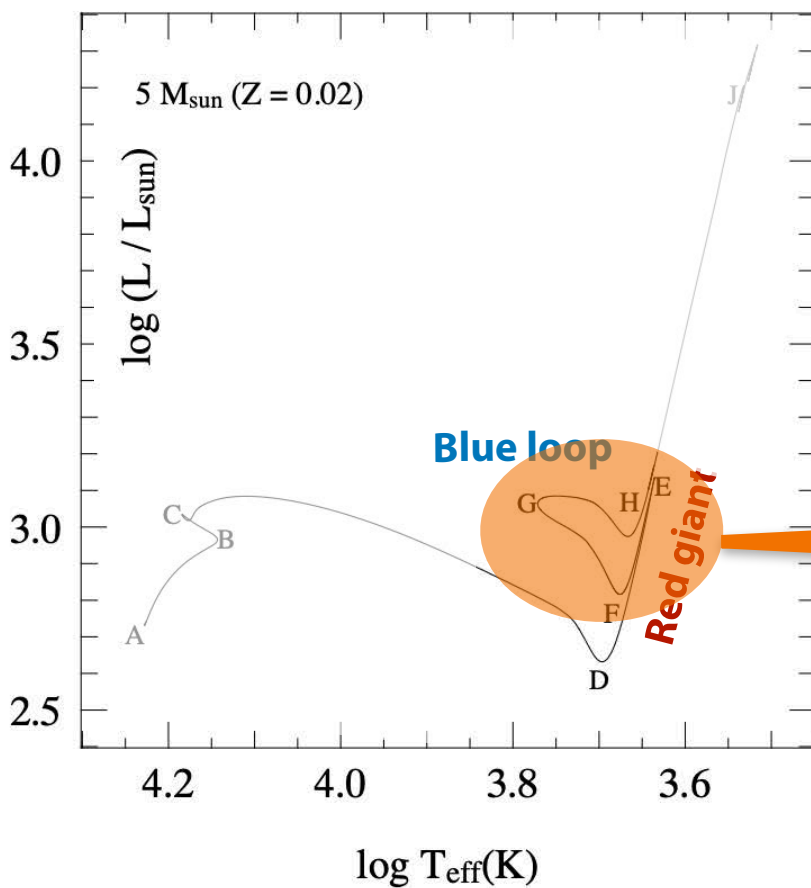
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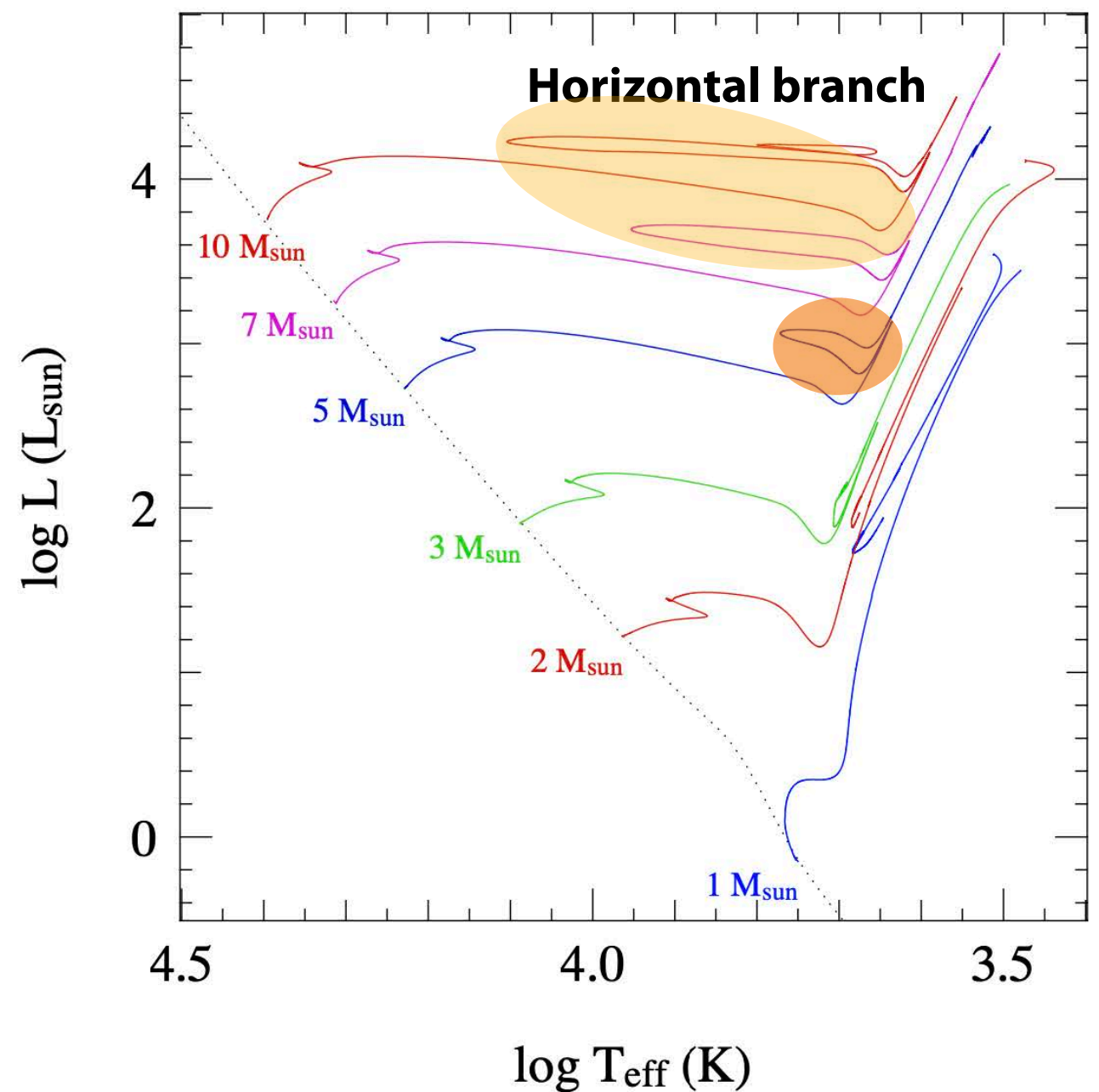
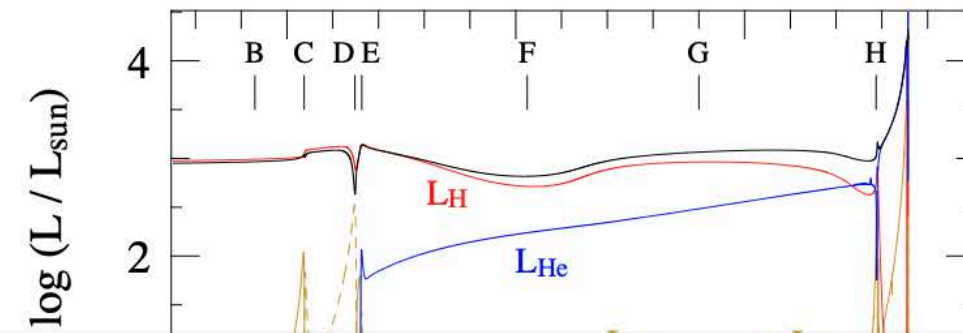
Post-main sequence evolution

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Red giant phase and blue loop



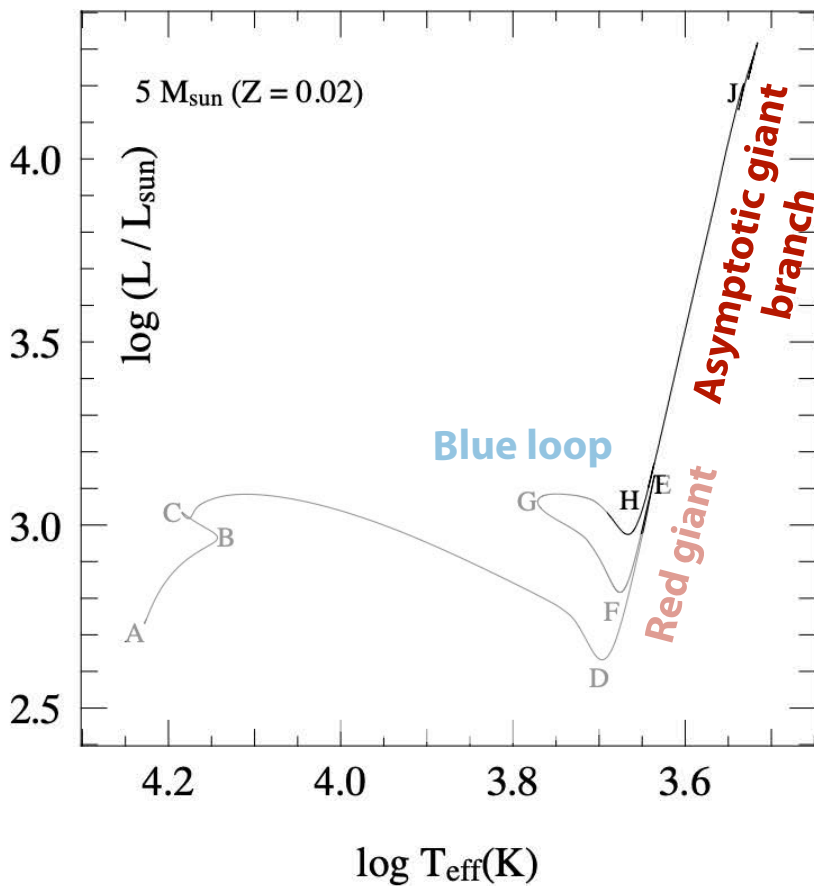
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- **E-F**: envelope contracts, stellar radius decreases
 - Star forced to evolve along its Hayashi line.
 - Outer convection zone becomes shallower, more radiative
- **F-G-H**: Blue loop — min. radius reached at G
- **H**: end of core He burning



age (10^6 yr)

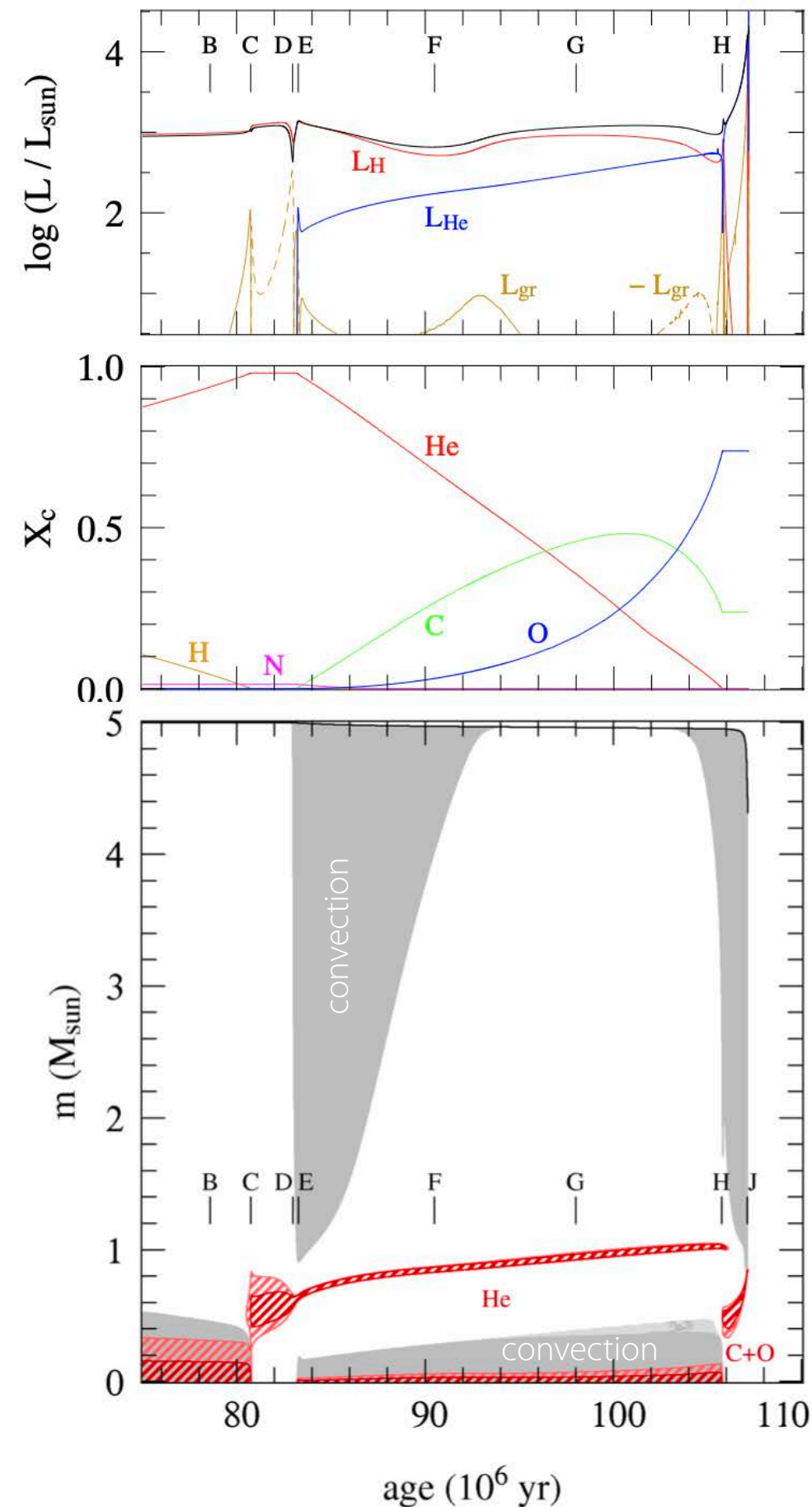
Post-main sequence evolution

Asymptotic Giant Branch



- **H**: end of core He burning
- ➡ back on Hayashi track (close to E)
- ➡ Beginning of asymptotic giant branch (AGB) phase

