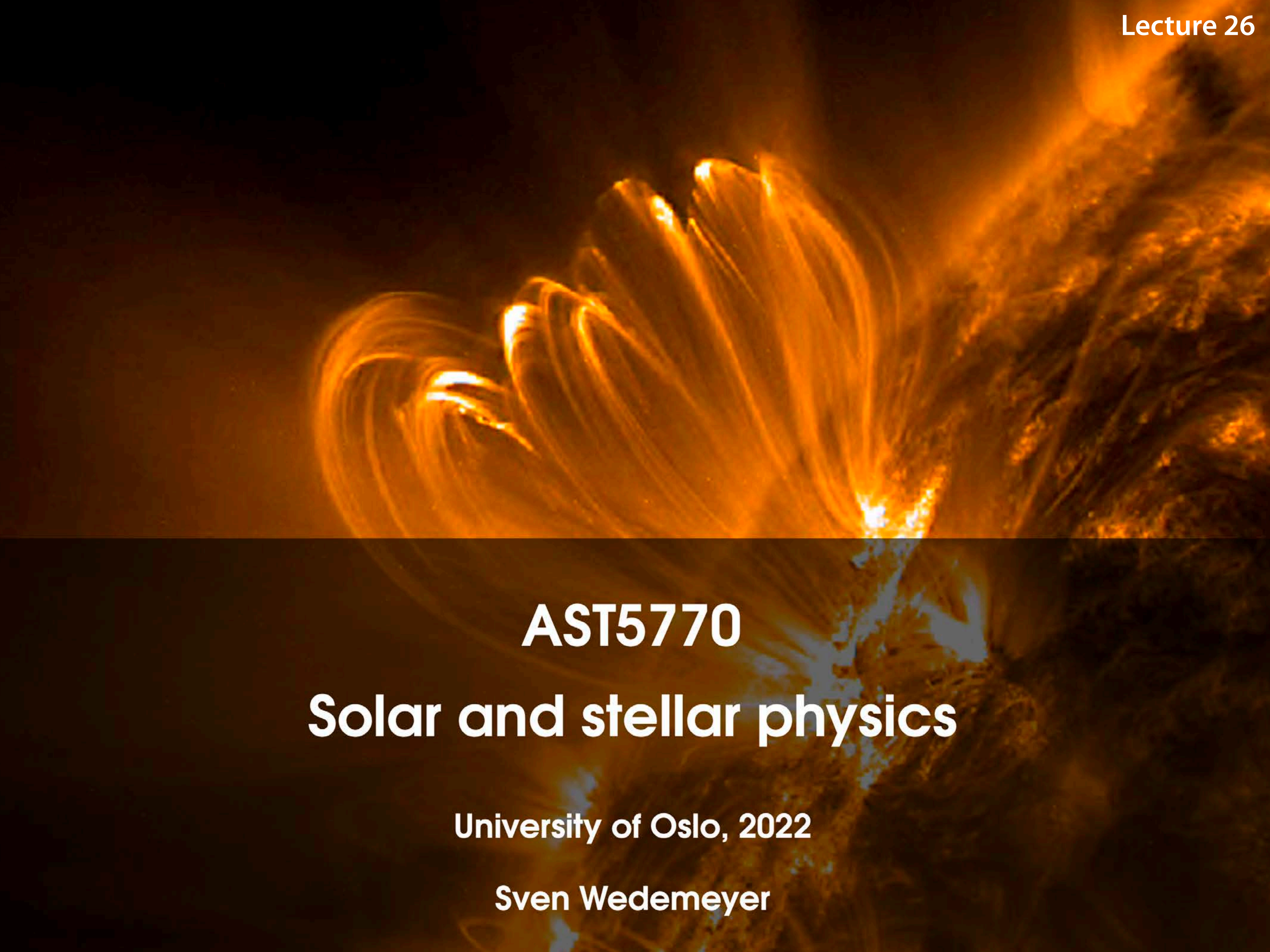
Lecture 26



AST5770

Solar and stellar physics

University of Oslo, 2022

Sven Wedemeyer

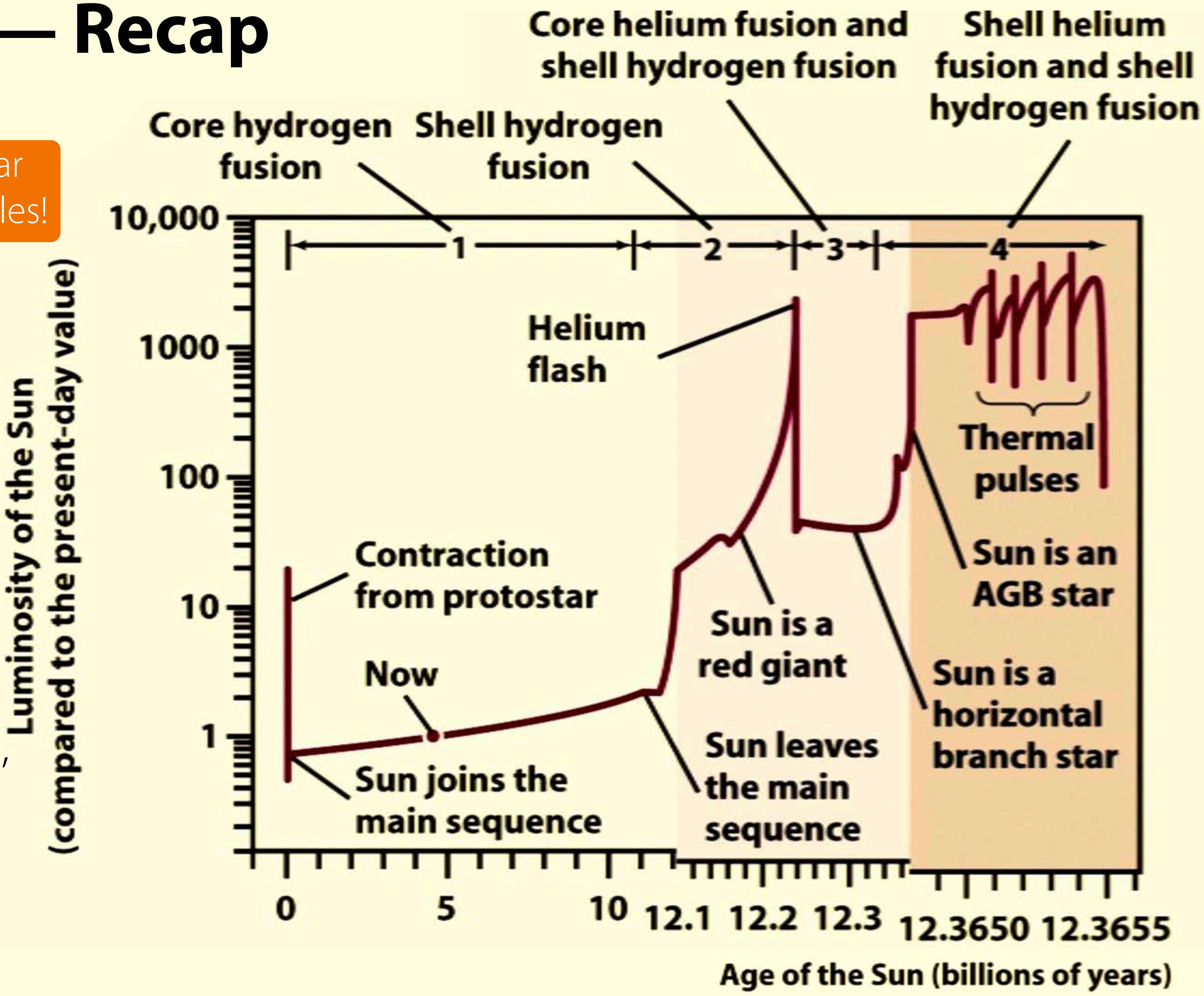
Stellar Evolution

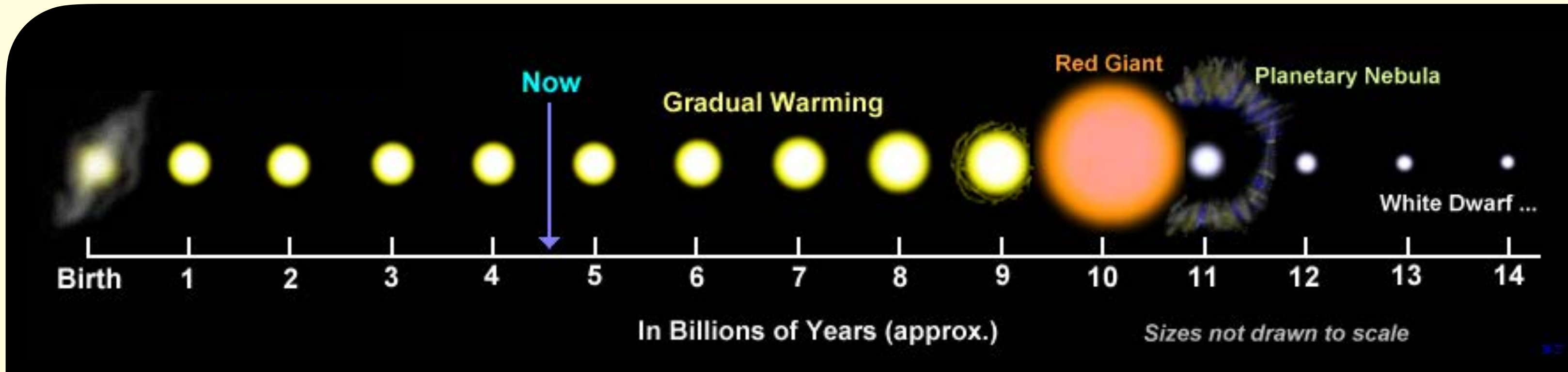
Evolution of the Sun — Recap

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

- **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 dermined by mass loss rate (typically ~10^6 yr, $f(M_0)$)
- **Post-AGB evolution**
  - Expulsion of envelope (planetary nebula due to UV radiation)
  - Exposed hot core (+small rest of previous envelope) ➡White Dwarf

Nuclear timescales!



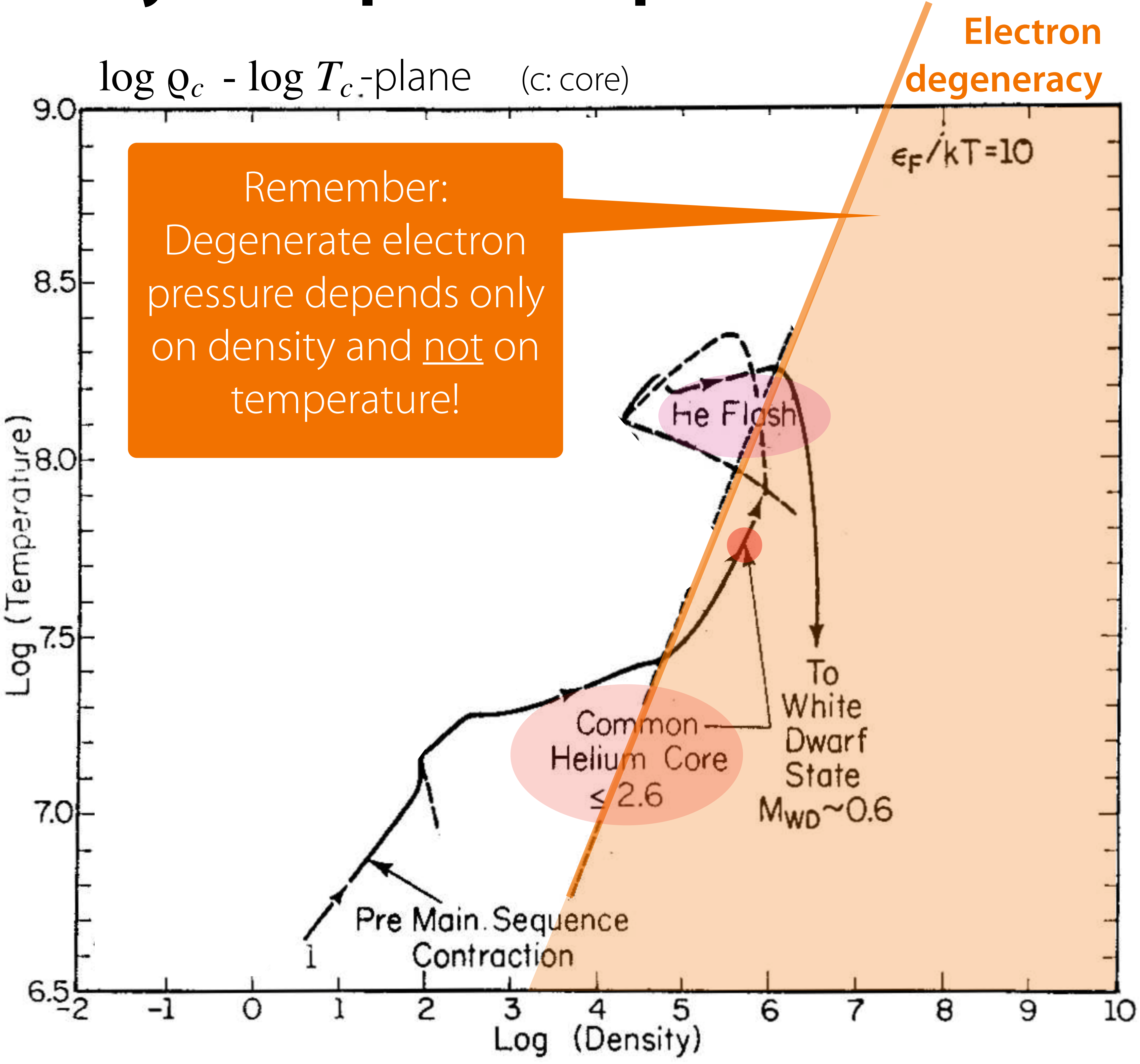


Stellar Evolution

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**)

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



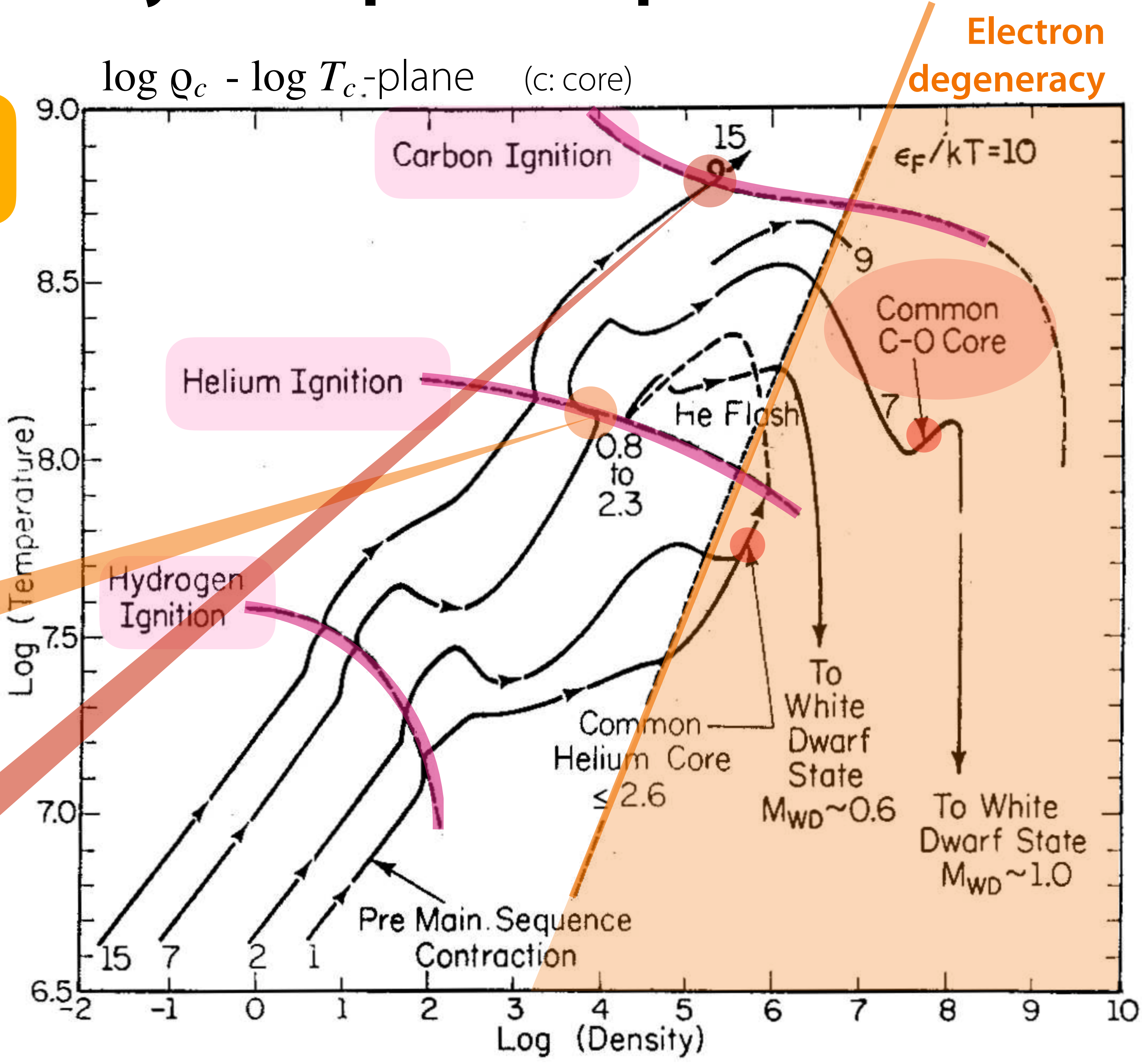
Remember: Degenerate electron pressure depends only on density and <u>not</u> on temperature!

