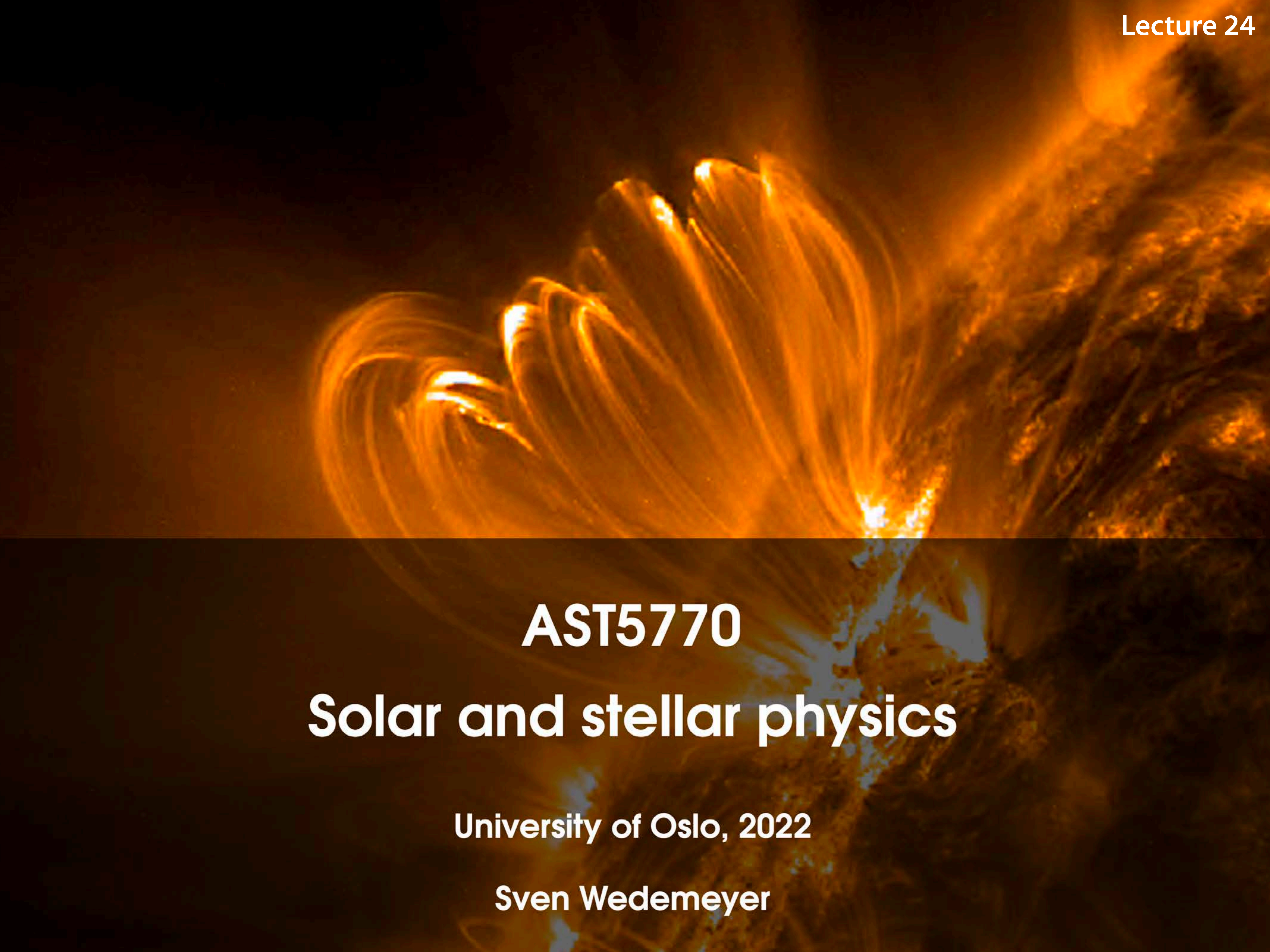


AST5770
Solar and stellar physics

University of Oslo, 2022

Sven Wedemeyer

Corona — Recap

- **Active Regions (AR)** (with prominent coronal loops)
- **Quiet Sun (QS)**
- **Coronal hole (CH)**

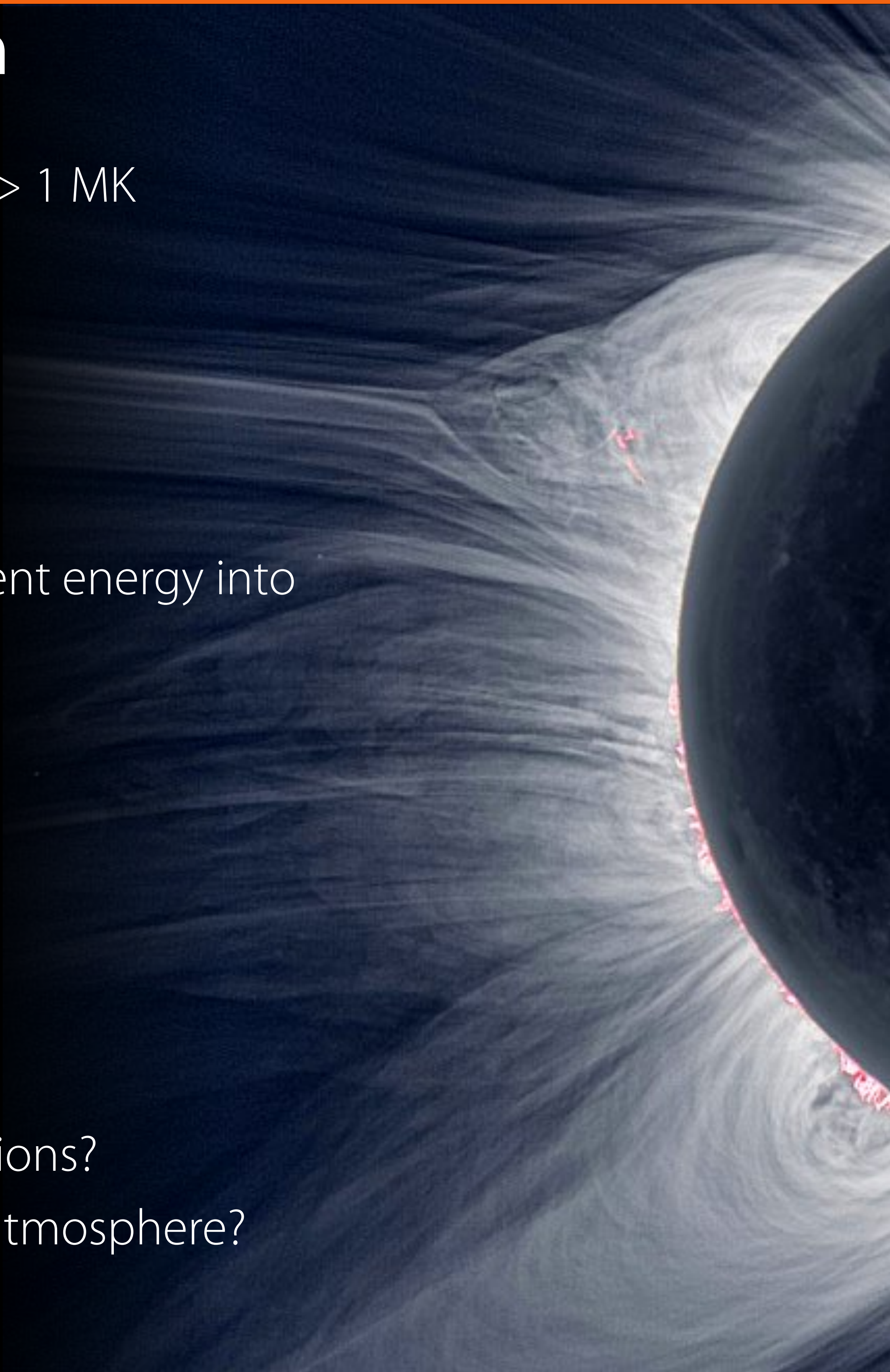
- QS corona ~ 1MK but several MK reached in AR

- Catastrophic cooling — plasma cooling, condensing, falling back down — “coronal rain”

- Many details like width of coronal loop strands, temperature distribution, and required heating still under research
  - Multi-stranded vs. monolithic loops?
  - Important for thermal structure and required heating

Coronal heating — recap

A long-standing central question



- Coronal heating in regions with high temperature >> 1 MK
  - Transient, localised
  - Magnetic reconnection (flares)

- Continuous heating of the "quiescent" parts:
  - Many processes known that can transport sufficient energy into upper atmosphere
  - Two classes:

    I. AC— MHD waves (Alfvén waves)

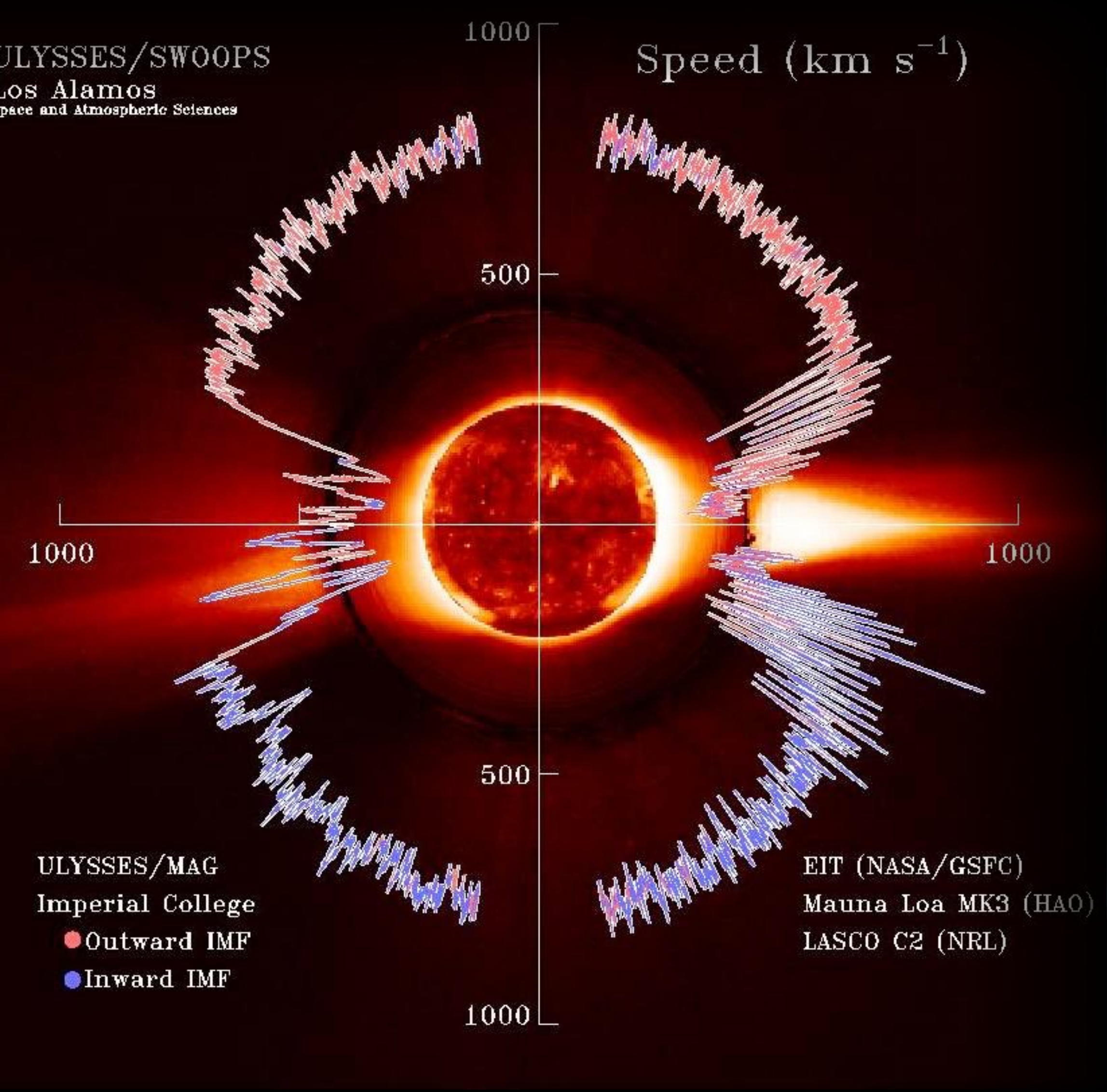
    II. DC— Small-scale reconnection (nano flares)