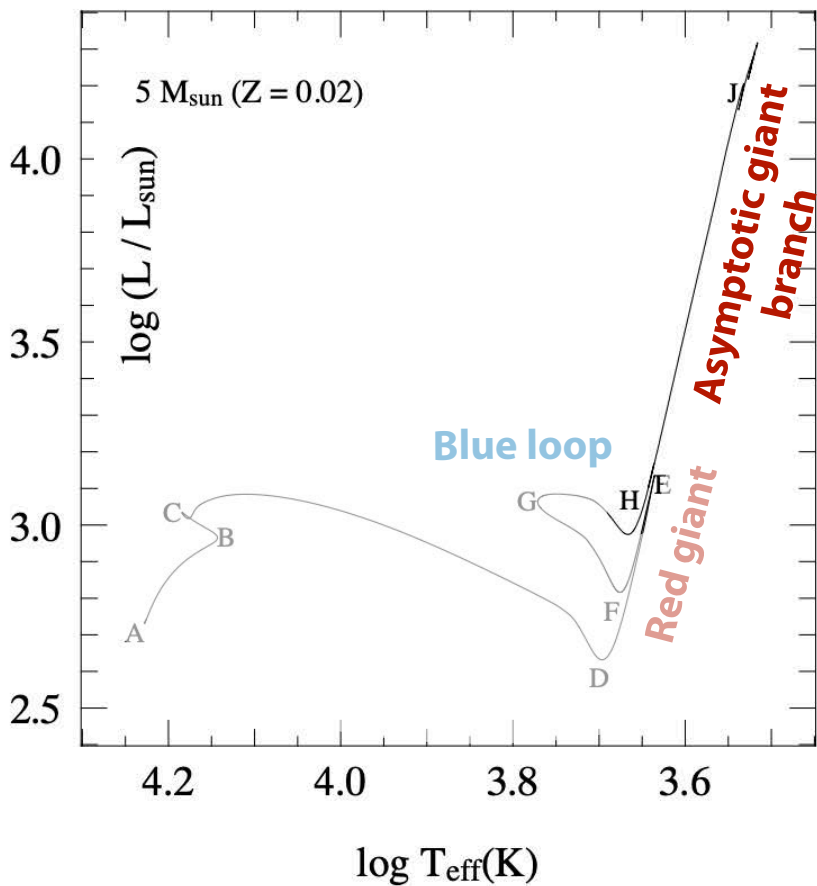
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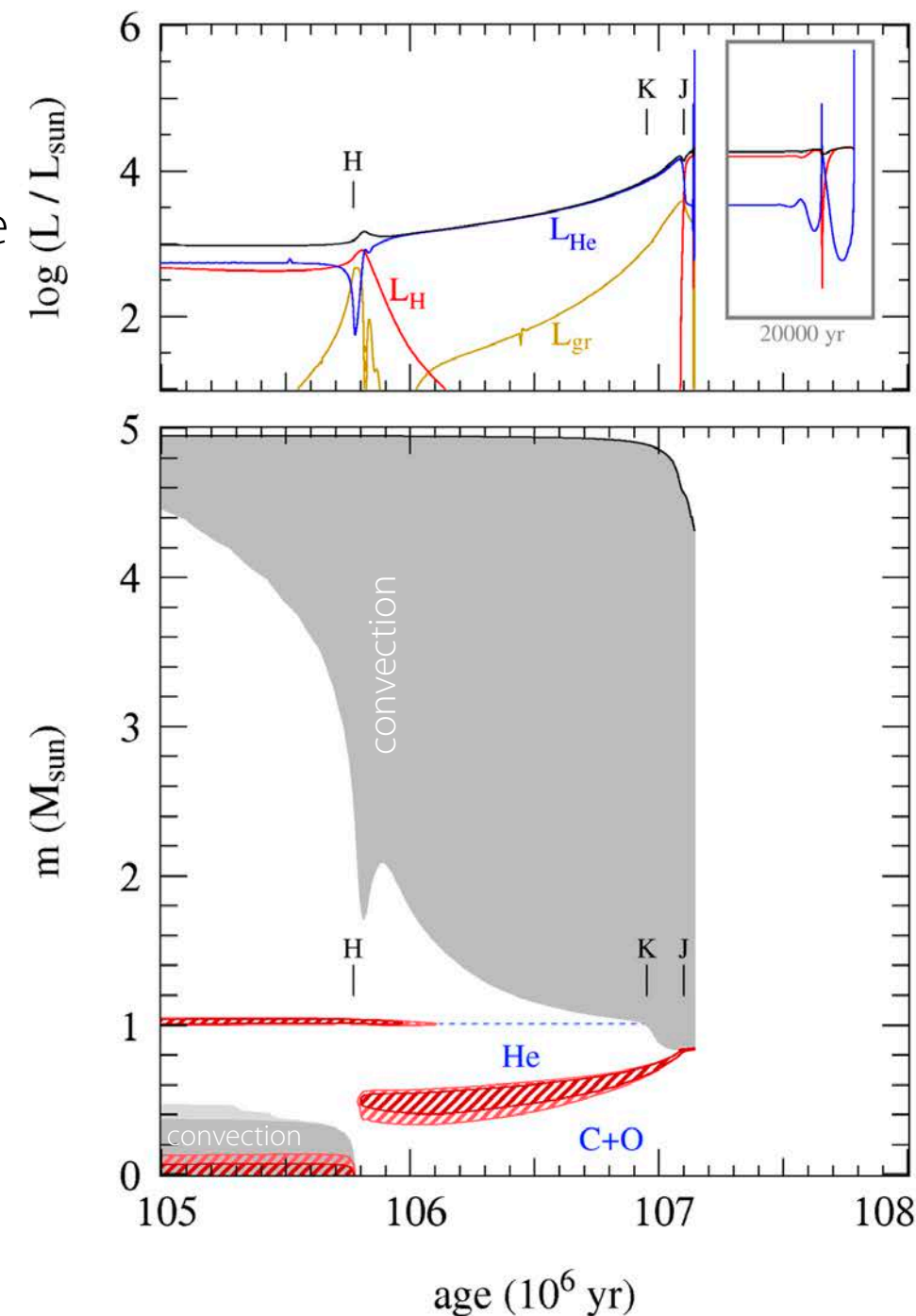
Post-main sequence evolution

Model of internal evolution of a $5 M_{\odot}$ star,
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Asymptotic Giant Branch



- **H**: end of core He burning
 - ➡ back on Hayashi track (close to E)
 - ➡ Beginning of asymptotic giant branch (AGB) phase
- **H**: start of early AGB phase — He-burning shifts rapidly from core to shell (around former convective core, now rich in C+O)
 - H-burning shell extinguishes
- **K**: outer convection zone reaches deep down again into region of previous H shell burning
 - ➡ second dredge-up.
- (For lower-mass stars: H-shell remained active, prevents convective envelope from extending deeper, no second dredge-up)

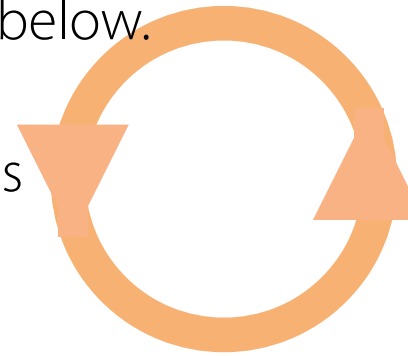


Post-main sequence evolution

Model of internal evolution of a $5 M_{\odot}$ star,
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Asymptotic Giant Branch

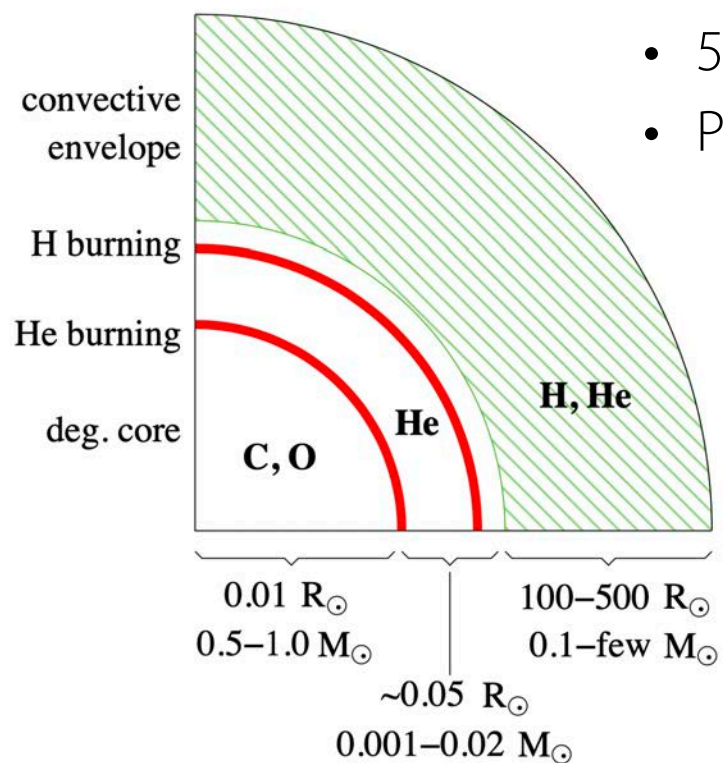
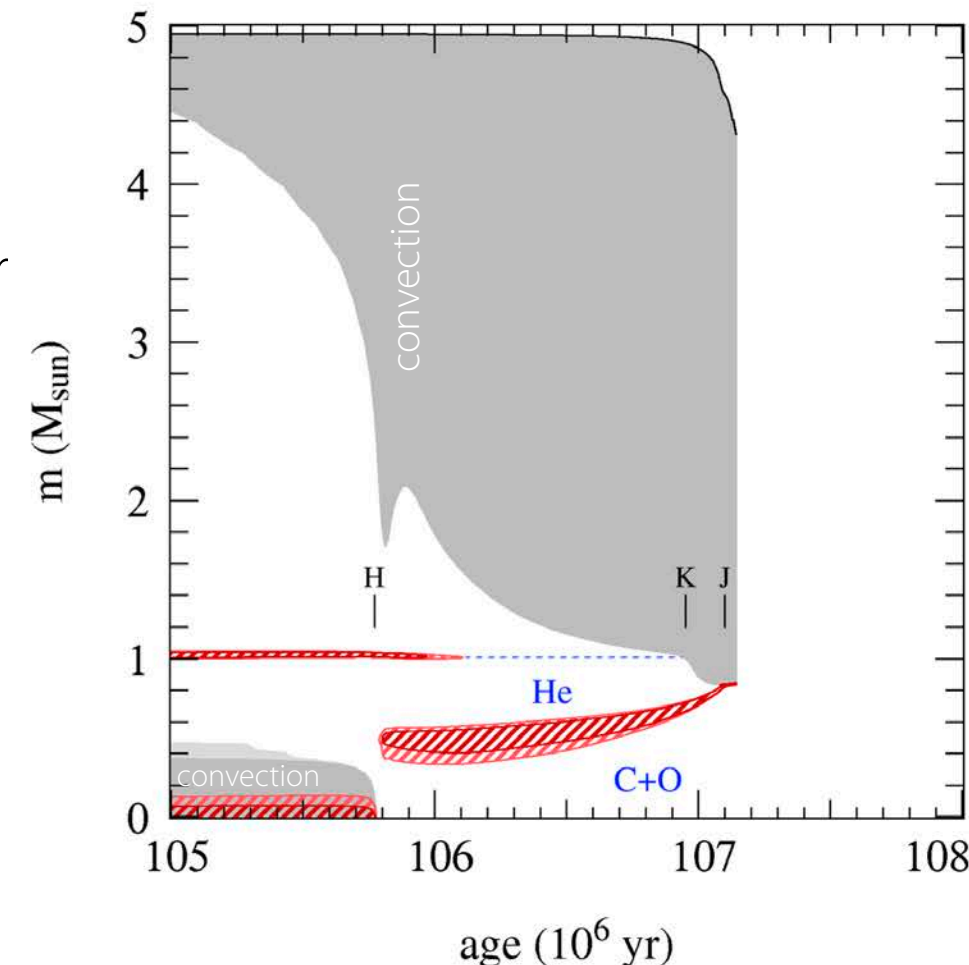
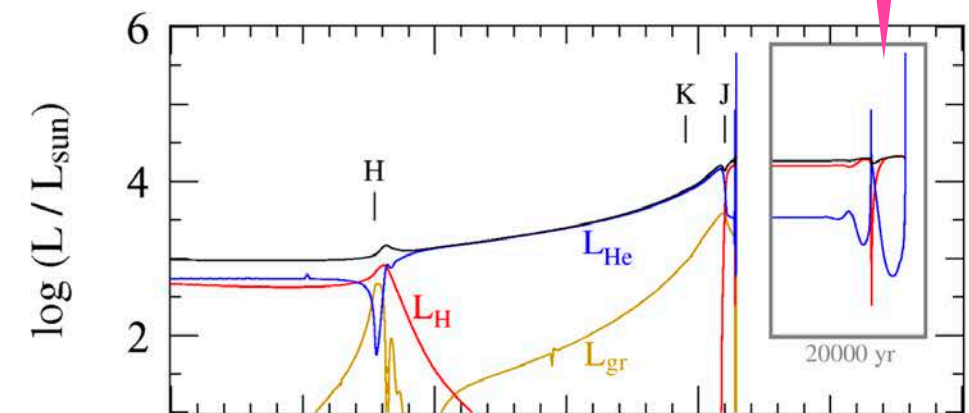
- **J**: H-burning shell re-ignites — Double shell-burning phase
- **Beyond J**: Radius of an AGB star typically (several) $1 \text{ AU} \sim 100$ solar radii
 - H shell active, providing “fresh” He to layers below.
 - He-shell burning switches on, pushes H-shell outwards, which then ceases
 - He burning eventually slows down again, H shell burning recovers
 - Several thermal pulses can occur pulses (not captured by shown model)



➡ Thermal Pulse (TP)-AGB phase

- $5 M_{\odot}$: period between initial pulses 10^3 - 10^5 yr
- Period is a function of mass

