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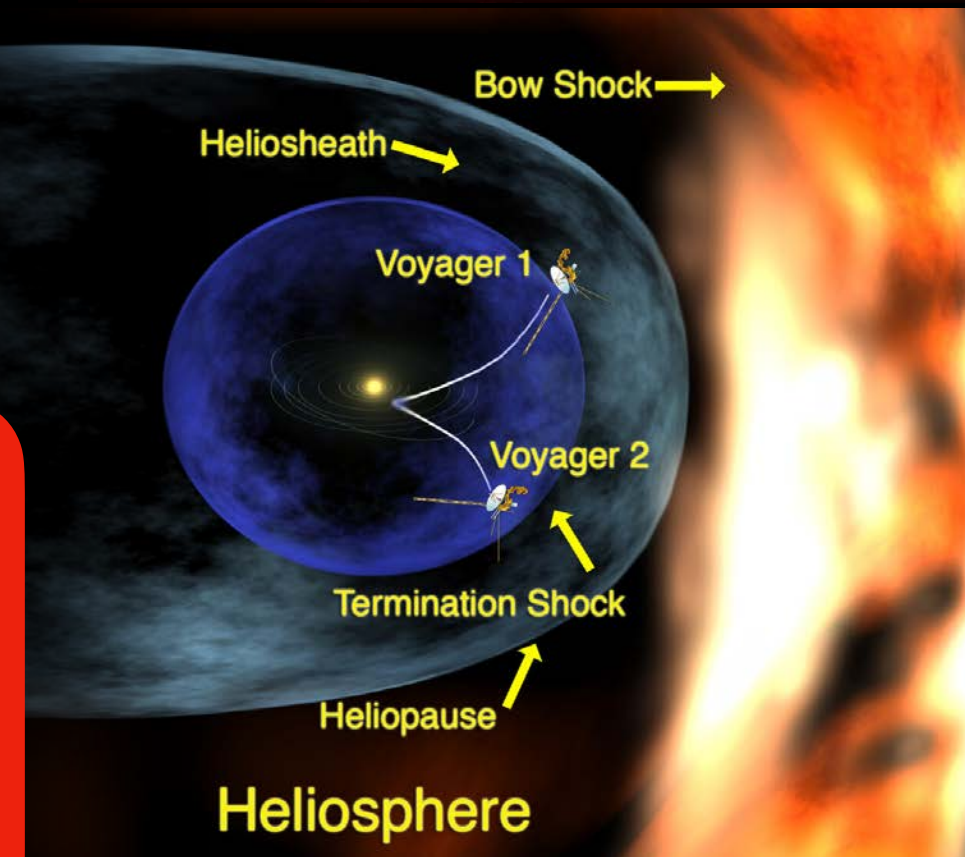
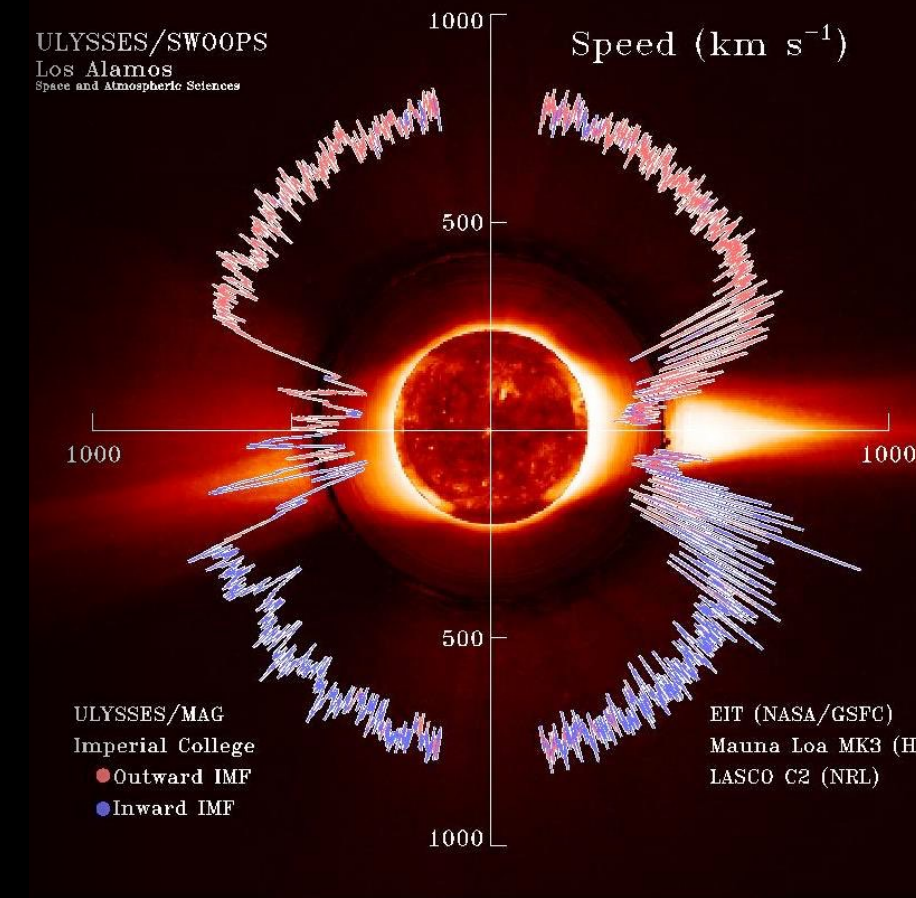
Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

The outer solar atmosphere, solar wind, heliosphere

Recap

1. What are the two major classes of physical mechanisms that could produce the continuous heating of the solar corona?
2. What is the big remaining question to be answered regarding chromospheric/coronal heating?
3. What is solar wind?
4. What are three different types of solar wind?
5. What is the FIP effect and why is that important for understanding how the solar wind is generated?
6. How does the solar wind interact with the interstellar medium far out in the solar system? What structures/regions are created?
7. How is the mass limit called beyond which molecular clouds collapse due to self-gravity? And how does help to break down a giant molecular cloud into "star-sized" portions?



Stellar Evolution

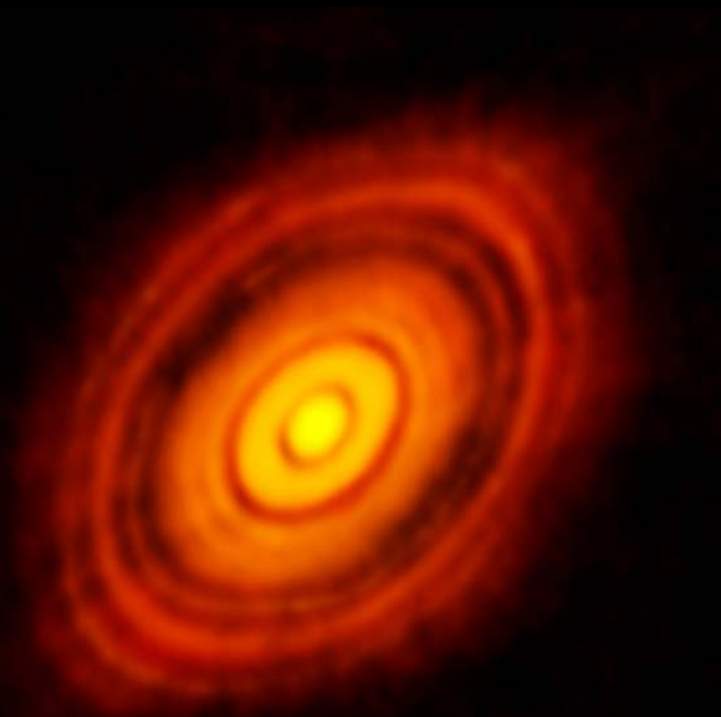
Stellar evolution

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 $\sim 10^6$ yr),
 accretion disk still
 optically thick,
 large IR excess
 observed



HL Tauri ALMA (ESO/NAOJ/NRAO)



Pleiades (M45)

Star formation and pre-main sequence evolution

Dissociation and ionisation

- Gas initially molecular hydrogen H_2 , behaves like an ideal gas ($\gamma_{\text{ad}} > 4/3$)

- Protostellar core dynamically stable.
- Core temperature reaches eventually ~ 2000 K

- H_2 starts to **dissociate**

➡ Strong increase of specific heat,
 γ_{ad} drops below critical value of $4/3$

➡ Hydrostatic equilibrium is no longer possible

➡ Another **dynamical collapse** phase!

- Released gravitational energy goes into further dissociation of H_2 molecules without significant rise in temperature.
- Hydrostatic equilibrium restored once H_2 is completely dissociated

- **Further dynamical collapse phases due to ionisation**

- occur when first H and then He are ionised at $T \sim 10^4$ K.
- Once ionisation of protostar complete, hydrostatic equilibrium established at much reduced radius

Dissociation of H_2 : $\chi_{\text{H}_2} = 4.48$ eV
per molecule

Ionisation of H: $\chi_{\text{H}} = 13.6$ eV
per atom

Ionisation of He: $\chi_{\text{He}} = 79$ eV
per atom

Star formation and pre-main sequence evolution

Pre-main sequence phase (PMS)

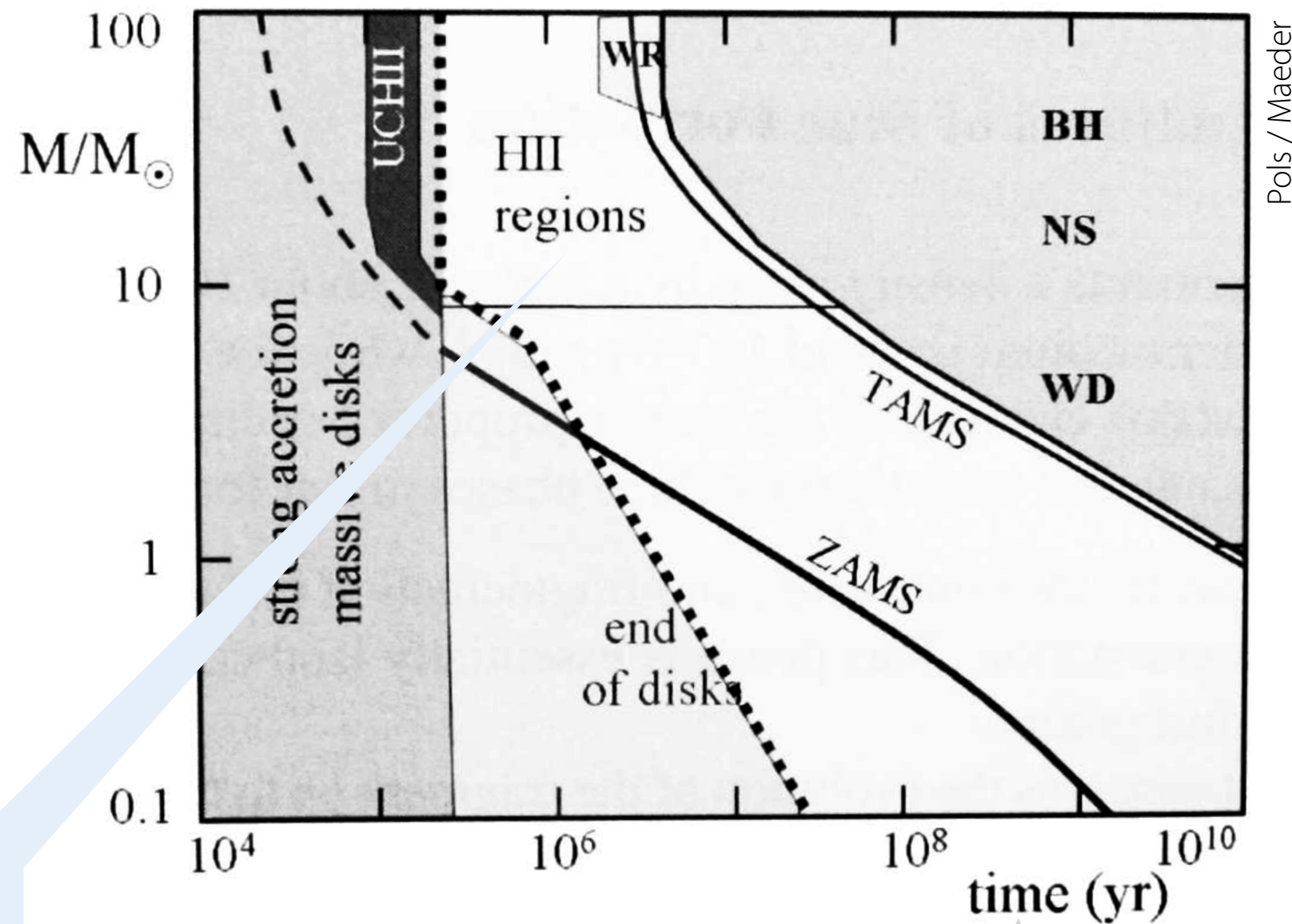
- Accretion finally slows down and stops
- ➔ **Pre-main sequence star.**
- Luminosity is now provided by gravitational contraction
 - Virial theorem — Gravitational potential energy exceeds internal energy:
1/2 original potential energy converted to internal kinetic energy, 1/2 to radiation (and stellar wind)
 - ➔ Internal temperature of star increases as $T \propto M^{2/3} \rho^{1/3}$
- Surface cools and a temperature gradient builds up
 - ➔ Outwards directed heat transport
 - ➔ Evolution now occurs on thermal timescale τ_{KH} .
- At that stage, average internal temperature also follows from virial theorem:
 - ➔ $T \sim 8 \cdot 10^4$ K (independent of the mass of the protostar !)
 - ➔ Low temperature results in high opacity and thus short mean free path of photons
 - ➔ Remember: Criterion for convective stability!
 - ➔ PMS star becomes fully convective!