Electron degeneracy

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⊙) reach C burning

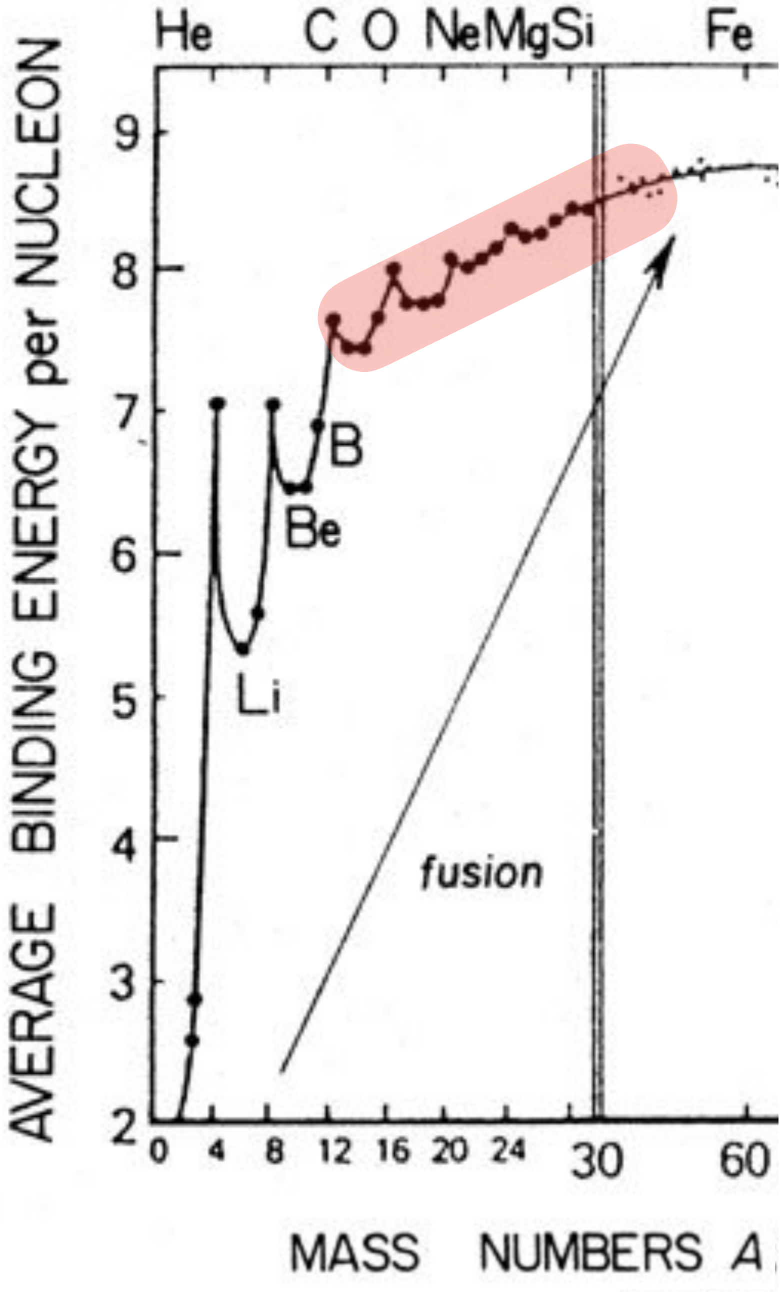


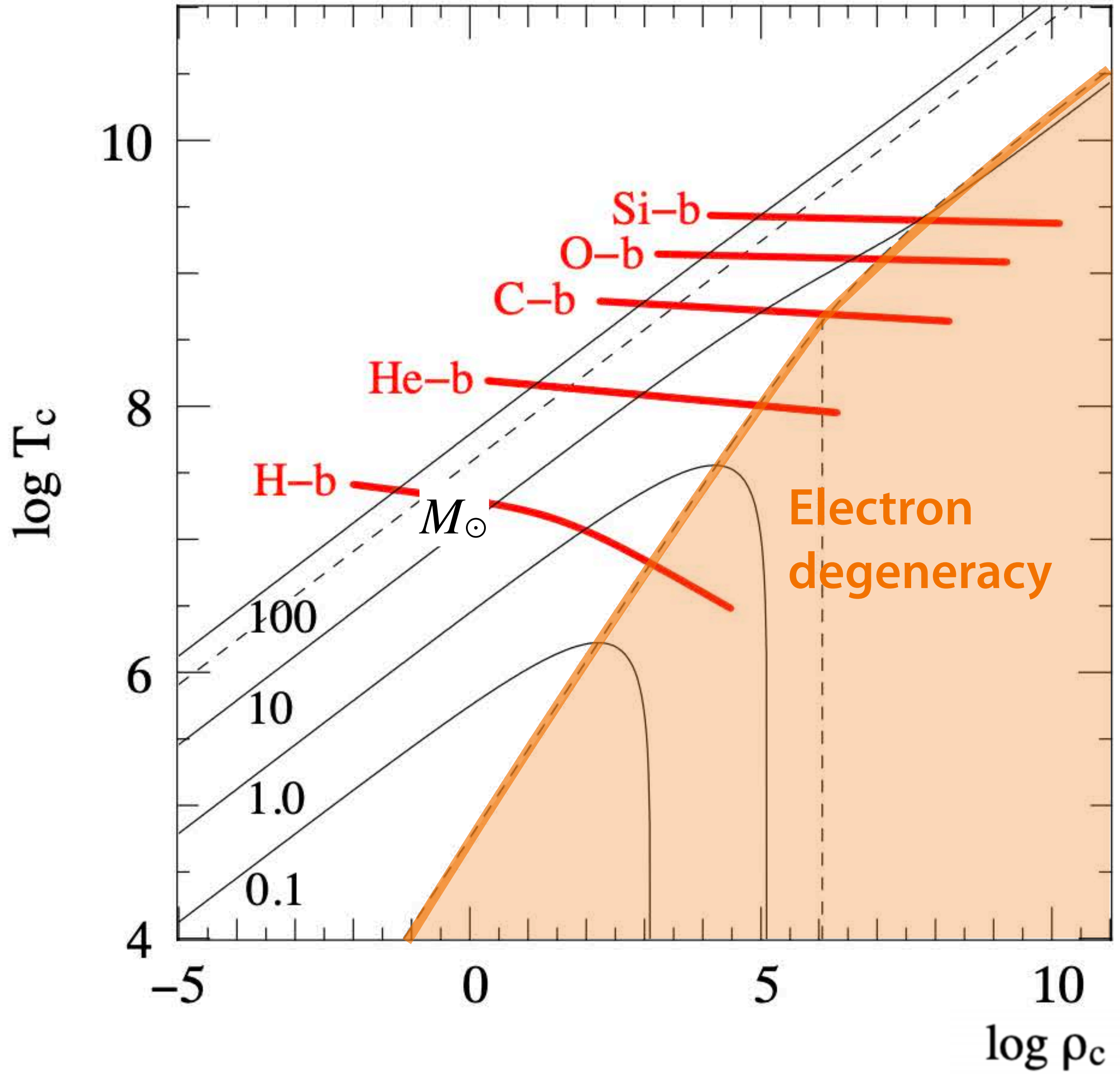
$\log \varrho_c$ - $\log T_c$-plane (c: core)

Evolution of high-mass stars

Evolution of high-mass stars

Higher burning stages



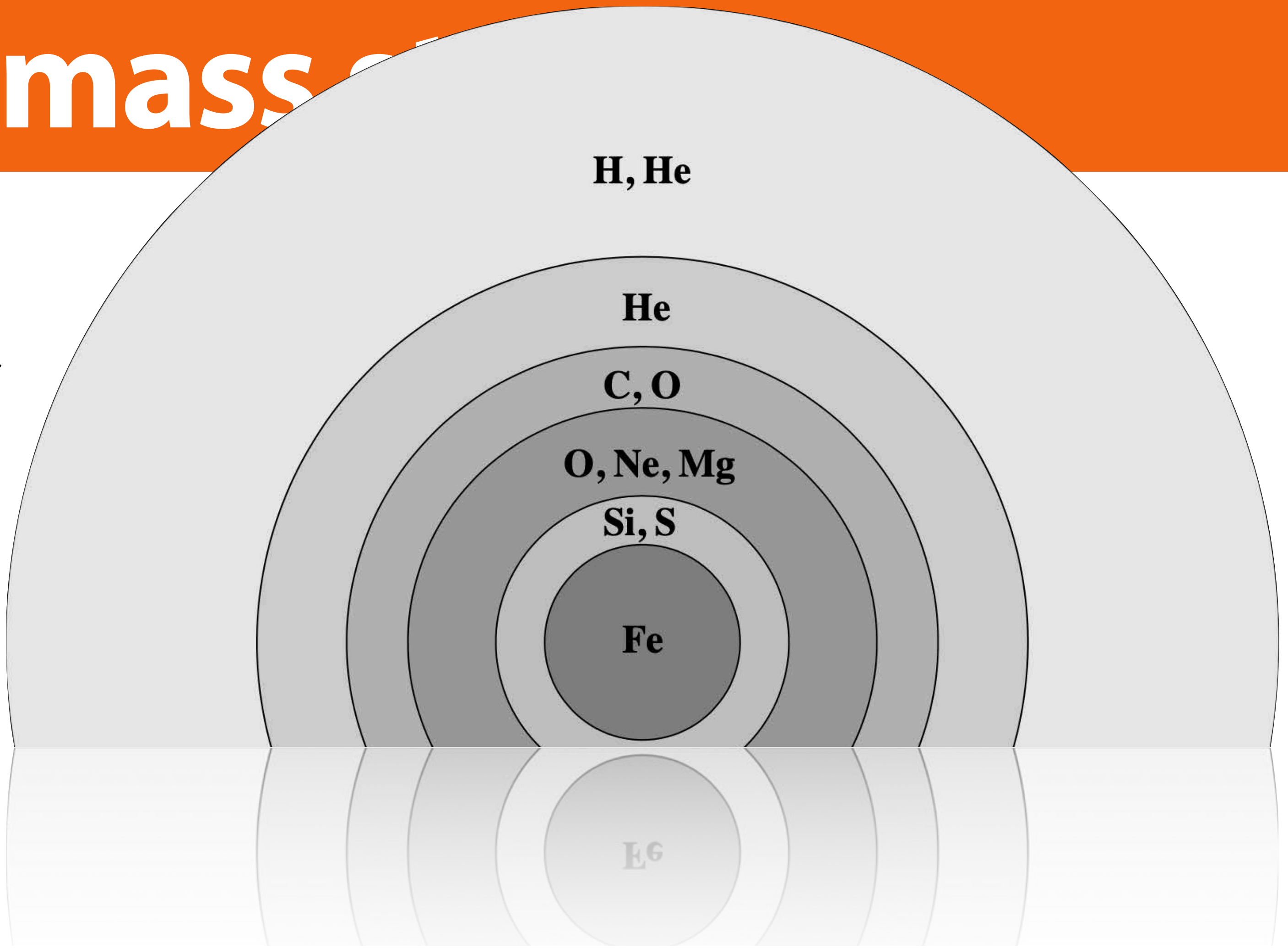


- Higher fusion stages need **higher temperatures** for particles to overcome higher and higher Coulomb barriers
- Energy gain per mass unit varies but tends to decrease towards Fe

Evolution of high-mass

Higher burning stages

- As for previous fusion stages: succession of core and shell burning
- Enrichment of core with increasingly heavier elements until Fe is formed
- Evolution speeds dramatically towards highest stages



Properties of nuclear burning stages in a 15 $M_\odot$ star (from Woosley et al. 2002).

burning stage	T (10^9 K)	ρ (g/cm^3)	fuel	main products	timescale
hydrogen	0.035	5.8	H	He	1.1×10^7 yr
helium	0.18	1.4×10^3	He	C, O	2.0×10^6 yr
carbon	0.83	2.4×10^5	C	O, Ne	2.0×10^3 yr
neon	1.6	7.2×10^6	Ne	O, Mg	0.7 yr
oxygen	1.9	6.7×10^6	O, Mg	Si, S	2.6 yr
silicon	3.3	4.3×10^7	Si, S	Fe, Ni	18 d

Pols

Evolution of high-mass stars

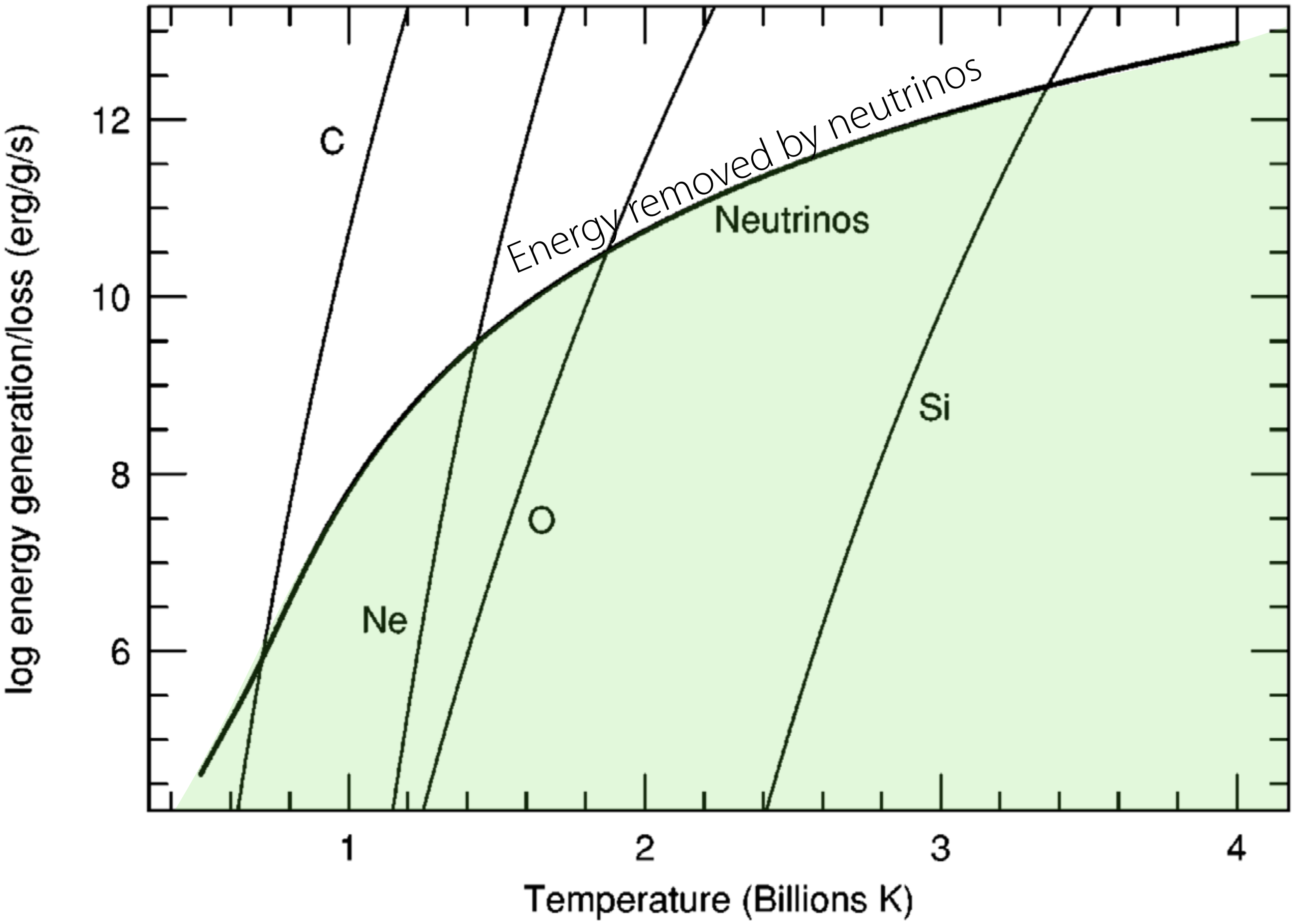
Neutrinos

- Spontaneous neutrino emission at high temperatures and densities
- Neutrino leave core (and the star), removing energy
- Energy transport by neutrinos more efficient than energy transport by radiation of convection!
- At $T_C > 5 \times 10^8$ K: neutrino losses become <u>dominant energy sink</u> in stellar core
- Neutrino luminosity L_ν exceeds luminosity radiated from surface: $L_\nu \gg L$

- Neutrino losses limit the possible energy generation rate! (energy production and neutrino cooling in balance during nuclear burning cycles)
  - Sets the burn temperature
- Lifetime of each nuclear burning stage $\tau_{nuc} \sim q/\epsilon_{nuc}$,

q = energy gain/unit mass from nuclear burning

	Burning stage			
	C	Ne	O	Si
q_{nuc} [10^{17} erg/g]	4.0	1.1	5.0	1.9



Pols

Evolution of high-mass stars

Successive contraction - burning phases

Alternation between **gravitational contraction** (leading to temperature increase) and increasingly higher **nuclear burning** stages

Fraction of released energy radiated away at surface (photons)

Core temperature

Fusion reactions

Total energy generation per particle

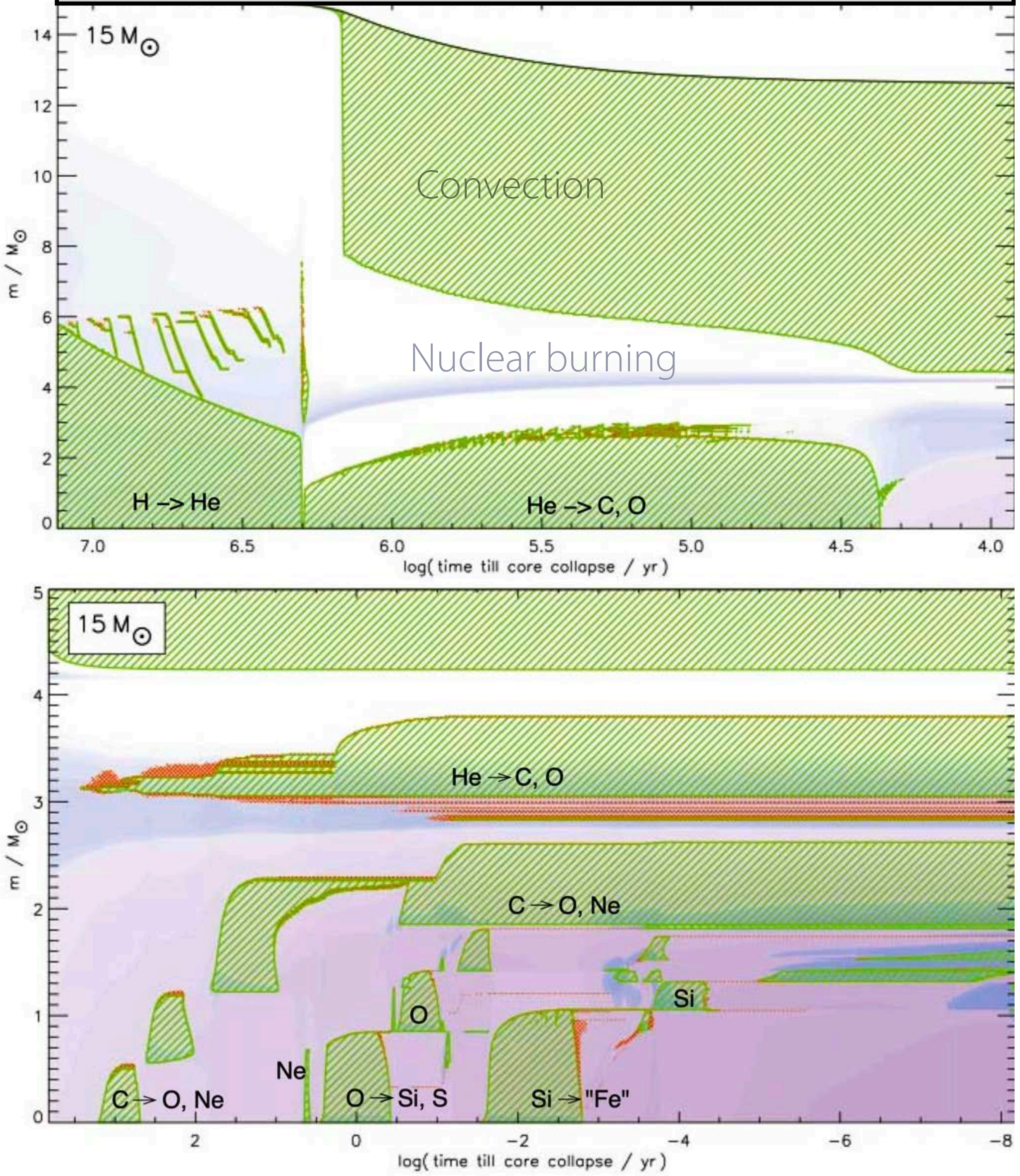
Minimum mass needed for igniting burning stage

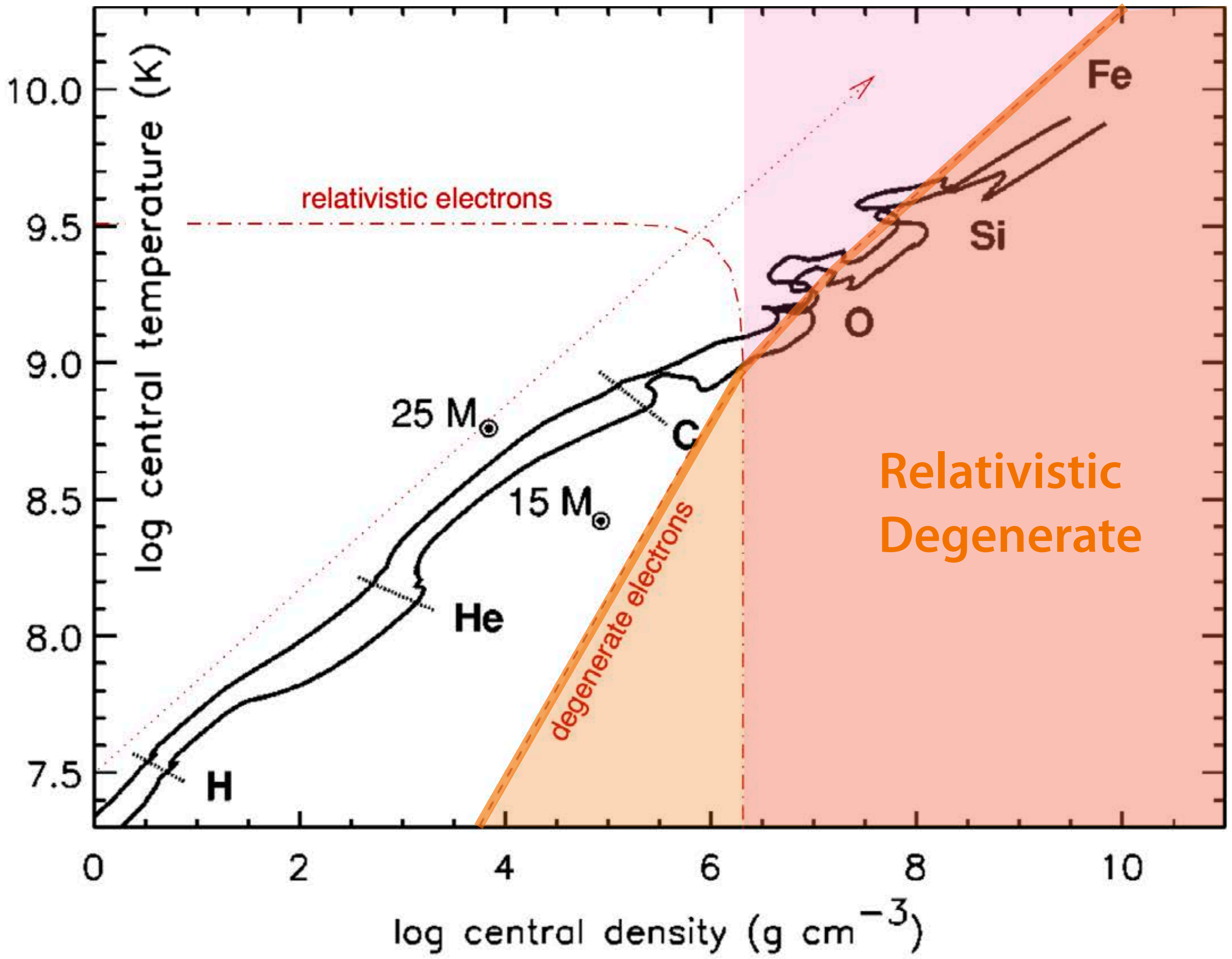
Fraction carried away by neutrinos

phase	T (10^6 K)	total E_{gr}/n	main reactions	total E_{nuc}/n	M_{min}	γ (%)	ν (%)
grav.	$0 \rightarrow 10$	$\sim$ 1 keV/n				100	
nucl.	$10 \rightarrow 30$		$^1H \rightarrow {}^4He$	6.7 MeV/n	$0.08\, M_\odot$	~95	~5
grav.	$30 \rightarrow 100$	$\sim$ 10 keV/n				100	
nucl.	$100 \rightarrow 300$		$^4He \rightarrow {}^{12}C, {}^{16}O$	$\approx$ 7.4 MeV/n	$0.3\, M_\odot$	~100	~0
grav.	$300 \rightarrow 700$	$\sim$ 100 keV/n				~50	~50
nucl.	$700 \rightarrow 1000$		$^{12}C \rightarrow Mg, Ne$	$\approx$ 7.7 MeV/n	$1.1\, M_\odot$	~0	~100
grav.	$1000 \rightarrow 1500$	$\sim$ 150 keV/n					~100
nucl.	$1500 \rightarrow 2000$		$^{16}O \rightarrow S, Si$	$\approx$ 8.0 MeV/n	$1.4\, M_\odot$		~100
grav.	$2000 \rightarrow 5000$	$\sim$ 400 keV/n	$Si \rightarrow \ldots \rightarrow Fe$	$\approx$ 8.4 MeV/n			~100