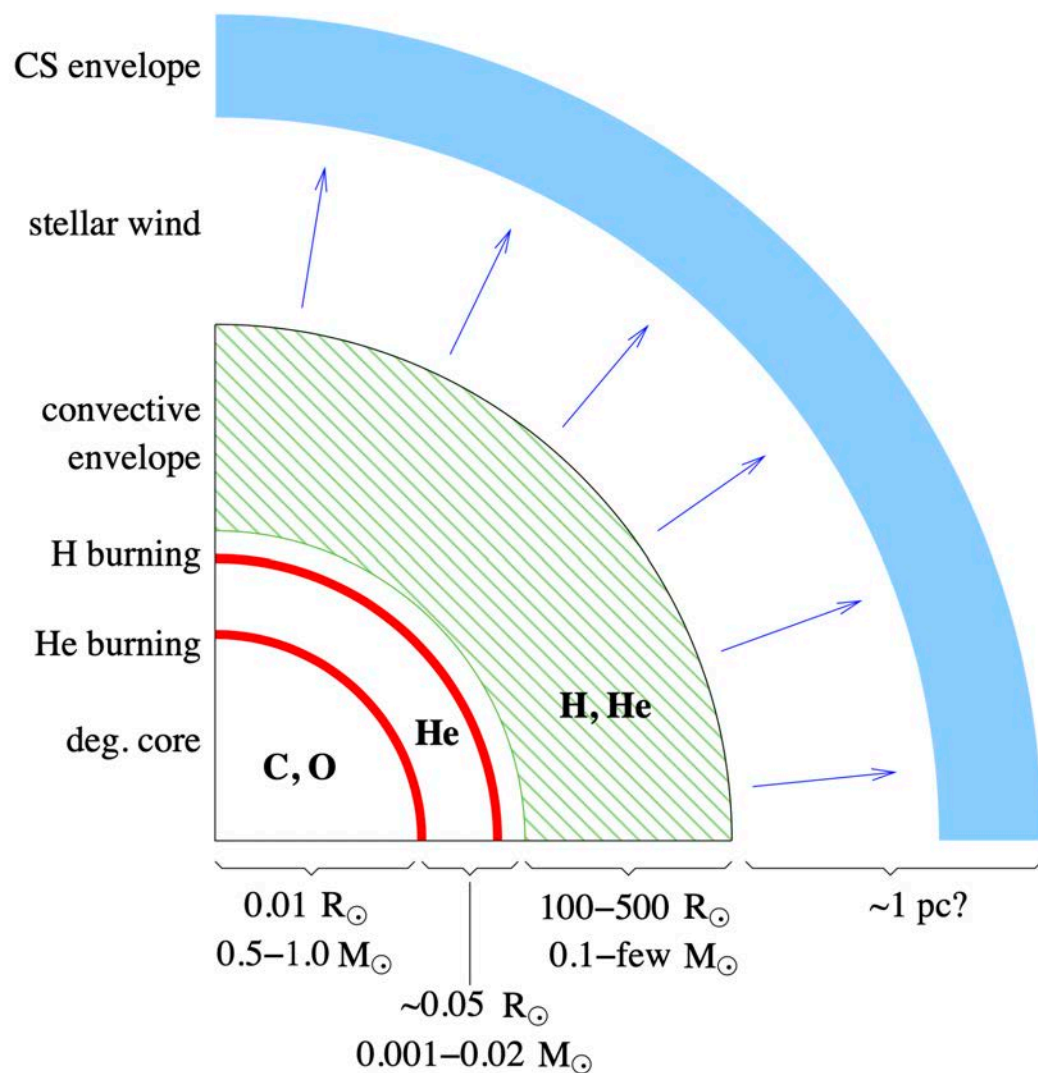
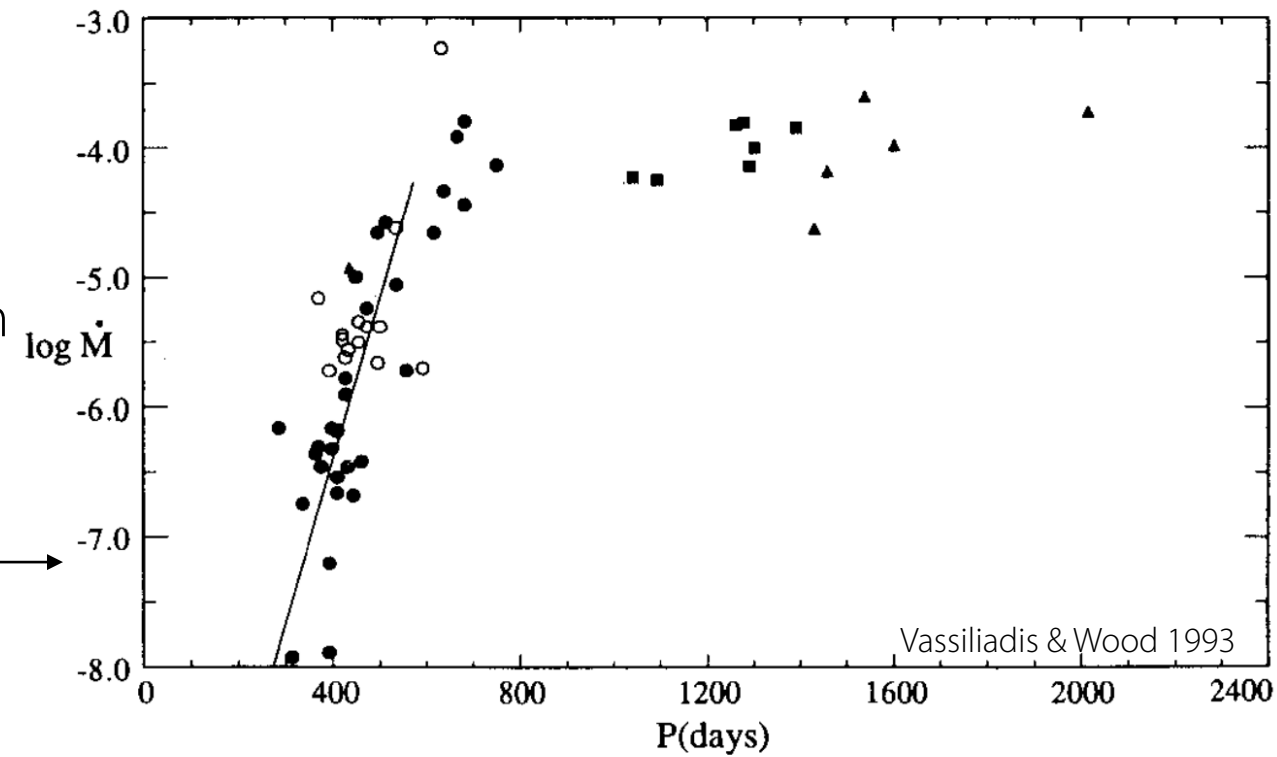
Thermal pulses



Post-main sequence evolution

Asymptotic Giant Branch

- **Thermal Pulse** (TP)-AGB phase
— several pulses can occur
- **Strong mass loss** occurs in connection with pulsation
but mechanism not fully understood
(pulsations + radiation pressure on dust particles !?)
 - Observed mass loss as function of pulsation period →

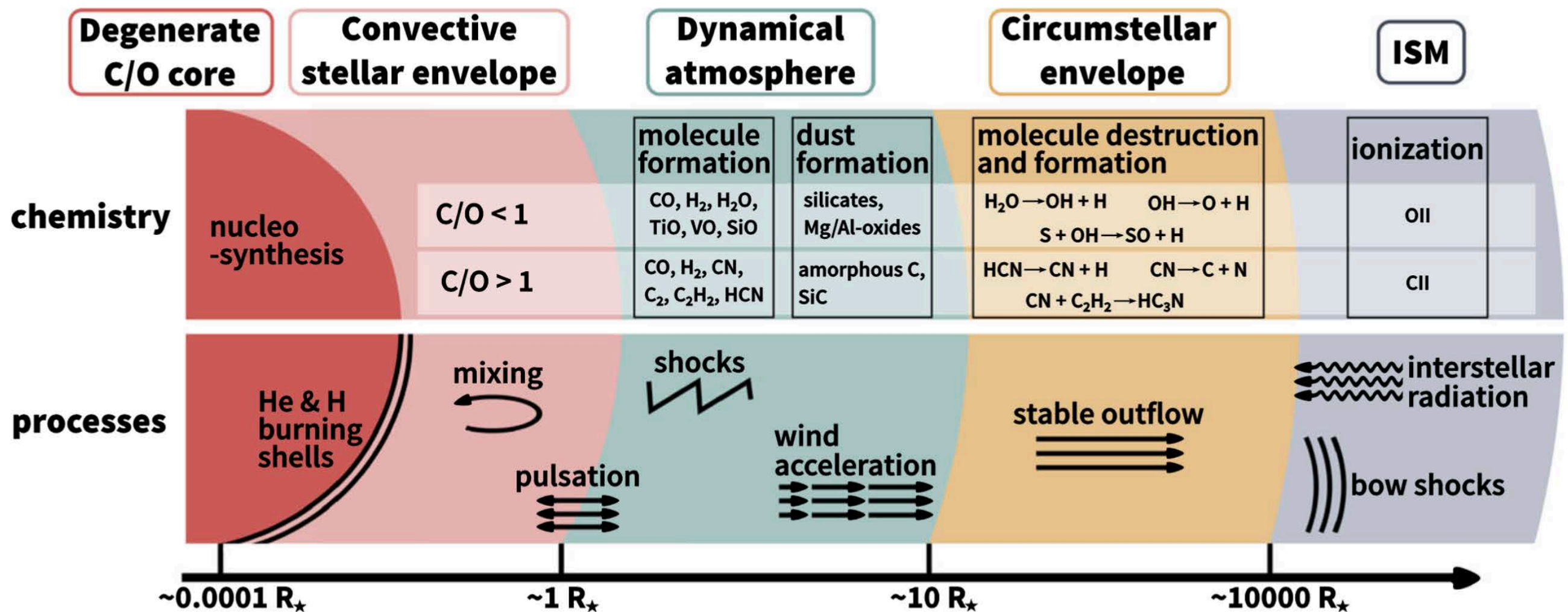


- Star evolves towards larger radii along AGB
 - ➡ Pulsation period increases
 - ➡ Mass-loss rate increases from $10^{-8} M_{\odot}/\text{yr}$ to $\sim 10^{-4} M_{\odot}/\text{yr}$
- Strongest mass loss sometimes referred to as **superwind** phase
- Pulsation periods of several years
- Pulsations induce shock waves
- Envelope expelled within $< 10^6$ yr
- Remnant: Degenerate CO core — cooling white dwarf.

Post-main sequence evolution

Asymptotic Giant Branch (AGB)

- Circumstellar environment around AGB stars:
 - Complicated chemistry of the CSE
 - Detailed formation and destruction of molecules and dust grain important
 - Impact on chemical abundances

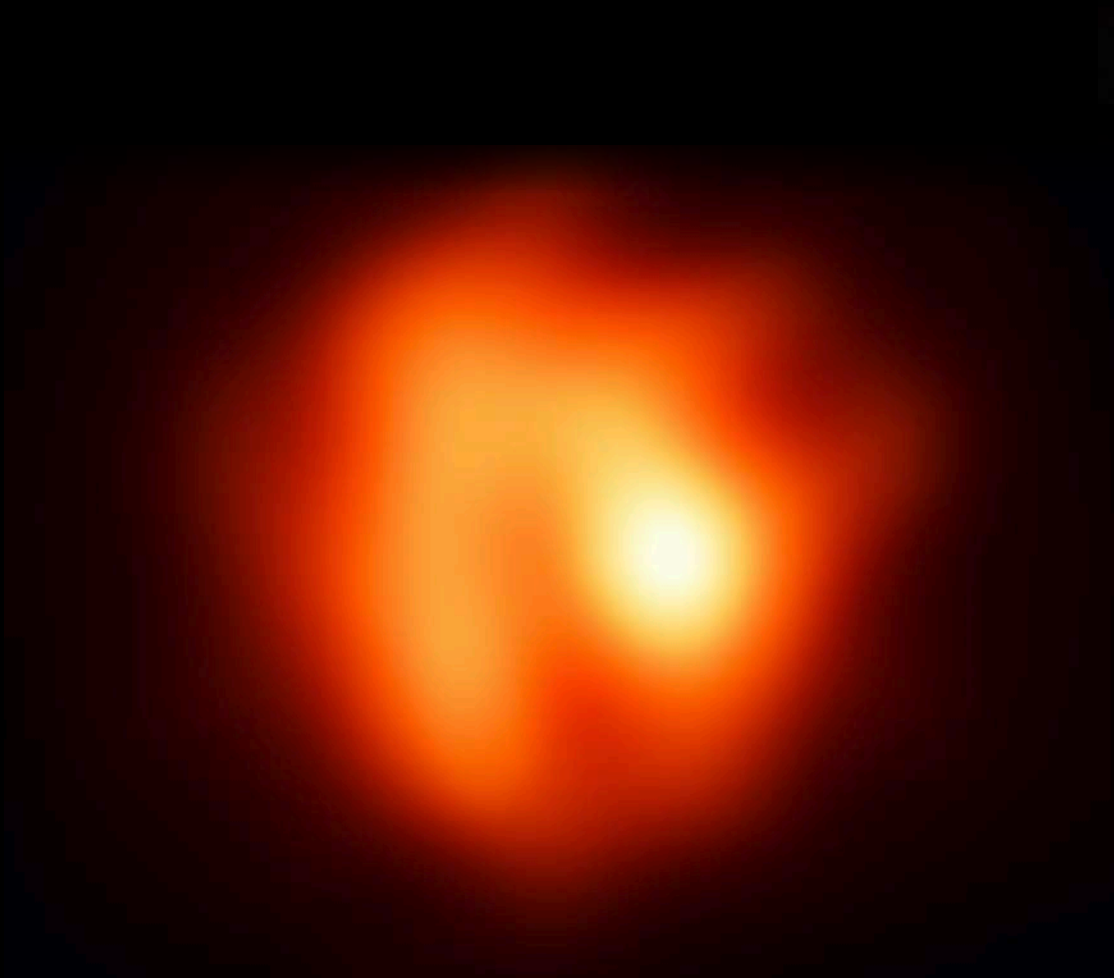


Post-main sequence evolution

Asymptotic Giant Branch (AGB)