Star formation and pre-main sequence evolution

Stages of star formation

1. Interstellar cloud collapse
2. Cloud fragmentation
3. Formation of a protostellar core
4. Accretion
5. Dissociation and ionization
6. Pre-main sequence phase

- Note: Massive stars reach the ZAMS while still undergoing strong accretion.
- ➡ Ionising their surroundings
- ➡ Creating an HII region around themselves



$t = 0$: Formation of a hydrostatic core
 ZAMS: Zero Age Main Sequence
 TAMS: Terminal Age Main Sequence.

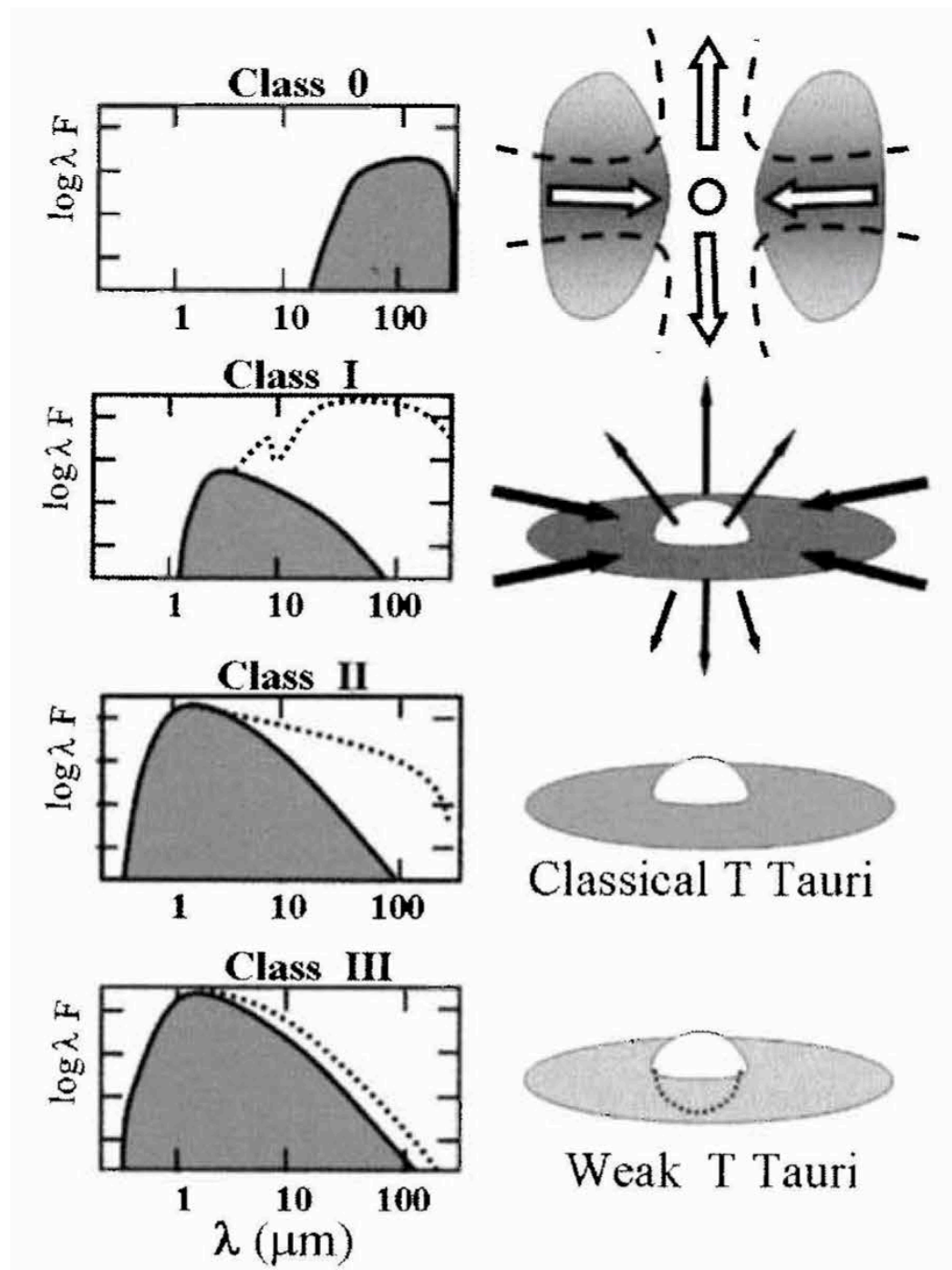


Figure 9.2. Schematic illustration of four stages in the evolution of protostars and their circumstellar disks. On the left, the stellar flux is depicted (shaded area) and the contribution from the disk (dotted line). On the right the corresponding geometry of the object is shown.

Class 0 objects are very young protostars ($\lesssim 10^4$ yrs) with almost spherical accretion at a high rate, emitting in the far-IR and sub-mm range. Class I protostars correspond to an advanced stage of accretion (age $\sim 10^5$ yrs), where the star is still embedded in a massive accretion disk, while jets or bipolar outflows are also observed. In class II the protostar has become visible as a classical T Tauri star on the pre-main sequence (age $\sim 10^6$ yrs), while the accretion disk is still optically thick giving rise to a large IR excess. Class III stars are already close to the main sequence (age $\sim 10^7$ yrs), with an optically thin accretion disk and weak emission lines. Figure from MAEDER.

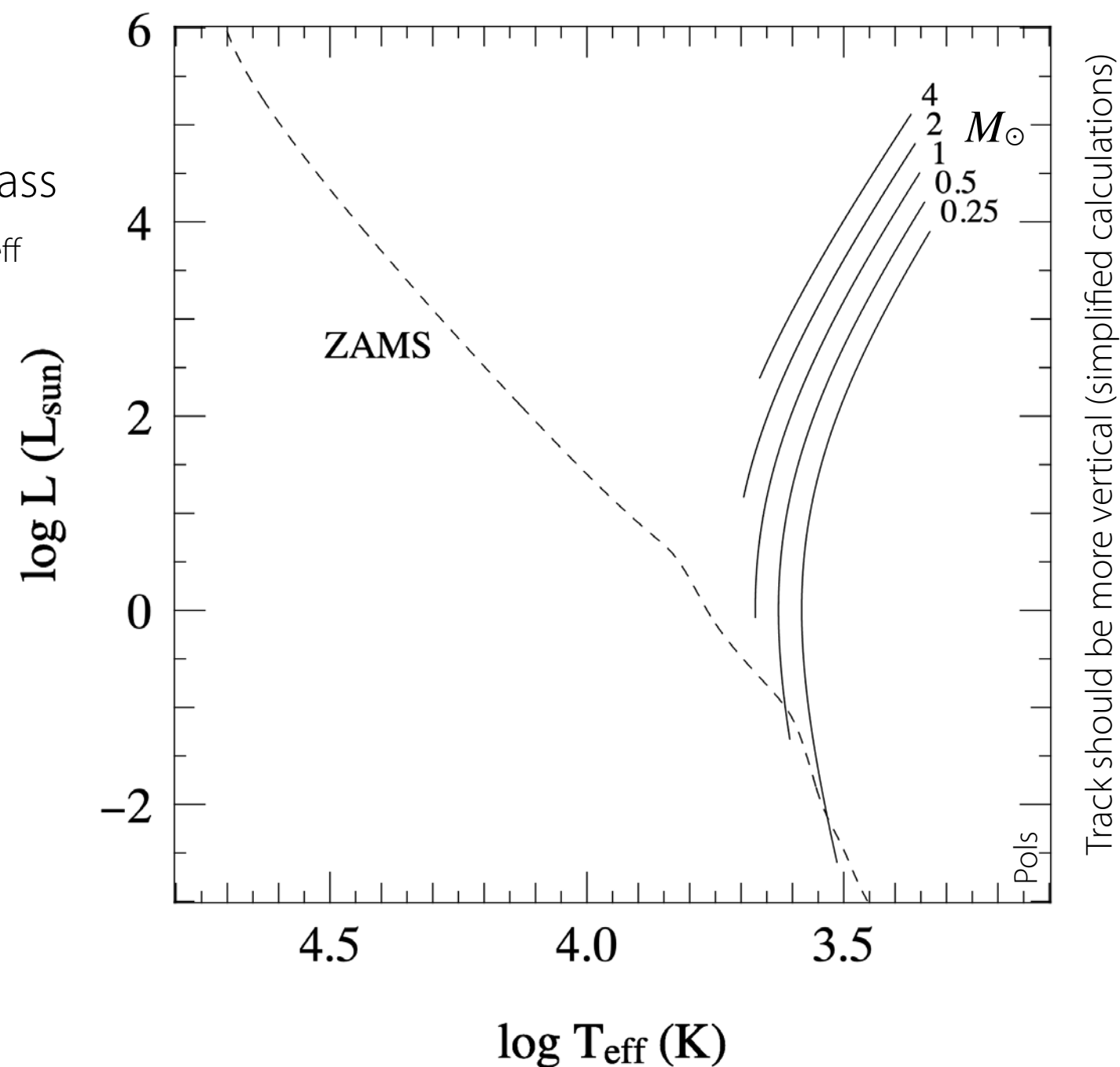
Star formation and pre-main sequence evolution

Hayashi line

- Fully convective stars of the same given mass placed along nearly vertical line in HRD ($T_{\text{eff}} \approx \text{constant}$)

➡ Hayashi line

- Region left of Hayashi line (higher T_{eff}): Stars cannot be fully convective, some part of stellar interior must be in radiative equilibrium.
 - Region right of Hayashi line (lower T_{eff}): Stars not in hydrostatic equilibrium.
 - Fully convective.
 - Very small superadiabaticity ($\nabla - \nabla_{\text{ad}}$) sufficient to transport very energy flux
 - Interior structure $\sim$ adiabatic
- ➡ Luminosity of a fully convective star basically independent of its structure!

