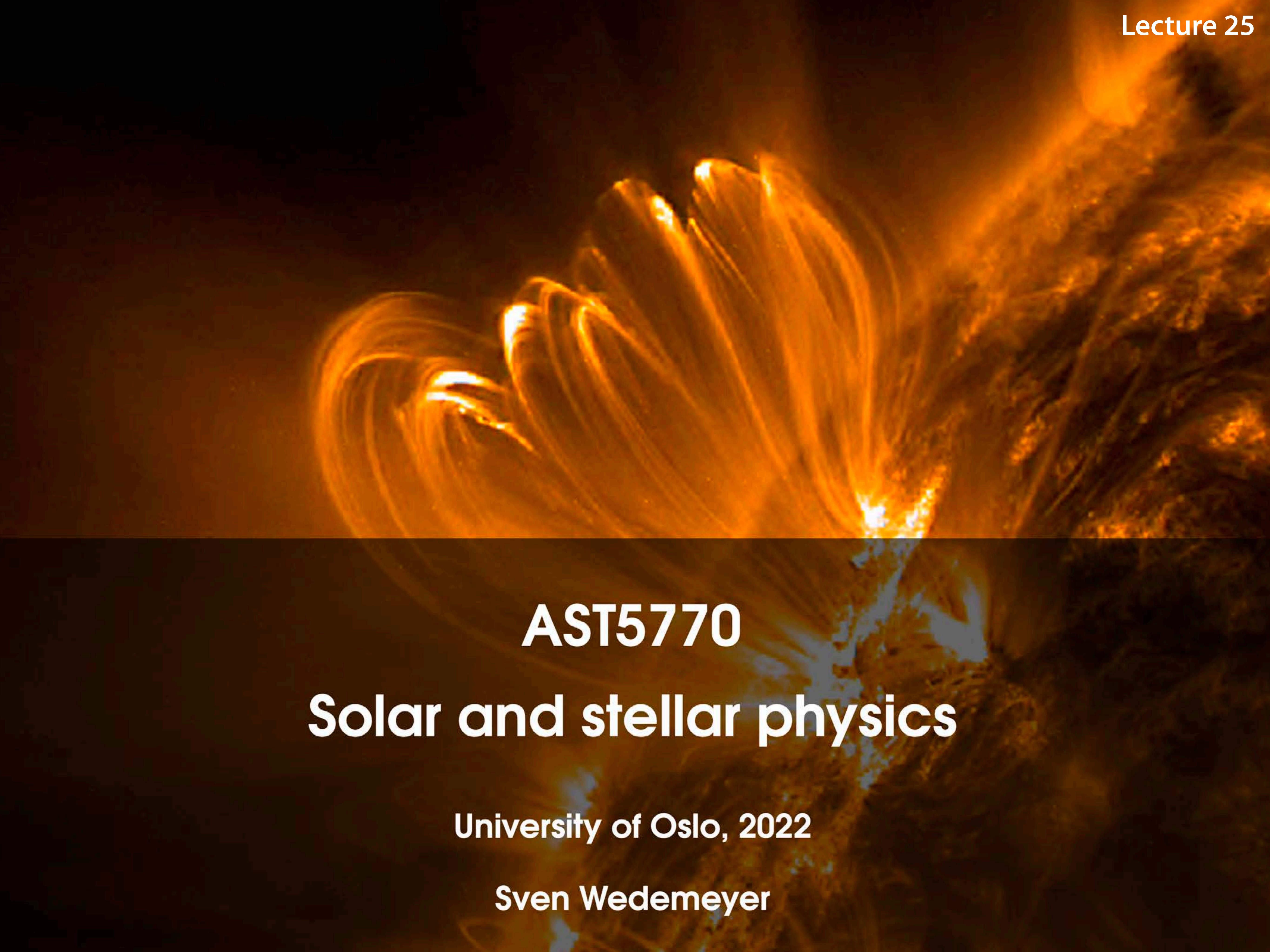


Lecture 25

AST5770

Solar and stellar physics

University of Oslo, 2022

Sven Wedemeyer

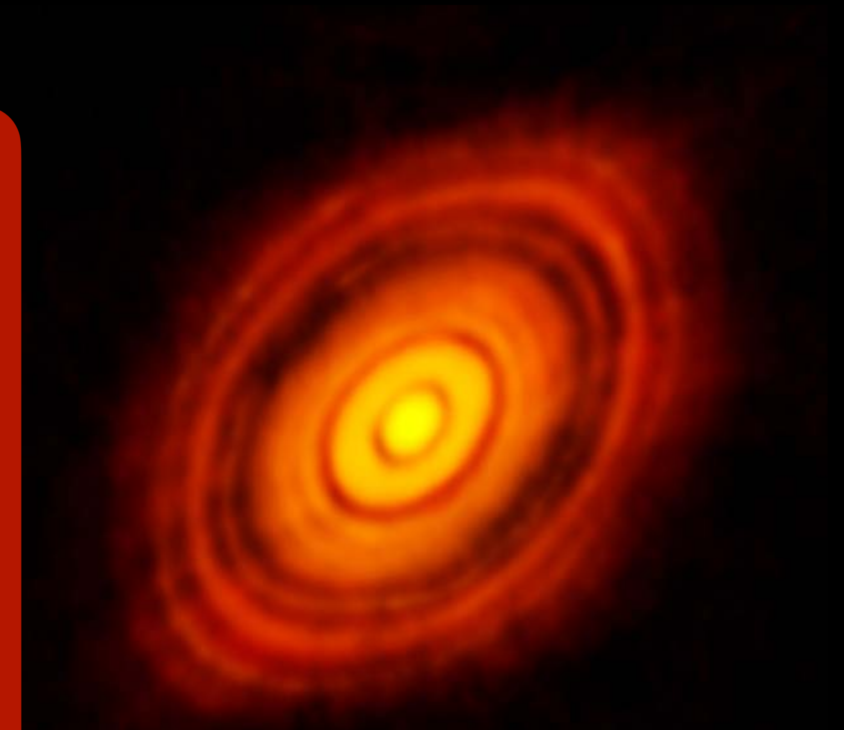
Stellar evolution

Star formation

- Star formation: Collapse of giant molecular cloud, fragmentation

  ➡ Stars typically form in groups (e.g., Pleiades)
- Formation of protostar once core becomes hot and dense enough to establish hydrostatic equilibrium
- Further contraction, approaching Zero Age Main Sequence (ZAMS) on Hayashi tracks (fully convective)

T Tauri stars:
pre-main sequence
(age ~ 10^6 yr),
accretion disk still
optically thick,
large IR excess
observed



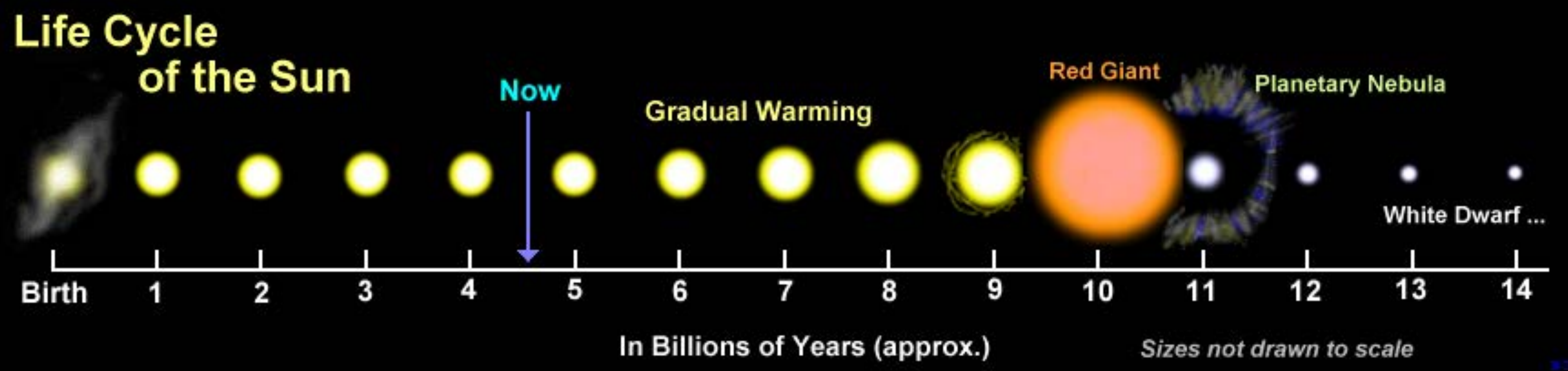
HL Tauri ALMA (ESO/NAOJ/NRAO)

Pleiades (M45)

Stellar evolution

Overview

- **Main sequence**
  - Begins when reaching Zero Age Main Sequence (ZAMS)
  - Hydrogen fusion (H burning) in the core
  - Longest evolution stage
- **Post-main sequence evolution**
  - More complicated due to different fusion stages (element) in the core and/or shells
  - Reached fusion stage highly mass-dependent
  - **Mirror principle** for stars with shell burning — expansion and contraction opposite of a shell (core — envelope)
  - **Equation of state** — beyond ideal gas



Post-main sequence evolution

Degenerate Matter

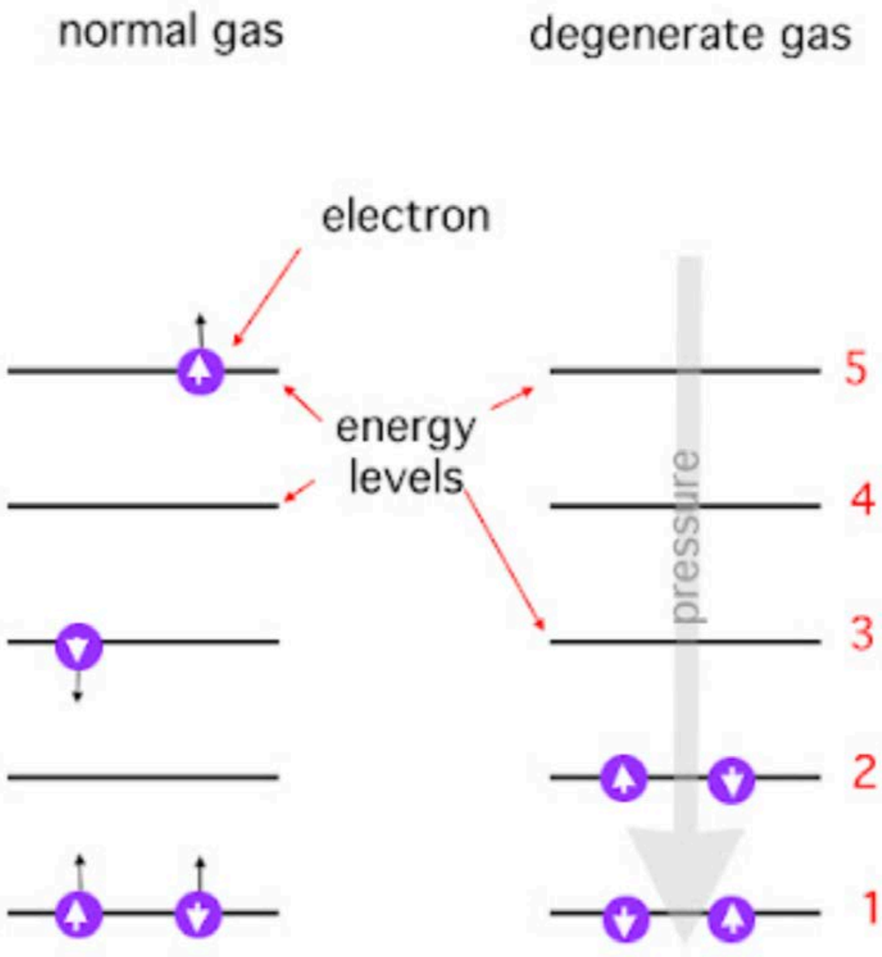
- He core: mixture of He nuclei and electrons.
- Electrons obey **Pauli Exclusion Principle**
  (2 electrons cannot occupy the same quantum state)
- If phase space is full at high density: Any additional electron cannot fit anymore unlike for an ideal gas at same temperature
- Higher pressure than for an ideal gas at same temperature

➡ **Electron Degeneracy Pressure**

  - Electrons would repel each other if tried to be forced closer together.
  - Repulsion much stronger than the usual repulsion between charged particles.

- Degeneracy pressure > thermal pressure

➡ Gas called **degenerate**.



white arrow = intrinsic spin
black arrow = electron movement

http://sciexplorer.blogspot.com/2013/03/the-sun-part-4-helium-eventually-seals.html

Post-main sequence evolution

Degenerate Matter

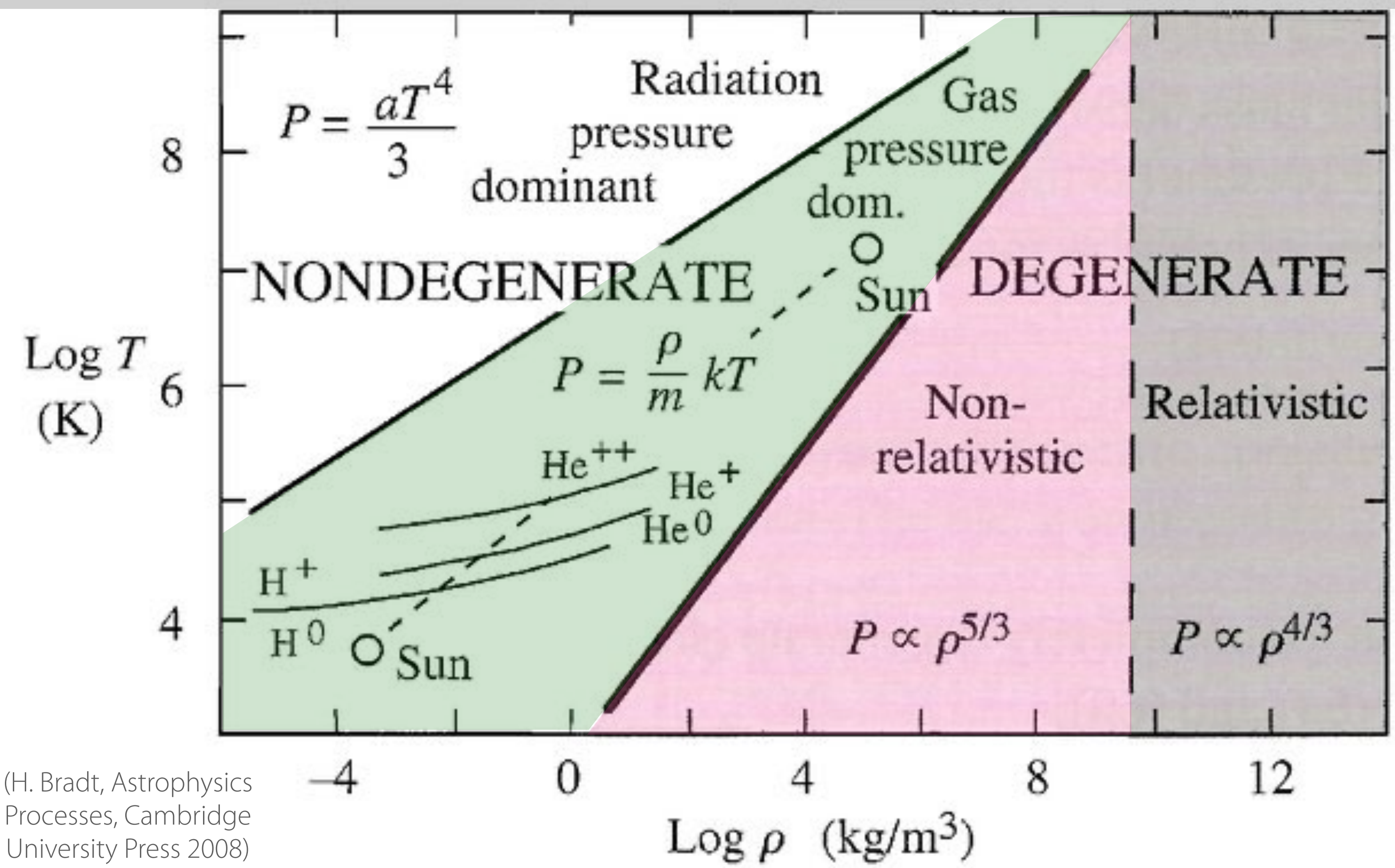
- Degenerate gas behaves differently than ideal gas.
  - Ideal gas: Pressure depends on density and temperature. $P_{gas} = \frac{kT\rho}{m} = \frac{kT\rho}{m_H \mu} = \frac{RT\rho}{\mu}$
  - Degenerate gas: Pressure depends only on density

➡ Pressure won't change if temperature changes
(as long as T low enough to stay in degeneracy regime)

$$P = K_1 \rho^{\frac{5}{3}} \qquad K_1 = \frac{h^2}{20 m_e}\left(\frac{3}{\pi}\right)^{\frac{2}{3}}\left[\frac{(1+X)}{2m_H}\right]^{\frac{5}{3}}$$

➡ For a relativistically degenerate gas (i.e. $p_0 >> m_e c$):

$$P = K_2 \rho^{\frac{4}{3}} \qquad K_2 = \left(\frac{hc}{8}\right)\left(\frac{3}{\pi}\right)^{\frac{1}{3}}\left[\frac{(1+X)}{2m_H}\right]^{\frac{4}{3}}$$



(H. Bradt, Astrophysics Processes, Cambridge University Press 2008)

The density (as the mean molecular weight) depends on chemical composition, which changes as result of nuclear fusion (He content!)

- Note: No sharp transition between ideal gas equation of state and the corresponding degenerate equation of state! Continuous transition!

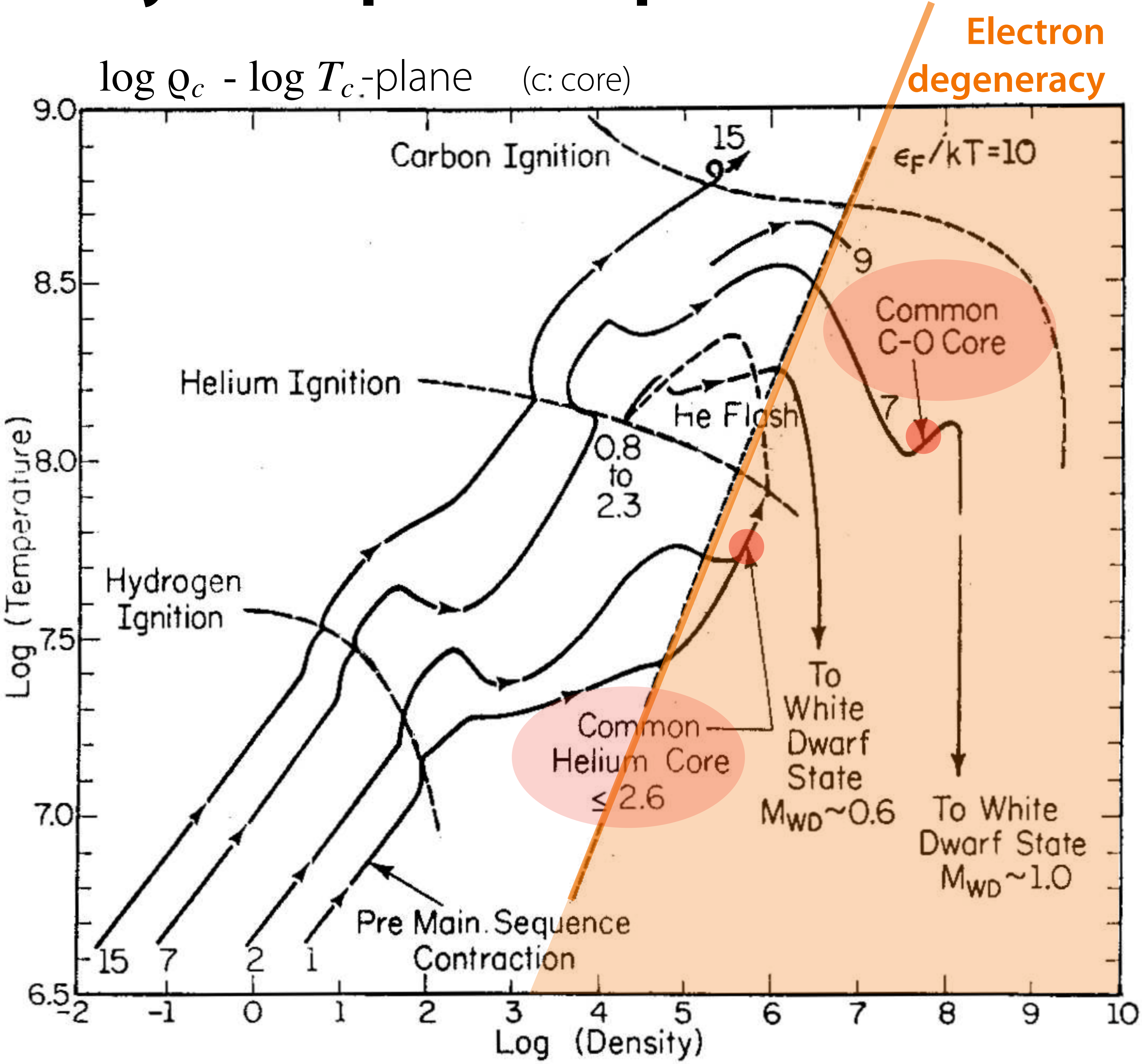
Post-main sequence evolution

Tracks in the core density—temperature plane

- Evolution tracks in core density-temperature plane ($\log \varrho_c$ - $\log T_c$)
- Sun’s core becomes degenerate at $\varrho_c > 10^6$ kg/m^3, $T \sim 2\ 10^7$ K.