R Sculptoris

- $R \sim 340 R_{\odot}$ — if at Sun's location, its photosphere would reach beyond the orbit of Mars!
- Strong mass loss — expulsion of envelope and production of (inhomogeneous) circumstellar envelope (CSE)
- Contains dust and molecules



VLTI/PIONEER — optical interferometry
(9mas diameter) [ESO/M. Wittkowski]



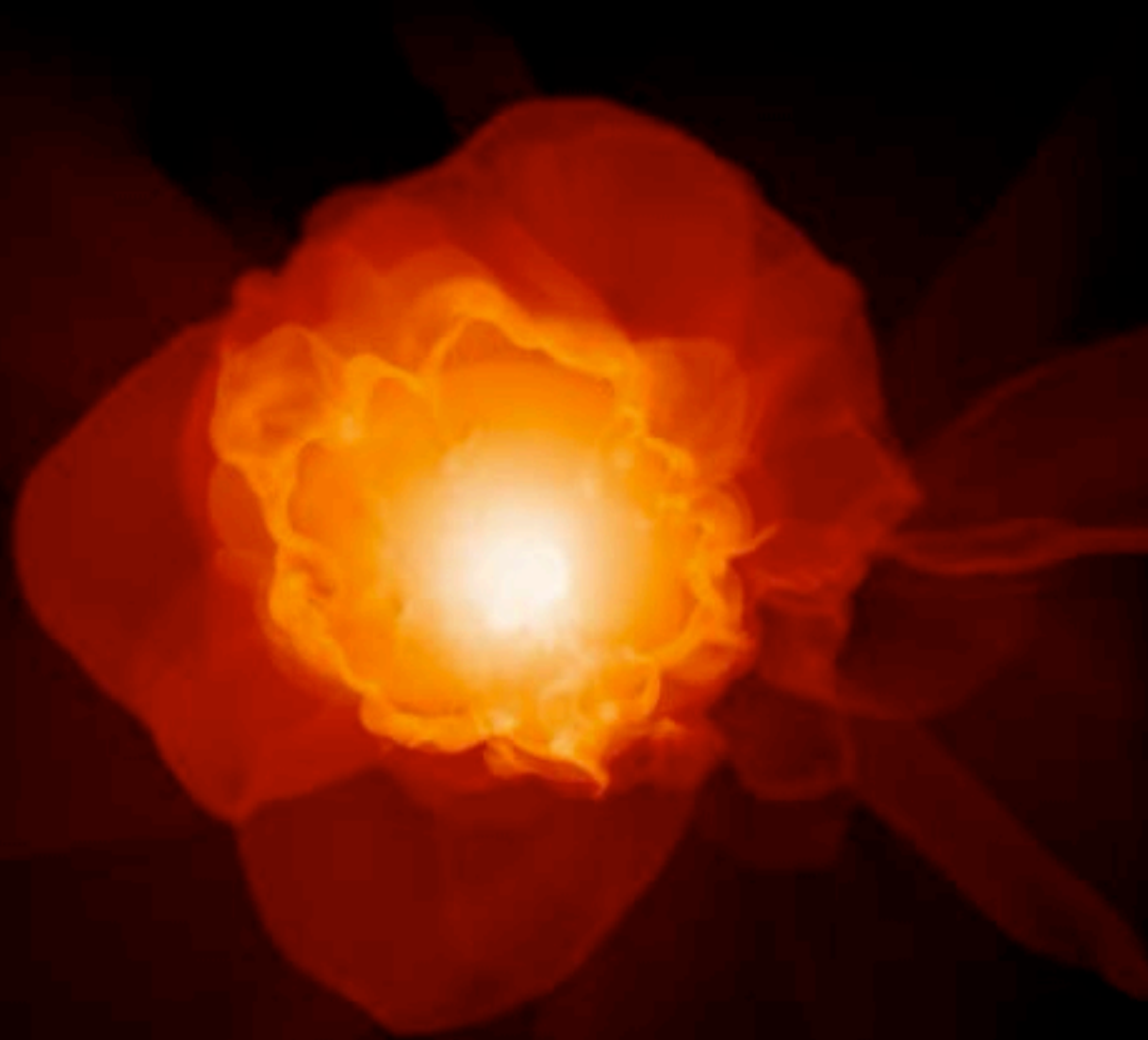
ALMA — mm interferometry
(345 GHz, CO) [ALMA / M. Maercker et al.]

Post-main sequence evolution

Asymptotic Giant Branch (AGB)

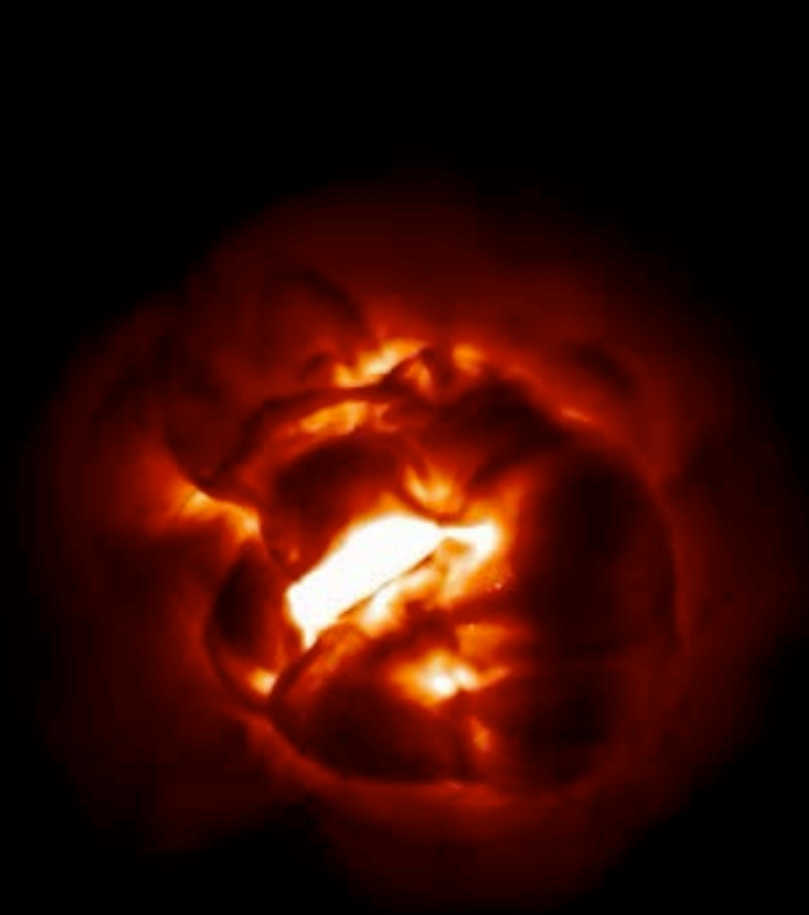
- Numerical simulation of an AGB star (star-in-a-box): $1 M_{\odot}$, $400 R_{\odot}$
 - Possible due to the large size of convection cells and long time scales

st28gm06n25: Density, time(1)= 6.346 yrs



Log. mass density

st28gm06n25: Surface Intensity(3r), time(1)= 6.346 yrs



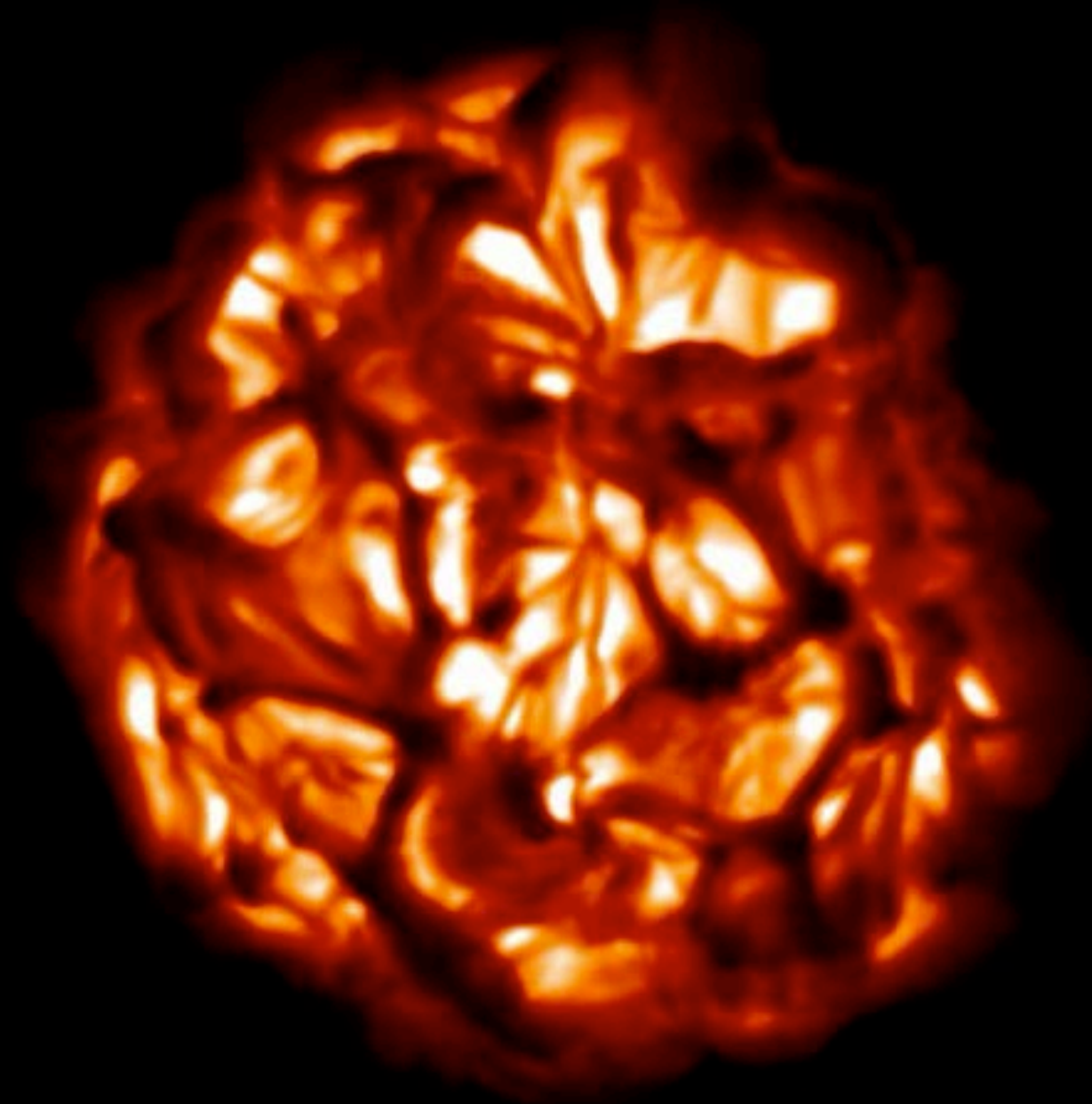
Emergent bolometric intensity

Post-main sequence evolution

Red supergiant

- Numerical simulation of a magnetic red supergiant ($5 M_{\odot}$)