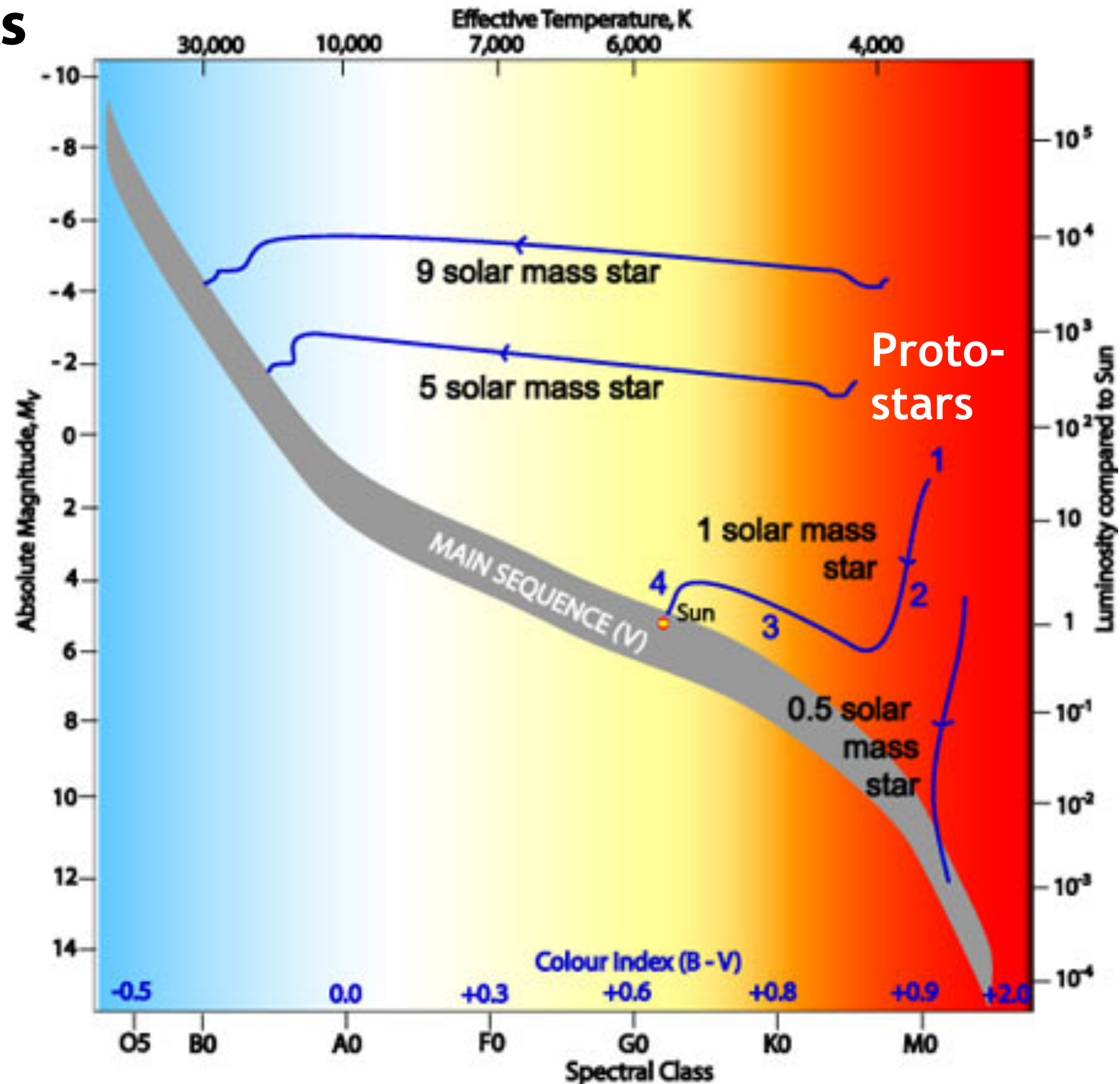


- Shape of Hayashi line determined by opacity in photosphere (dependence on ρ, T).
- Fully convective stars: low T_{eff}
 - ➡ Opacity mostly due to H- absorption which increases strongly with temperature

Star formation and pre-main sequence evolution

Evolutionary tracks

- Time to reach ZAMS
 - $1 M_{\odot}$: 50 million yr
 - $5 M_{\odot}$: 600 000 yr
 - $15 M_{\odot}$: 60 000 yr



Star formation and pre-main sequence evolution

Pre-main-sequence evolution tracks for $0.3 - 2.5 M_{\odot}$

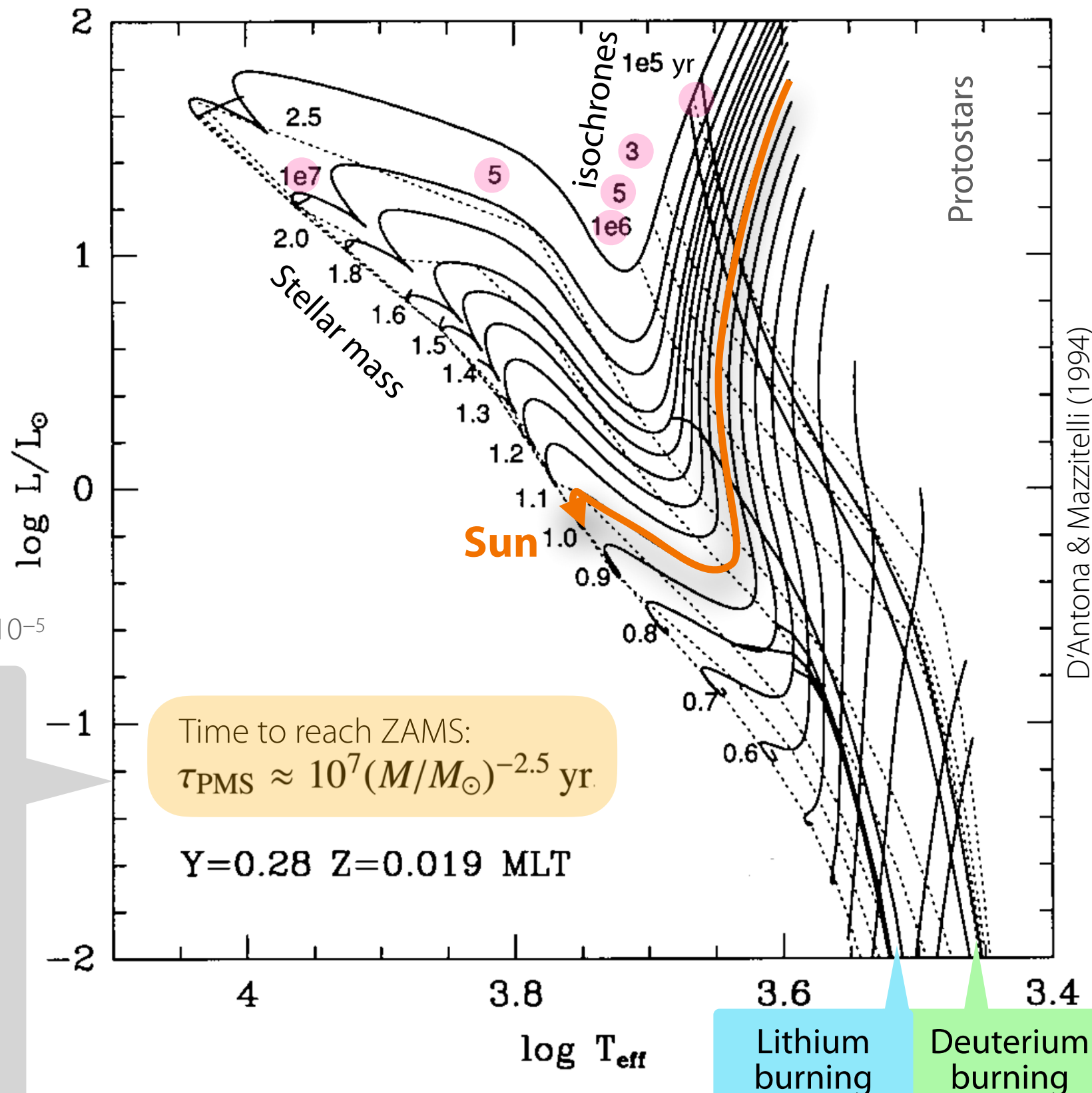
- Newly formed star after dynamical collapse phase: settles on Hayashi line appropriate for its mass
- Further evolution (PMS) follows track depending on mass (and chemical composition)

➡ Gravitational contraction and increase of T_{eff}

➡ Deuterium and lithium burning

Mass fraction of deuterium in interstellar gas $\sim 10^{-5}$

- Solid lines = evolution tracks for a given mass
- Dotted lines = **isochrones** (connecting points on tracks with same age ($t = 10^5 - 10^7$ yr))
- Nearly vertical solid lines: approximate locations of deuterium and lithium burning

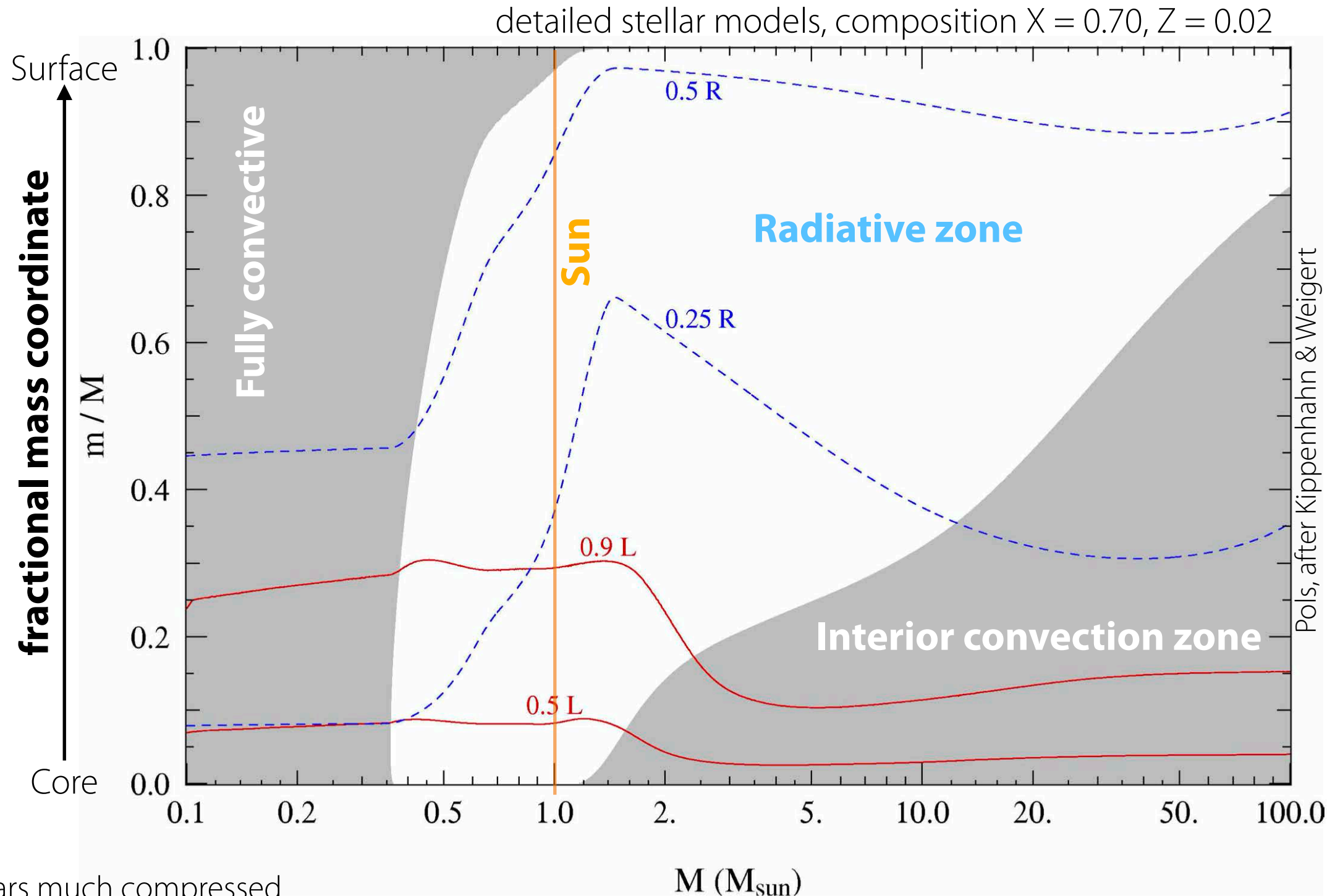


Main sequence evolution

Interior structure on the ZAMS

- Occurrence of convective regions (gray)

- Convective regions (gray)
- Solid red lines:** mass shells inside which 50% and 90% of total luminosity are produced
- Dashed (blue) lines:** mass coordinate corresponding to 25% and 50% of the stellar radius R .



