# Astrophysics of gravitational wave sources

Lecture 4: Single star evolution

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# Separation of stellar timescales

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

# Two-point boundary value problem

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

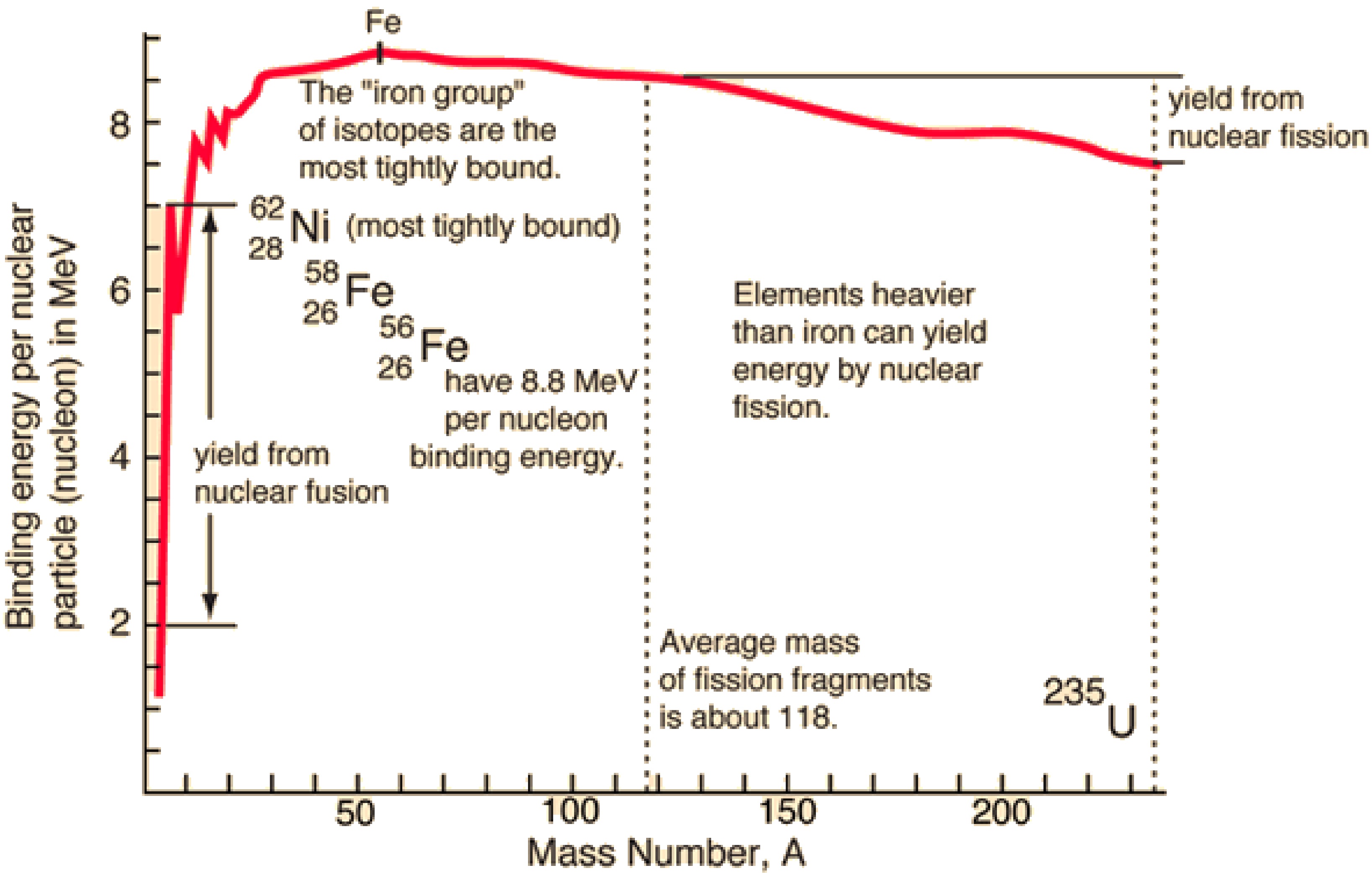
$$\frac{dr}{dM_r} = \frac{1}{4\pi r^2 \rho},$$