st35gm04b1n004: Surface Intensity(3r), time(1)= 51.383 yrs



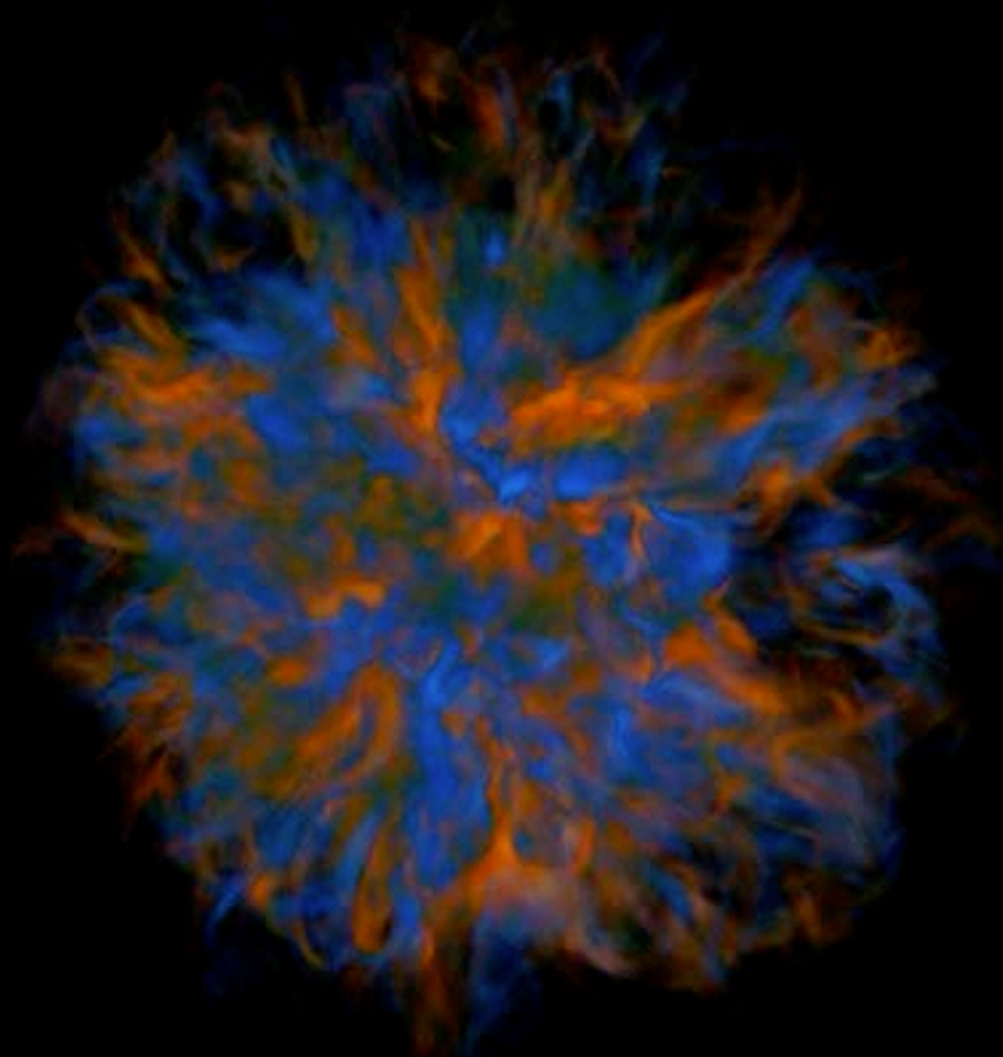
Surface intensity

Post-main sequence evolution

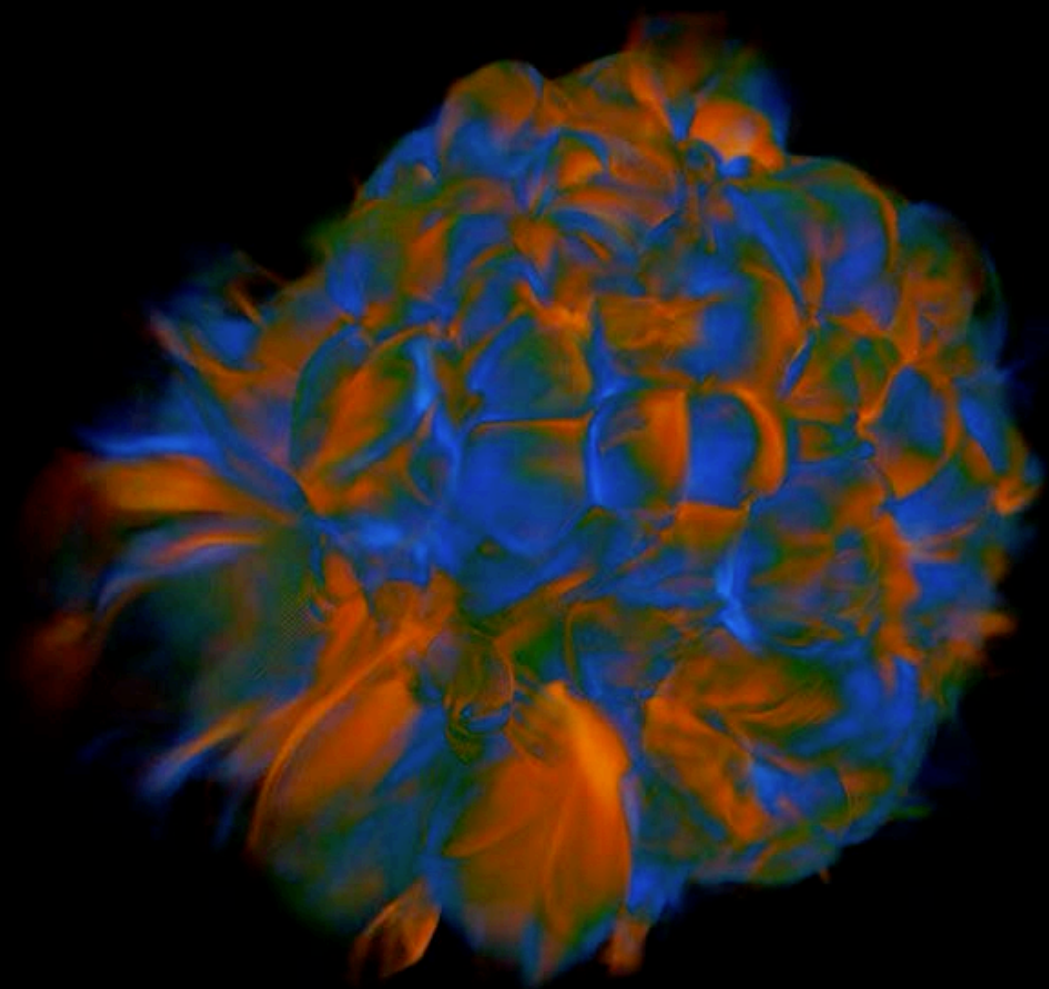
Red supergiant

- Numerical simulation of 5 $M_{\odot}$ red supergiant

Volume rendering of the magnetic field



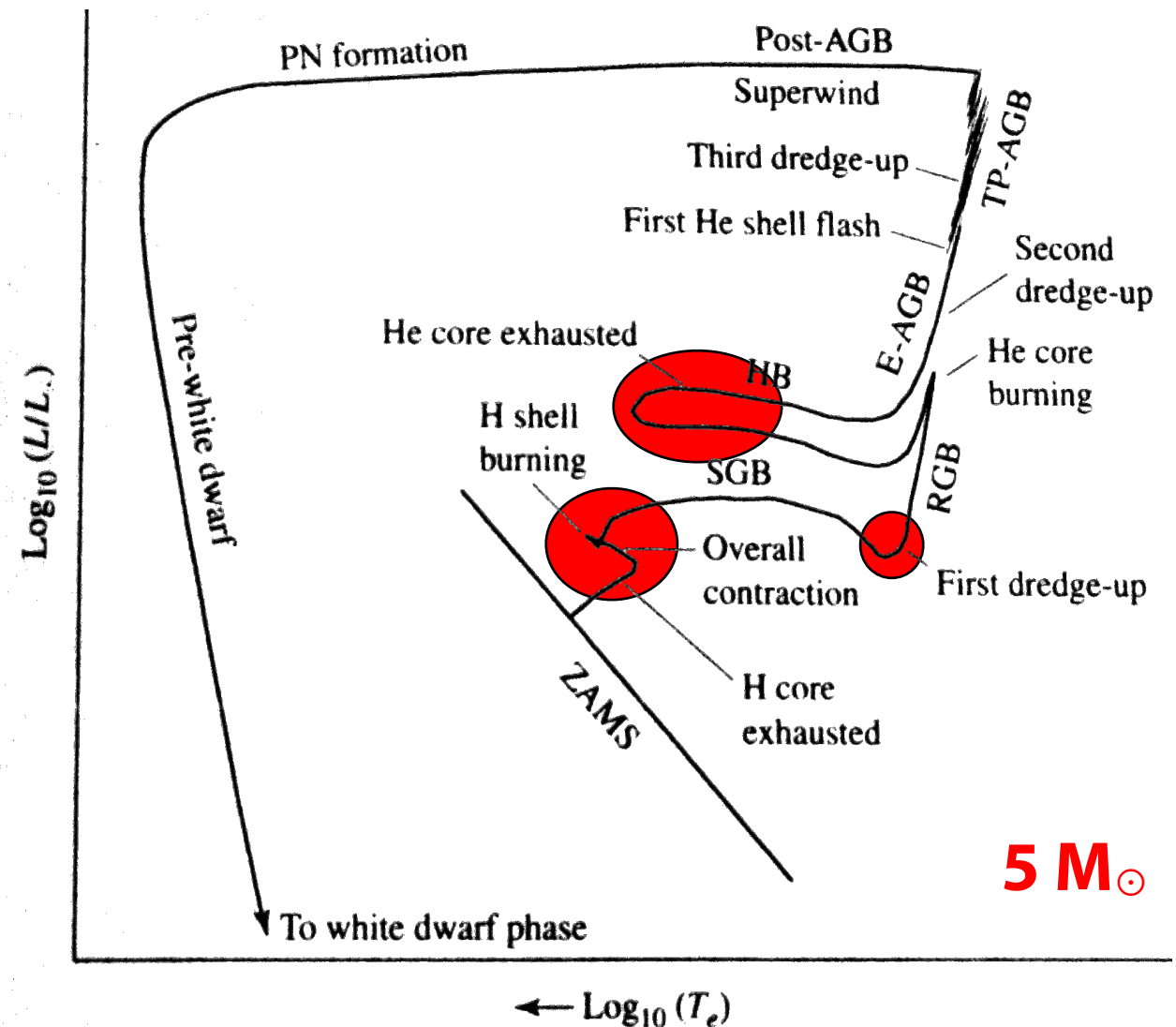
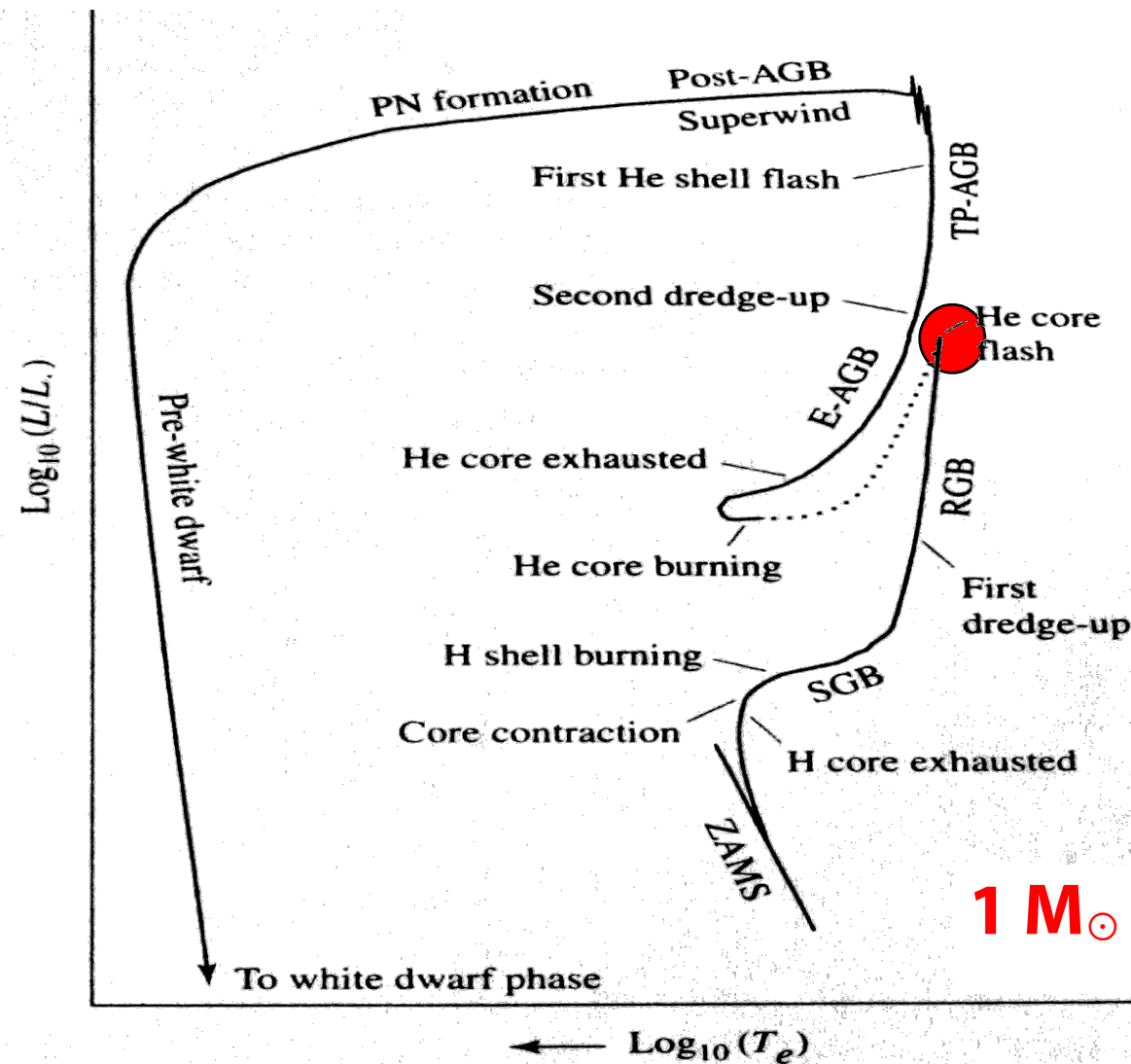
Interior