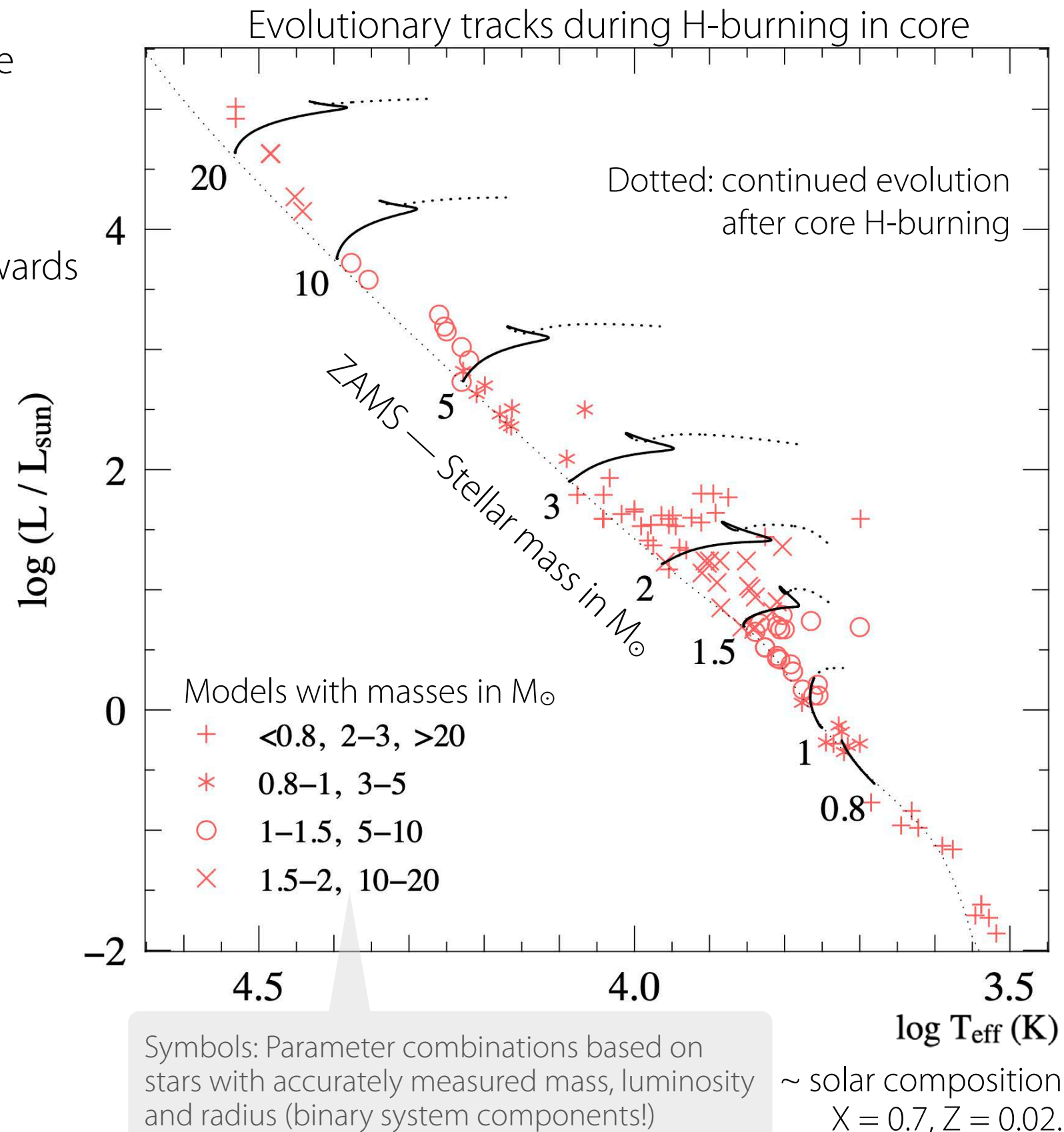
Note: Outer interior appears much compressed due to strong decrease in density with radius

Main sequence evolution

Leaving the ZAMS

- Slow gradual formation of inert He core
- ➡ Adjustments of interior structure
- ➡ Away from ZAMS towards higher luminosities and larger radii
- Low-mass stars ($M < 1 M_{\odot}$) evolve towards higher T_{eff} , radius increases slightly
- Higher-mass stars evolve towards lower T_{eff} , 2-3 times increase in radius

- Nuclear energy generation rate ϵ_{nuc} very sensitive to (core) temperature.
- Nuclear reactions act like a thermostat
- Keep core temperature almost constant.
- CNO cycle a better thermostat than the pp chain due to higher exponent of temperature dependence

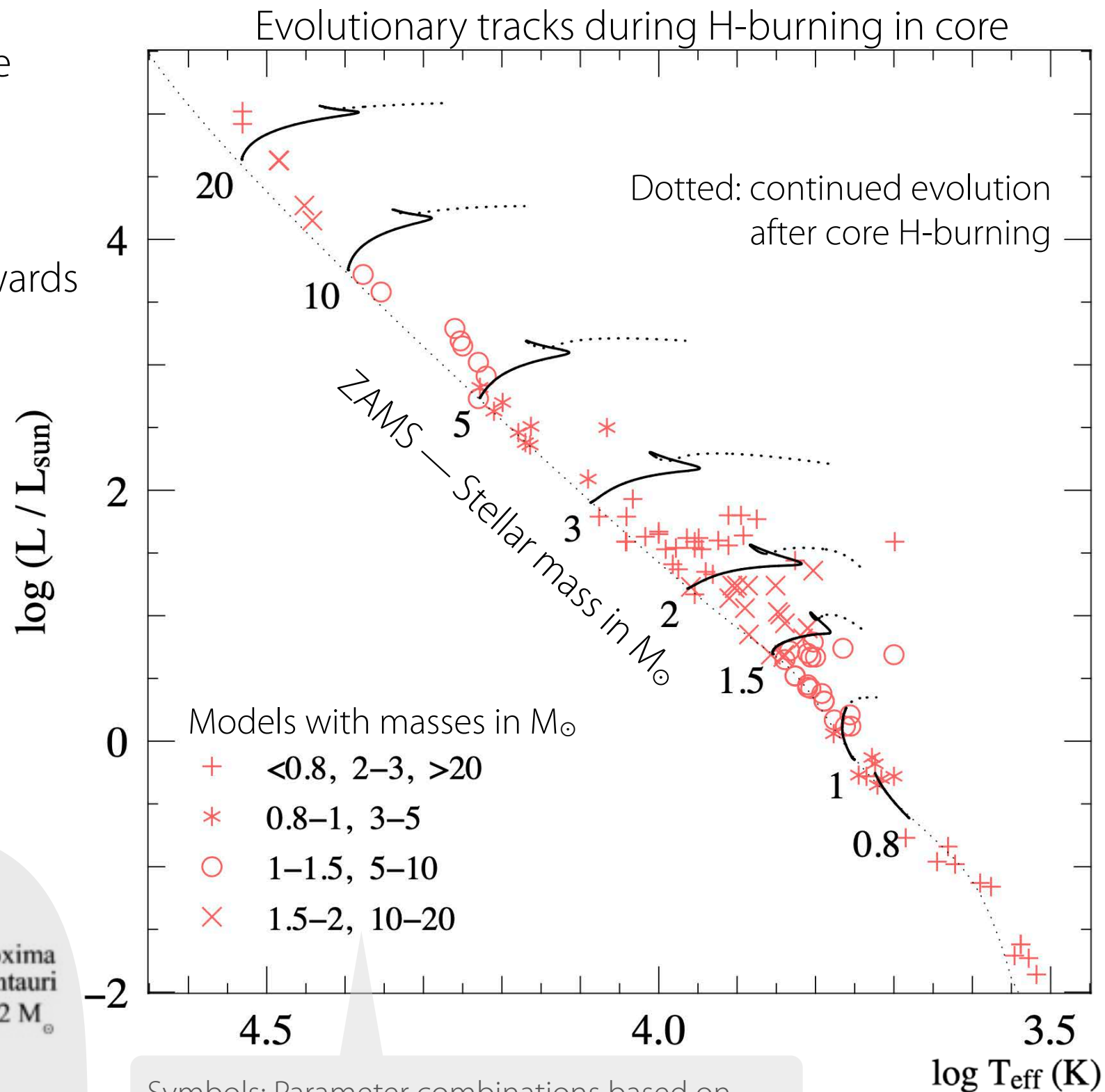
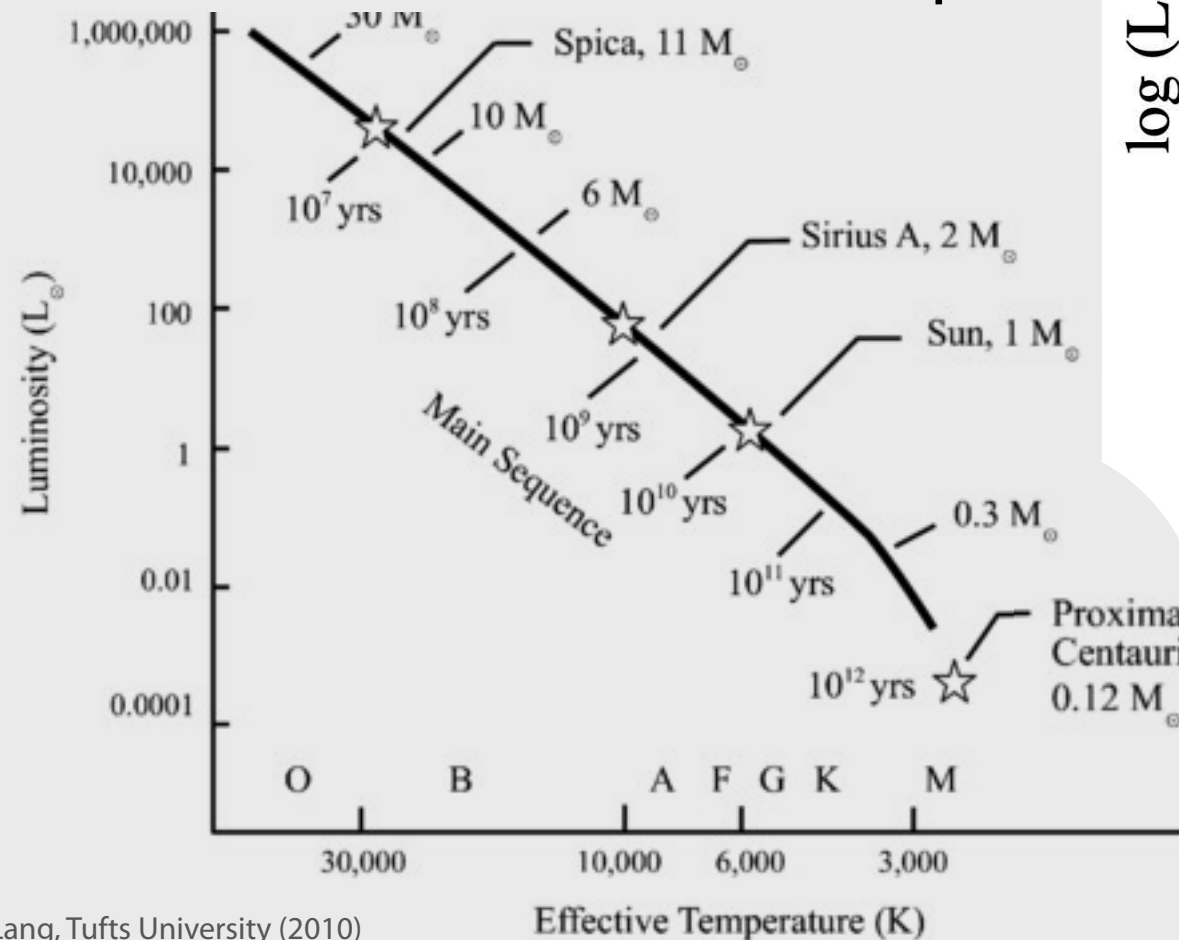


Main sequence evolution

Leaving the ZAMS

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Evolution times on the main sequence



Symbols: Parameter combinations based on stars with accurately measured mass, luminosity and radius (binary system components!)

~ solar composition
 $X = 0.7, Z = 0.02$.