  ➡ Degenerate core early during red giant phase.
- All low-mass stars, degenerate He core during red giant phase.
- Intermediate and high-mass stars not degenerate while red giants.

$\log \varrho_c$ - $\log T_c$-plane (c: core)

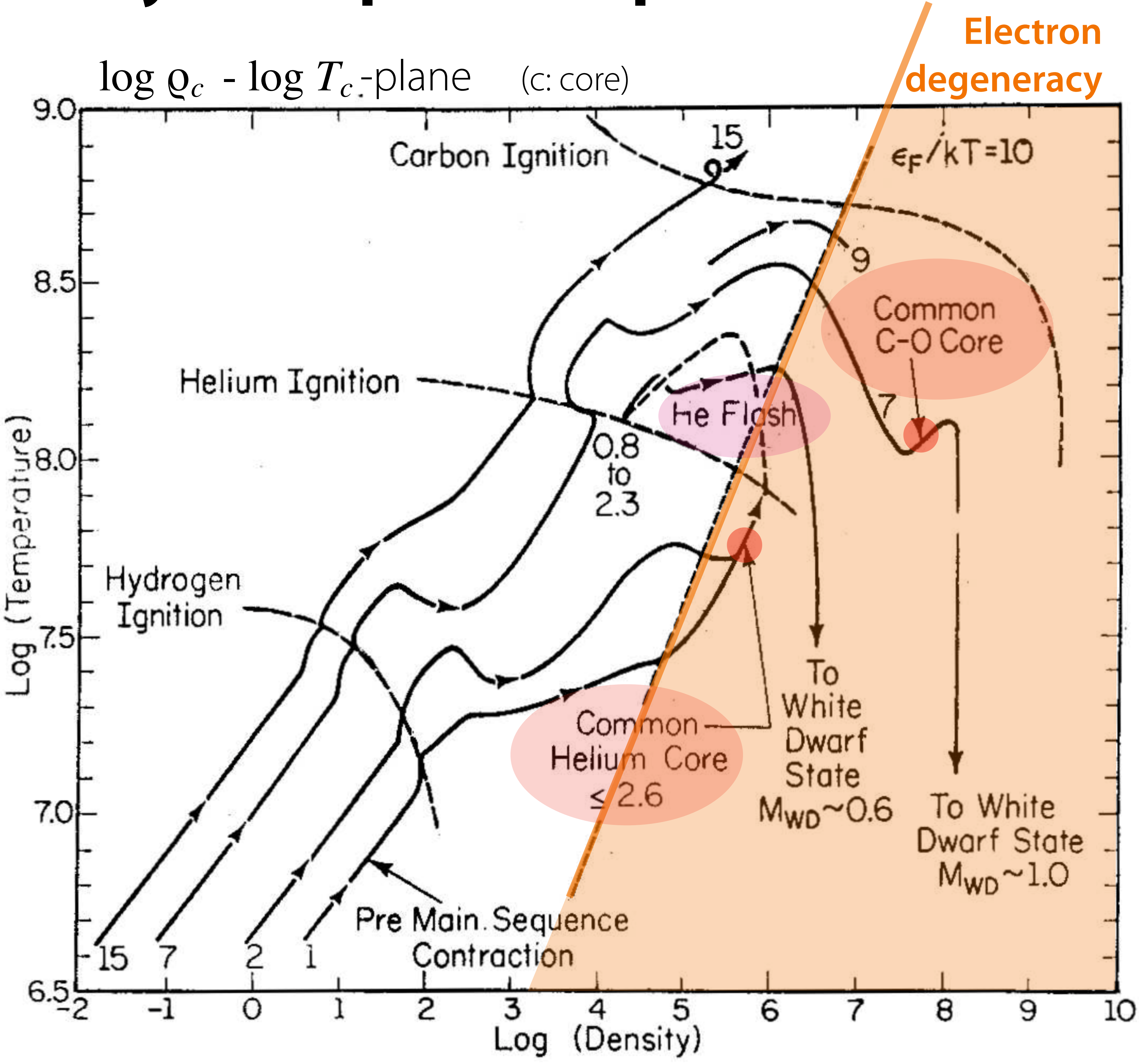


Post-main sequence evolution

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.
- **Core of 7 $M_\odot$ stars**: electron degeneracy before C-ignition temperature is reached,
  ➡ C-O white dwarf.
- **Core of 1 and 2 $M_\odot$ stars**:
  - low mass (0.3 $M_\odot$),
  - become 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**)

$\log \varrho_c$ - $\log T_c$-plane (c: core)



Post-main sequence evolut

Tracks in the core density—temperature

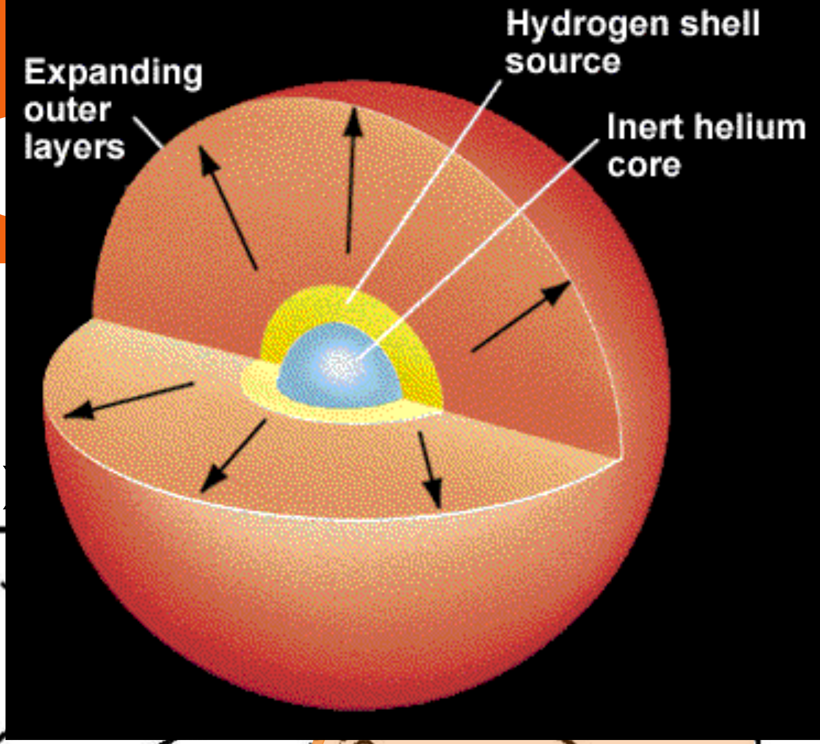
- **Schönberg-Chandrasekhar** (S-C) limit: Max. mass of an inert (isothermal) He core that can be supported (unstable if core more exceeds limit):

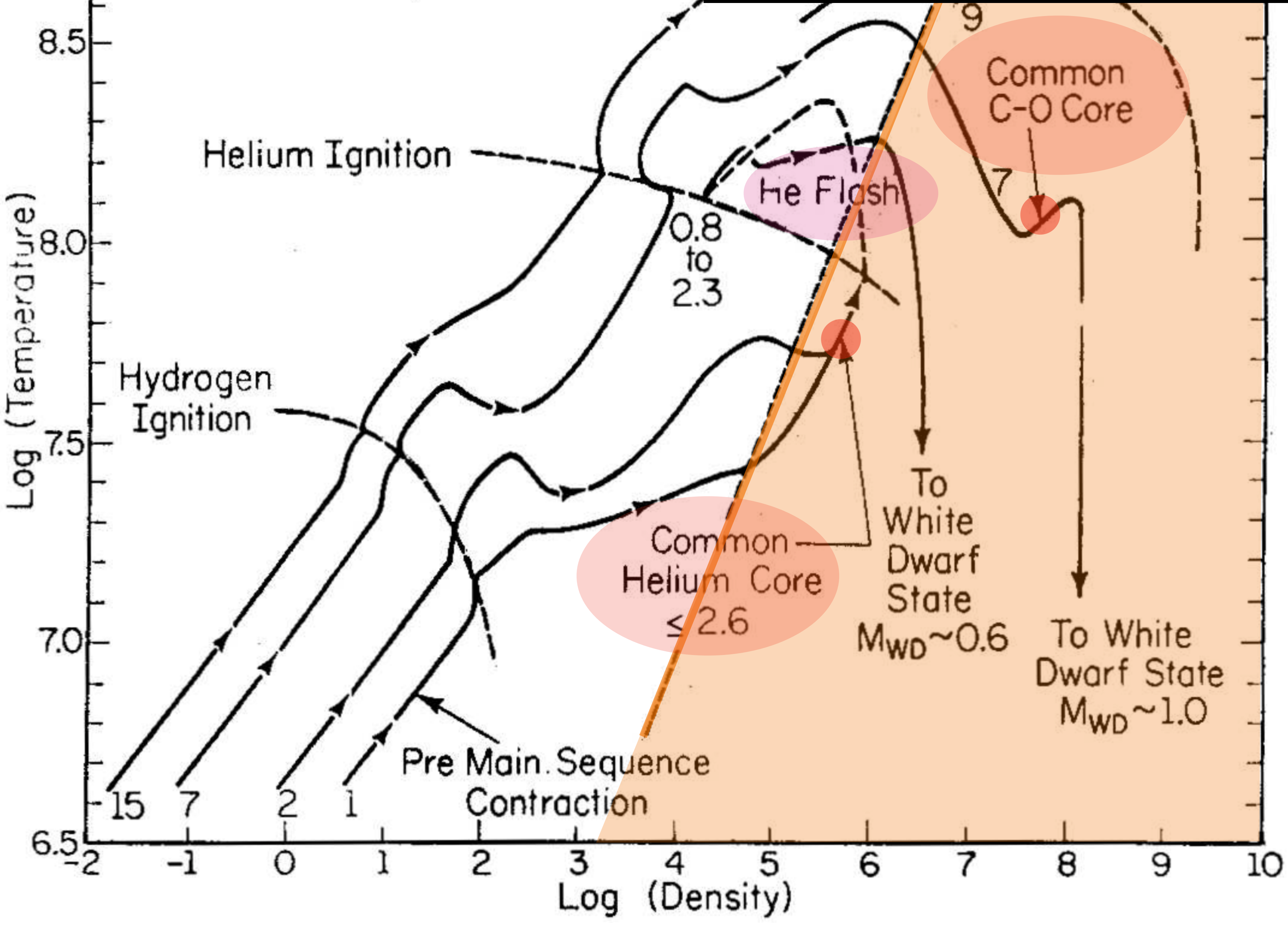
$$M_c/M < q_{sc} \approx 0.10$$

(M_c: core mass, M: total mass)

- M<1.5 M$_\odot$: core becomes degenerate before reaching S-C limit
- M>6 M$_\odot$: star leaves main sequence with core > S-C limit (core never isothermal before He-burning)
- 1.5 M$_\odot$ >M < 6 M$_\odot$: core grows until reaching S-C limit, then contracts rapidly until He-burning ignites in core

log ϱ_c - log T_c-plane (c: core)





Post-main sequence evolution

Helium flash in low-mass stars

- He burning (3α reaction) thermally unstable under conditions in degenerate He core
- Degenerate pressure is independent of *T*! (ideal gas: pressure increases, expands and cools)
- Energy released by fusion does not increase the pressure (negligible expansion / work)
- All nuclear energy released goes instead into raising the internal energy

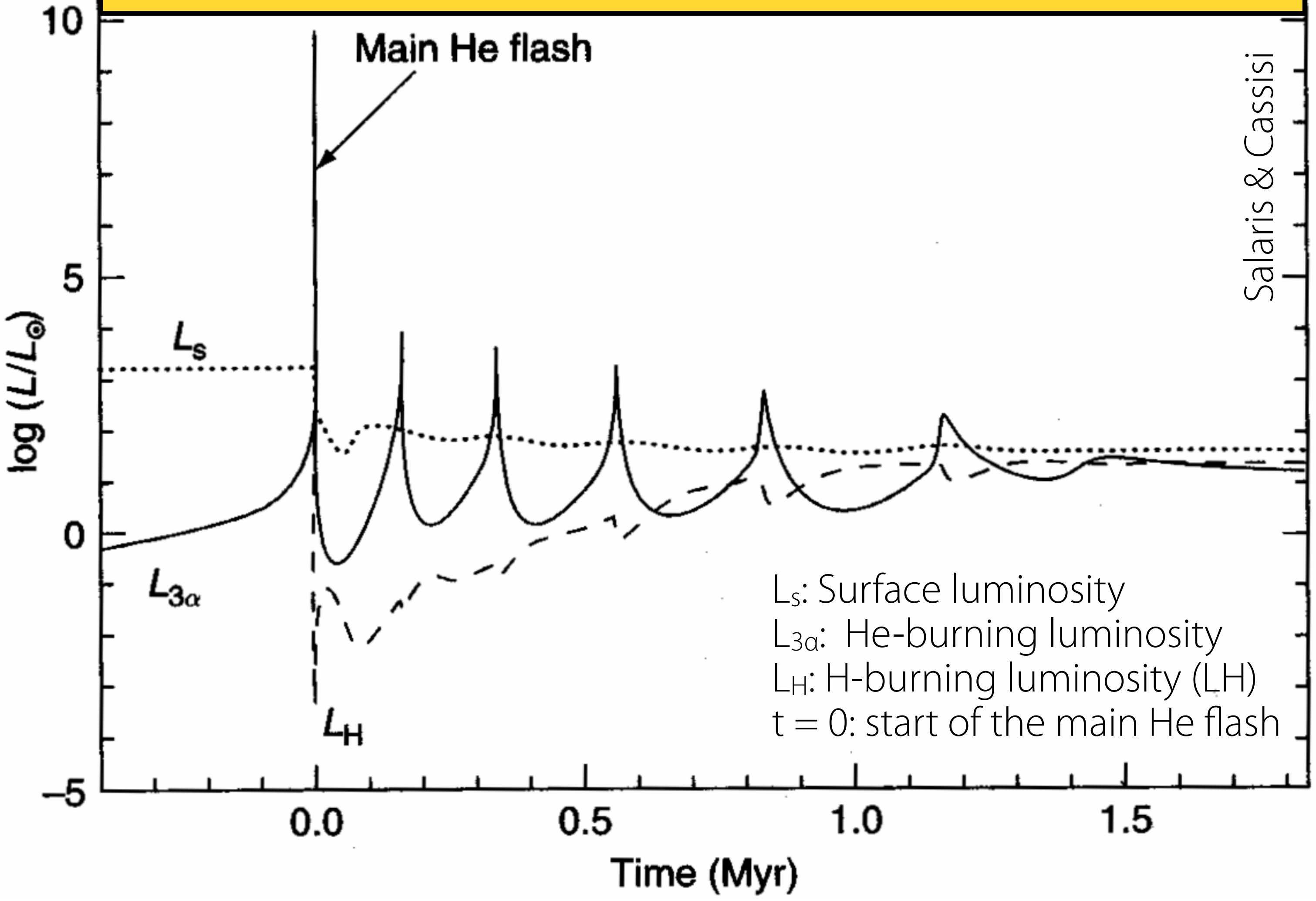
➡ Temperature increases.

➡ Nuclear energy production rate increases.

➡ **Thermonuclear runaway.**

- Energy output at max. equivalent to small galaxy (but only for a few seconds)
- Eventually temperature increased so much that degeneracy is lifted, gas starts behaving like an ideal gas
- Released energy increases pressure, causes expansion and cooling.
- All released energy absorbed in expansion of core, none reaches the surface!

Luminosity as function of time during onset of He burning (at tip of RGB in a low-mass star)

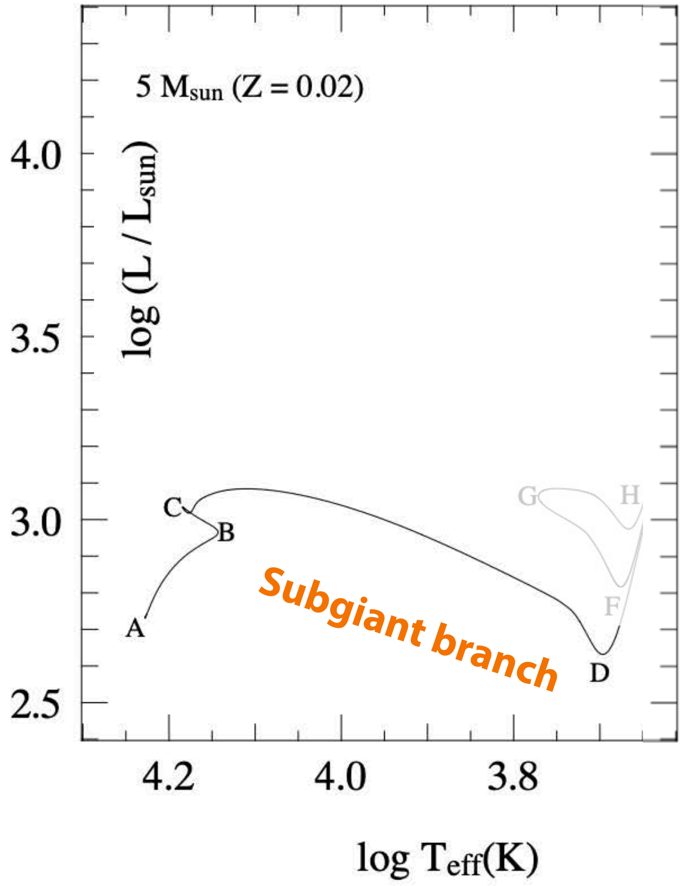


L_S: Surface luminosity
$L_{3\alpha}$: He-burning luminosity
L_H: H-burning luminosity (LH)
t = 0: start of the main He flash

Salaris & Cassisi

Post-main sequence evolution

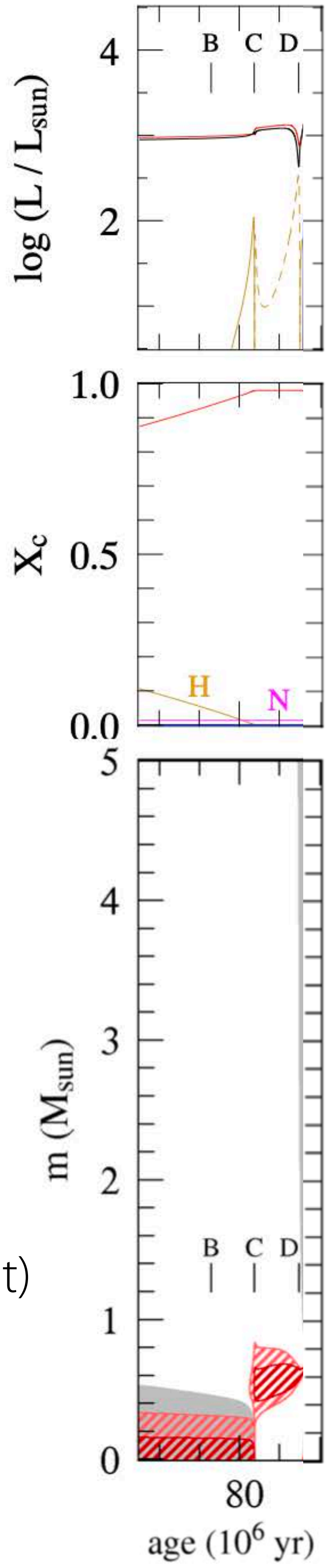
Hydrogen-shell burning in intermediate-mass stars



- **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

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

Kippenhahn diagram: Internal structure as function of mass coordinate m

Gray areas: convective

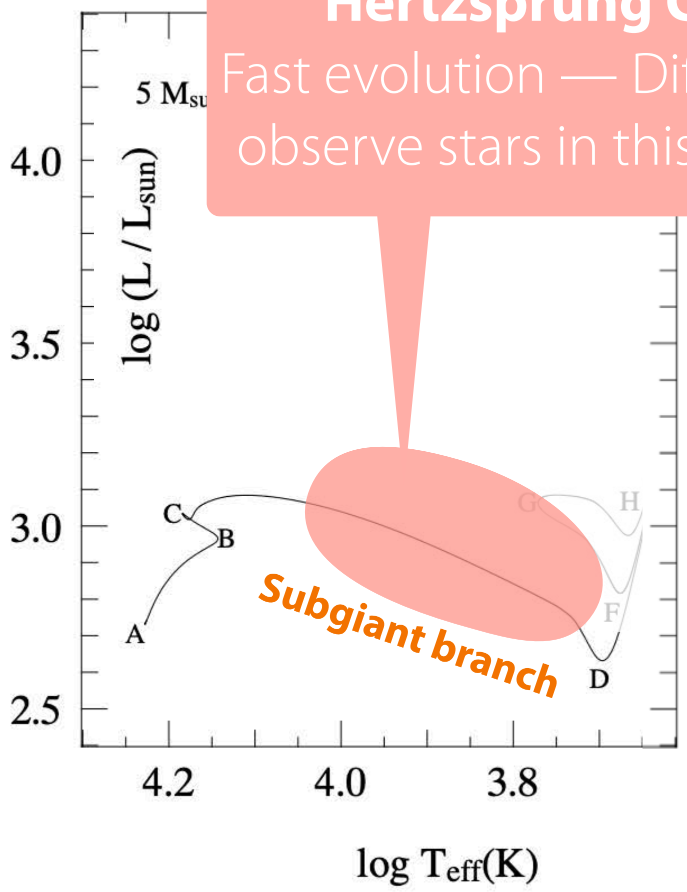
Red hatched: nuclear energy generation

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

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

Post-main sequence evolution

Hydrogen-shell burning in intermediate-mass stars



Hertzsprung Gap
Fast evolution — Difficult to observe stars in this phase.