Evolution of high-mass stars

Evolution of a 15 $M_\odot$ star (Z = 0.02) (Kippenhahn diagram)





- As for previous fusion stages: succession of core and shell burning
- Multiple convection zones
- Enrichment of core and mixing of envelope with increasingly heavier elements
- End: Iron core unstable, grav. collapse

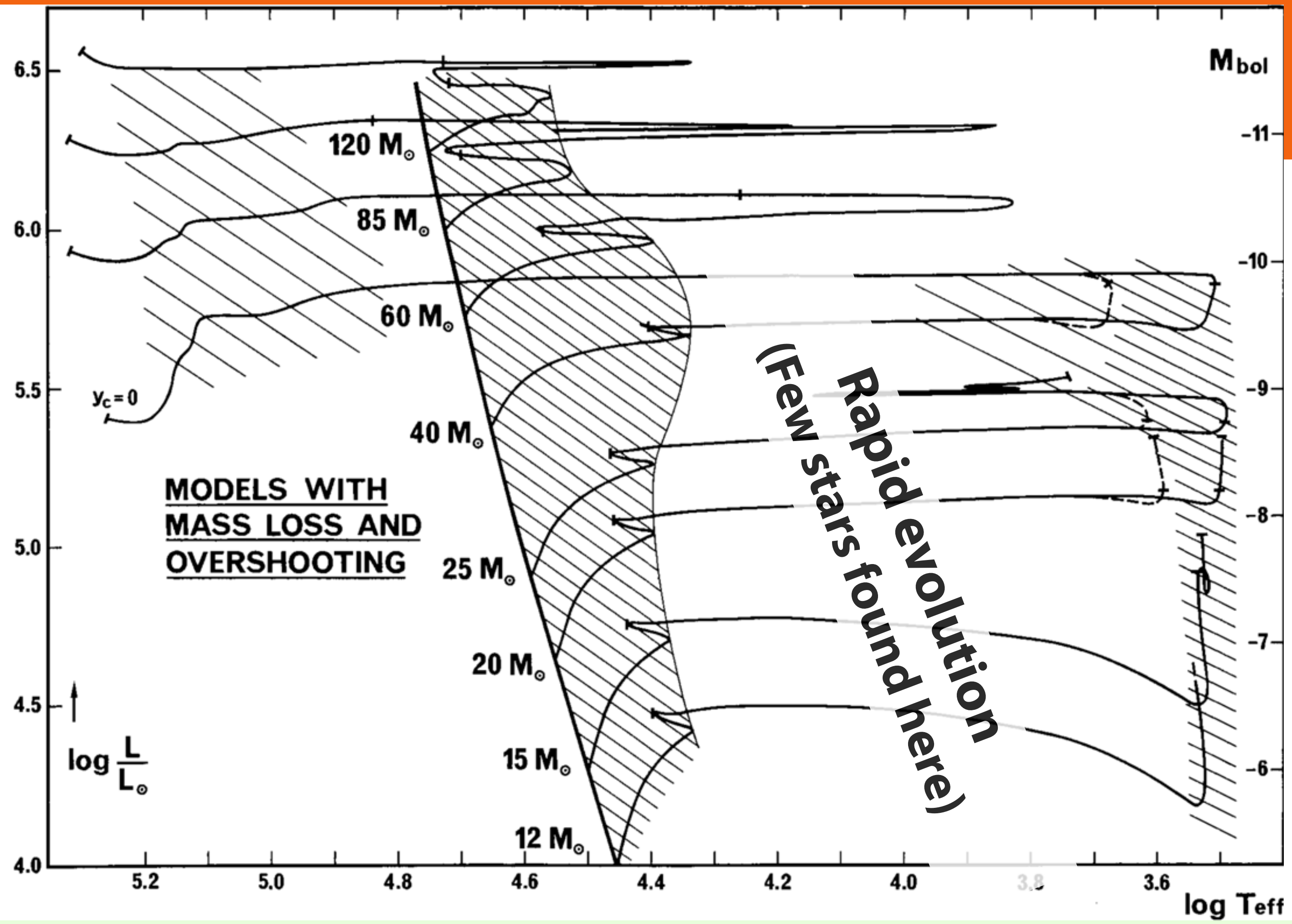
Pols / Woosley, Heger, Weaver 20002

Evolution of high-mass stars

Mass loss

- Mass loss becomes increasingly more important with increasing initial mass

  ➡ Essential impact on the evolution of high-mass stars



Rapid evolution (Few stars found here)

Initial mass

$M \lesssim 15\,M_\odot$	MS (OB) → RSG (→ BSG in blue loop? → RSG) → SN II mass loss is relatively unimportant, $\lesssim$ few $M_\odot$ is lost during entire evolution
$15\,M_\odot \lesssim M \lesssim 25\,M_\odot$	MS (O) → BSG → RSG → SN II mass loss is strong during the RSG phase, but not strong enough to remove the whole H-rich envelope
$25\,M_\odot \lesssim M \lesssim 40\,M_\odot$	MS (O) → BSG → RSG → WNL → WNE → WC → SN Ib the H-rich envelope is removed during the RSG stage, turning the star into a WR star
$M \gtrsim 40\,M_\odot$	MS (O) → BSG → LBV → WNL → WNE → WC → SN Ib/c an LBV phase blows off the envelope before the RSG can be reached

Mass loss

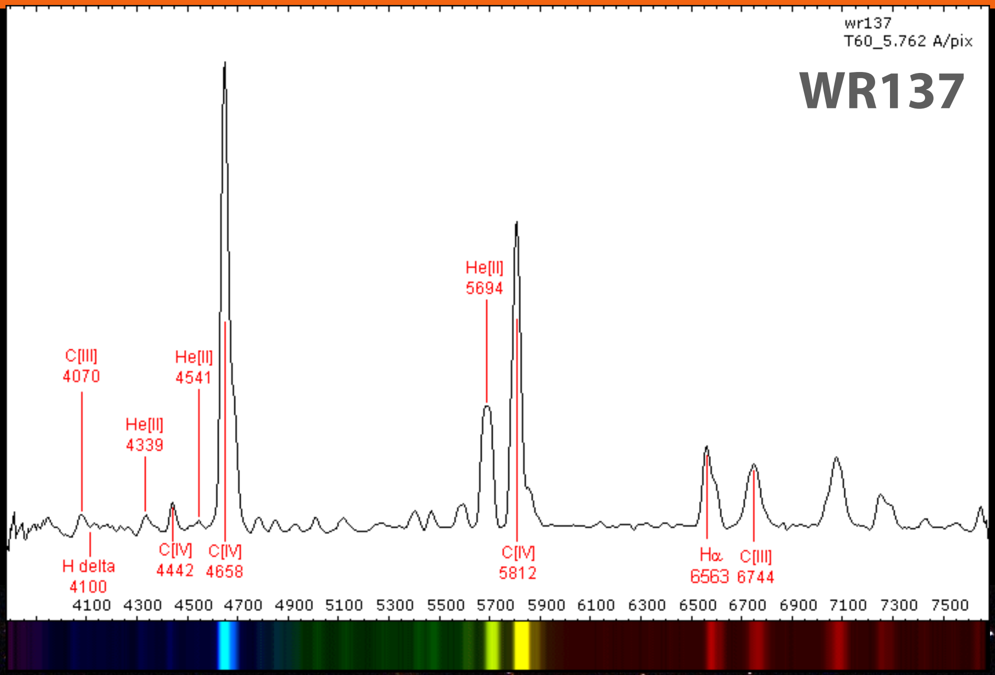
LBV: Luminous Blue Variable

Pols / Conti

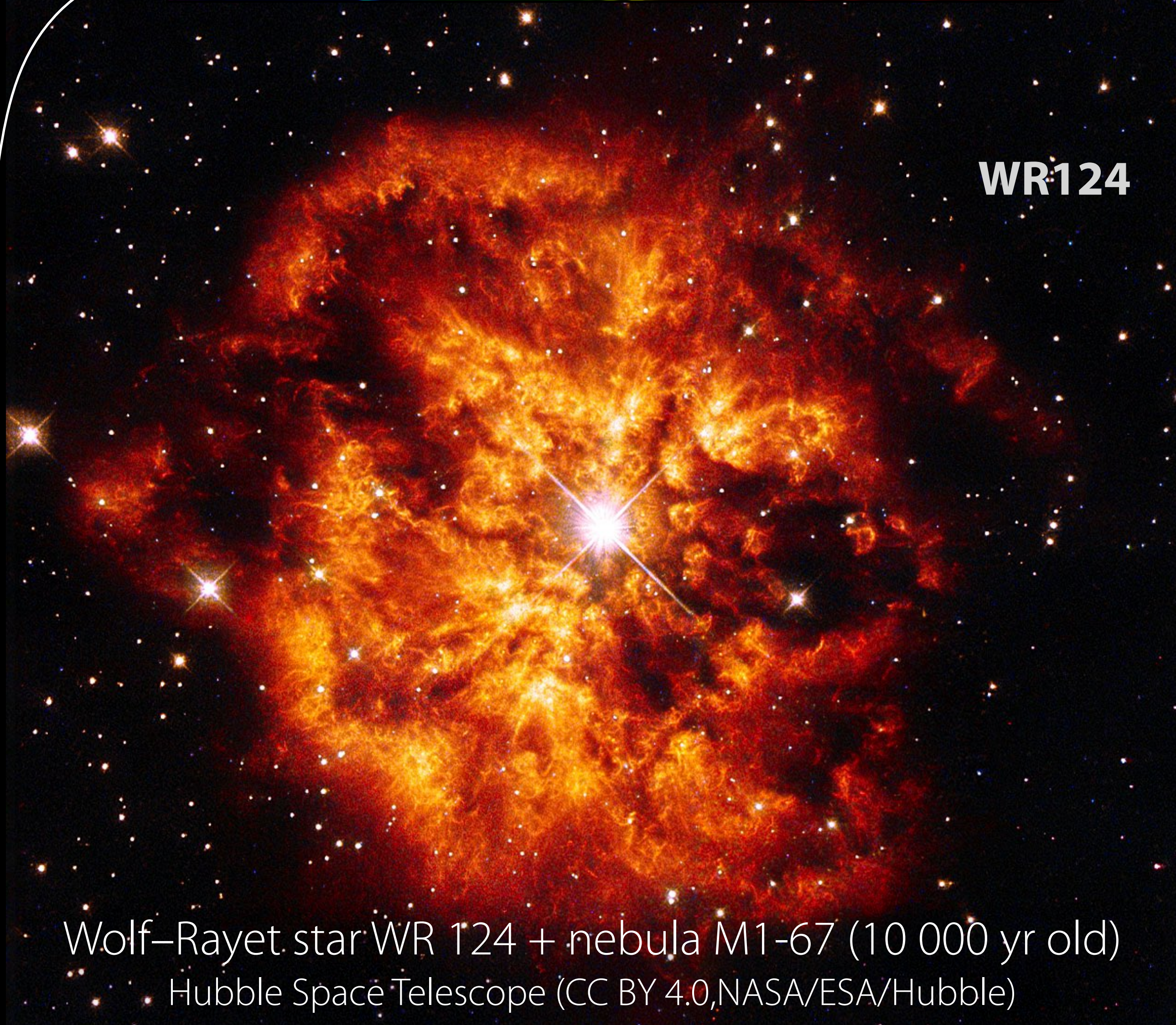
Late evolution stages of massive stars

Wolf-Rayet (WR) stars

- (Super-)**Hot** + **very luminous** stars
  - T_{eff} from 20 000 K up to ~210 000 K!
  - L from several10^3 $L_\odot$ to > 10^6 $L_\odot$
  - Rare: only ~ 500 known in Milky Way
- Spectra: Increased abundances of C, N, O
  - Several subtypes based on composition (WNL, WNE, WC, WO)
  - ➡ WR stars = **exposed H- or He-burning cores of massive stars**
  - Bright, broad emission lines (He, C, N)
  - ➡ Very strong, optically thick **stellar winds**, mass-loss rates of ~10^{-4} – 10^{-5} $M_\odot$/yr
  - ➡ Often surrounded by circumstellar envelope
  - Stellar winds likely driven by **radiation pressure** (Remember: Eddington limit)



Gypaete/T60 Pic du Midi



Wolf–Rayet star WR 124 + nebula M1-67 (10 000 yr old)

Hubble Space Telescope (CC BY 4.0,NASA/ESA/Hubble)

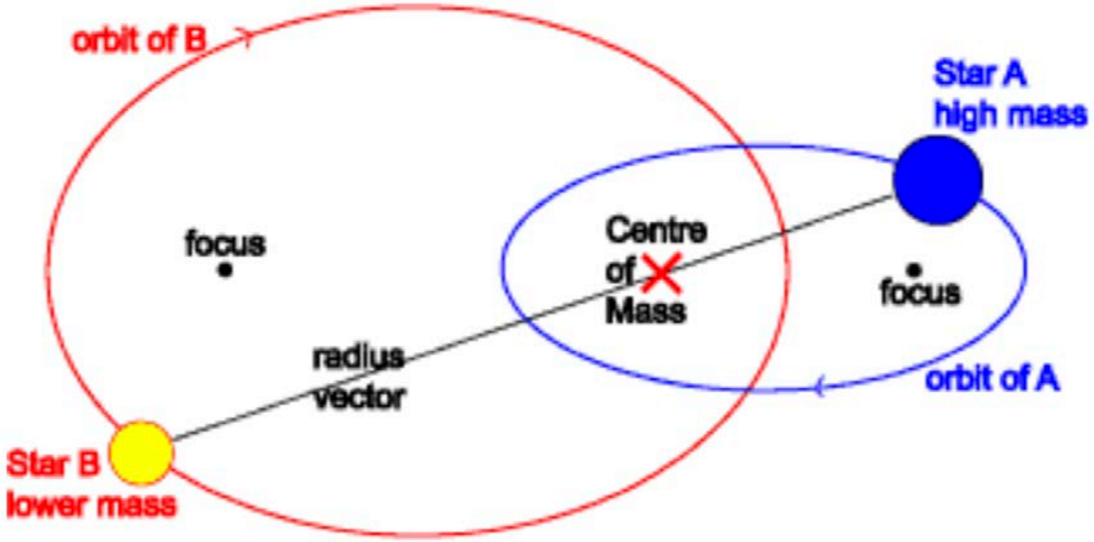
Binary stars

Binary stars

Overview

- ~80% (?) of stars in our galaxy not single stars but part of multiple star systems (binaries, triplets, …)
  - Exact percentage still debated.
  - Not always observed separated
    (depends on distance to and between them, apparent separation in sky)
    - Spectroscopic binaries (unresolved but hints in combined spectrum)
- Important: Binary stars allow for measuring stellar masses!

- **Example — α Cen** (A+B+Proxima): G2V + K1V + M5.5V
- **Example — Antares** (α Scorpii):
  red supergiant (M1.5Ia/b)
  \+ hot blue main-sequence star (B2.5V)

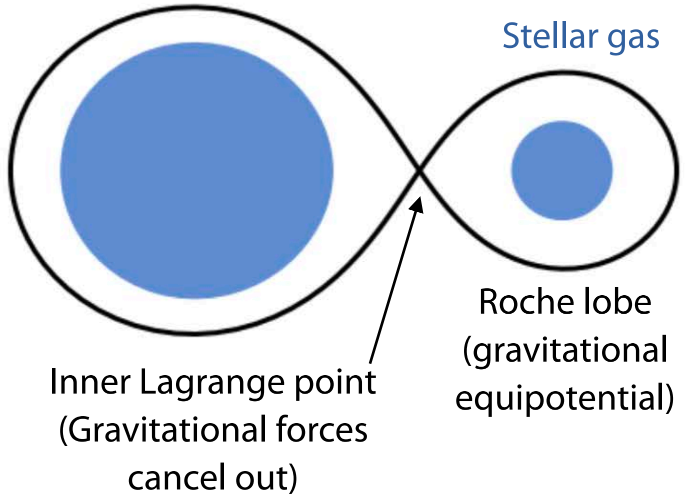


Binary stars

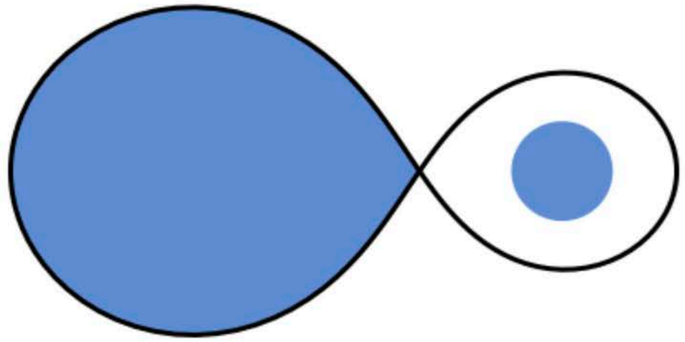
Configuration

- Initial masses not the same
- Initial mass differences lead to different evolution of the components!
- Components can influence their evolution via transfer of angular momentum and mass, stellar winds, ionising UV radiation, …
    - Depends on the properties of components and orbital parameters (distance)
    - Binary components can be very different!
- Expansion of one component (e.g., red giant) in a close binary can fill it Roche lobe, mass can flow over to the other star
- Adding / removing mass alters the evolution of the components!

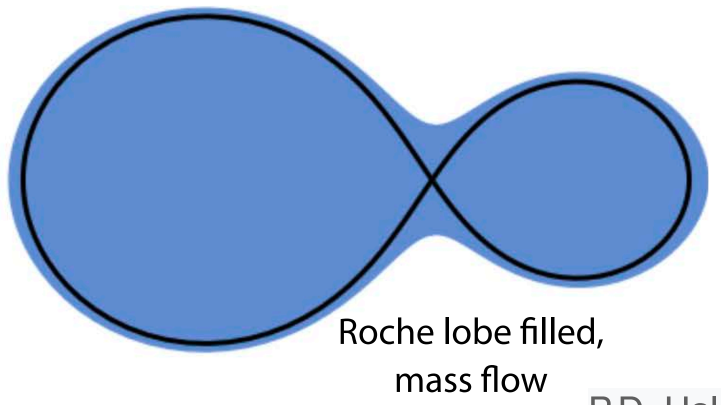
Detached binary



Semi-detached binary



Contact binary



P.D. Hall

White Dwarfs

End stage of low/intermediate mass stars

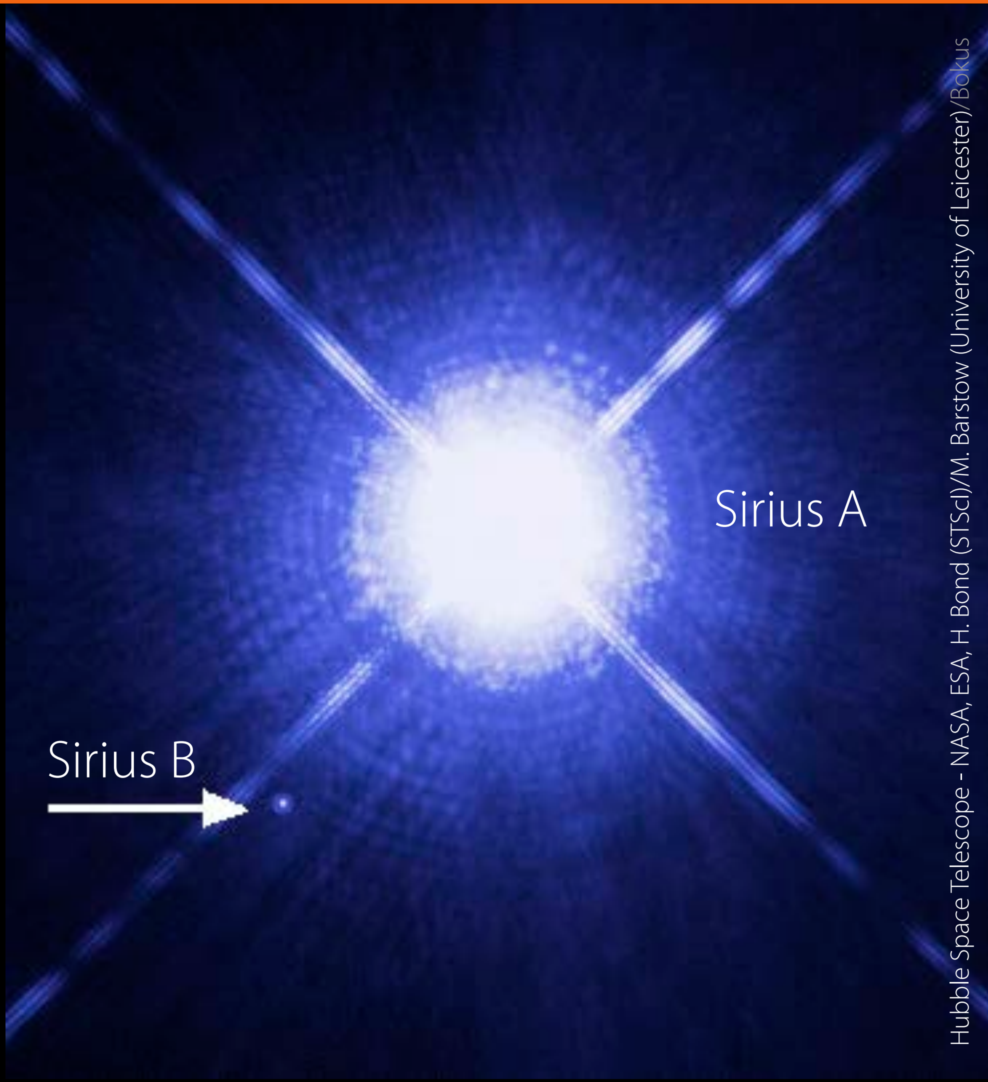
White Dwarfs

Overview

- **White Dwarf (WD) = exposed stellar core** with initial surface temperature > 100 000 K
- Emission peak in **UV** — Ionises surrounding gas
  - Planetary nebulae (always with a hot WD at their centre!)
- No more nuclear reactions inside a white dwarf, so there is no source of energy.