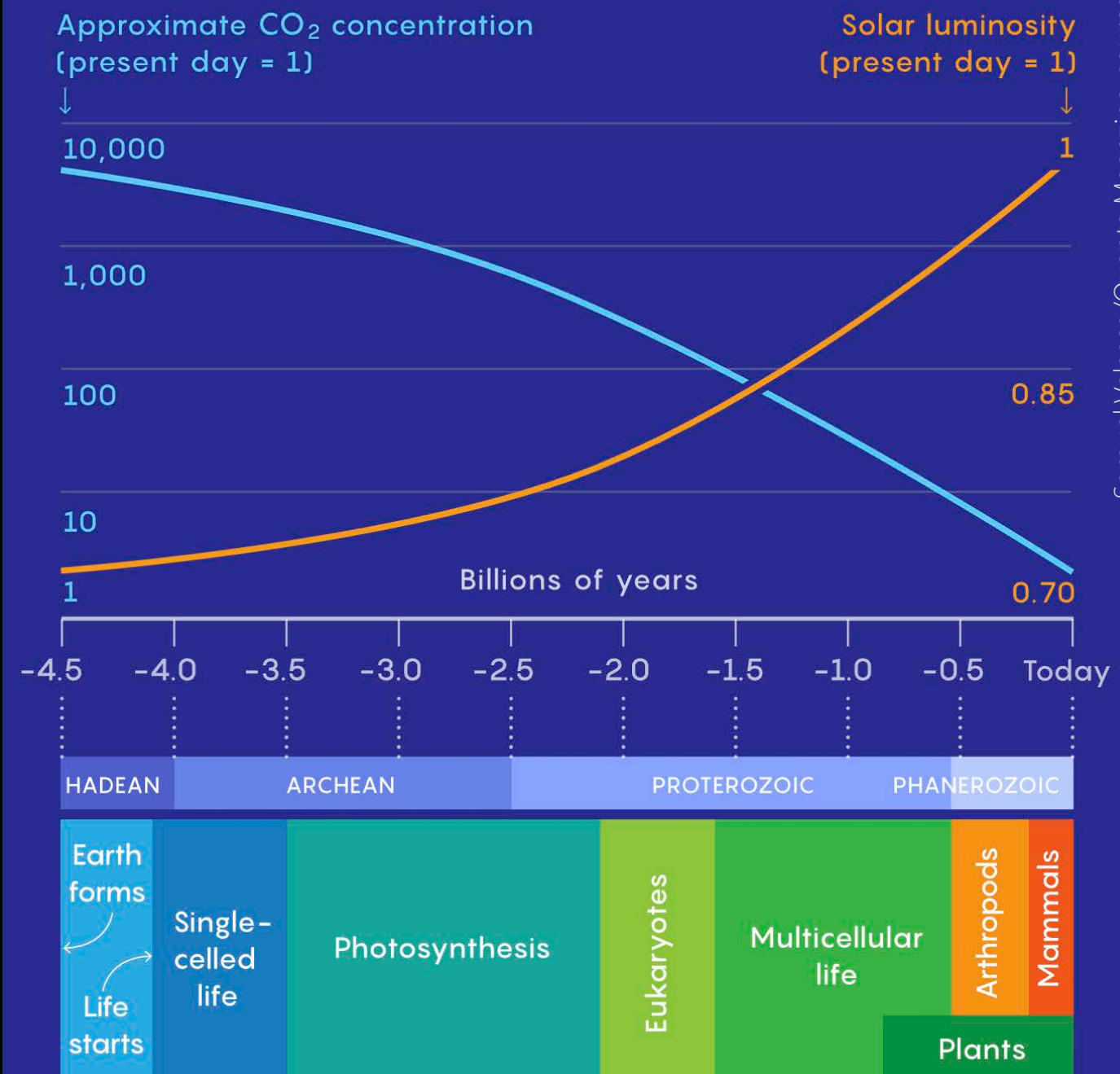
Solar evolution

Faint Young Sun paradox

- Models imply that Sun's brightness slowly increased (and will continue to increase)
 - ➔ 4.5 billion years ago: **~30% fainter than today!**
 - ➔ But evidence for liquid water on Earth already 4 billion years ago!
 - ➔ How was that possible at much lower solar irradiation levels?
- Most likely compensated by other factors like green house effect (outgassing of CO₂), increased volcanism stimulated by gravitational influence of a much closer moon, ...
- ➔ Implications for habitability of Earth and of exoplanets in general (formation of life!?)

What Made Earth Habitable

Life began not long after Earth formed, even though the sun was only 70% as bright as it is now. Scientists think that high levels of greenhouse gasses such as carbon dioxide helped keep the early planet warm.



Post-main sequence evolution

Post-main sequence evolution

Overview — Dependence on mass

- Evolution depends on mass — Basic division:
- **Low-mass stars** (up to $\sim 2 M_{\odot}$)
 - Develop a degenerate helium core — long-lived red giant branch phase.
 - Unstable ignition of He-burning: helium flash (for $0.8 M_{\odot}$ to $\sim 2 M_{\odot}$)
 - Shed envelopes by a strong stellar wind at end of evolution, remnants: white dwarfs.
- **Intermediate-mass stars**
 - Develop helium core that remains non-degenerate
 - Stable ignition of He-burning
 - After central He burning phase: formation of carbon-oxygen core (becomes degenerate)
 - Shed envelopes by a strong stellar wind at end of evolution, remnants: white dwarfs.
- **Massive stars** ($> 8 M_{\odot}$)
 - Ignition of carbon burning in non-degenerate core
 - For $M > 11 M_{\odot}$: Burning of heavier elements in core until Fe core formed (which collapses)
 - Catastrophic final stage (supernova, remnant: neutron star, black hole)

Post-main sequence evolution

Schönberg-Chandrasekhar limit

Discovered by Schönberg and Chandrasekhar in 1942.

- Main sequence (MS): central hydrogen burning, stars in thermal equilibrium $\tau_{\text{nuc}} \gg \tau_{\text{KH}}$
 - ➡ Hydrogen-exhausted core is gradually formed
- End of MS phase: nuclear energy production in core has ceased.
 - ➡ Inert helium core surrounded by a H-burning shell and a H-rich envelope.
 - ➡ $l(m) = \int_m \epsilon_{\text{nuc}} dm = 0 \quad dT/dr \propto l = 0$
- He core is isothermal
 - ➡ Pressure gradient needed to support such star against own gravity: $dP/dr = (RT/\mu)d\rho/dr$ must be due density gradient alone
 - ➡ Would require steep gradients!!
- Stability possible if only isothermal core has a small mass M_c compared to total mass M

$$\frac{M_c}{M} < q_{\text{SC}} = 0.37 \left(\frac{\mu_{\text{env}}}{\mu_c} \right)^2 \approx 0.10$$

- $M_c/M > q_{\text{SC}}$: Pressure in isothermal core cannot sustain weight of overlying envelope! Unstable.
- Typical value $q_{\text{SC}} \approx 0.10$ (He-core with $\mu_c = 1.3$ and H-rich envelope).

Post-main sequence evolution

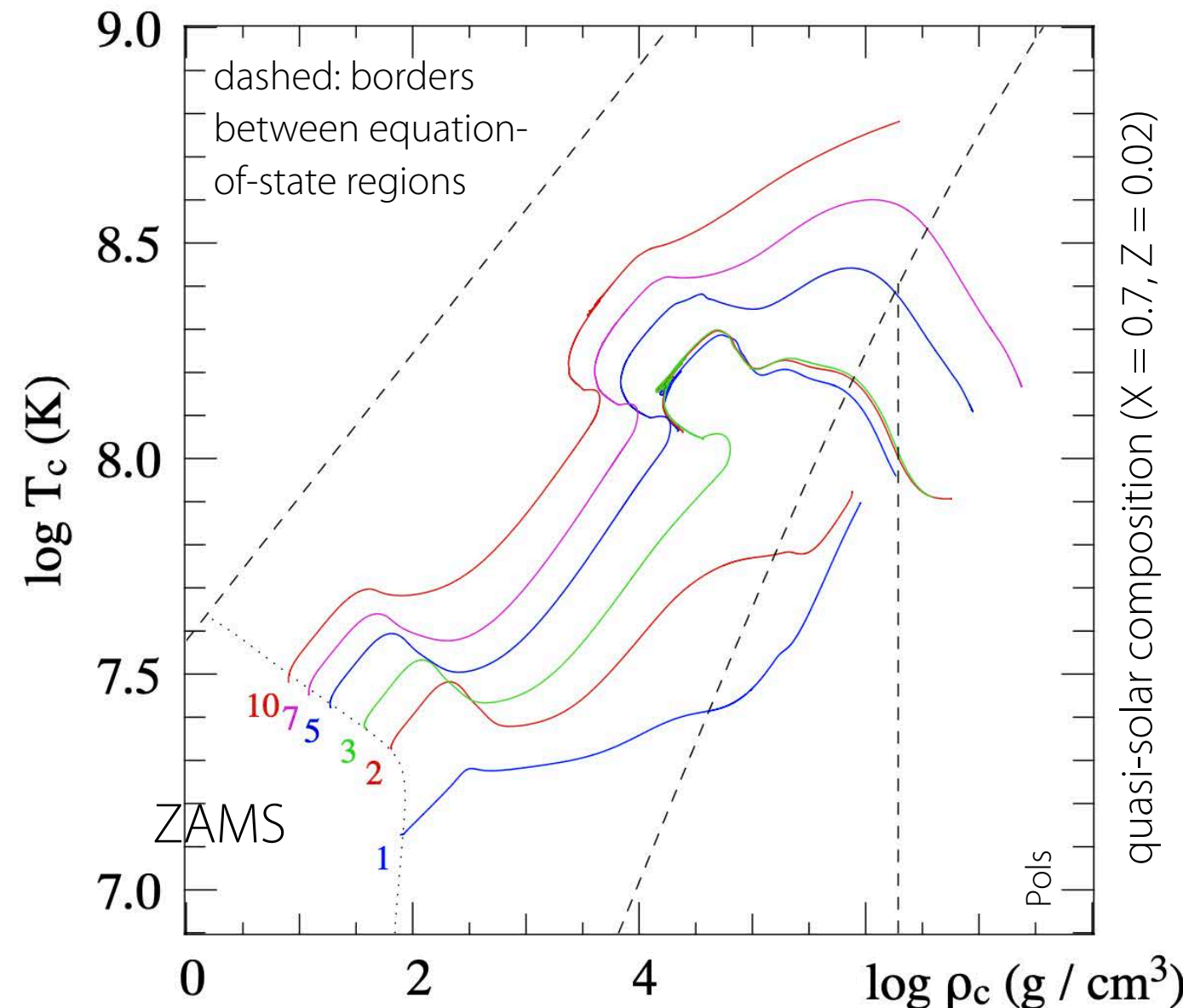
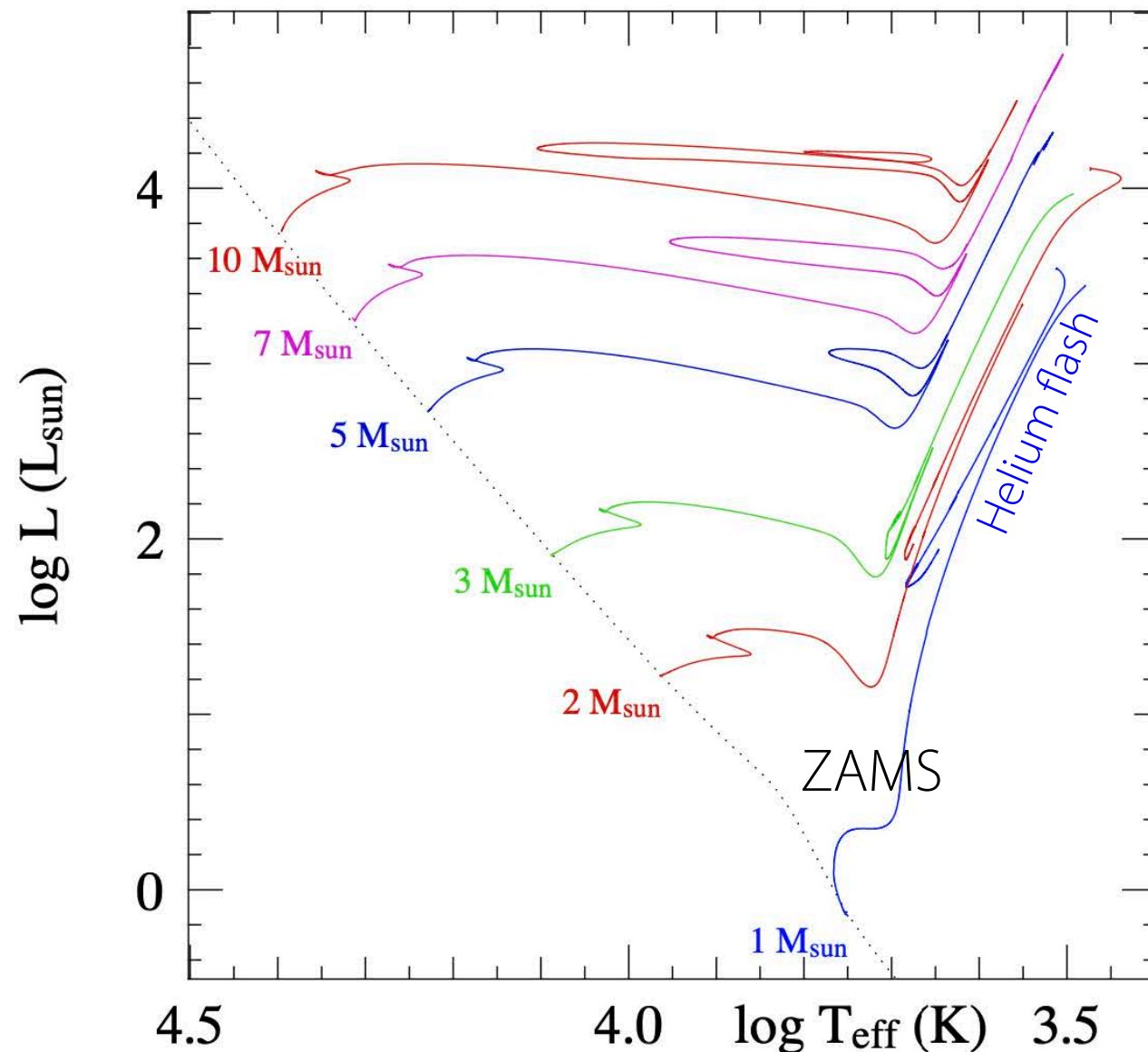
Mirror principle