Subgiant branch

- tart at ZAMS
- art of overall contraction phase, near end of MS phase
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  - convective core disappears
  - core mass remains below Schönberg-Chandrasekhar (S-C) limit, in thermodyn. equilibrium at beginning of H-shell burning
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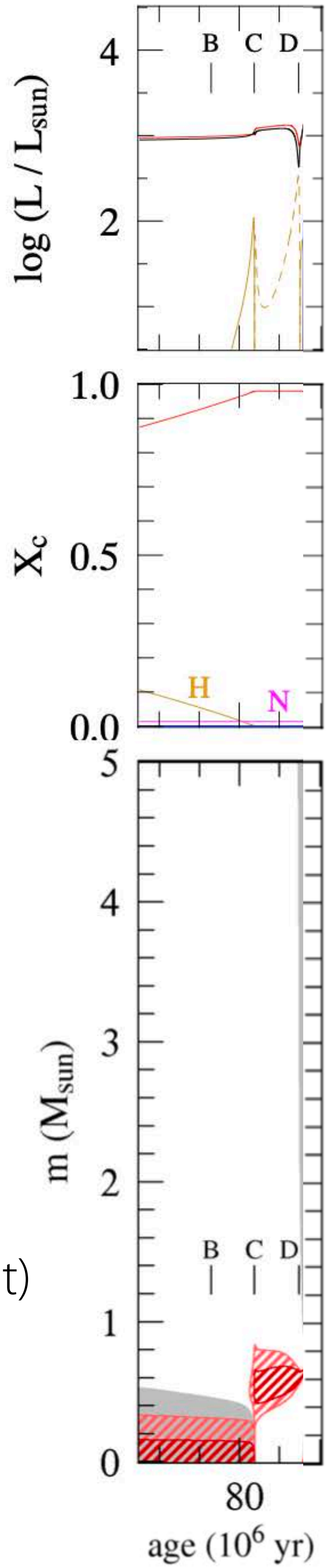

Luminosity contributions

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

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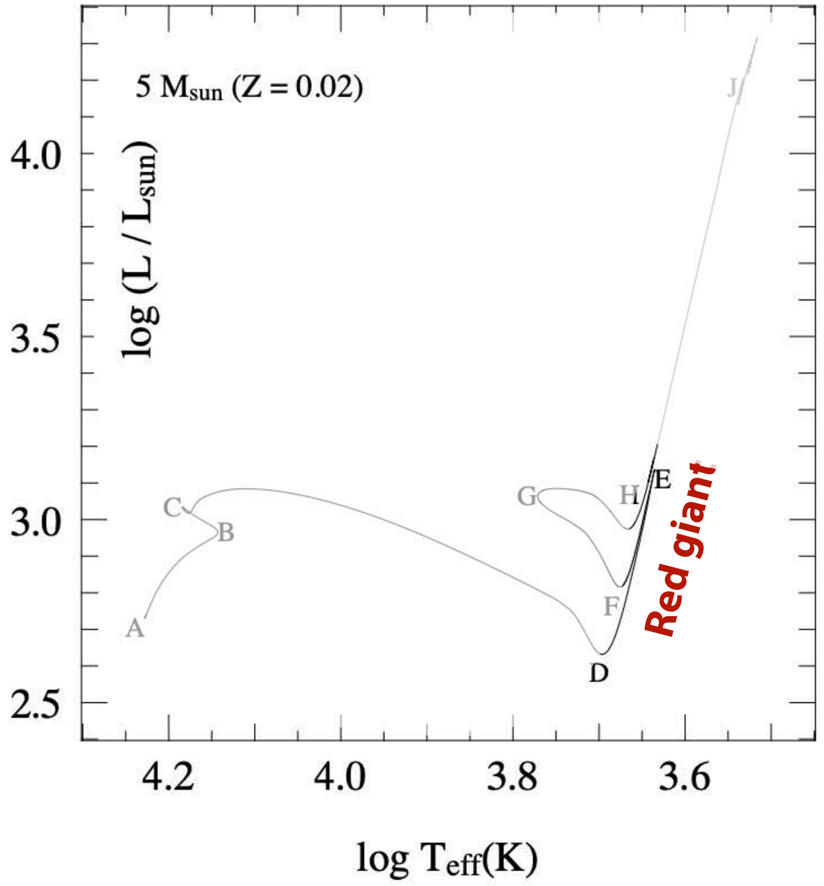
Light red $\varepsilon_{nuc} > 2$ L/M

Post-main sequence evolution

Red giant phase

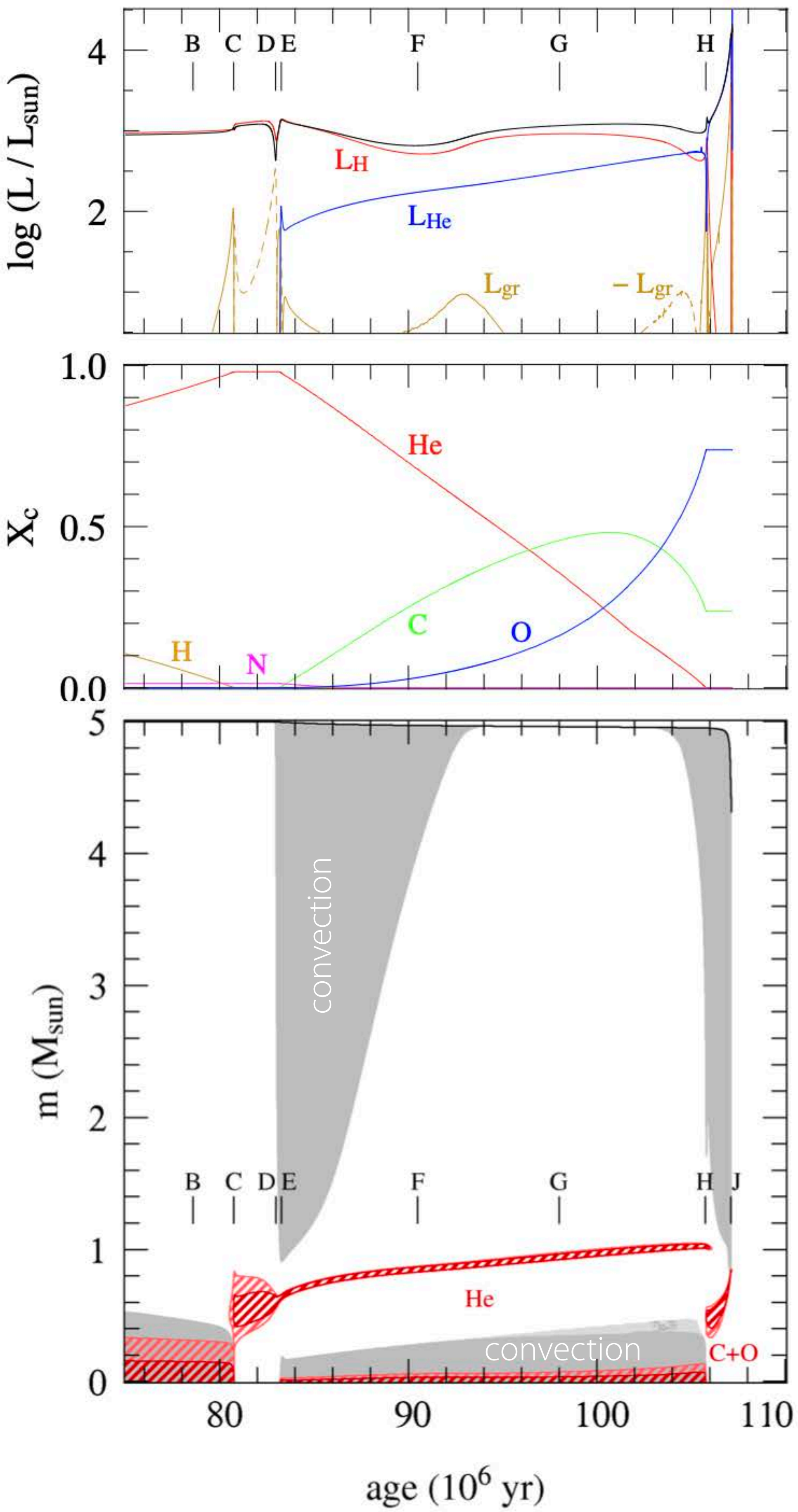


- **D**: Opacity in thin shell increases
  - Radiative energy transport inefficient, convection sets in
- **D-E**: Red giant phase
  - Convection in core + deep convection zone (up to surface)
  - Relatively short lived phase (~ 10% of main sequence) lifetime
- **E**: Outer convection zone reaches into 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)

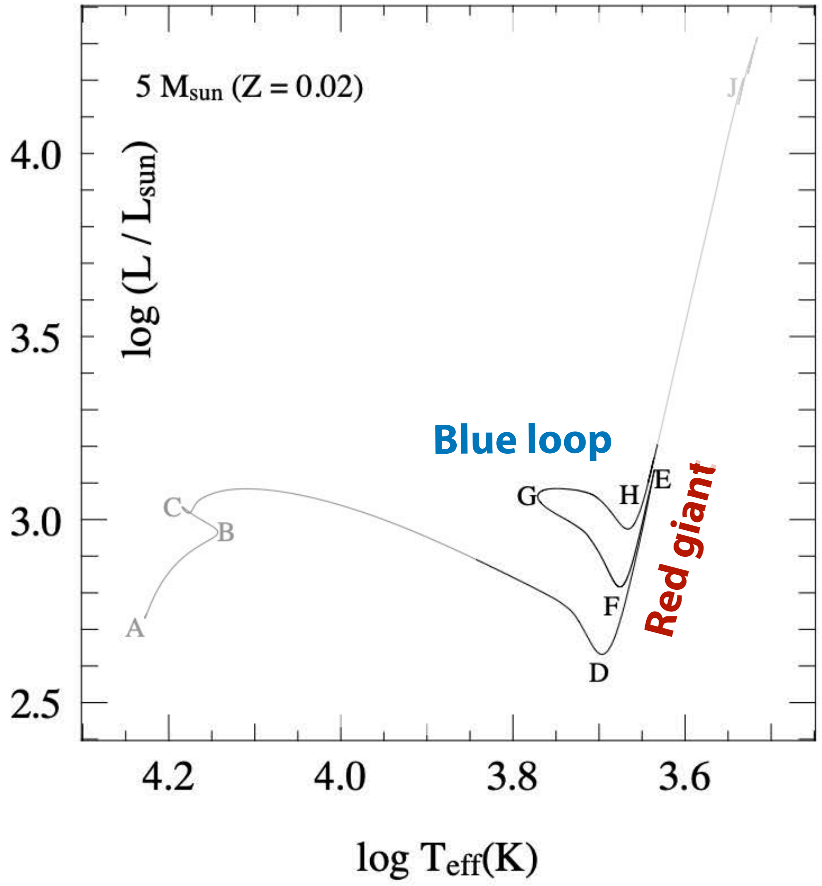
  - Mass loss rate (Reimers): $$\dot{M} = -4\times 10^{-13}\,\eta\,\frac{L}{L_\odot}\,\frac{R}{R_\odot}\,\frac{M_\odot}{M}\,M_\odot/\mathrm{yr}$$
  - Typically used: η ~ 0.25 – 0.5
  - 1 $M_\odot$ star lost about 0.3 $M_\odot$ when reaching tip of giant branch (E).

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



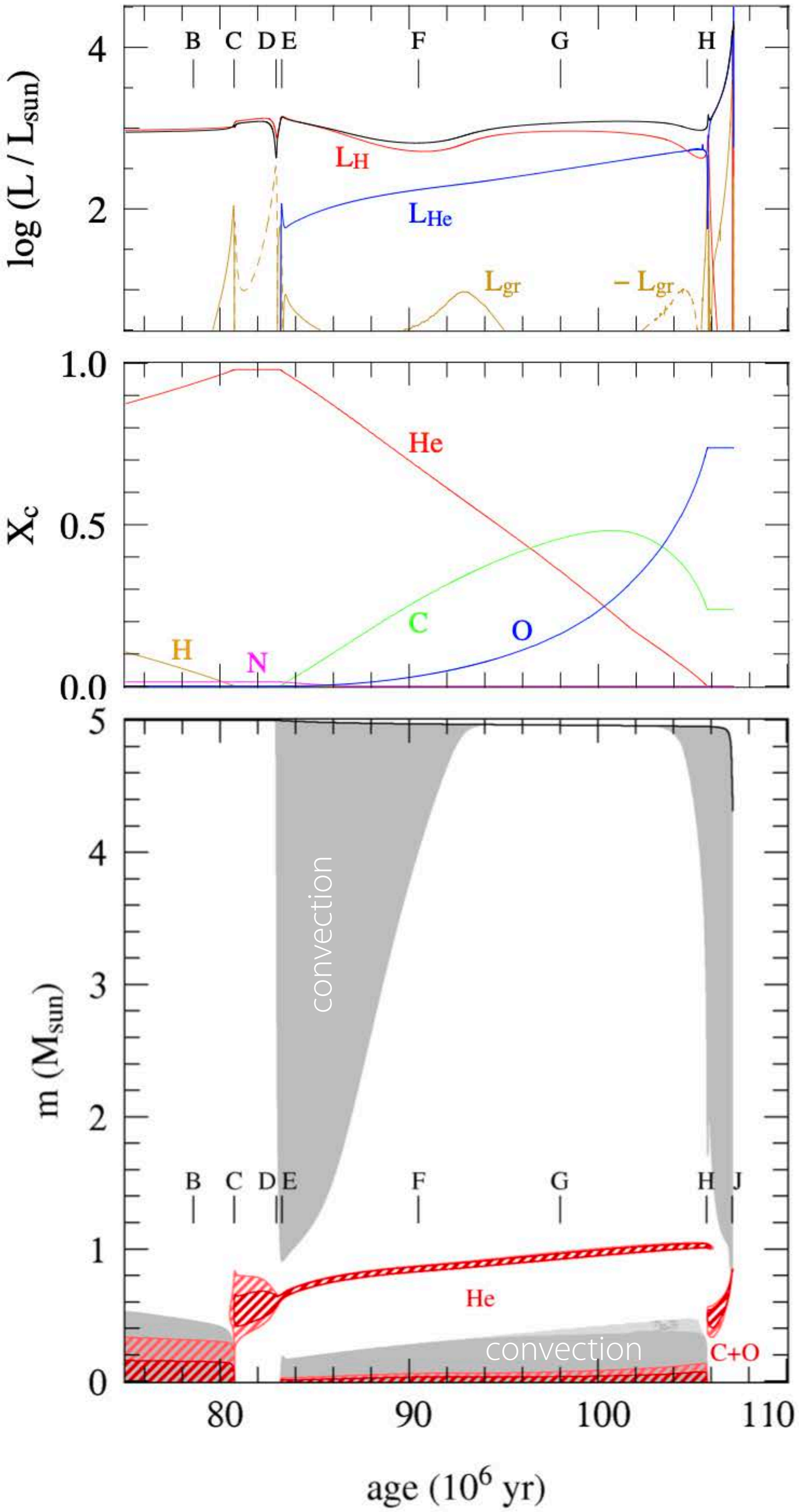
Post-main sequence evolution

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

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



Post-main sequence evolution

Red giant phase and blue loop

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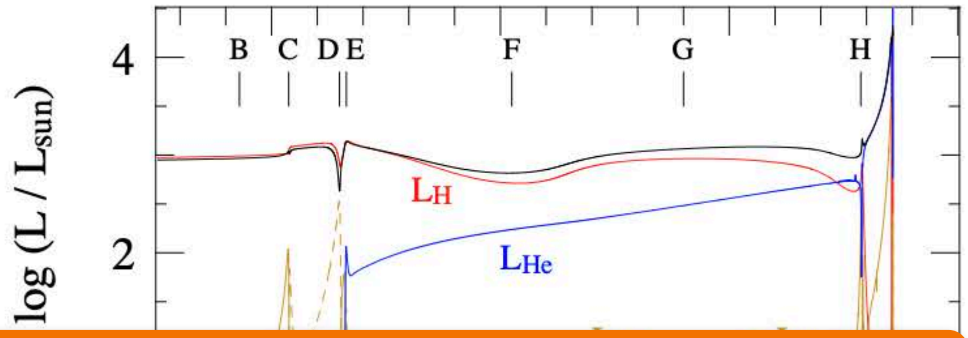