  ➡ **WDs cool slowly**
- Electron degeneracy pressure independent of temperature

  ➡ WD does not collapse, radius stays constant.



Hubble Space Telescope - NASA, ESA, H. Bond (STScI)/M. Barstow (University of Leicester)/Bokus

White Dwarfs

Overview

- WD does not collapse, radius stays constant.

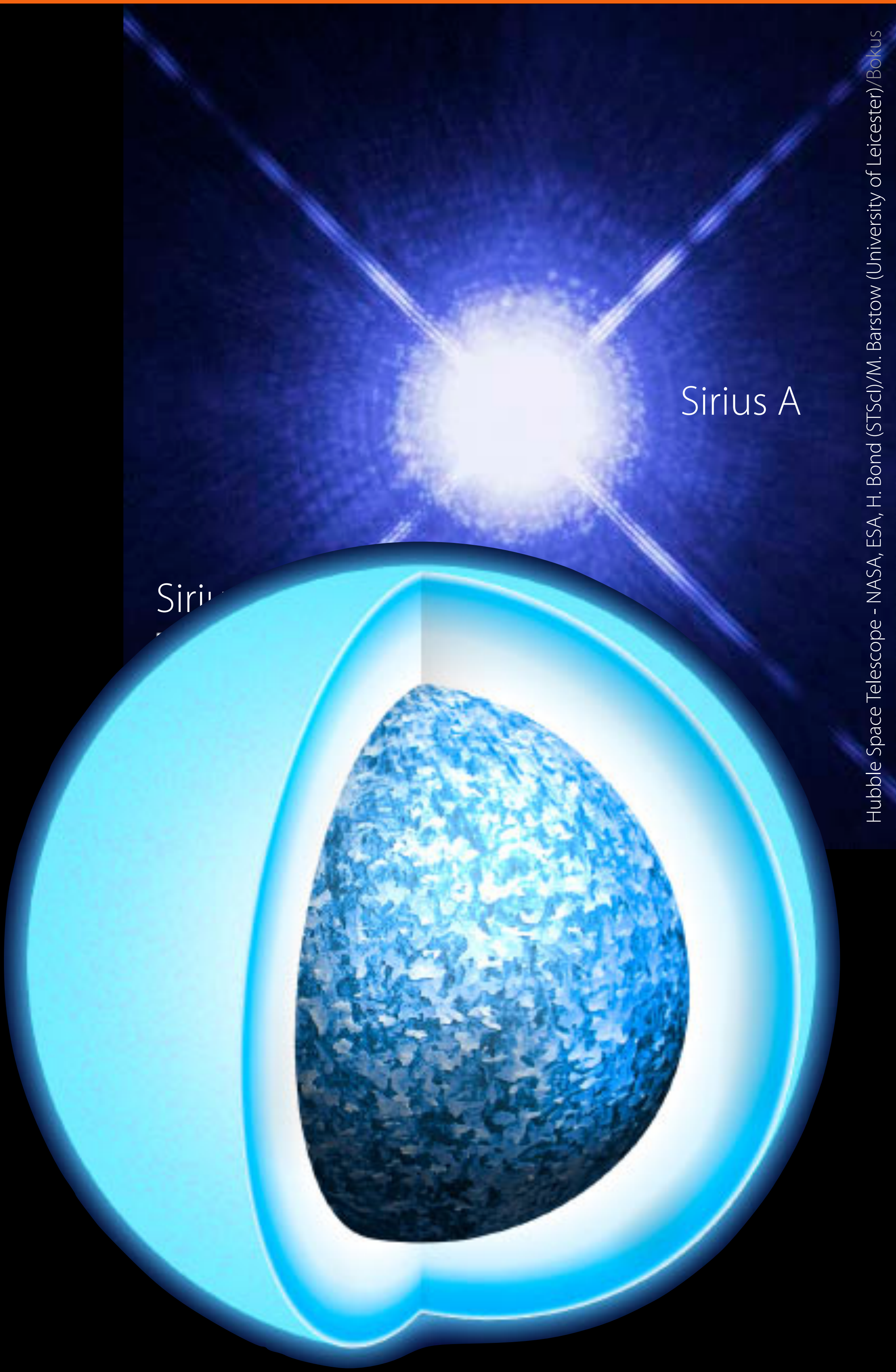
➡ Constant radius and decreasing surface temperature

➡ Stefan-Boltzman law:
  - Luminosity of WD decreases with time (slowly fading away)
  - **Example:** WD with $0.1\,L_\odot$: down to $10^{-4}\,L_\odot$ after ~5 billion years
  - Emission peak shifts to longer wavelengths, less ionising UV radiation

  ➡ Planetary nebula fades (expands and mixes with surrounding interstellar medium)

- At low temperatures carbon ions can "freeze" (i.e. form bonds) into a crystal lattice structure (phase transition)

  ➡ WD gets solid (slowly).



Hubble Space Telescope - NASA, ESA, H. Bond (STScI)/M. Barstow (University of Leicester)/Bokus

An artist's impression of crystallization in a white dwarf star. Image credit: Mark Garlick / University of Warwick.

White Dwarfs

Mass and radius

- For non-relativistic electrons: WD structure approximated as a n = 3/2 polytrope

➡ Mass radius relation $R \propto M^{-1/3}$

- Relativistic theory by Chandrasekhar
  - **Chandrasekhar mass**

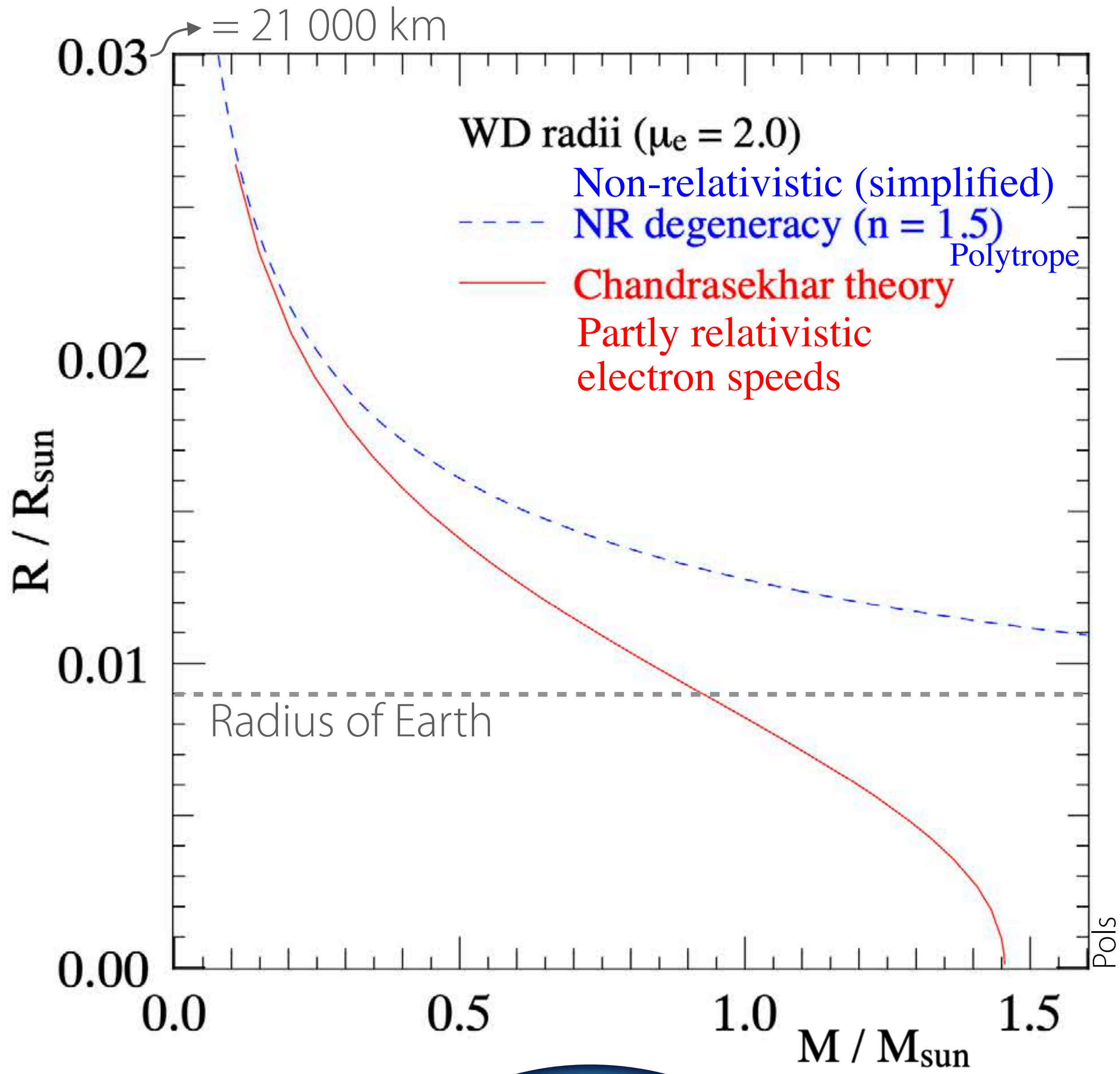
$$M_{\mathrm{Ch}} = 1.459 \left(\frac{2}{\mu_e}\right)^2 M_\odot$$

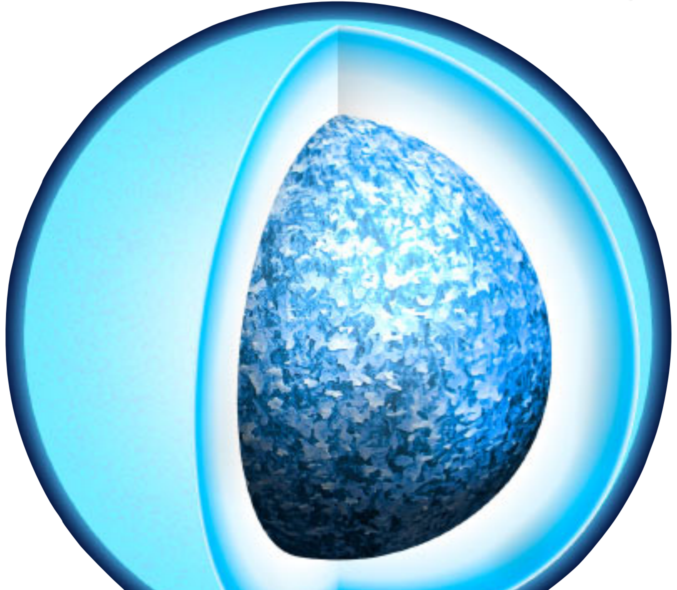
$\mu_e = 2$

  - Max. mass of that can be supported by relativistic electron degeneracy pressure against gravity.

Max. mass due to max. possible degeneracy pressure.

Electrons would have to move faster than the speed of light for more degeneracy pressure …





White Dwarfs

Cores with higher mass: relativistic degeneracy pressure insufficient to balance gravity
➡ **Catastrophic core collapse**

Mass and radius

- For non-relativistic electrons: WD structure approximated as a n = 3/2 polytrope

  ➡ Mass radius relation $R \propto M^{-1/3}$

- Relativistic theory by Chandrasekhar
  - **Chandrasekhar mass**

$$M_{\mathrm{Ch}} = 1.459 \left(\frac{2}{\mu_e}\right)^2 M_\odot$$

$\mu_e = 2$

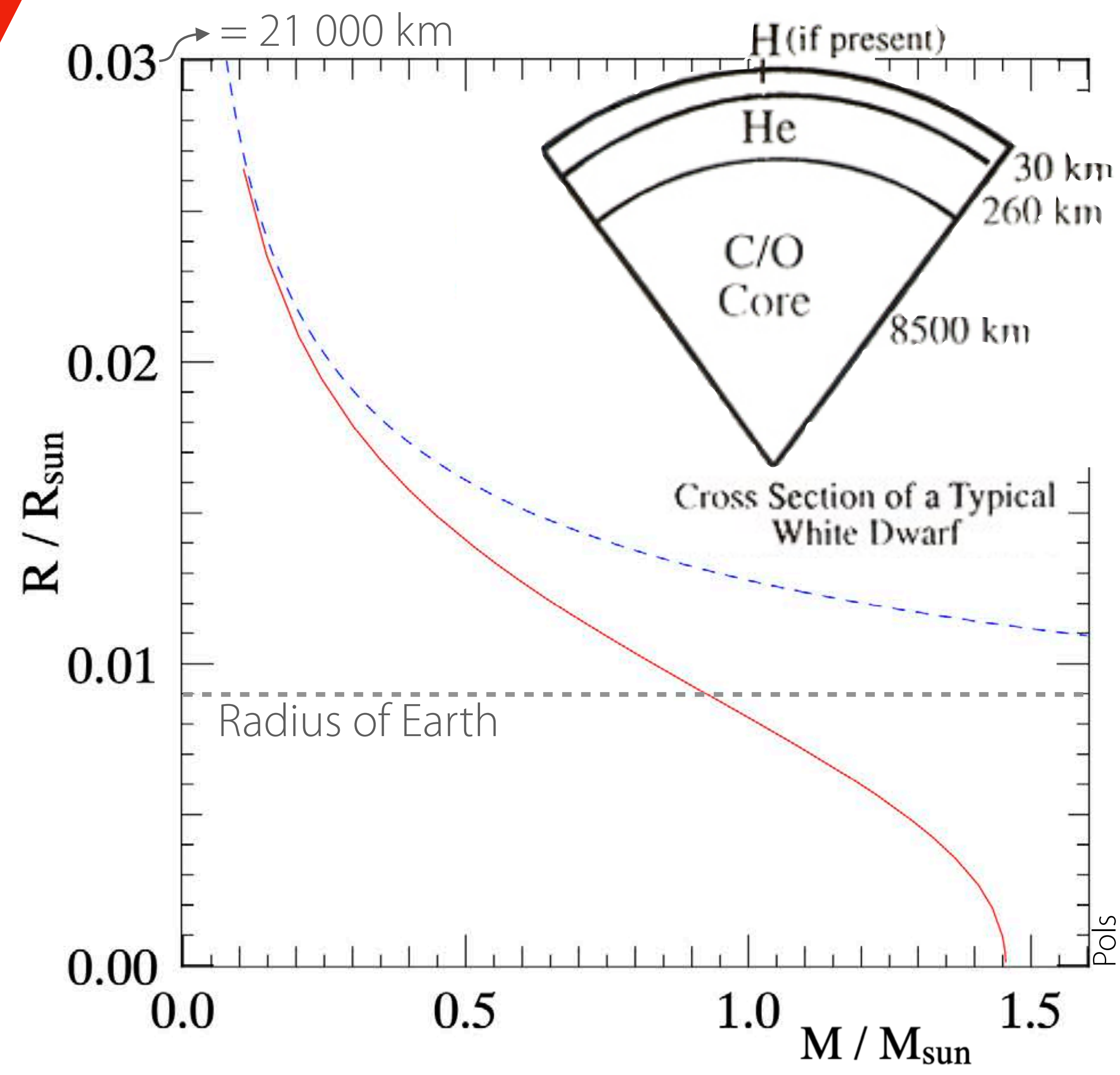
  - Max. mass of that can be supported by relativistic electron degeneracy pressure against gravity.

- More precisely: Pressure in central region a bit smaller than pressure for a purely non-relativistic electron gas.

  ➡ Smaller WD radii

  ➡ Mass limit for C-O WDs rather **~1.4 M$_\odot$**

- Typical masses rather around 0.6 M$_\odot$, corresponds to CO core mass of low-mass AGB progenitors (M < 2 M$_\odot$)



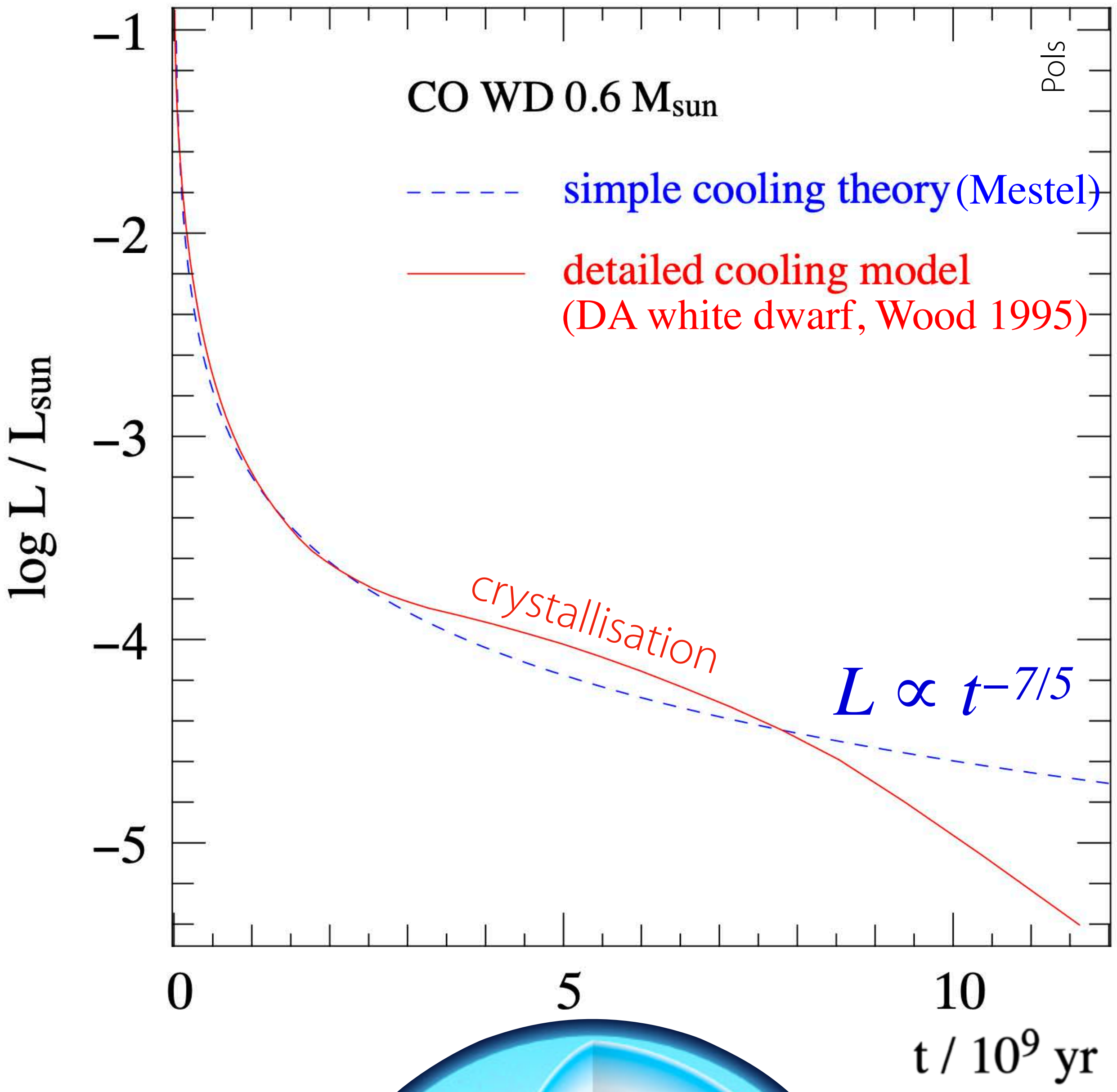
- M < 0.45 M$_\odot$: usually He WDs, formed by low-mass star that lost envelope already on RGB (likely the result of star-star interaction in binary systems)
- M > 1.2 M$_\odot$: mostly ONe WDs, stars that underwent C burning in core but developed degenerate ONe cores (only for small initial mass range around 8 M$_\odot$).