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

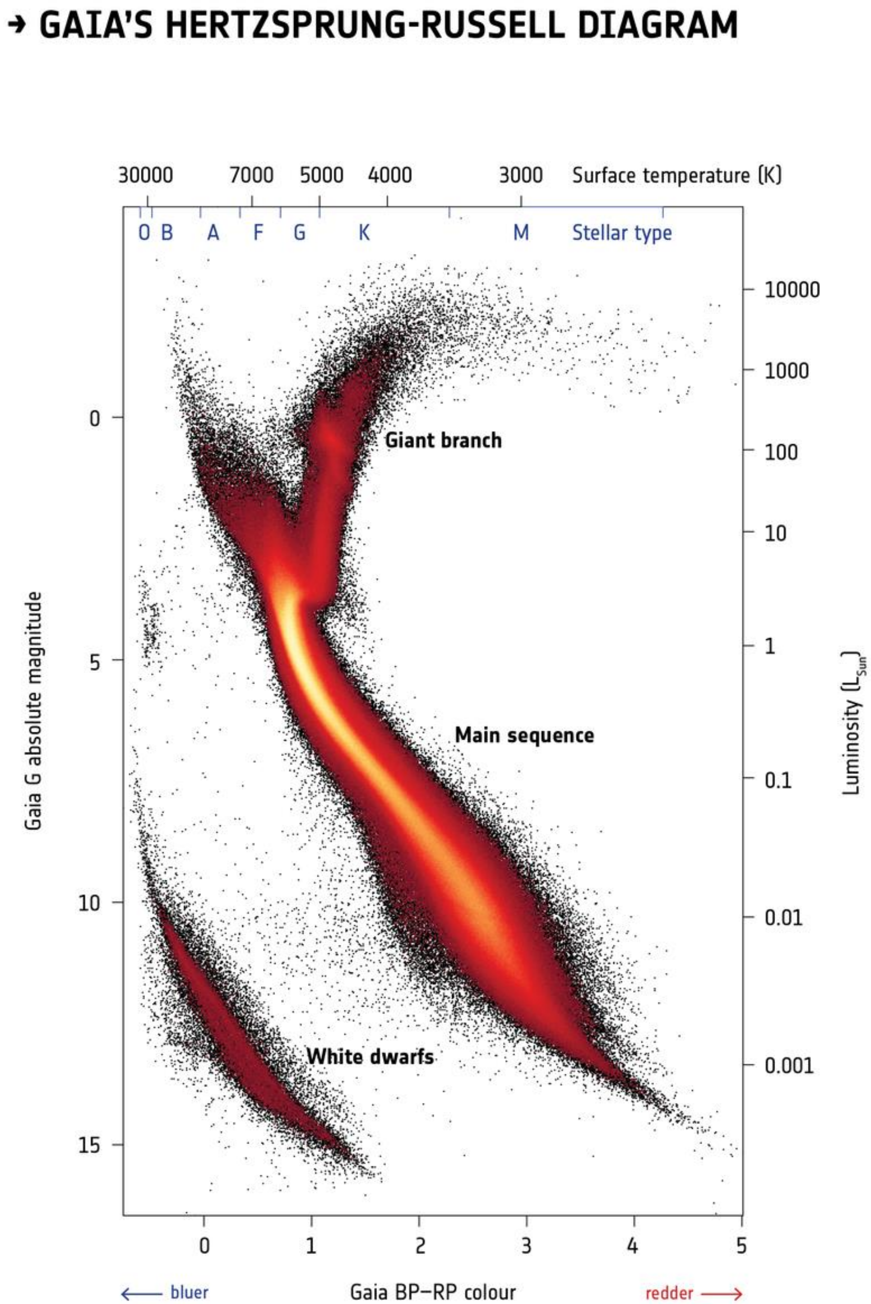
but convection!