- “Mirror principle” for stars with active shell-burning source:
Burning shell acts as mirror between the core and envelope
 - core contraction $\Rightarrow$ envelope expansion
 - core expansion $\Rightarrow$ envelope contraction

Post-main sequence evolution

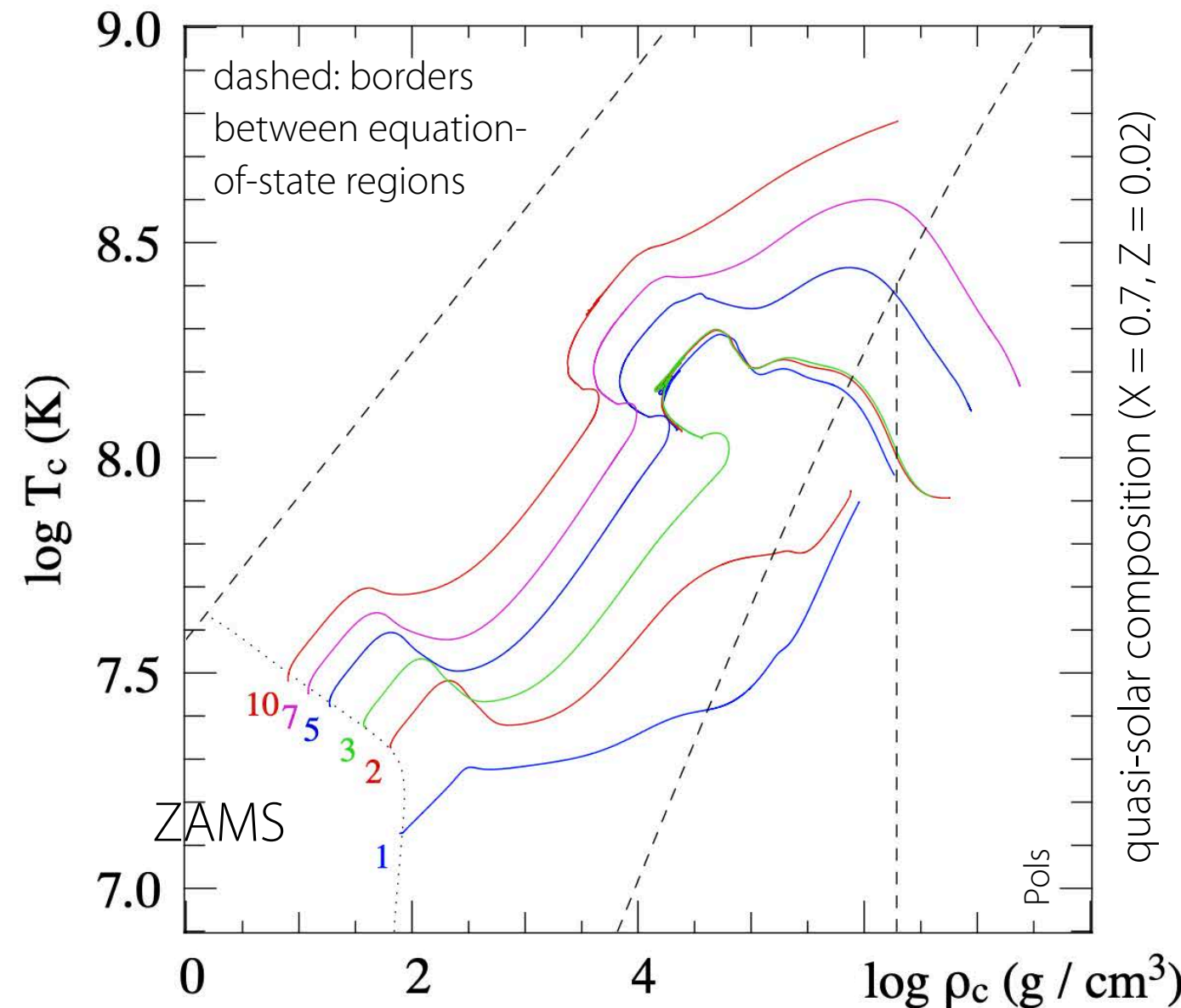
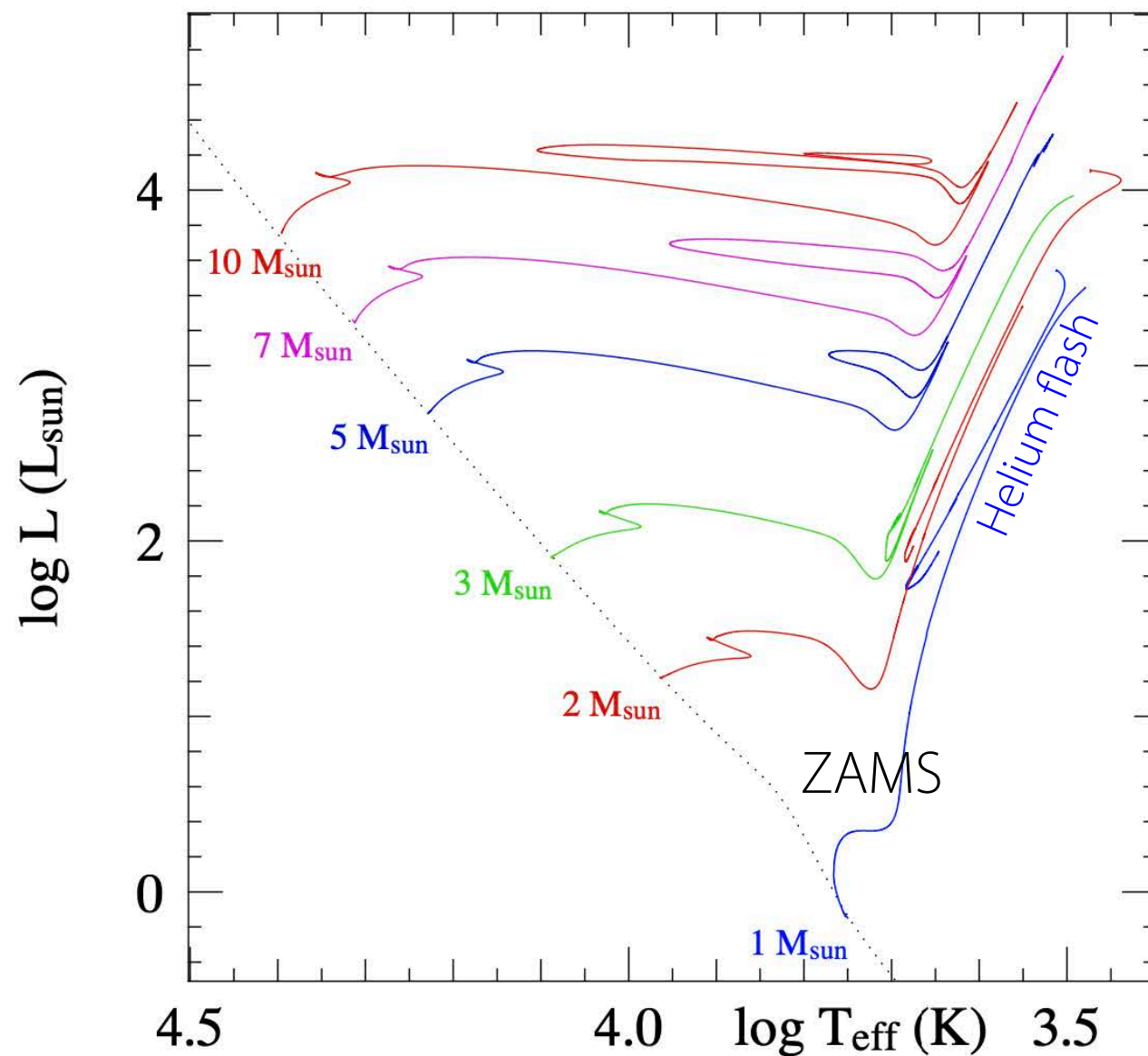
- **1 $M_{\odot}$ (representative of low-mass stars):**

- Central core becomes degenerate after leaving MS
- Helium flash at top of red giant branch
- Degeneracy eventually lifted, He burning becomes stable — star moves to the zero-age horizontal branch ($\log L \approx 1.8$).



Post-main sequence evolution

- **$2 M_{\odot}$** : Borderline case exhibiting He flash
- **$5 M_{\odot}$** (representative of intermediate-mass stars): Quiet He ignition and He burning in a loop
- **$7 M_{\odot}$** : At end of evolution: Core becomes strongly degenerate.
- **$10 M_{\odot}$** (qualitatively similar to $7 M_{\odot}$): At end of evolution: carbon burning in the centre