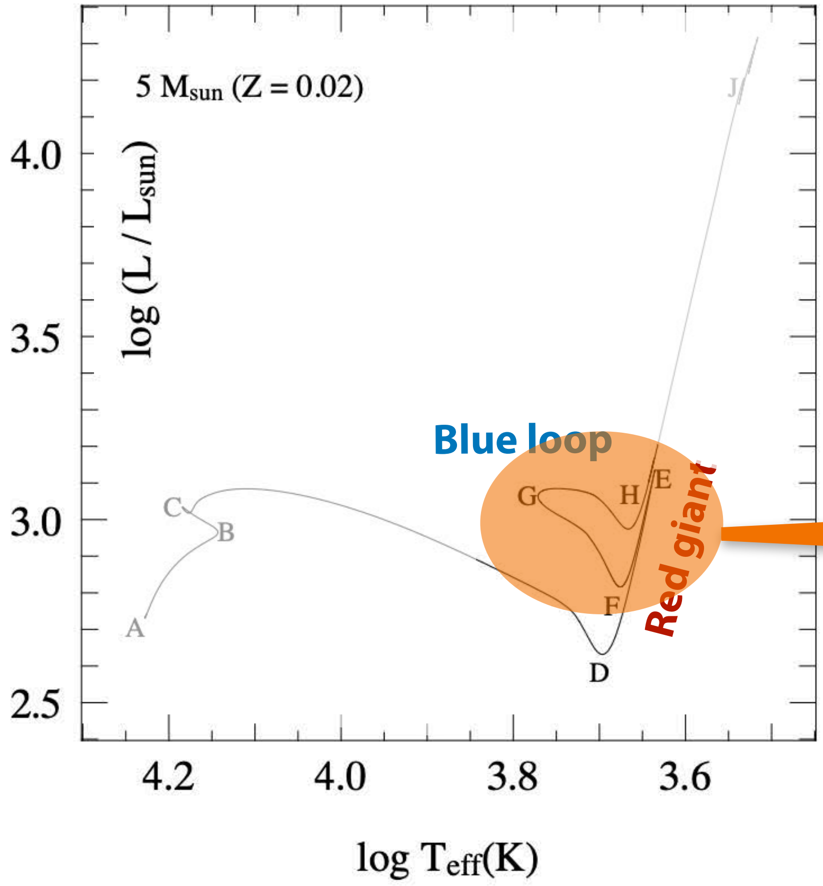

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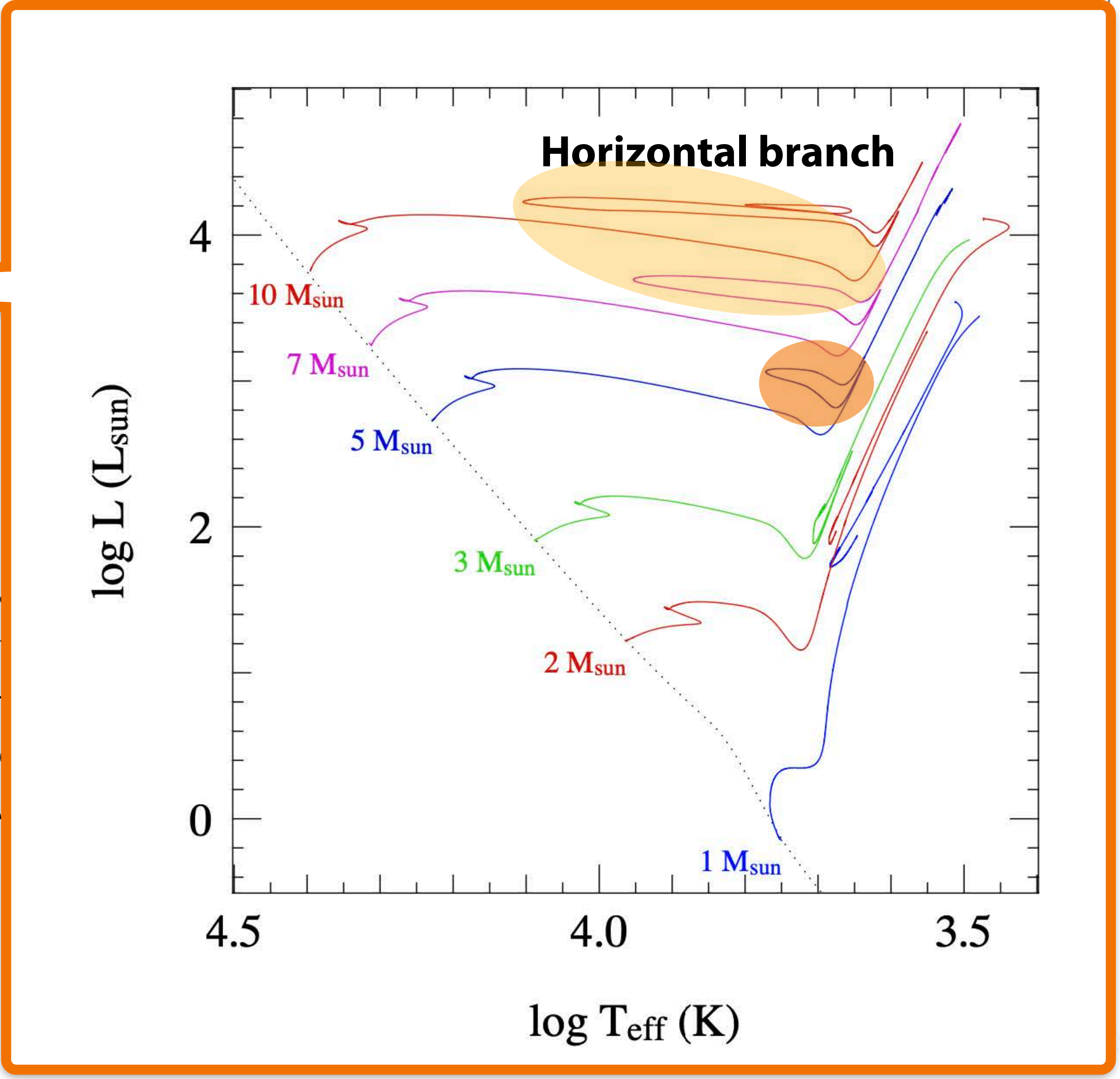
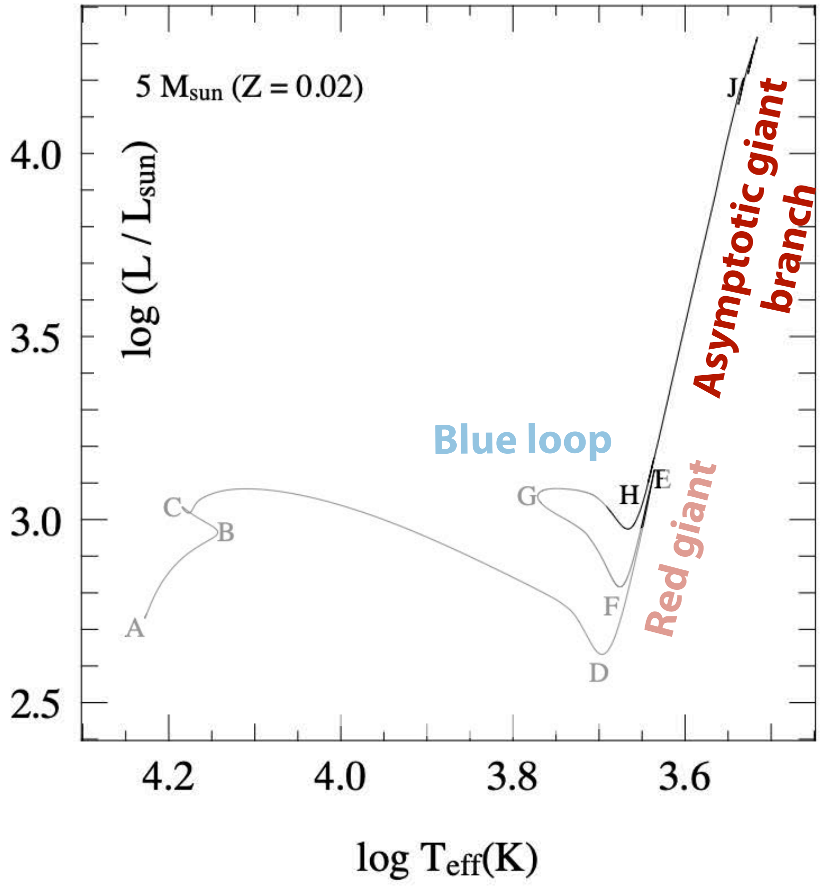


Post-main sequence evolution

Asymptotic Giant Branch

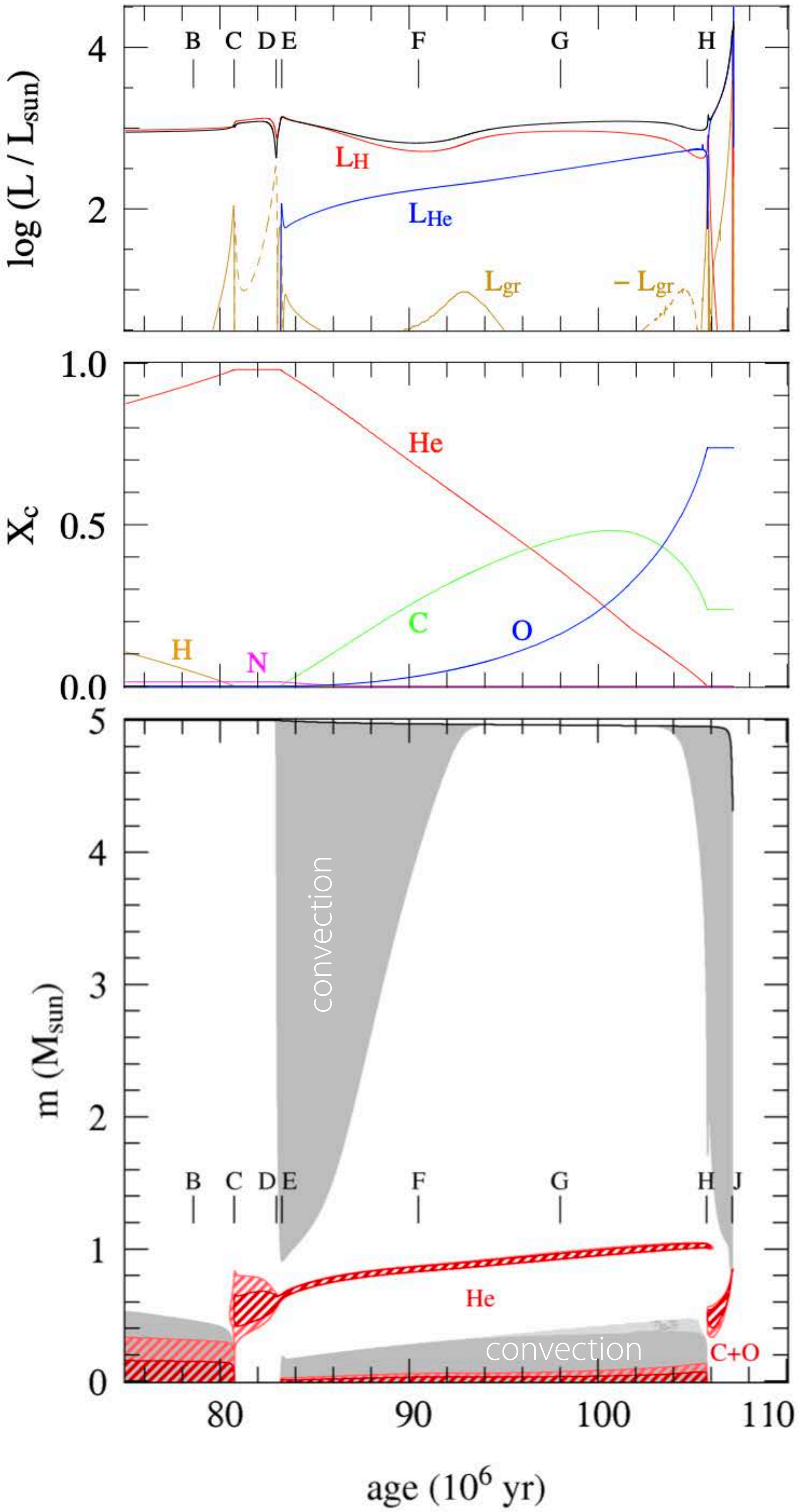


- **H**: end of core He burning

➡back on Hayashi track (close to E)

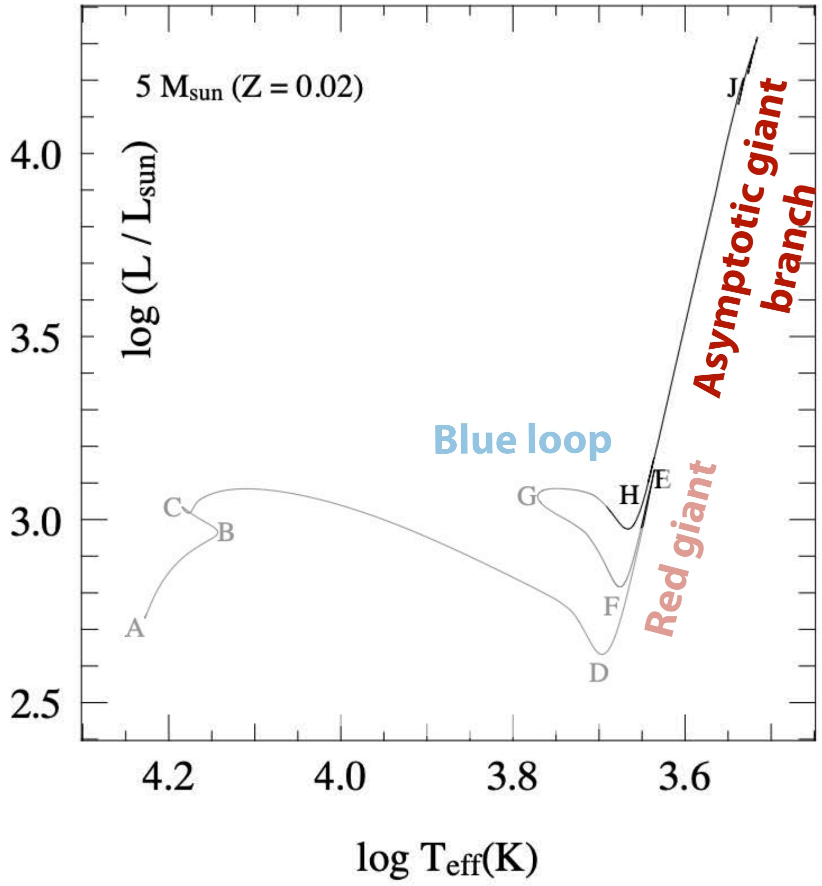
➡Beginning of asymptotic giant branch (AGB) phase

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



Post-main sequence evolution

Asymptotic Giant Branch



- **H**: end of core He burning

➡back on Hayashi track (close to E)

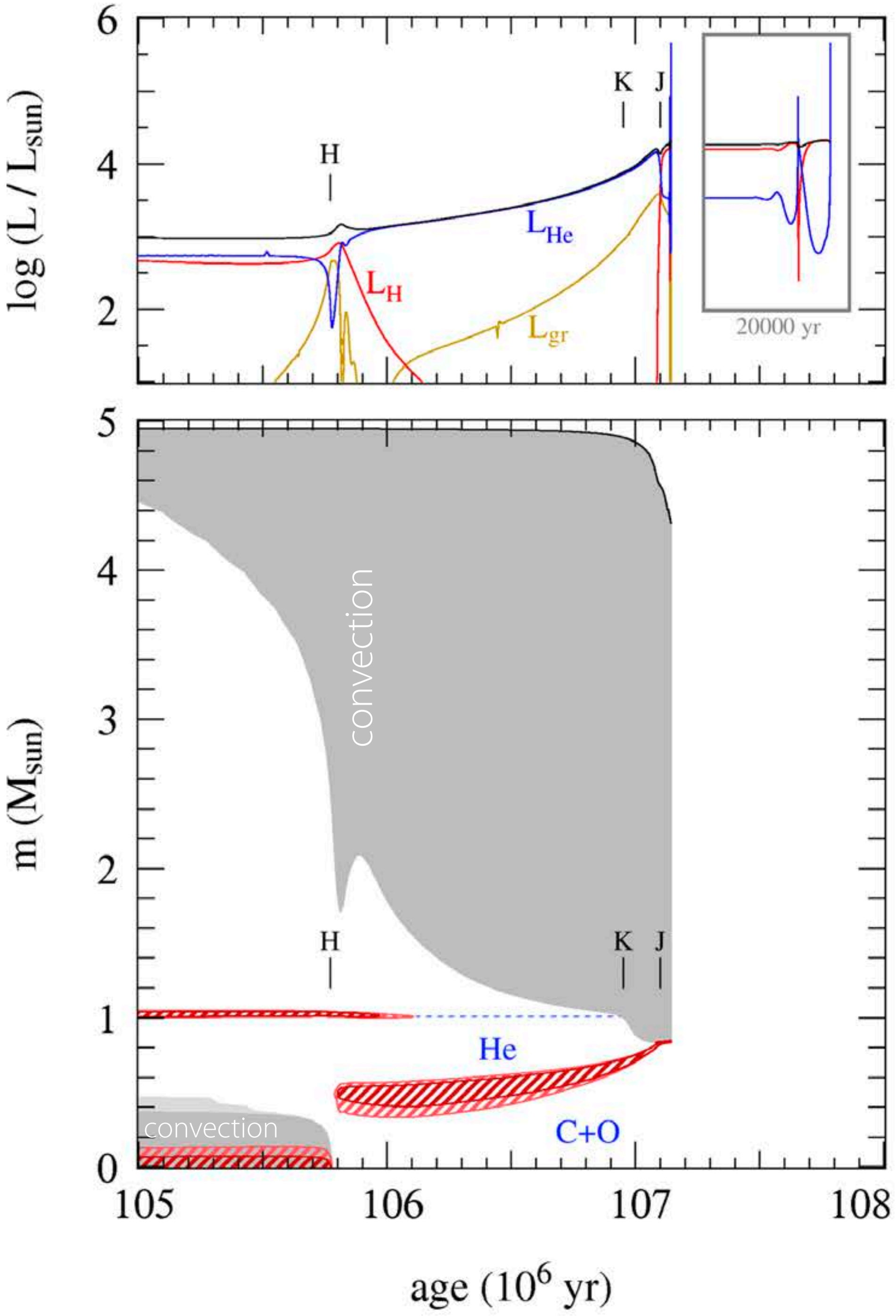
➡Beginning of asymptotic giant branch (AGB) phase

- **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)

Model of internal evolution of a 5 M$_\odot$ star, initial composition $X = 0.7$, $Z = 0.02$.



Post-main sequence evolution

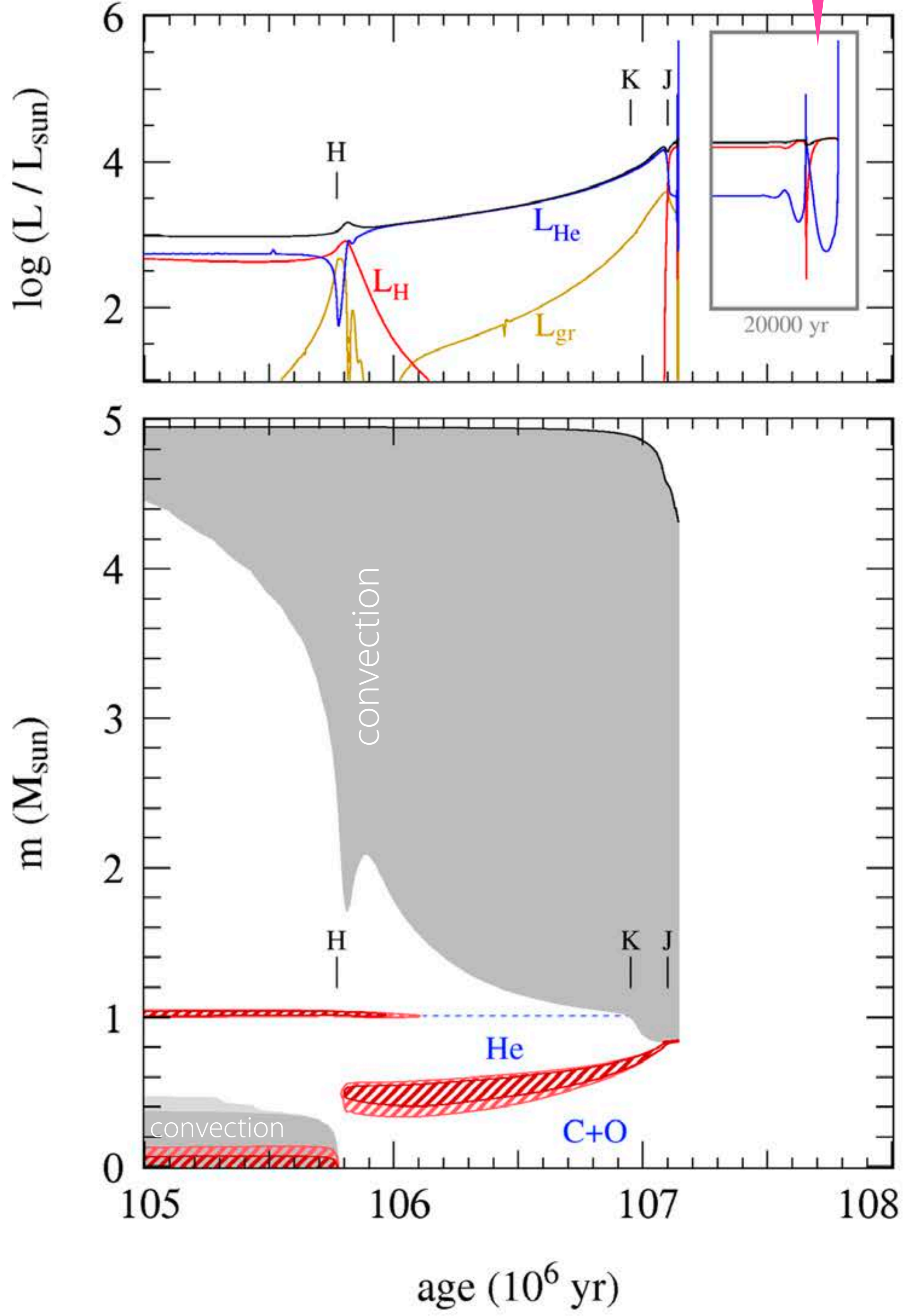
Asymptotic Giant Branch

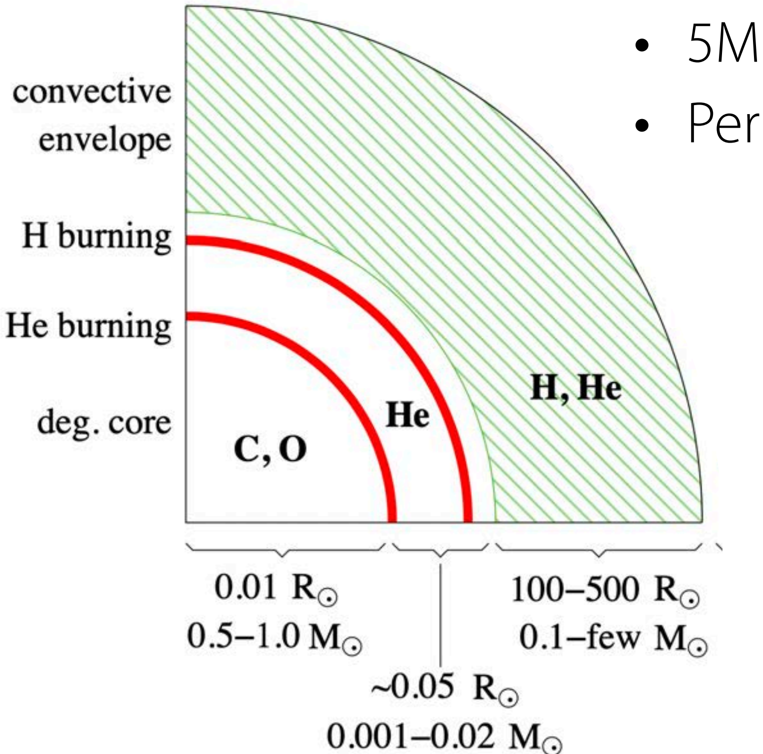
- **J**: H-burning shell re-ignites — Double shell-burning phase
- **Beyond J**: Radius of an AGB star typically (several) 1 AU ~ 100 solar radii
  - H shell active, providing "fresh" He to layers below.
  - He-shell burning switches on, pushes H-shell outwards, which then ceases
  - He burning eventually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