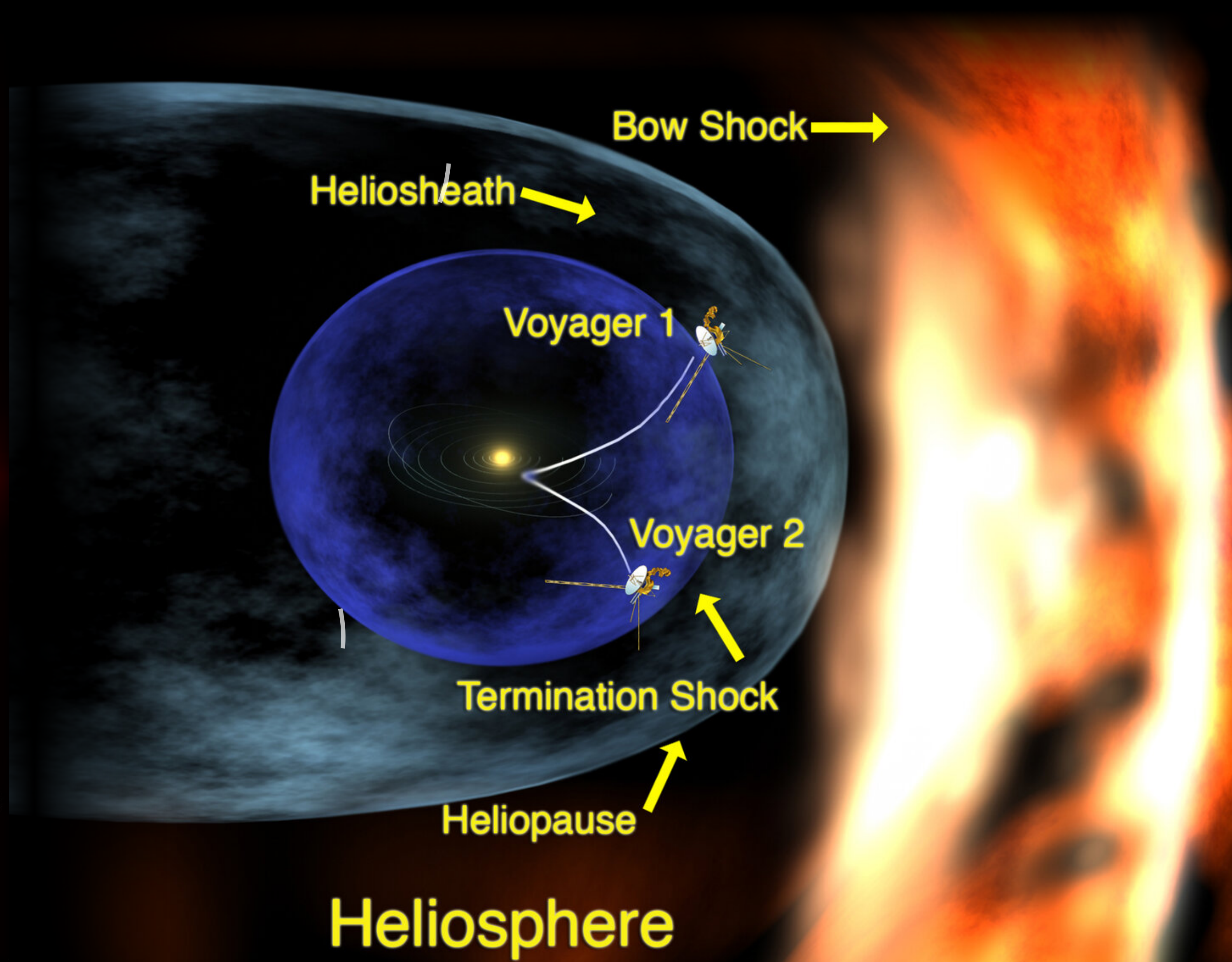
  - Remaining questions:
    - Which process contributes how much?
    - How does that differ between different regions?
    - How to dissipate the energy in the upper atmosphere?

Solar Wind and Heliosphere — Recap

Heliosphere

- Solar magnetic field extends into interplanetary space (Parker spirals!)
- Fast and slow solar wind: Fast wind emerges from coronal holes (open field!)
    - Wind depends on magnetic field, varies with solar cycle
- Solar wind meets interstellar medium — creates heliosphere, our "local bubble" (heliopause at ~120 AU)





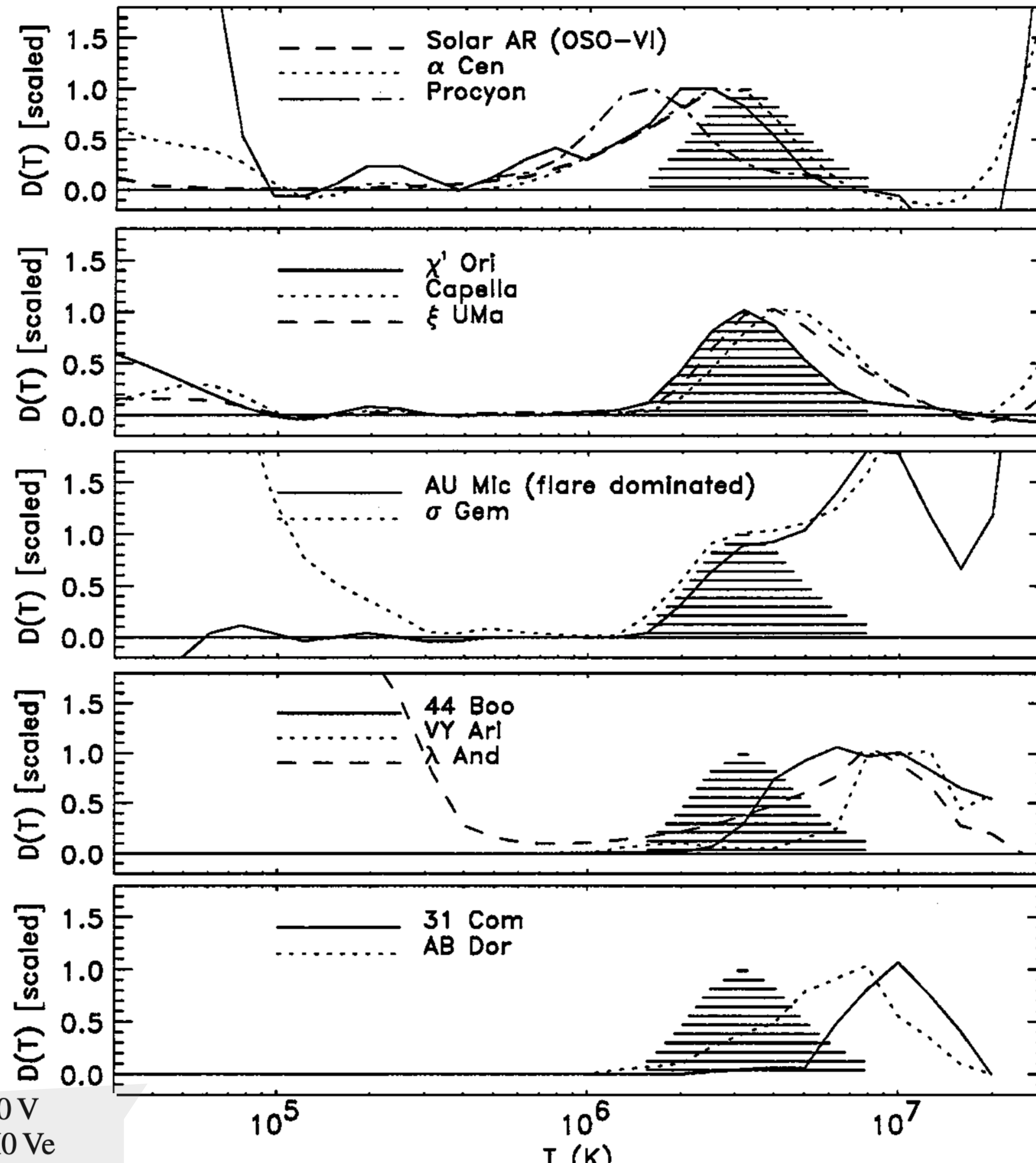
Rough positions in ~2008. Illustration only.

ESA

Stellar coronae

Observations

- Spectral line observations of other stars (incl. differential emission measure) compared to AR/Sun
- Clear indications for existence of coronae for late-type stars (spectral type F and cooler)
- Also observed emission at shorter wavelengths (EUV, X-rays) and radio wavelengths consistent with coronal emission expected for this type of stars



Dashed region = χ^1 Ori, repeated for reference

α Cen	G2 V + K2 V	Procyon	F5 IV–V	χ^1 Ori	G0 V
Capella	G5 III+G0 III	ξ Uma B	G0 V	AU Mic	M0 Ve
σ Gem	K1 III	44 Boo	G0 V	VY Ari	K3–4 V–IV
λ And	G8 IV–III	31 Com	G0 III	AB Dor	K0 V*

Schrijver et al (1996), S; Data from Mewe et al (1995), Schrijver et al (1995), Schmitt et al (1996), Dere(1982)

Stellar coronae

Observations

- Plasma properties can be derived, e.g. electron densities from EUV observations
- Note: Stellar observations are spatially unresolved

  ➡ Average properties only

- Caution: How are these properties affected by unresolved variations?!?

Just as an example…

Table 9.3. *Electron densities, n_e, for quiescent stellar coronae, derived from spectra obtained with the Extreme Ultraviolet Explorer,* EUVE[a]

Source	$n_e(\mathrm{cm}^{-3})$	Fe Lines	Ref.[b]
Procyon (F5 IV–V)	$(1\text{–}10) \times 10^9$	X–XIV	1
	$(1\text{–}30) \times 10^9$	X–XIV	2
α Cen (G2 V+K2 V)	$(2\text{–}20) \times 10^8$	X–XIV	3
Capella (G5 III+G0 III)	10^9	XII–XIV	4
($P = 104$d, $d = 167 R_\odot$)	$(1\text{–}20) \times 10^{11}$	XXI–XXII	4
	$(1\text{–}20) \times 10^{12}$	XIX–XXII	1
σ Gem (K1 III+…)	10^{12}	XXI–XXII	1
($P = 19.6$d, $d = 59 R_\odot$)	$< 3\,10^{12}$	XXI–XXII	5
ξ UMa B (G0 V+…)	5×10^{12}	XXI–XXII	1
($P = 3.98$d, $d = 12 R_\odot$)			

[a] For binary stars, the components expected to dominate the observed spectrum have been underlined. For close binaries, the orbital period P and mean separation d are also listed. For comparison, the electron density in bright loops in solar active regions is $\sim 3 \times 10^8$ cm^{-3} (Section 8.6).

