Astrophysics of gravitational wave sources

Lecture 6: Single star evolution

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Why do stars shine?

(wrong answers only)

Two-point boundary value problem

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4},$$

$$\frac{dr}{dM_r} = \frac{1}{4\pi r^2 \rho},$$

$$\frac{dT}{dM_r} = -\frac{3\kappa L_r}{64\pi^2 acT^3 r^4},$$

but convection!

$$\frac{dL_r}{dM_r} = \epsilon.$$

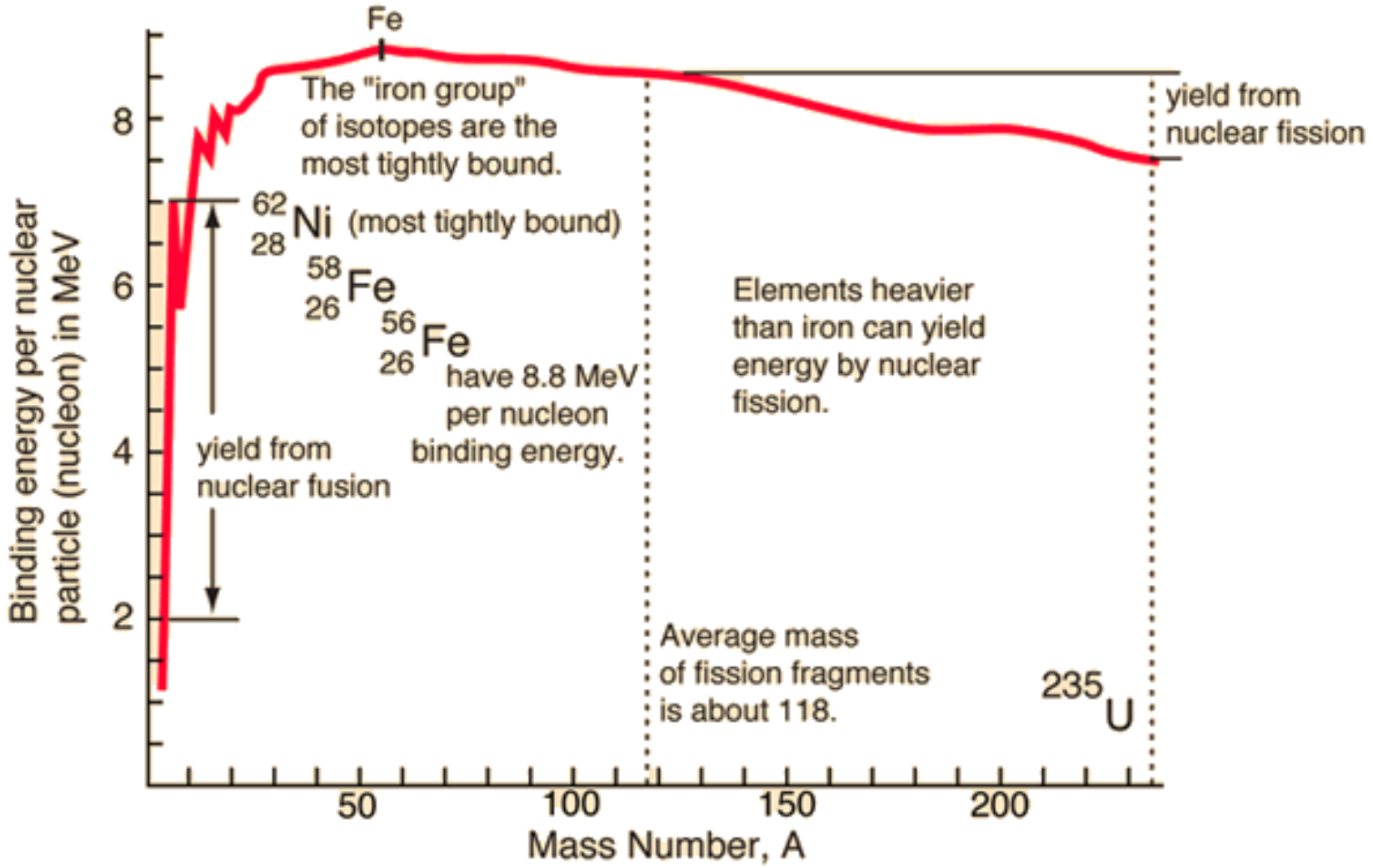
Separation of stellar timescales

- Dynamical (free-fall, sound-crossing) timescale
- (Viscous timescale)
- Thermal (Kelvin-Helmholtz) timescale
- Nuclear timescale

Transport of energy in stars

- Diffusion
- Convection
- Advection

Why do stars evolve?