Surface

Post-main sequence evolution

Comparison low-mass to intermediate-mass evolution

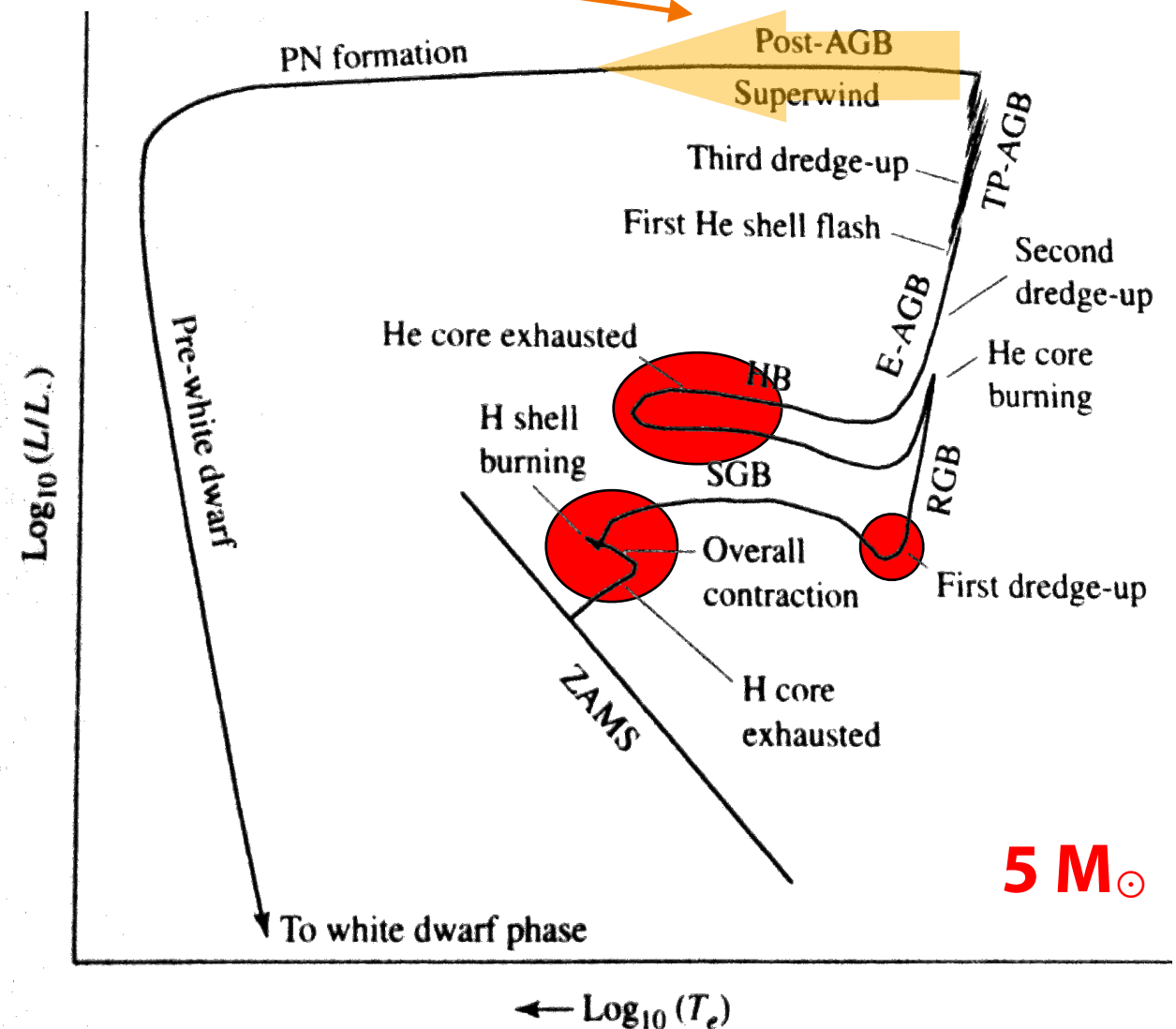
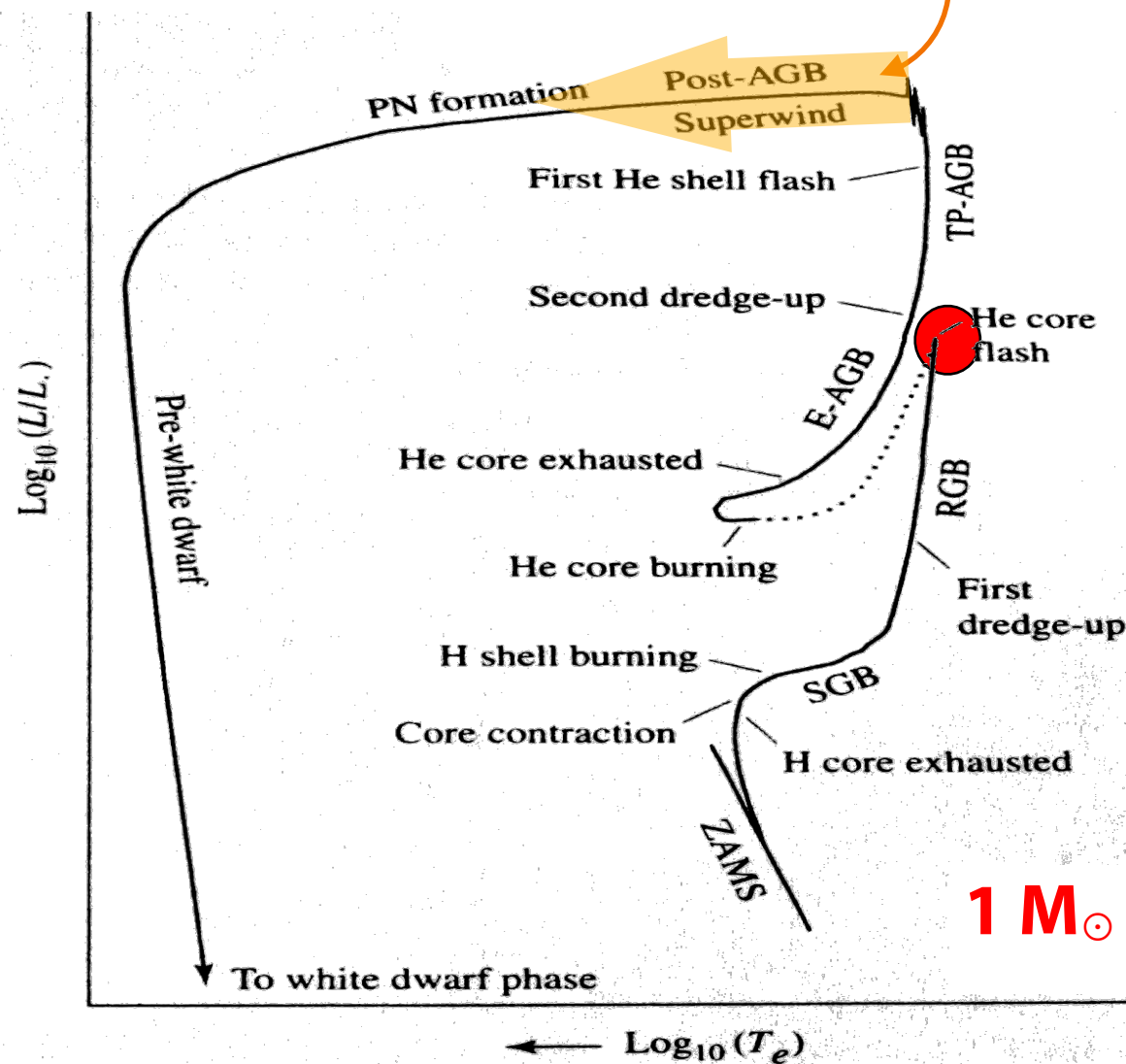


- He core flash at tip of RGB phase

- Larger temperature differences on the horizontal branch
- Helium flash in shell
- Instabilities - variable stars

Post-main sequence evolution

Post-AGB evolution

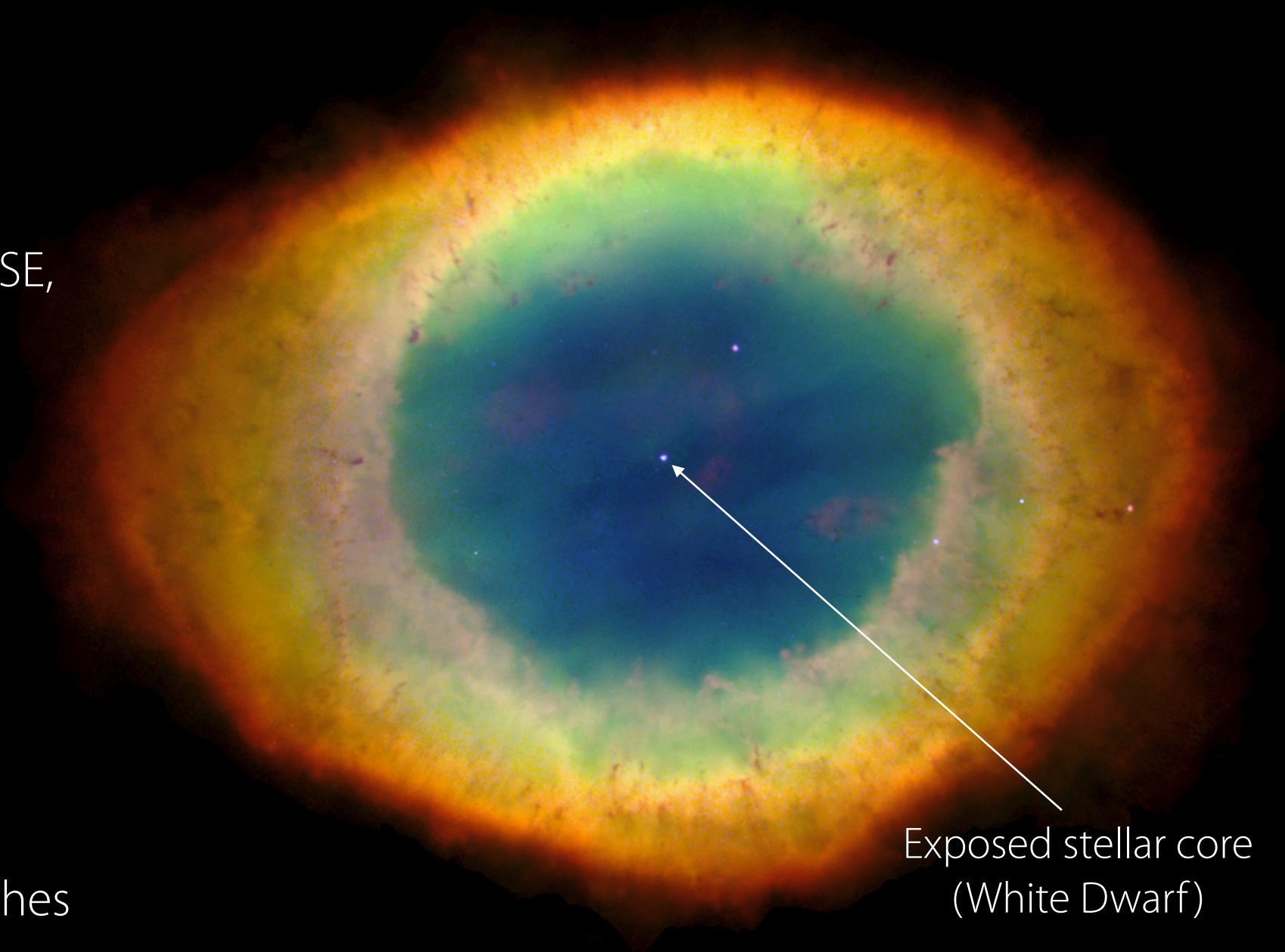


- H-rich envelope becomes very small due to mass loss (only 10^{-3} - $10^{-2} M_{\odot}$ left depending on core mass)
- Star leaves AGB — stellar radius decreases at $\sim$ constant luminosity (horizontal track in HRD) as H-burning shell is still fully active (obeys core mass-luminosity relation)
- Typical timescale for post-AGB phase is $\sim 10^4$ yrs.

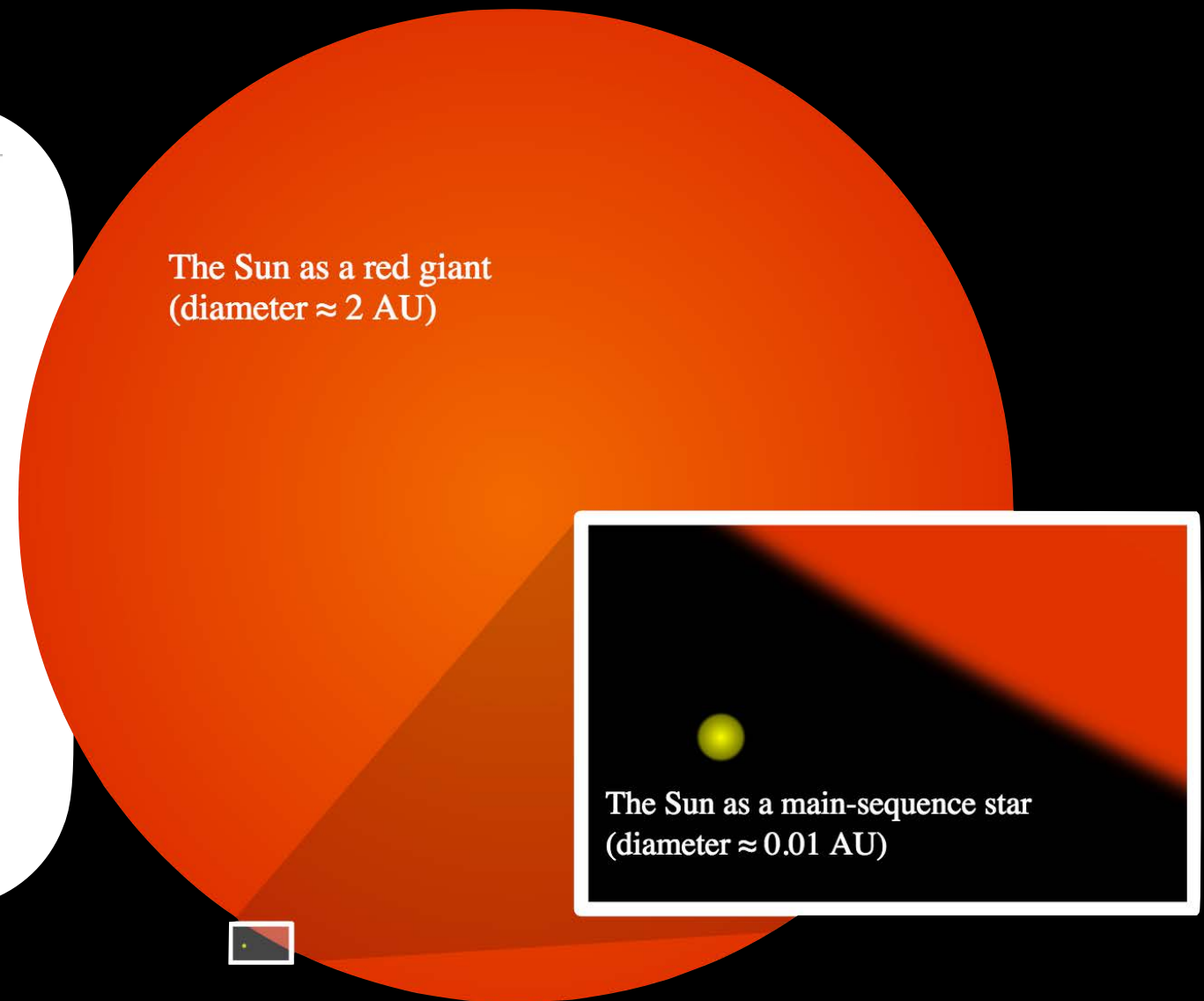
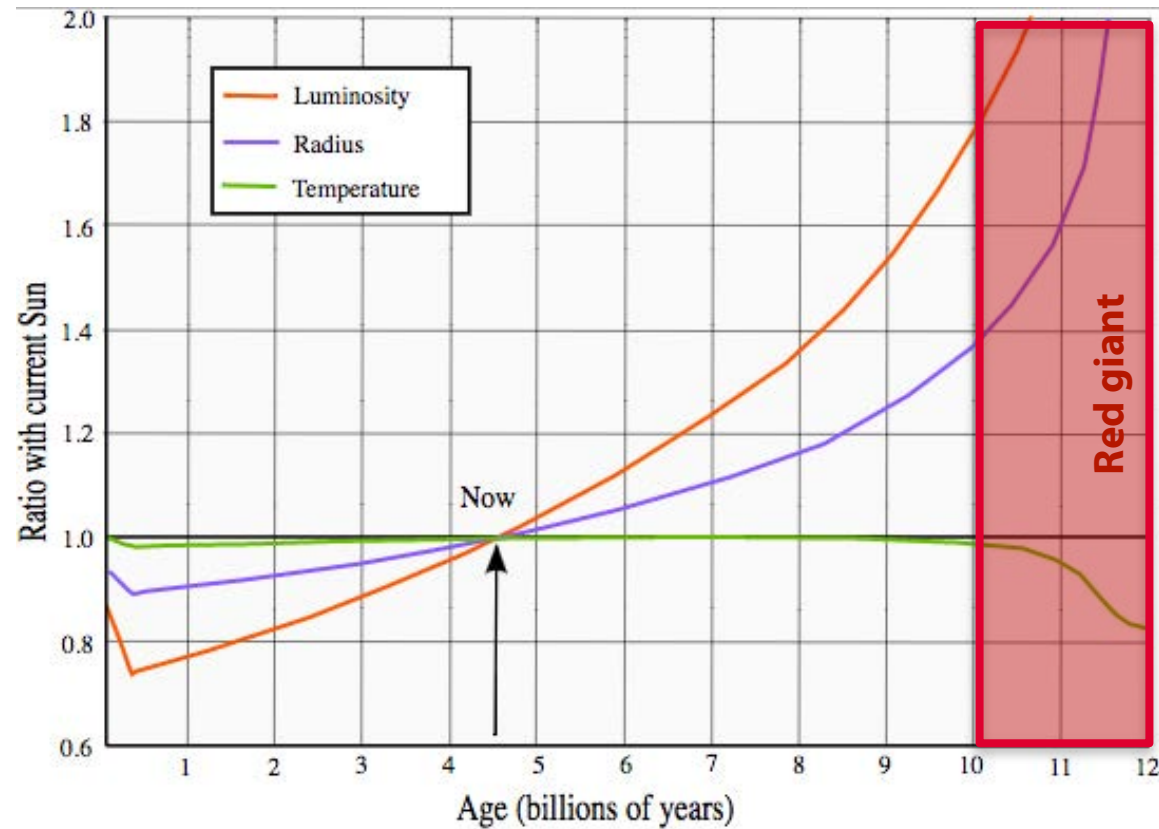
Post-main sequence evolution