[b] References: 1, Schrijver *et al.* (1995); 2, Schmitt *et al.* (1996a); 3, Mewe *et al.* (1995); 4, Brickhouse (1996); 5, Monsignori-Fossi and Landini (1994).

Stellar Evolution

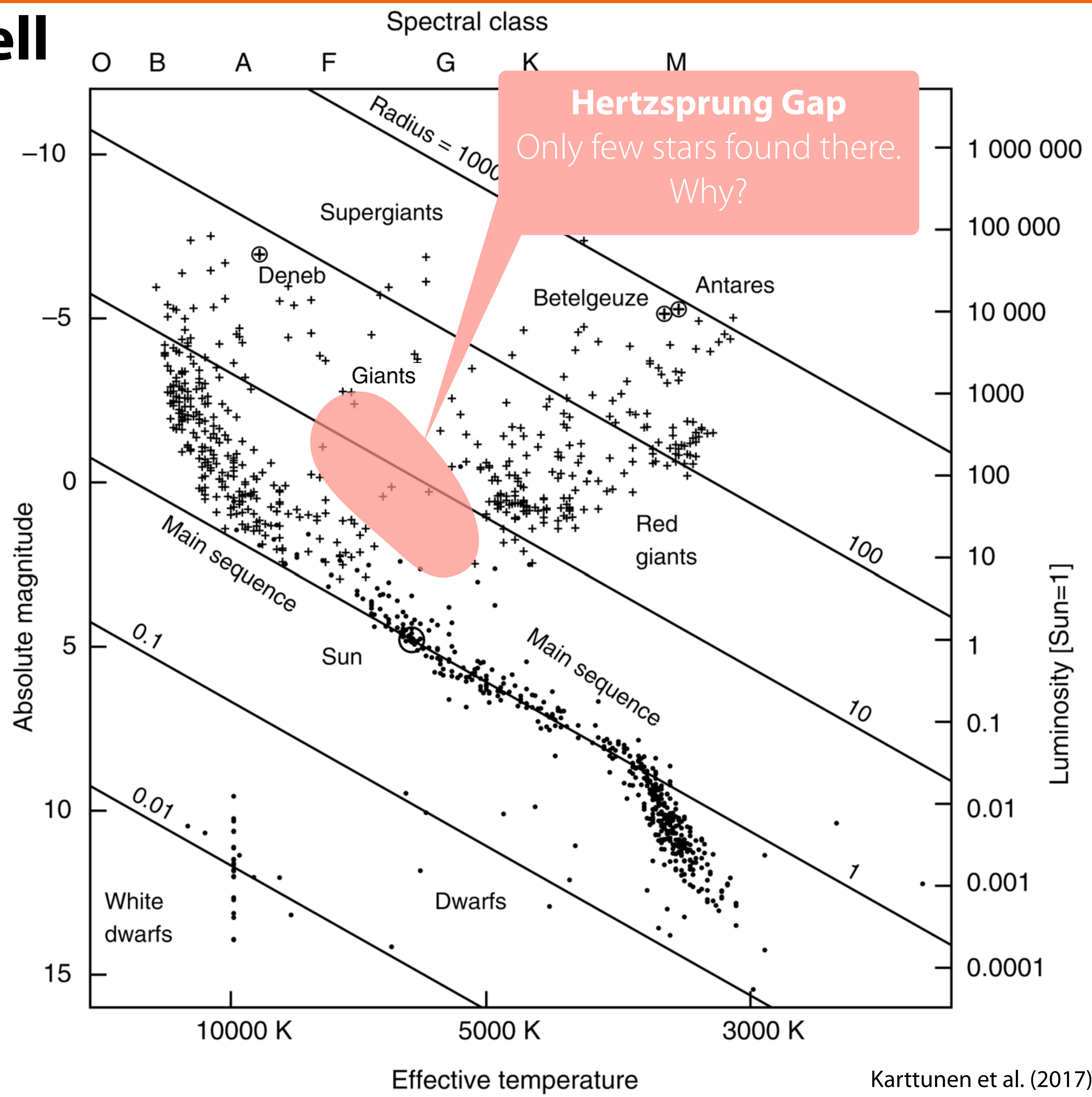
Stellar evolution

Hertzsprung-Russell diagram

- Stars clearly not distributed randomly
- Connections between
  - T_{eff}/Spectral class
  - Luminosity/absolute brightness
  - Radius

➡ Constraints for models of structure and evolution of stars

- Theory shows: Groups of stars represent different stages of their evolution but depends on mass (and chemical composition)



Karttunen et al. (2017).

Stellar evolution

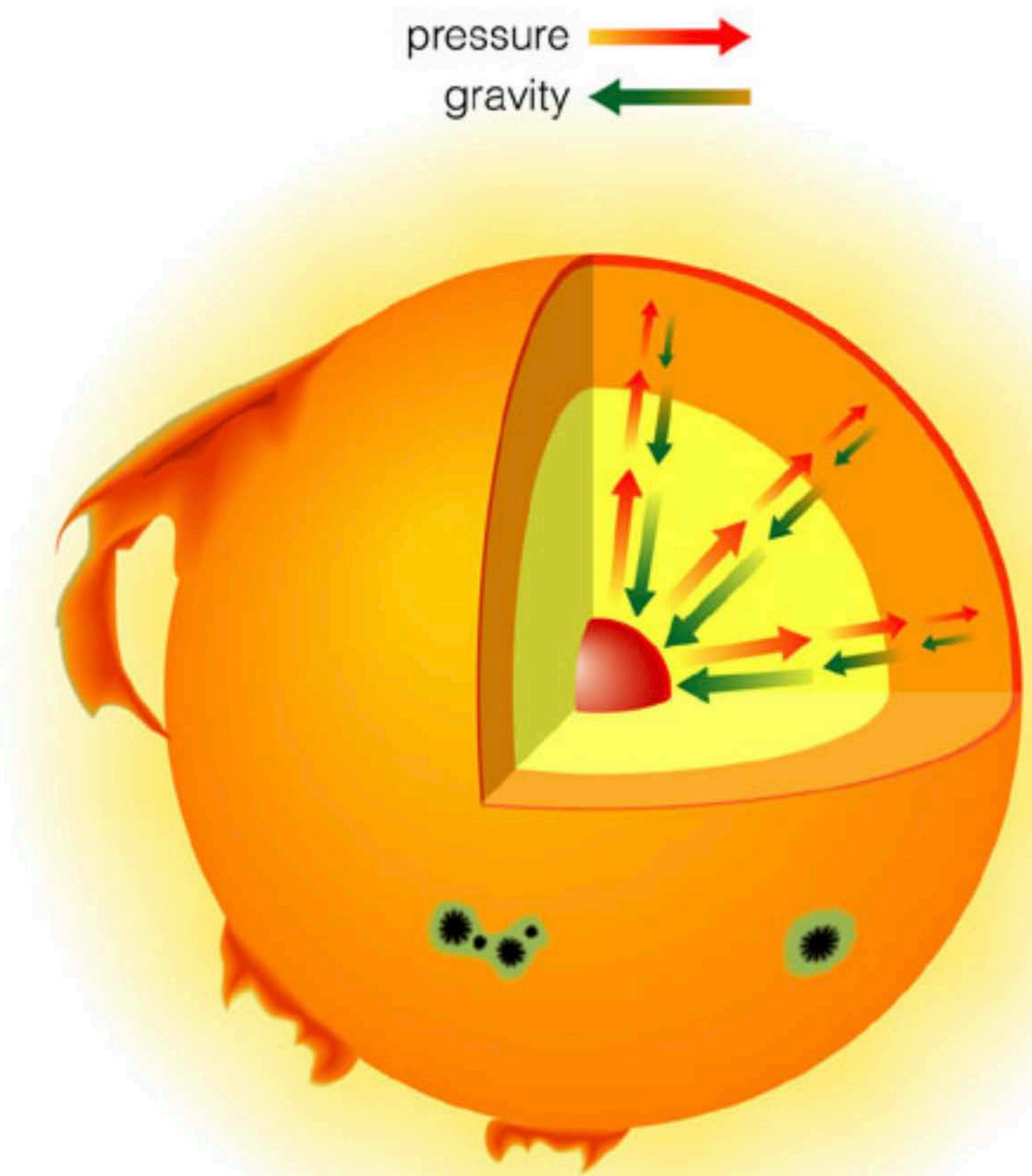
Introduction

- Stellar evolution equations highly non-linear

➡ Complicated solutions that cannot always be anticipated based on fundamental principles, much depends on detailed numerical computations

- Simplifications and approximations usually needed (e.g., for convection, rotation, magnetism,…)

- **Basic principles**
    - Hydrostatic equilibrium required to keep a star stable and shining for extended time
    - The battle against gravity — energy source needed to keep the star stable
    - Slow adjustments of structure during evolution to maintain stability, some phase with more rapid changes
    - Time scales important — determine which processes are matter the most at a given evolution stage



Star formation and pre-main sequence evolution

Star formation and pre-main sequence evolution

- Process of star formation still poorly understood
- Predictions not easily possible

  ➡ How much of the gas in an interstellar cloud at given density and temperature will end up in stars?

  ➡ Star formation efficiency? Initial mass function?

- Stars formed in **(giant) molecular clouds**
  - Mass ~ 10^5 $M_\odot$
  - Extent ~ 10 parsec
  - Temperatures 10 – 100 K
  - Densities of 10 – 300 molecules/cm^3
  - Dust content ~1 % (makes clouds very opaque at visual wavelengths)
  - In hydrostatic equilibrium with surrounding interstellar medium

Star formation and pre-main sequence evolution

Interstellar cloud collapse and fragmentation

- Cloud initially in hydrostatic equilibrium
- Now: Perturbation (e.g., shock wave from nearby supernova, collision with another cloud)
- (Critical) **Jeans mass**

$$M_{\rm J} \approx 4 \times 10^4\, M_\odot \left(\frac{T}{100\,{\rm K}}\right)^{3/2} \left(\frac{n}{{\rm cm}^{-3}}\right)^{-1/2}$$

T: temperature
n: molecular density

  - Cloud with $M < M_{\rm J}$ remains stable (pressure equilibrium)
  - Cloud with $M > M_{\rm J}$ starts to collapse under its own gravity (free-fall collapse)
  - $M_{\rm J} \sim 10^3 - 10^4\, M_\odot$ for typical T and n in molecular clouds

- **Collapse** — dynamical timescale $\tau_{\rm dyn} \propto \varrho^{-1/2}$
  - ~millions of years due to low densities
  - Cloud transparent in far-infrared radiation

  ➡ Cools efficiently.

  ➡ Early stages of the collapse are isothermal.

- Density increases.

➡ Jeans mass decreases

➡ Only smaller fragments can remain stable

➡ **Fragmentation**

  - Continues until mass of smallest fragments becomes $M < 0.1\, M_\odot$.

Star formation and pre-main sequence evolution

Formation of a protostellar core and disk

- Density increases.

➡ Gas becomes increasingly opaque in IR, cools less.