Nuclear reaction rates

pp

$$p + p \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e$$
$${}^{2}\mathrm{H} + p \rightarrow {}^{3}\mathrm{He}$$
$${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2p$$

$$\epsilon_{pp} \approx 10^{6} X_1^2 \rho T_6^{-2/3} e^{-33.81 T_6^{-1/3}}$$

CNO

$${}^{12}\mathrm{C} + p \rightarrow {}^{13}\mathrm{N} + \gamma$$
$${}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + e^{+} + \nu_e$$
$${}^{13}\mathrm{C} + p \rightarrow {}^{14}\mathrm{N} + \gamma$$
$${}^{14}\mathrm{N} + p \rightarrow {}^{15}\mathrm{O} + \gamma$$
$${}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + e^{+} + \nu_e$$
$${}^{15}\mathrm{N} + p \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$$

$$\epsilon_{CNO} \approx 10^{28} \rho X_1 X_{14} \rho T_6^{-2/3} e^{-152.313 T_6^{-1/3}}$$

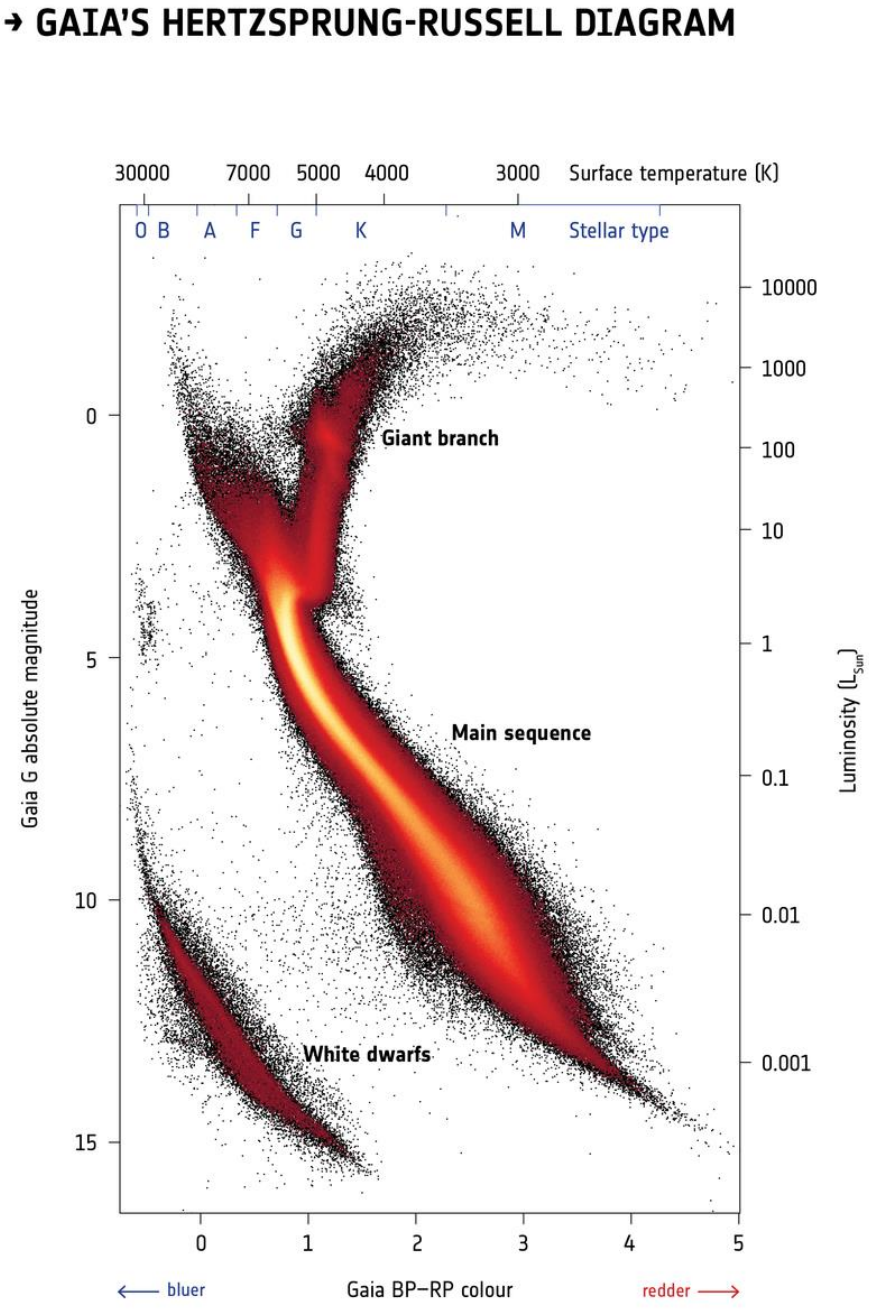
Minor reaction channels:

$$2p + e^{-} \rightarrow {}^{2}\mathrm{H} + \nu_e$$

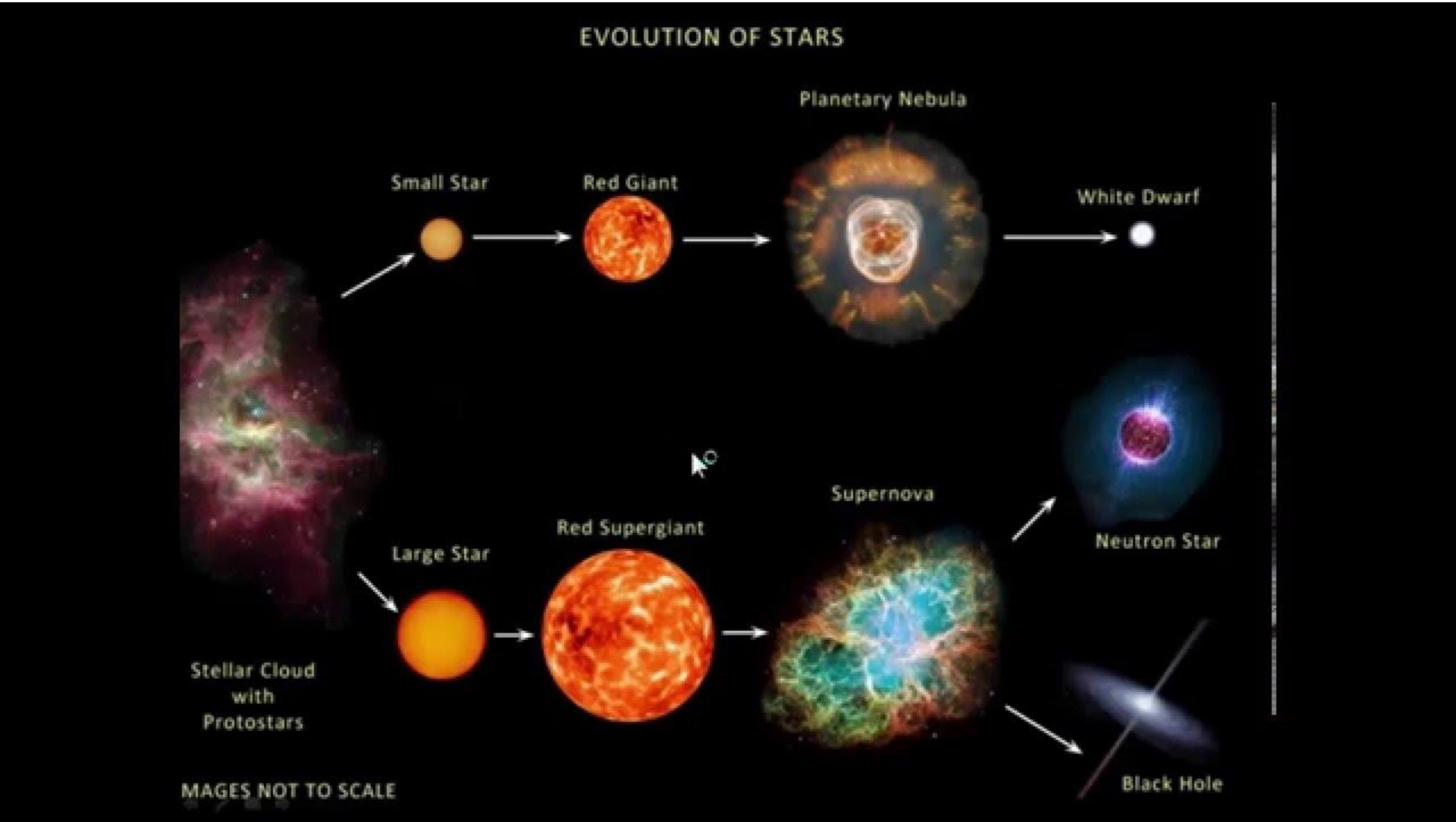
$${}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$$
$${}^{7}\mathrm{Be} + e^{-} \rightarrow {}^{7}\mathrm{Li} + \nu_e$$
$${}^{7}\mathrm{Li} + p \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