    ➡**Thermal Pulse** (TP)-AGB phase

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

Thermal pulses



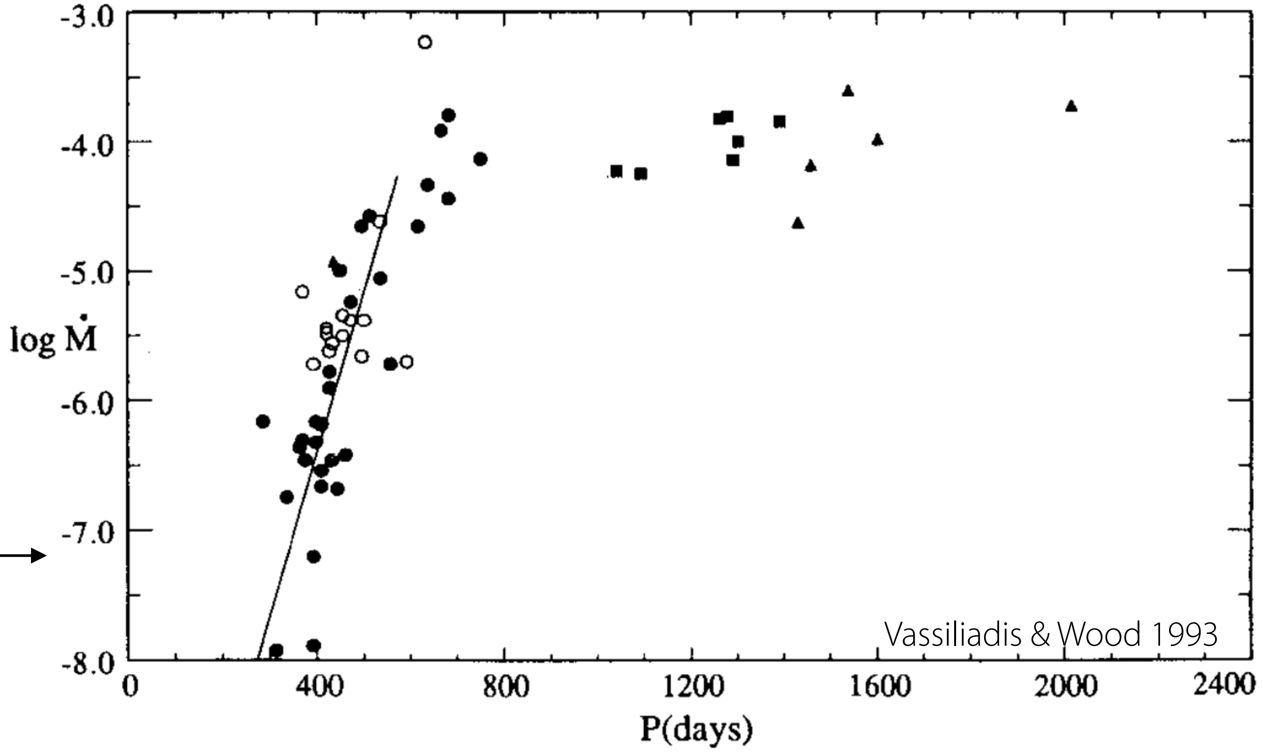


- $5M_\odot$: period between initial pulses 10^3-10^5 yr
- Period is a function of mass

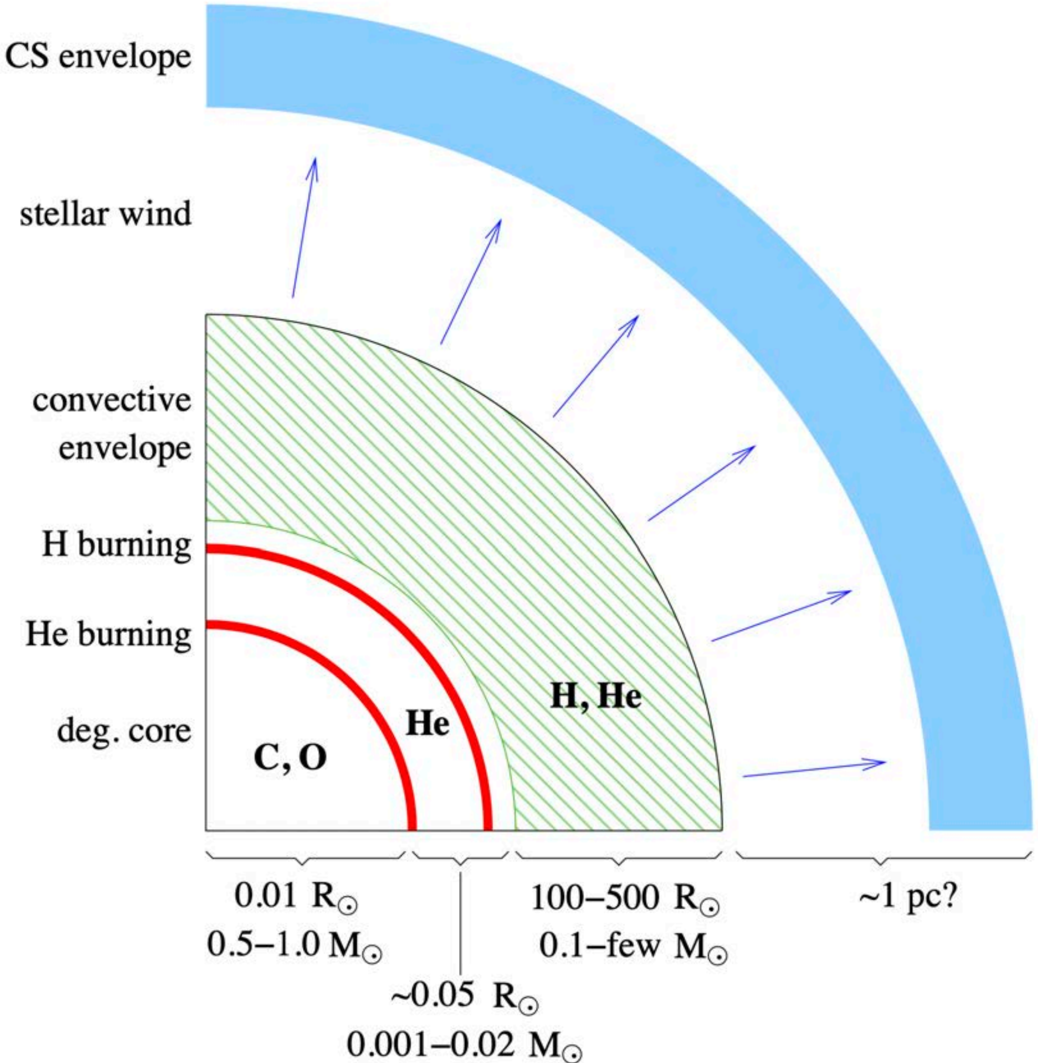
Post-main sequence evolution

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 ⟶



Vassiliadis & Wood 1993



- Star evolves towards larger radii along AGB

➡Pulsation period increases

➡Mass-loss rate increases from $10^{-8}\ M_{\odot}$/yr to ~ $10^{-4}\ M_{\odot}$/yr

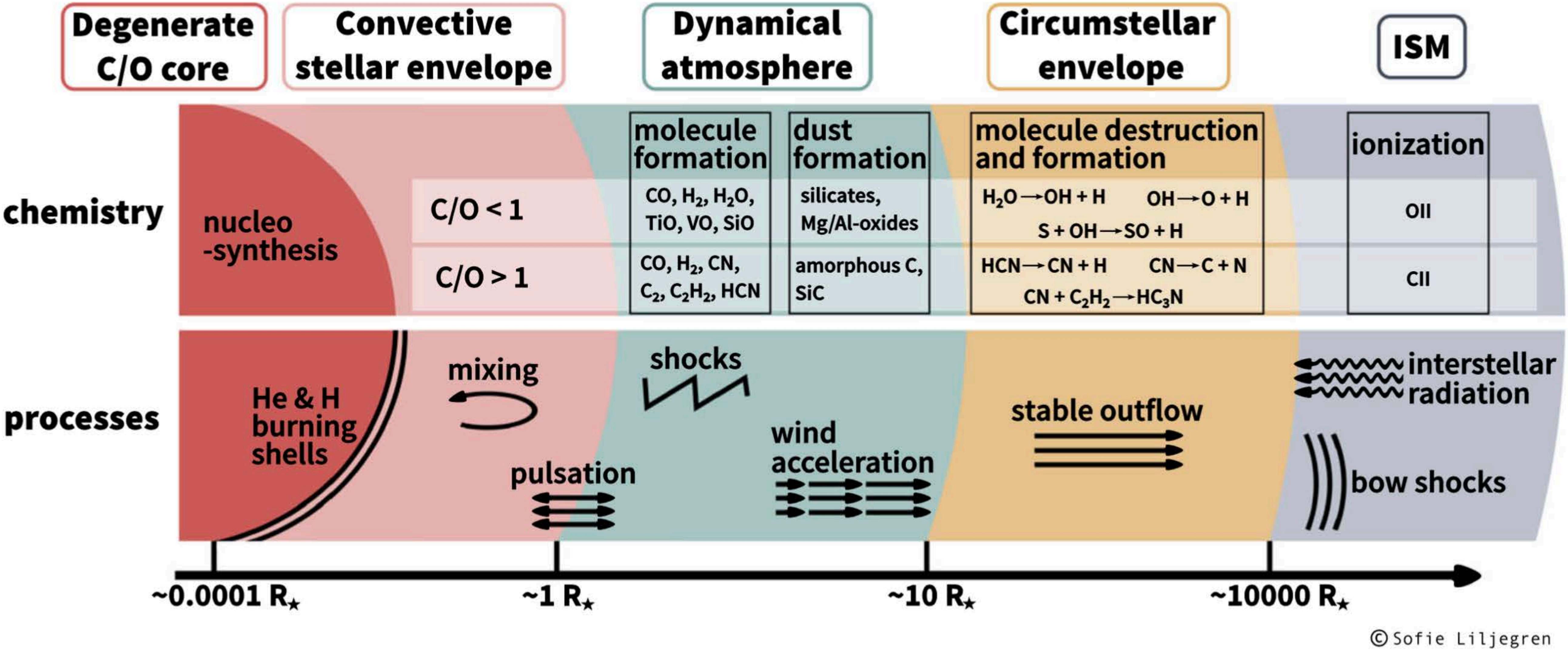
- Strongest mass loss sometimes referred to as **superwind** phase
- Pulsation periods of several years
- Pulsations induce shock waves

- Envelope expelled within <10^6yr
- 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



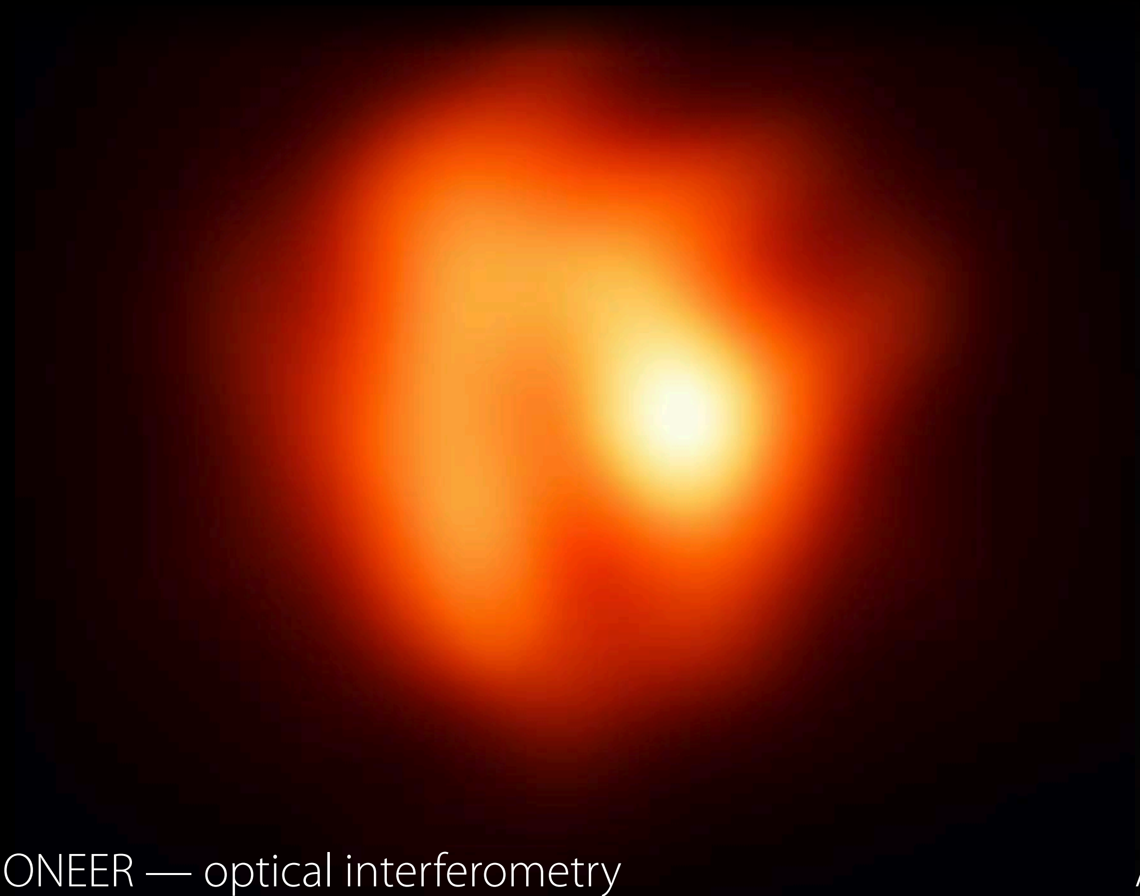
Liljegren / Höfner & Olofsson 2018

Post-main sequence evolution

Asymptotic Giant Branch (AGB)

R Sculptoris

- R ~ 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



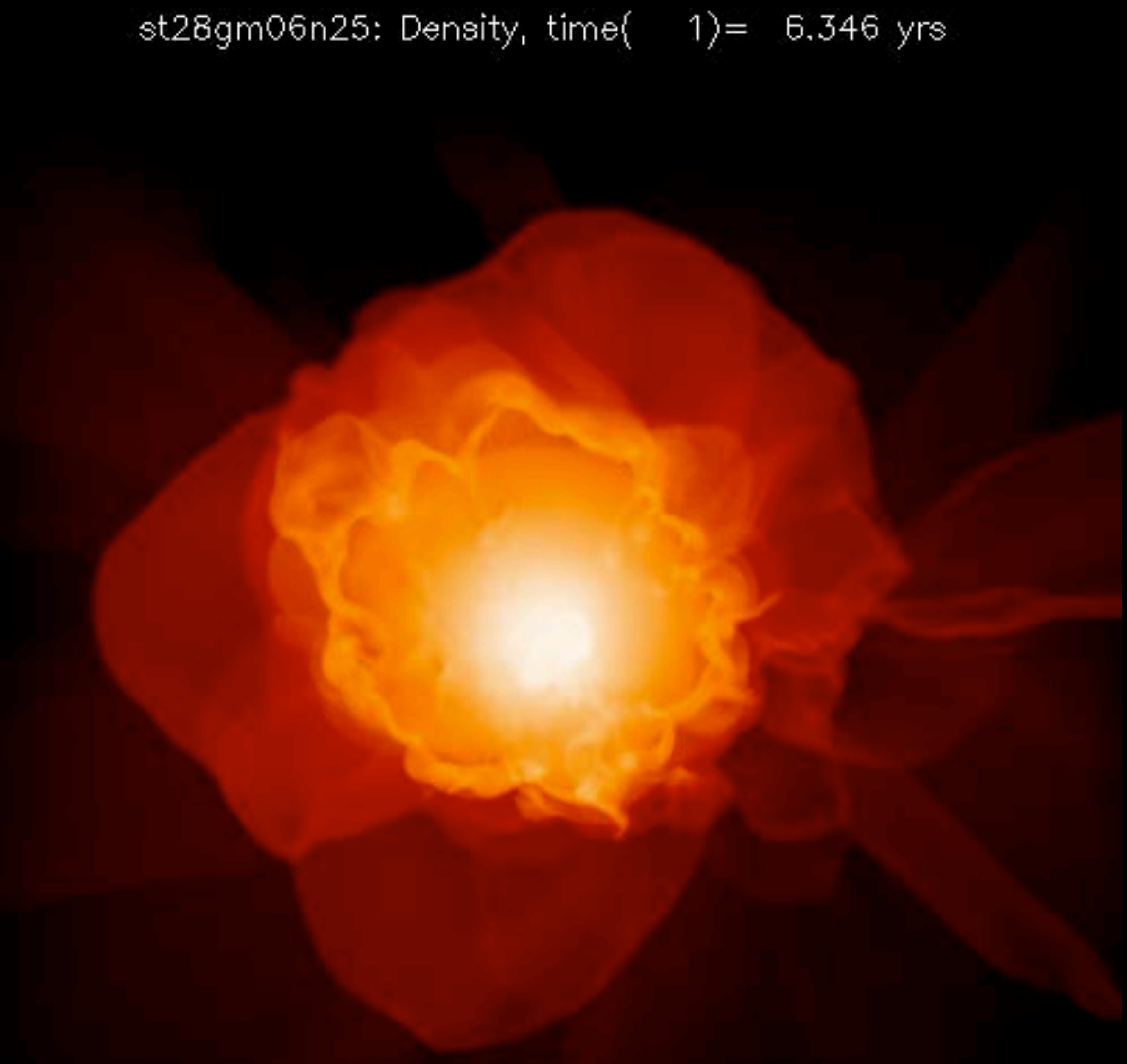
VLTI/PIONEER — optical interferometry
(9mas diameter) [ESO/M. Wittkowski]

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

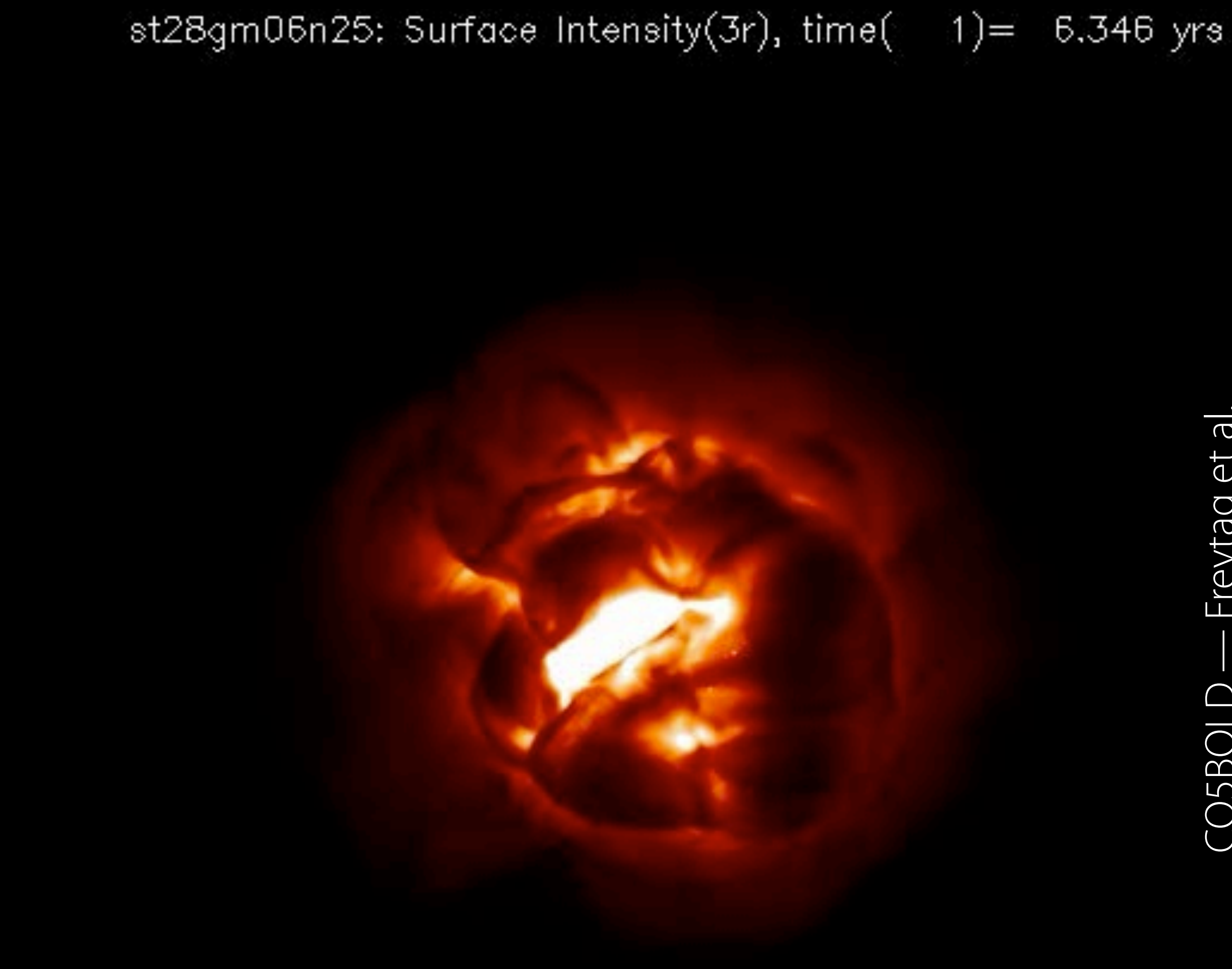
Post-main sequence evolution

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



Log. mass density



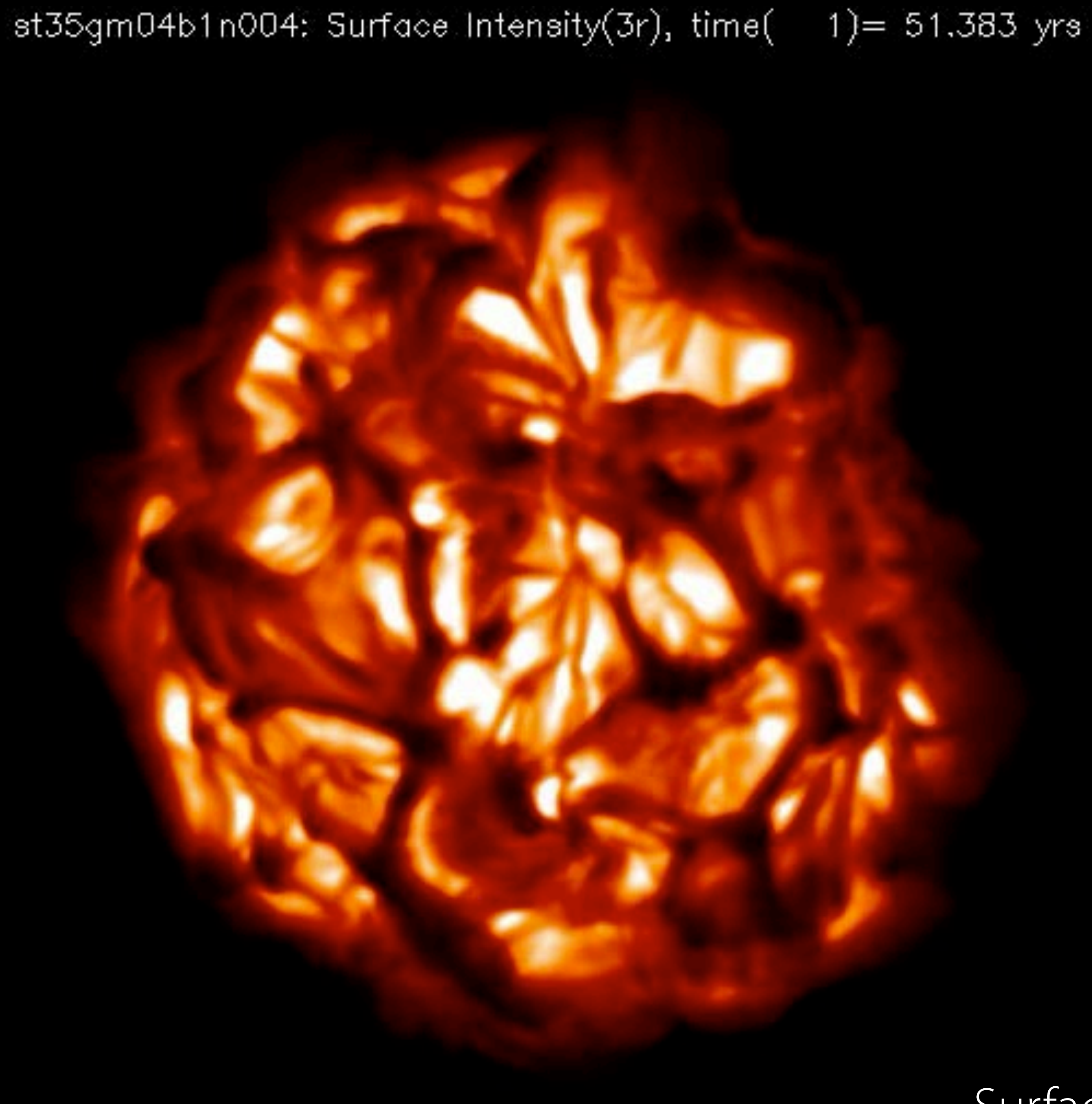
Emergent bolometric intensity

CO5BOLD — Freytag et al.