➡ Temperature and gas pressure increase

➡ Cloud core establishes hydrostatic equilibrium

➡ Dynamical collapse slowed down to slow contraction

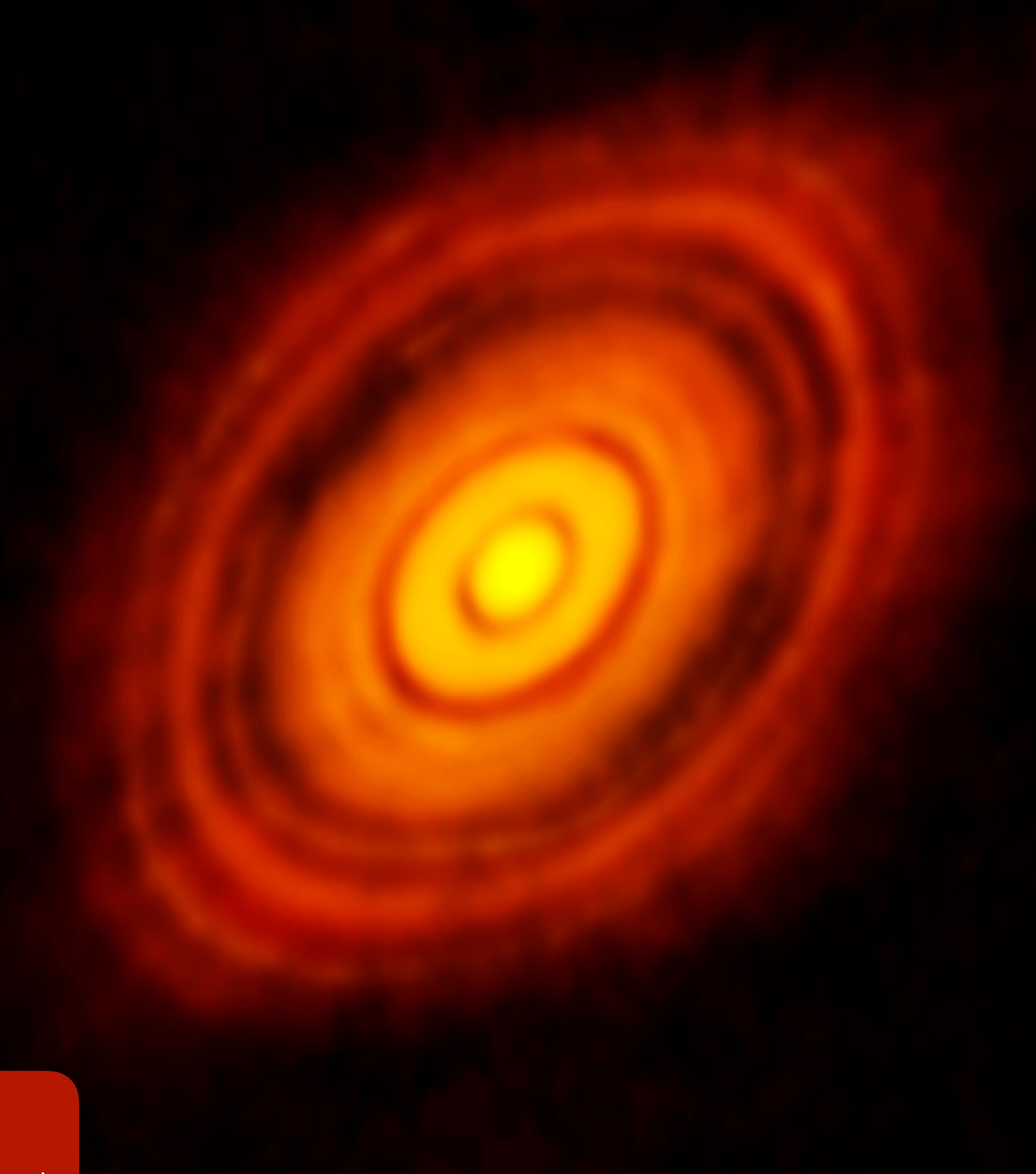
➡ **A protostar if formed!**

- Conservation of angular momentum of infalling gas

➡ **Accretion disk** around protostar is formed

- Can be observed at infrared to sub-millimeter wavelengths

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



HL Tauri ALMA (ESO/NAOJ/NRAO)

Star formation and pre-main sequence evolution

Dissociation and ionisation

- Gas initially molecular hydrogen H_2, behaves like an ideal gas ($\gamma_{\rm ad} > {}^4/_3$)
  - Protostellar core dynamically stable.
  - Core temperature reaches eventually ~2000 K
  - H_2 starts to **dissociate**

  ➡ Strong increase of specific heat, $\gamma_{\rm ad}$ 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

Dissociation of H_2:	$\chi_{H_2} = 4.48$ eV per molecule
Ionisation of H:	$\chi_H = 13.6$ eV per atom
Ionisation of He:	$\chi_{He} = 79$ eV per atom

- **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

Pleiades (M45)

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 $T \propto M^{2/3} \varrho^{1/3}$

- 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:

  ➡ $T \sim 8\ 10^4$ 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!

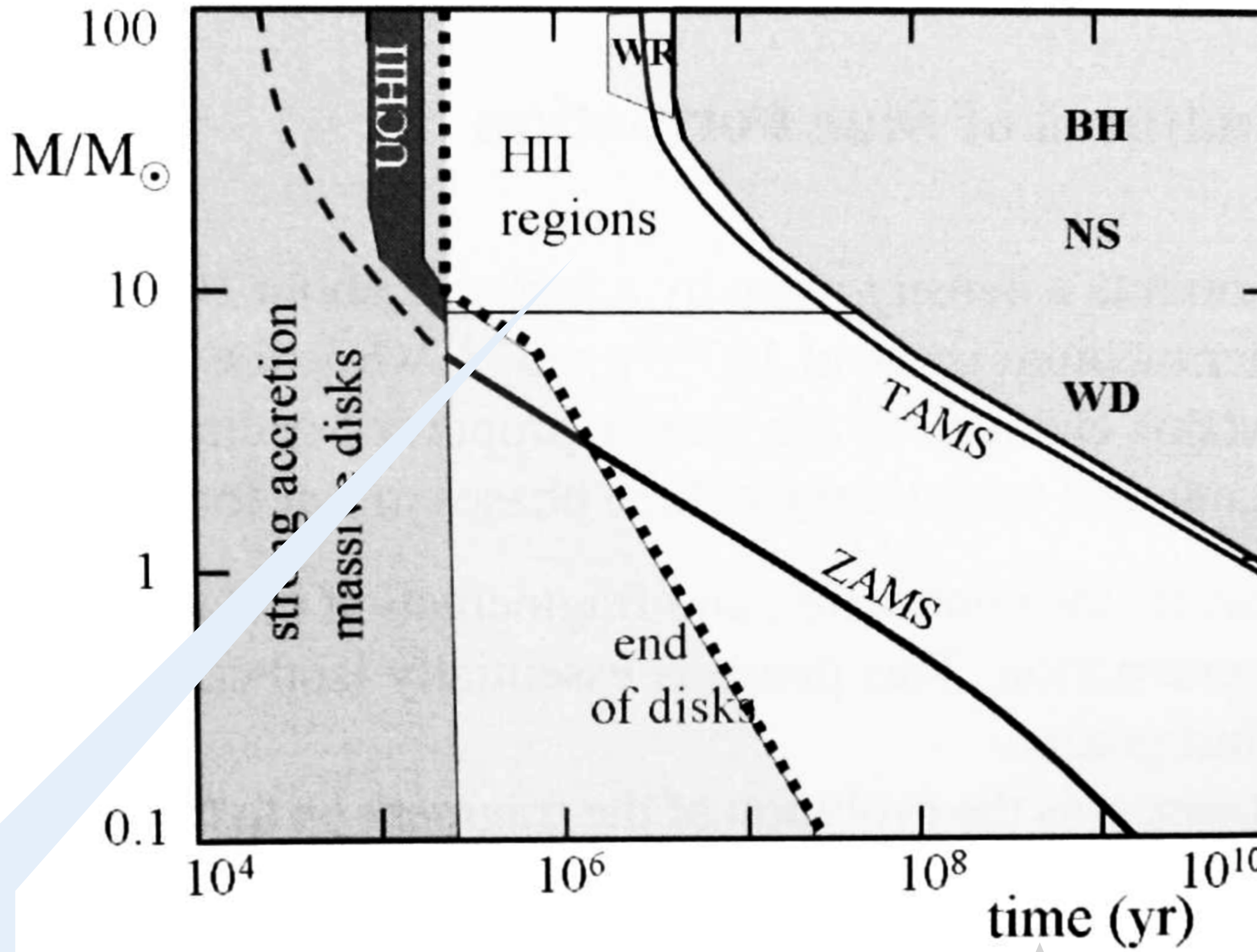
  ➡ PMS star becomes fully convective!

Pleiades (M45)

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



Pols / Maeder

- 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.

Star formation and pre-main sequence evolution

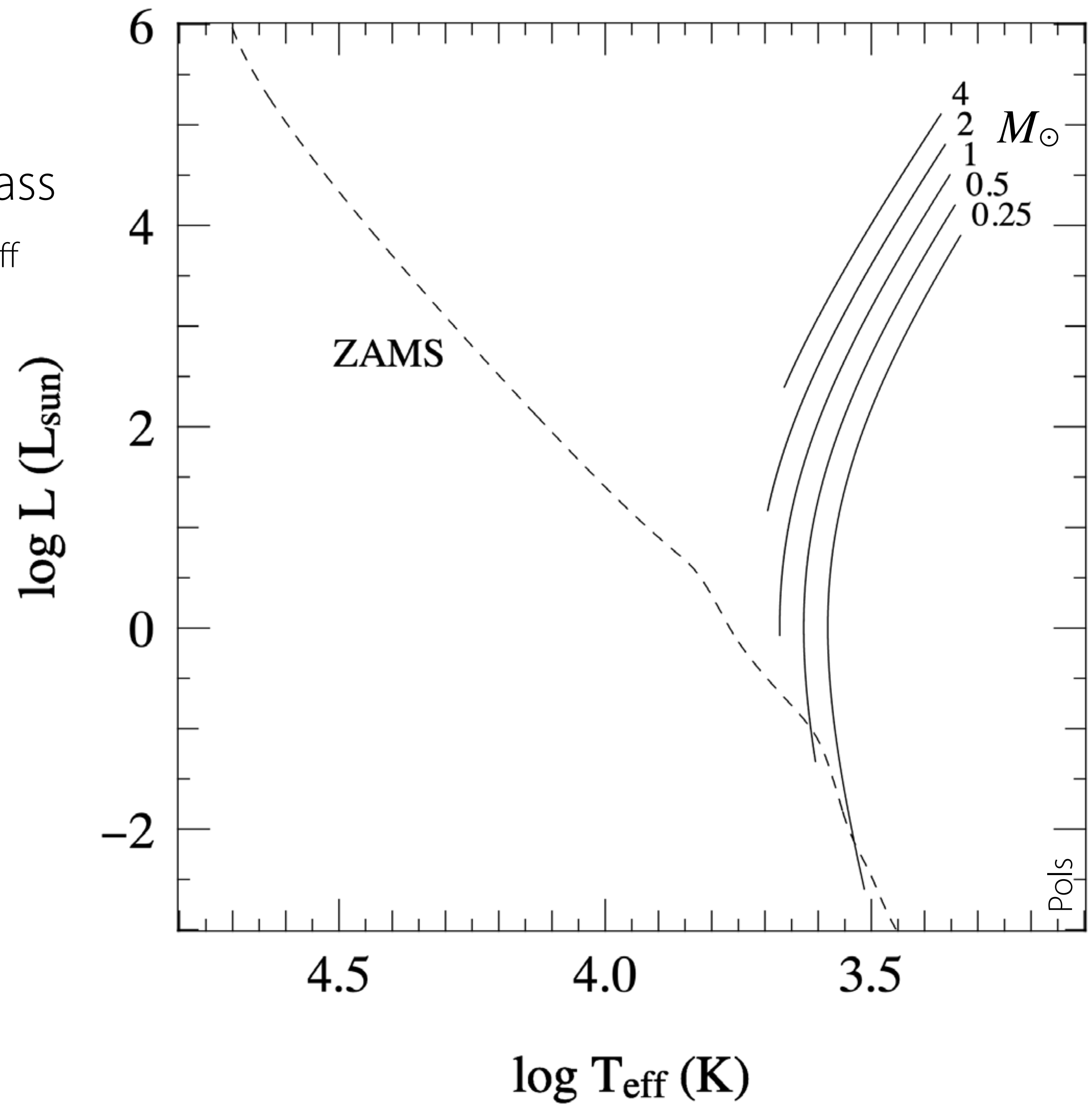
Hayashi line

- Fully convective stars of the same given mass placed along nearly vertical line in HRD (T_{eff} ≈ 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 ($\nabla - \nabla_{ad}$) sufficient to transport very energy flux
  - Interior structure ~ adiabatic

  ➡ Luminosity of a fully convective star basically independent of its structure!