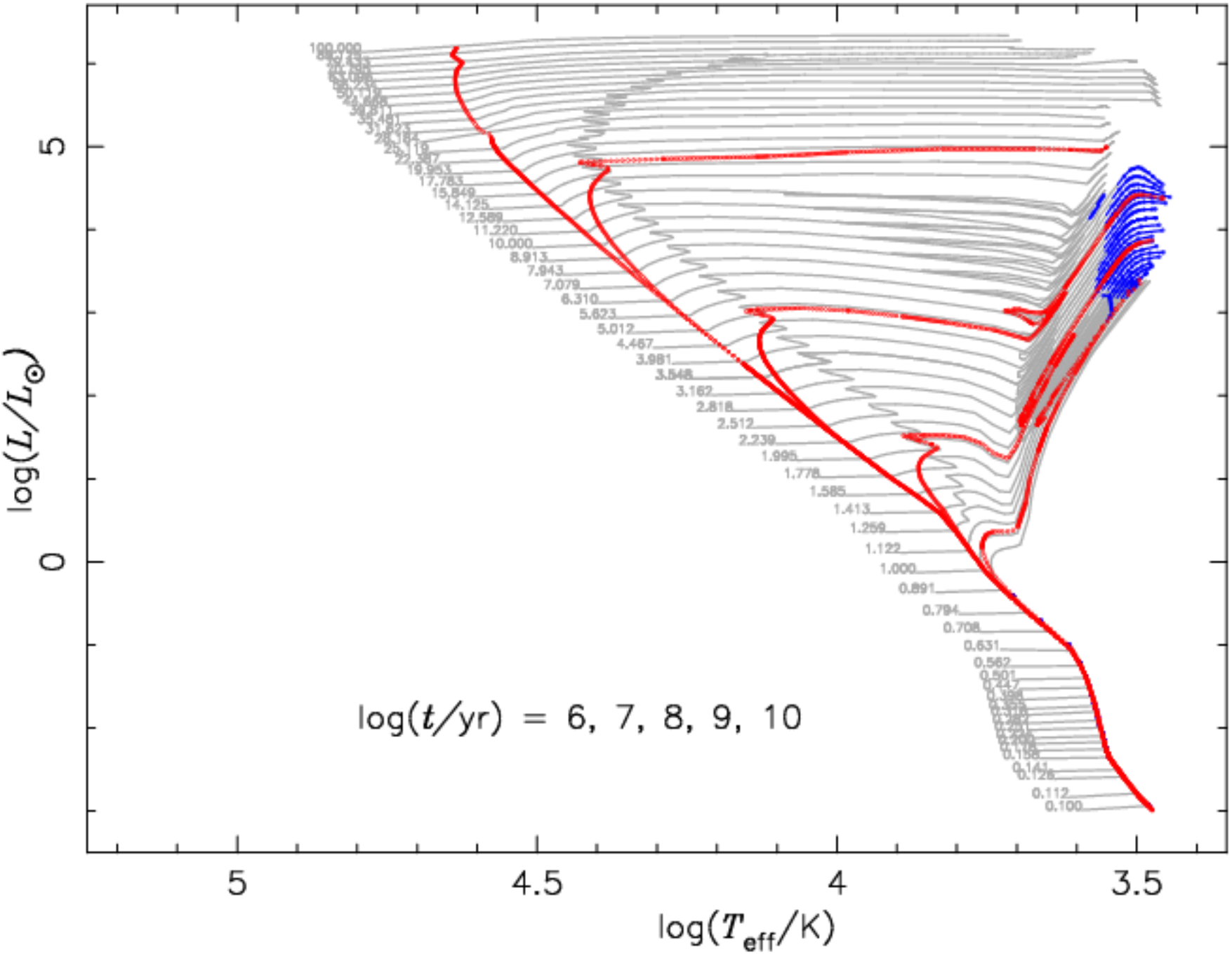
$${}^{7}\mathrm{Be} + p \rightarrow {}^{8}\mathrm{B} + \gamma$$
$${}^{8}\mathrm{B} + p \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \nu_e$$
$${}^{8}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

Main parameters of stars



Stellar evolution




log(L/L⊙)
5
0
log(T_eff/K)
5
4.5
4
3.5
log(t/yr) = 6, 7, 8, 9, 10

Homework

- Make plots of HR diagram and stellar isochrones
- Label major phases of evolution (ZAMS, subgiant, RGB, red clump, AGB, red supergiant, Wolf-Rayet, WD, …)
- Violate as many figure-making rules as possible