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

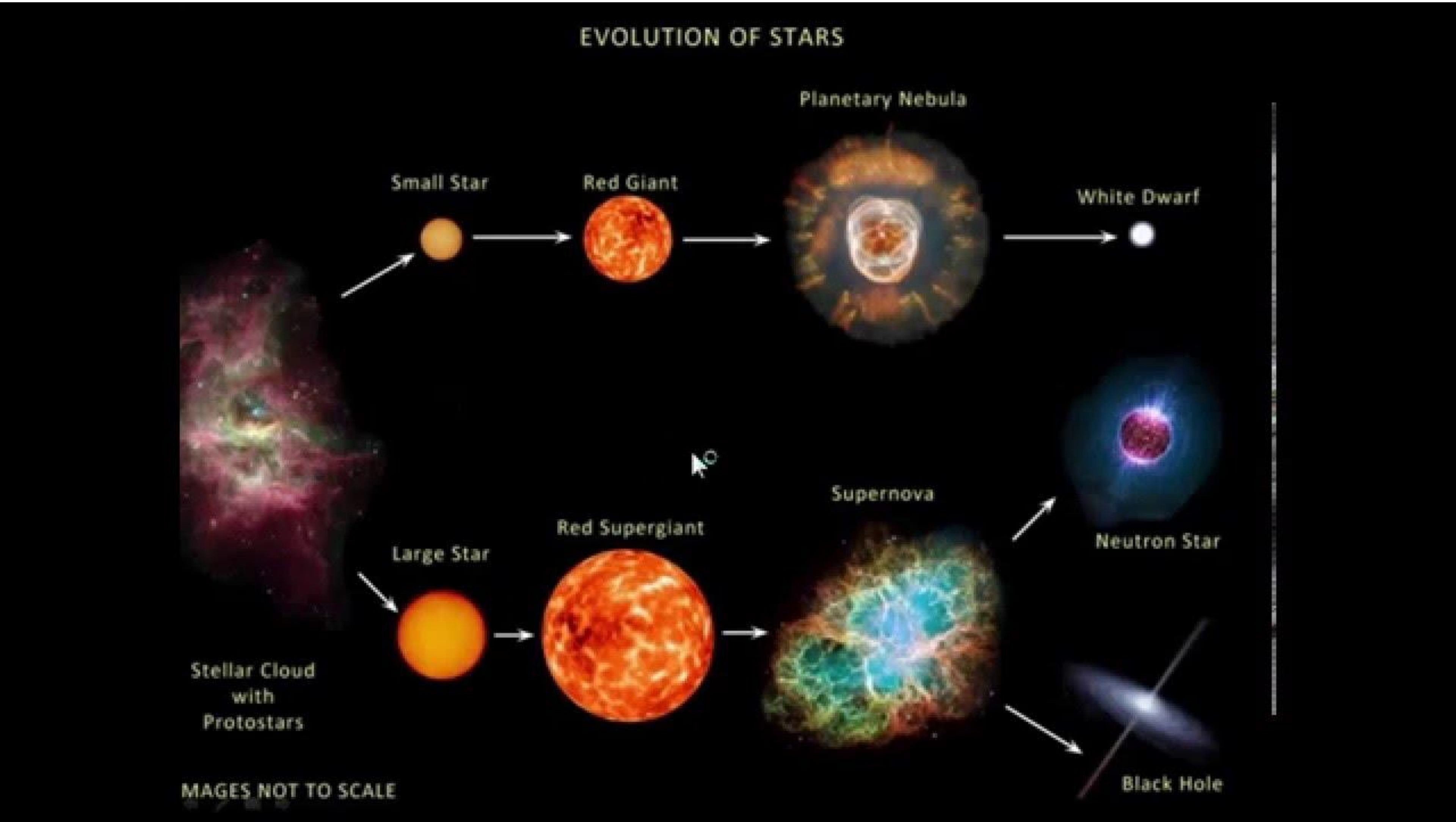
# Why do stars evolve?