Planetary nebula

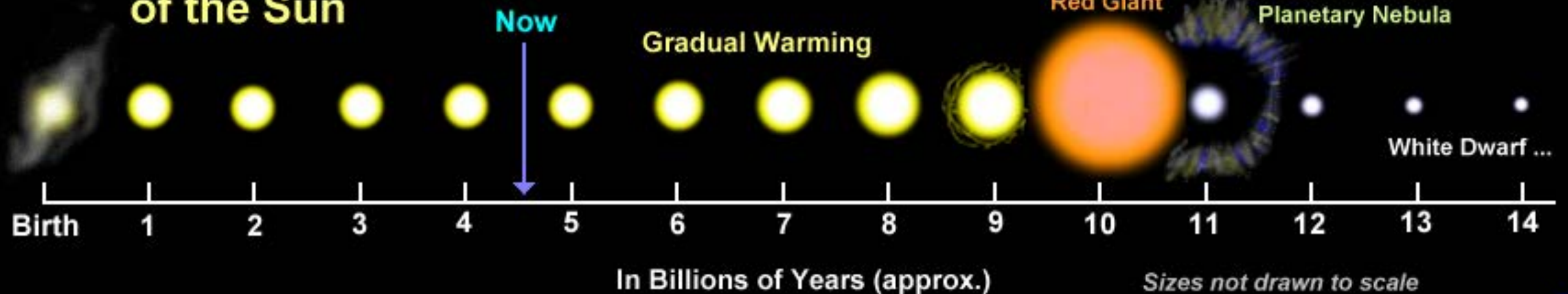
- When reaching $T_{\text{eff}} > 30\,000\text{ K}$:
 - weak but fast wind develops
 - strong **UV** flux
- ➔ Destroys the dust grains in CSE, dissociates molecules, ionises gas
- ➔ Part of CSE turns into an HII region, appears as **planetary nebula**
 - (Emission: fluorescence from recombination)
- H-burning shell finally extinguishes once envelope mass down to $\sim 10^{-5} M_{\odot}$ (at $T_{\text{eff}} \approx 10^5\text{ K}$)
- Exposed stellar core = White Dwarf



Solar evolution



Life Cycle of the Sun

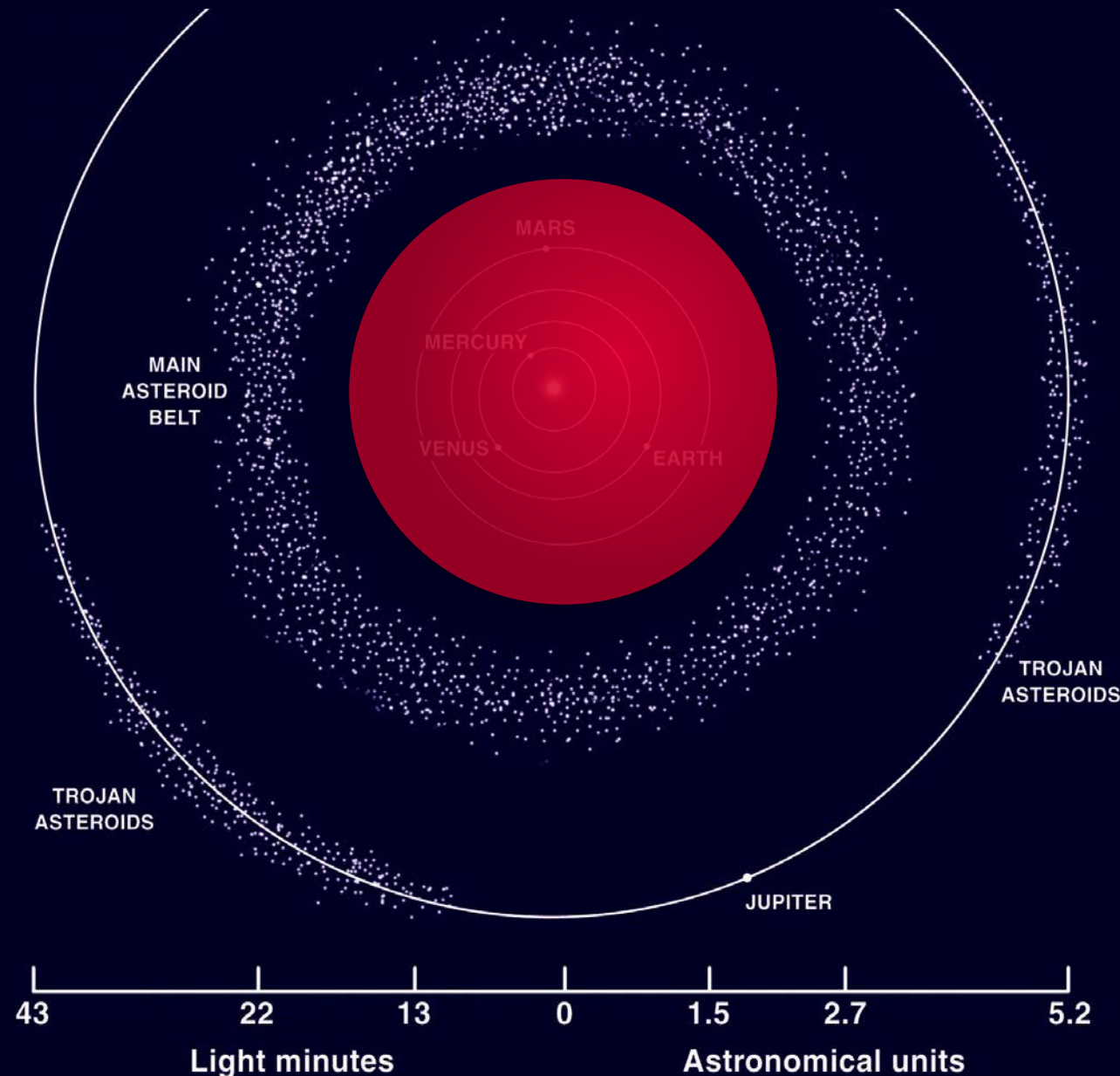


Solar evolution

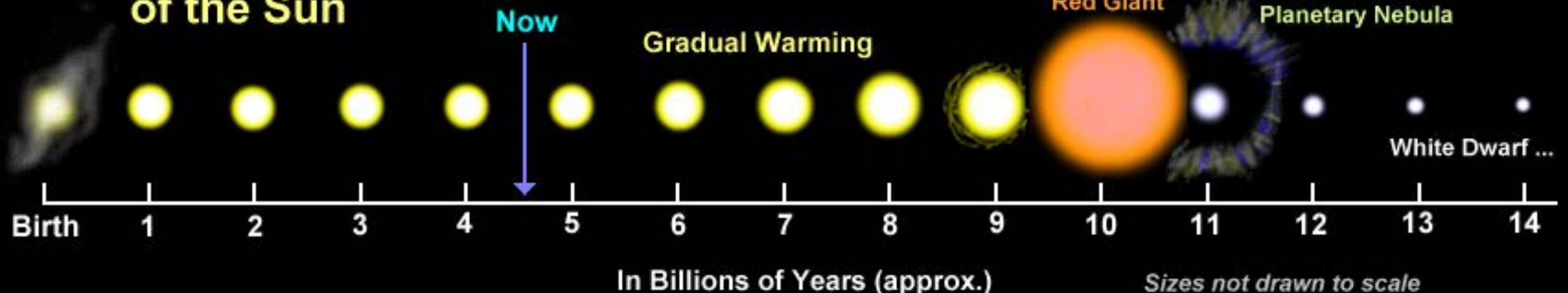
Late evolution stages

- **Red giant star**
- High radiation pressure in the star's interior makes the radius large
- The surface becomes large.
- Radiation is spread over a large area:
 - ➡ Low surface temperature
 - ➡ Low surface gravity

Increase of the Sun's diameter from 0.01 AU to 2 AU



Life Cycle of the Sun

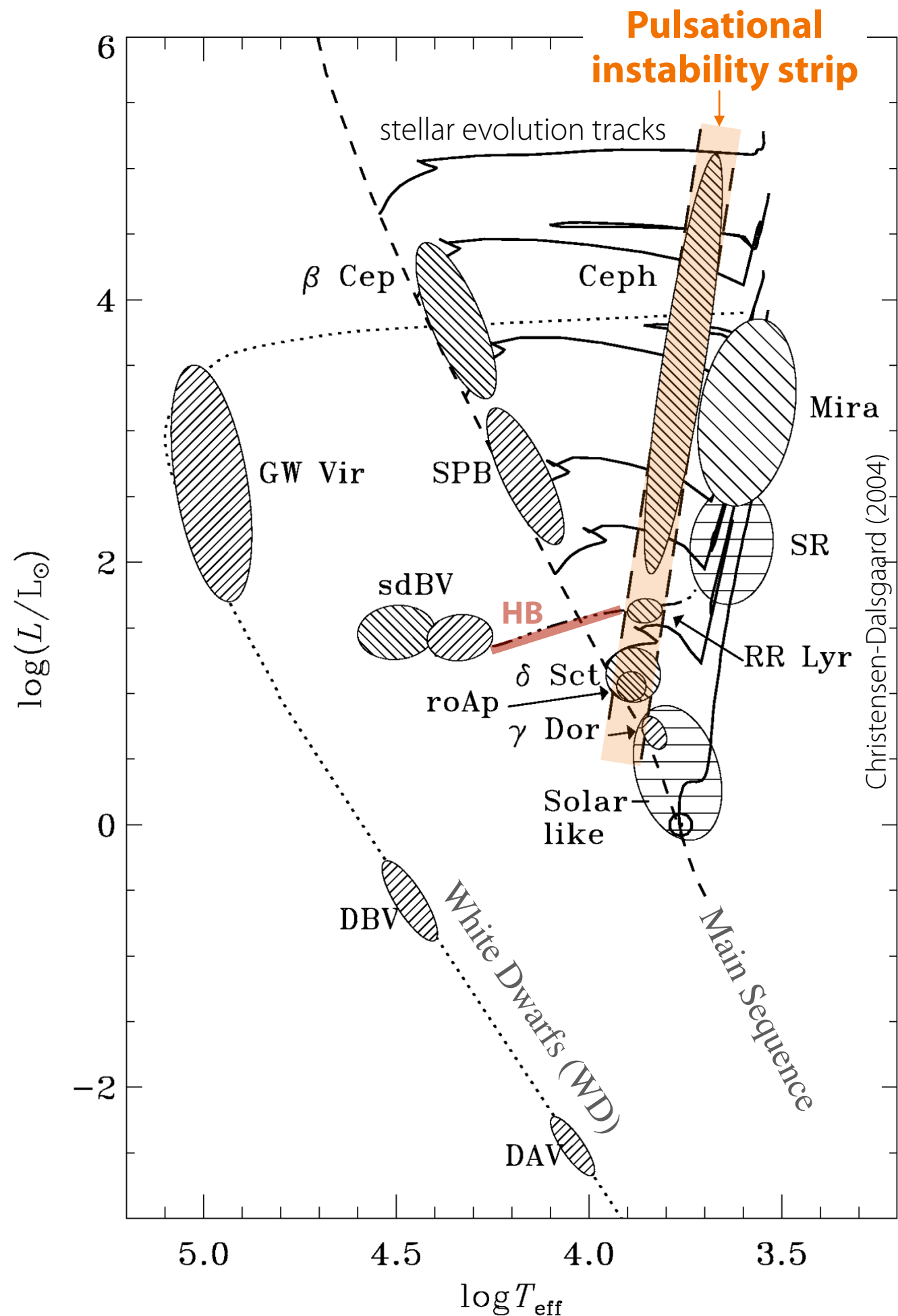


Pulsating and Variable stars

Pulsating and Variable stars

Classes

- Different classes of variables within the **pulsational instability strip**:
 - Cepheid variables: He-burning stars during blue loop (3 - 18 $M_{\odot}$)
 - RR Lyrae variables (0.5 - 0.7 $M_{\odot}$, on horizontal branch, HB)
 - δ Scuti stars on main-sequence
 - Mira variables: luminous red giants
 - β Cep variables and slowly pulsating B (SPB) stars: massive main-sequence stars
 - Subdwarf B stars (sdBV) on extreme end of HB
 - White dwarfs
- Intermediate-mass stars cross instability strip up to three times during evolution: once during H-shell burning, twice during blue loop phase