Post-main sequence evolution

Red supergiant

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



CO5BOLD — Freytag et al.

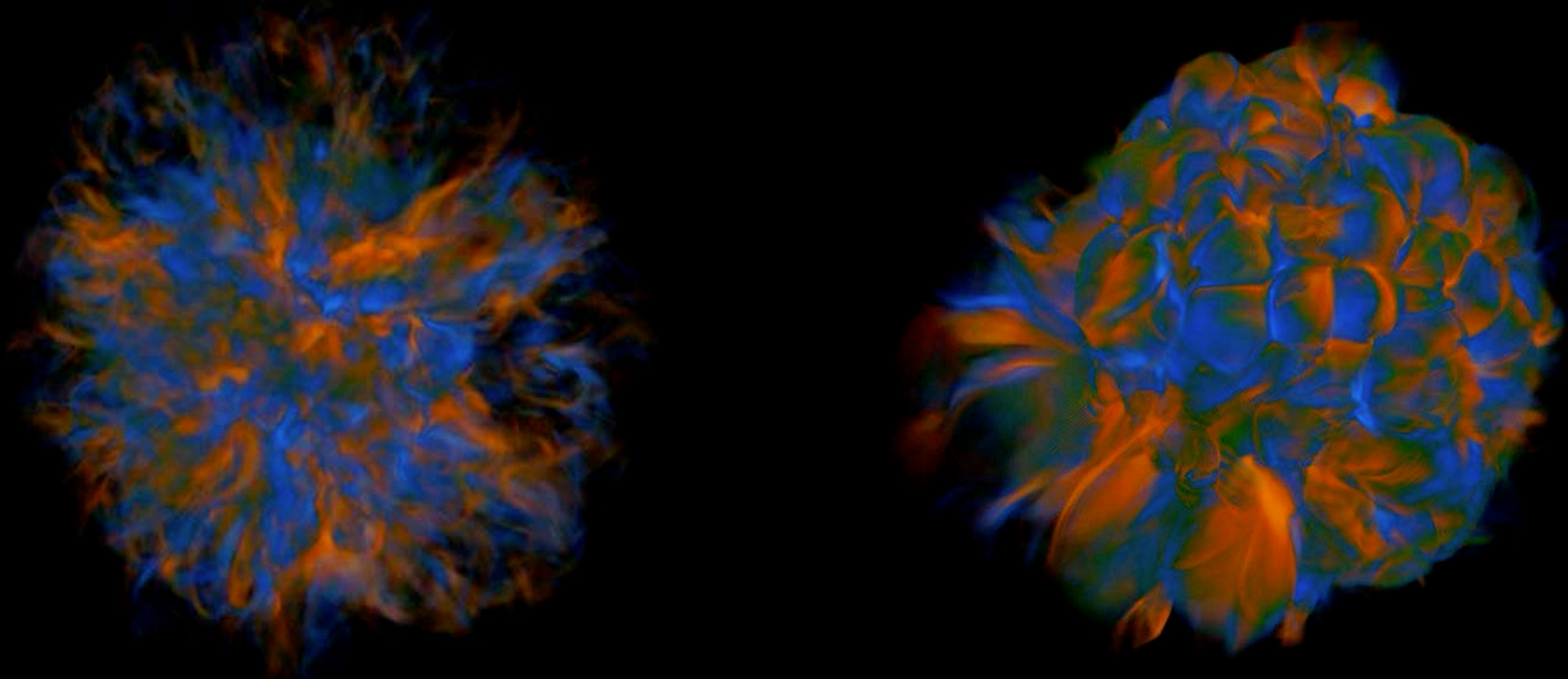
Surface intensity

Post-main sequence evolution

Red supergiant

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

Volume rendering of the magnetic field



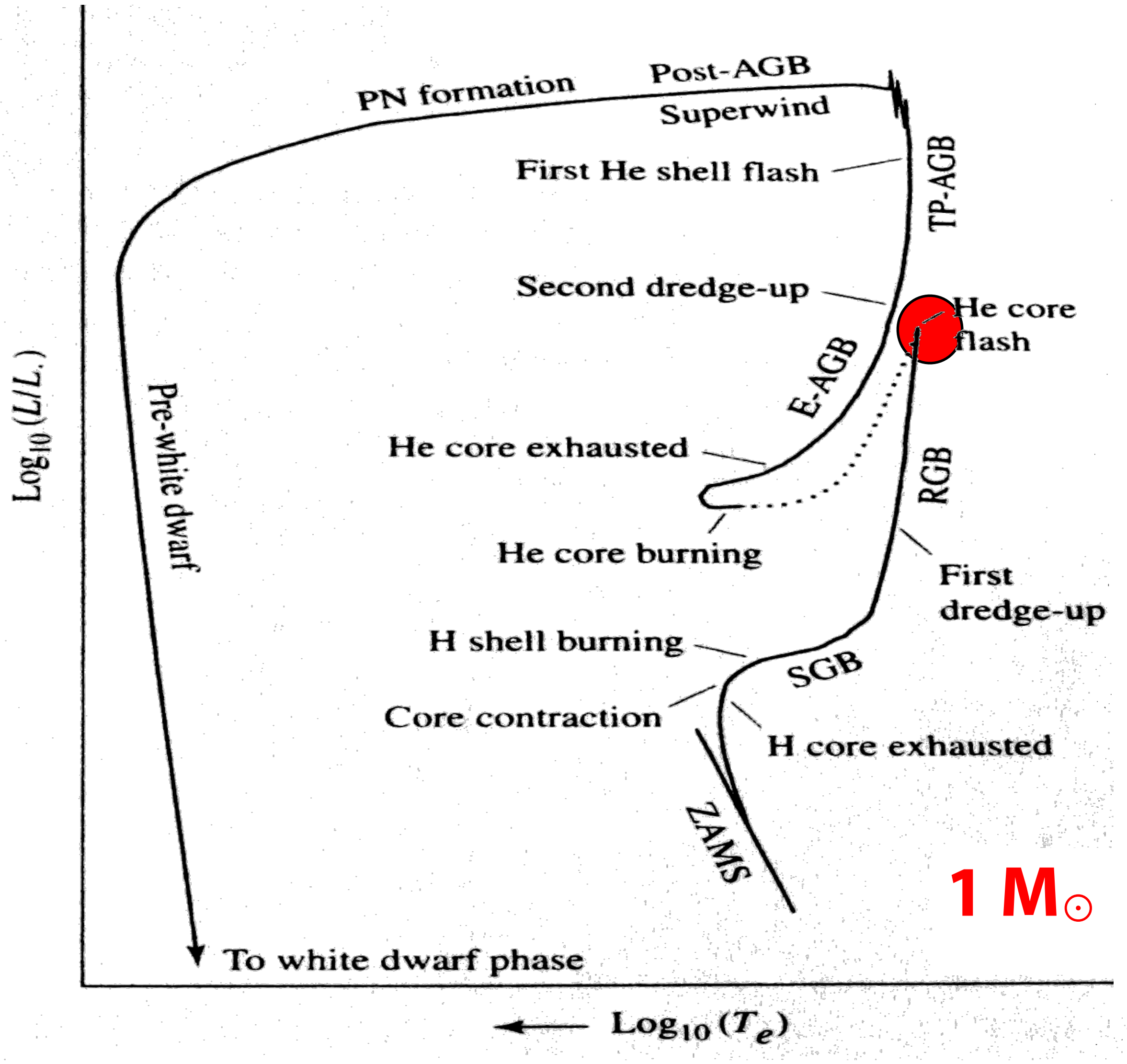
Interior

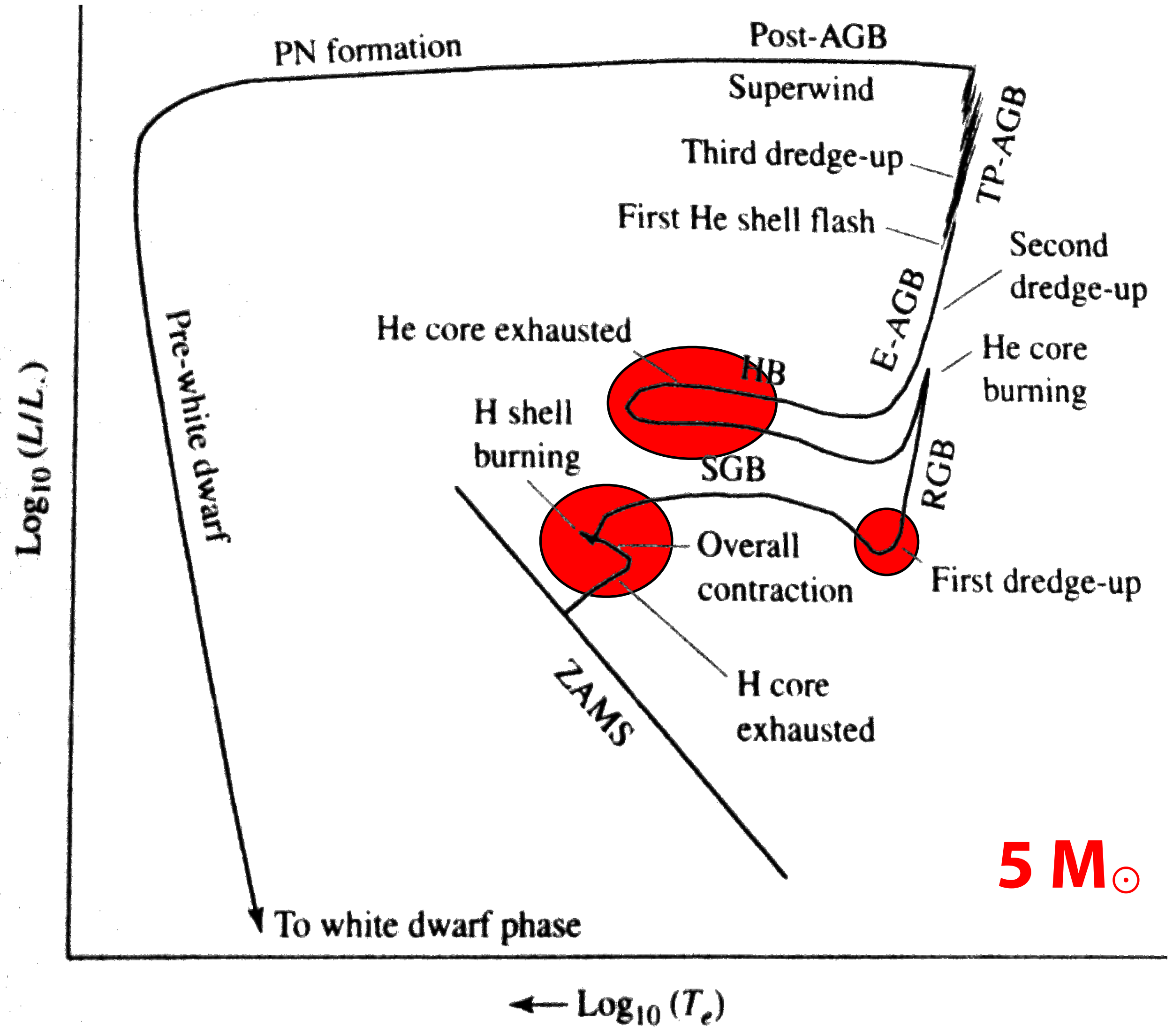
Surface

CO5BOLD — Freytag et al.

Post-main sequence evolution

Comparison low-mass to intermediate-mass evolution

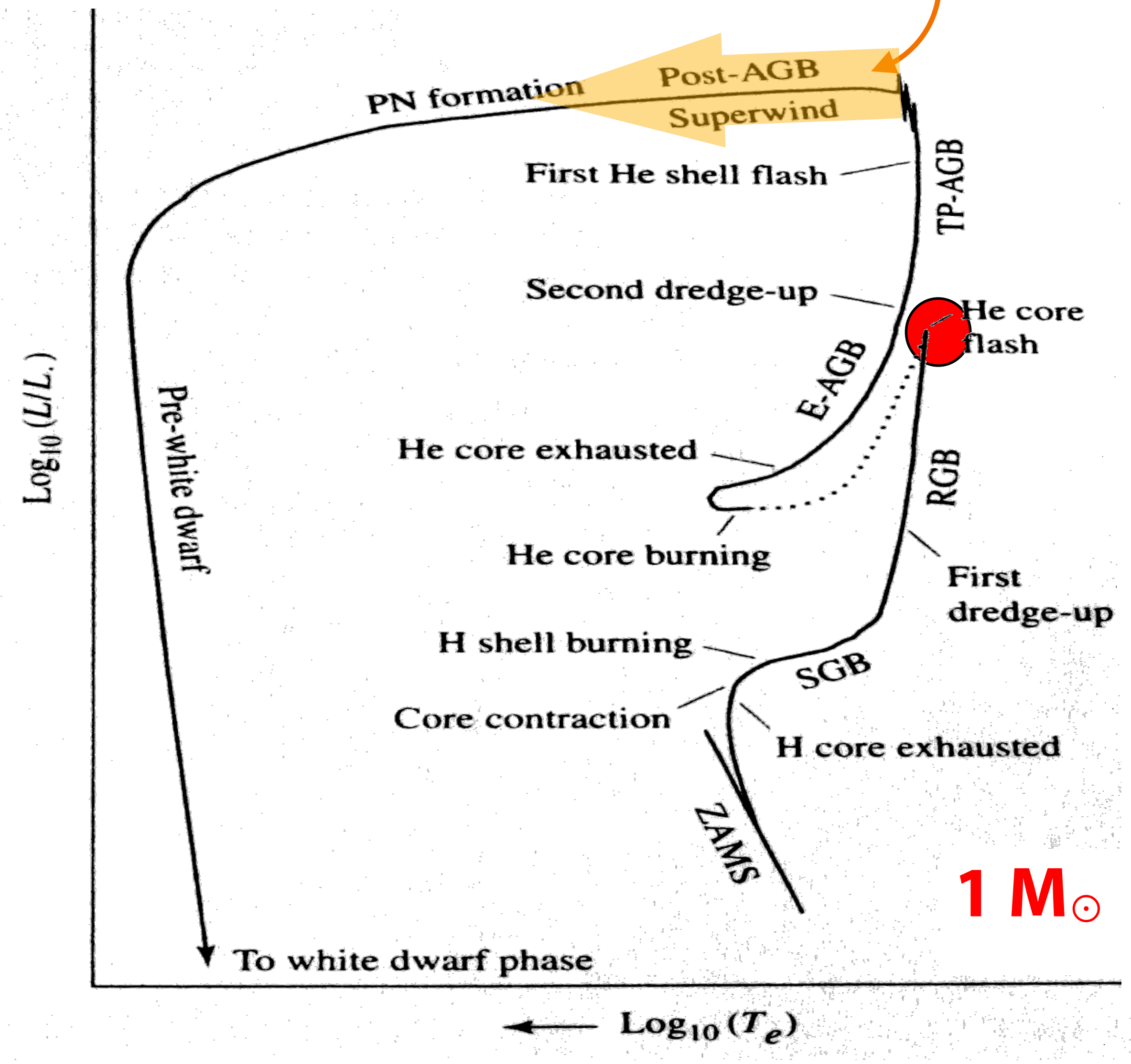


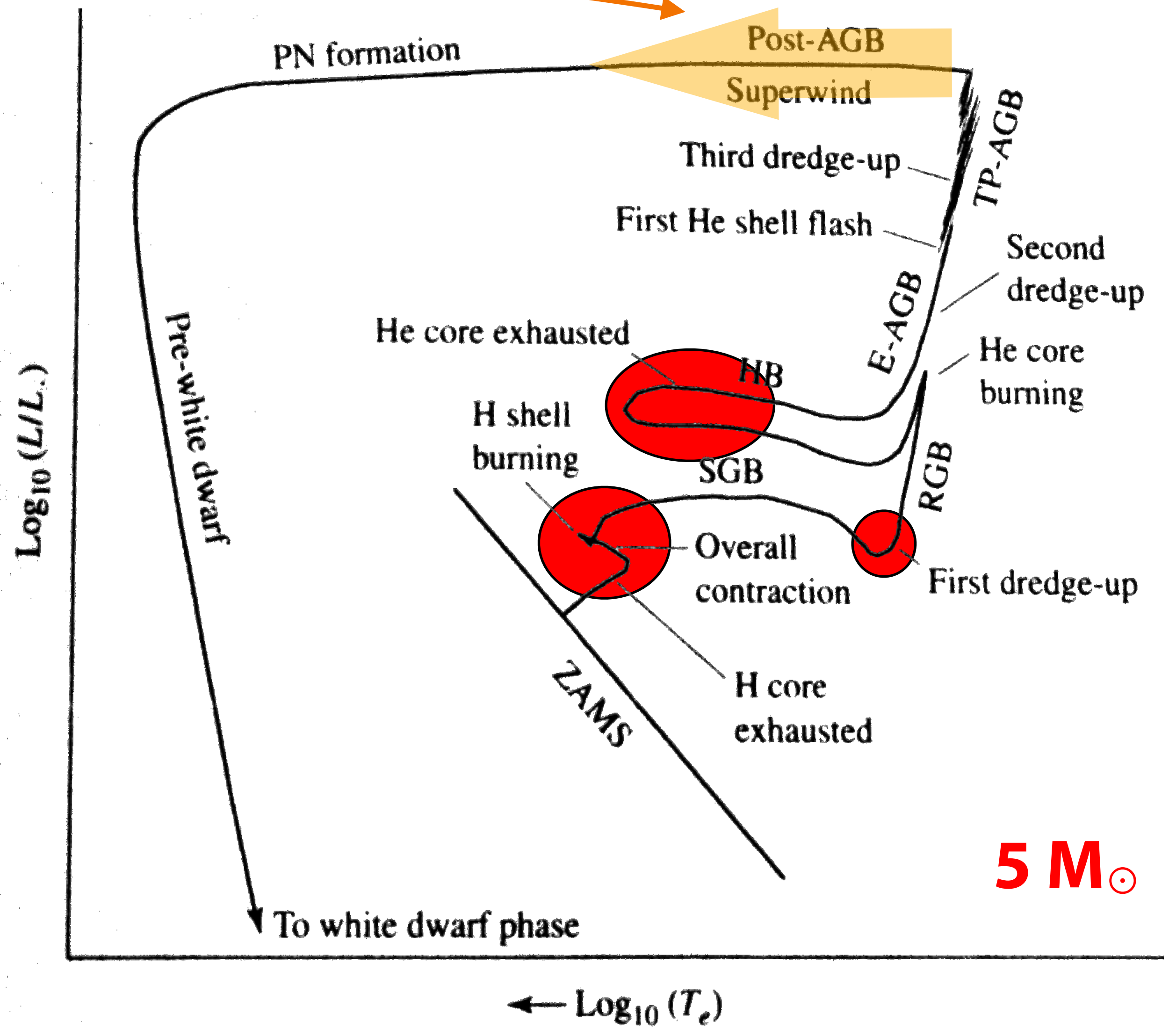


• He core flash at tip of RGB phase	• Larger temperature differences on the horizontal branch • Helium flash in shell • Instabilities - variable stars

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 ~ 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 ~ 10^4 yrs.