Track should be more vertical (simplified calculations)

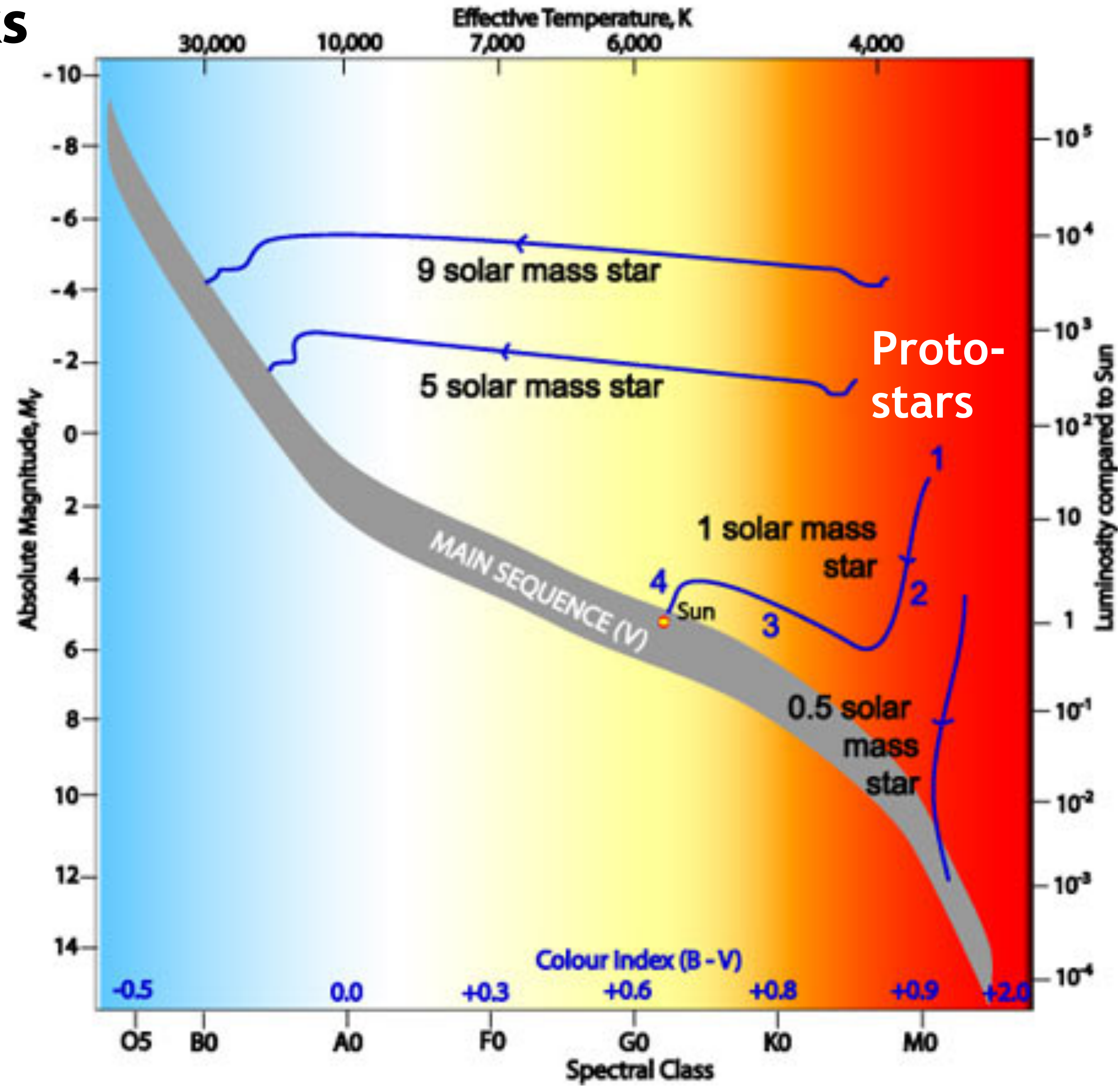
- Shape of Hayashi line determined by opacity in photosphere (dependence on ρ, *T*) .
- Fully convective stars: low T_{eff}

  ➡ 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 $M_\odot$

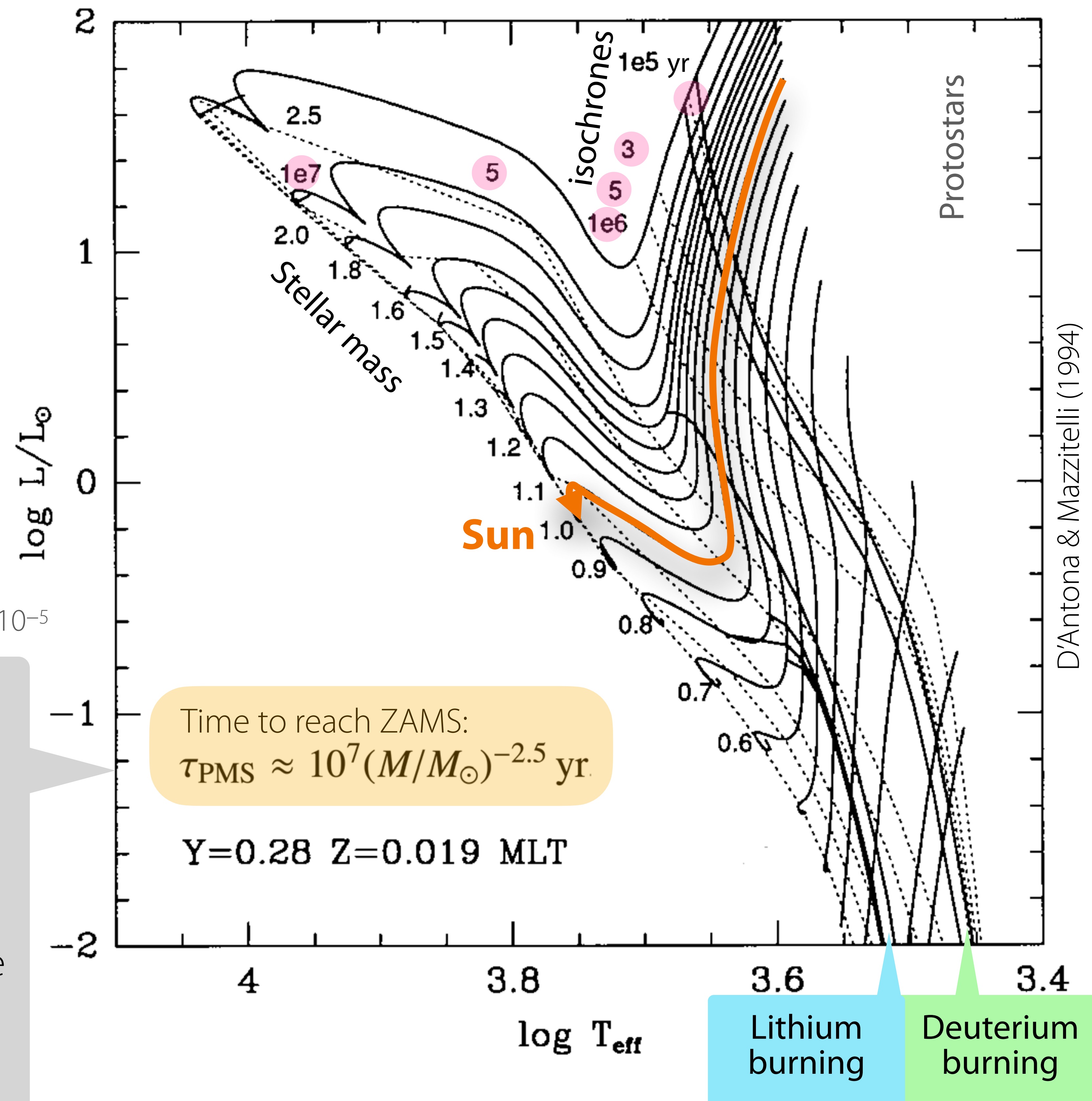
- Newly formed star after dynamical collapse phase: settles on Hayashi line appropriate for its mass
- Further evolution (PMS) follows track depending on mass (and chemical composition)

➡ Gravitational contraction and increase of T_{eff}

➡ Deuterium and lithium burning

Mass fraction of deuterium in interstellar gas ~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



Time to reach ZAMS:
$\tau_{PMS} \approx 10^7 (M/M_\odot)^{-2.5}$ yr

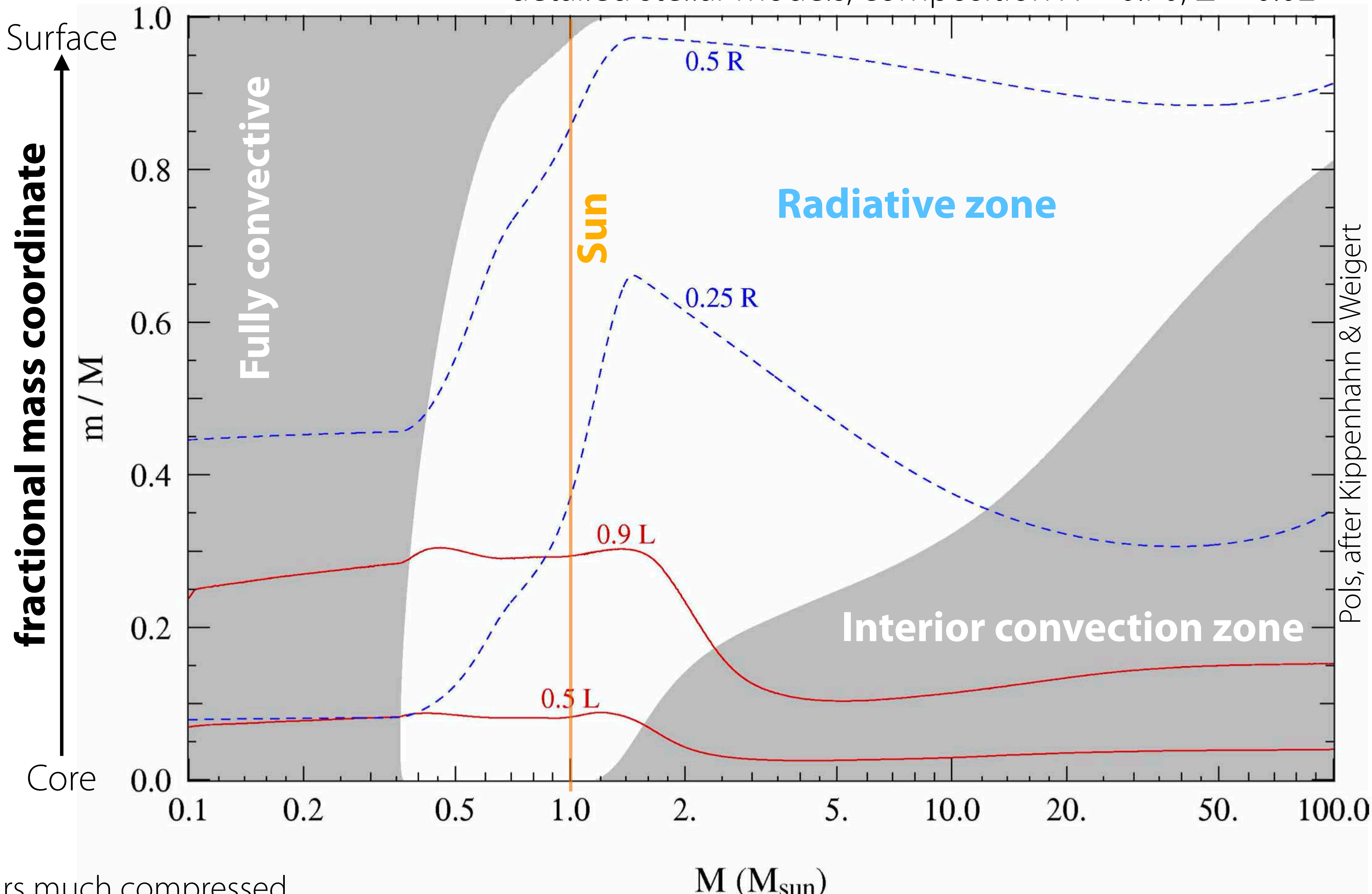
Main sequence evolution

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.