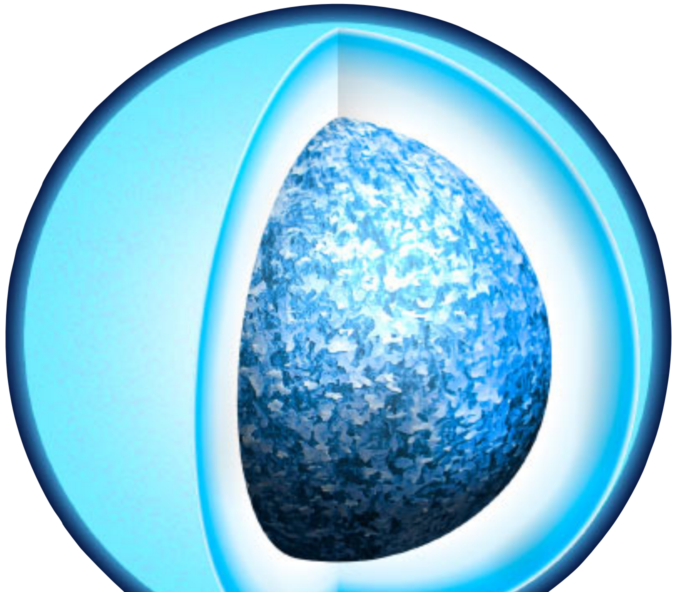
White Dwarfs

Temperature and cooling

- Interior: Degenerate electrons provide high thermal conductivity
  ➡ Small temperature gradient inside WD
- Outer layers: non-degenerate (much lower density!)
  ➡ Radiative energy transport
  - Much less effective than conduction due to high opacity

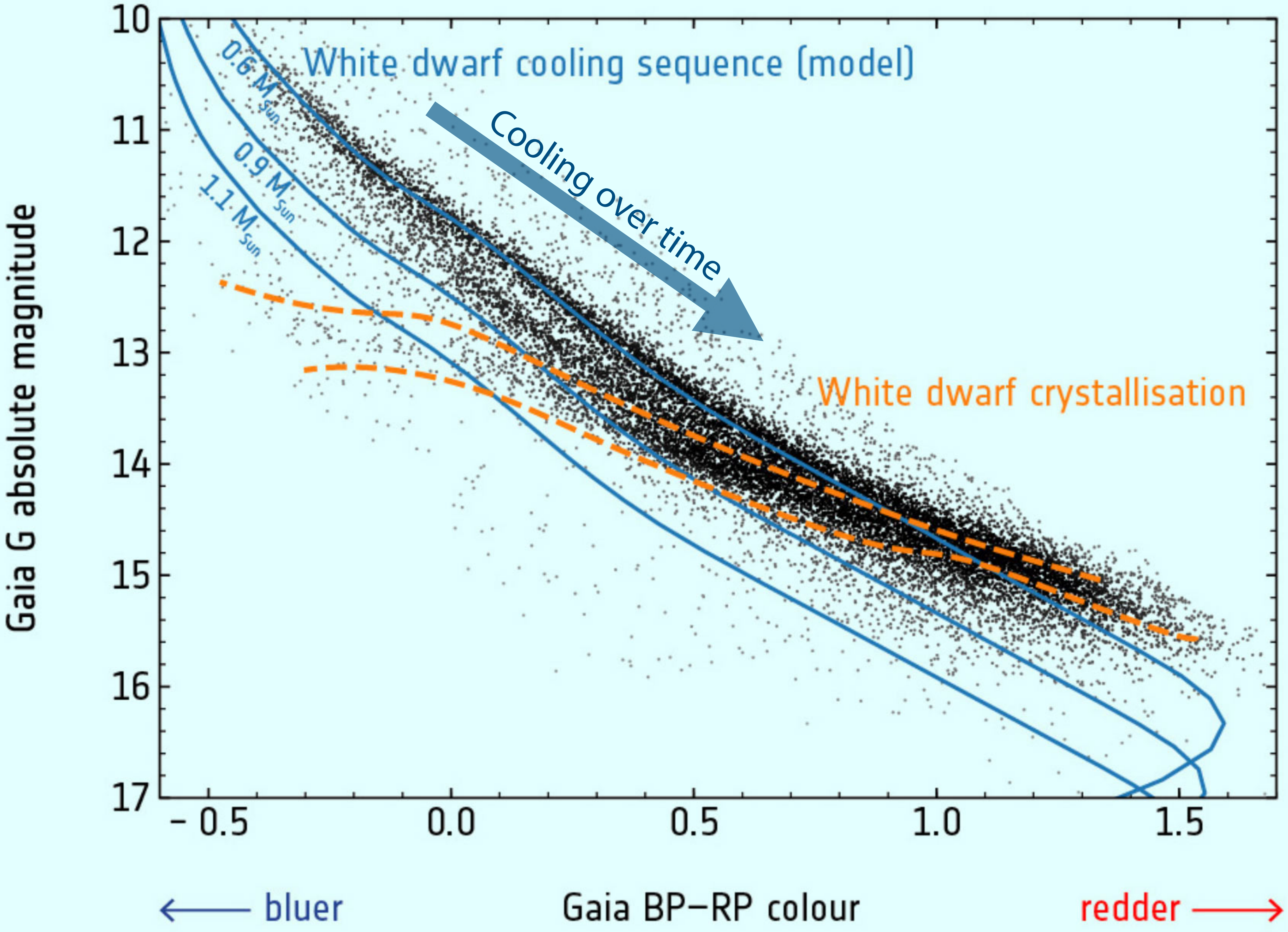
  ➡ Insulates hot core from space
  ➡ Slow cooling
    - Simplified model: $L \propto t^{-7/5}$
- Detailed model: Slower cooling due to crystallisation, faster cooling once crystallisation complete (t > 7 Gyr)





White Dwarfs

Temperature and cooling



Tremblay *et al*, doi: 10.1038/s41586-018-0791-x.

White Dwarfs

Spectra

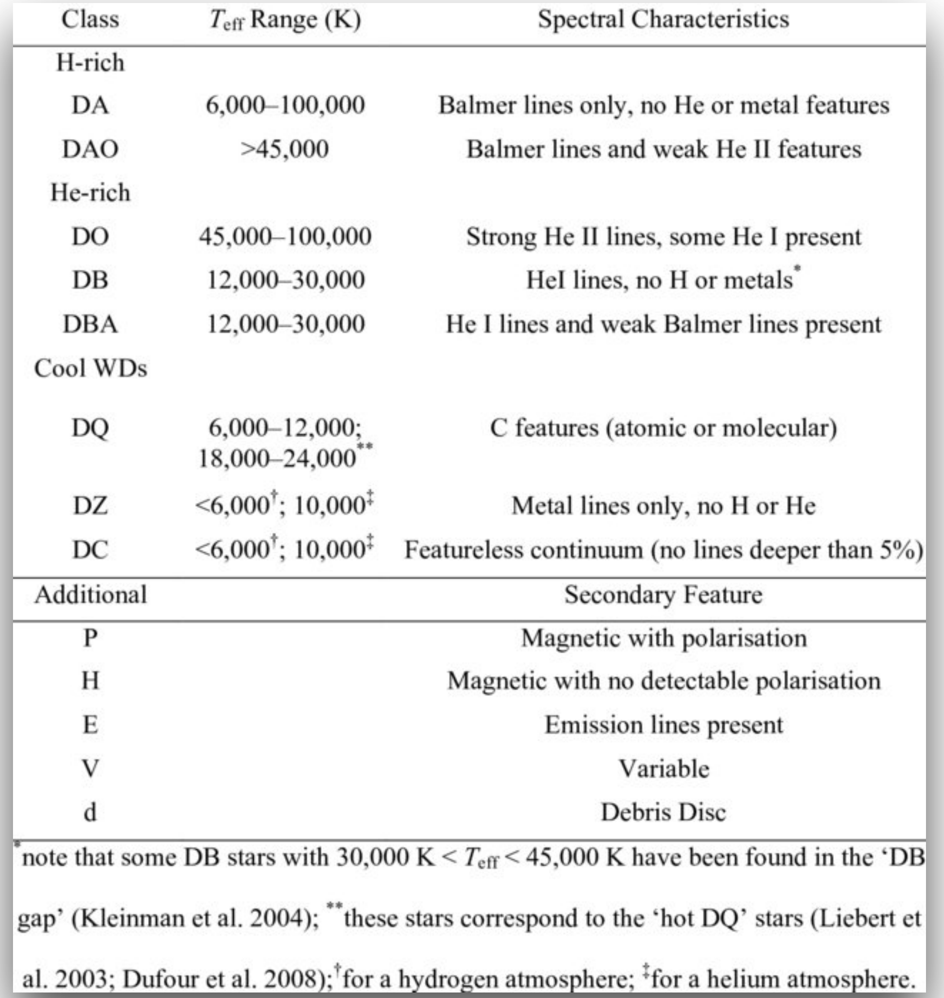
- **Element separation due to strong surface gravity**

➡ Surface composition usually completely different from interior composition.

➡ Leftover H at surface, heavier elements deeper

➡ Spectra of most WDs dominated by H lines (**spectral class DA**), irrespective of interior composition

- Spectral class **DB** (fewer WDs): only He lines (no H left, probably lost due late thermal pulse)



Class	T_{eff} Range (K)	Spectral Characteristics
H-rich		
DA	6,000–100,000	Balmer lines only, no He or metal features
DAO	>45,000	Balmer lines and weak He II features
He-rich		
DO	45,000–100,000	Strong He II lines, some He I present
DB	12,000–30,000	HeI lines, no H or metals*
DBA	12,000–30,000	He I lines and weak Balmer lines present
Cool WDs		
DQ	6,000–12,000; 18,000–24,000**	C features (atomic or molecular)
DZ	<6,000†; 10,000‡	Metal lines only, no H or He
DC	<6,000†; 10,000‡	Featureless continuum (no lines deeper than 5%)
Additional		Secondary Feature
P		Magnetic with polarisation
H		Magnetic with no detectable polarisation
E		Emission lines present
V		Variable
d		Debris Disc

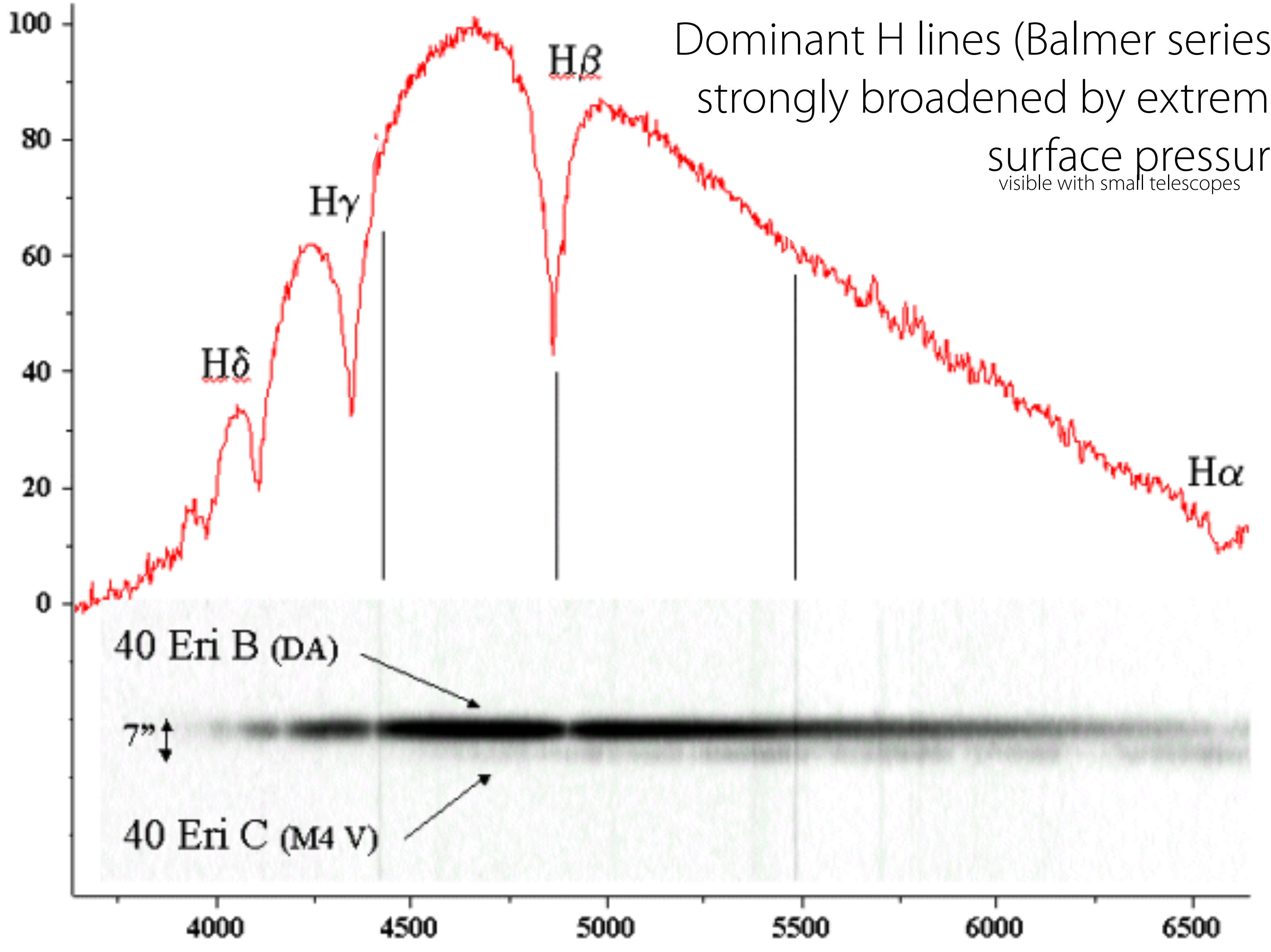
*note that some DB stars with 30,000 K < T_{eff} < 45,000 K have been found in the 'DB gap' (Kleinman et al. 2004); **these stars correspond to the 'hot DQ' stars (Liebert et al. 2003; Dufour et al. 2008); †for a hydrogen atmosphere; ‡for a helium atmosphere.

N. Dickinson

40 Eri B: DA WD

Dominant H lines (Balmer series), strongly broadened by extreme surface pressure

visible with small telescopes



https://www.astrogeo.va.it/astronom/spettri/nane-bien.htm

White Dwarfs

Numerical simulations

CO^{5}BOLD — Tremblay et al 2015

T_{eff} ~ 10 000 K

log g = 8.0 *(~3600 times more than on Sun!)*

B_z = 0 G ———— 500 G ———— 5 000 G

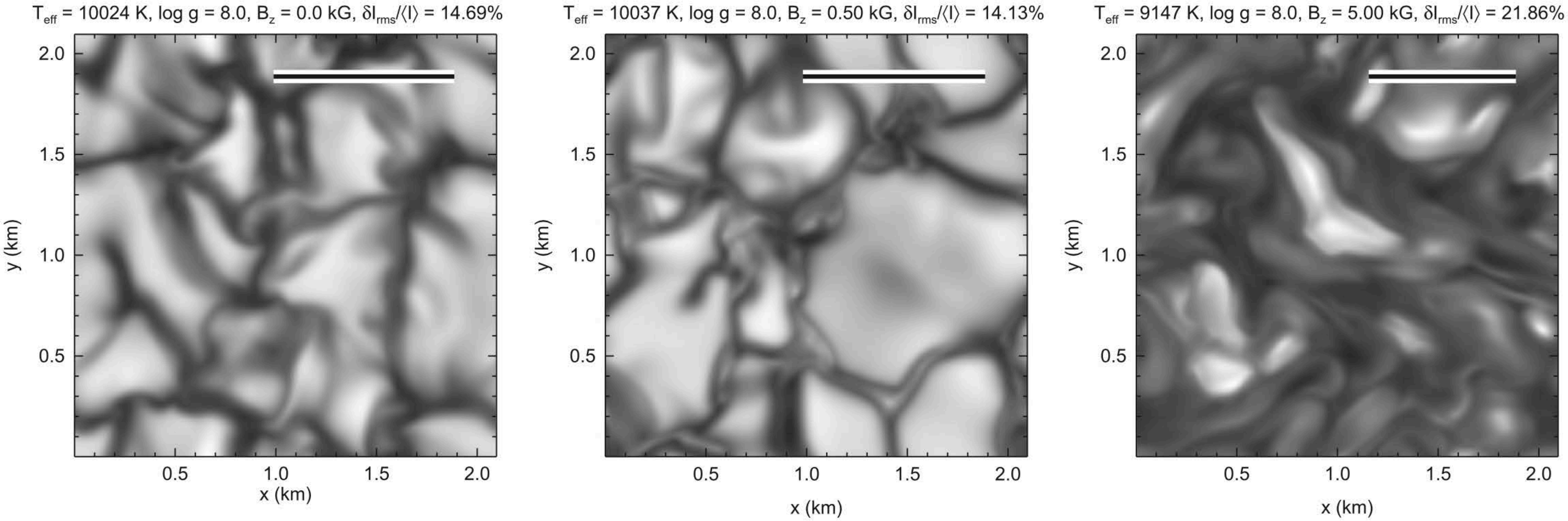


Figure 1. Bolometric intensity emerging from the *xy* plane at the top of the computational domain for CO^{5}BOLD 3D simulations computed with the MHD solver. All simulations have a constant surface gravity of log $g = 8.0$, a pure-hydrogen composition, and rely on the same entropy value for the inflowing material through the open bottom boundary. At the bottom of the simulations shown in the middle and right panels there are imposed average vertical magnetic fields of 0.5 and 5 kG, respectively. The rms intensity contrast with respect to the mean intensities and $T_{\rm eff}$ values are also shown above the panels. The length of the bar in the top right is 10 times the pressure scale height at $\tau_R = 2/3$.

White Dwarfs

Consequences of mass flow in close binaries (with a White Dwarf)

- Mass flow from other star (accretion) adds mass to White Dwarf (WD)
- Mass flows not directly onto other star but forms an **accretion disk** due to conservation of angular momentum (or even common envelope)
- Accreted material mostly consisting of hydrogen is thermally heated by the hot WD

➡ Eventually reaches a critical temperature causing ignition of rapid runaway fusion

- **Nova** (increased brightness, was mistaken for a new star)
  - Dwarf nova: in accretion disk
  - Classical nova: Accreted envelope around WD, released energy expels envelope (2-3/yr classical observed in our galaxy)
- All novae involve WDs in close binary systems.
- Recurrent nova —
  if system survived and mass flow continues

- If WD then exceeds Chandrasekhar limit:
  Collapse of degenerate WD!

➡ Explosive fusion (“carbon bomb”):
Supernova Type Ia

Third possible scenario:
Collision of two WDs!

Final stages of high-mass stars

Final stages of high-mass stars

Core collapse

“**The Iron Catastrophe**”

- Iron core — no more exothermic nuclear reactions possible!
- BUT: core is degenerate (like an "iron white dwarf") and remains stable without energy source (if not exceeding Chandrasekhar mass limit of 1.4 $M_\odot$)
- Core mass of > 1.4 $M_\odot$) (initial mass of > 8 $M_\odot$) cannot be supported by electron degeneracy pressure

➡ Core collapse (free fall!)

➡ Core Collapse Supernova (Type II Supernova)

- During collapse: **Conservation of angular momentum and magnetic flux**

➡ Rotation rate and magnetic field strength (of the core) increase

Supernovae

Supernovae in stars with 8 $M_\odot < M < 20\ M_\odot$

- Iron core collapses rapidly (free-fall), becomes denser.
- **Inverse beta decay** at high density: protons + electrons combine to form neutrons + neutrinos:

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

- **Neutrinos** carry away energy and neutron gas gets denser (under continued collapse)
- At density > 10^{14} g cm^{-3} : **Neutron degeneracy pressure** provides an outward pressure (equivalent to electron degeneracy pressure)
- Gravitational collapse halts, a **stable core (=neutron star)** is formed!