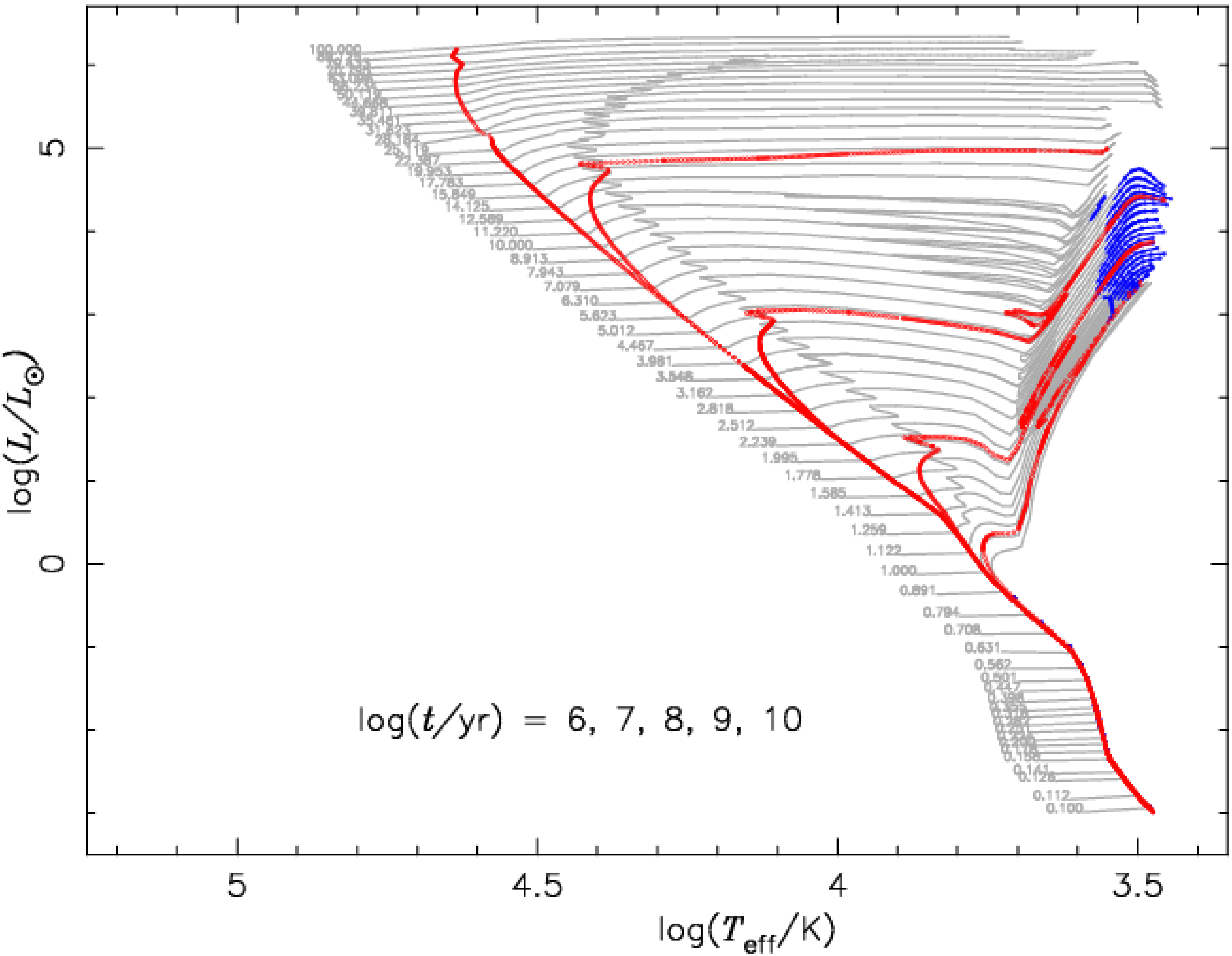


# Main parameters of stars



# Stellar evolution

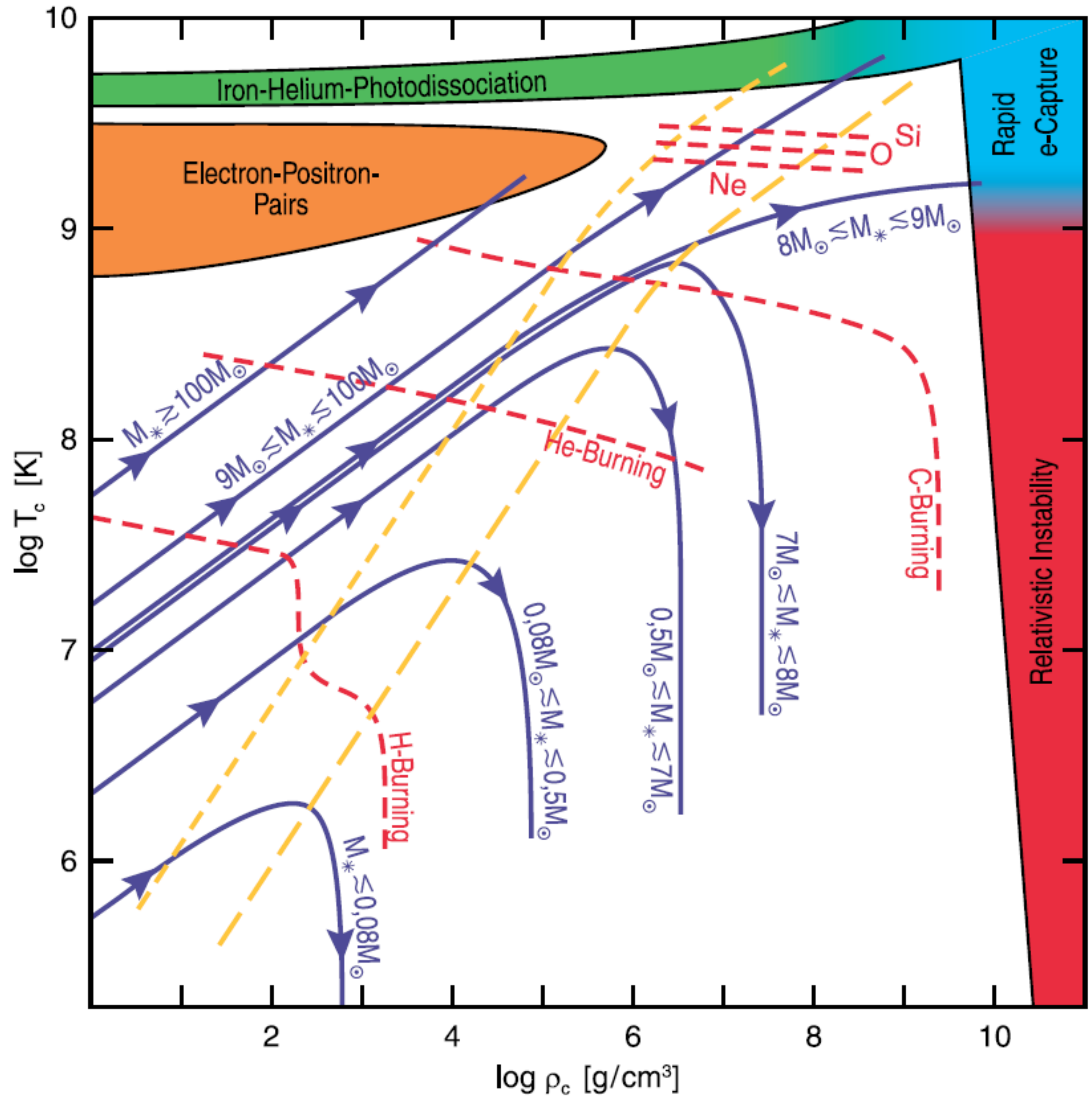




log(L/L☉)
5
0
log(T_eff/K)
5
4.5
4
3.5
log(t/yr) = 6, 7, 8, 9, 10
100.000
19.953
17.783
15.849
14.125
12.589
11.220
10.000
8.913
7.943
7.079
6.310
5.623
5.012
4.467
3.981
3.548
3.162
2.818
2.512
2.239
1.995
1.778
1.585
1.413
1.259
1.122
1.000
0.891
0.794
0.708
0.631
0.562
0.501
0.447
0.112
0.100