Stellar evolution

Overview

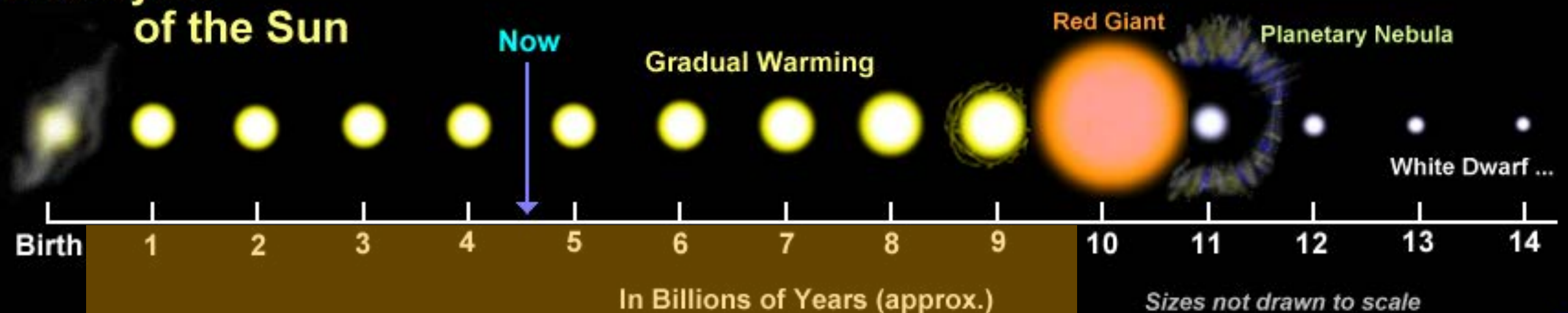
- **Main sequence**

- 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

Life Cycle of the Sun



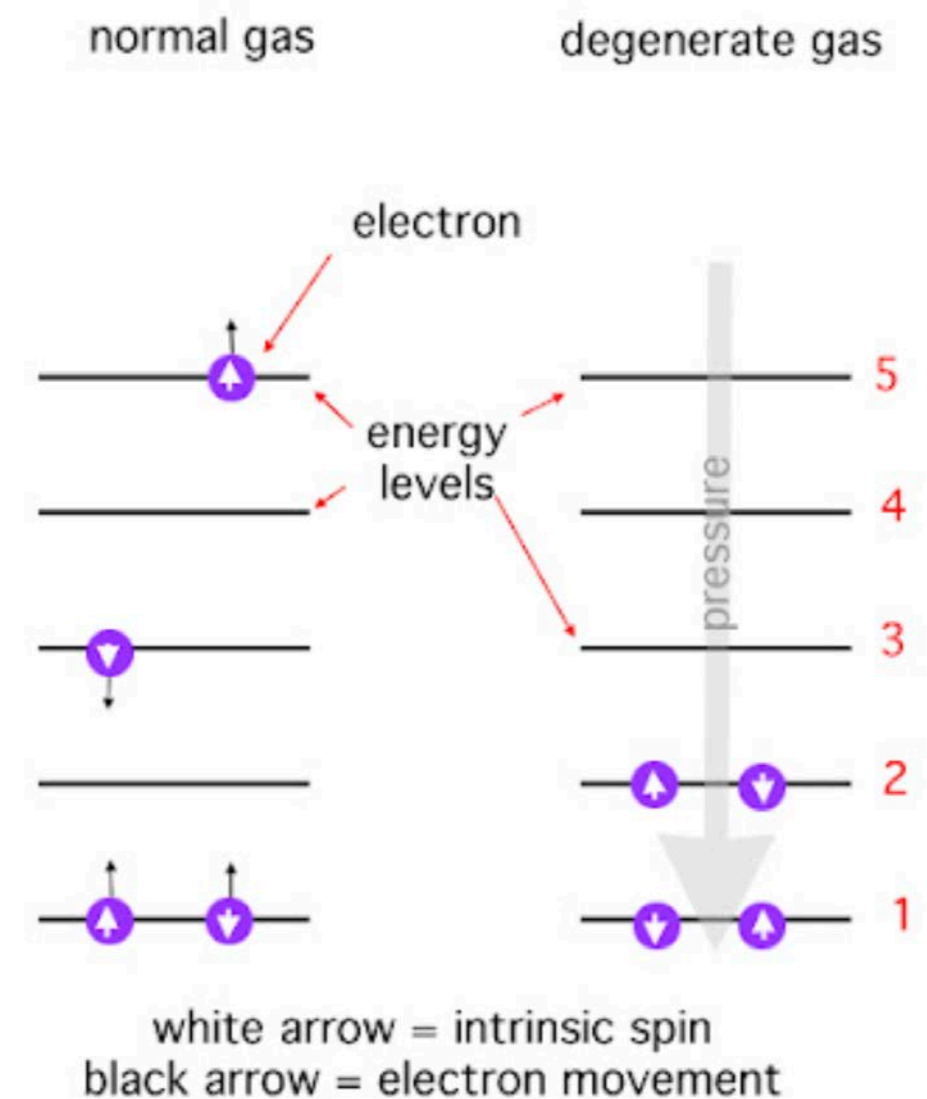
Post-main sequence evolution

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**.



Post-main sequence evolution

Degenerate Matter

- Degenerate gas behaves differently than ideal gas.

- Ideal gas: Pressure depends on density and temperature.
$$P_{\text{gas}} = \frac{kT\rho}{m} = \frac{kT\rho}{m_H \mu} = \frac{RT\rho}{\mu}$$

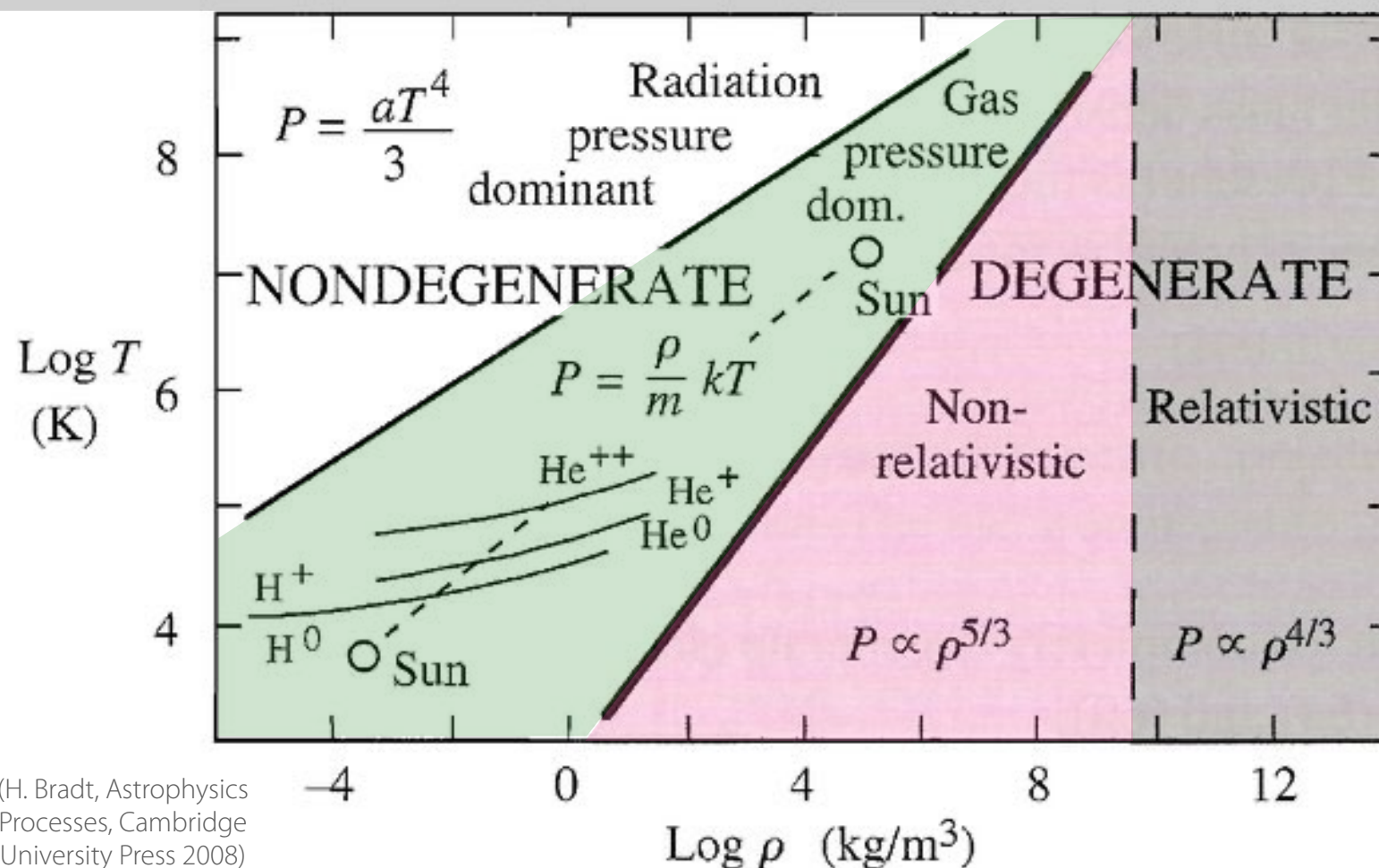
- Degenerate gas: Pressure depends only on density
 ➔ Pressure won't change if temperature changes
 (as long as T low enough to stay in degeneracy regime)

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

- ➔ For a relativistically degenerate gas (i.e. $p_0 \gg m_e c$):

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

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

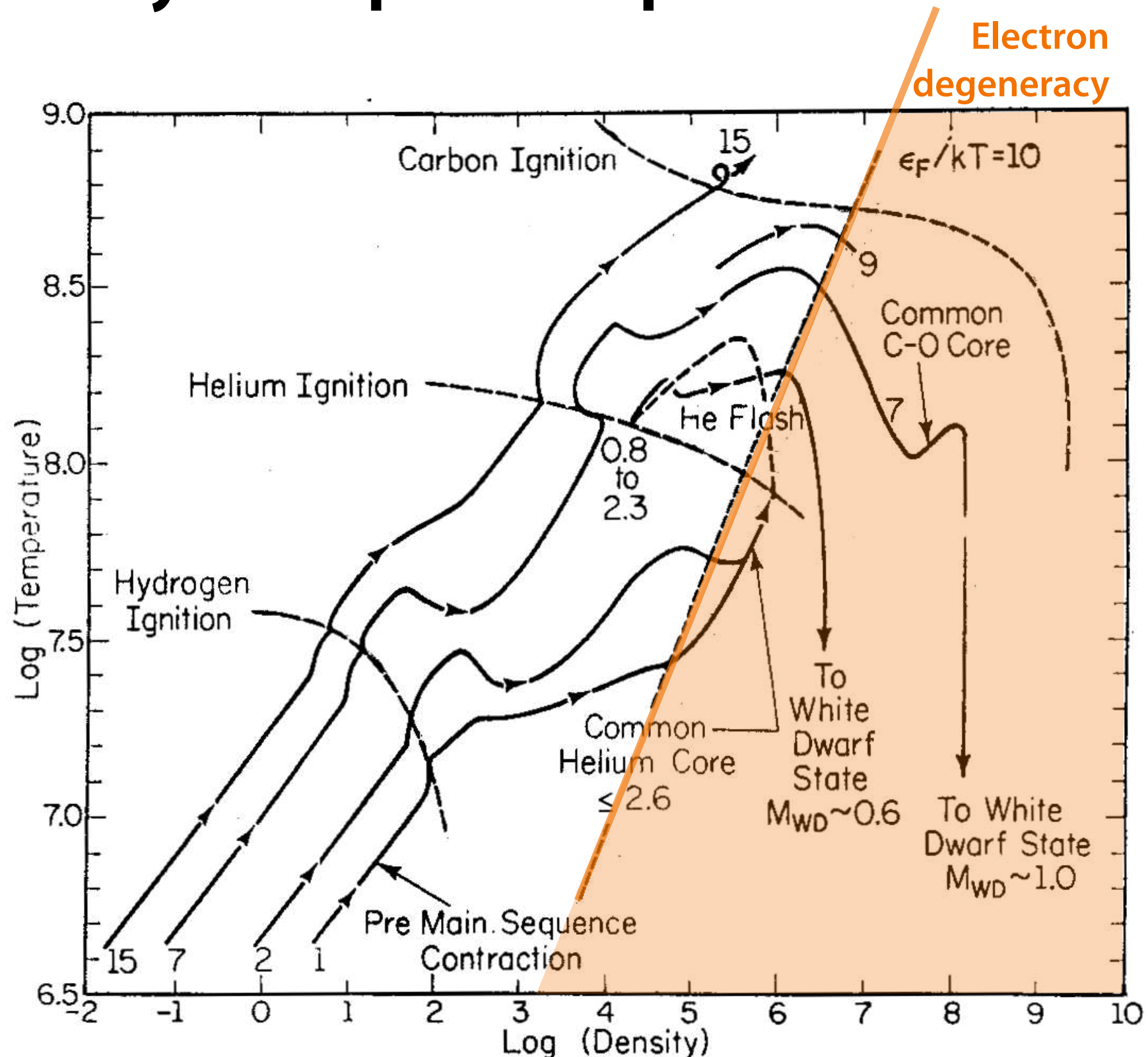


- Note: No sharp transition between ideal gas equation of state and the corresponding degenerate equation of state!
 Continuous transition!