detailed stellar models, composition X = 0.70, Z = 0.02



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

Main sequence evolution

Leaving the ZAMS

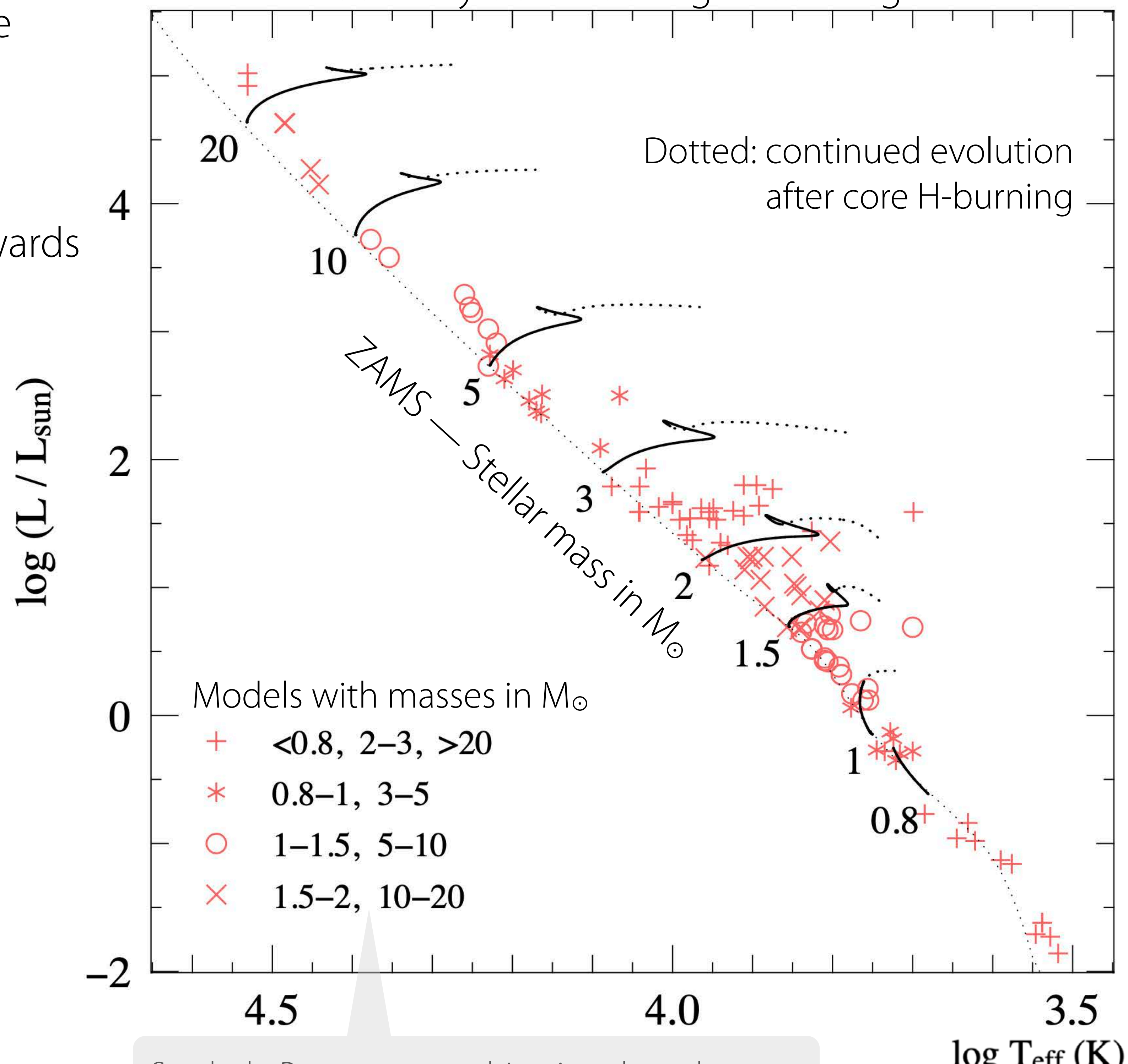
- Slow gradual formation of inert He core

➡ Adjustments of interior structure

➡ Away from ZAMS towards higher luminosities and larger radii

- Low-mass stars (M < 1 M⊙) evolve towards higher T_{eff} , radius increases slightly
- Higher-mass stars evolve towards lower T_{eff}, 2-3 times increase in radius

Evolutionary tracks during H-burning in core



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

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

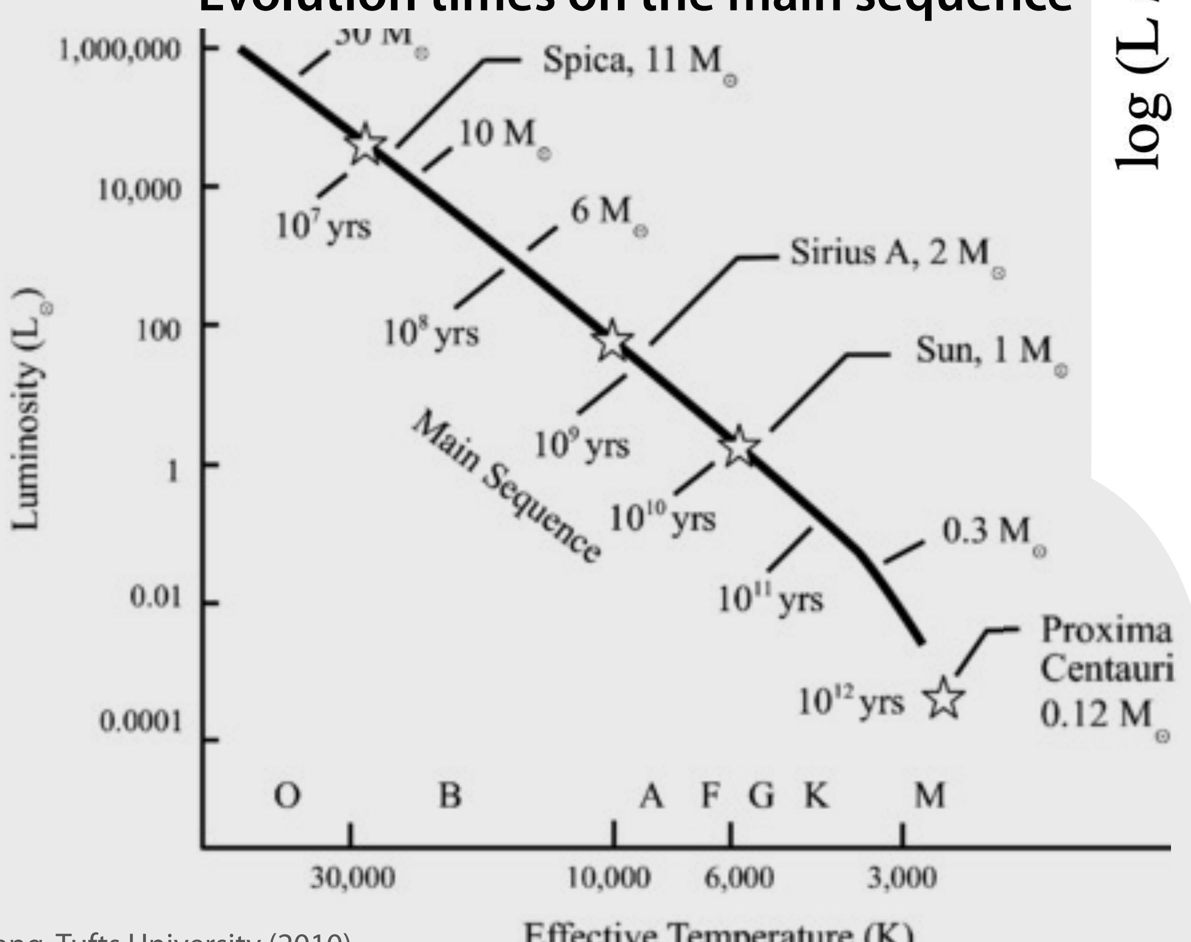
- Nuclear energy generation rate ε_{nuc} very sensitive to (core) temperature.
- Nuclear reactions act like a *thermostat*
- Keep core temperature almost constant.
- CNO cycle a better thermostat than the pp chain due to higher exponent of temperature dependence