Post-main sequence evolution

Planetary nebula

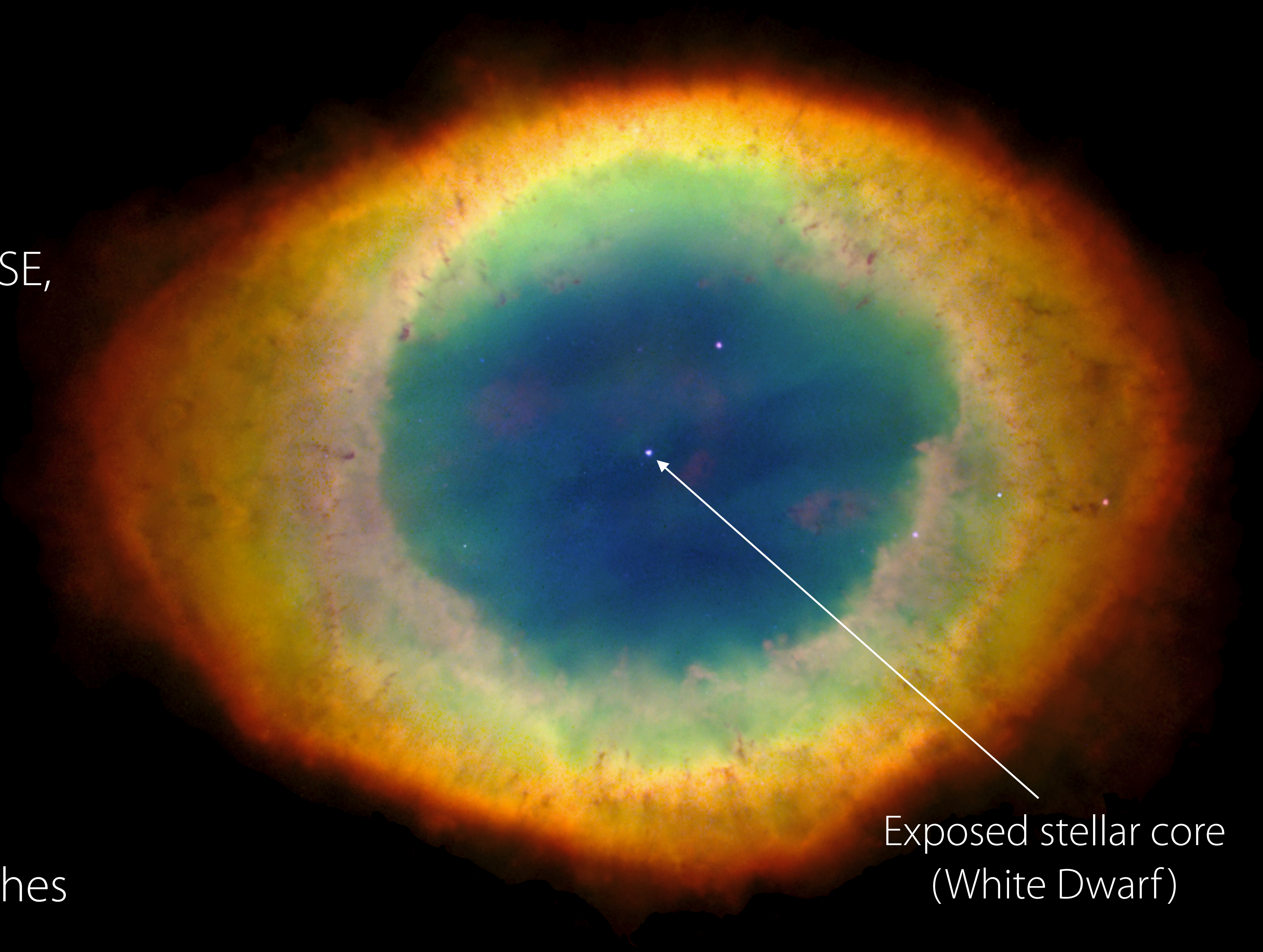
- When reaching $T_{\mathrm{eff}} > 30\,000$ K:
  - weak but fast wind develops
  - strong **UV** flux

➡ Destroys the dust grains in CSE, dissociates molecules, ionises gas

➡ Part of CSE turns into an HII region, appears as **planetary nebula**

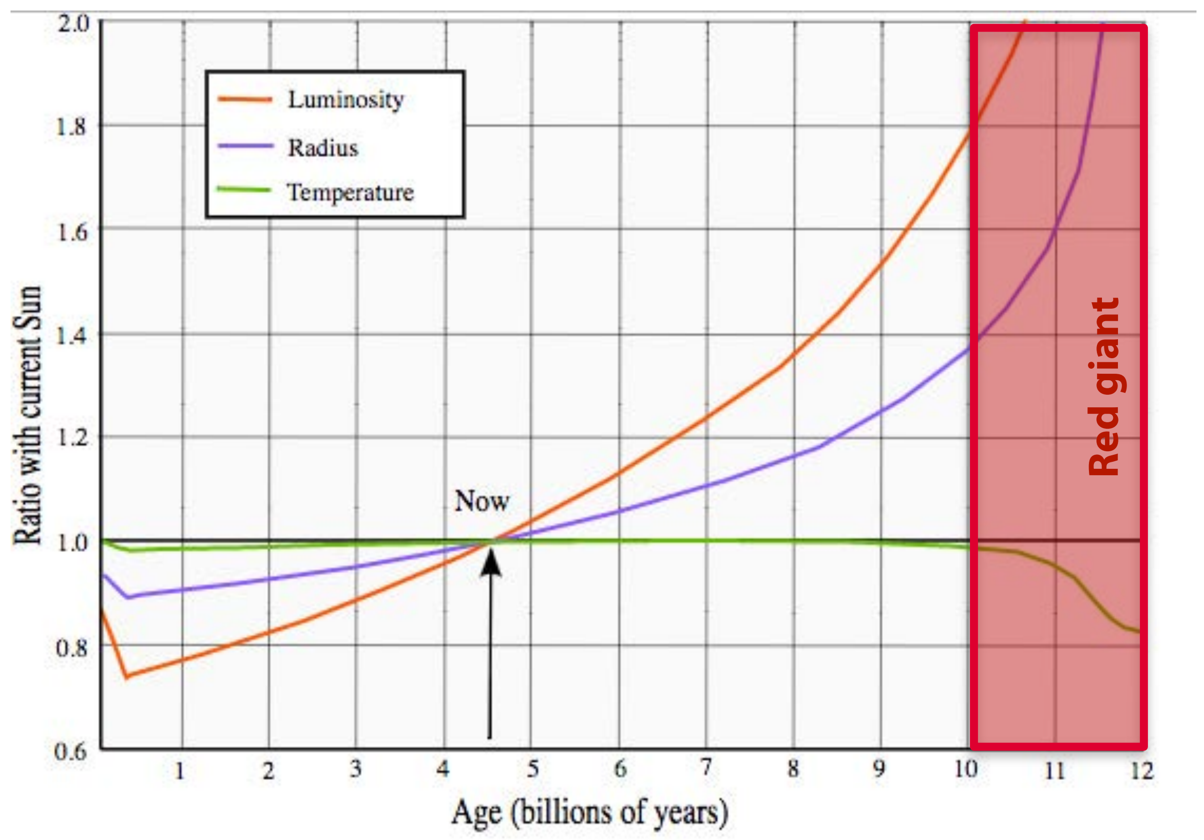
  - (Emission: fluorescence from recombination)

- H-burning shell finally extinguishes once envelope mass down to $\sim 10^{-5}\ M_\odot$ (at $T_{\mathrm{eff}} \approx 10^5$ K)
- Exposed stellar core = White Dwarf

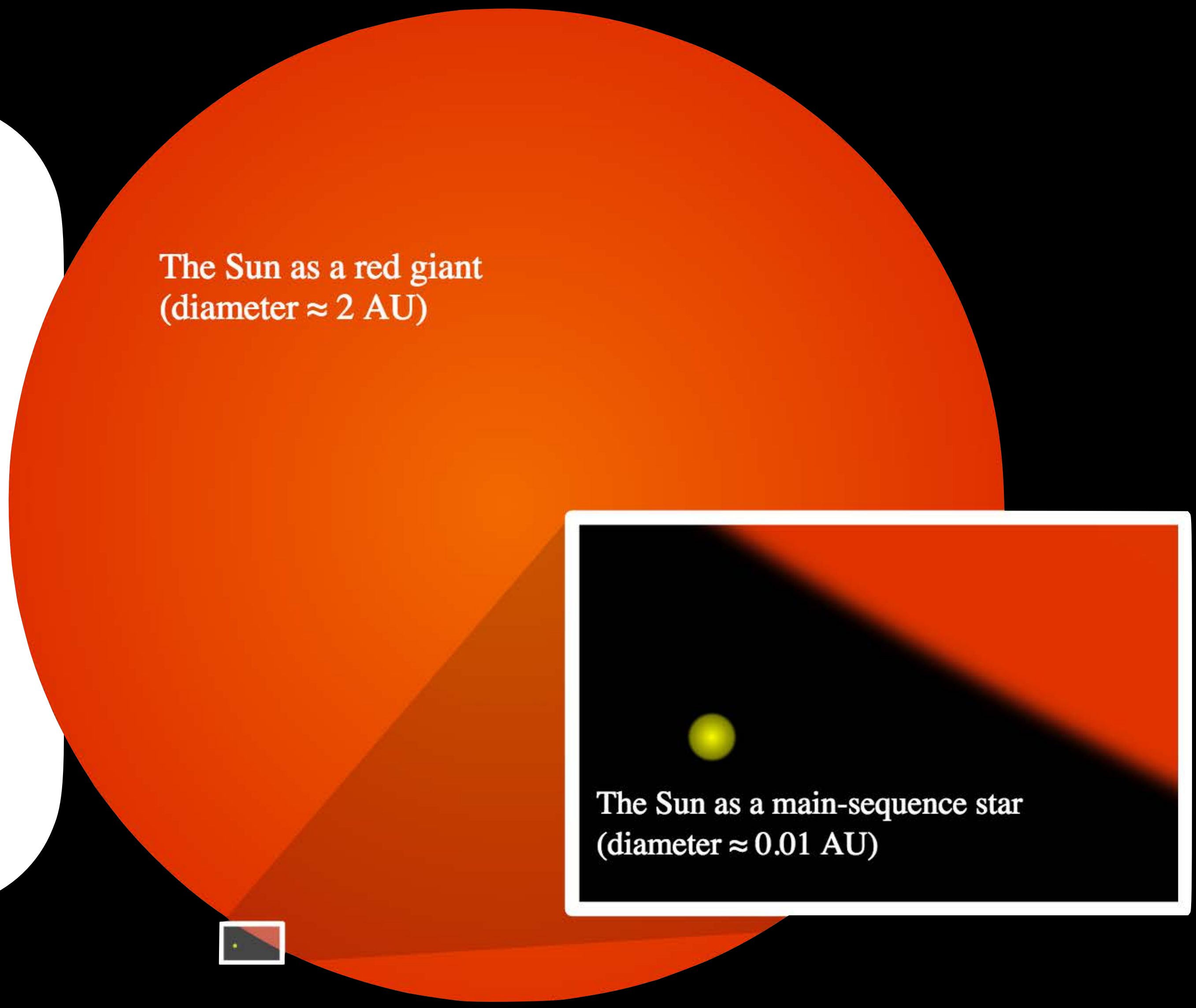


Exposed stellar core (White Dwarf)

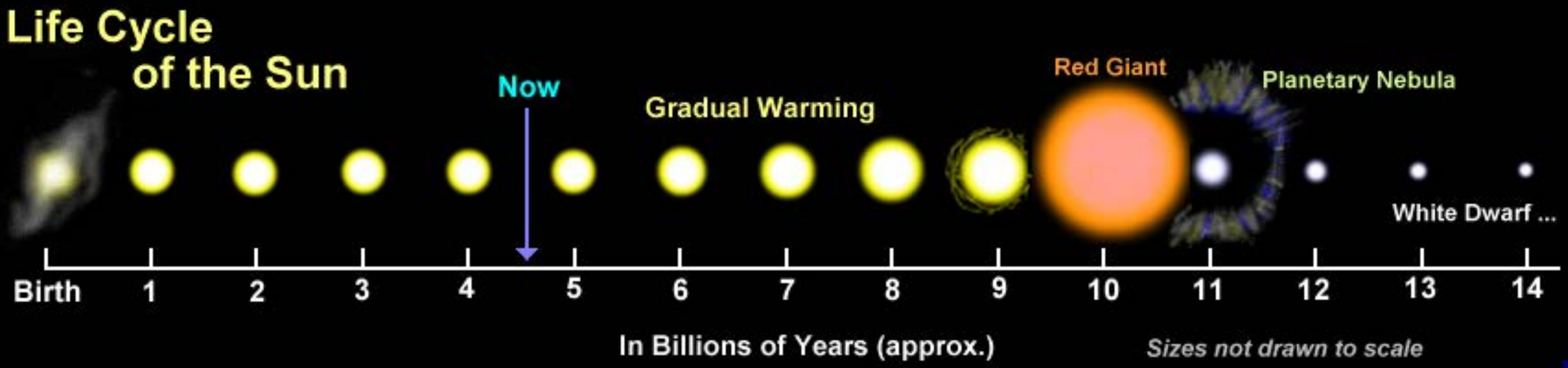
Solar evolution



RJHall/Ribas, Ignasi; DOI:10.1017/S1743921309992298, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16799327



By Oona Räisänen (User:Mysid), User:Mrsanitazier. - Vectorized in Inkscape by Mysid on a JPEG by Mrsanitazier (en:Image:Sun Red Giant2.jpg)., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2585107



Solar evolution

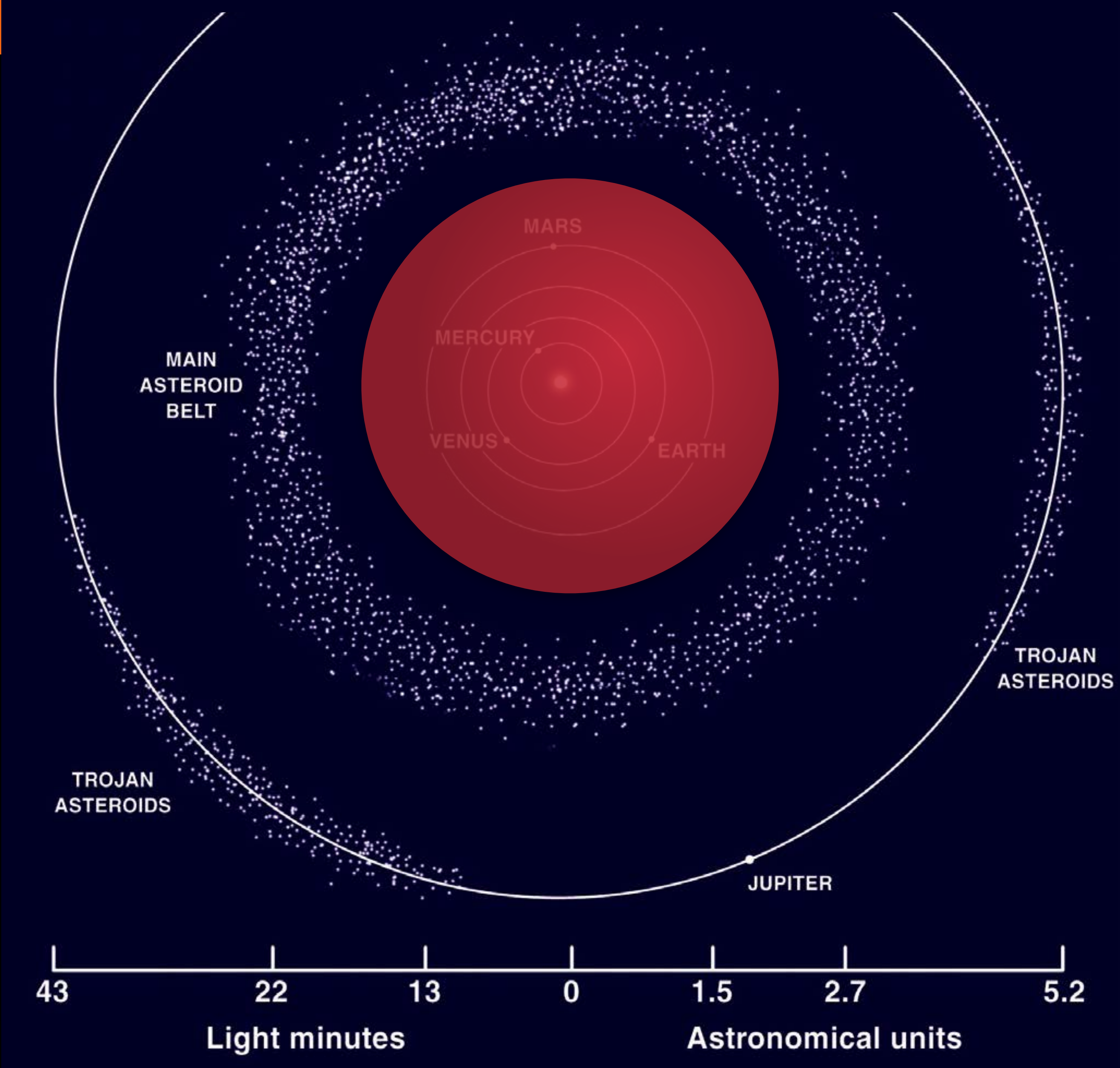
Late evolution stages

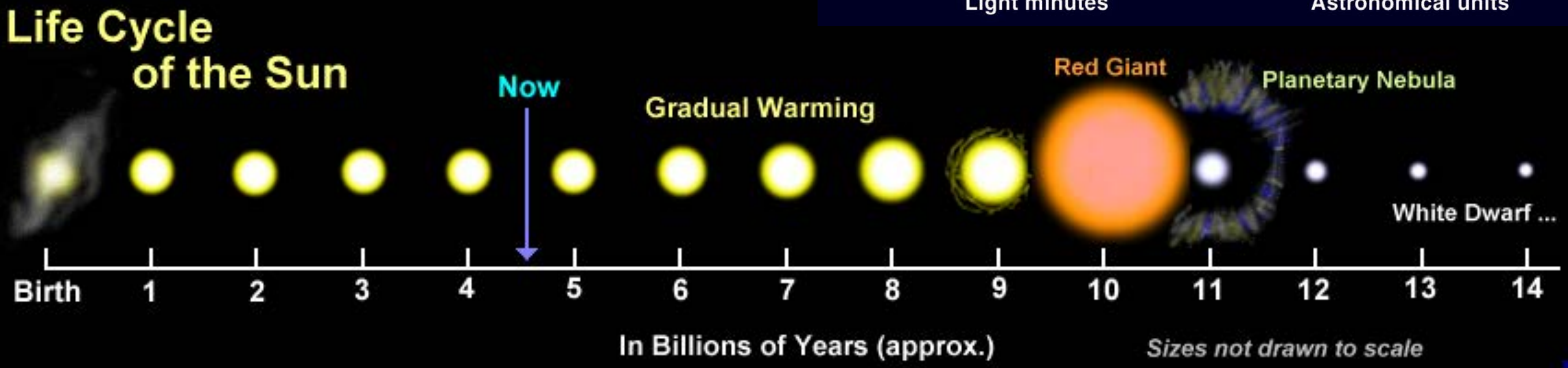
- **Red giant star**
- High radiation pressure in the star's interior makes the radius large
- The surface becomes large.
- Radiation is spread over a large area:

➡ Low surface temperature

➡ Low surface gravity

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



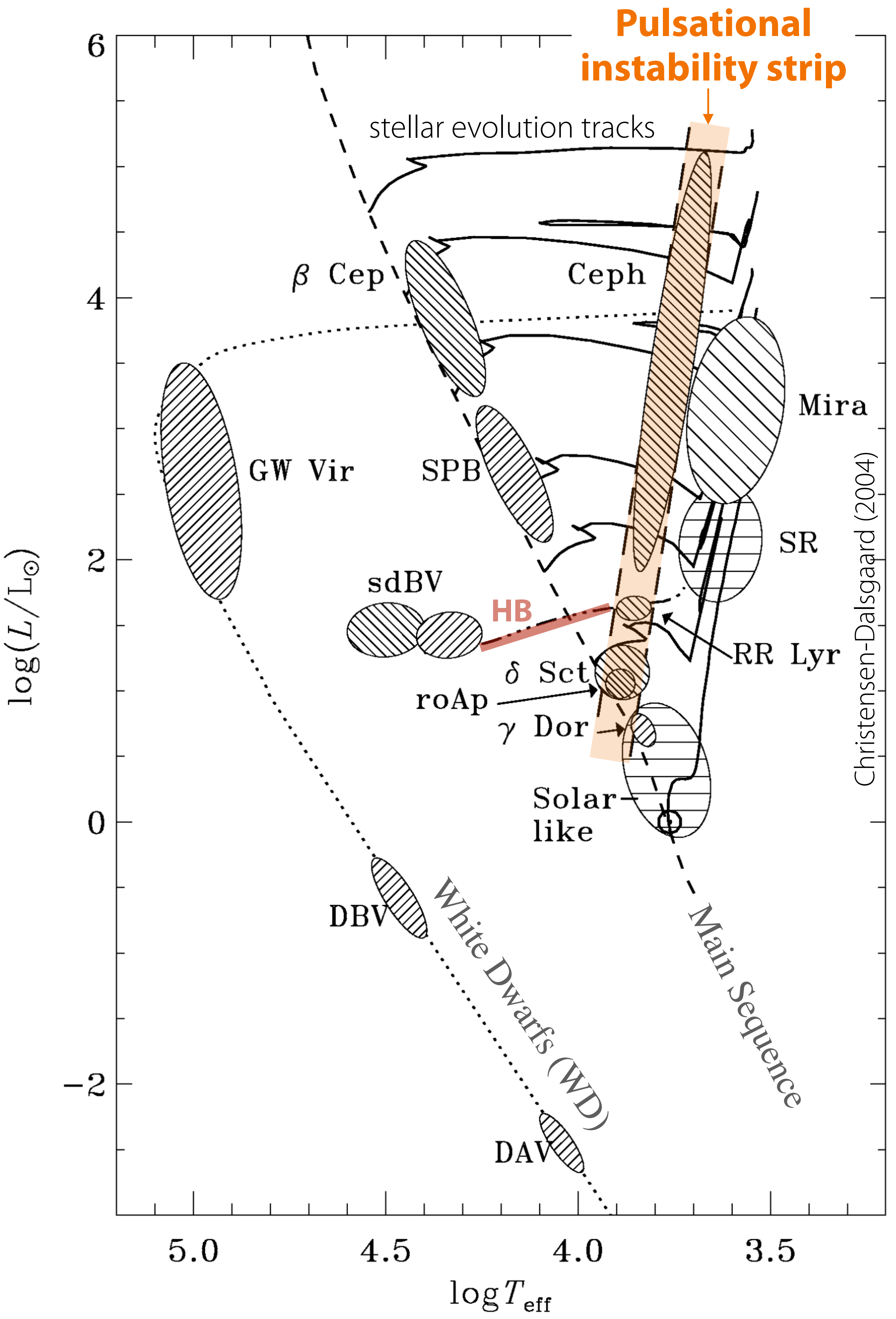


Pulsating and Variable stars

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⊙)
    - RR Lyrae variables (0.5 - 0.7 M⊙, 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



Christensen-Dalsgaard (2004)

Pulsating and Variable stars

Prominent classes

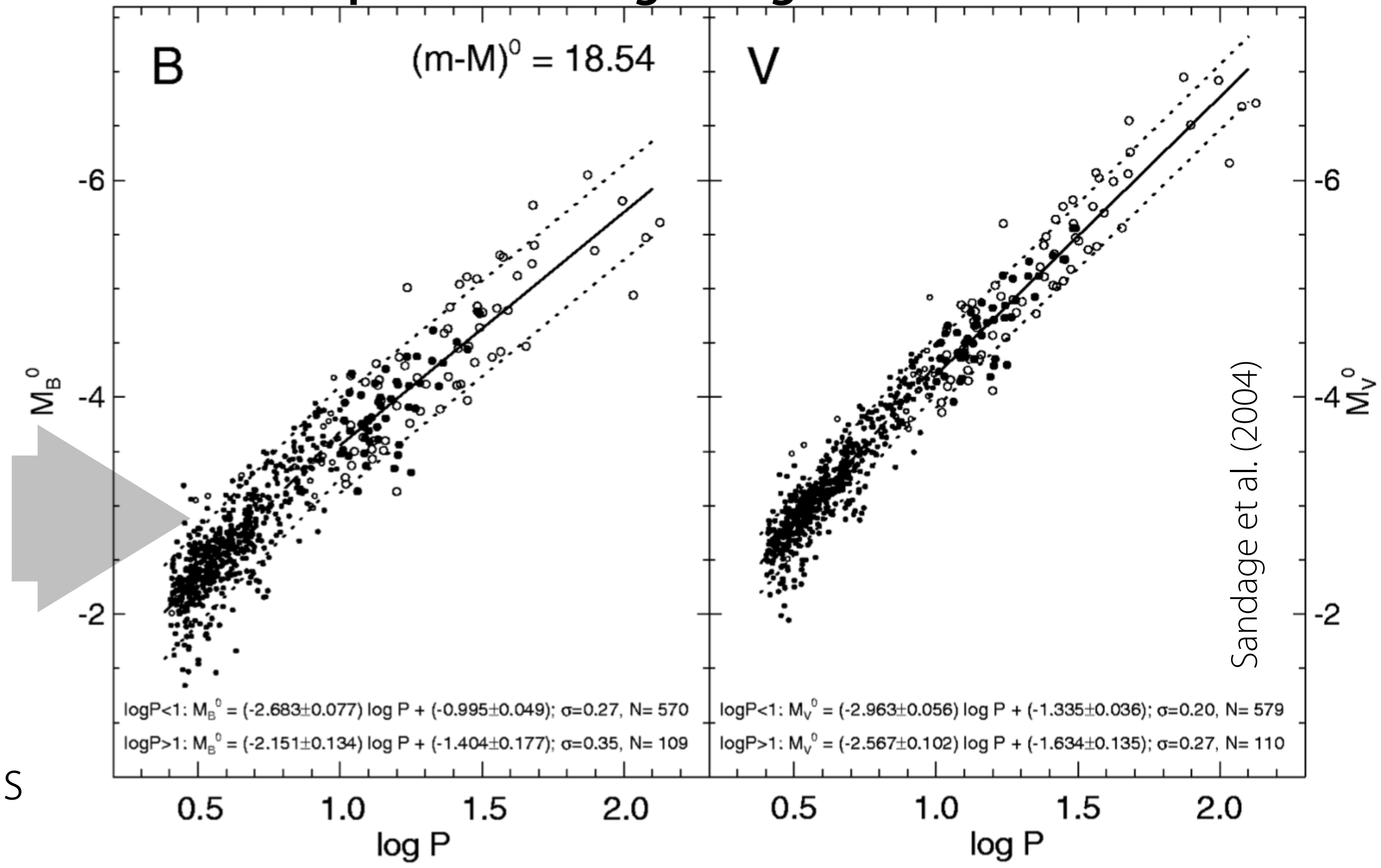
Cepheid variables:
luminous pulsating stars with periods ~2-100 days

- 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.

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

Period-luminosity relation for Cepheids in Large Magellanic Cloud



Sandage et al. (2004)

RR Lyrae stars: Short periods of 1.5 - 2.4 h

- L~100 L⊙ ($M_V = 0.5 = $ const) independent of period.
- Fainter, seen in globular clusters, but not in other galaxies

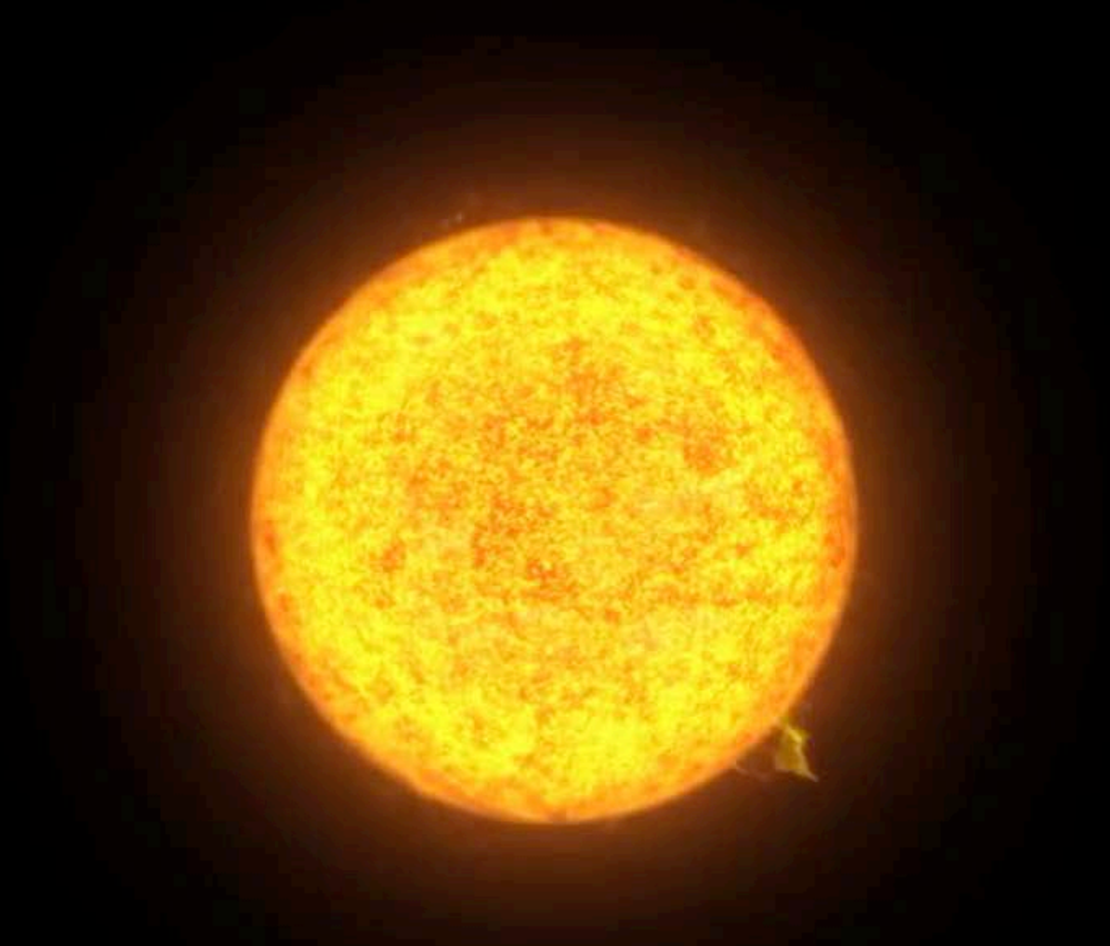
Mira variables: Periods ~100-700 days

- 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.



SpaceRip

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 $T \approx 1.5\ 10^4$ K: ionisation and recombination of H and He (singly ionised)
2. At $T \approx 4\ 10^4$ K: ionisation and recombination of He (fully ionised, He III)

➡ location of instability strip in H-R diagram!

T_{eff}>7500 K — 'blue edge'	**Instability strip**	T_{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.

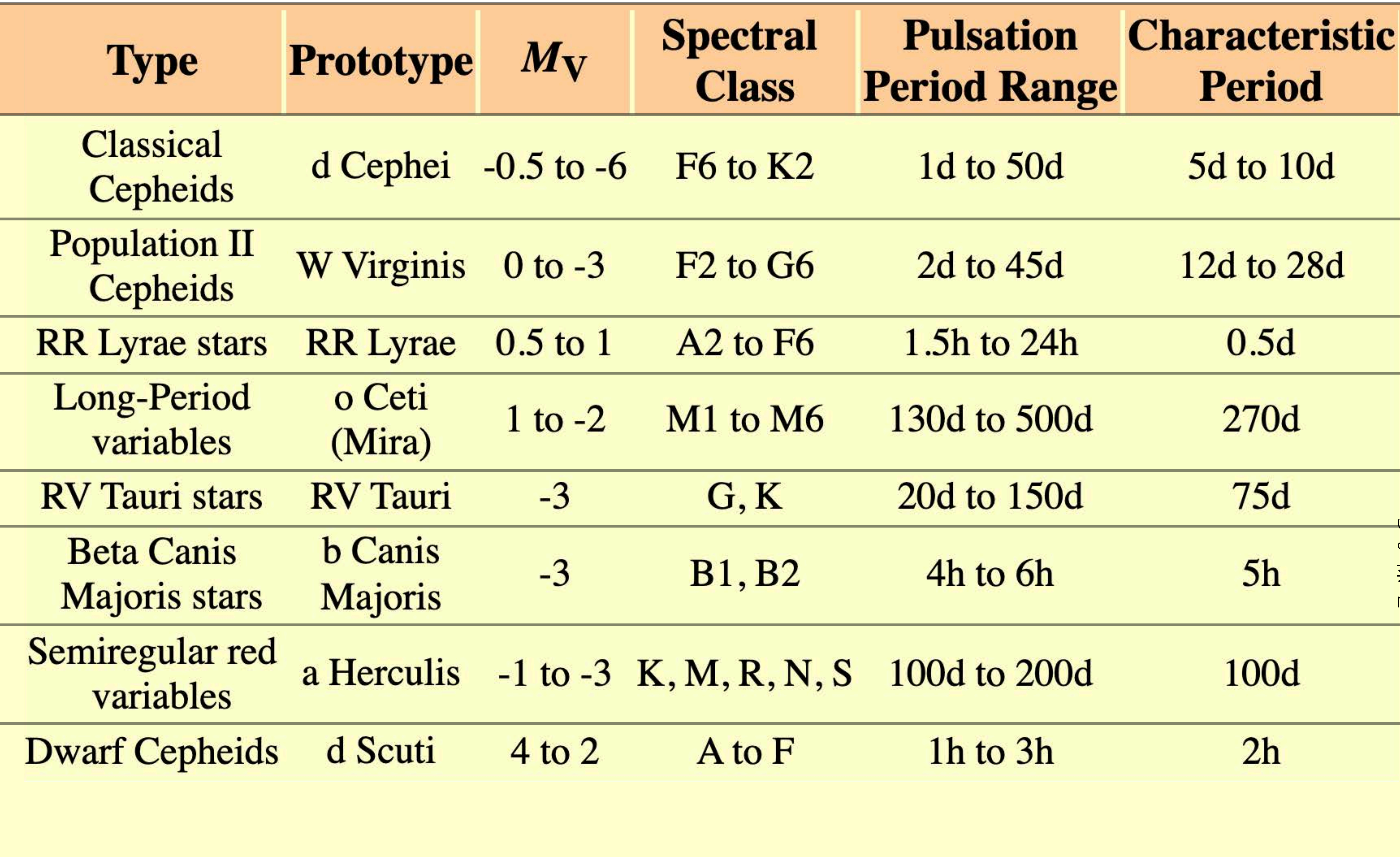
Pulsating and Variable stars

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

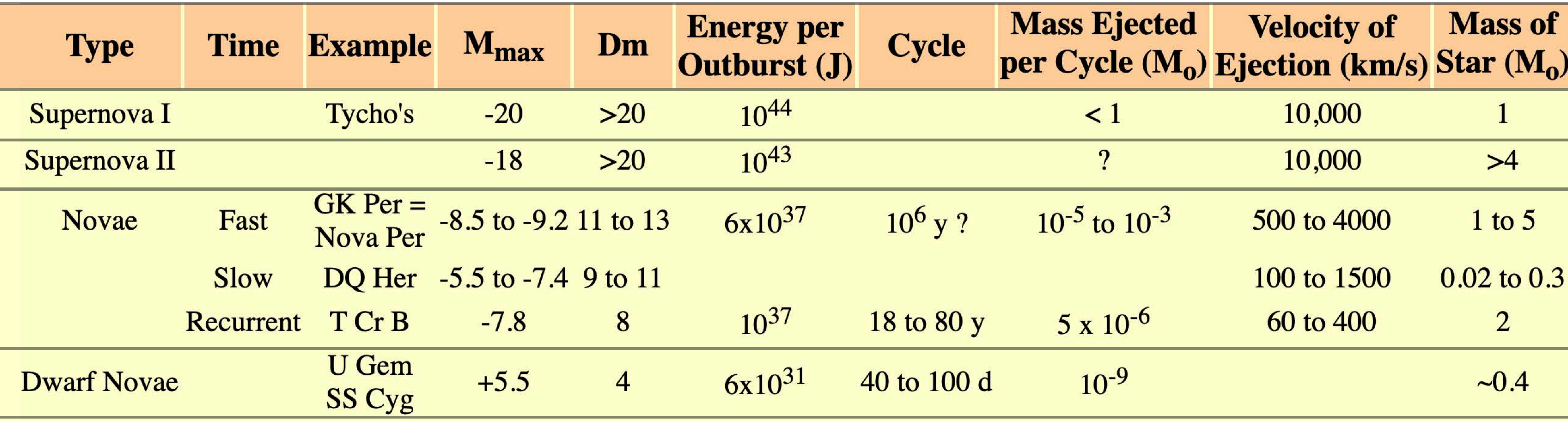


Type	Prototype	M_V	Spectral Class	Pulsation Period Range	Characteristic Period
Classical Cepheids	d Cephei	-0.5 to -6	F6 to K2	1d to 50d	5d to 10d
Population II Cepheids	W Virginis	0 to -3	F2 to G6	2d to 45d	12d to 28d
RR Lyrae stars	RR Lyrae	0.5 to 1	A2 to F6	1.5h to 24h	0.5d
Long-Period variables	o 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

Zeilik & Gregory

Pulsating and Variable stars

Overview over classes of cataclysmic variable stars

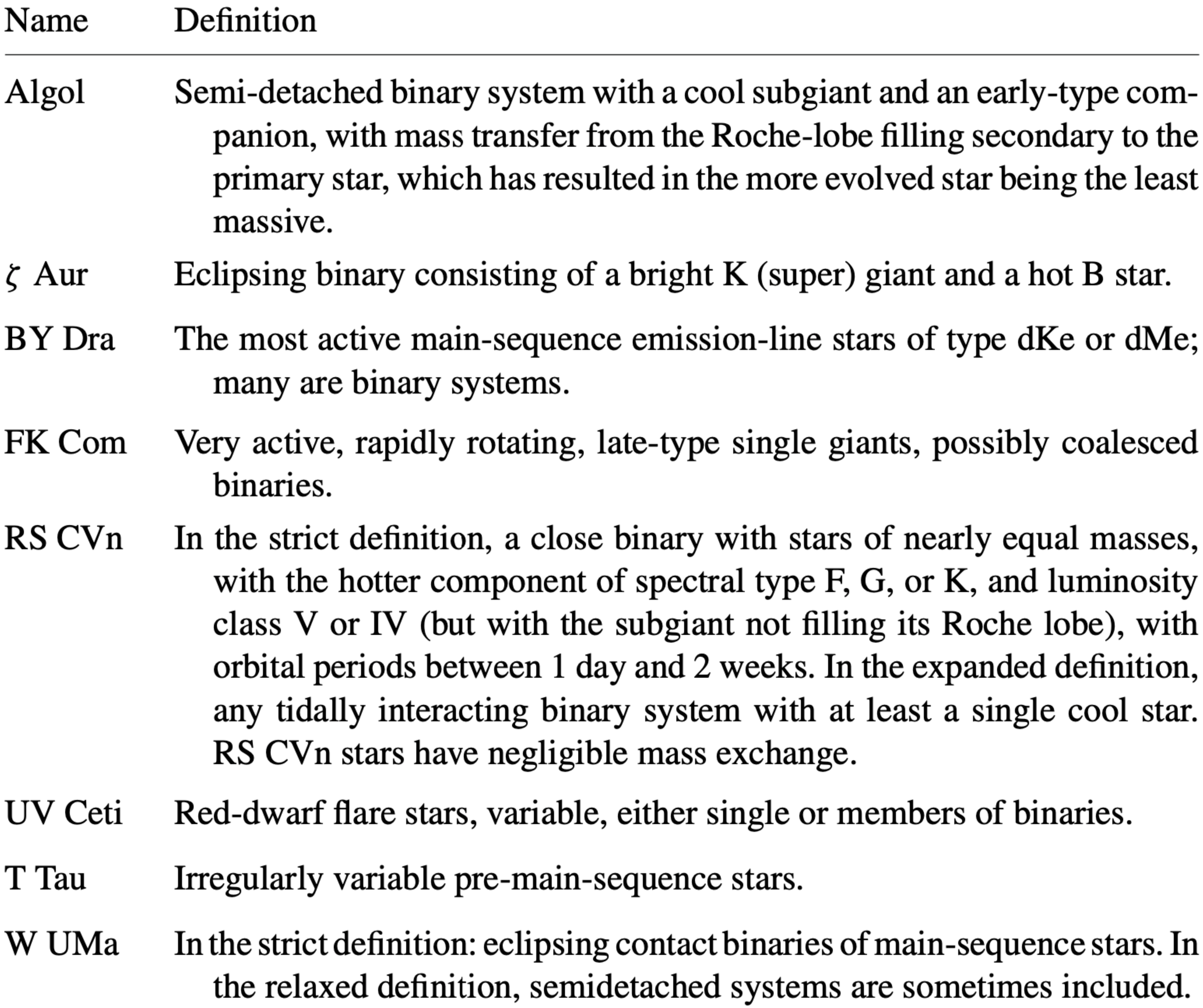


Type	Time	Example	M_{max}	Dm	Energy per Outburst (J)	Cycle	Mass Ejected per Cycle (M_o)	Velocity of Ejection (km/s)	Mass of Star (M_o)
Supernova I		Tycho's	-20	>20	10^{44}		< 1	10,000	1
Supernova II			-18	>20	10^{43}		?	10,000	>4
Novae	Fast	GK Per = Nova Per	-8.5 to -9.2	11 to 13	6×10^{37}	10^6 y ?	10^{-5} 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

Zeilik & Greg

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.