- Outer layers still collapsing inwards, collide with hard surface of newly formed neutron star.
  - Matter rebounds, a **shock wave propagates outwards**, collides with outer layers of the star.
  - Expanding wave carries an extraordinary amount of energy!
  - Enables endothermic fusion reactions — creation of very high-mass elements (e.g., Uranium) (All elements heavier than Fe formed in supernovae)

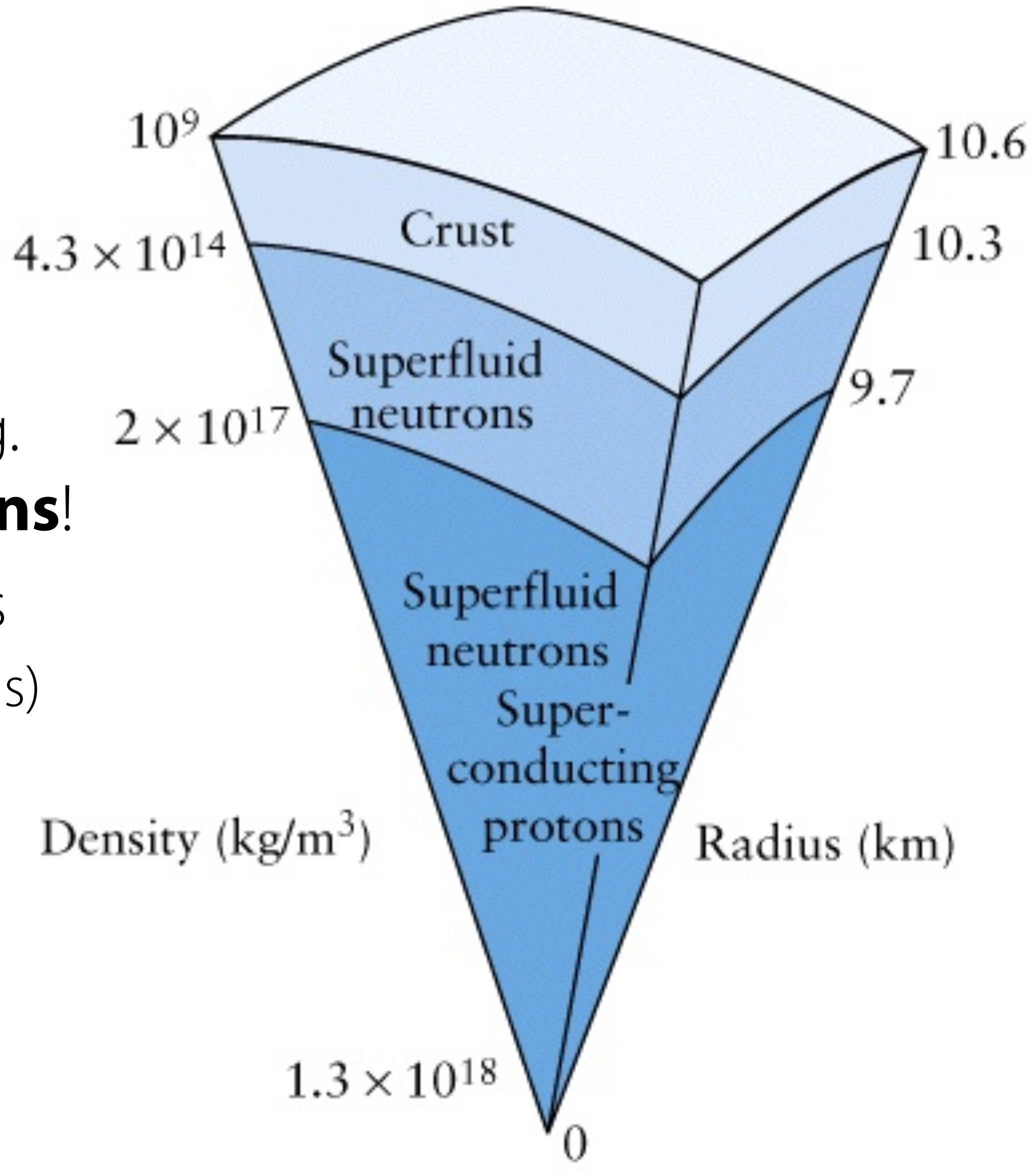
Final stages of high-mass stars

Neutron stars

- Initially very hot (~10^{11} K), glowing in X-rays
- Rapid cooling during first few 100 yr, down to 10^6 K
- Young neutron stars found inside supernova remnants.
- Neutron degeneracy pressure equivalent to electron deg. pressure but **neutron ~1800 more mass than electrons**!
  - Remember: particle momentum and speed of light as limit (Chandrasekhar limit for relativistic degenerate electrons)
  - For same pressure, neutrons must be 1800 times closer to each other than electrons in WD

    ➡ Neutron star with same mass as WD would have ~1000 times smaller radius
  - Typical radius for a neutron star is ~10 km.

  ➡ Average density of 10 km neutron star with 2 M⊙: 10^{18} kg/m^{-3} (10^9 denser than WDs!)



- Composition of core uncertain — may contain exotic particles like pions or unbound quarks

  ➡ Uncertainties regarding forces opposing gravity

  ➡ Uncertainty about internal structure and actual size! (10 - 20 km!?)

Final stages of high-mass stars

Neutron stars — Consequences of collapse

- During collapse: **Conservation of angular momentum and magnetic flux**
  - Rotation rate and magnetic field strength increase
- **Example:** If the Sun would collapse the size of a neutron star (It won't due to too little mass.)
  - Sun: ~10^5 larger than typical neutron star.

- Spin period prop. to R^2 (R: radius)
- Collapse to neutron star size

➡ Rotation period 10^{-10} times smaller: 0.2 ms!

- Already slow initial rotation will be amplified into very fast rotation
- Neutron stars can spin with period **near 1ms!**
- Limit at ~0.5ms for neutron stars, faster rotation would tear apart star due to centrifugal forces

- Magnetic field strength prop. to R^{-2}
- Collapse to neutron star size

➡ Magnetic field 10^{10} times stronger!

- Typical magnetic fields on neutron stars ~10^{12} times stronger than the Sun's
- Some (few) neutron stars reach 10^{14} times stronger fields (called **magnetars**)
- Even weak initial magnetic field amplified to extreme values!

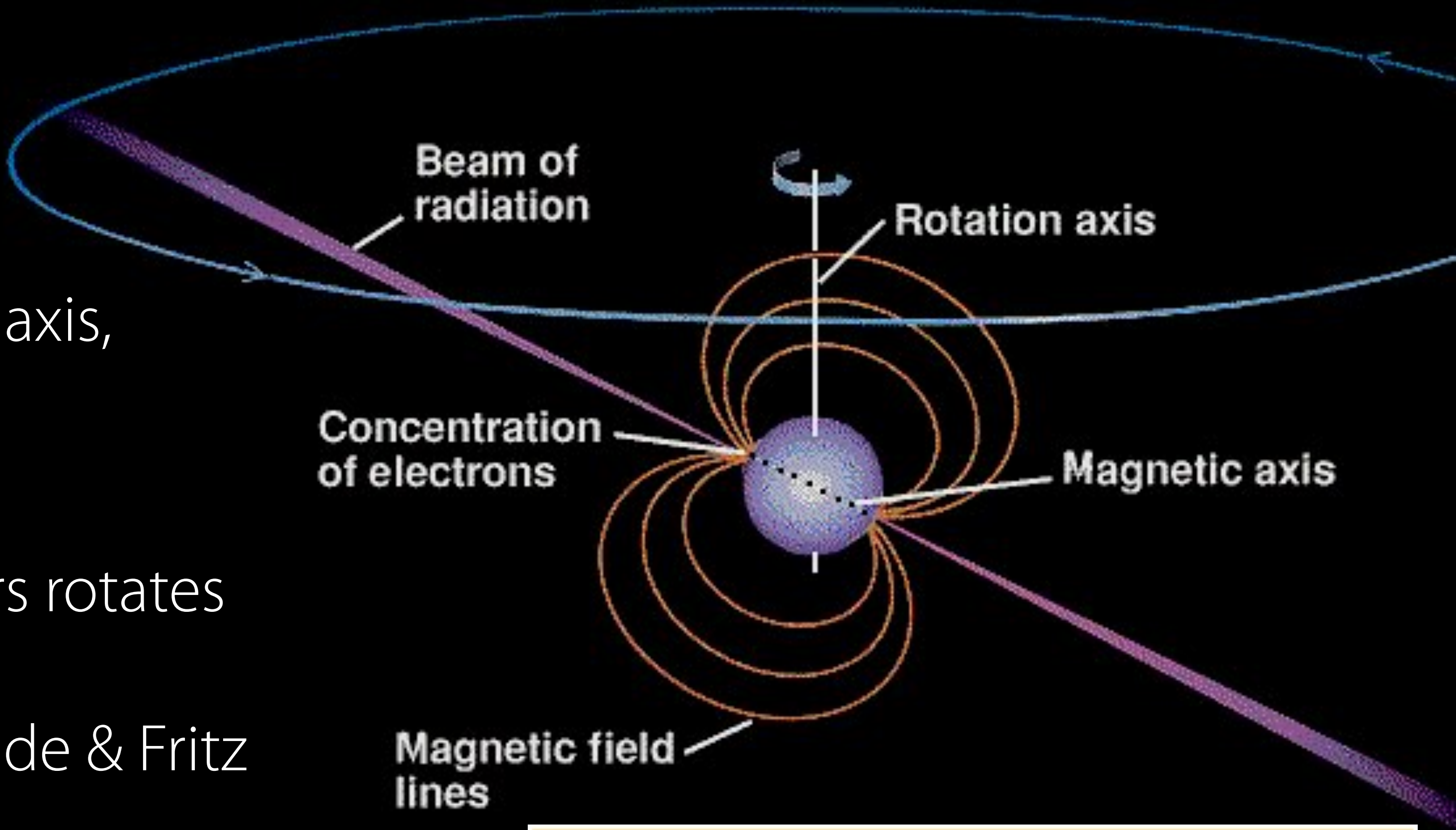
Final stages of high-mass stars

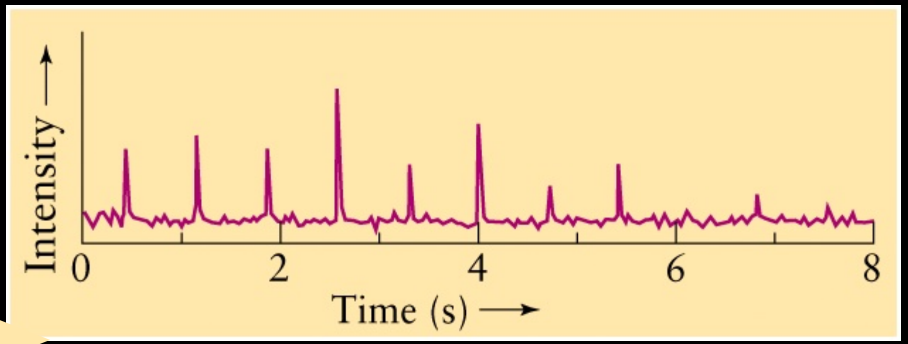
Pulsars

- Fast rotating neutron star with strong magnetic field
  - ➡ Electrons accelerated along magnetic axis, emit synchrotron radiation
  - ➡ Radiation beams along magnetic axis
  - ➡ Sweeps through space as neutron stars rotates

- First theoretically predicted by Walter Baade & Fritz Zwicky in 1930's
- Discovered in 1967 by Jocelyn Bell (Ph.D. thesis!) with new radio telescope:
  - Radio signal at one sky location showing <u>regular</u> pulsations (on/off) with period of **1.337 s.**
  - First thought of as alien signal … LGM = Little Green Men

- Now > 1000 neutron stars discovered.
  - Among them 200 very fast millisecond pulsars
    - Pulsars observed in gamma-rays, x-rays, visible light, infrared, and radio

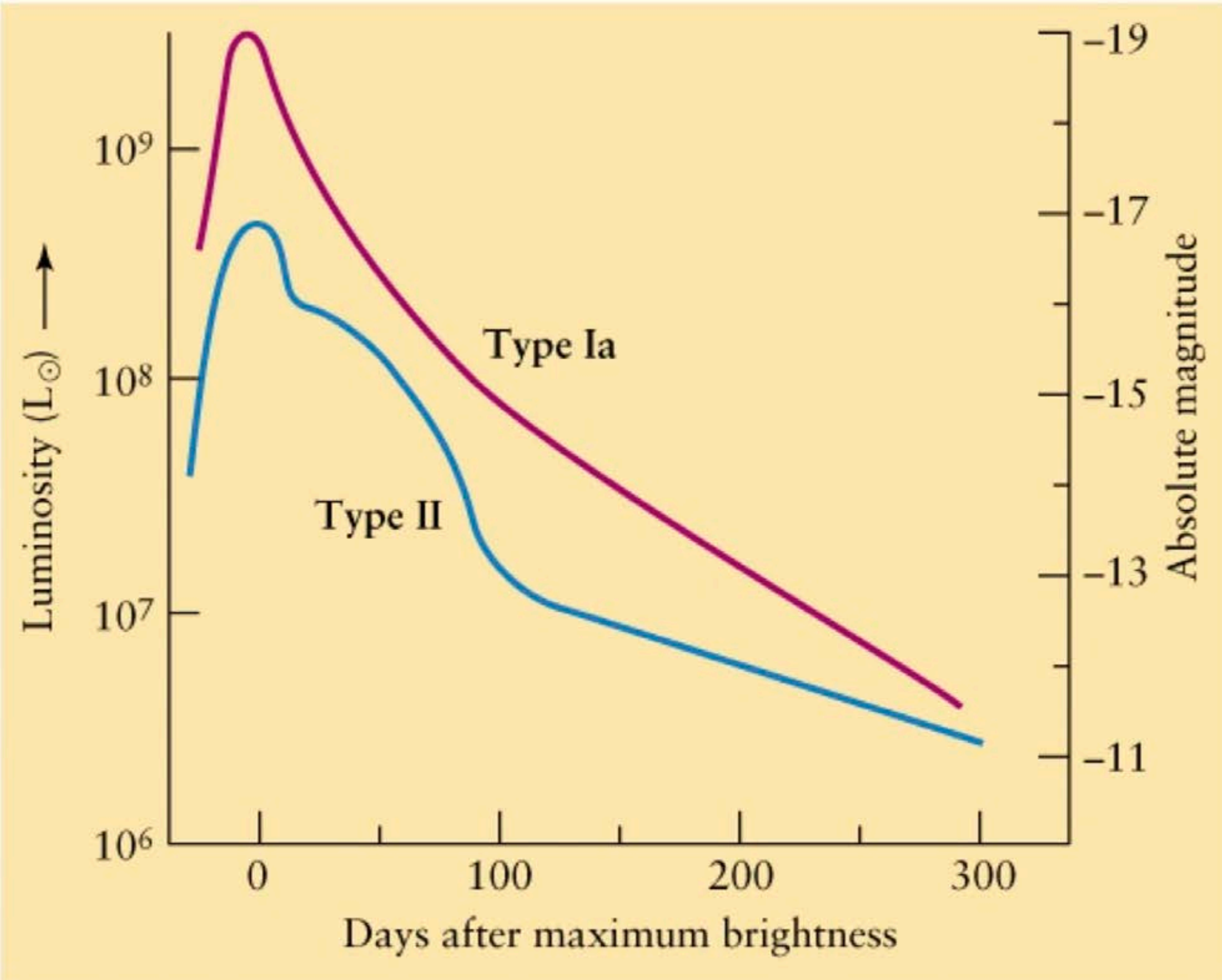




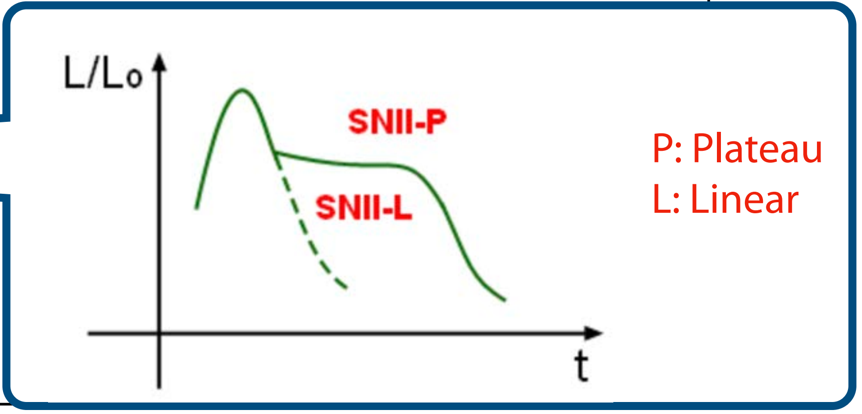
Supernovae (SN)

Overview

- Classification based on observed spectra and lightcurve (i.e. change over time)
- Type Ia supernovae: Very uniform properties (luminosity/lightcurve)
  - Used to determine (intergalactic) distances (standard candles)
- Different ways to exceed mass limit leading to core collapse



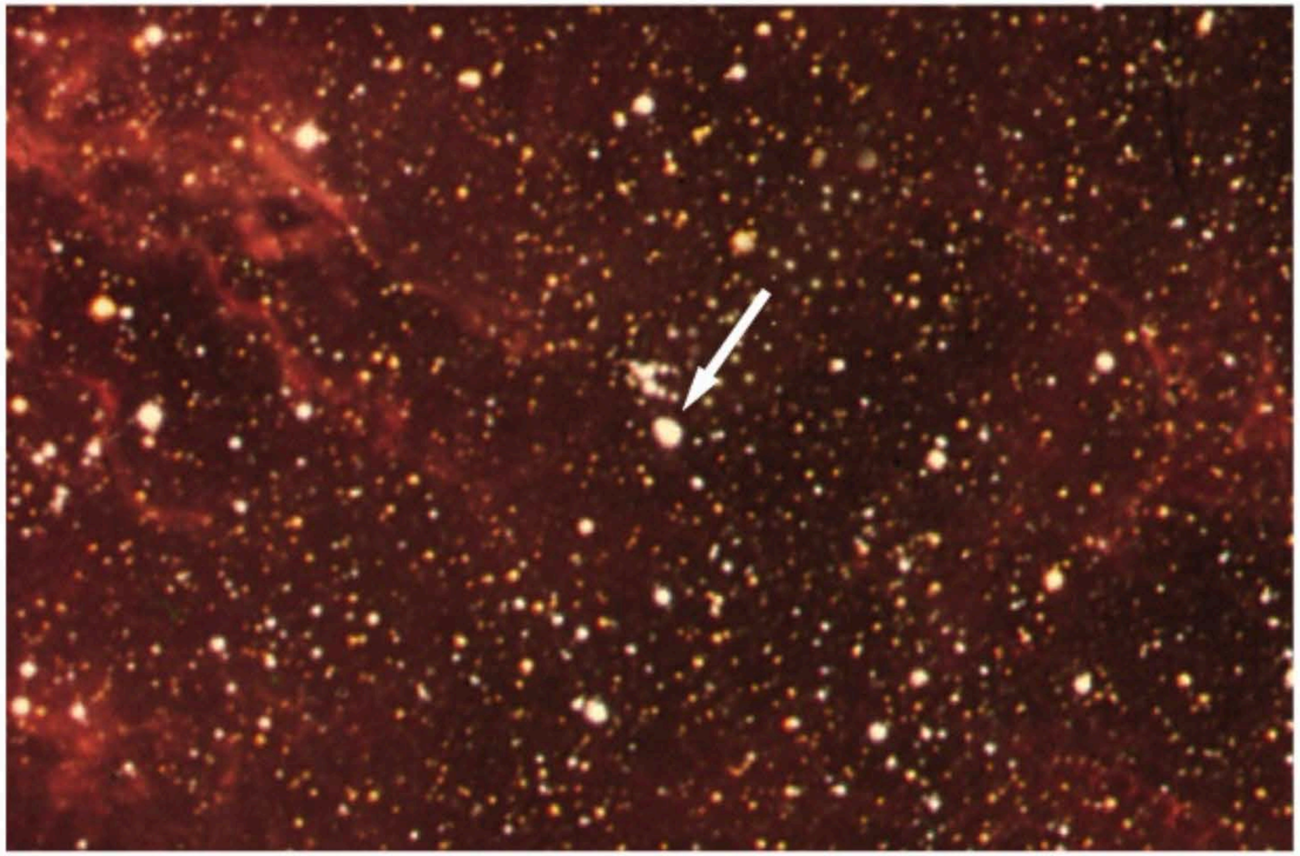
Type		Observation	Mechanism
I	Ia	Si II line	**Thermonuclear runaway**
	Ib	Weak/no Si II line + He I line	**Core collapse**
	Ic	Weak/no Si II + weak/no He I line	
II	II	Broad H lines	
	IIb	Spectrum changes, becomes like Type Ib	



Supernovae

SN 1987A

- Core Collapse Supernovae occur ~ once every 50 years in our galaxy (most hidden by dust)
- 1987: supernova in Large Magellenic Cloud (our "companion" galaxy)
- Nearest supernova observed since Kepler's supernova in 1604.
- Progenitor: blue supergiant, $L \approx 1.1 \times 10^5\, L_\odot$ and $T_{\rm eff} \approx 16\,000$ K, initial mass ~ $18\, M_\odot$.
- 20 neutrinos (8 - 40 MeV) detected within 10s (time it takes to transform Fe core into hot (proto-)neutron star during core collapse



a

The B3 I star before the supernova

b

The supernova explosion

Supernovae

Supernovae in very massive stars (M > 20 $M_\odot$)

- **Maximum mass** for neutron stars (equivalent to Chandrasekhar limit) but uncertain: **~3 $M_\odot$** (1.5 - 4 $M_\odot$)
- If stellar core exceeds maximum mass: neutron degeneracy pressure cannot balance gravity.