Main sequence evolution

Leaving the ZAMS

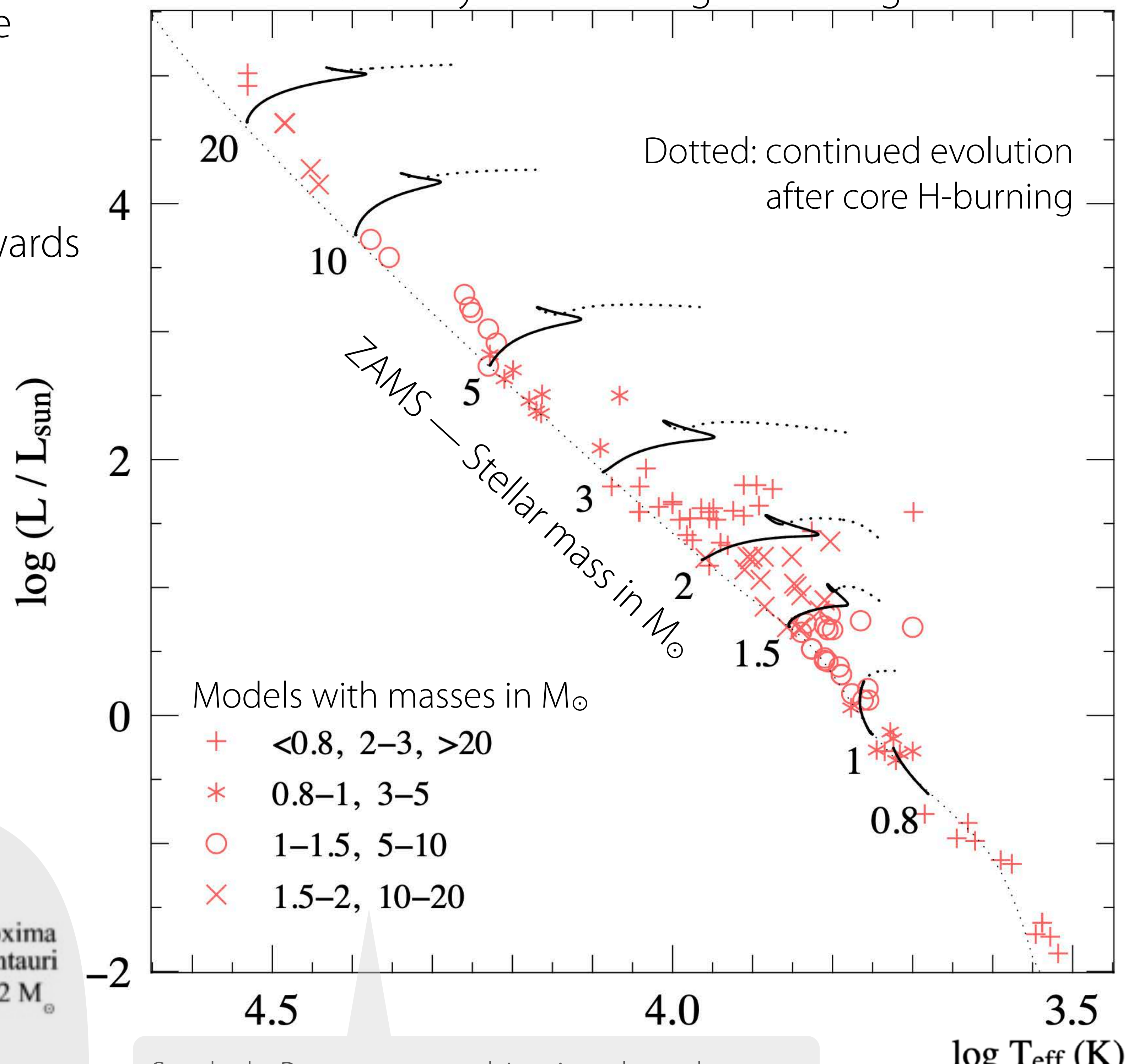
- Slow gradual formation of inert He core
- ➡ Adjustments of interior structure
- ➡ Away from ZAMS towards higher luminosities and larger radii
- Low-mass stars (M < 1 M⊙) evolve towards higher T_{eff}, radius increases slightly
- Higher-mass stars evolve towards lower T_{eff}, 2-3 times increase in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

Evolution times on the main sequence



Lang, Tufts University (2010)

Evolutionary tracks during H-burning in core



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)

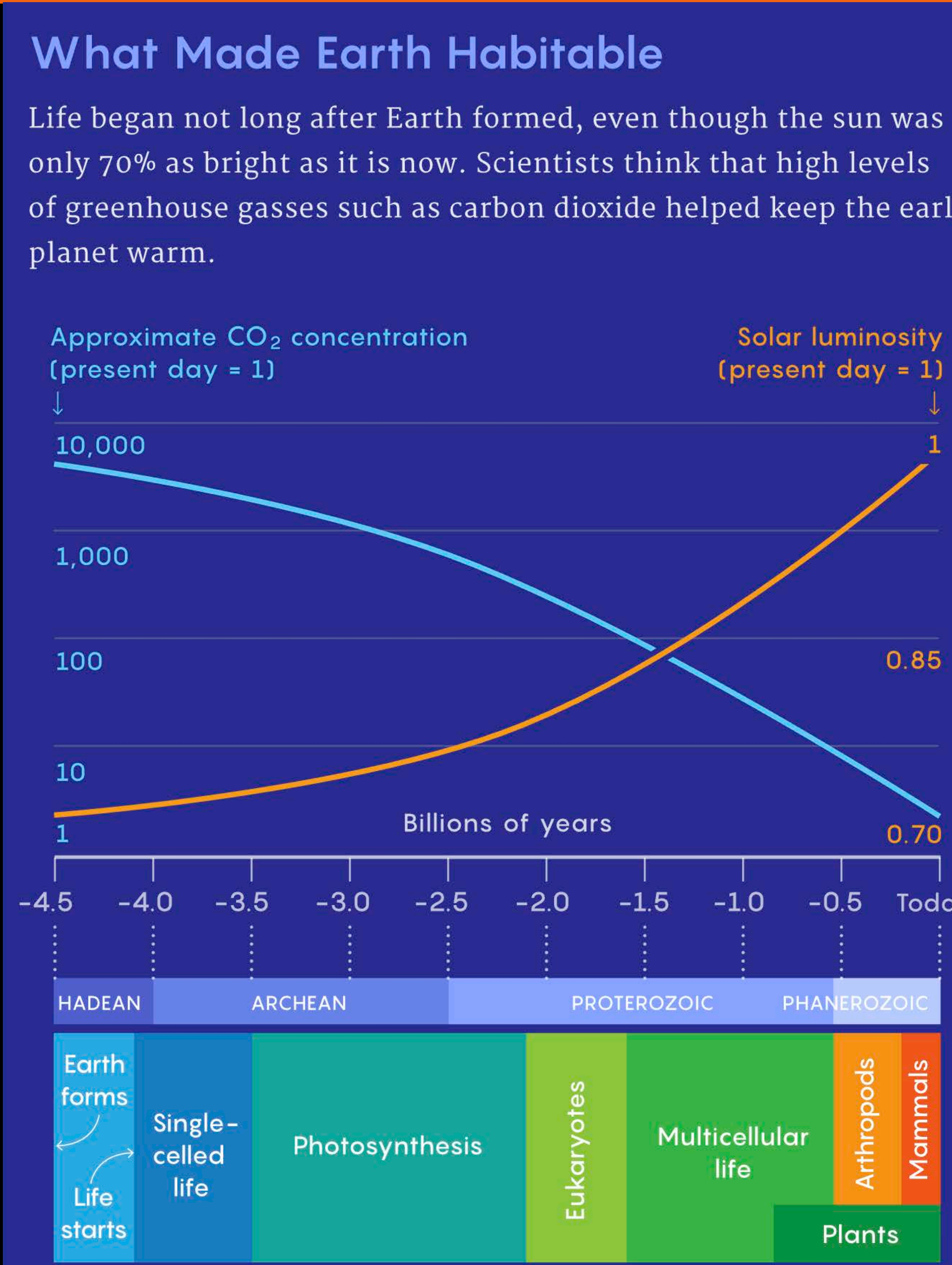
  ➡ 4.5 billion years ago:
  ~30% fainter than today!

  ➡ 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!?)



Samuel Velasco/Quanta Magazine; source: Catling and Kasting (2017)

Post-main sequence evolution

Post-main sequence evolution

Overview — Dependence on mass

- Evolution depends on mass — Basic division:
- **Low-mass stars** (up to ~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 ~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 $\tau_{\mathrm{nuc}} \gg \tau_{\mathrm{KH}}$
  ➡ Hydrogen-exhausted core is gradually formed I
- 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.

➡ $l(m) = \int_m \epsilon_{\mathrm{nuc}}\, \mathrm{d}m = 0$ $\quad \mathrm{d}T/\mathrm{d}r \propto l = 0$

- He core is isothermal
  ➡ Pressure gradient needed to support such star against own gravity: $\mathrm{d}P/\mathrm{d}r = (\mathrm{R}T/\mu)\mathrm{d}\varrho/\mathrm{d}r$ 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

$$\frac{M_{\mathrm{c}}}{M} < q_{\mathrm{SC}} = 0.37 \left(\frac{\mu_{\mathrm{env}}}{\mu_{\mathrm{c}}}\right)^2 \approx 0.10$$