# Single star evolution before core-collapse

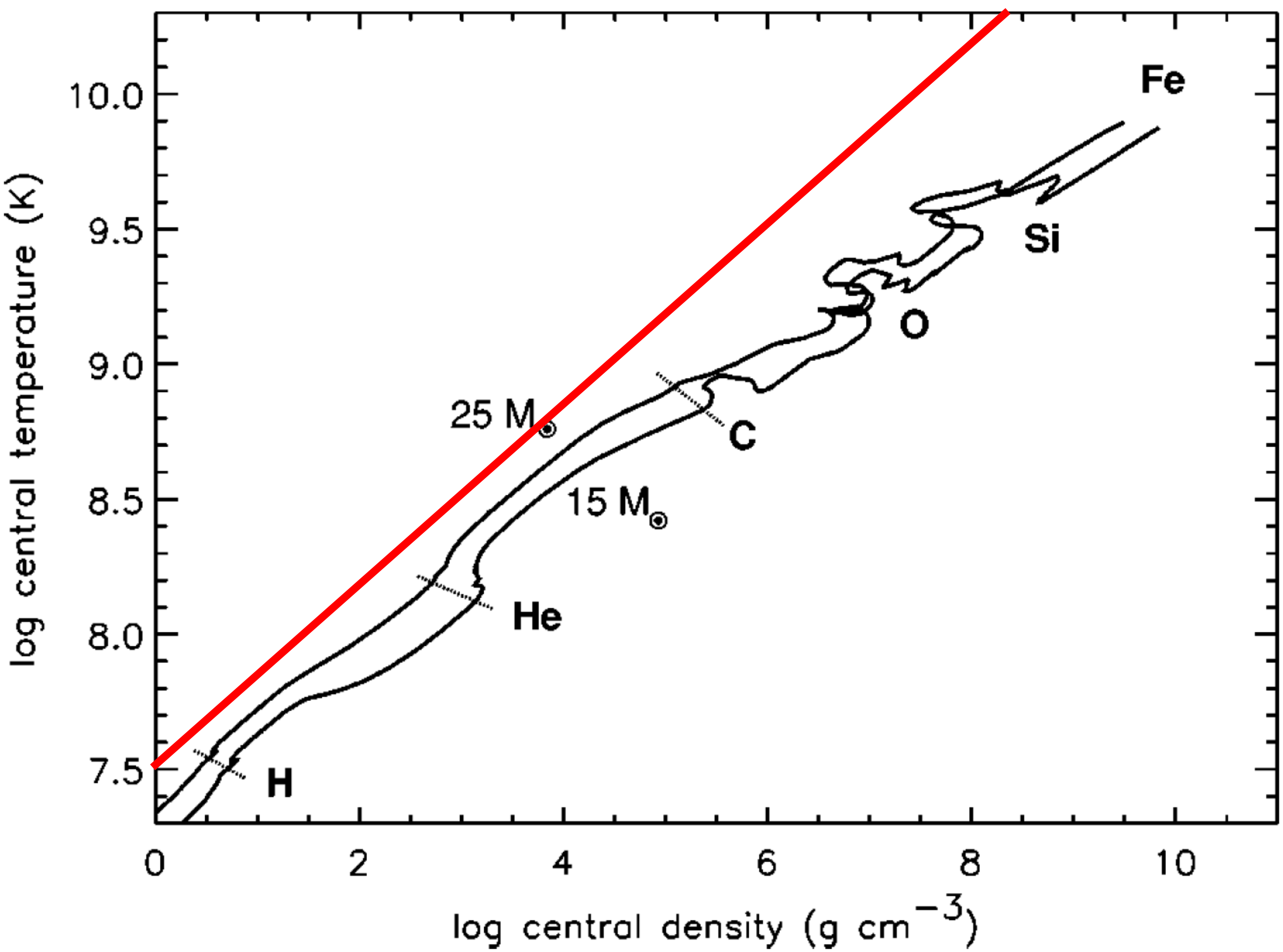
Central temperature and pressure



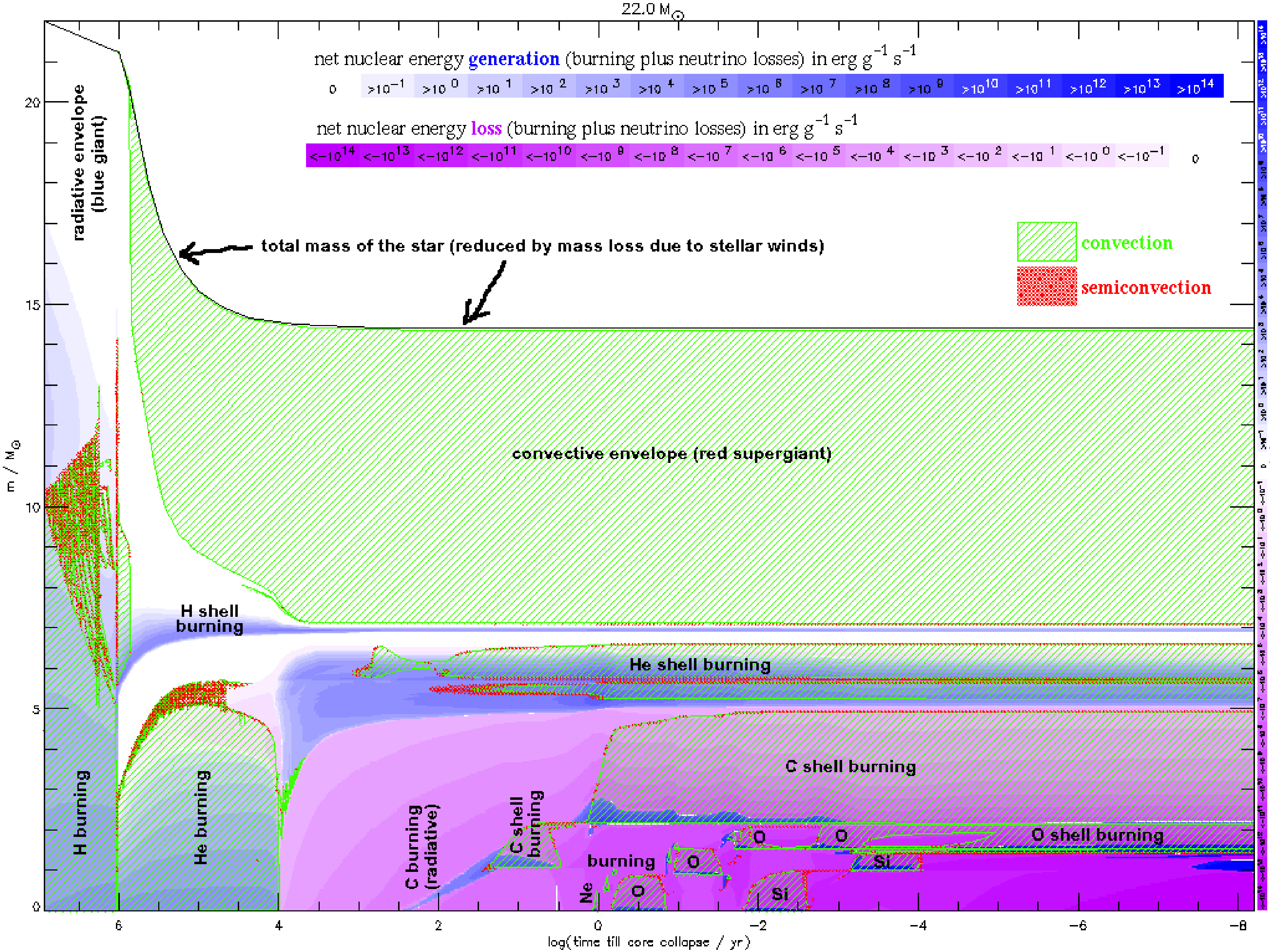

Janka (2012)

# Single star evolution before core-collapse

Central temperature and pressure




Woosley et al. (2002)




A. Heger website 2sn.org

# Physical processes inside massive star

- Neutrino losses
  - Mostly due to thermal processes (T^9), later due to neutronization (T^6)
  - Accelerates evolution (~day timescale for silicon)
- Convection
  - Mixing length theory, but convective and nuclear timescales comparable
  - Mixing as a diffusive process
- Semi-convection
  - Schwarzschild – instability only due to temperature/pressure gradients
  - Ledoux – also takes into account chemical composition
  - Unstable by Schwarzschild & stable by Ledoux = semi-convection
  - Diffusion coefficient uncertain
- Overshoot mixing
  - Modeled by diffusion
- Rotation & magnetic fields
  - Coupling of core to envelope – affected by mass loss
- Mass loss