Pulsating and Variable stars

Prominent classes

Cepheid variables:

luminous pulsating stars with periods ~ 2 -100 days

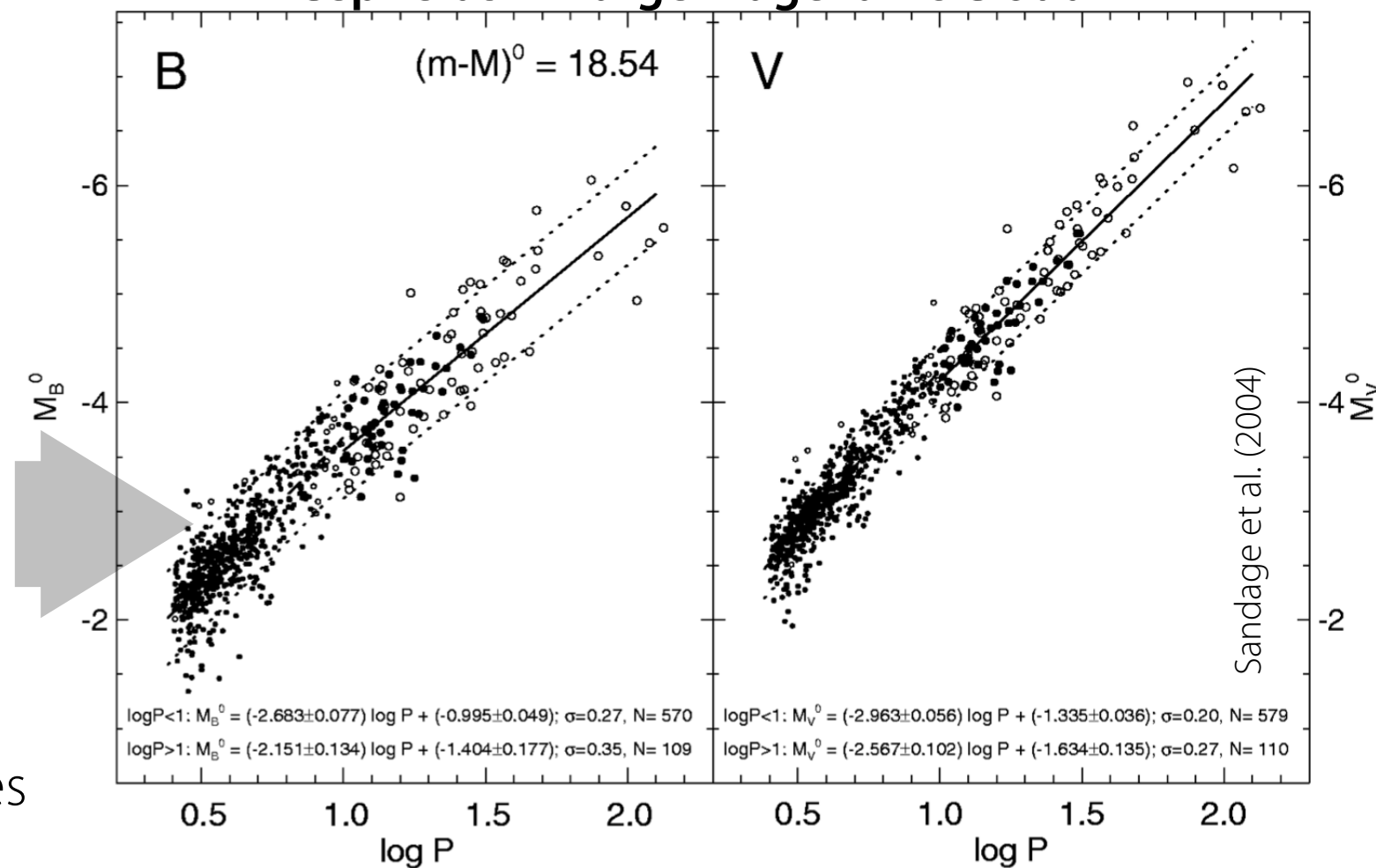
- Well-defined correlation between pulsation period and luminosity
 - Can be seen in other galaxies
 - Measured period gives luminosity / absolute brightness
 - Absolute vs. apparent brightness (distance modulus!) gives distance
- ➔ Cepheids important standard candles for the extragalactic distance scale.

$$m * M = 5 \log r [\text{pc}] * 5 + A$$

RR Lyrae stars: Short periods of 1.5 - 2.4 h

- $L \sim 100 L_{\odot}$ ($M_v = 0.5 = \text{const}$) independent of period.
- Fainter, seen in globular clusters, but not in other galaxies

Period-luminosity relation for Cepheids in Large Magellanic Cloud



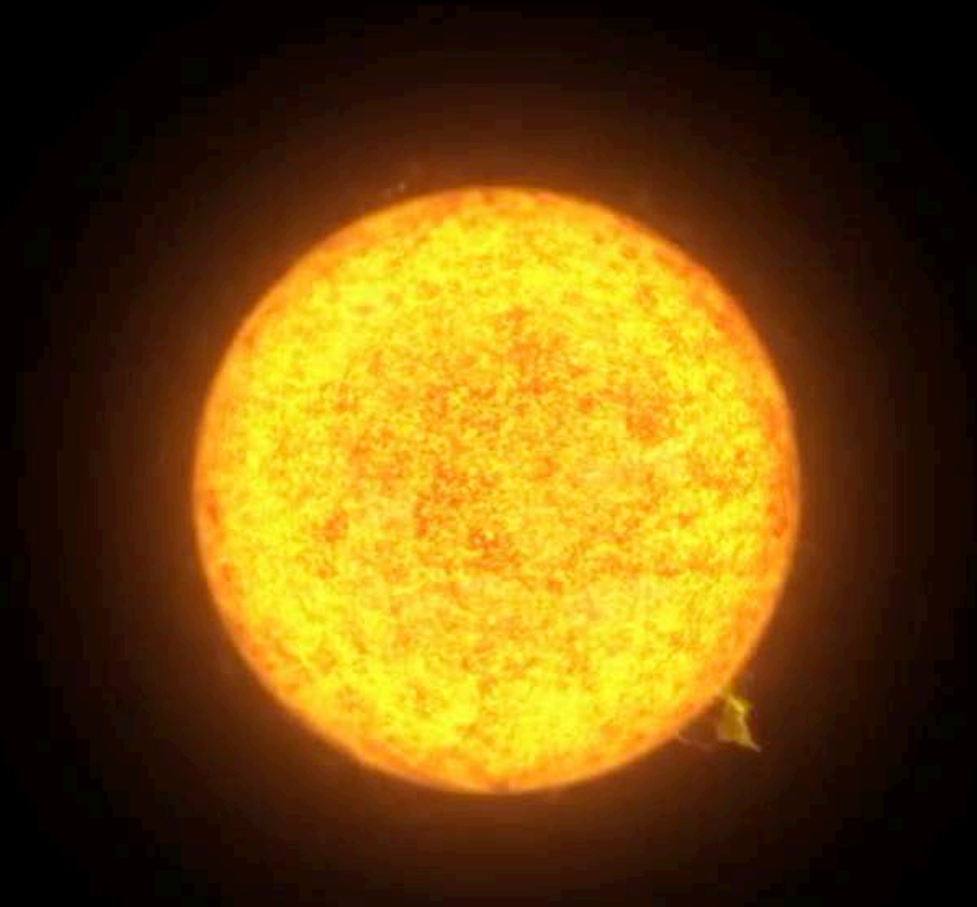
Mira variables: Periods ~ 100 -700 days

- Large, irregular brightness variations
- Cool stars (2000 K) (He-shell burning)
- Strong absorption by dust + molecules
- Local T enhancements dissociate molecules, lead to increased L

Pulsating and Variable stars

Pulsational instability

- **Pulsation = radial oscillation** = standing sound wave (pressure!) resonating in stellar interior
- Radial pulsation modes:
 - Fundamental mode (one node at the centre, open end at stellar surface)
 - Overtone modes (additional nodes between the centre and surface)
 - Most radially pulsating stars, such as Cepheids, oscillate in fundamental mode.



Pulsating and Variable stars

Pulsational instability

- Two possible mechanisms that can drive pulsations:
 - **ϵ -mechanism**: Compression of region with nuclear burning results in temperature increase and thus increased energy generation rate ϵ_{nuc} .
➡ Instability
 - In principle always present but amplitudes of induced oscillations usually too small to drive significant pulsations (potentially relevant for very massive stars though)
 - **κ -mechanism**: Layer is compressed so that density and opacity increases
 - Energy flux through this layer impeded, heating of the layer locally
 - Pressure increases and expands / pushes the layer outward.
 - Gas becomes more transparent again and releases trapped heat.
 - Can drive radial pulsations.
- Note: Some layers absorb heat and do work to drive the pulsation, while other layers may lose heat and thus damp pulsations

Pulsating and Variable stars

Pulsational instability

- Condition for κ -mechanism: opacity must increase when gas is compressed.
 - ➡ Depends on the temperature dependence of opacity sources in driving layer
 - ➡ Interior stratification (temperature, density)
 - ➡ Partial ionisation zones inside star
 1. At $T \approx 1.5 \cdot 10^4$ K: ionisation and recombination of H and He (singly ionised)
 2. At $T \approx 4 \cdot 10^4$ K: ionisation and recombination of He (fully ionised, He III)
 - ➡ location of instability strip in H-R diagram!

$T_{\text{eff}} > 7500$ K — 'blue edge'	Instability strip	$T_{\text{eff}} < 5500$ K — 'red edge'
Both ionisation zones near surface (very low density!)	Ionisation zones located deeper in interior	Partial ionisation zones lie at very high density
Region non-adiabatic, mass and heat capacity too small to drive pulsations effectively	Mass and heat larger but still non-adiabatic enough to absorb sufficient heat to drive pulsations	Gas near adiabatic. Cannot absorb enough heat to drive pulsation.

Pulsating and Variable stars

Non-pulsating Variables

- **T Tauri stars:** PMS objects of $0.2 - 2 M_{\odot}$: Young objects with rapid rotation, fully convective, strong magnetic fields, flares, stellar wind; circumstellar absorbing clouds
- **Flare stars:** "solar-like" stars, rapid rotation + deep convection, magnetic fields — can exhibited super/megaflares
- **Magnetic variables - Ap stars** (spectral type A, peculiar): strong magnetic fields, relatively small brightness changes possibly due to star spots.
- **RS CVn (Canum Venaticorum) stars:** very close double stars (orbital periods of 0.5 day to several months), starspots. probably magnetically interacting, resulting in strong flares
 - Components of different luminosity classes (V + IV, i.e main-sequence + sub-giant)
- **Luminous blue variable (P Cygni):** Very massive stars (hypergiant, $>50 M_{\odot}$) with irregular outbursts, possibly due to mass inflow from binary companion
- **Eclipsing binaries**

Pulsating and Variable stars

Overview over classes of pulsating variables

Type	Prototype	M_V	Spectral Class	Pulsation Period Range	Characteristic Period
Classical Cepheids	d Cephei	-0.5 to -6	F6 to K2	1d to 50d	5d to 10d
Population II Cepheids	W Virginis	0 to -3	F2 to G6	2d to 45d	12d to 28d
RR Lyrae stars	RR Lyrae	0.5 to 1	A2 to F6	1.5h to 24h	0.5d
Long-Period variables	o Ceti (Mira)	1 to -2	M1 to M6	130d to 500d	270d
RV Tauri stars	RV Tauri	-3	G, K	20d to 150d	75d
Beta Canis Majoris stars	b Canis Majoris	-3	B1, B2	4h to 6h	5h
Semiregular red variables	a Herculis	-1 to -3	K, M, R, N, S	100d to 200d	100d
Dwarf Cepheids	d Scuti	4 to 2	A to F	1h to 3h	2h

Pulsating and Variable stars

Overview over classes of cataclysmic variable stars

Type	Time	Example	$M_{\max}$	Dm	Energy per Outburst (J)	Cycle	Mass Ejected per Cycle ($M_{\odot}$)	Velocity of Ejection (km/s)	Mass of Star ($M_{\odot}$)
Supernova I		Tycho's	-20	>20	10^{44}		< 1	10,000	1
Supernova II			-18	>20	10^{43}		?	10,000	>4
Novae	Fast	GK Per = Nova Per	-8.5 to -9.2	11 to 13	6×10^{37}	10^6 y ?	10^{-5} to 10^{-3}	500 to 4000	1 to 5
	Slow	DQ Her	-5.5 to -7.4	9 to 11				100 to 1500	0.02 to 0.3
	Recurrent	T Cr B	-7.8	8	10^{37}	18 to 80 y	5×10^{-6}	60 to 400	2
Dwarf Novae		U Gem SS Cyg	+5.5	4	6×10^{31}	40 to 100 d	10^{-9}		~0.4

Variable stars / Binary stars

- List of common types of variable and binary stars

Name	Definition
Algol	Semi-detached binary system with a cool subgiant and an early-type companion, with mass transfer from the Roche-lobe filling secondary to the primary star, which has resulted in the more evolved star being the least massive.
ζ Aur	Eclipsing binary consisting of a bright K (super) giant and a hot B star.
BY Dra	The most active main-sequence emission-line stars of type dKe or dMe; many are binary systems.
FK Com	Very active, rapidly rotating, late-type single giants, possibly coalesced binaries.
RS CVn	In the strict definition, a close binary with stars of nearly equal masses, with the hotter component of spectral type F, G, or K, and luminosity class V or IV (but with the subgiant not filling its Roche lobe), with orbital periods between 1 day and 2 weeks. In the expanded definition, any tidally interacting binary system with at least a single cool star. RS CVn stars have negligible mass exchange.
UV Ceti	Red-dwarf flare stars, variable, either single or members of binaries.
T Tau	Irregularly variable pre-main-sequence stars.
W UMa	In the strict definition: eclipsing contact binaries of main-sequence stars. In the relaxed definition, semidetached systems are sometimes included.