Post-main sequence evolution

Tracks in the core density—temperature plane

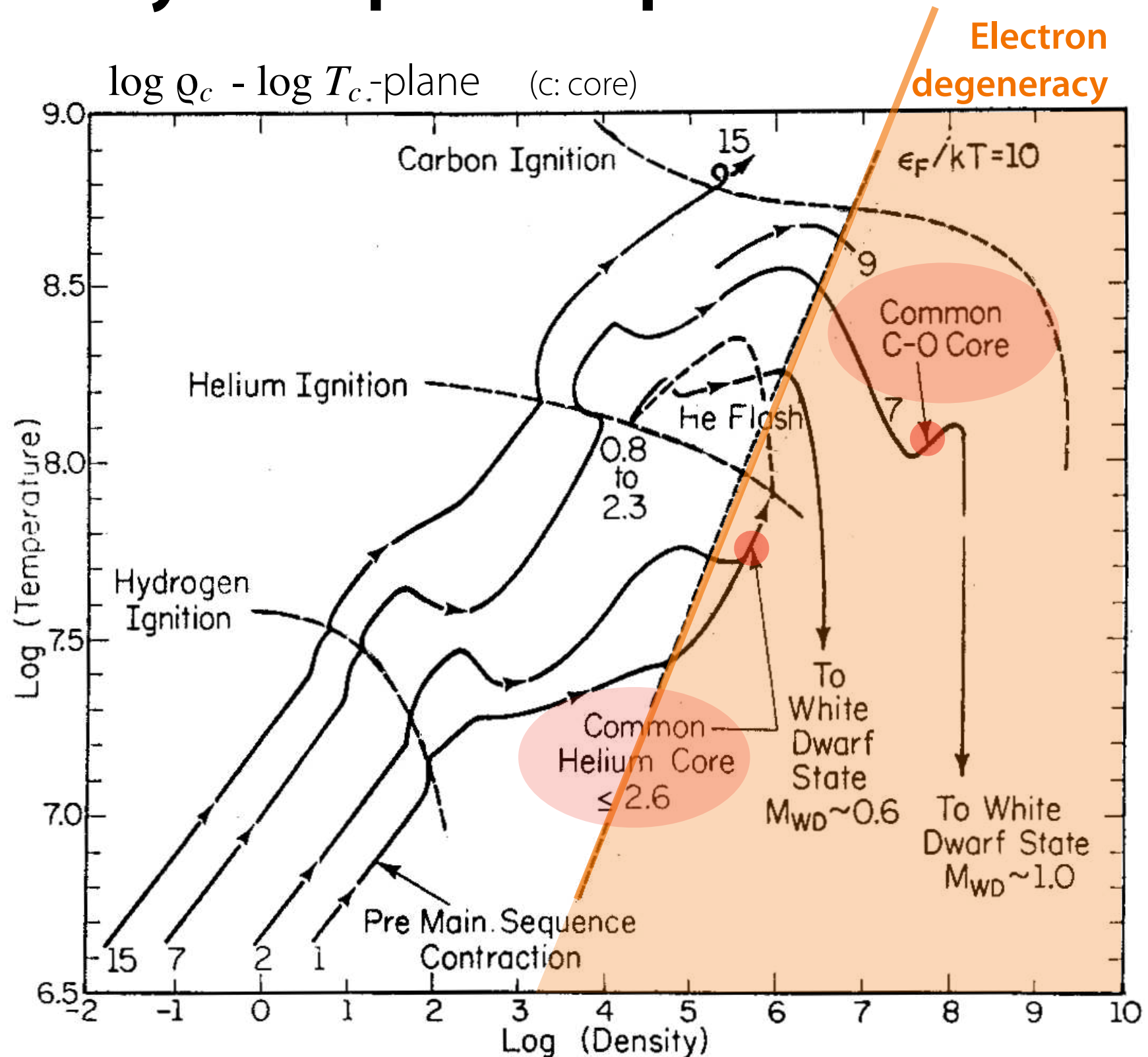
- Evolution tracks in $\log \rho_c - \log T_c$ -plane (c: core)
- **At end of H-burning:** core contracts while outer layers expand (higher density)
 - Occurs for each nuclear burning stage.
- **Core of 7 $M_\odot$ stars:** electron degeneracy before C-ignition temperature is reached, $\Rightarrow$ C-O 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)



Post-main sequence evolution

Tracks in the core density—temperature plane

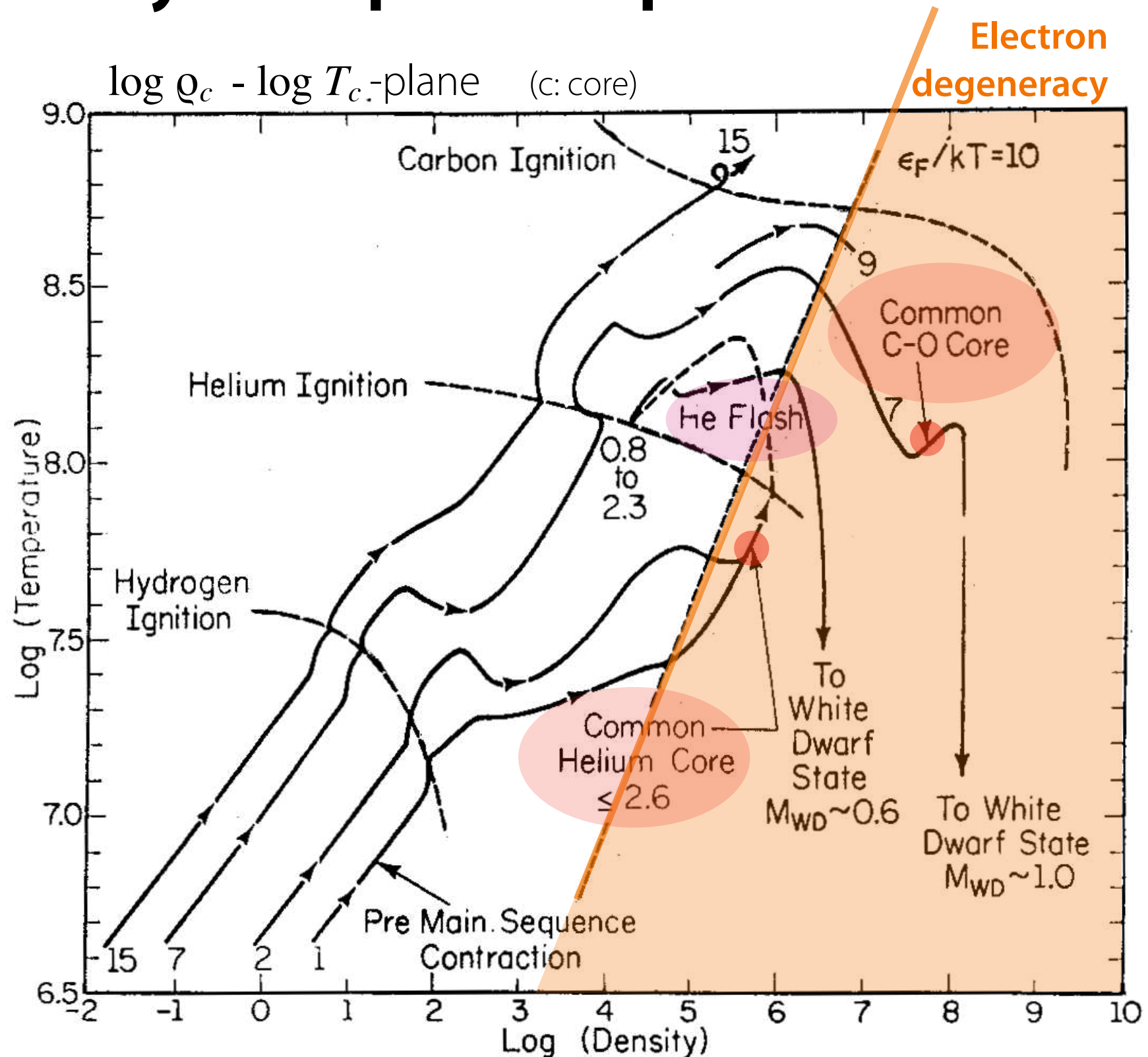
- Evolution tracks in core density-temperature plane ($\log \rho_c - \log T_c$)
- Sun's core becomes degenerate at $\rho_c > 10^6 \text{ kg/m}^3$, $T \sim 2 \cdot 10^7 \text{ K}$.
 ➡ Degenerate core early during red giant phase.
- All low-mass stars, degenerate He core during red giant phase.
- Intermediate and high-mass stars not degenerate while red giants.



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**)



Post-main sequence evolution

Tracks in the core density—temperature

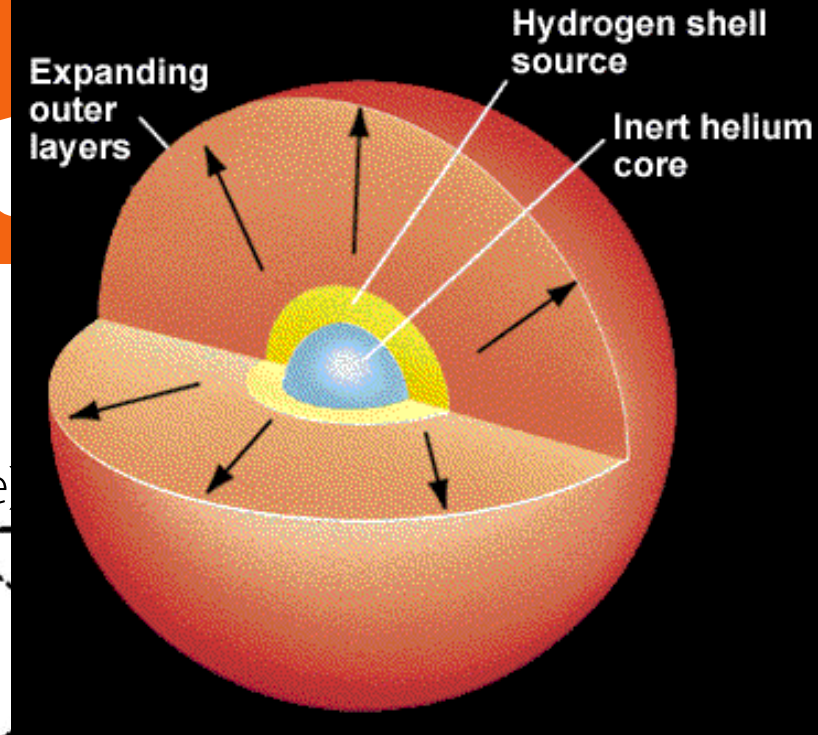
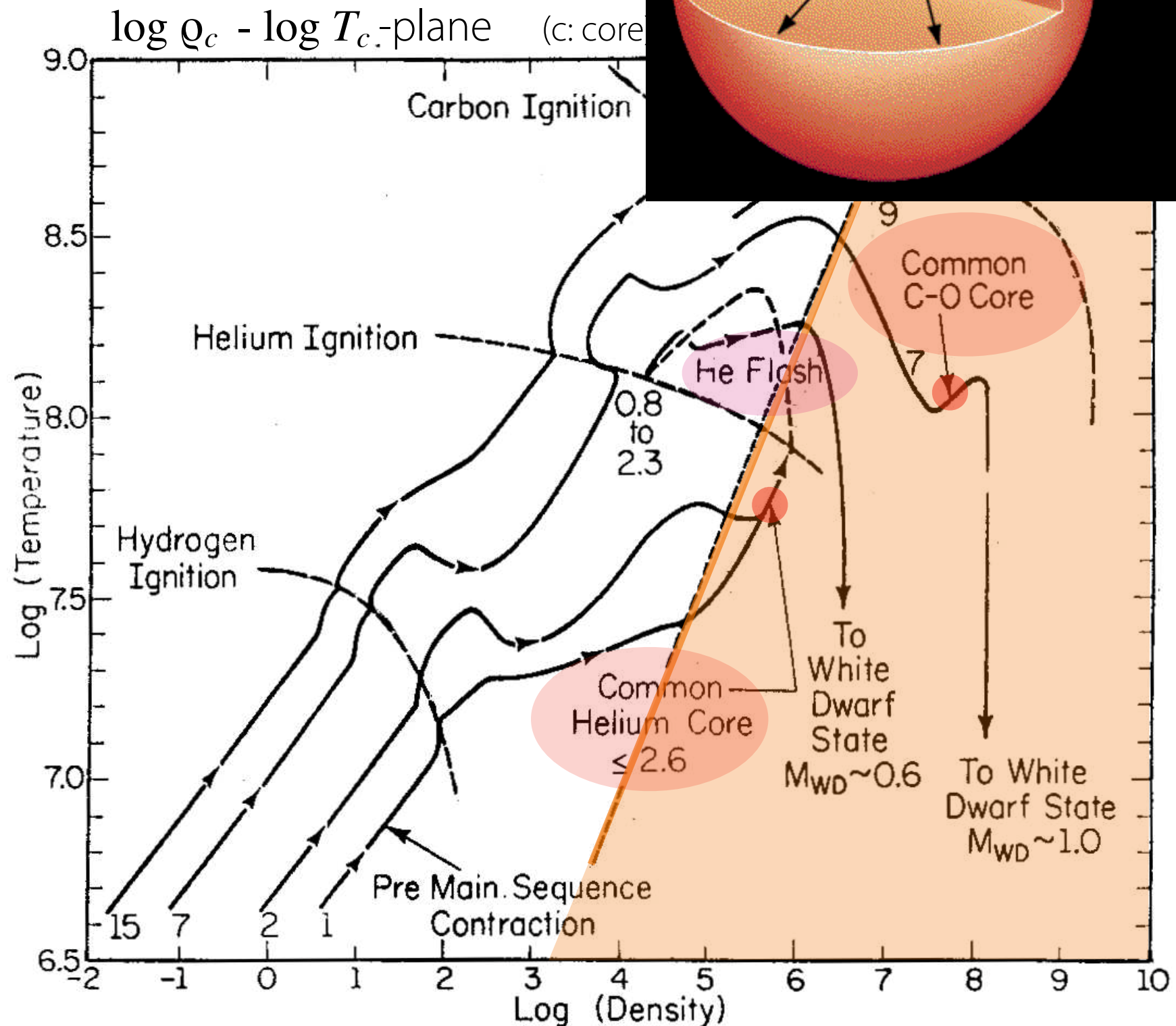
- Schönberg-Chandrasekhar**

(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



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!