➡ Further collapse

➡ Formation of a **black hole**.

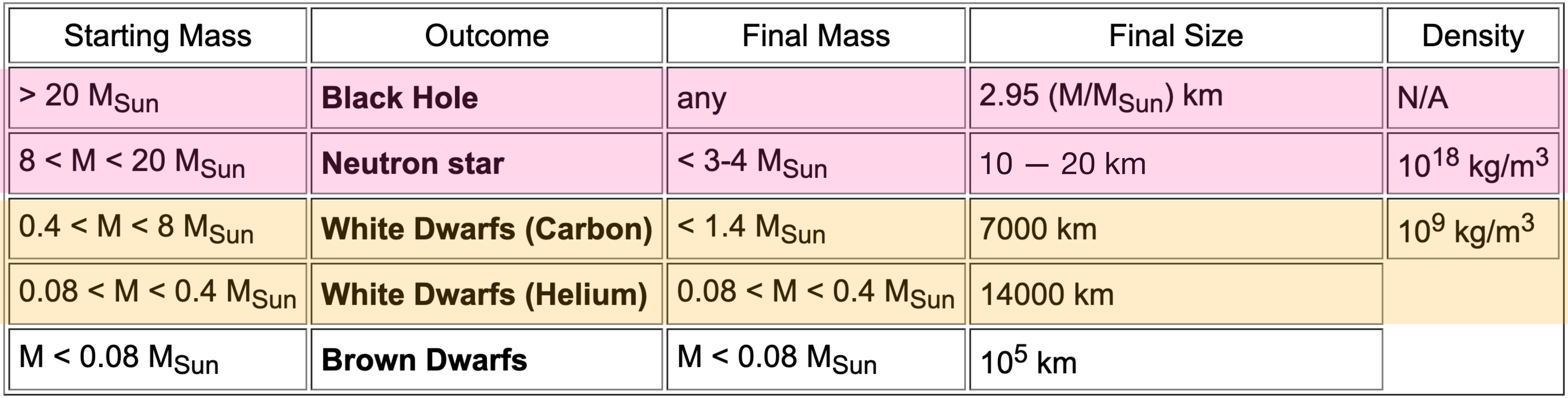
- In principle no mass limit (as far as we know)
- Gathering many stellar black holes creates supermassive black holes:
  - Sagittarius A*, at the centre of the Milky Way: $4\ 10^6\ M_\odot$

Event Horizon Telescope collaboration

Final stages of high-mass stars

Stellar evolution

- **Stellar evolution (and final stage) depends on initial mass!**
  - Conditions in the core — electron degeneracy pressure!
  - Mass loss in late evolution stages, extreme for massive stars! (Expulsion of envelope as planetary nebula)
  - Interaction with a (close) companion can influence evolution!
- Stars with initial masses > 8 $M_\odot$ explode as supernovae (iron core collapse), neutron stars (neutron degeneracy pressure) or black holes as remnant



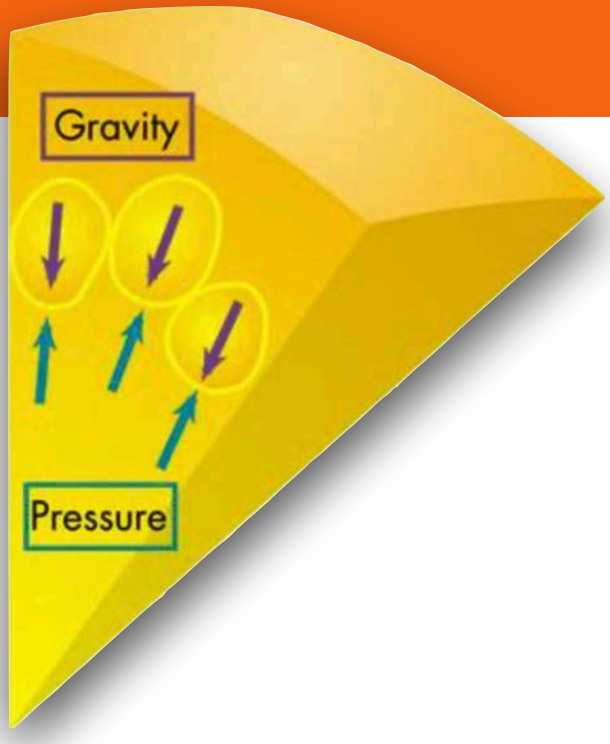
Starting Mass	Outcome	Final Mass	Final Size	Density
$> 20\ M_{Sun}$	**Black Hole**	any	$2.95\ (M/M_{Sun})$ km	N/A
$8 < M < 20\ M_{Sun}$	**Neutron star**	$< 3\text{-}4\ M_{Sun}$	10 — 20 km	10^{18} kg/m^3
$0.4 < M < 8\ M_{Sun}$	**White Dwarfs (Carbon)**	$< 1.4\ M_{Sun}$	7000 km	10^9 kg/m^3
$0.08 < M < 0.4\ M_{Sun}$	**White Dwarfs (Helium)**	$0.08 < M < 0.4\ M_{Sun}$	14000 km	
$M < 0.08\ M_{Sun}$	**Brown Dwarfs**	$M < 0.08\ M_{Sun}$	10^5 km	

Course summary

The essential take-aways

Essential take-aways

The workings of stars



- **Hydrostatic equilibrium** required to keep a star stable for extended time
  - Slow adjustments of structure during evolution to maintain stability, some phases with more rapid changes

- **The battle against gravity** — Pressure needed to keep the star stable
  - Thermal pressure (energy releases by nuclear fusion)
  - Degeneracy pressure (electrons or neutrons) at high densities
    - Mass limits for core/star stable against gravity:

Electrons: 1.4 $M_\odot$ (White Dwarfs)
Neutrons: ~3 $M_\odot$ (neutron stars)

- **Time scales** — determine which processes matter most at a given evolution stage

Dynamical Time Scale	time needed to collapse if pressure supporting against gravity were suddenly removed.
Thermal Time Scale	time needed to radiate away all thermal energy if nuclear energy production suddenly stopped
Nuclear Time Scale	time needed to radiate away all energy that can be released by nuclear reactions

Essential take-aways

“Follow the energy”

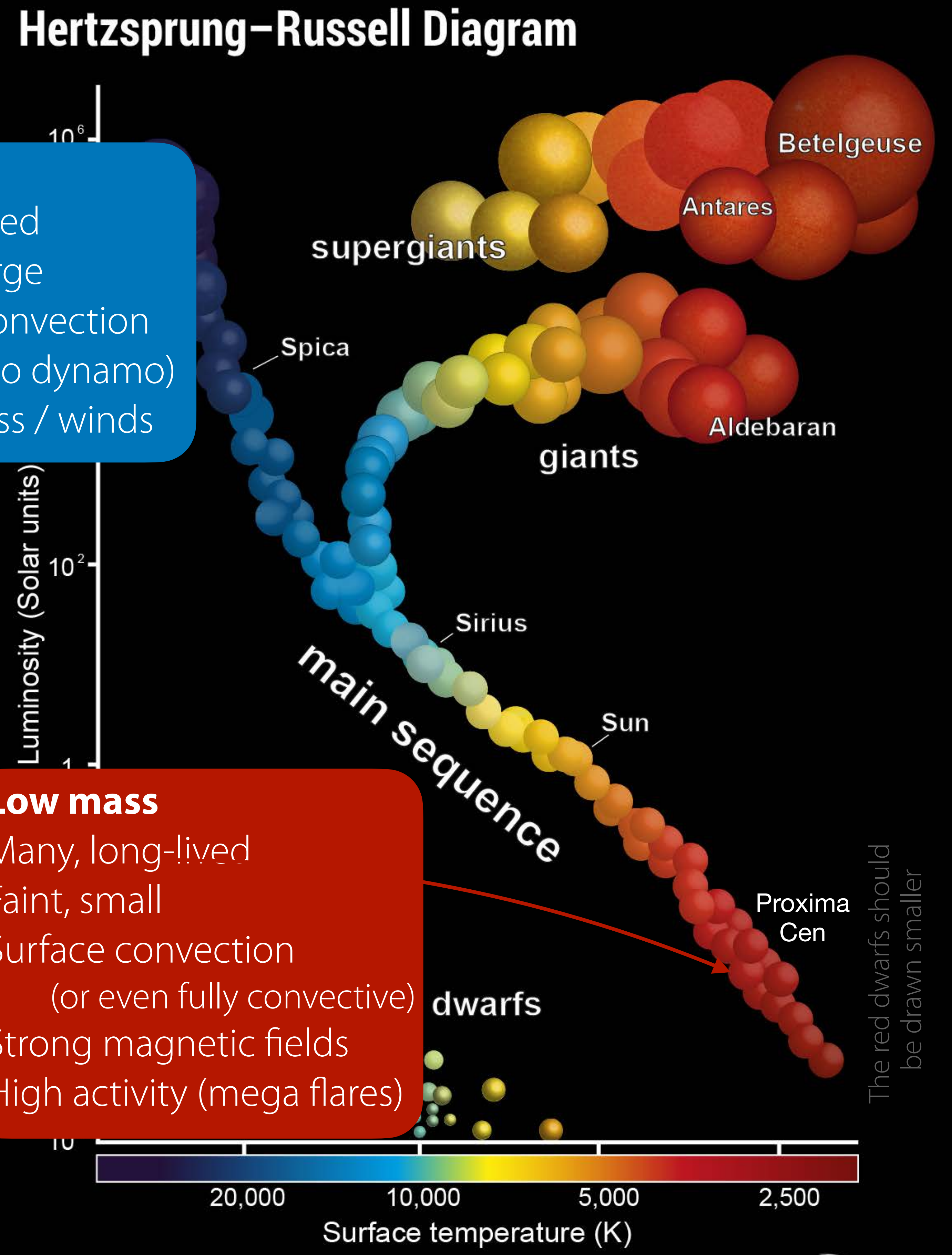
- **Energy is conserved but will be converted between different forms.**
  - **Source:** nuclear fusion as the by far dominant source (for the Sun: in the core)
  - **Transport** outwards
  - **Leaves** the star at the “surface”, mostly in form of radiation — **luminosity**

- **Energy transport mechanisms:**
  - **Radiation**: Photons carry energy as propagate through the star (emission/absorption).
  - **Convection**: Net rise of buoyant (hot) gas towards surface.
  - **Conduction**: Transfer of kinetic energy between gas particles during collisions (usually not important except for solar corona)
  - **Neutrinos**: Neutrinos carry away energy (important for massive stars)
  - The efficiency / contribution of the different mechanisms depends on the local plasma conditions (such as density, opacity)

  ➡ Radiative or convection zone(s) form accordingly

Essential take-aways

- **Evolution and final final state strongly mass- dependent!**
- Adjustment of structure: core and shell burning of increasingly higher stages (stops depending on mass), change in radiative / convective zones
- Extreme mass loss (in late stages) influences evolution



High mass
Few, short-lived
Luminous, large
No surface convection
No activity (no dynamo)
High mass loss / winds

Low mass
Many, long-lived
Faint, small
Surface convection
(or even fully convective)
Strong magnetic fields
High activity (mega flares)

The red dwarfs should be drawn smaller

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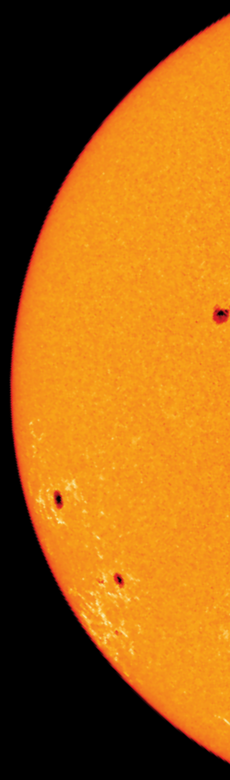
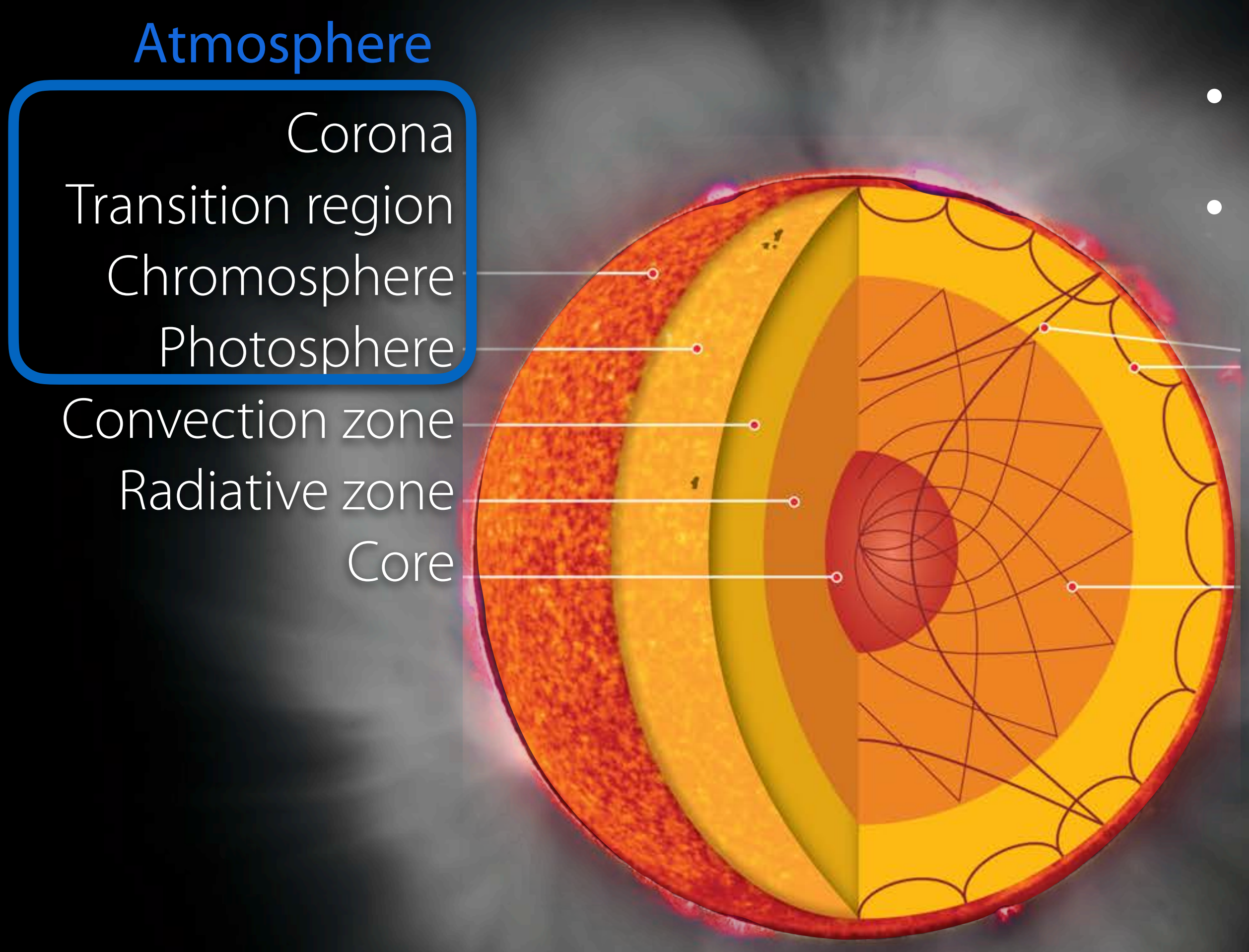
Essential take-aways

The Sun

- Magnetic field structure covers large ranges in strength and spatial scales
    - **Active Sun** (with sunspots) vs. **Quiet Sun** (with smaller, fewer & weaker field concentrations)
    - Prominences/filaments (up to 200 Mm long)
    - Feature extending through atmosphere: Loops, spicules …
    - MHD wave modes





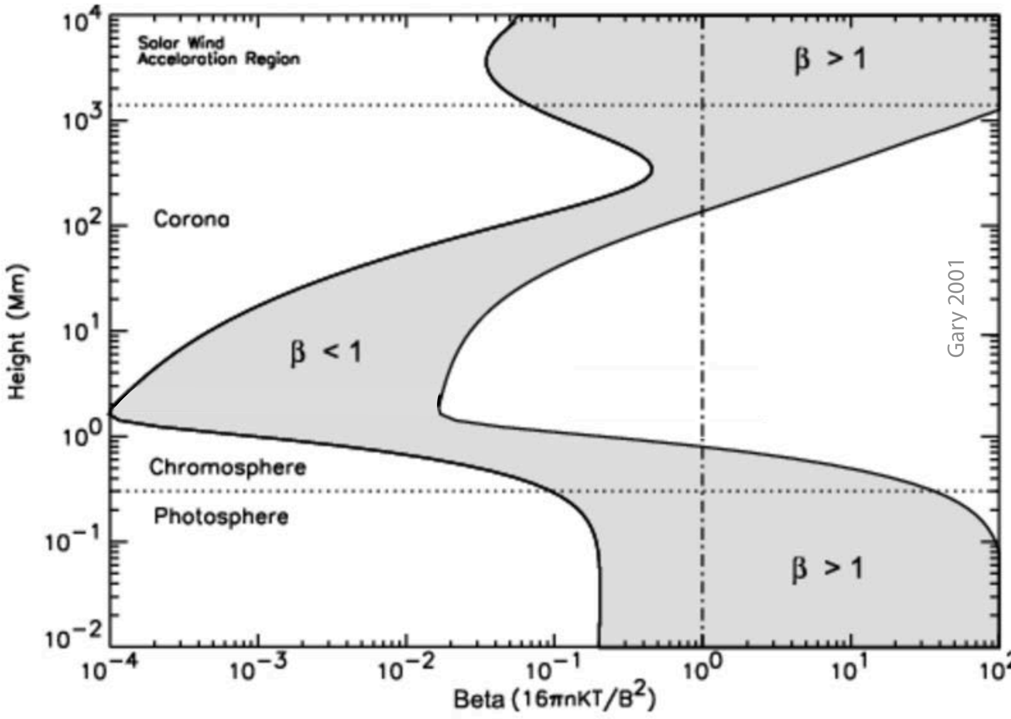
Atmosphere

Corona
Transition region
Chromosphere
Photosphere
Convection zone
Radiative zone
Core

- Granule sizes according to convection cells
- Helio/asteroseismology — to probe interiors (solar 5 min oscillation)
    - Differential rotation
    - Tachocline between radiative / convection zone
- Corona T > 10^6 K — How? **Coronal Heating Problem**
    - **Solar Wind** — creating bubble around solar system (heliosphere)

Essential take-aways

Magnetic fields



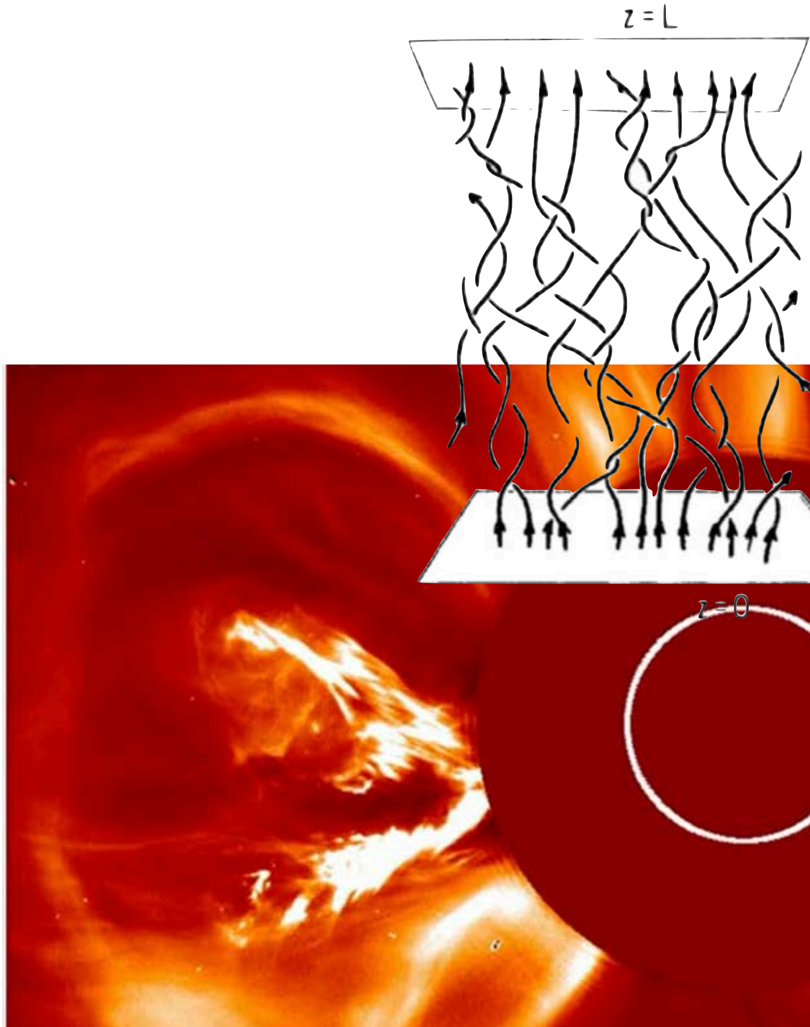
Gary 2001

- **Plasma-β** (ratio thermal to magnetic pressure) determines if gas motion ("frozen-in") or magnetic field dominates