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

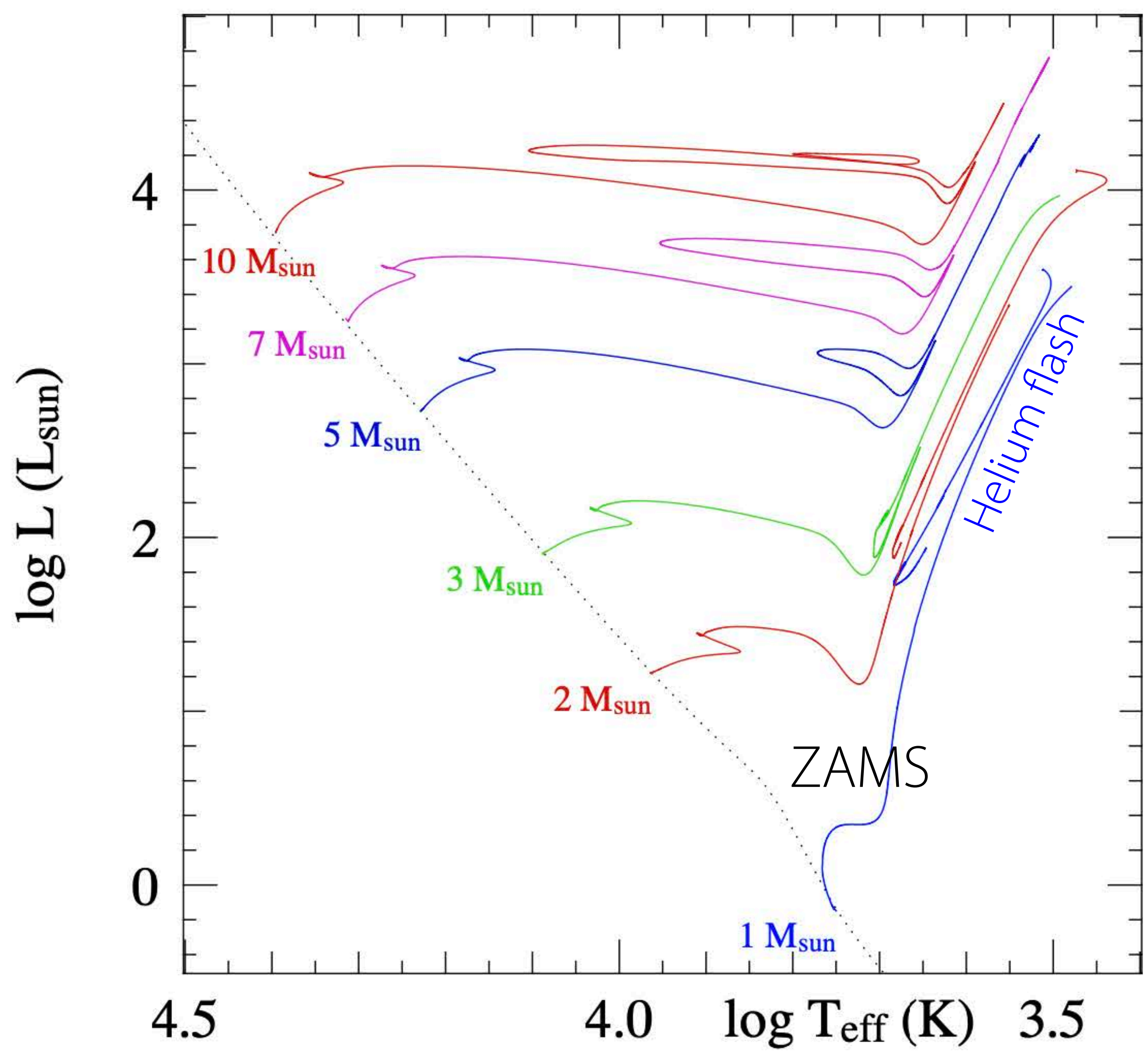
Post-main sequence evolution

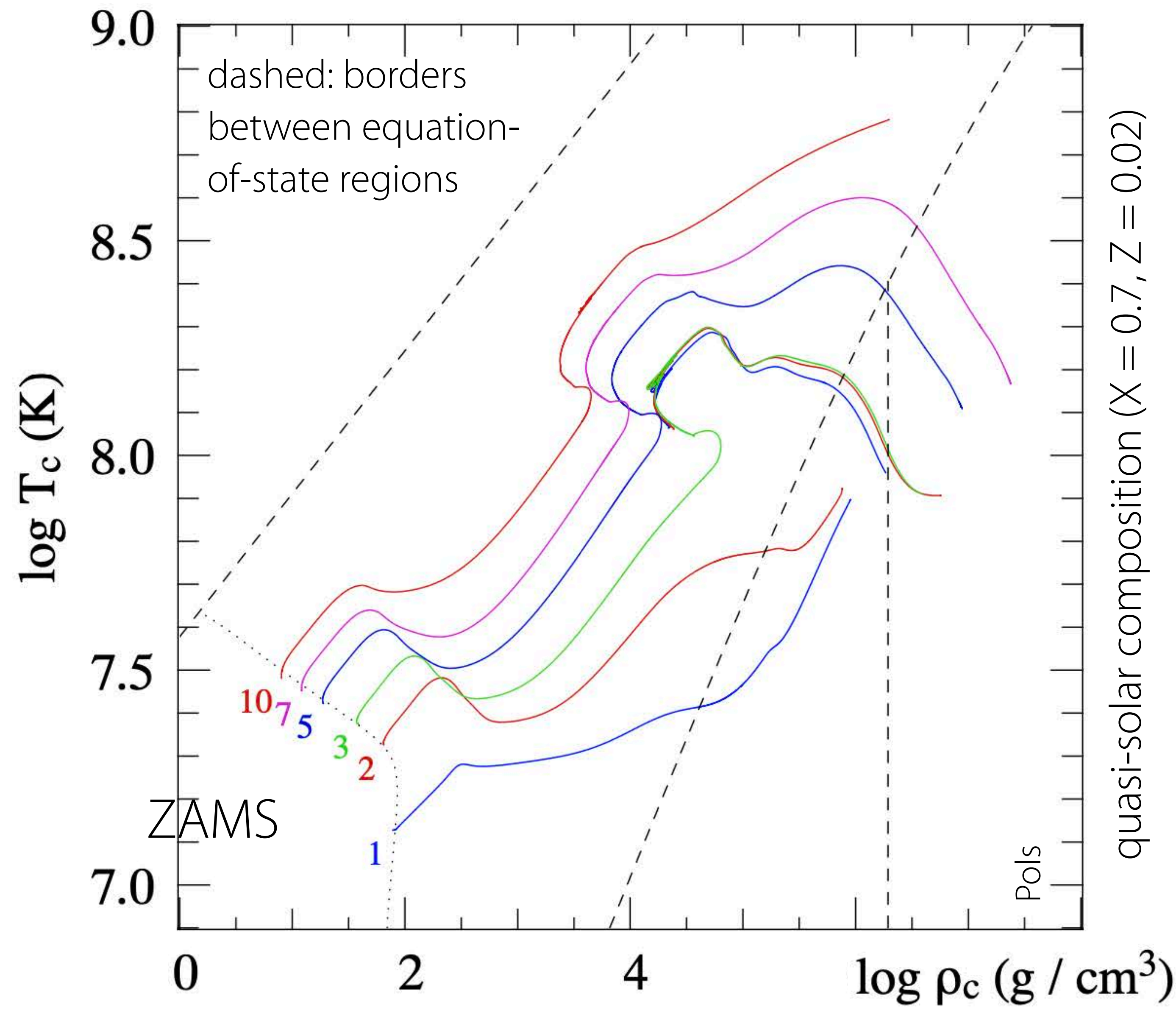
Mirror principle

- “Mirror principle" for stars with active shell-burning source:
  Burning shell acts as mirror between the core and envelope
  - core contraction ⇒ envelope expansion
  - core expansion ⇒ envelope contraction

Post-main sequence evolution

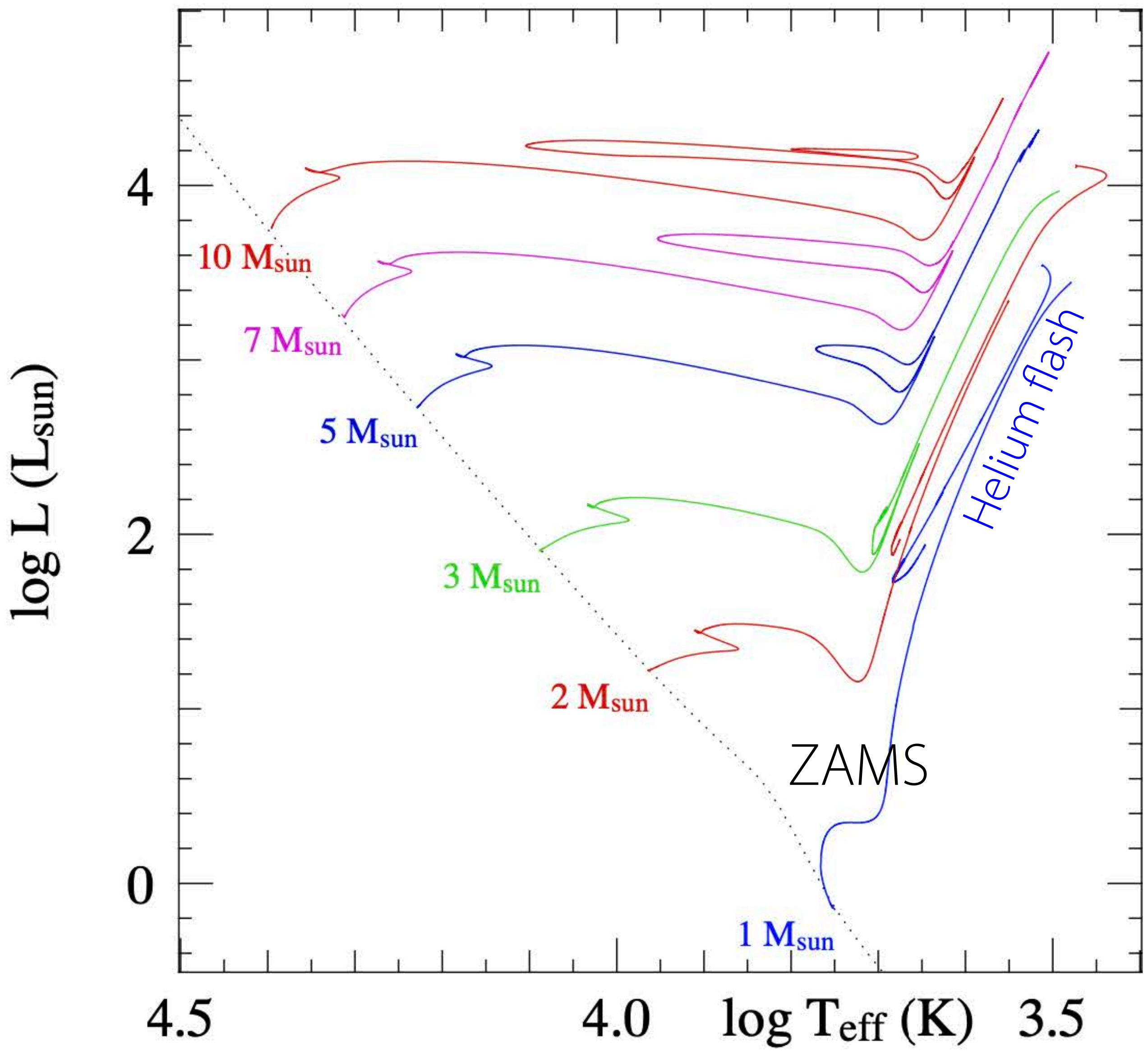
- **1 M⊙ (representative of low-mass stars):**
  - Central core becomes degenerate after leaving MS
  - Helium flash at top of red giant branch
  - Degeneracy eventually lifted, He burning becomes stable — star moves to the zero-age horizontal branch (log L ≈ 1.8).

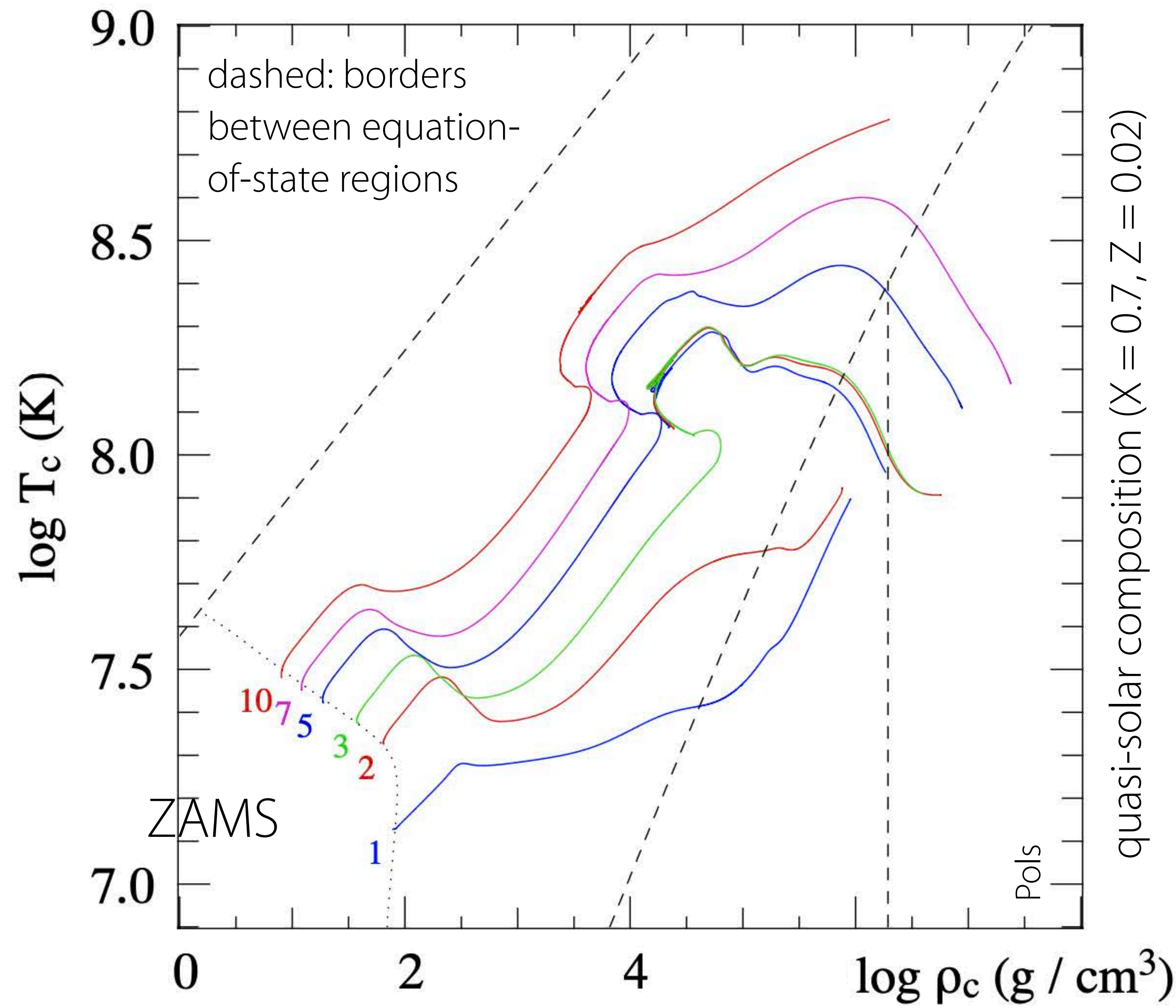




Post-main sequence evolution

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





Post-main sequence evolution

Tracks in the core density—temperature plane

- Evolution tracks in
  $\log \varrho_c$ - $\log T_c$ -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,
  ➡ 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)