- **Dynamo** (αΩ-dynamo in the Sun, local dynamos?)
  - Rotation + convection
  - 2 x 11yr solar activity cycle as visible in number of sunspots

- Braiding / stressing of magnetic field
— energy stored in magnetic field
- Sudden release via **magnetic reconnection** produces flares (from nano- to megaflares), jets, surges etc.
  - Prominence eruptions / Coronal Mass Ejections (CME)

- **Zeeman-Doppler Imaging** for reconstructing starspots



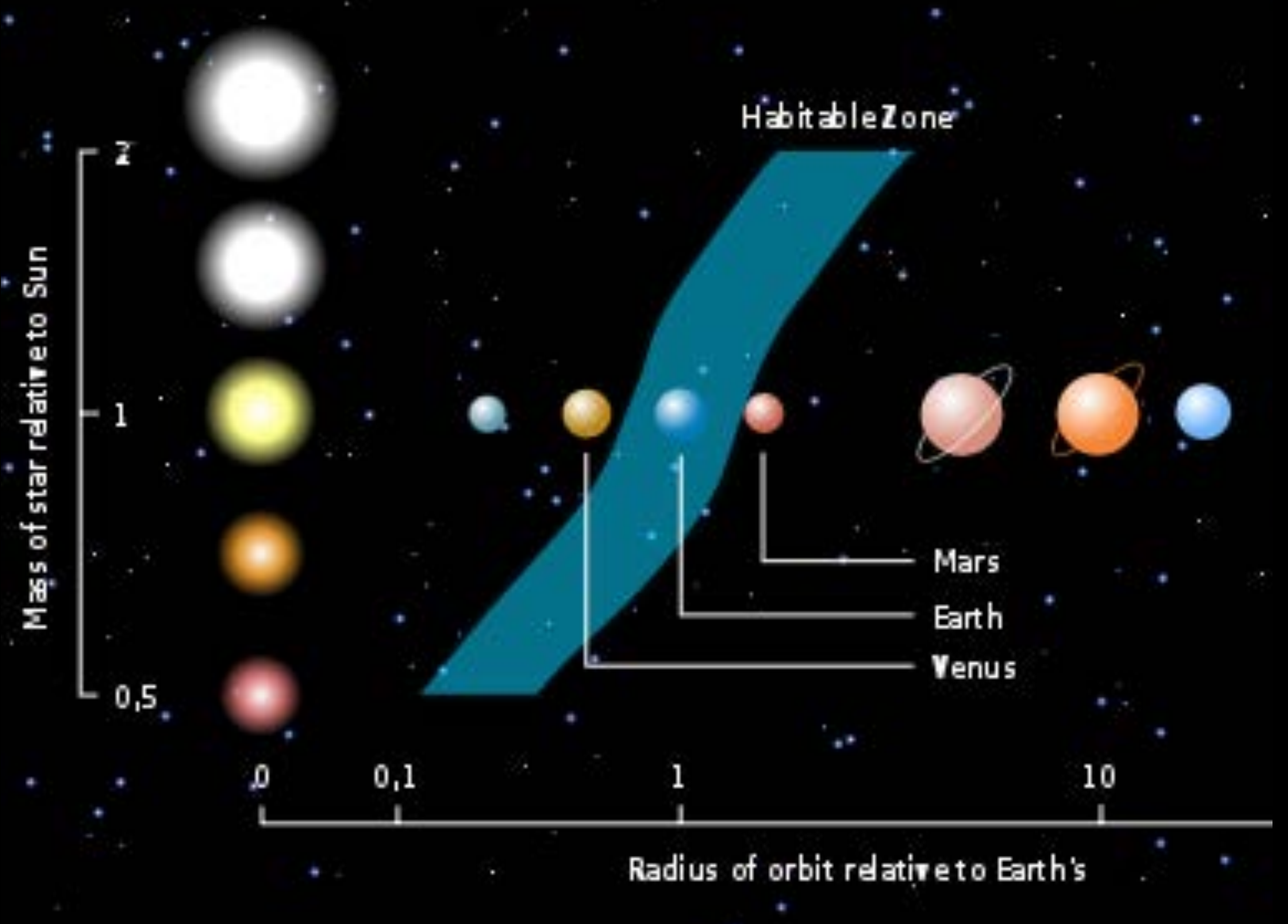
Bonus

Stars as hosts of extrasolar planets

Stars as hosts of extrasolar planets

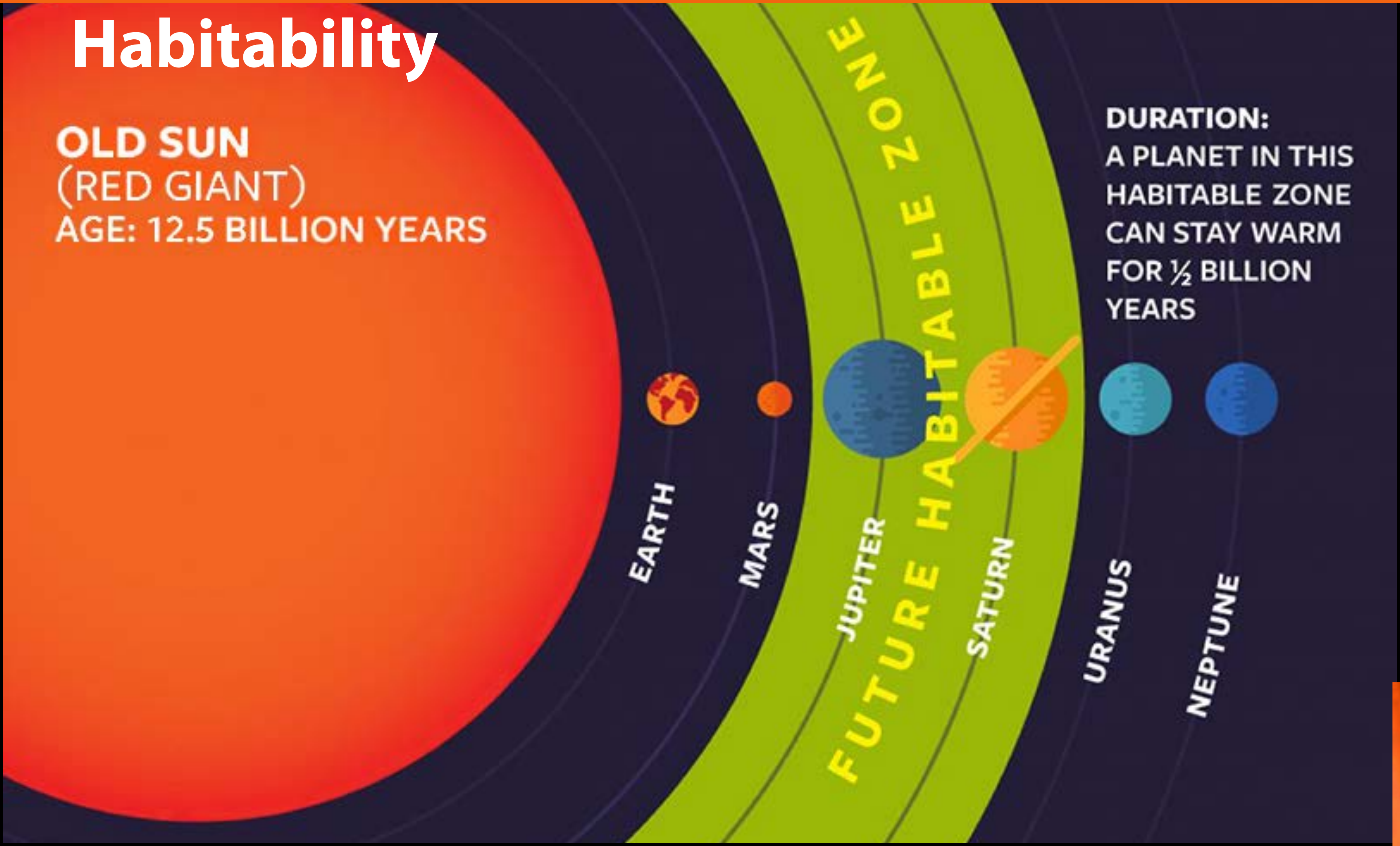
Habitability

- **Habitable zone** = distance from star where water can (in principle) exist in liquid form
  - Does not mean that there has to be water on a planet within the HZ!
- Defined by the irradiation of a planet and thus by the **luminosity** of the host star and the distance to it!
- Habitable zone closer to the host star for the red dwarf stars with low luminosity

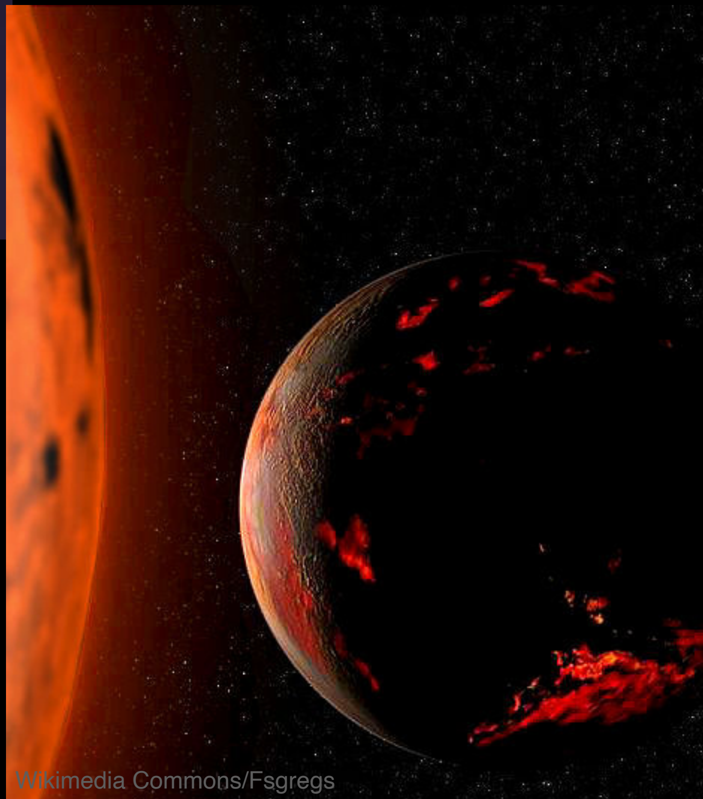


Stars as hosts of extrasolar planets

Habitability



- Habitable zone changes with luminosity as stars evolve
- Further out when the Sun turns into a red giant
- Planets move further out due to Sun’s mass loss
- Will Earth “survive”?



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Stars as hosts of extrasolar planets

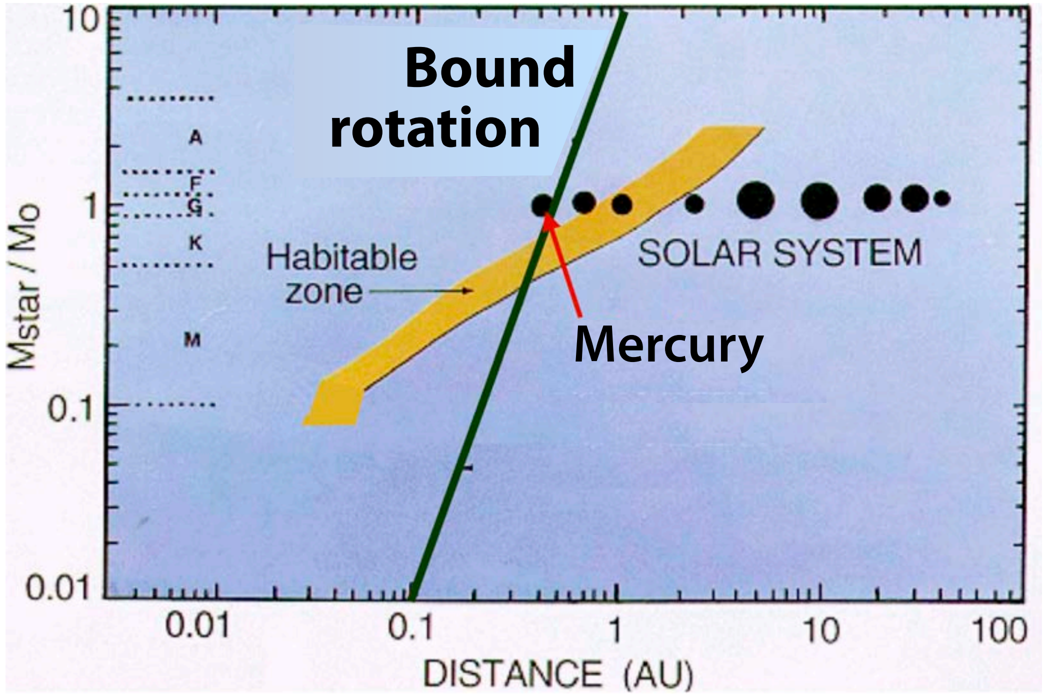
Low-mass stars (M-dwarfs)

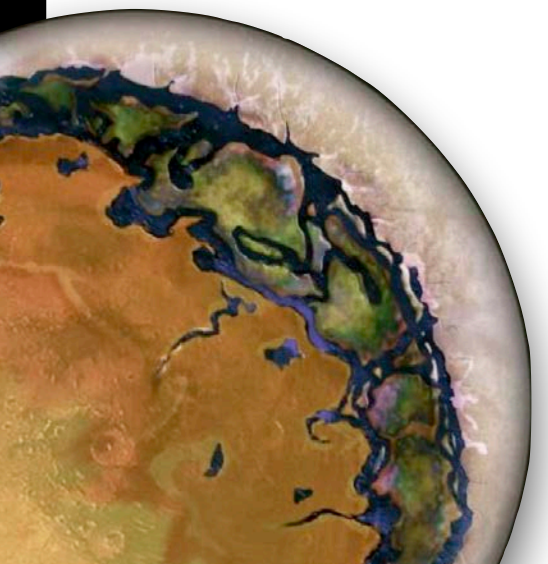
High-mass stars (O/B-type)

Faint — **Luminosity** — Very bright

Close to star — **Habitable Zone: Distance to star** — Far away

- **Tidal locking** of planets if too close to the host star: bound rotation, showing always same side to star (like Earth-Moon)
  - Permanent day and permanent night side with large temperature differences
  - May trigger strong winds
  - Implications for habitability?

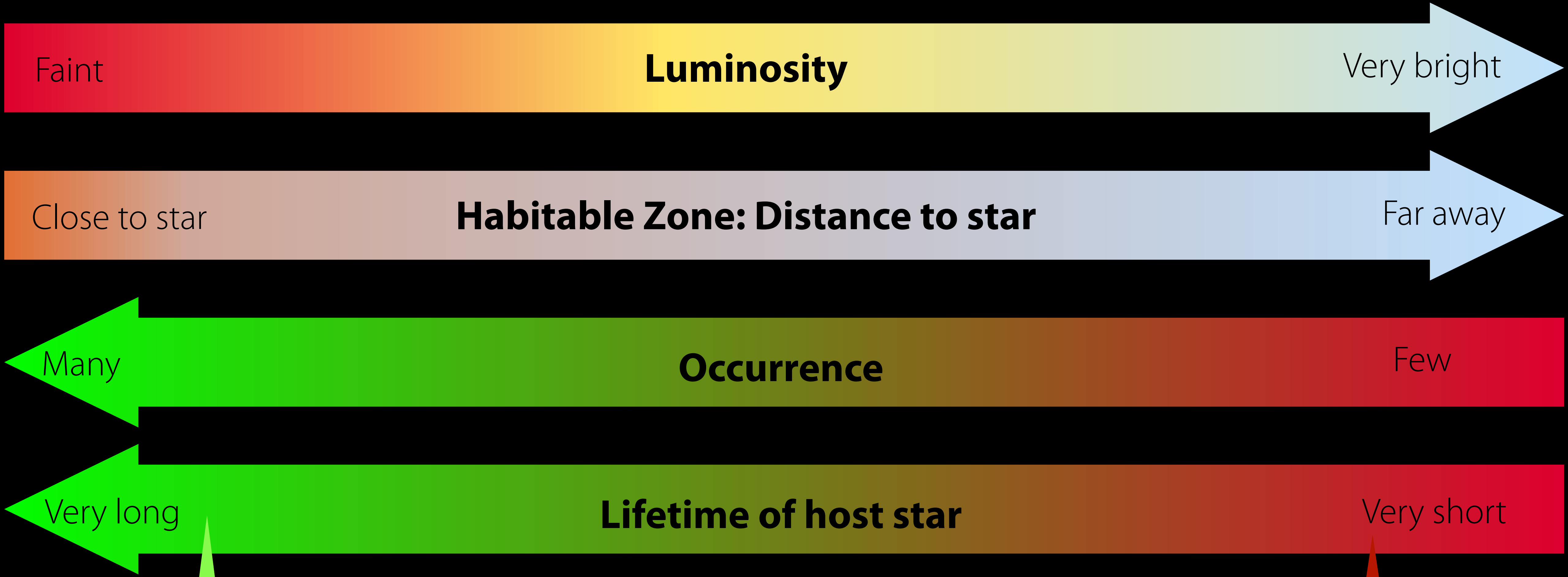




Stars as hosts of extrasolar planets

Low-mass stars
(M-dwarfs)

High-mass stars
(O/B-type)



Faint — **Luminosity** — Very bright

Close to star — **Habitable Zone: Distance to star** — Far away

Many — **Occurrence** — Few

Very long — **Lifetime of host star** — Very short

- More time for geological changes of planets and formation of adequate atmosphere
- More time for the (potential) development of life

- Too short lifetime!

Stars as hosts of extrasolar planets

Low-mass stars (M-dwarfs)

High-mass stars (O/B-type)

Faint — **Luminosity** → Very bright

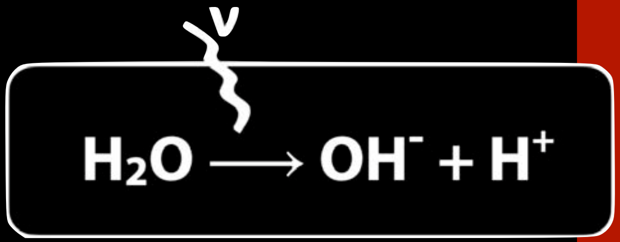
Close to star — **Habitable Zone: Distance to star** → Far away

Many ← **Occurrence** — Few

Very long ← **Lifetime of host star** — Very short

Not much ← **Harmful (high-energy) radiation (UV, X-rays)** — Intense

- Depends also on distance to host star!



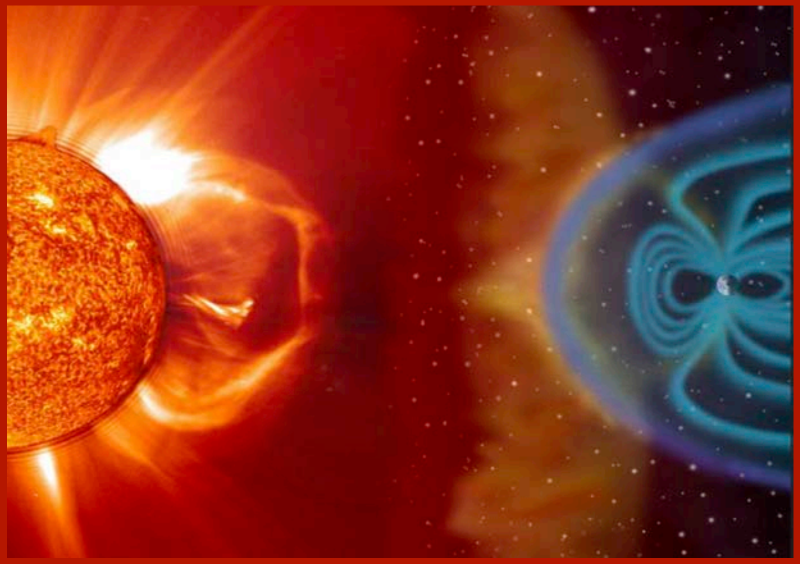
$H_2O \xrightarrow{\nu} OH^- + H^+$

- Harmful for organic material
- Dissociates water, can lead to (partial) loss of planetary atmosphere

Stars as hosts of extrasolar planets

Low-mass stars (M-dwarfs)

High-mass stars (O/B-type)



Faint — Very bright

Close to star — **nce to star** — Far away

Many — **Occurrence** — Few

st star — Very short

iation (UV, X

Activity — **Activity and winds** — Winds

- Habitable zone close to star
- M-dwarfs known for **megaflares**
- Tidal locking may inhibit planetary magnetic field - no protection!

➡ Large doses of harmful radiation and particles!

- Planets would be affected by strong mass loss of the host star (strong stellar winds)

Thanks for your attention
and
good success for the final assignment